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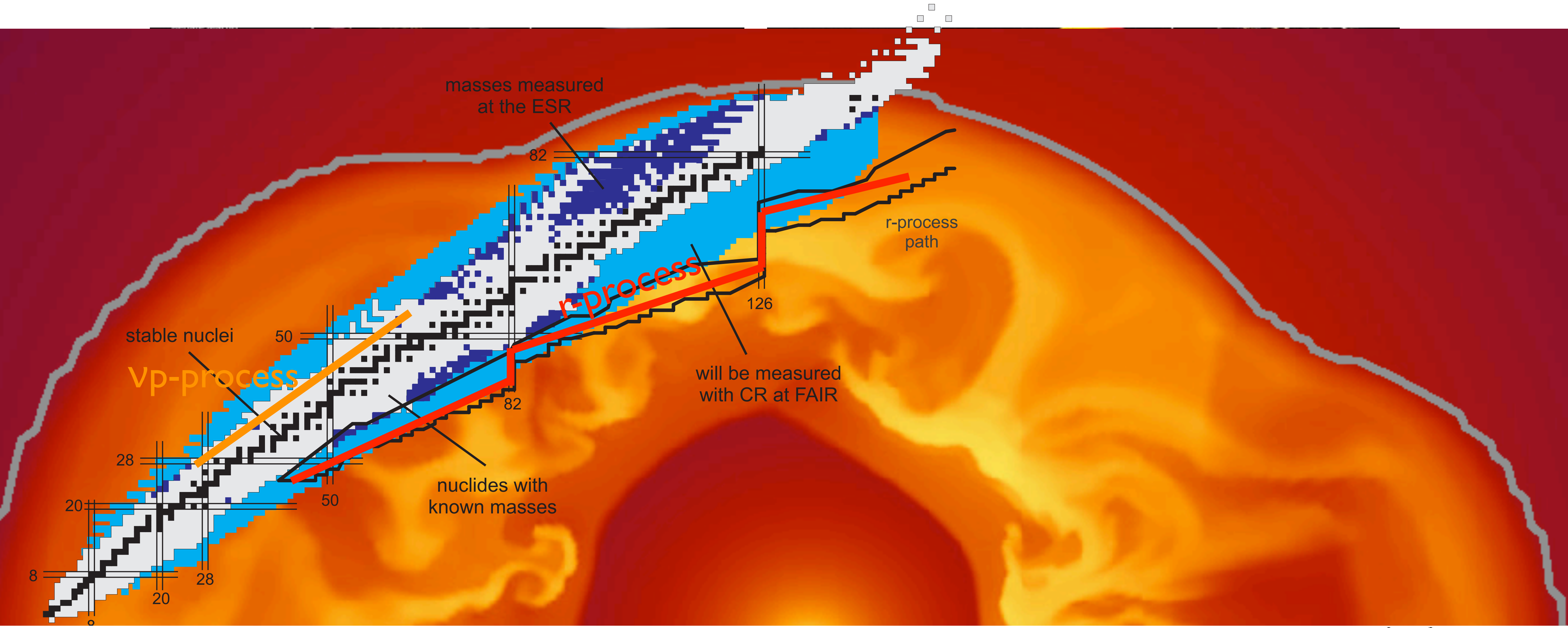
EMMI Physics Days 2011

Nucleosynthesis beyond iron in core-collapse supernovae



Almudena Arcones
Feodor Lynen Fellow, Basel University

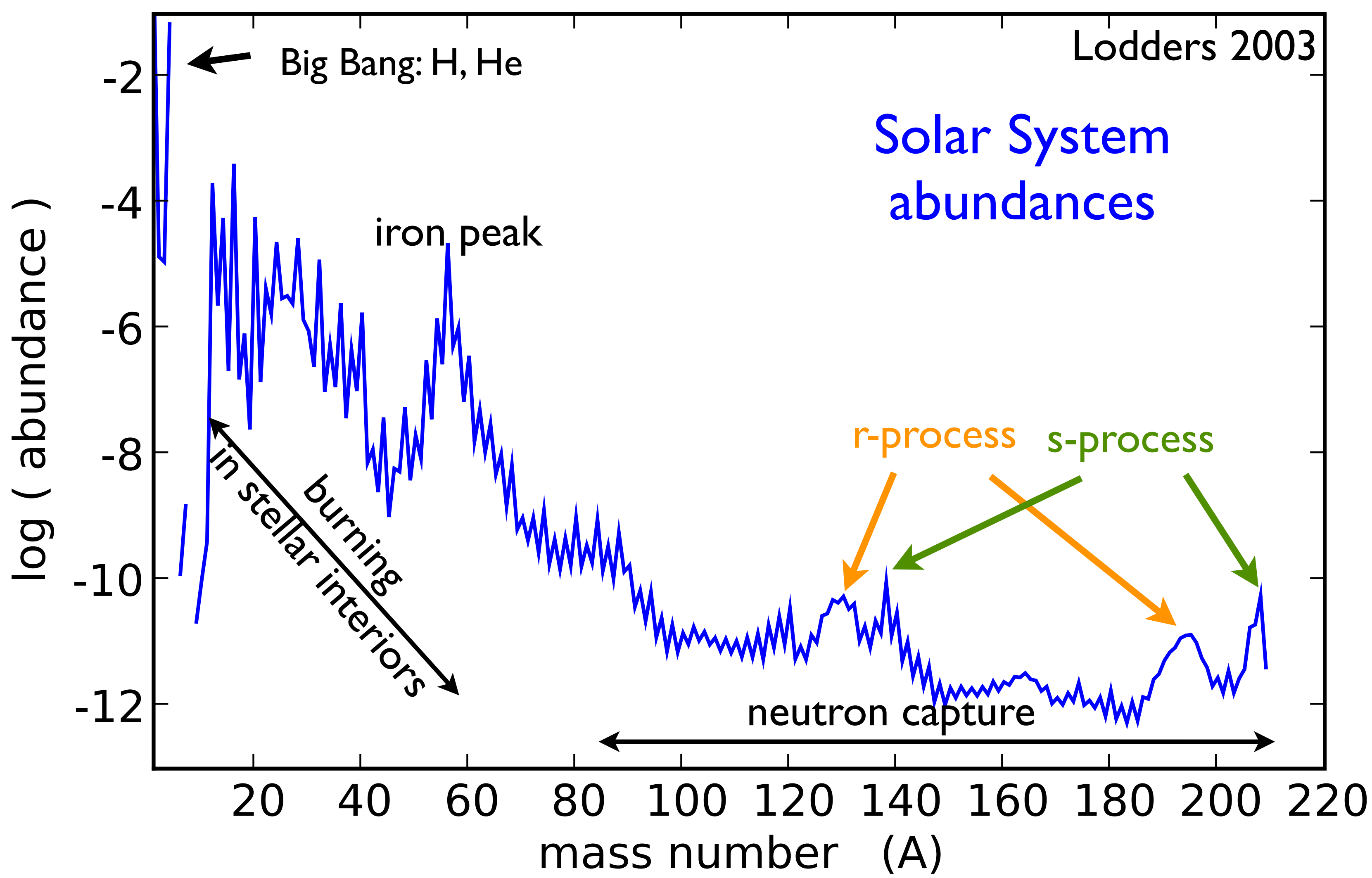
Alexander von Humboldt
Stiftung/Foundation

UNI
BASEL

Nucleosynthesis beyond iron

Solar photosphere and meteorites: chemical signature of the gas cloud where the Sun formed.

Contribution of all nucleosynthesis processes.

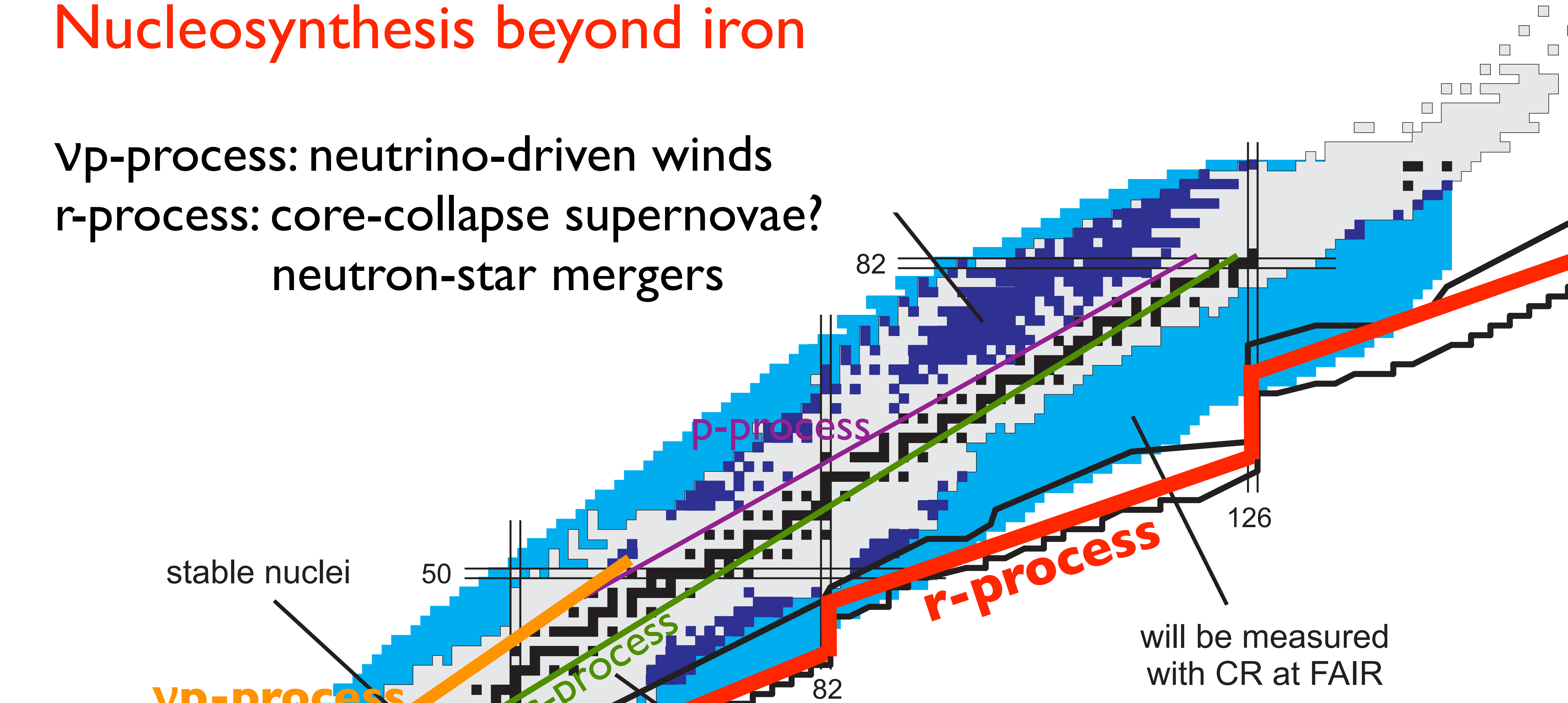


s-process: slow neutron capture in stellar envelopes.

r-process: rapid neutron capture in core-collapse supernovae and neutron star mergers.

Nucleosynthesis beyond iron

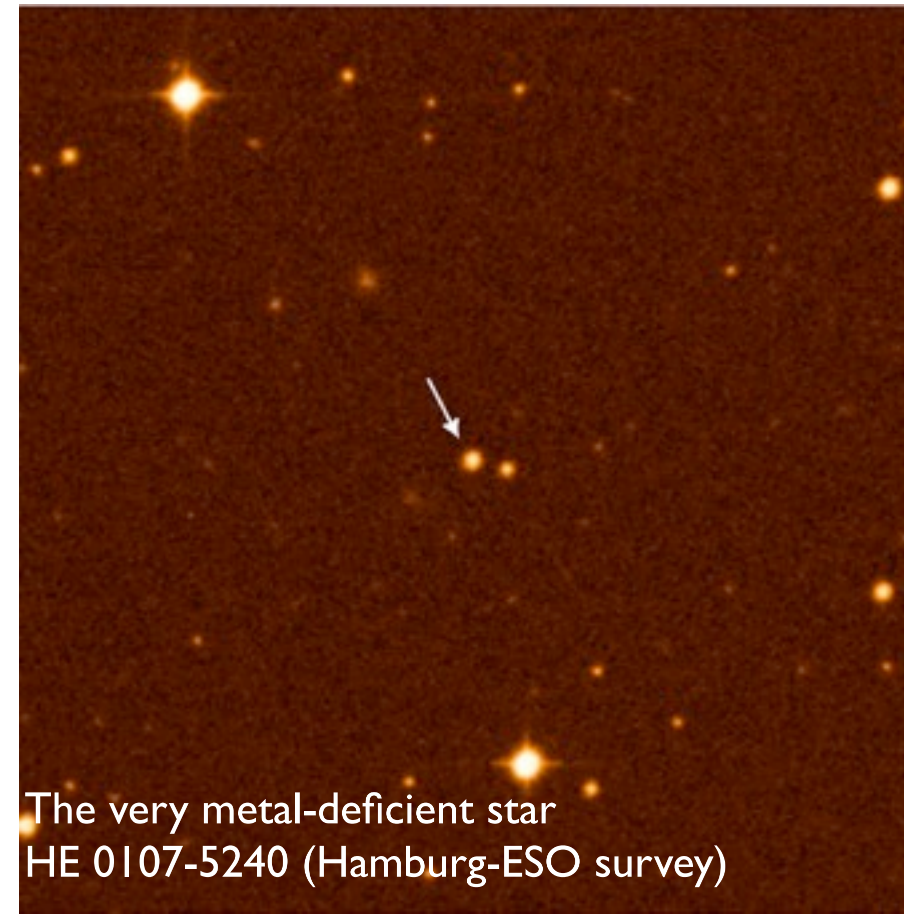
νp-process: neutrino-driven winds
r-process: core-collapse supernovae?
neutron-star mergers

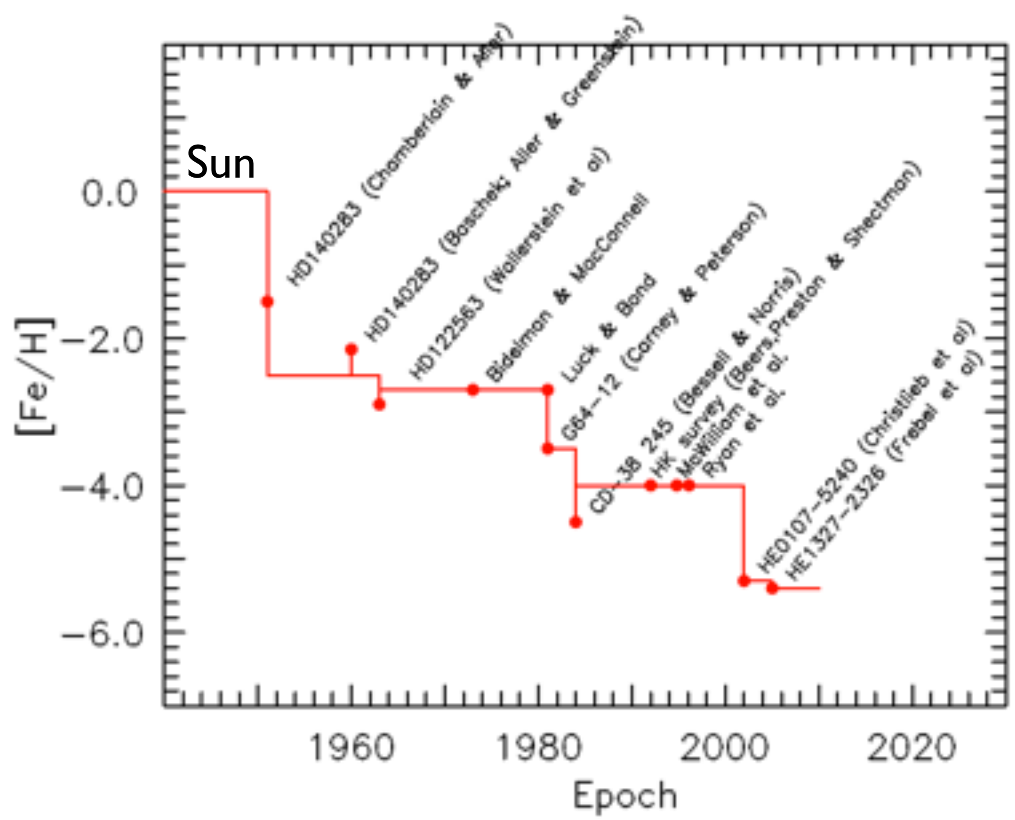


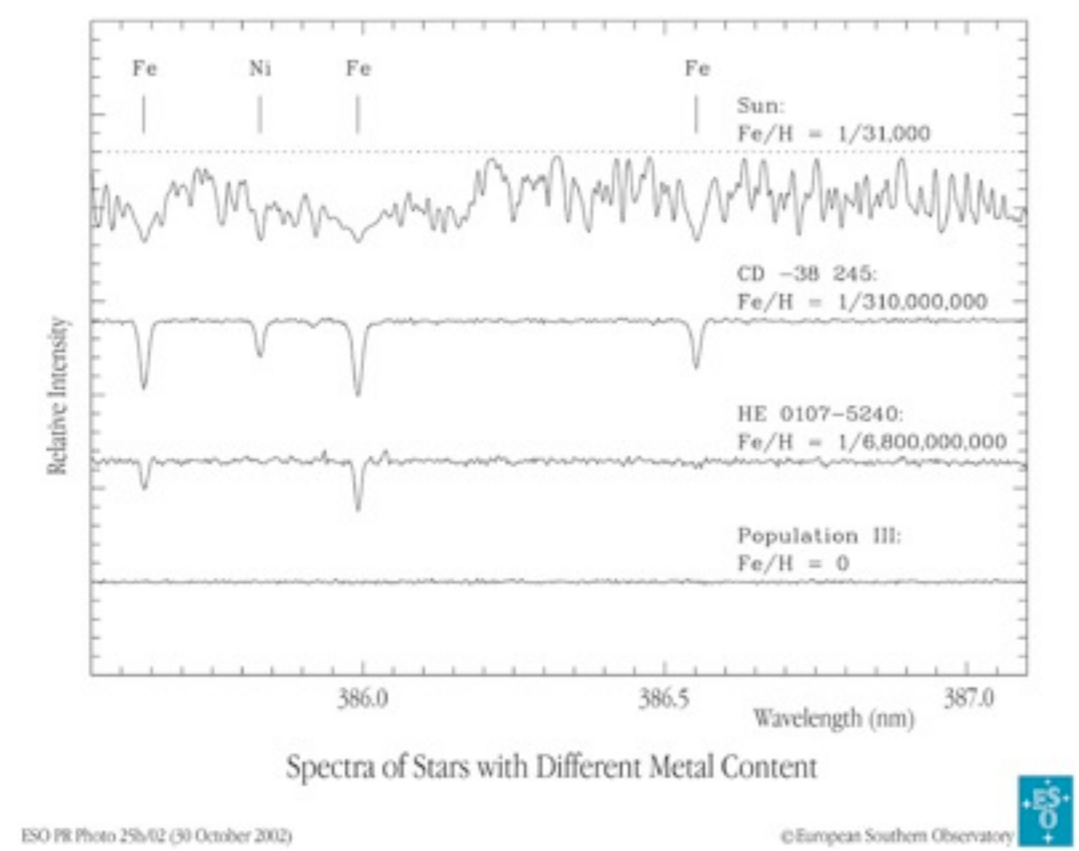
Ultra metal-poor stars = very old stars

- First generation of stars only H and He
- Next generations: enriched with metals,

  ultra metal-poor stars
- Their atmospheres show fingerprint of only few nucleosynthesis events that enriched the interstellar medium.
- Metal-poor stars are very rare, large-scale surveys and new large telescopes are providing new insights in the origin of elements!


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



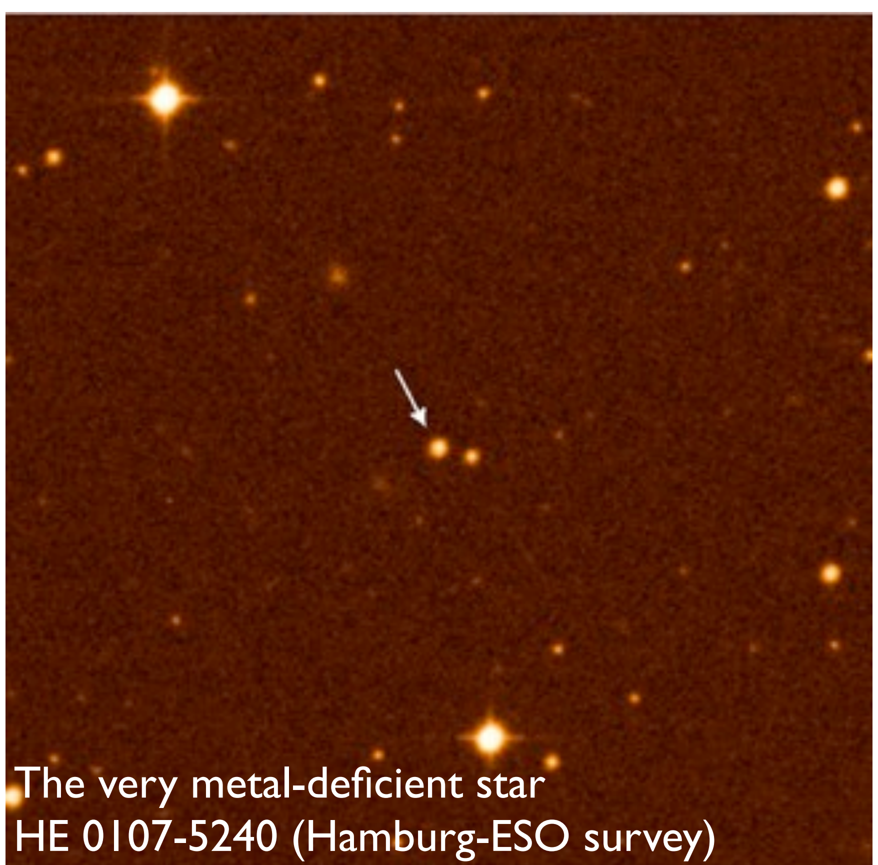


Ultra metal-poor stars

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

Robust r-process for 56<Z<83

Scatter for lighter heavy elements, Z~40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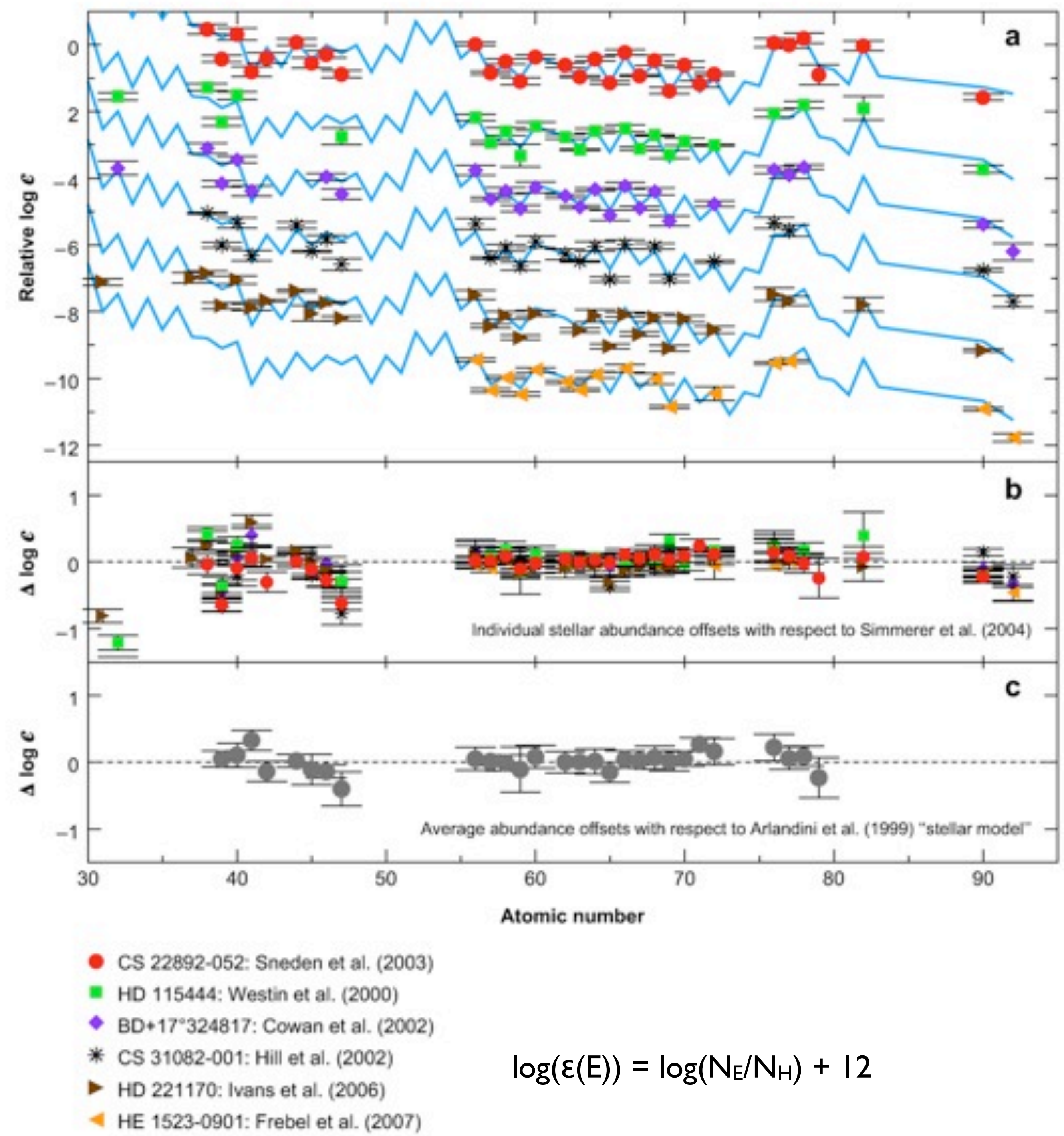
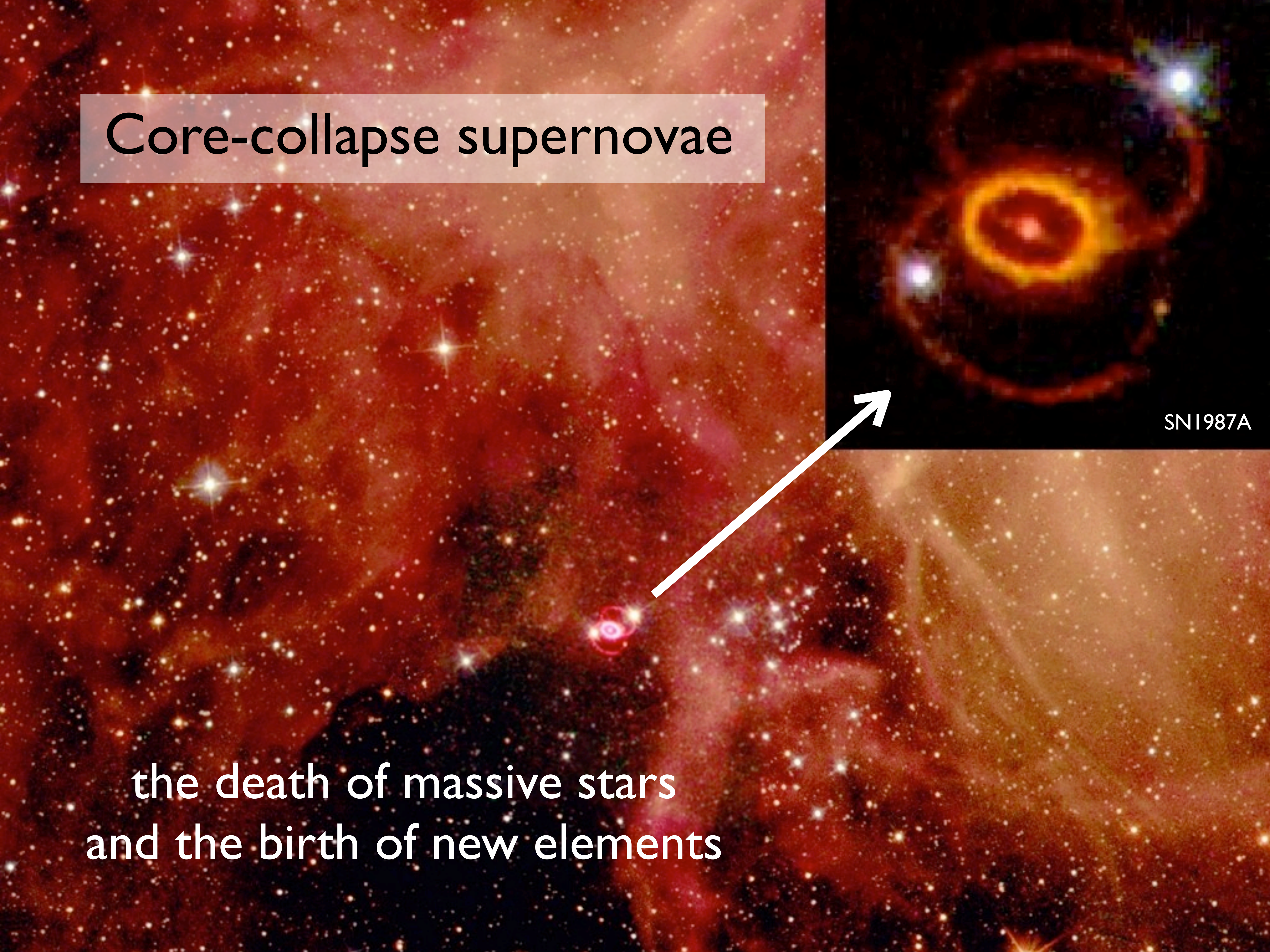


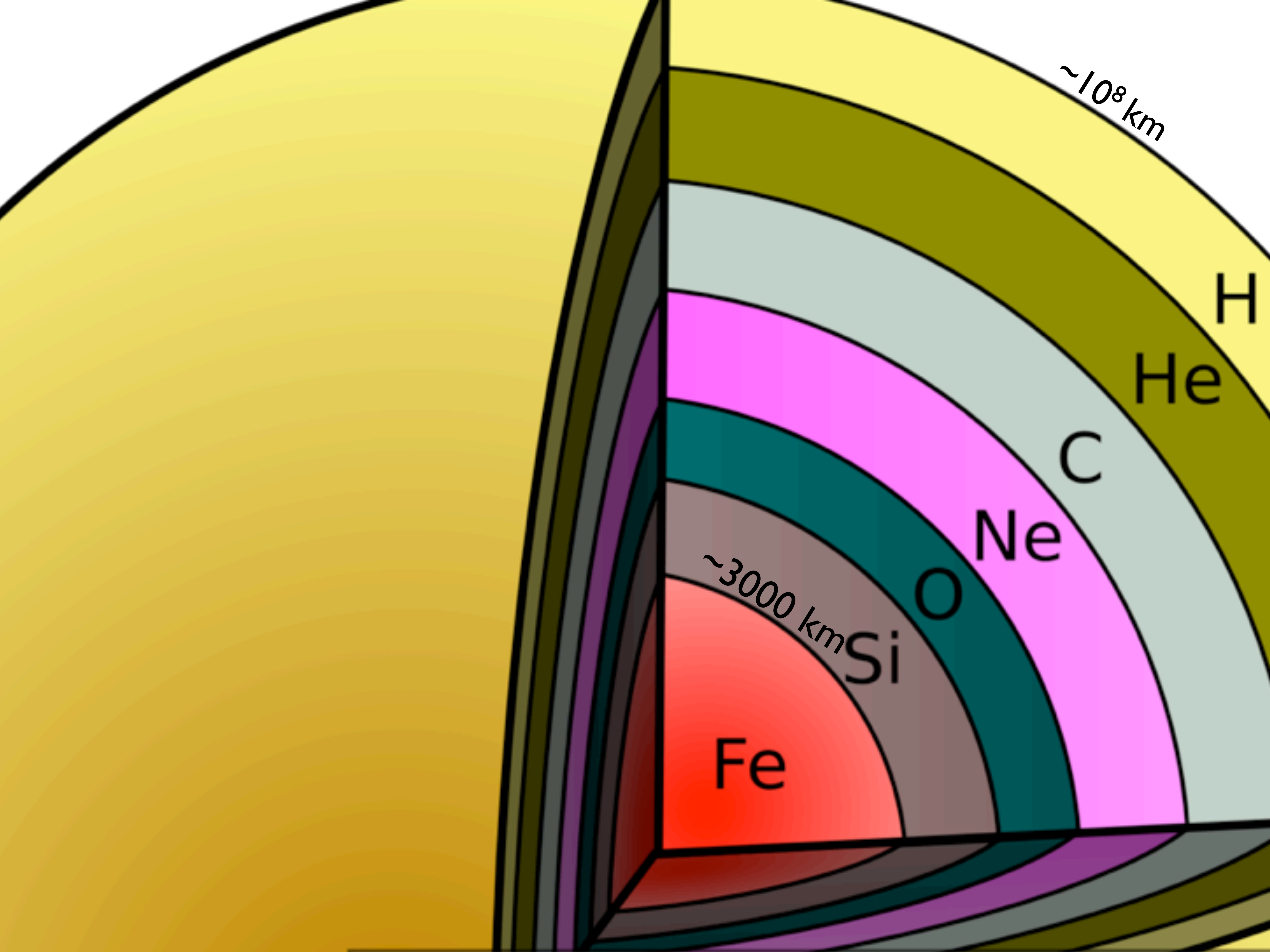
$\log(\varepsilon(E)) = \log(N_E/N_H) + 12$

Sneden, Cowan, Gallino 2008

Core-collapse supernovae

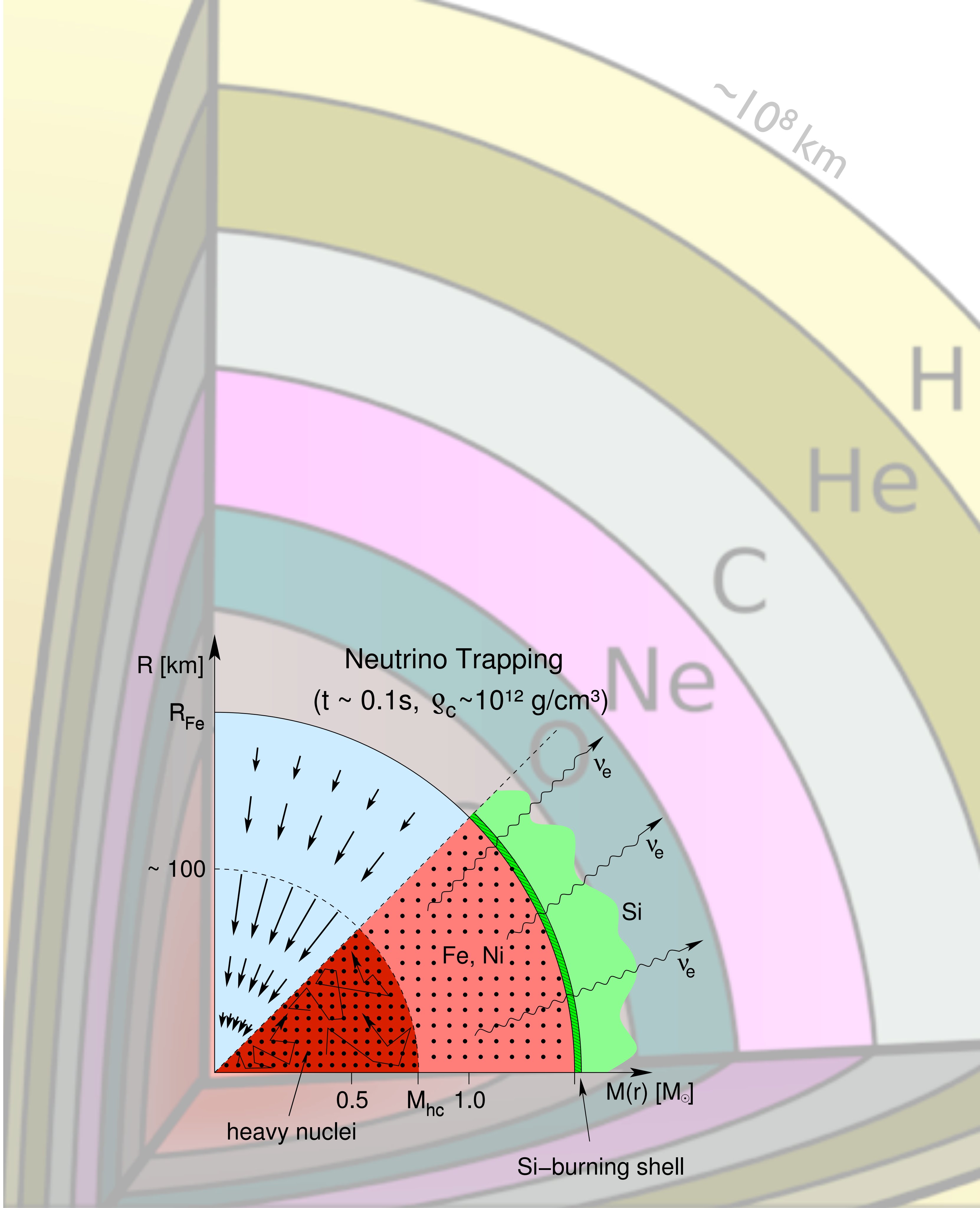


the death of massive stars
and the birth of new elements

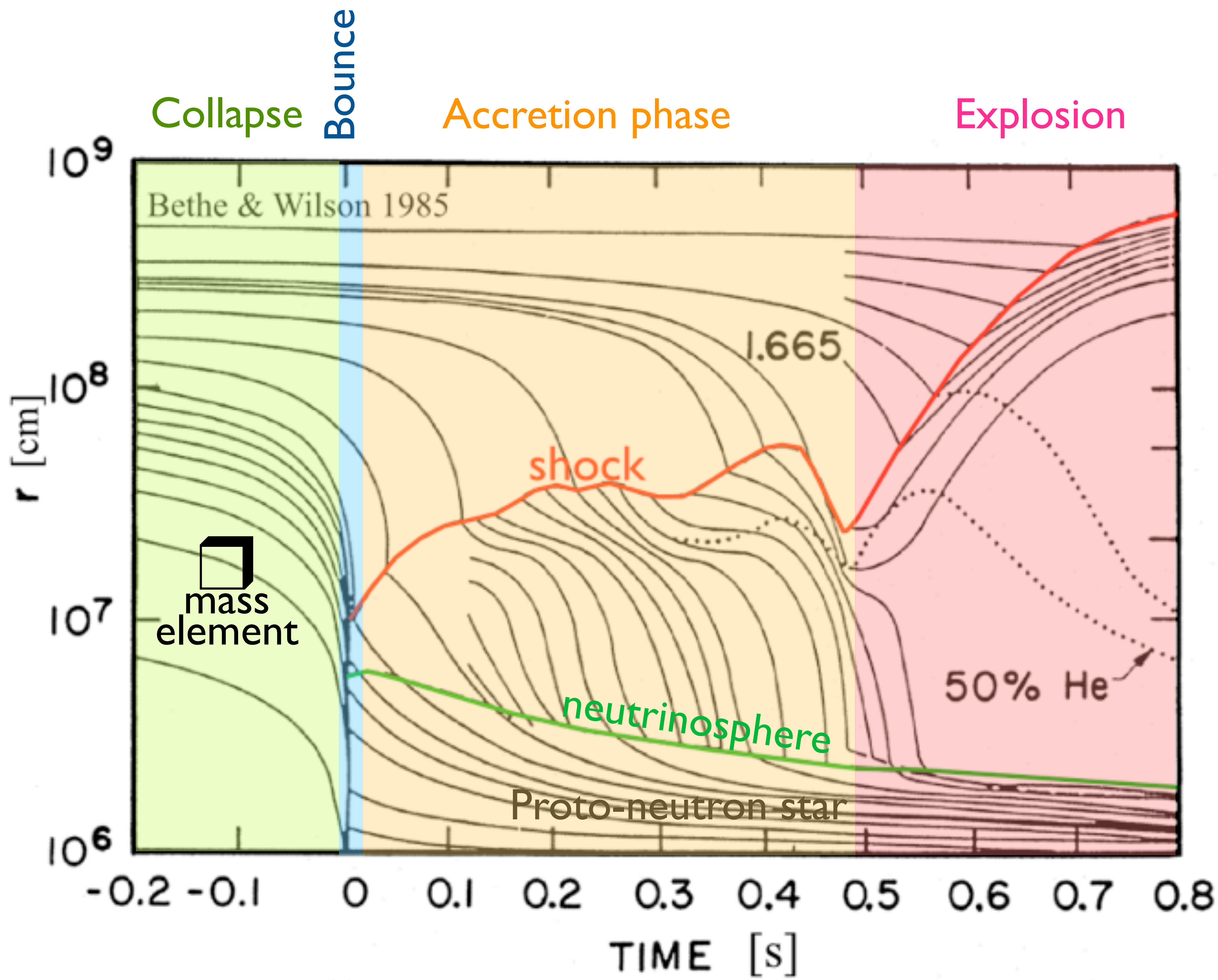

~10^8 km
H
He
C
Ne
O
~3000 km
Si
Fe

Collapse

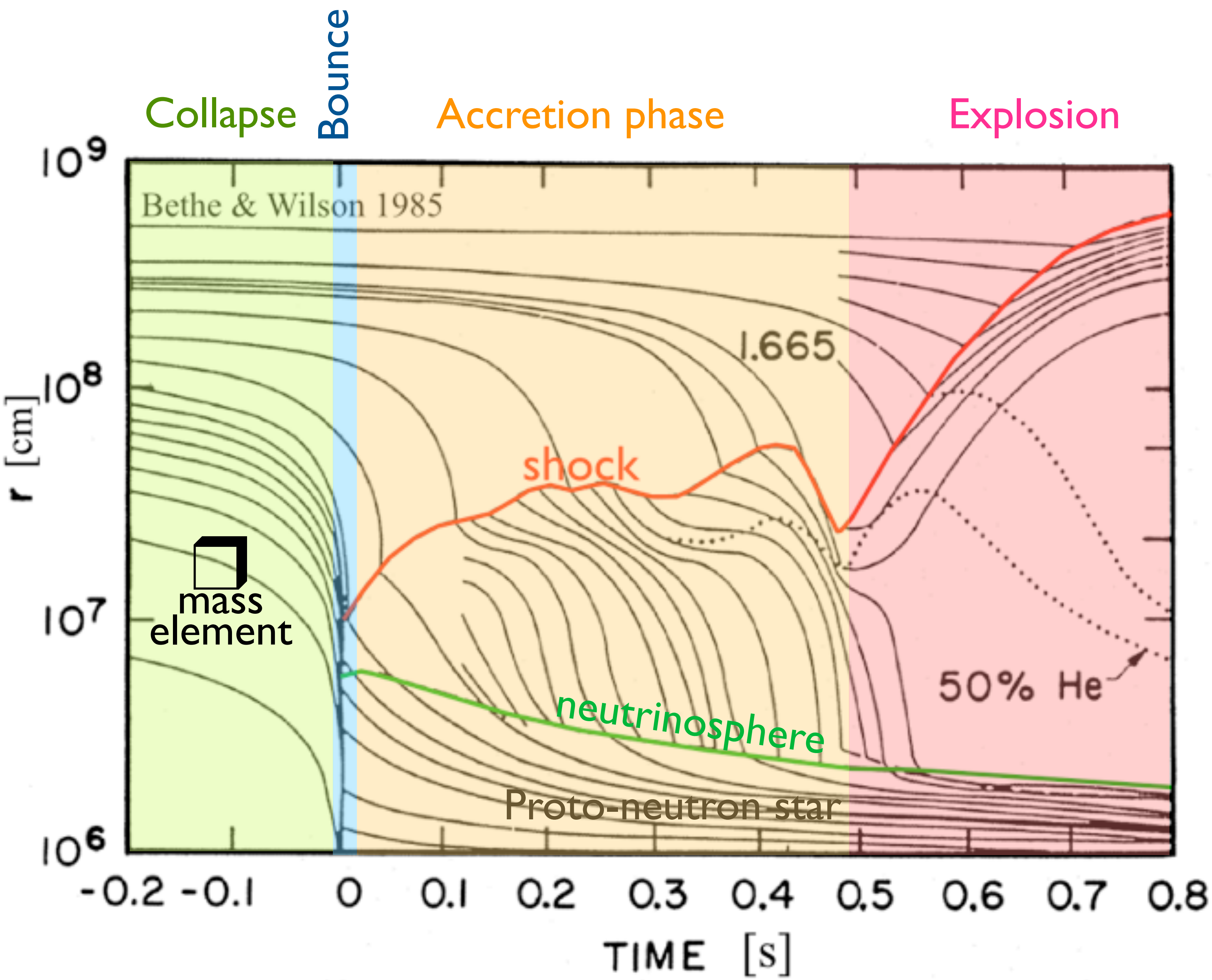
- Pressure is dominated by degenerate electrons
- Si burning at core surface increases Fe-core mass
- Chandrasekhar mass limit
- Collapse starts: gravitational energy is transformed into internal energy: $E \sim 10^{53}$ erg
- Most of the internal energy escapes in form of neutrinos
- $\rho_{crit} \sim 10^{12}$ g/cm^3 neutrinos are trapped



Delayed explosion



Delayed explosion

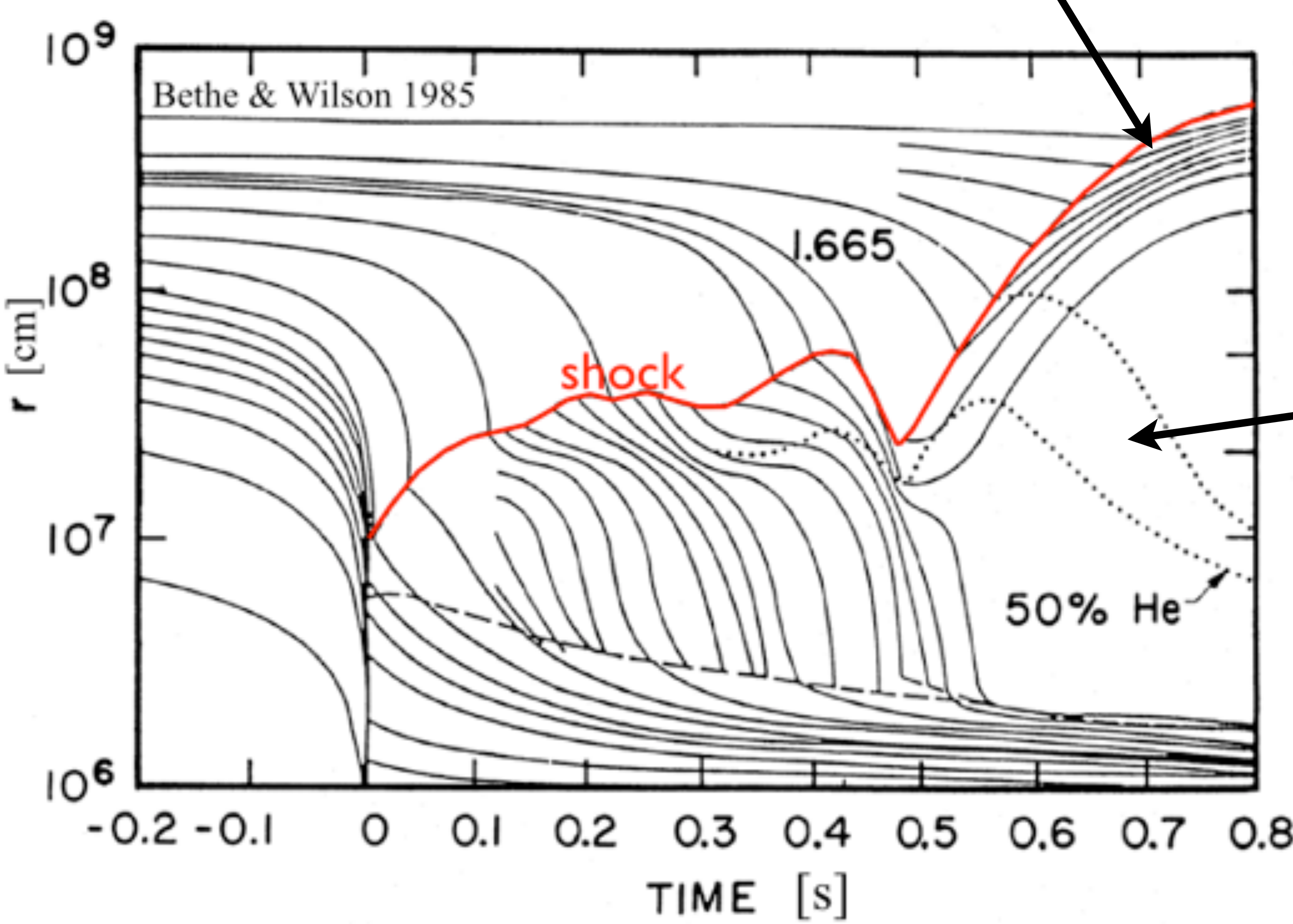


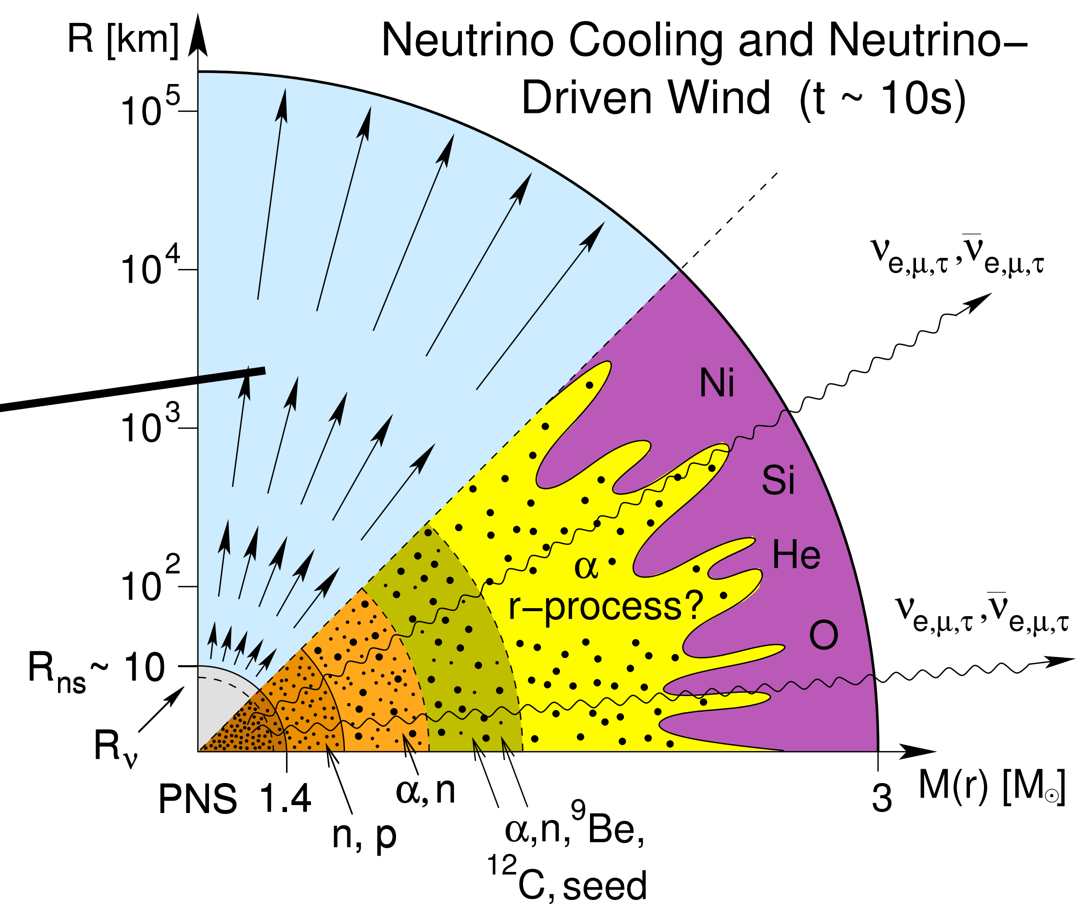
- Neutrino-driven explosion (Colgate 1966,..., Bethe & Wilson 1985,..., Janka et al. 2007): works in 1D for M=8 $M_\odot$, in 2D for M=11 $M_\odot$, 15 $M_\odot$, in 3D?
- Acoustic explosion (Burrows et al. 2006) to be confirmed
- Phase transition to quark matter (Sagert et al. 2009)?
- Magnetic fields and rotation: work in progress

Nucleosynthesis in core-collapse supernovae

Explosive nucleosynthesis:
shock wave heats the falling matter
explosive burning produces alpha elements (C, O, Mg, Si, S, Ca).

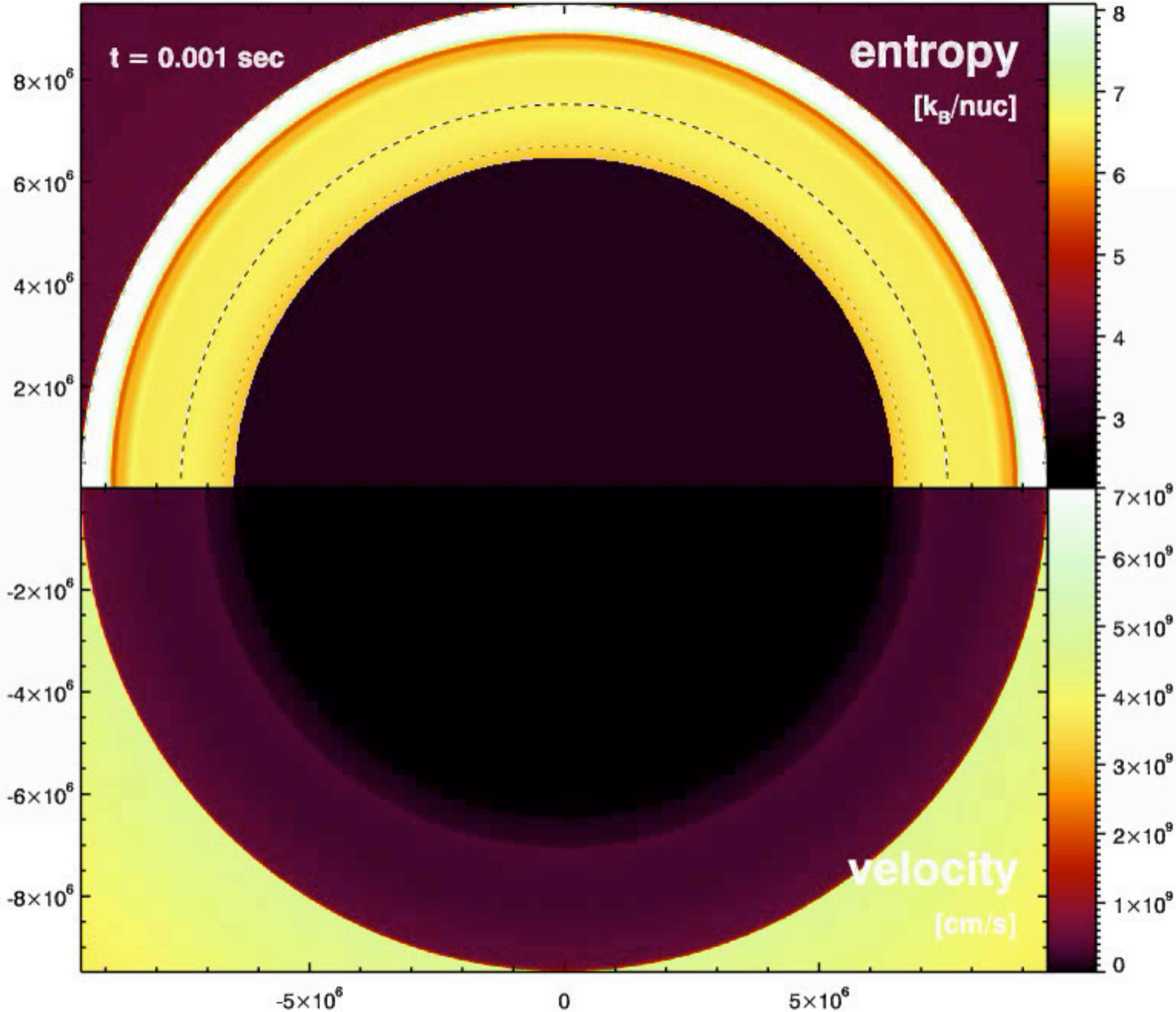
Neutrino-driven wind nucleosynthesis:
fast expansion with high entropy,
nucleons combine in alpha particles,
alpha particles form seed nuclei.





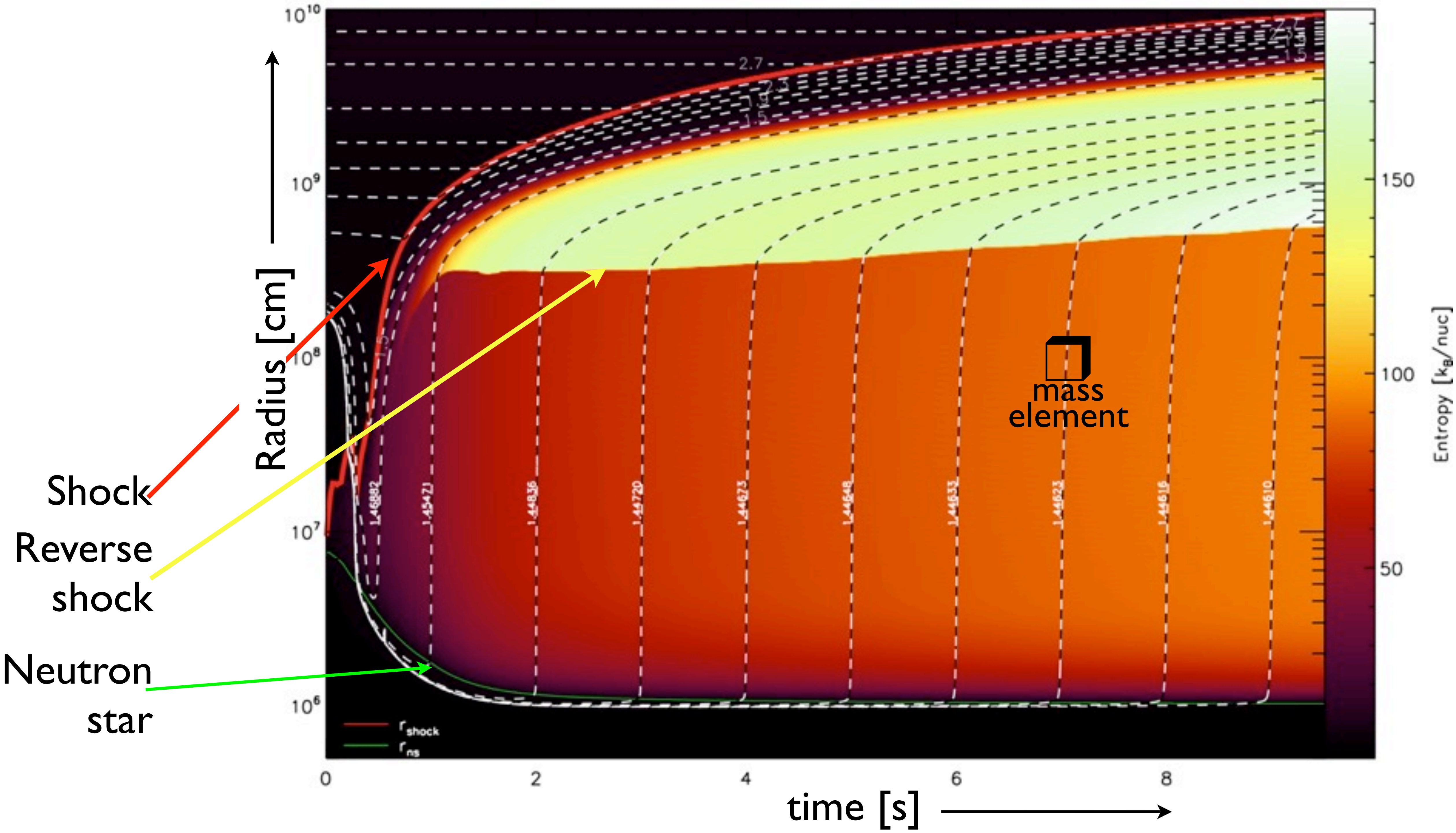
IF enough neutrons: rapid neutron capture process on seed nuclei

Arcones & Janka (2011)



1D simulations for nucleosynthesis studies

Arcones et al 2007



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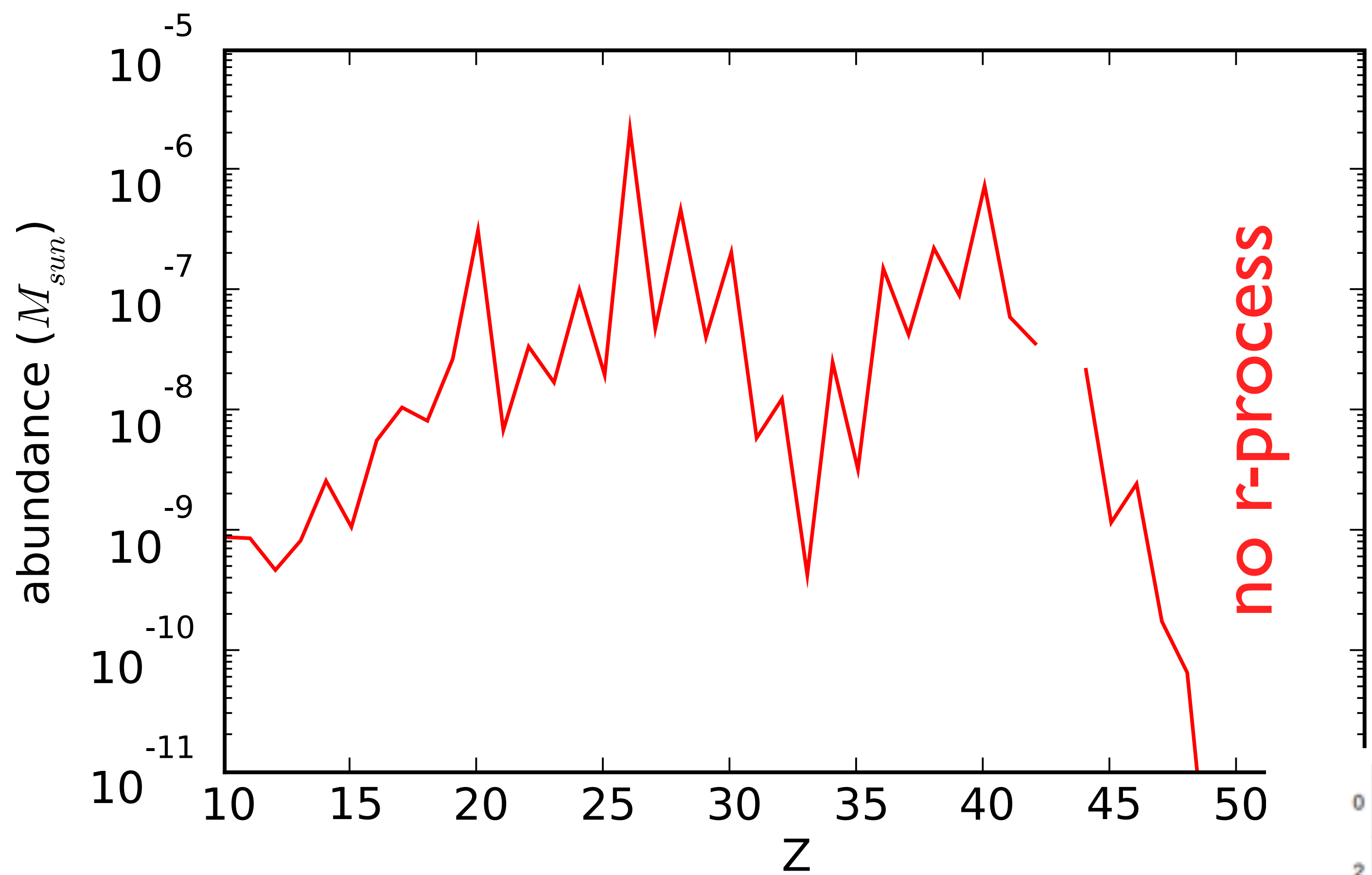
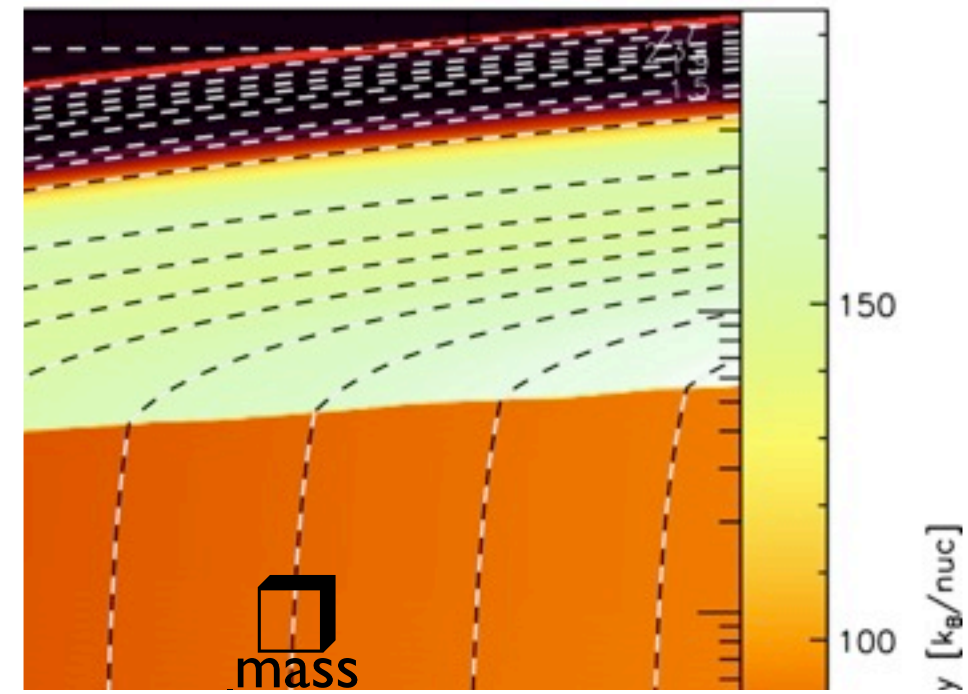
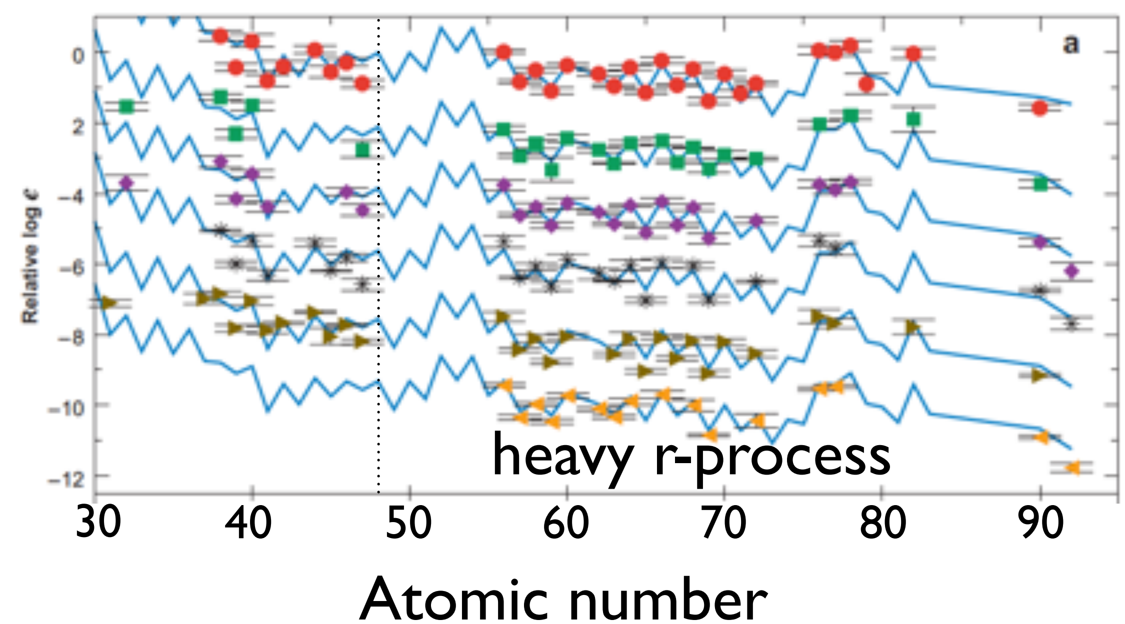
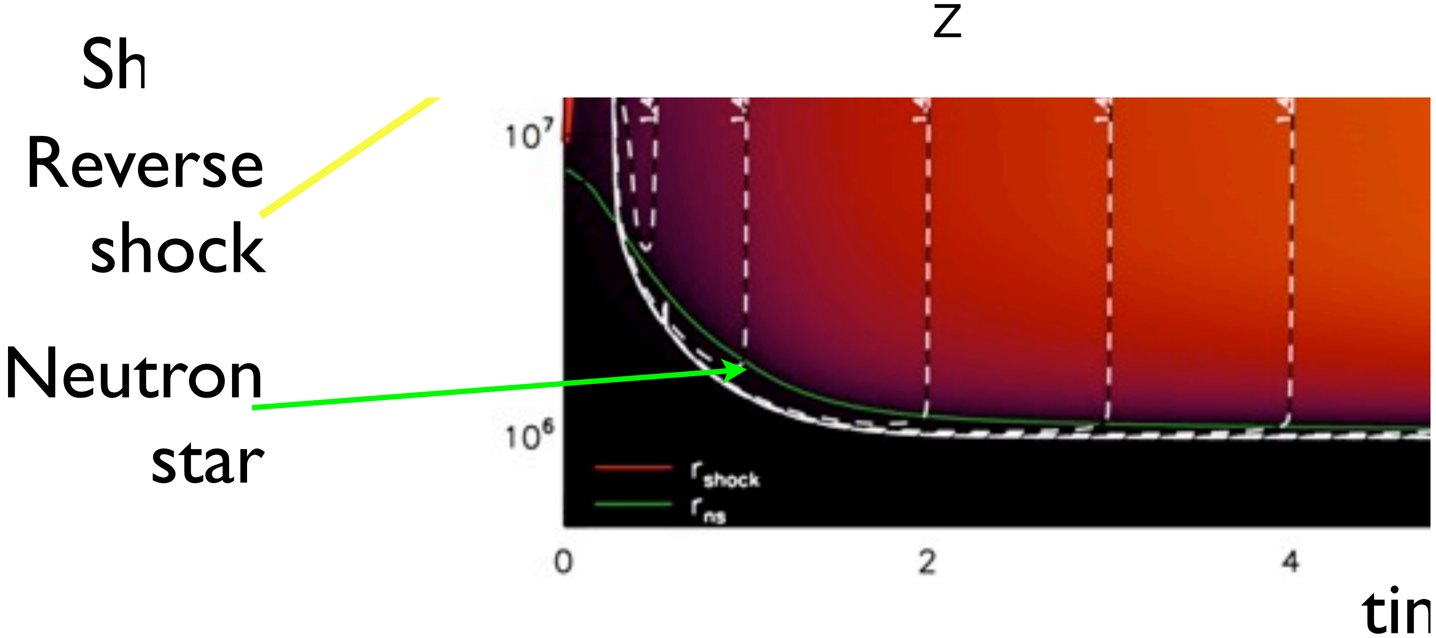








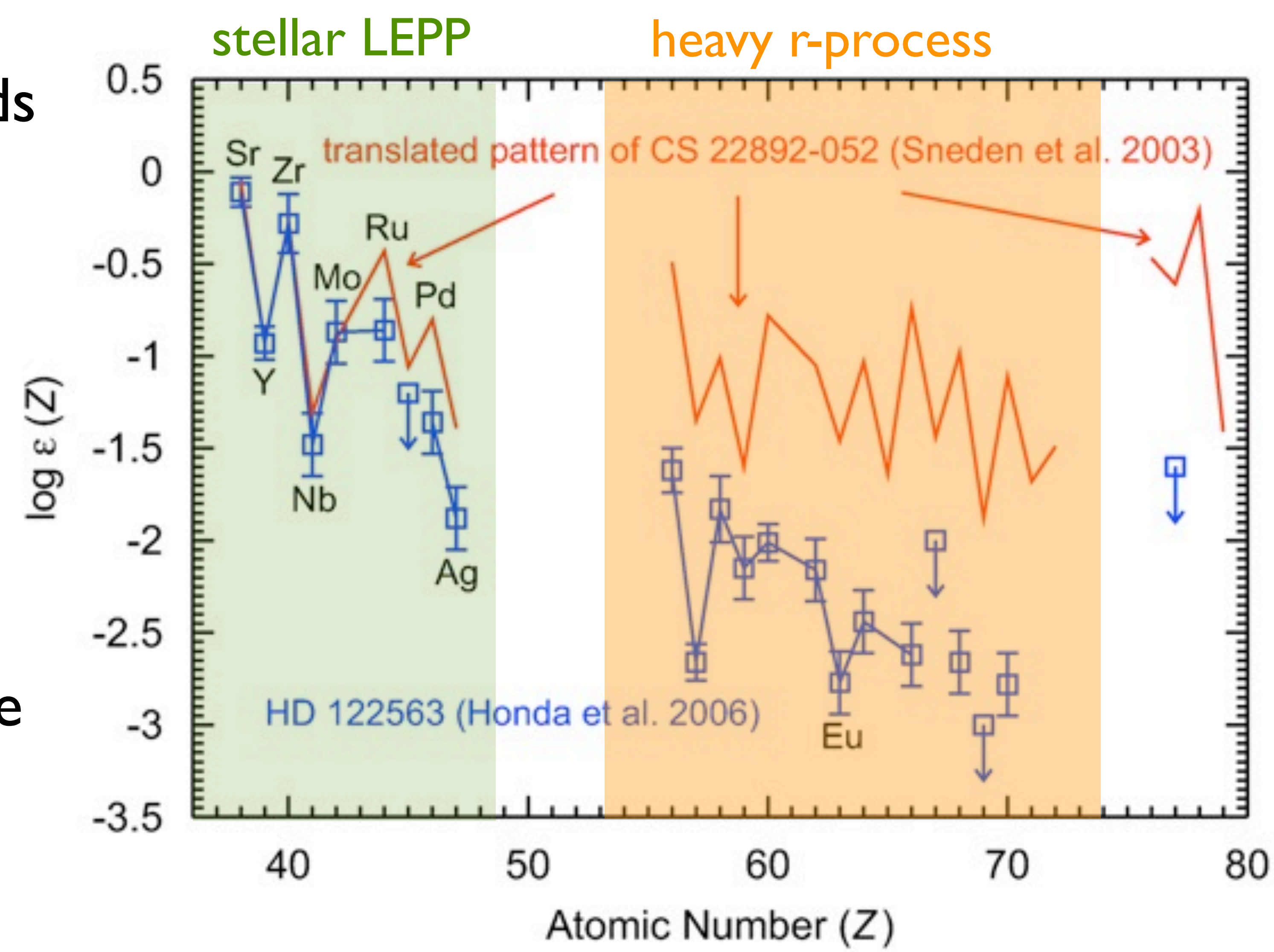
LEPP: Lighter Element Primary Process

Ultra metal-poor stars with high and low enrichment of heavy r-process nuclei suggest: two components or sites (Qian & Wasserburg):

- stellar LEPP: neutrino-driven winds
- heavy r-process?

Travaglio et al. 2004:
solar=r-process+s-process+LEPP

Montes et al. 2007:
solar LEPP ~ stellar LEPP → unique



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

LEPP: Lighter Element Primary Process

Ultra metal-poor sta[r ... r-process nuclei]
suggest: two compon

• stellar LEPP: neutrin
• heavy r-process?

Travaglio et al. 2004:
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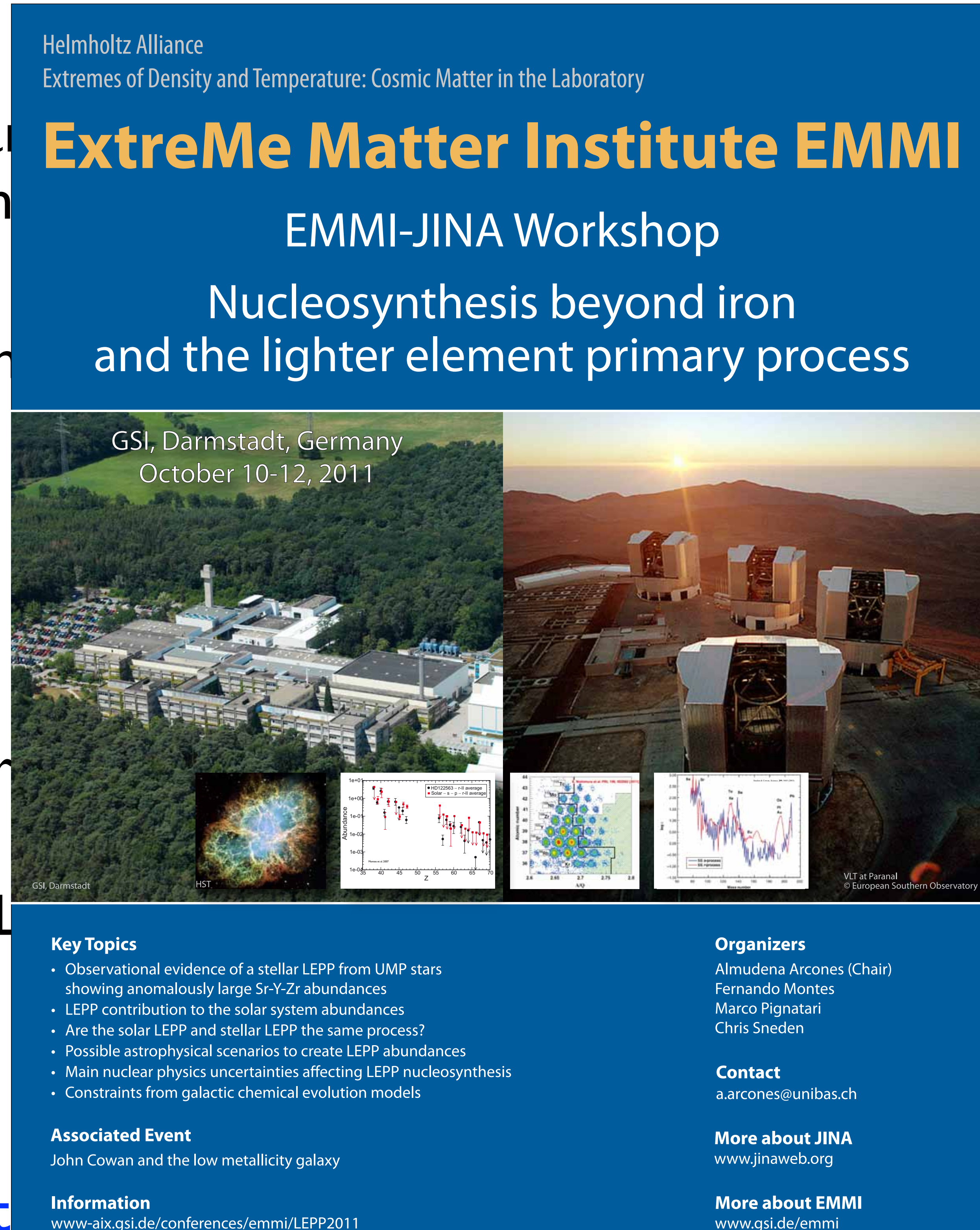
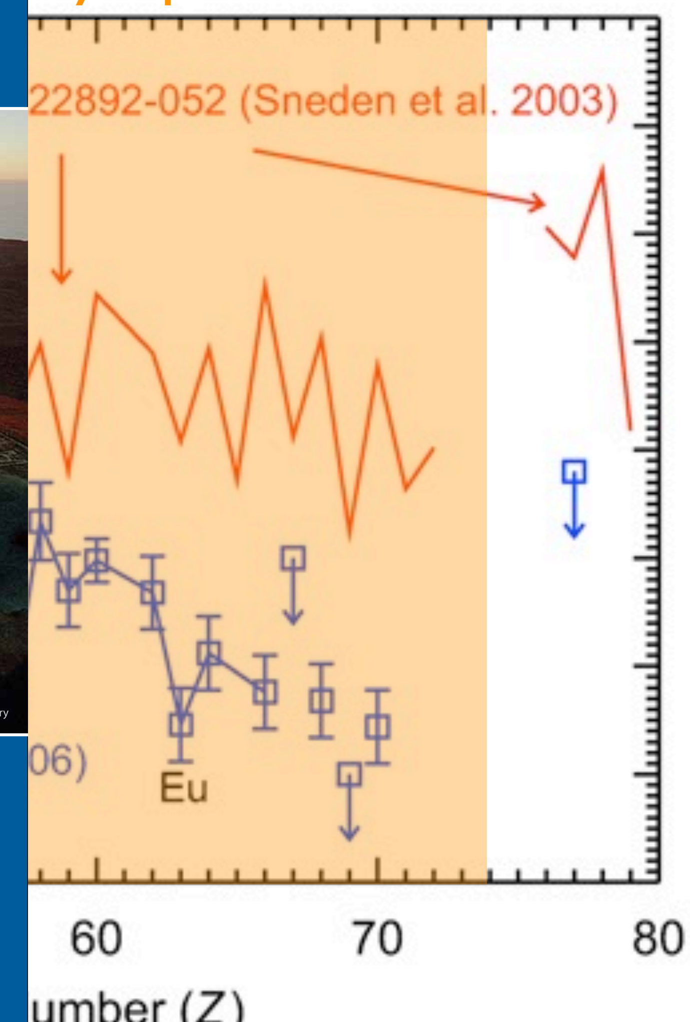


avy r-process



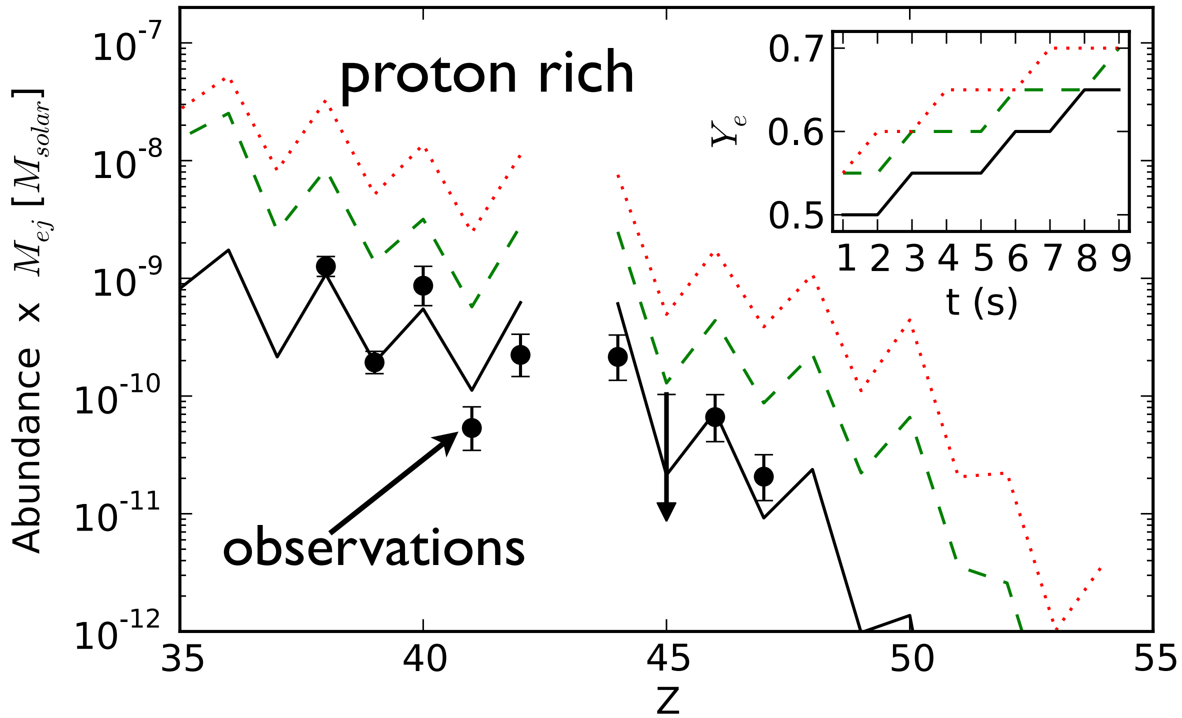
Can the LEPP patt[ern ...] nd simulations?

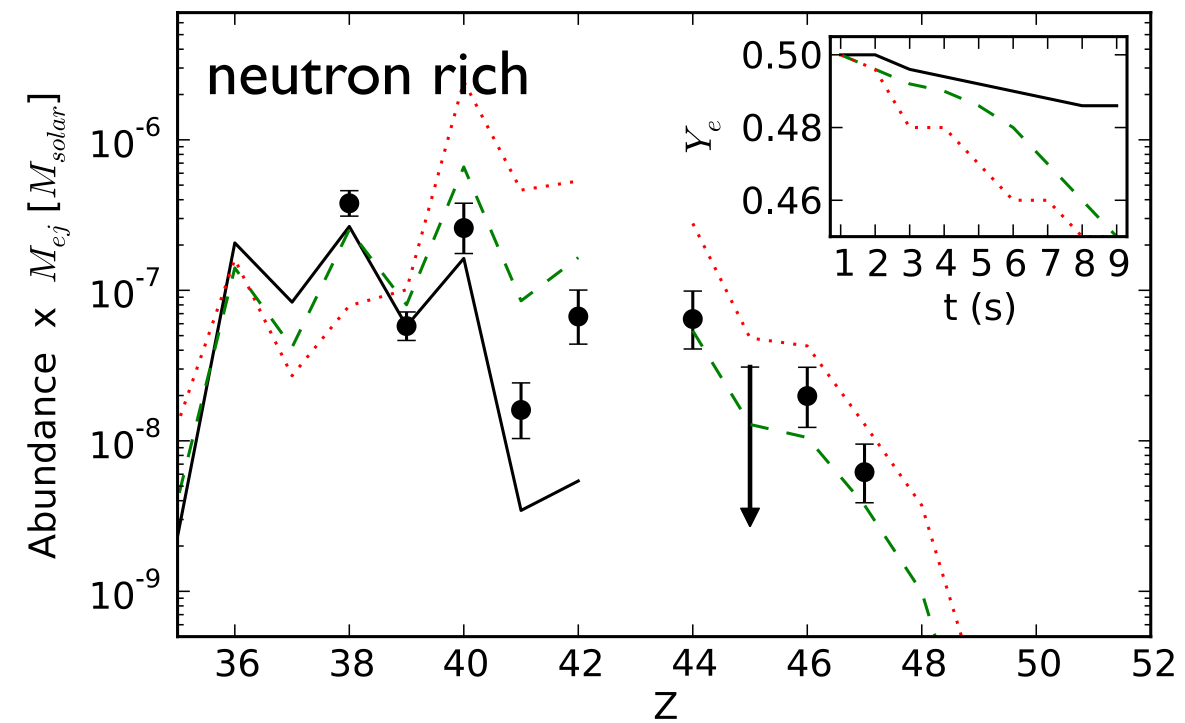
Lighter heavy elements in neutrino-driven winds

(Arcones & Montes, 2011)

Y_e depends on details of neutrino interactions and transport

Impact of the electron fraction: $Y_e = n_p/(n_p+n_n)$





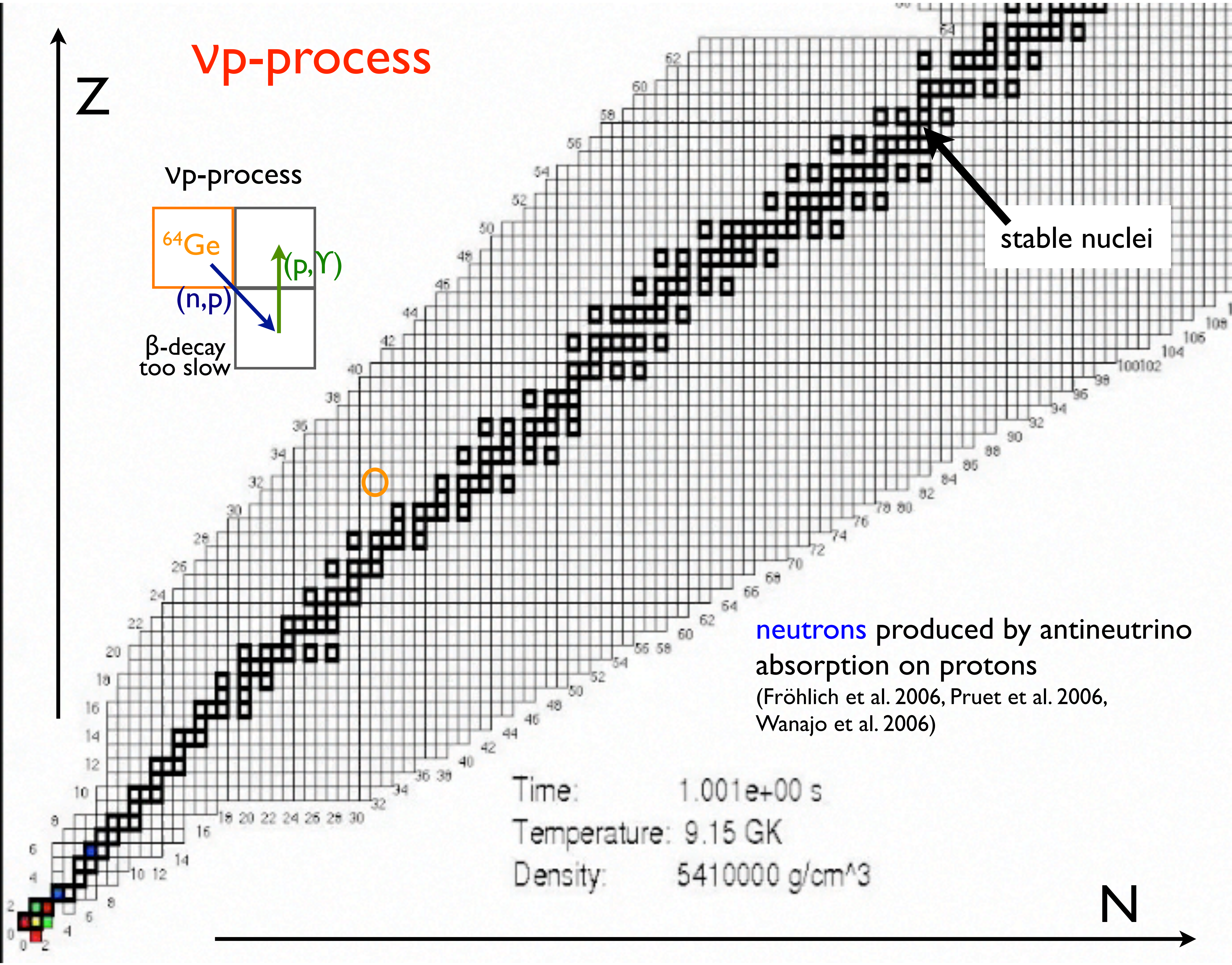
Observation pattern can be reproduced!

Production of p-nuclei (neutron-deficient nuclei)

Overproduction at A=90, magic neutron number N=50 (Hoffman et al. 1996) suggests: only a fraction of neutron-rich ejecta

Isotopic abundances from old stars will give rise to new insights!

νp-process



neutrons produced by antineutrino absorption on protons
(Fröhlich et al. 2006, Pruet et al. 2006, Wanajo et al. 2006)

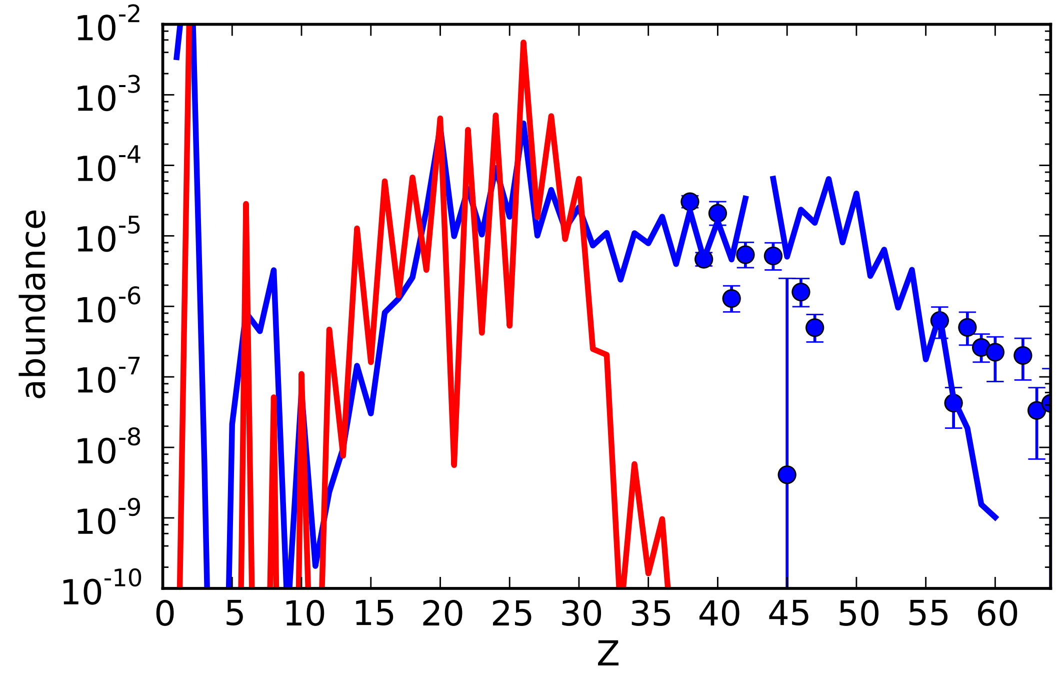
νp-process and dynamical evolution

high temperature

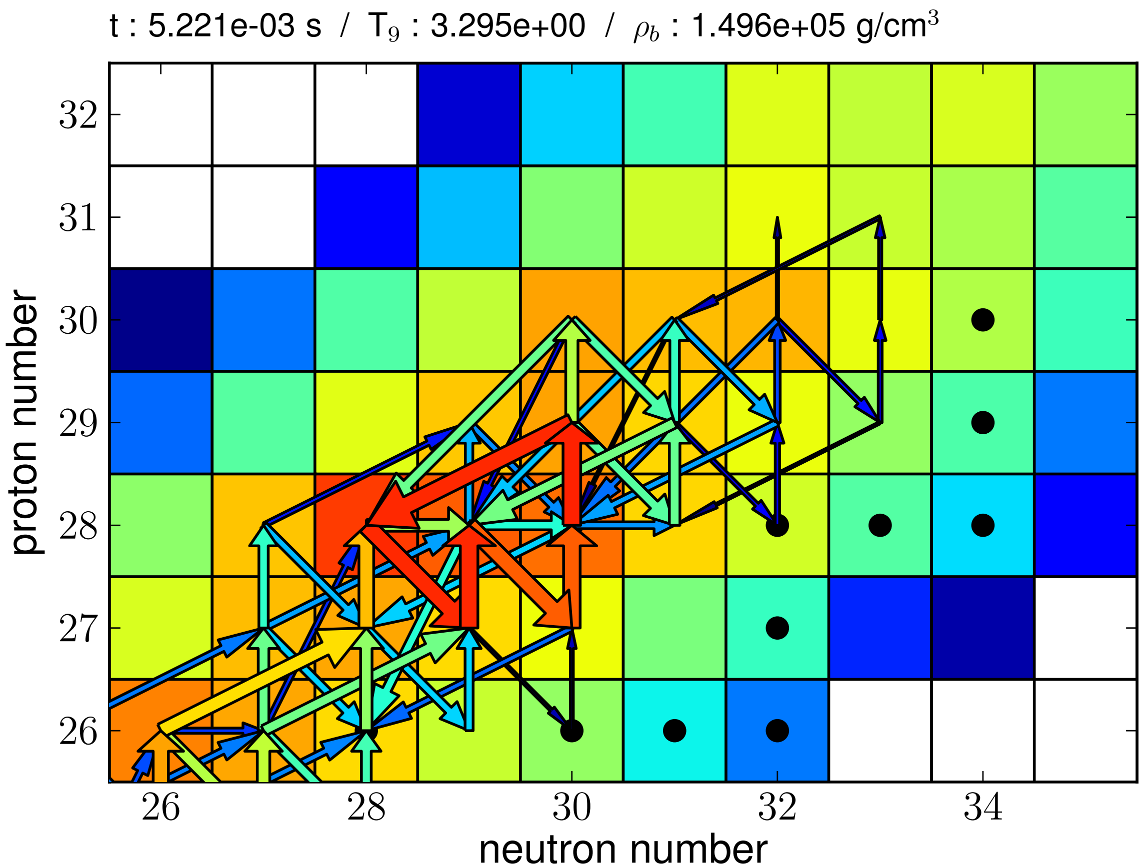
$^{59}Cu(p,\alpha)^{56}Ni \rightarrow$ NiCu cycle

low temperature

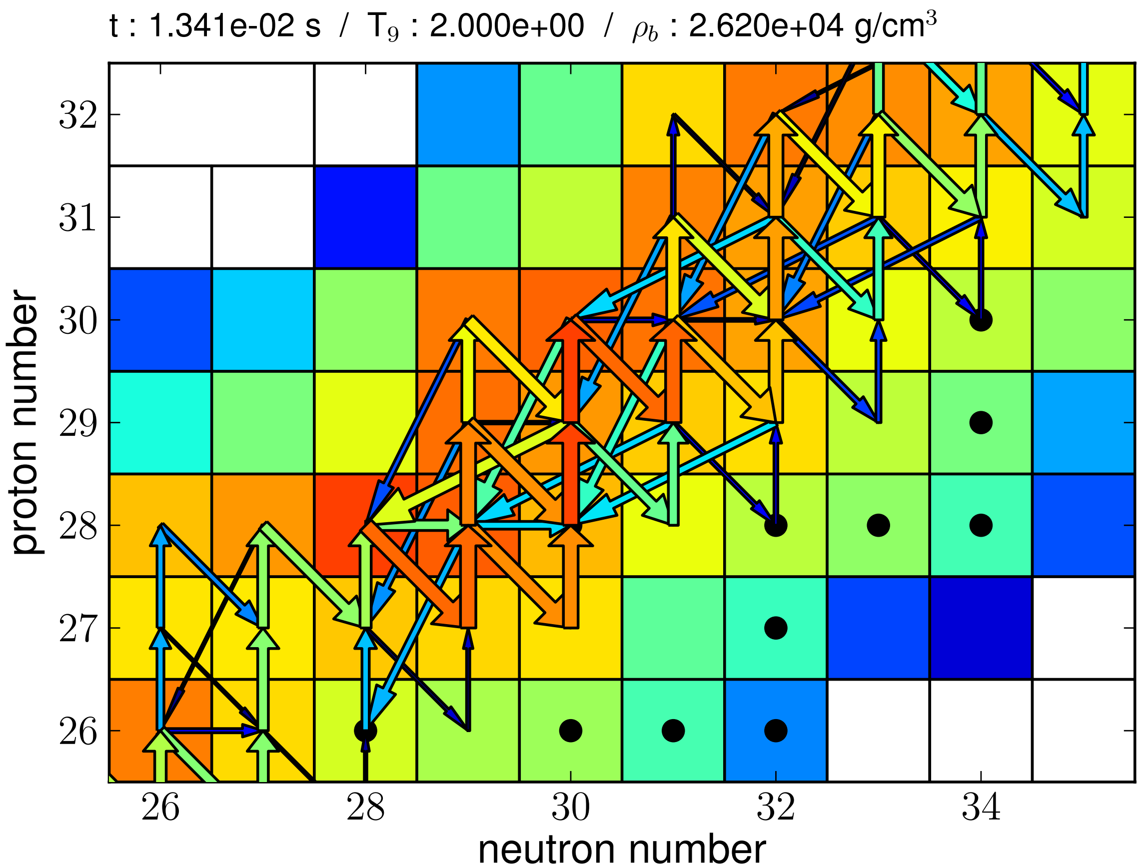
$^{59}Cu(p,\gamma)^{60}Zn$



high temperature



low temperature



Arcones, Fröhlich, Martinez-Piendo (in prep)

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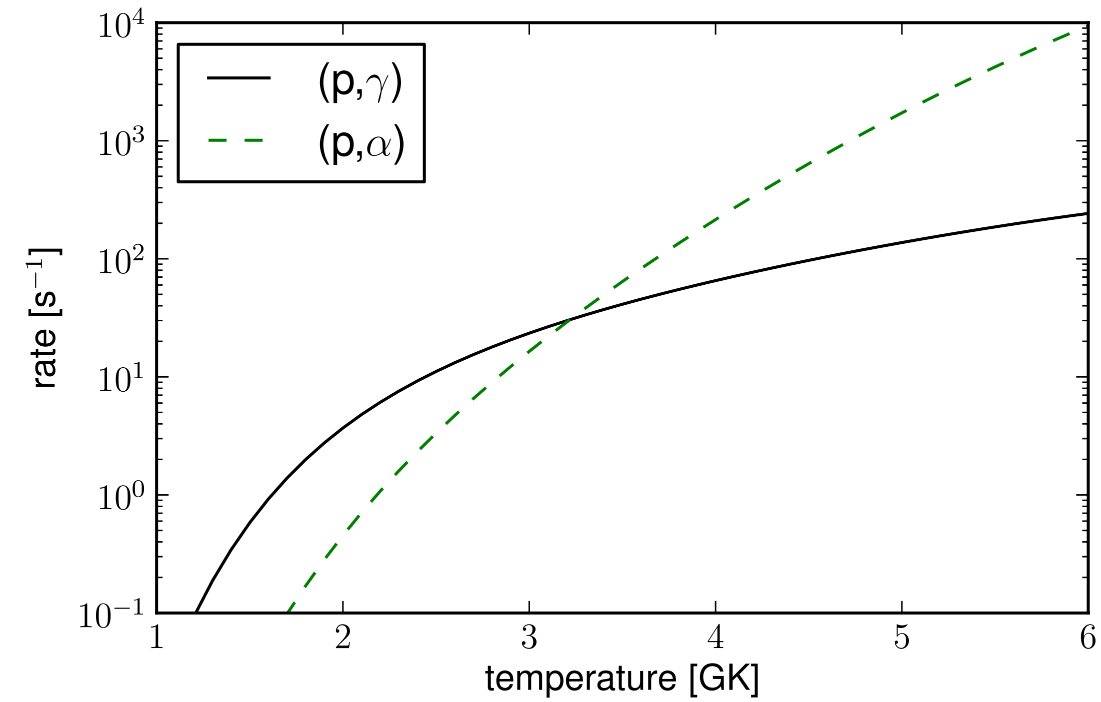
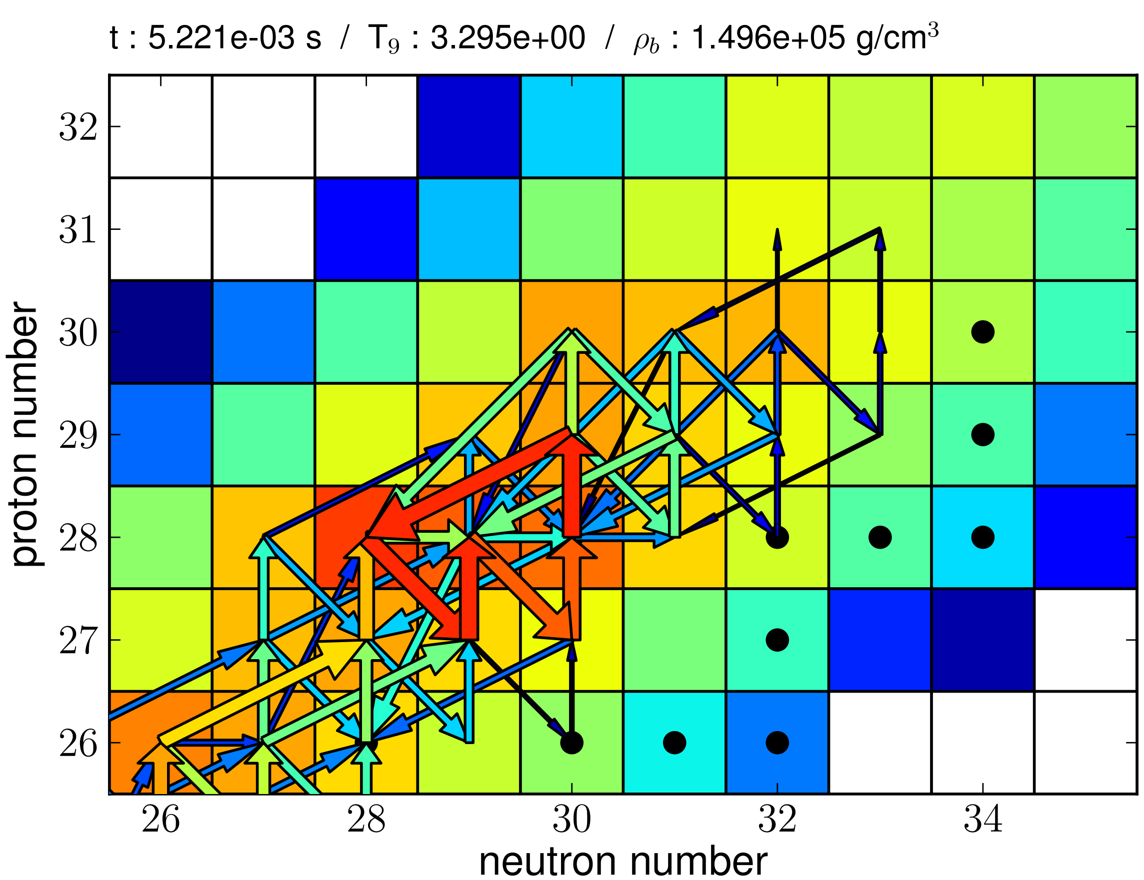
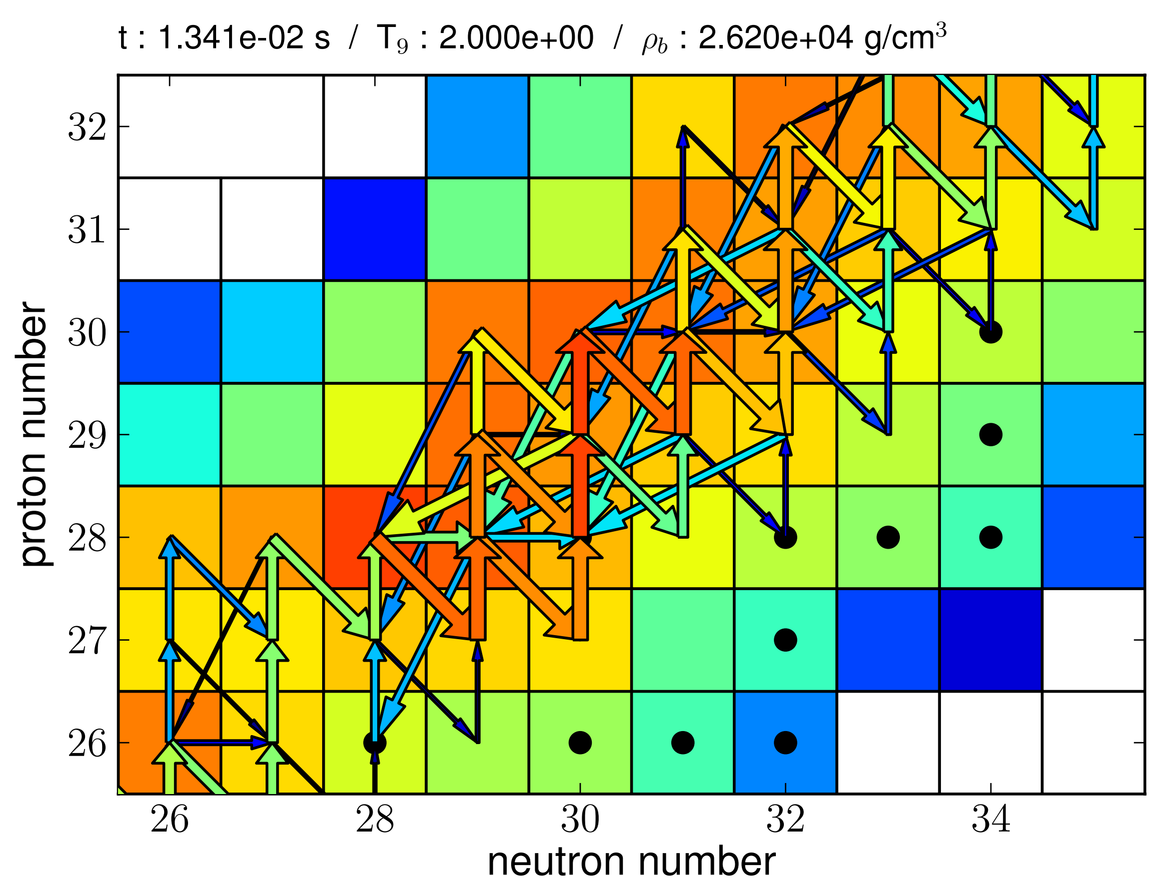


high temperature



low temperature



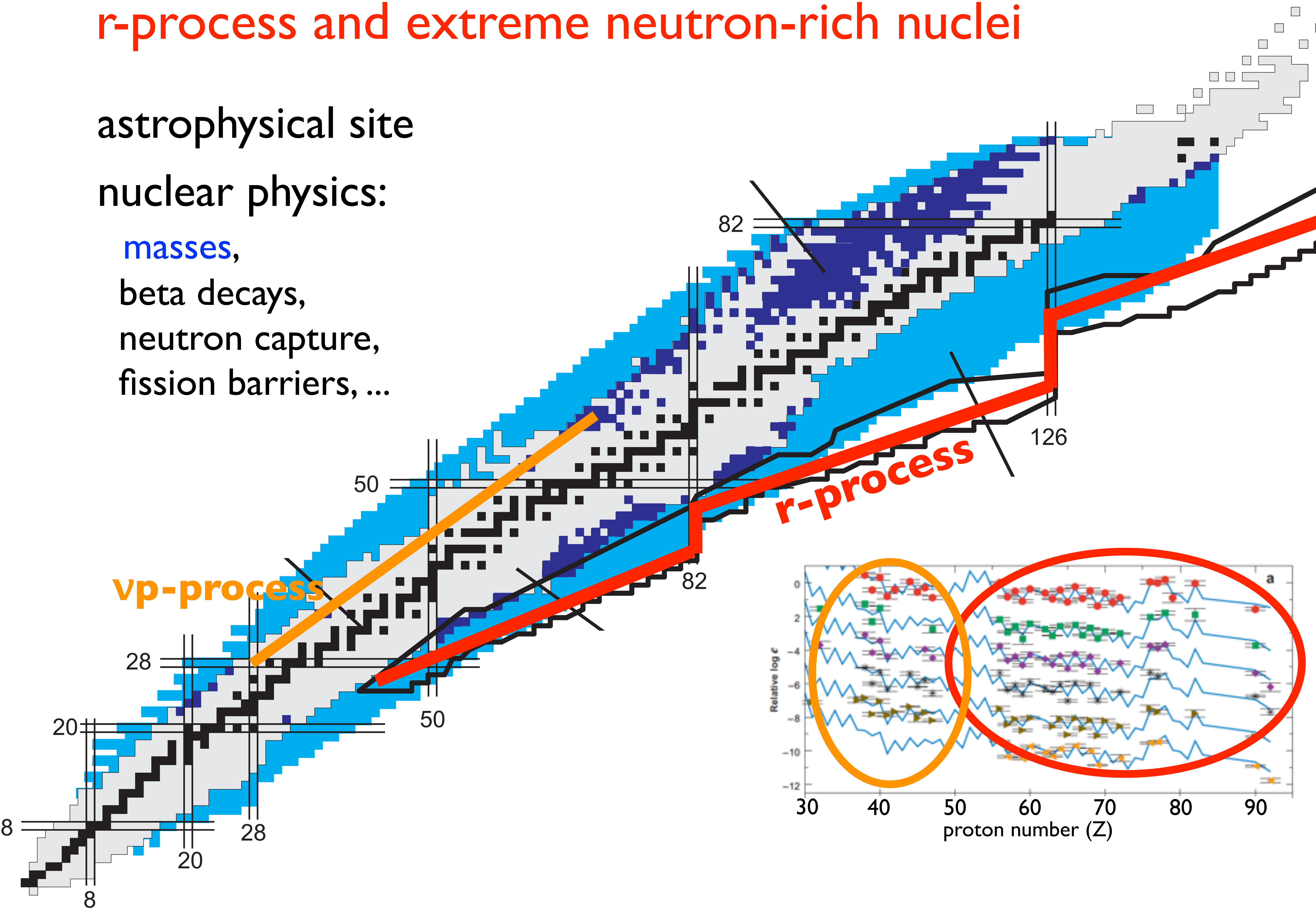
Arcones, Fröhlich, Martinez-Piendo (in prep)

r-process and extreme neutron-rich nuclei

astrophysical site

nuclear physics:

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



Astrophysical site(s) of the r-process

core-collapse supernovae

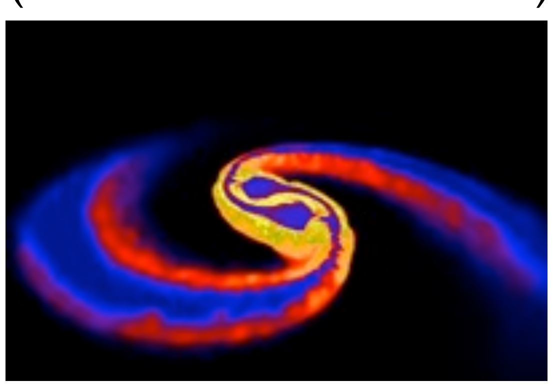
(B^2FH 1957)

- neutrino-driven wind (Meyer et al. 1992, 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, ...?
- prompt explosion (Hillebrandt 1978, Hillebrandt et al. 1984): excluded
- shocked surface layers (Ning, Qian, Meyer 2007): possible?
- neutrino-induced in He shells (Banerjee, Haxton, Qian 2011): low metallicity
- jets: potential, very preliminary magneto hydrodynamic simulations (e.g., Nishimura et al. 2006)

neutron star mergers

(Lattimer & Schramm 1976)

Rosswog

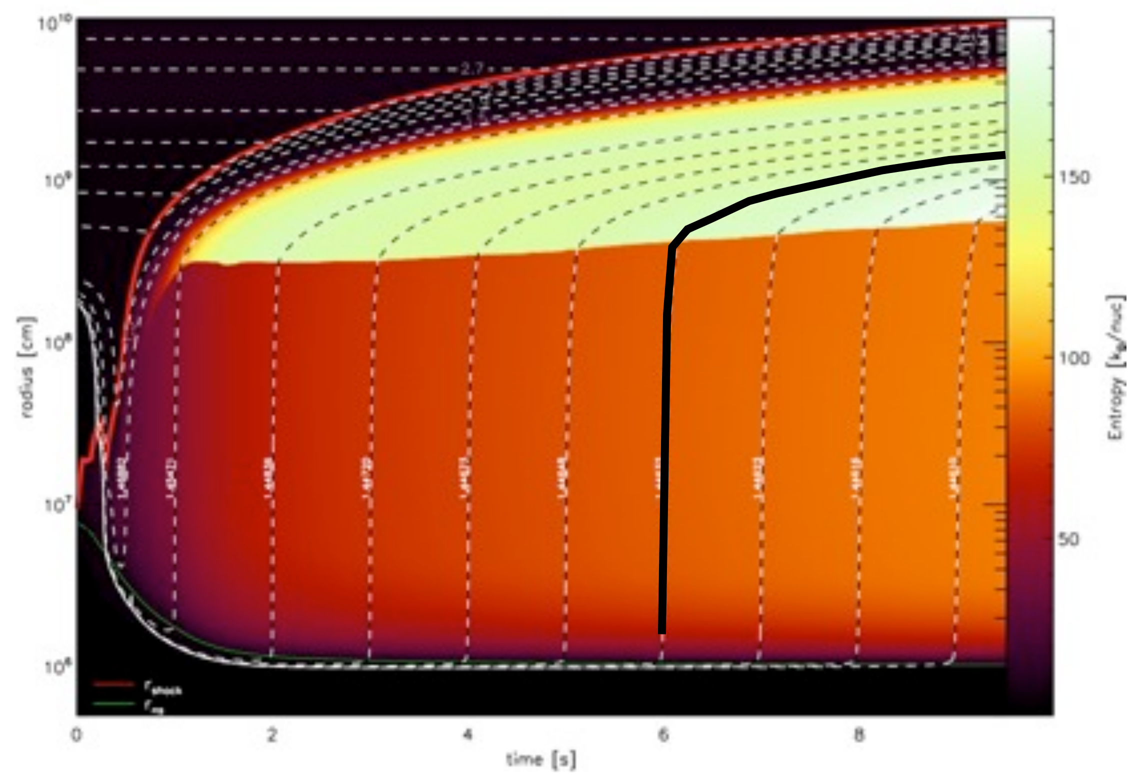


- Right conditions for a successful r-process (Freiburghaus et al. 1999)
- No only r-process site: they do not occur early and frequently enough to account for the heavy elements observed in old stars and their scatter in the Galaxy (Qian 2000, Argast et al. 2004)?
- r-process heating affects merger dynamics (Metzger, Arcones, Quataert, Martinez-Pinedo 2010)

Nuclear masses and r-process

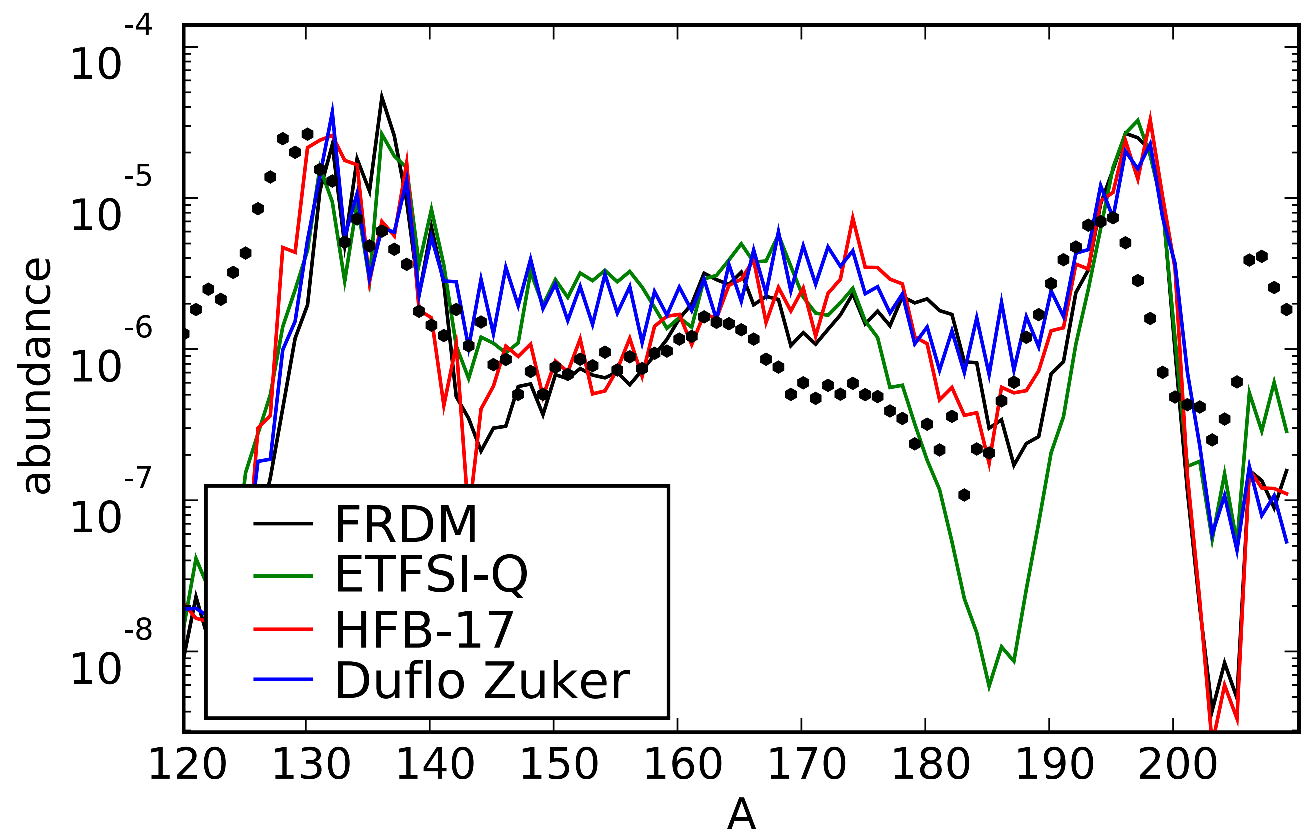
We use one trajectory from the hydrodynamical simulations of Arcones et al. 2007 with the entropy ($S \sim T^3/\rho$) increased by a factor two

→ 3rd r-process peak (A~195)



Compare four different nuclear mass models

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



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

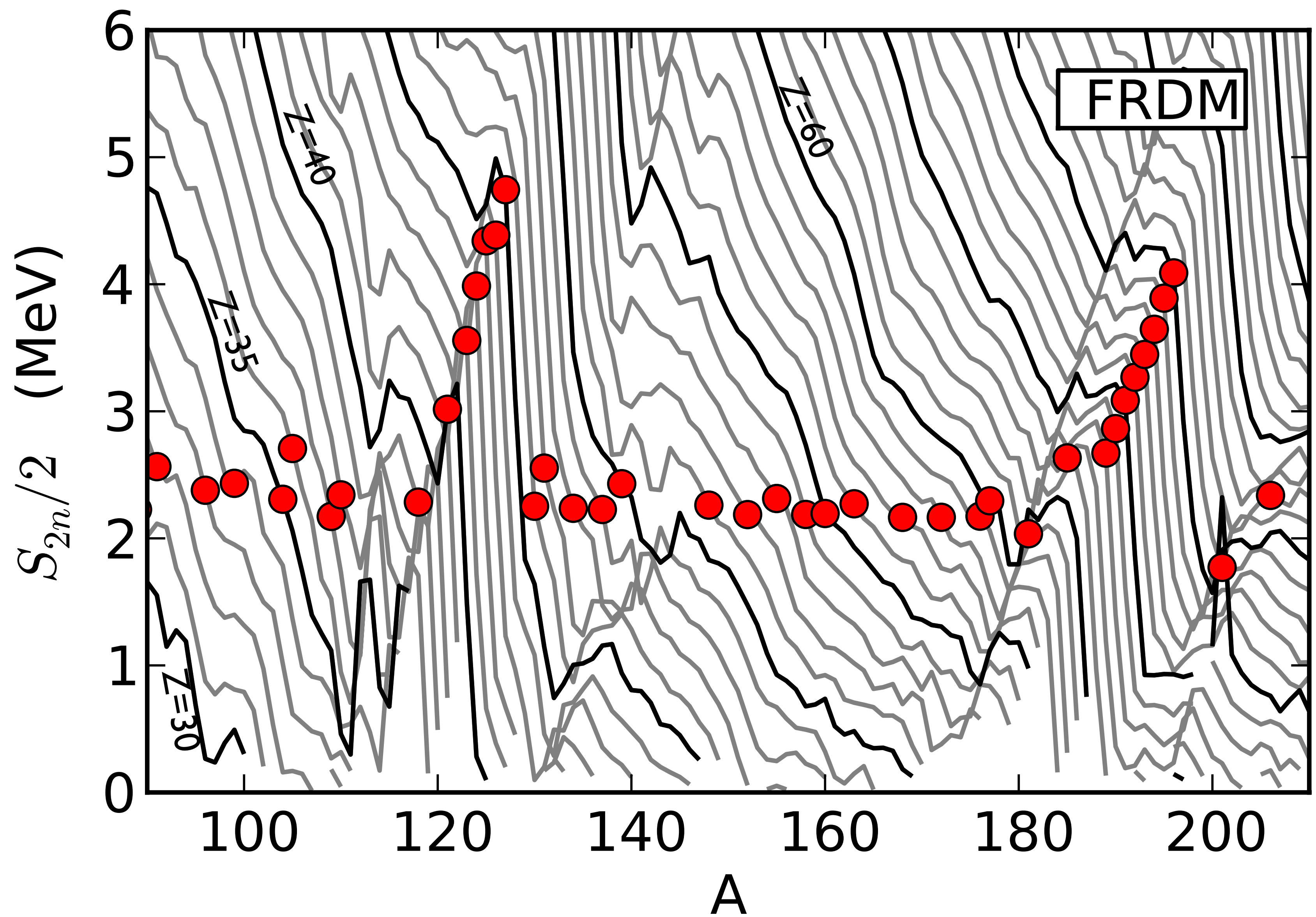
Arcones & Martinez-Pinedo, 2011

Two neutron separation energy

Abundances

↕ S_{2n}

Nuclear properties

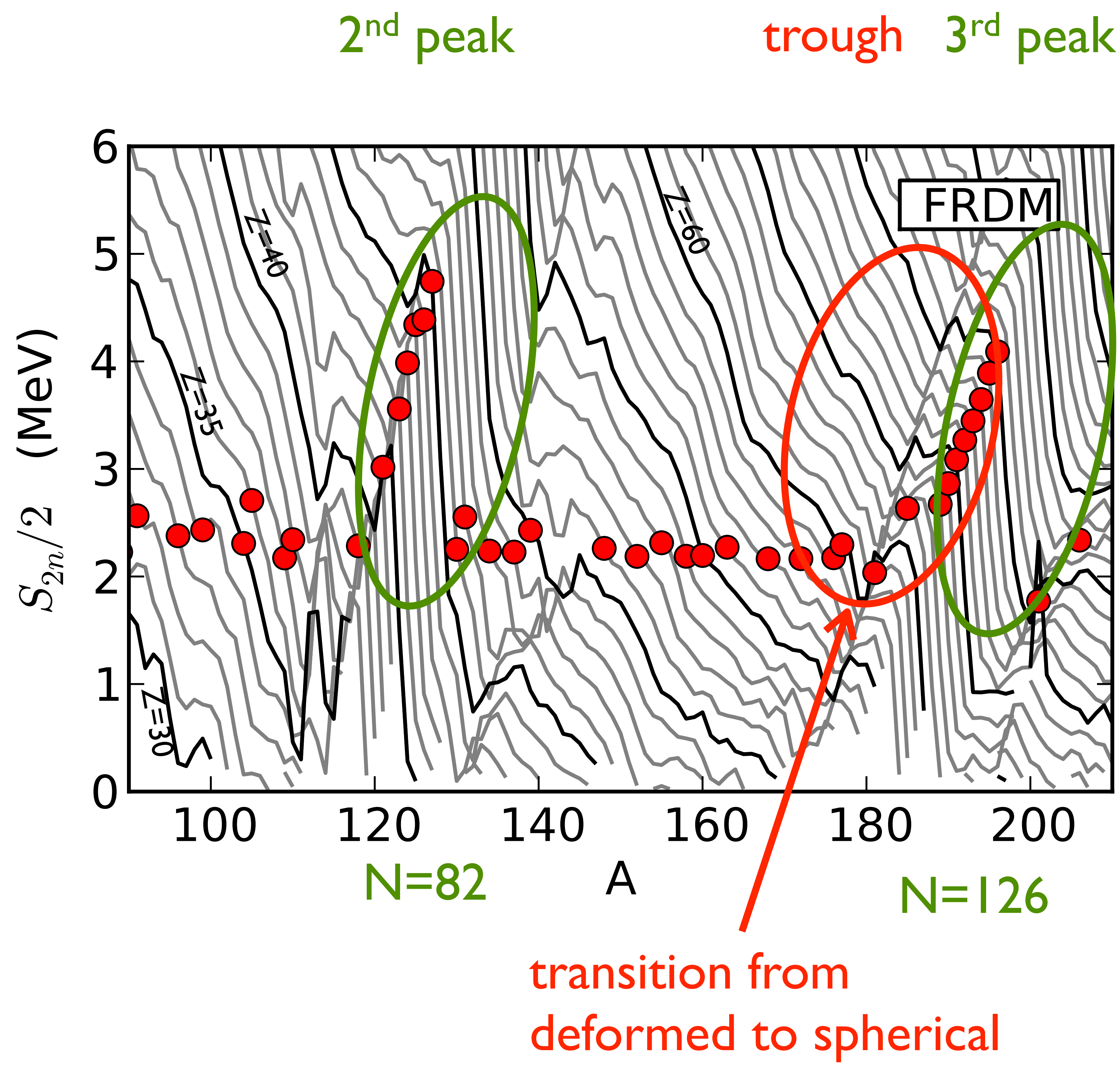


Two neutron separation energy

Abundances

S_{2n}

Nuclear properties



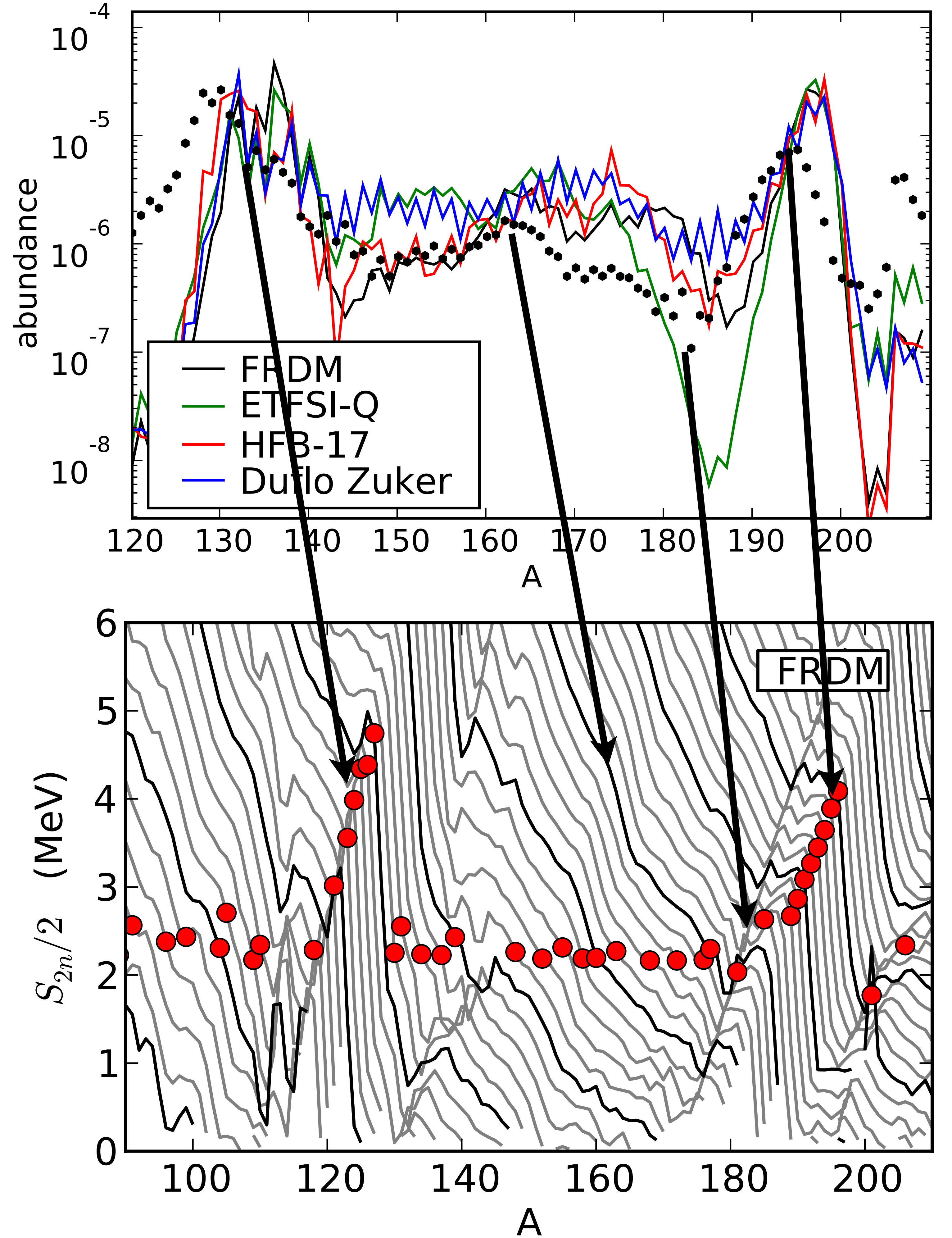
masses ↔ abundances

At magic number: S_{2n} abrupt drop
- → decrease neutron capture
  increase photo-dissociation
- → matter accumulation

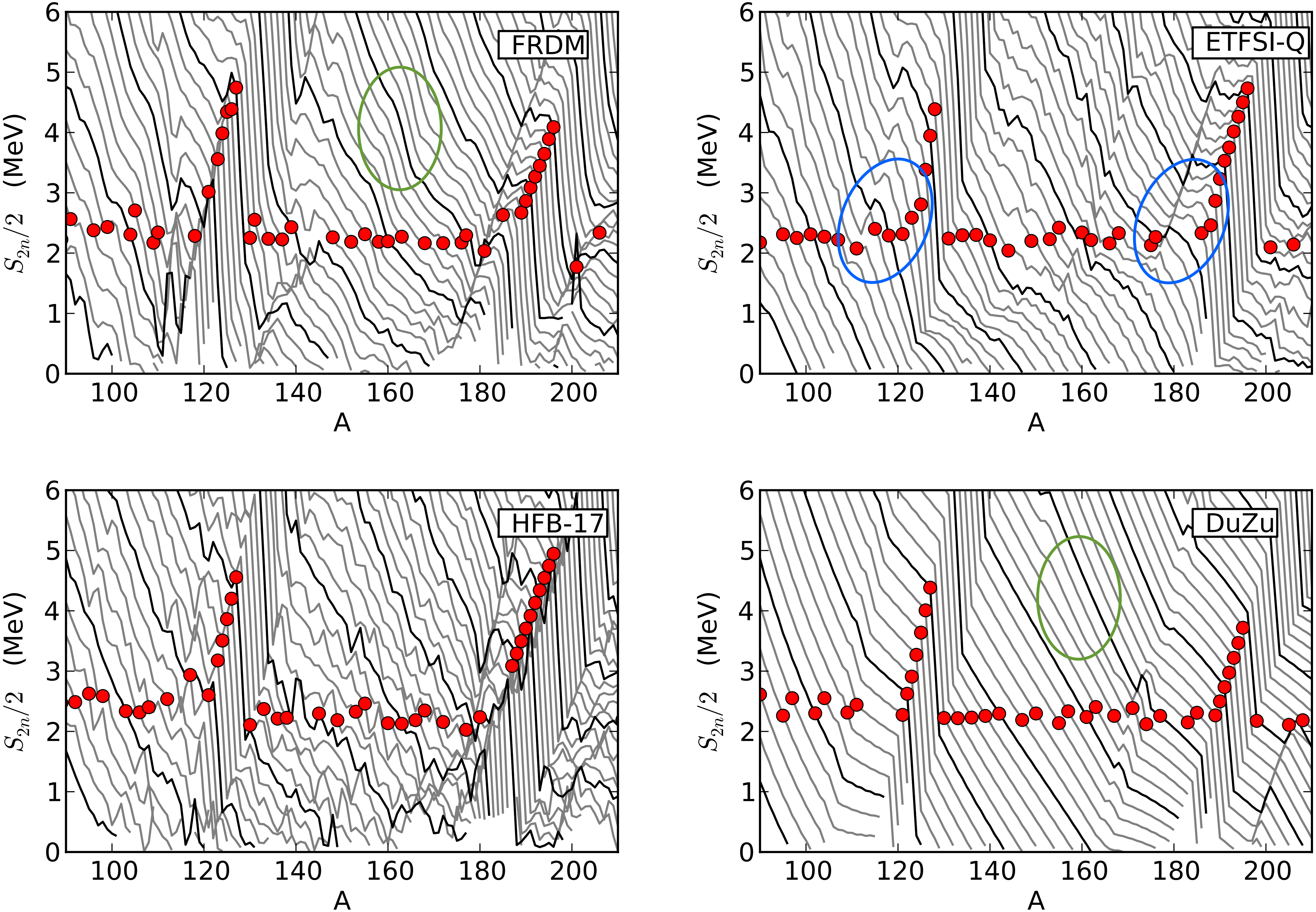
Transition from deformed to spherical: S_{2n} flat or oscillate
- → fast neutron capture
- → trough

● r-process path at freeze out
Yn/Yseed<1

Arcones & Martinez-Pinedo, 2011



Aspects of different mass models



Decay to stability

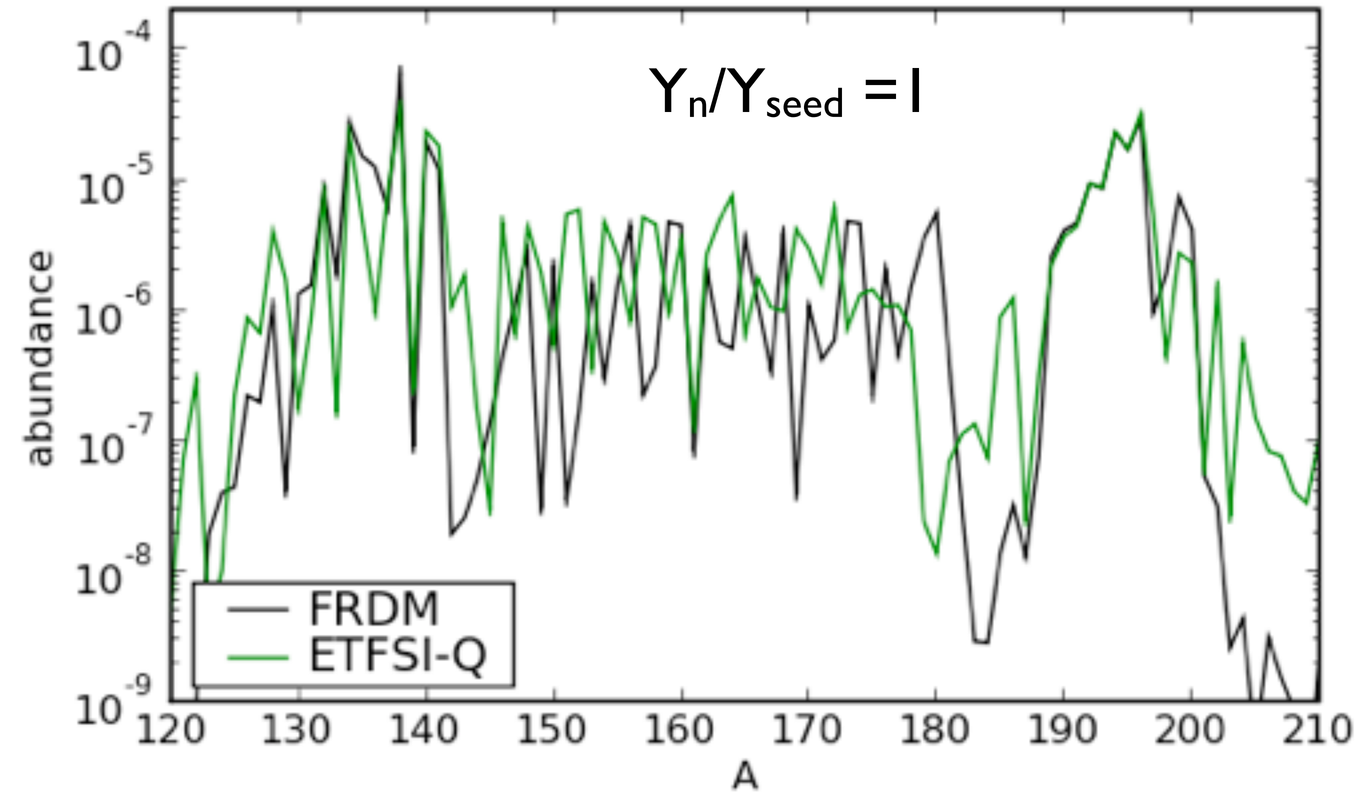
Abundances at freeze-out (Y_n/Y_{seed}=1): odd-even effects

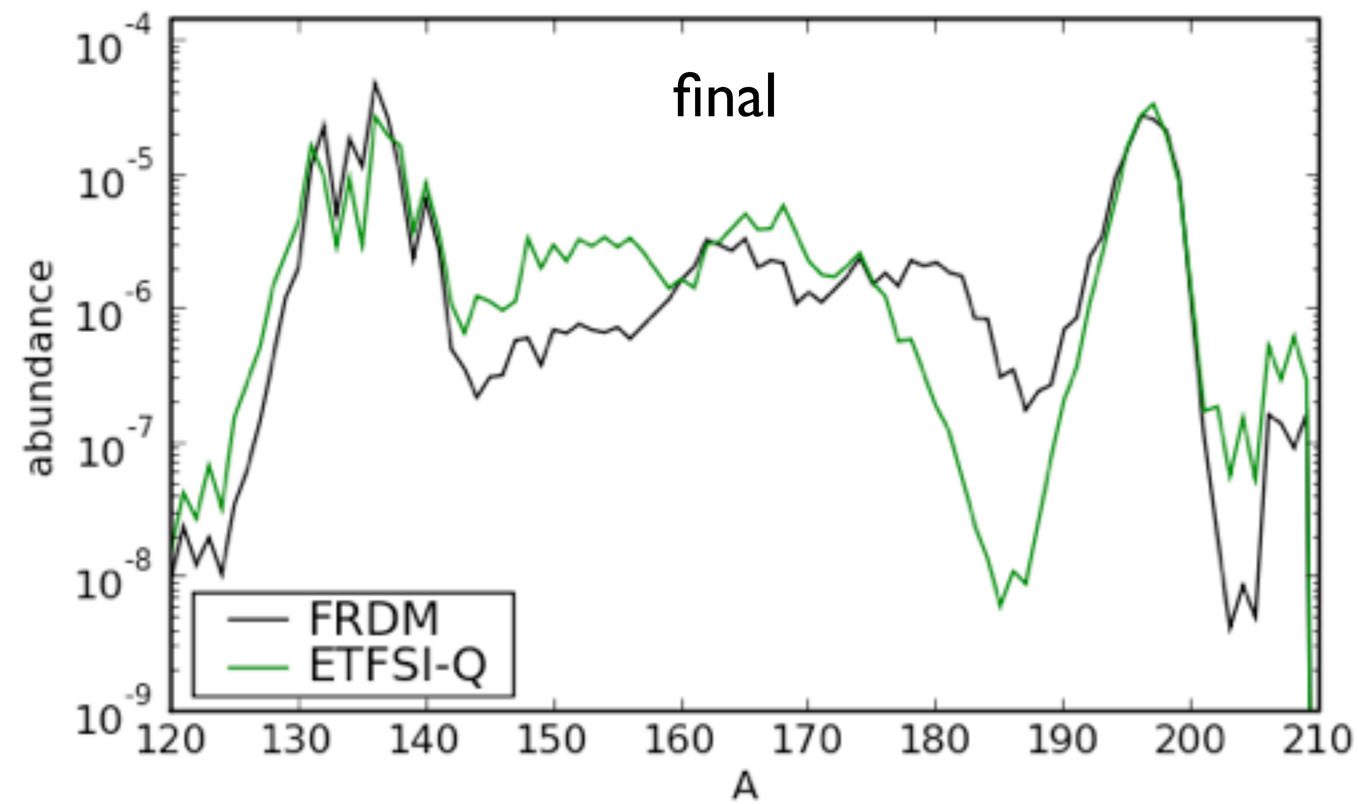
Final abundances are smoother like solar abundances.

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

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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*
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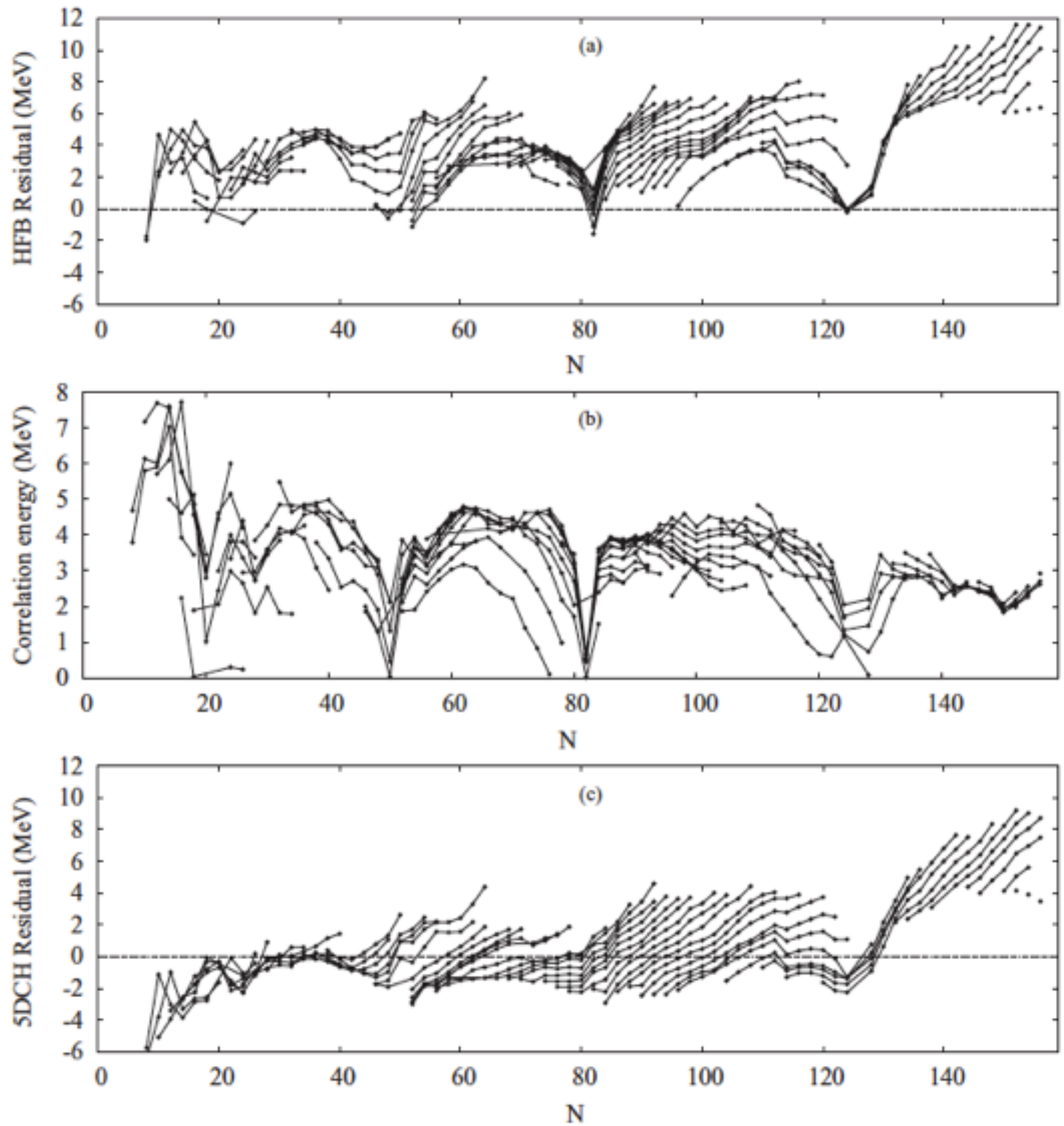
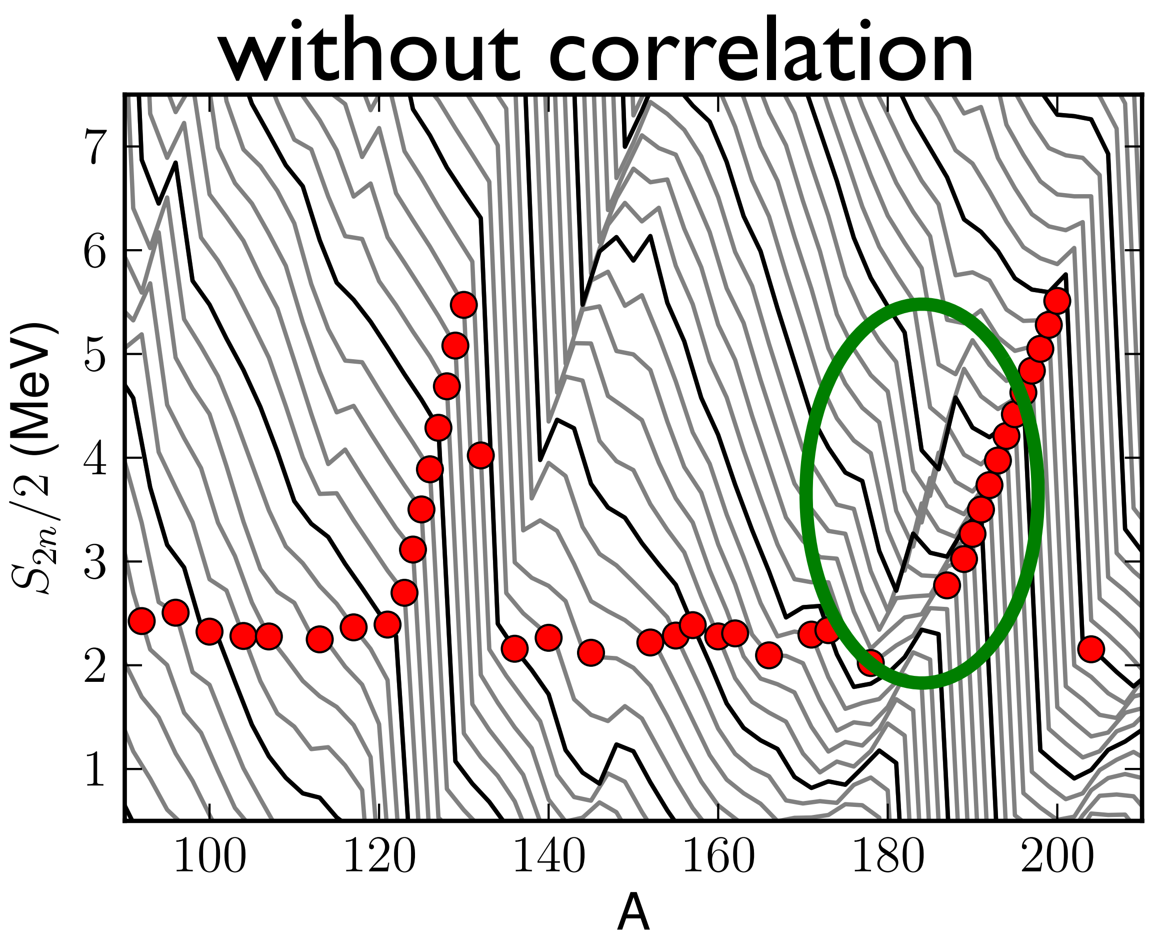
[3]*Department of Physics and Institute of Nuclear Theory, Box 351560, University of Washington Seattle, Washington 98915, USA*

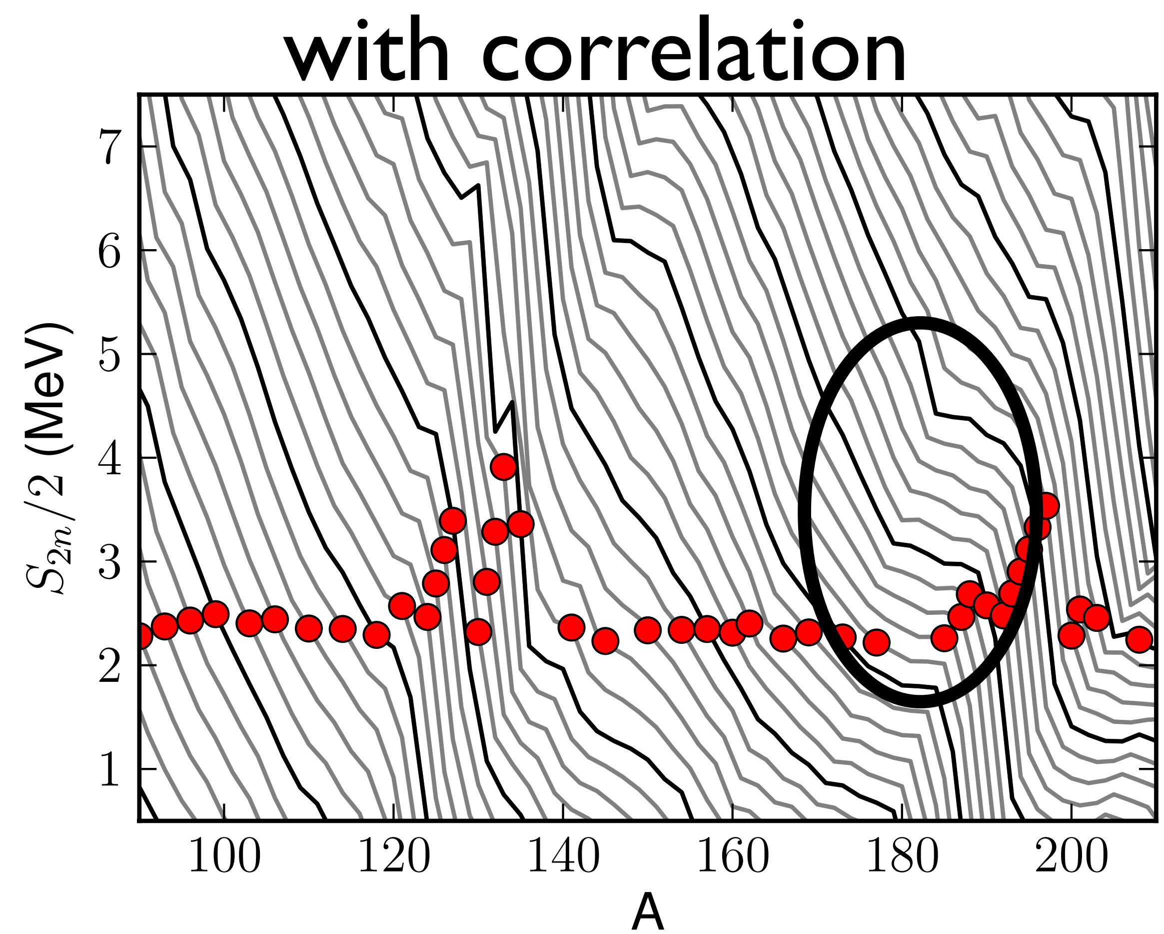


Impact of nuclear correlations on the r-process

Nuclear correlations and r-process

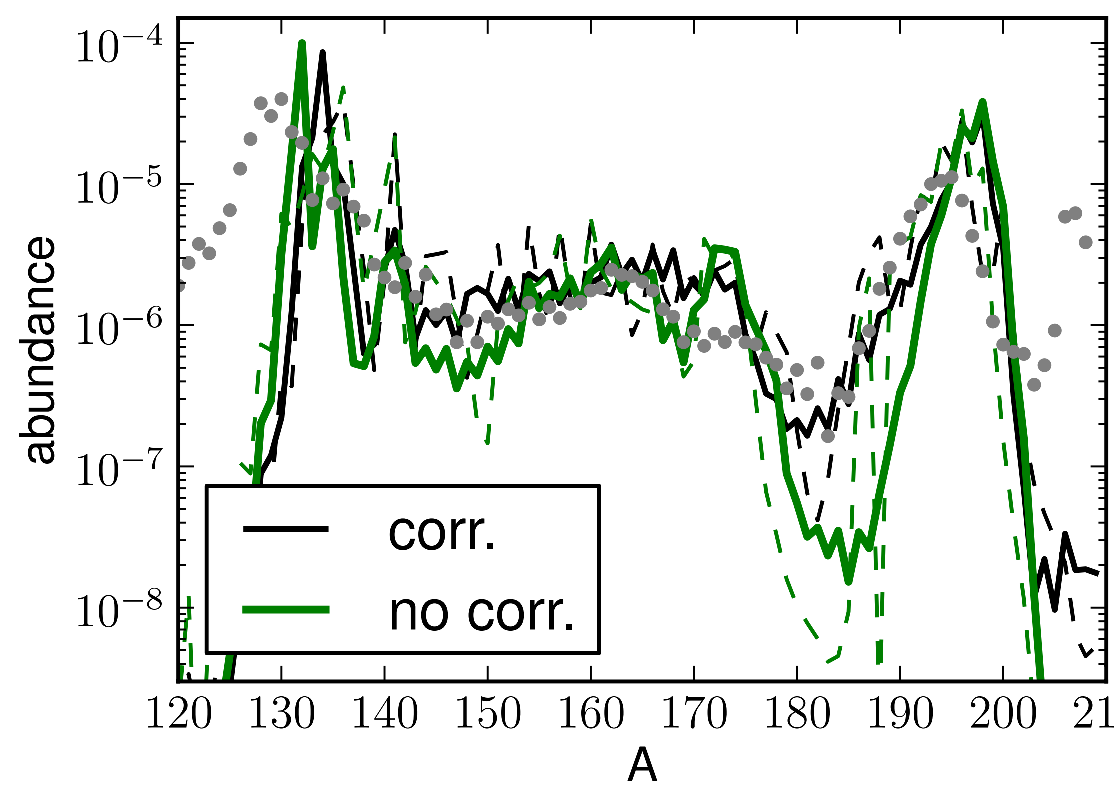
(Arcones & Bertsch, in prep.)



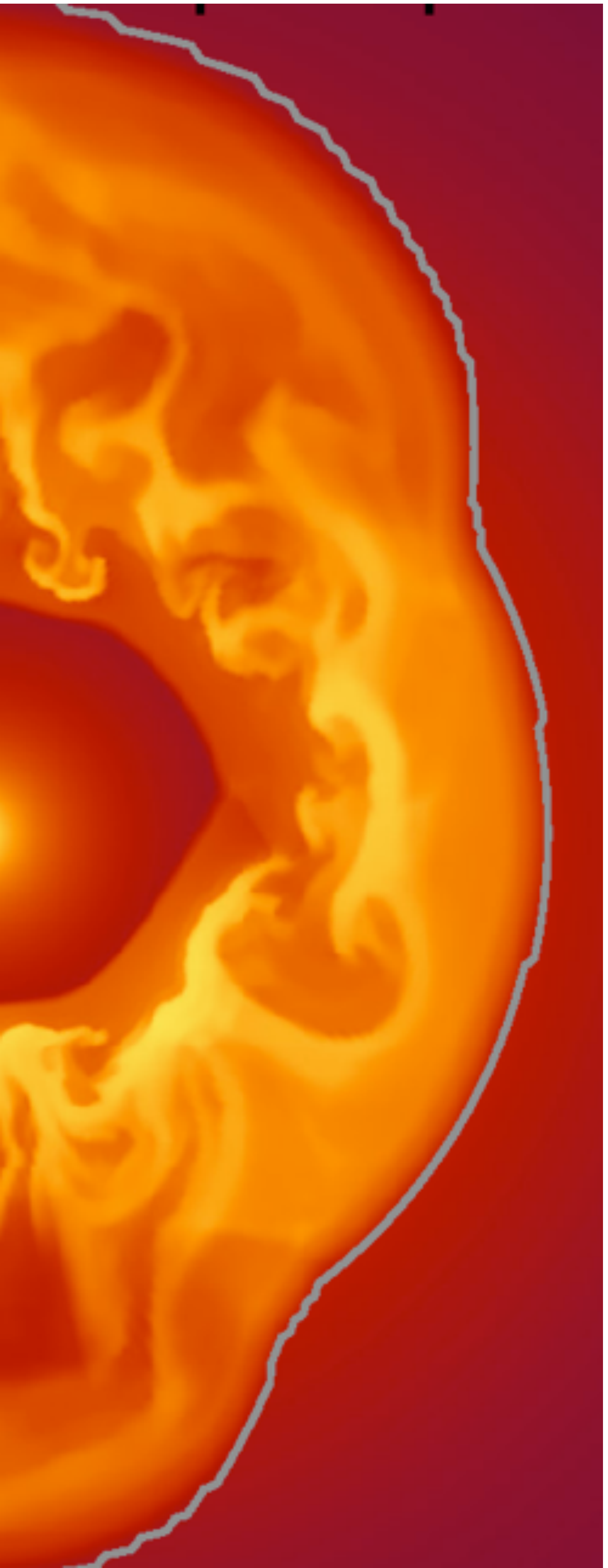


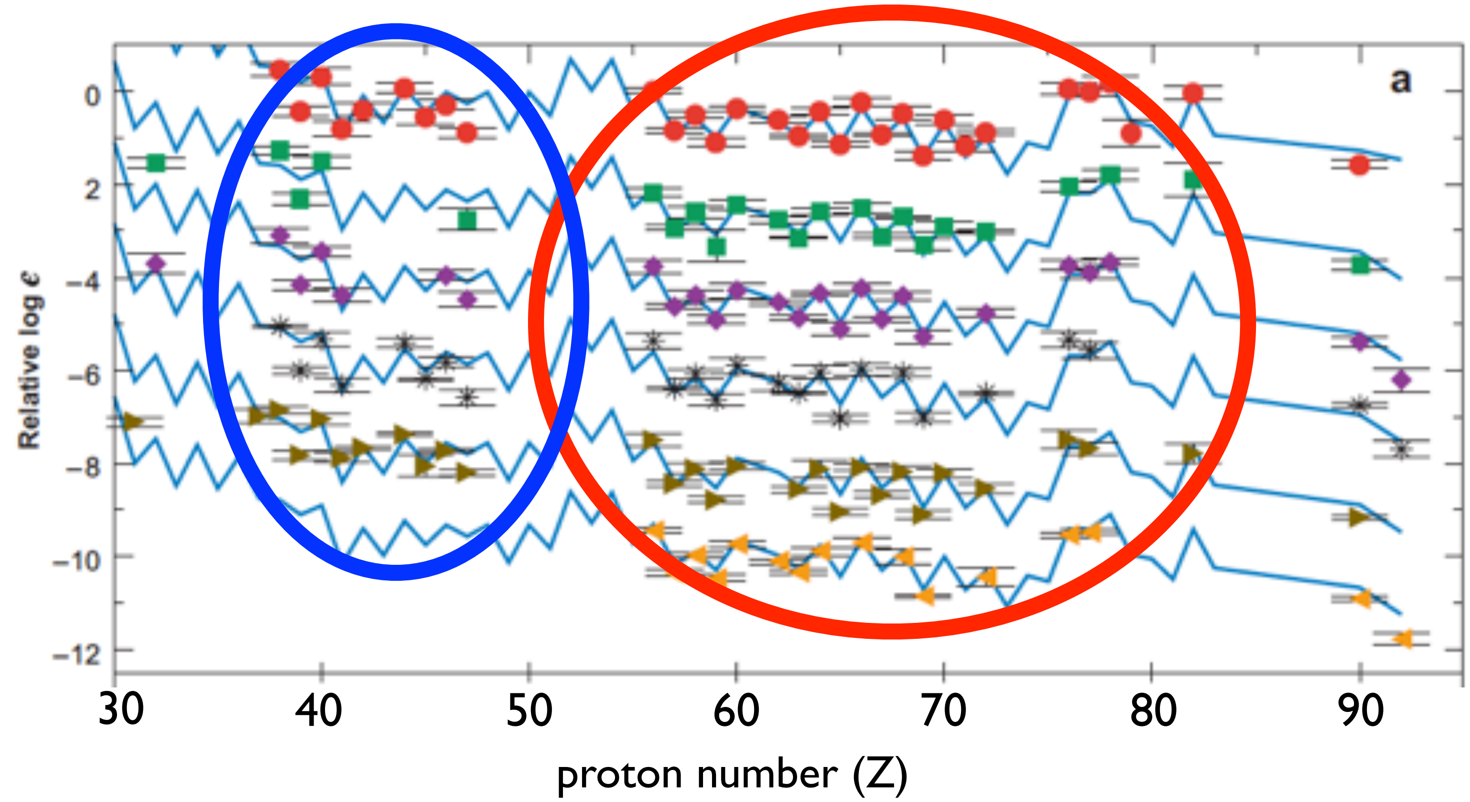
nuclear correlations are key:
trough formation and evolution
peak position

freeze out
final



Conclusions





Lighter heavy elements (LEPP: Sr, Y, Zr)
produced in neutrino-driven winds
νp-process: NiCu cycle

Heavy r-process elements
uncertainties on nuclear physics input
→ big impact on abundances
key masses: from deformed to spherical
→ nuclear correlations