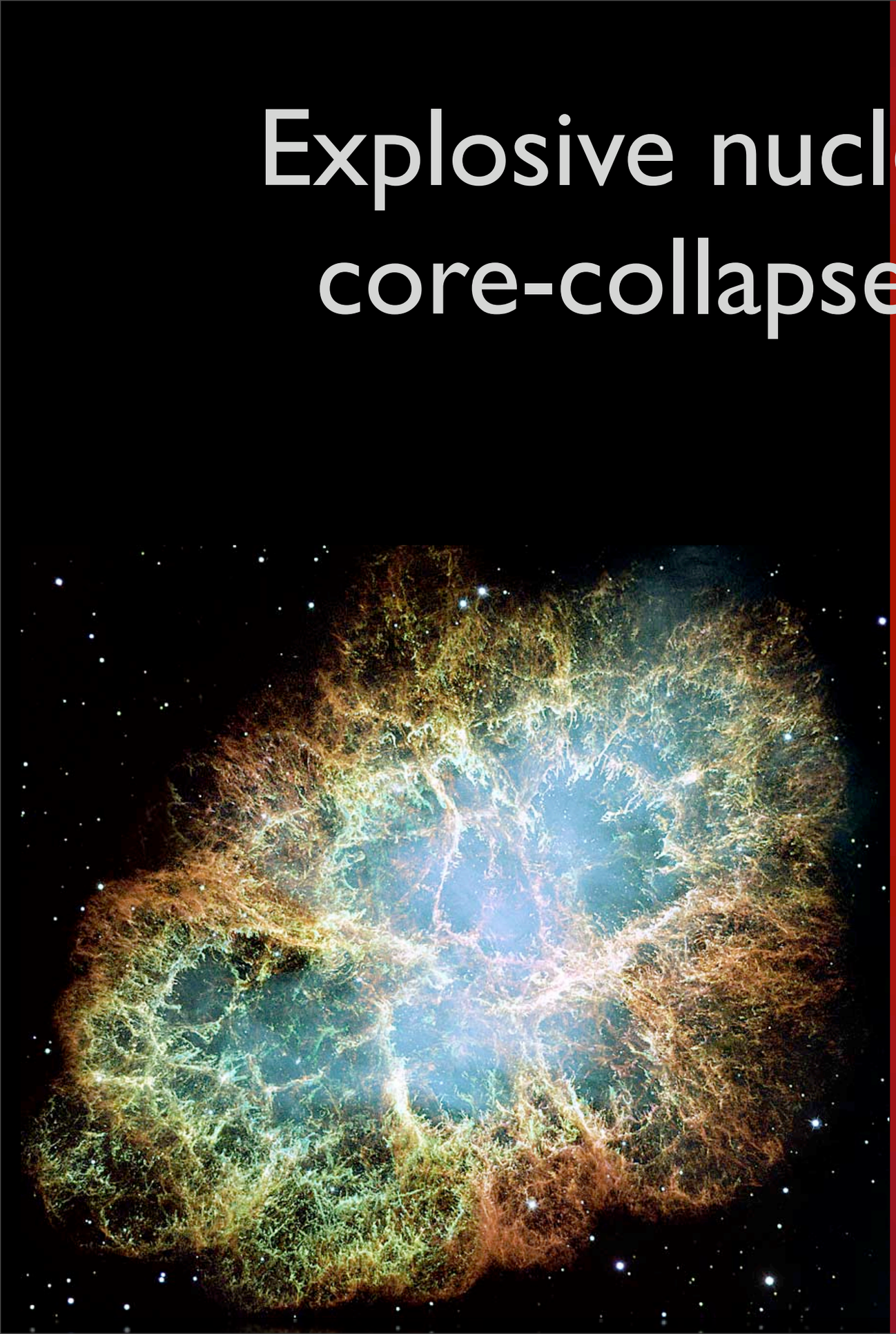
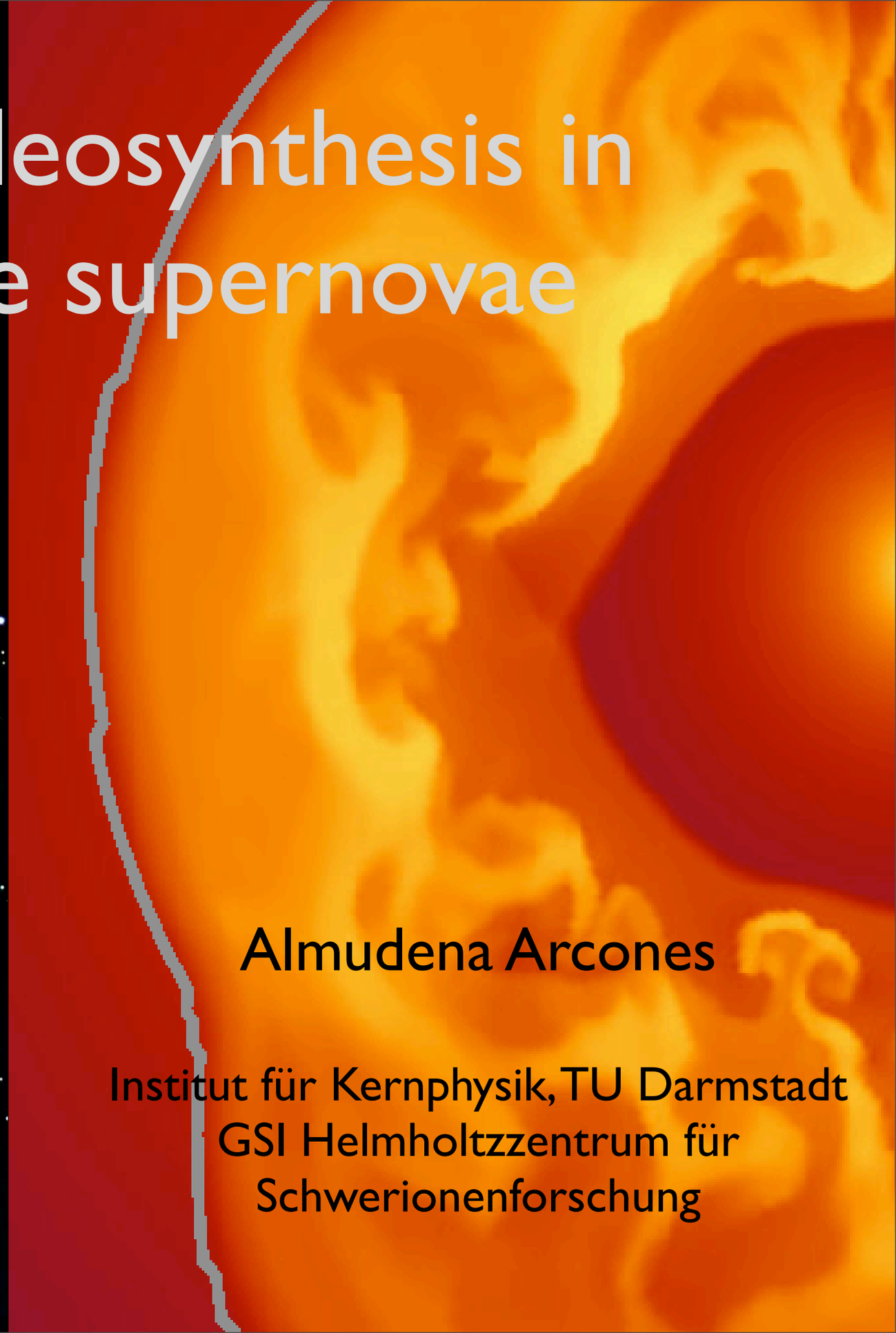
# Explosive nucleosynthesis in core-collapse supernovae





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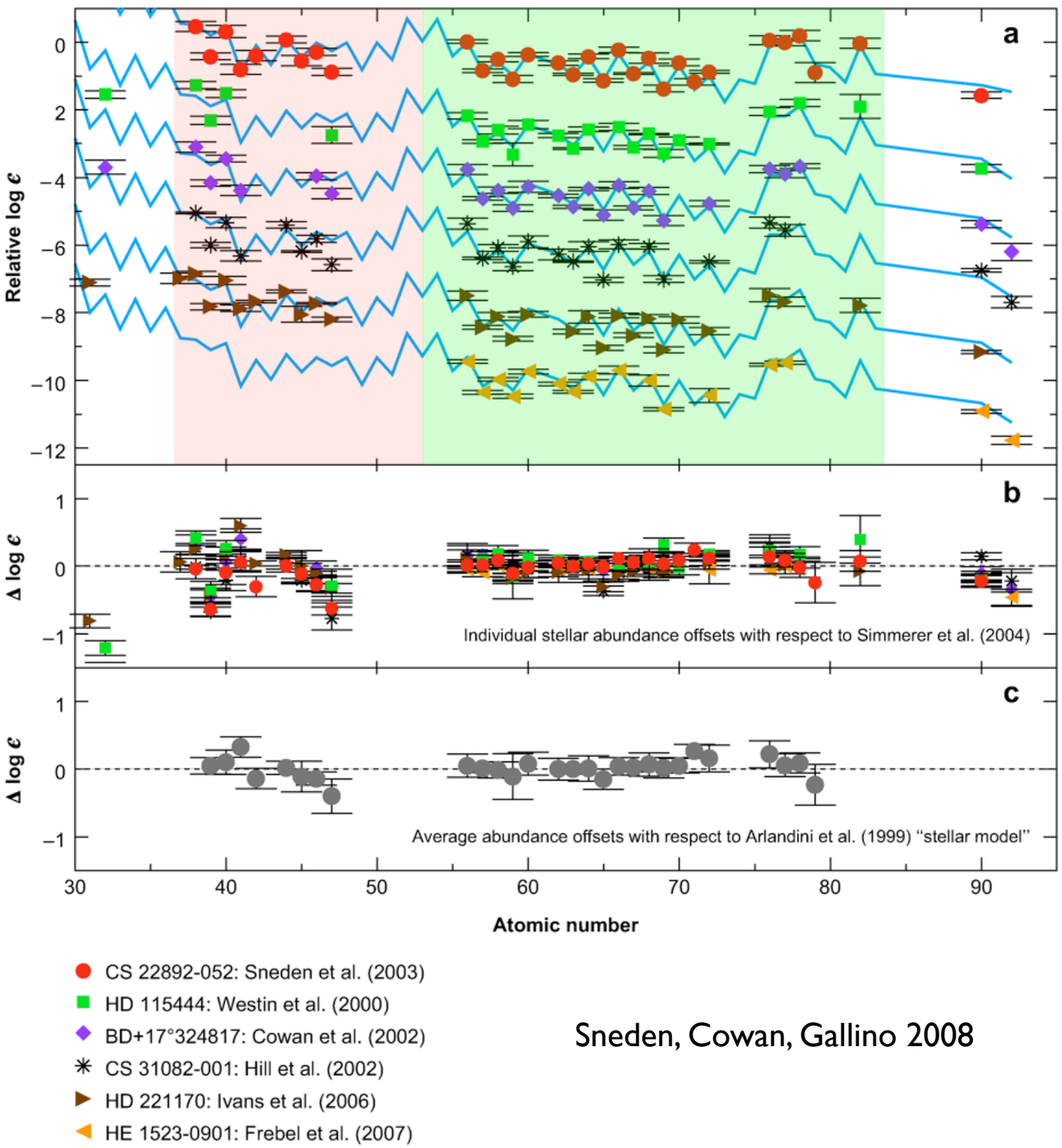
# Outline

- Introduction and motivation
  - observations
  - core-collapse supernovae
  - 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
- Conclusions

# Observations




Sneden, Cowan, Gallino 2008

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

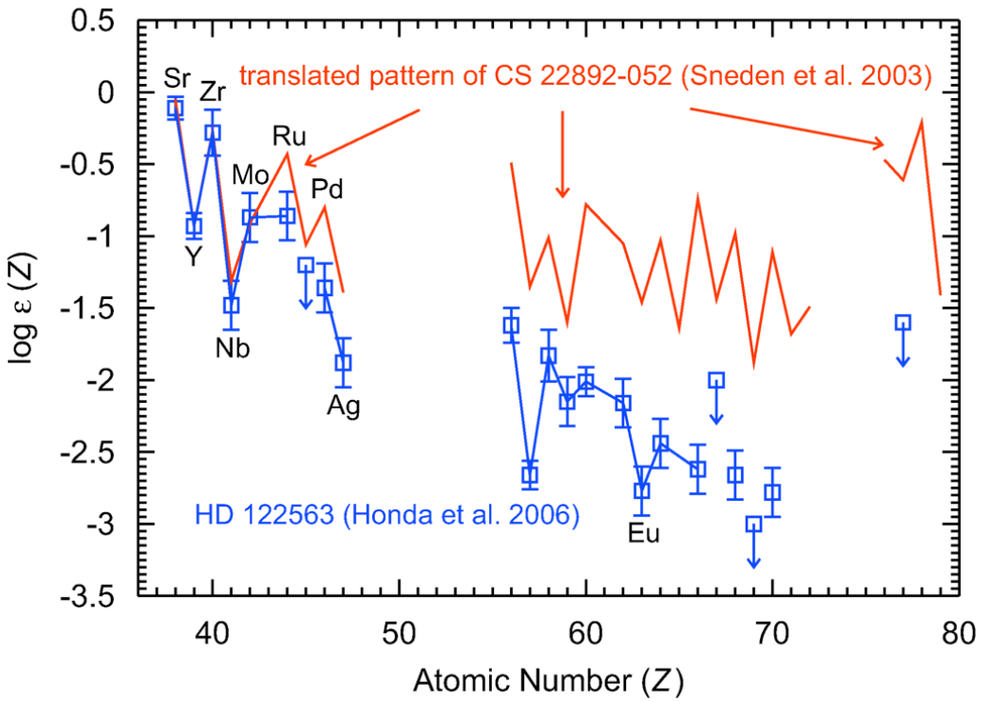
Only few nucleosynthesis events have contributed to the abundances present in old stars.

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 Galactic chemical evolution 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)
Montes et al. 2007: LEPP creates a uniform and unique pattern

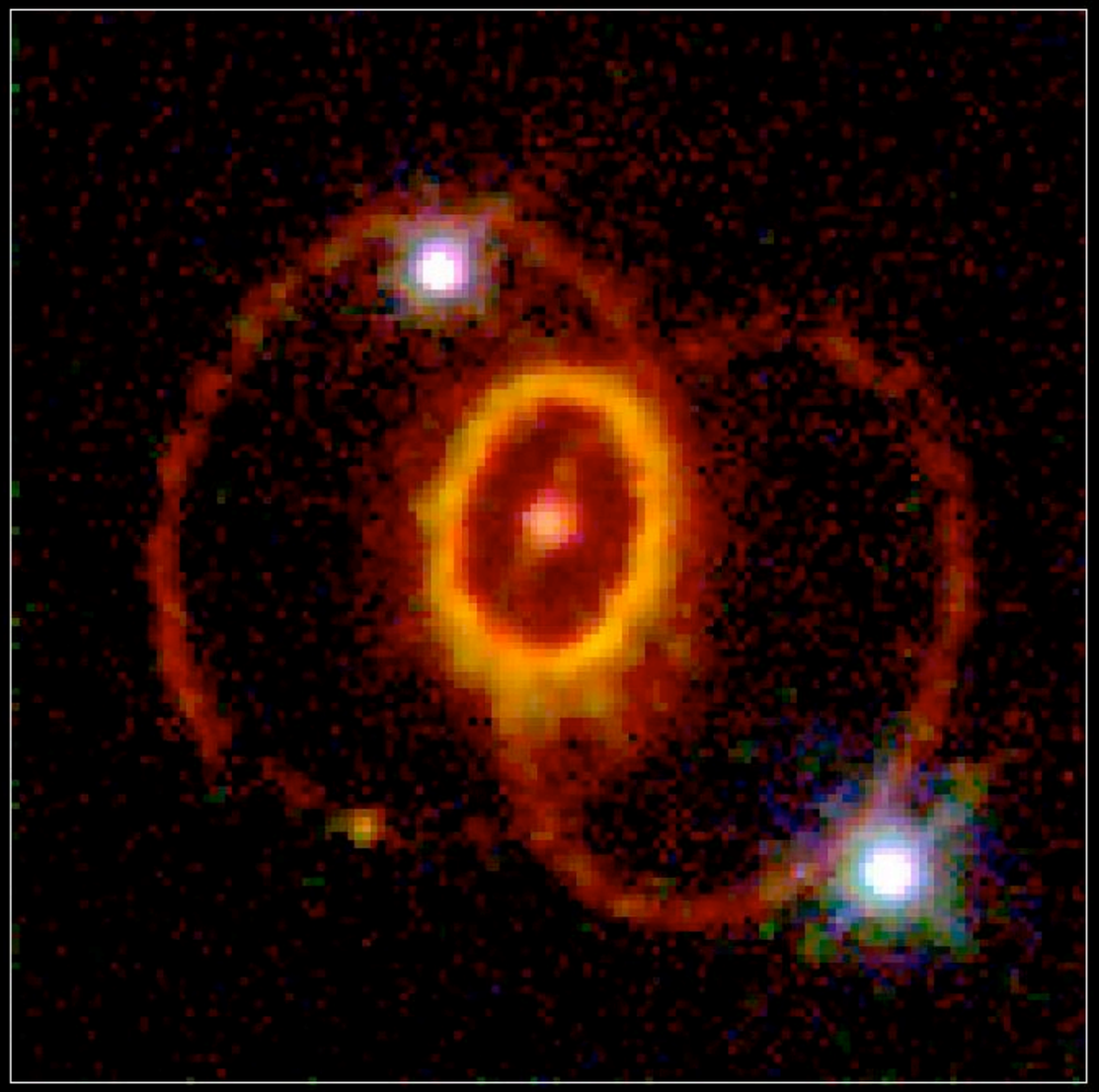
Can this be confirmed by state-of-the-art neutrino-driven wind simulations?
Do they produce the LEPP pattern?

# Core-collapse supernova

The Crab Nebula from Hubble

NASA, ESA, J. Hester, A. Loll (ASU

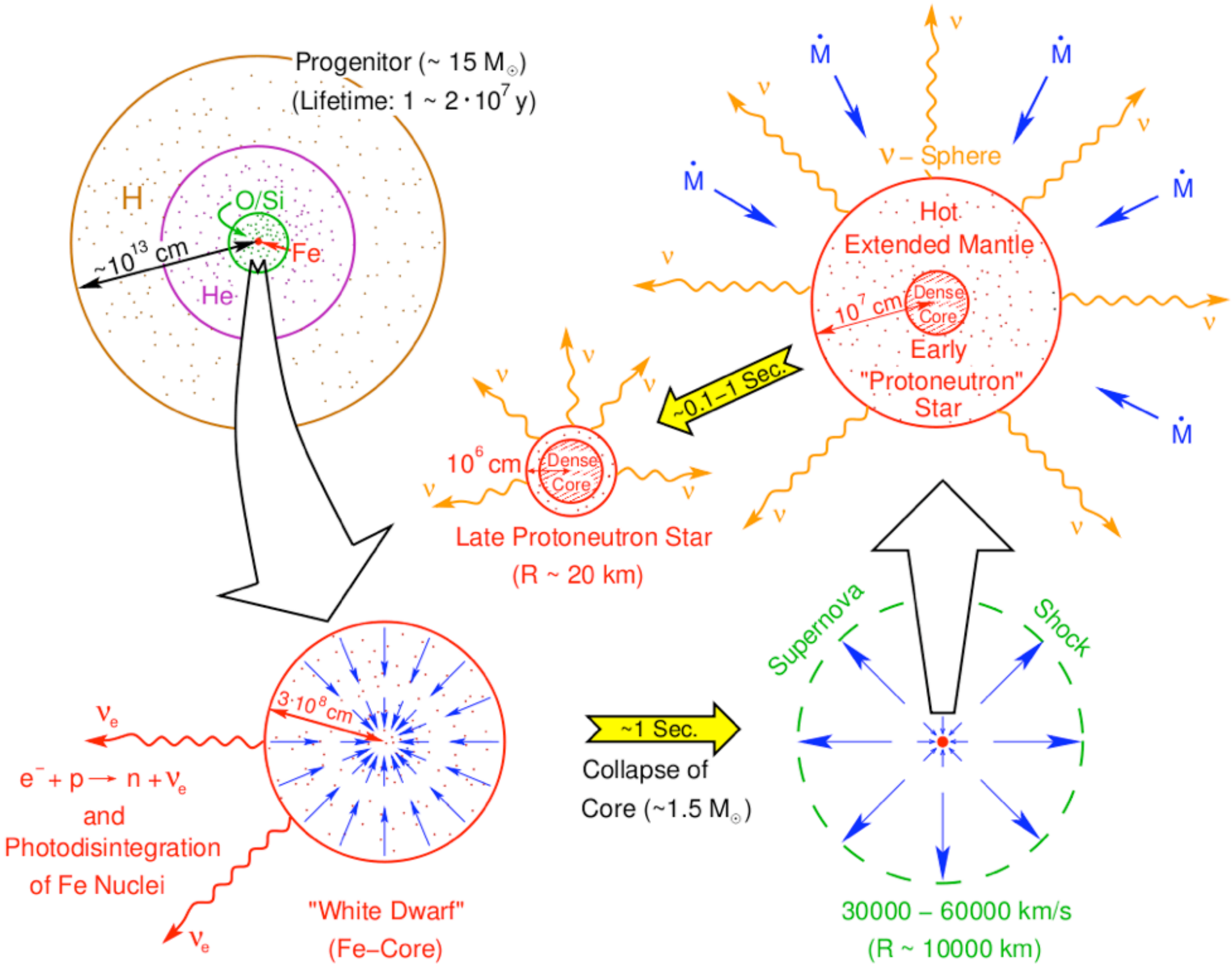
Supernova 1987A Rings



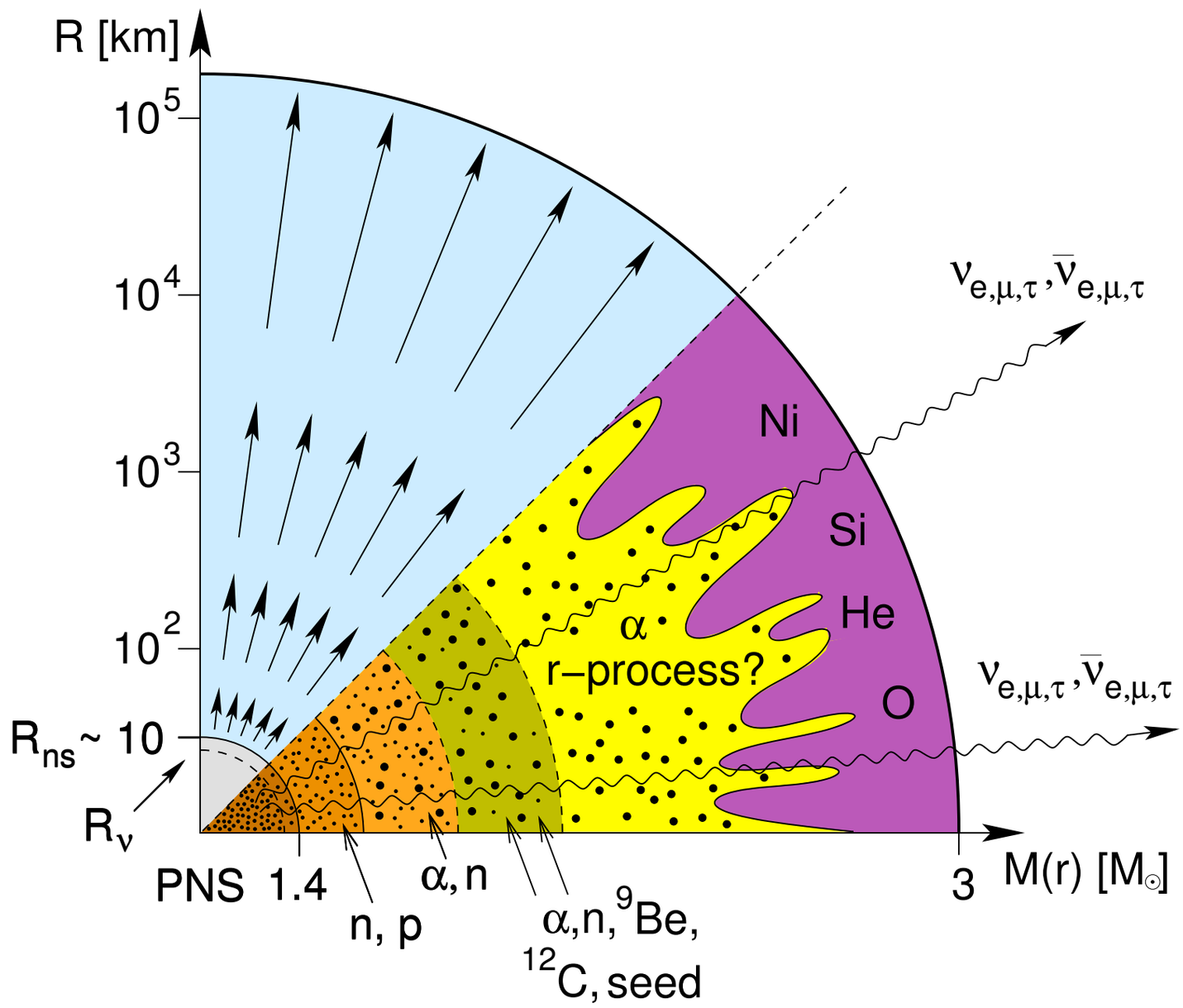
Hubble Space Telescope
Wide Field Planetary Camera 2

SPACE TELESCOPE SCIENCE INSTITUTE

# Core-collapse supernova mechanism



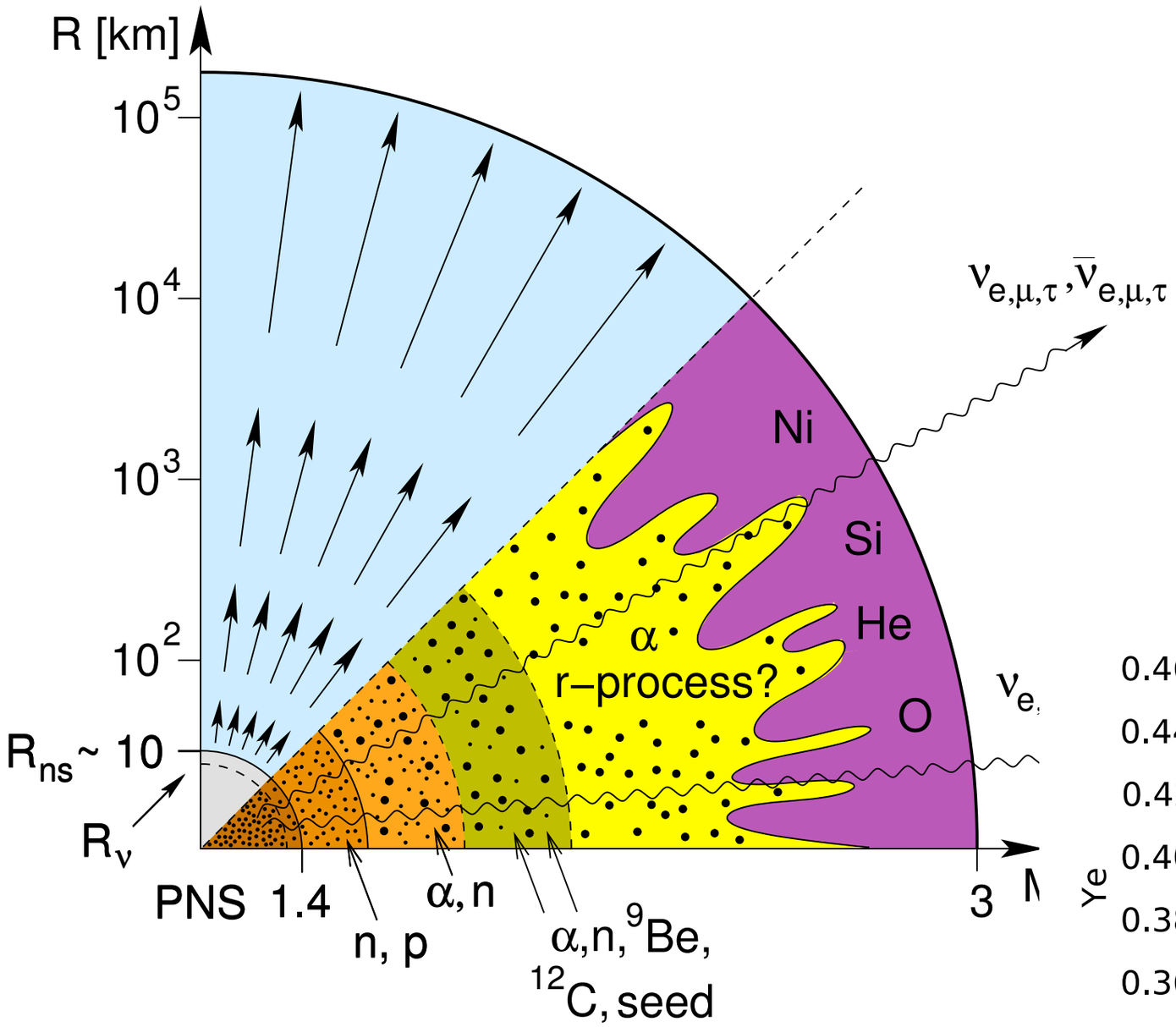
# Neutrino-driven winds




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

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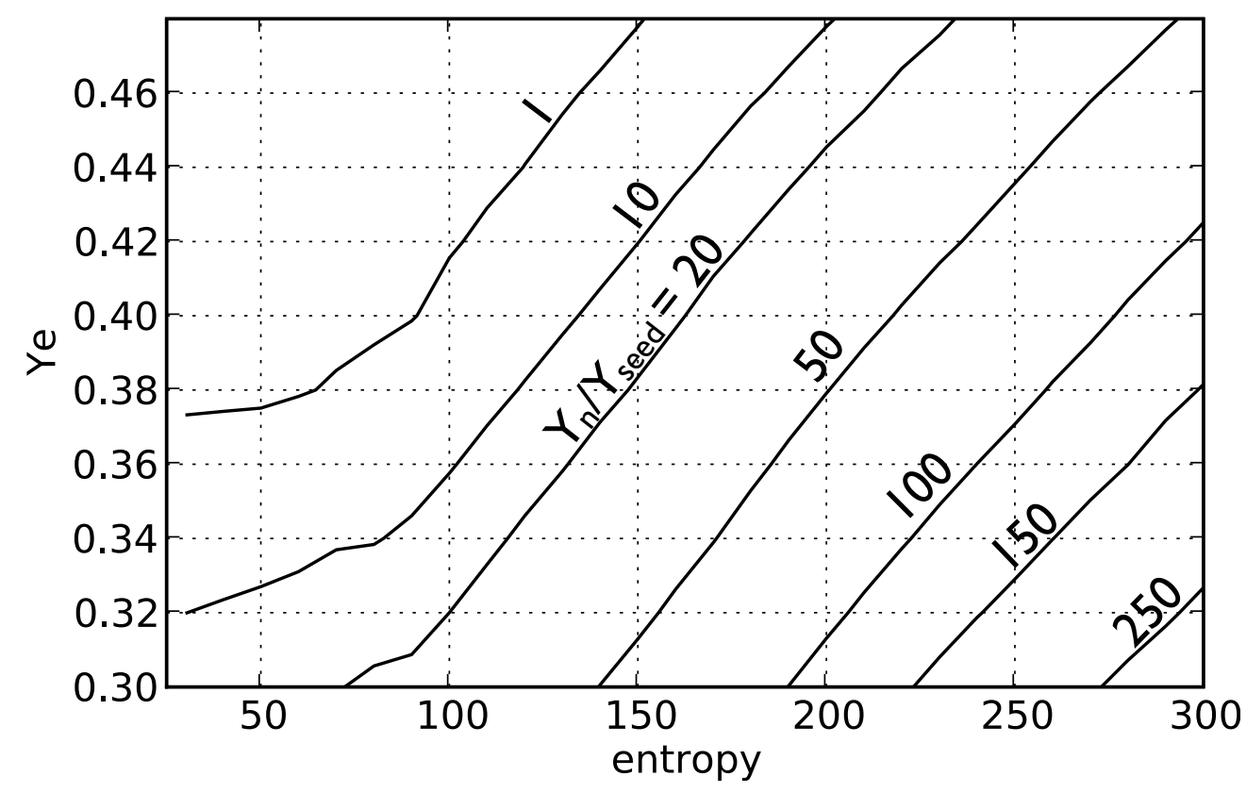

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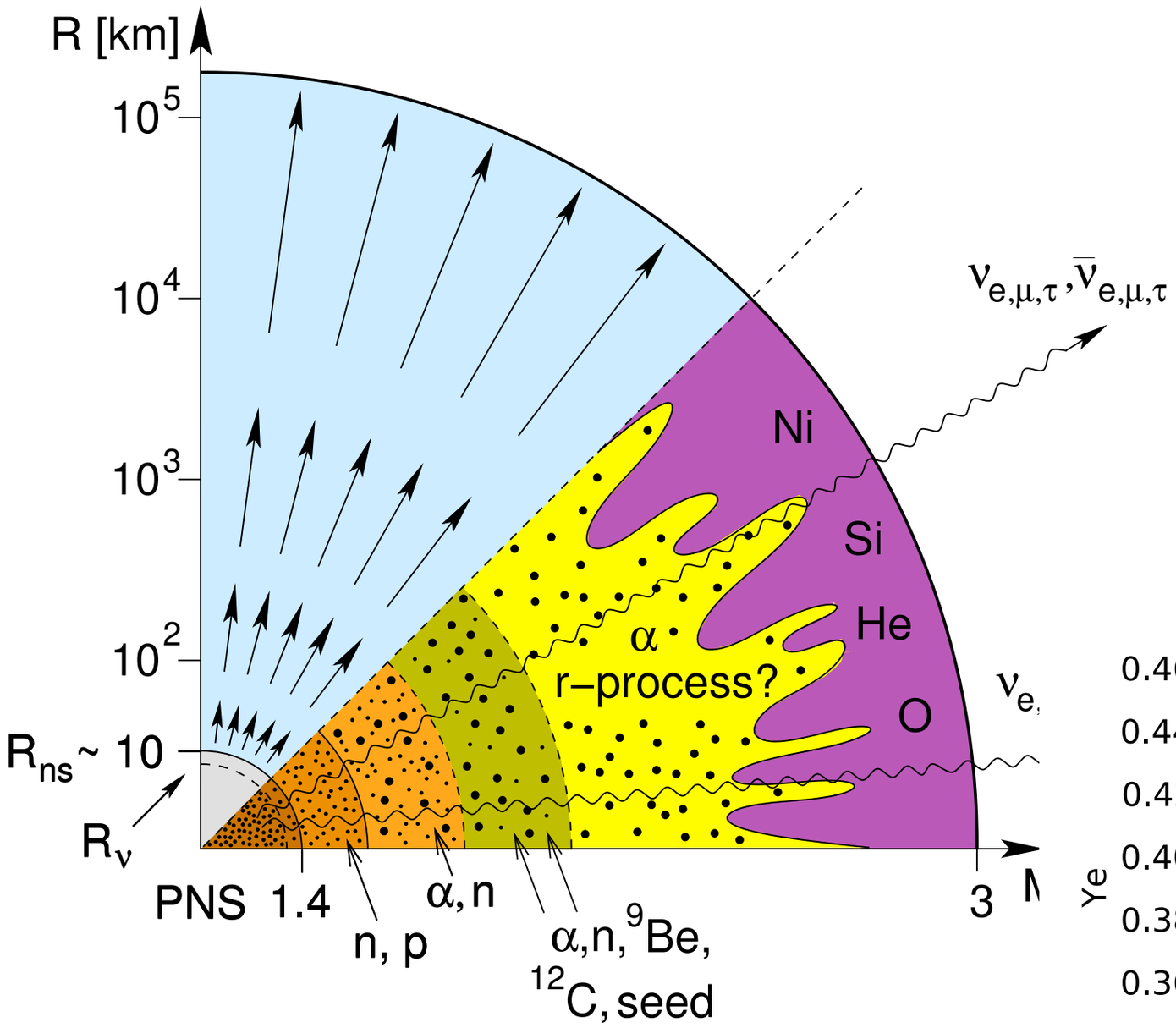


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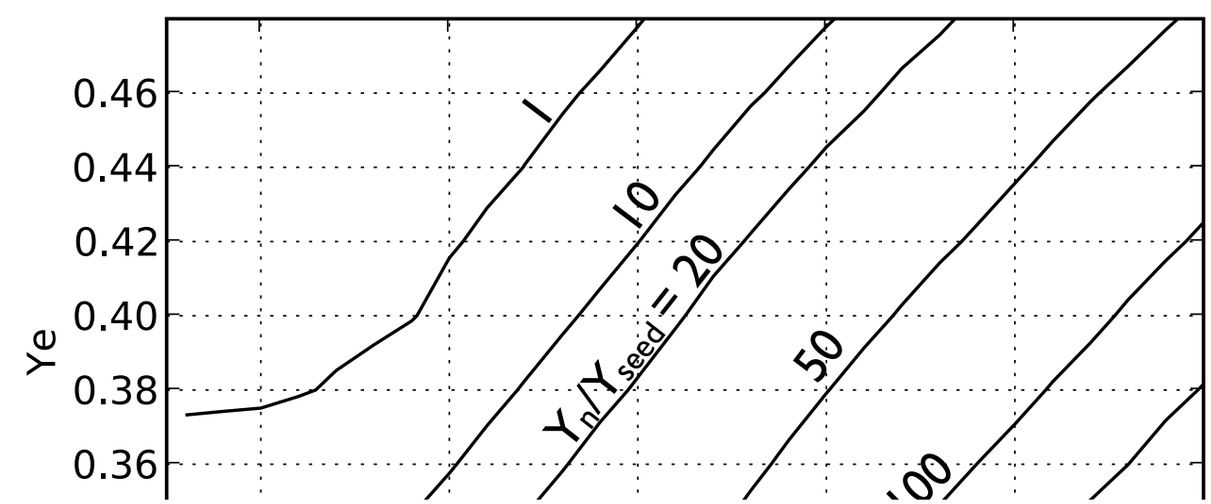
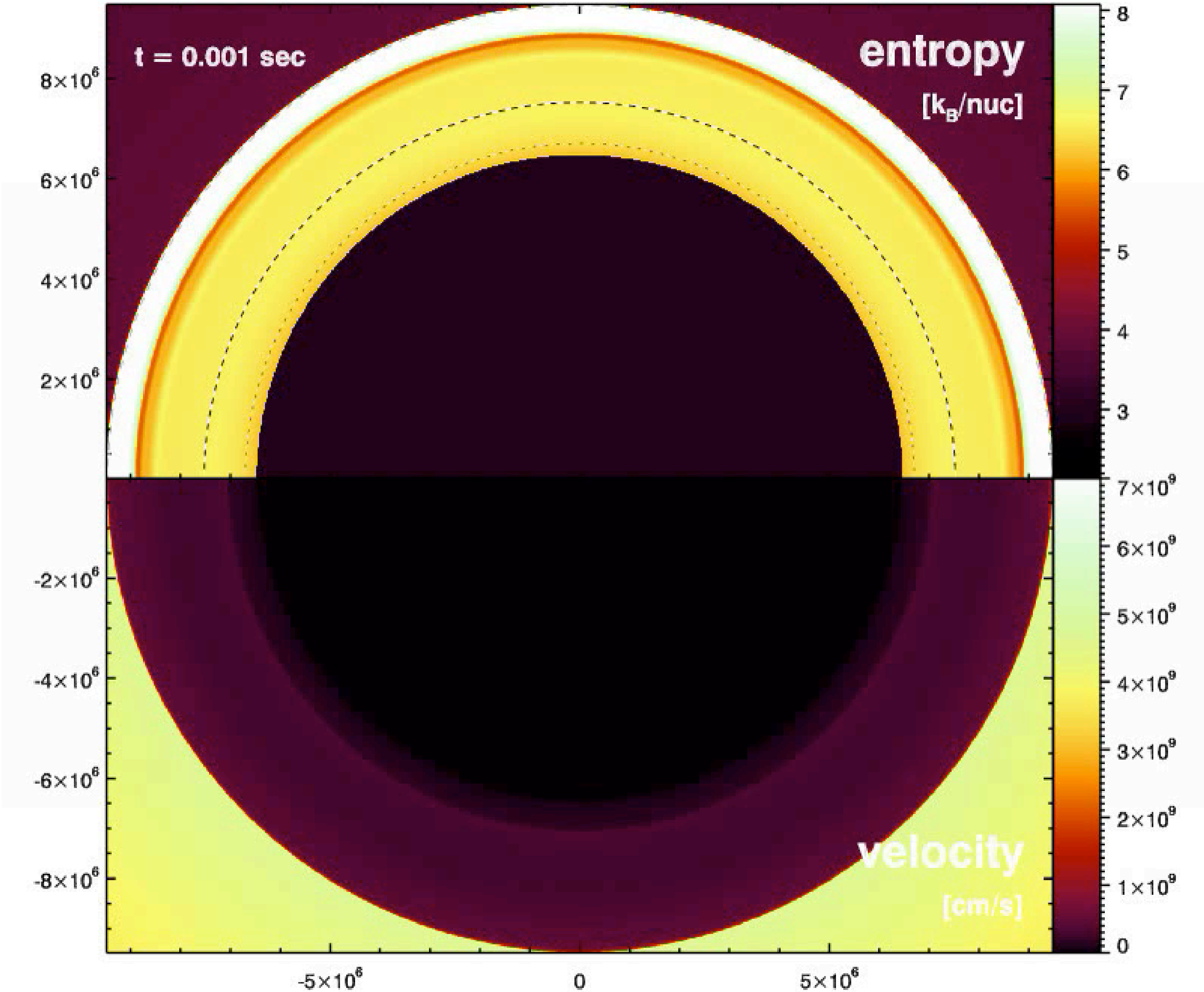



Are these conditions reached in state-of-the-art neutrino-driven wind simulations?
Do they produce the heavy r-process nuclei?

Arcones & Janka



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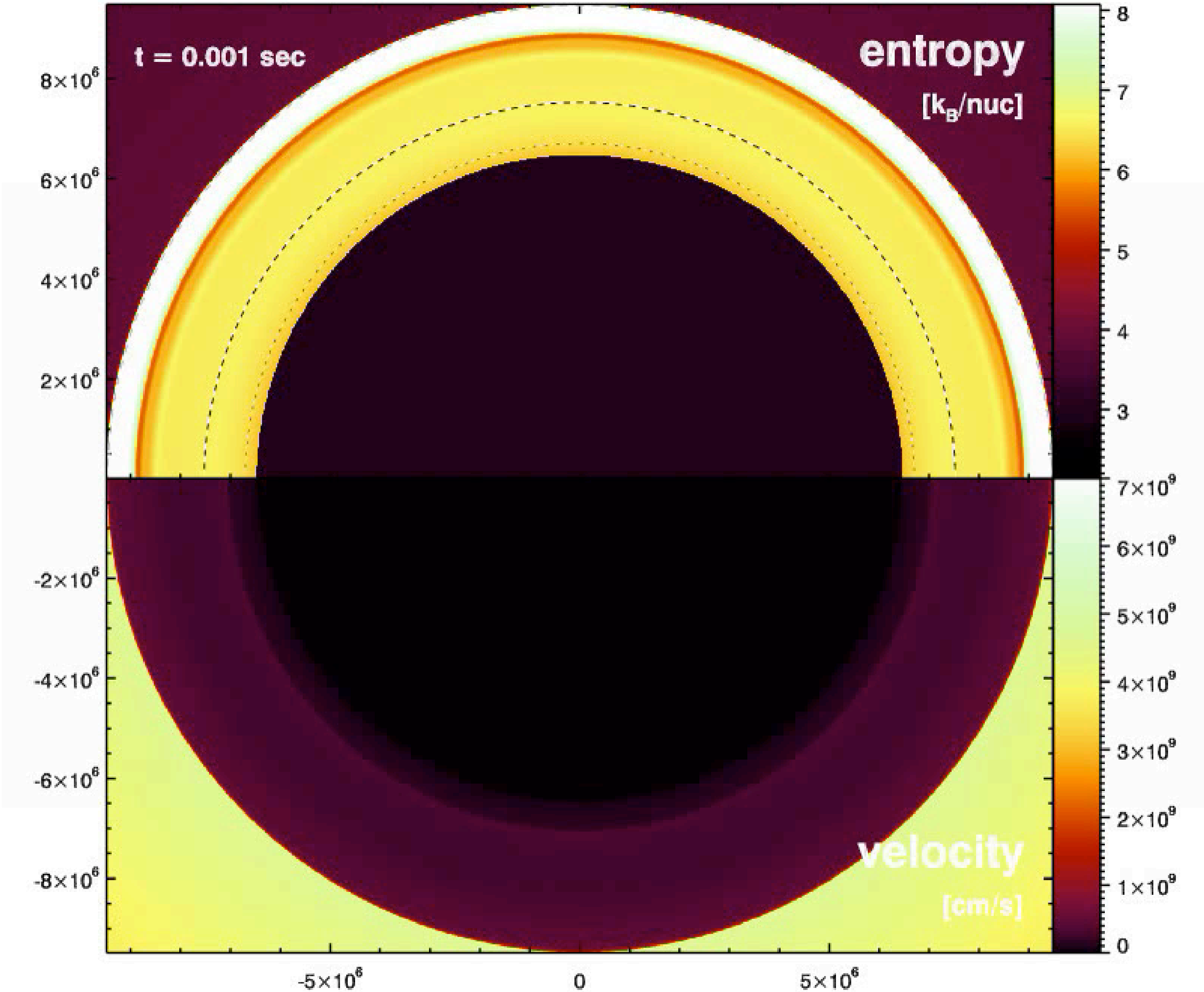


# Neutrino-driven wind simulations and nucleosynthesis networks

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

Problems: - only weak explosions for low-mass progenitor stars (Janka et al. 2007)
- simulations are computationally very expensive to follow the wind phase

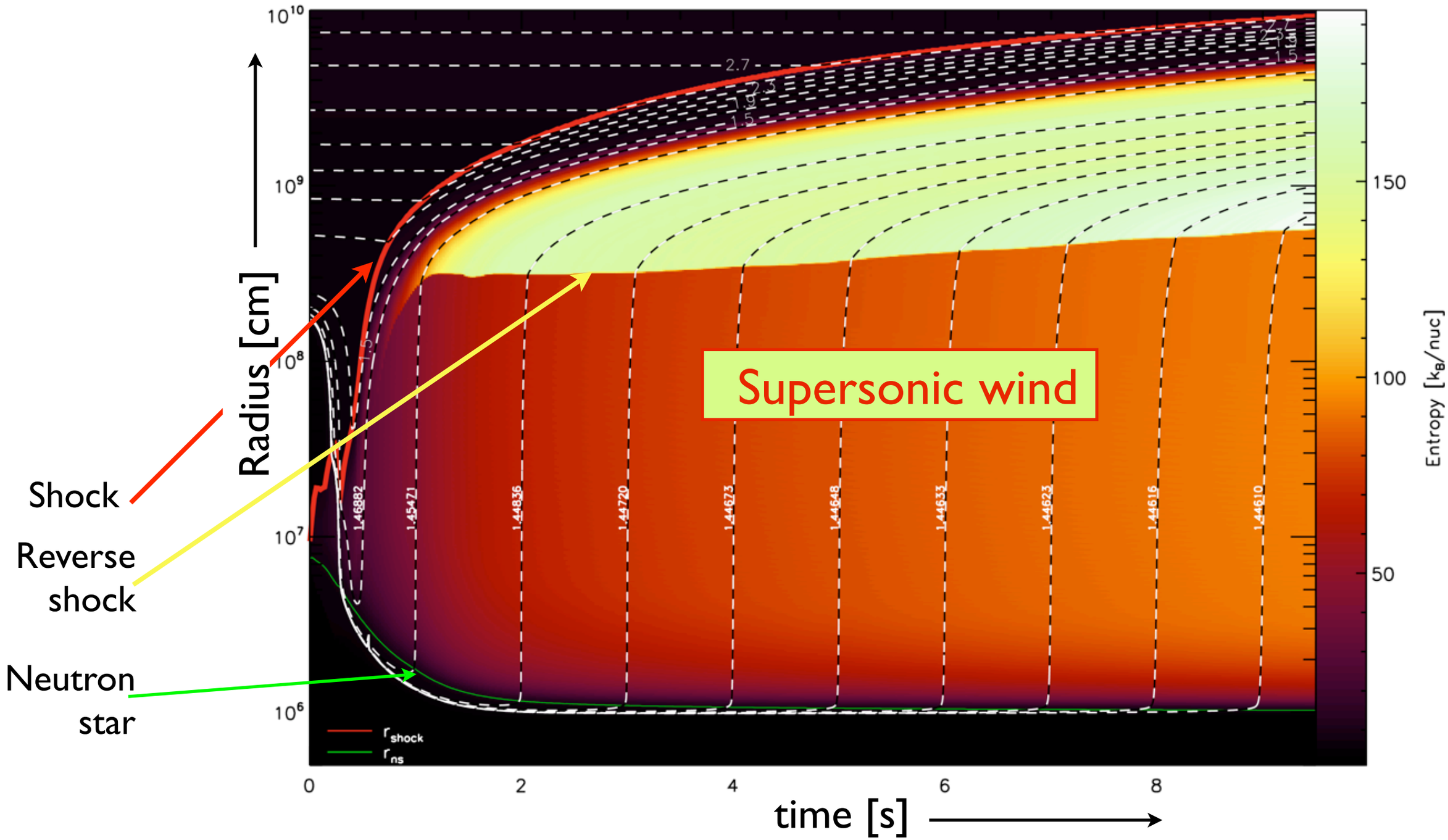
Solutions: - steady-state wind models (Otsuki et al 2000, Thompson el al 2001)
- one-dimensional simulations with an artificial explosion (Arcones et al. 2007 (also 2d), Fischer et al. 2009)

Nucleosynthesis network including over 5000 nuclei from stability to drip lines

- Network input: trajectories ($\rho$,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. 19, 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 results

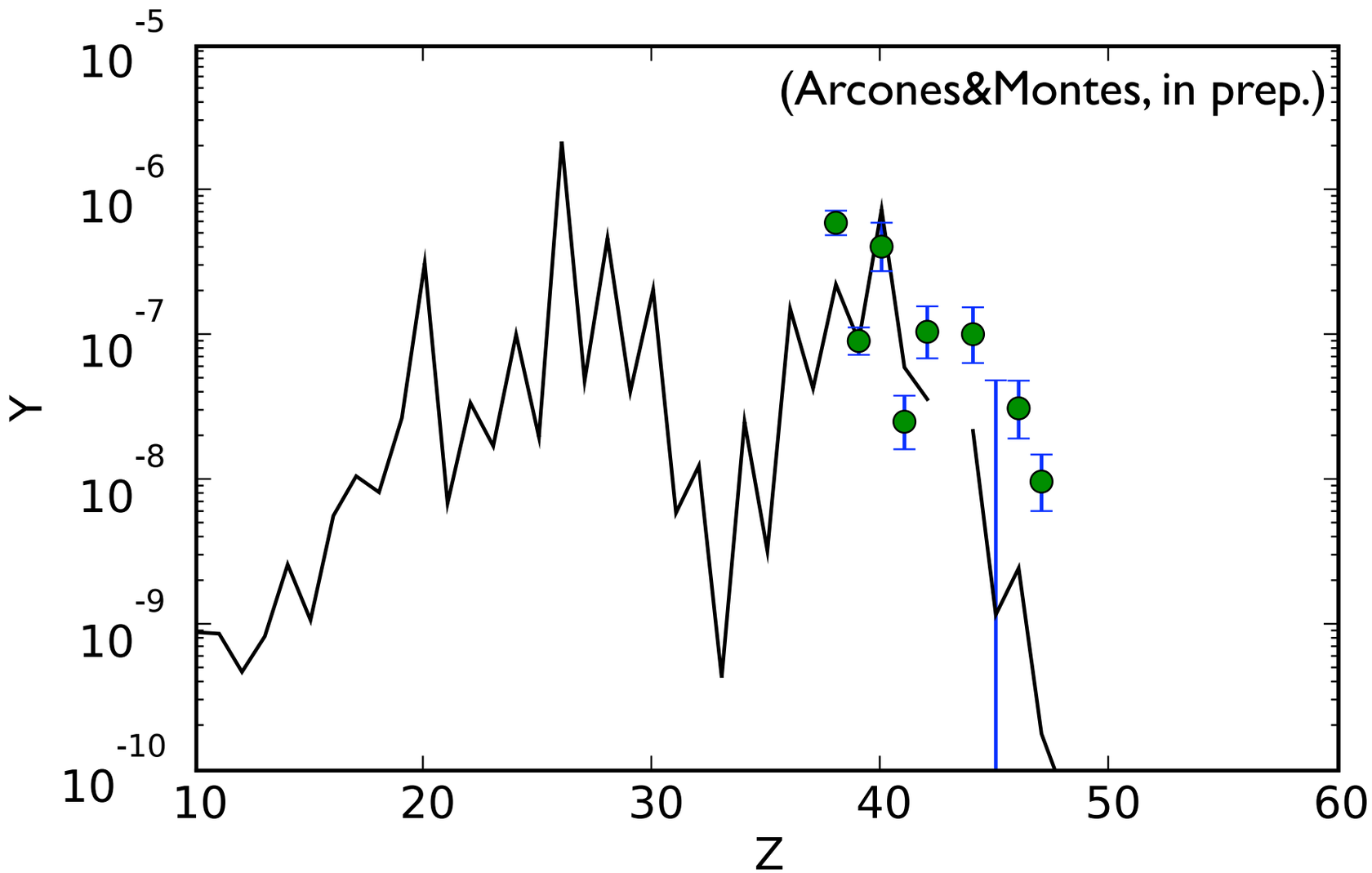
Arcones et al 2007



# 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.



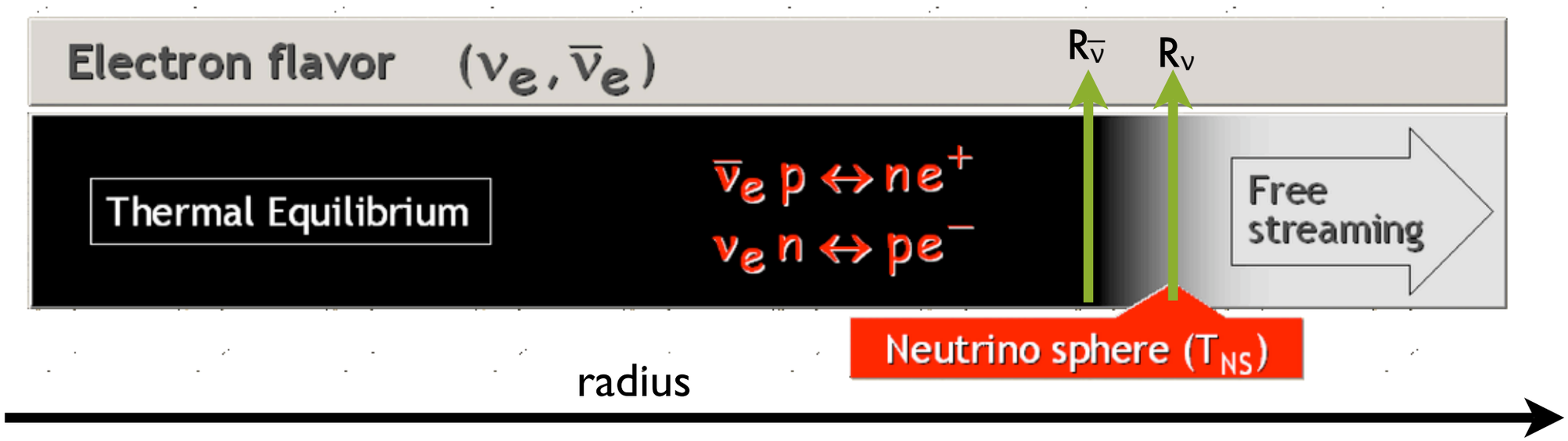
# Electron fraction and uncertainties

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).

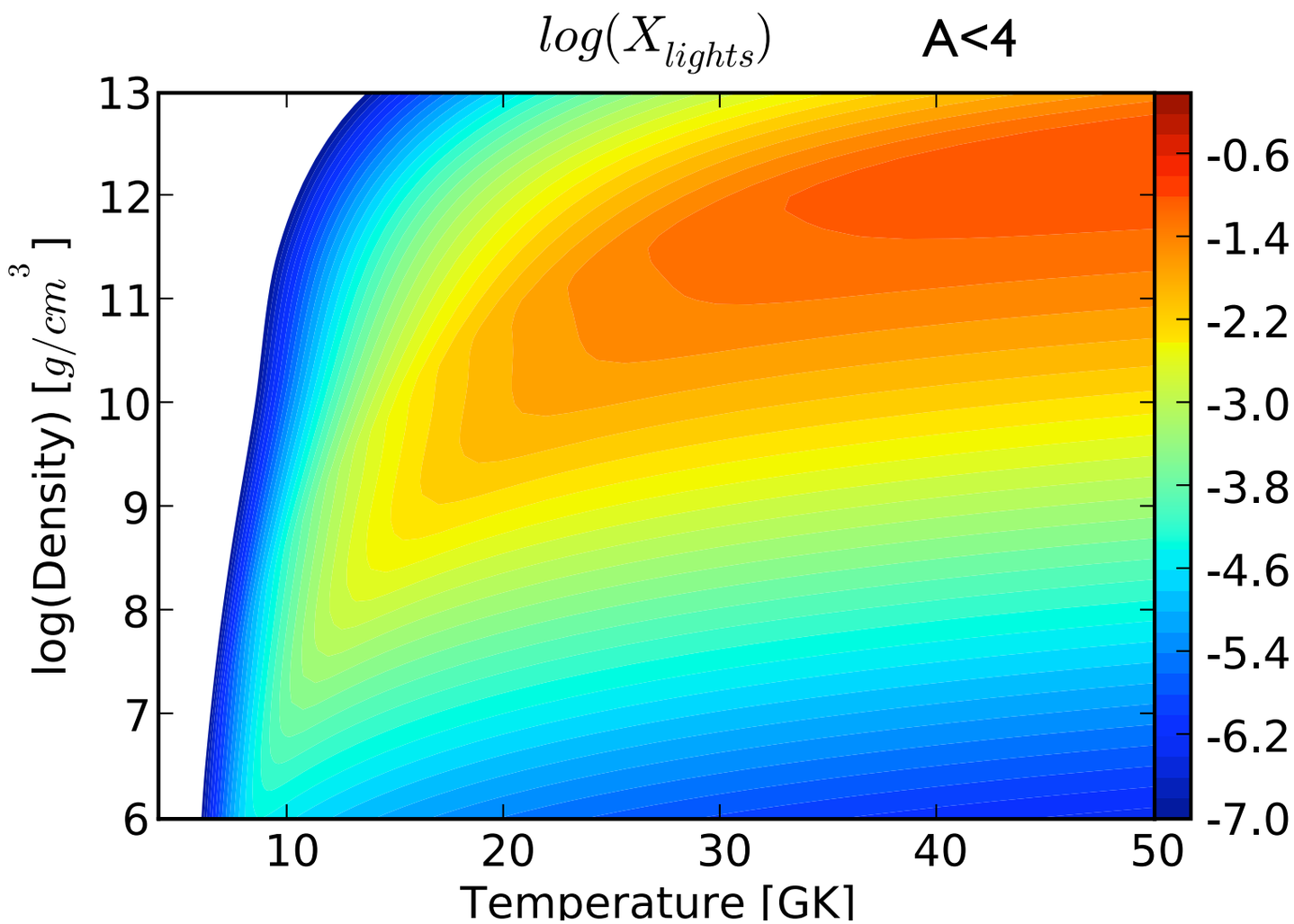
# Electron fraction and uncertainties

Entropy ar action
depends o utrino
interactior

$Y_e =$ $_p$)

The neutri utrinos
decouple f

Under general assumptions (NSE+beta equilibrium)




Arcones,Martinez-Pinedo&Woosley (to be submitted)

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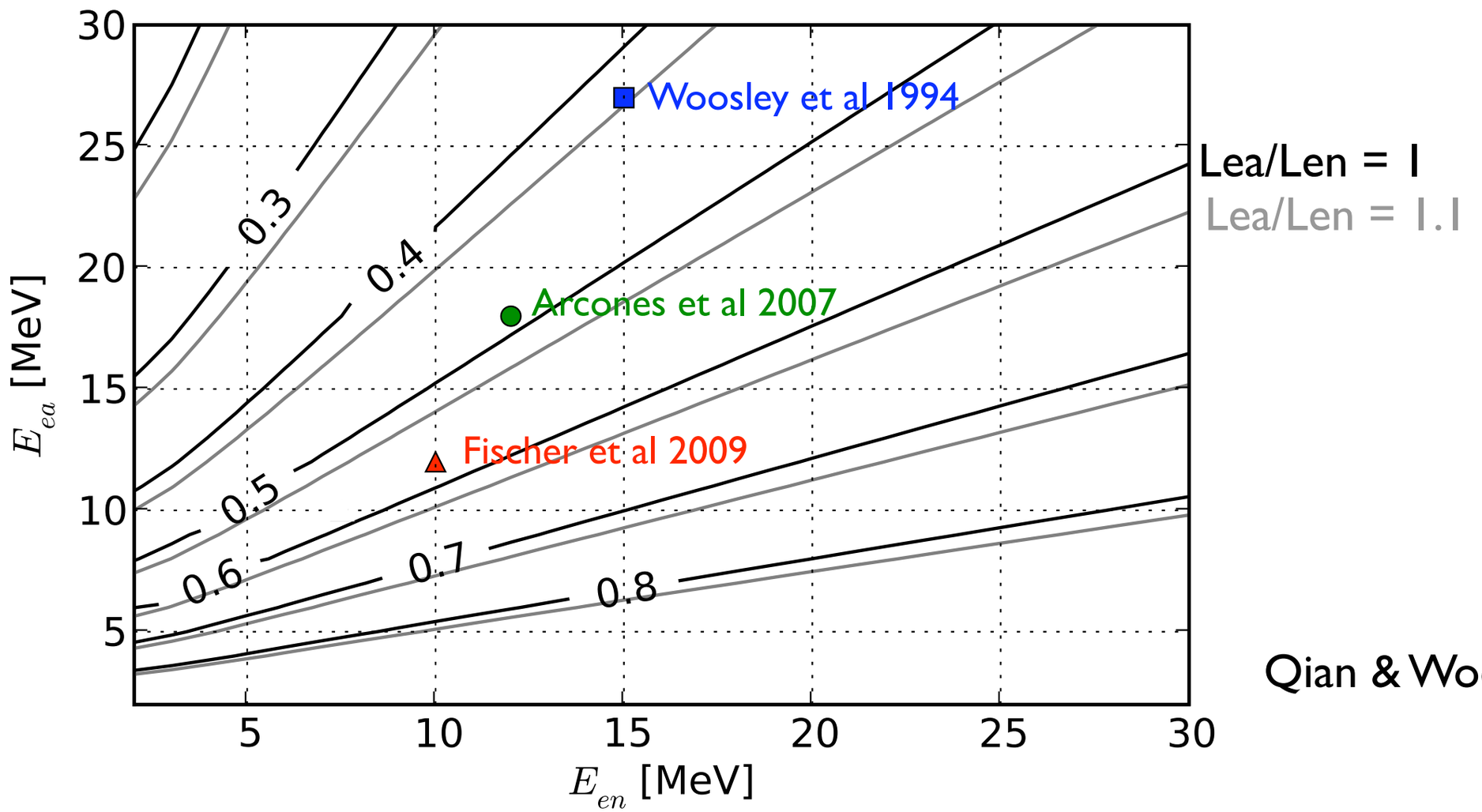
# Wind models and electron fraction

Neutrino energies change with more realistic neutrino physics input
More recent simulations obtain lower neutrino energies and therefore proton-rich conditions




Qian & Woosley 1996

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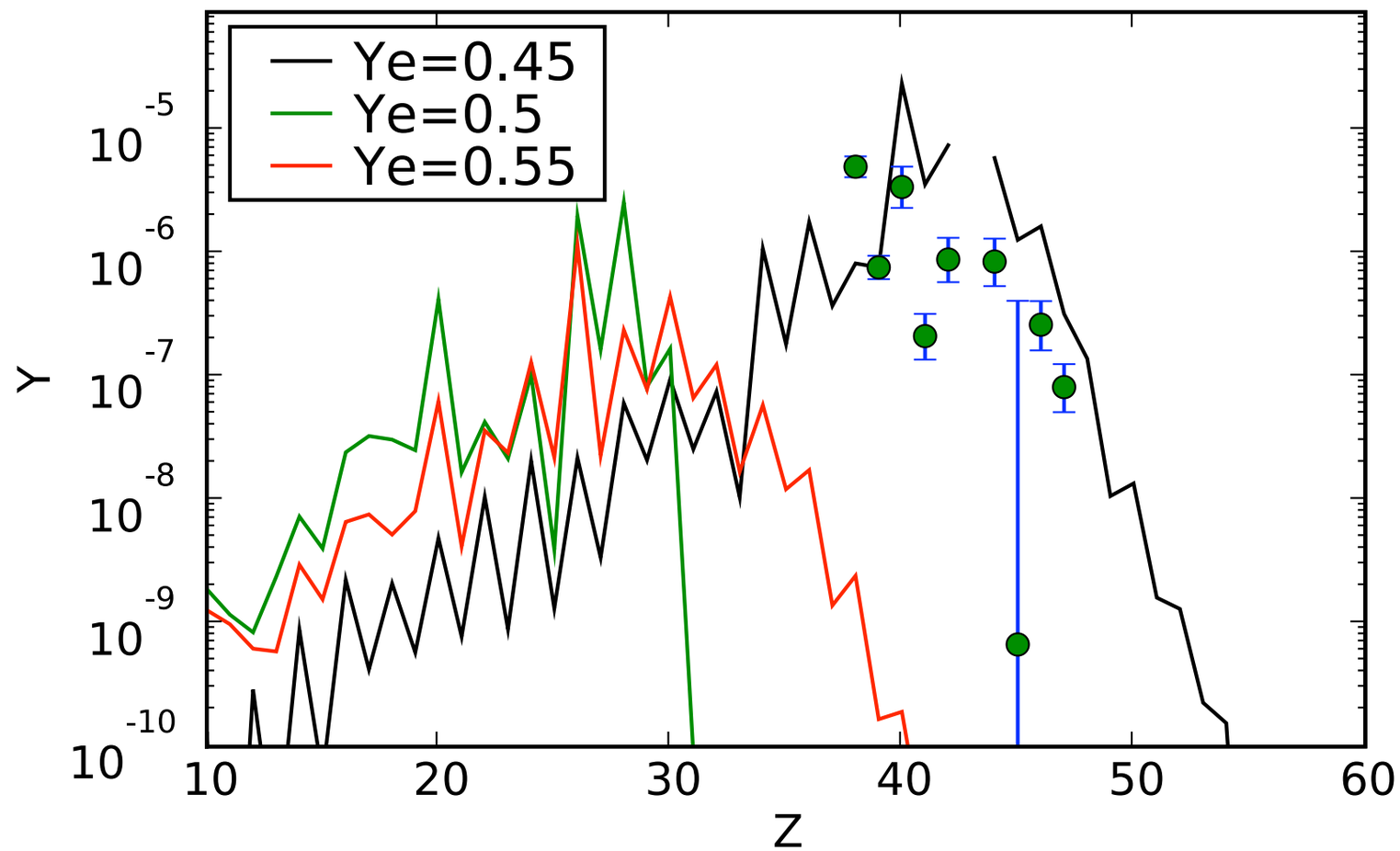
# Nucleosynthesis and electron fraction

Study different values for the electron fraction, taken to be constant for all trajectories (Arcones & Montes, in prep.)

Compare to LEPP pattern (rescaled to Z=39)

For typical Ye values obtained in supernova simulations:



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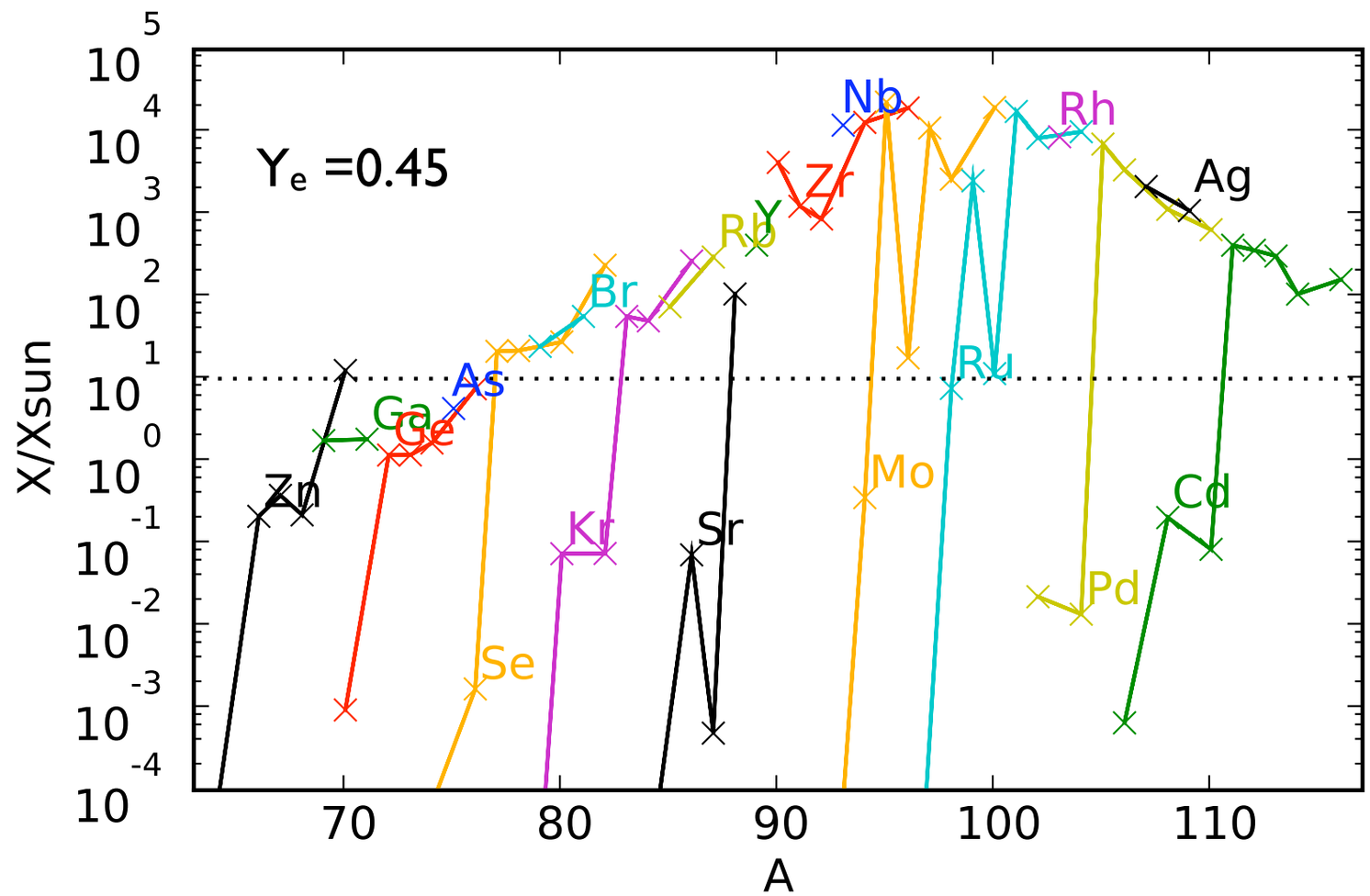

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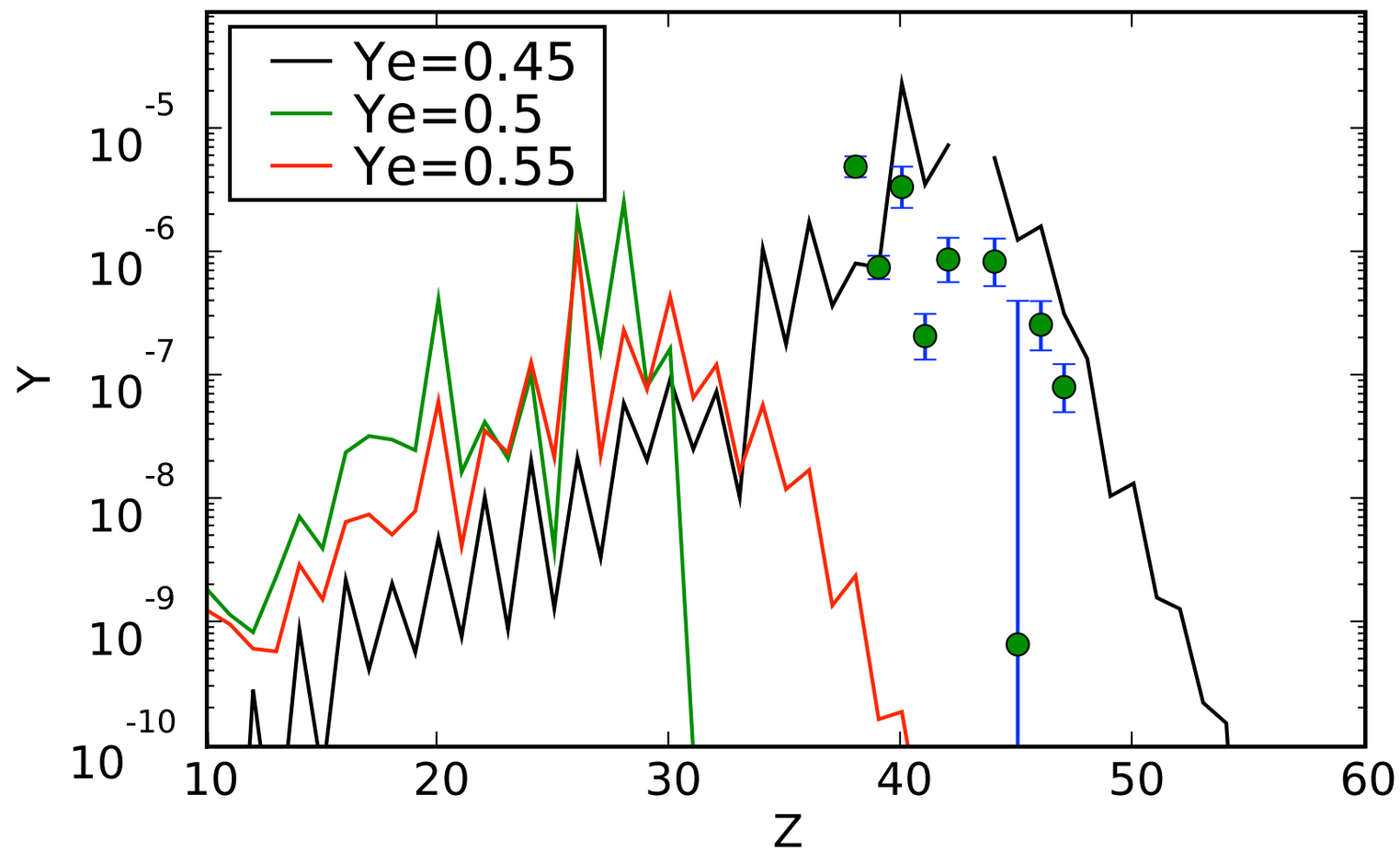

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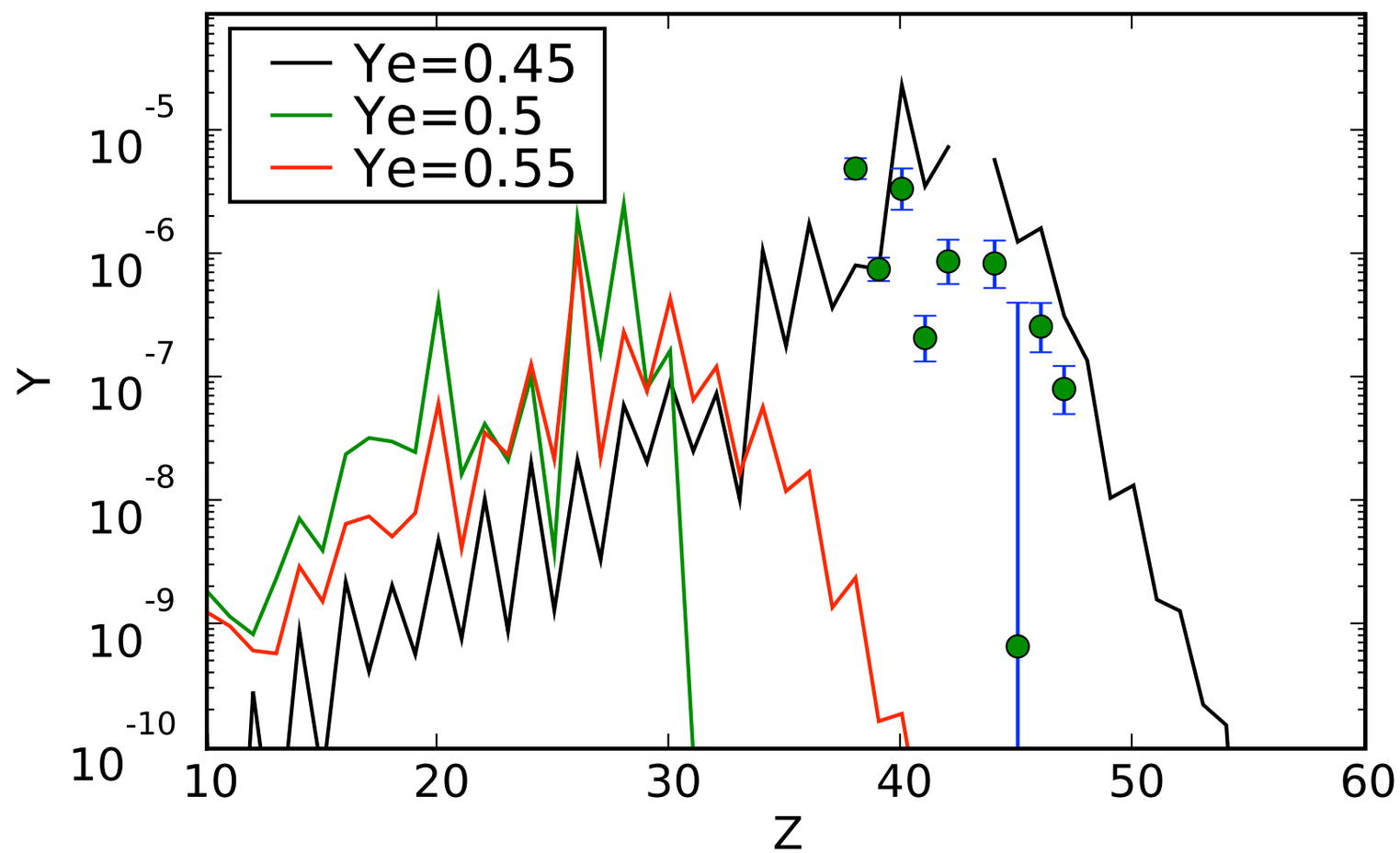
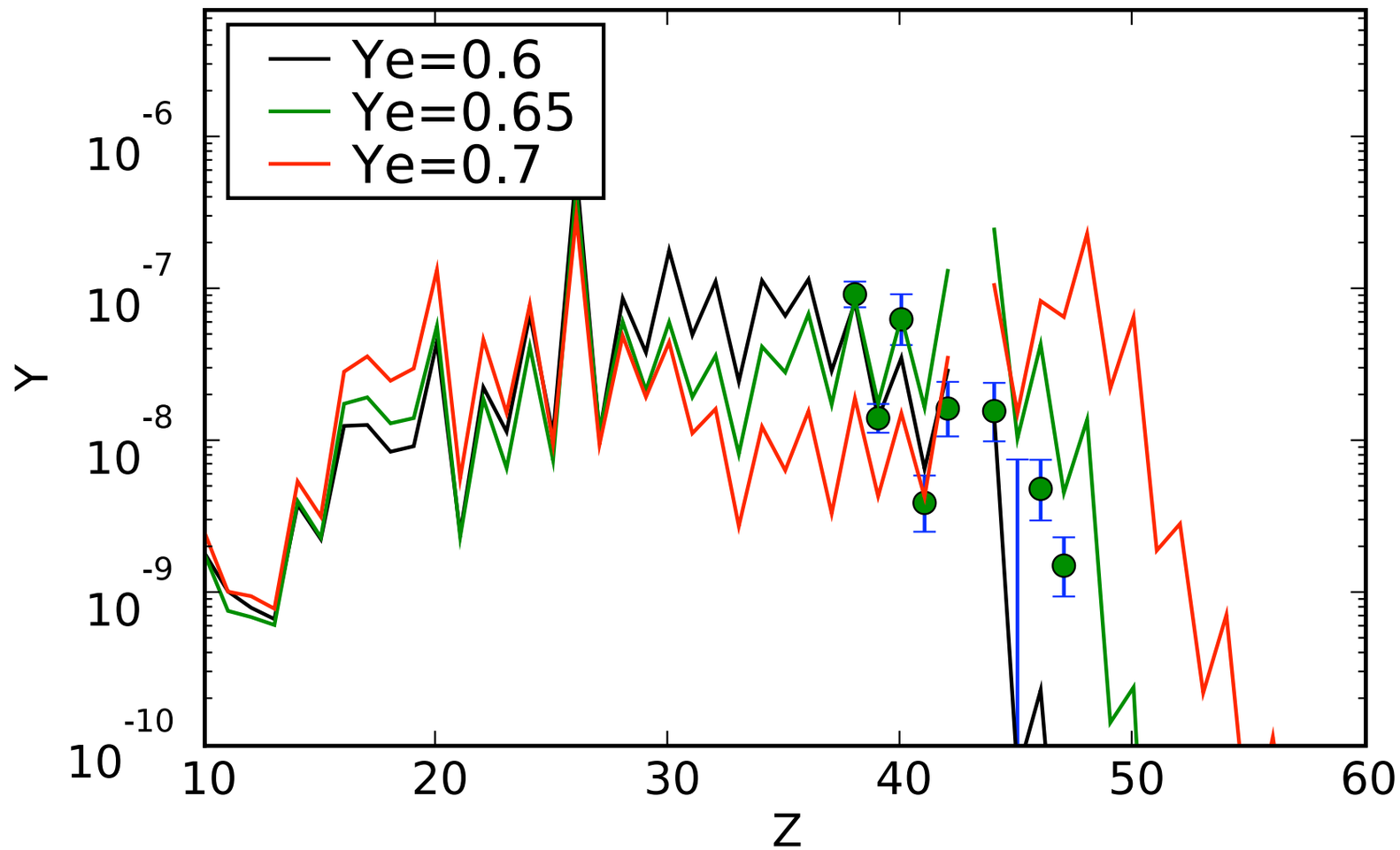
- Ye=0.5: only Fe group nuclei
- Ye=0.55: proton and neutron captures (νp-process) create elements with larger Z.



# Nucleosynthesis and electron fraction

Most recent simulations (Pruet et al. 2006, Fischer et al. 2009) show that ejecta are proton-rich.

We find that the LEPP pattern can be reproduced under such conditions!!



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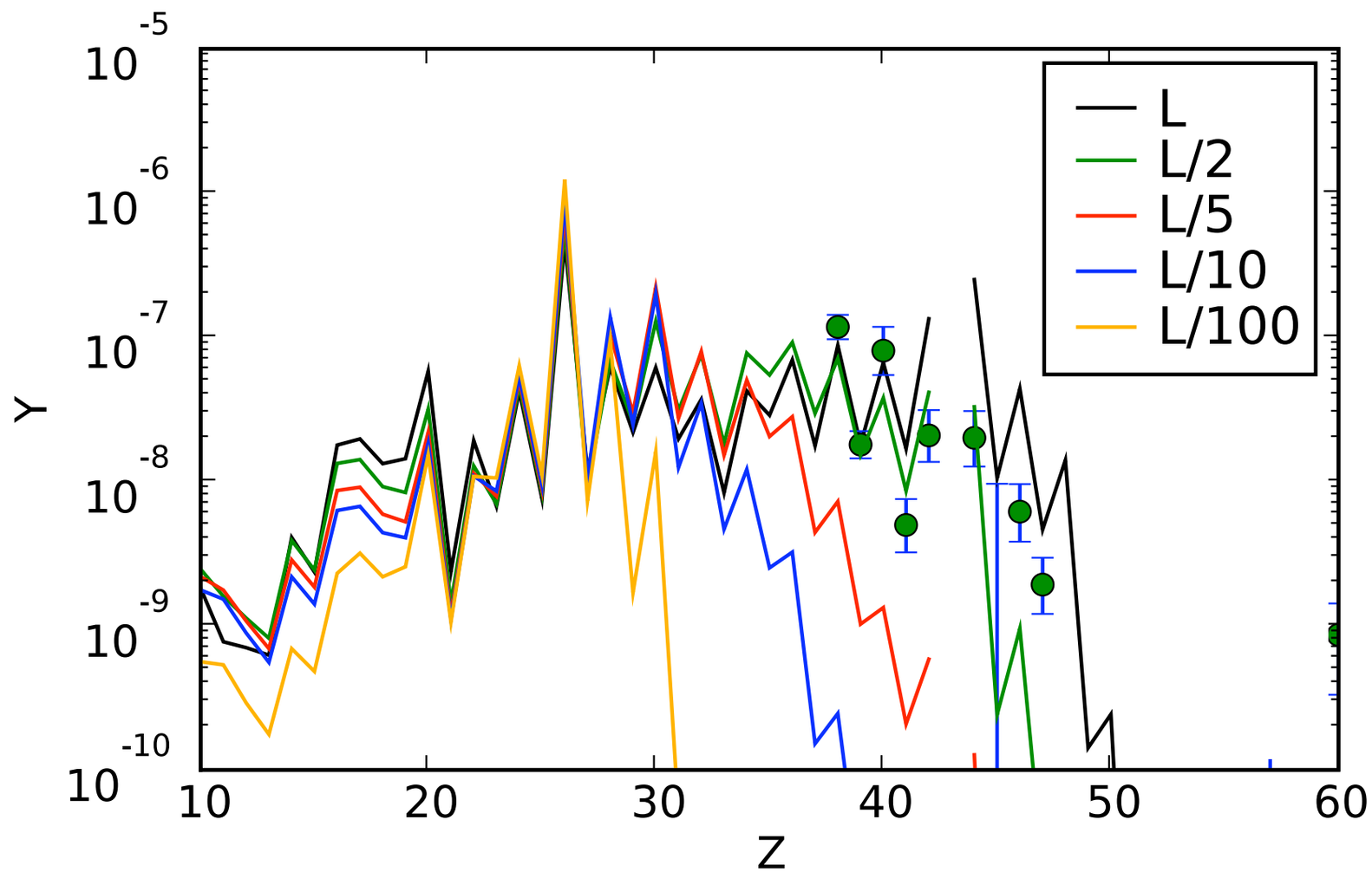


Final abundances depend on neutrino luminosities and on how long matter is expose to neutrinos (expansion velocity).

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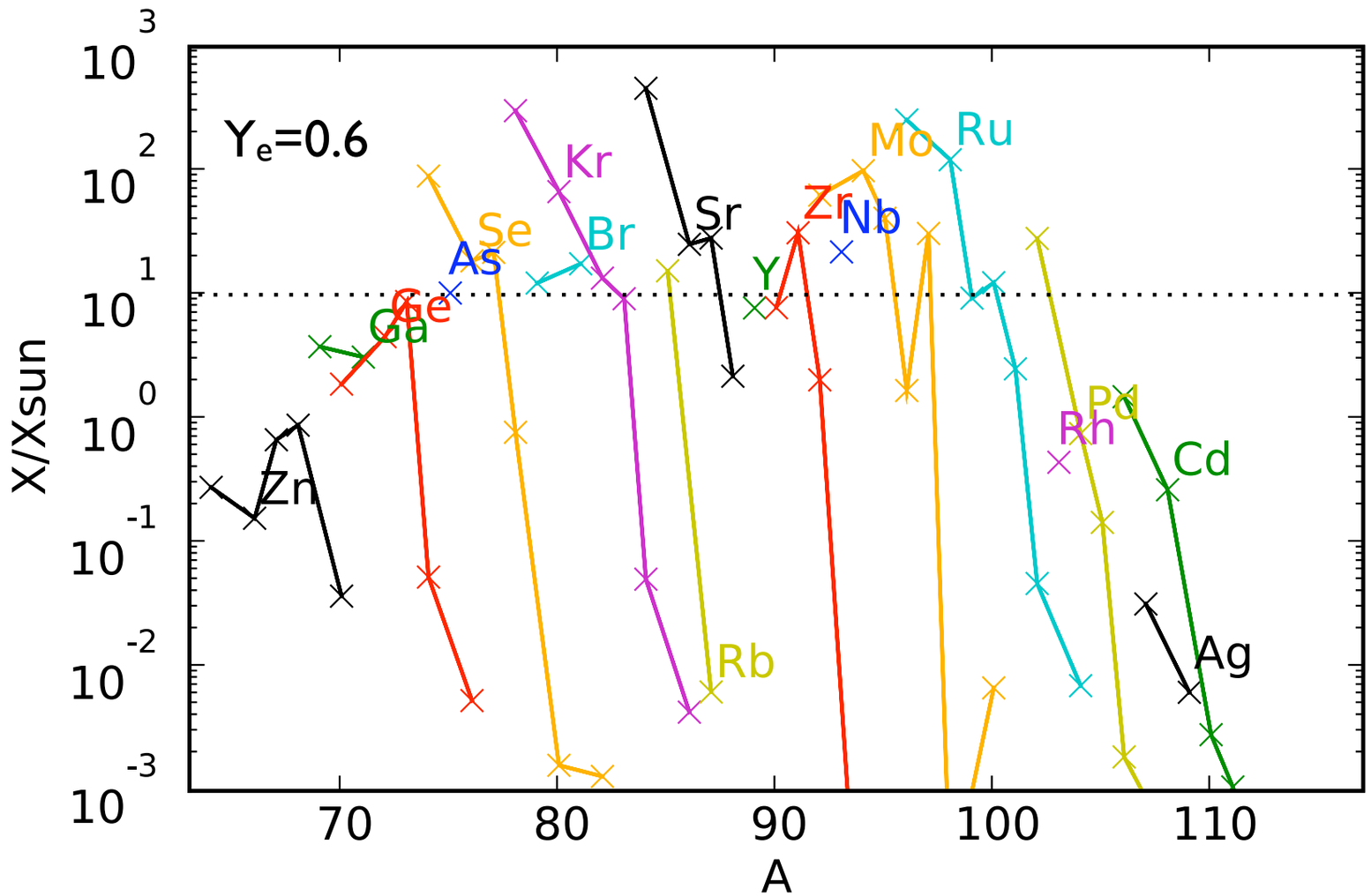


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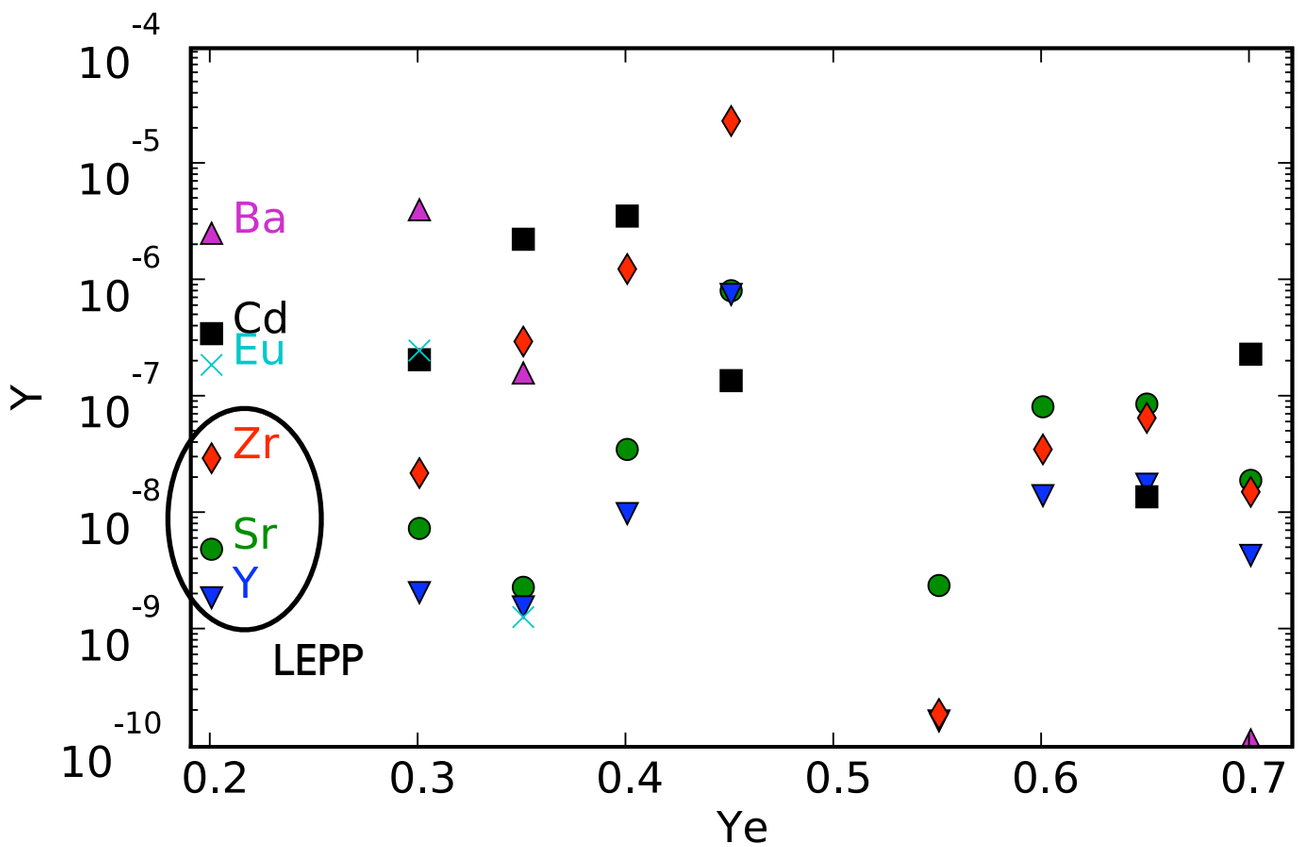
Neutron deficient isotopes are overproduced: observations of isotopic abundance needed

# LEPP: conclusions (Arcones & Montes, in prep)

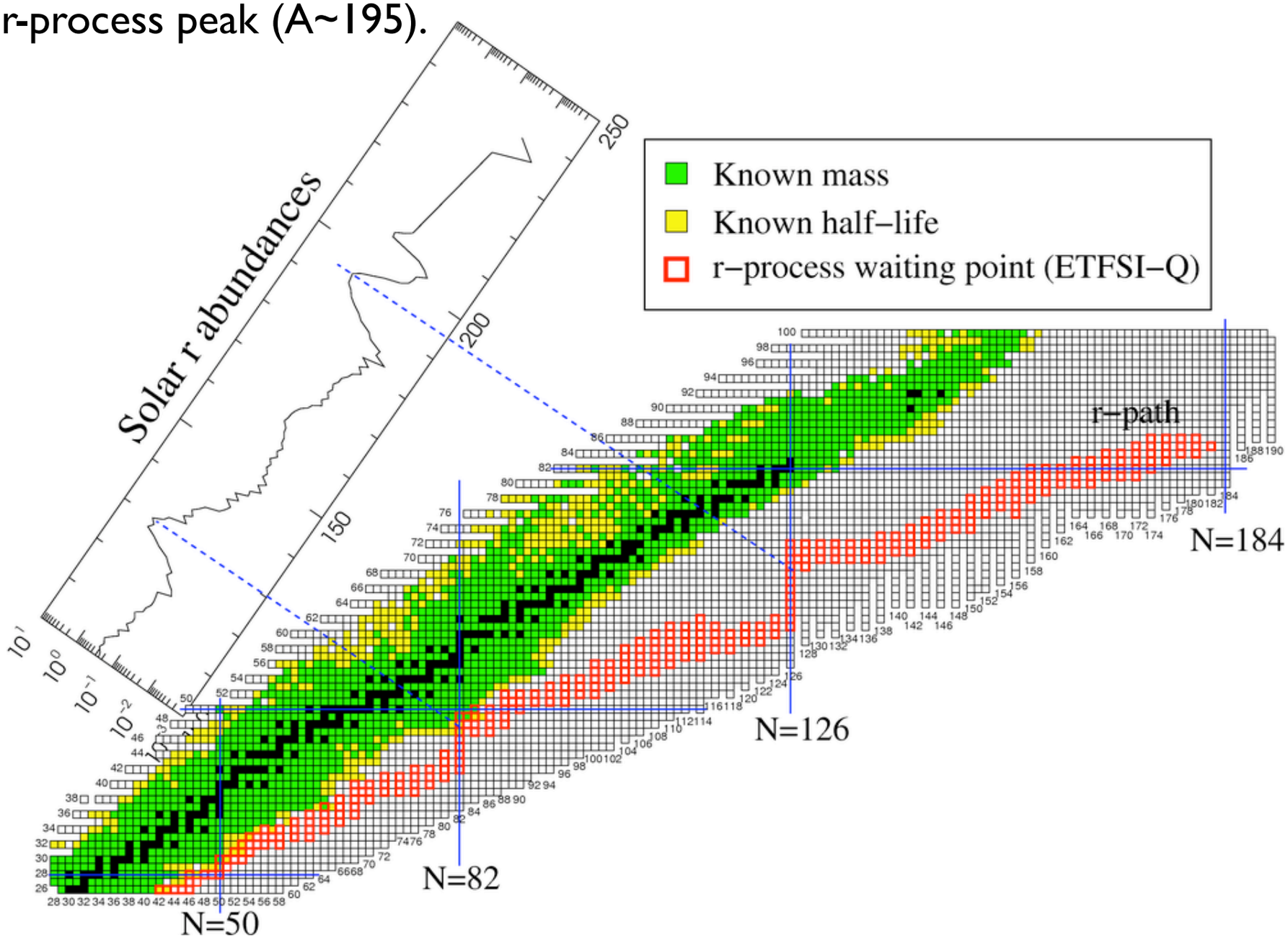
- First comparison of results based on neutrino-driven wind simulations and LEPP observations
- Composition of the ejecta is very sensitive to the electron fraction.
- LEPP distribution can be obtained in proton- and neutron-rich conditions.
- More observations are needed, especially of isotopical abundances in old halo stars and of meteorites.




- Outlook: explore time dependence of the electron fraction

# 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

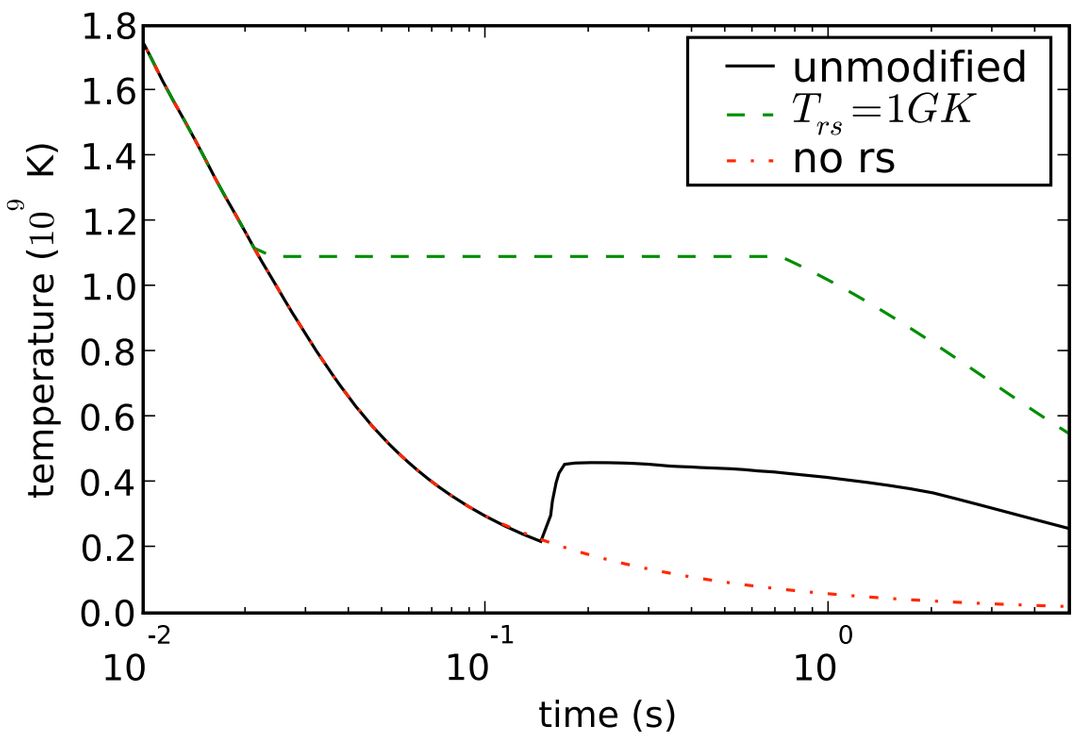
Evolution of T and ρ during the alpha-process determines the neutron-to-seed ratio and thus the possibility of forming heavy elements.

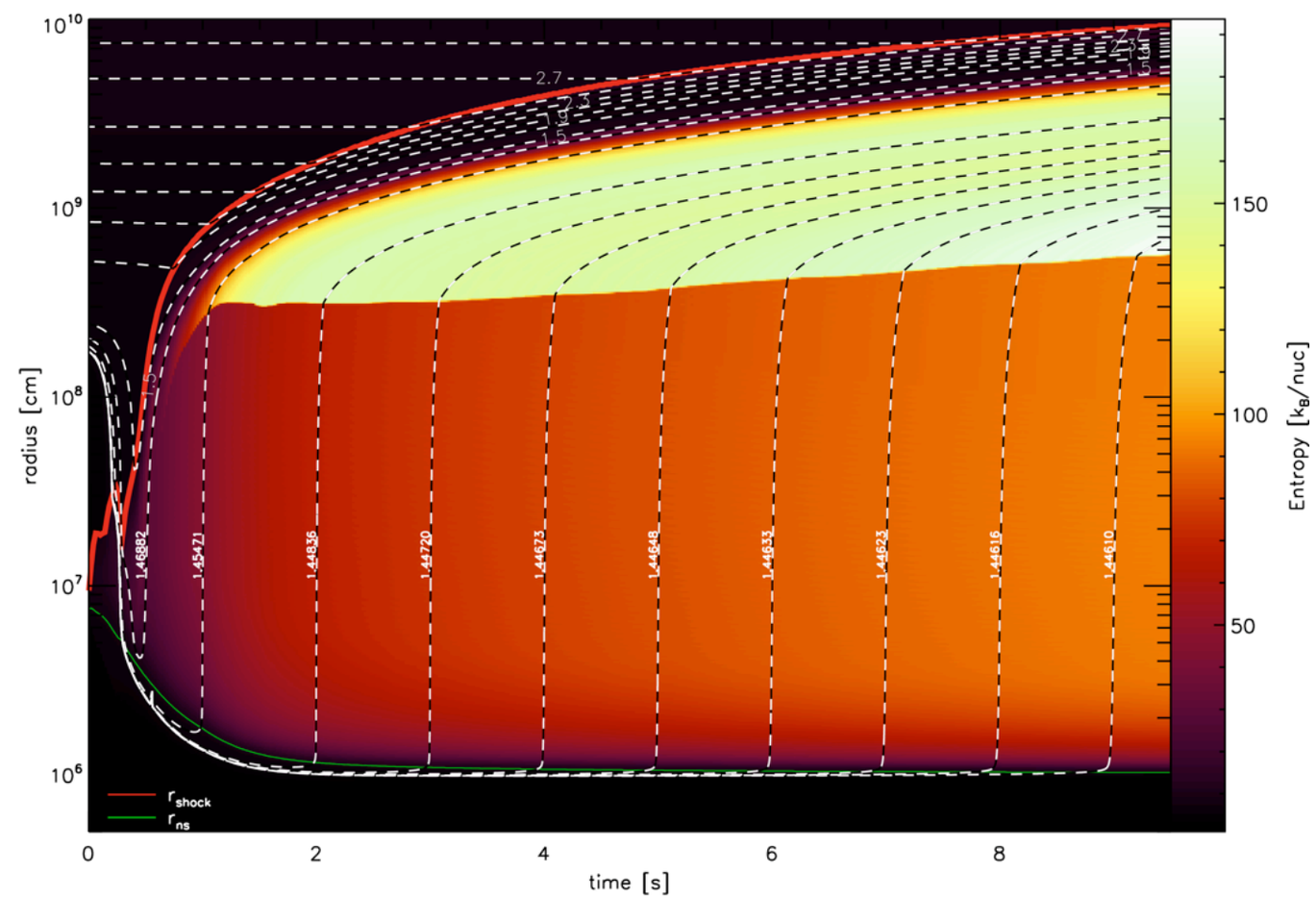
However, the dynamical evolution after the freeze-out of charged-particle reactions is also important for understanding the final abundances.

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



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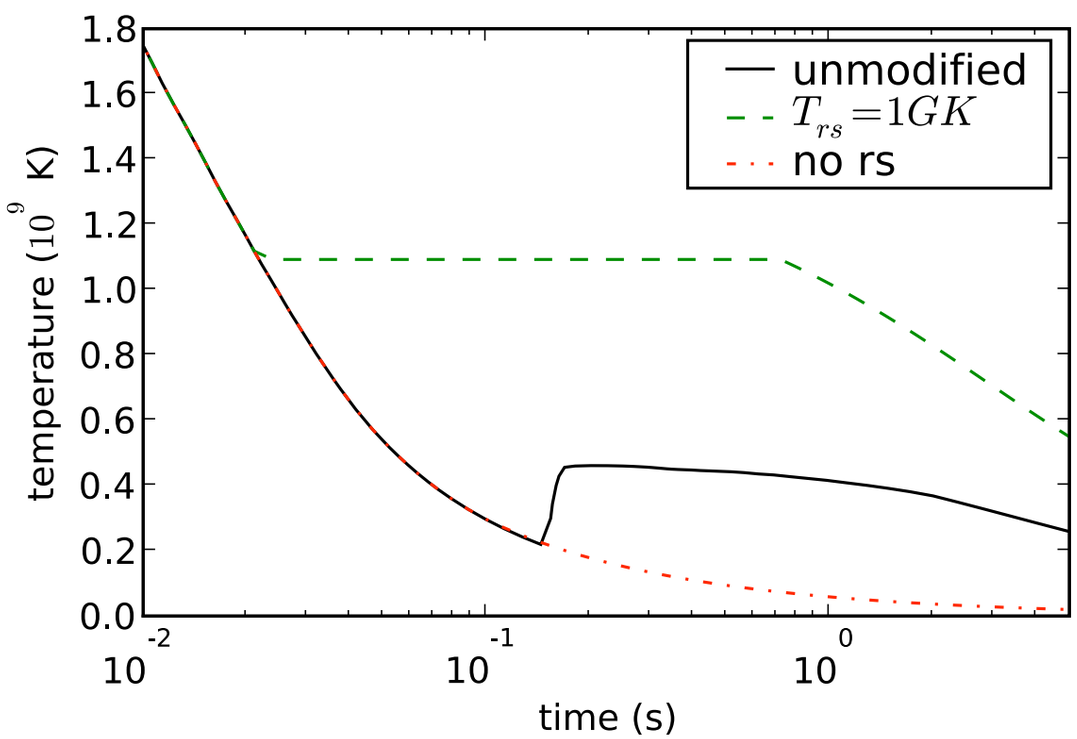
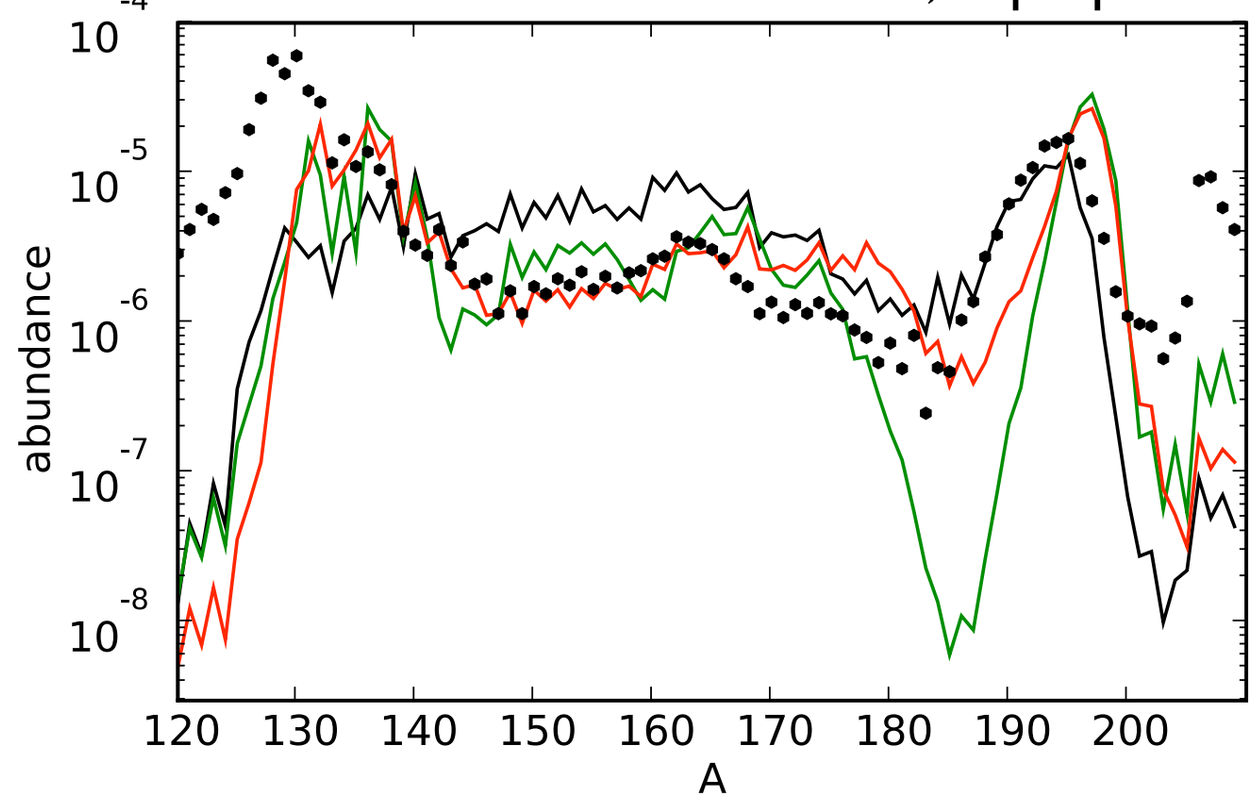
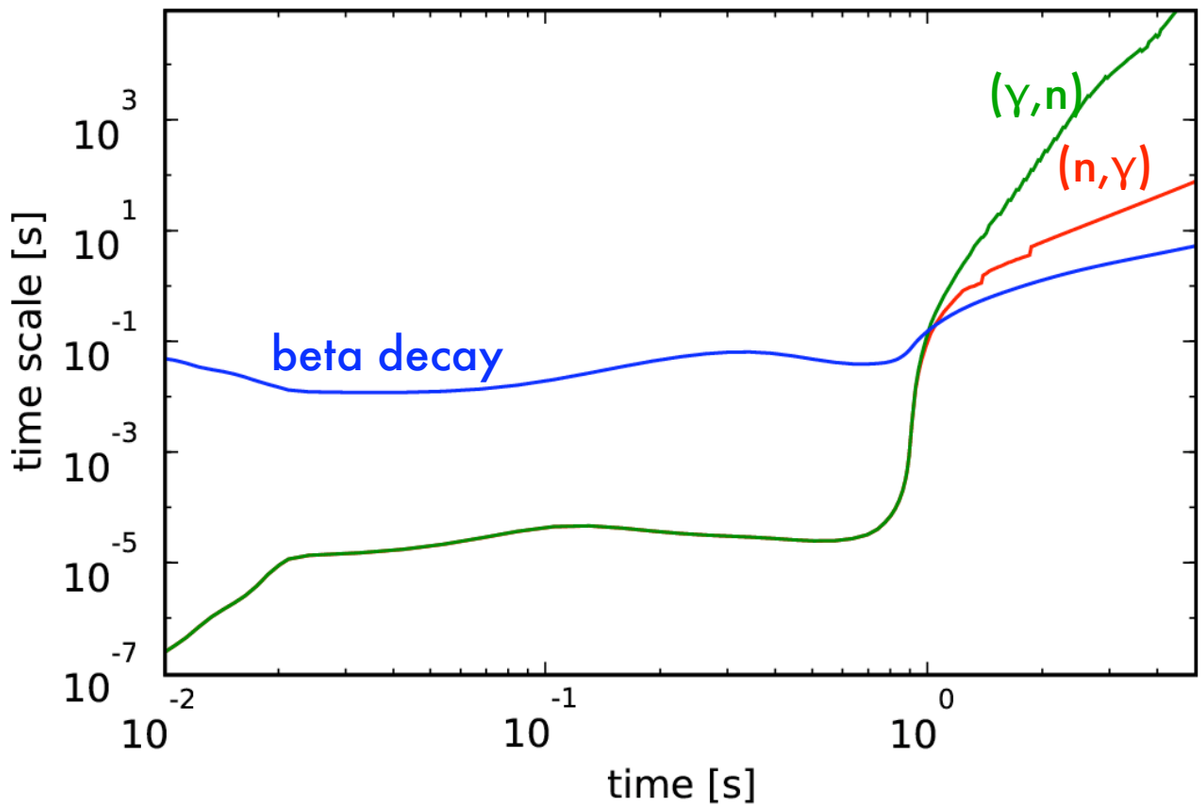



Arcones & Martinez-Pinedo, in prep.

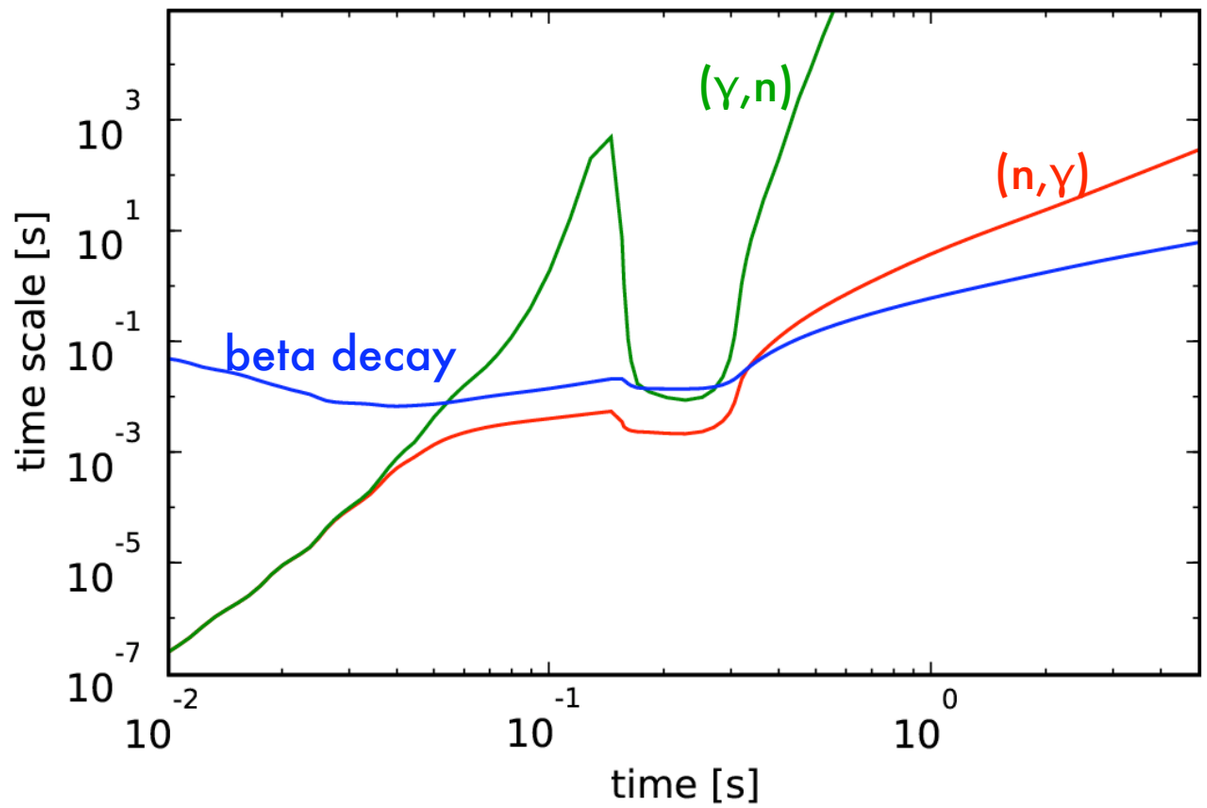


# Long-time evolution: high vs. low temperature

High temperature




Low temperature




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

Competition between beta decay and neutron capture (Blake & Schramm 1976)

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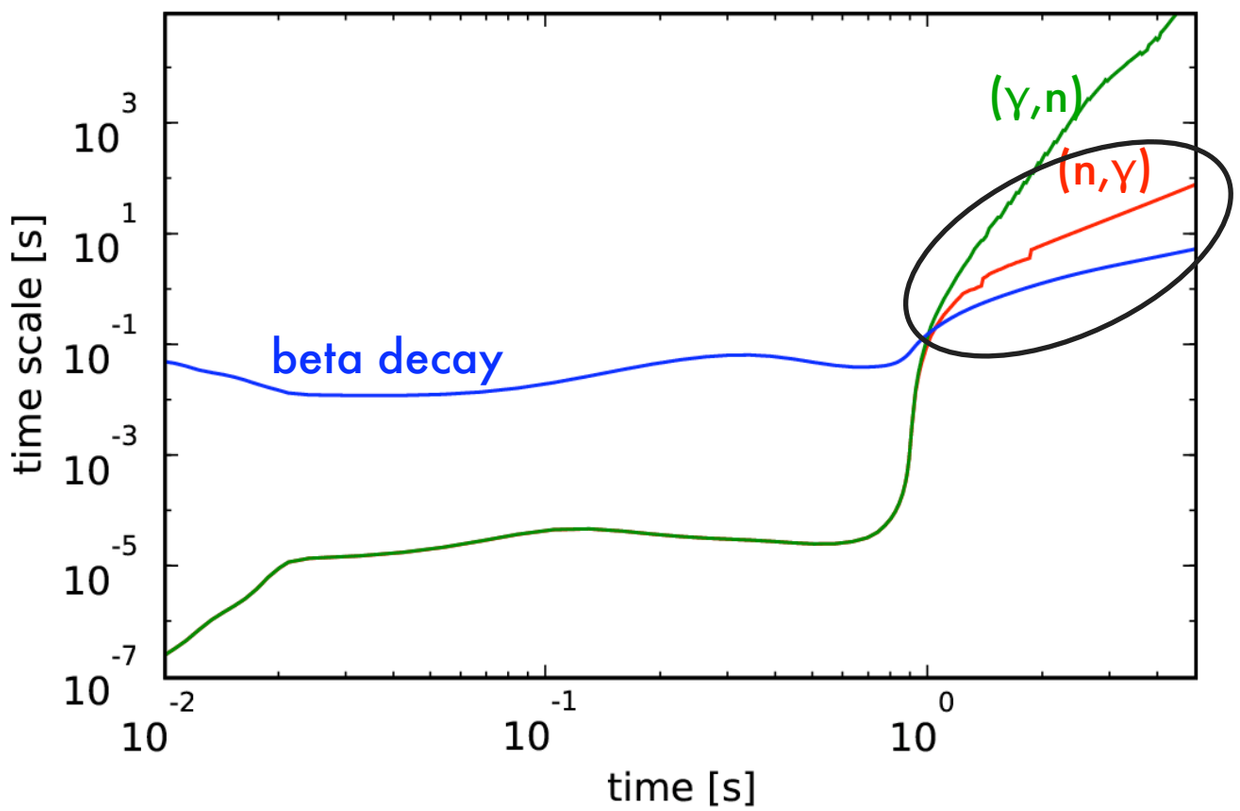


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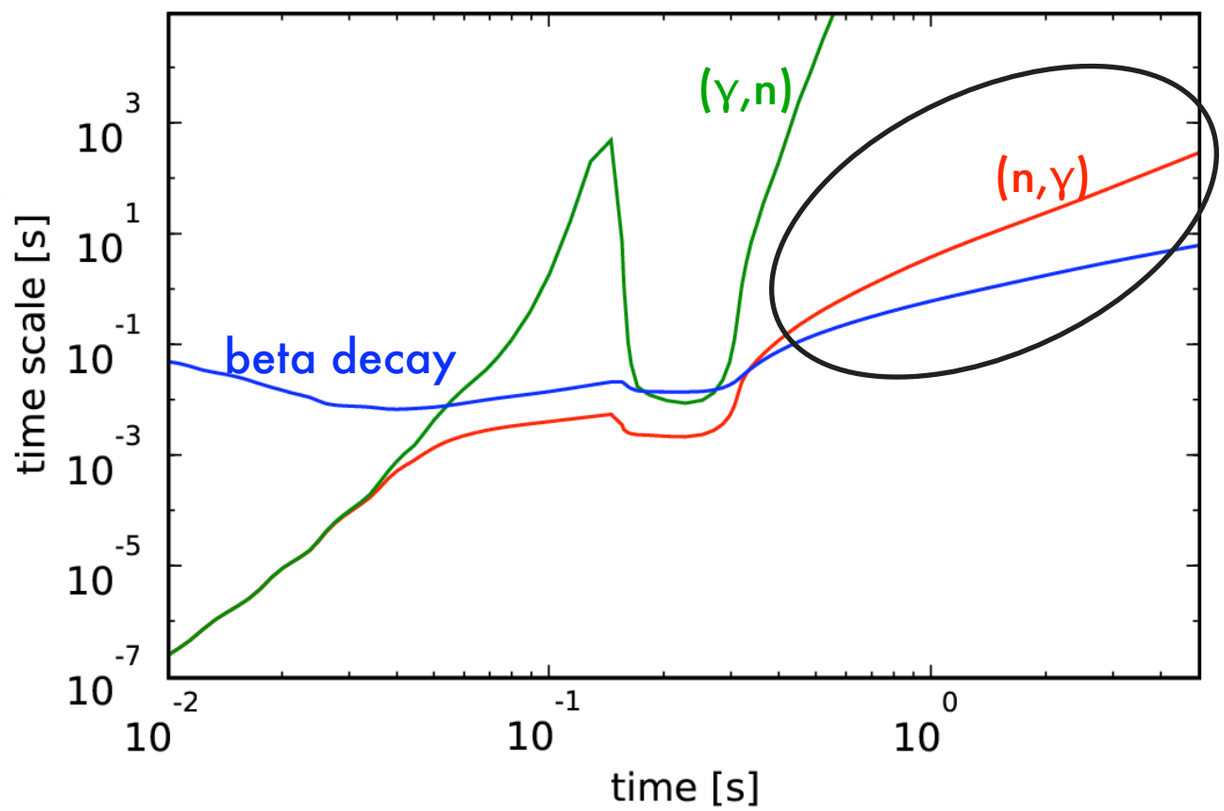


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Competition between beta decay and neutron capture (Blake & Schramm 1976)

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

# Sensitivity to mass models

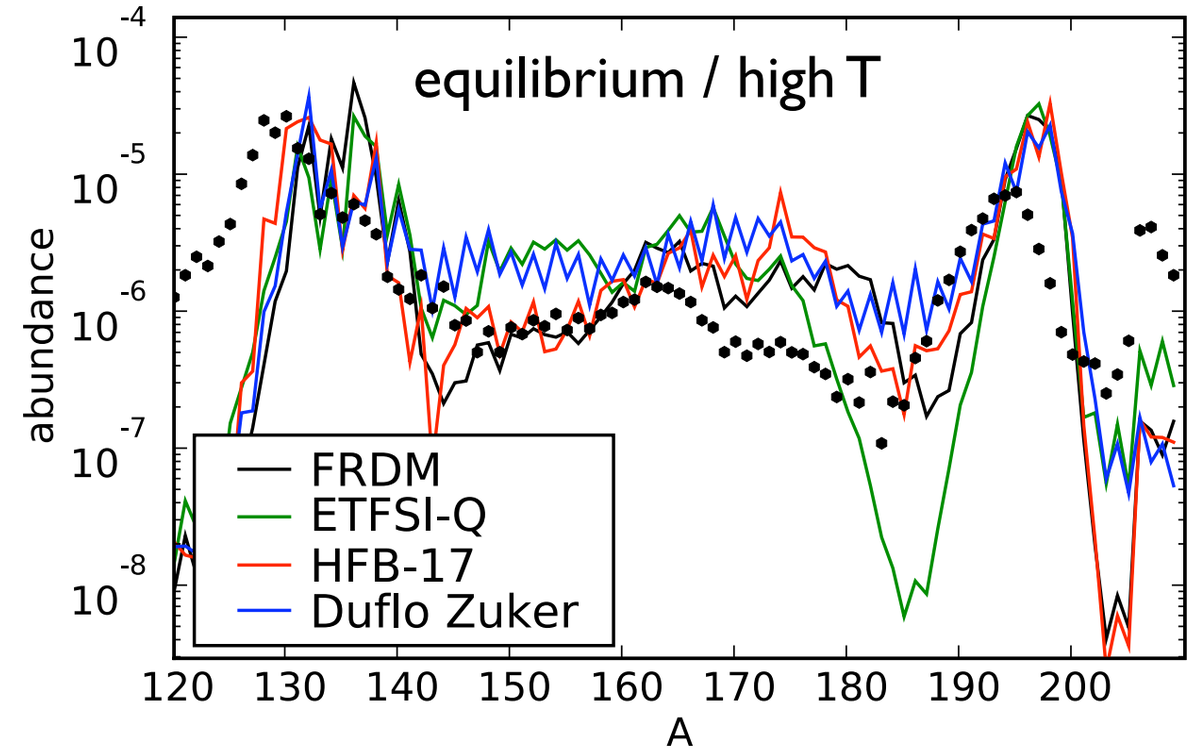
Compare four different mass models:

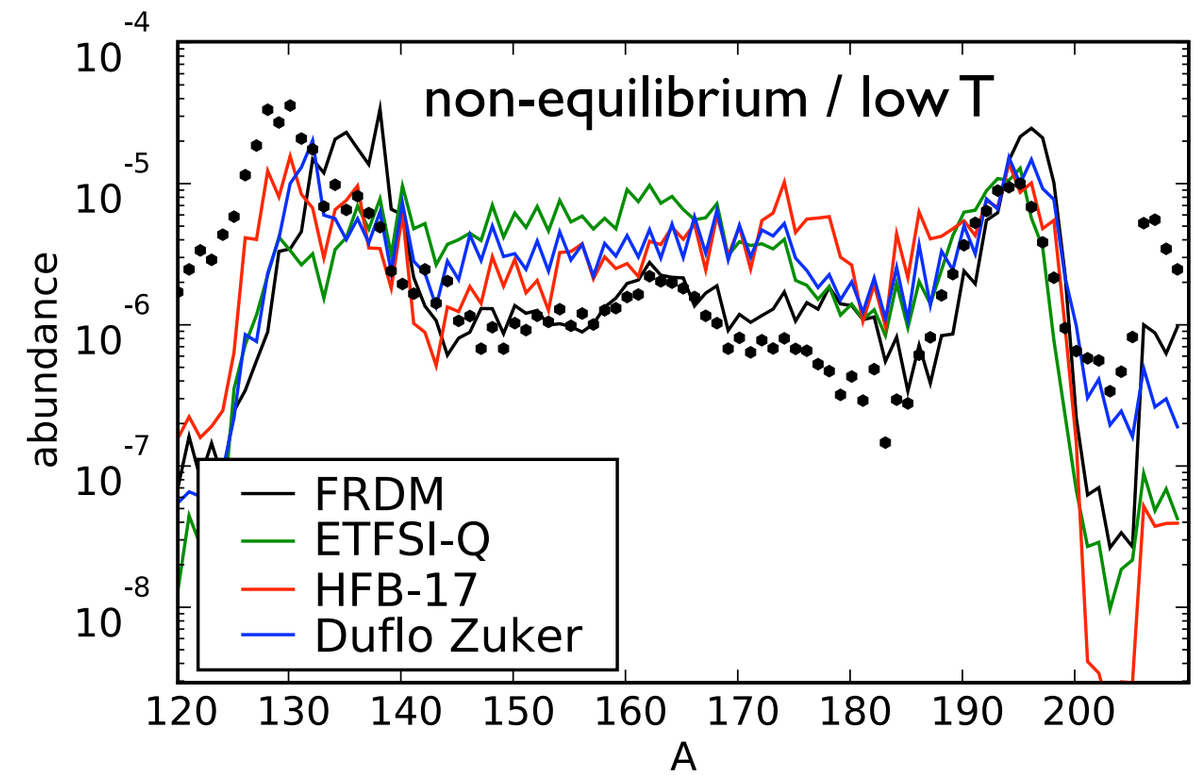
- FRDM (Möller et al. 1995)
- ETFSI-Q (Pearson et al. 1996)
- HFB-17 (Goriely et al. 2009)
- Duflo&Zuker mass formula

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

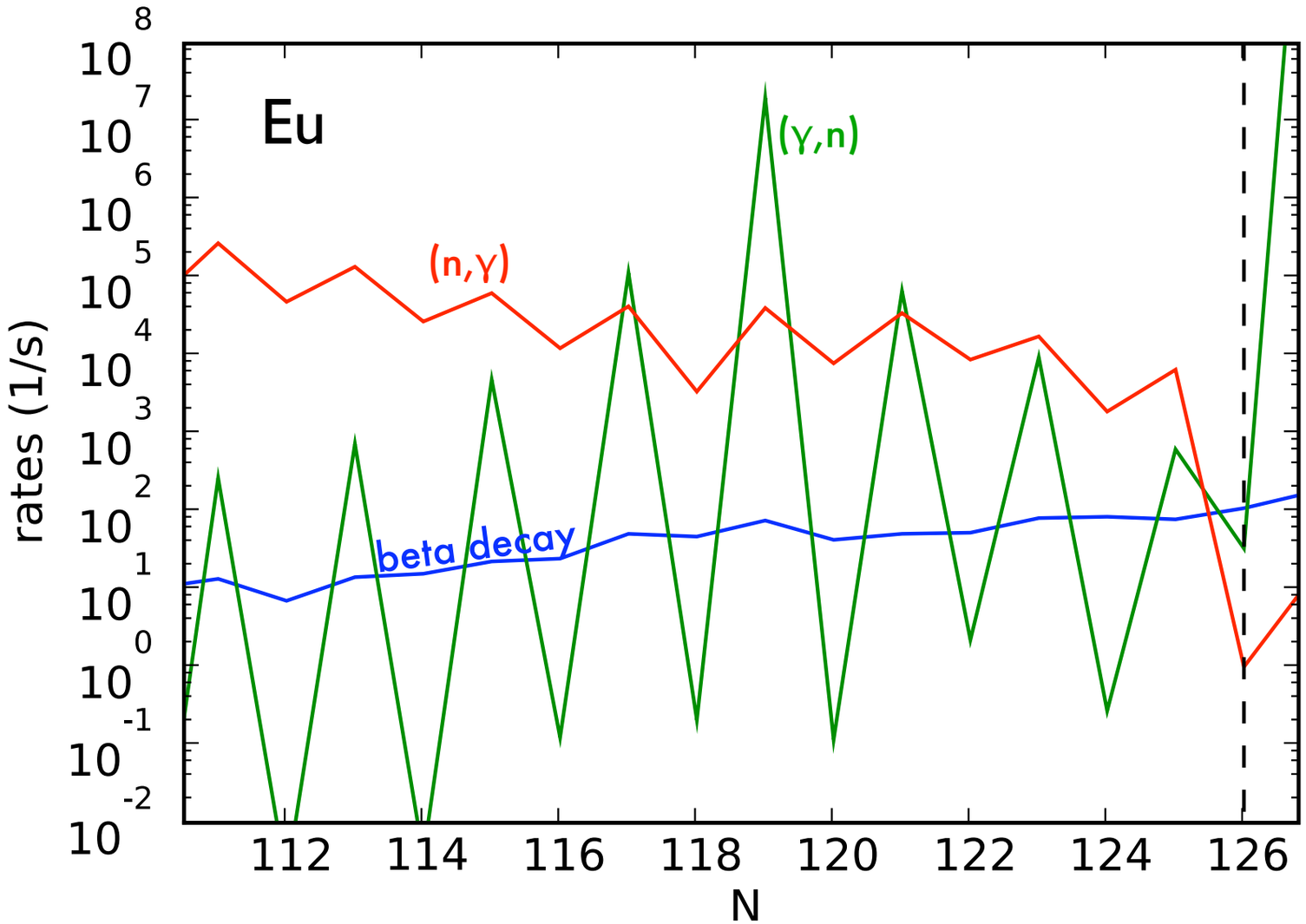
The nuclear physics input affects the final abundances differently depending on the long-time dynamical evolution.

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



# Neutron separation energy and rates




Neutron capture:

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

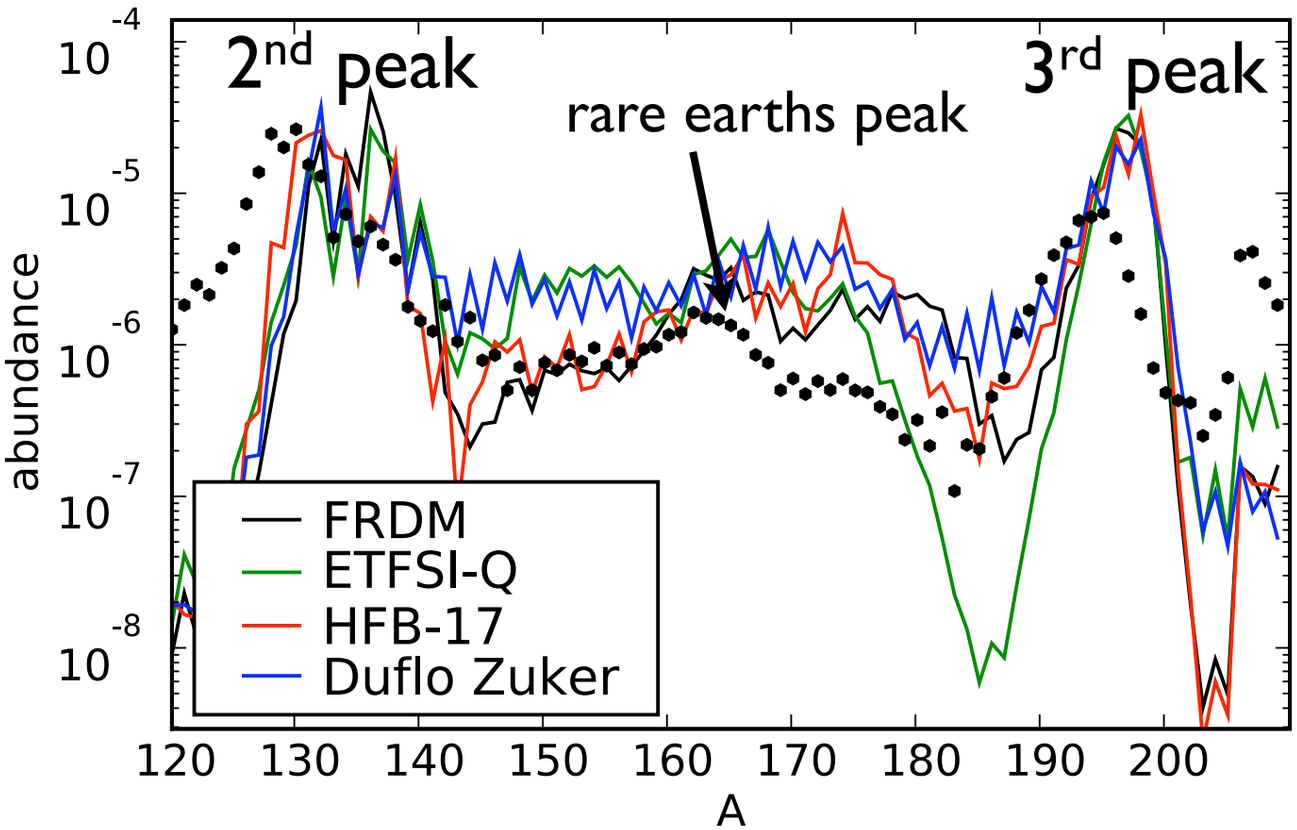
Photo-dissociation:

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

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

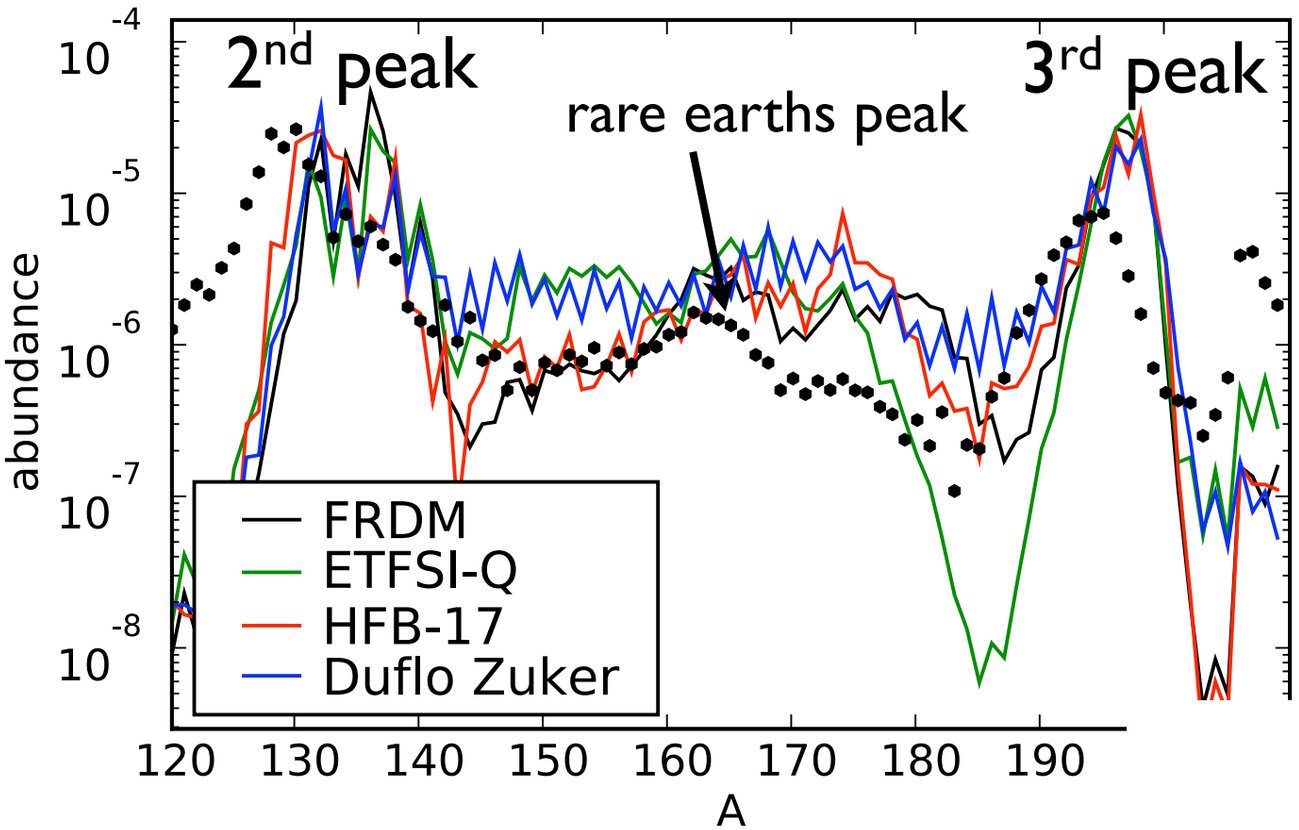
Constant $S_n$: neutrons are captured inmediatly and a **hole** appears.

# Peaks and holes

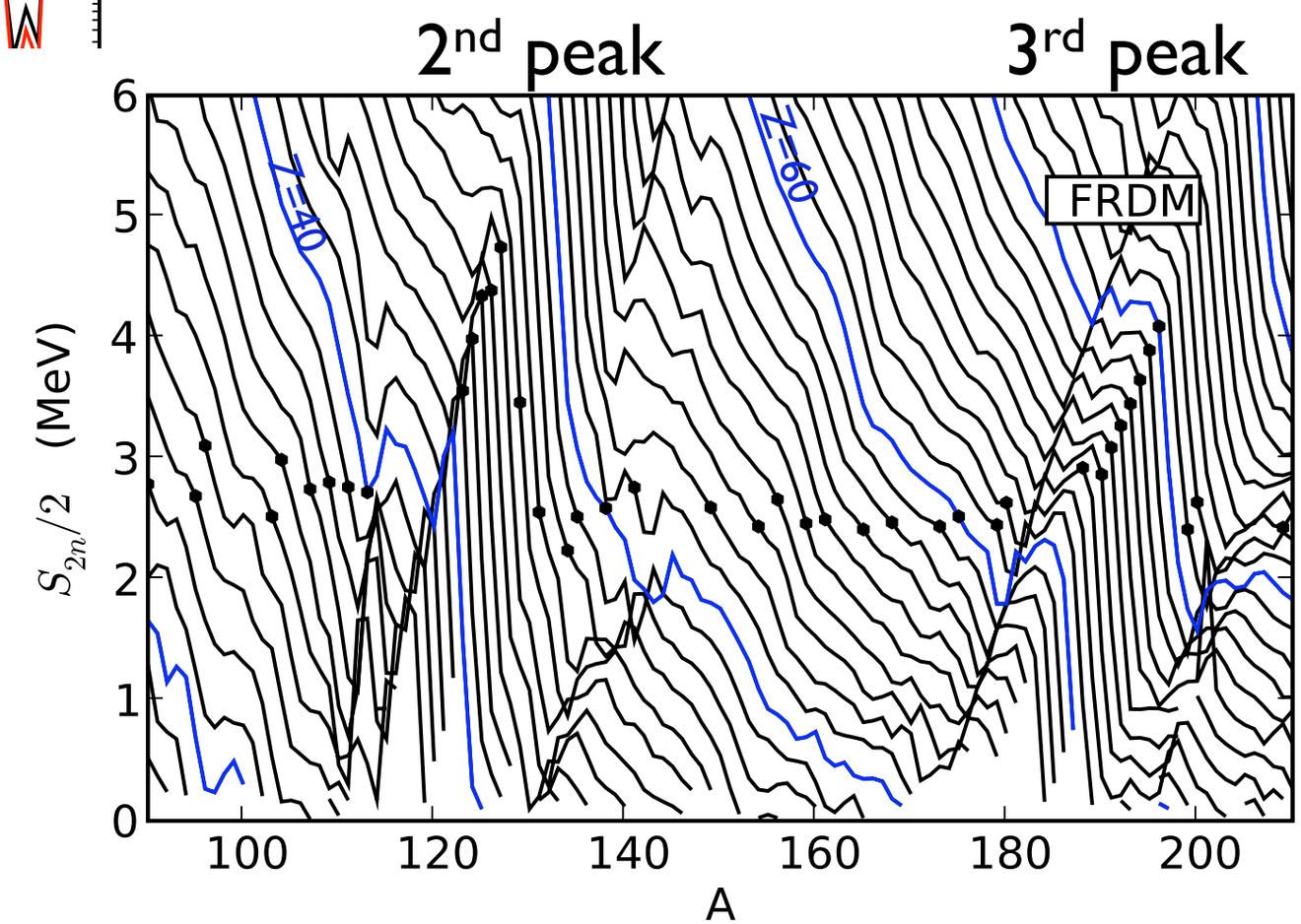



equilibrium / high T

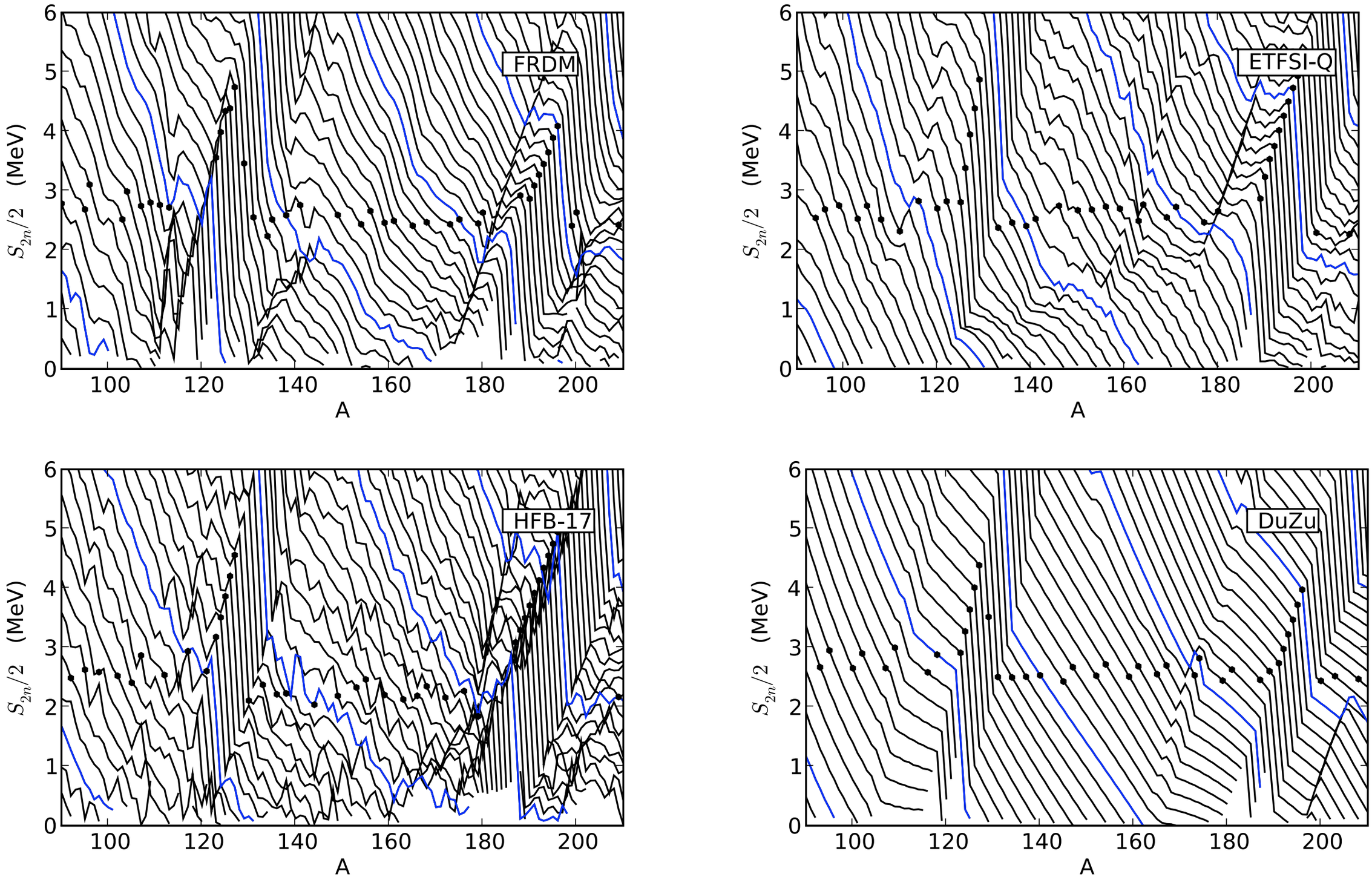
# Peaks and holes




equilibrium / high T



# Aspects of different mass models



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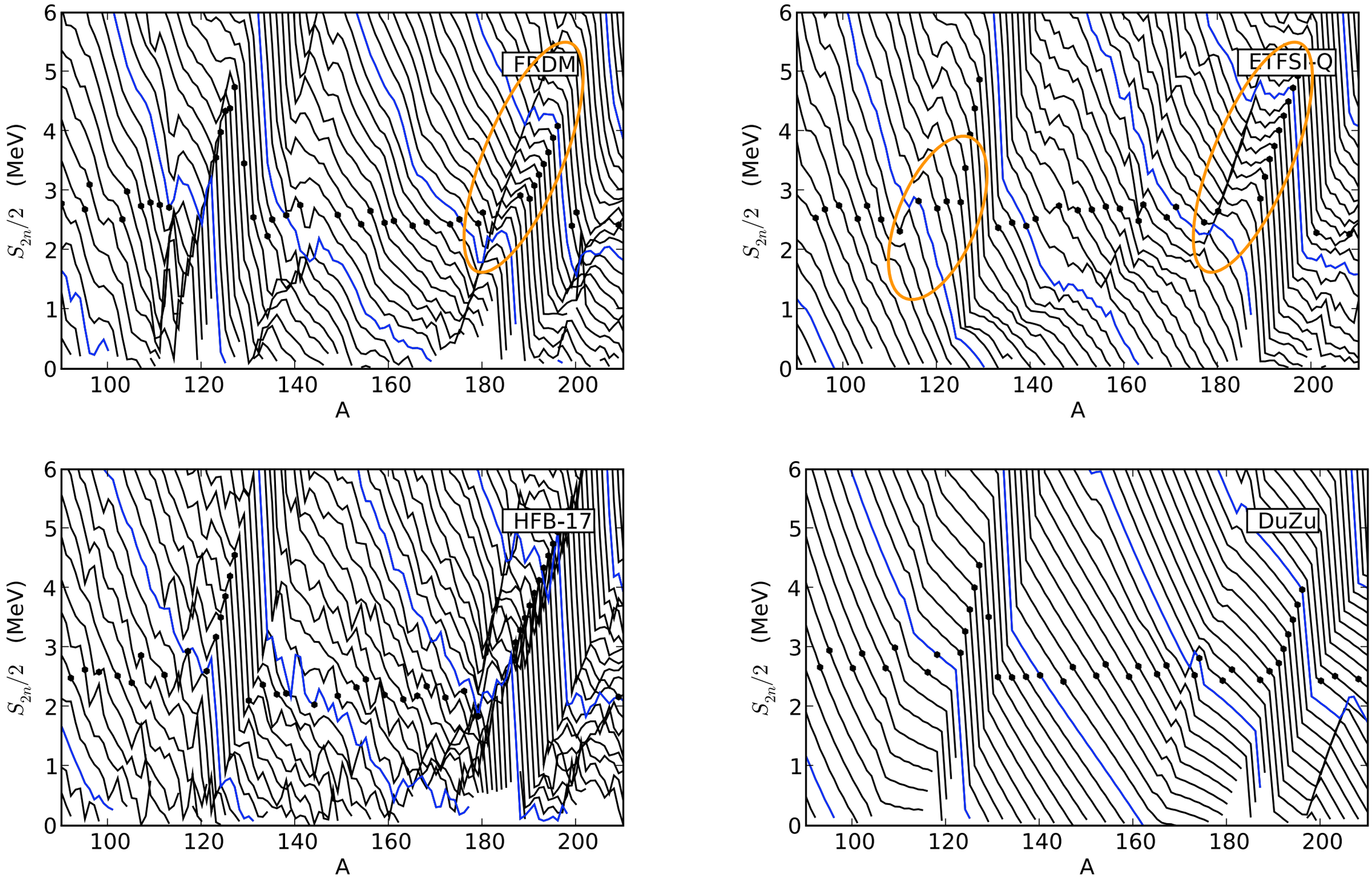

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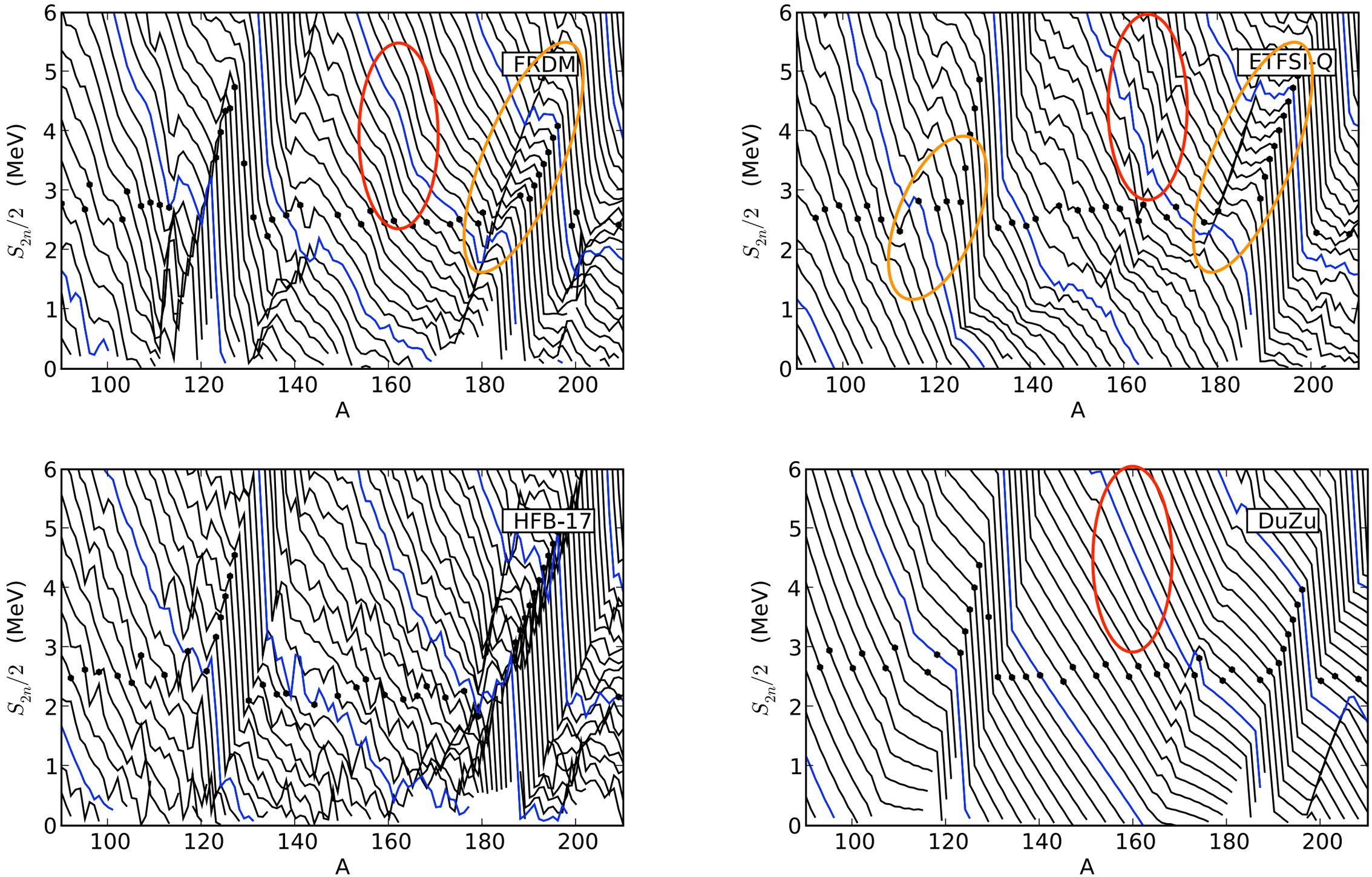


# Way back to stability

High temperature evolution:

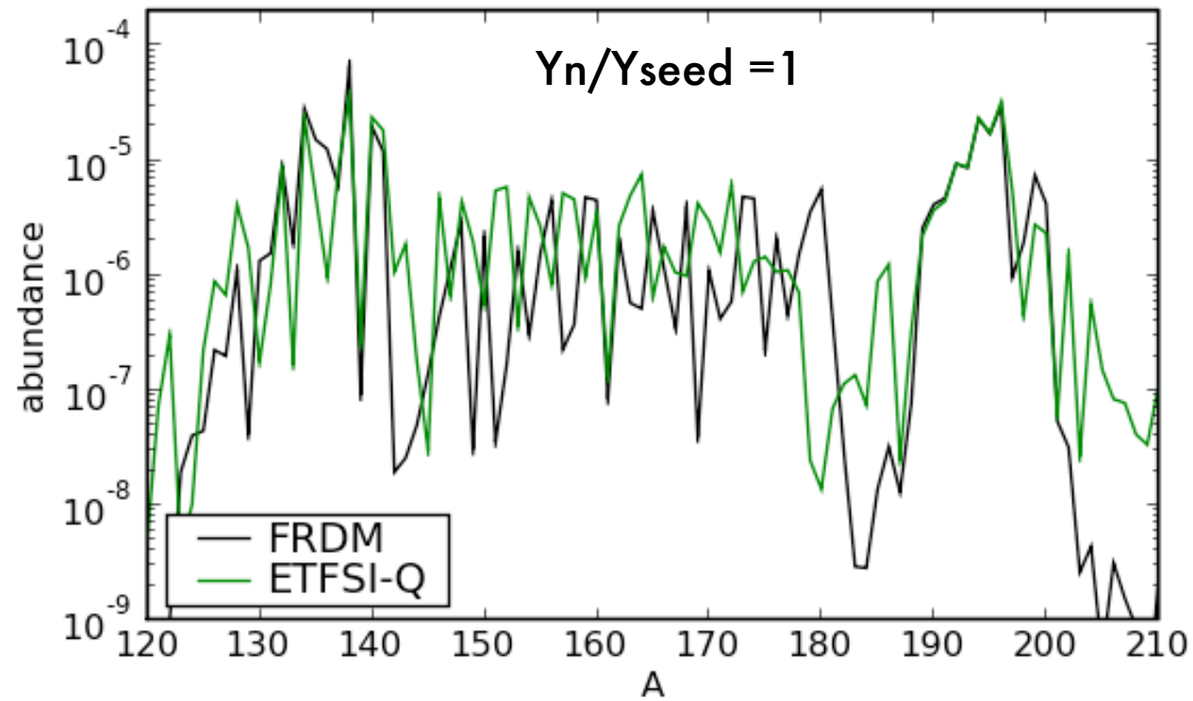
Abundances at freeze-out (Yn/Yseed=1) show odd-even effects following the behavior of the neutron separation energy.

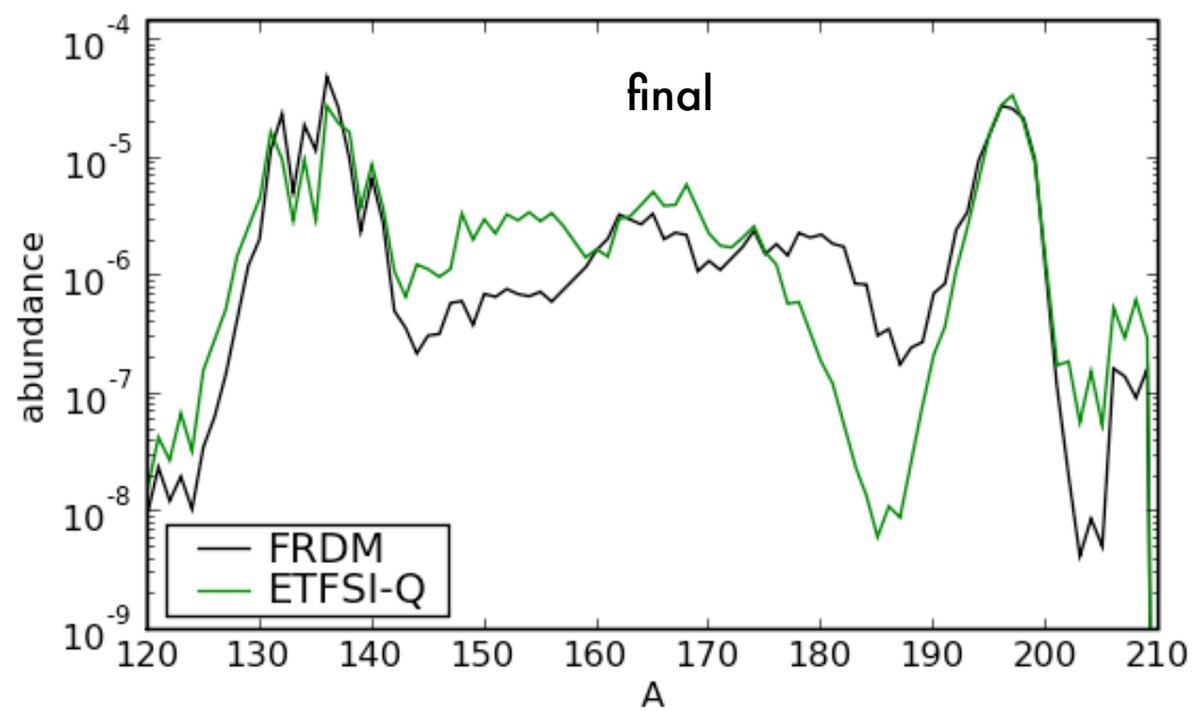
While final abundances are smoother like solar abundances.

Why does the abundance pattern change?

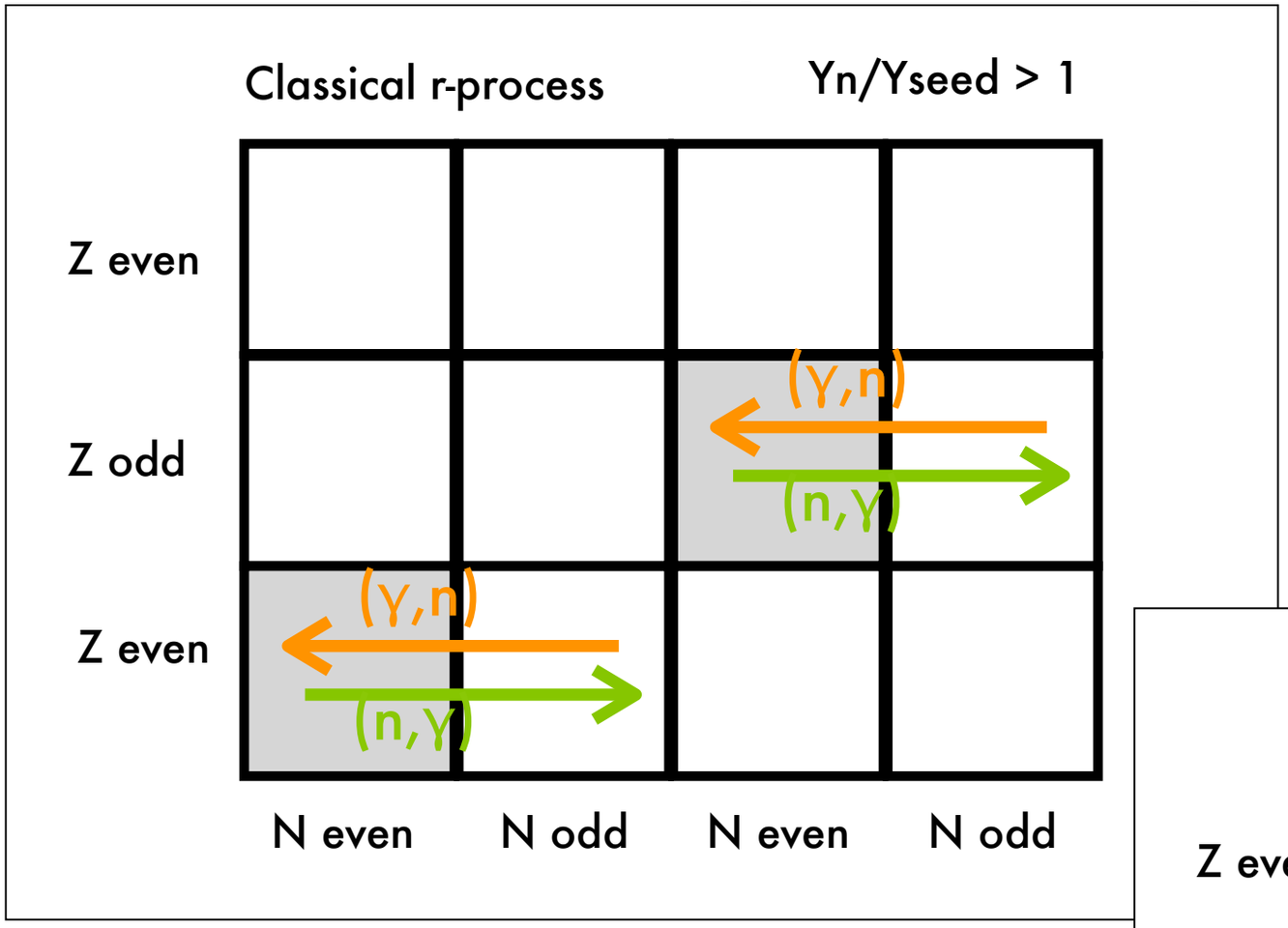
In the classical r-process (waiting point approximation) this is explained by beta delayed neutron emission (Kodama & Takahashi 1973, Kratz et al. 1993).

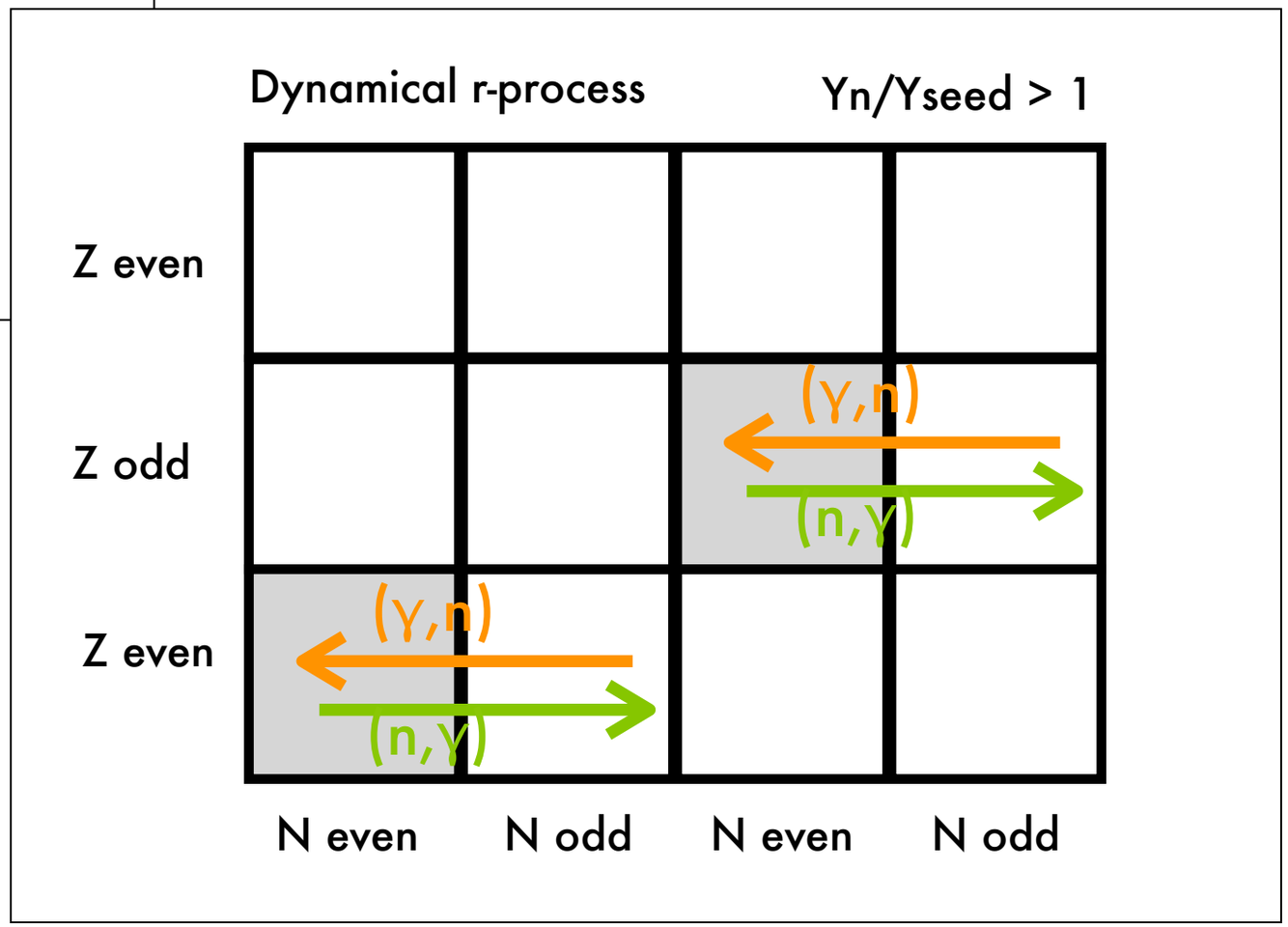
Dynamical r-process: neutron capture and beta-delayed neutron emission



# Classical vs. dynamical r-process



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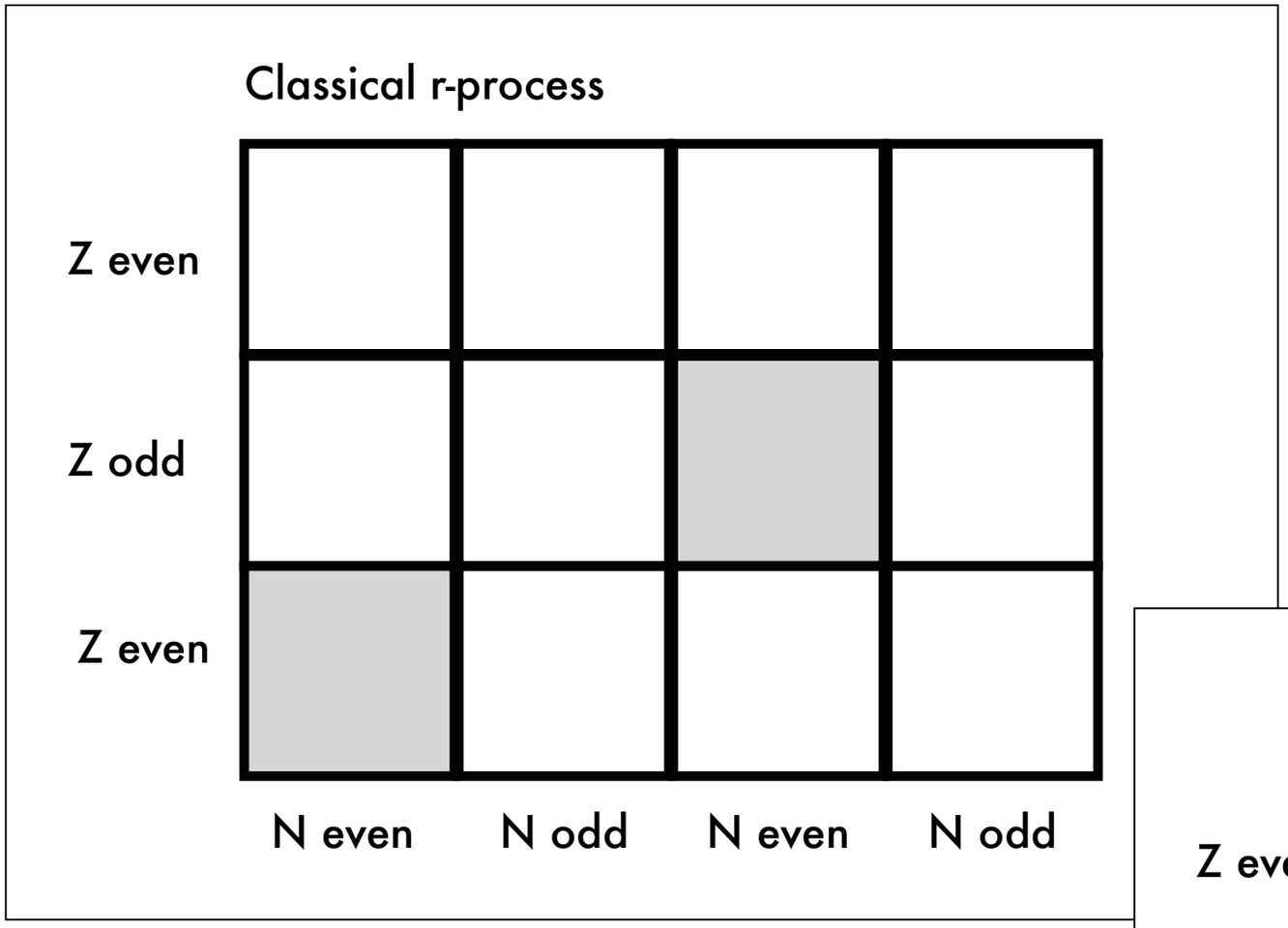


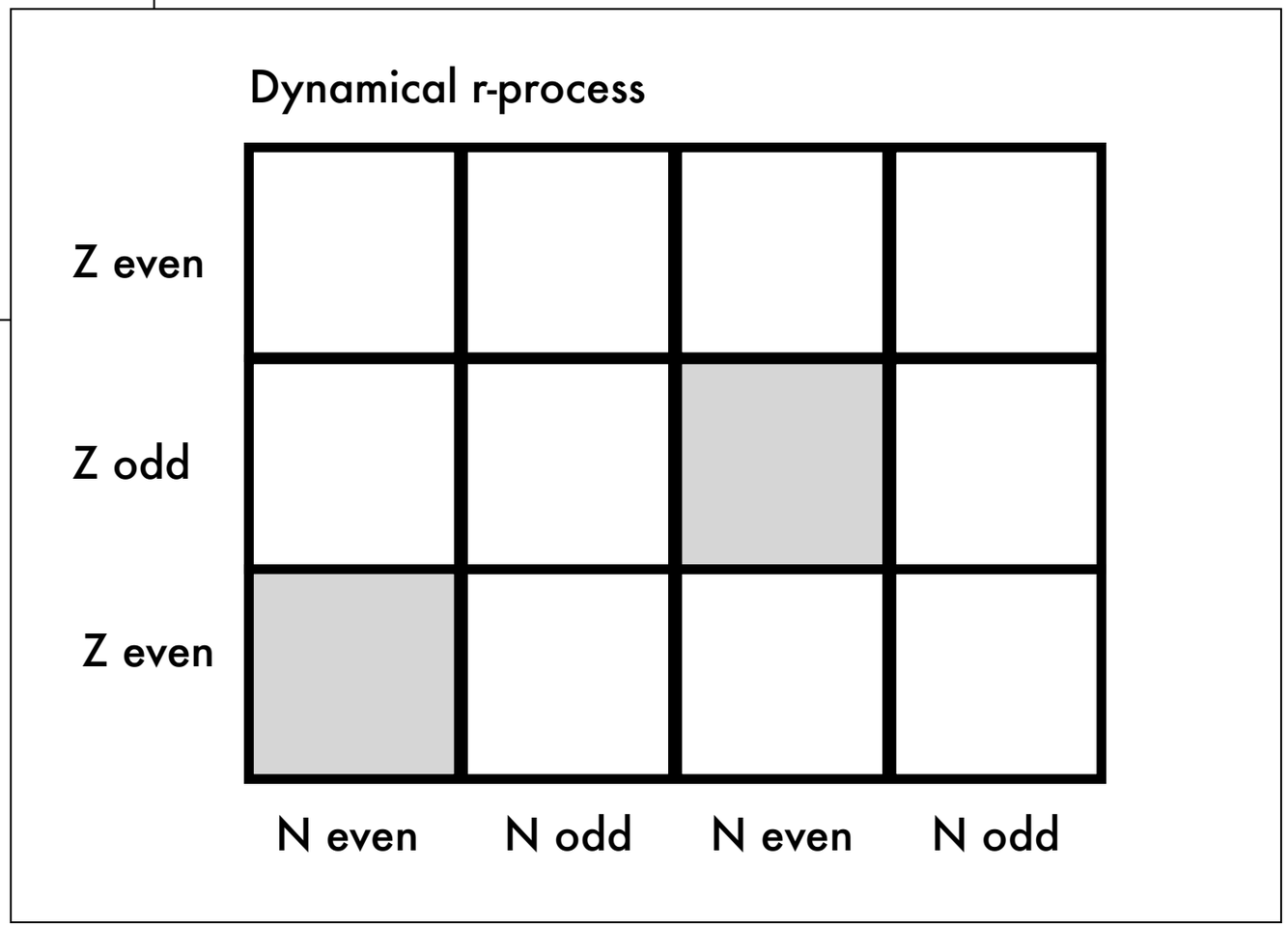

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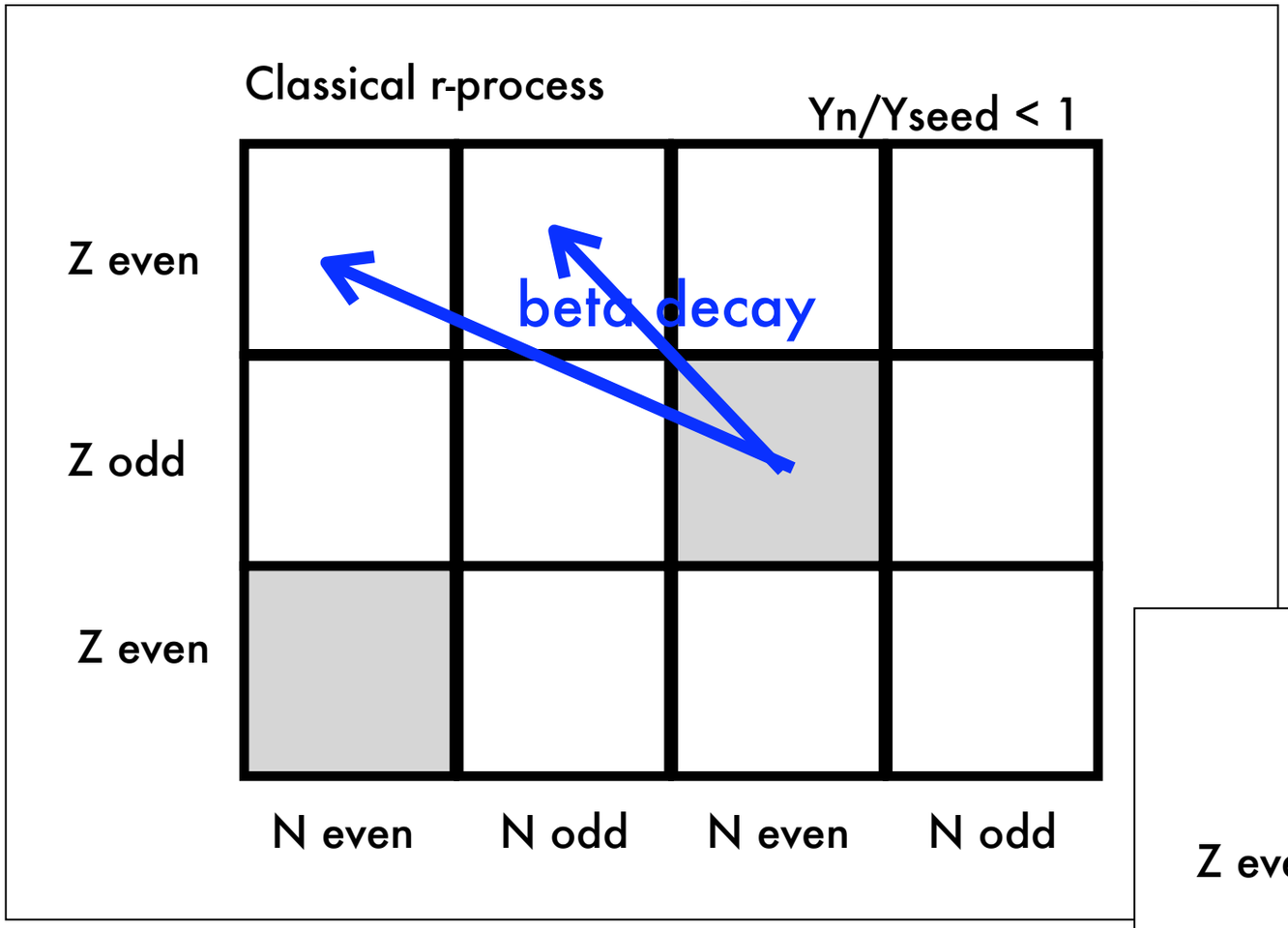


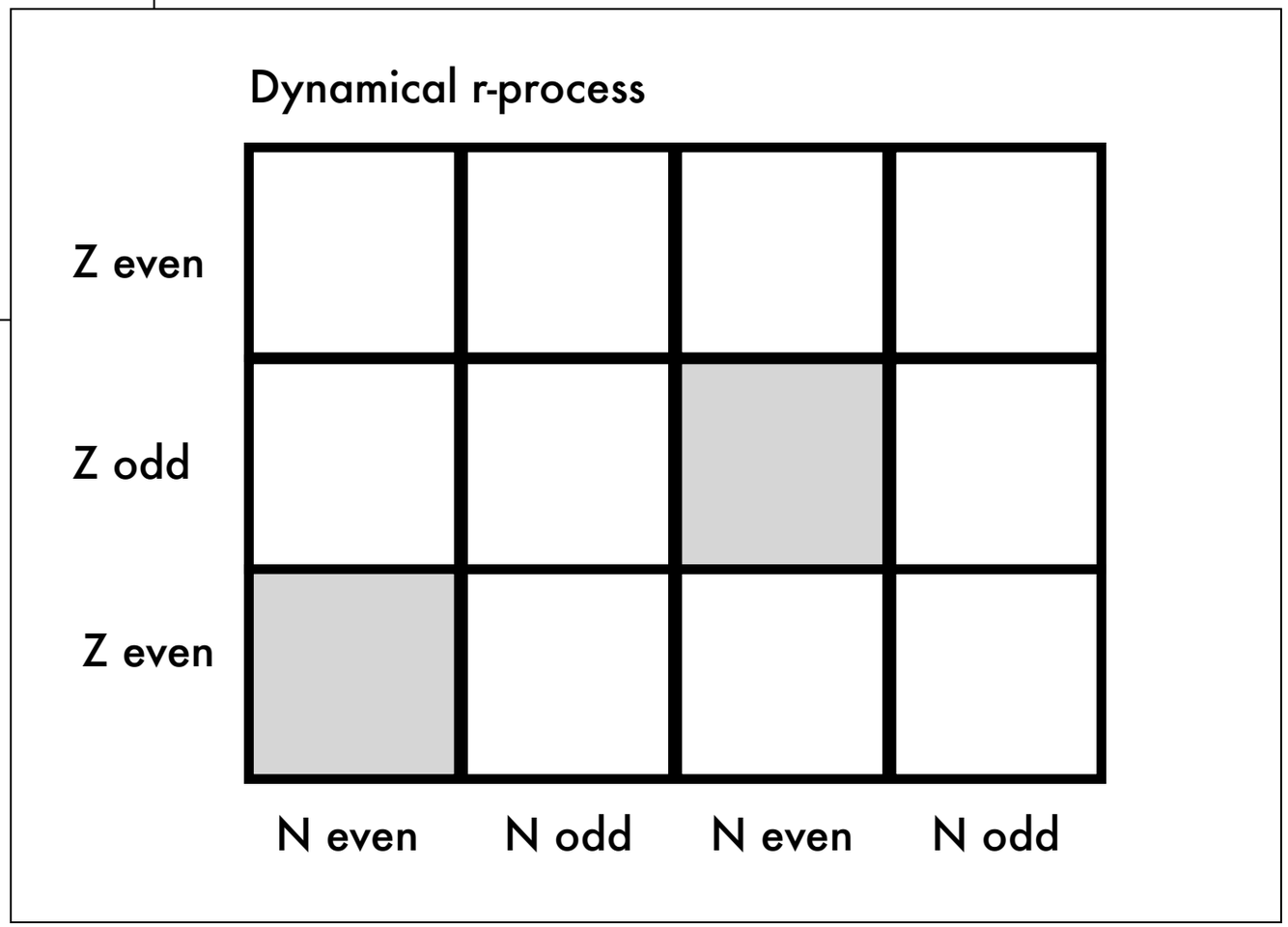

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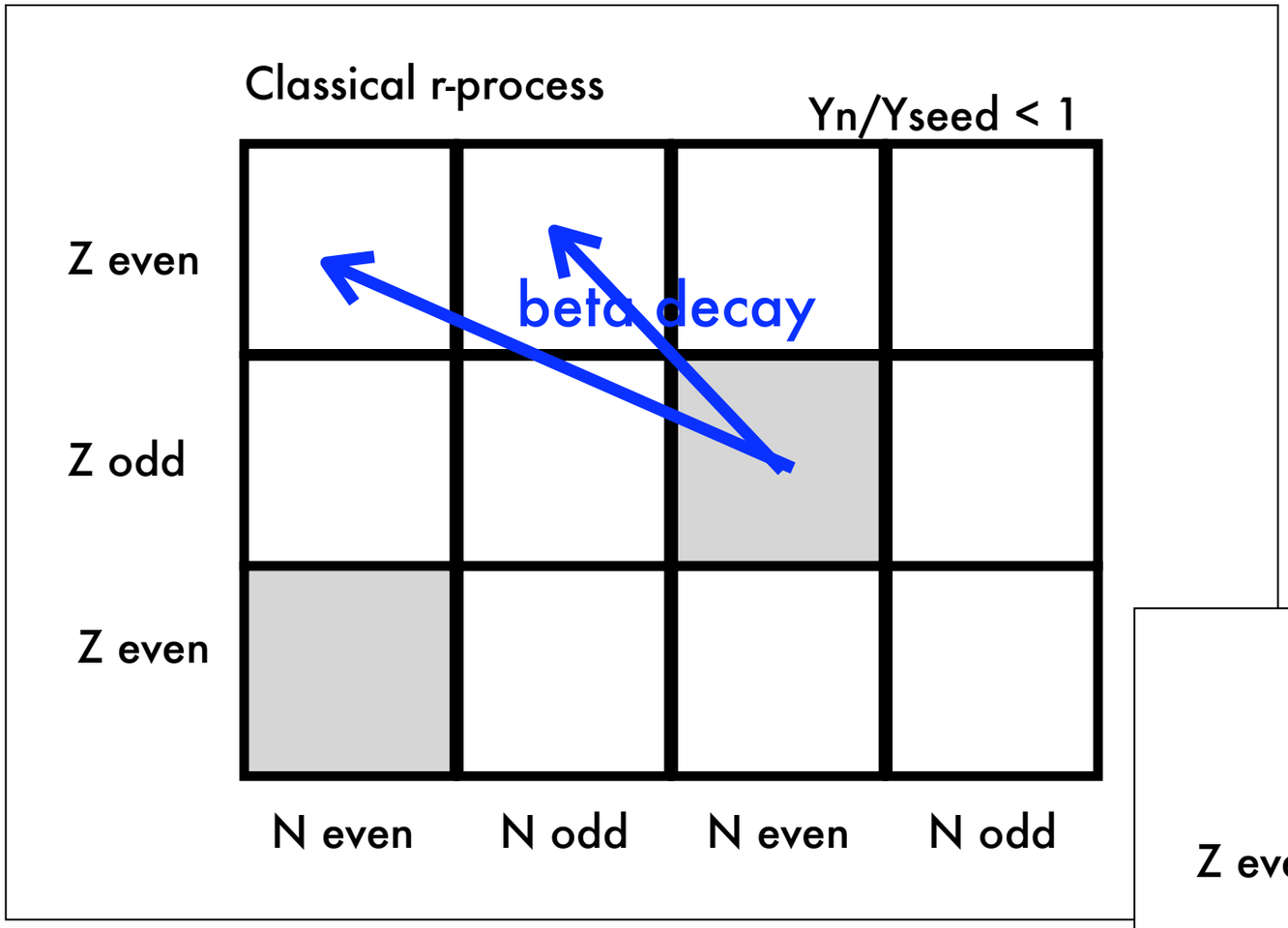
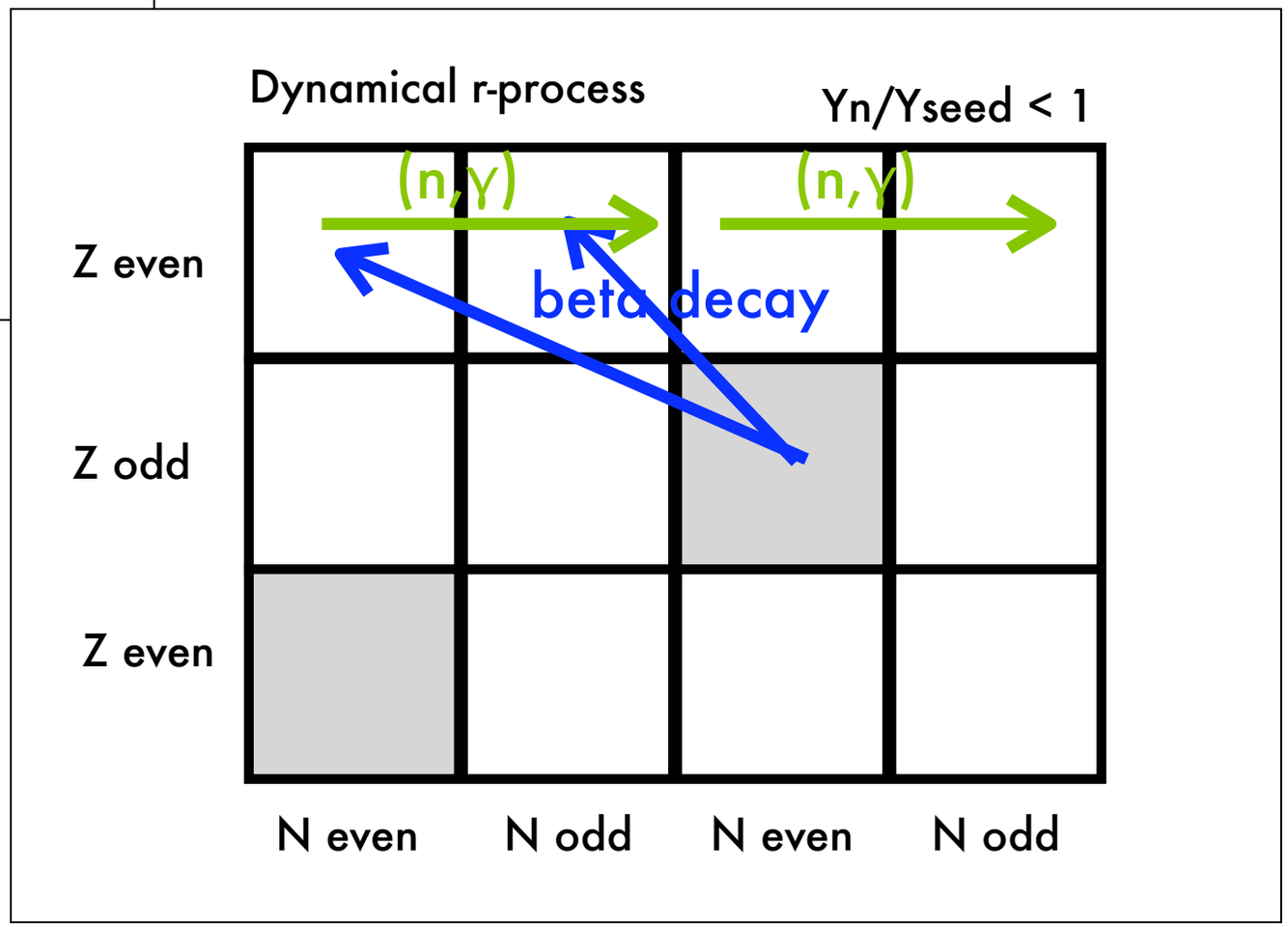
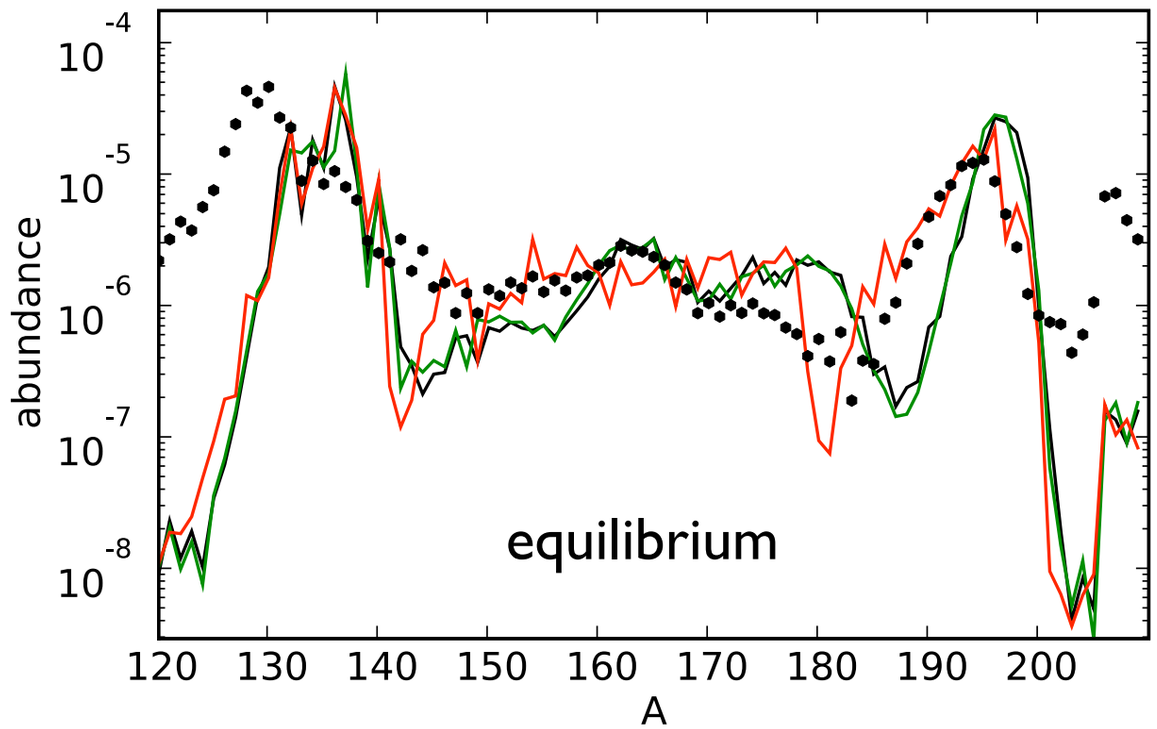



Neutron captures on the way back to stability determine final abundances!



# Neutron captures and beta-delayed neutron emission

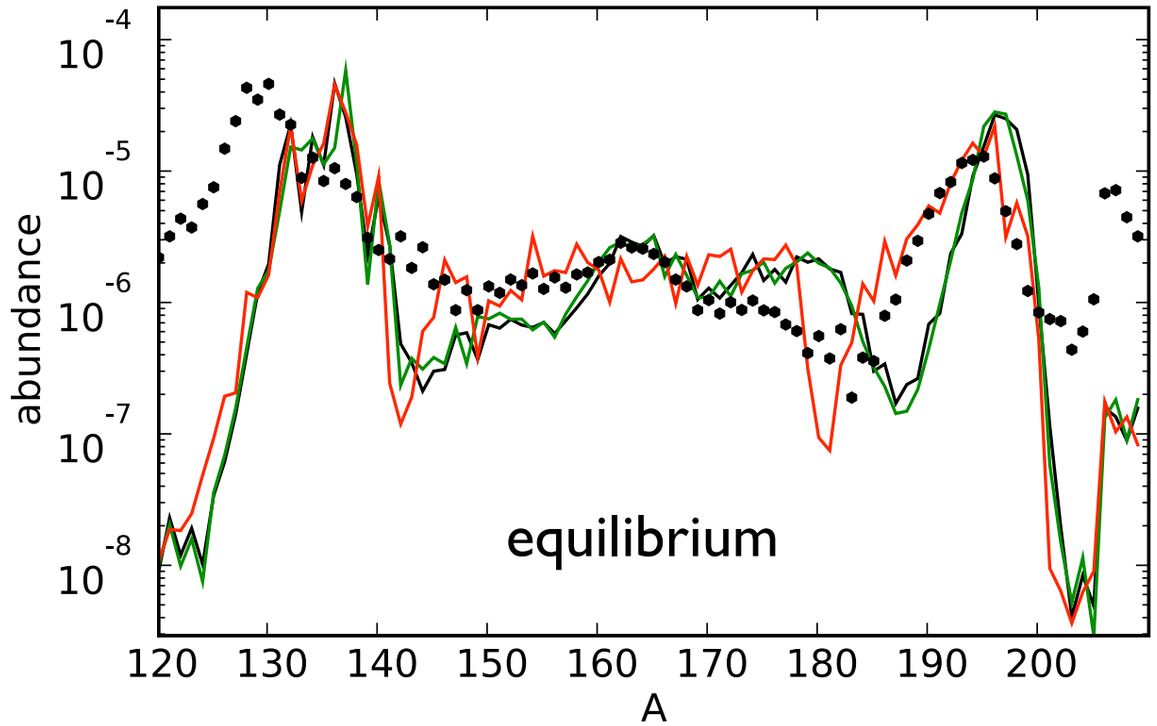



We compare final abundances with and without beta-delayed neutron emission and with and without neutron captures.

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

Arcones & Martinez-Pinedo, in prep.

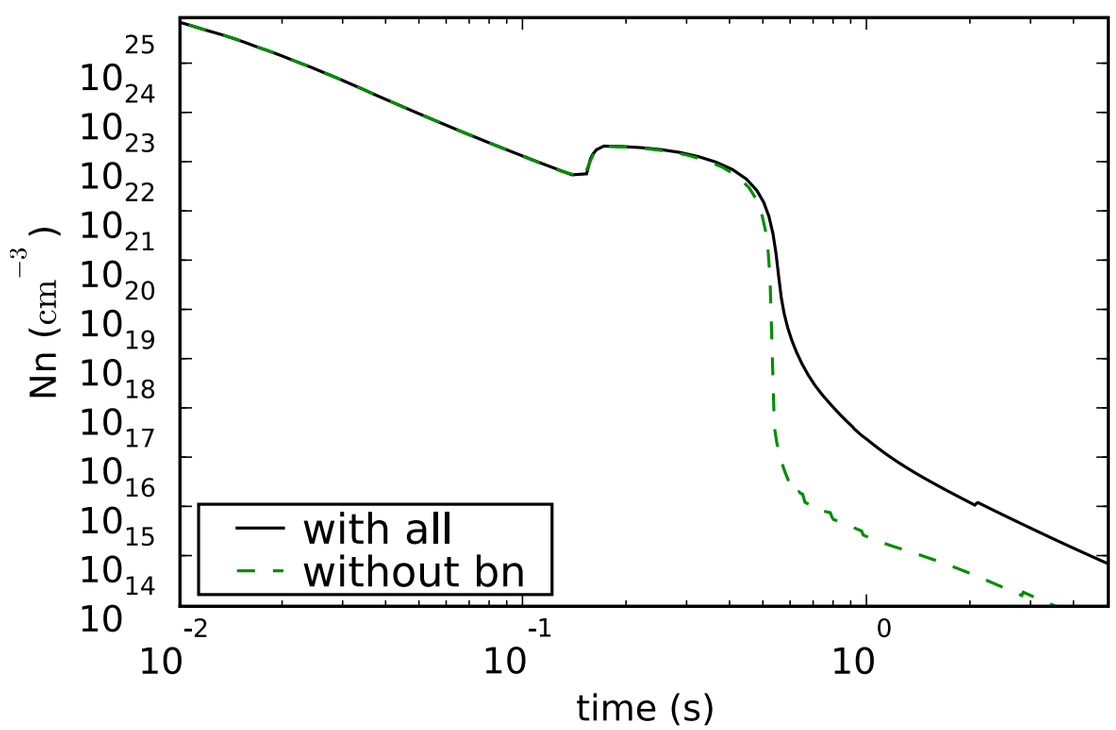
# Neutron captures and beta-delayed neutron emission

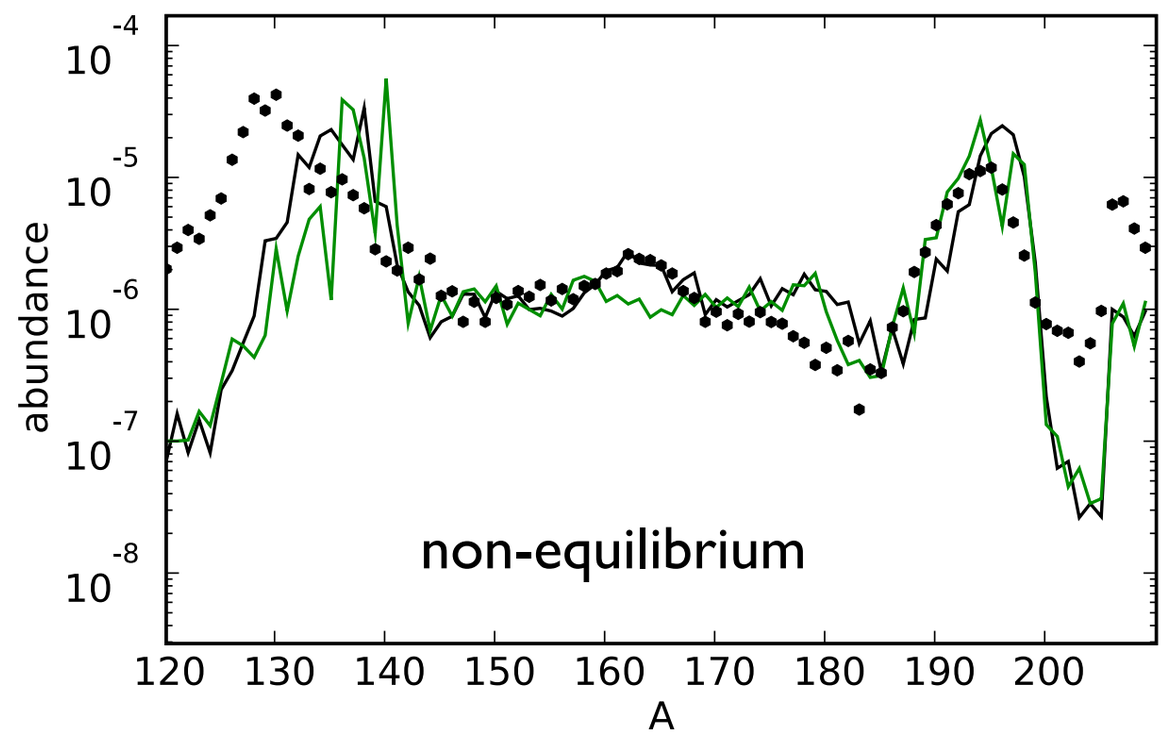



We compare final abundances with and without beta-delayed neutron emission and with and without neutron captures.

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.

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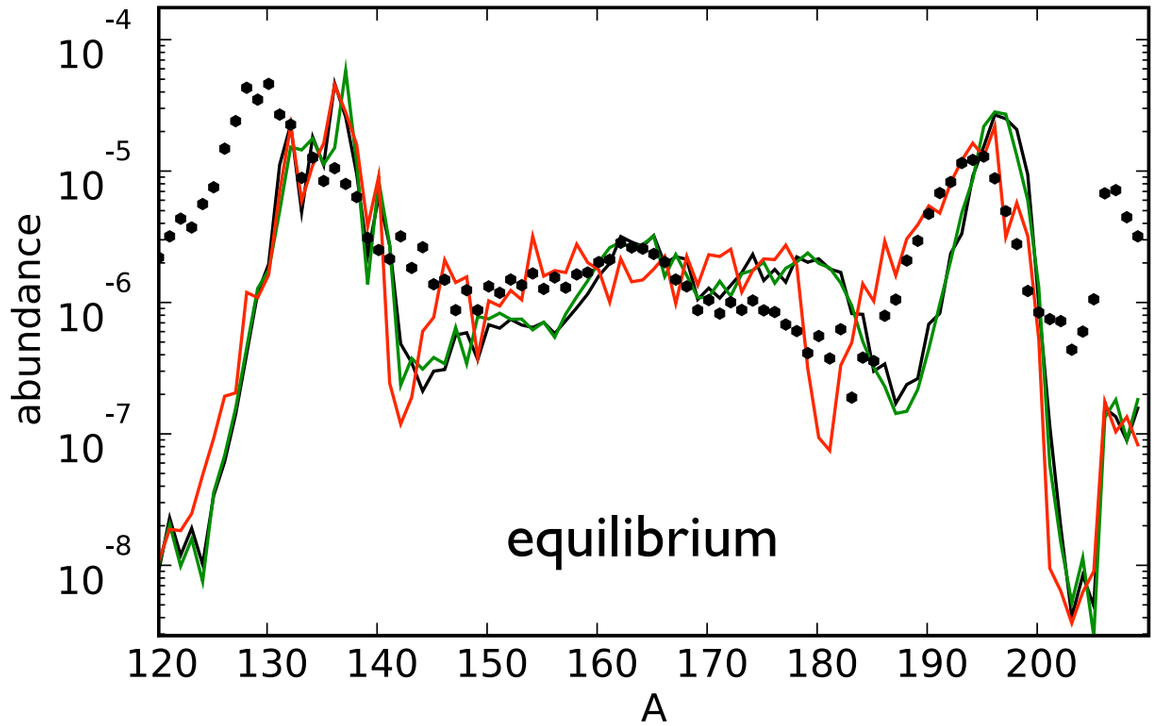


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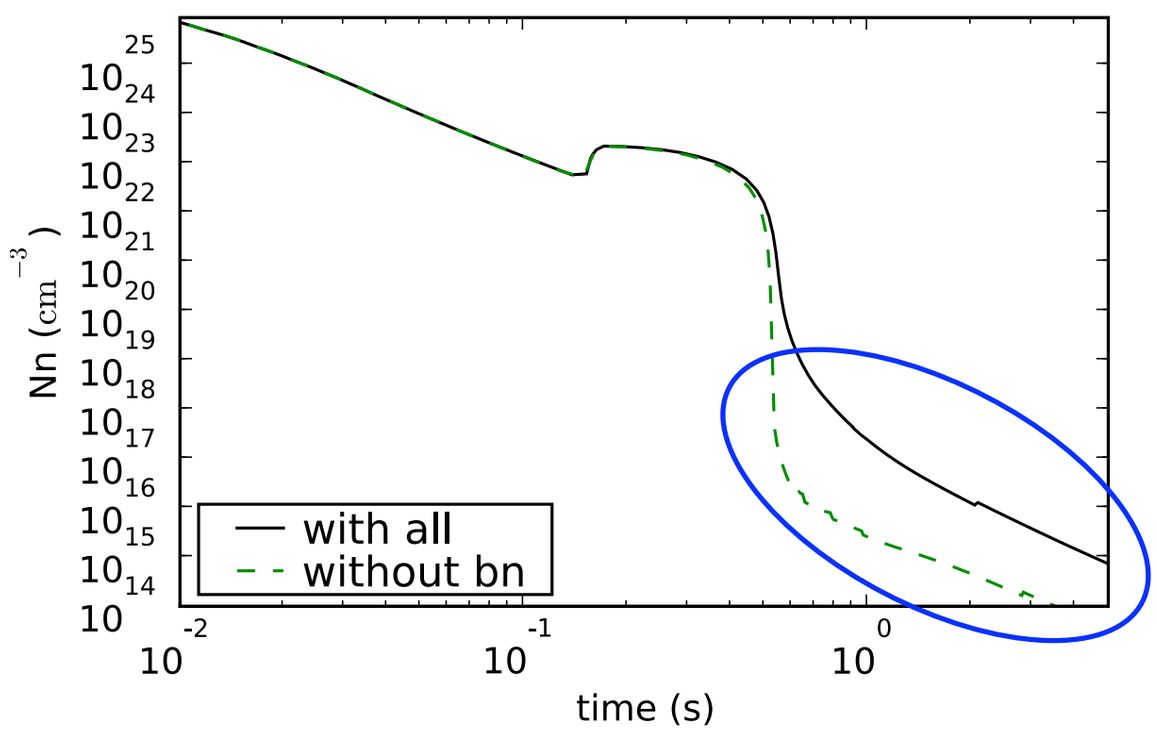
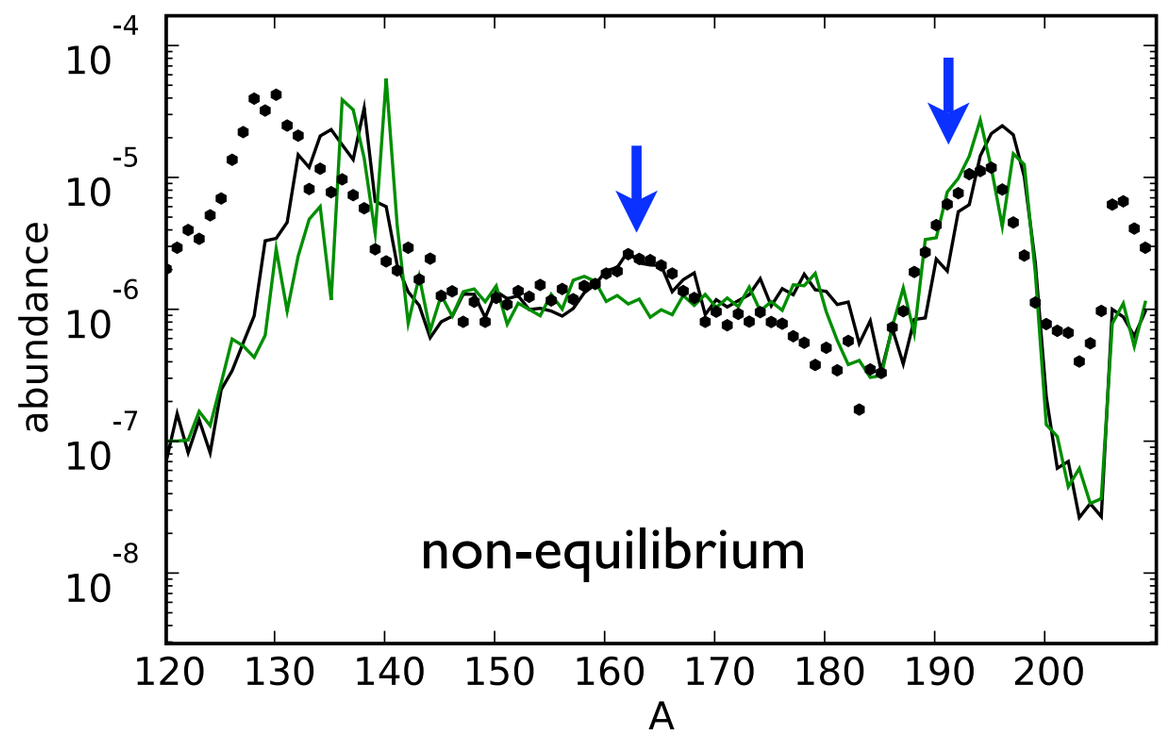
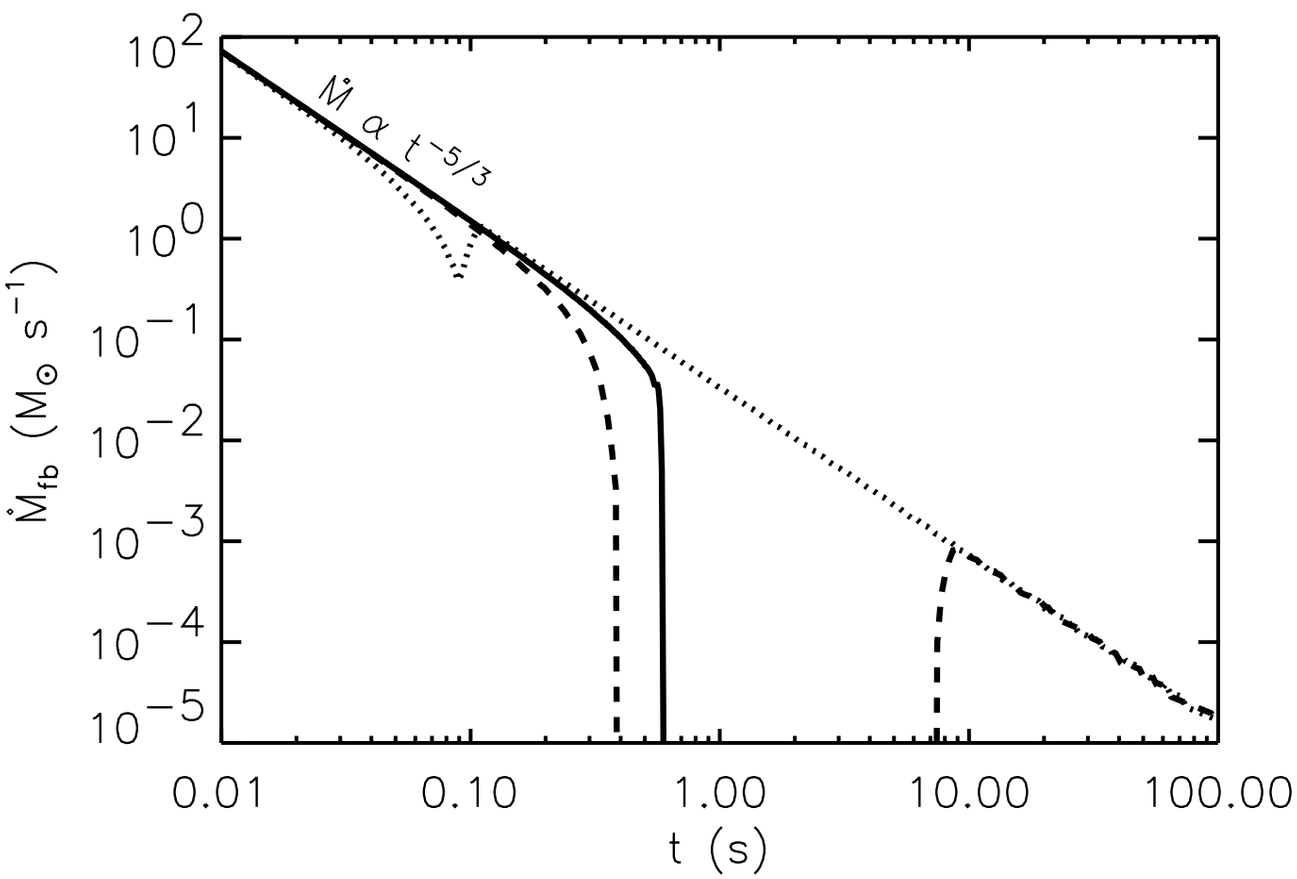


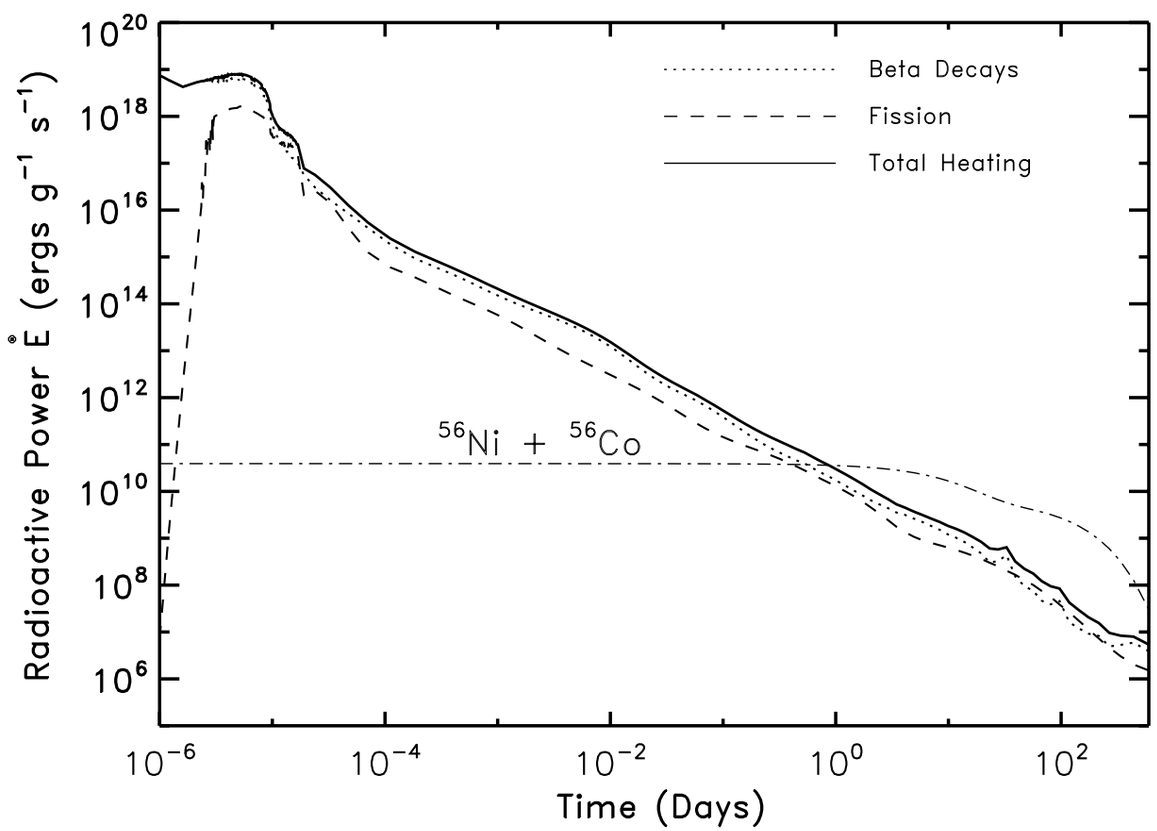




Arcones & Martinez-Pinedo, in prep.

# 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 (submitted): first calculations of the light curve.



# 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).

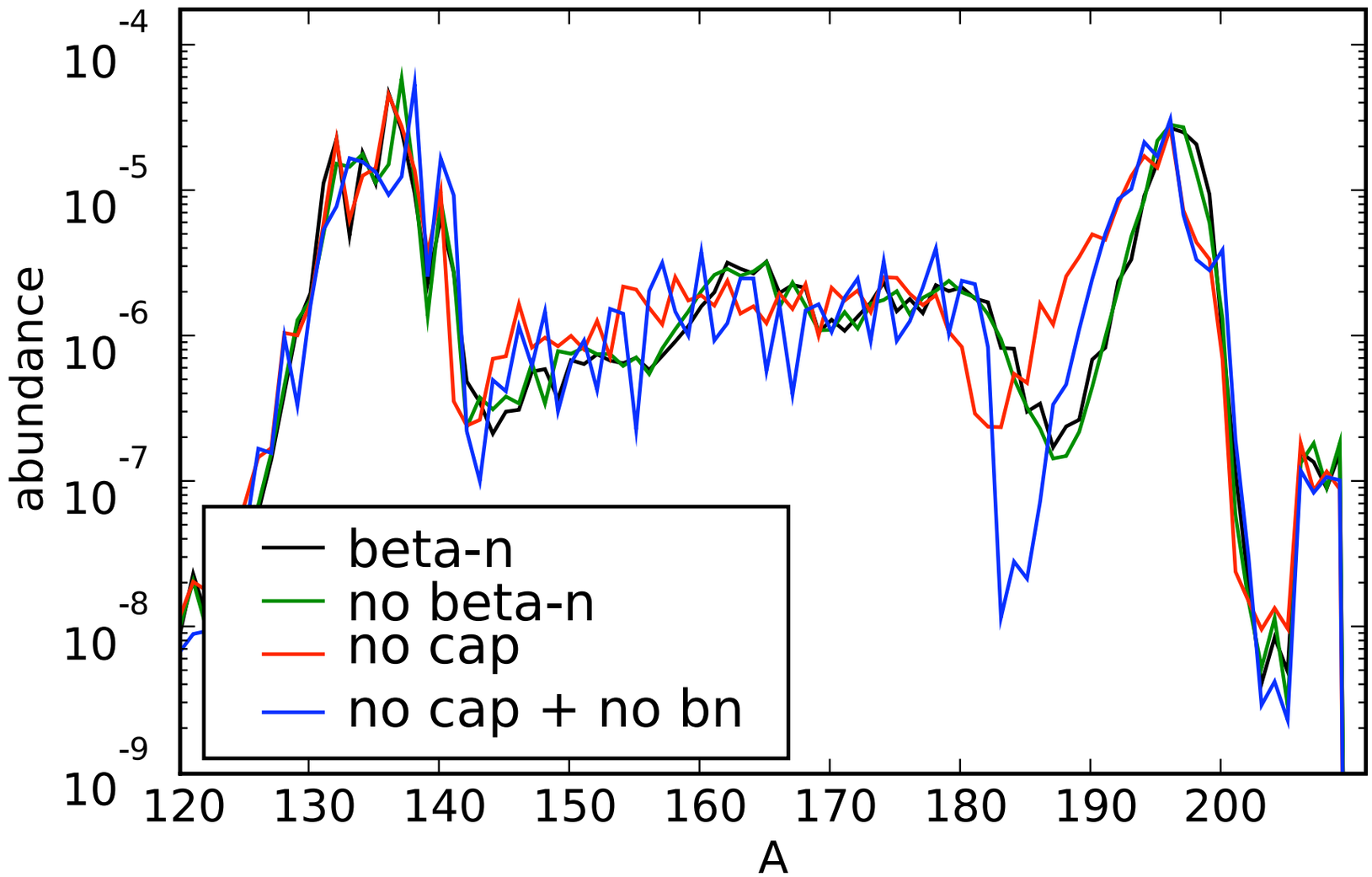
- LEPP pattern is reproduced in neutron- and proton-rich ejecta.

- 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 and direct capture
- 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


abundance
A
beta-n
no beta-n
no cap
no cap + no bn
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
120
130
140
150
160
170
180
190
200