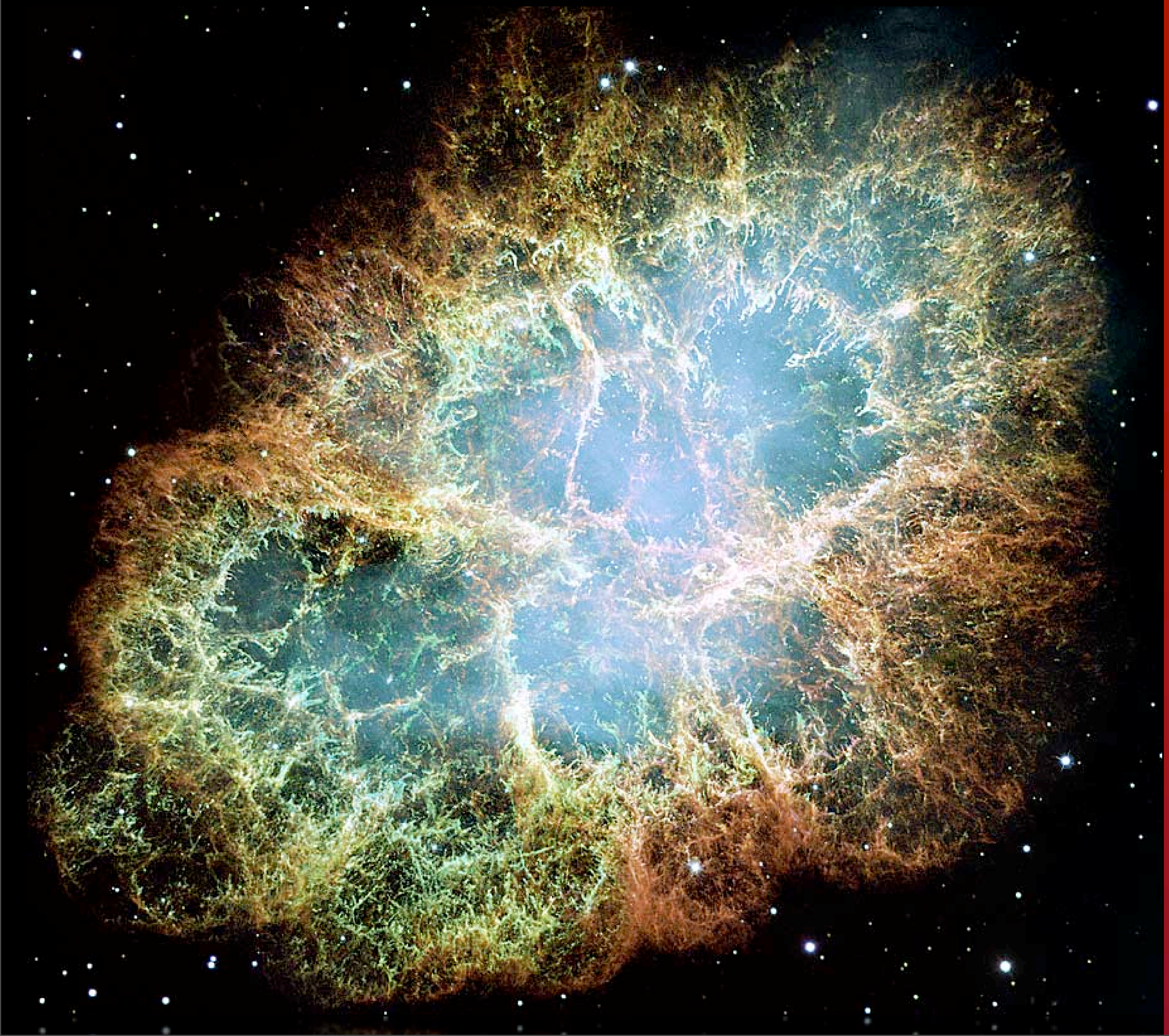
Nucleosynthesis in core-collapse supernovae



Almudena Arcones

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BASEL

Outline

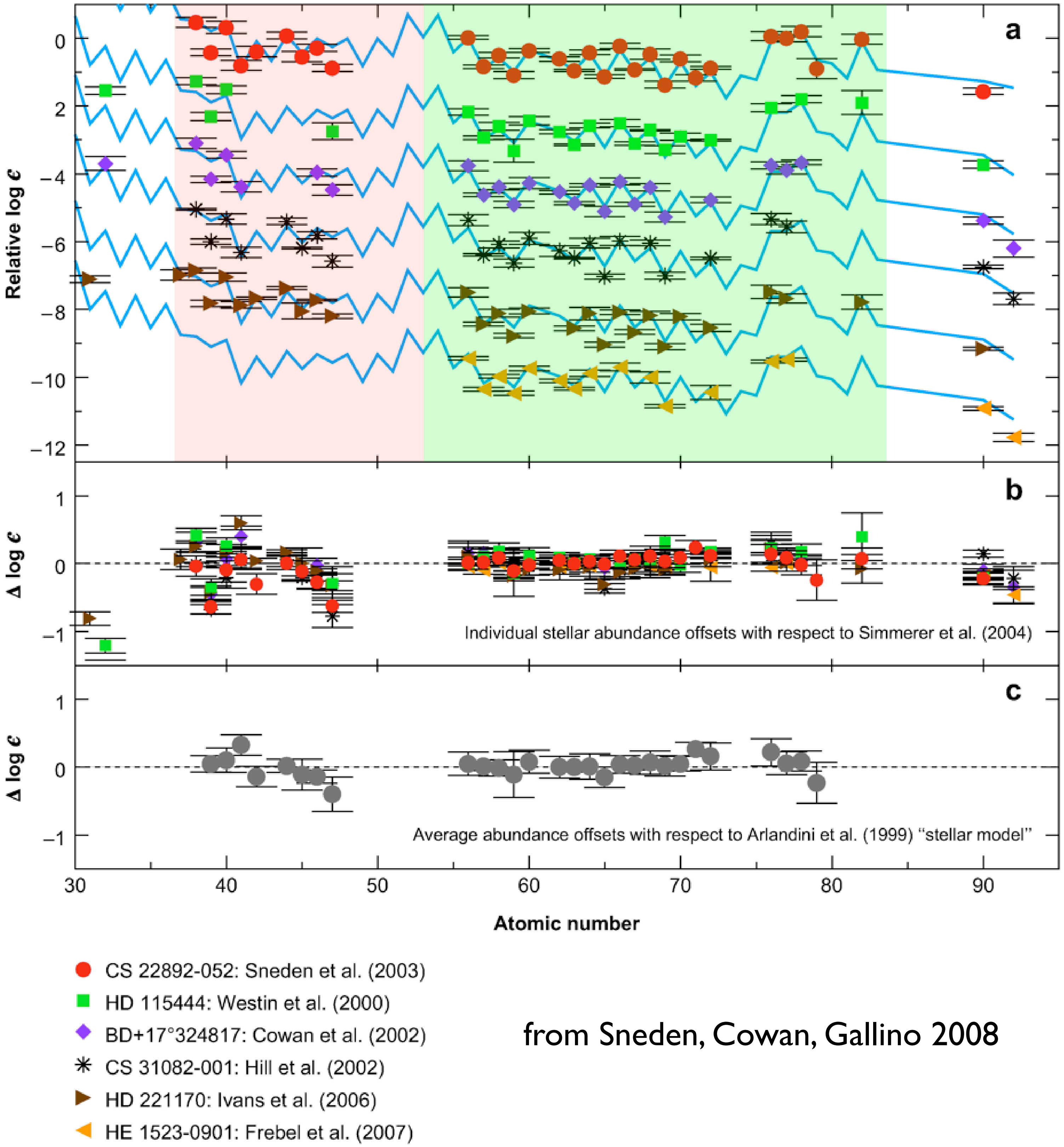
- Introduction and motivation
    - observations
    - neutrino-driven wind

- 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



from Sneden, Cowan, Gallino 2008

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

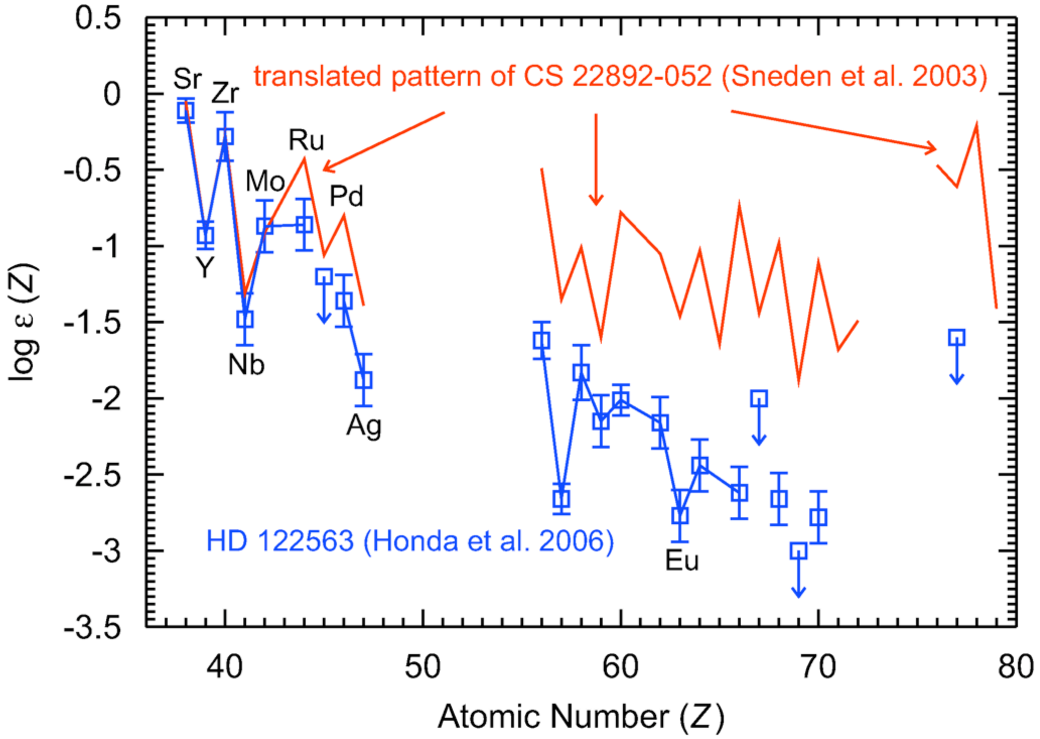
Only few nucleosynthesis events have contributed to the abundances present in old stars.

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, 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.

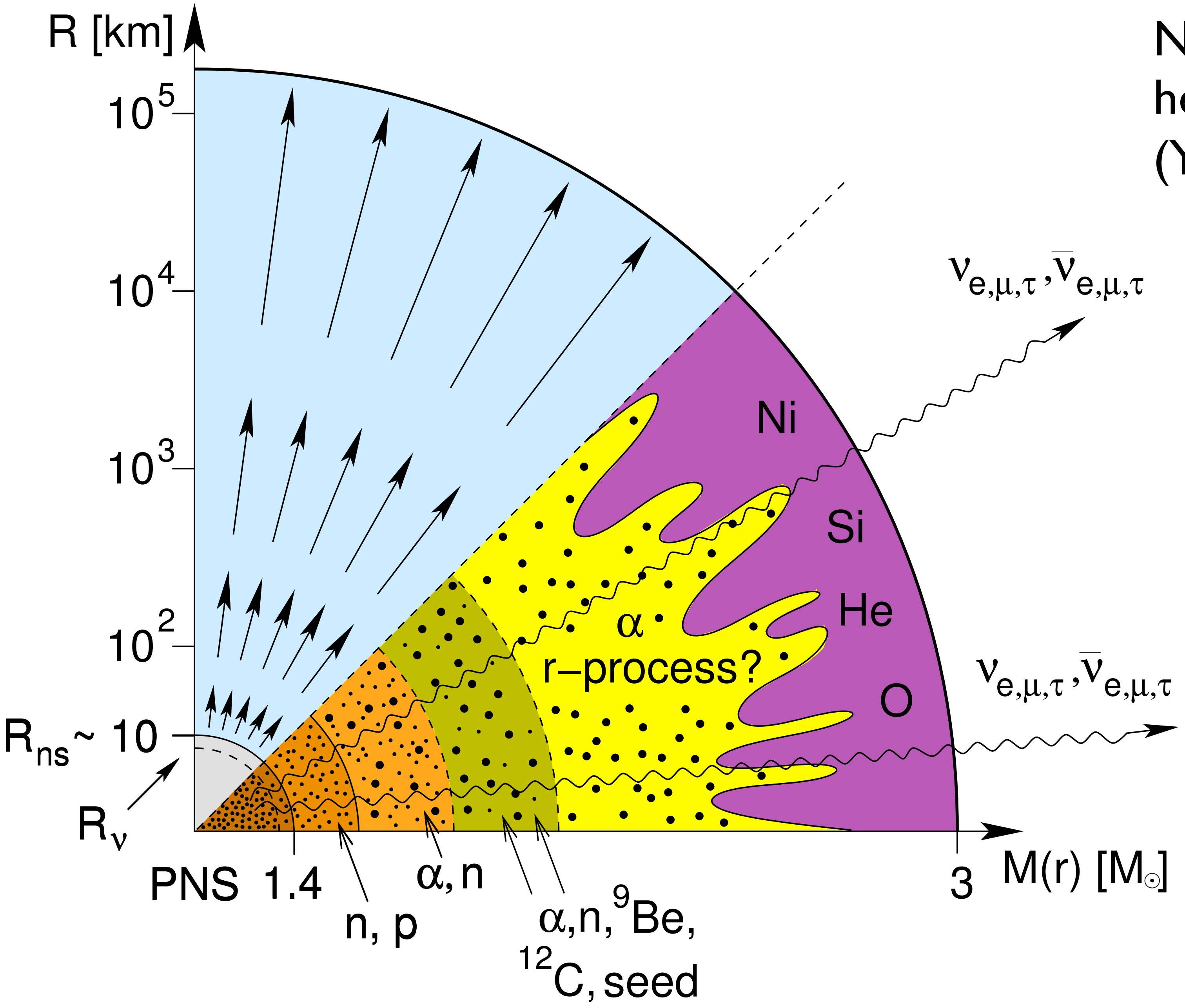


- In neutrino-driven winds when a neutron star forms, charged-particle reactions (CPR) produce nuclei with A~90-110 (Z<47).
- Observations of low-metallicity stars show that sites producing heavy r-nuclei do not produce Fe or any other elements between N and Ge. This suggest that heavy r-nuclei with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

Travaglio et al 2004: Light element primary process: LEPP = solar – r-proces – s-process
Montes et al. 2007: LEPP creates a uniform and unique pattern

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

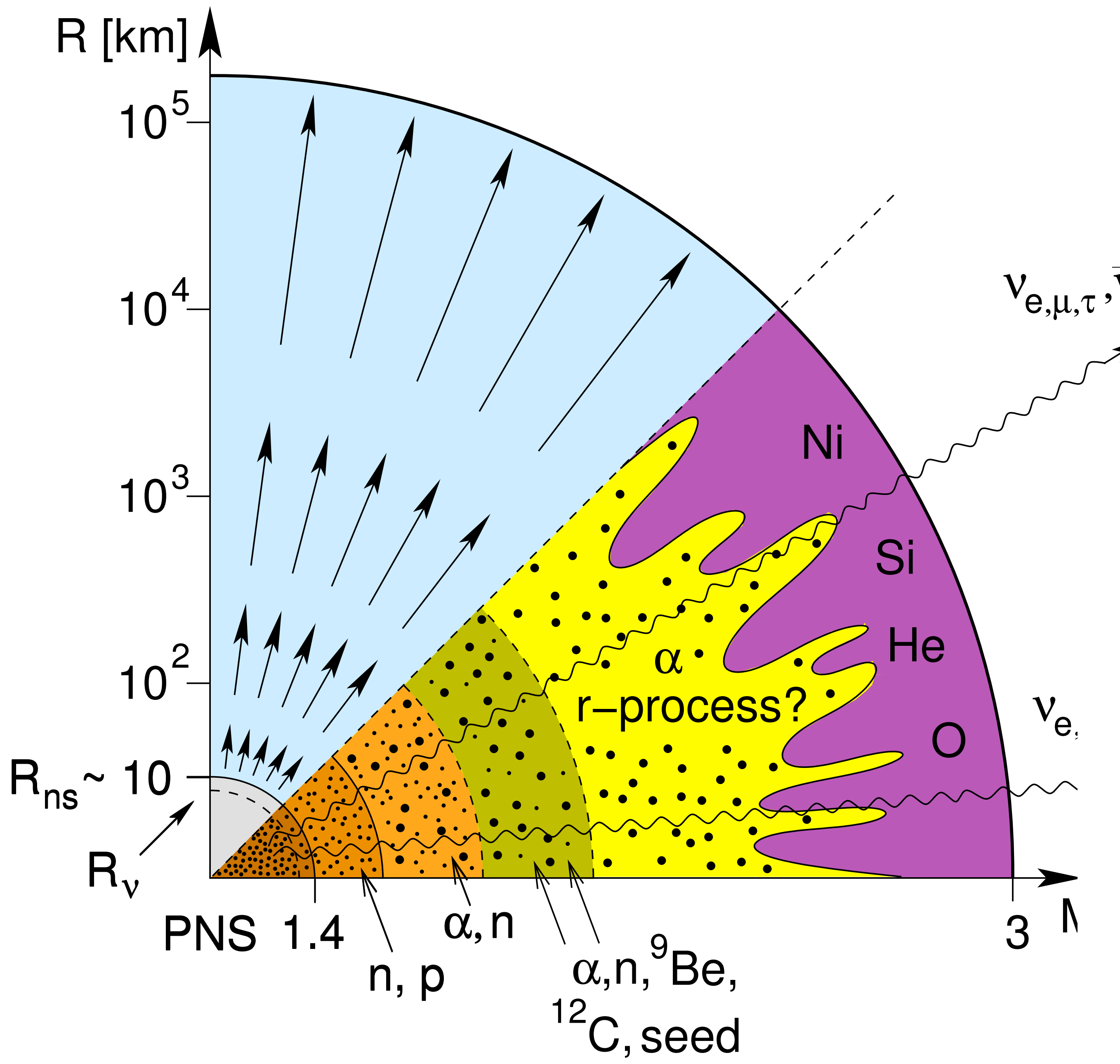
Neutrino-driven winds



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



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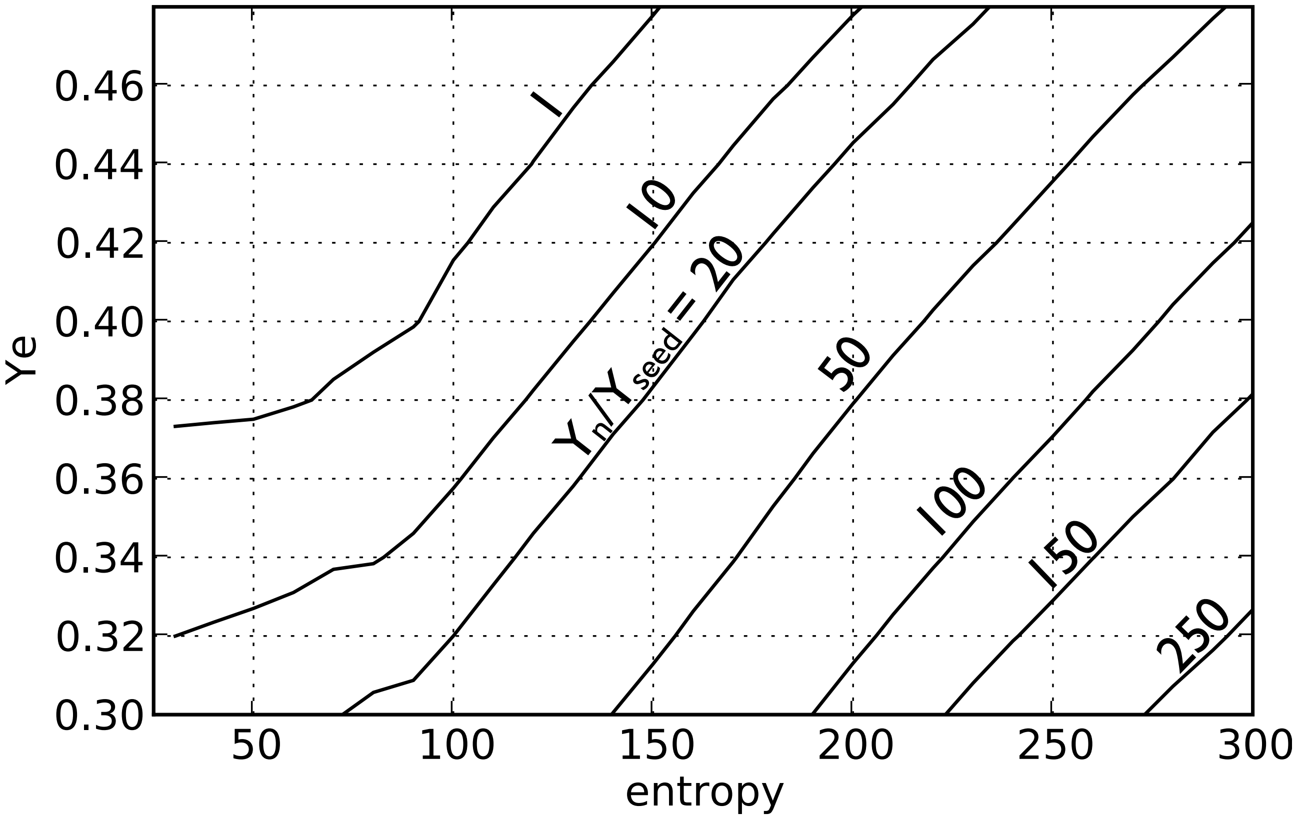
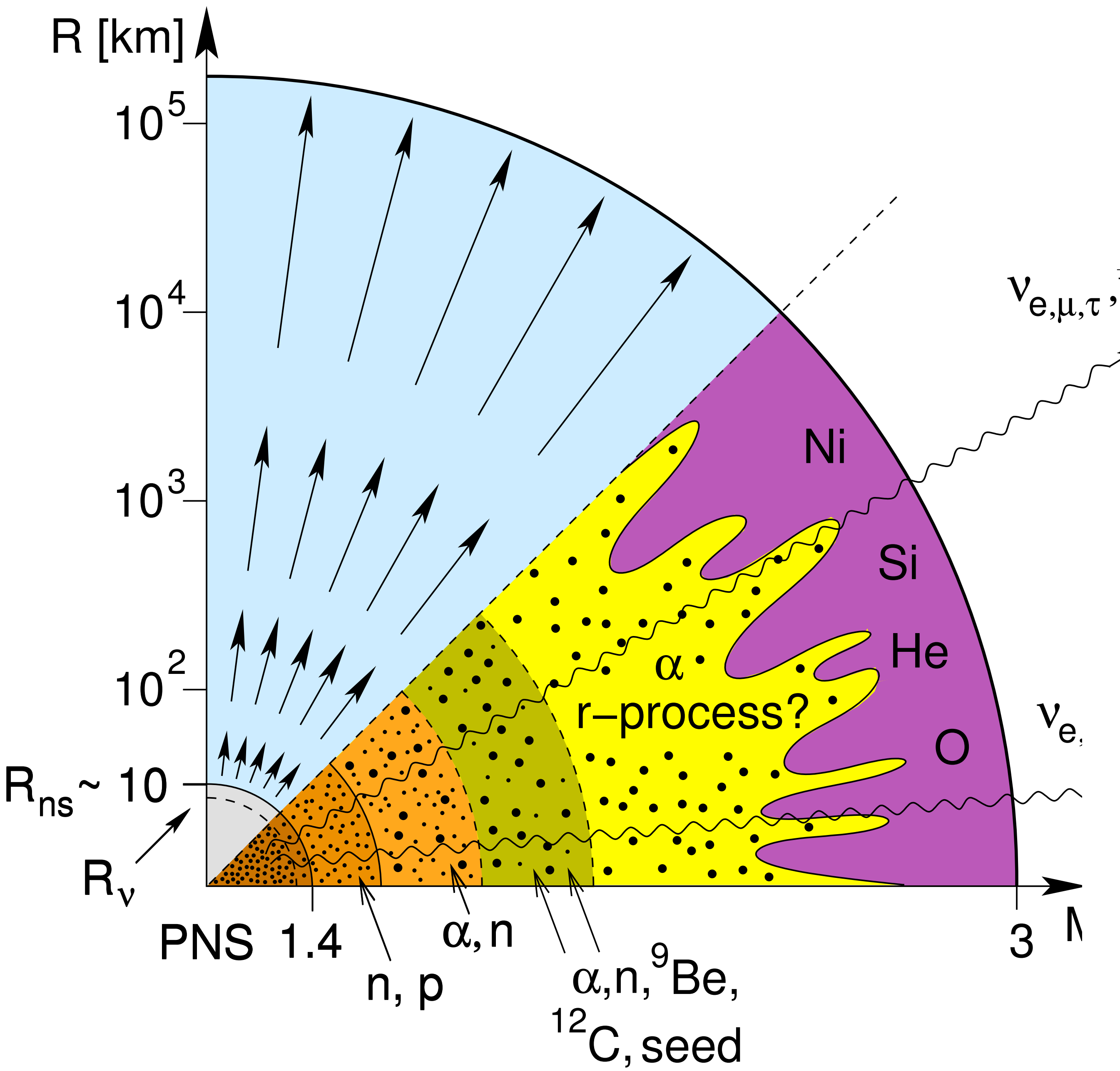


Neutrino-driven winds



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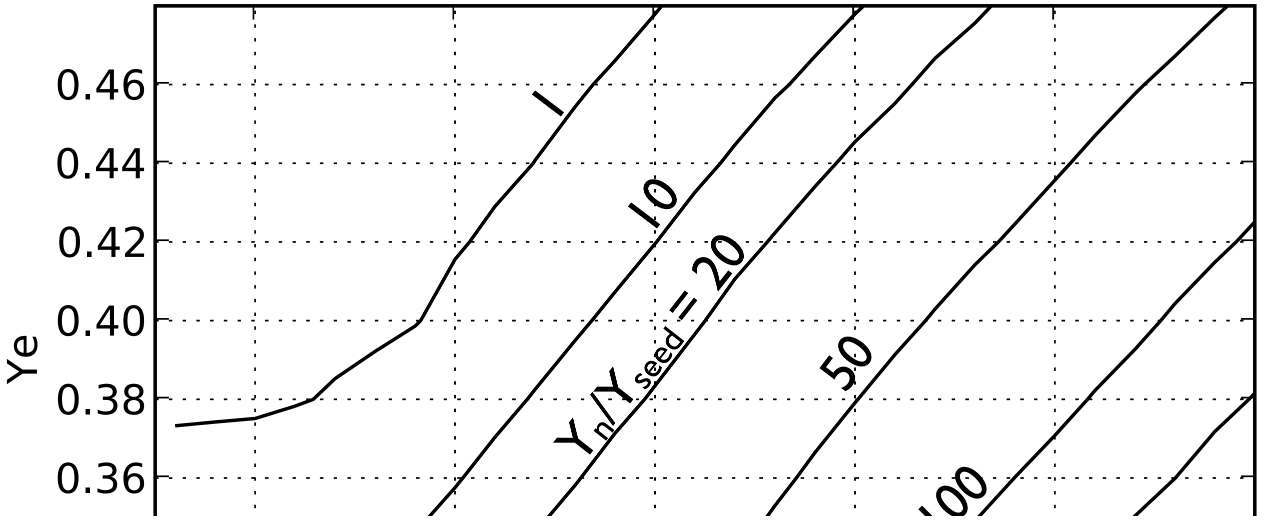
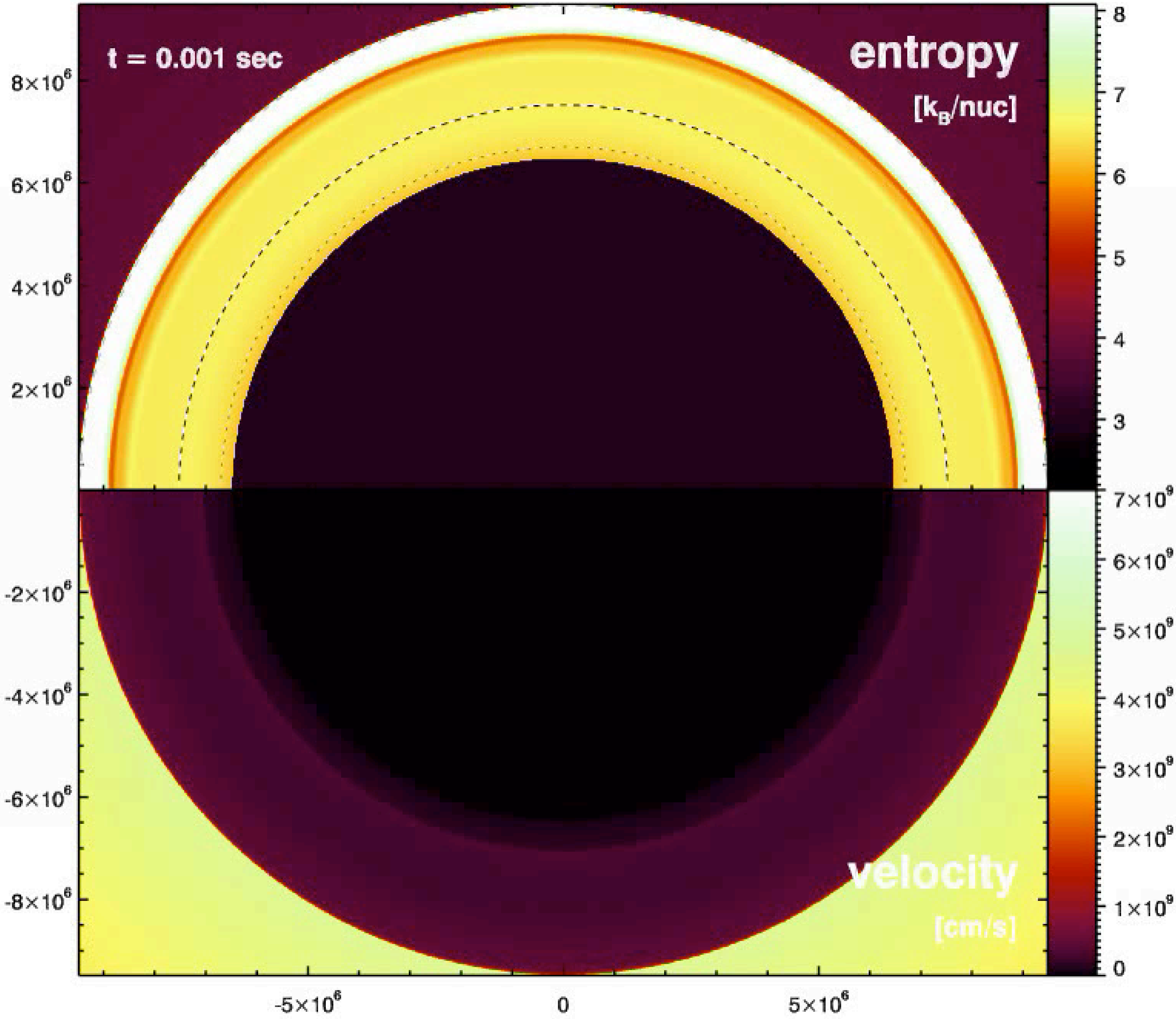


Are these conditions reached in state-of-the-art neutrino-driven wind simulations?
Do supernovae produce the heavy r-process nuclei?

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

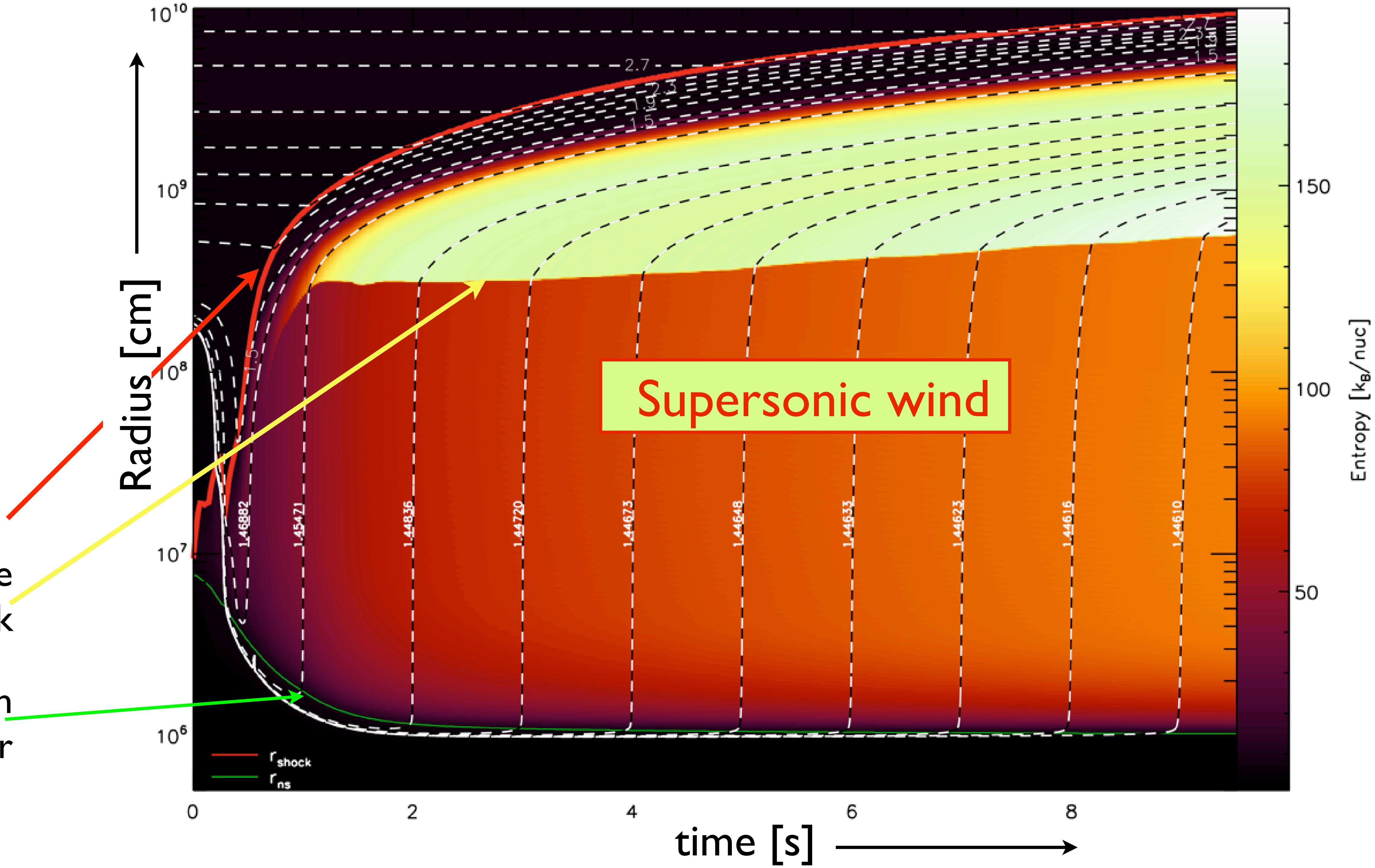
Solutions: - steady-state wind models (Otsuki et al. 2000, Thompson et al. 2001, Wanajo 2000-2010)
- one-dimensional simulations with an artificial explosion (Arcones et al. 2007 (also 2d), Fischer et al. 2009)

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 results

Arcones et al 2007



Supersonic wind

Shock

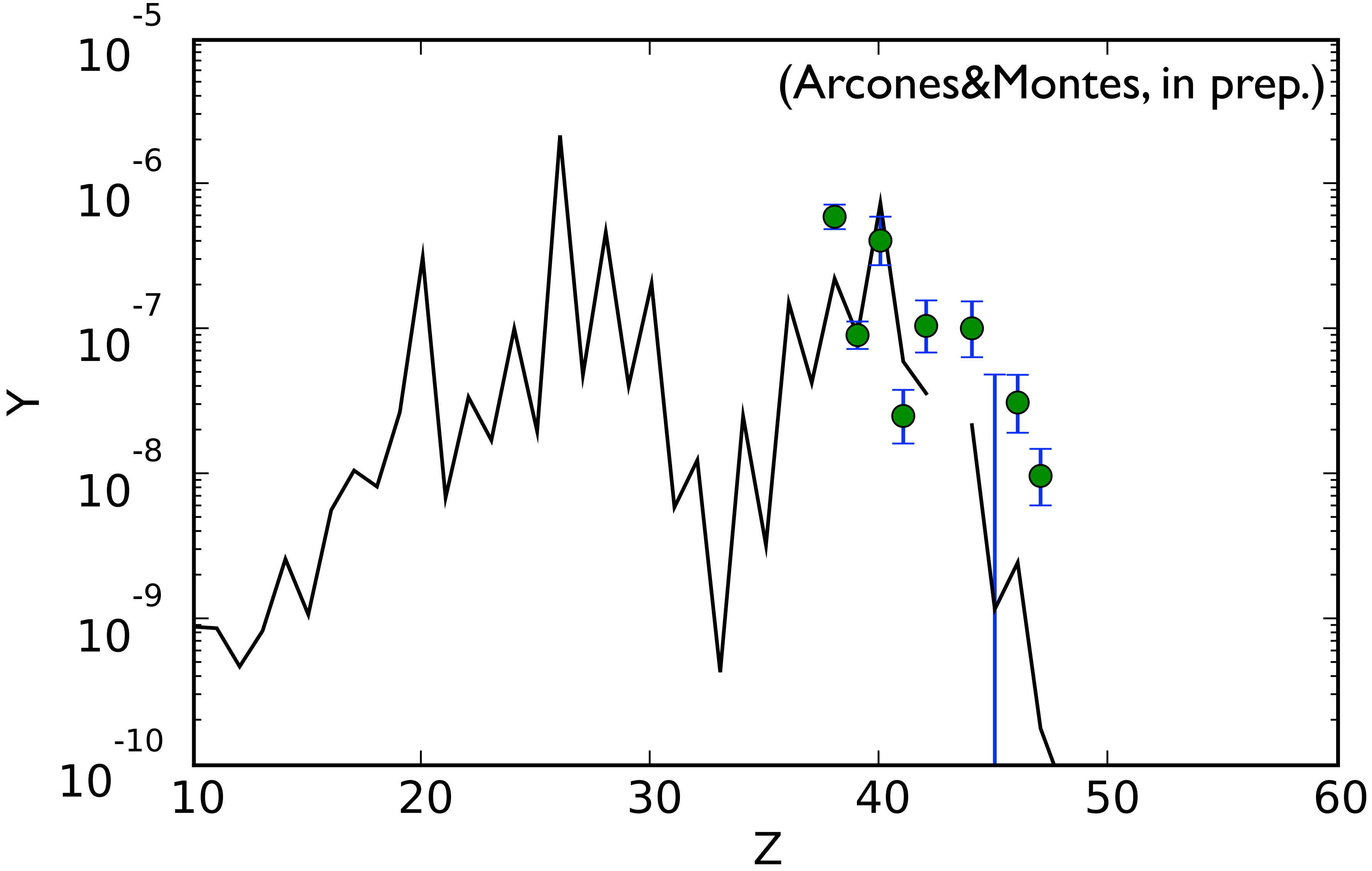
Reverse shock

Neutron star

Nucleosynthesis results

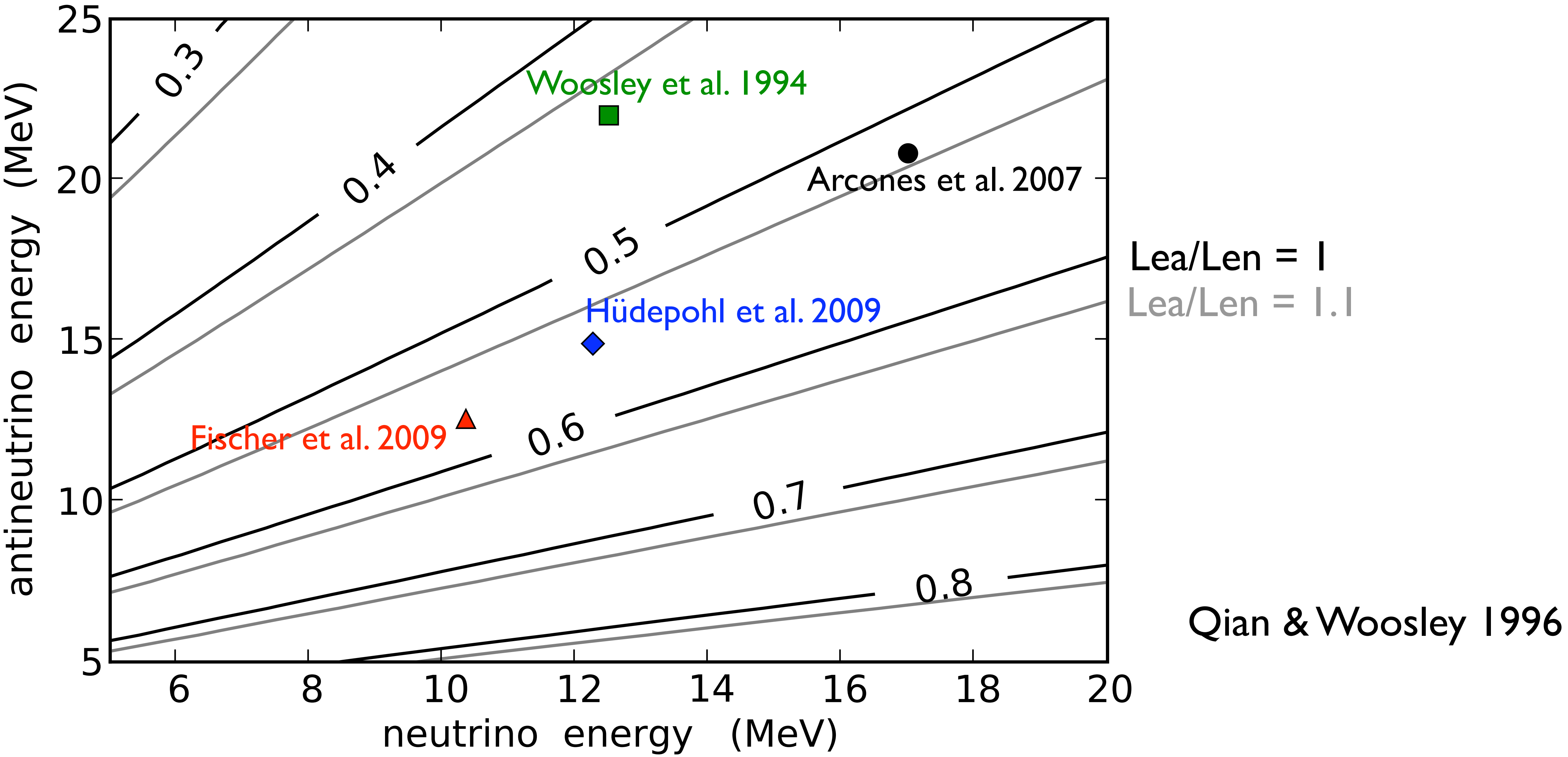
Integrated abundances based on the neutrino-driven wind trajectories compared to LEPP pattern (Montes et al. 2007)

LEPP elements are produced, but no heavy r-nuclei.



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.

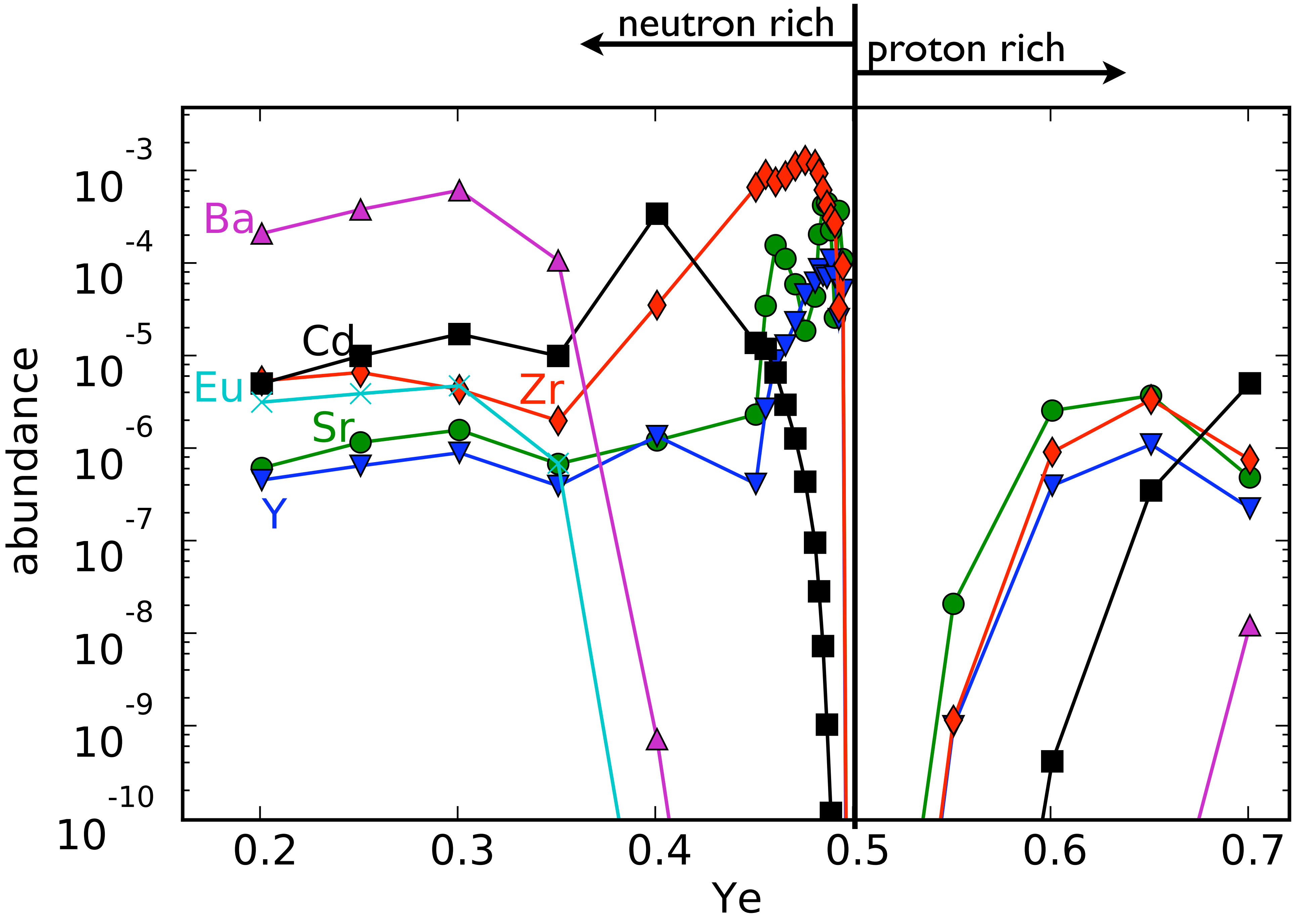


Qian & Woosley 1996

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

Nucleosynthesis and electron fraction

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



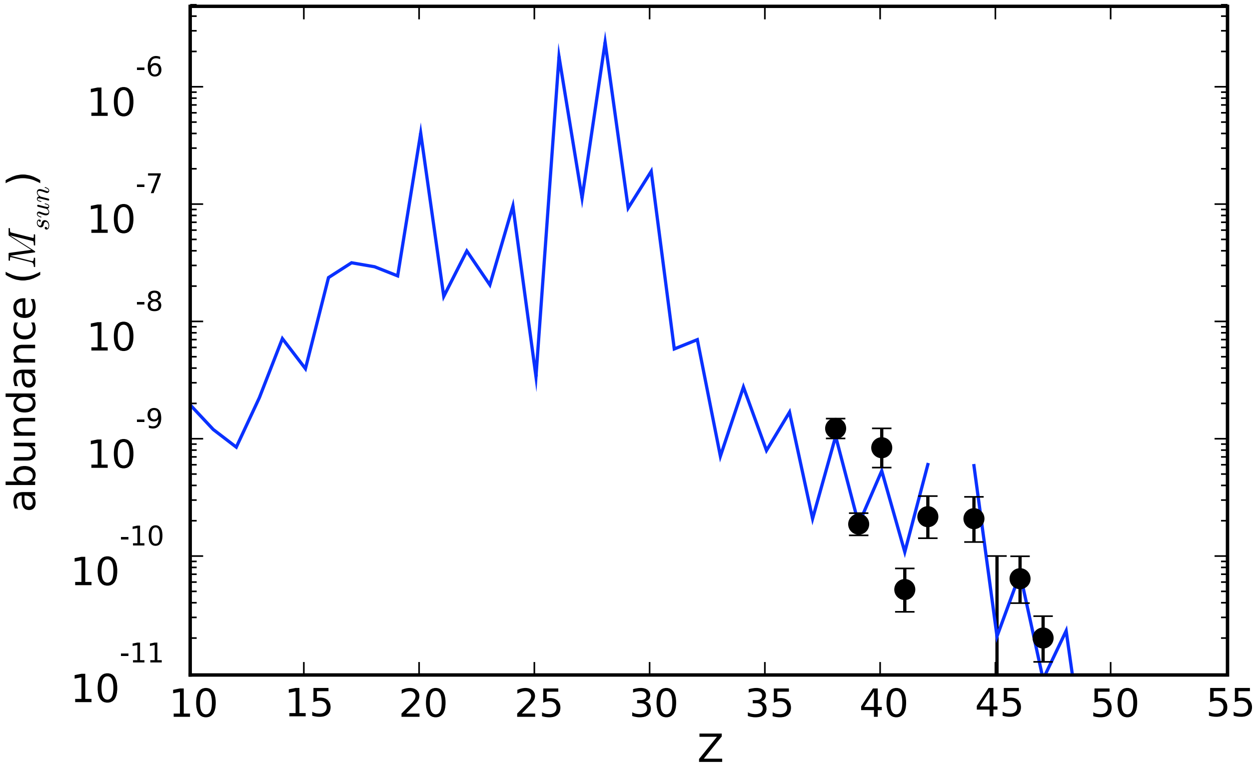
LEPP elements in neutron- and proton-rich conditions

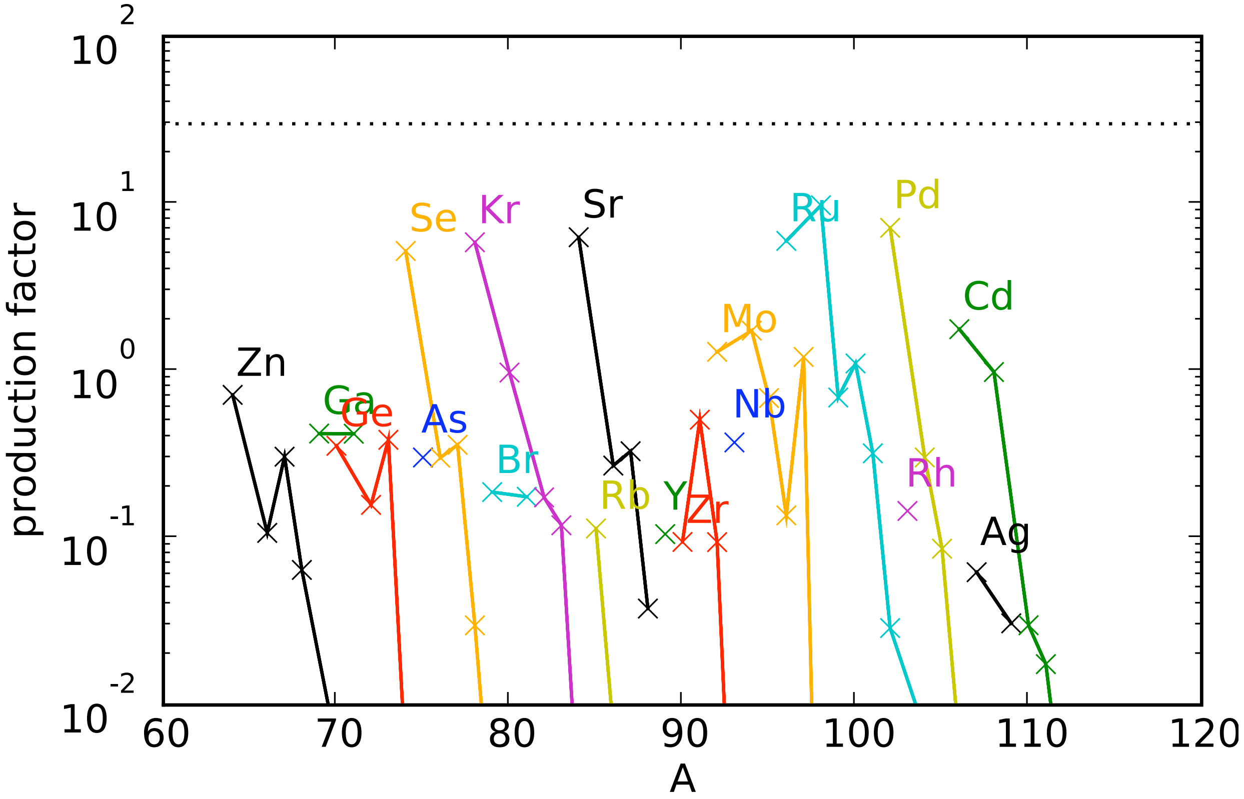
LEPP in proton-rich ejecta

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.





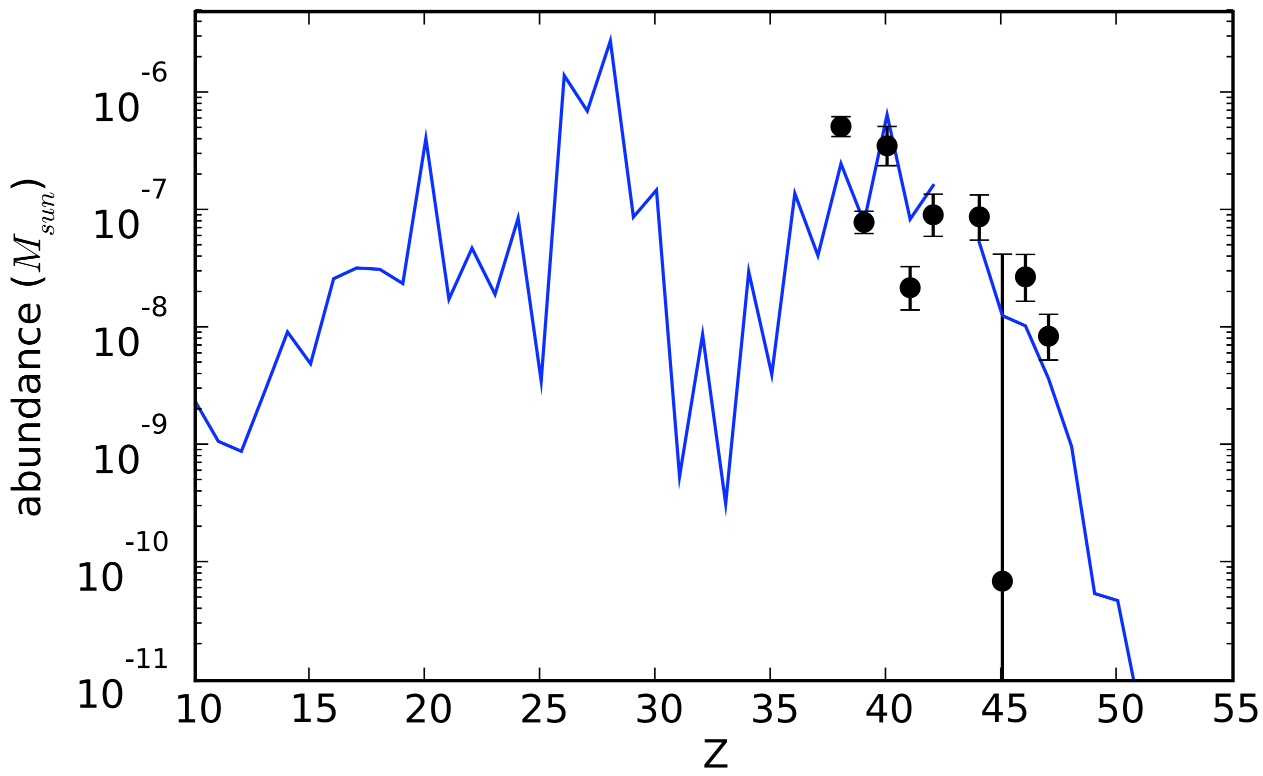
Problem: in the LEPP component of the solar system there are also neutron-rich nuclei.

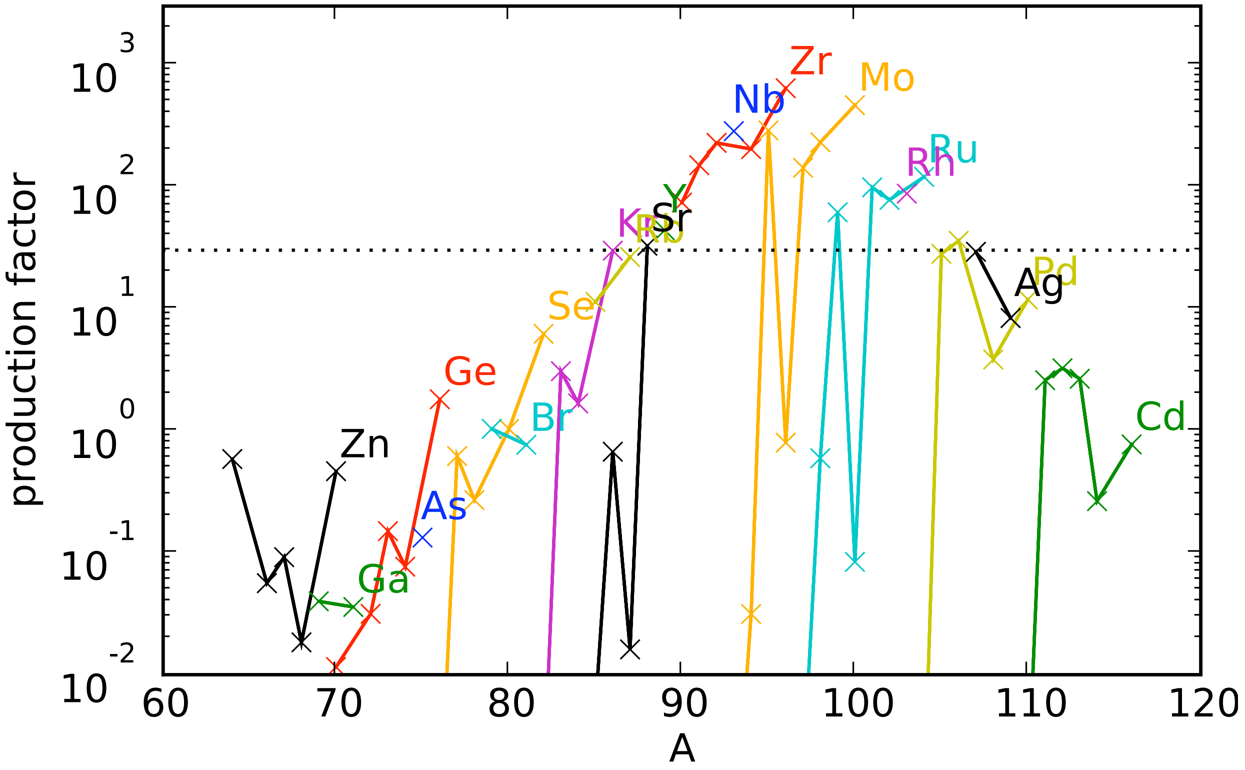
Isotopic abundances from UMP stars will give rise new insights.

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).

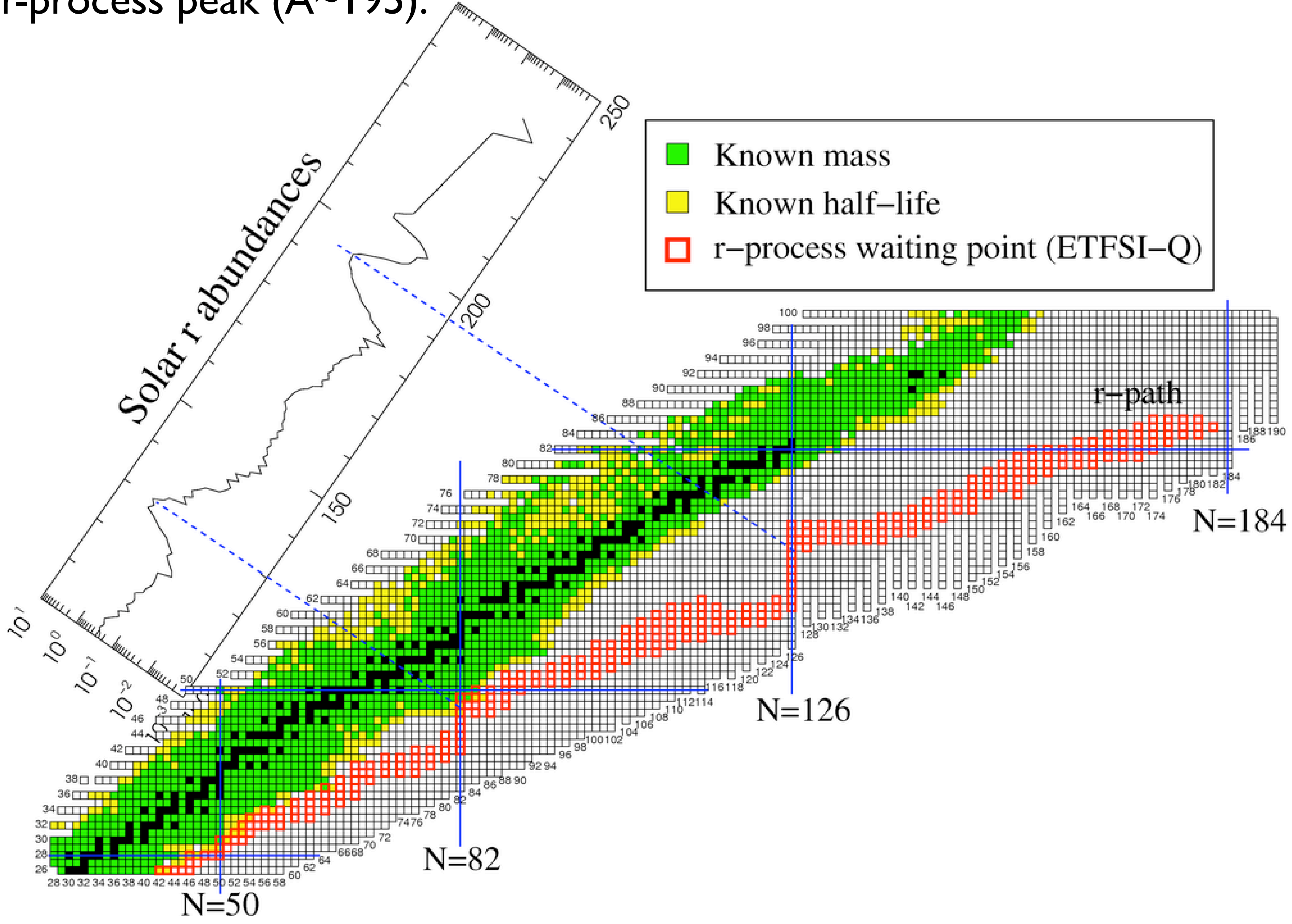
Suggest that if only a fraction of the supernovae eject neutron-rich material ⟶ can explain LEPP in the solar system.

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

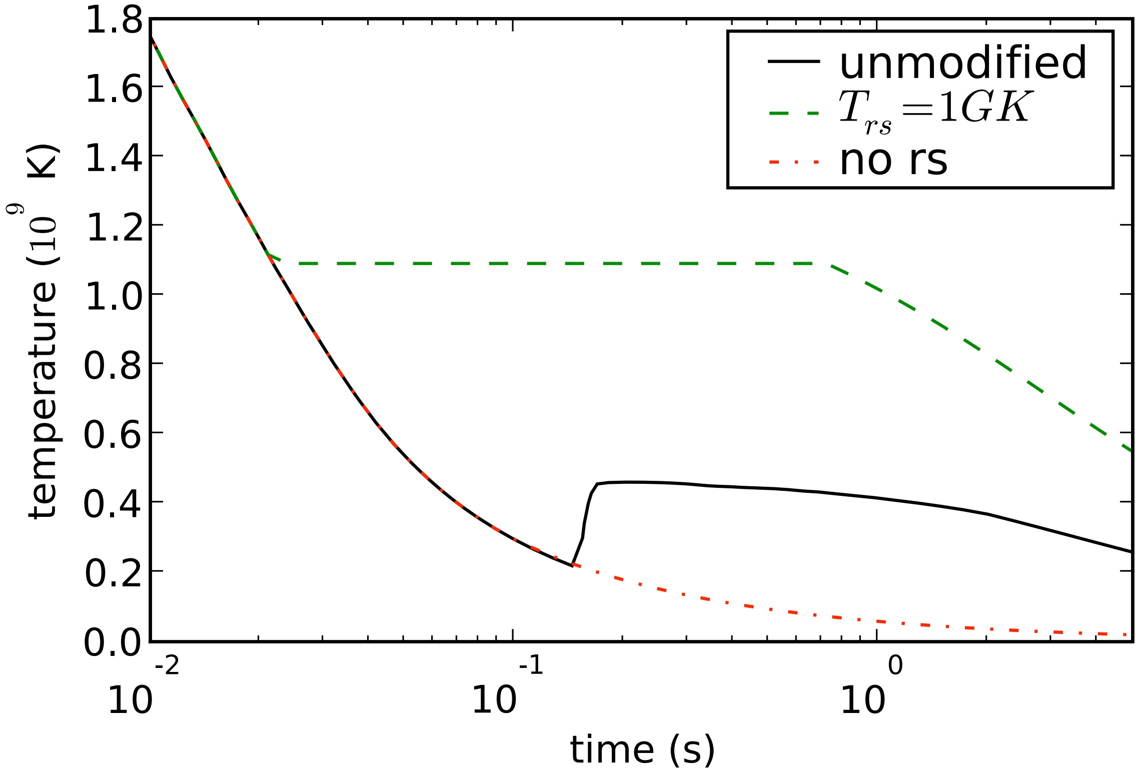
Evolution of T and ρ during the alpha-process determines the neutron-to-seed ratio and thus the possibility of forming heavy elements.

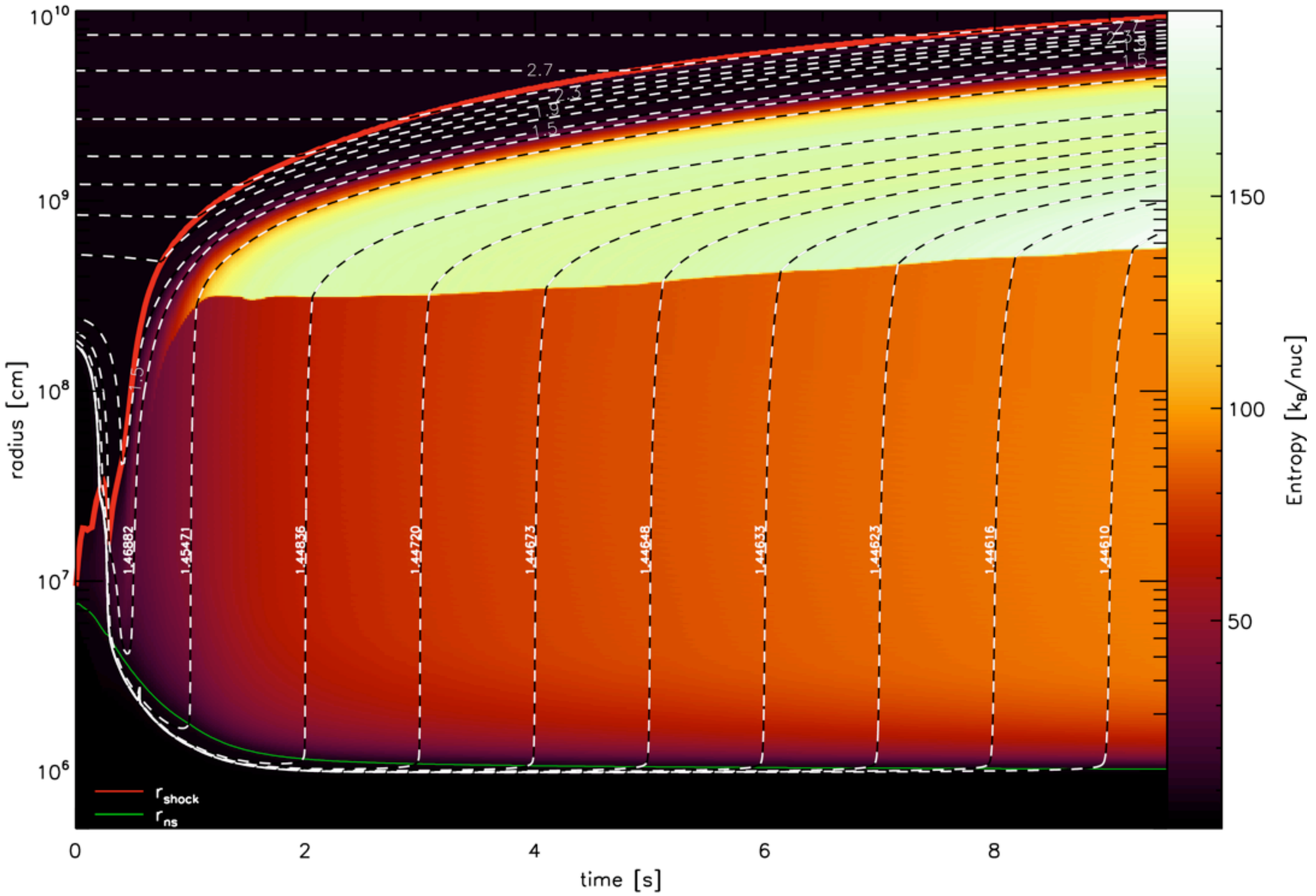
However, the dynamical evolution after the freeze-out of charged-particle reactions is also important for understanding the final abundances.

We use one trajectory from our 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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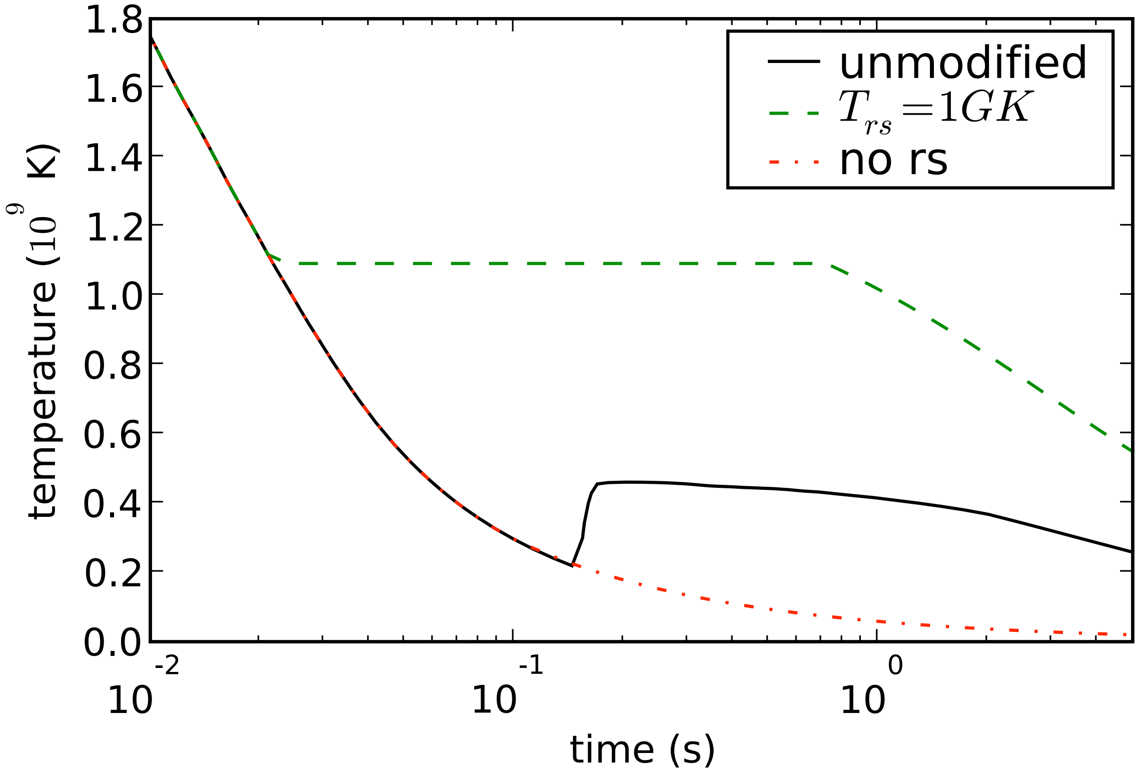
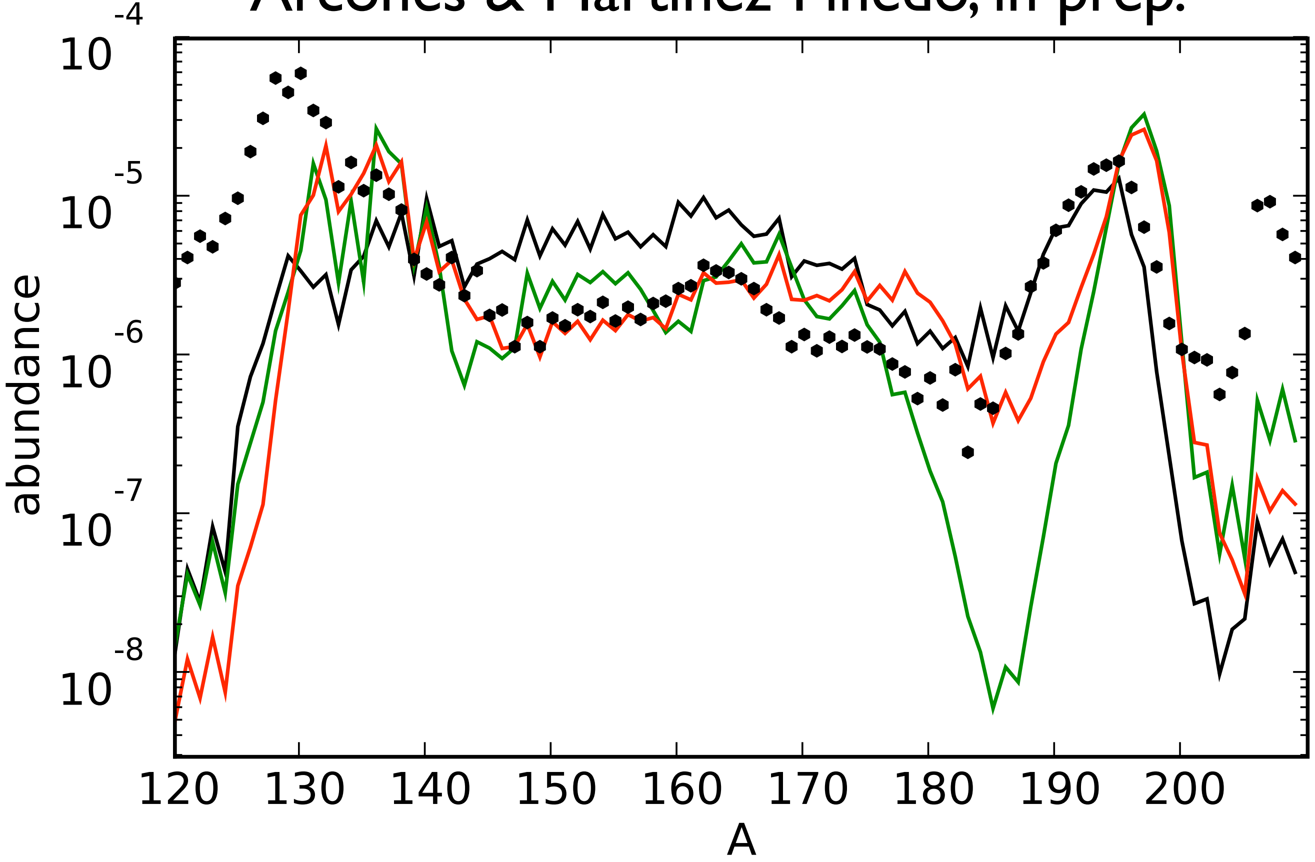
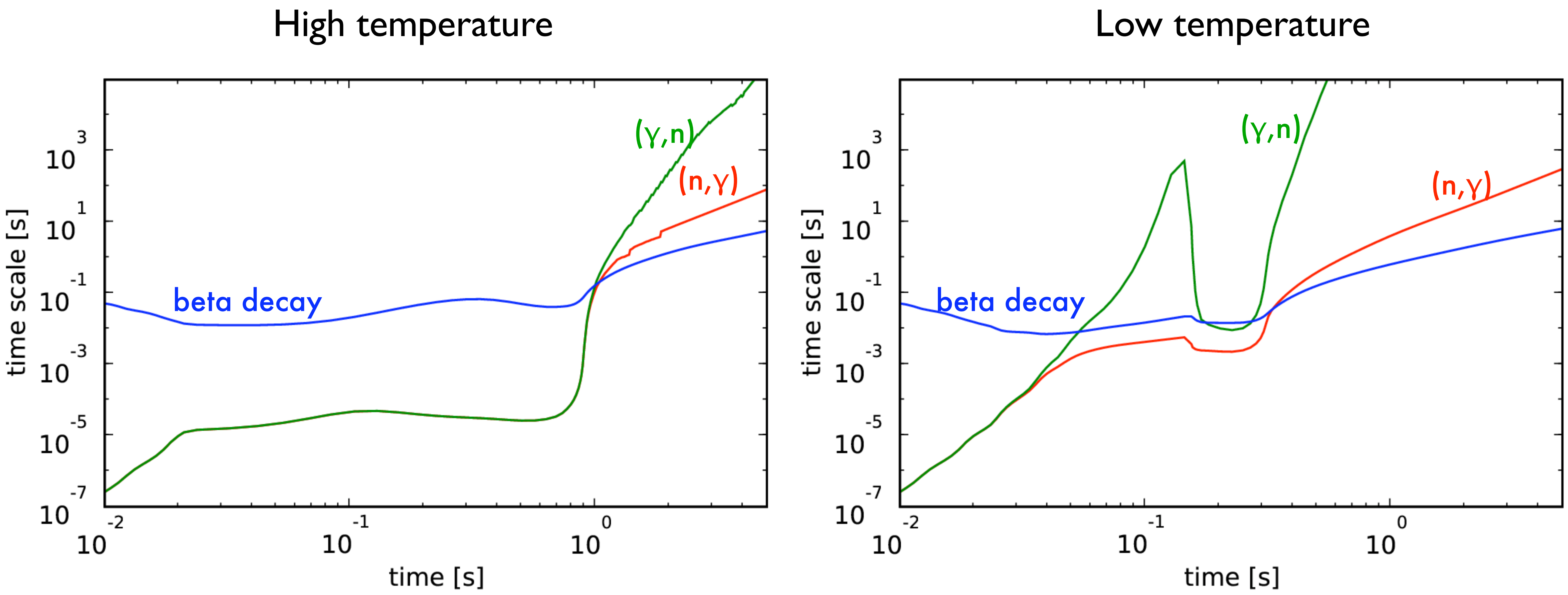


Arcones & Martinez-Pinedo, in prep.



Long-time evolution: high vs. low temperature

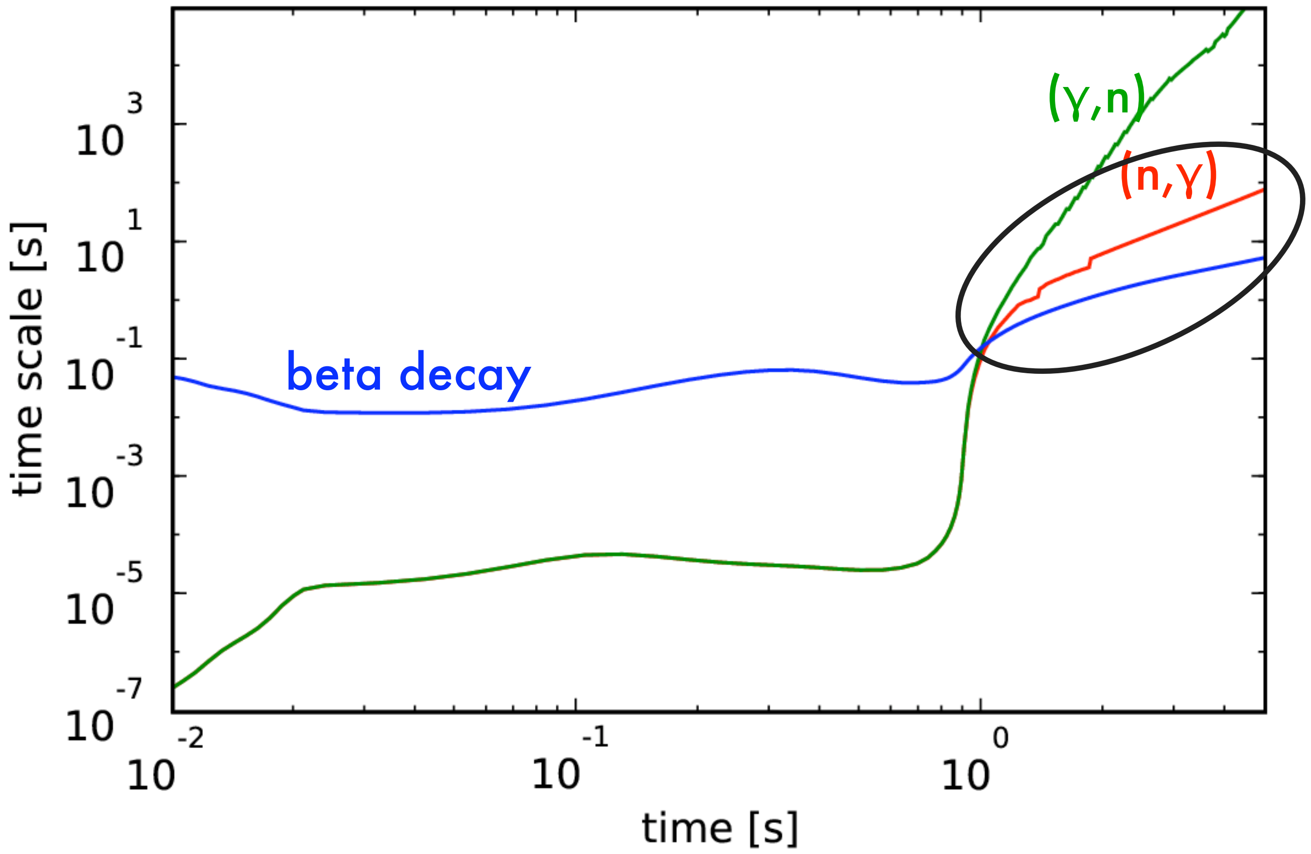


The evolution takes place under (n,γ)-(γ,n) equilibrium (classical r-process, Kratz et al. 1993).

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

Long-time evolution: high vs. low temperature

High temperature



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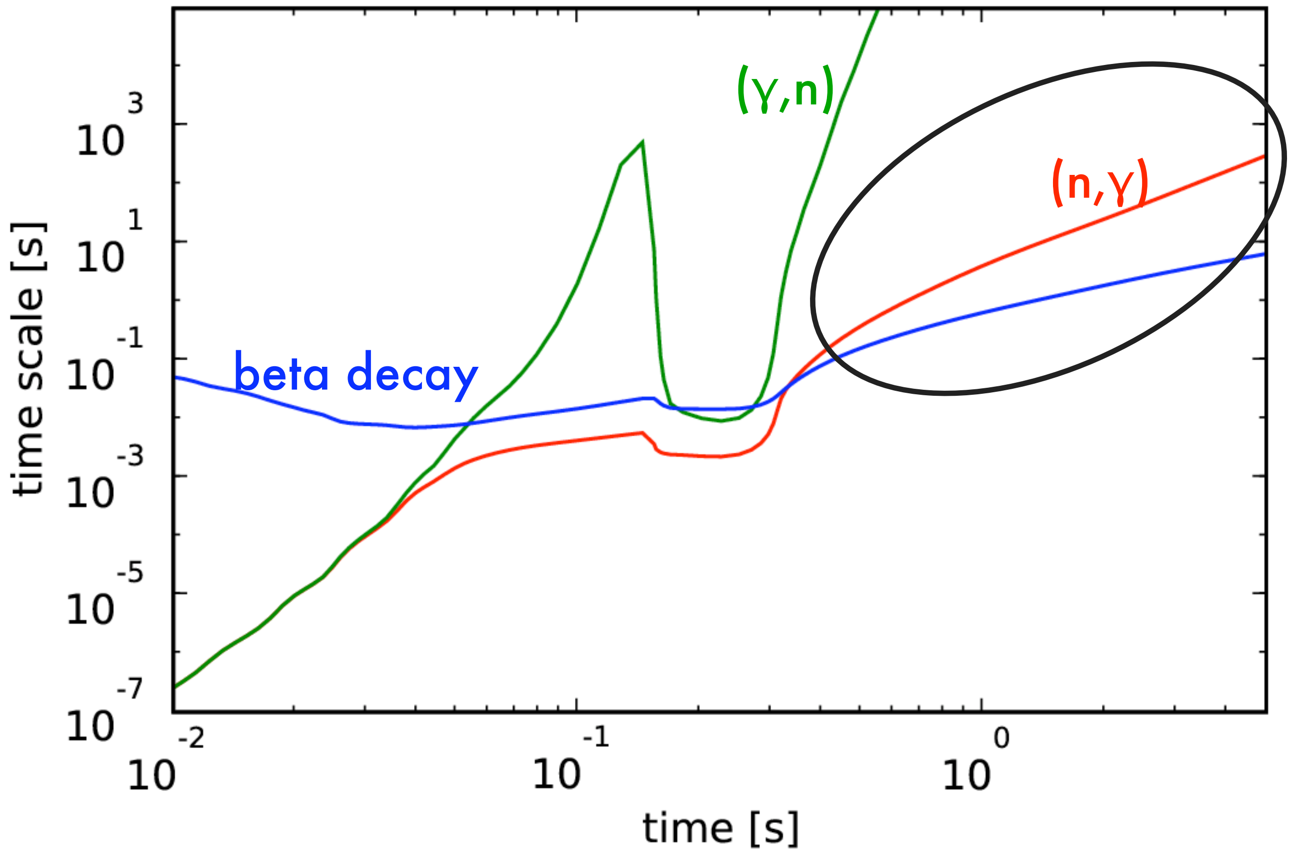
Low temperature



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

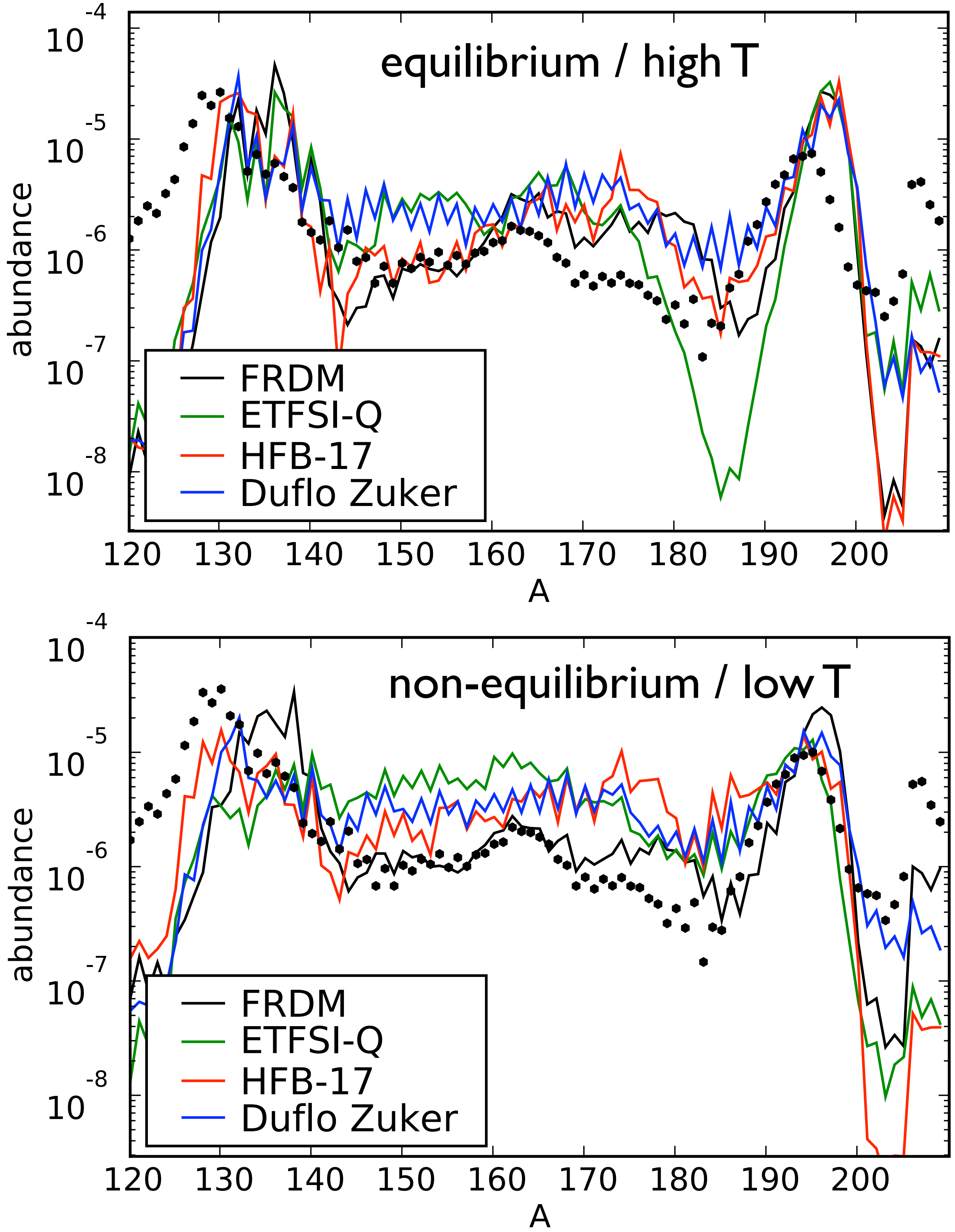
Compare four different mass models:

- 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.

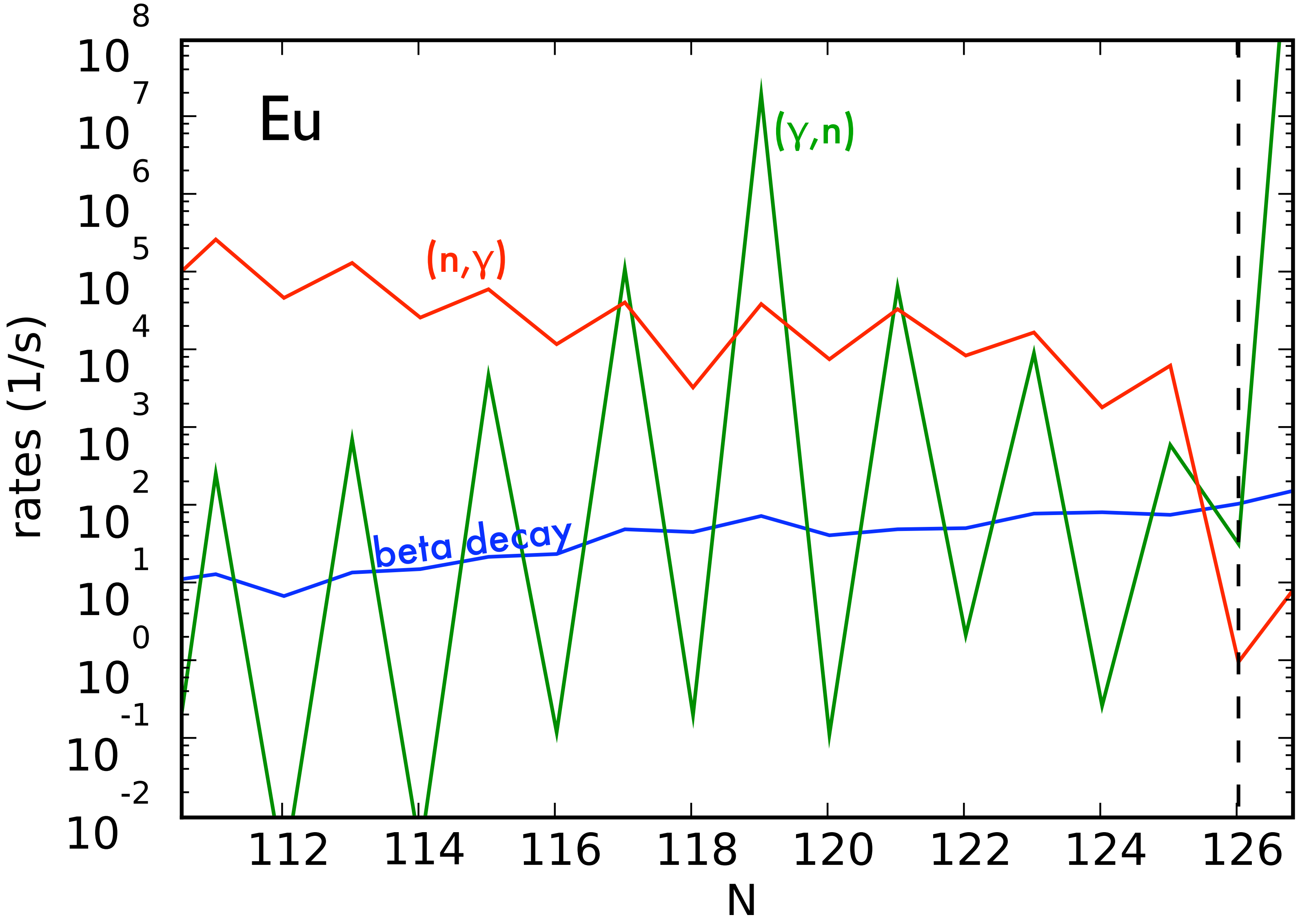
The nuclear physics input affects the final abundances differently depending on the long-time dynamical evolution.

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:

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

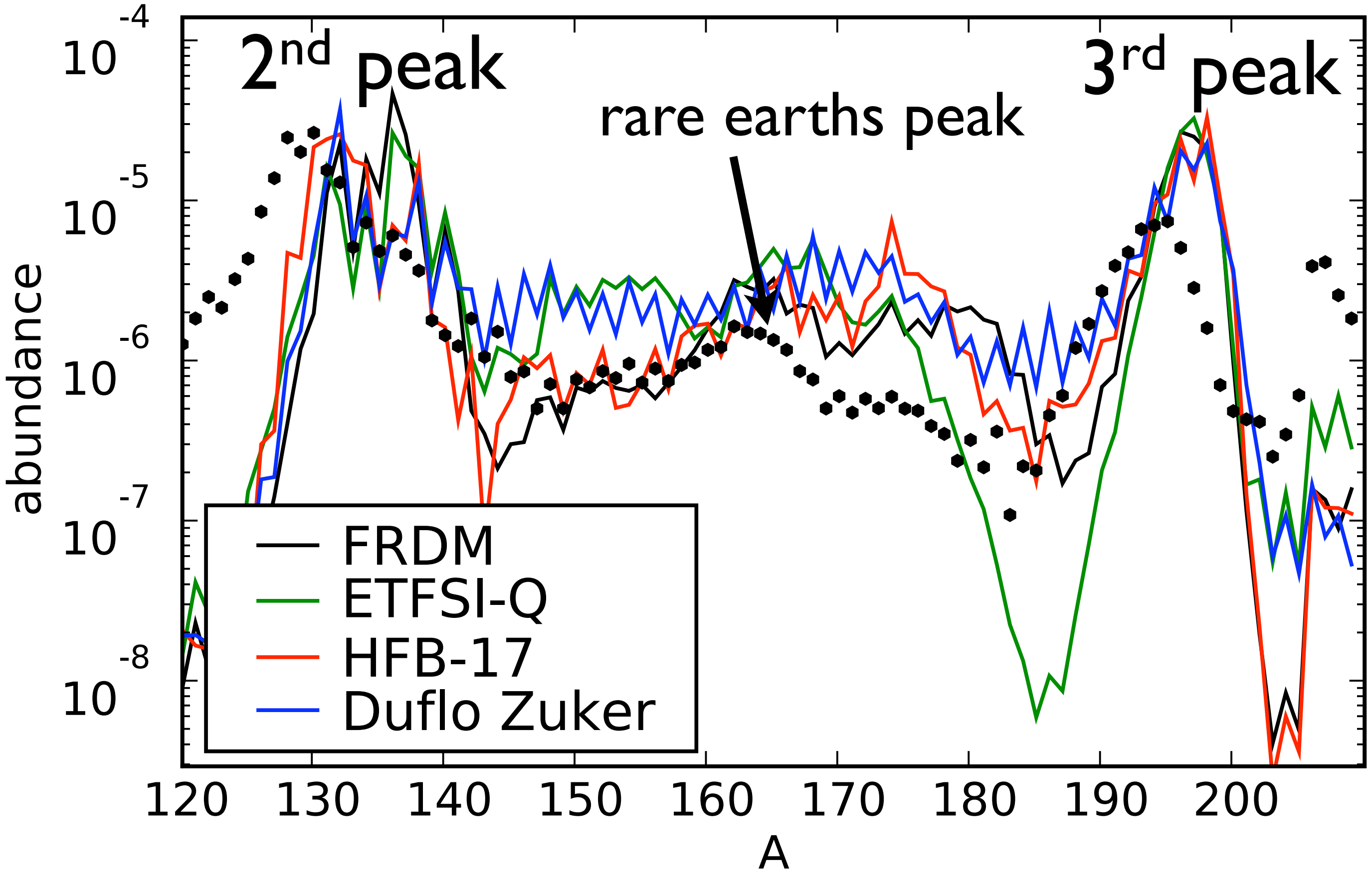
Photo-dissociation:

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

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.

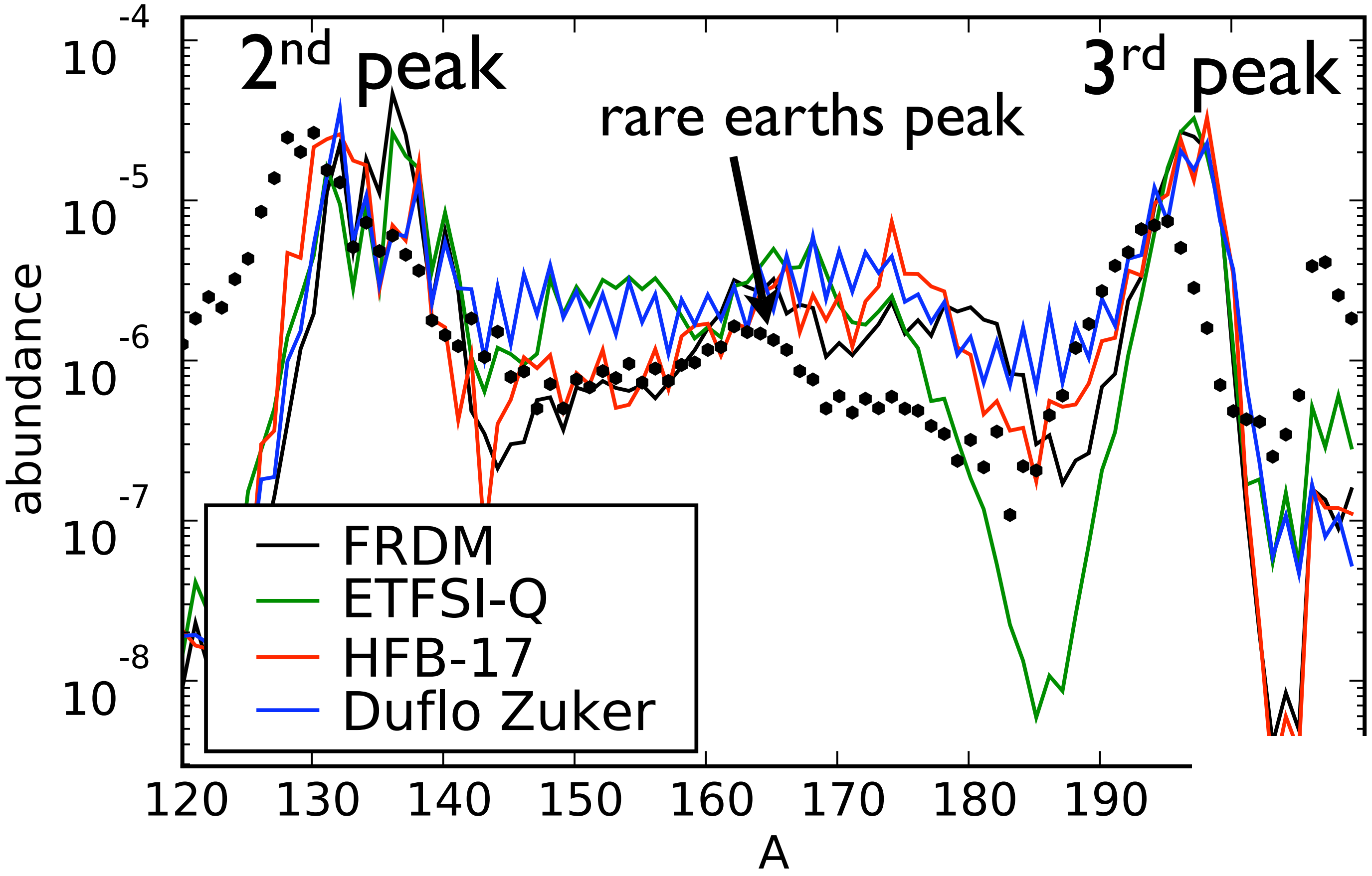
Peaks and holes



equilibrium / high T

Rare earth peak: Surman et al. 2008

Peaks and holes



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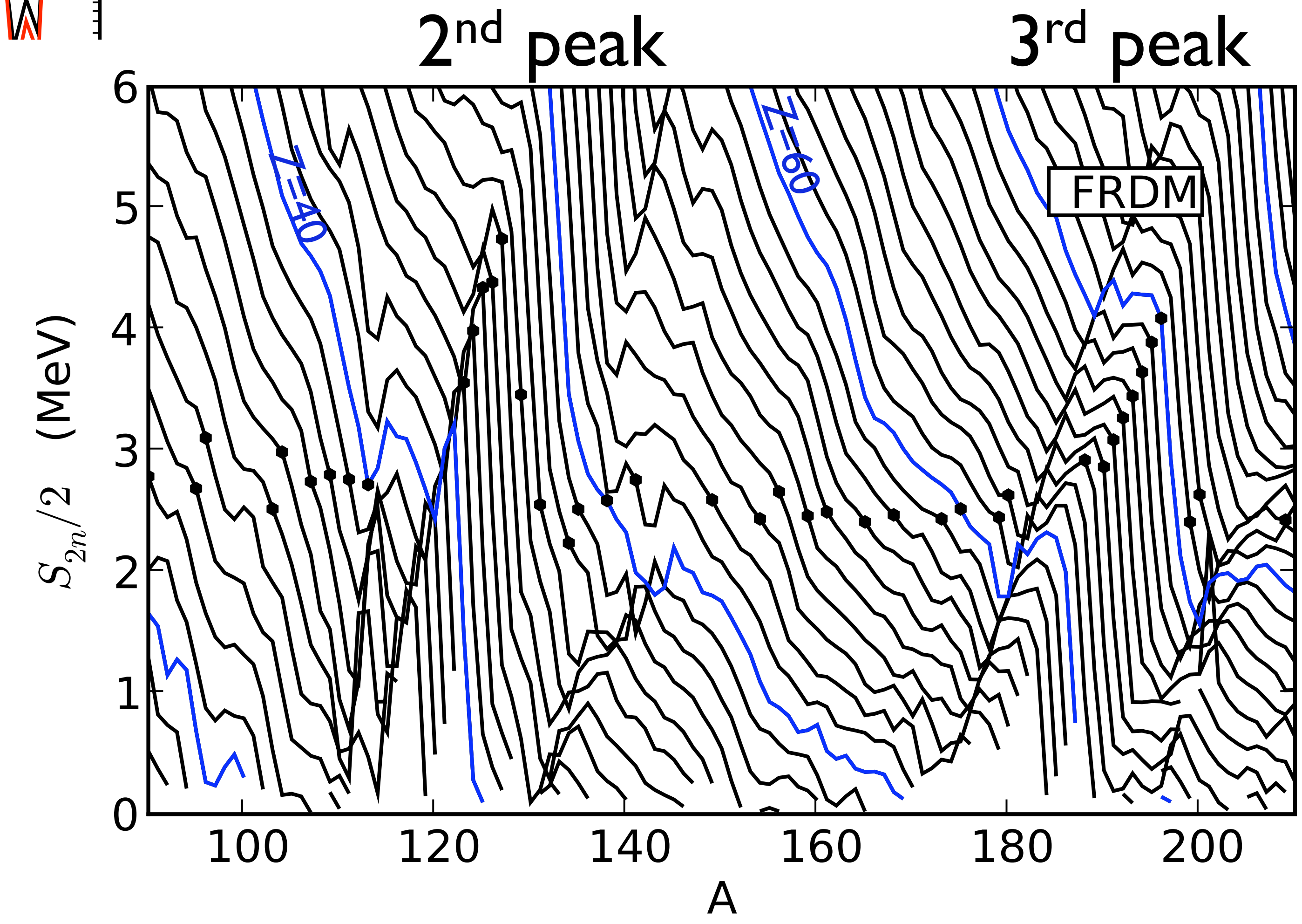
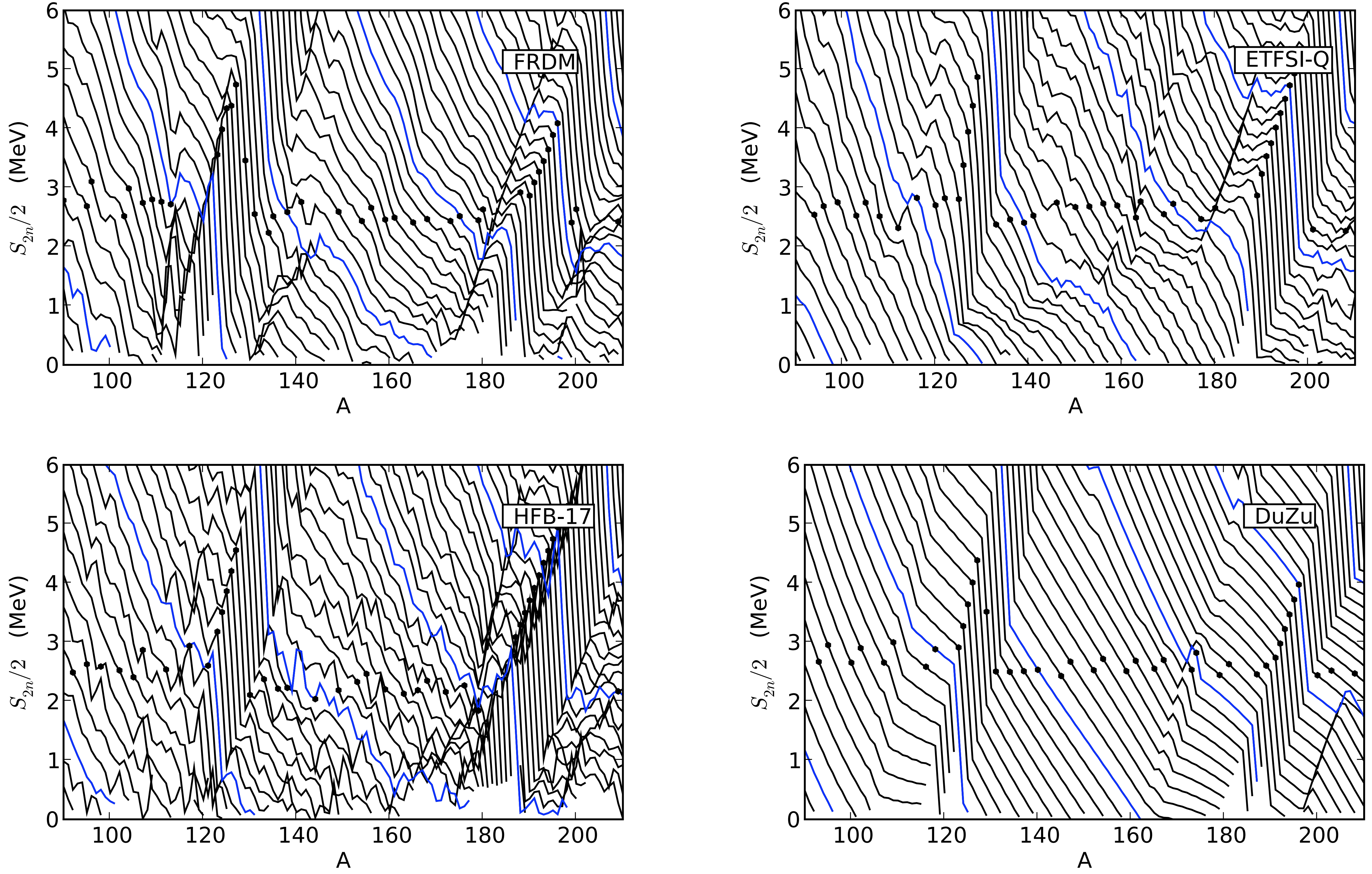


Rare earth peak: Surman et al. 2008

Aspects of different mass models



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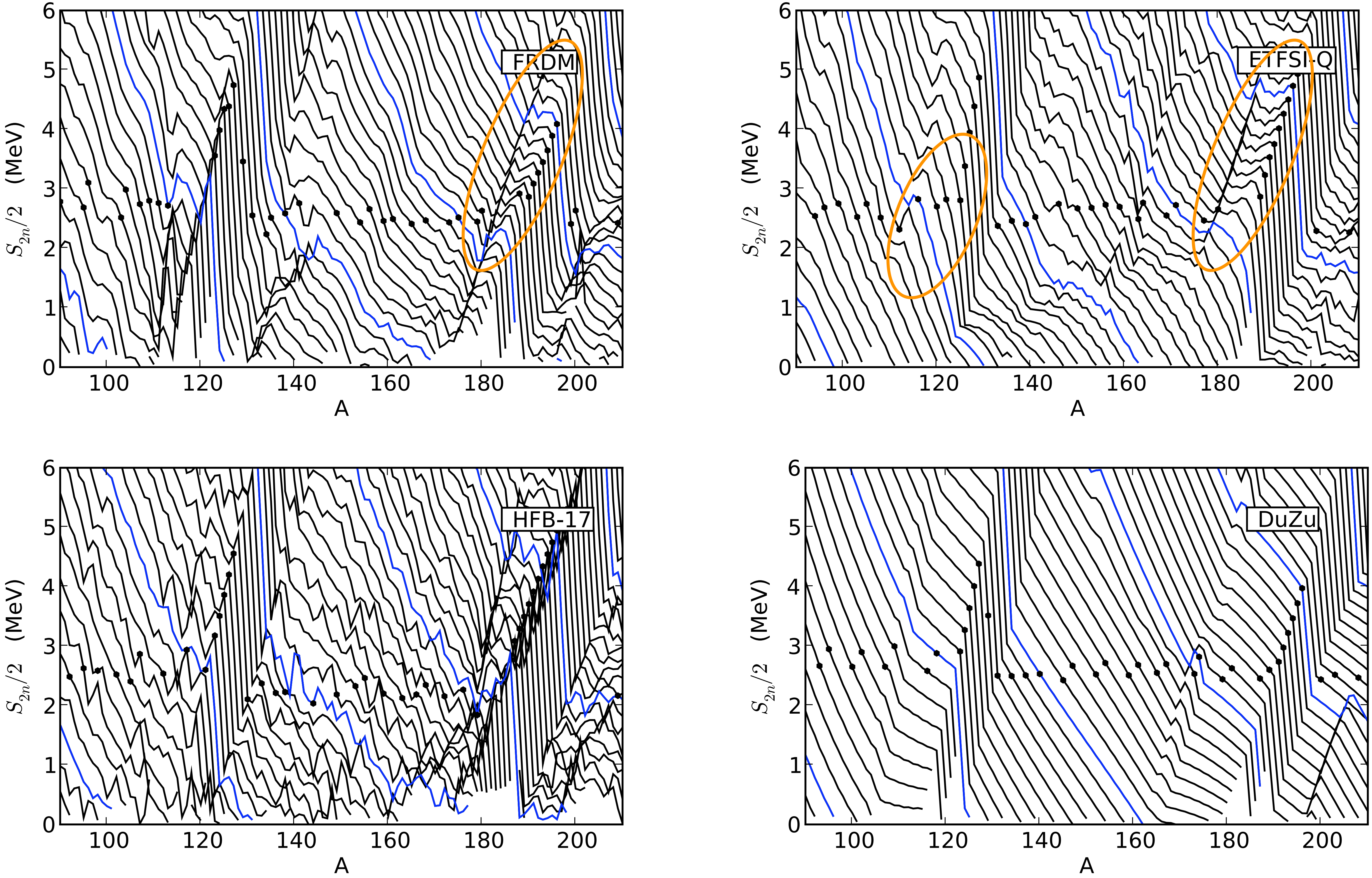

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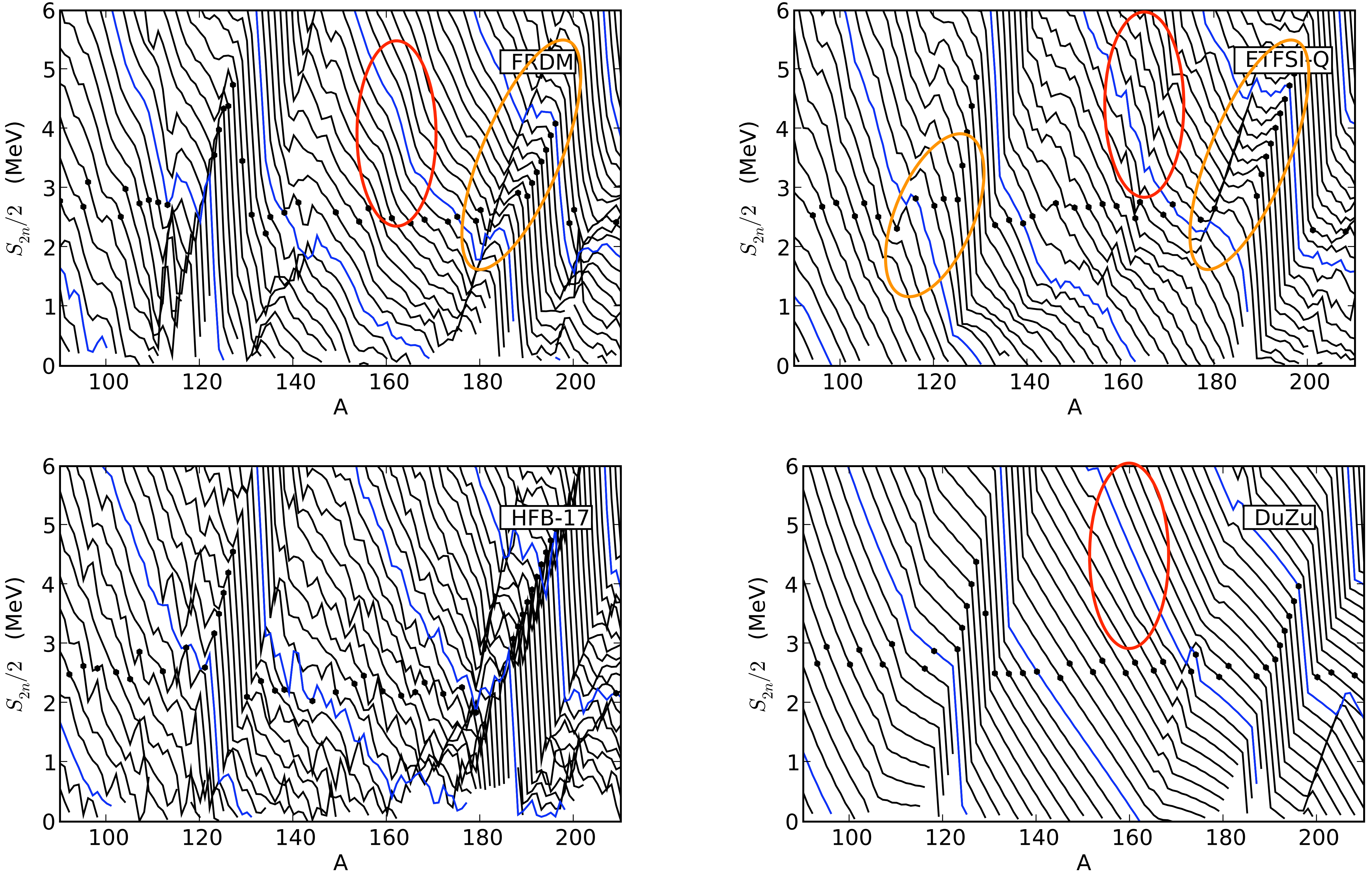


Way back to stability

High temperature evolution:

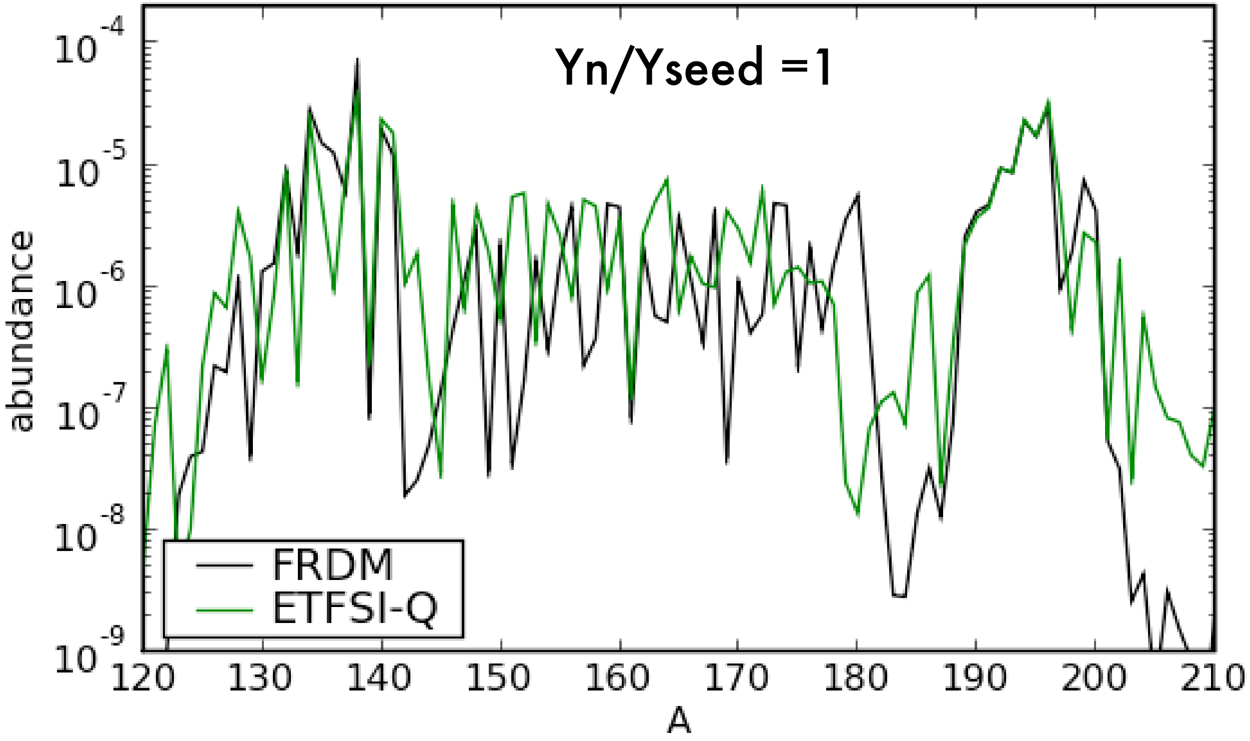
Abundances at freeze-out (Yn/Yseed=1) show odd-even effects following the behavior of the neutron separation energy.

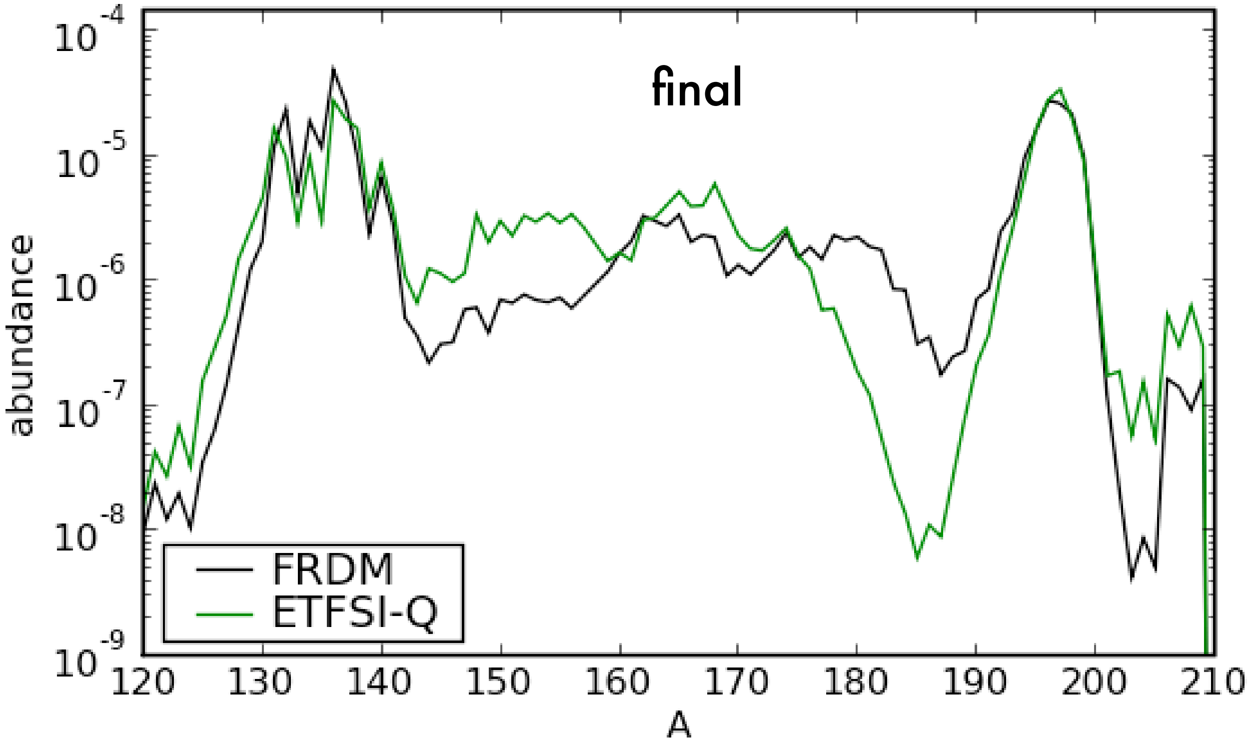
While final abundances are smoother like solar abundances.

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

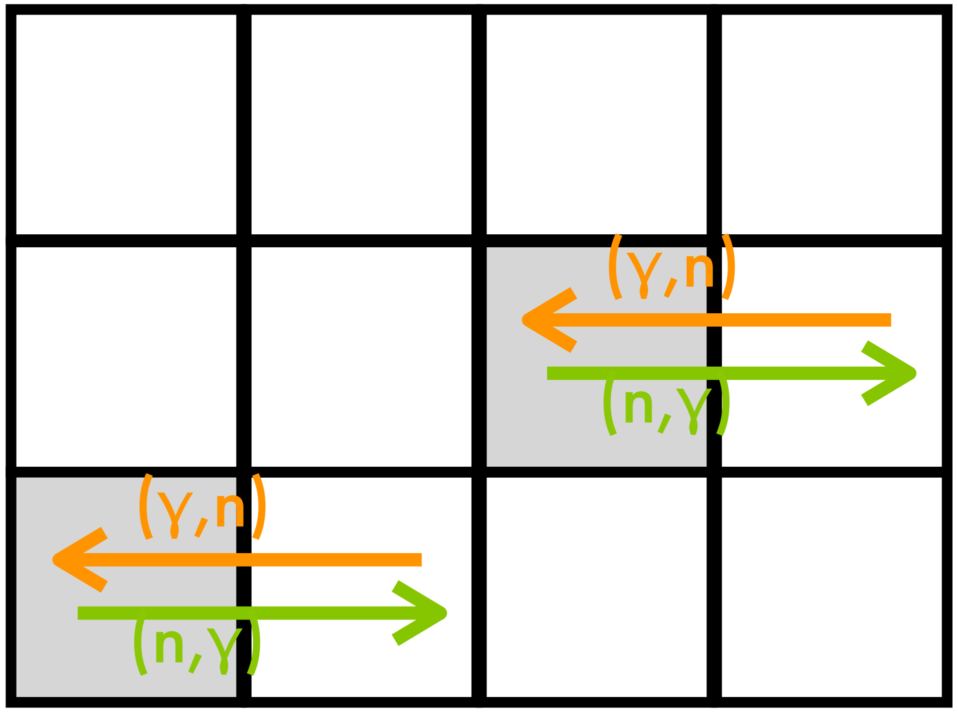
Classical r-process

Yn/Yseed > 1

Z even

Z odd

Z even



N even N odd N even N odd

Dynamical r-process

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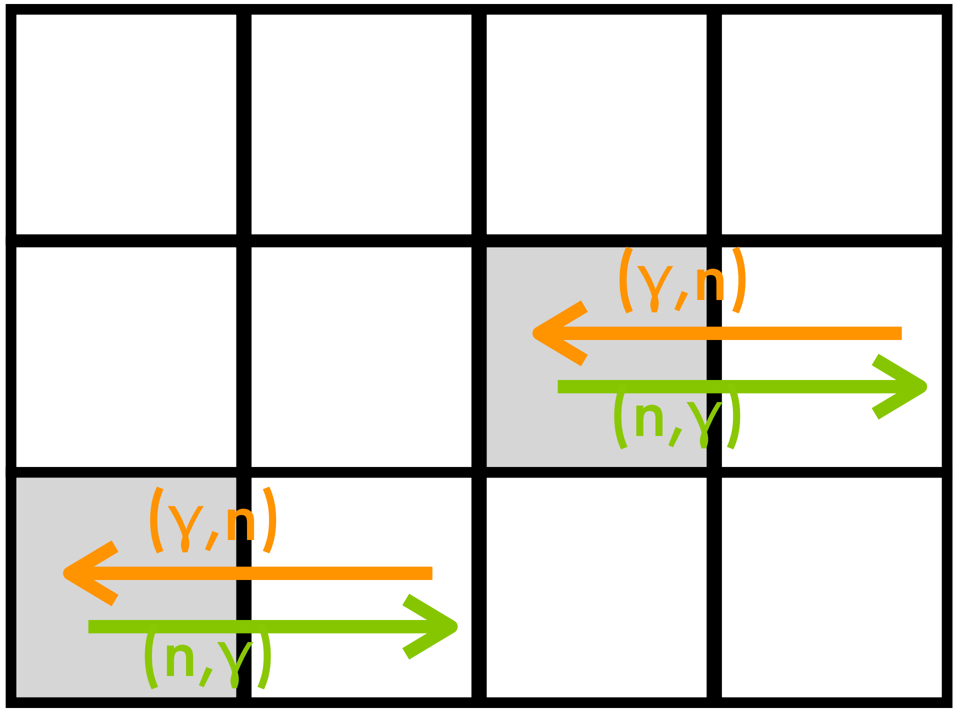
Z even

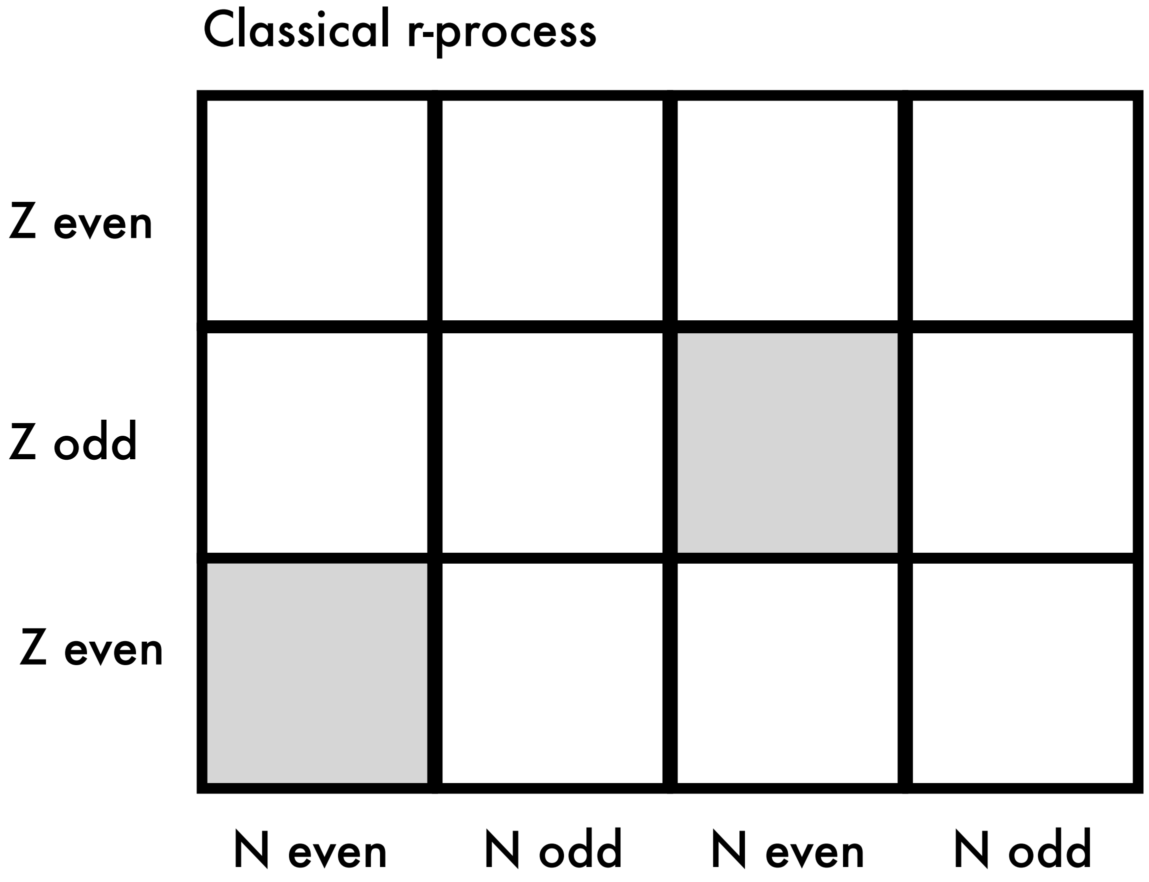
Z odd

Z even



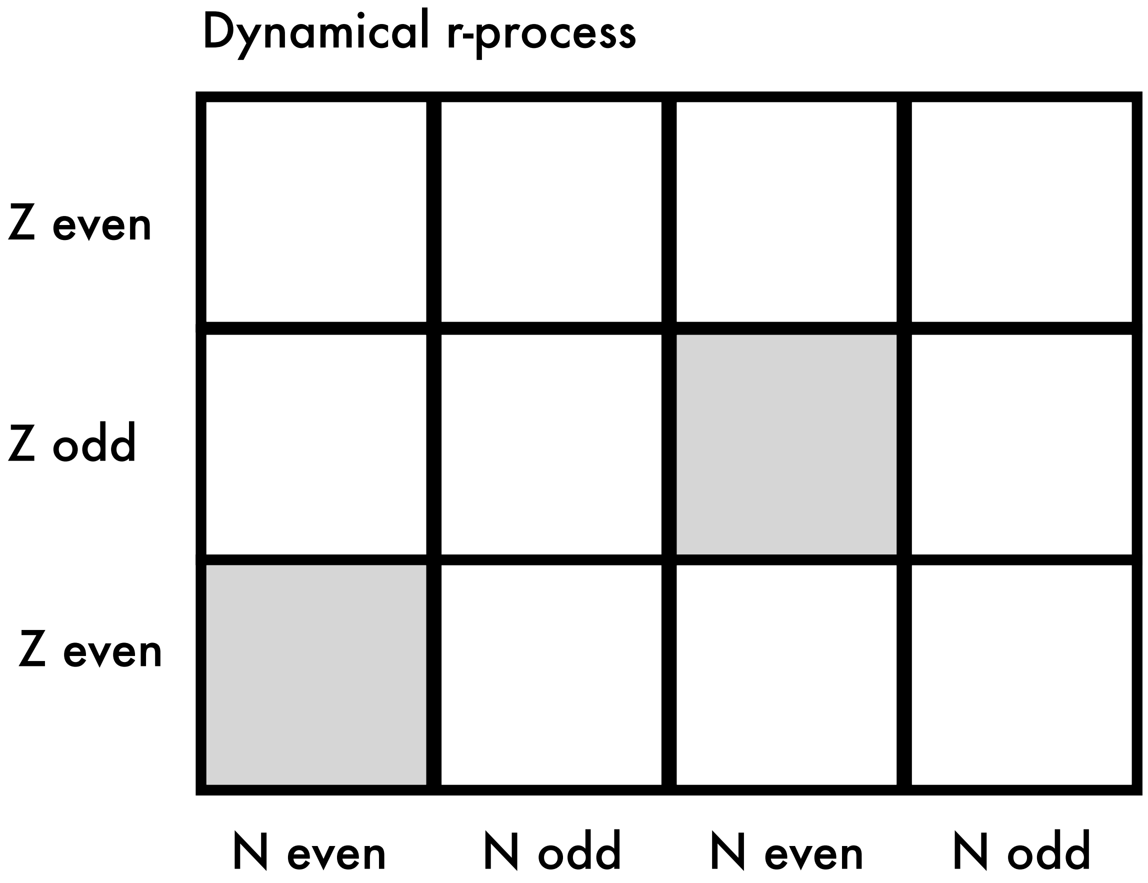
N even N odd N even N odd

Classical vs. dynamical r-process



Classical r-process

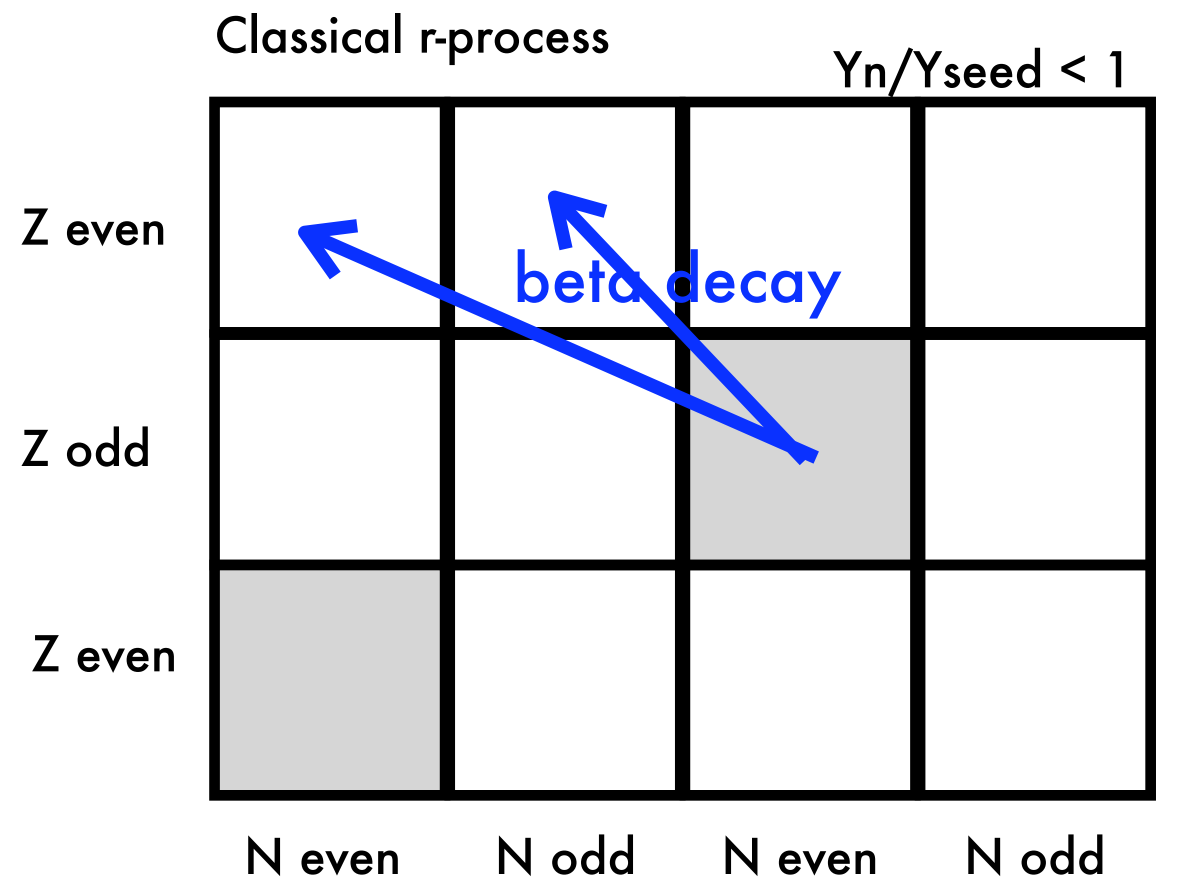
	N even	N odd	N even	N odd
Z even				
Z odd			▨	
Z even	▨			



Dynamical r-process

	N even	N odd	N even	N odd
Z even				
Z odd			▨	
Z even	▨			

Classical vs. dynamical r-process



Classical r-process

Yn/Yseed < 1

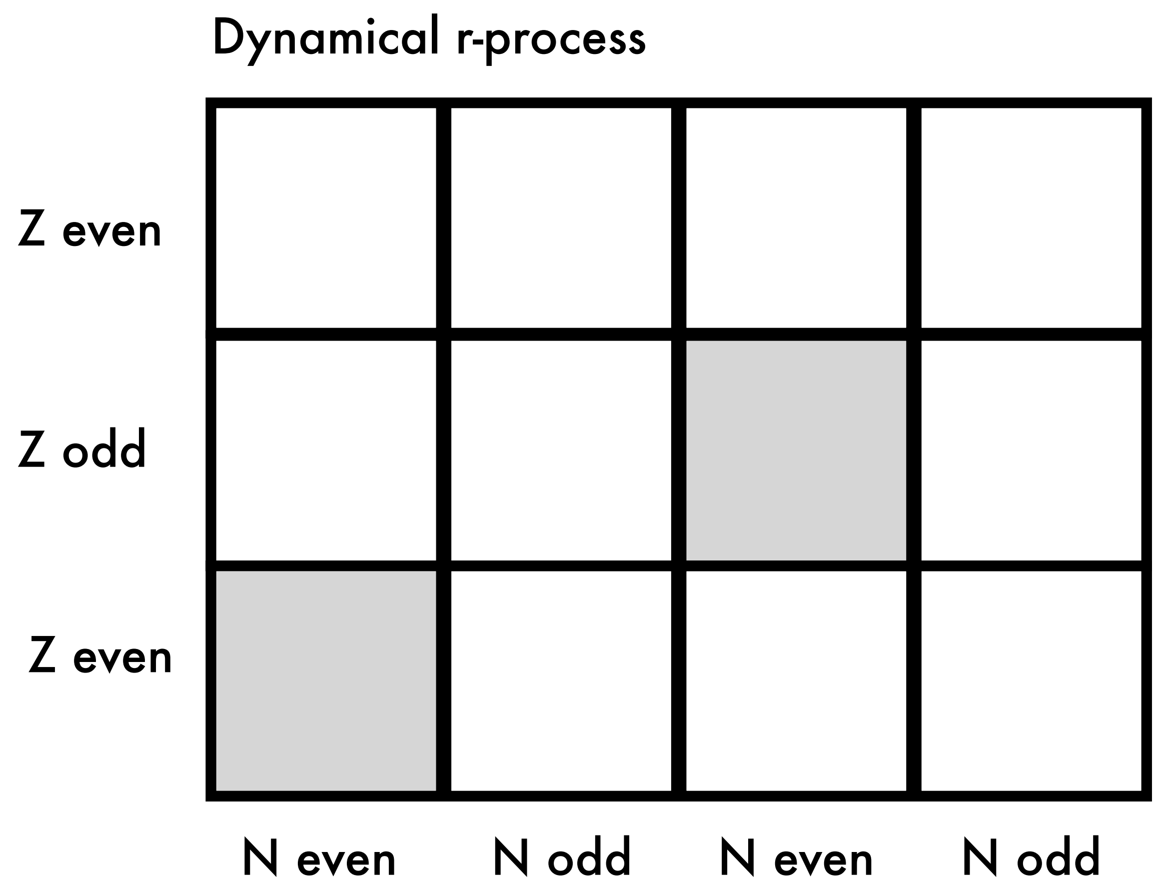
Z even

Z odd

Z even

beta decay

N even N odd N even N odd



Dynamical r-process

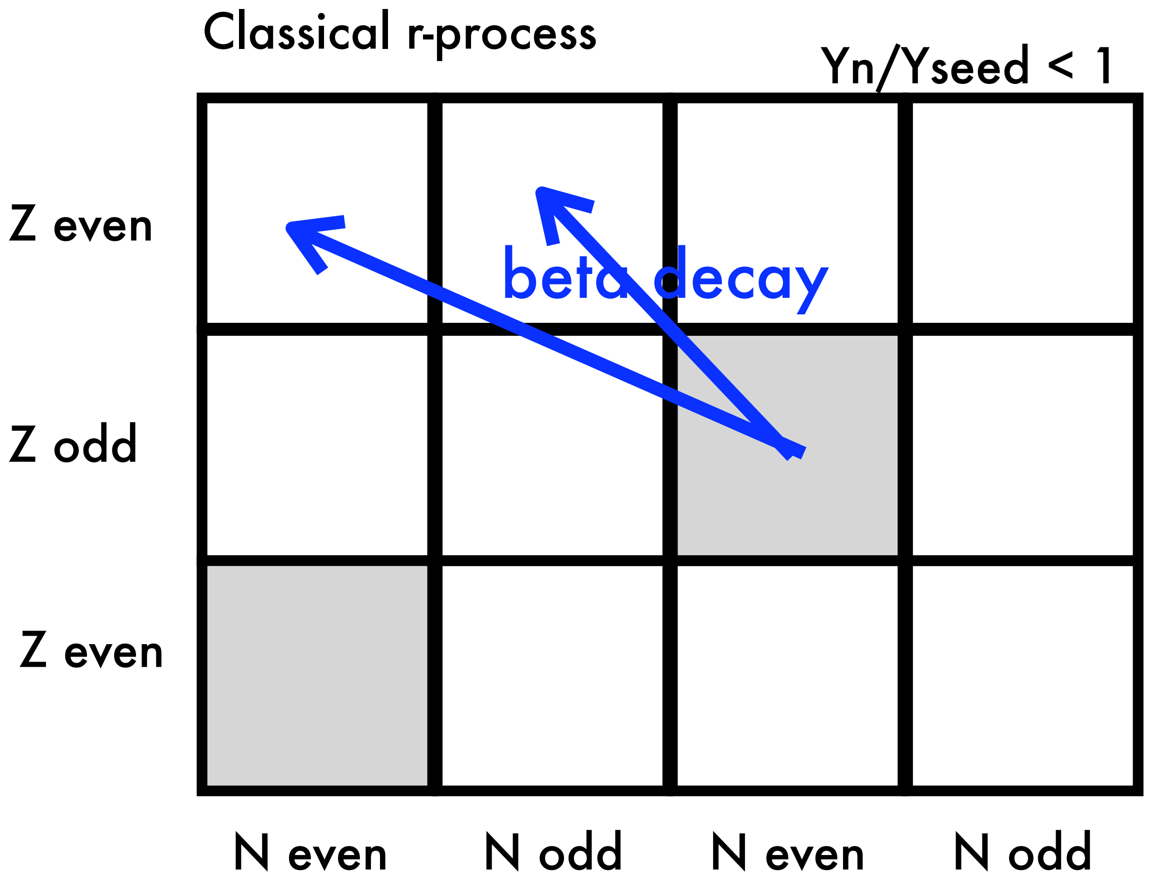
Z even

Z odd

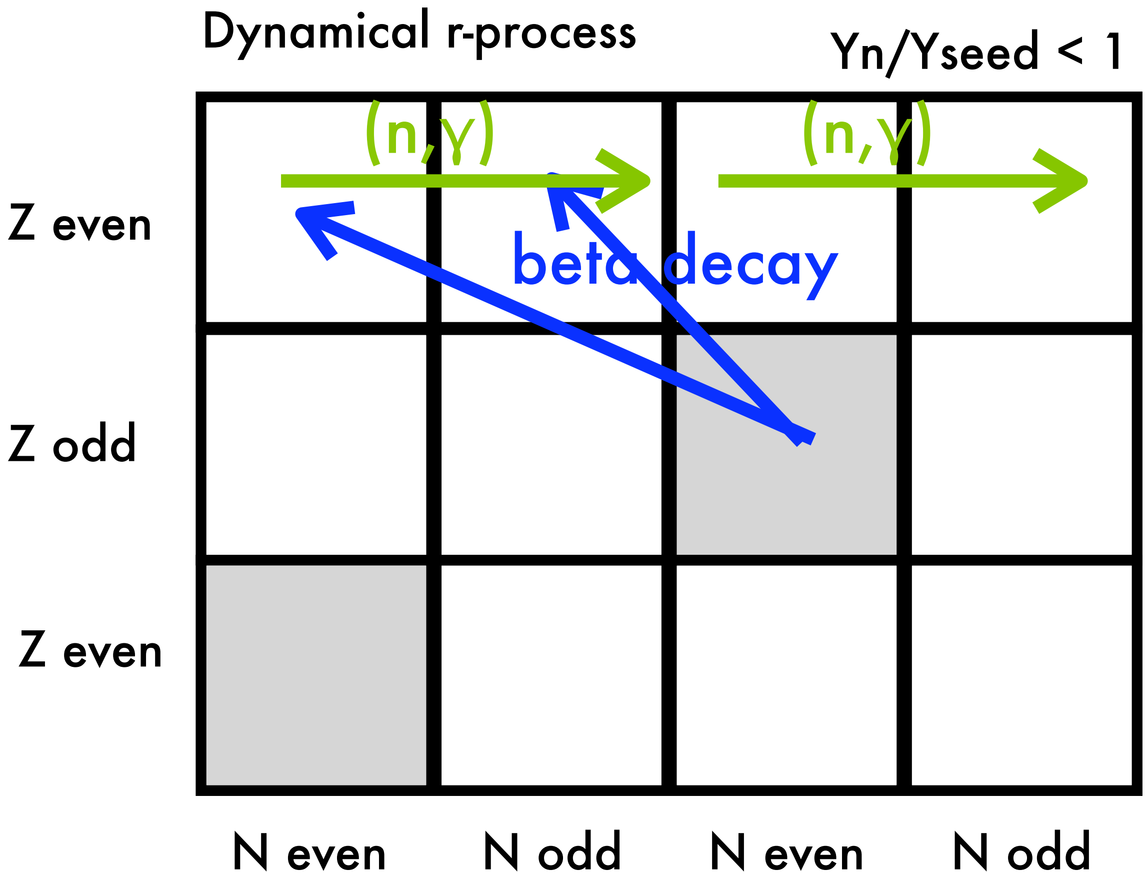
Z even

N even N odd N even N odd

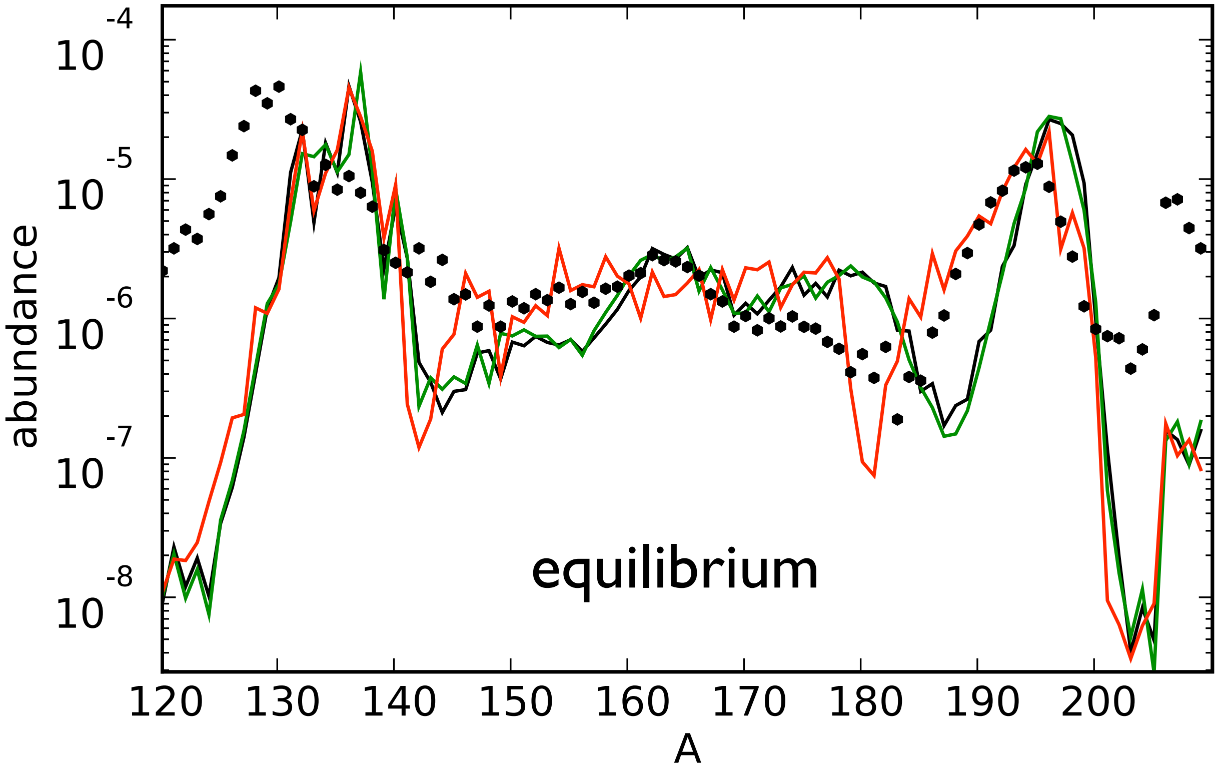
Classical vs. dynamical r-process



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



Neutron captures and beta-delayed neutron emission

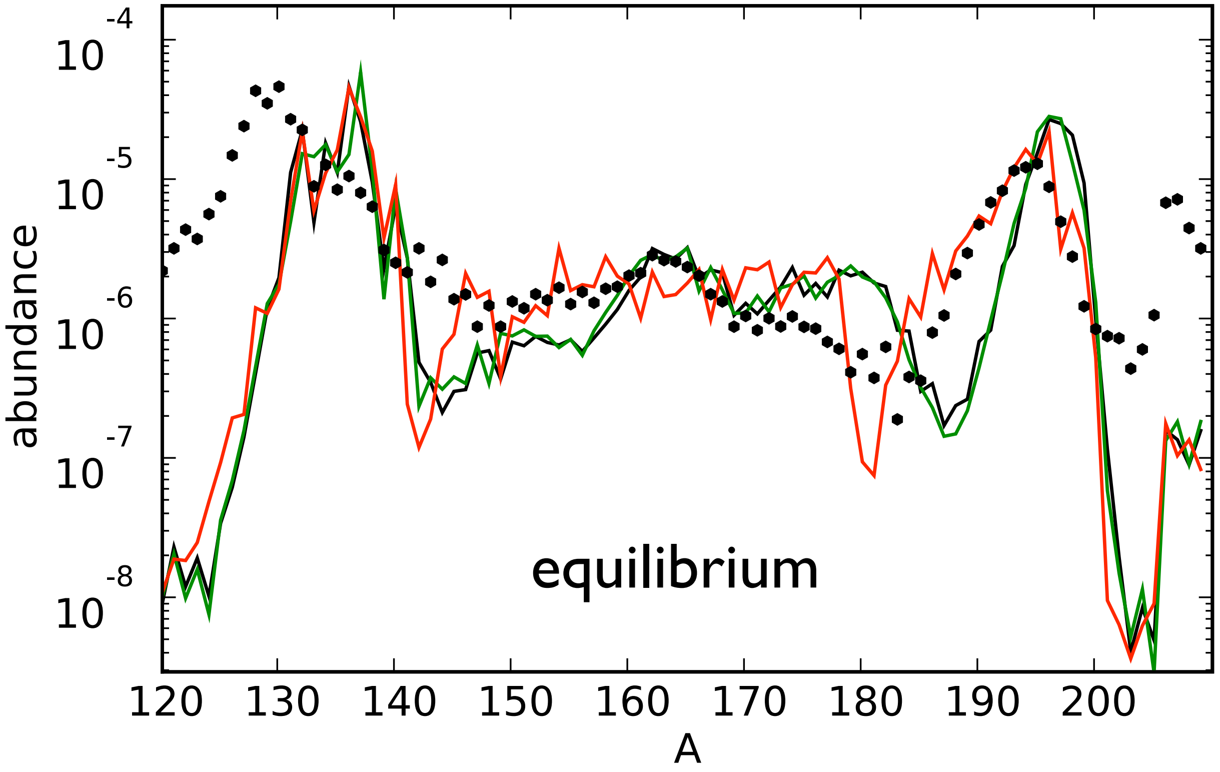


We compare final abundances with and without beta-delayed neutron emission and with and without neutron captures.

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

Arcones & Martinez-Pinedo, in prep.

Neutron captures and beta-delayed neutron emission



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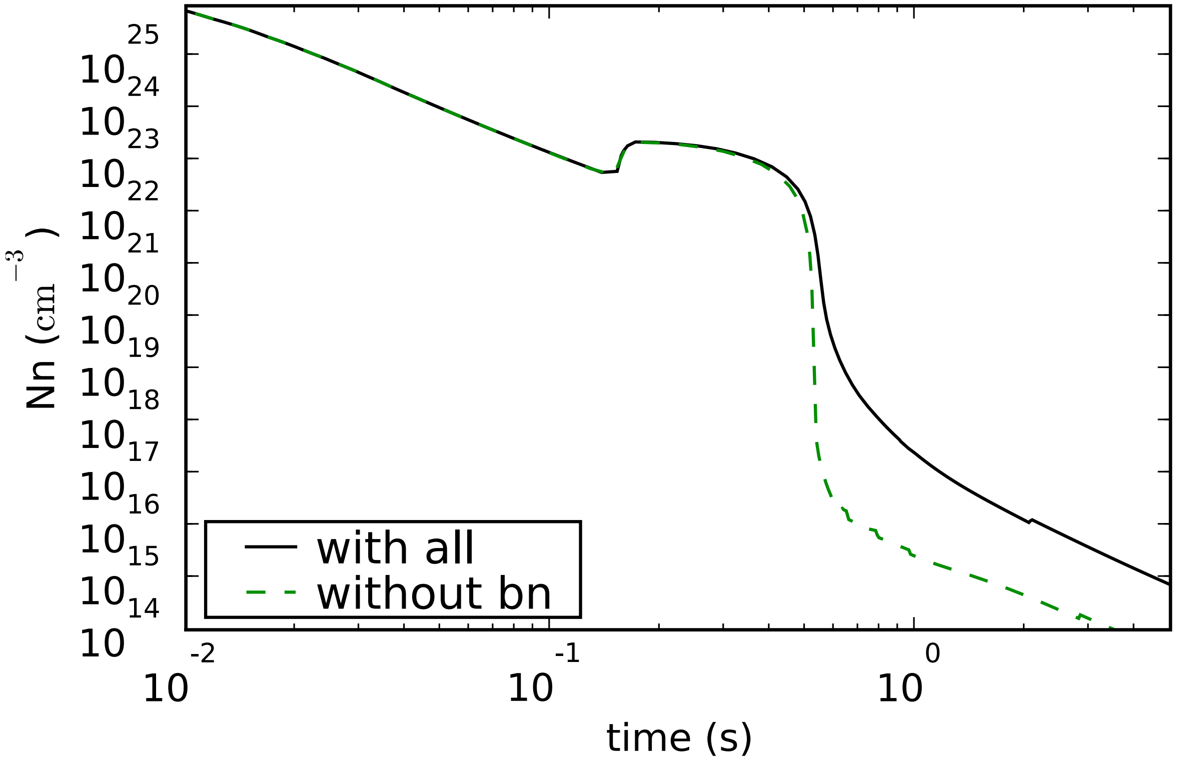
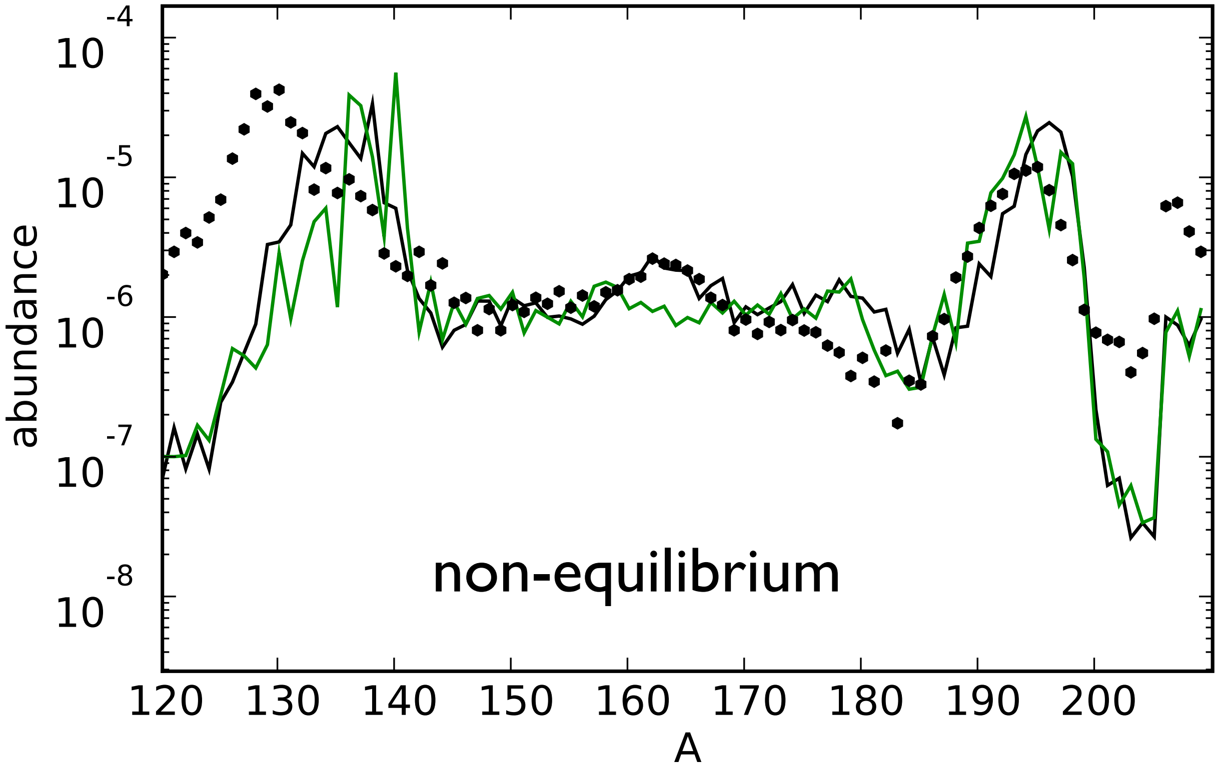
Neutron captures important for the final abundances (for example A=180-190).

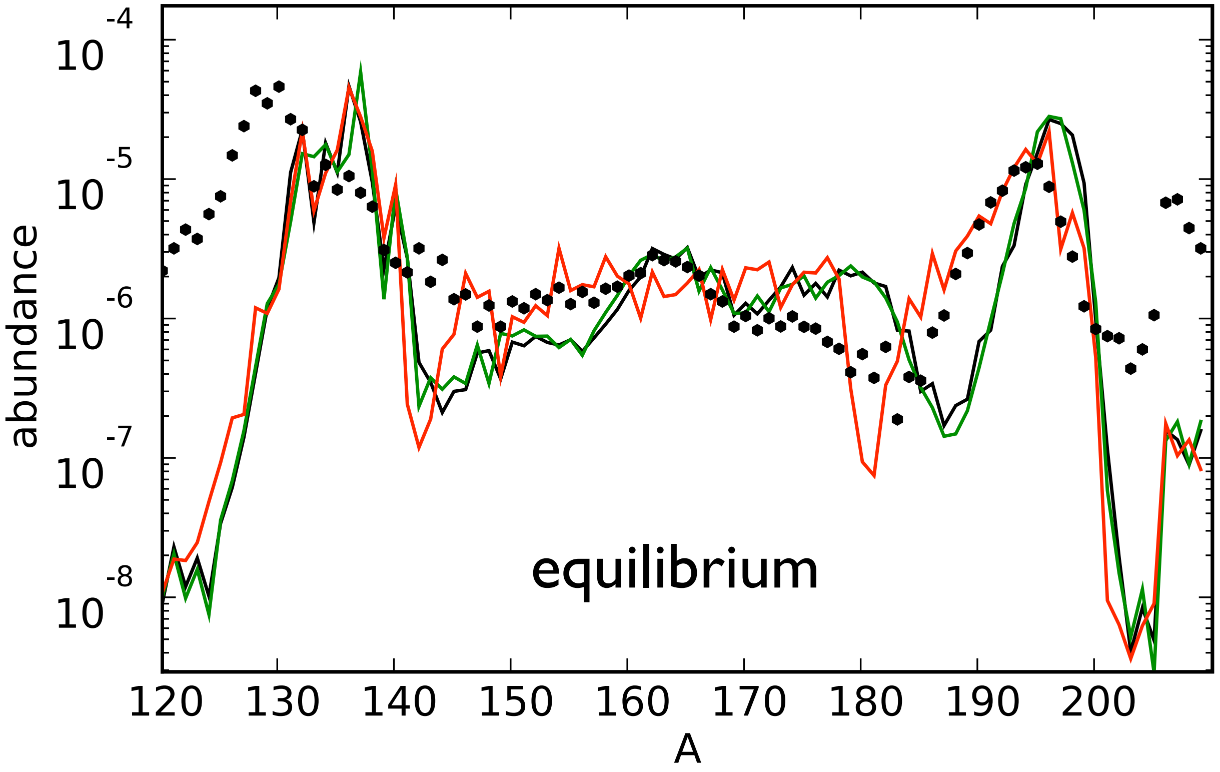
The main role of the beta-delayed neutron emission is to supply neutrons.





Arcones & Martinez-Pinedo, in prep.

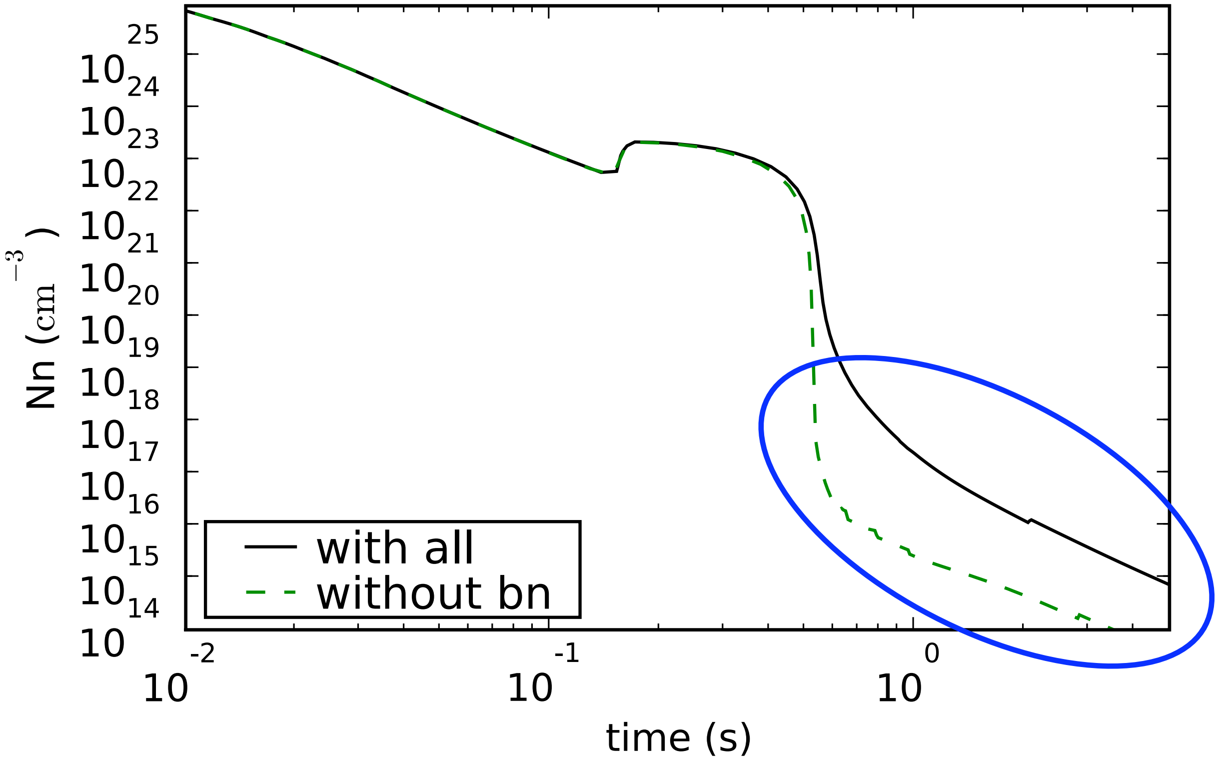
Neutron captures and beta-delayed neutron emission

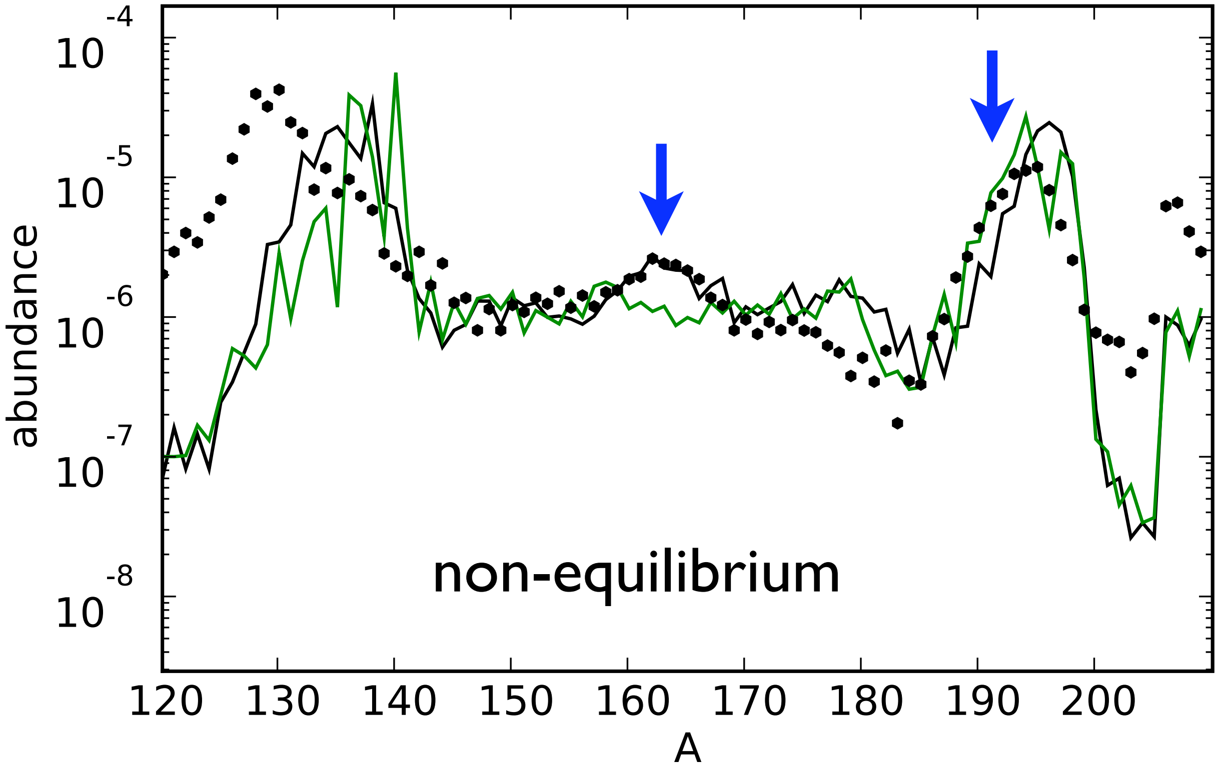


We compare final abundances with and without beta-delayed neutron emission and with and without neutron captures.

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.

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.
- 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.

Conclusions and outlook

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  → multi-dimensional simulations with detailed neutrino transport

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Thank you

G. Martinez-Pinedo, F. Montes and K.-F. Thielemann.