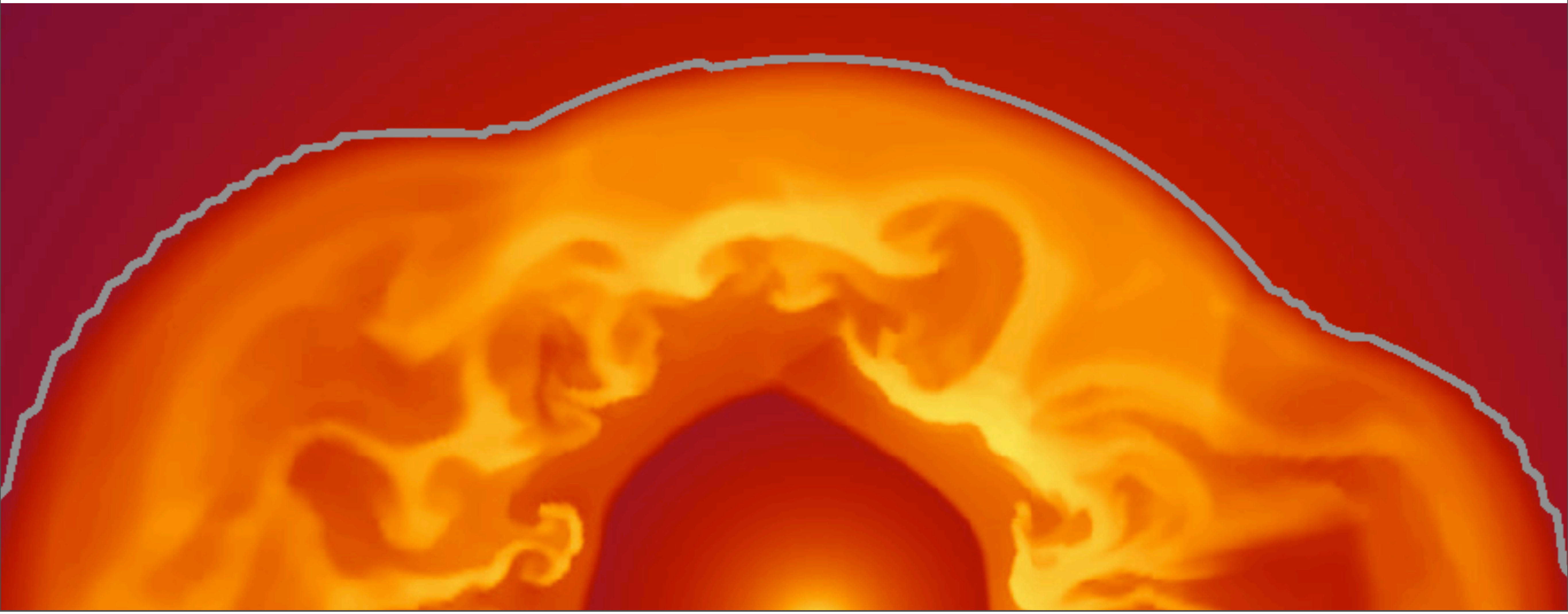
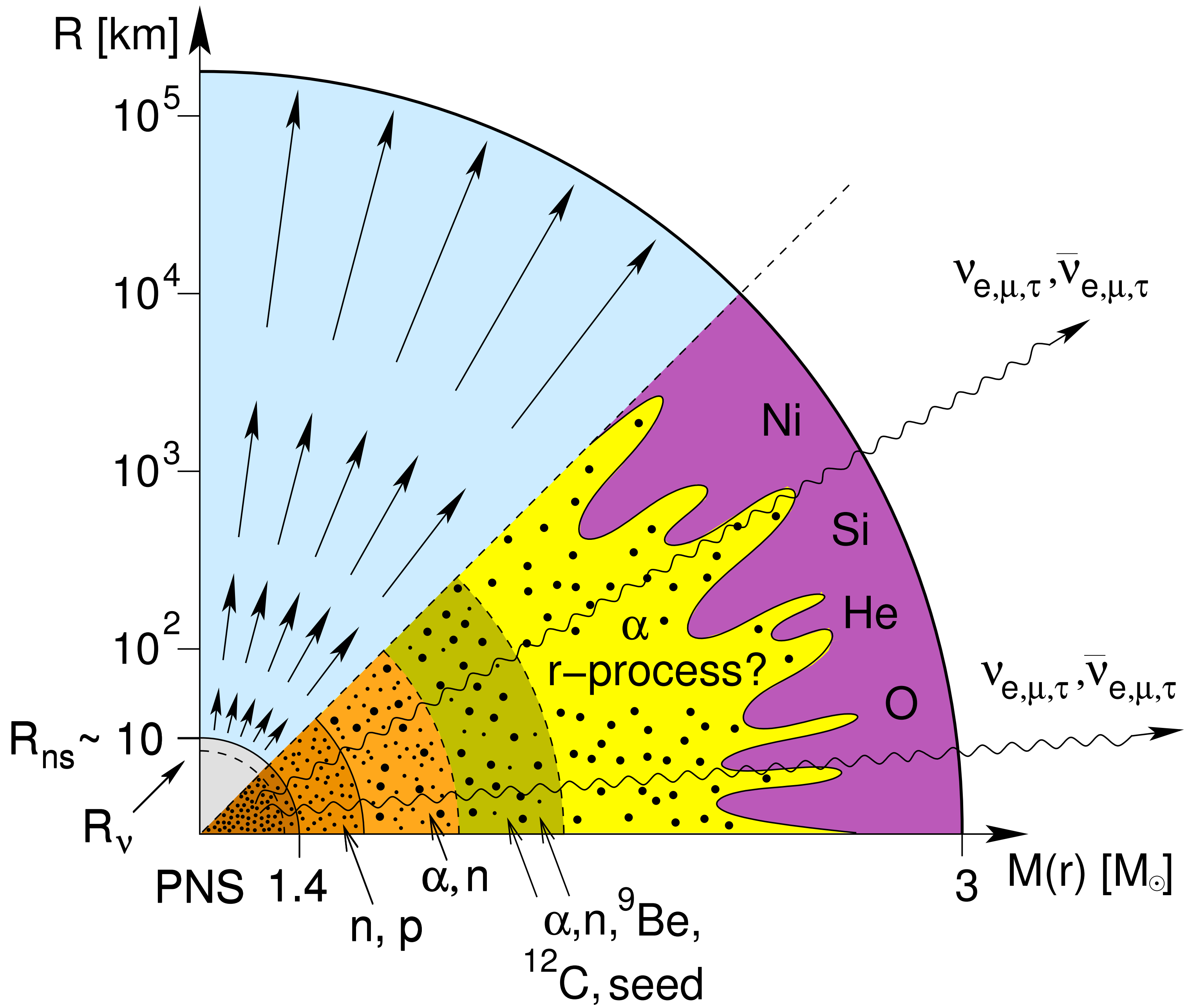
Explosive nucleosynthesis: nuclear physics impact using neutrino-driven wind simulations

Almudena Arcones
in collaboration with Gabriel Martínez-Pinedo



Neutrino-driven winds



Production of heavy elements (A>130) requires high neutron-to-seed ratio (Y_n/Y_{seed}~100).

Necessary conditions for the r-process:

- fast expansion: inhibits the alpha-process and thus the formation of seed nuclei
- neutron rich ejecta: Y_e<0.5
- high entropy is equivalent to high photon-to-baryon ratio. Photons dissociate seed nuclei into nucleons.

(Meyer et al. 1992, Hoffman et al. 1997, Otsuki et al. 2000, Thompson et al. 2001...)

These conditions are not reached in state-of-the-art neutrino-driven wind simulations
Do supernovae produce the heavy r-process nuclei?

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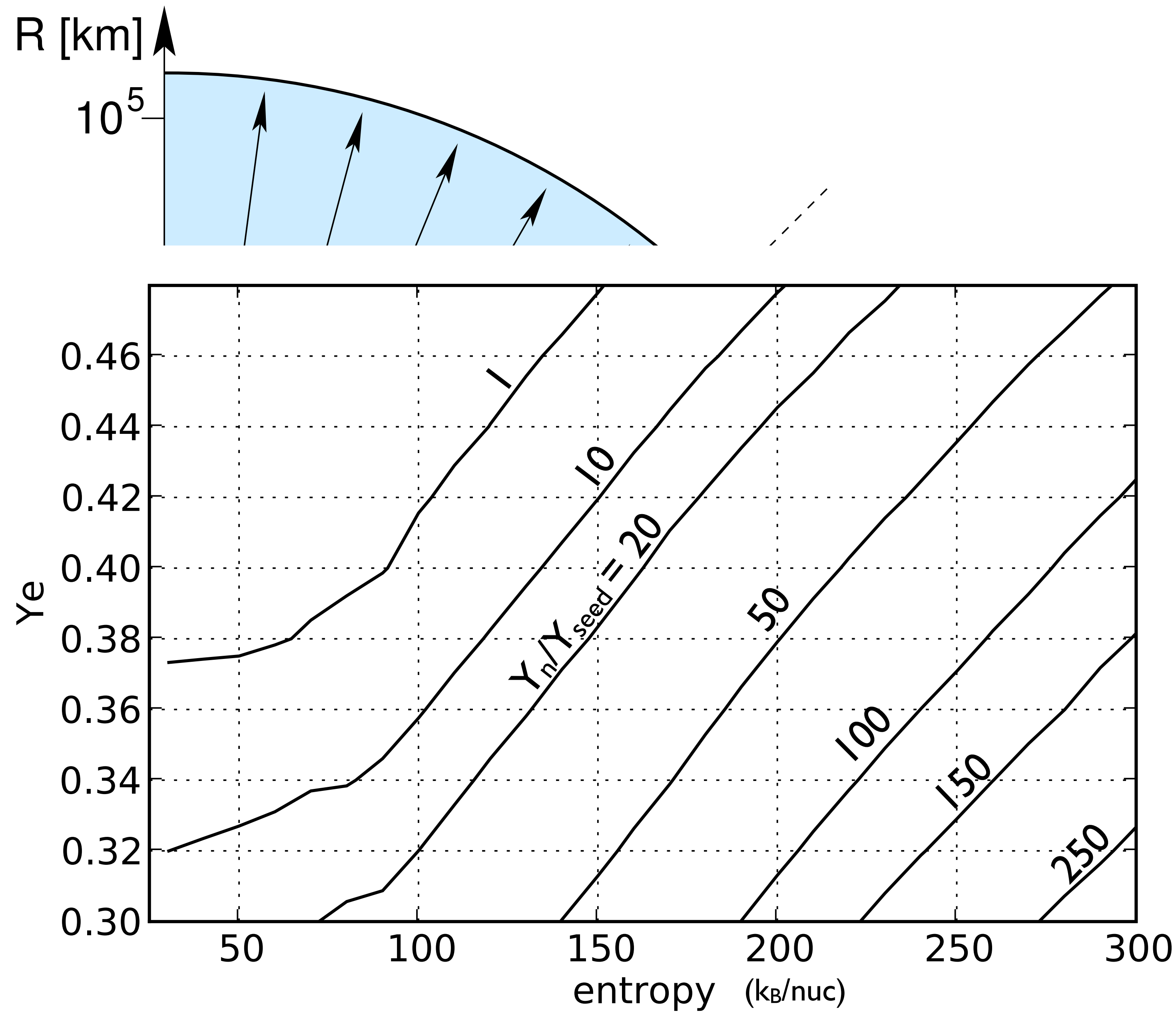

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Neutrino-driven wind simulations and nucleosynthesis networks

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

Problems: - explosion mechanism (Janka et al. 2007)
- simulations are computationally very expensive to follow the wind phase

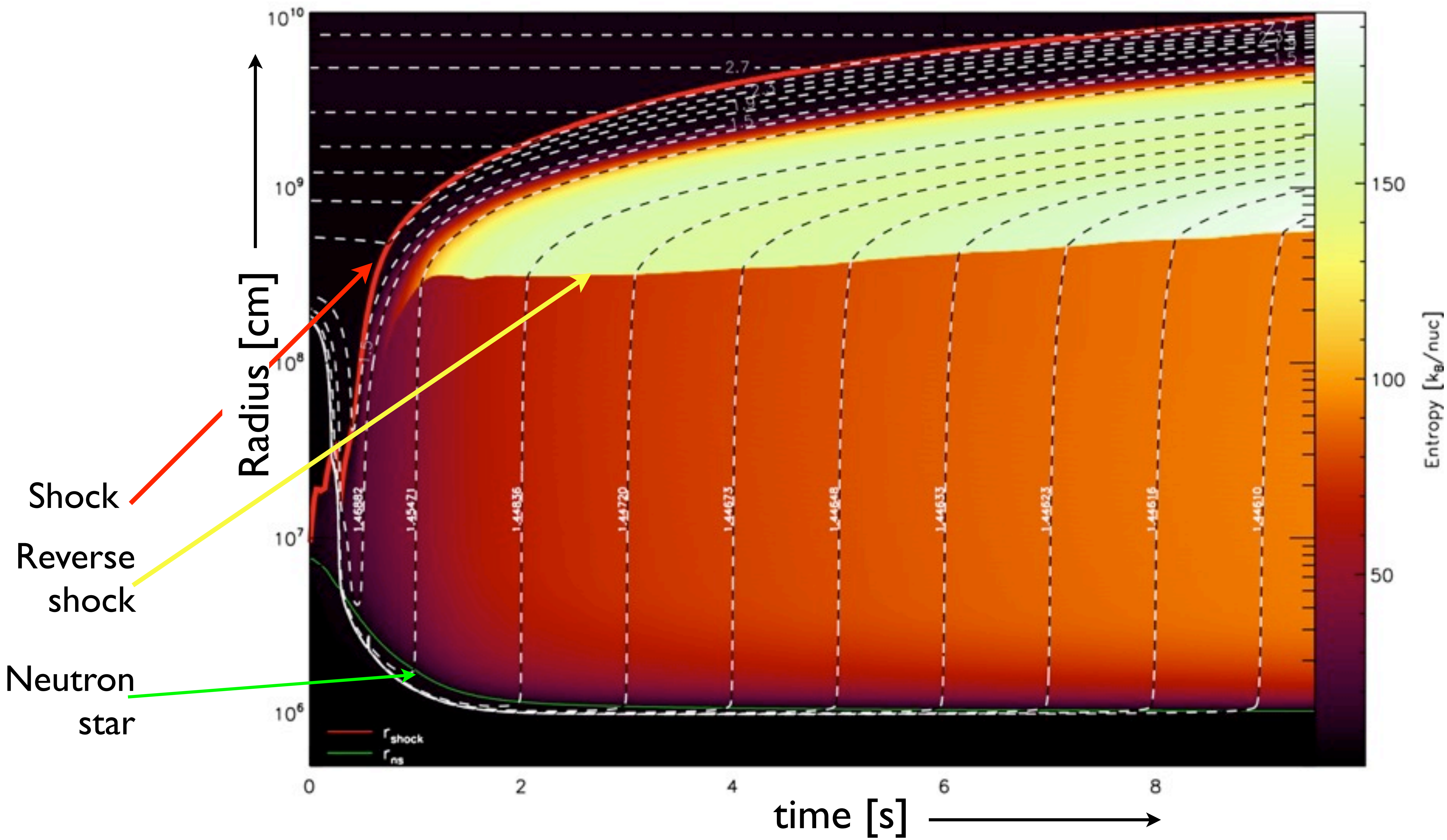
Solutions: - steady-state wind models (Otsuki et al. 2000, Thompson el al. 2001, Wanajo 2000-2010)
- one-dimensional simulations with an artificial explosion (Arcones et al. 2007 (also 2d), Fischer et al. 2009)

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 nuclear statistical equilibrium.
- 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, photodissotiation (Rauscher & Thielemann 2000), beta decay (experimental + Möller et al. 2003), and fission (Panov et al. 2009).

Neutrino-driven wind results

Arcones et al. 2007



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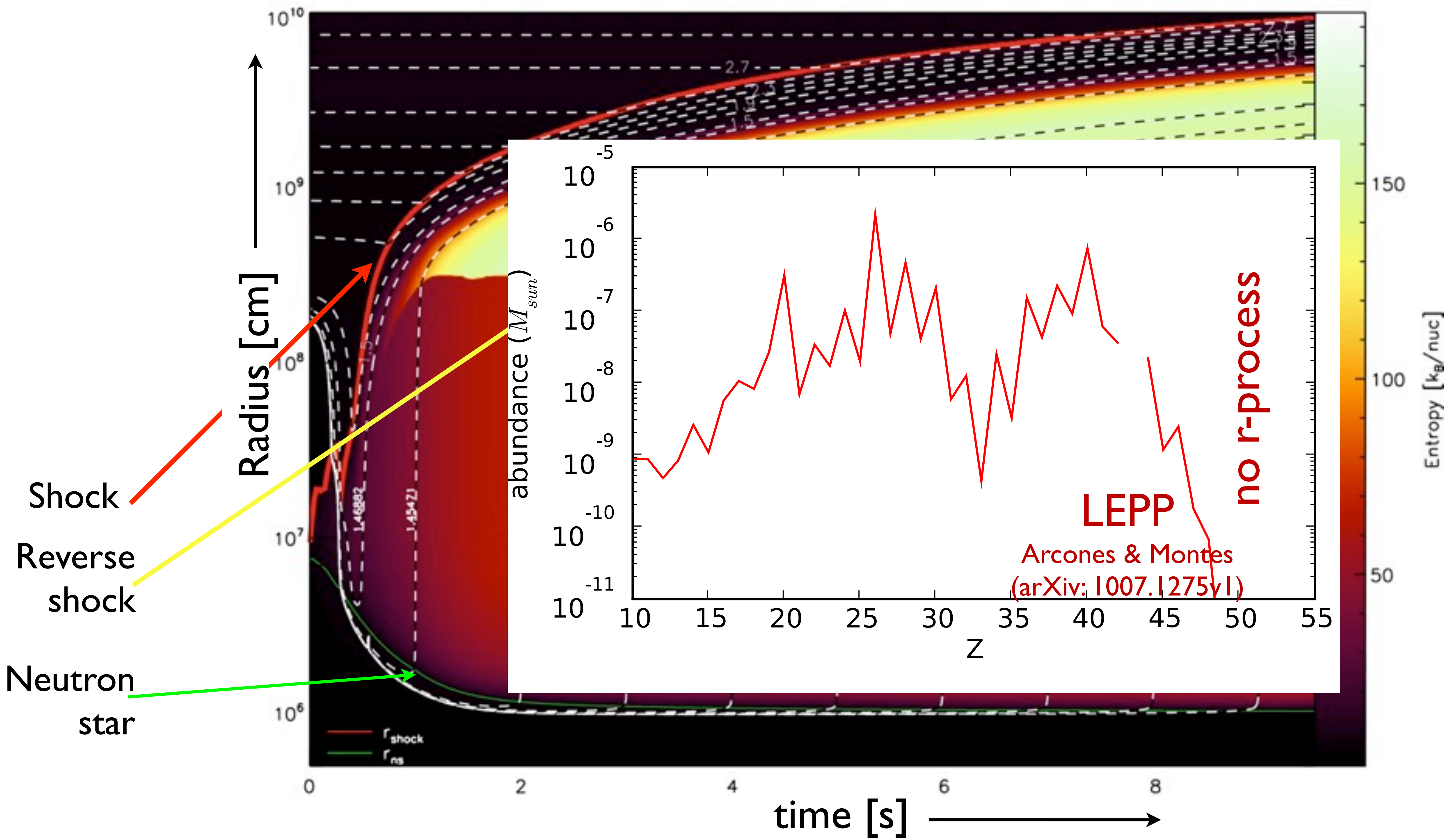


r-process in neutrino-driven winds

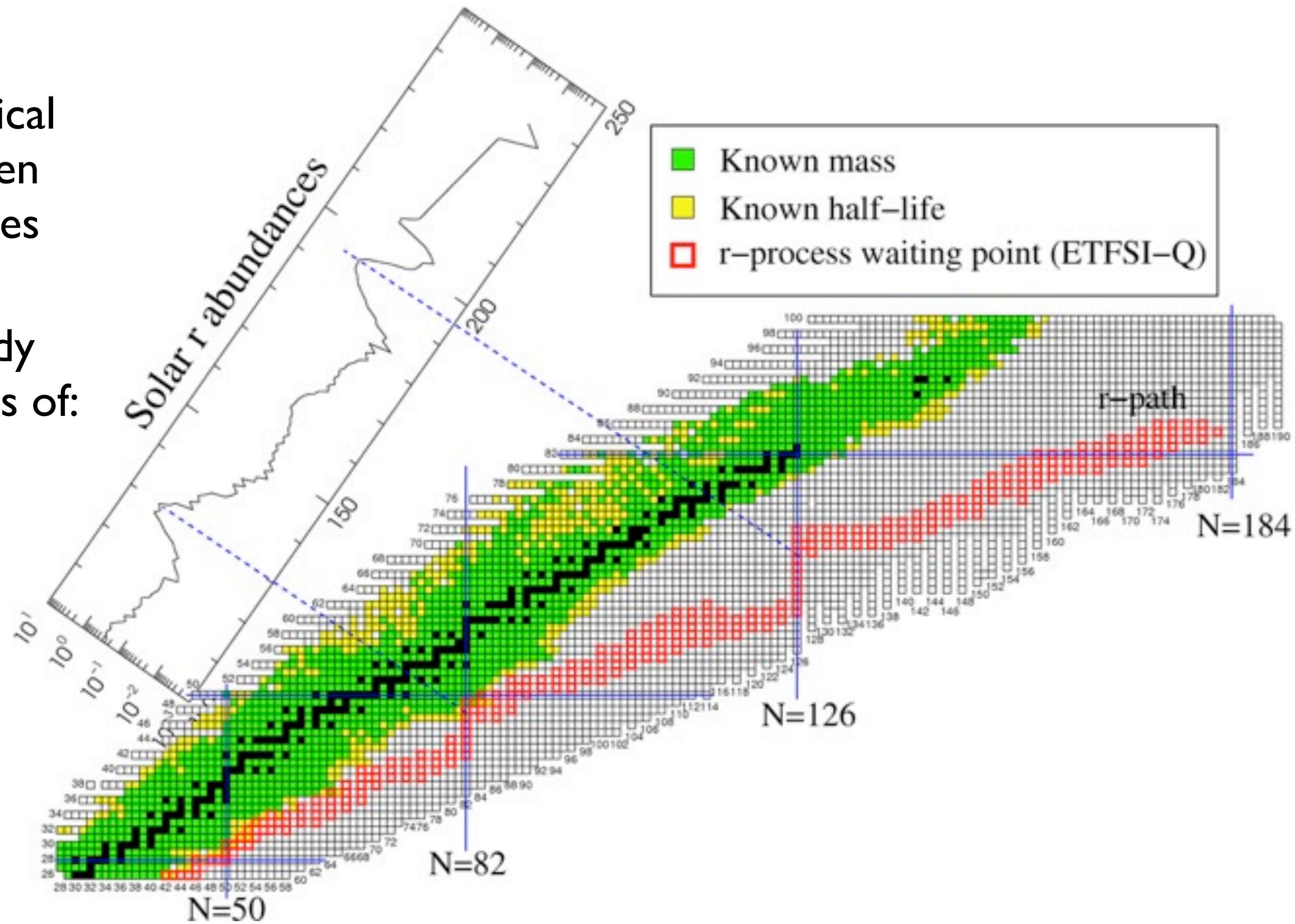
We artificially increase the entropy to reach high enough neutron-to-seed ratio to produce the third r-process peak (A~195).

This mimics the hydrodynamical conditions of a neutrino-driven wind where the r-process does occur and thus

it can be used as basis to study the impact on the abundances of:

long-time evolution and

nuclear physics input.

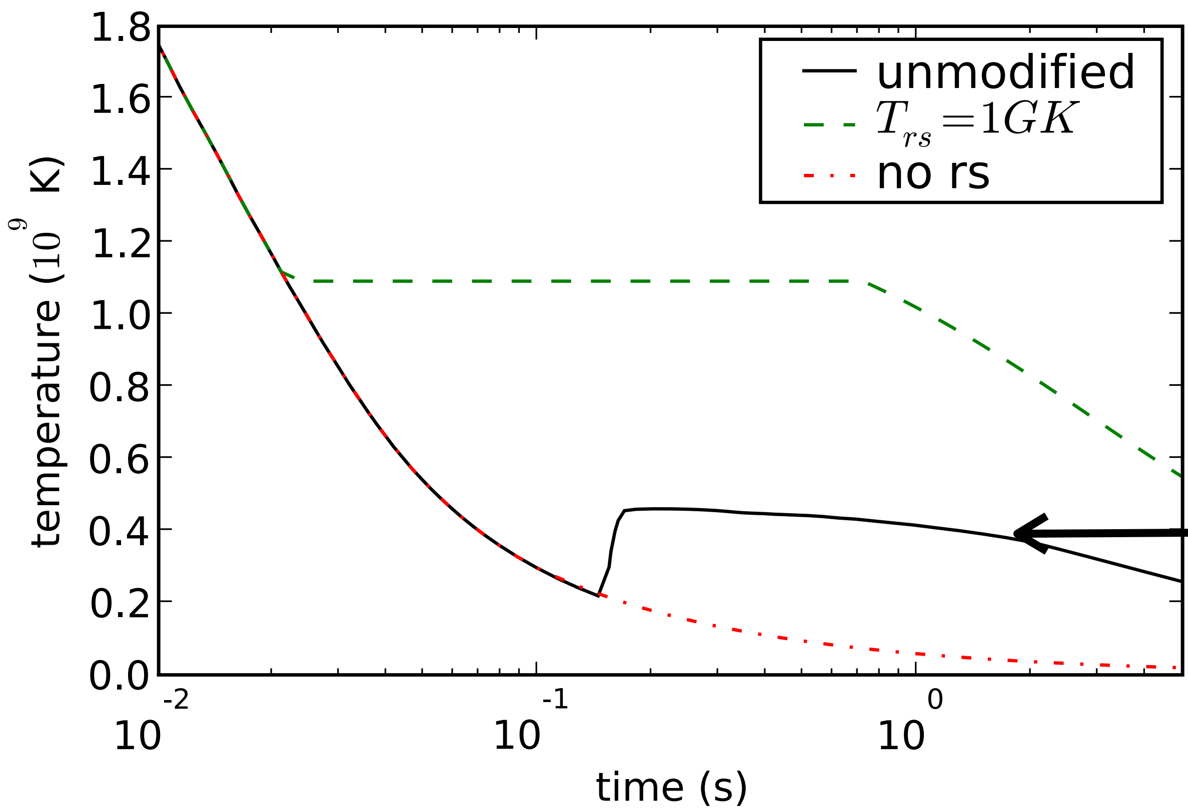


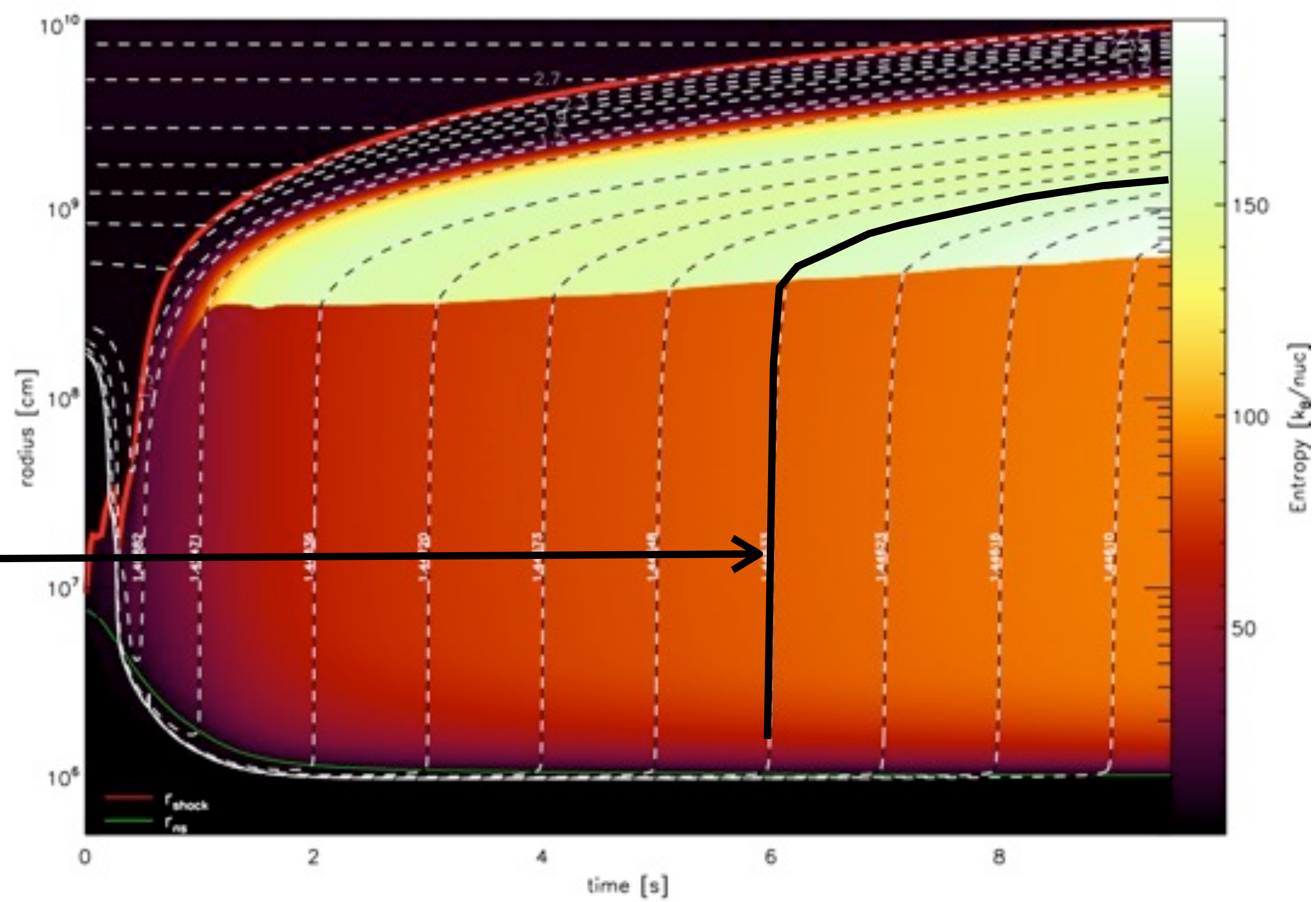
r-process: long-time evolution and reverse shock

We use one trajectory from the hydrodynamical simulations of Arcones et al. 2007 with the entropy increased by a factor two.

Vary the long-time evolution:

- reverse shock at 1GK
- no reverse shock





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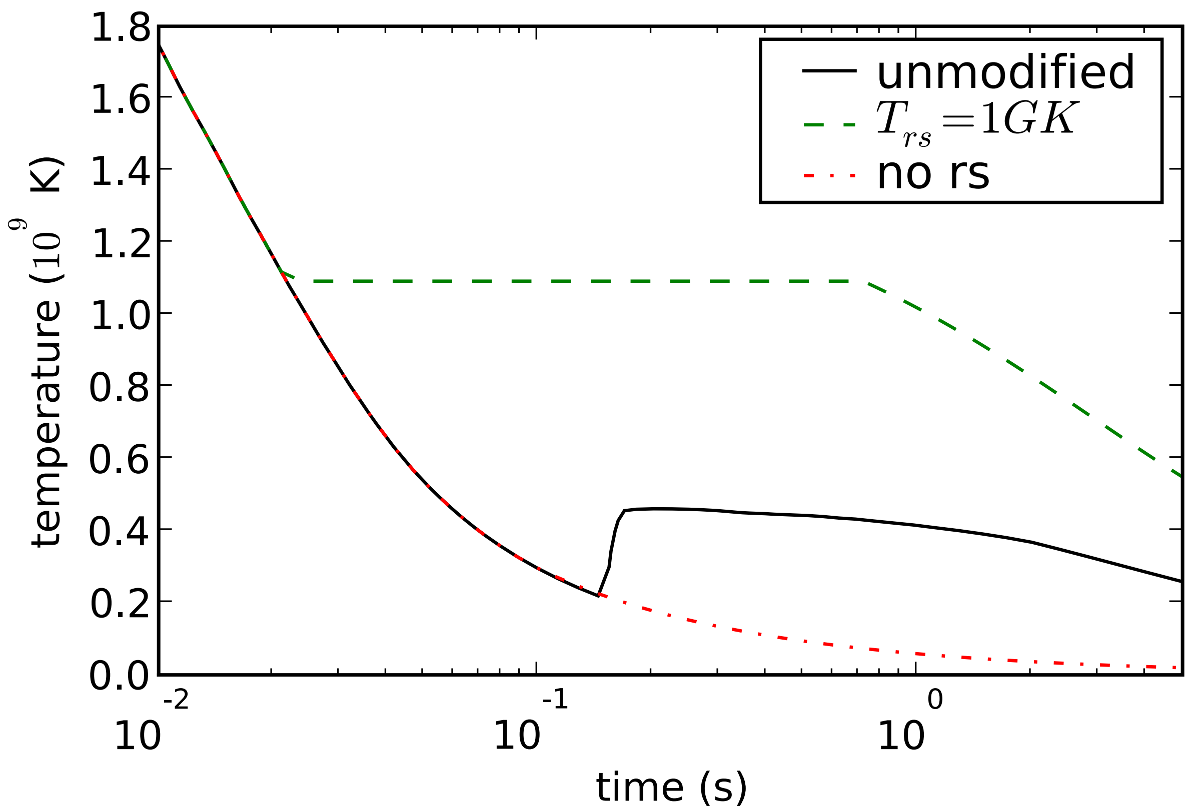

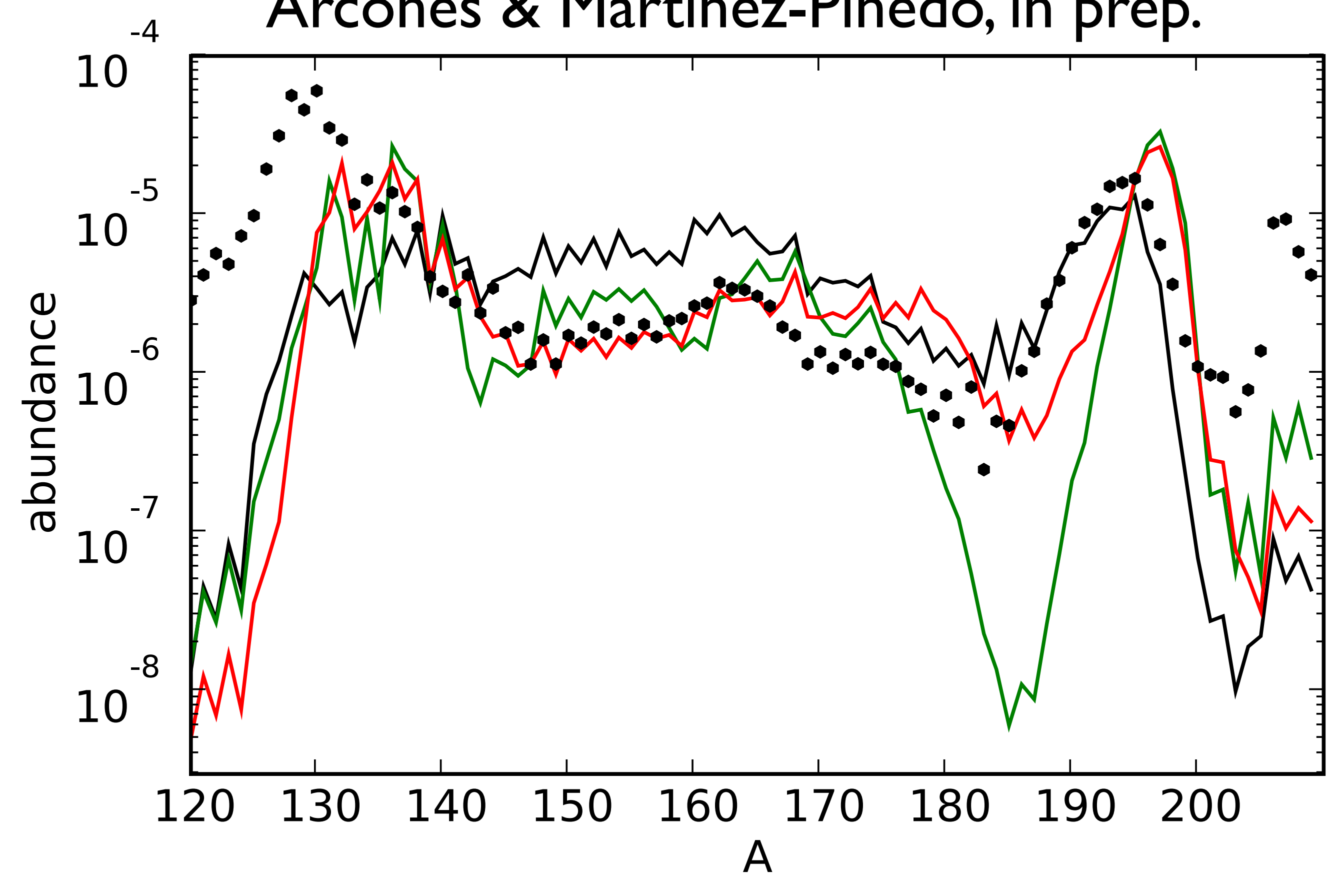

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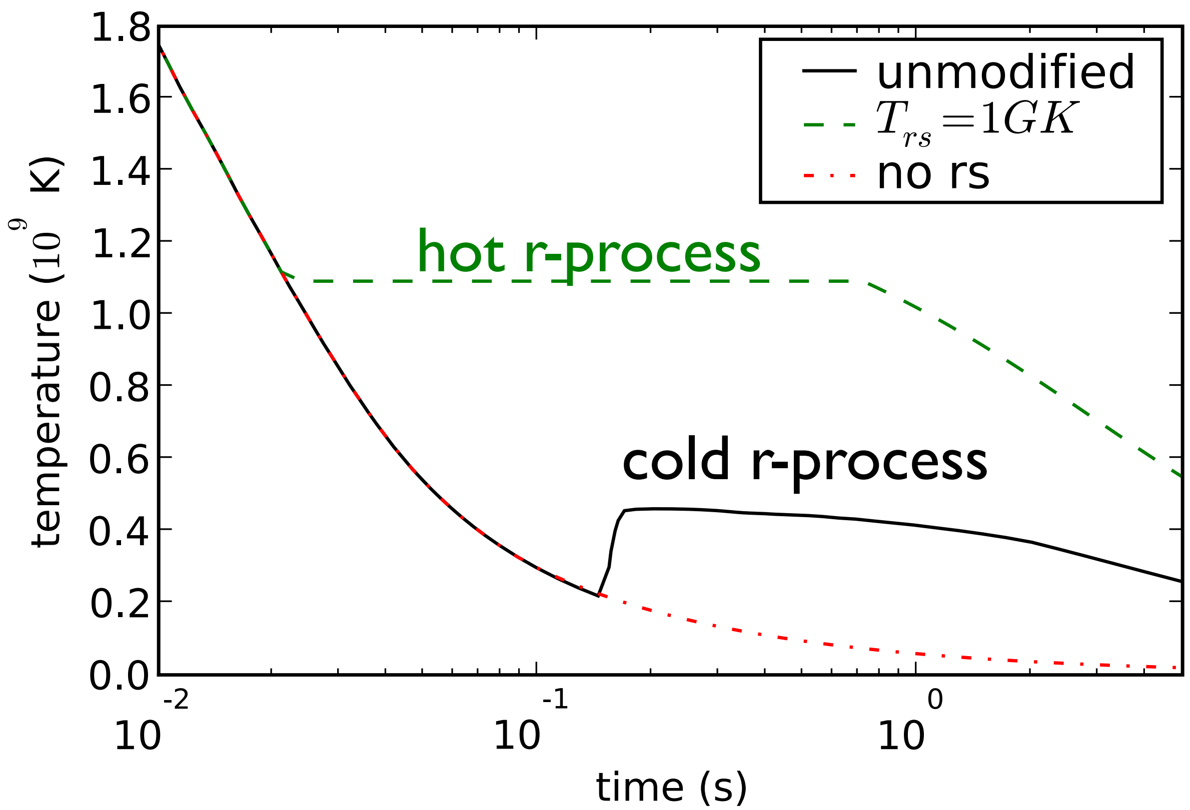
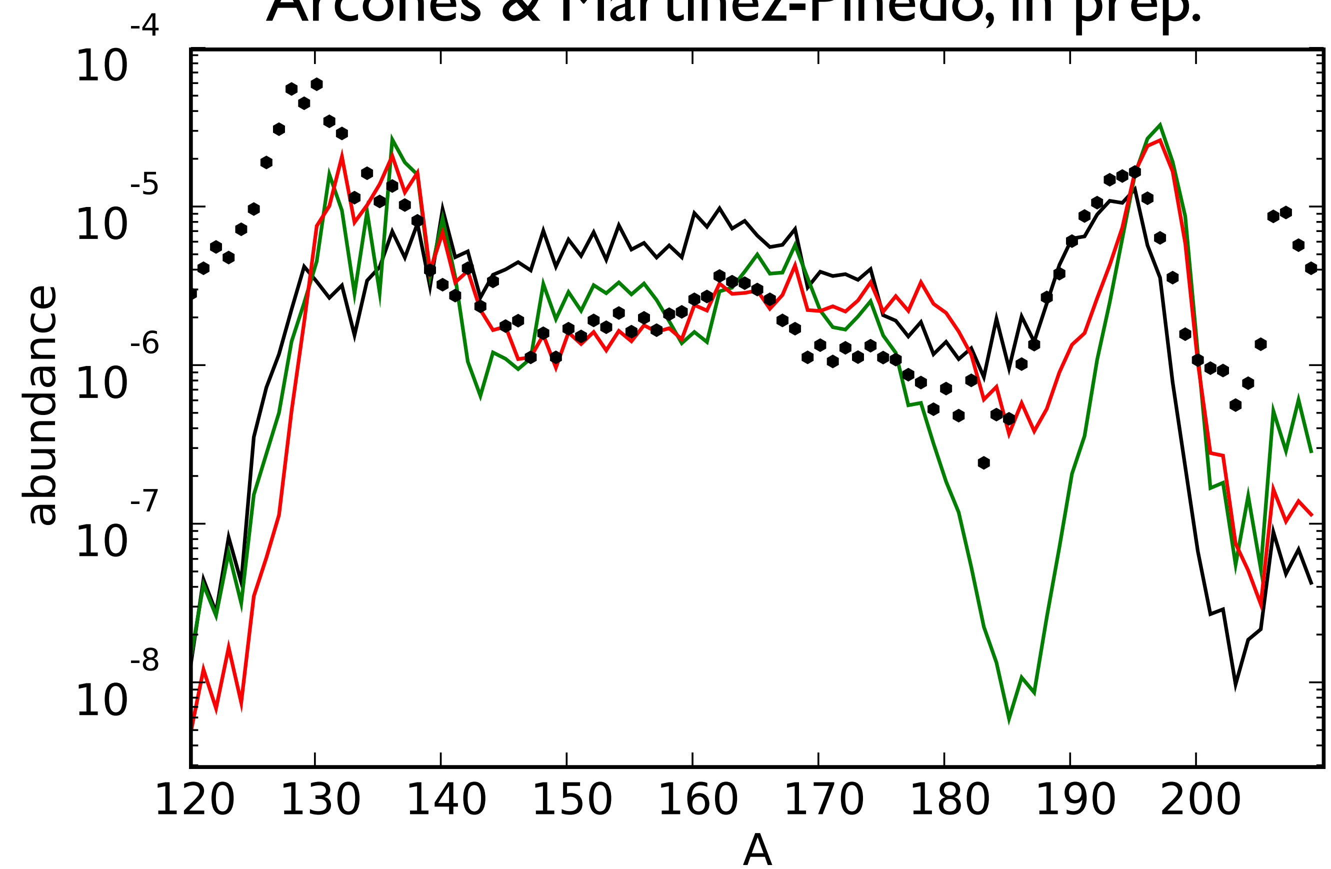
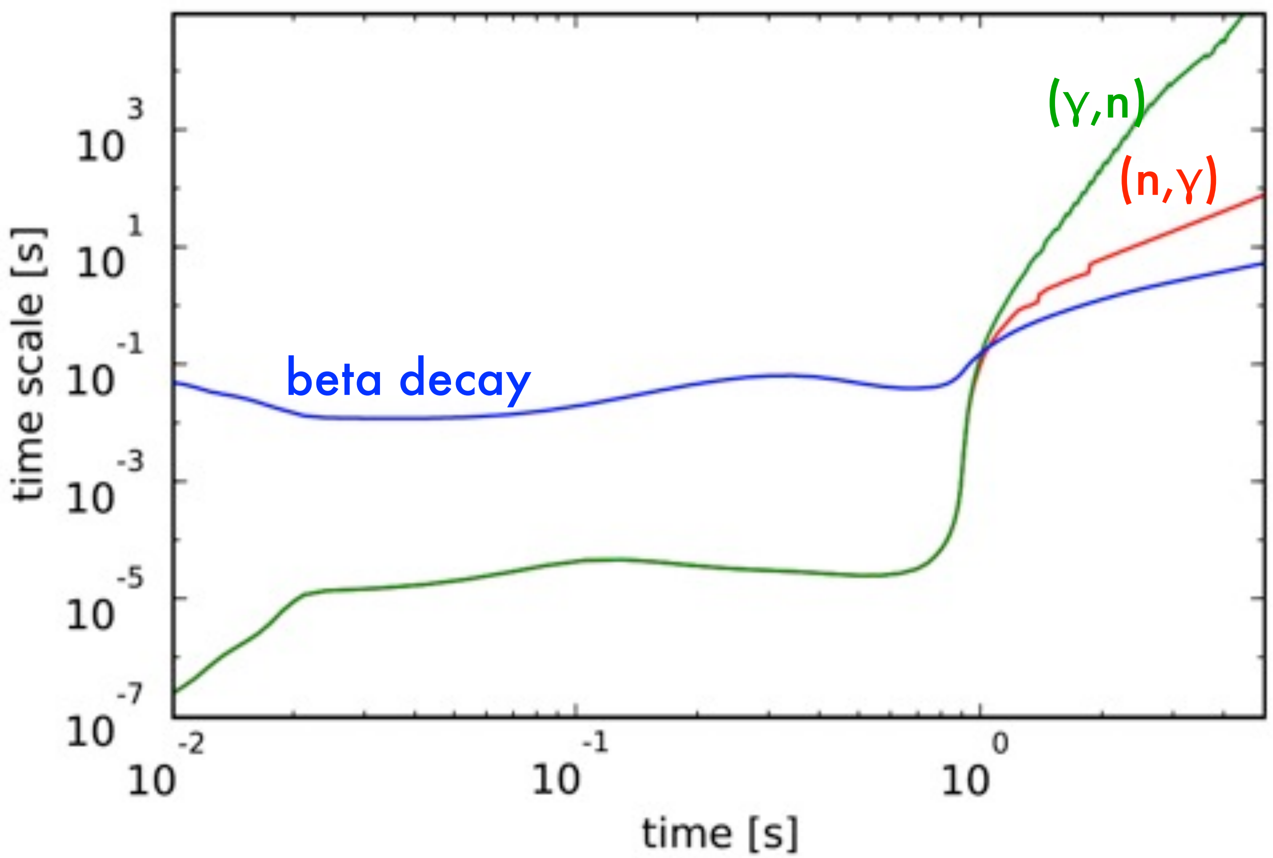


Arcones & Martinez-Pinedo, in prep.

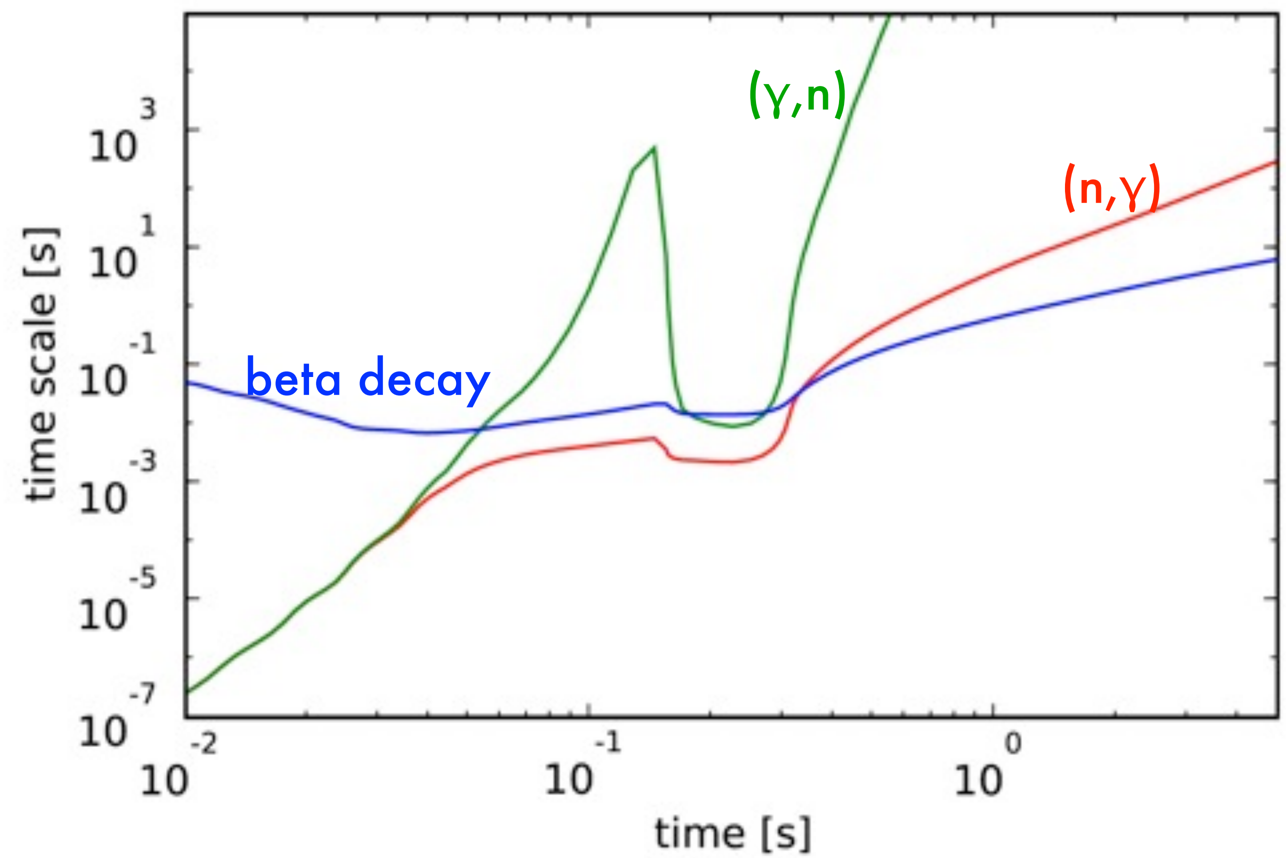


Long-time evolution: high vs. low temperature

Hot r-process



Cold r-process



The evolution takes place under (n,γ)-(γ,n) equilibrium (classical r-process, Seeger, Fowler and Clayton1965, Kratz et al. 1993).

Competition between beta decay and neutron capture (Blake & Schramm 1976, Wanajo 2007, Janka & Panov 2009)

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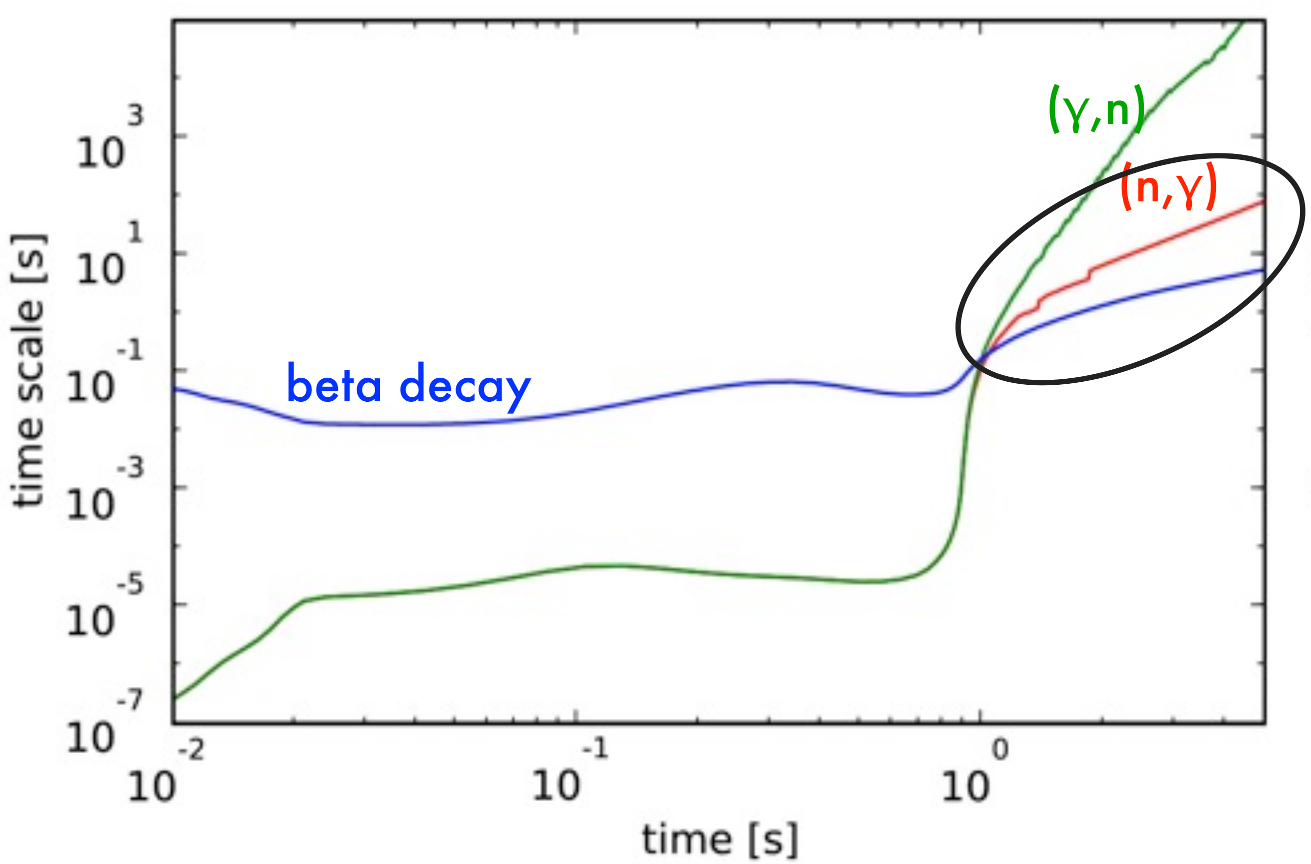

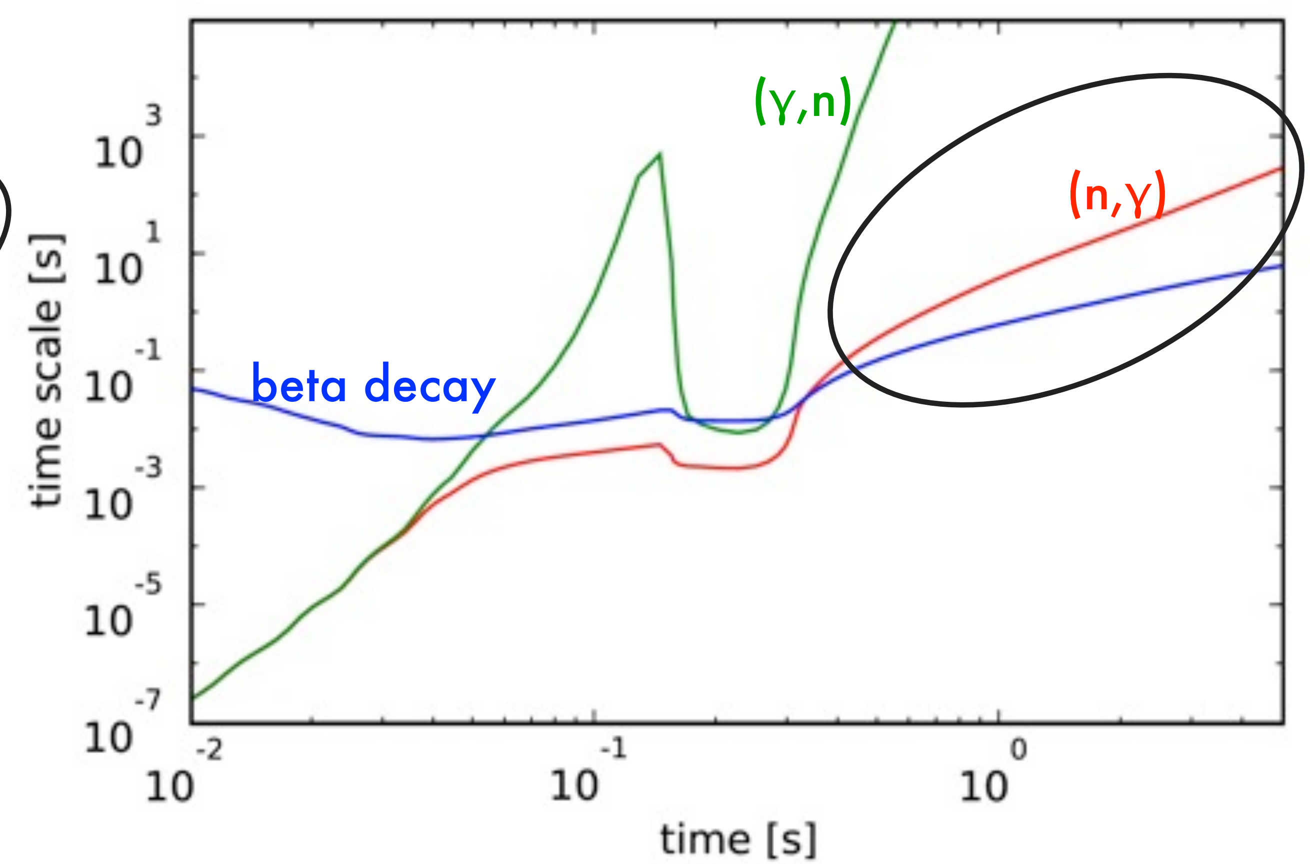

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Final abundances are strongly affected by neutron captures and beta decays that compete when matter moves back to stability.

Sensitivity to mass models

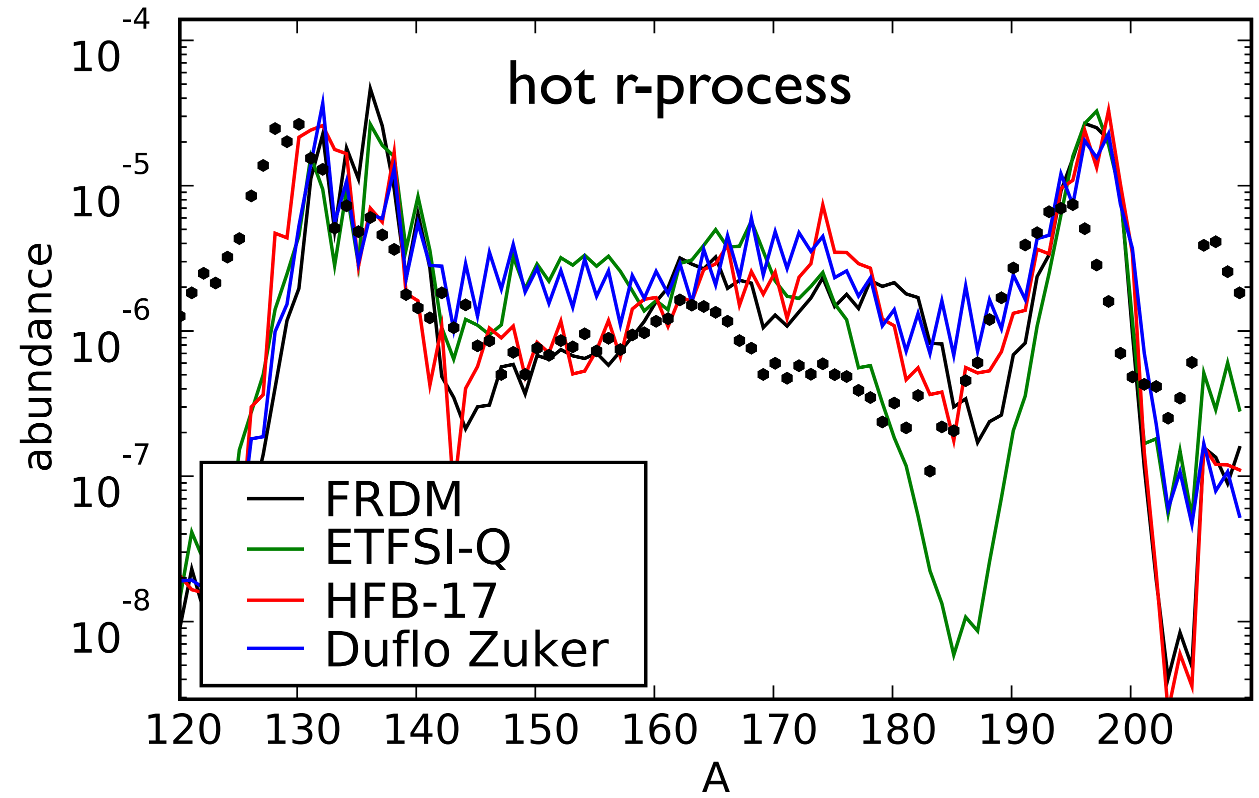
Compare four different mass models:

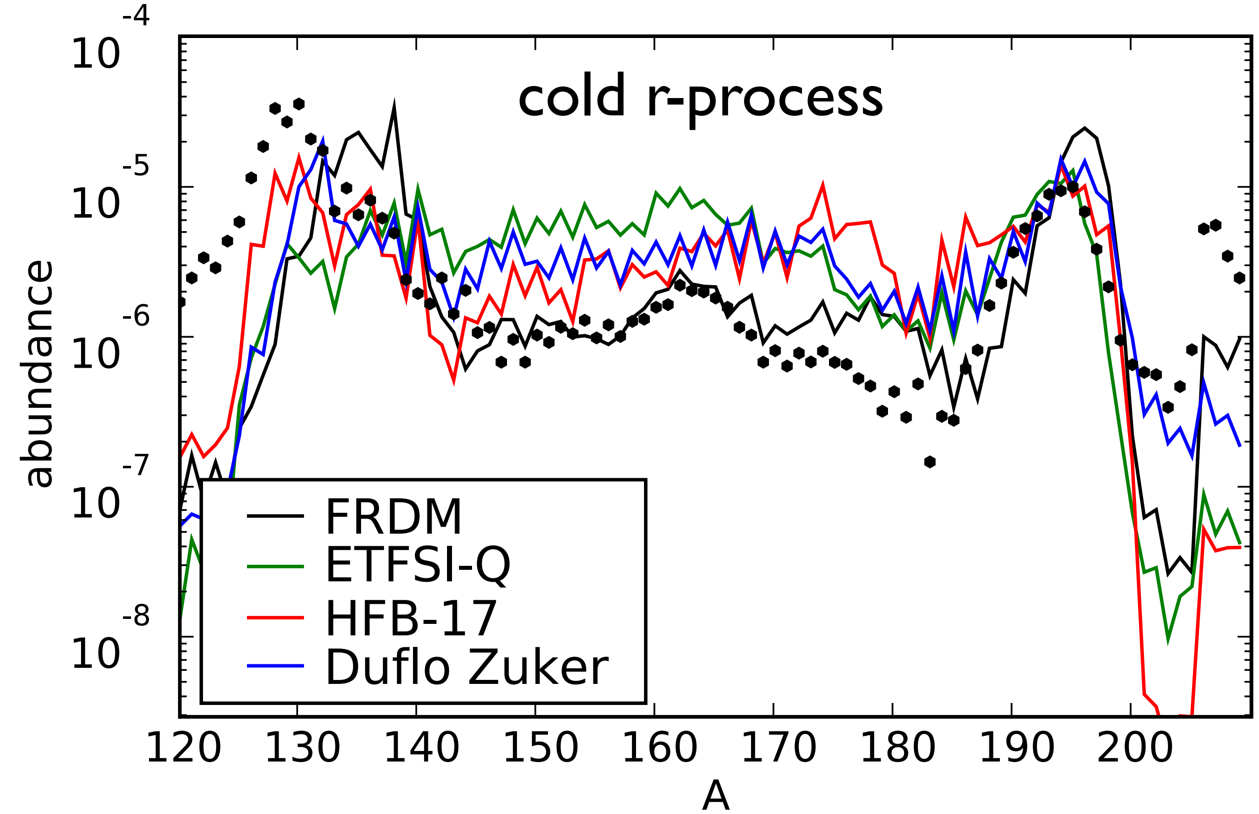
- FRDM (Möller et al. 1995)
- ETFSI-Q (Pearson et al. 1996)
- HFB-17 (Goriely et al. 2009)
- Duflo&Zuker mass formula

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 masses (neutron separation energies) to the final r-process abundances?





Arcones & Martinez-Pinedo (in prep.)

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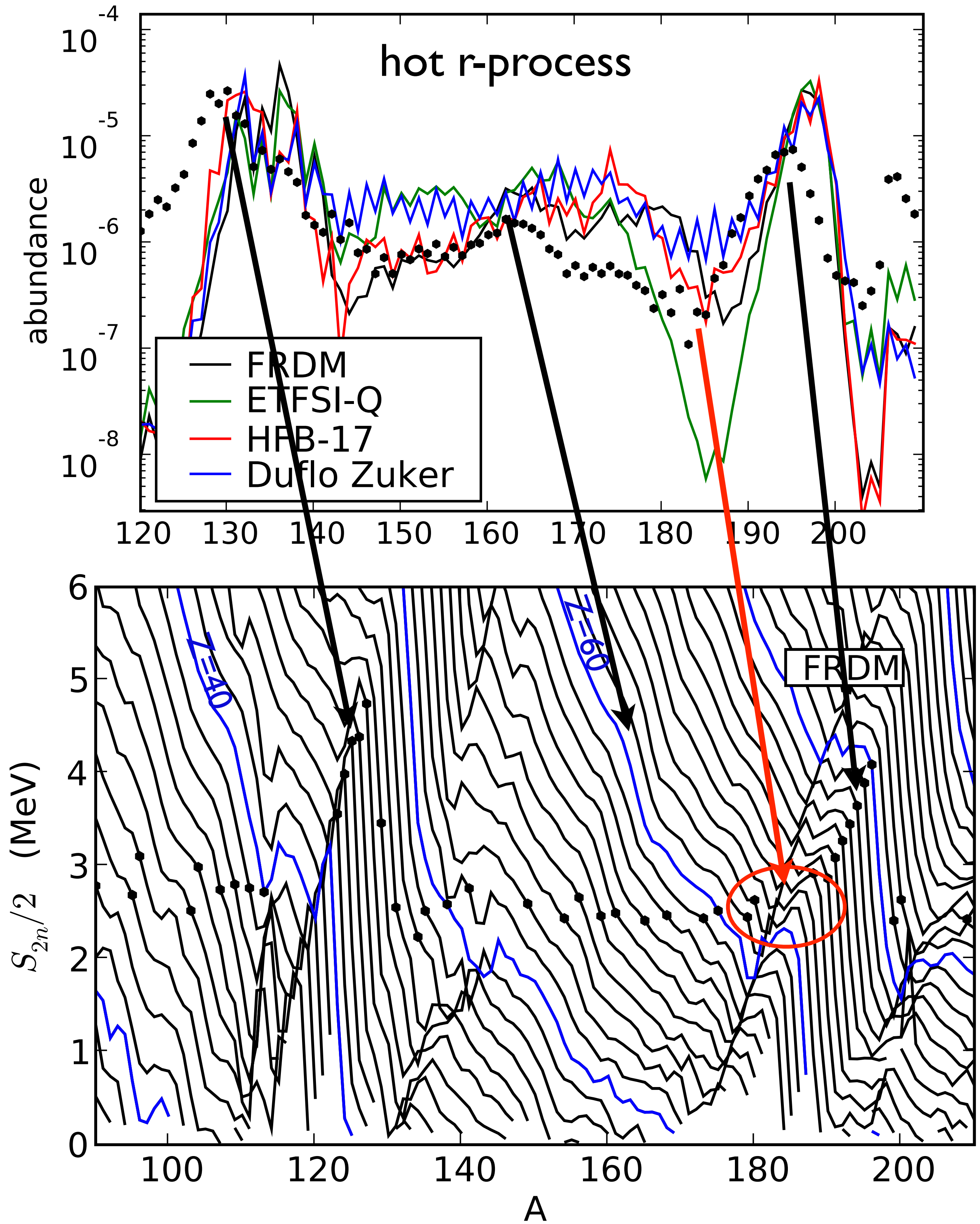

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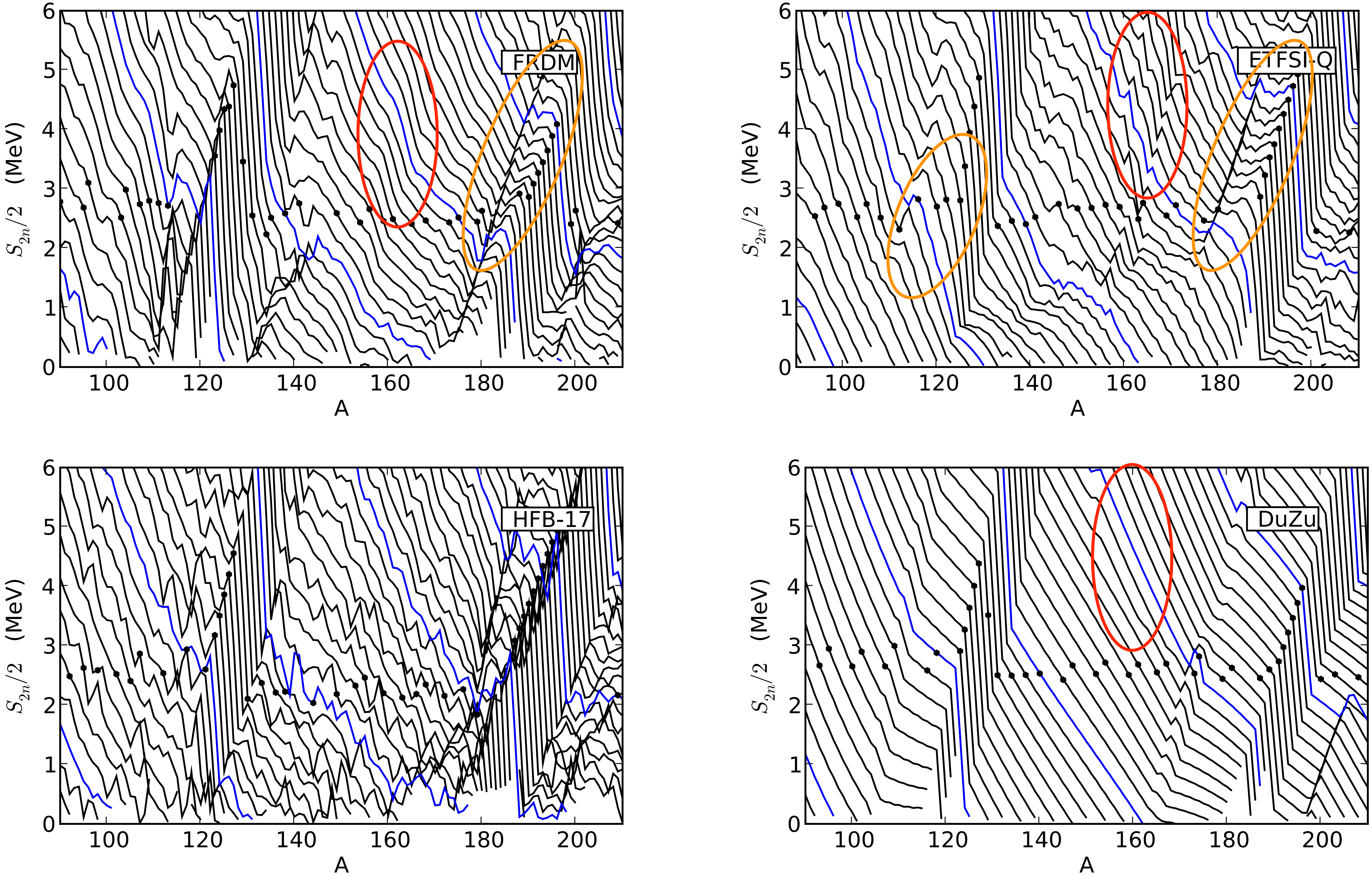
Aspects of different mass models



Way back to stability

Hot r-process (~classical r-process):

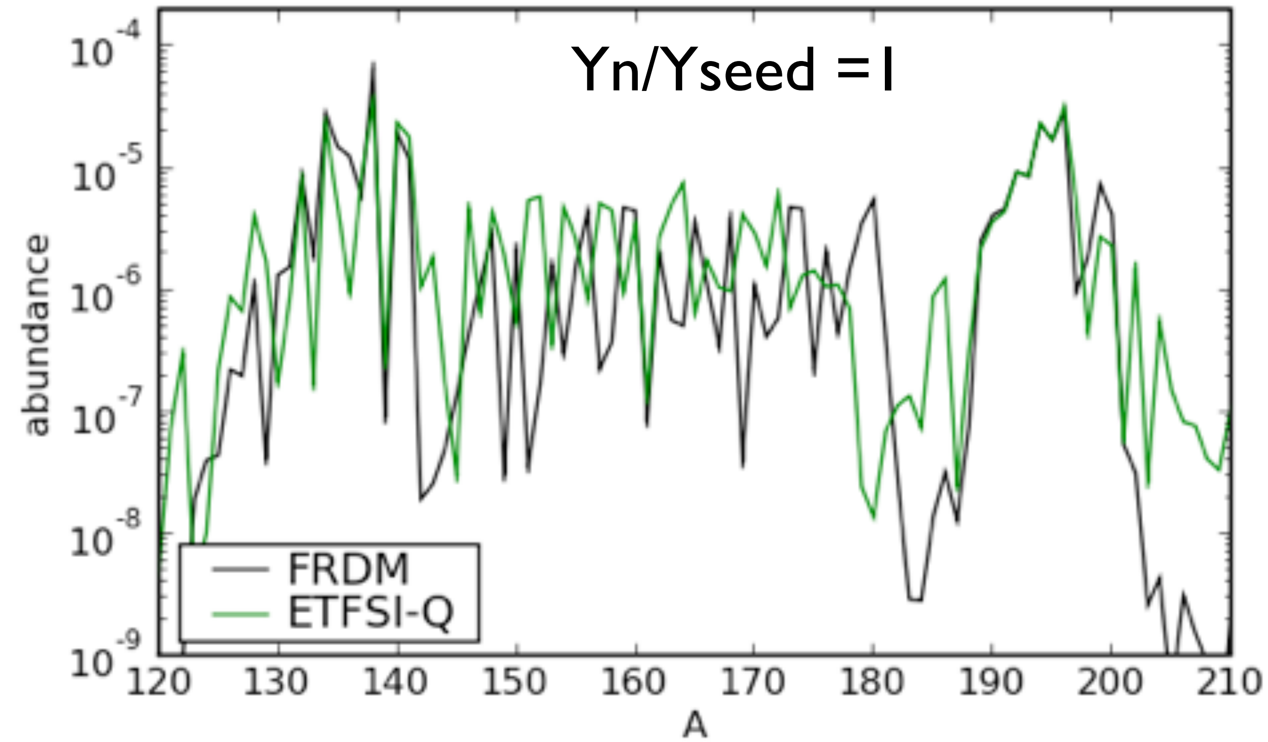
Abundances at freeze-out (Yn/Yseed=1) show odd-even effects following the behavior of the neutron separation energy.

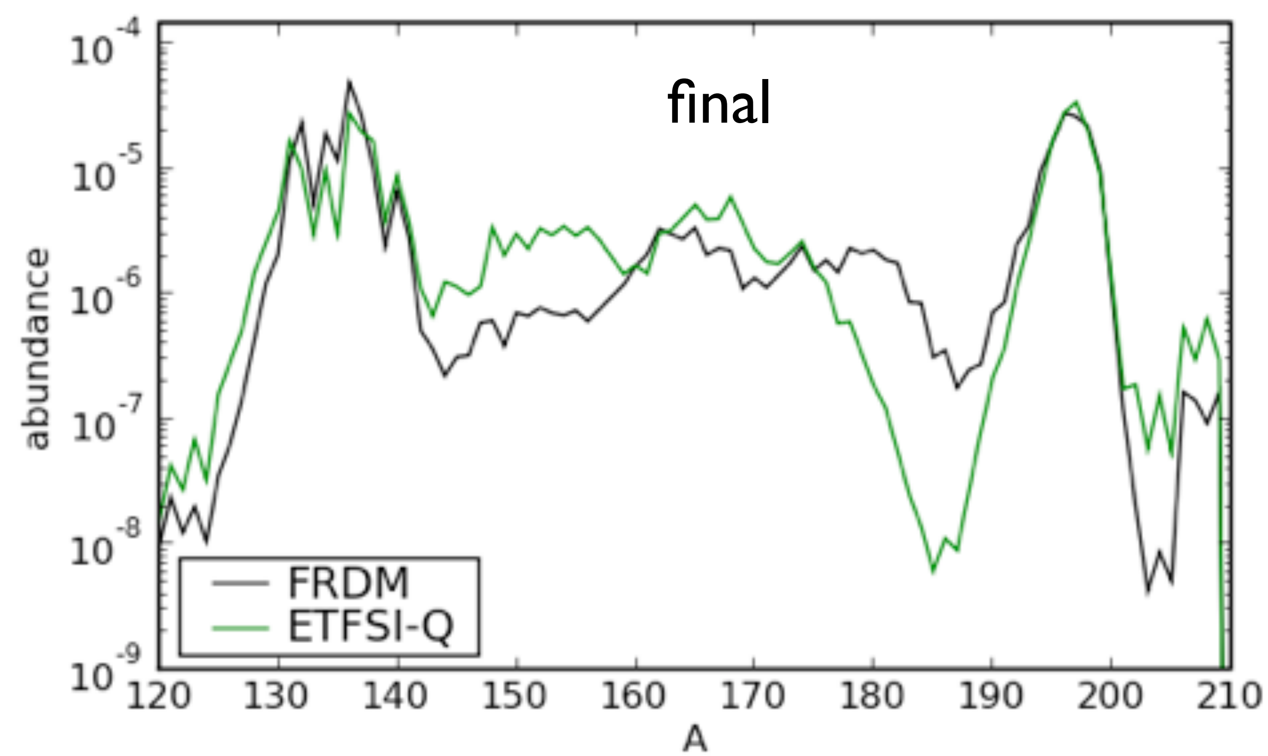
While final abundances are smoother like solar abundances.

Why does the abundance pattern change?

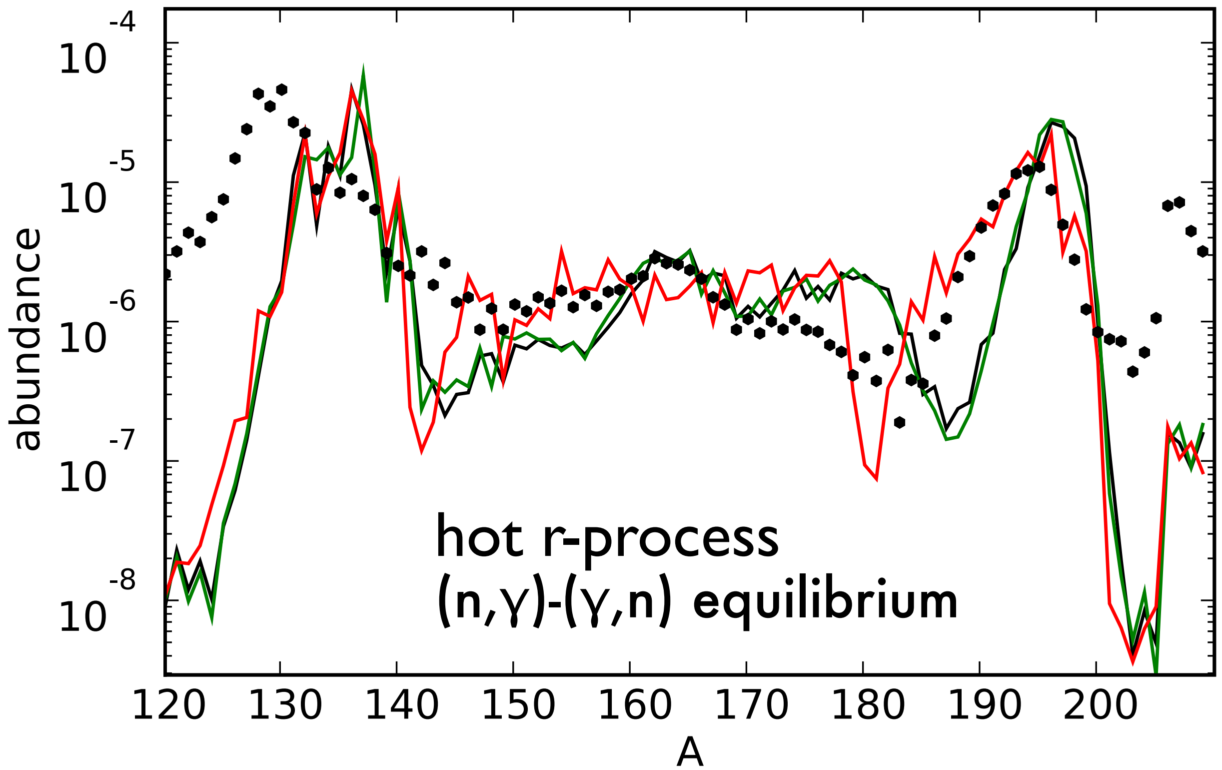
In the classical r-process (waiting point approximation) this is explained by beta delayed neutron emission (Kodama & Takahashi 1973, Kratz et al. 1993).

Dynamical r-process: neutron capture and beta-delayed neutron emission (Surman et al. 1997, Surman & Engel 2001, Surman et al. 2009, Buen et al. 2009)





Neutron captures and beta-delayed neutron emission



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

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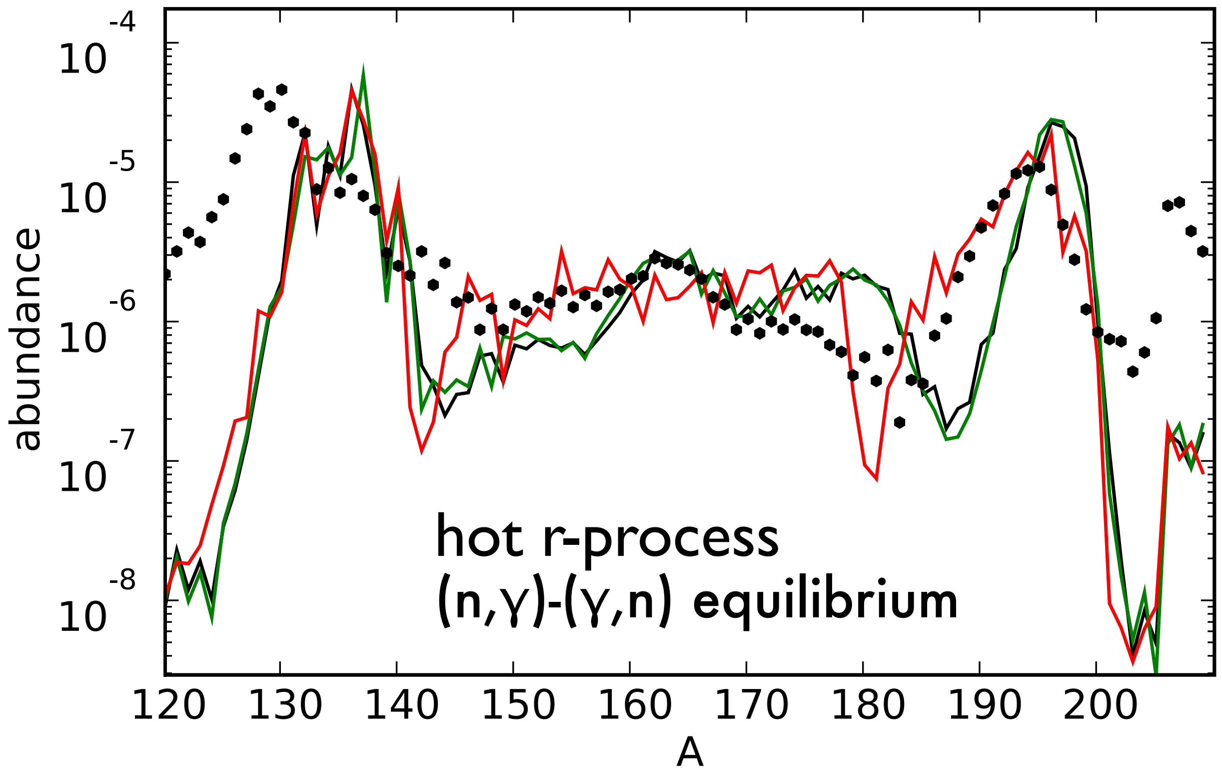

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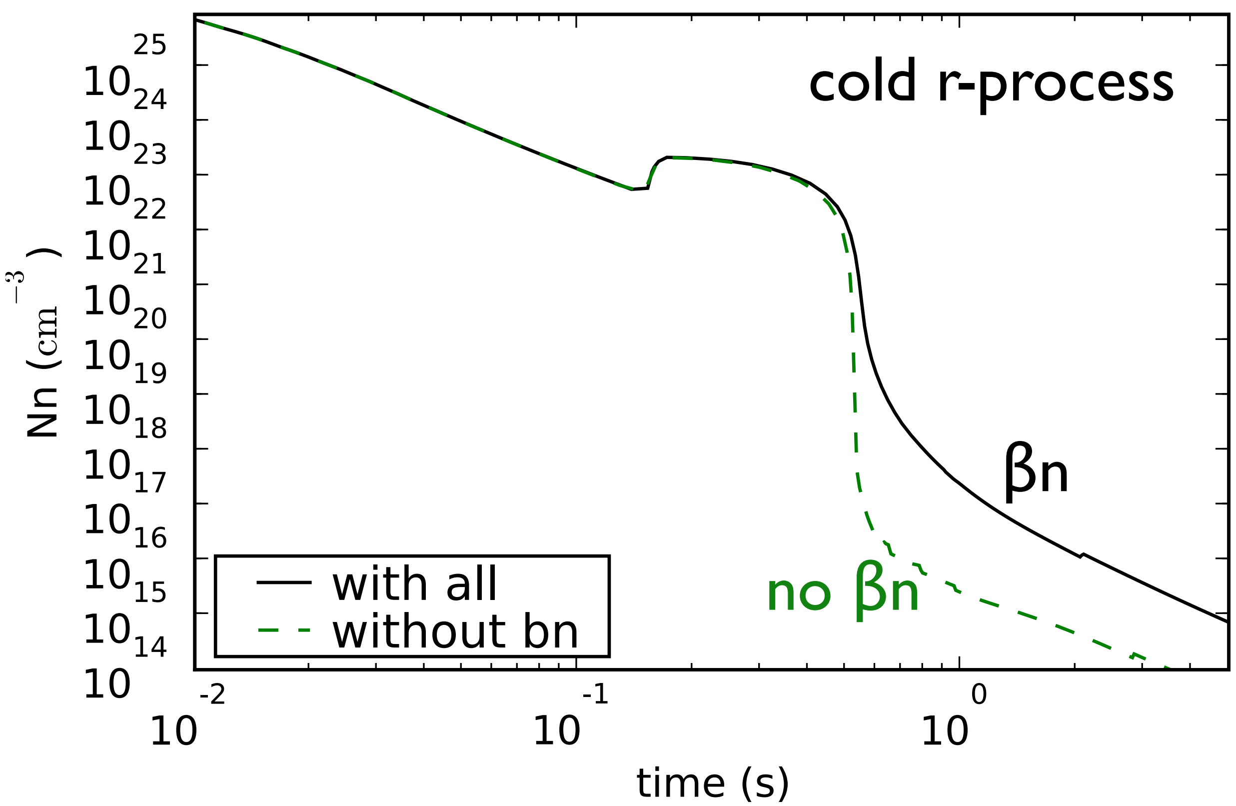
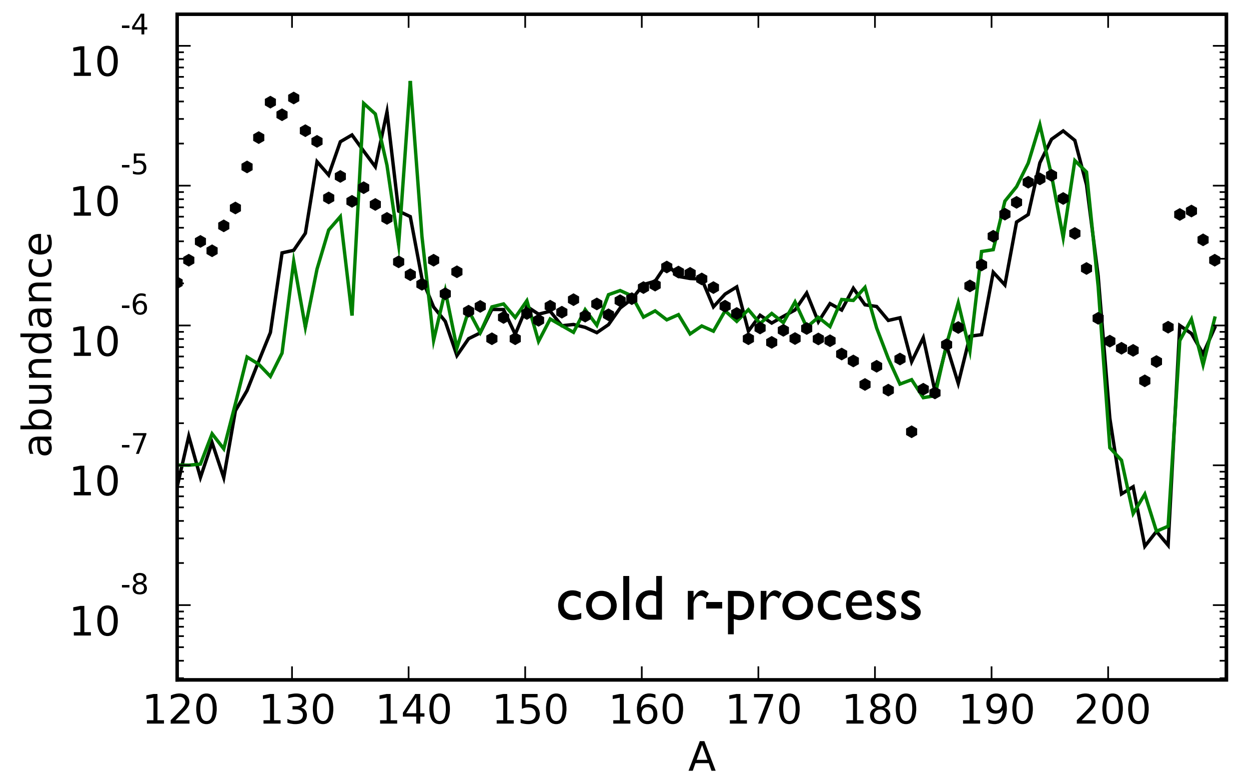
The main role of the beta-delayed neutron emission is to supply neutrons.





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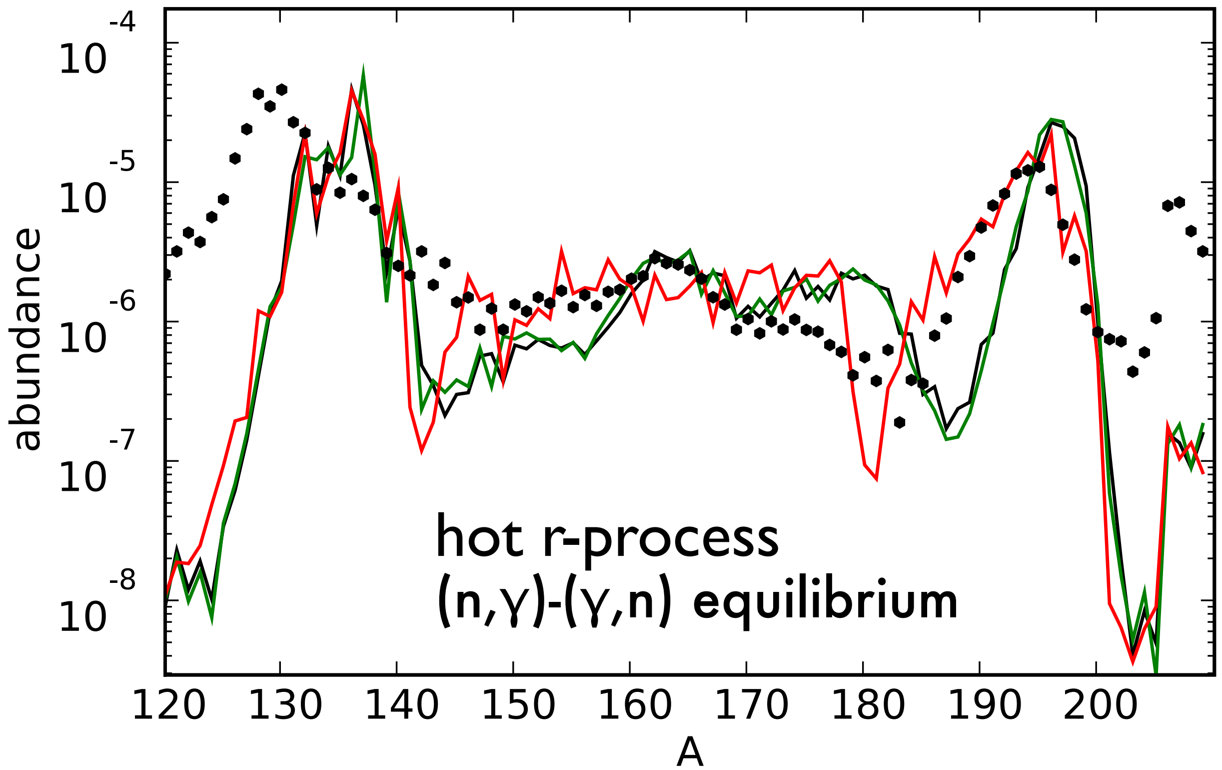

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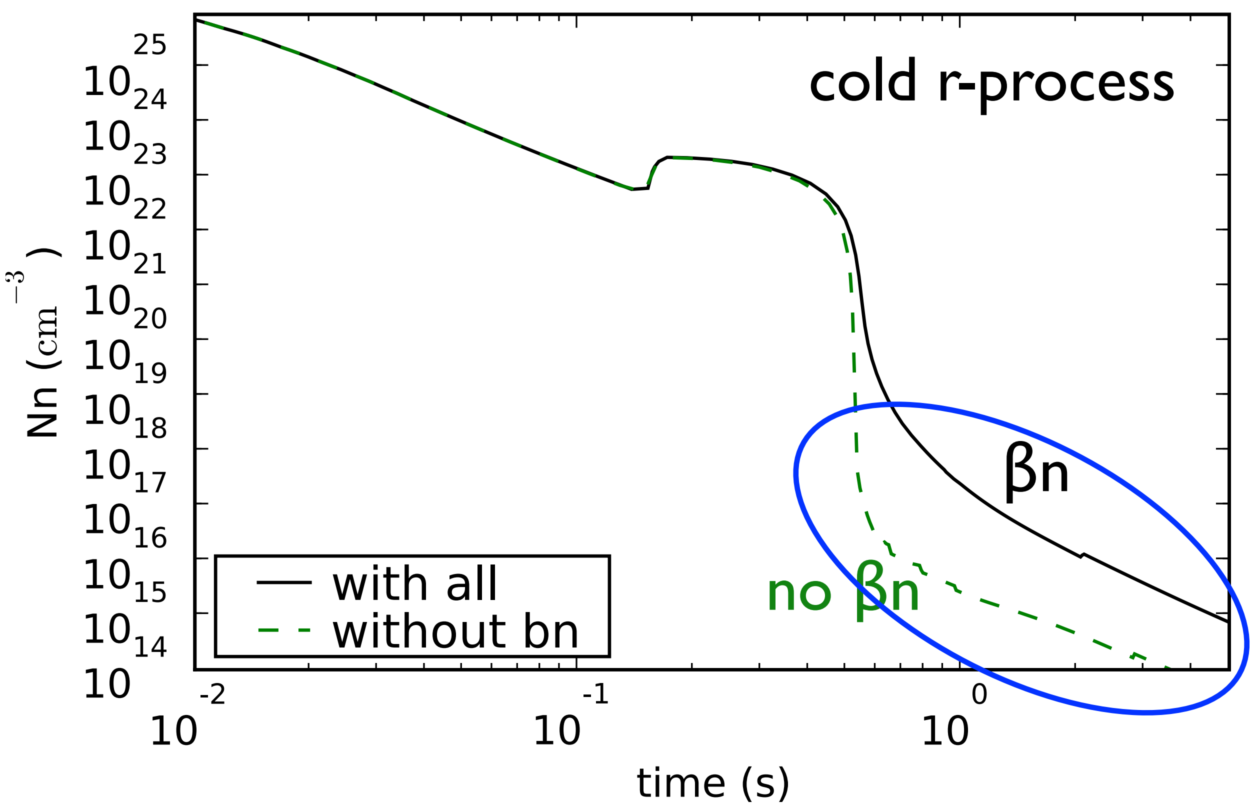

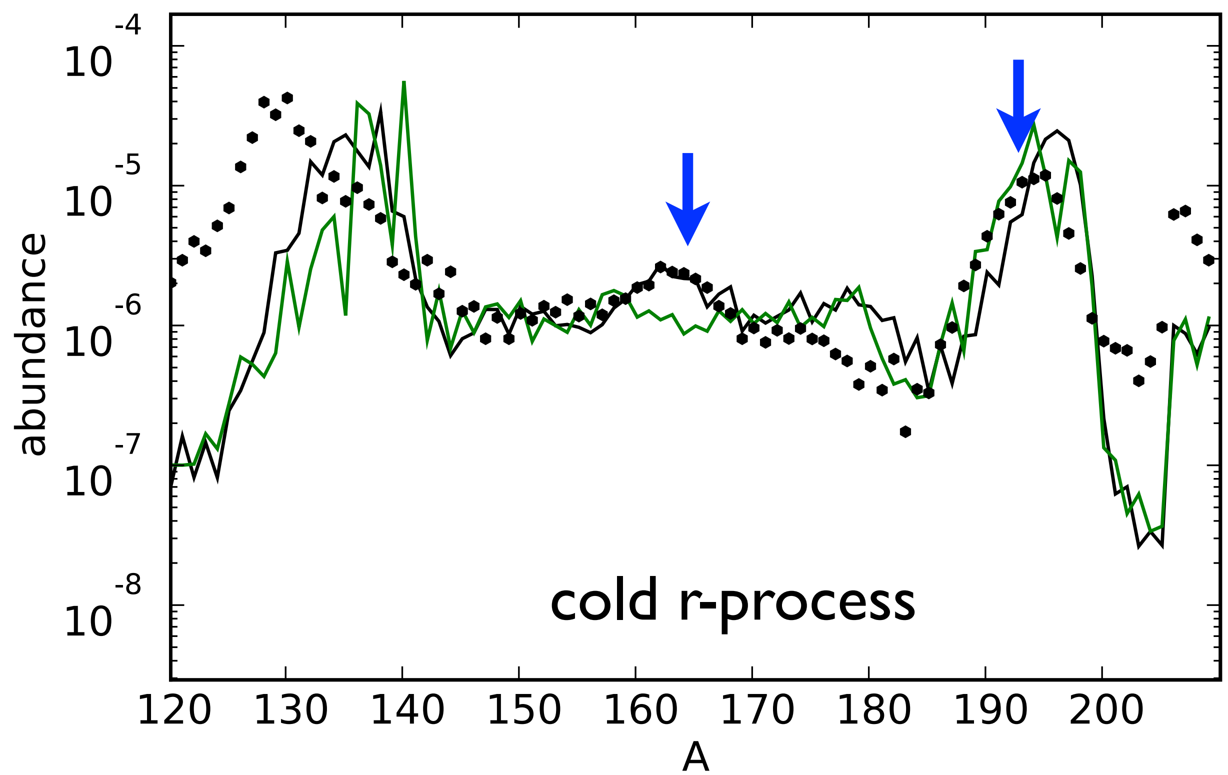

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Conclusions

- Recent long-time supernova simulations do not produce r-process elements: find too low entropies and too high electron fractions.
- By artificially increasing the entropy, our hydrodynamical simulations provide a realistic basis to study and understand the major impacts of the long-time dynamical evolution and of nuclear masses on the abundances.
- As matter moves back to stability neutron captures are as important as beta-delayed neutron emission.

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and outlook

- Multi-dimensional simulations with improved neutrino transport.
- Experiments for masses, improve theoretical models.
- Explore the impact of beta decays (Ivan Borzov: Poster 292).

Arcones & Janka (to be submitted)