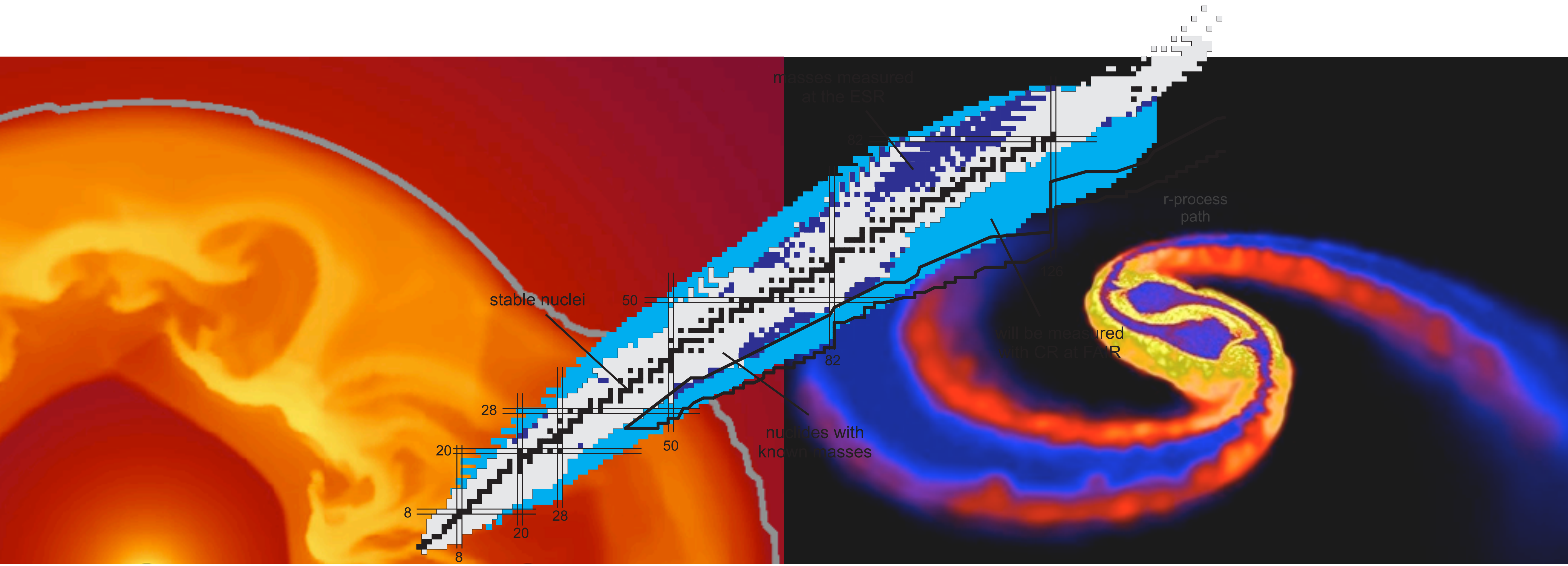
Thermonuclear Reaction Rates for Astrophysics Applications
24-25 November 2011, Athens, Greece

Impact of nuclear physics input on the r-process



Almudena Arcones
Feodor Lynen Fellow, Basel University

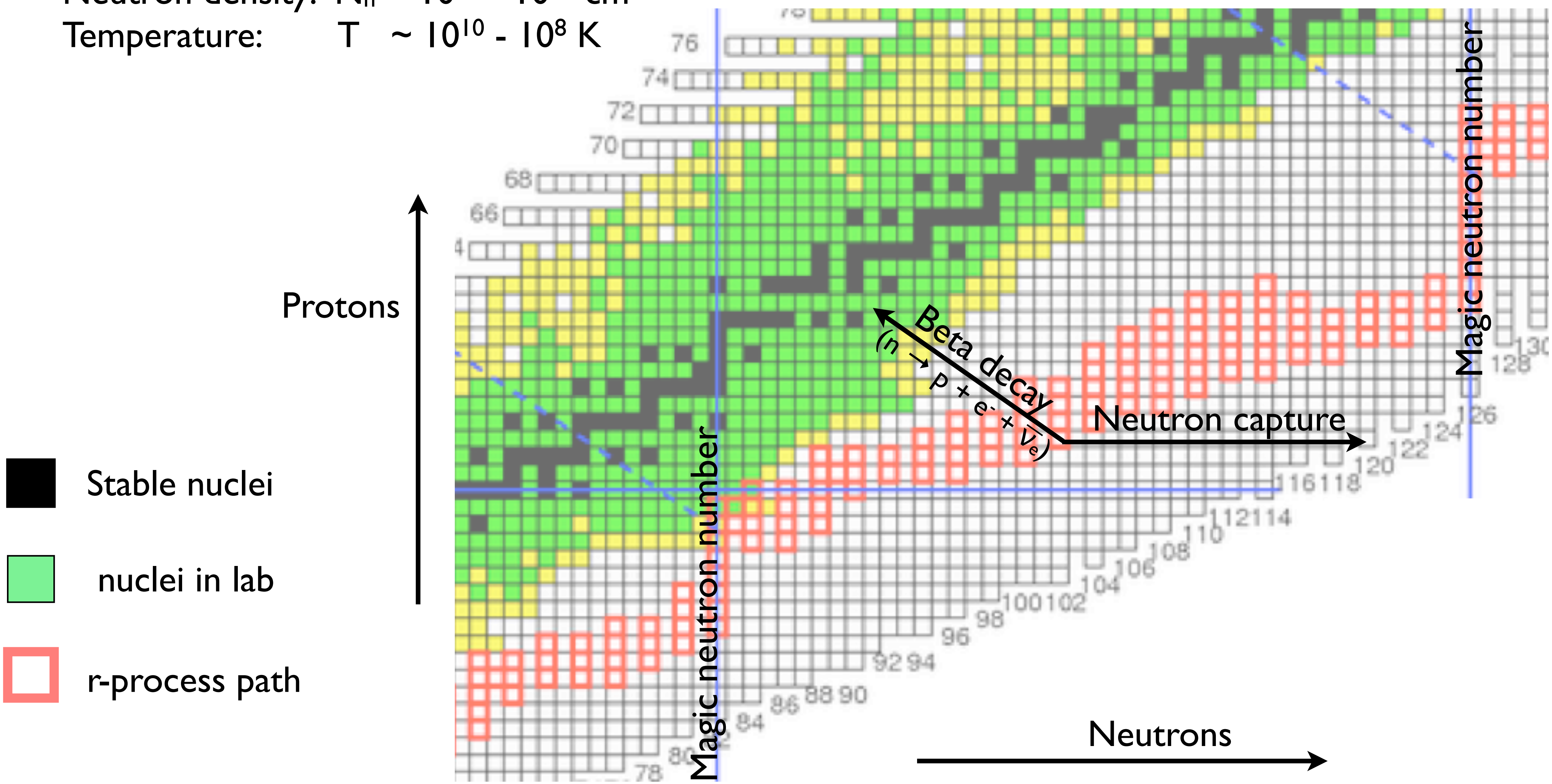
Alexander von Humboldt
Stiftung/Foundation

UNI
BASEL

r-process

Rapid neutron capture compared to beta decay

Neutron density: $N_n \sim 10^{27} - 10^{20}$ cm^{-3}
Temperature: $T \sim 10^{10} - 10^{8}$ K

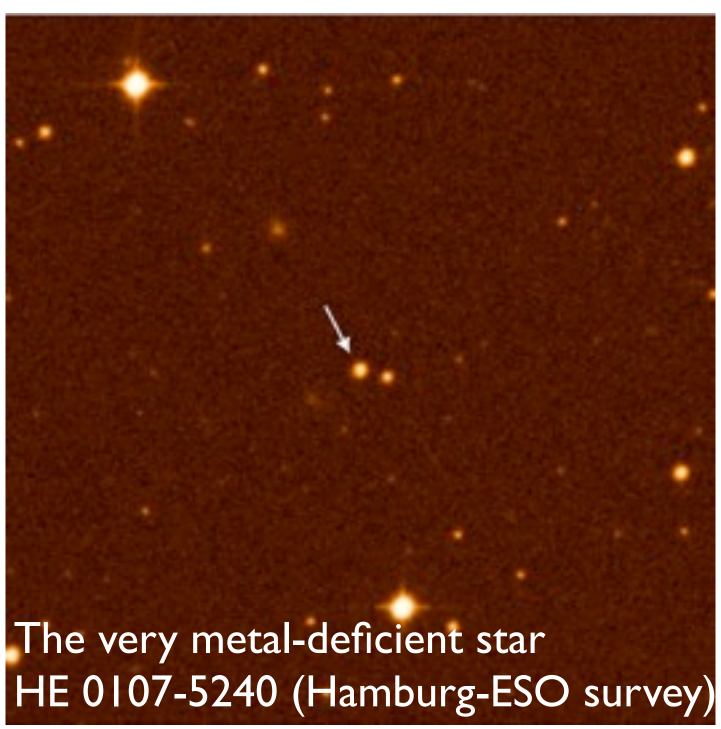


Ultra metal-poor stars = very old stars

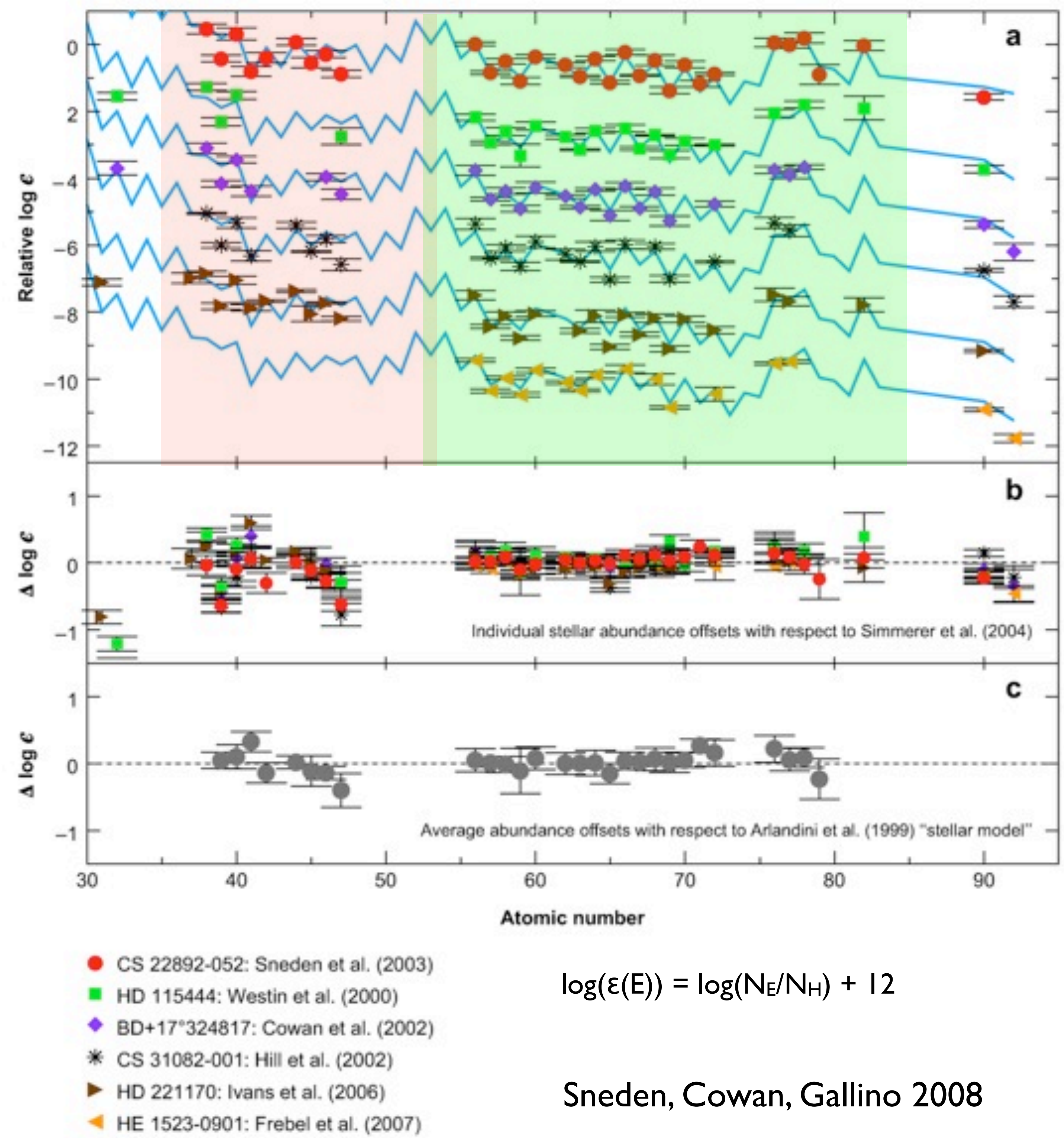
Their atmospheres show fingerprints of only few nucleosynthesis events that enriched the interstellar medium.

Abundances of r-process elements in:
- ultra metal-poor stars and
- solar system

Two components or sites:
- robust r-process for 56<Z<83
- scatter for lighter heavy elements Z~40



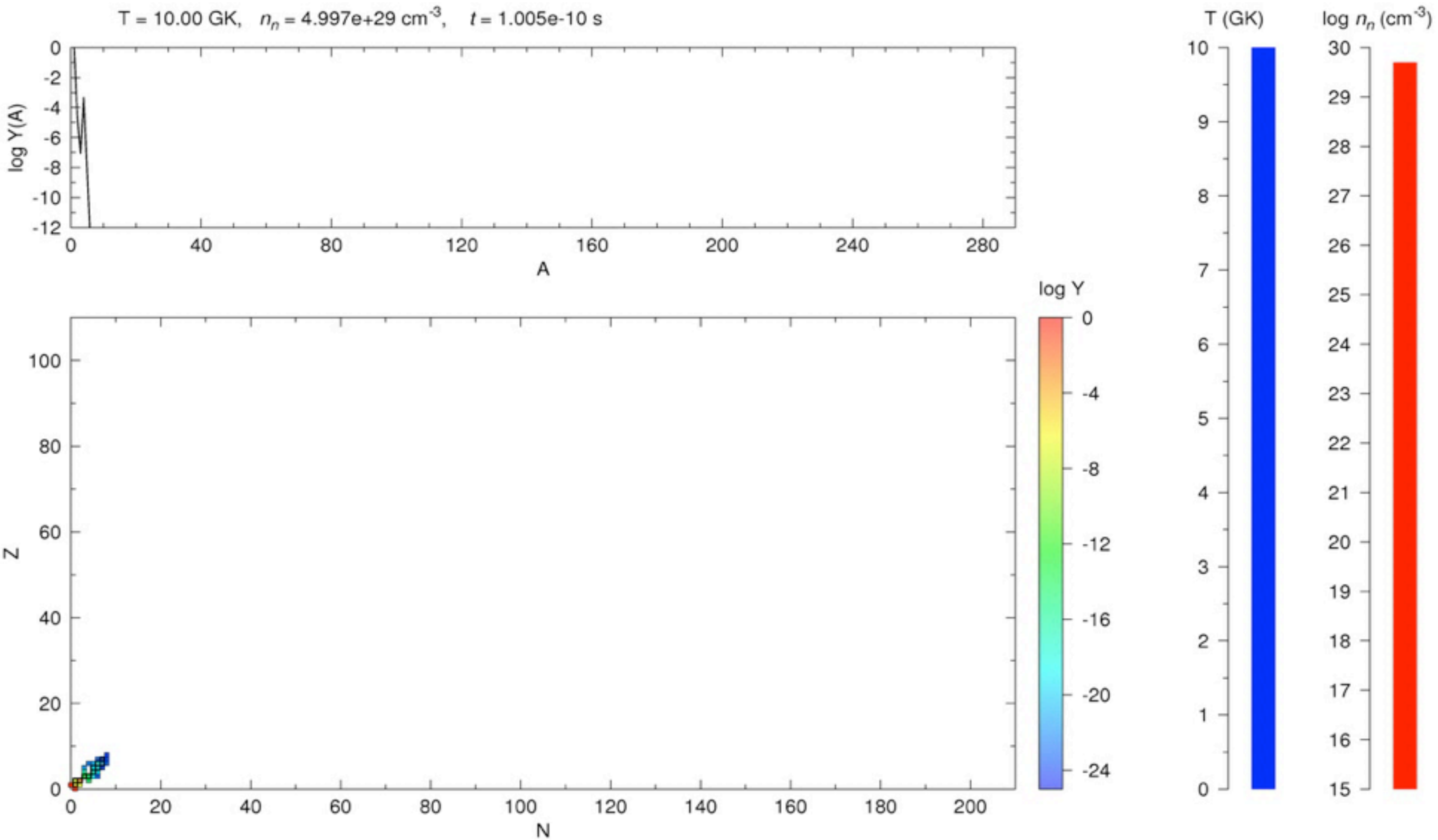
The very metal-deficient star
HE 0107-5240 (Hamburg-ESO survey)



$\log(\varepsilon(E)) = \log(N_E/N_H) + 12$

Sneden, Cowan, Gallino 2008

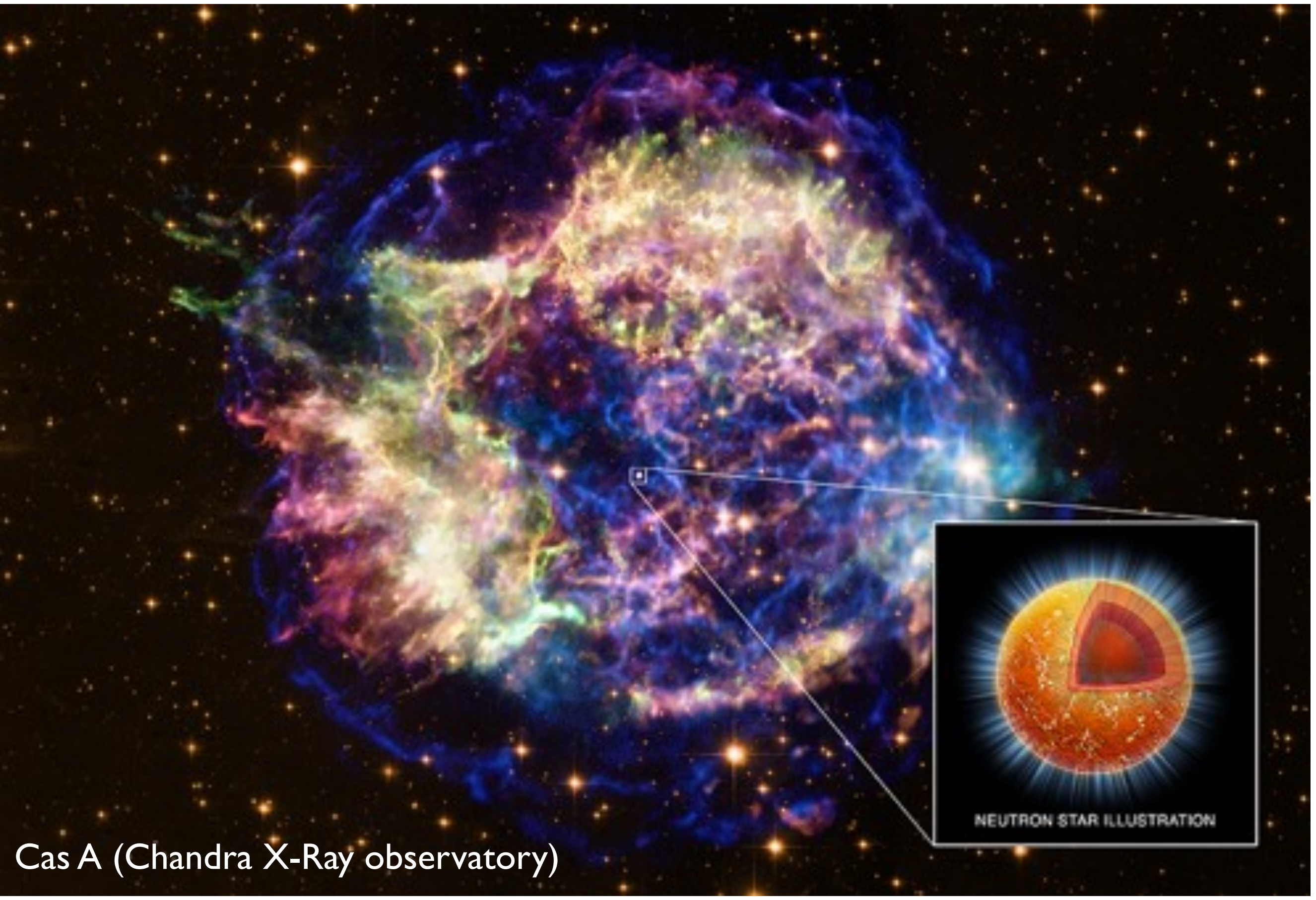
r-process



T = 10.00 GK, n_n = 4.997e+29 cm^{-3}, t = 1.005e-10 s
log Y(A)
0
-2
-4
-6
-8
-10
-12
0
40
80
120
160
200
240
280
A
log Y
0
-4
-8
-12
-16
-20
-24
Z
100
80
60
40
20
0
0
20
40
60
80
100
120
140
160
180
200
N
T (GK)
10
9
8
7
6
5
4
3
2
1
0
log n_n (cm^{-3})
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15

Where does the r-process occur?

Core-collapse supernovae



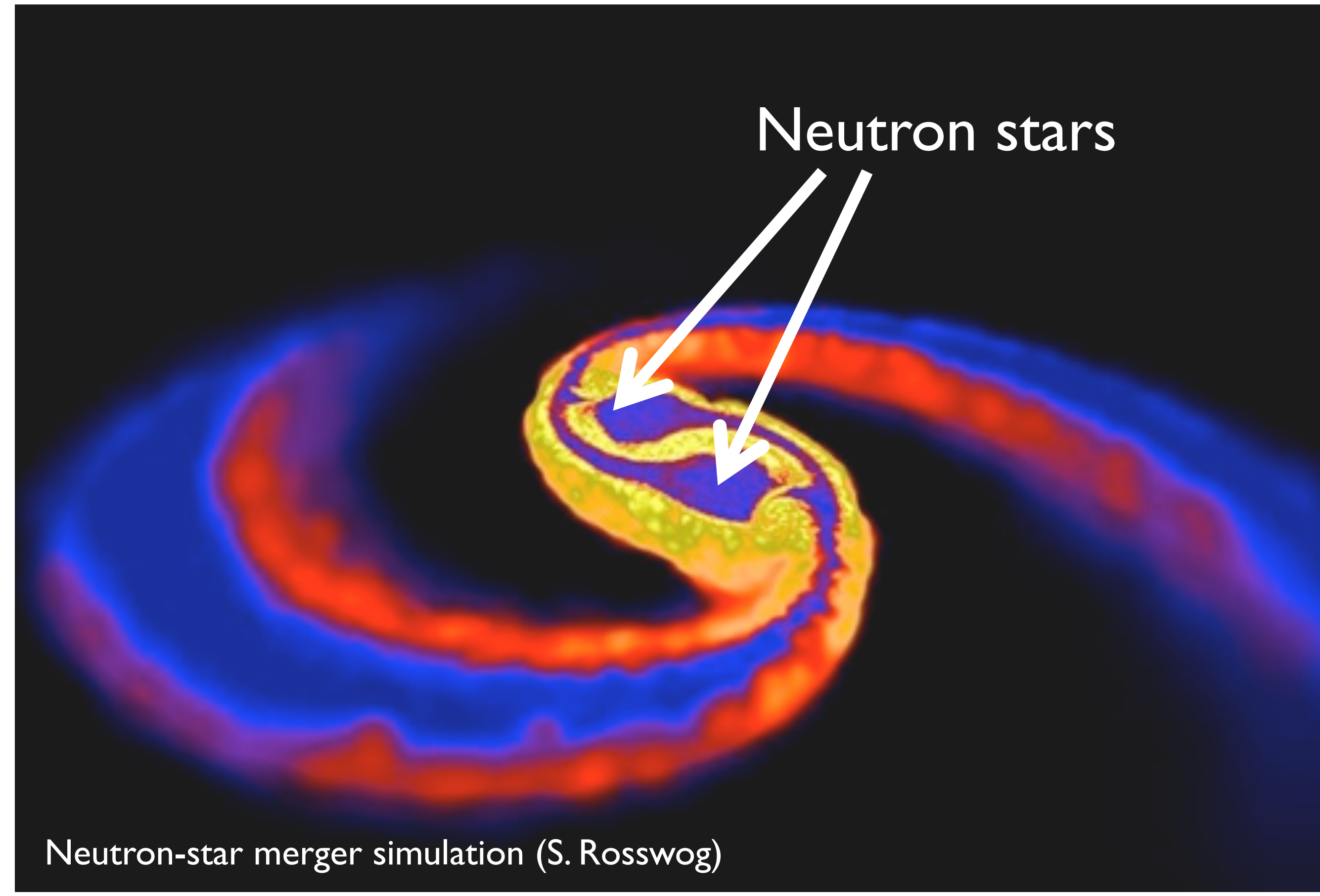
neutrino-driven wind (Woosley et al. 1994):

proton rich (Fischer et al. 2010, Hüdepohl et al. 2010)

entropy too low (Woosley et al. 1994 → Roberts et al. 2010)

→ multidimensional effects,
neutrino collective oscillations, ...?

Neutron star mergers

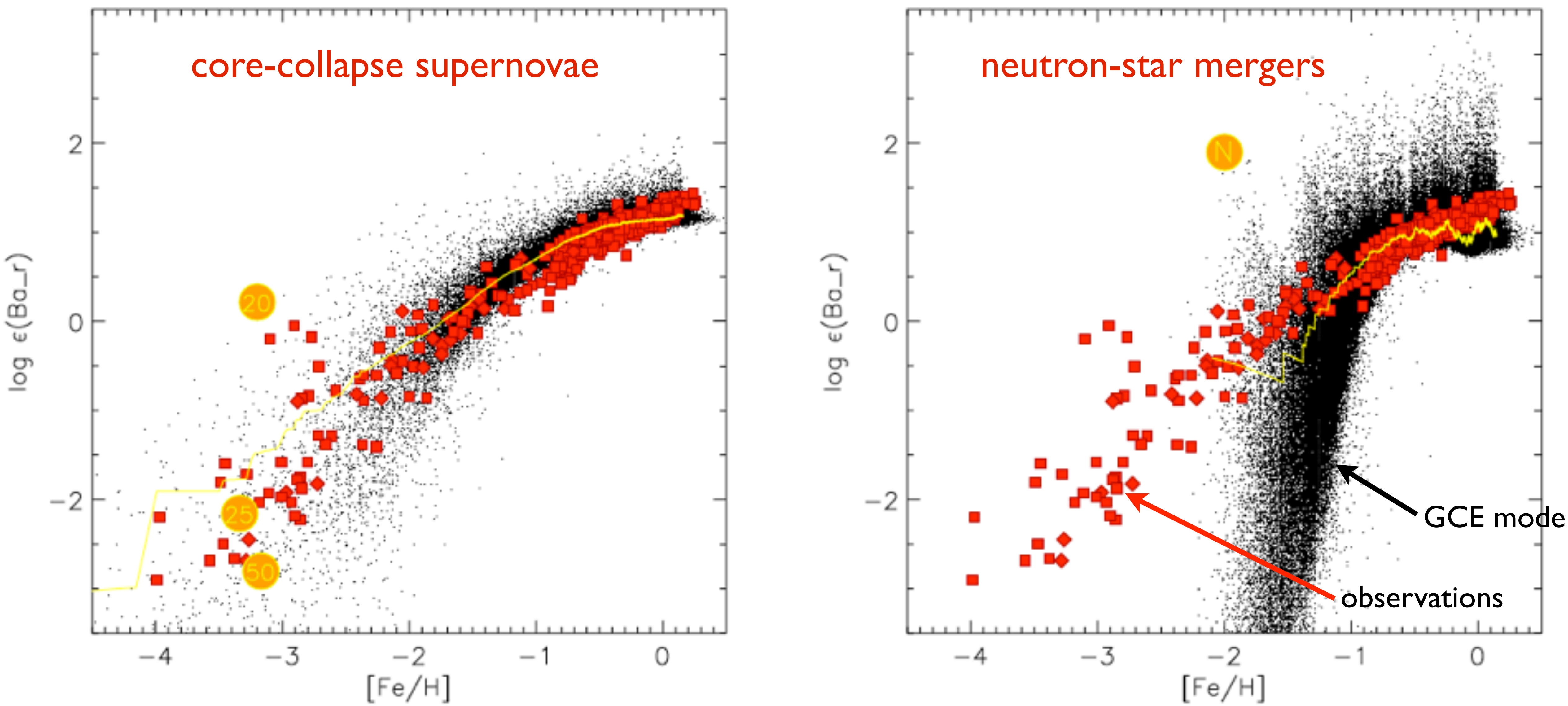


Right conditions for a successful r-process (Freiburghaus et al. 1999, ..., Goriely et al. 2011)

They do not occur early enough to explain UMP star abundances (Qian 2000, Argast et al. 2004)

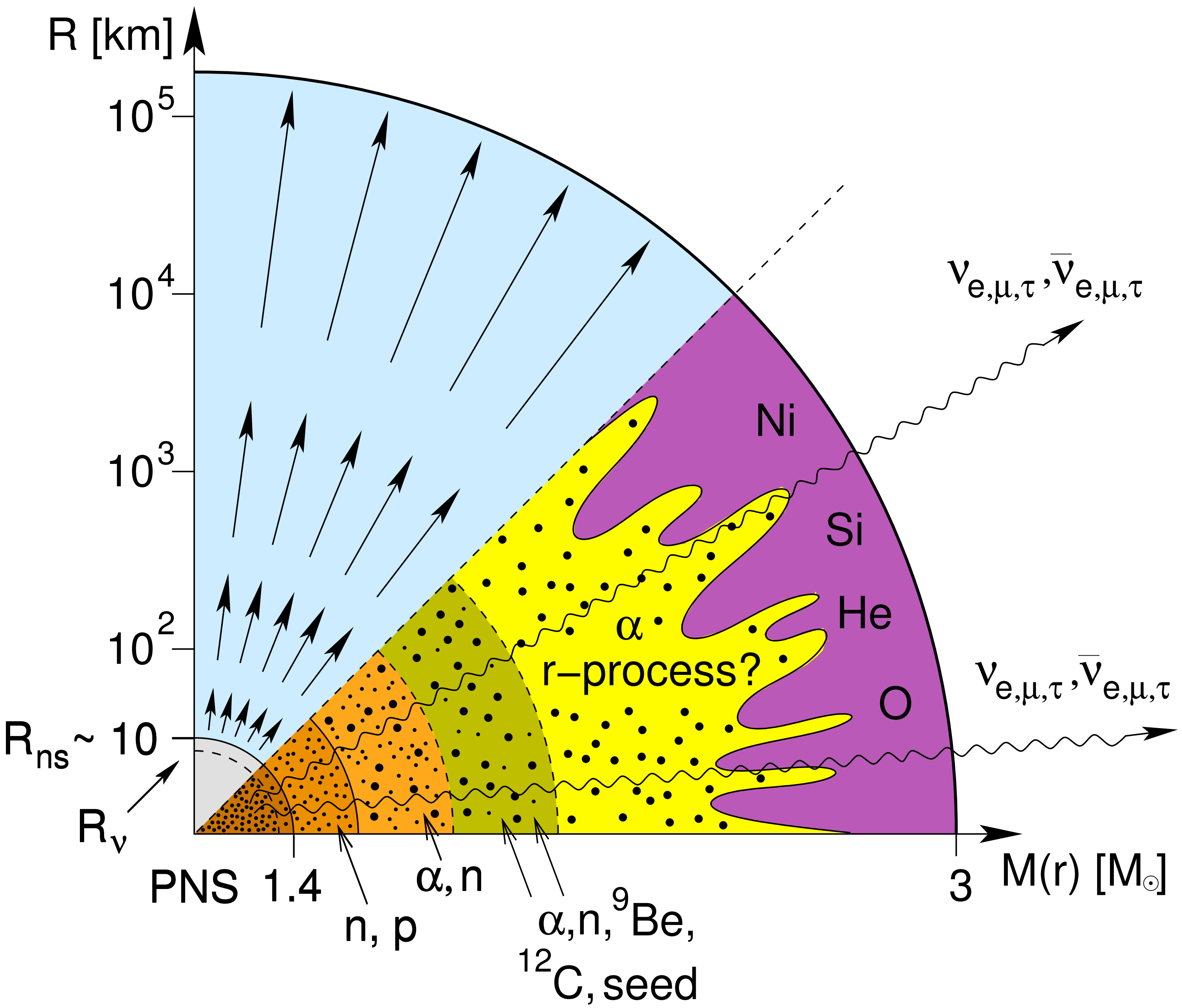
Chemical chemical evolution: supernovae vs. mergers

Argast et al. 2004: galactic chemical evolution models r-process from:



Open questions: amount of mass ejected
event rate

Nucleosynthesis in neutrino-driven winds



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

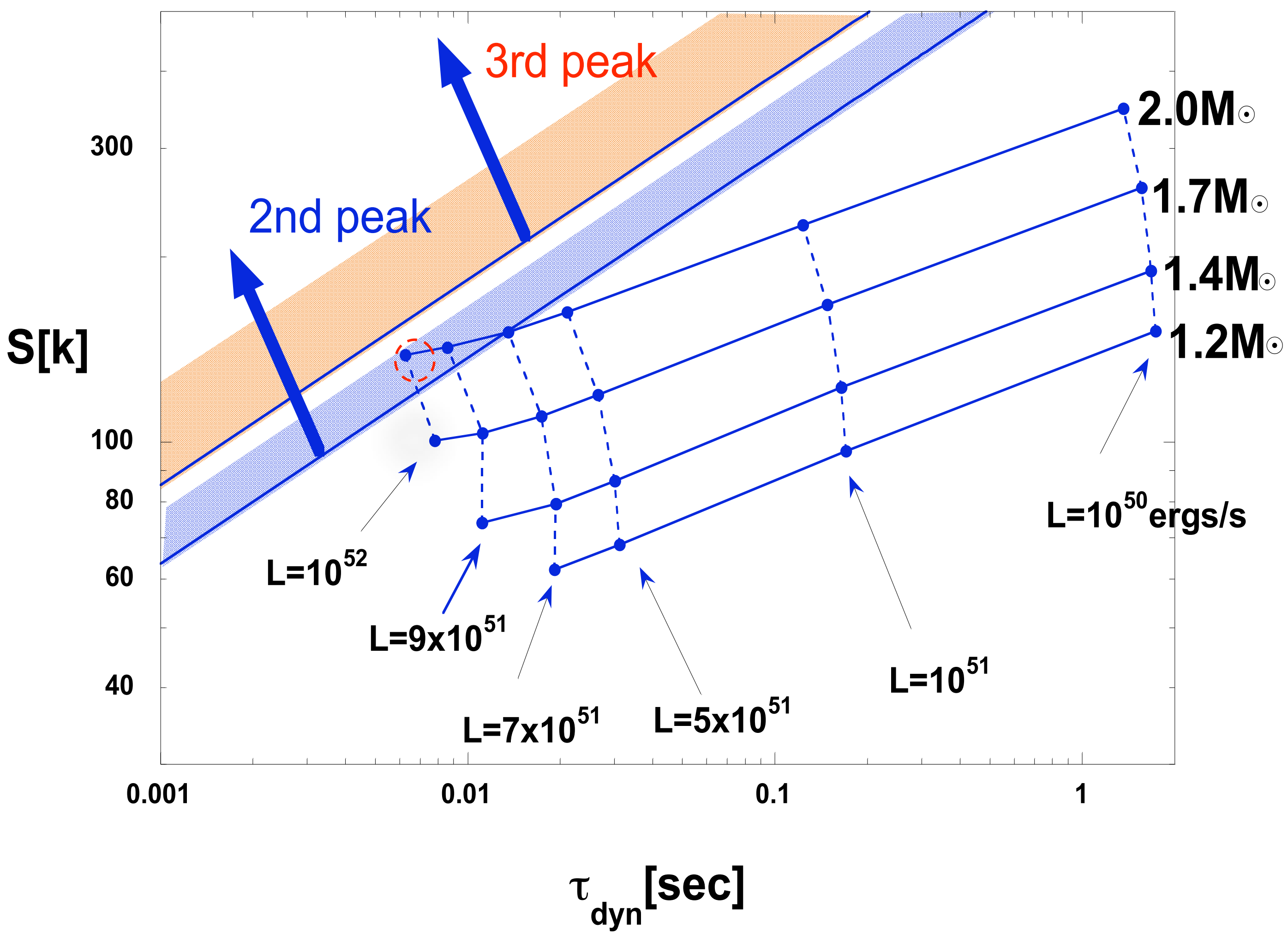
Necessary conditions for the r-process:

- 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...)

Nucleosynthesis in neutrino-driven winds

Otsuki et al. 2000



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

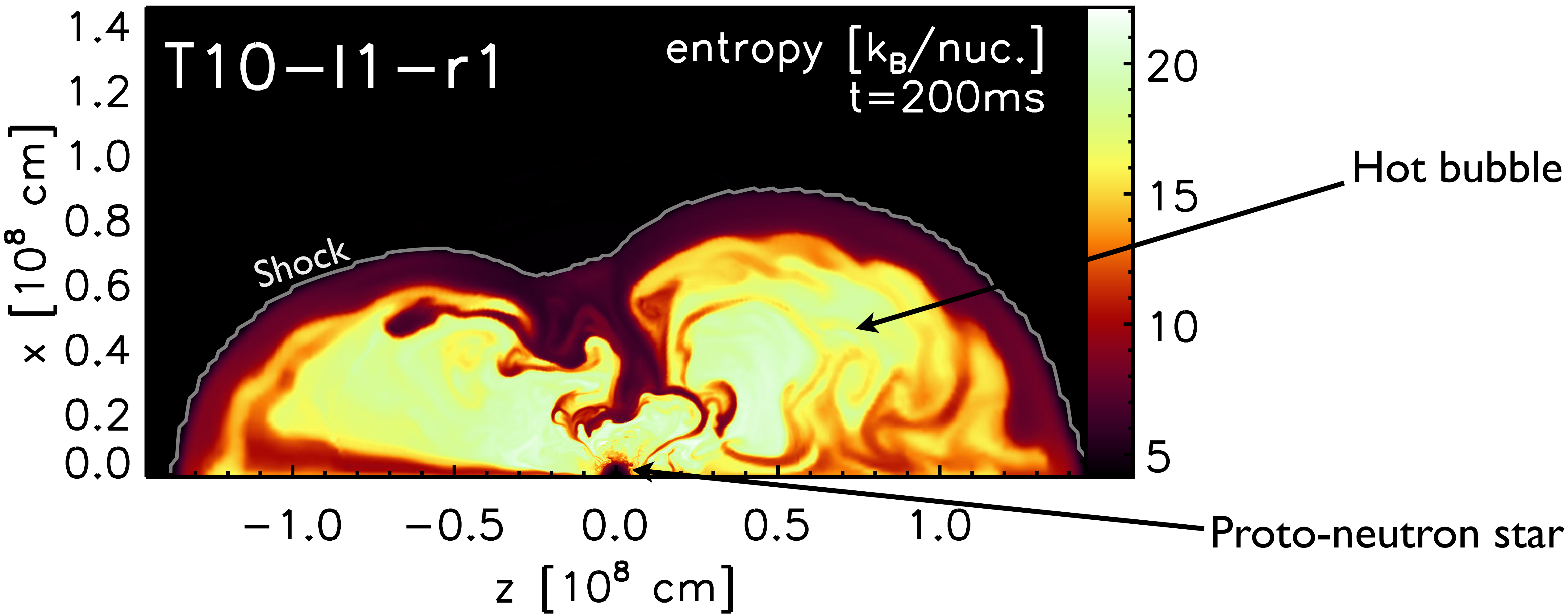
Necessary conditions for the r-process:

- 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.

Necessary conditions identified by steady-state models (e.g. Otsuki et al. 2000, Thompson et al. 2001) are not realized in recent simulations (Arcones et al. 2007, Fischer et al. 2010, Hüdepohl et al. 2010, Roberts et al. 2010)

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

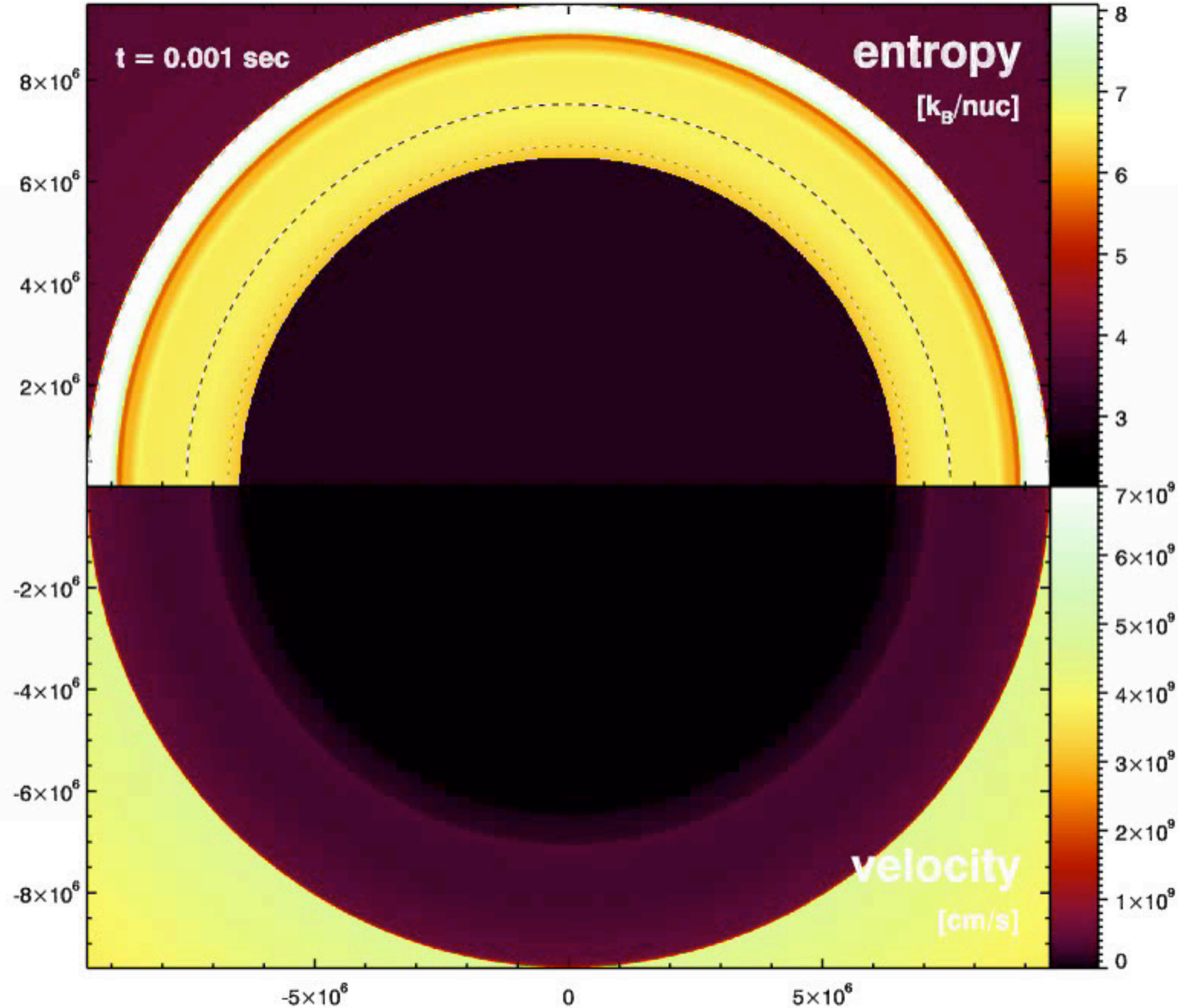
Core-collapse supernova simulations



Long-time hydrodynamical simulations:

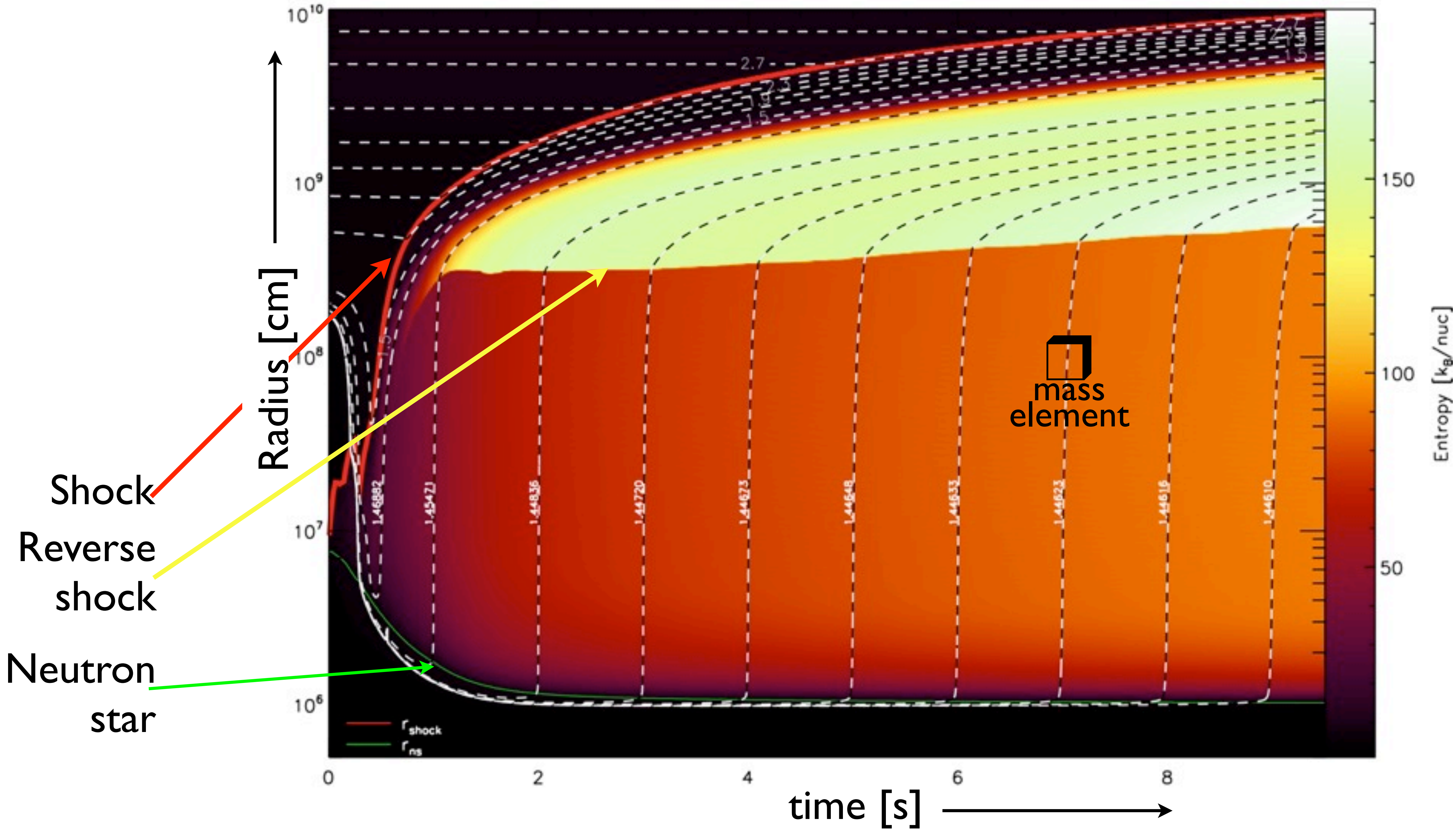
- ejecta evolution from ~5ms after bounce to ~3s in 2D (Arcones & Janka 2011)
  and ~10s in 1D (Arcones et al. 2007)
- explosion triggered by neutrinos
- detailed study of nucleosynthesis-relevant conditions

Arcones & Janka (2011)

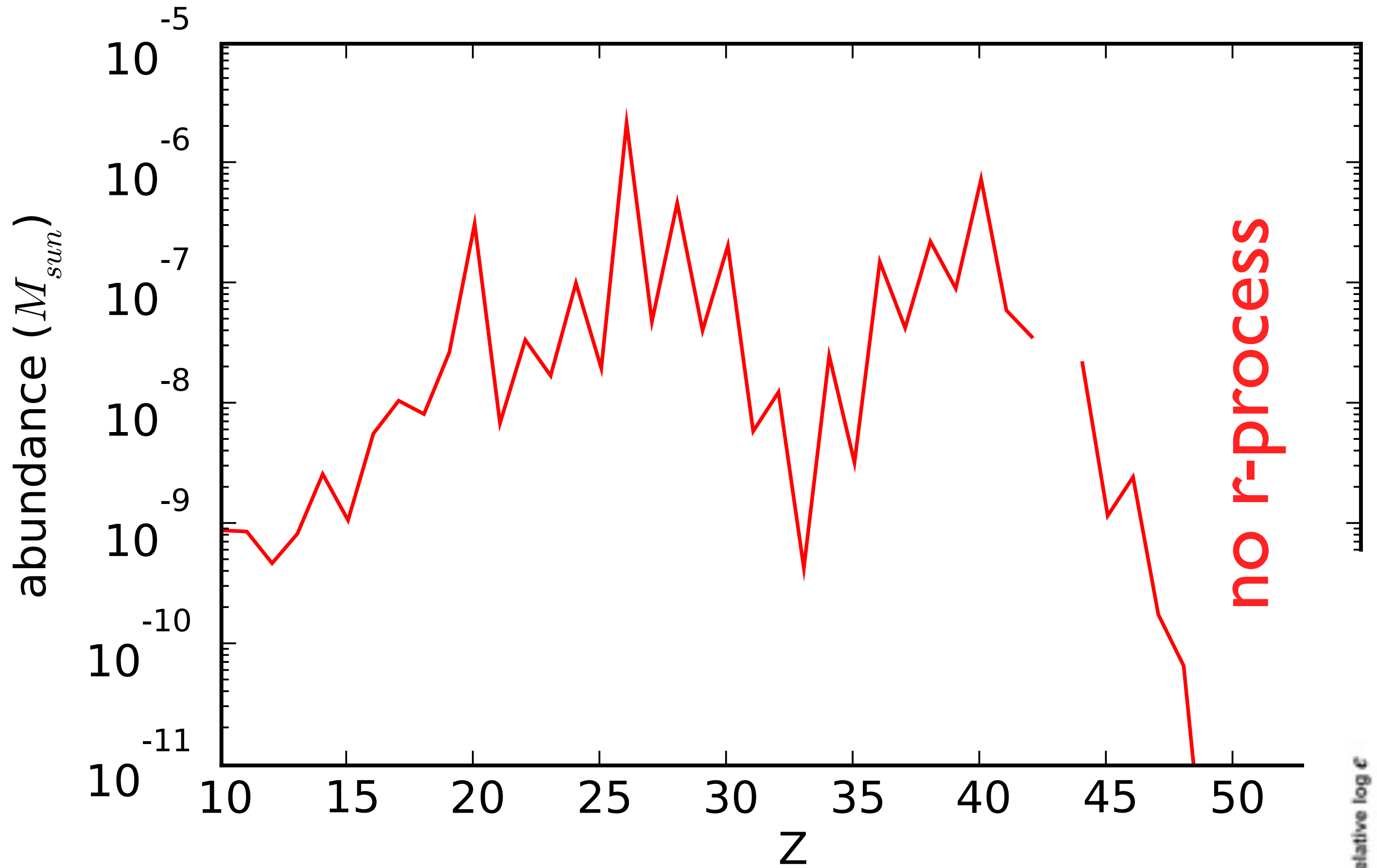


1D simulations for nucleosynthesis studies

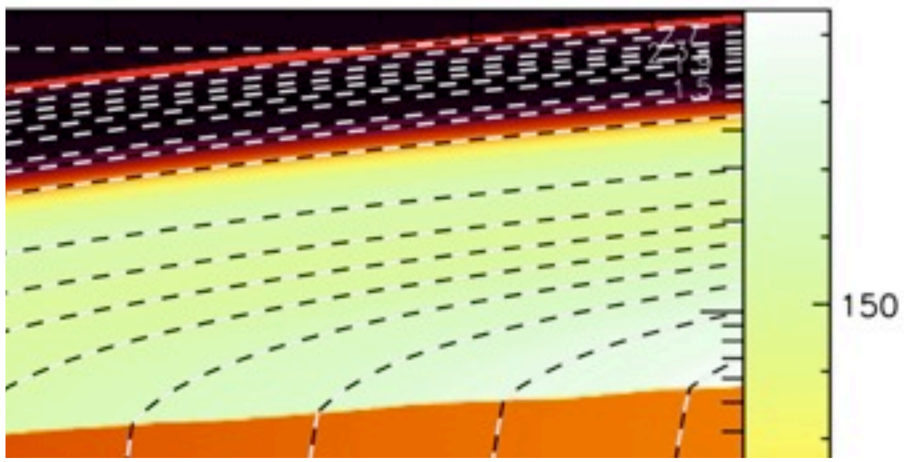
Arcones et al 2007

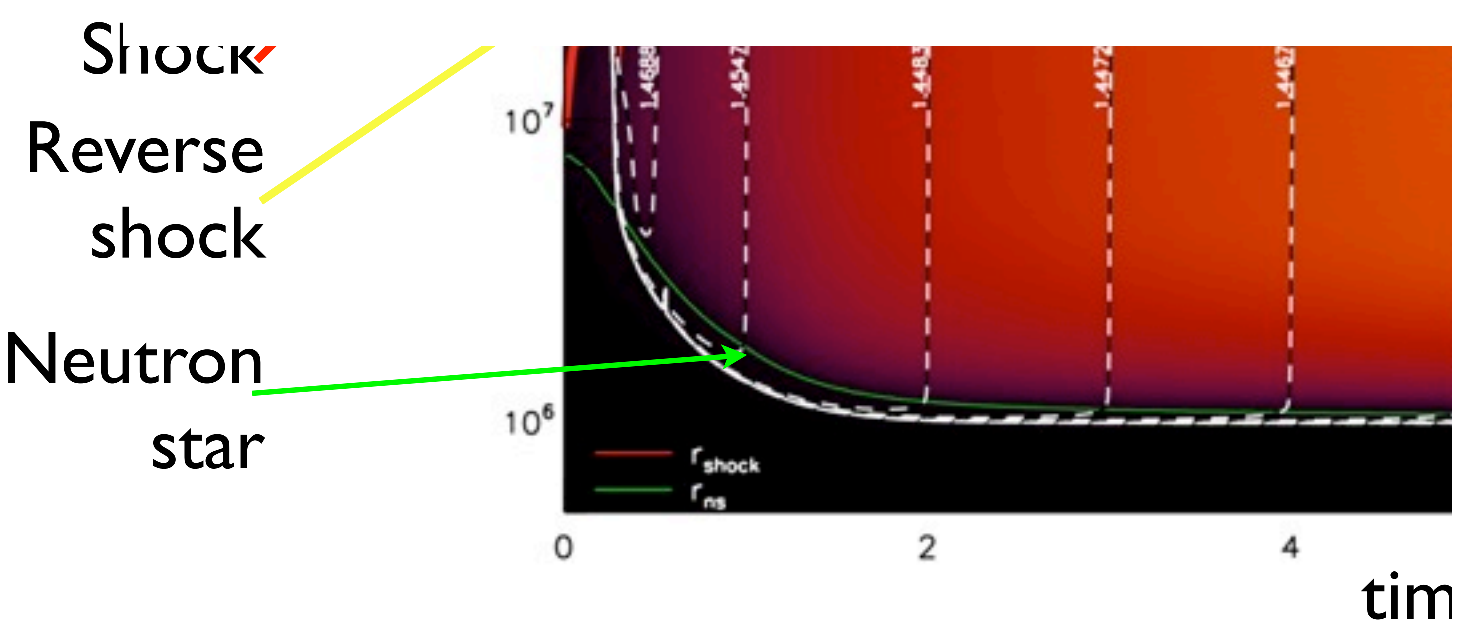


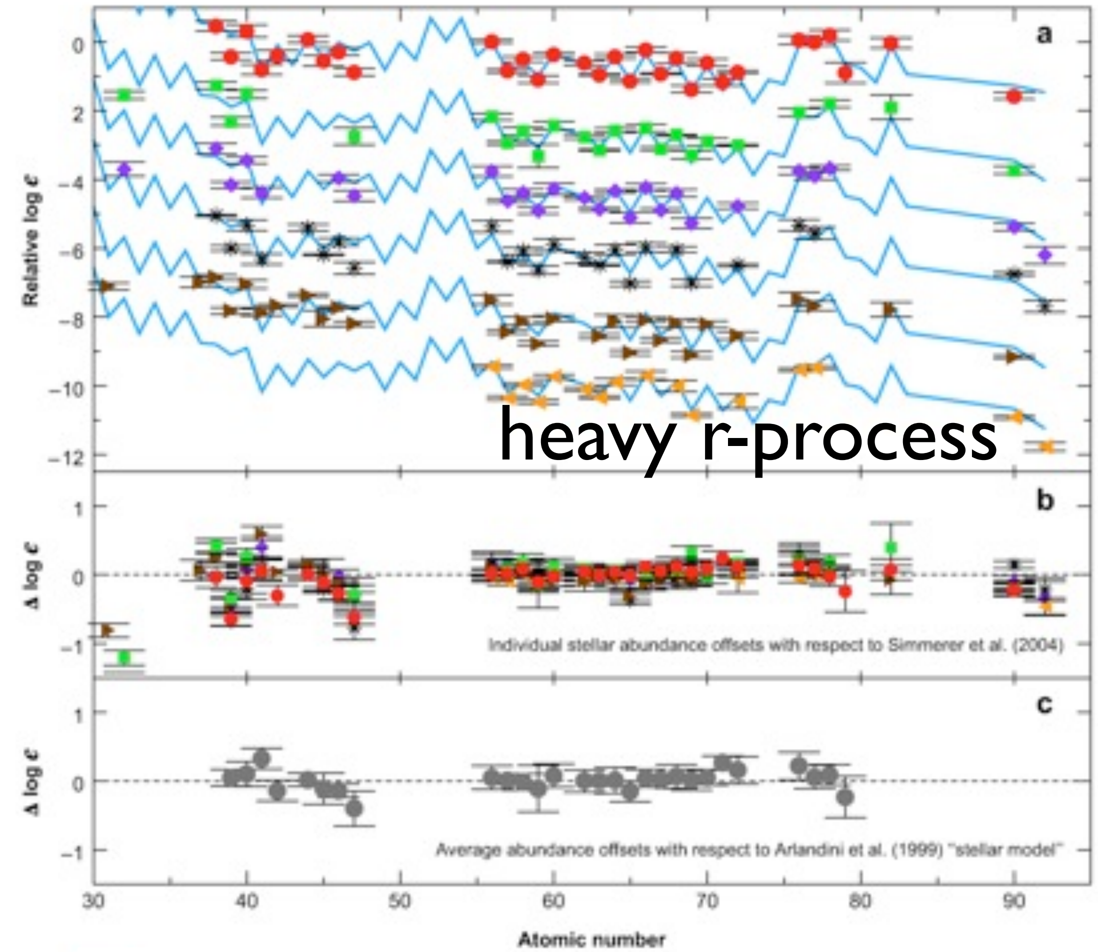
1D simulations for nucleosynthesis studies



Arcones et al 2007





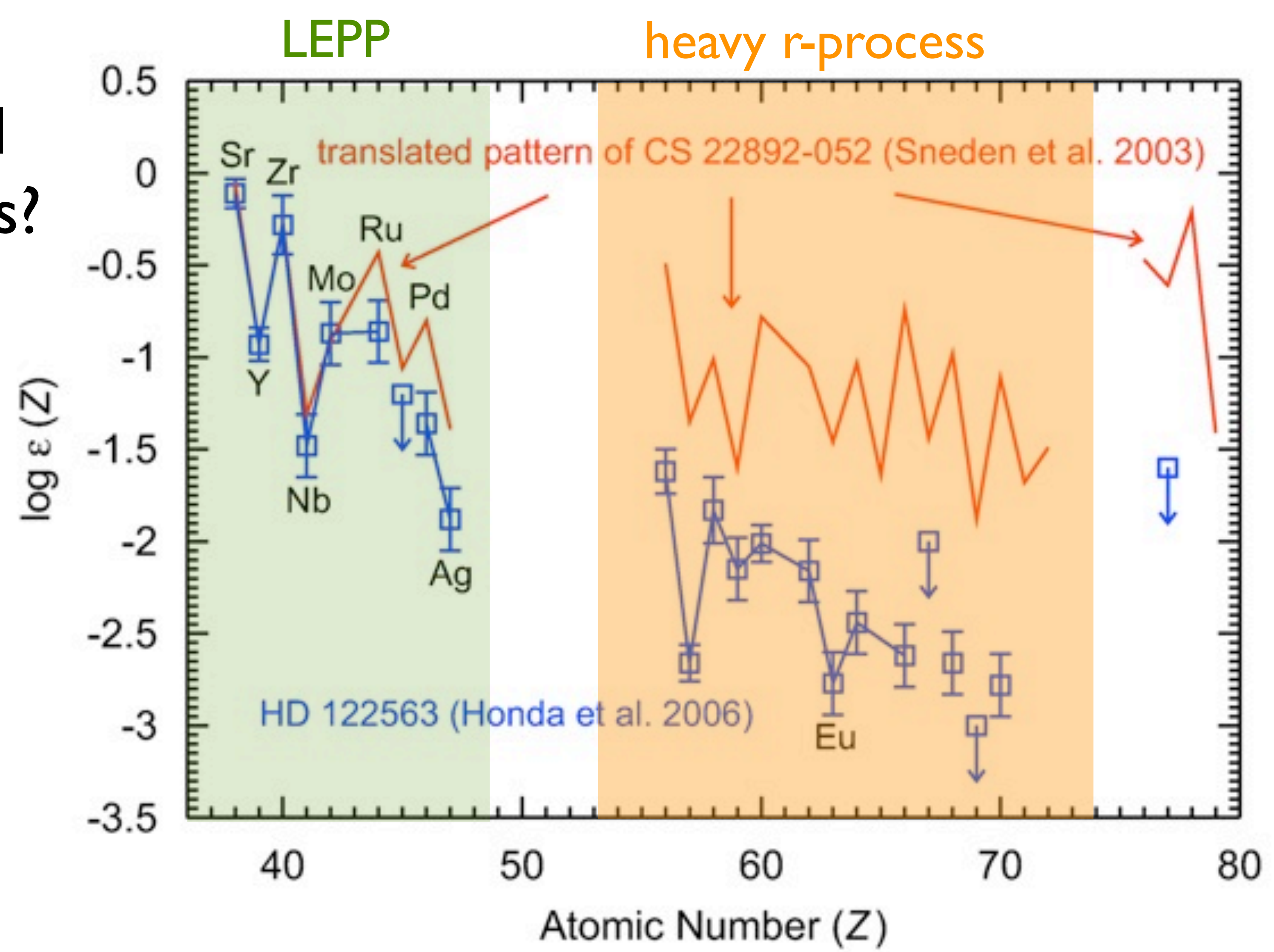


Sneden, Cowan, Gallino 2008

LEPP: Lighter Element Primary Process

Ultra metal-poor stars with high and low enrichment of heavy r-process nuclei suggest: two components or sites (Qian & Wasserburg, 2001, Travaglio et al. 2004)

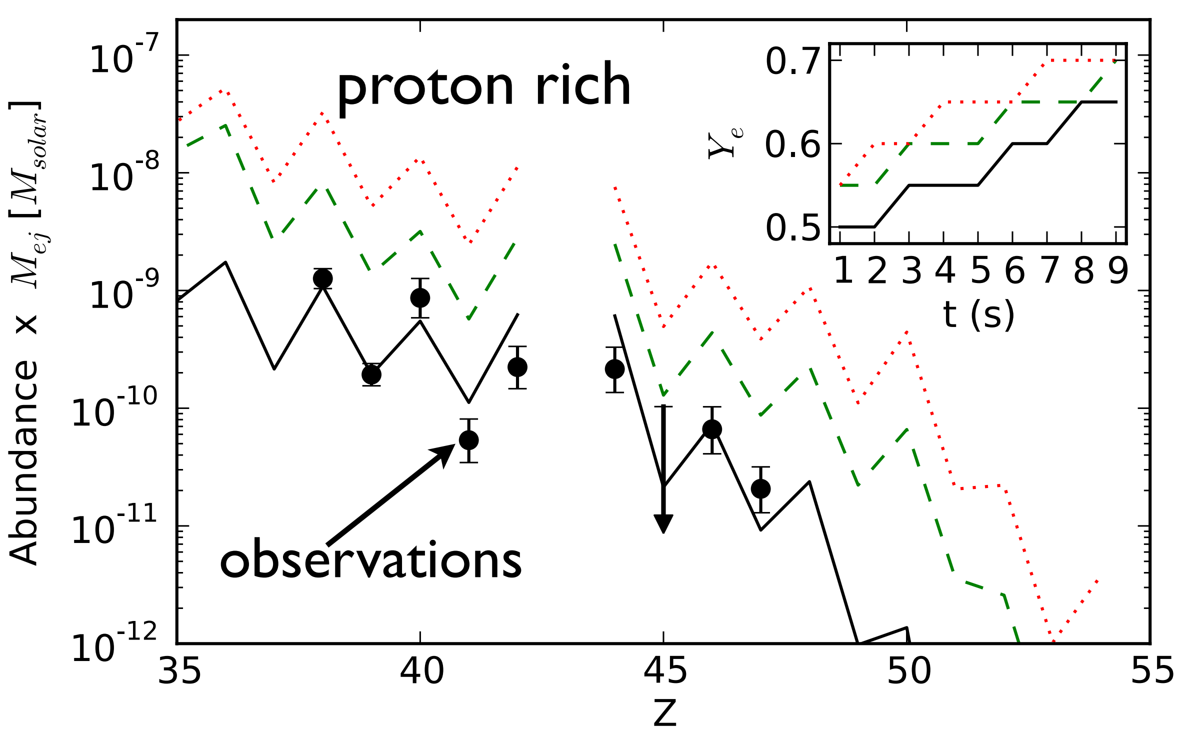
Can the LEPP pattern be produced in neutrino-driven wind simulations?



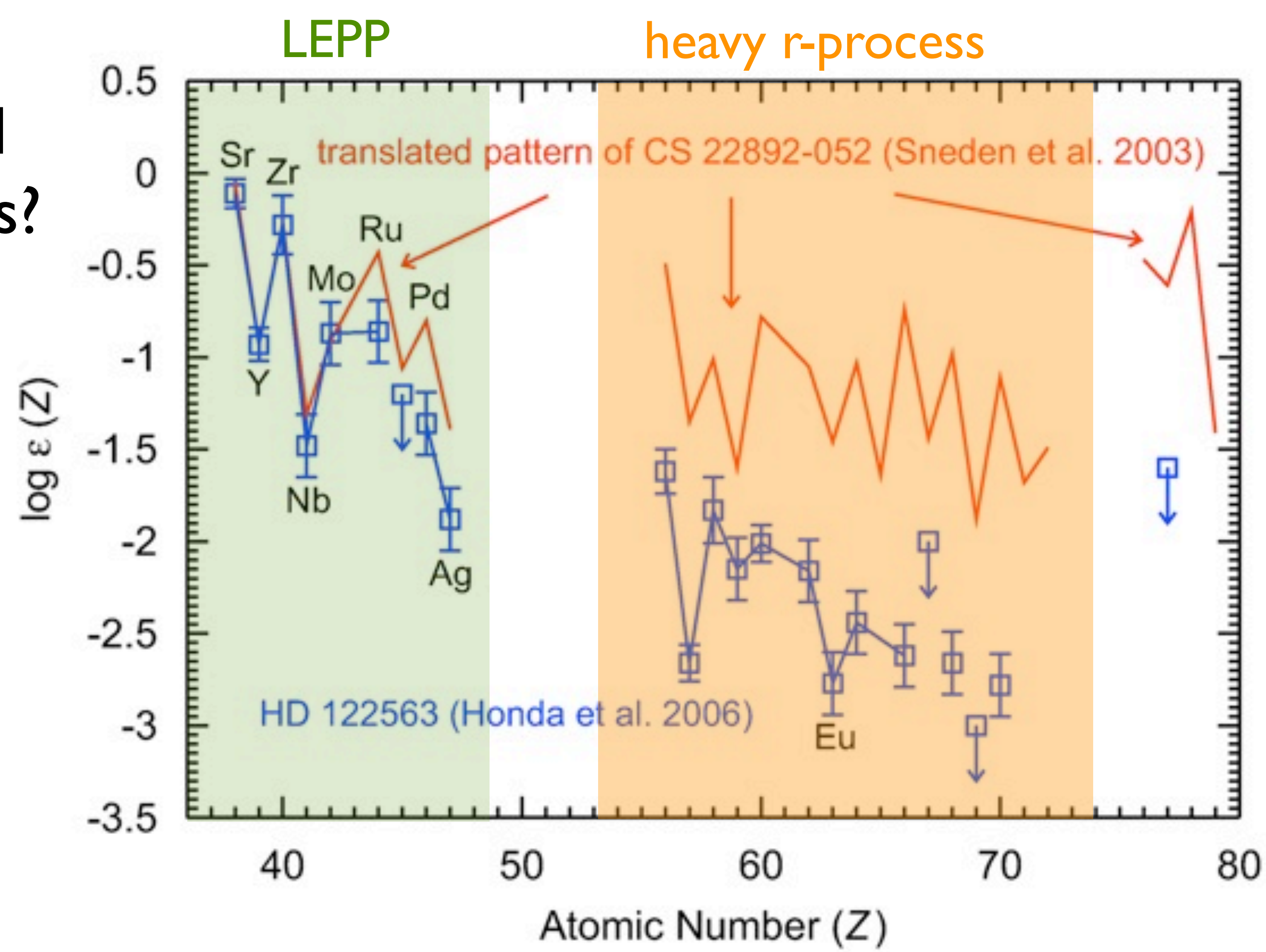
LEPP: Lighter Element Primary Process

Ultra metal-poor stars with high and low enrichment of heavy r-process nuclei suggest: two components or sites (Qian & Wasserburg, 2001, Travaglio et al. 2004)

Can the LEPP pattern be produced in neutrino-driven wind simulations?



Arcones & Montes, 2011

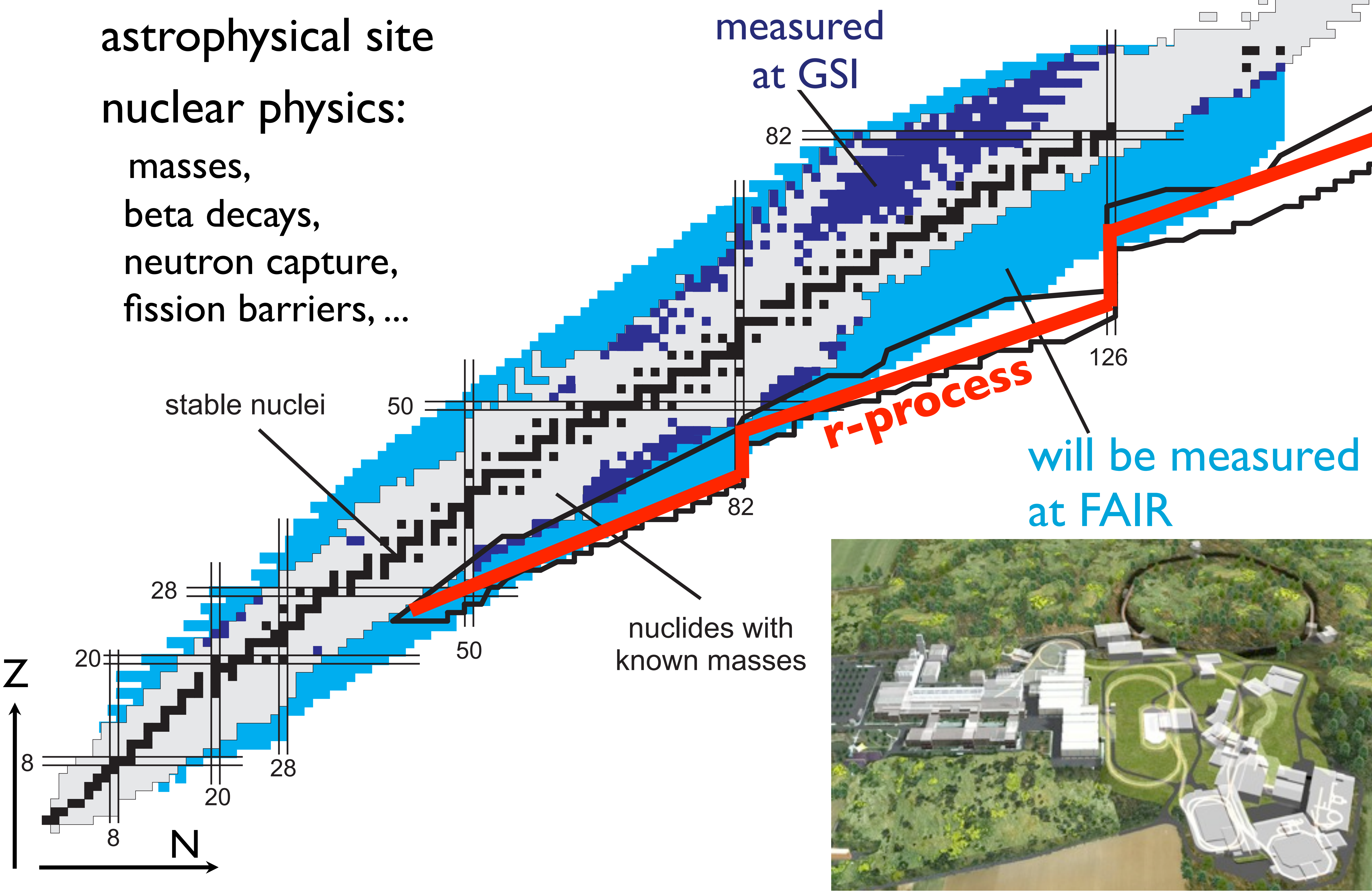


r-process and extreme neutron-rich nuclei

astrophysical site

nuclear physics:

- masses,
- beta decays,
- neutron capture,
- fission barriers, ...

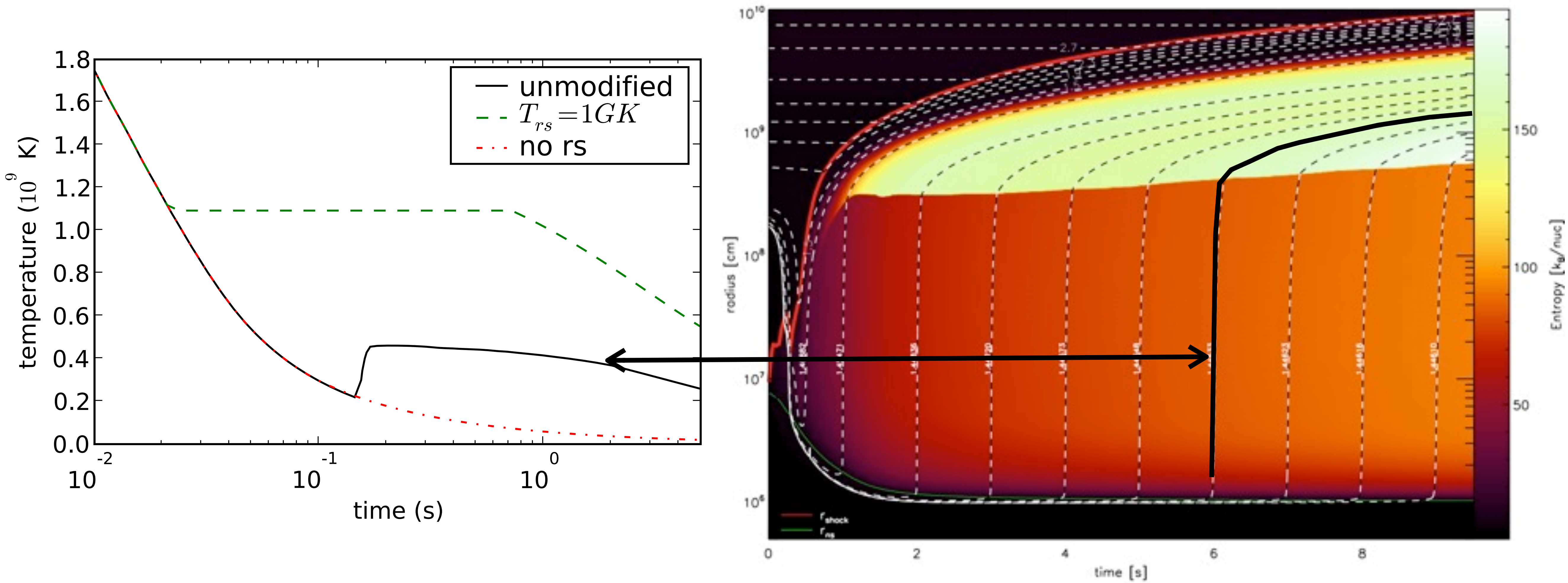


r-process: long-time evolution and reverse shock

We use one trajectory from our hydrodynamical simulations with entropy increased by factor two.

Vary the long-time evolution:

- reverse shock at 1GK
- no reverse shock

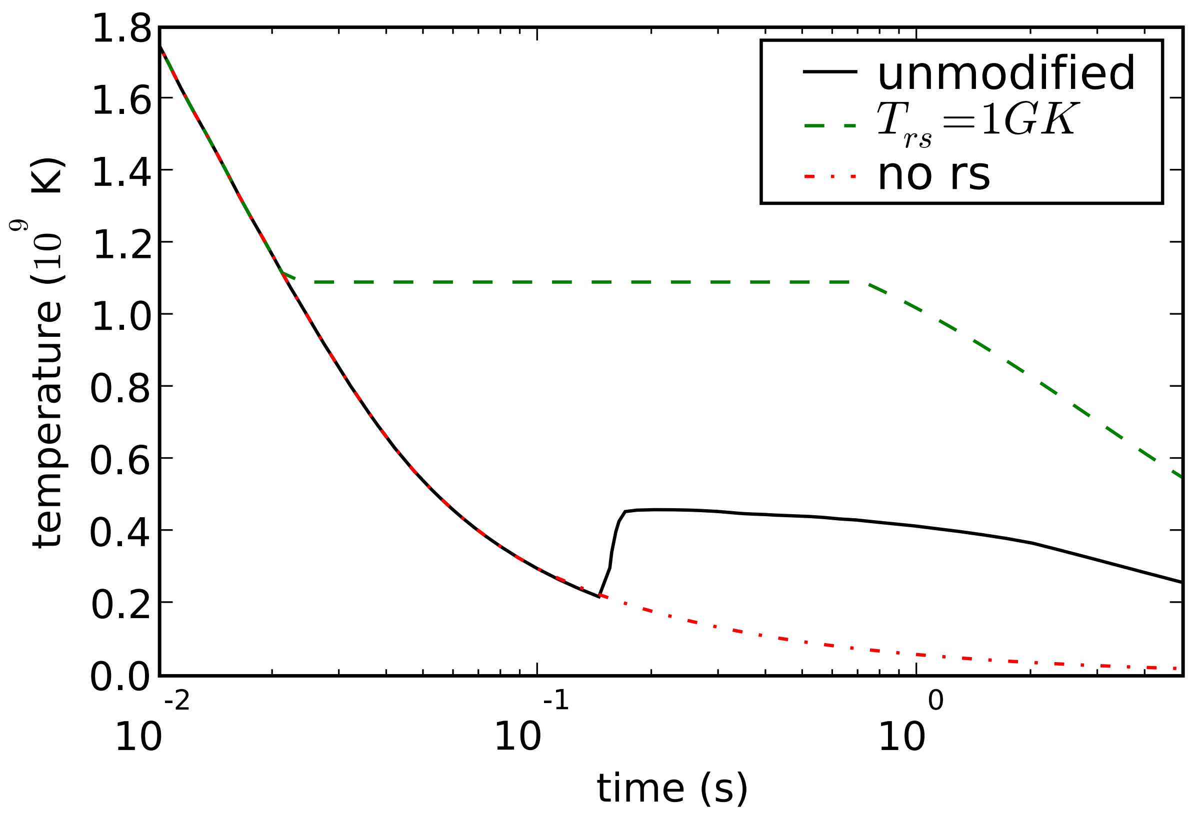


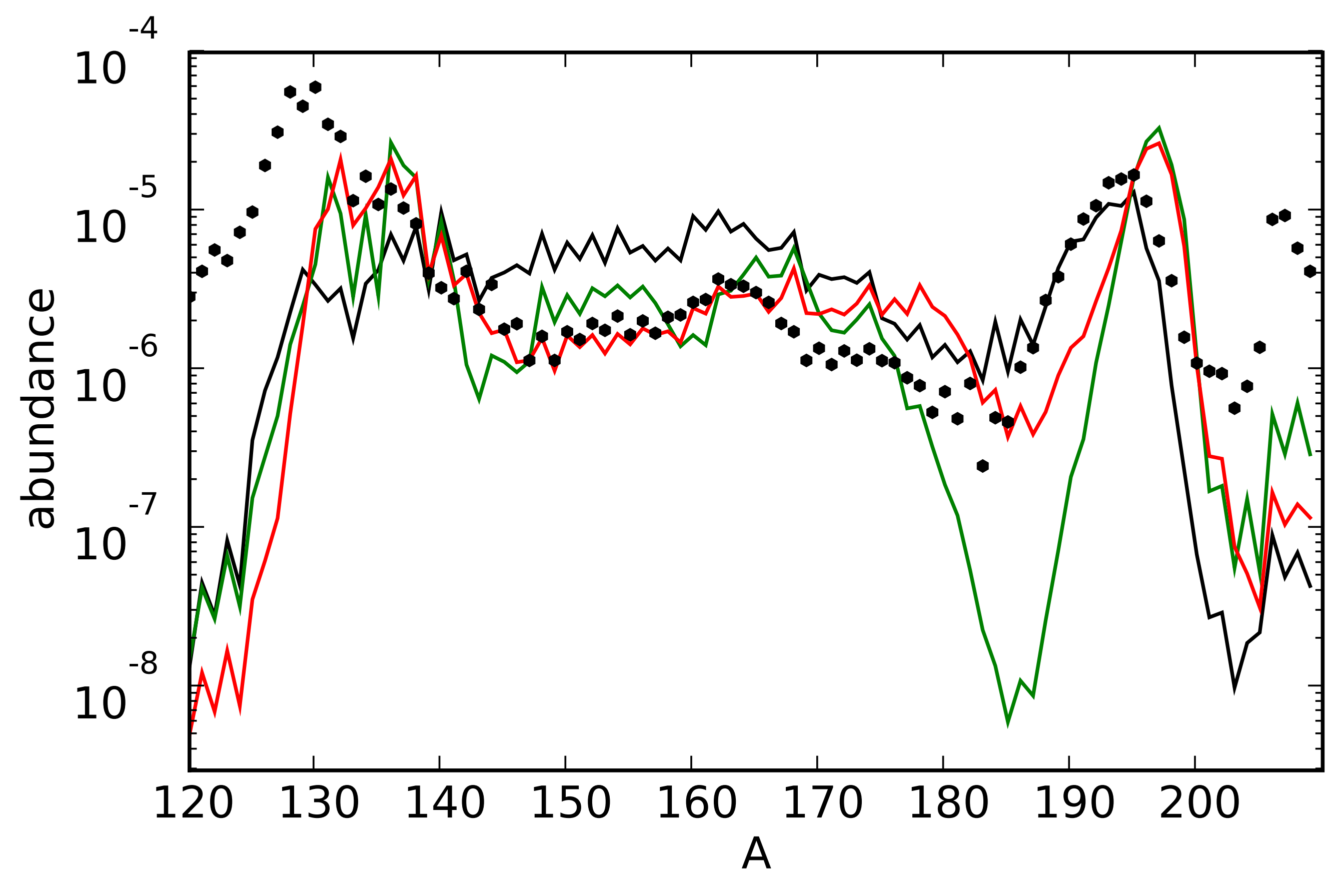
Arcones & Martinez-Pinedo, 2011

r-process: long-time evolution and reverse shock

We use one trajectory from our hydrodynamical simulations with entropy increased by factor two.

Vary the long-time evolution:
- reverse shock at 1GK
- no reverse shock





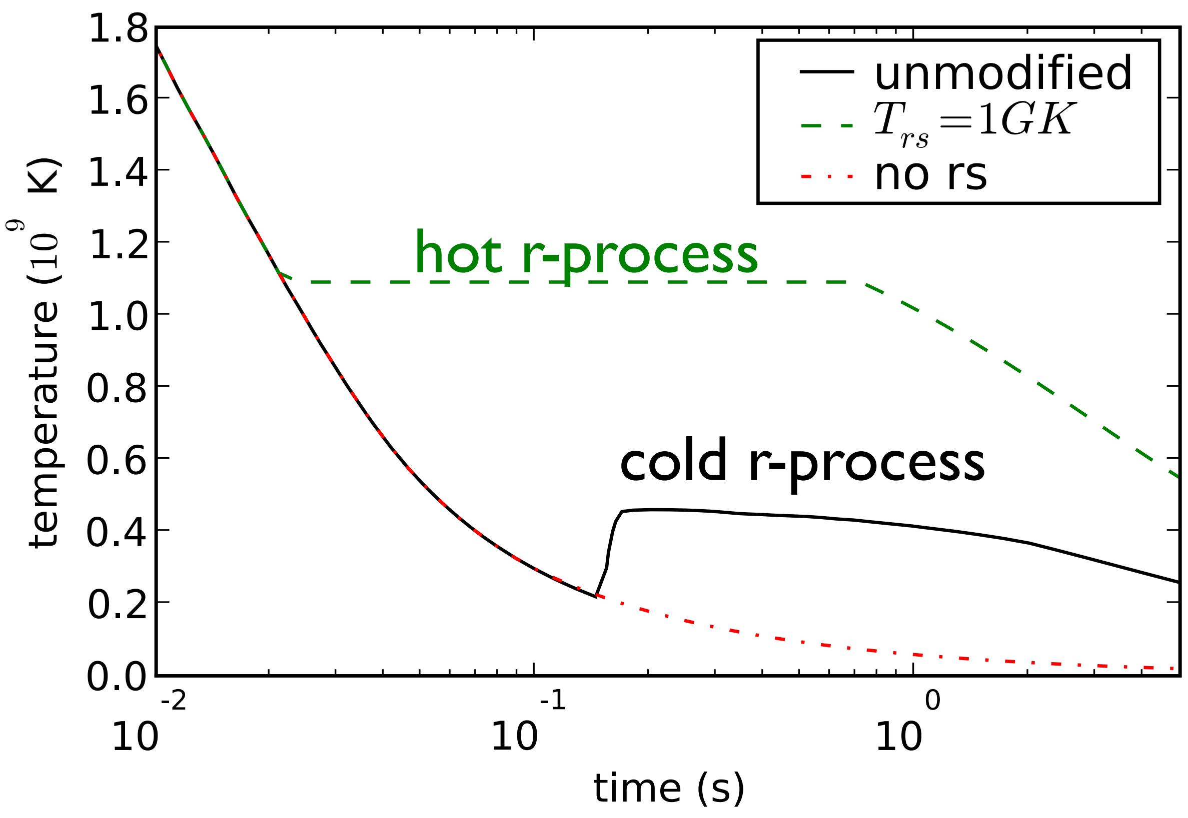
Arcones & Martinez-Pinedo, 2011

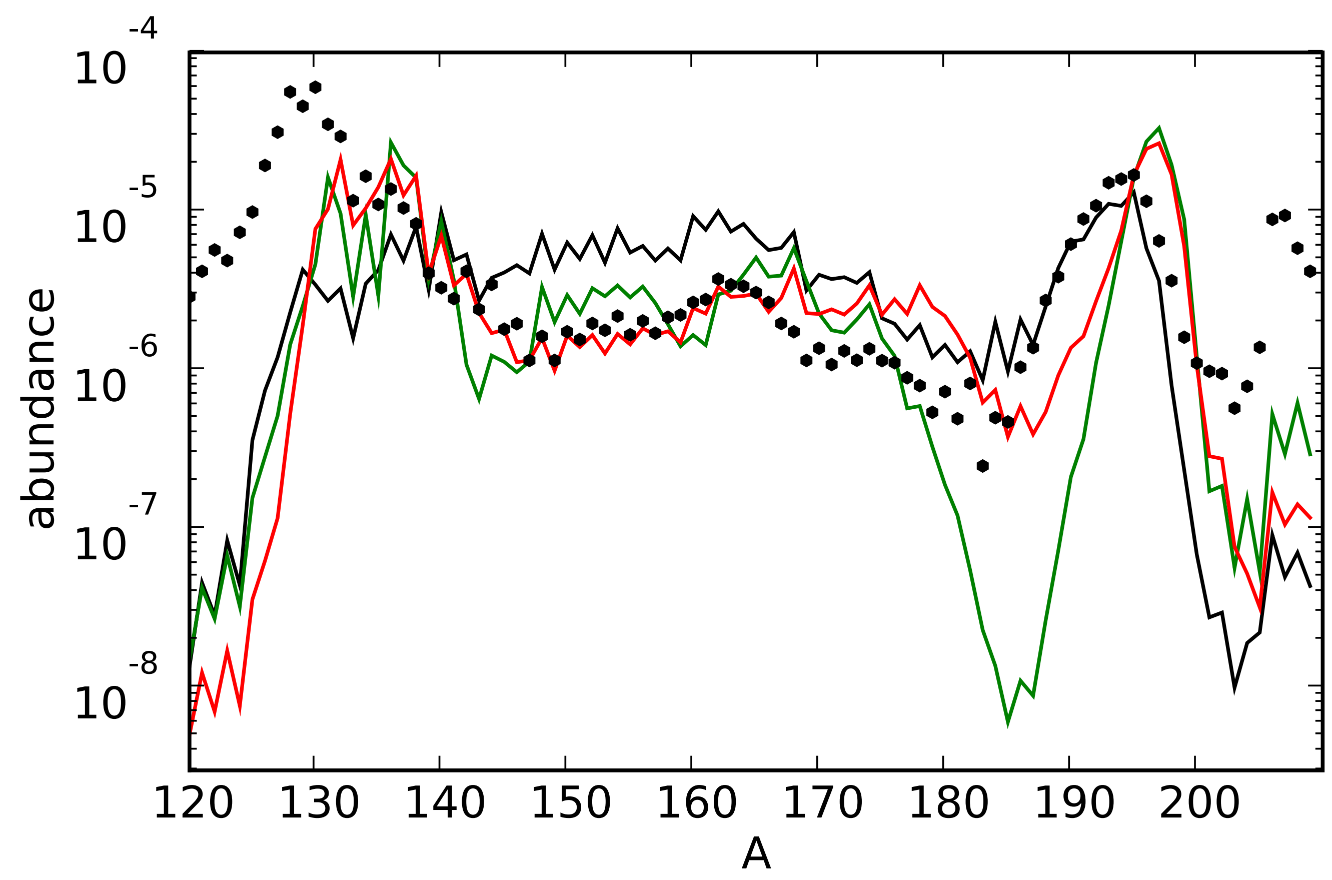
r-process: long-time evolution and reverse shock

We use one trajectory from our hydrodynamical simulations with entropy increased by factor two.

Vary the long-time evolution:

- reverse shock at 1GK
- no reverse shock

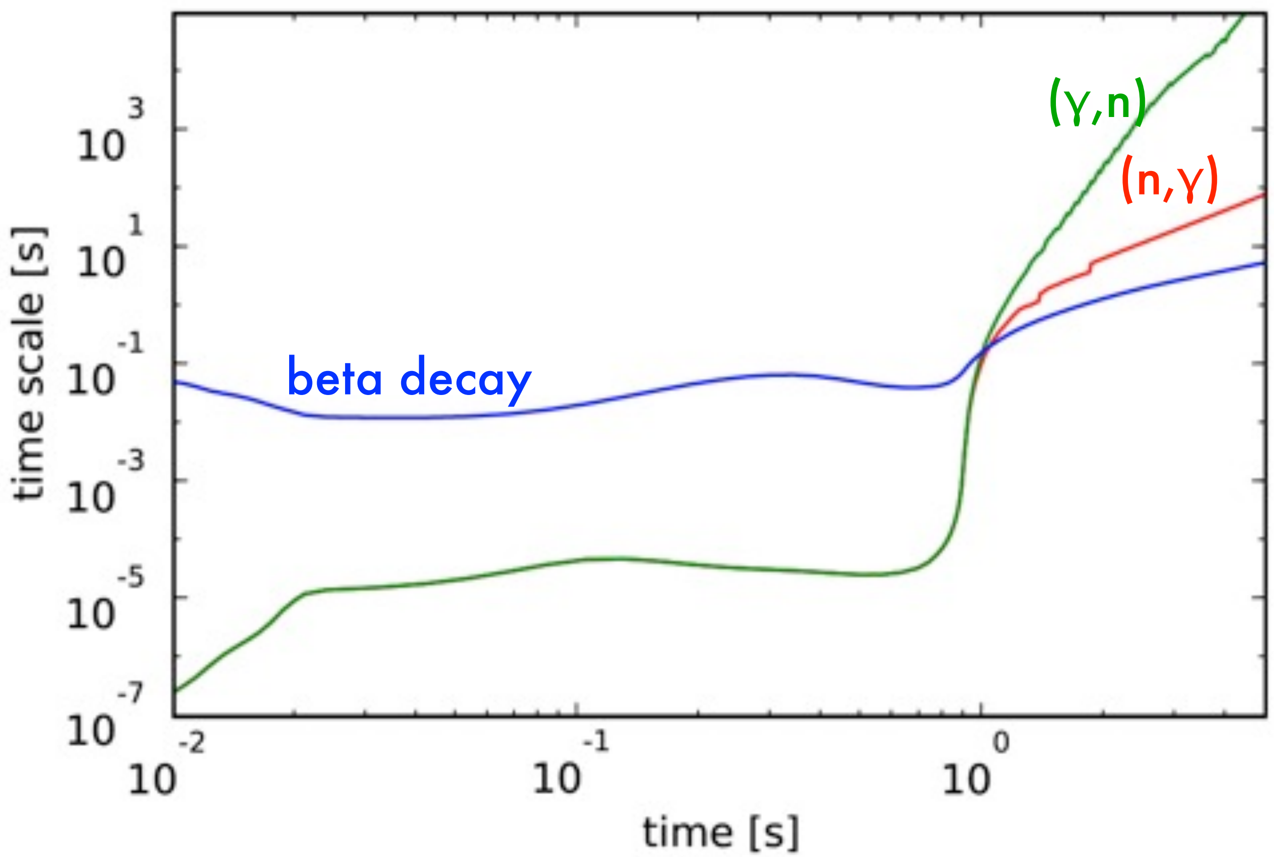




Arcones & Martinez-Pinedo, 2011

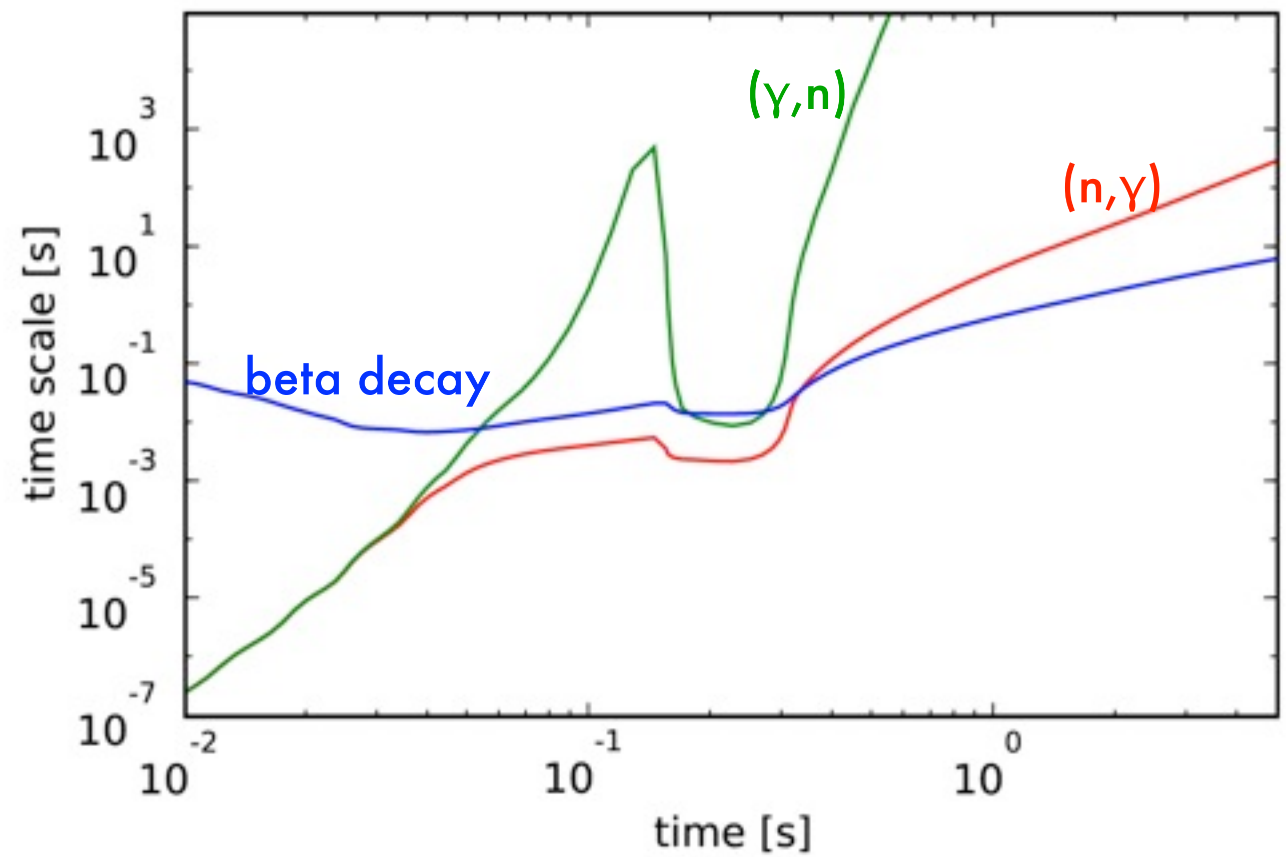
Long-time evolution: high vs. low temperature

Hot r-process



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

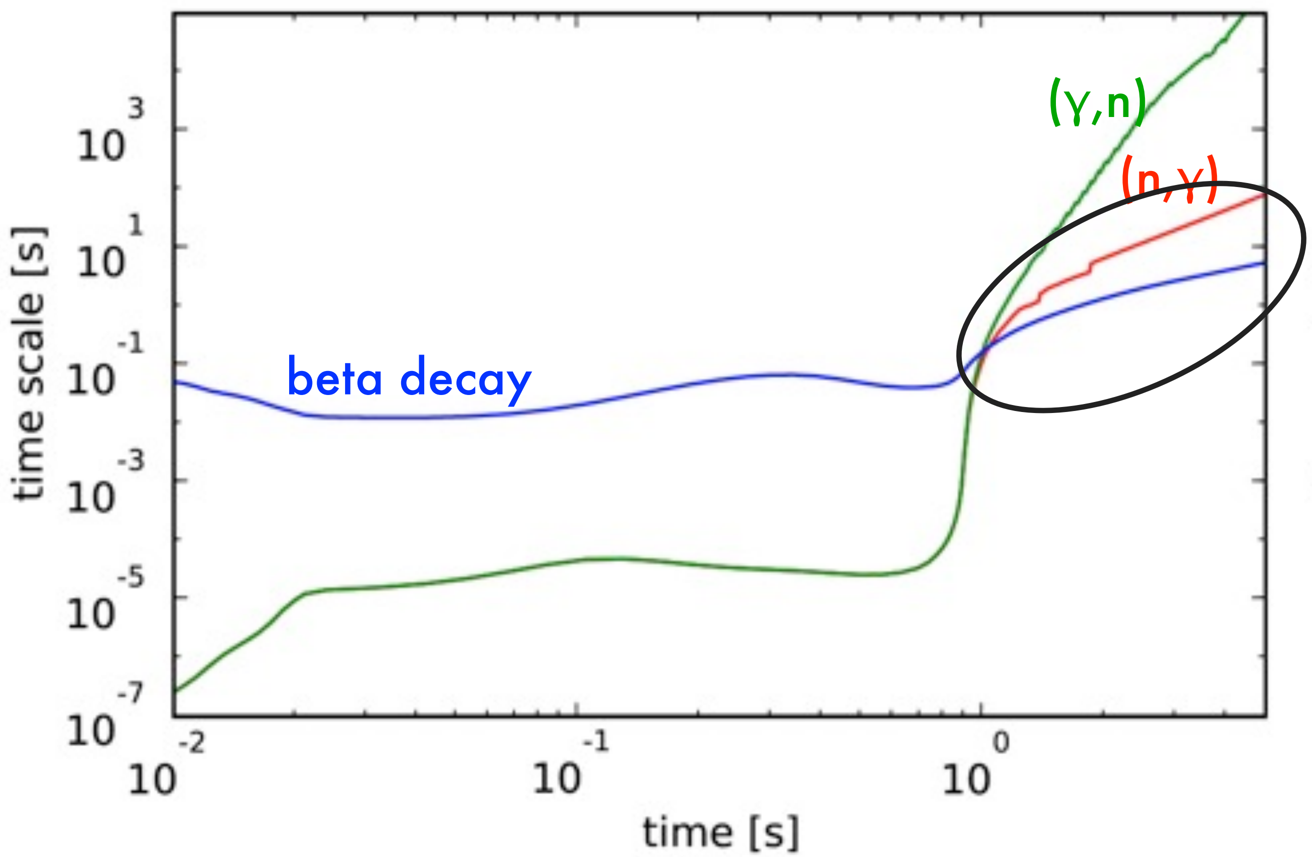
Cold r-process



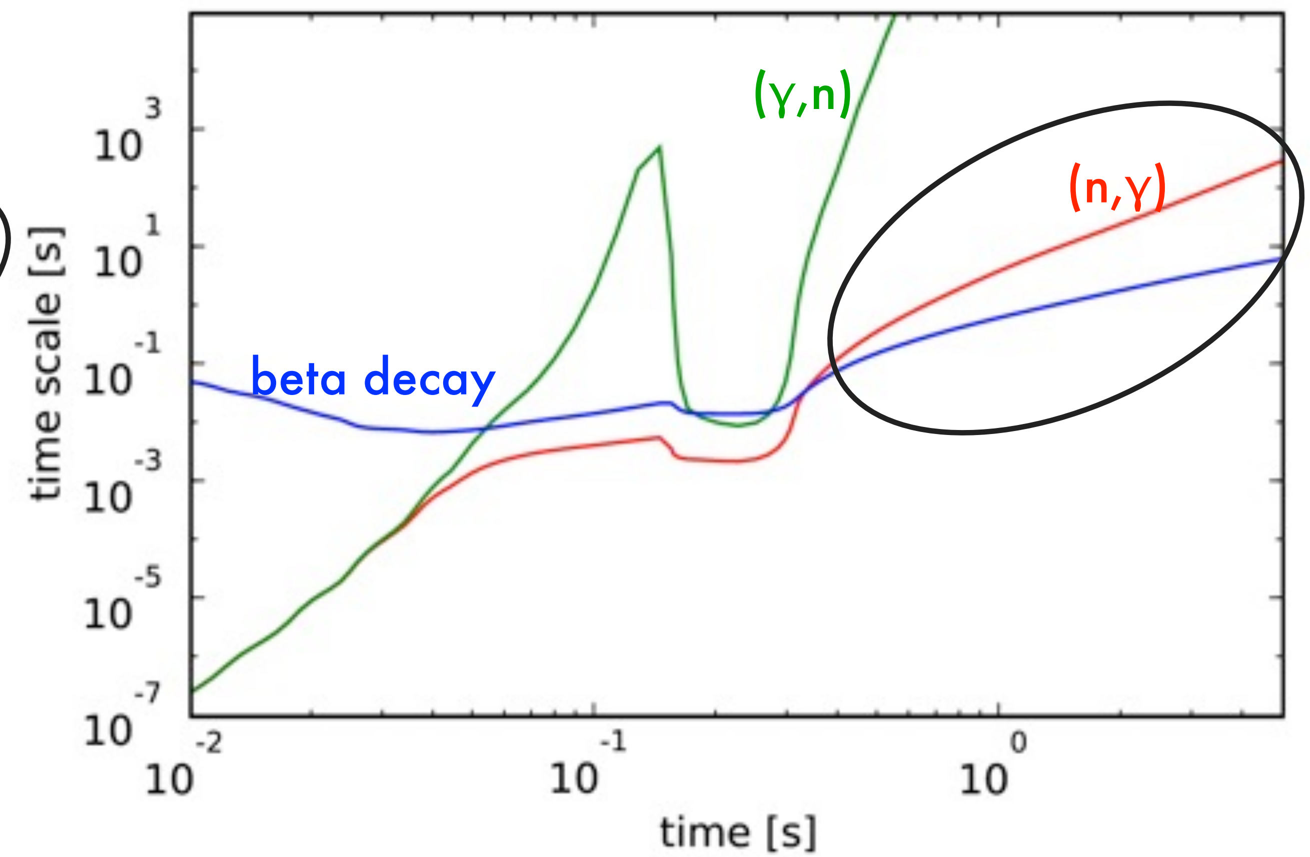
Competition between beta decay and neutron capture (Blake & Schramm 1976, Wanajo 2007, Janka & Panov 2009)

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)

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

Sensitivity to mass models

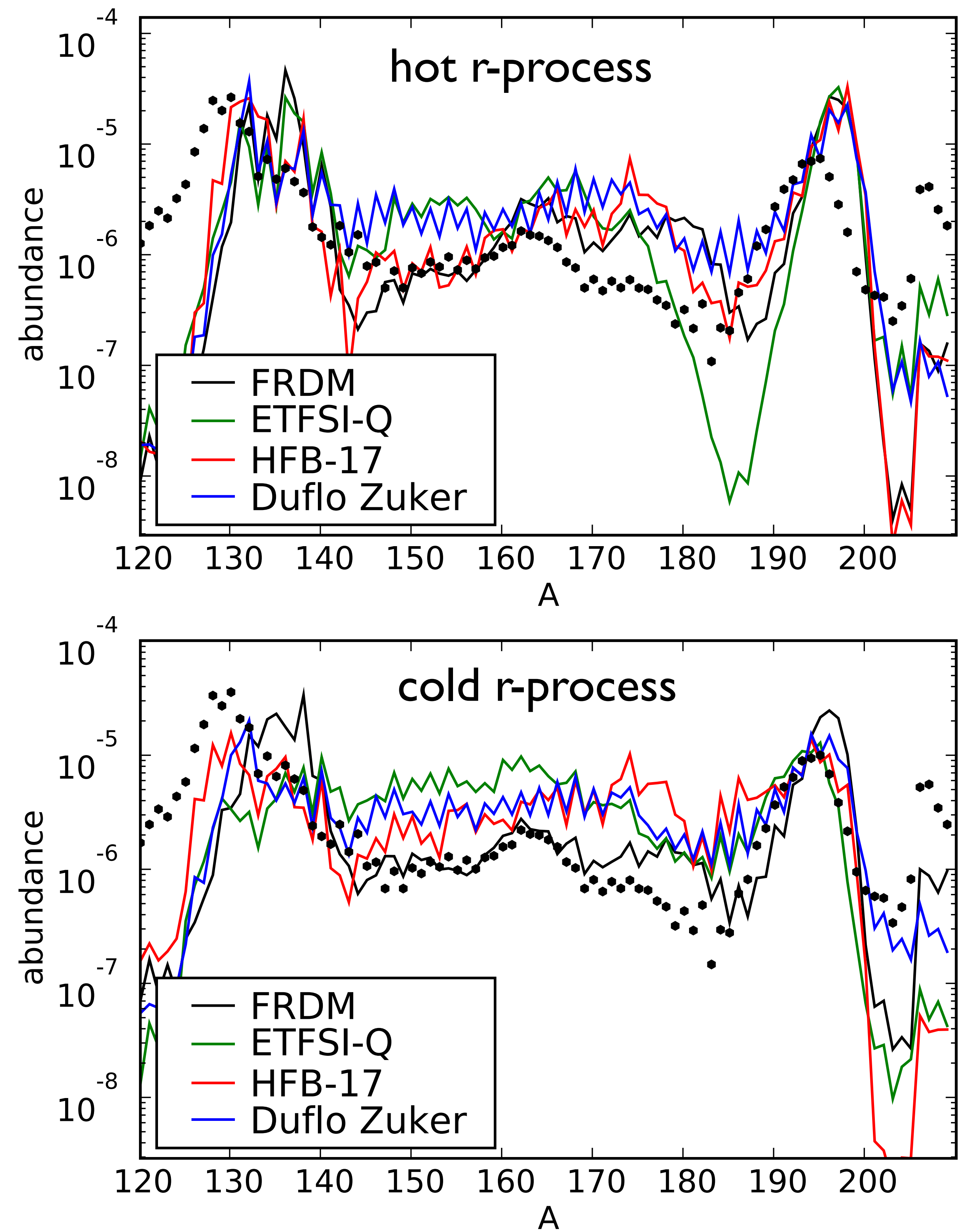
Compare four different mass models:

- 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?



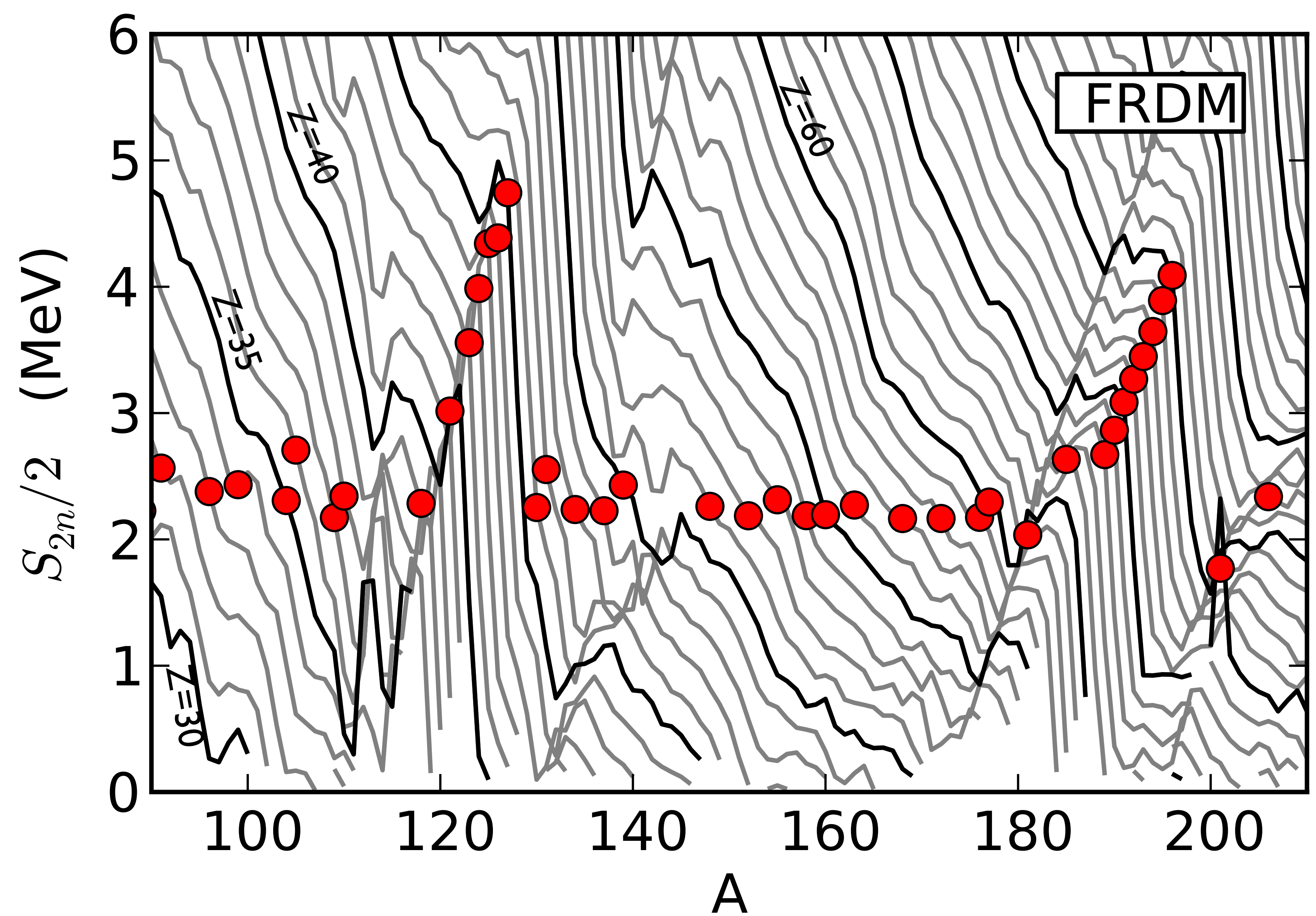
Arcones & Martinez-Pinedo, 2011

Two neutron separation energy

Abundances

S_{2n}

Nuclear properties

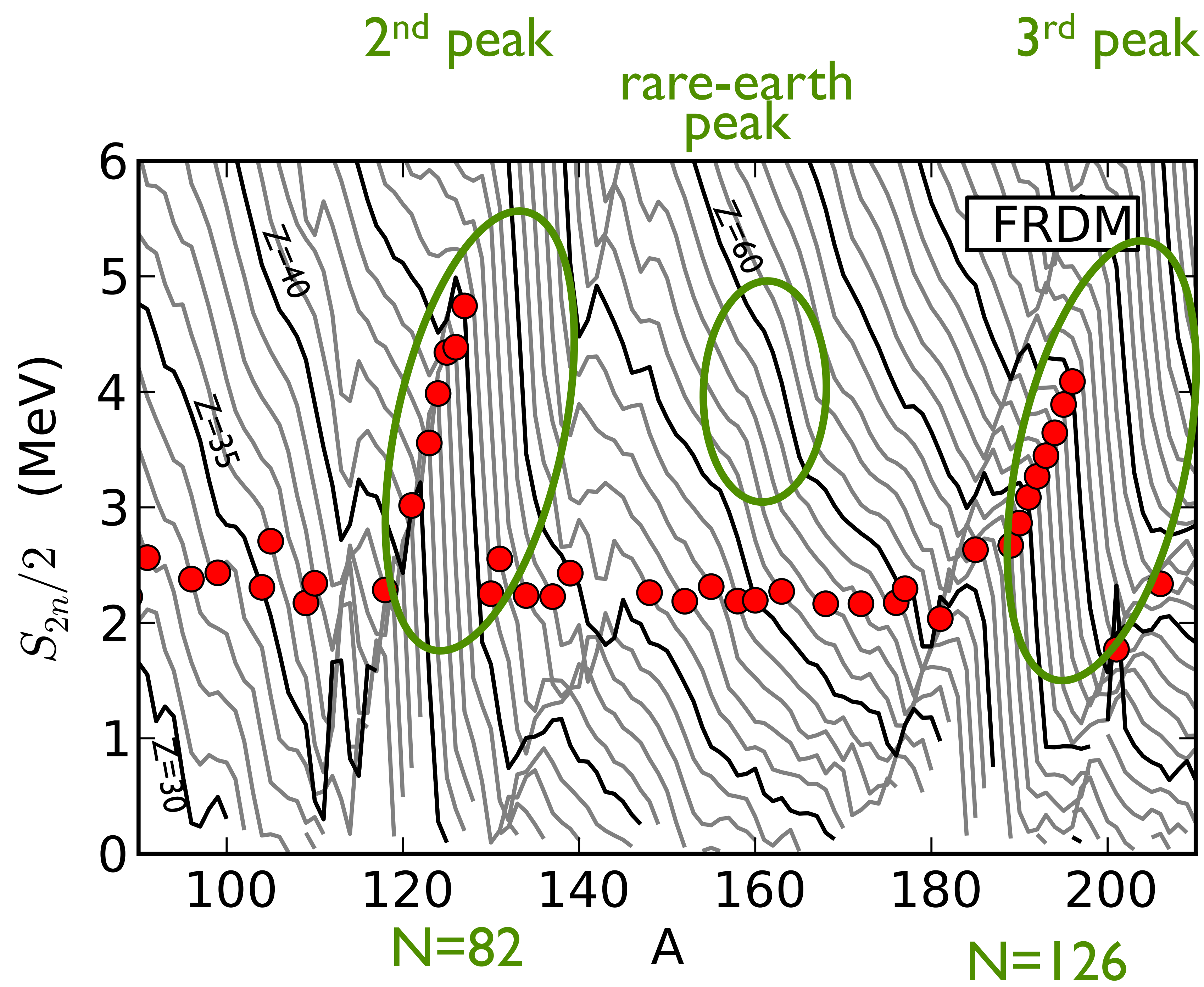


Two neutron separation energy

Abundances

S_{2n}

Nuclear properties

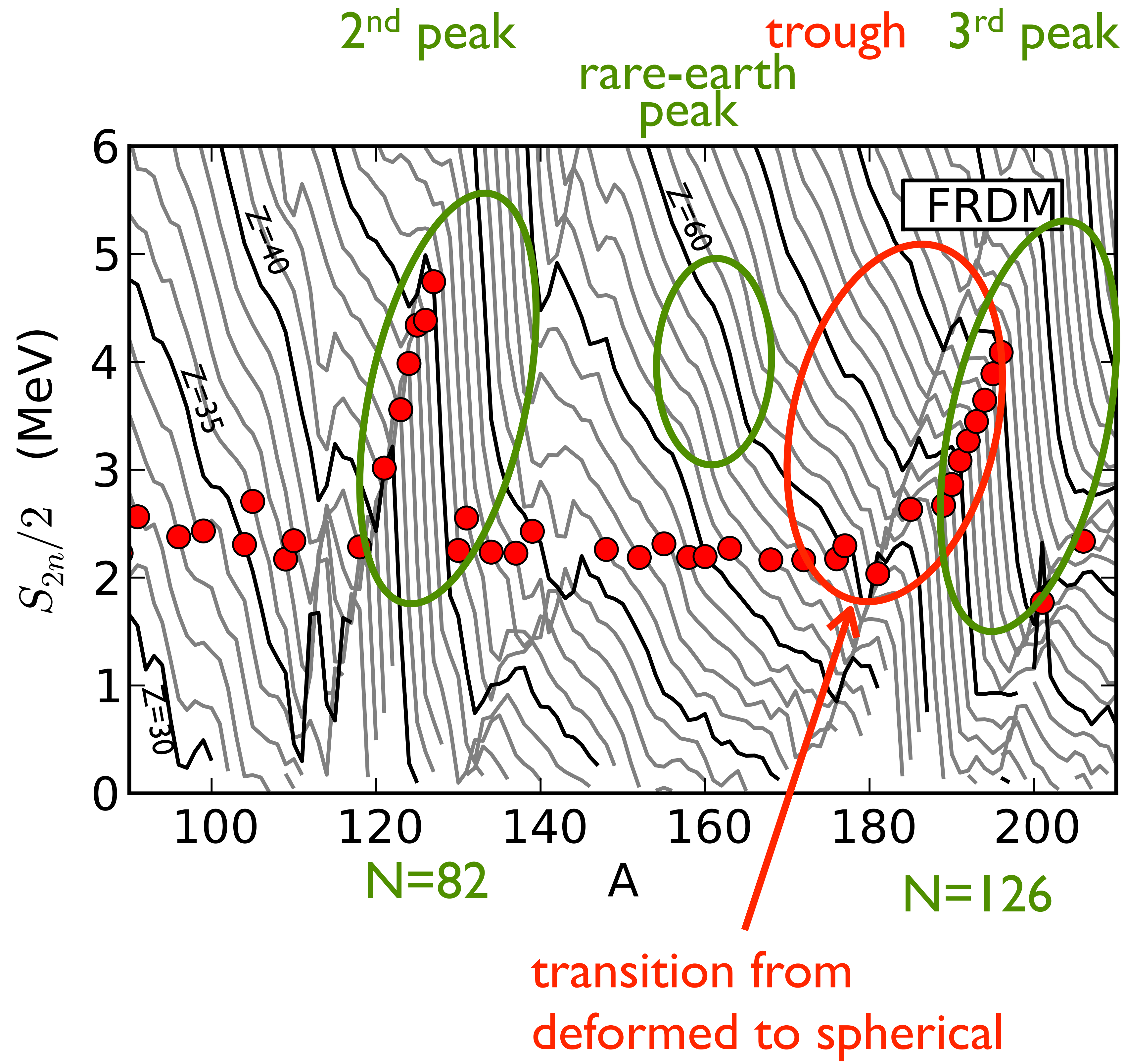


Two neutron separation energy

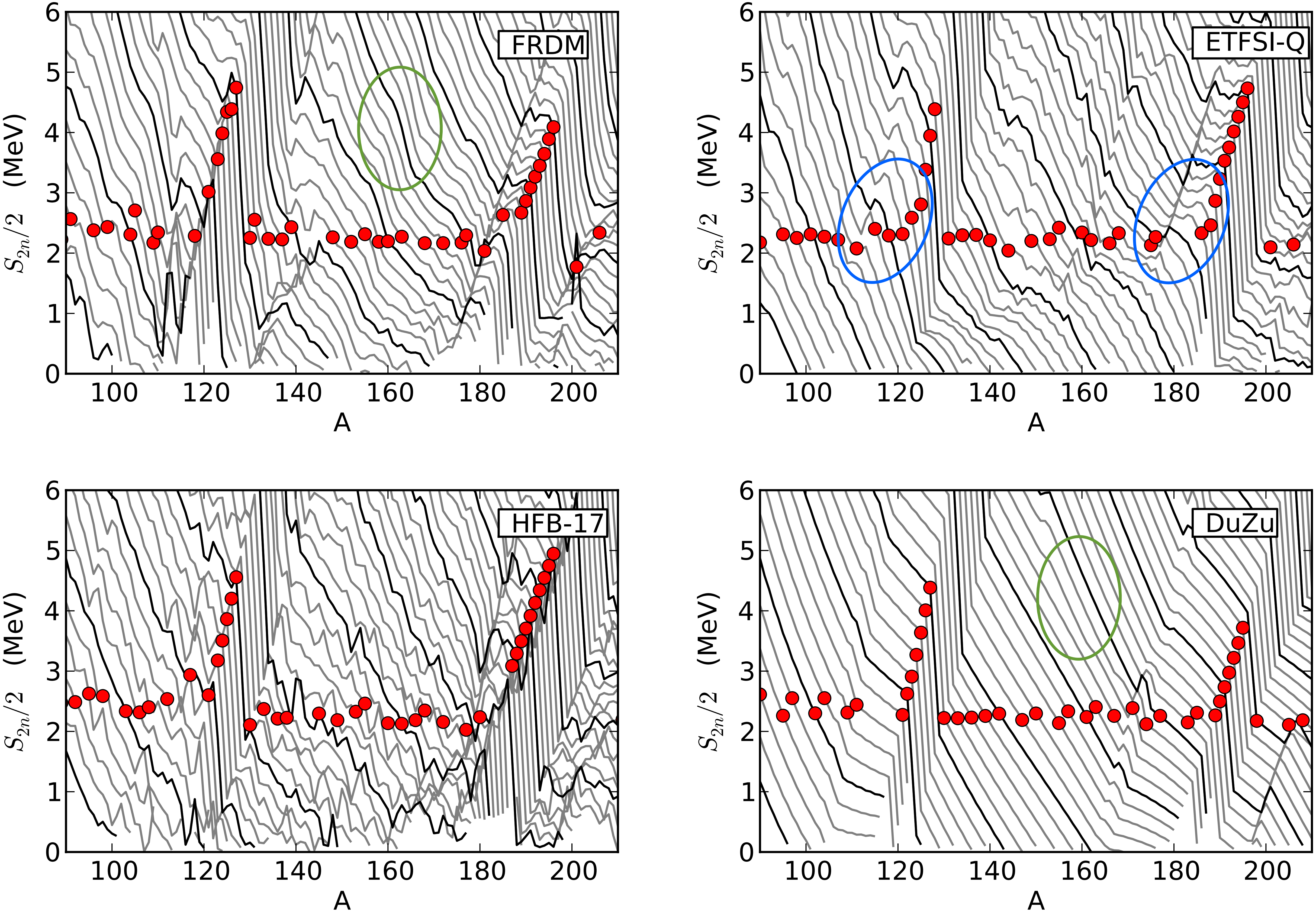
Abundances

S_{2n}

Nuclear properties



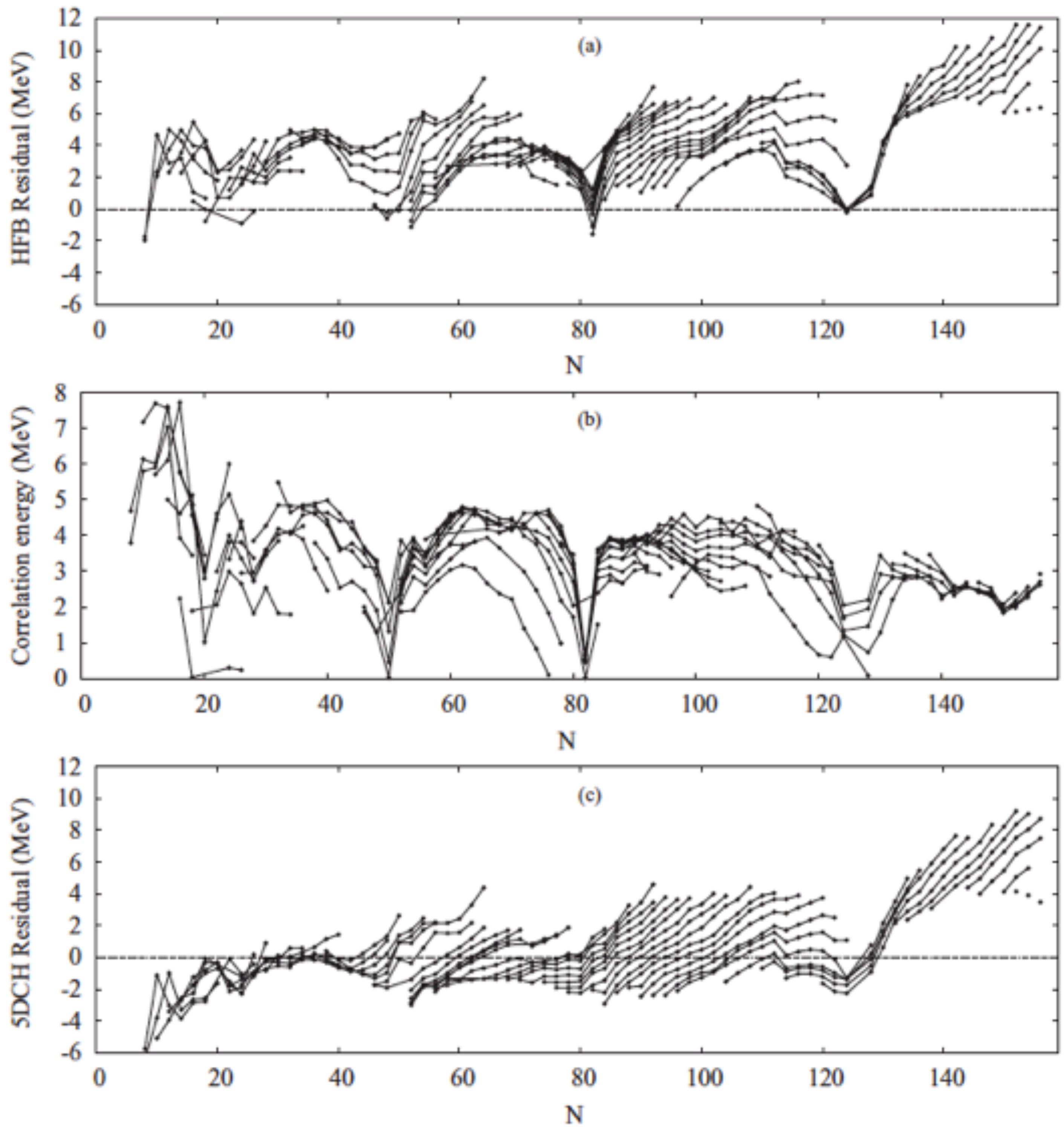
Aspects of different mass models



PHYSICAL REVIEW C **81**, 014303 (2010)

Structure of even-even nuclei using a mapped collective Hamiltonian and the D1S Gogny interaction

J.-P. Delaroche,[1,*] M. Girod,[1] J. Libert,[2] H. Goutte,[1] S. Hilaire,[1] S. Péru,[1] N. Pillet,[1] and G. F. Bertsch[3,*]
[1]*CEA, DAM, DIF, F-91297 Arpajon, France*
[2]*Institut de Physique Nucléaire IN2P3-CNRS/Université Paris-Sud, 91406 Orsay Cedex, France*
[3]*Department of Physics and Institute of Nuclear Theory, Box 351560, University of Washington Seattle, Washington 98915, USA*

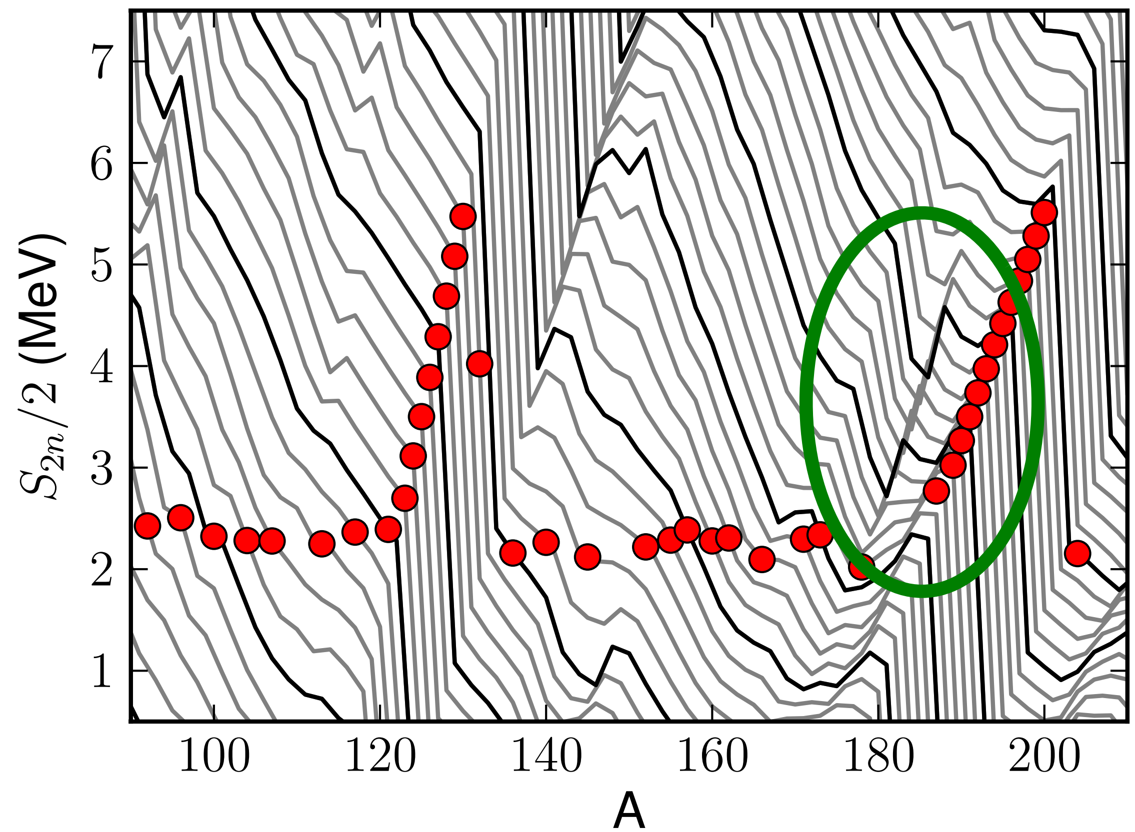


Impact of nuclear correlations on the r-process

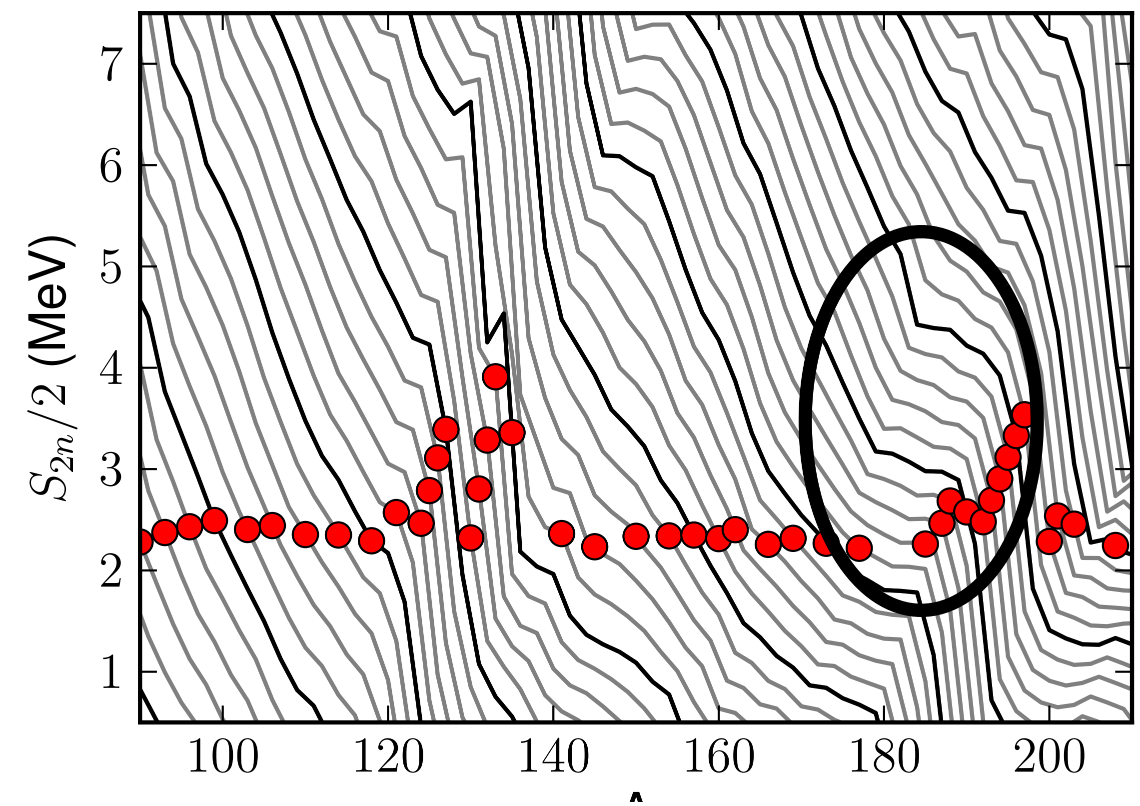
Nuclear correlations and r-process

(Arcones & Bertsch, arXiv:1111.4923)

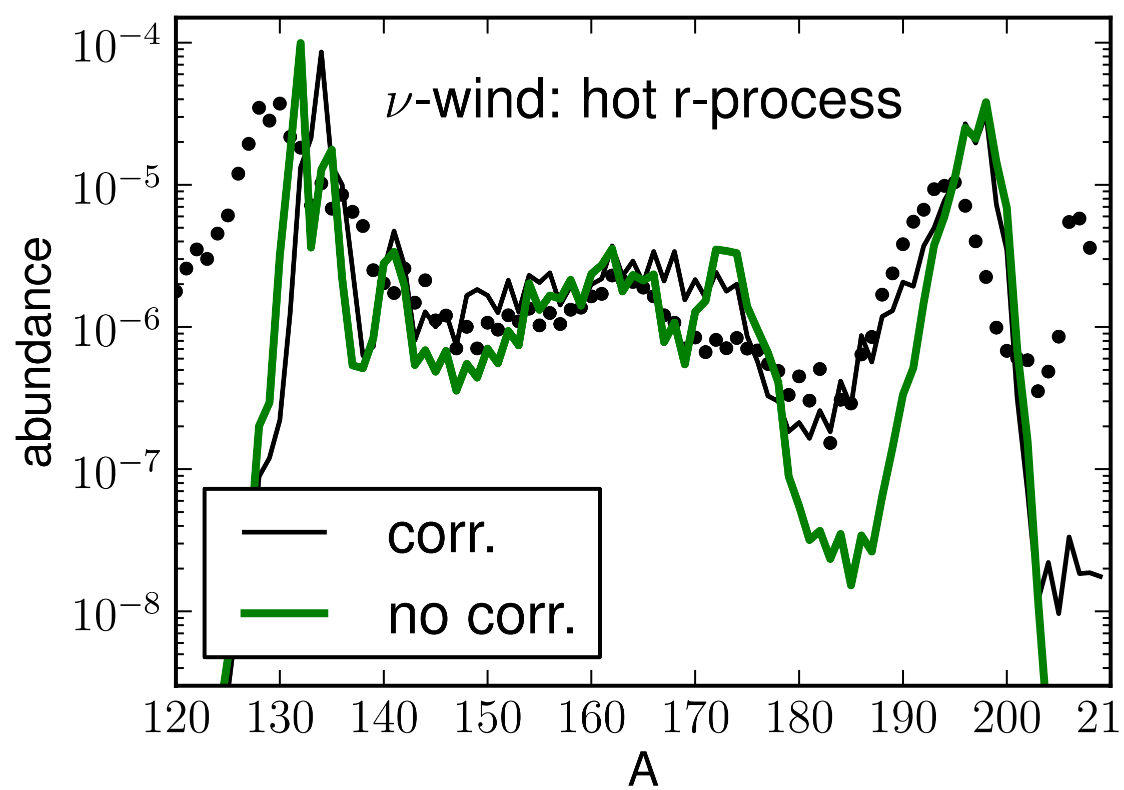
without correlations



with correlations



nuclear correlations: strong impact on trough before third peak!



Decay to stability

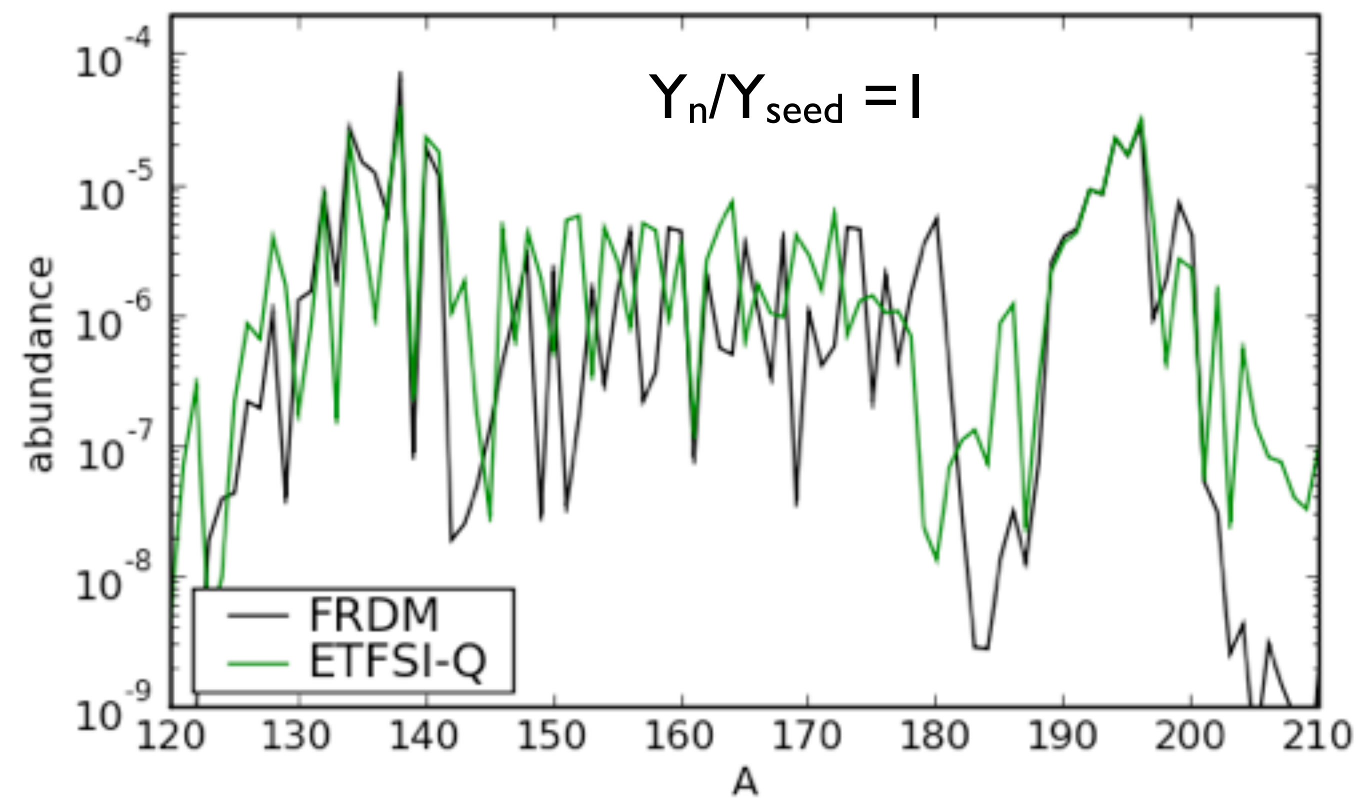
Abundances at freeze-out (Y_n/Y_{seed}=1): odd-even effects

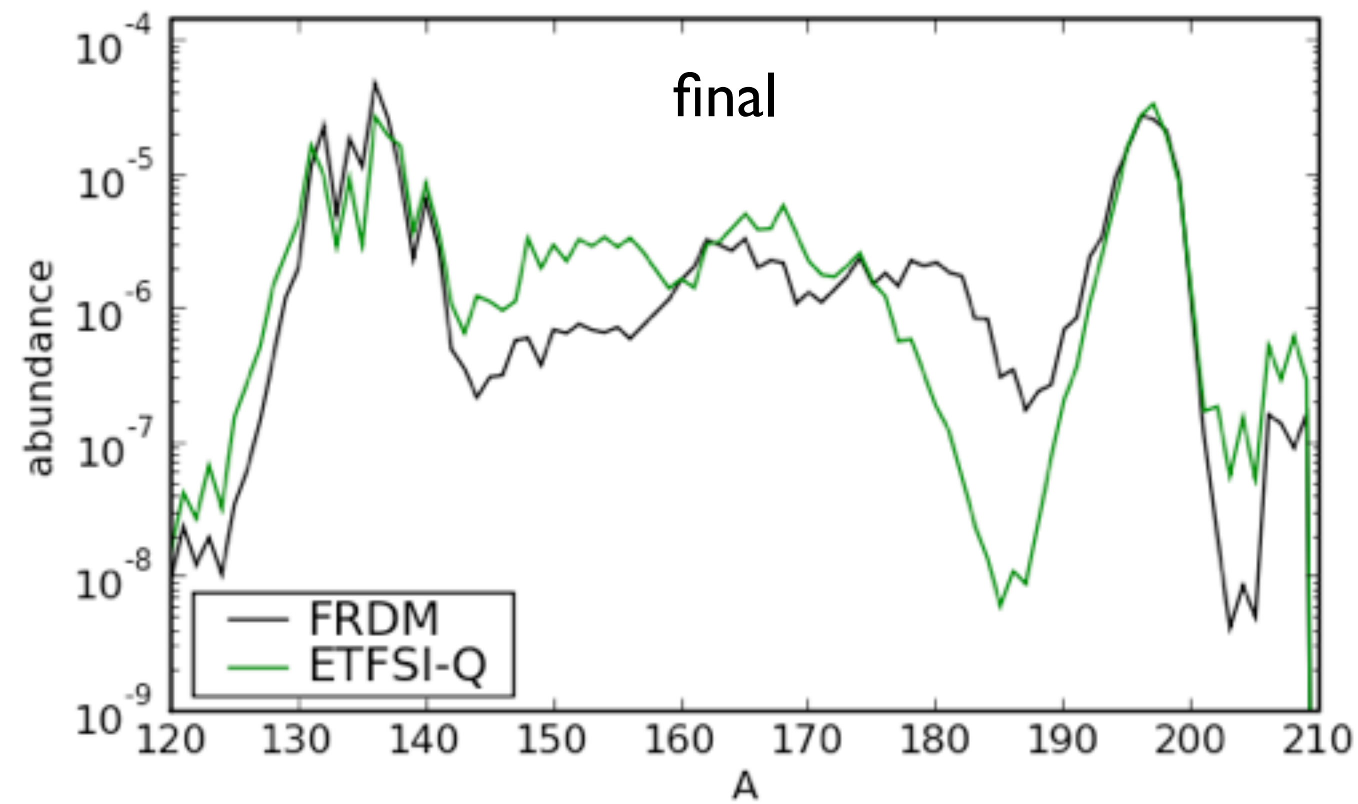
Final abundances are smoother like solar abundances.

Why does the abundance pattern change?

Classical r-process (waiting point approximation): beta-delayed neutron emission (Kodama & Takahashi 1973, Kratz et al. 1993)

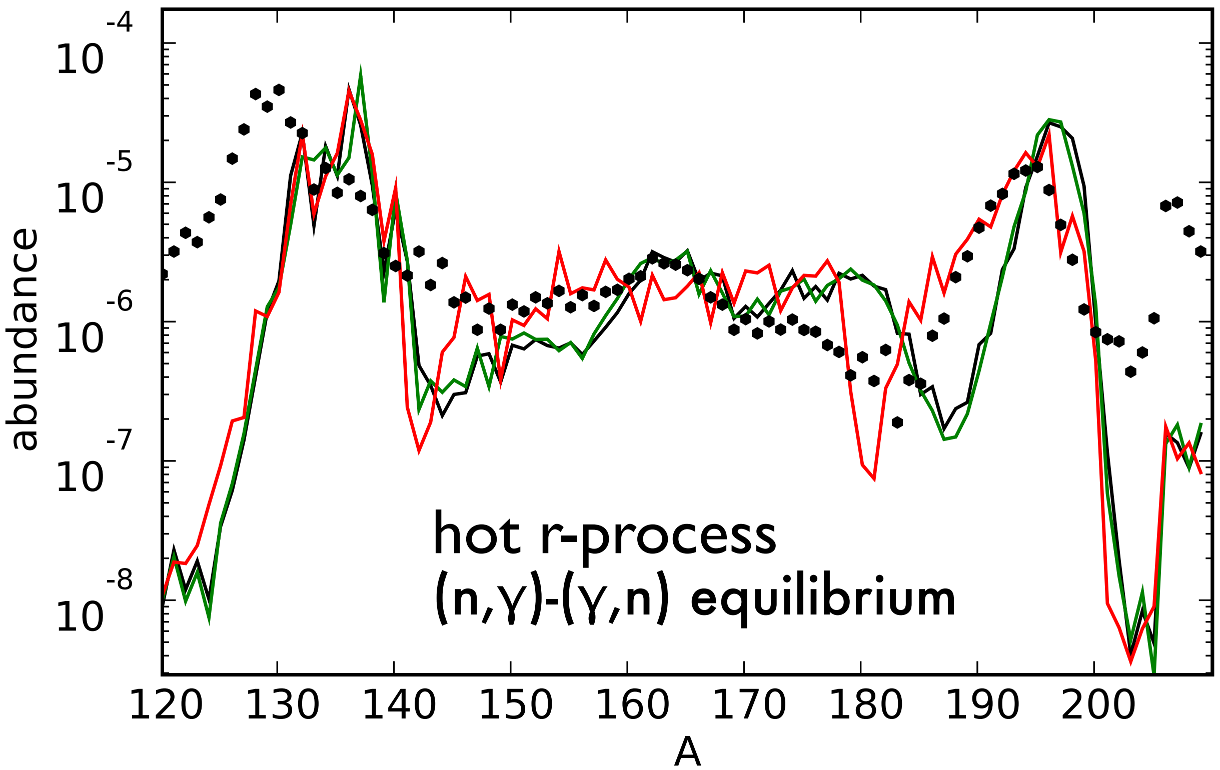
Dynamical r-process: neutron capture and beta-delayed neutron emission (Surman et al. 1997, Surman & Engel 2001, Surman et al. 2009, Buen et al. 2009)





Arcones & Martinez-Pinedo, 2011

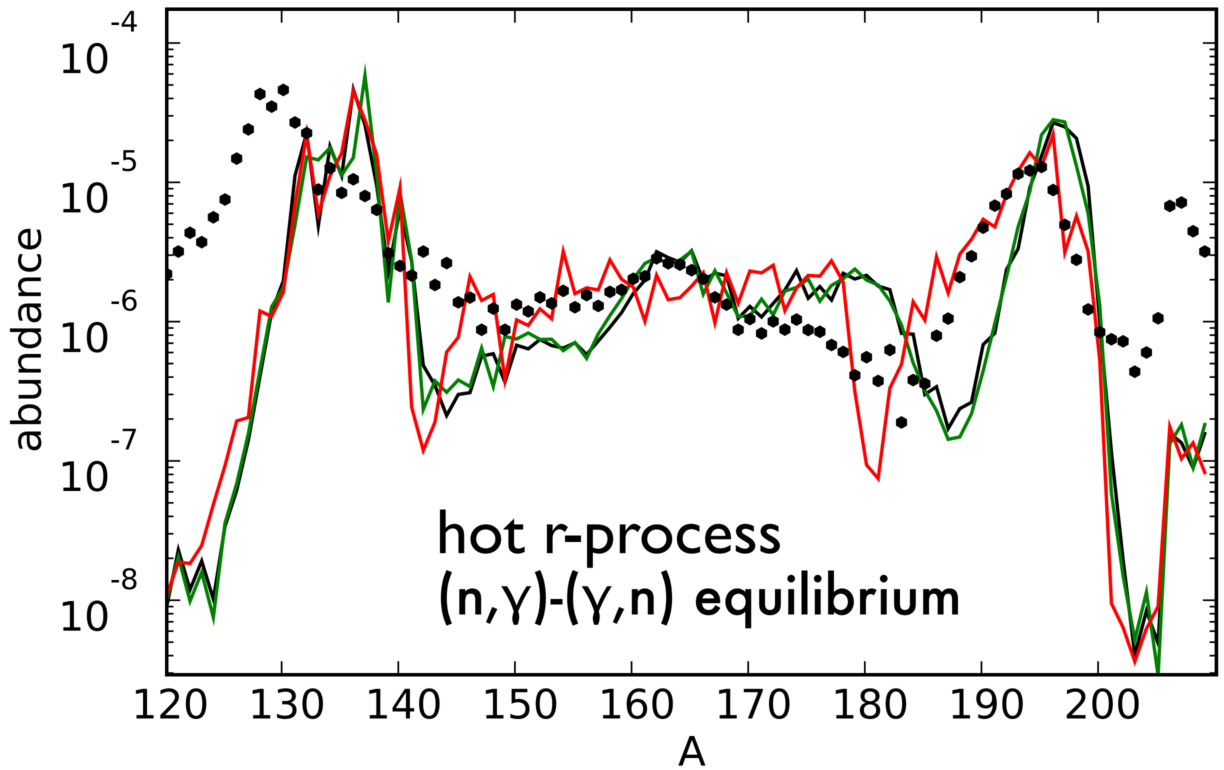
Neutron captures and beta-delayed neutron emission



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

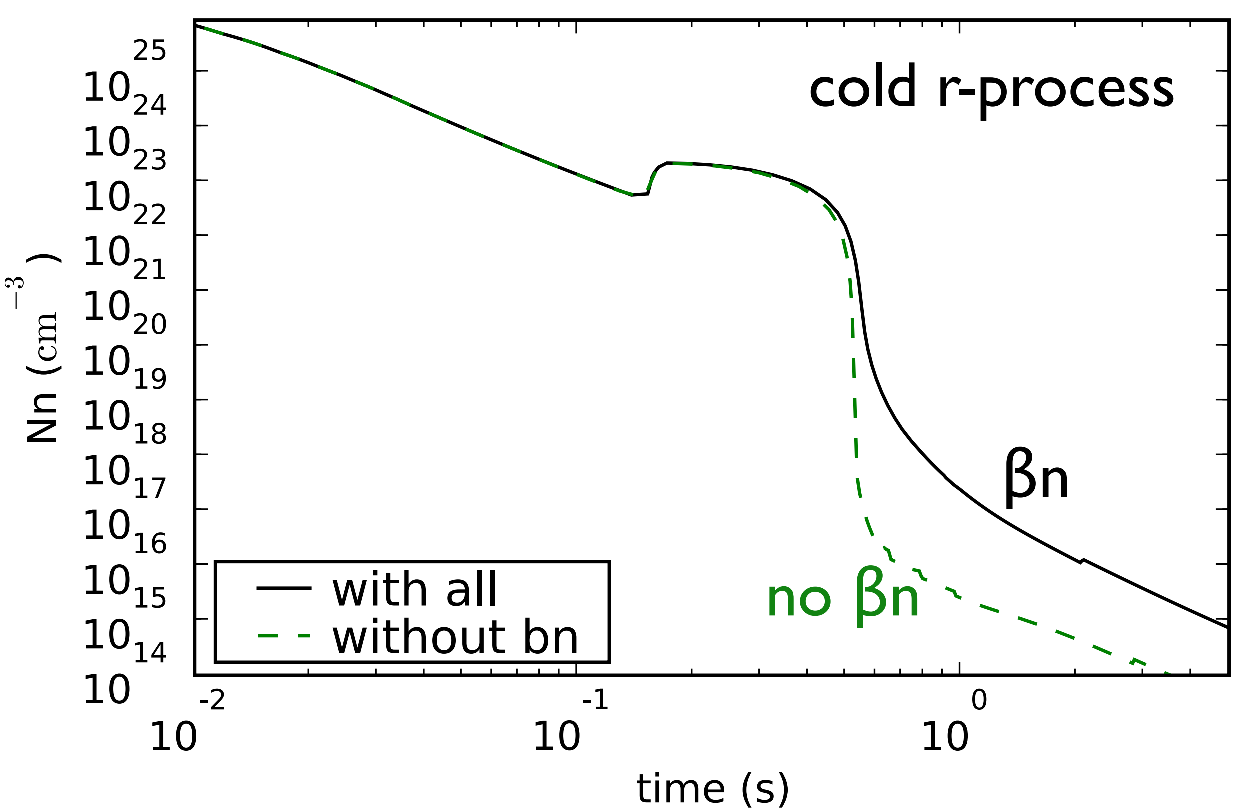
Arcones & Martinez-Pinedo, 2011

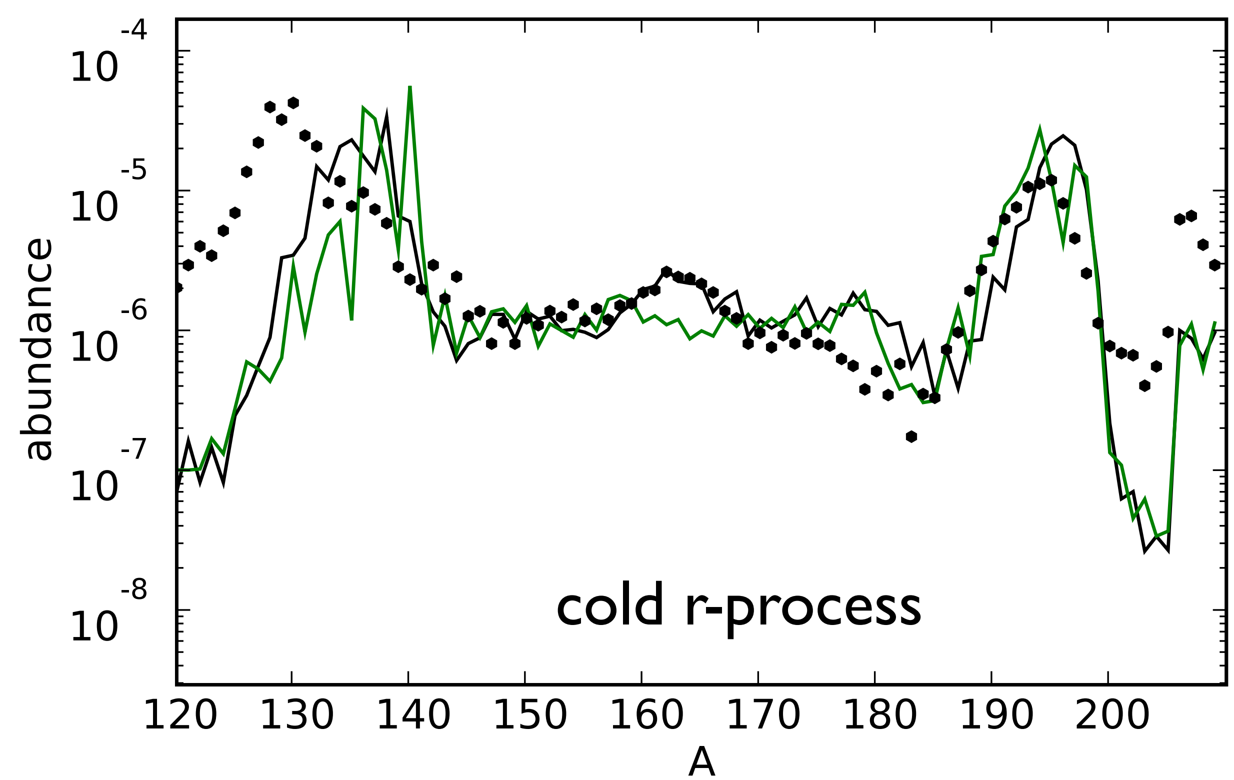
Neutron captures and beta-delayed neutron emission



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

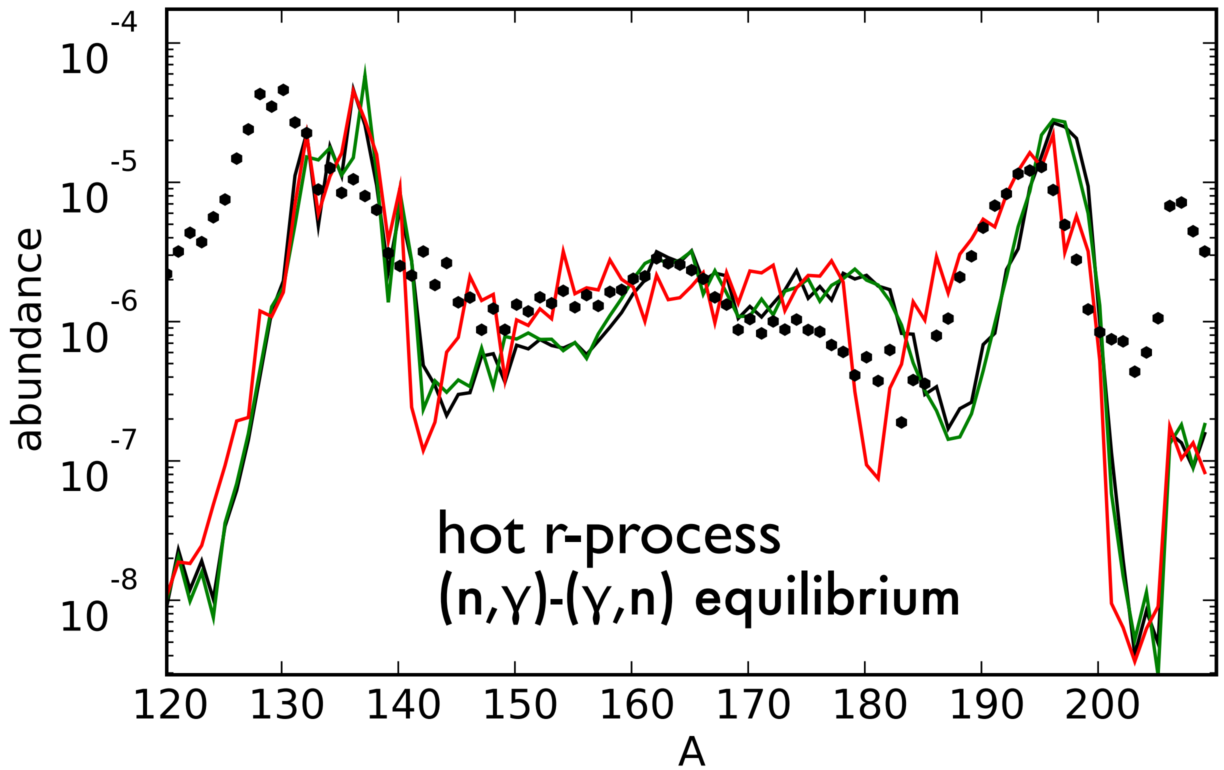
The main role of the beta-delayed neutron emission is to supply neutrons.





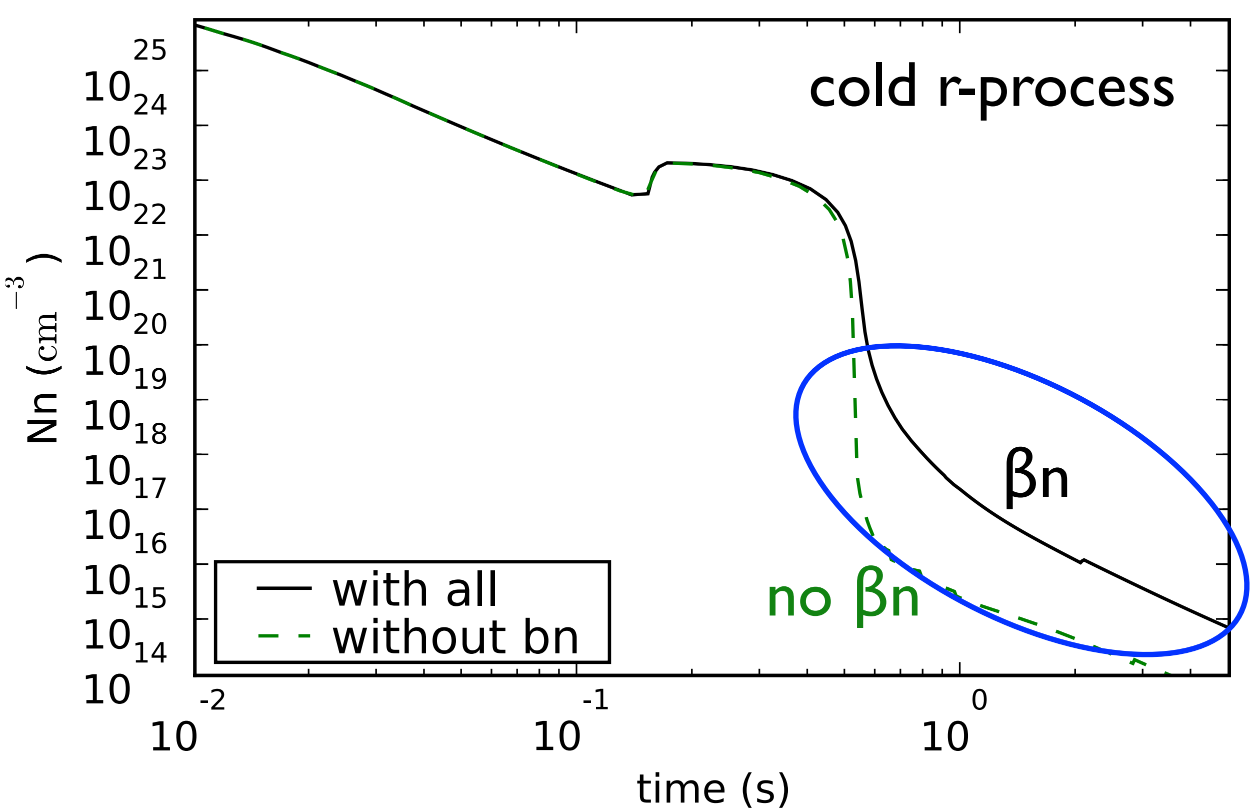
Arcones & Martinez-Pinedo, 2011

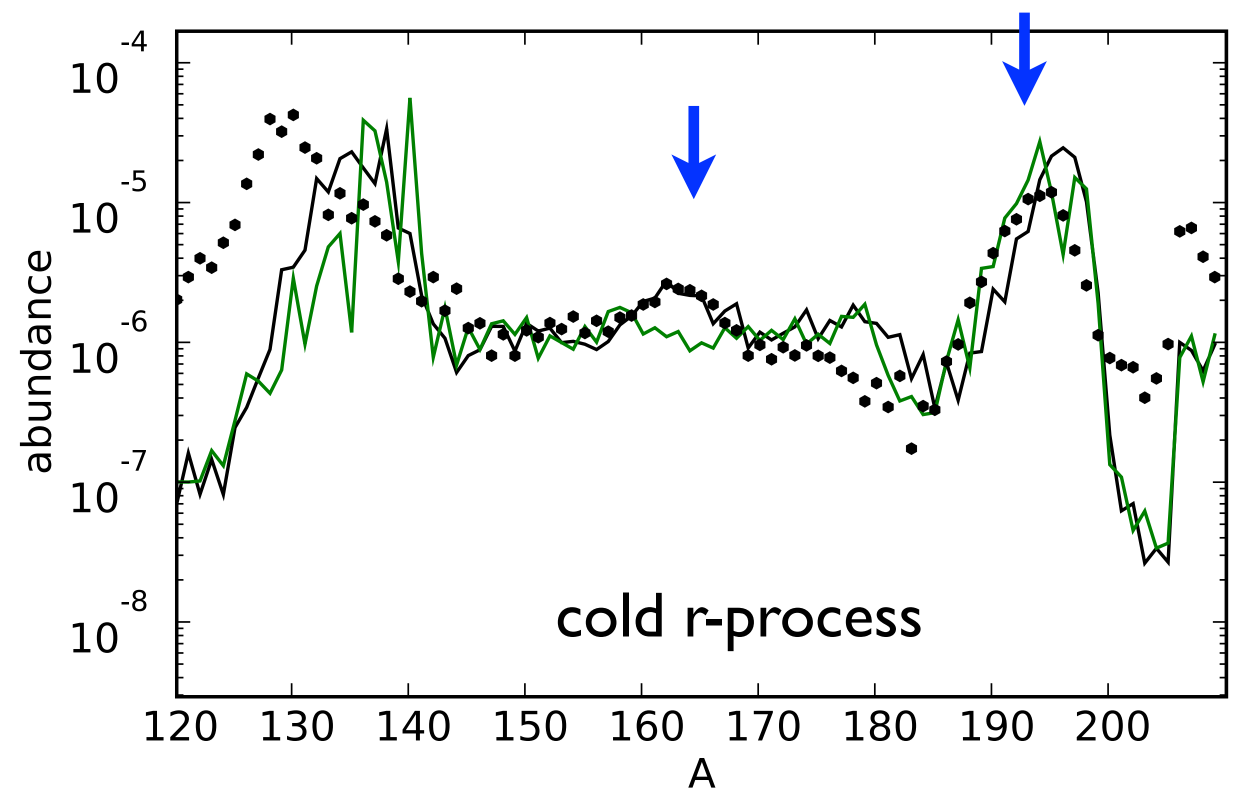
Neutron captures and beta-delayed neutron emission



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

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



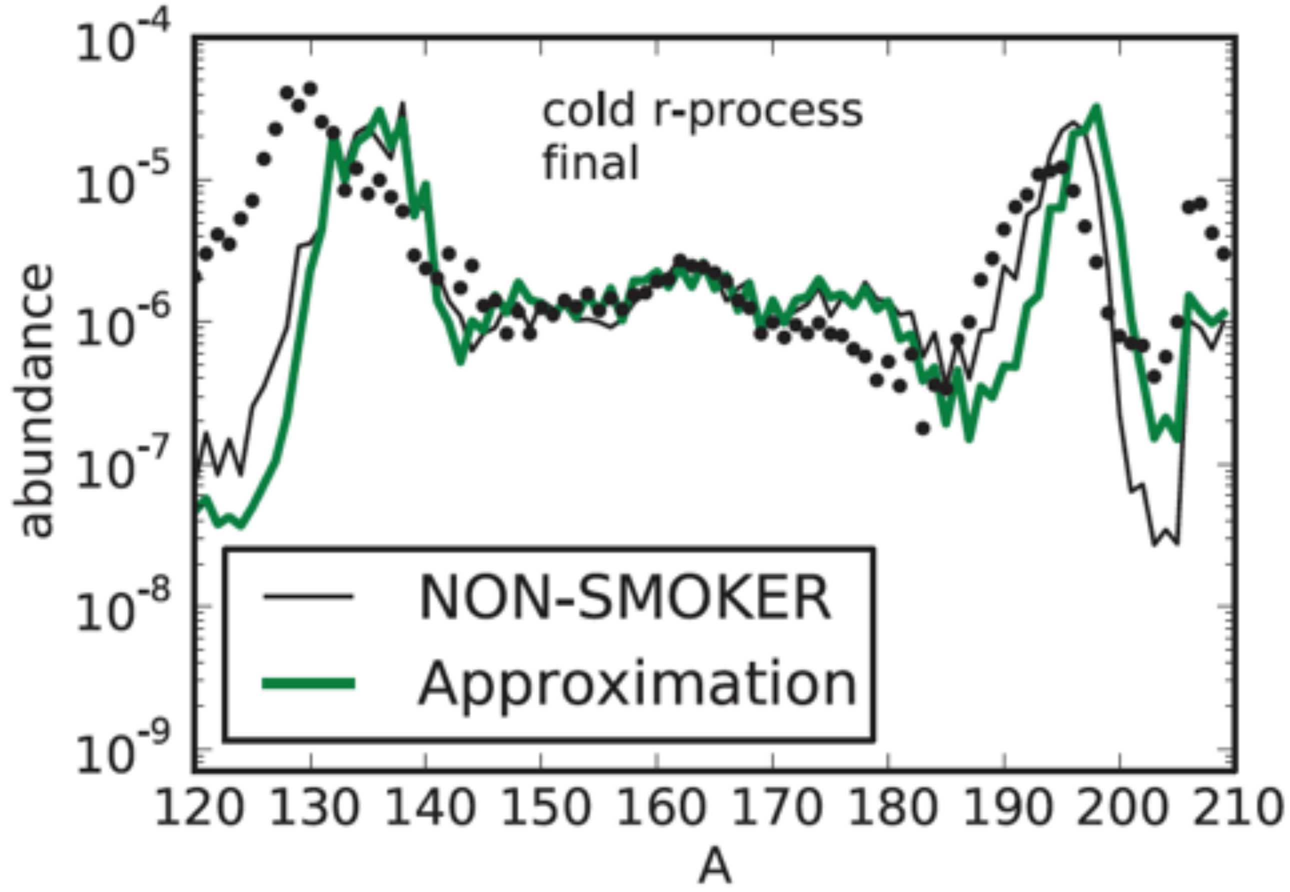


Arcones & Martinez-Pinedo, 2011

Neutron captures

Compare neutron capture calculations:

- NON-SMOKER
  (Rauscher & Thielemann, 2000)
- Approximation
  (Woosley, Fowler et al. 1975)

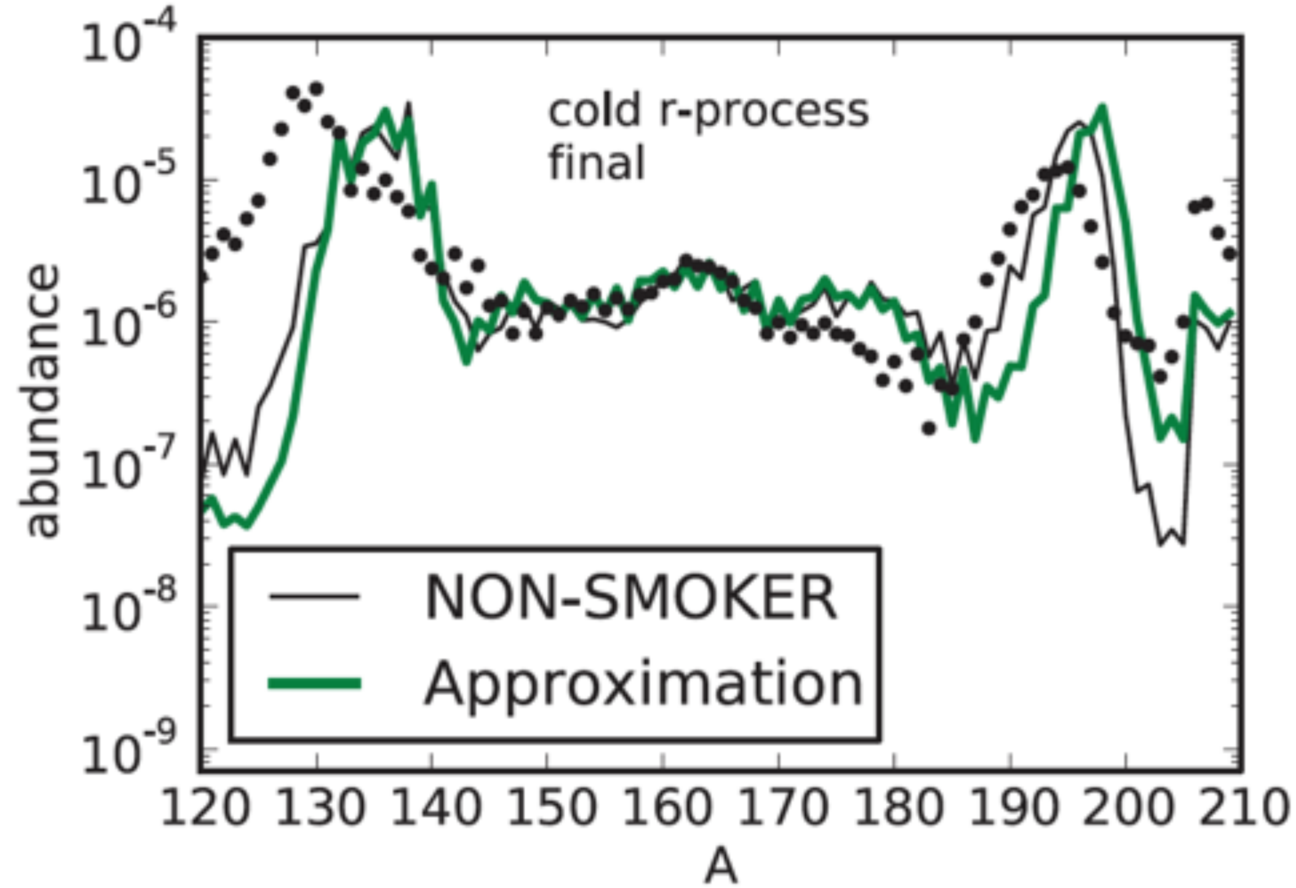


Arcones & Martinez-Pinedo, 2011

Neutron captures

Compare neutron capture calculations:

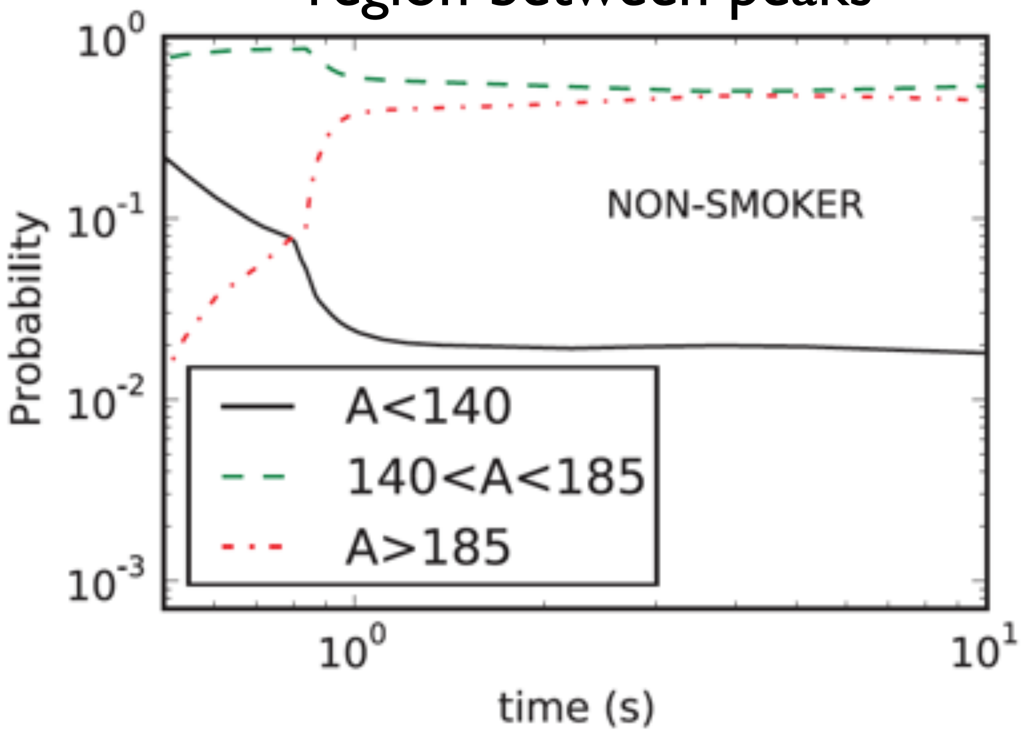
- NON-SMOKER
  (Rauscher & Thielemann, 2000)
- Approximation
  (Woosley, Fowler et al. 1975)



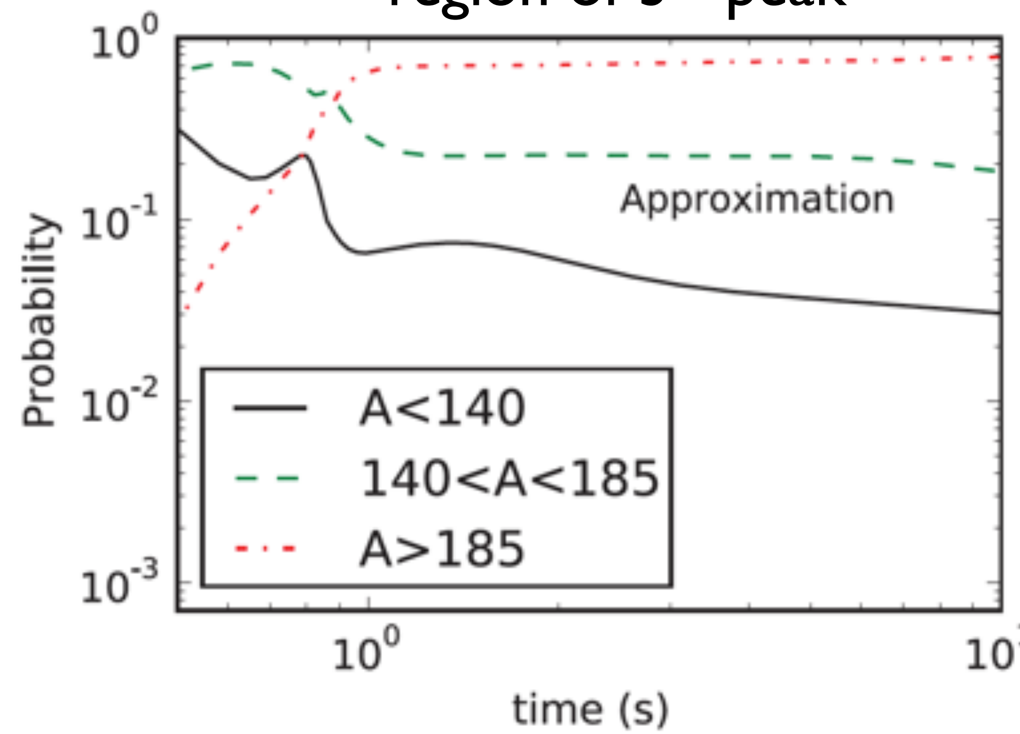
Arcones & Martinez-Pinedo, 2011

Neutron capture probability:

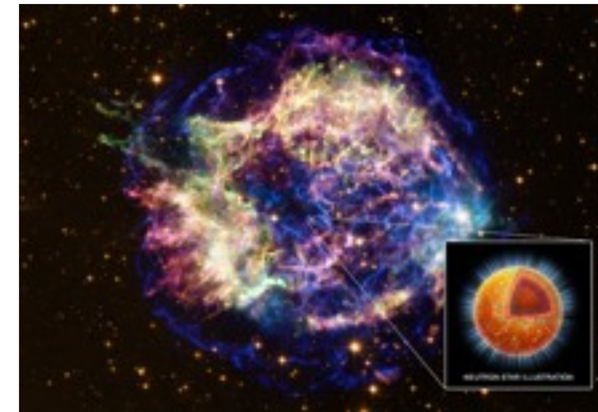
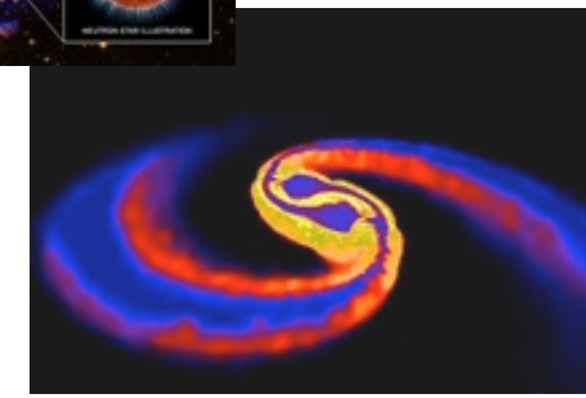
region between peaks



region of 3rd peak

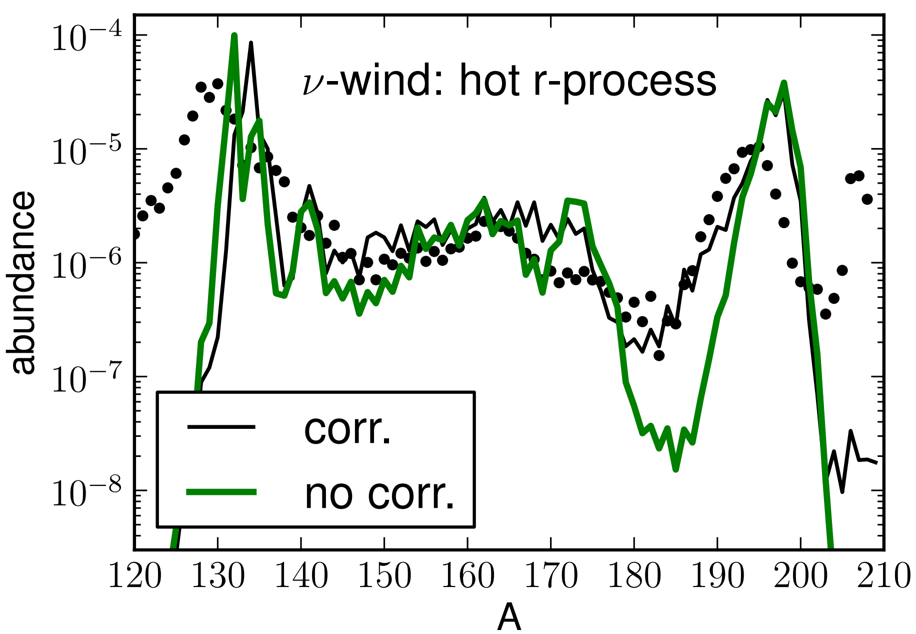


Conclusions

Where is the r-process?
Not found in recent supernova simulations

Long-time evolution and nuclear masses have big impact



Nuclear correlations:
masses in transition regions
from deformed to spherical
→ trough before 3rd peak

Decay to stability: beta-delayed neutron emission and neutron captures still change the abundances