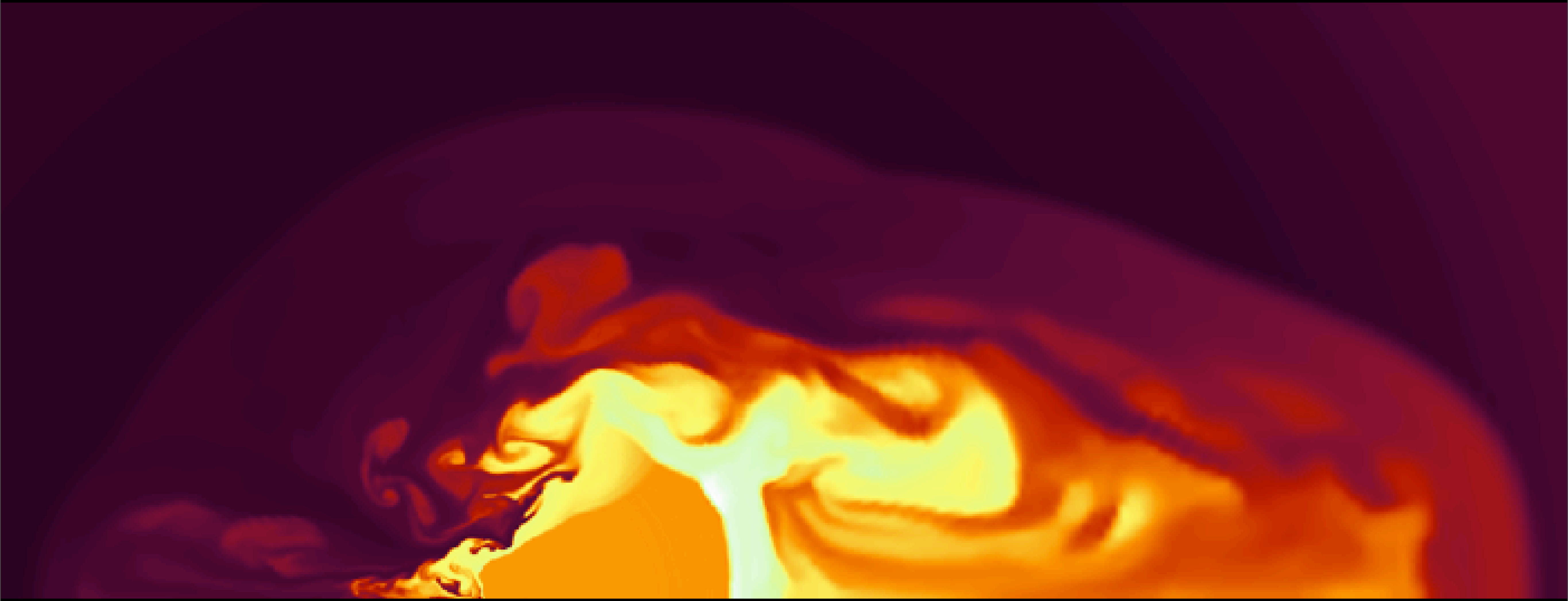
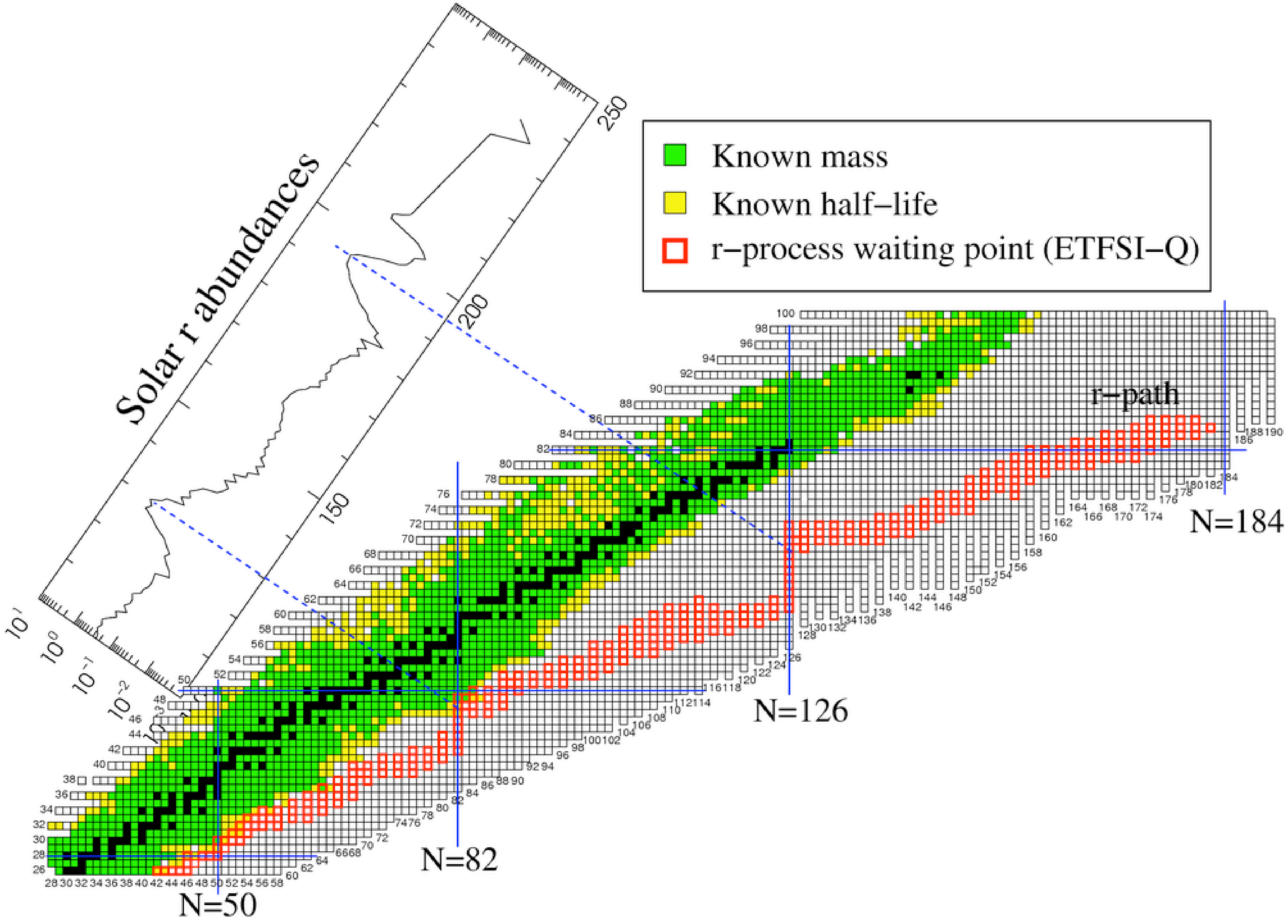
Nucleosynthesis in neutrino-driven winds



Almudena Arcones (GSI & TU Darmstadt)
Gabriel Martinez-Pinedo (GSI) and H. Thomas Janka (MPA)

R-process

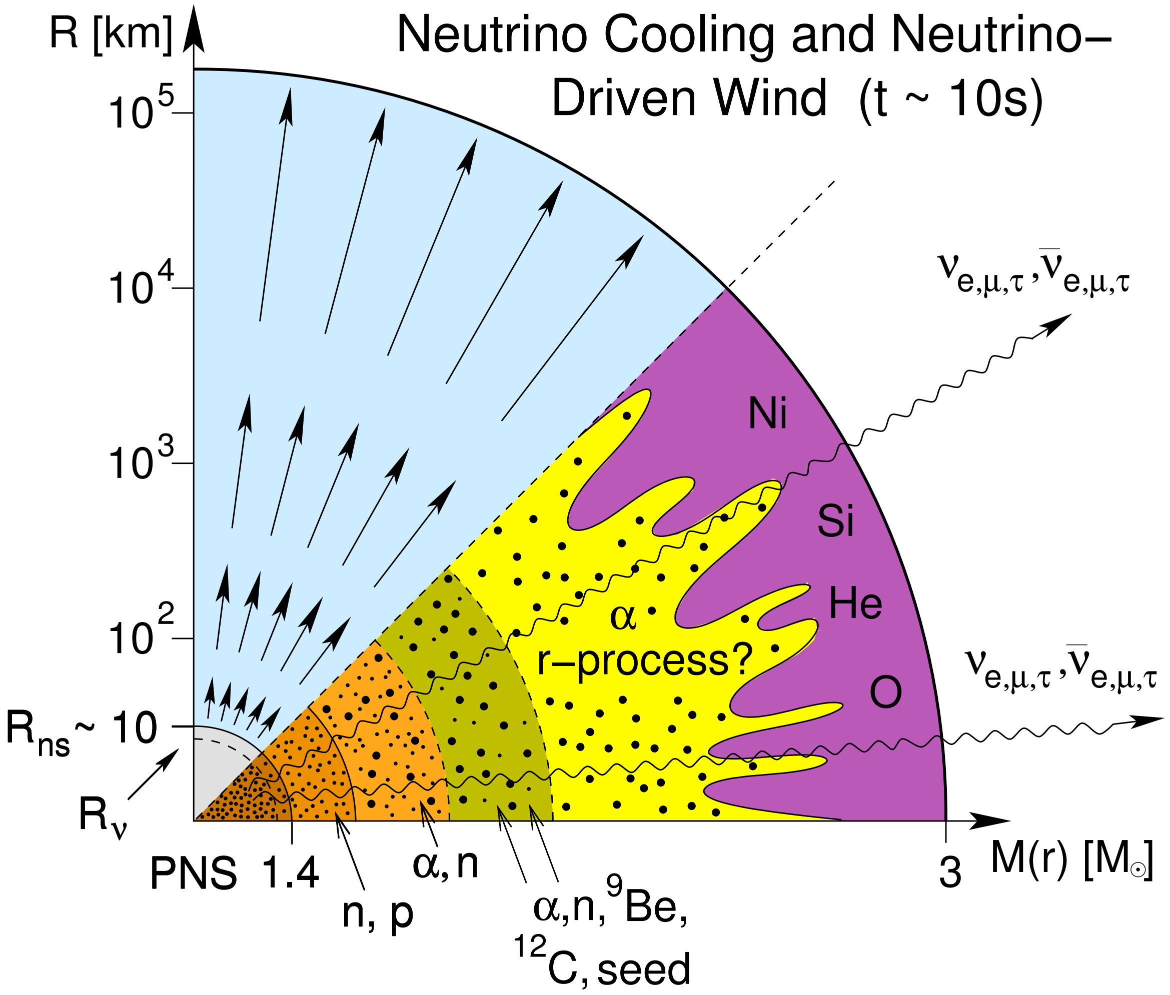
Half of the heavy elements are produced by rapid neutron capture.



- neutron-to-seed ratio has to be high (~100)→ which astrophysical scenario fulfils this?
- observations (solar and old stars abundances) have to be reproduced → details along the r-process path are relevant: dynamical evolution and nuclear physics.

Neutrino-driven wind and r-process

After the onset of a supernova explosion the density around the proto-neutron star decreases. The ongoing energy deposition by neutrinos in this region leads to the formation of a neutrino-driven wind (independent of the details of the explosion mechanism).



Conditions for the r-process (Y_n/Y_{seed} ↑):

- fast expansion: not enough time for the alpha process to form seeds,
- $Y_e = n_p/(n_n+n_p) < 0.5$,
- high entropy.

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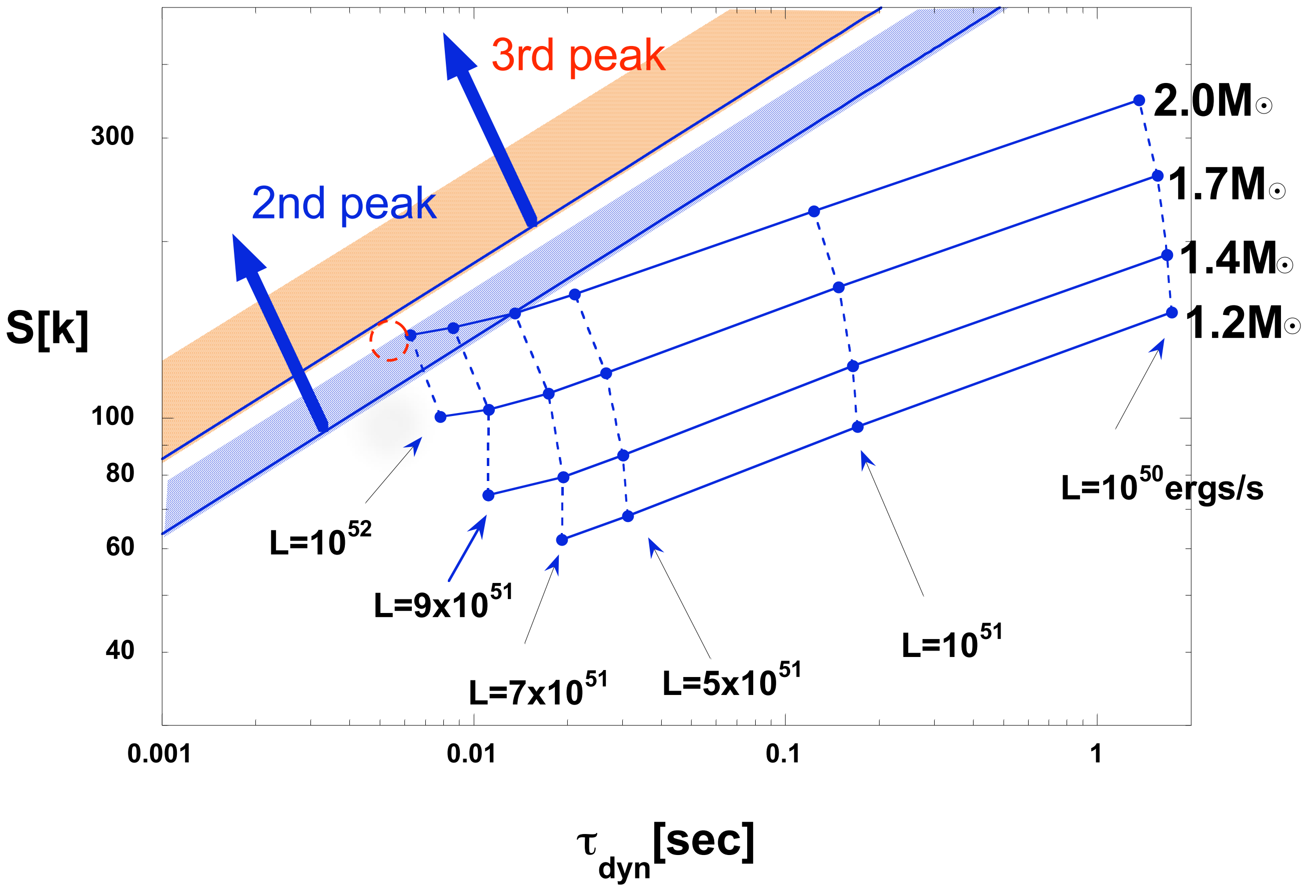
Otsuki et al. 2000



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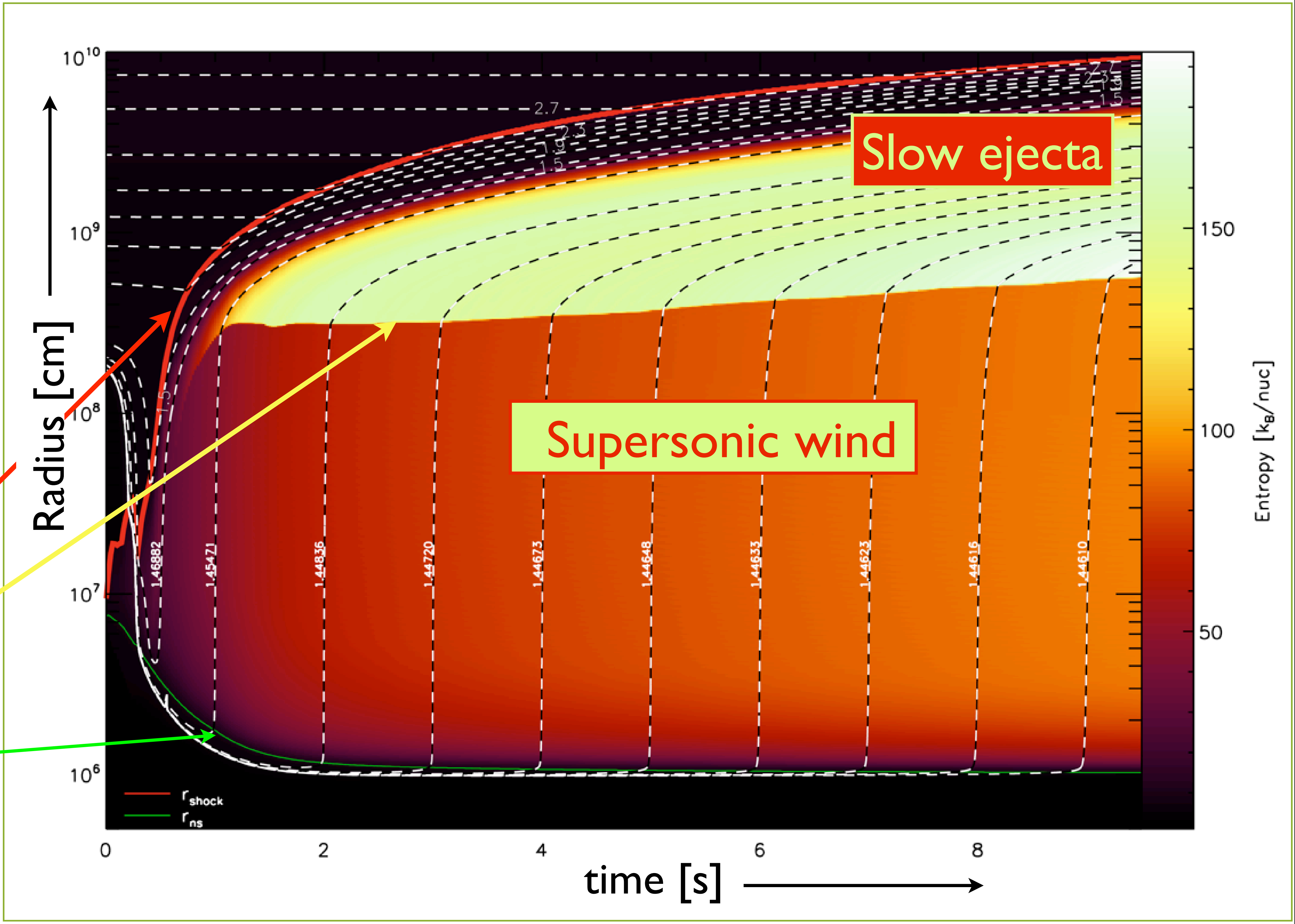
Seed production is understood but conditions required for the r-process are not found in standard winds (Otsuki et al 2000, Thompson et al 2001). What is missing? Other scenario?

Supernova simulations

Wind velocities become supersonic in the frame of the slow-moving ejecta → reverse shock forms.

Mass shell trajectories + entropy



Shock

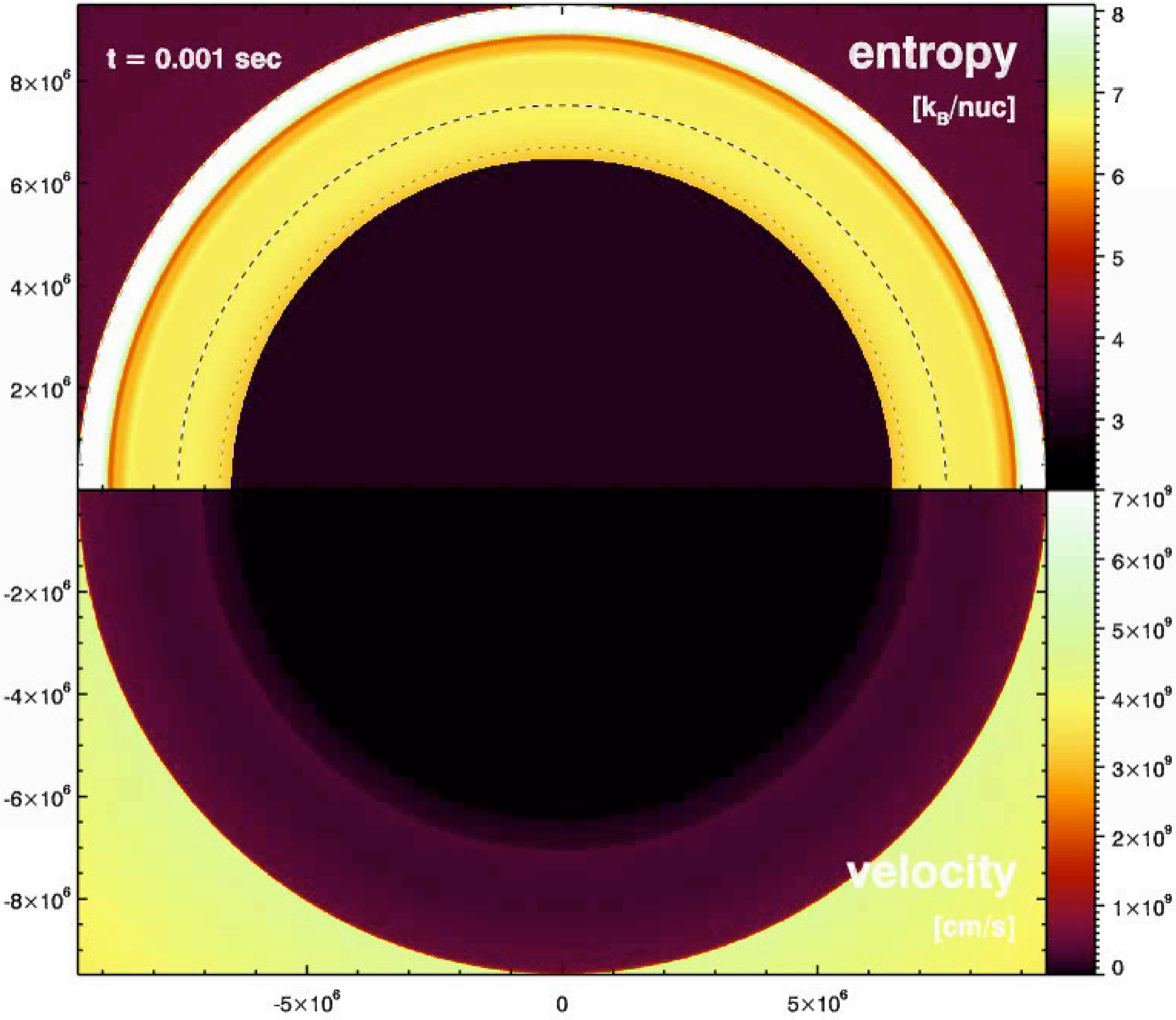
Reverse shock

Neutron star

$15M_{sun}$ progenitor

A.Arcones et al. (2007)

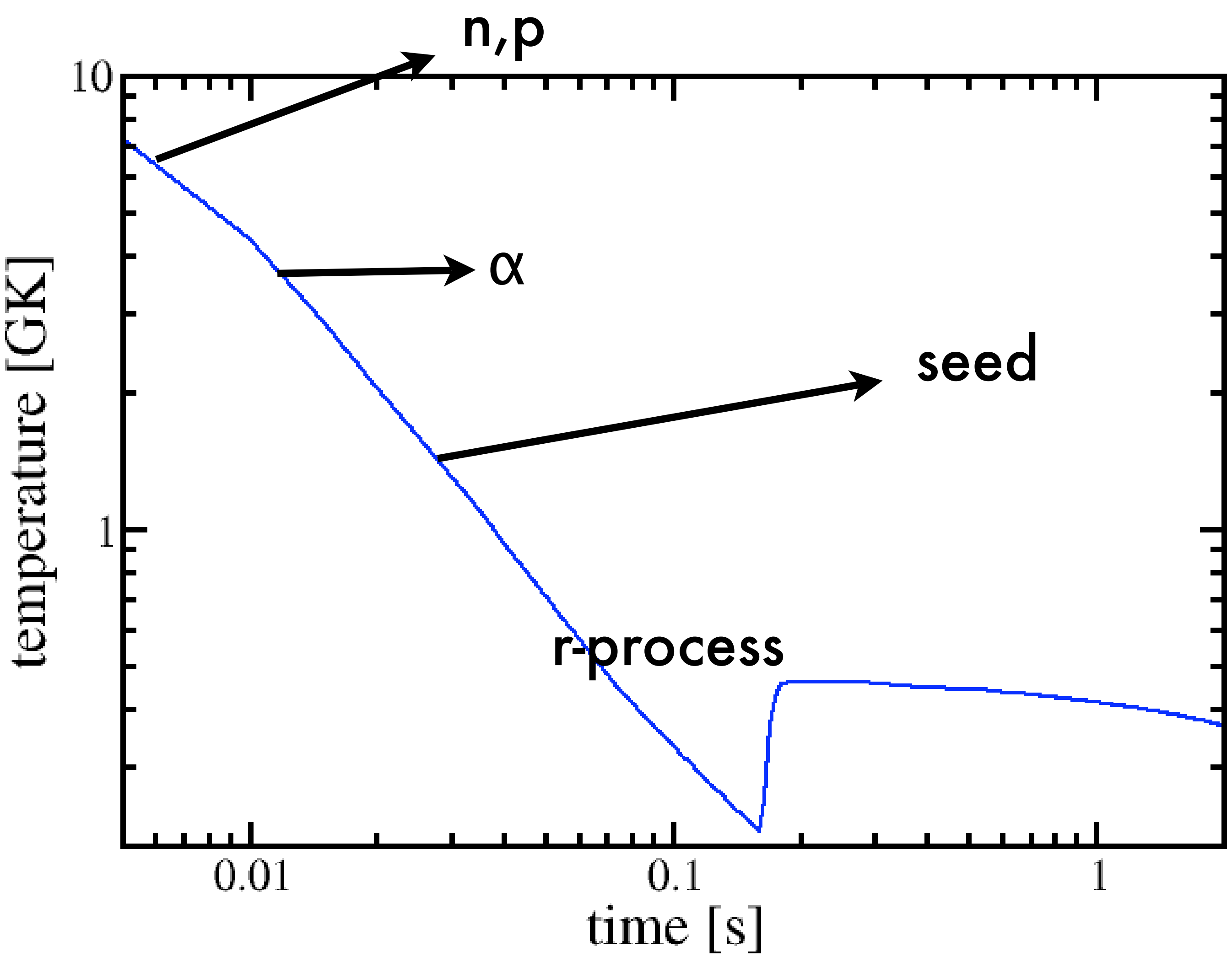
Two-dimensional simulations



Nucleosynthesis

Our aim is to analyze the influence that both the reverse shock and the nuclear physics input have in the final abundances (A.Arcones, G. Martinez-Pinedo (in prep.)).

- The reverse shock determines the late time evolution in density and temperature and consequently determined the relevant nuclear physics input.
- For a given conditions we want to find out the relevant nuclear physics input that determined the final abundances.

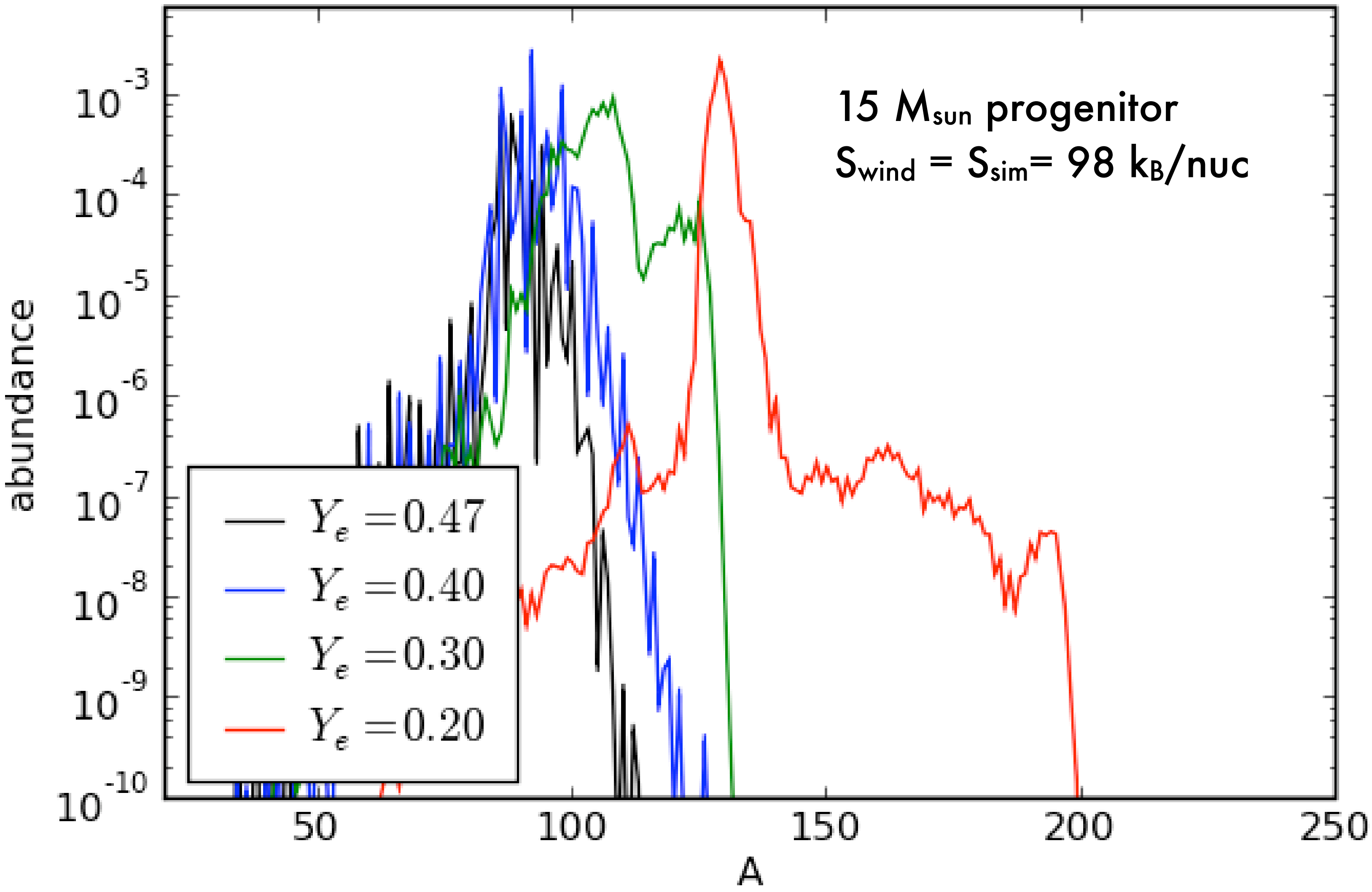


Density and temperature from the hydrodynamical simulations are used as input for the nucleosynthesis network. Electron fraction is taken as a parameter.

Seed formation and conditions for high neutron-to-seed ratio are well understood, but not fulfilled, therefore we reduce the electron fraction or increase the entropy. That allows us to study the later r-process phase.

Nucleosynthesis: initial electron fraction variations

One possibility the get heavier nuclei is to start the network calculation with more neutron rich material, i.e. lower electron fraction.
This is justified since Y_e depends strongly on the neutrino luminosities and spectra, which are affected by details on the region where neutrinos decouple from matter (A.Arcones et al. 2008).



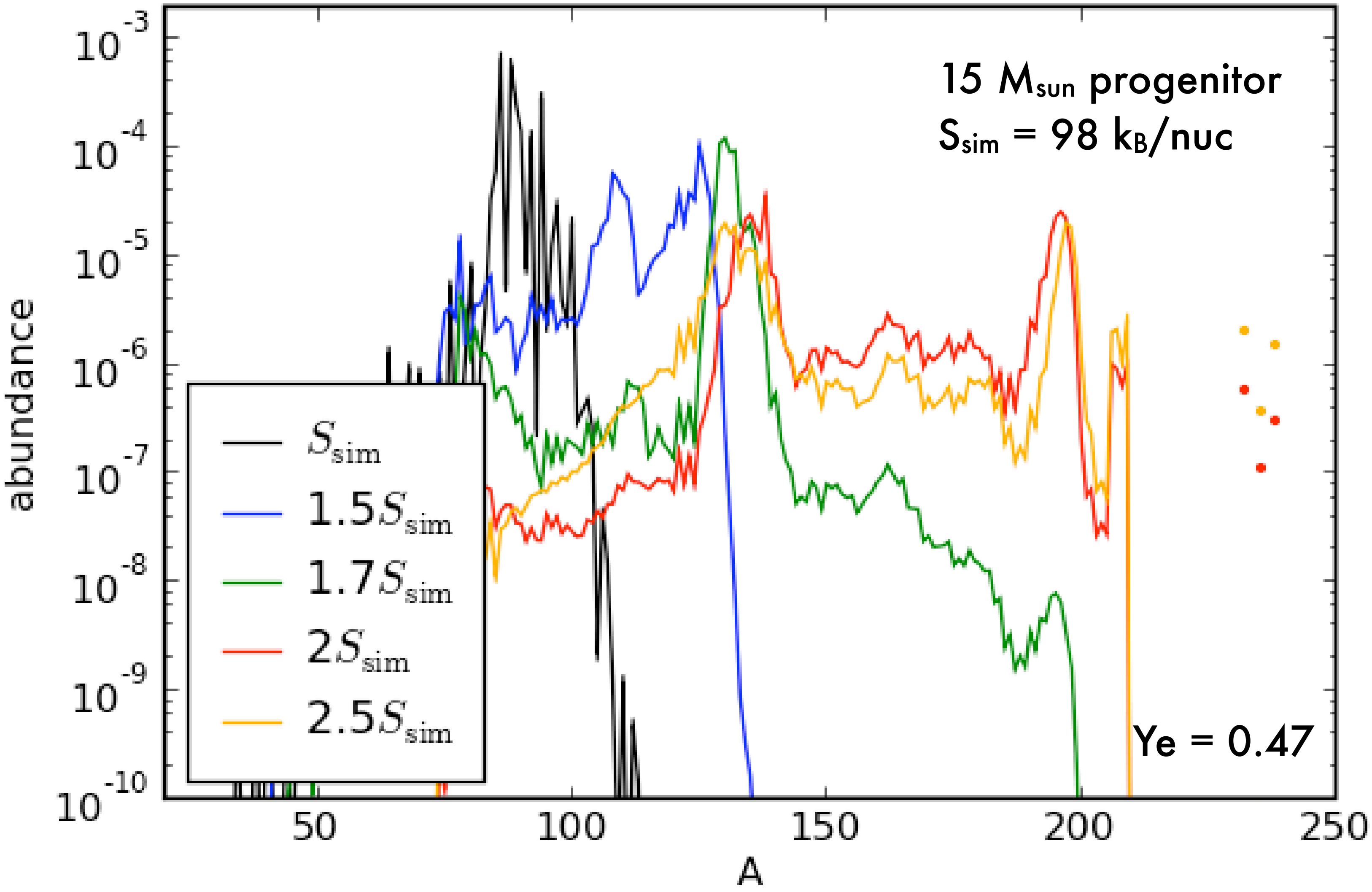
Estimation of the wind electron fraction:

$$Y_e^{\mathrm{w}} = \frac{\lambda_{\nu_e n}}{\lambda_{\nu_e n} + \lambda_{\bar{\nu}_e p}}\,.$$

with $\lambda \propto e_\nu^2 L_\nu$

Nucleosynthesis: entropy variations

Entropy has to be increased by a factor of 2 to reach the region of A =195.
This factor is still lower than the factor 5 needed in previous studies (Takahashi et al. (1994)) where the expansion was slower.
For more massive progenitor (25M_{sun}) also smaller factor is required since neutron star is more massive.



We take S_{wind}=2S_{sim} =200 and Ye like in the simulation in the following studies.

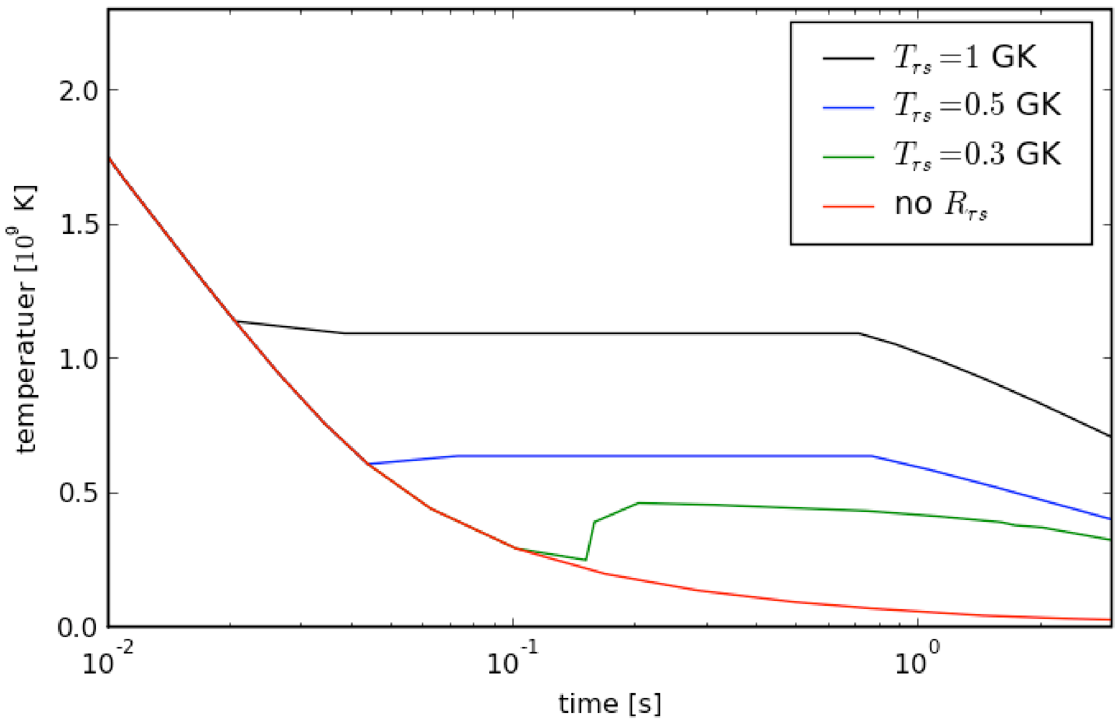
Nucleosynthesis: reverse shock

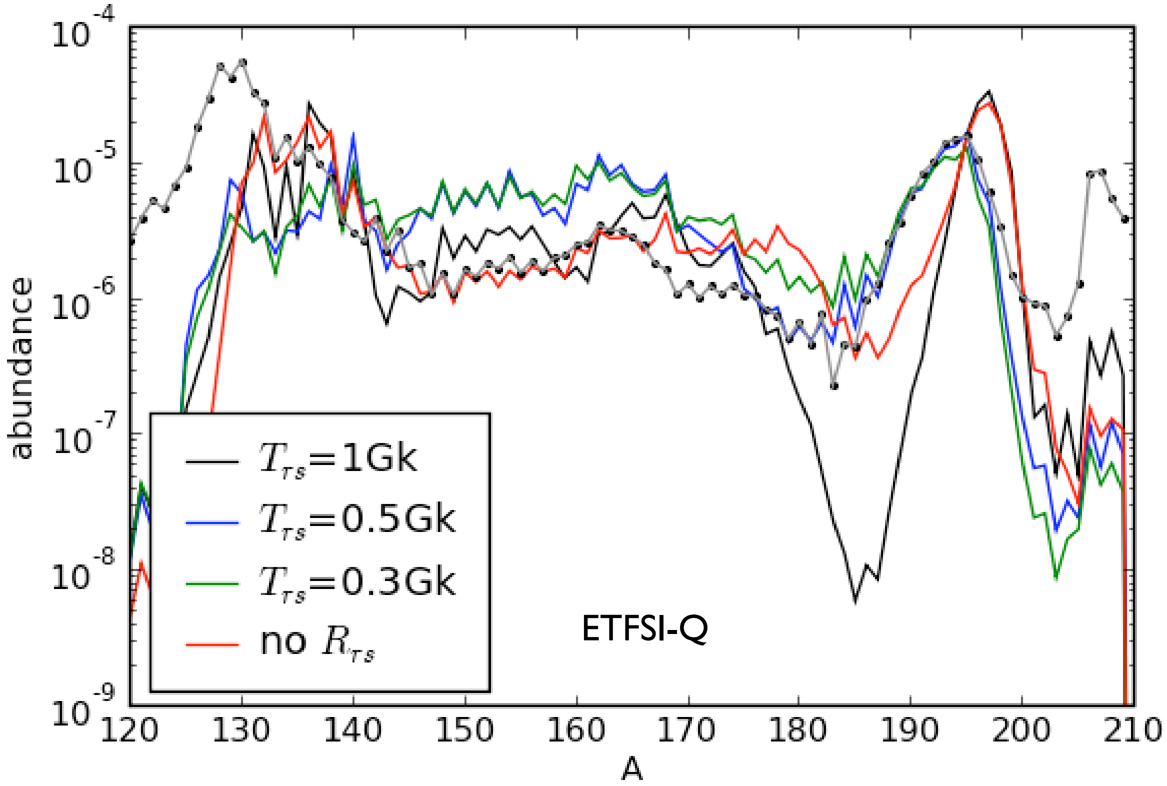
To evaluate the influence of the wind termination shock, we artificially vary its position. If the reverse shock is placed at:

- high temperatures => the evolution takes place under (n,γ)-(γ,n) equilibrium (classical r-process, Kratz et al. 1993)
- low temperatures => there is competition between neutron capture and beta decay (Blake & Schramm 1976).

This translates into different r-process paths and, therefore, changes in the final abundances.

Moreover, the relevant nuclear physics input also changes depending on the evolution.

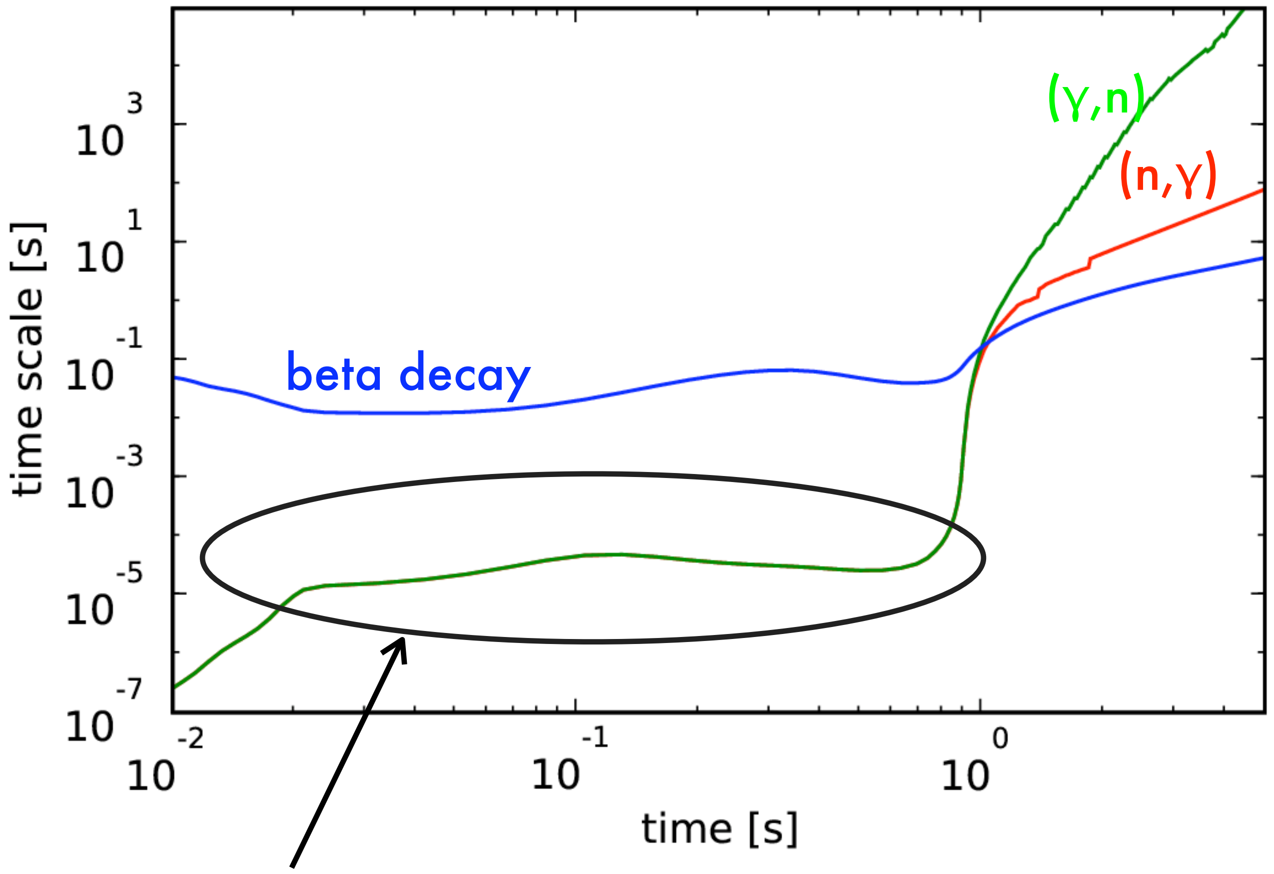




15 M_{sun} & S ≈ 200 k_B/nuc

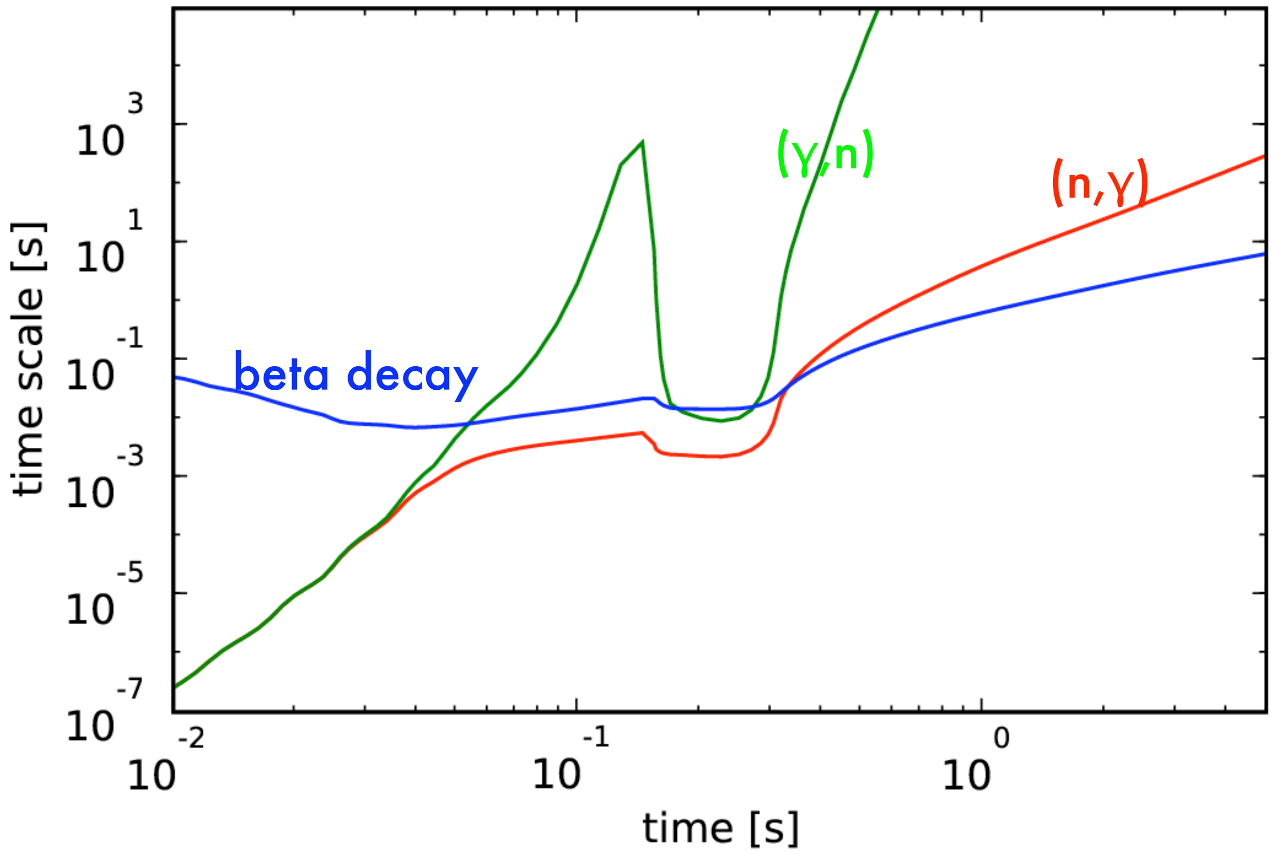
Nucleosynthesis: different evolutions

high temperatures: (n,γ)-(γ,n) equilibrium



In equilibrium the masses (neutron separation energies) play an important role: $Y(Z,A+1)/Y(Z,A) \propto \exp(Sn/kT)$

low temperatures: no equilibrium



At low temperature, there is a competition between beta decay and neutron capture

Nucleosynthesis: different evolutions

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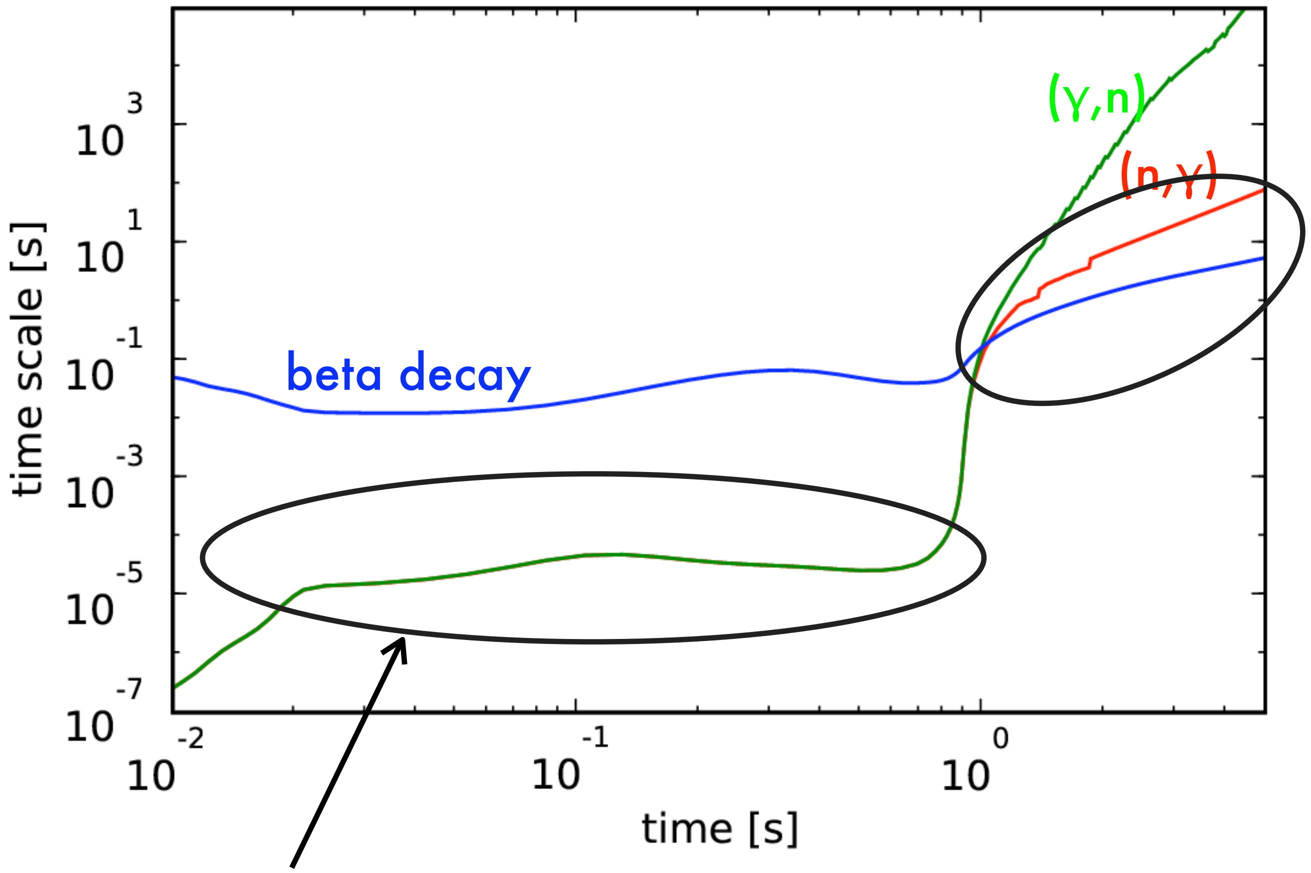

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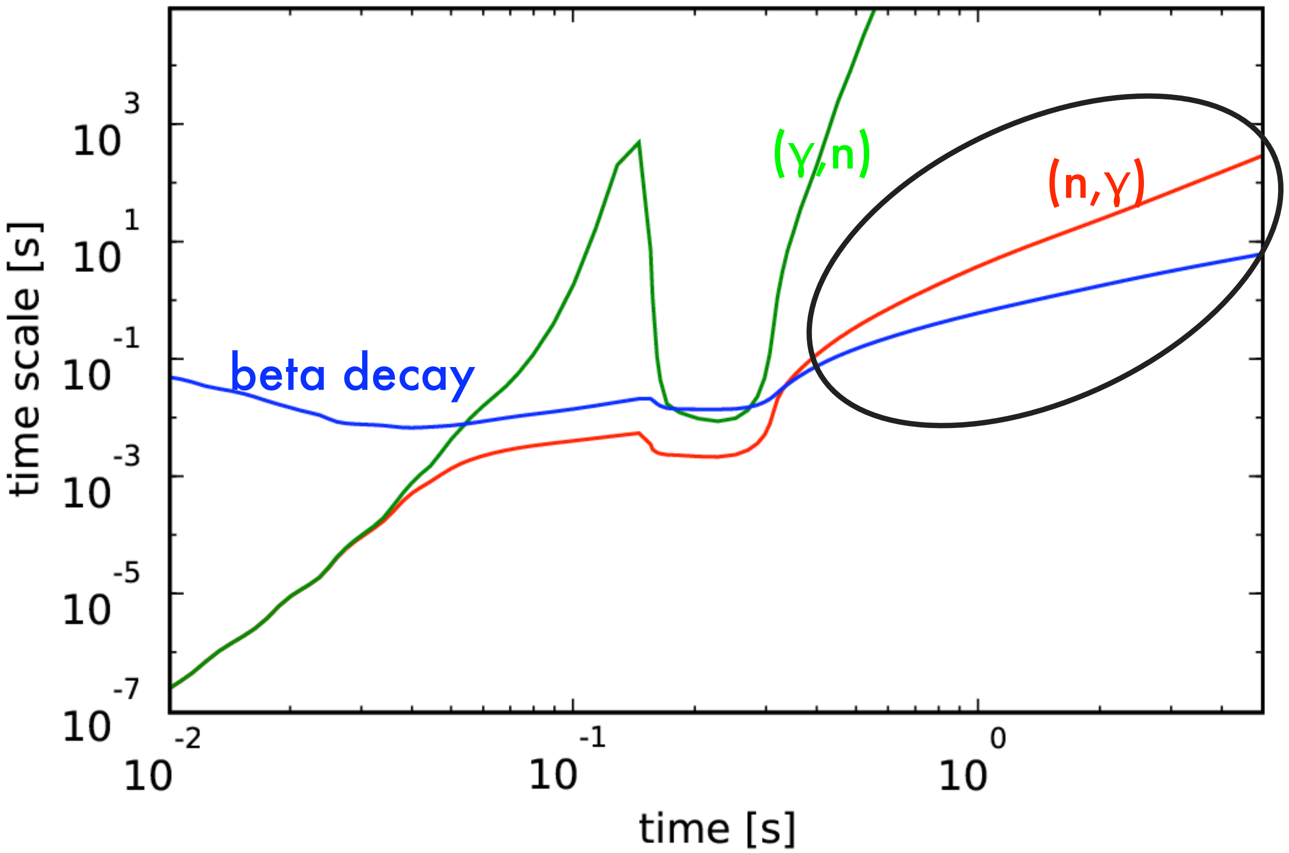
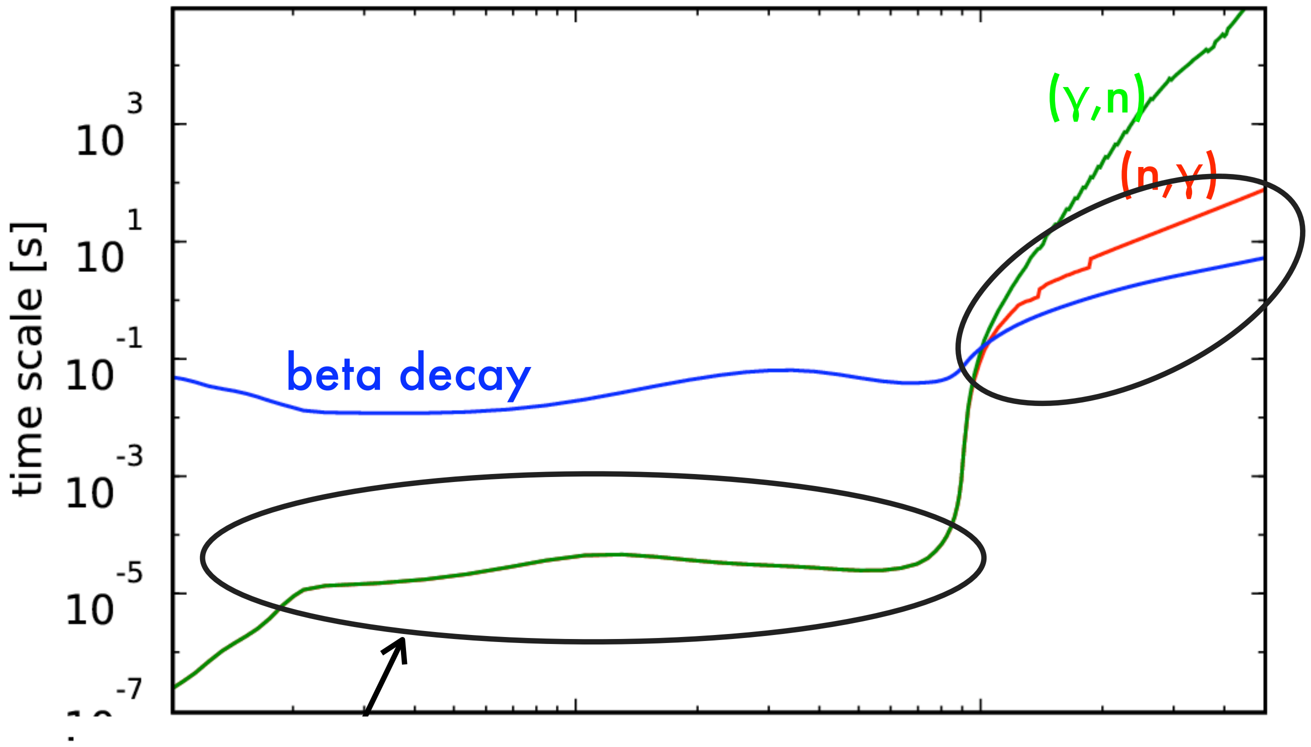


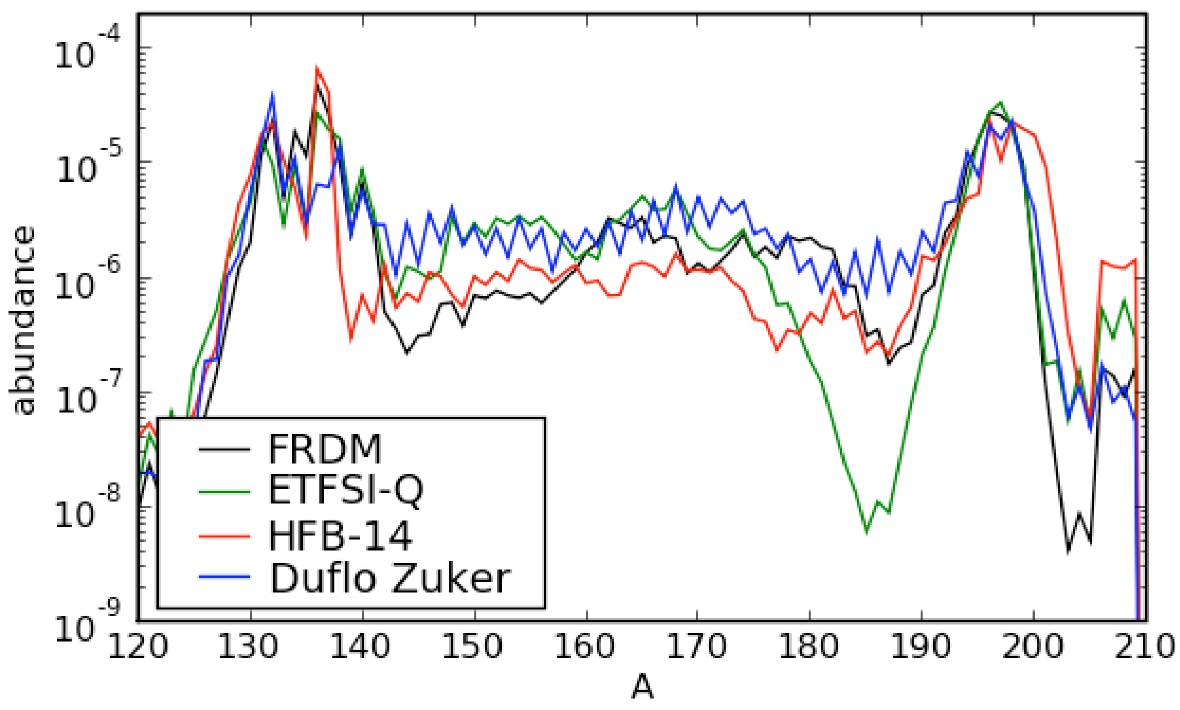
At low temperature, there is a competition between beta decay and neutron capture

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

Nucleosynthesis: different evolutions

high temperatures: (n,γ)-(γ,n) equilibrium





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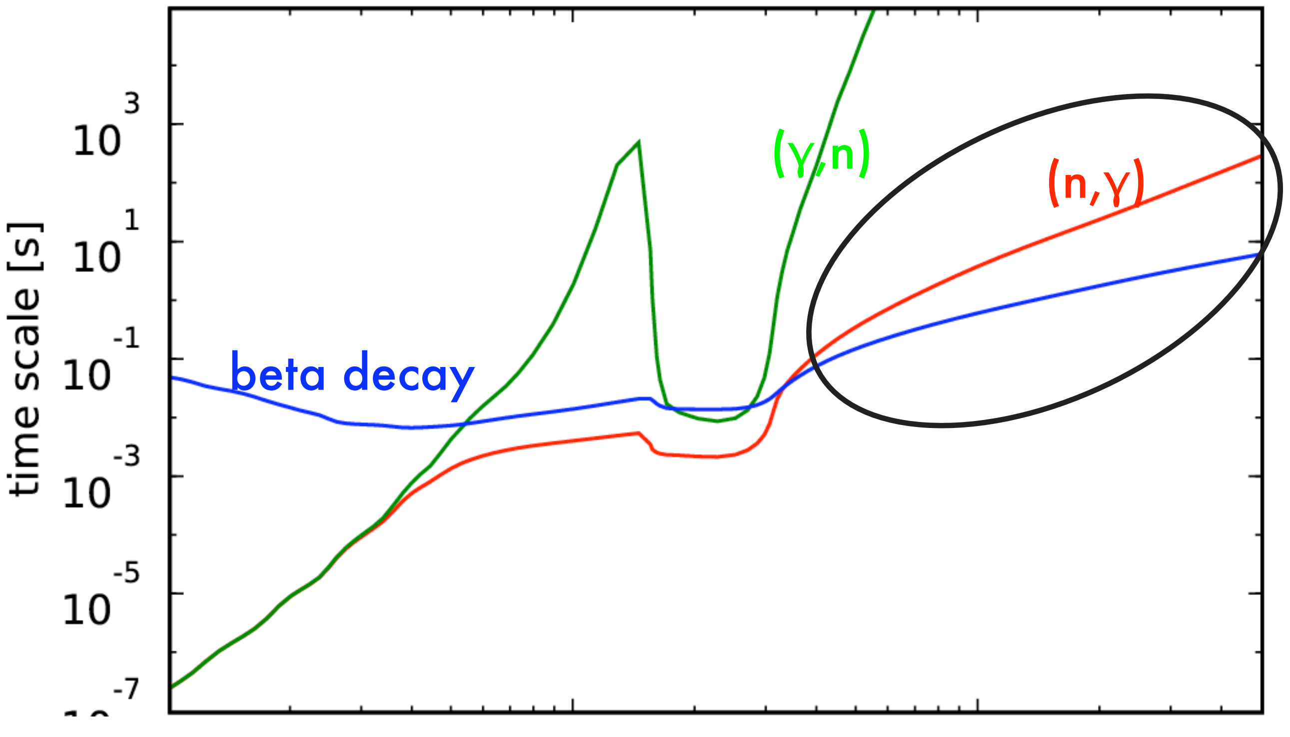
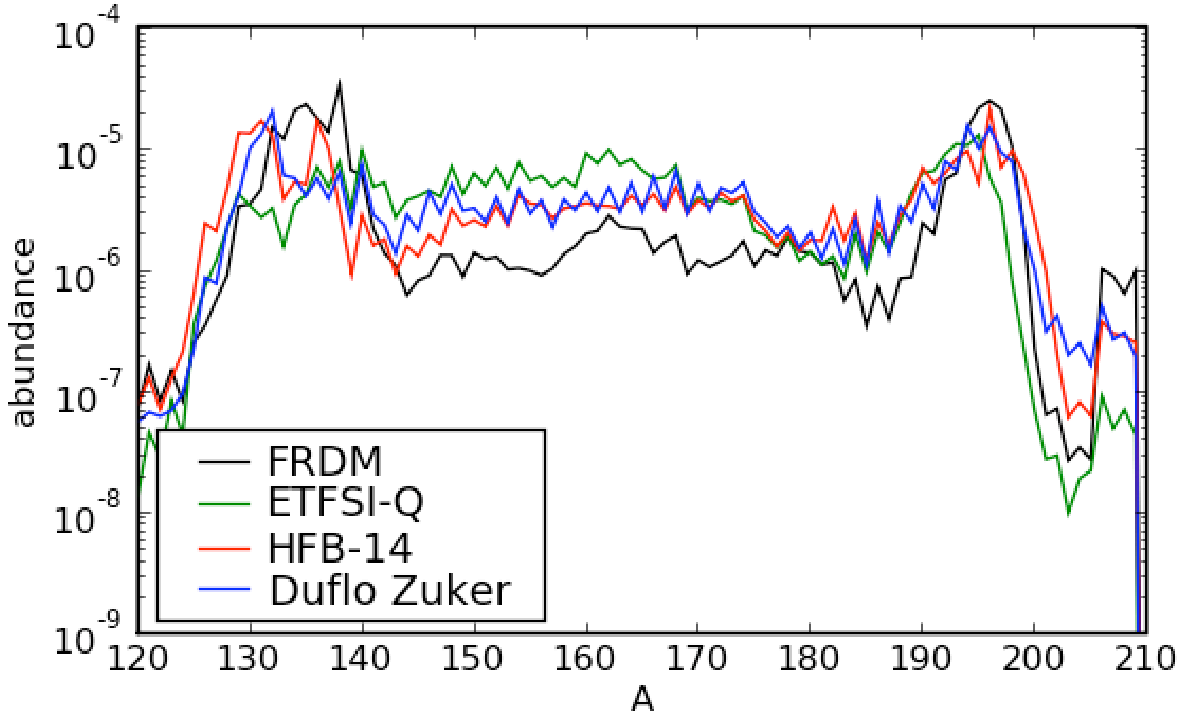
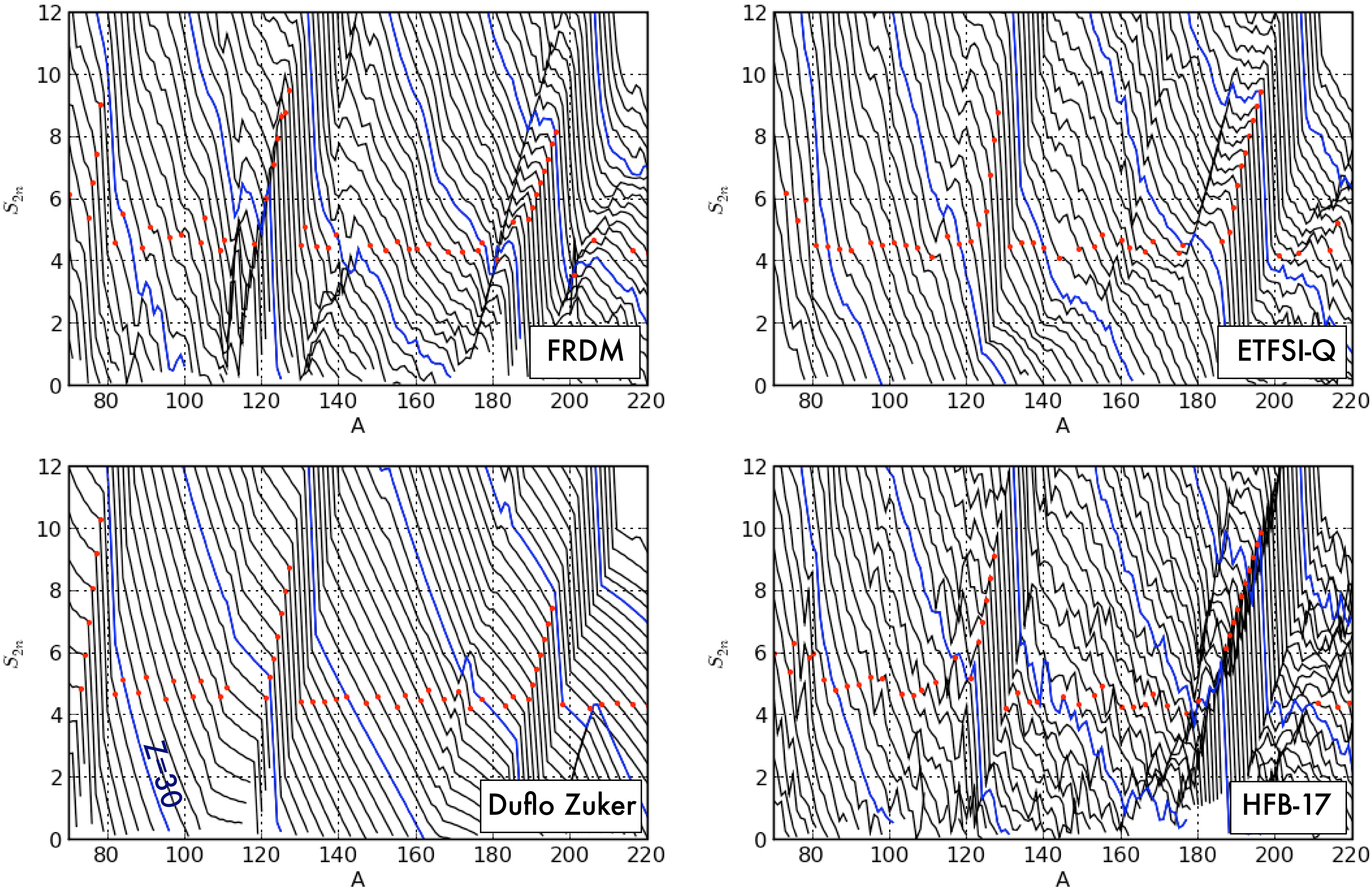




Mass models

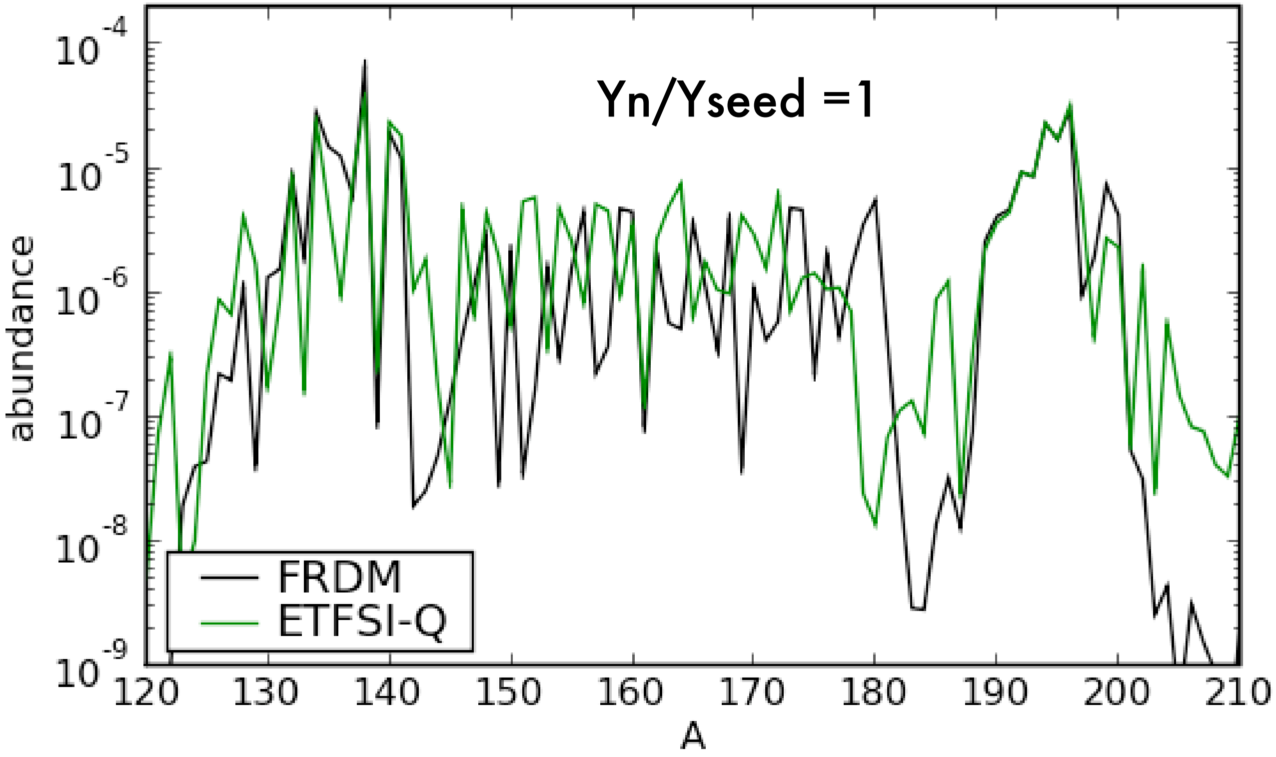

FRDM
ETFSI-Q
Duflo Zuker
HFB-17
Z=30
S_{2n}
A
0
2
4
6
8
10
12
80
100
120
140
160
180
200
220

Mass models and long time evolution

High temperature evolution:

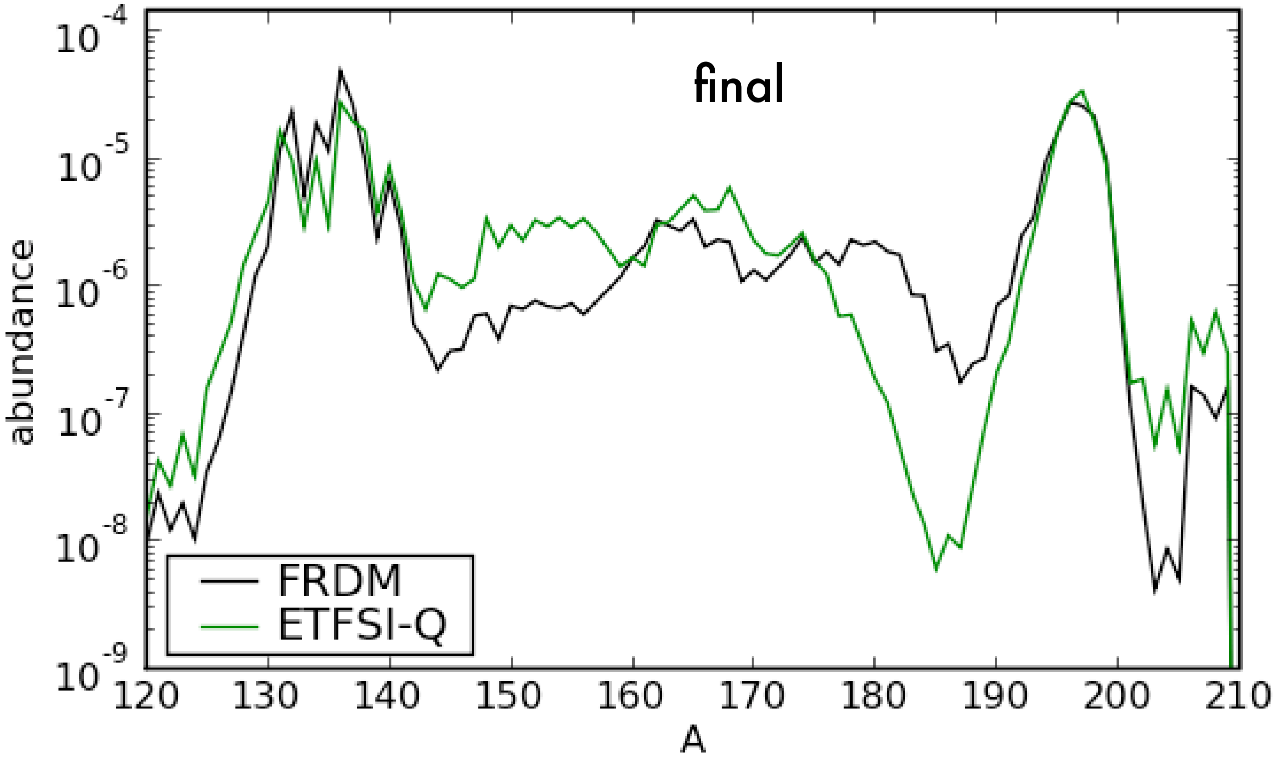
Abundances at freeze-out (Yn/Yseed=1) show odd-even effects following the behavior of the neutron separation energy.

While final abundances are smoother like solar abundances.



Why do 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).

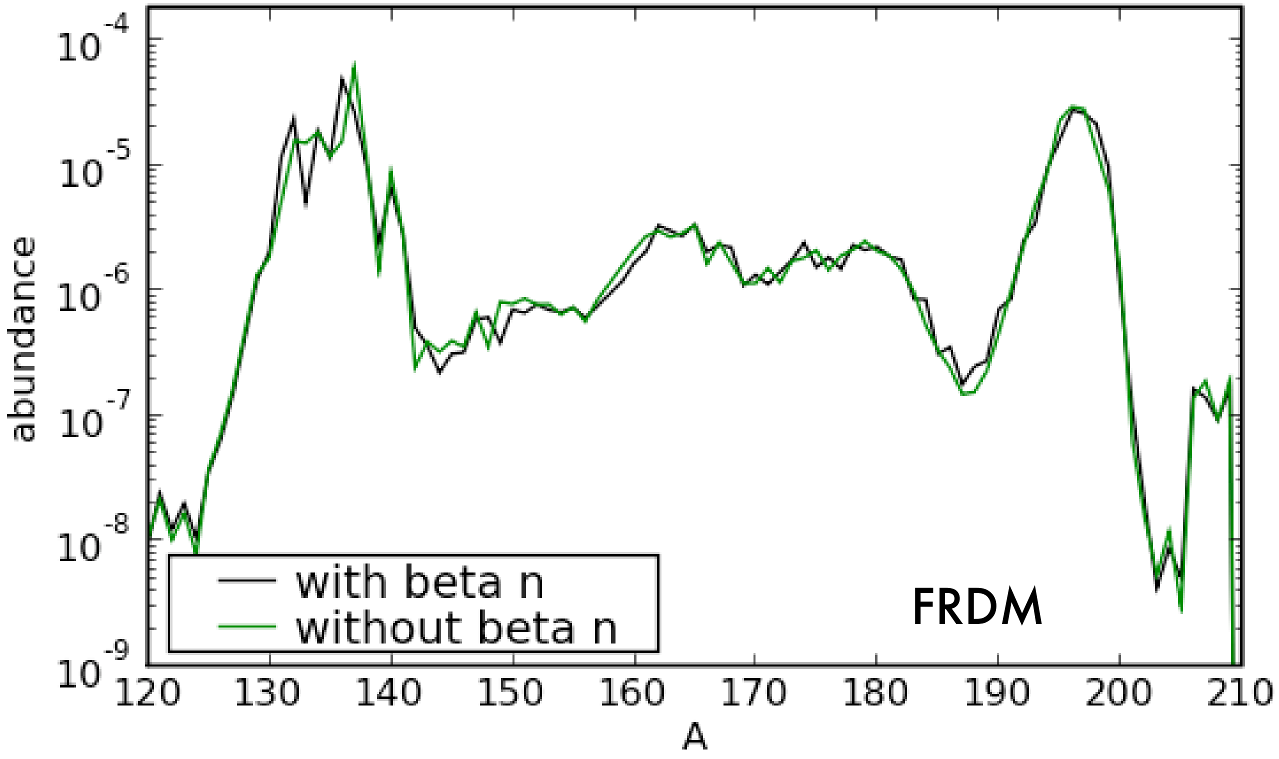


Way back to stability...

Why do the abundance pattern change?

Beta delayed neutron emission is not the responsible of the smoothness.

Neutron captures in the way back to stability will determine the final pattern.



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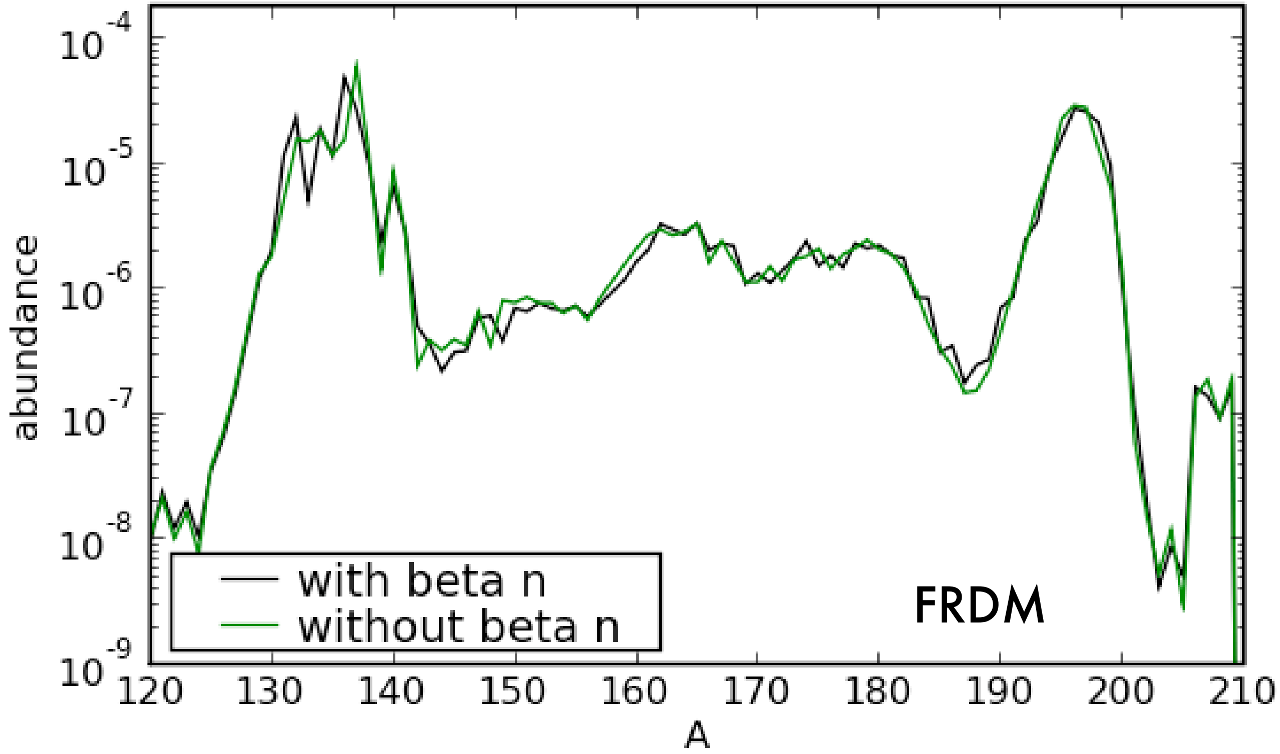
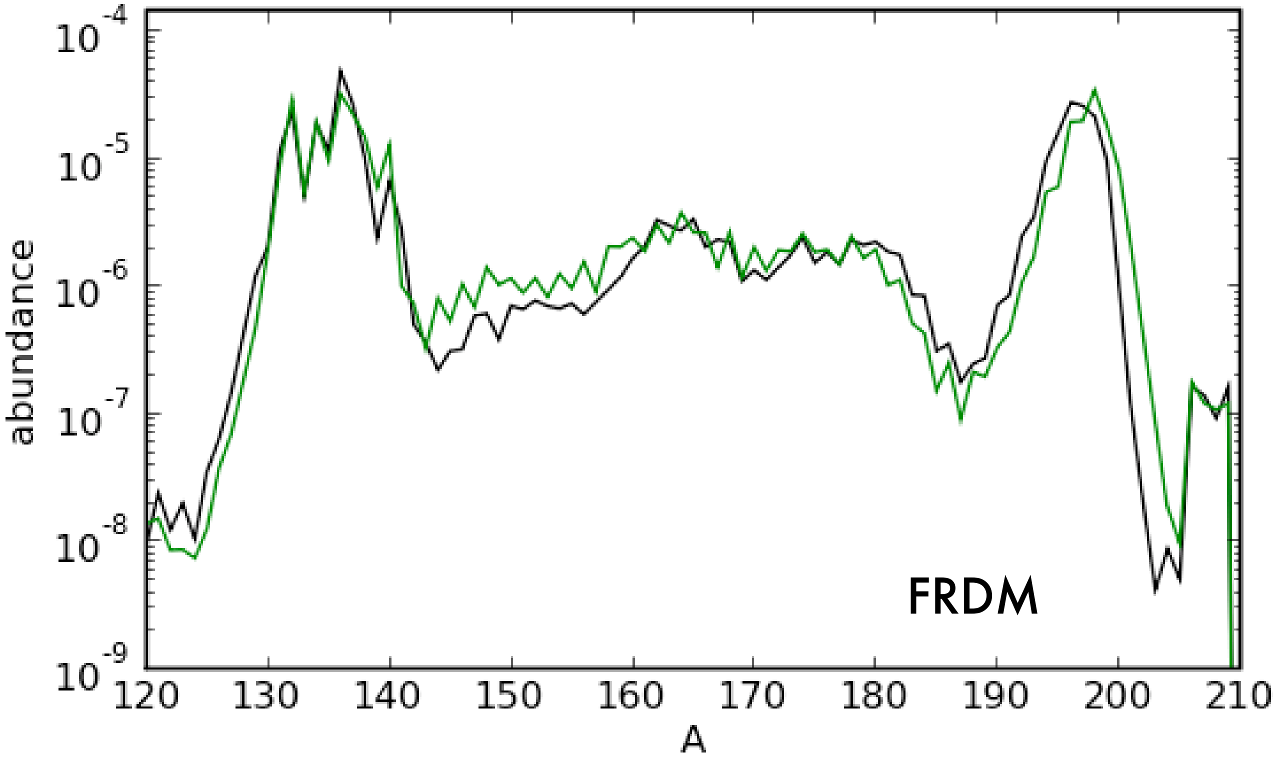
Two calculations for the neutron capture cross section give different final abundances.

With Hauser-Feshbach (NON-SMOKER, Rauscher & Thielemann 2000) rates (black line) more neutrons are captured between peaks: smoother pattern.

Approximation of Woosley, Fowler, Holmes, & Zimmerman (1975) (green line): captures occur more in the peak regions, therefore peaks get shifted to higher masses.





Conclusions

- Nucleosynthesis studies in neutrino-driven winds require long time hydrodynamical simulations of core-collapse supernova explosion.
- The conditions found in the simulations (low wind entropies and/or high electron fraction) do not allow the formation of heavy elements. However, an artificial increase in entropy by a factor two is enough to reach A=195 and allow us to explore the sensitivity of other aspects: reverse shock and nuclear physics input.
- The long time evolution is crucial for the determination of final abundances. Depending on whether the evolution take place at high or low temperatures the relevant nuclear physics will change.
- When (n, γ)-(γ,n) equilibrium is achieved the masses and beta decays determine the abundances. In the low temperatures case beta decays and neutron capture are crucial.
- In both cases, the final abundance distribution is determined by a competition between neutron capture and beta decays.