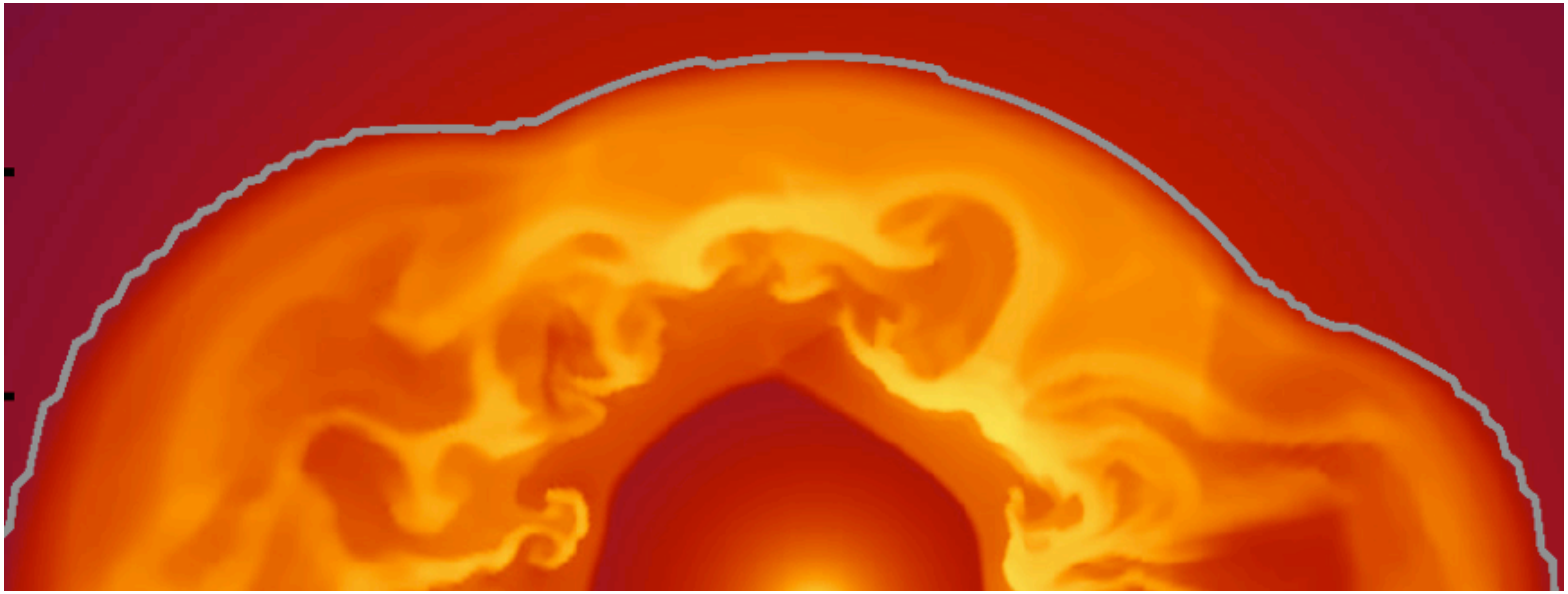
INT Program INT-12-2a
Core-Collapse Supernovae:
Models and Observable Signals

Workshop: Nuclear and neutrino physics

Nucleosynthesis in core-collapse supernovae

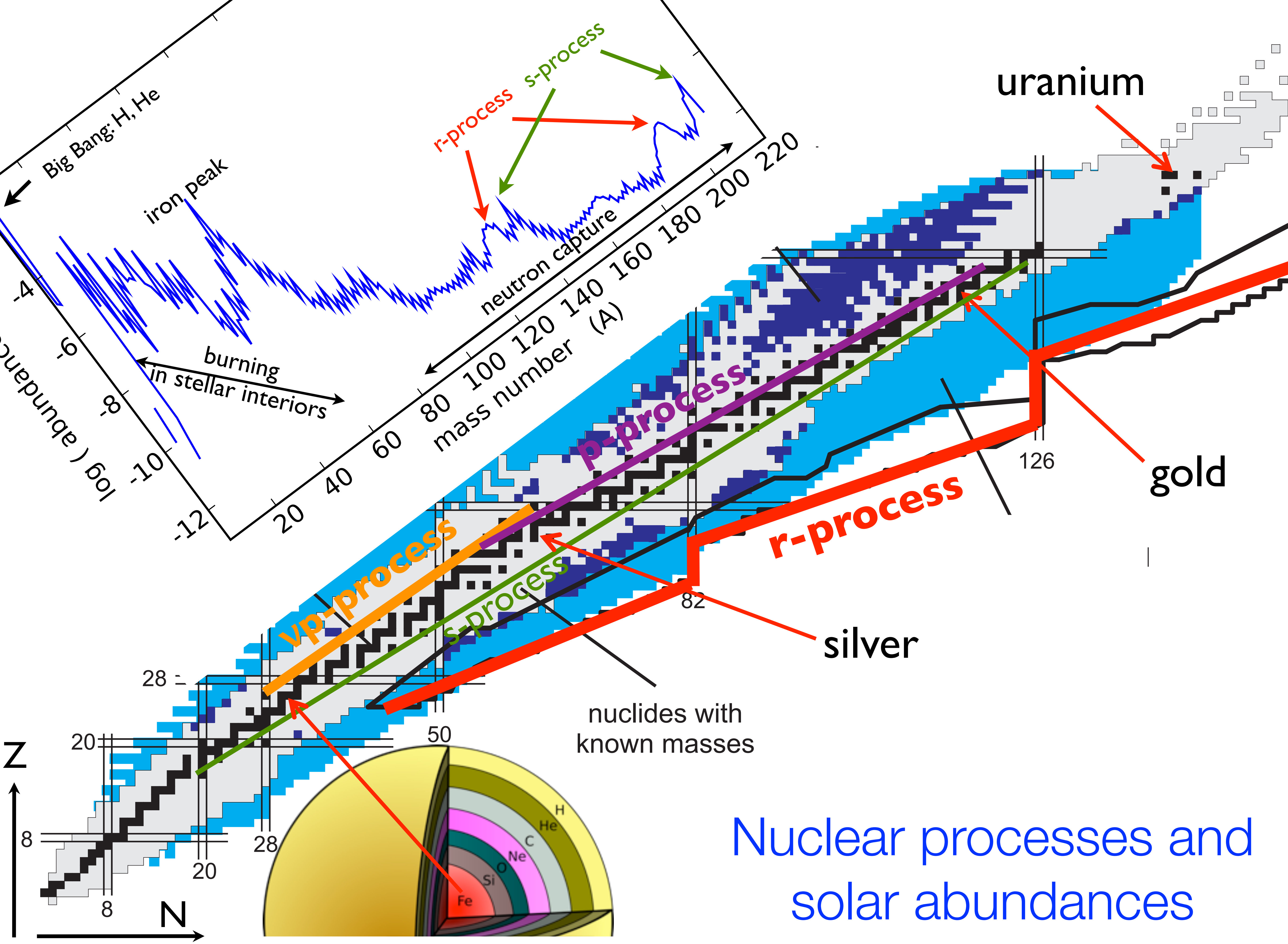


TECHNISCHE
UNIVERSITÄT
DARMSTADT

Almudena Arcones

HELMHOLTZ
GEMEINSCHAFT

GSI



Nuclear processes and solar abundances

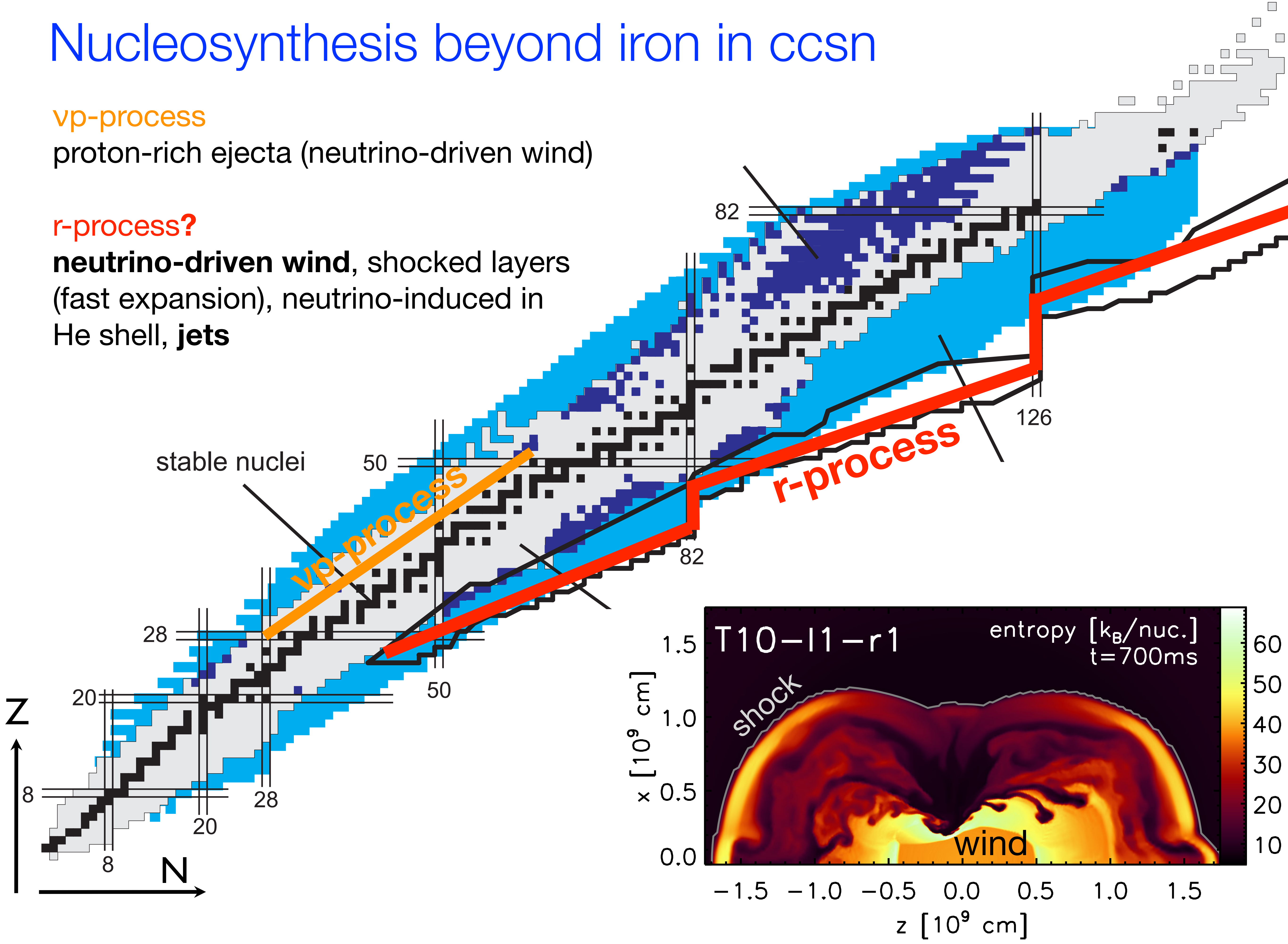
Nucleosynthesis beyond iron in ccsn

νp-process

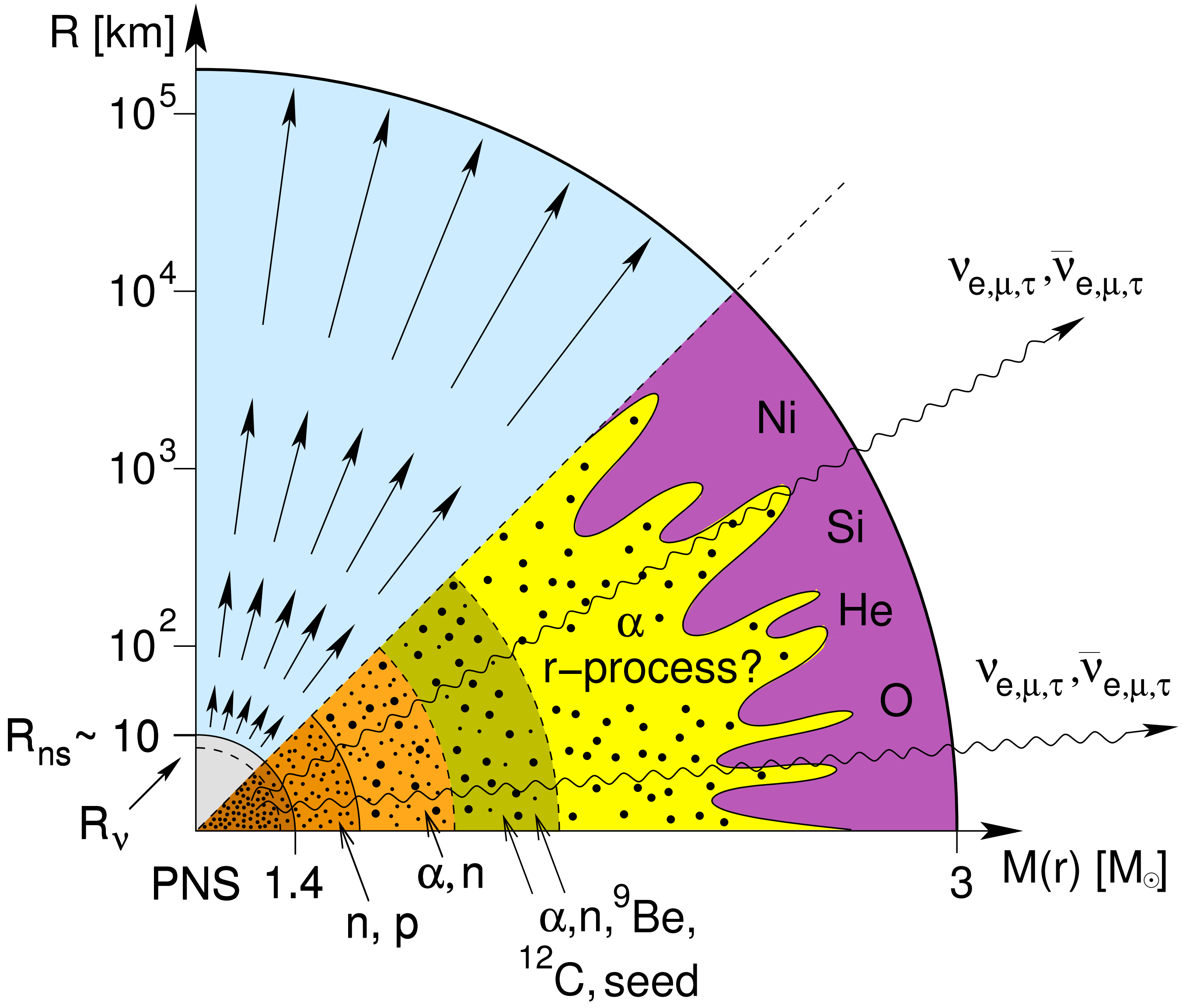
proton-rich ejecta (neutrino-driven wind)

r-process**?**

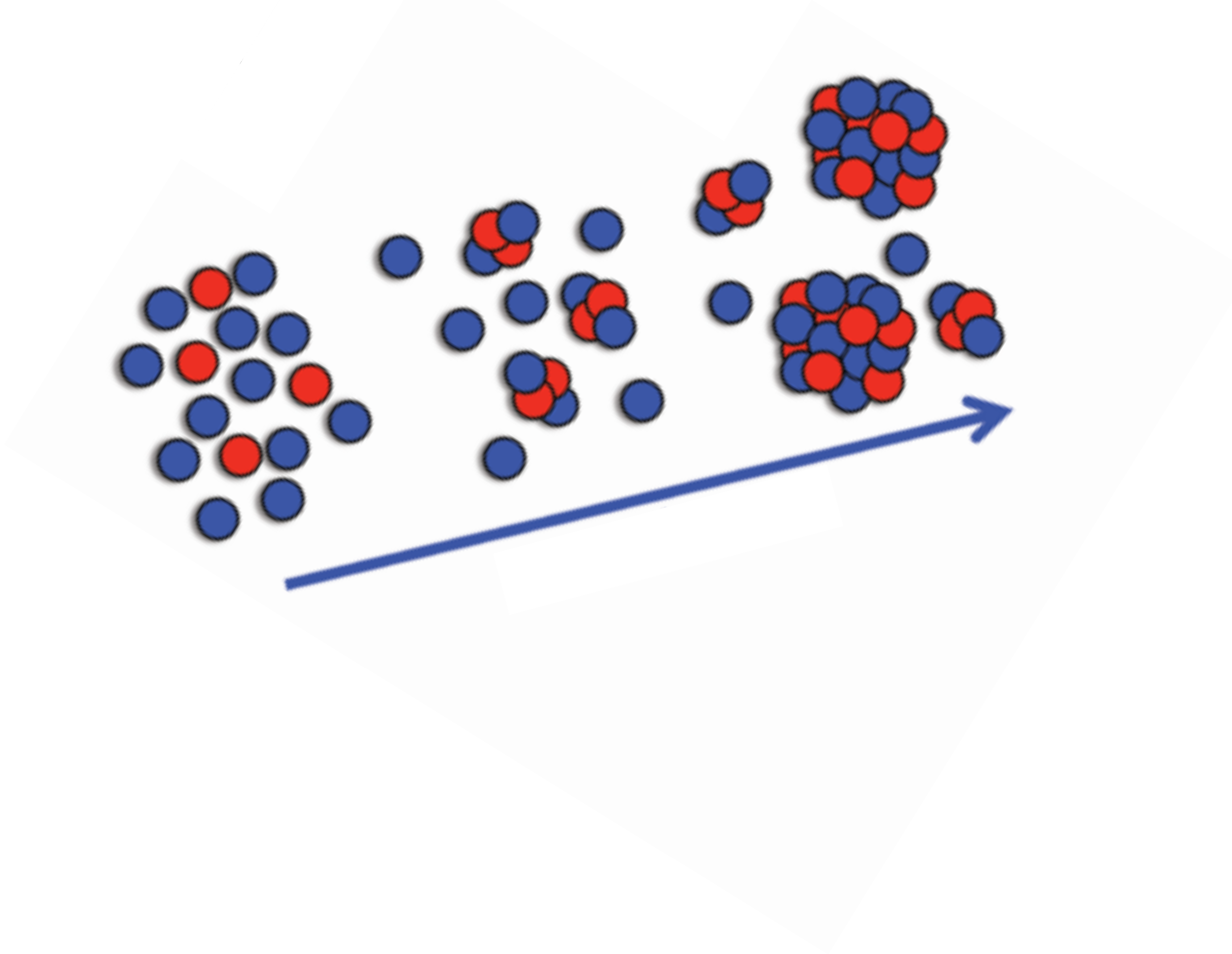
neutrino-driven wind, shocked layers (fast expansion), neutrino-induced in He shell, **jets**



Neutrino-driven winds



neutrons and protons form alpha particles
alpha particles recombine into seed nuclei



NSE → charged particle reactions / α-process → r-process
weak r-process
νp-process

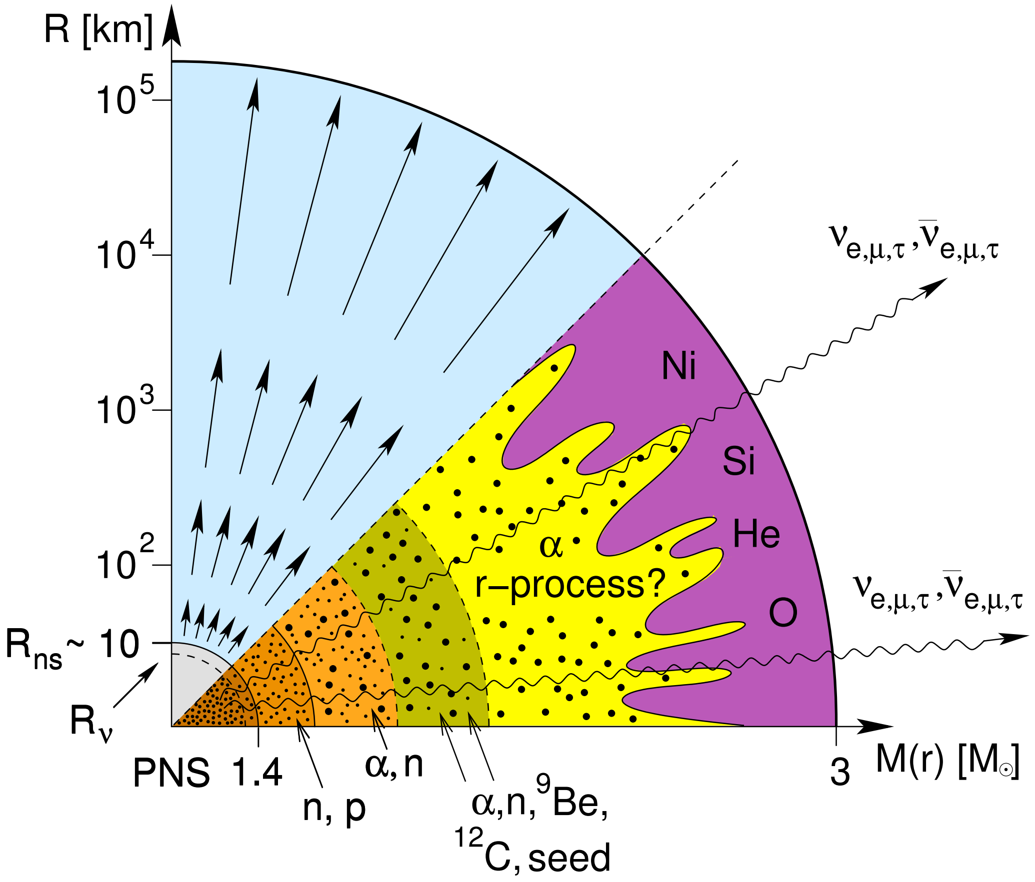
T = 10 - 8 GK   8 - 2 GK

T < 3 GK

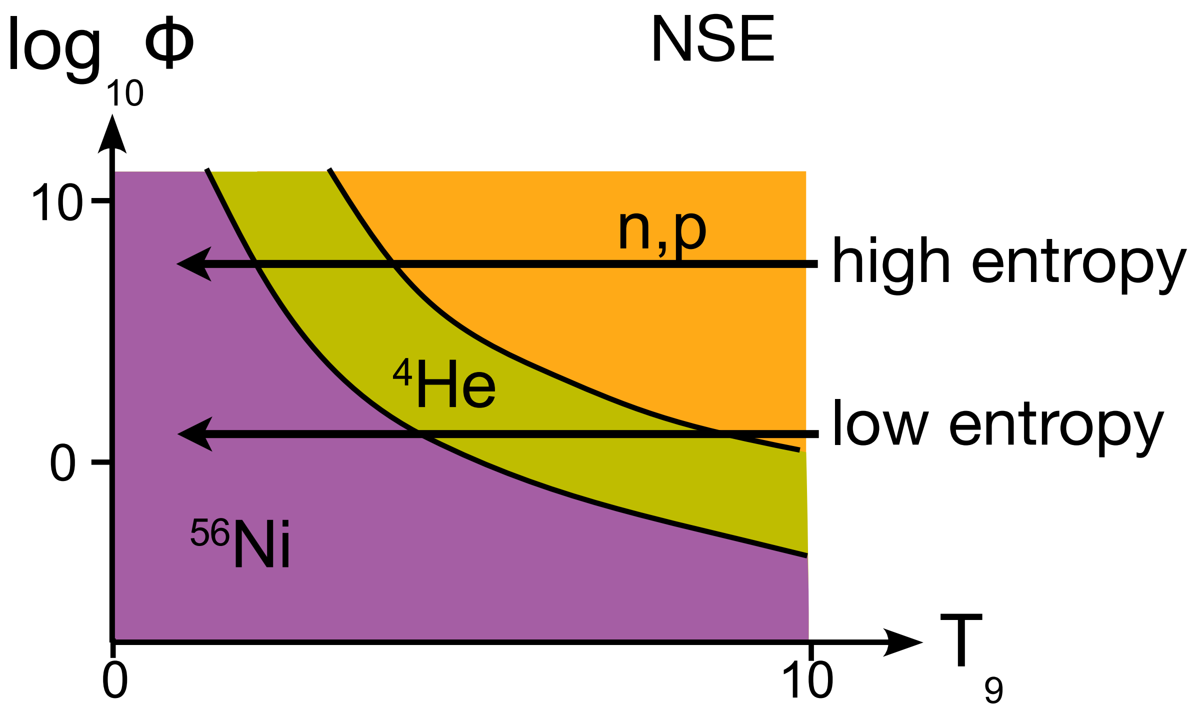
Neutrino-driven wind parameters

r-process ⇒ high neutron-to-seed ratio (Y_n/Y_{seed}~100)

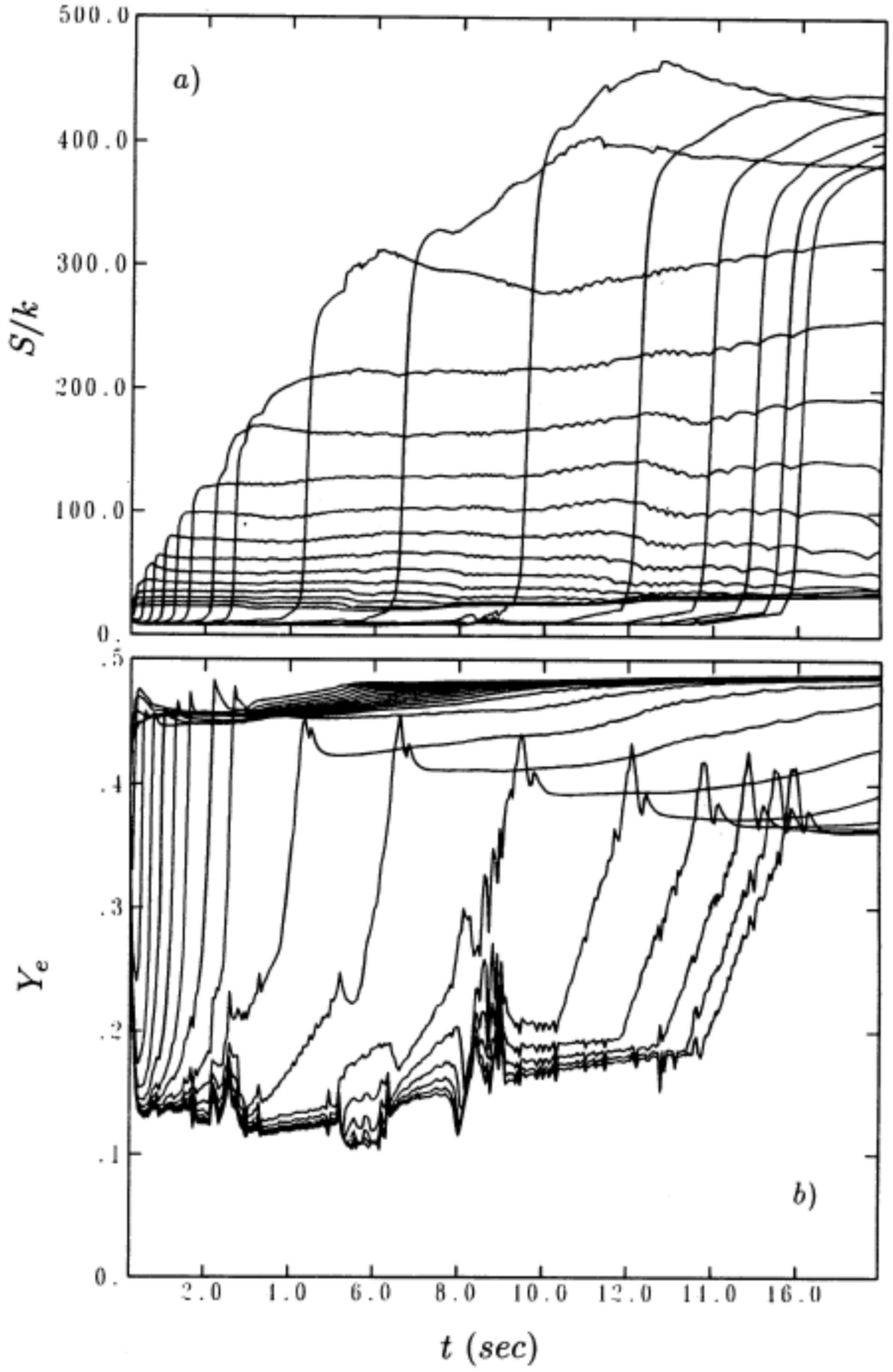
- Short expansion time scale to inhibit α-process and formation of seed nuclei
- High entropy is equivalent to high photon-to-baryon ratio: photons dissociate seed nuclei into nucleons
- Electron fraction: $Y_e<0.5$



Entropy per baryon in relativistic gas:
$s \propto (kT^3) / (\rho N_A) \Rightarrow s = 10/\Phi$



Photon-to-baryon ratio:
$\Phi = n_\gamma / (\rho N_A) \propto (kT^3) / (\rho N_A)$



Wind and r-process

Meyer et al. 1992 and Woosley et al. 1994:
r-process: high entropy and low Y_e

Witti et al., Takahasi et al. 1994 needed factor 5.5 increased in entropy

Qian & Woosley 1996: analytic model

$$
\begin{aligned}
\dot{M} &\propto L_\nu^{5/3}\,\epsilon_\nu^{10/3}\,R_{ns}^{5/3}\,M_{ns}^{-2}\,,\\
s &\propto L_\nu^{-1/6}\,\epsilon_\nu^{-1/3}\,R_{ns}^{-2/3}\,M_{ns}\,,\\
\tau &\propto L_\nu^{-1}\,\epsilon_\nu^{-2}\,R_{ns}\,M_{ns}\,.
\end{aligned}
$$

Thompson, Otsuki, Wanajo, ... (2000-...)
parametric steady state winds

Electron fraction

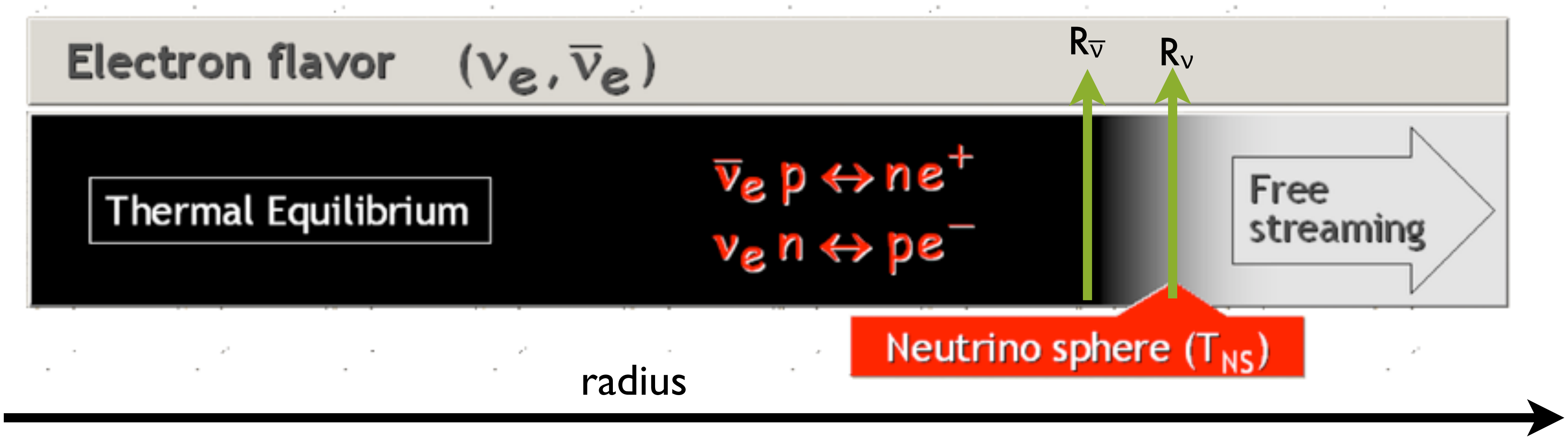
depends on accuracy of supernova neutrino transport and on details of neutrino interactions in outer layers of neutron star.

$$Y_e \approx \left[1 + \frac{L_{\bar{\nu}_e}(\epsilon_{\bar{\nu}_e} - 2\Delta + 1.2\Delta^2/\epsilon_{\bar{\nu}_e})}{L_{\nu_e}(\epsilon_{\nu_e} + 2\Delta + 1.2\Delta^2/\epsilon_{\nu_e})}\right]^{-1}$$

Qian & Woosley 1996

($\Delta = m_n - m_p$)

The neutrino energies are determined by the position (temperature) where neutrinos decouple from matter: neutrinosphere



Raffelt 2001

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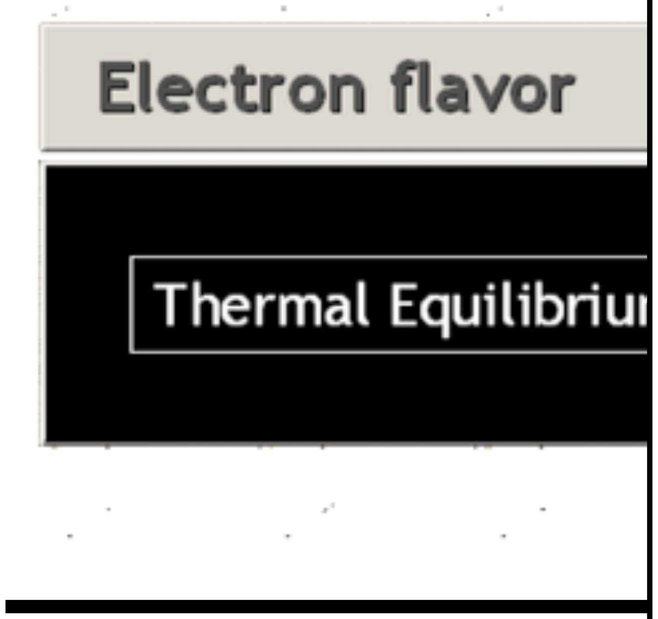
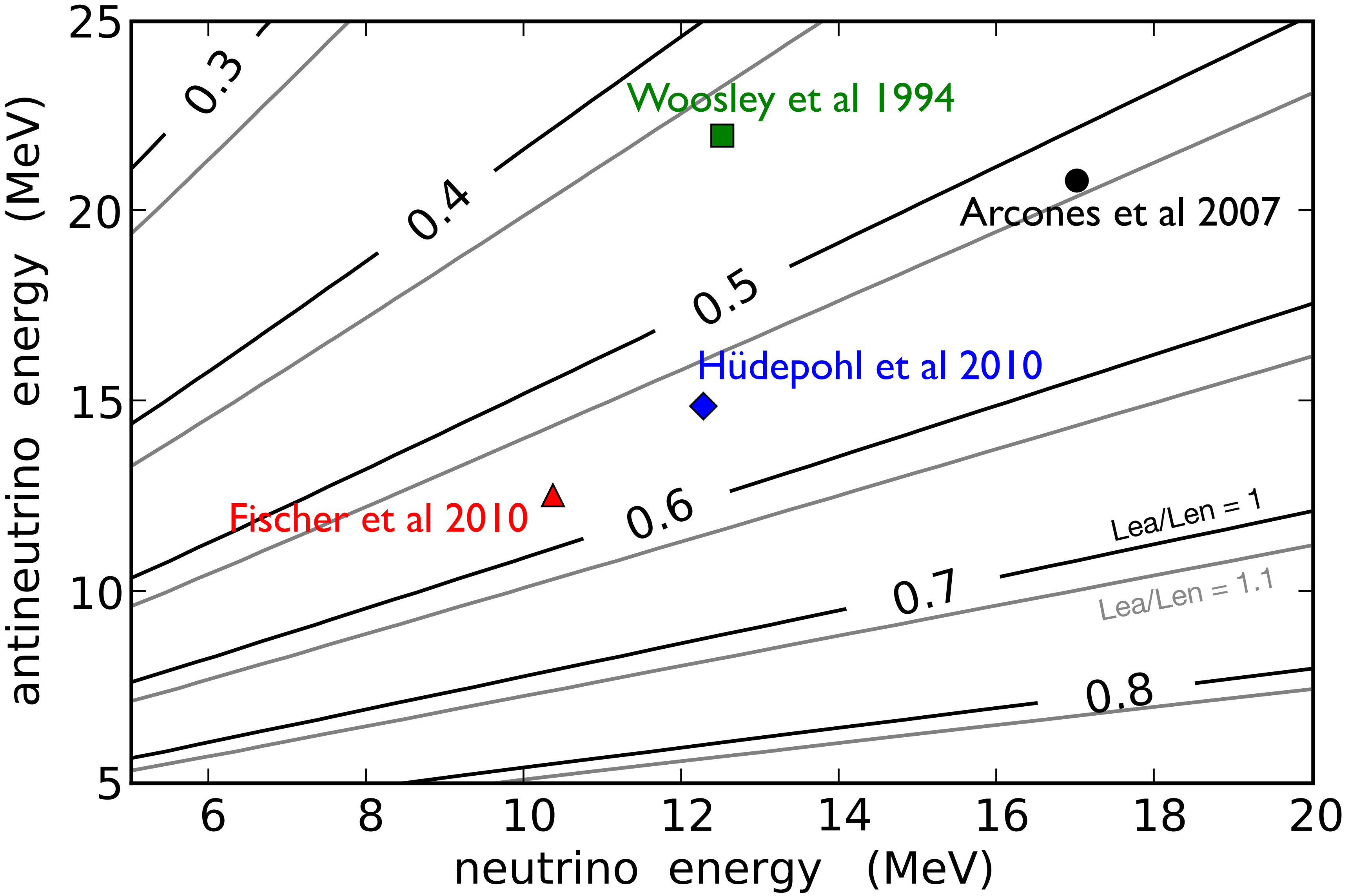
The neutrino energies ar
decouple from matter: n

Raffelt 2001



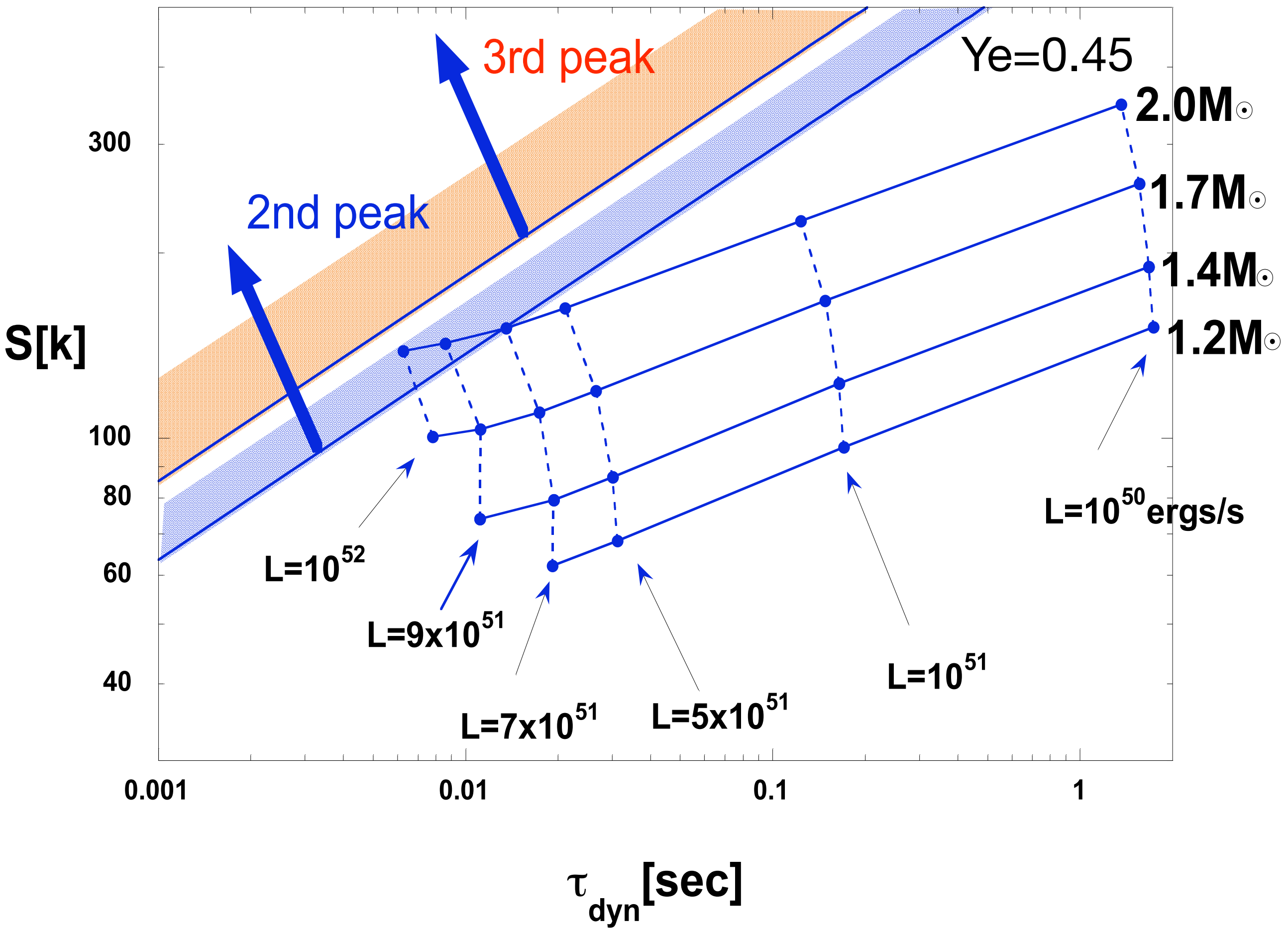
$Y_e < 0.5$ if $\epsilon_{\bar{\nu}_e} - \epsilon_{\nu_e} \gtrsim 4\Delta \approx 5\ \mathrm{MeV}$

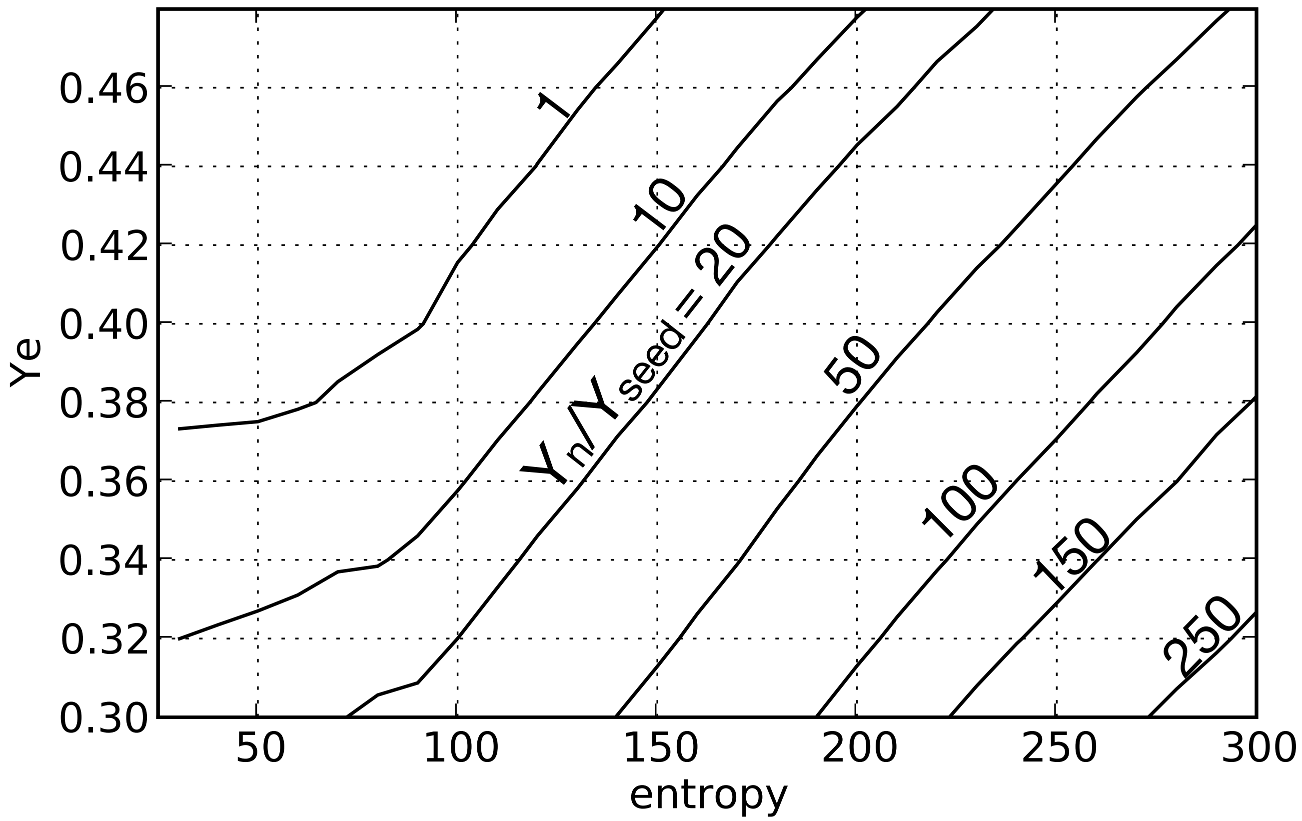


Wind parameters and r-process

Necessary conditions identified by steady-state models (e.g., Otsuki et al. 2000, Thompson et al. 2001)

Otsuki et al. 2000



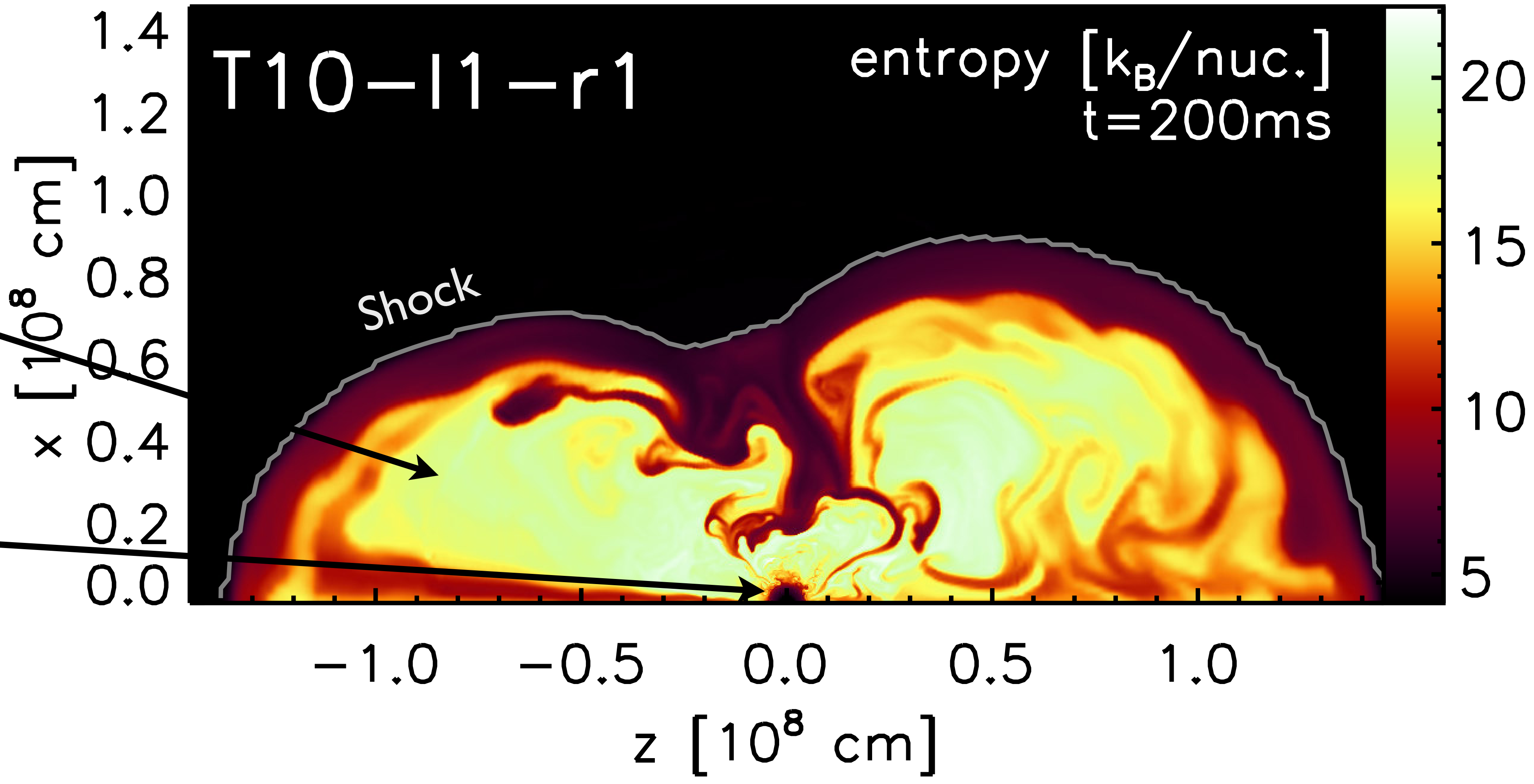


Conditions are not realized in recent simulations
(Arcones et al. 2007, Fischer et al. 2010, Hüdepohl et al. 2010, Roberts et al. 2010, Arcones & Janka 2011)

$S_{wind} = 50 - 120\ k_B/\text{nuc}$ $\tau = \text{few ms}$ $Y_e > 0.5?$

Additional ingredients: wind termination, extra energy source, rotation and magnetic fields, neutrino oscillations

Core-collapse supernova simulations



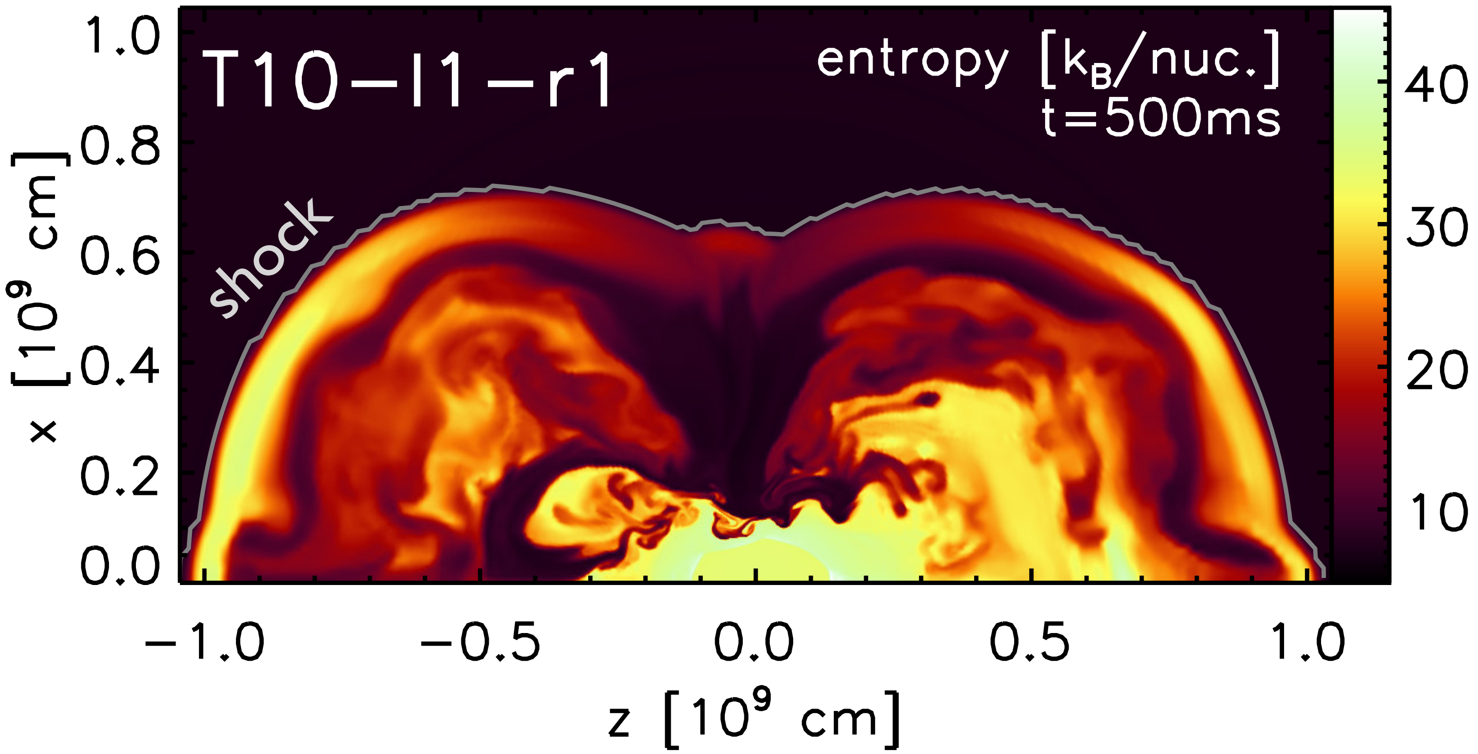
Hot bubble

Proto-neutron star

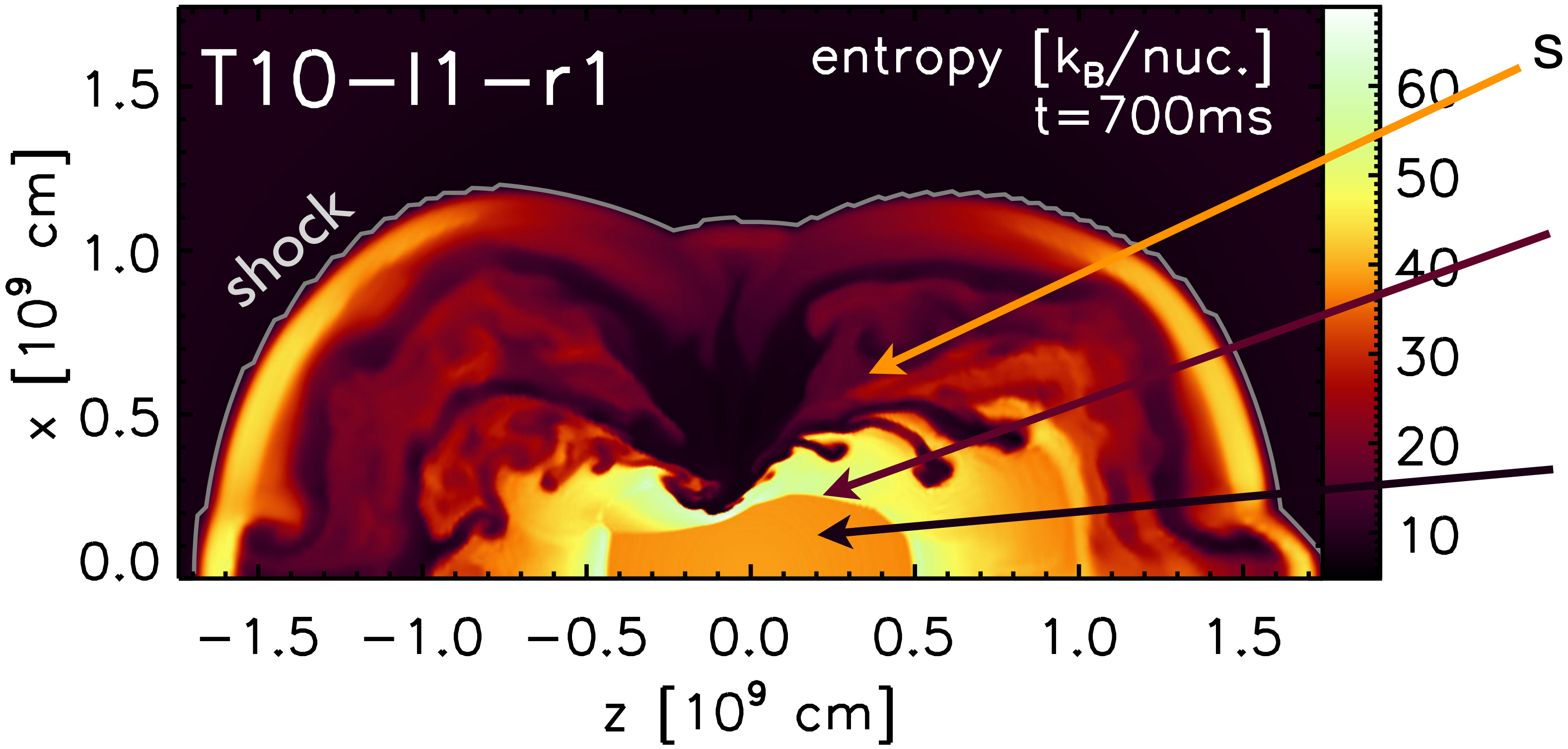
Long-time hydrodynamical simulations:

- 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

Neutrino-driven wind in 2D



Supersonic neutrino-driven wind collides with slow supernova ejecta: reverse shock

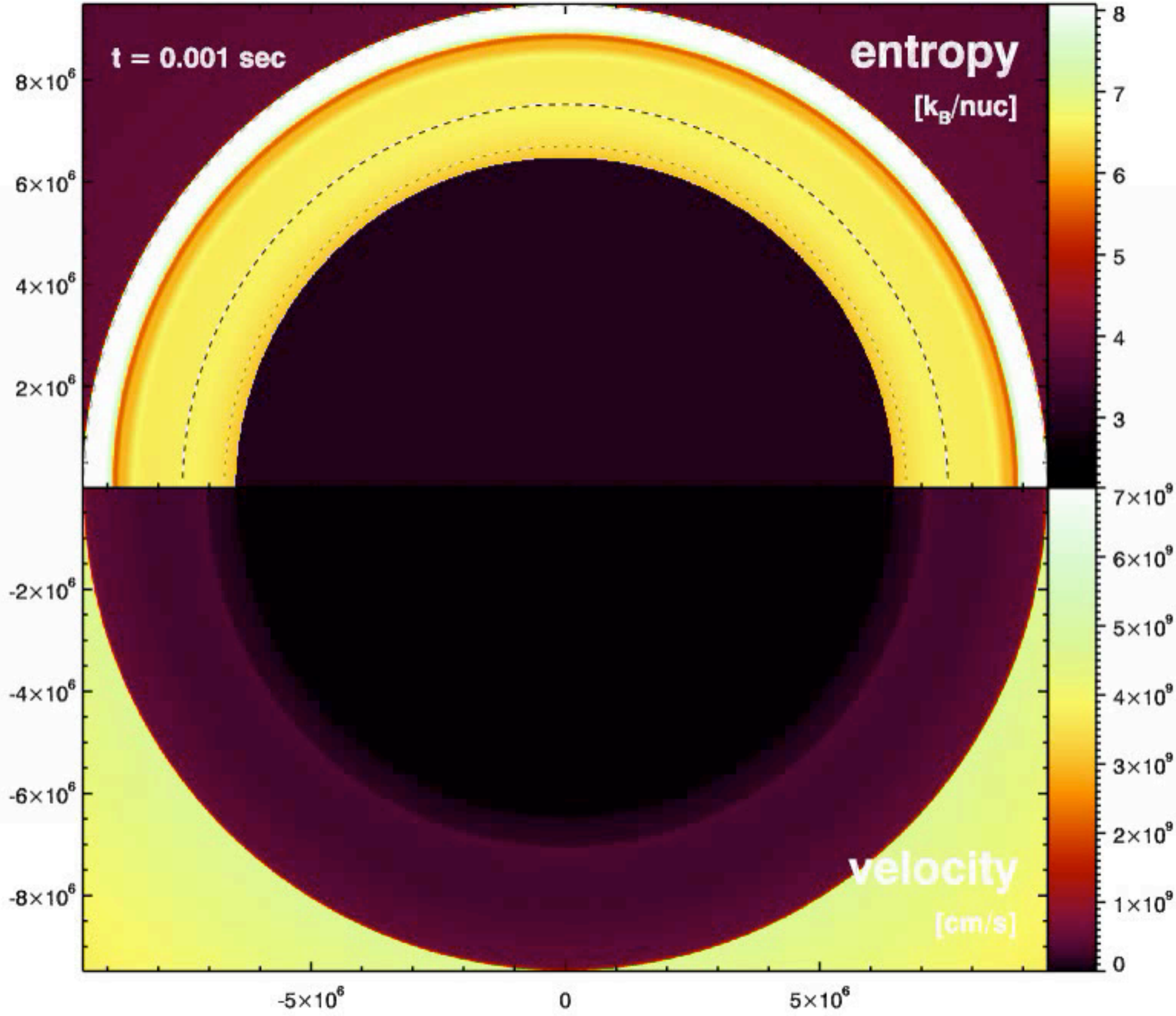


slow ejecta

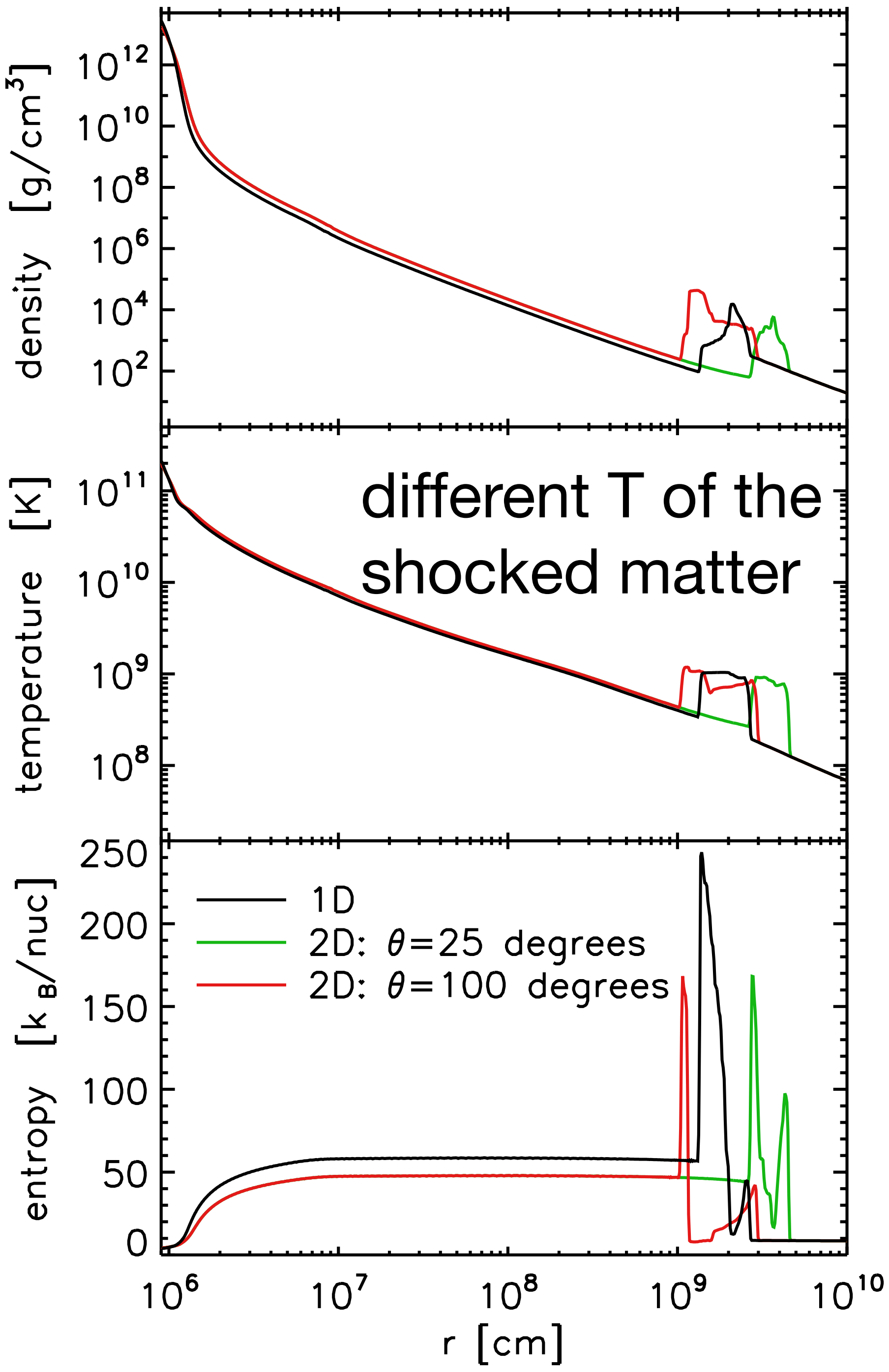
reverse shock

neutrino-driven wind

Arcones & Janka (2011)

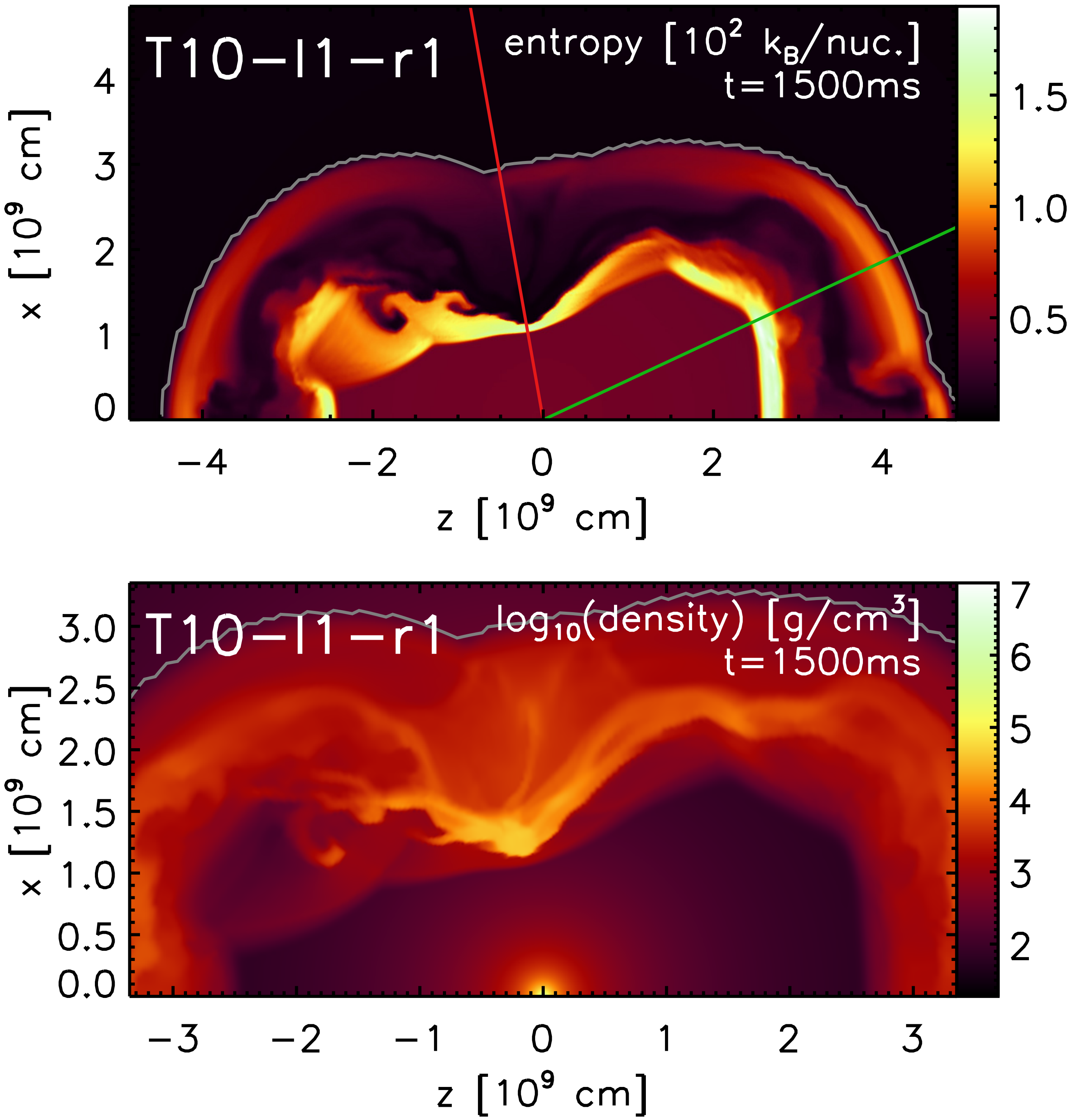


Neutrino-driven wind in 2D and 1D

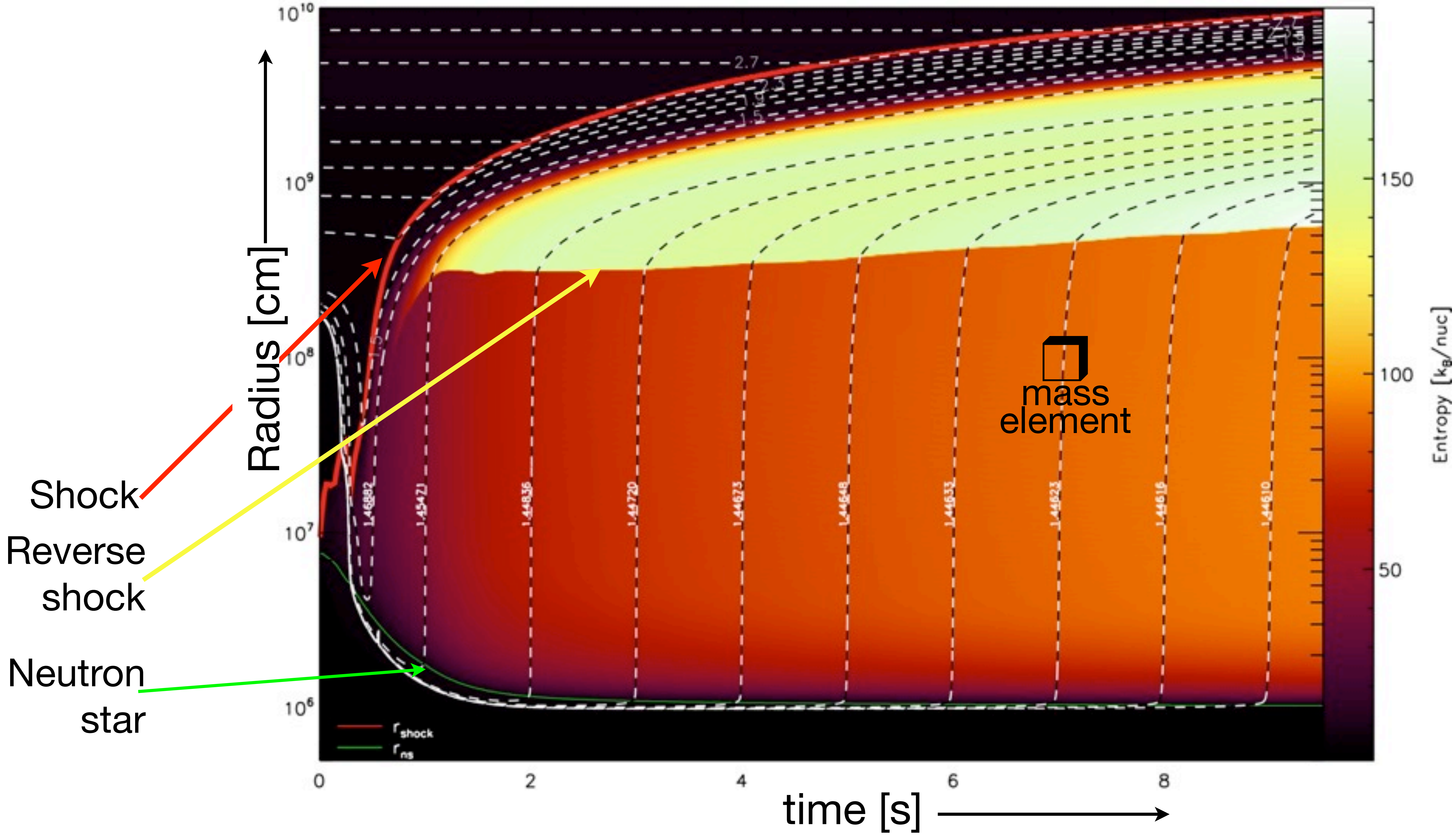


Spherically symmetric wind

different T of the shocked matter



1D simulations for nucleosynthesis studies



Arcones et al 2007

Radius [cm]

time [s]

mass element

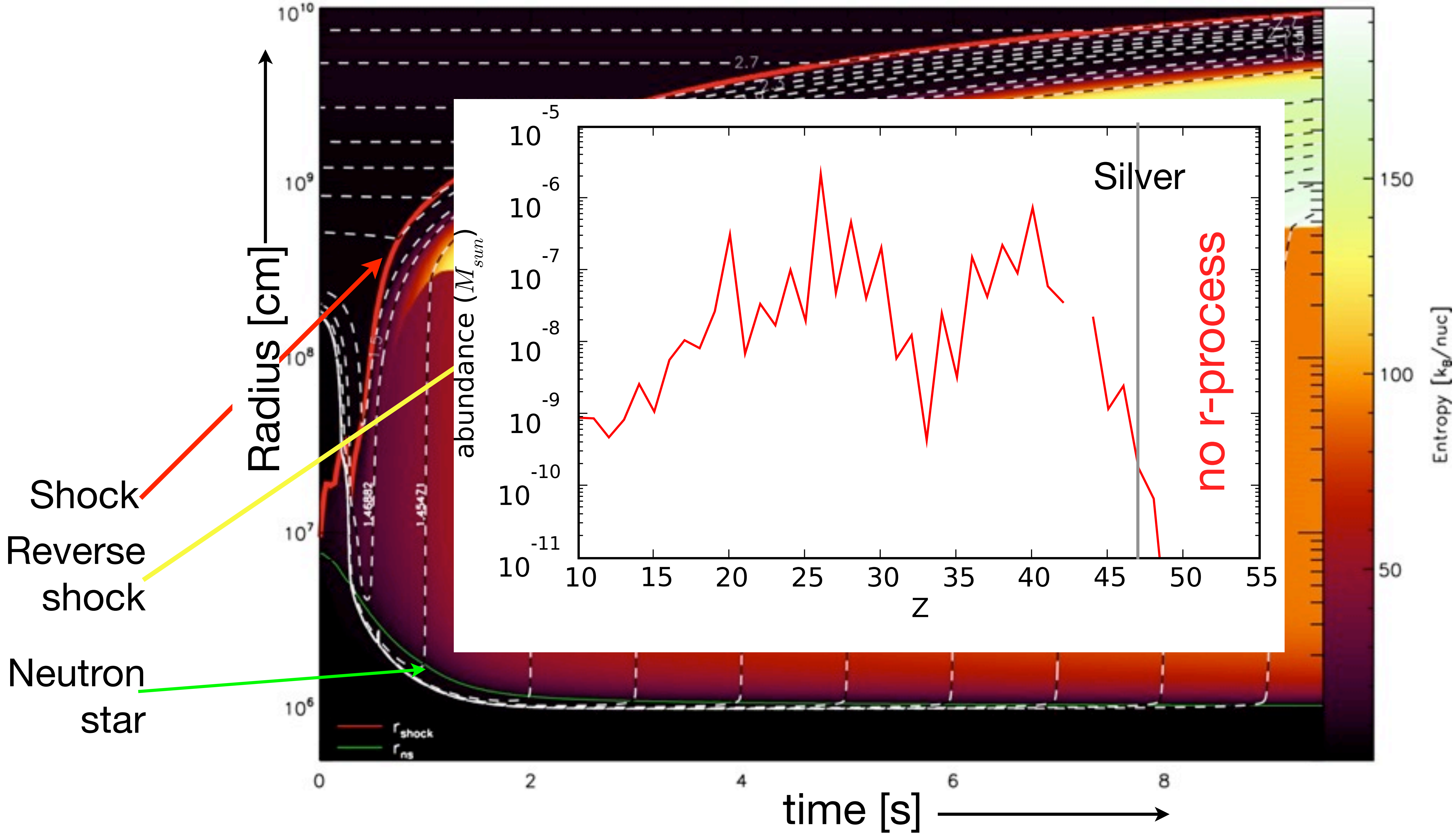
Shock

Reverse shock

Neutron star

1D simulations for nucleosynthesis studies

Arcones et al 2007



no r-process

Shock

Reverse shock

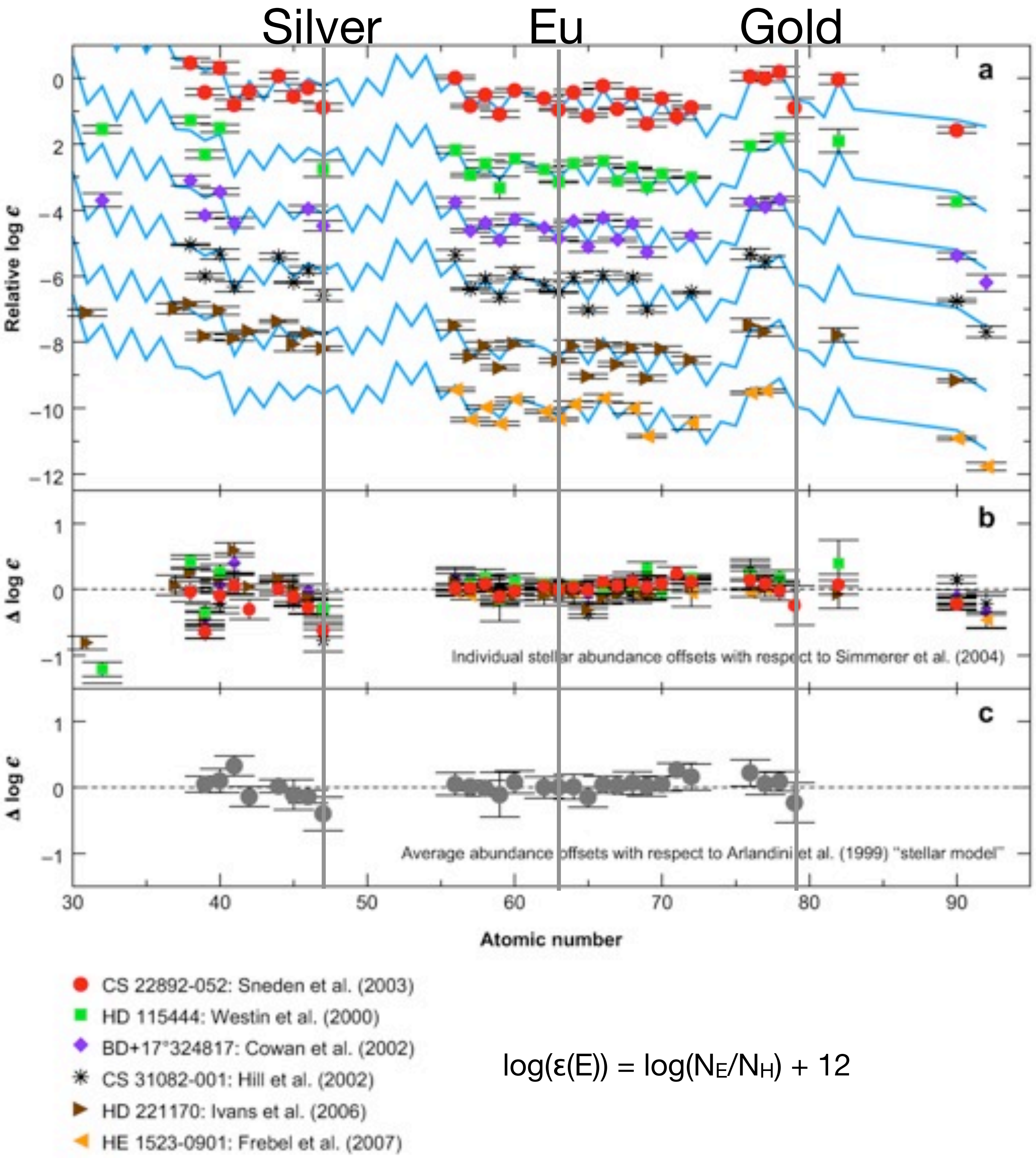
Neutron star

Nucleosynthesis beyond iron in ultra metal-poor stars

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

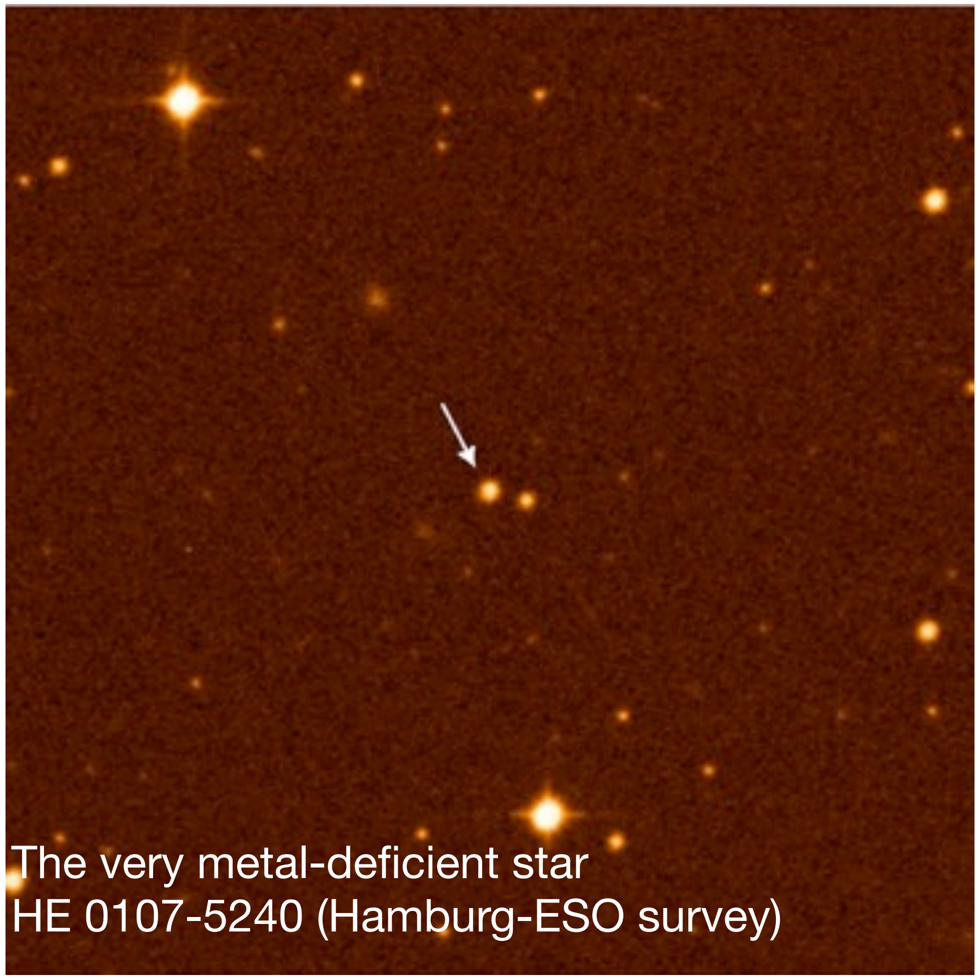
Robust r-process for 56<Z<83

Scatter for lighter heavy elements, Z~40



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

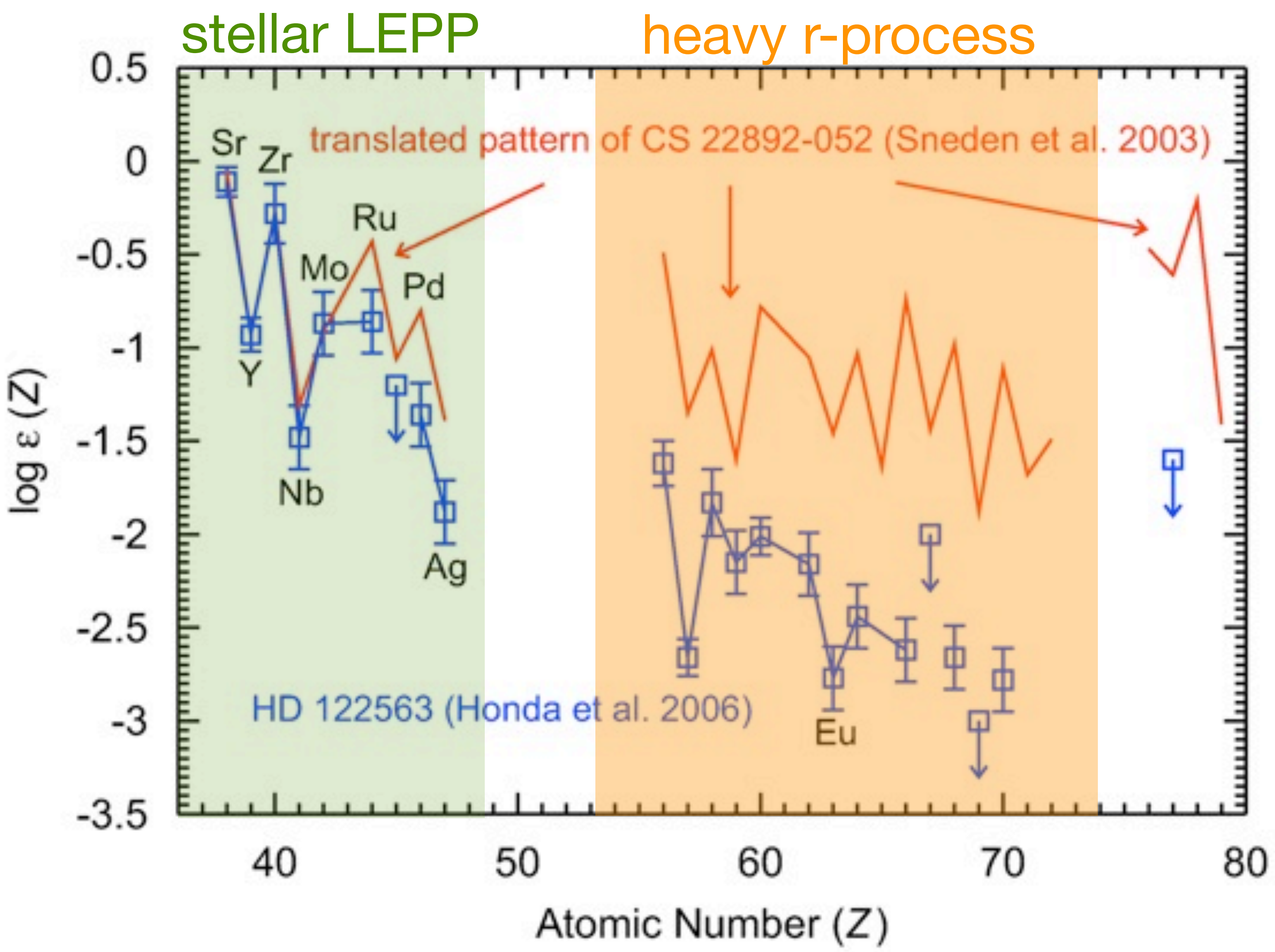
Sneden, Cowan, Gallino 2008



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

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):



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

LEPP contributes 20-30% of solar Sr-Y-Zr and explains under-productions of “s-only” isotopes from ^{96}Mo to ^{130}Xe

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

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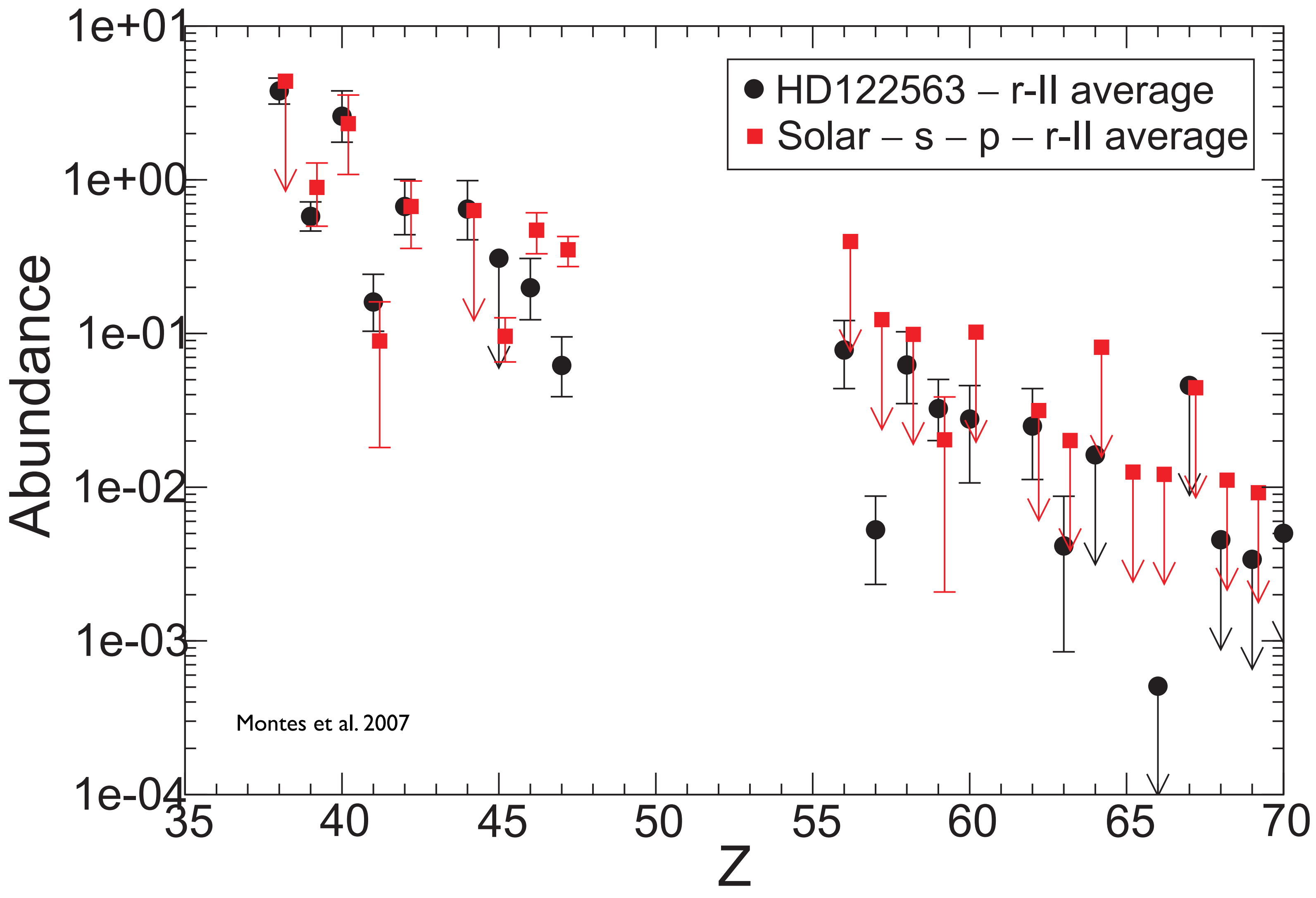

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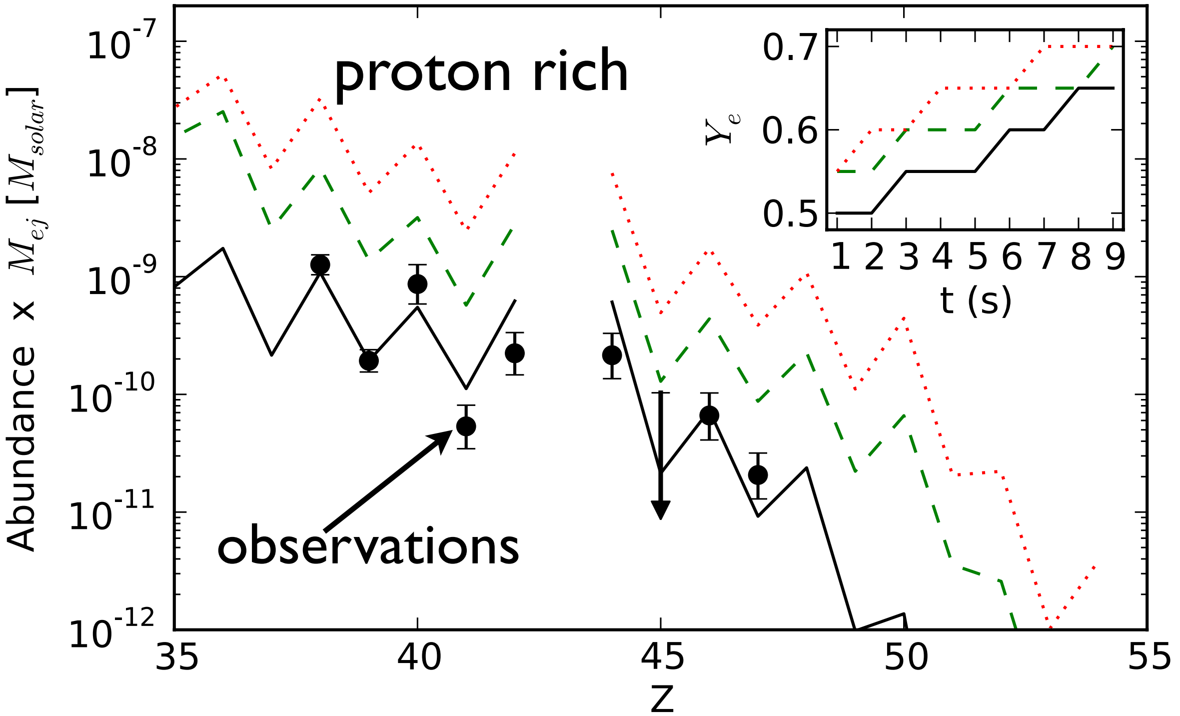
Lighter heavy elements in neutrino-driven winds

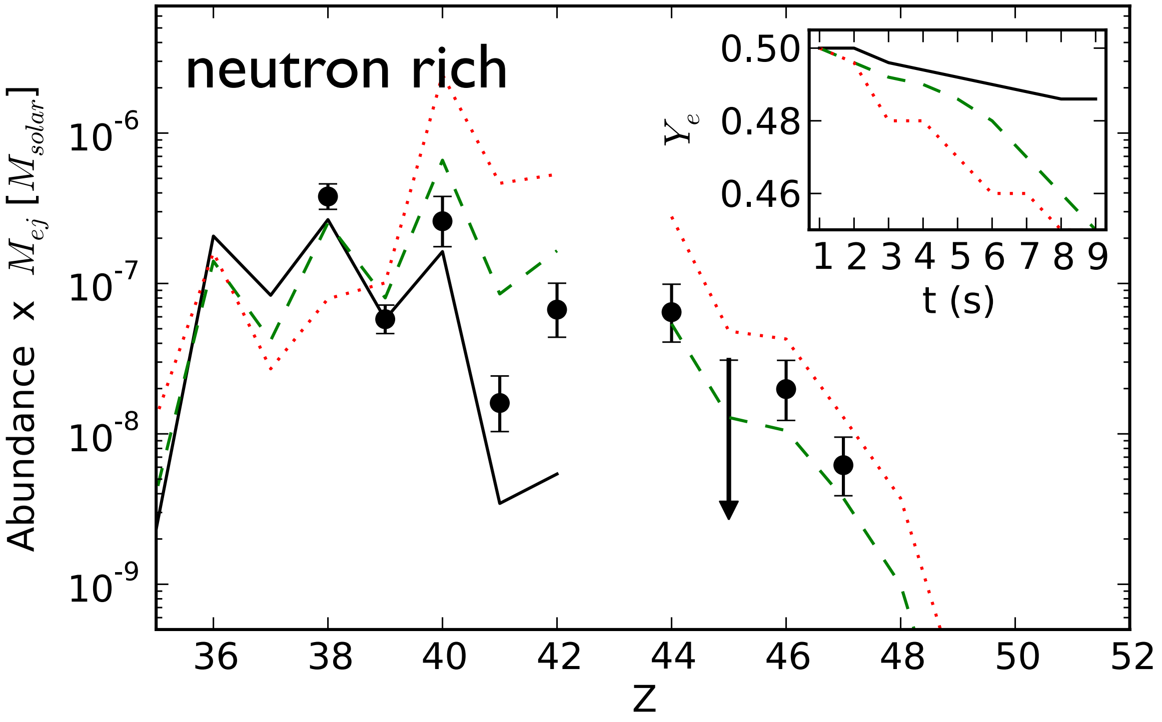
Can the LEPP pattern be produced based on neutrino-driven simulations?

Which nuclear process is the LEPP? Charged-particle reactions (Qian & Wasserburg 2001)

νp-process



weak r-process



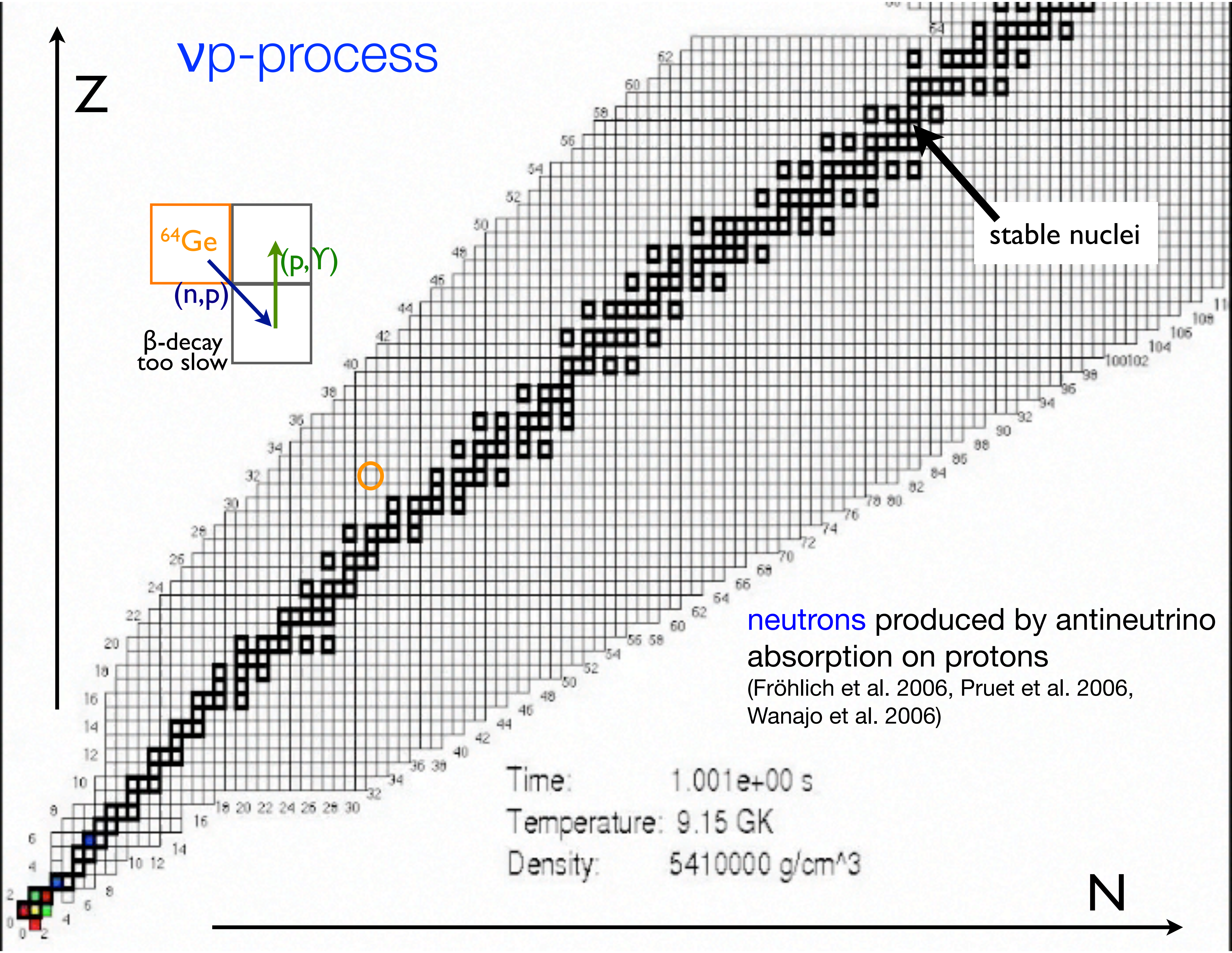
Observation pattern can be reproduced!

Production of p-nuclei

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

(Arcones & Montes, 2011)

νp-process



^{64}Ge

(n,p)

(p,γ)

β-decay
too slow

stable nuclei

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

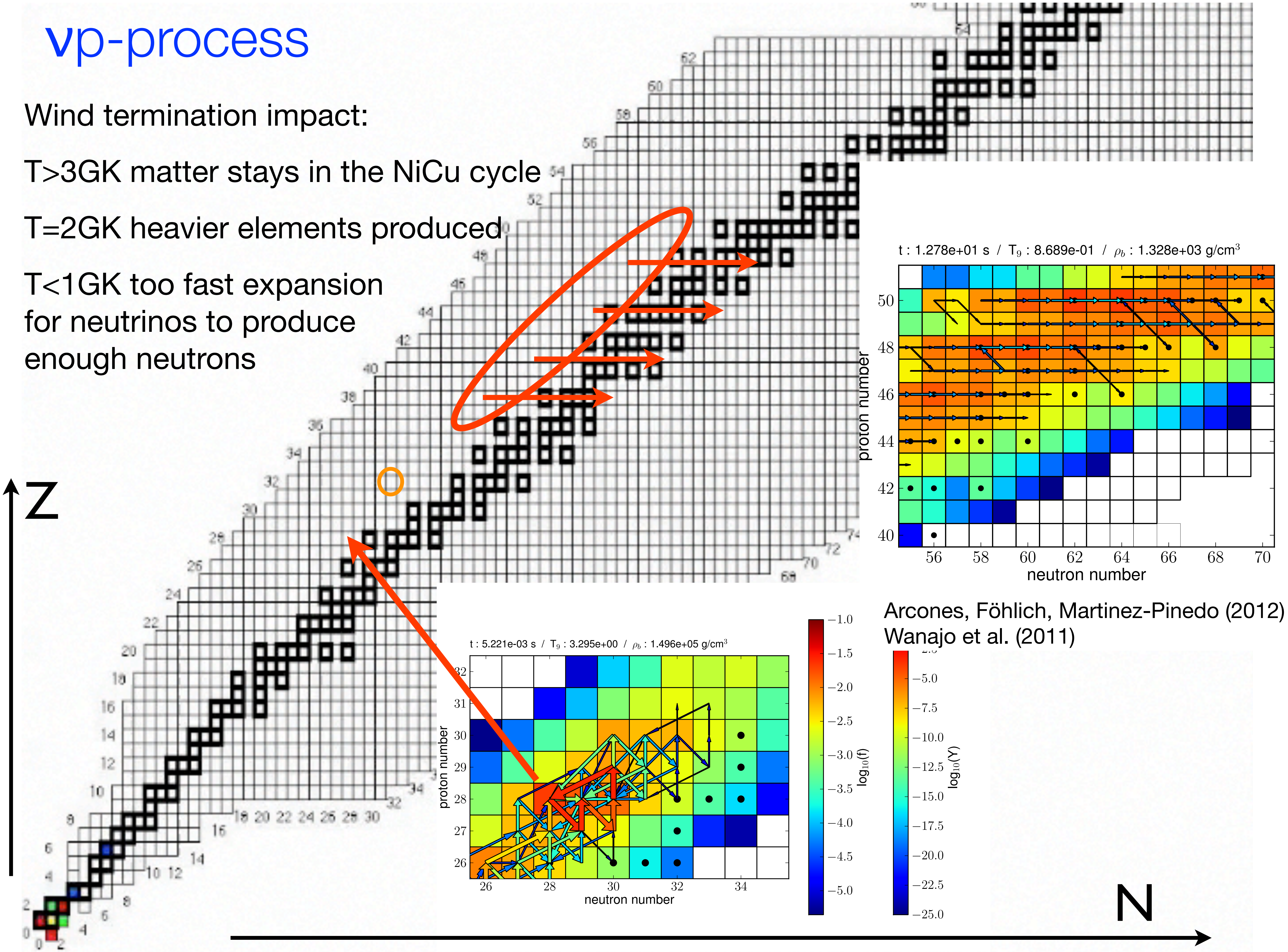
νp-process

Wind termination impact:

T>3GK matter stays in the NiCu cycle

T=2GK heavier elements produced

T<1GK too fast expansion for neutrinos to produce enough neutrons



Arcones, Föhlich, Martinez-Pinedo (2012)
Wanajo et al. (2011)

νp-process

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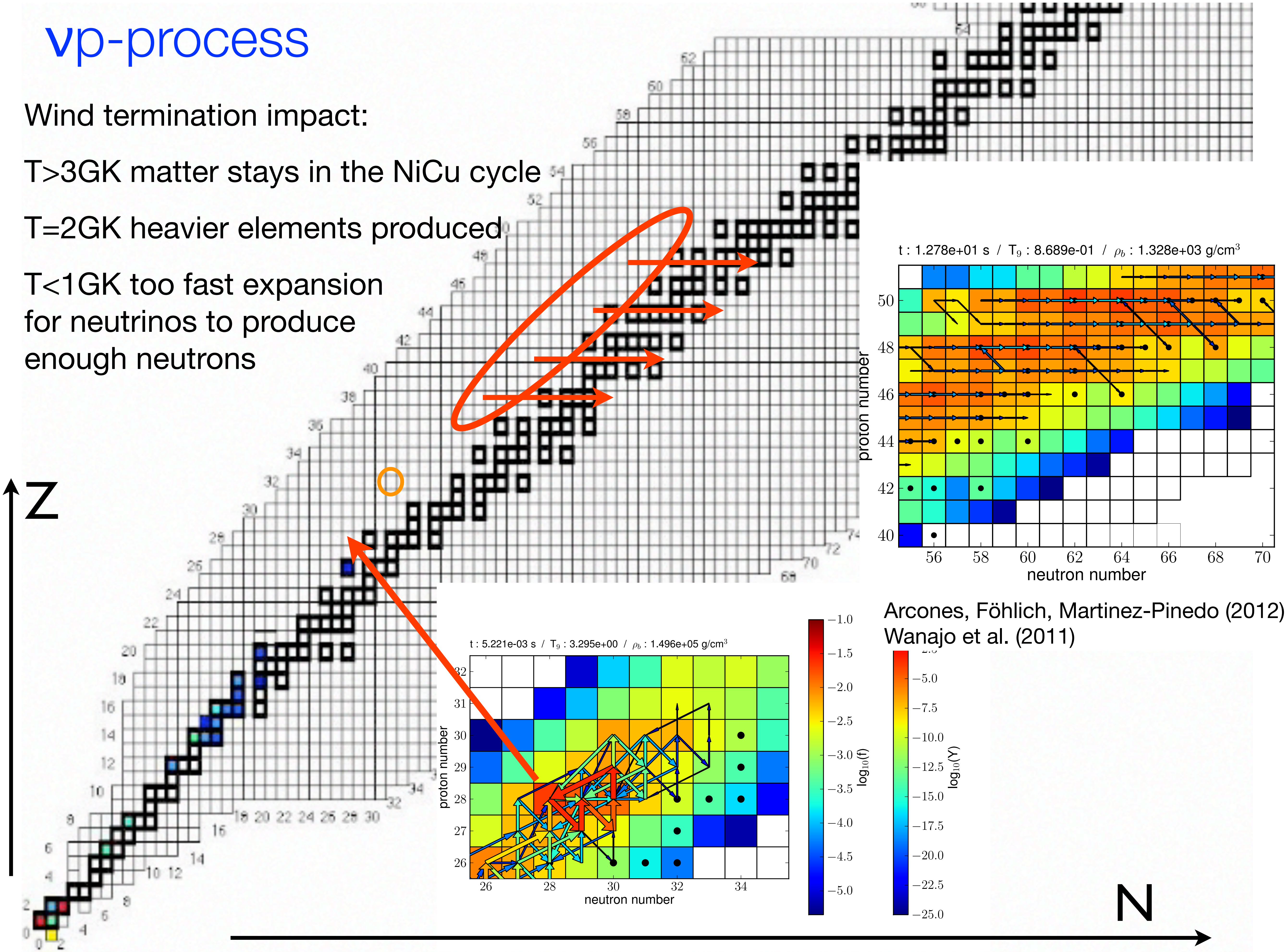


Arcones, Föhlich, Martinez-Pinedo (2012)
Wanajo et al. (2011)

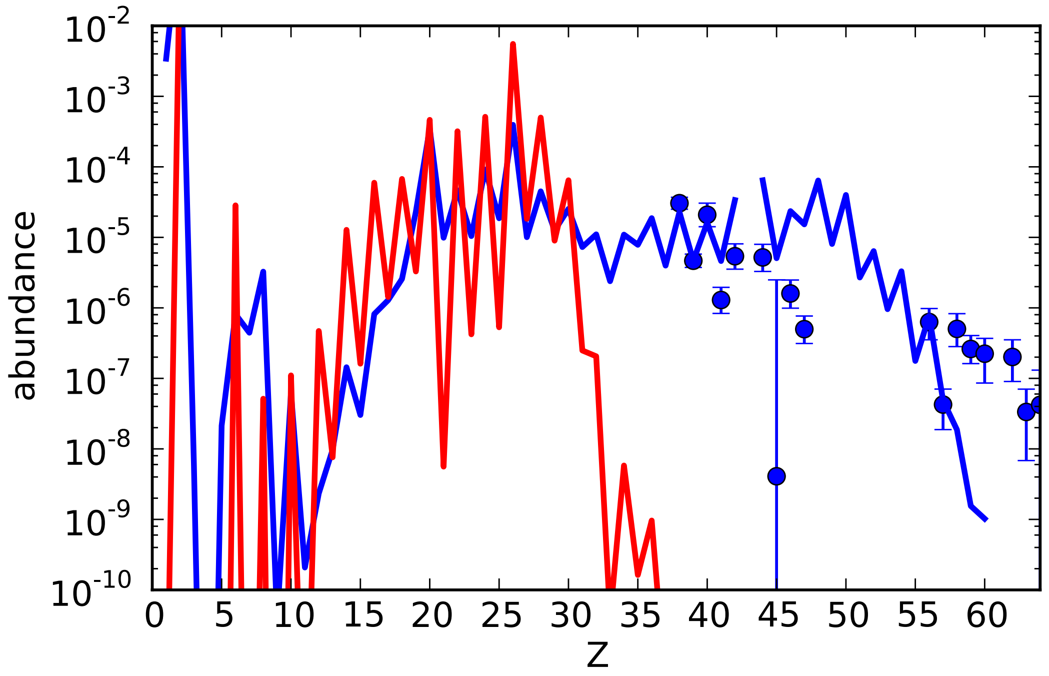
νp-process and dynamical evolution

high temperature

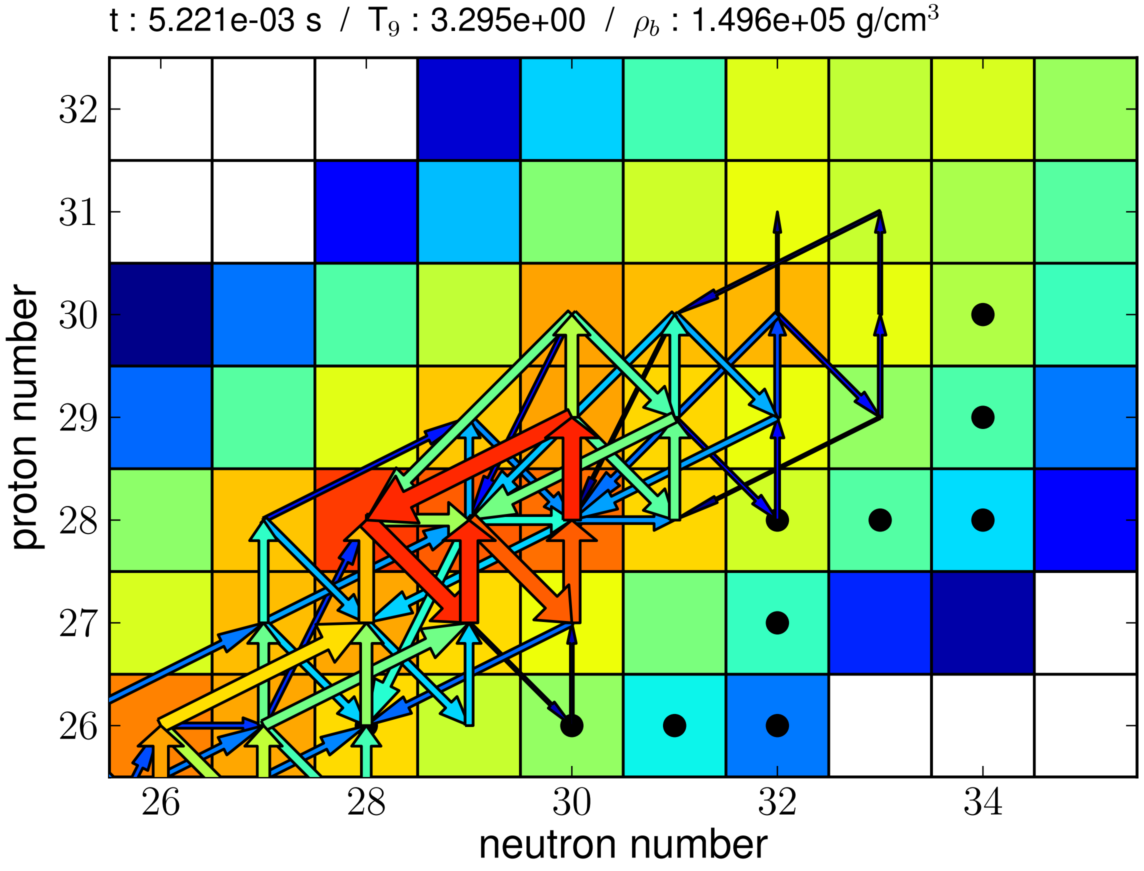
$^{59}\mathrm{Cu}(p,\alpha)^{56}\mathrm{Ni}$ → NiCu cycle

low temperature

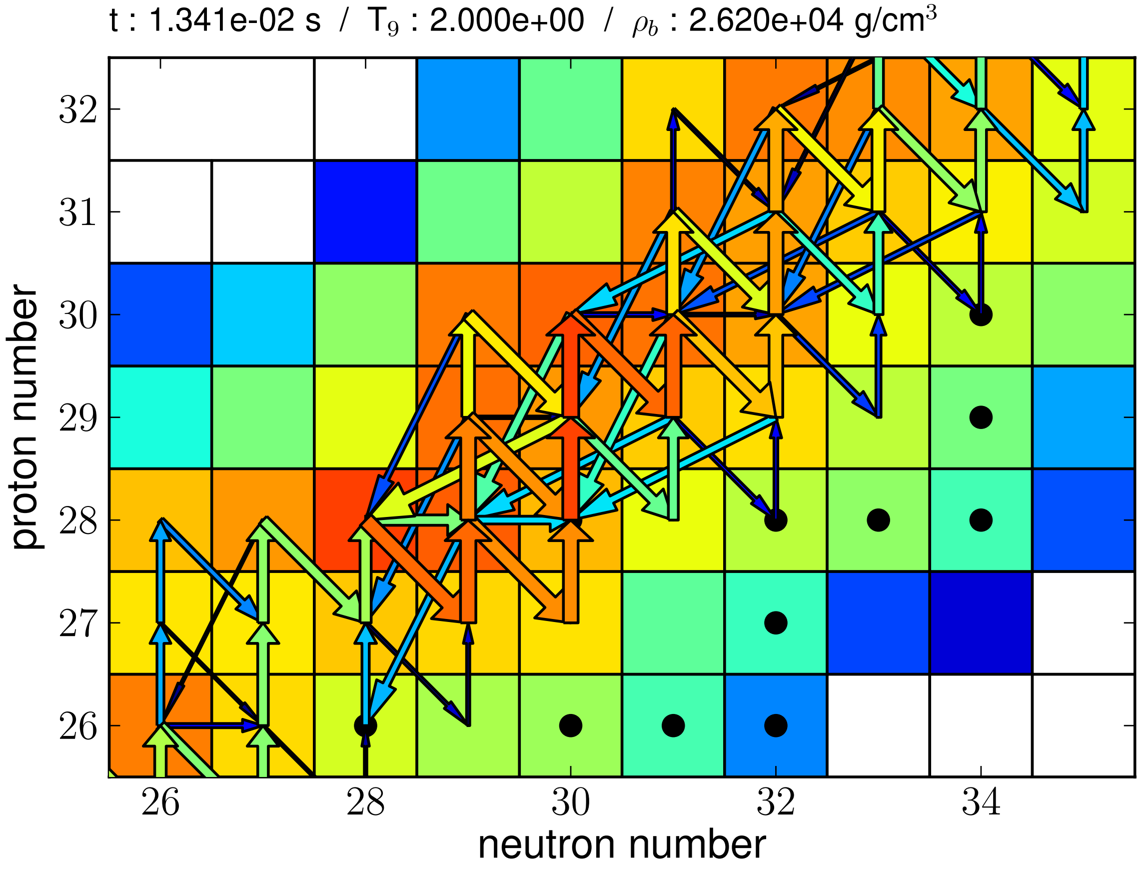
$^{59}\mathrm{Cu}(p,\gamma)^{60}\mathrm{Zn}$



high temperature


t : 5.221e-03 s / T_9 : 3.295e+00 / ρ_b : 1.496e+05 g/cm^3

low temperature


t : 1.341e-02 s / T_9 : 2.000e+00 / ρ_b : 2.620e+04 g/cm^3

Arcones, Fröhlich, Martinez-Piendo (2012)

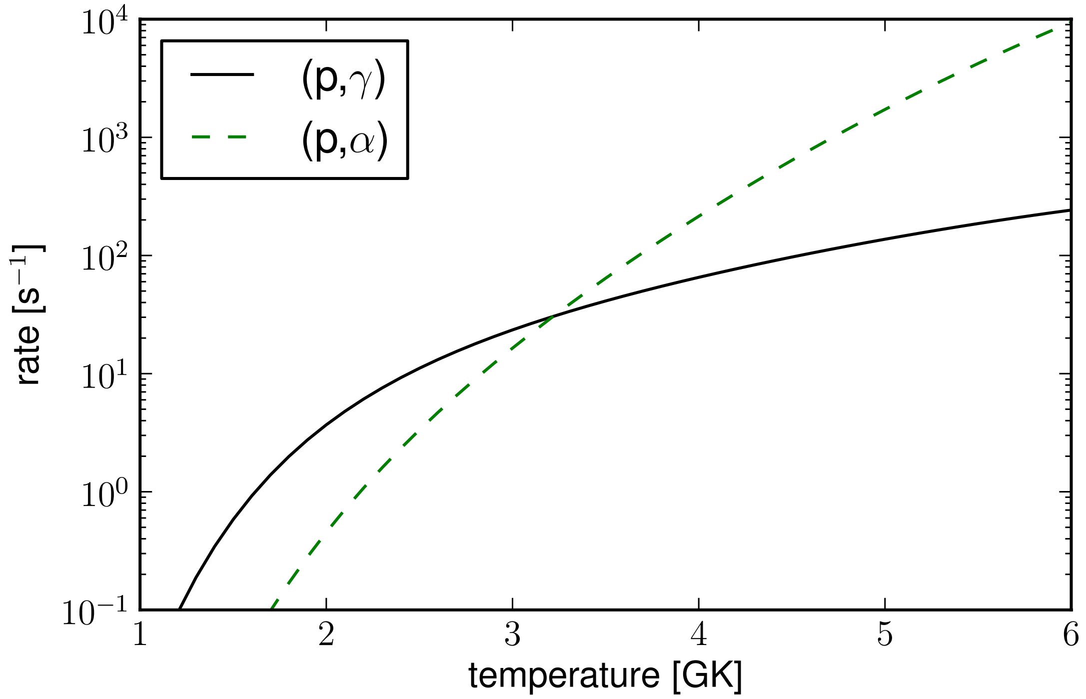
νp-process and dynamical evolution

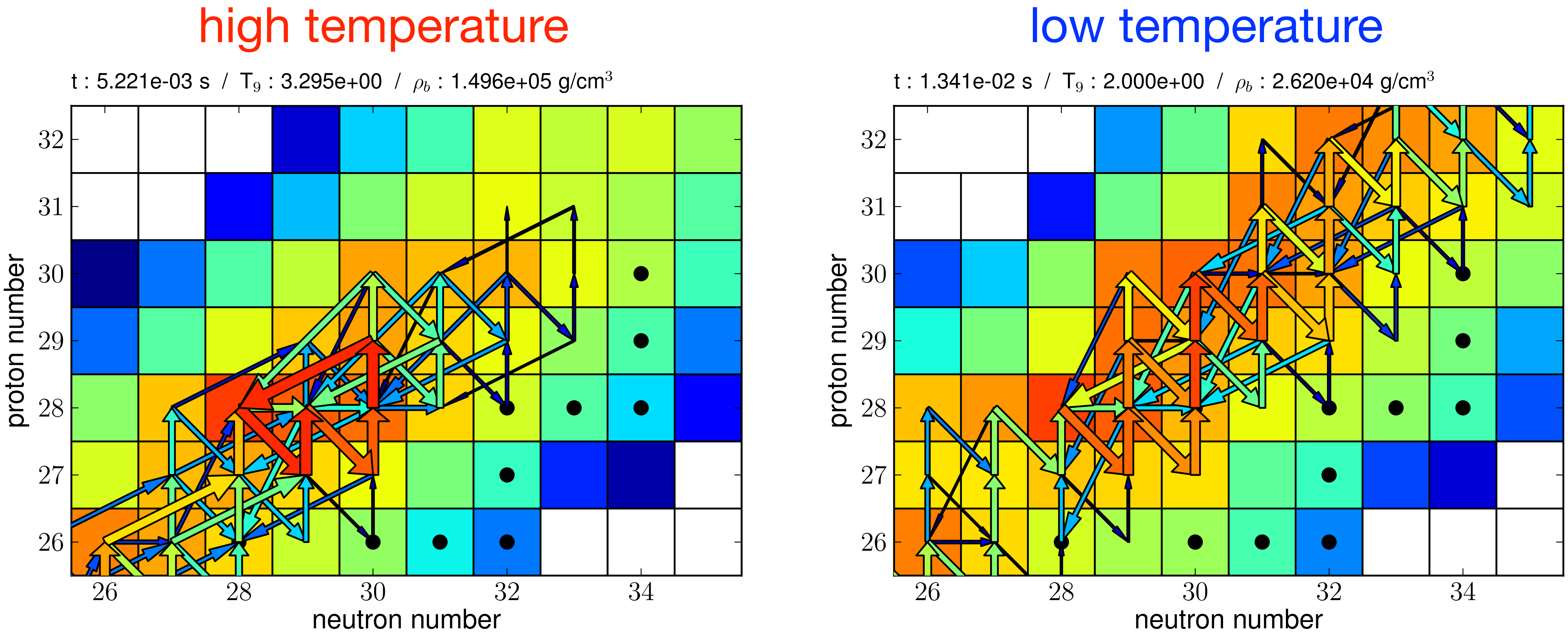
high temperature

^{59}Cu(p,α)^{56}Ni → NiCu cycle

low temperature

^{59}Cu(p,γ)^{60}Zn





Arcones, Fröhlich, Martinez-Piendo (2012)

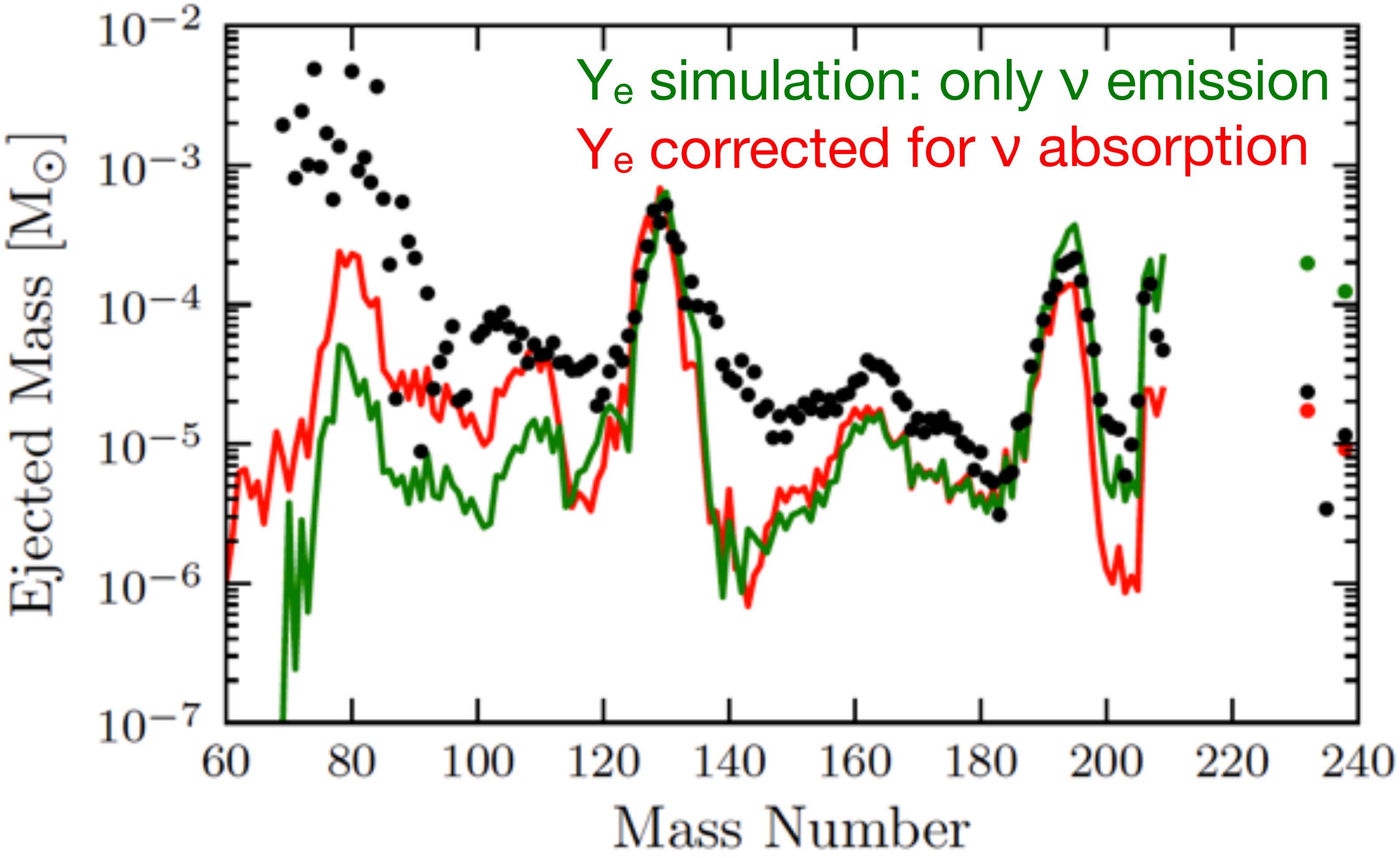
Where is the r-process?

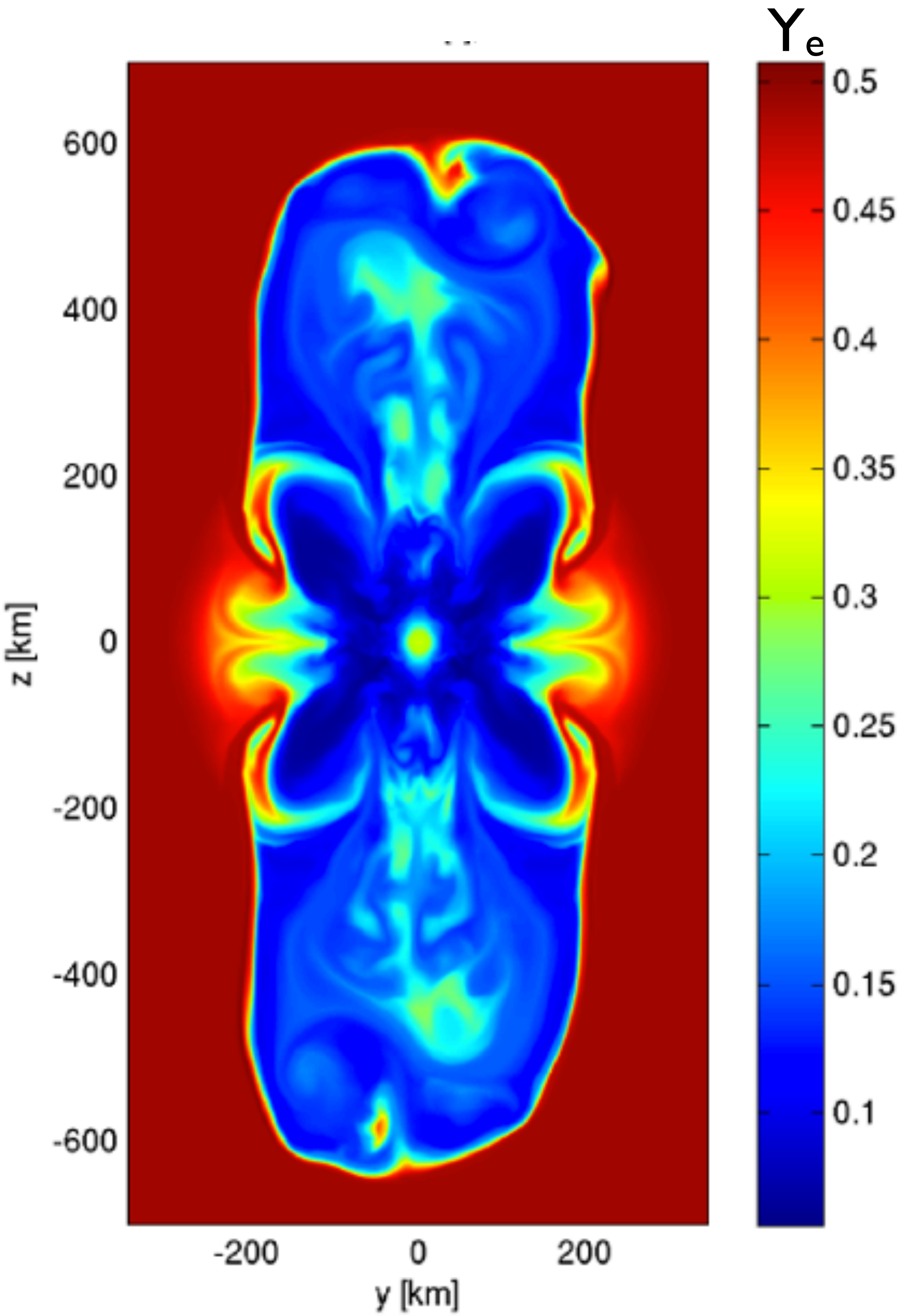
Supernova-jet-like explosion

3D magneto-hydrodynamical simulations:
rapid rotation and strong magnetic fields (?)

matter collimates: neutron-rich jets

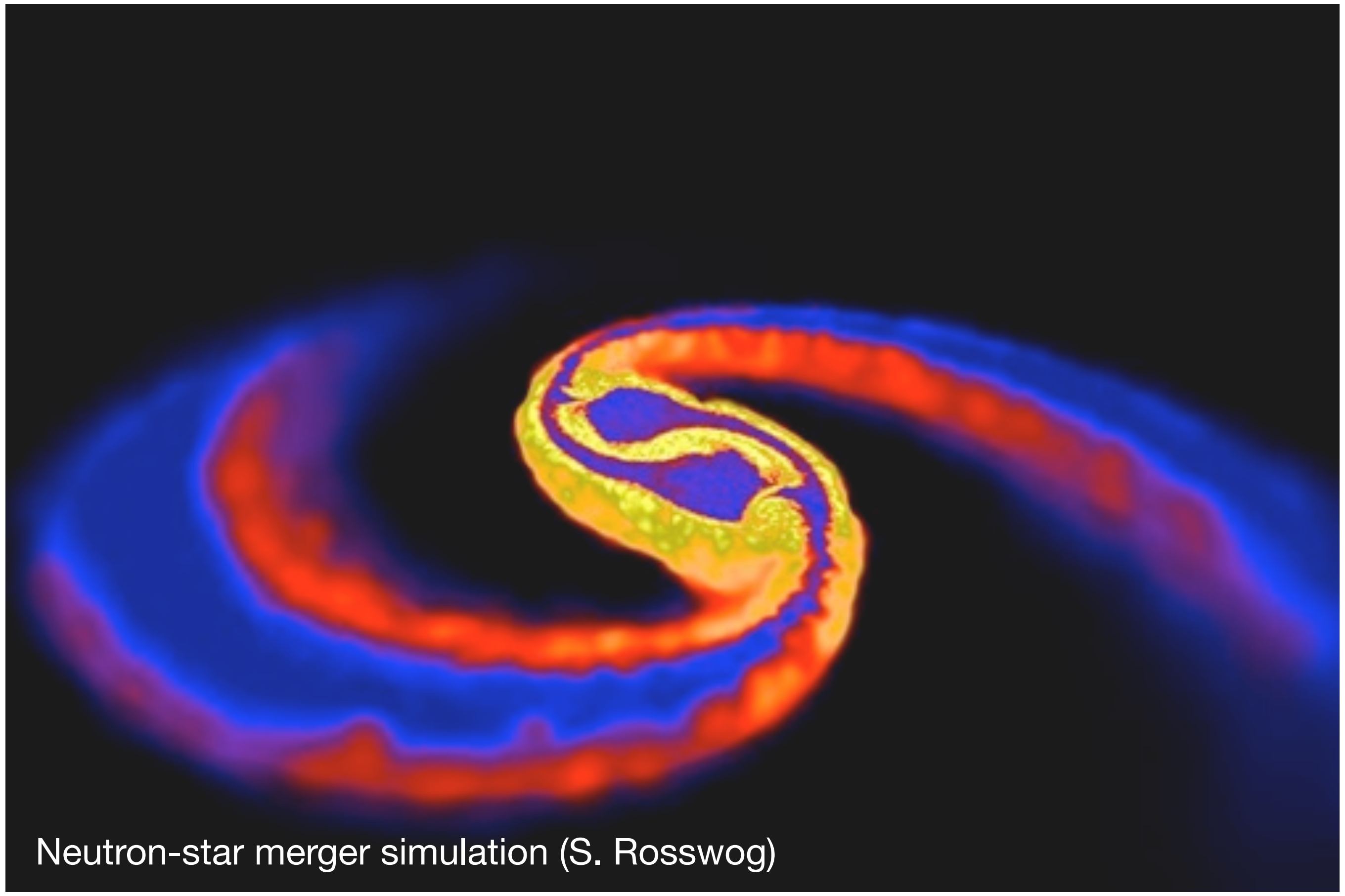
right r-process conditions

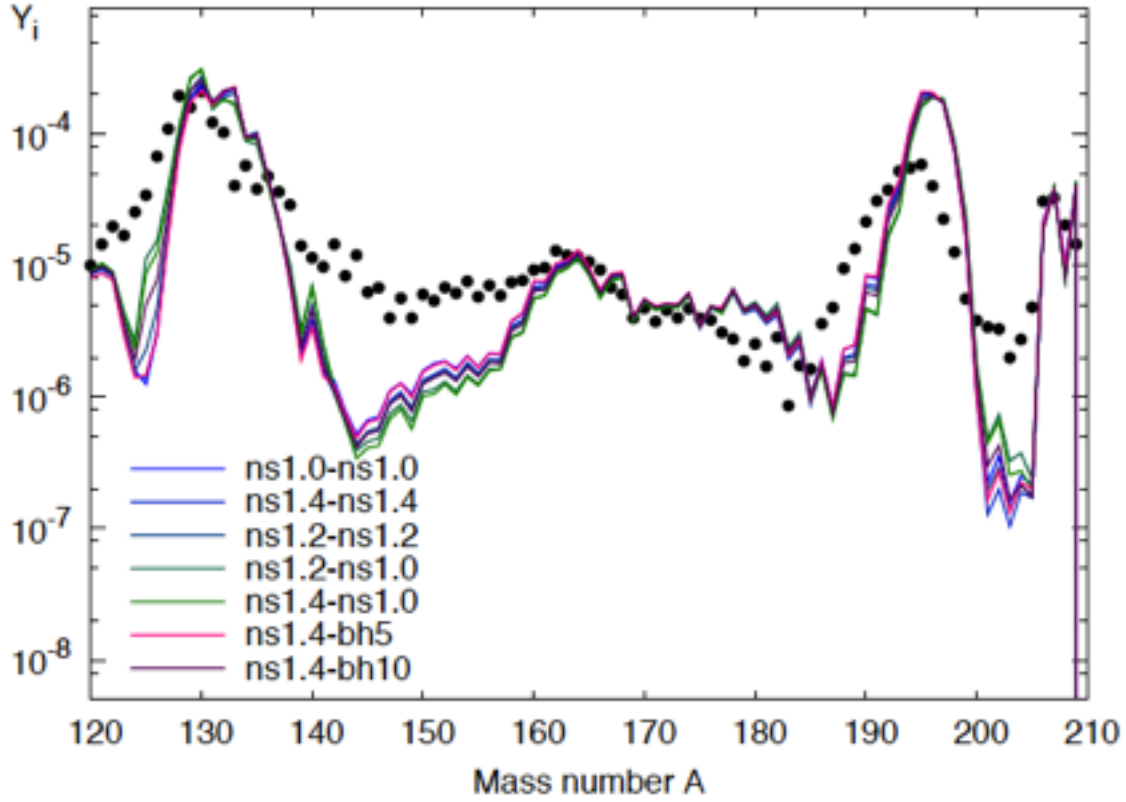




Winteler, Käppeli, Perego, et al. 2012

Neutron star mergers


Neutron-star merger simulation (S. Rosswog)



Korobkin, Rosswog, Arcones, Winteler

(submitted MNRAS)

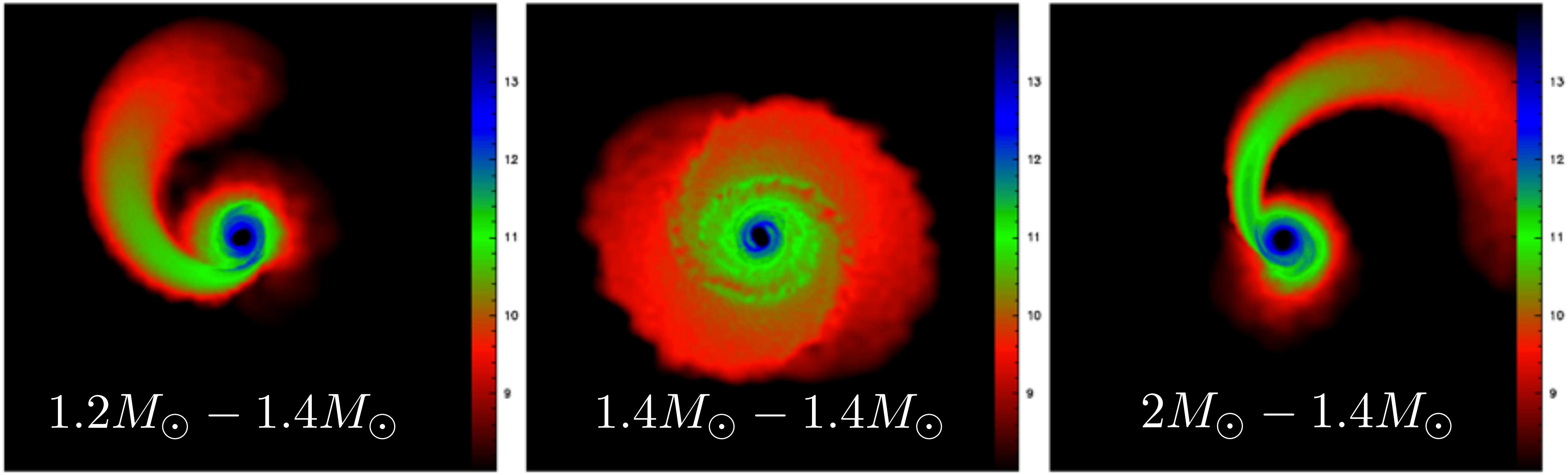
Right conditions for a successful r-process
(Lattimer & Schramm 1974, Freiburghaus et al. 1999, ..., Goriely et al. 2011)

Do they occur early enough to explain UMP star abundances (Argast et al. 2004)?

r-process heating affects merger dynamics: late X-ray emission in short GRBs
(Metzger, Arcones, Quataert, Martinez-Pinedo 2010)

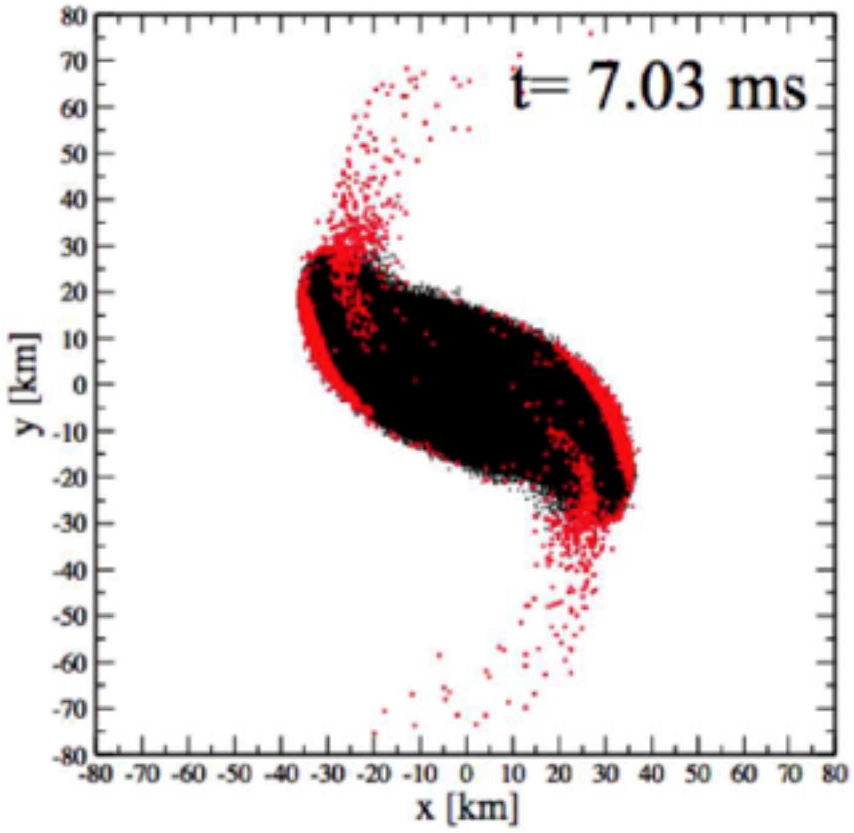
Transient with kilo-nova luminosity (Metzger et al. 2010): direct observation of r-process, EM counter part to WG

Neutron star mergers

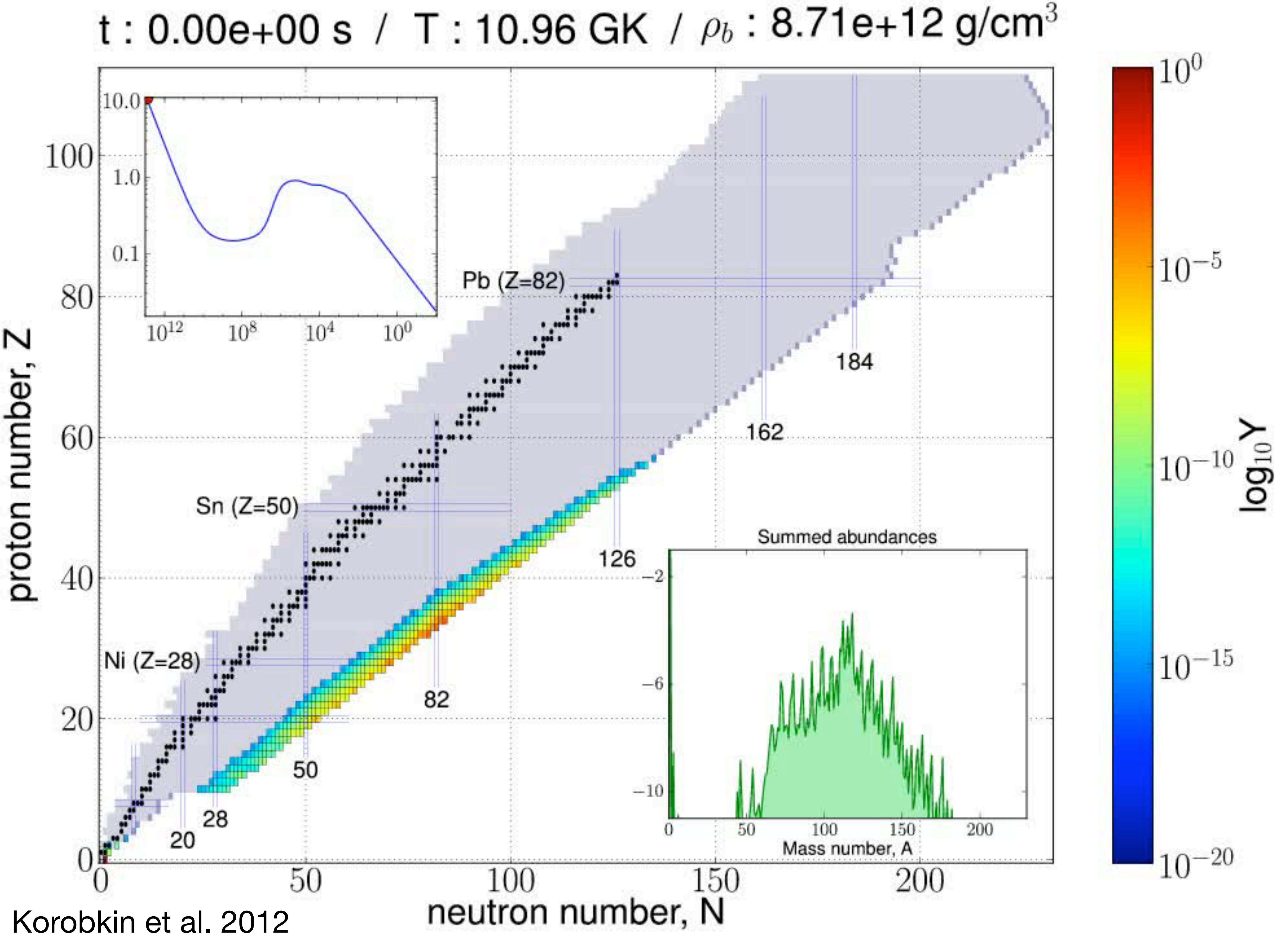


simulations: 21 mergers of 2 neutron stars
2 of neutron star black hole

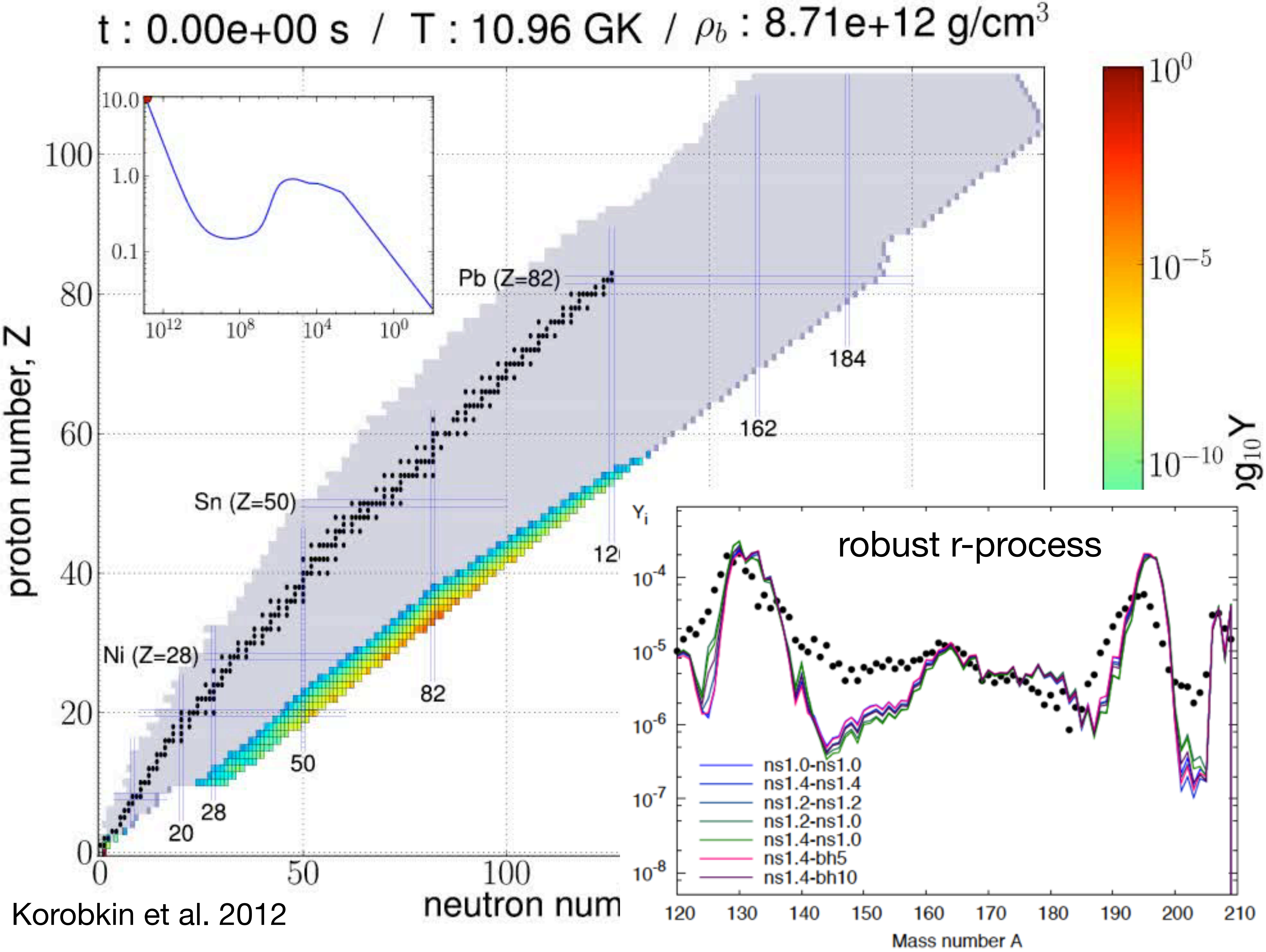
nucleosynthesis of ejecta
robust r-process:
- extreme neutron-rich conditions (Y_e =0.04)
- several fission cycles



Korobkin et al. 2012



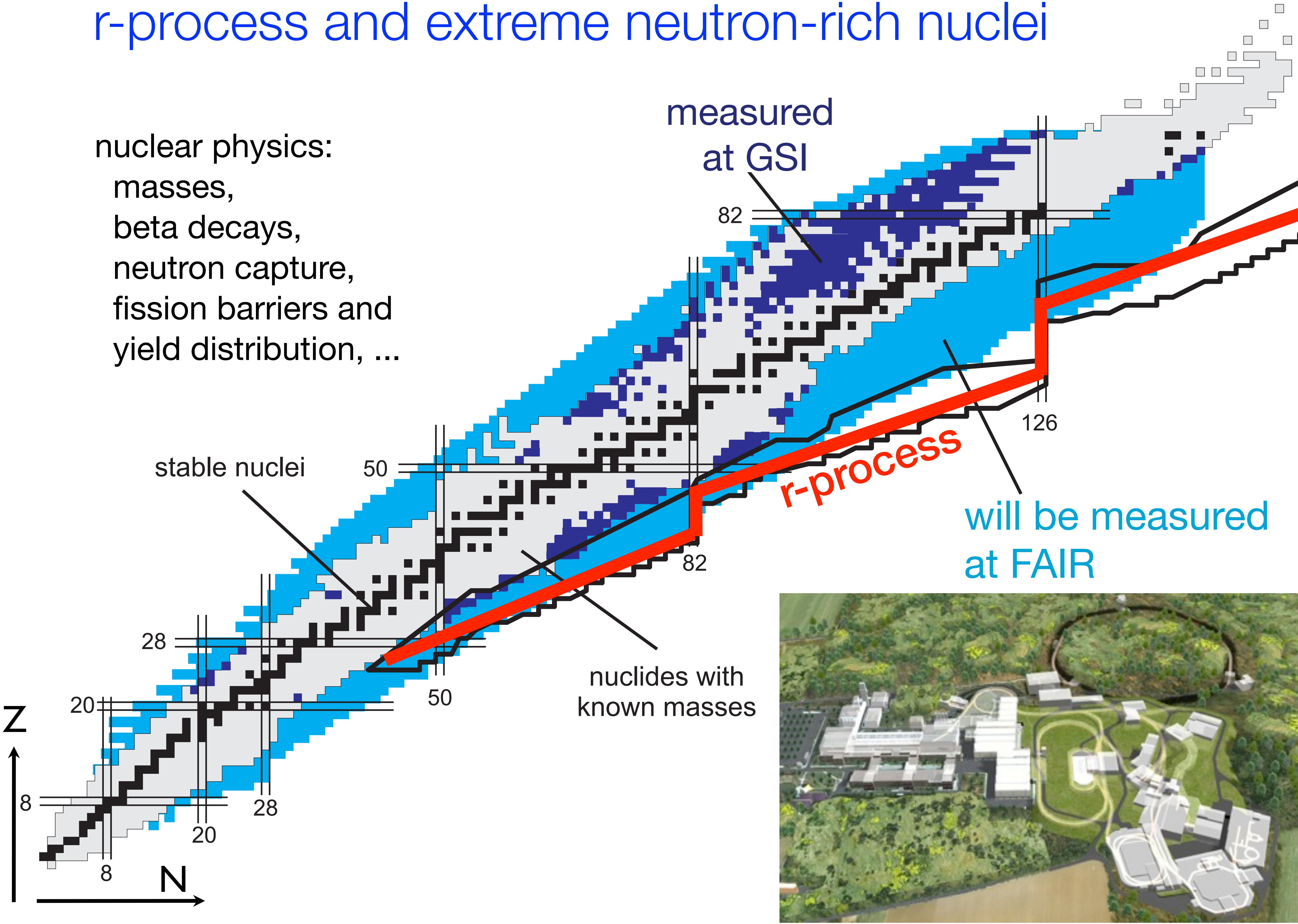
Korobkin et al. 2012



Korobkin et al. 2012

r-process and extreme neutron-rich nuclei

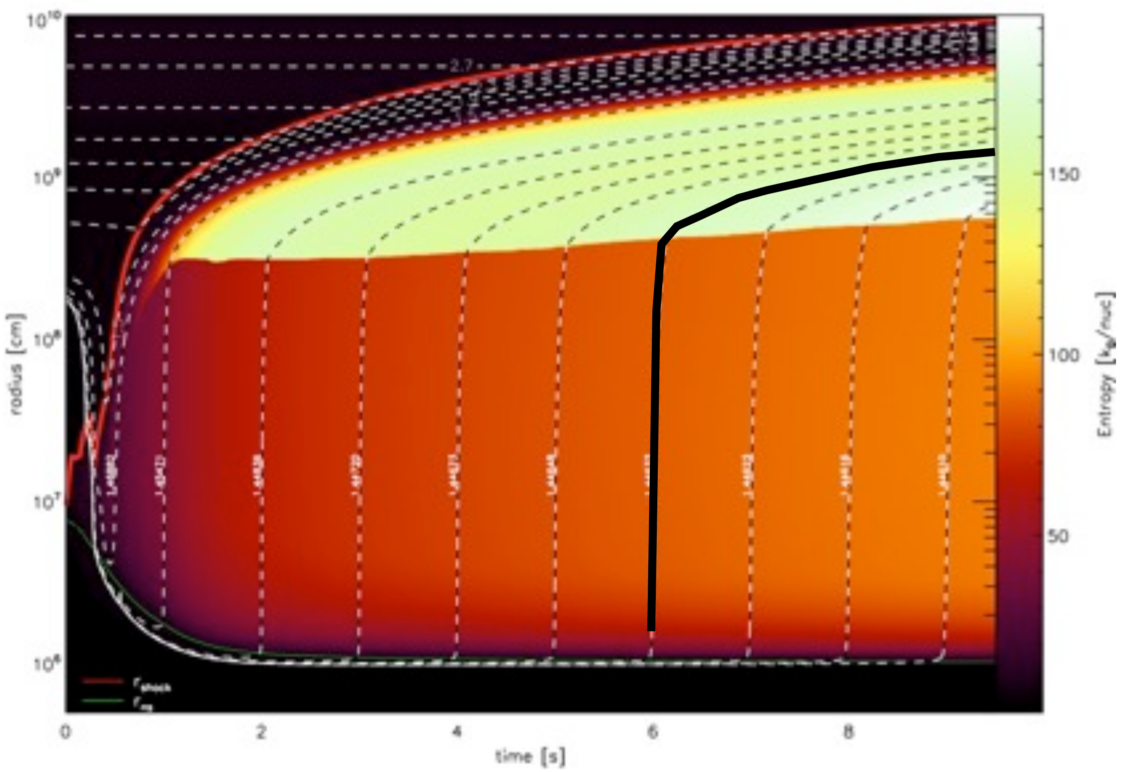
nuclear physics:
- masses,
- beta decays,
- neutron capture,
- fission barriers and
- yield distribution, ...



Nuclear masses and r-process

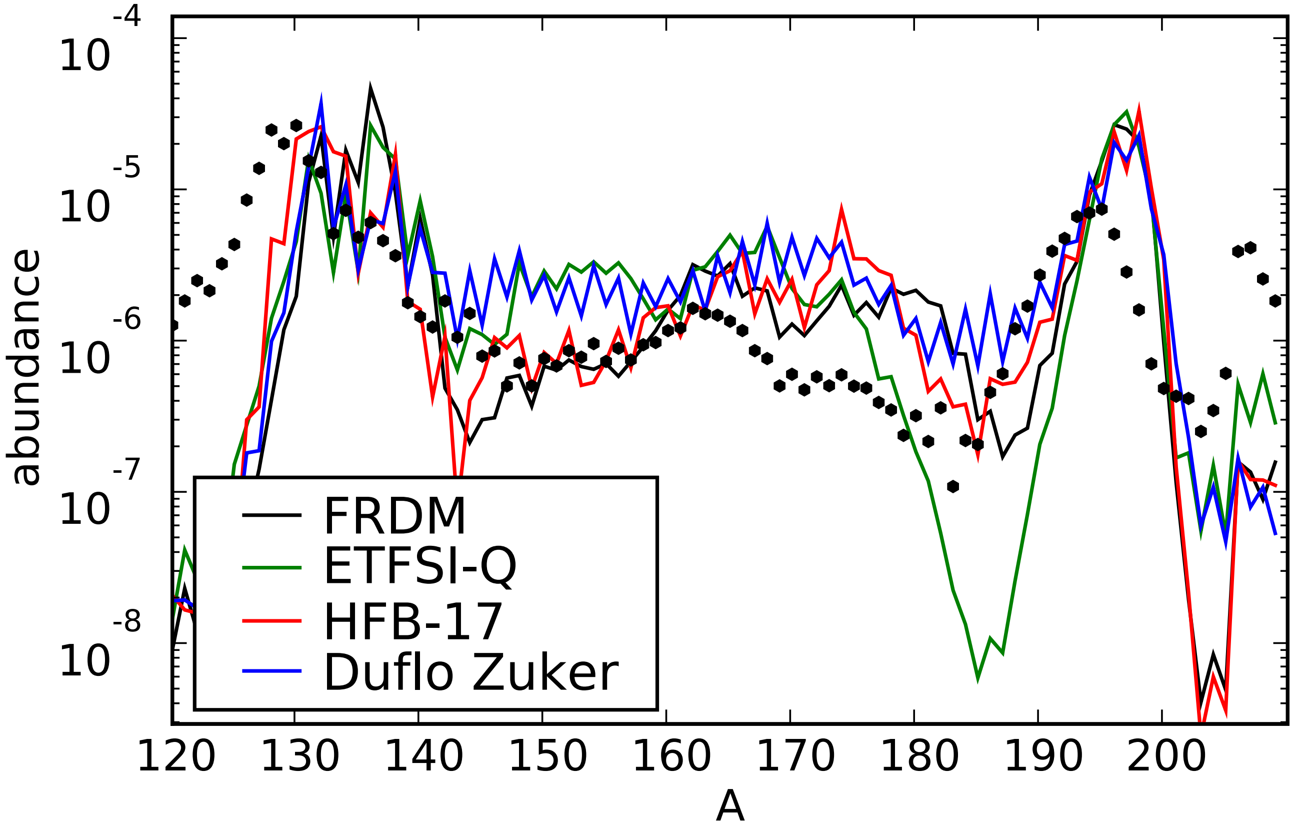
We use one trajectory from the hydrodynamical simulations of Arcones et al. 2007 with the entropy ($S \sim T^3/\rho$) increased by a factor two

→ 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?

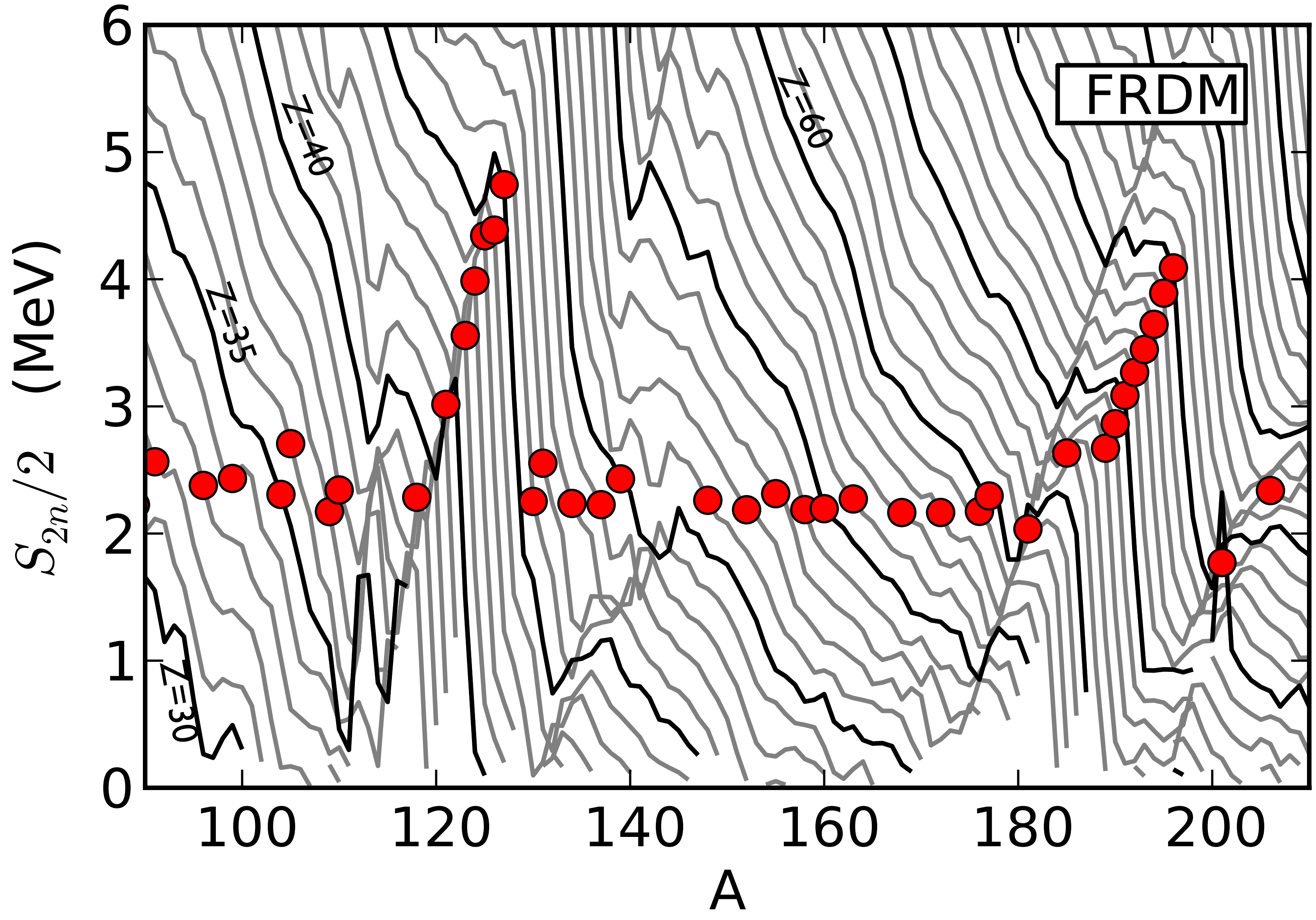
Arcones & Martinez-Pinedo, 2011

Two neutron separation energy

Abundances

S_{2n}

Nuclear properties



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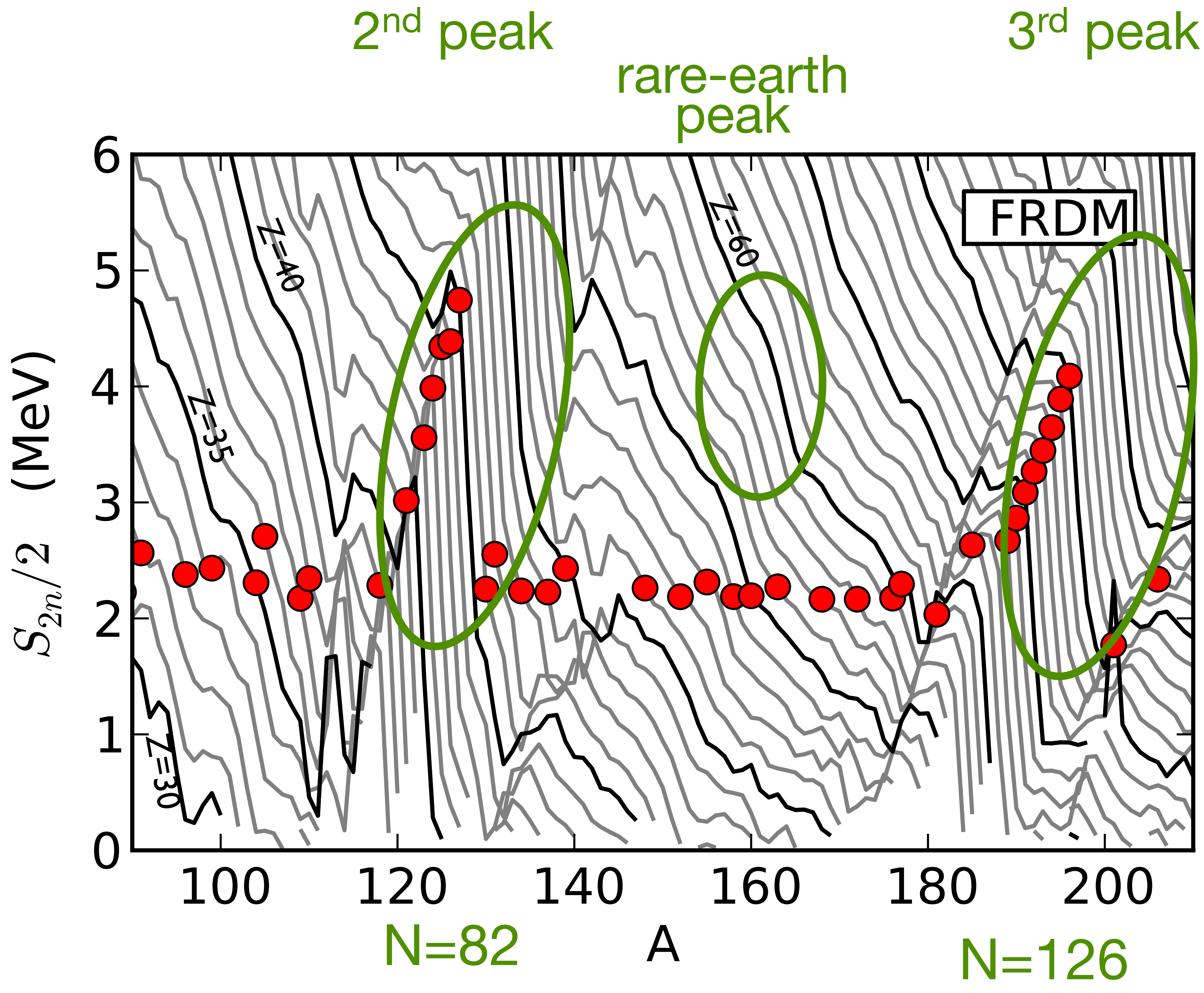

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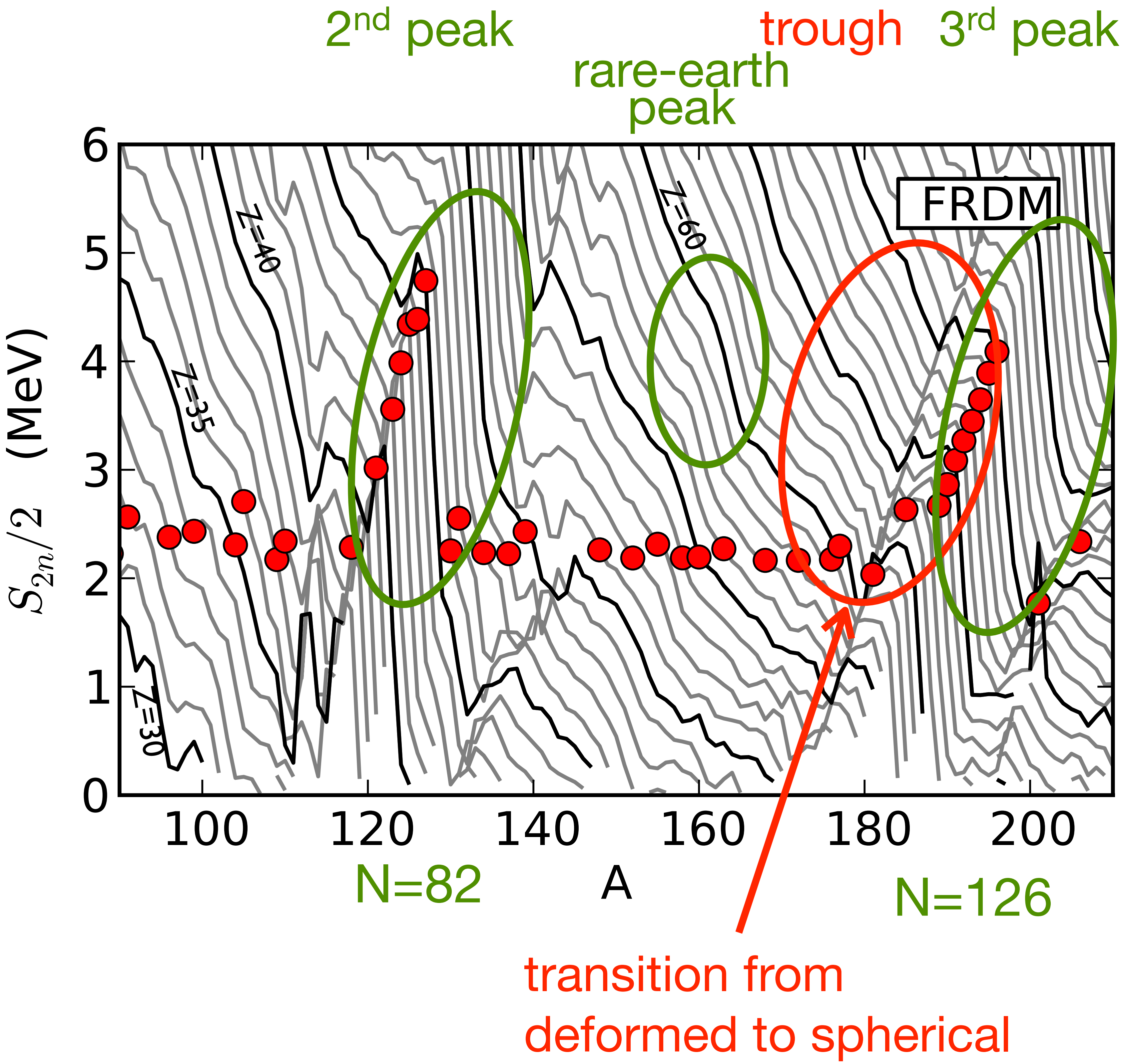
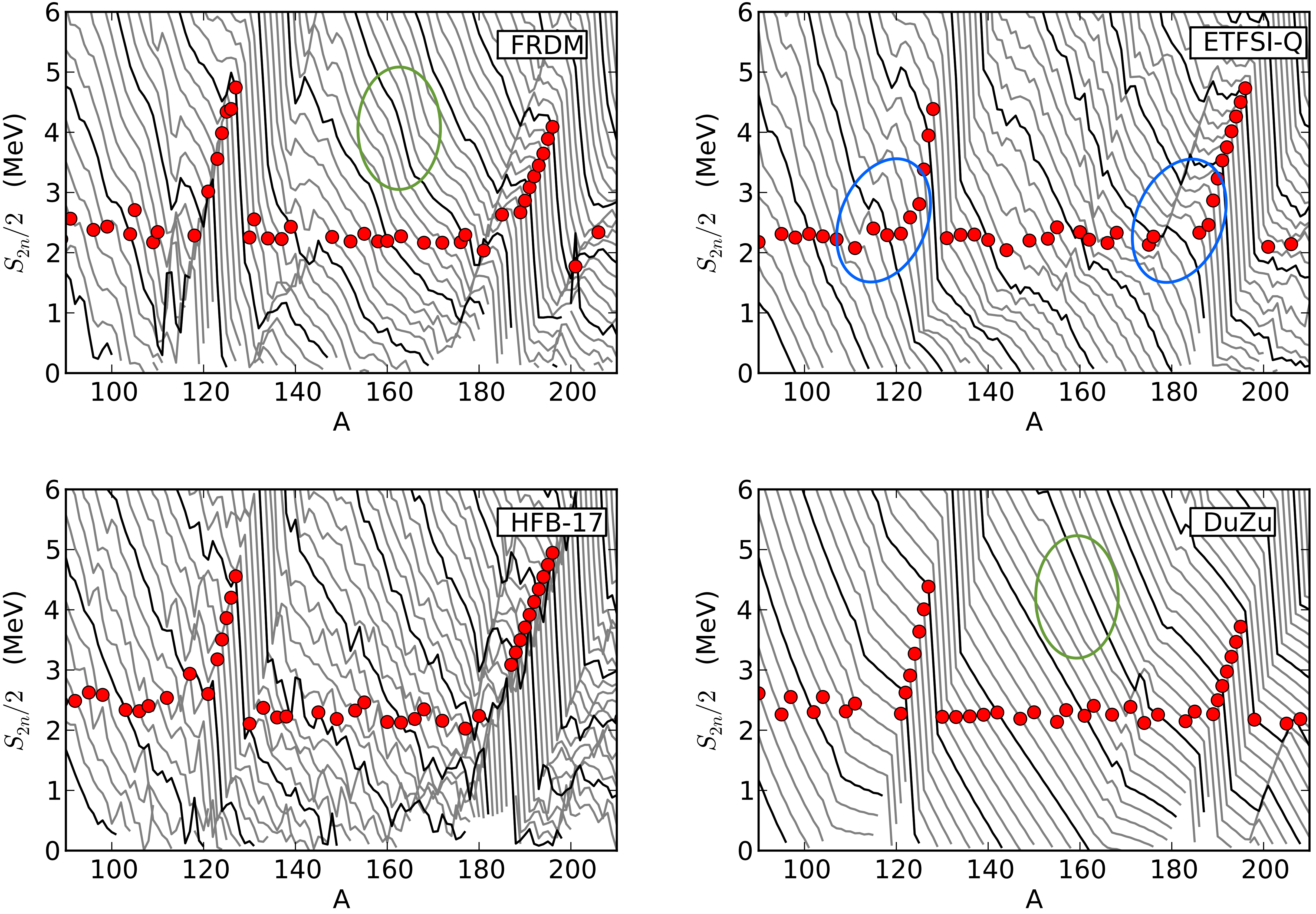
S_{2n}

Nuclear properties



Aspects of different mass models

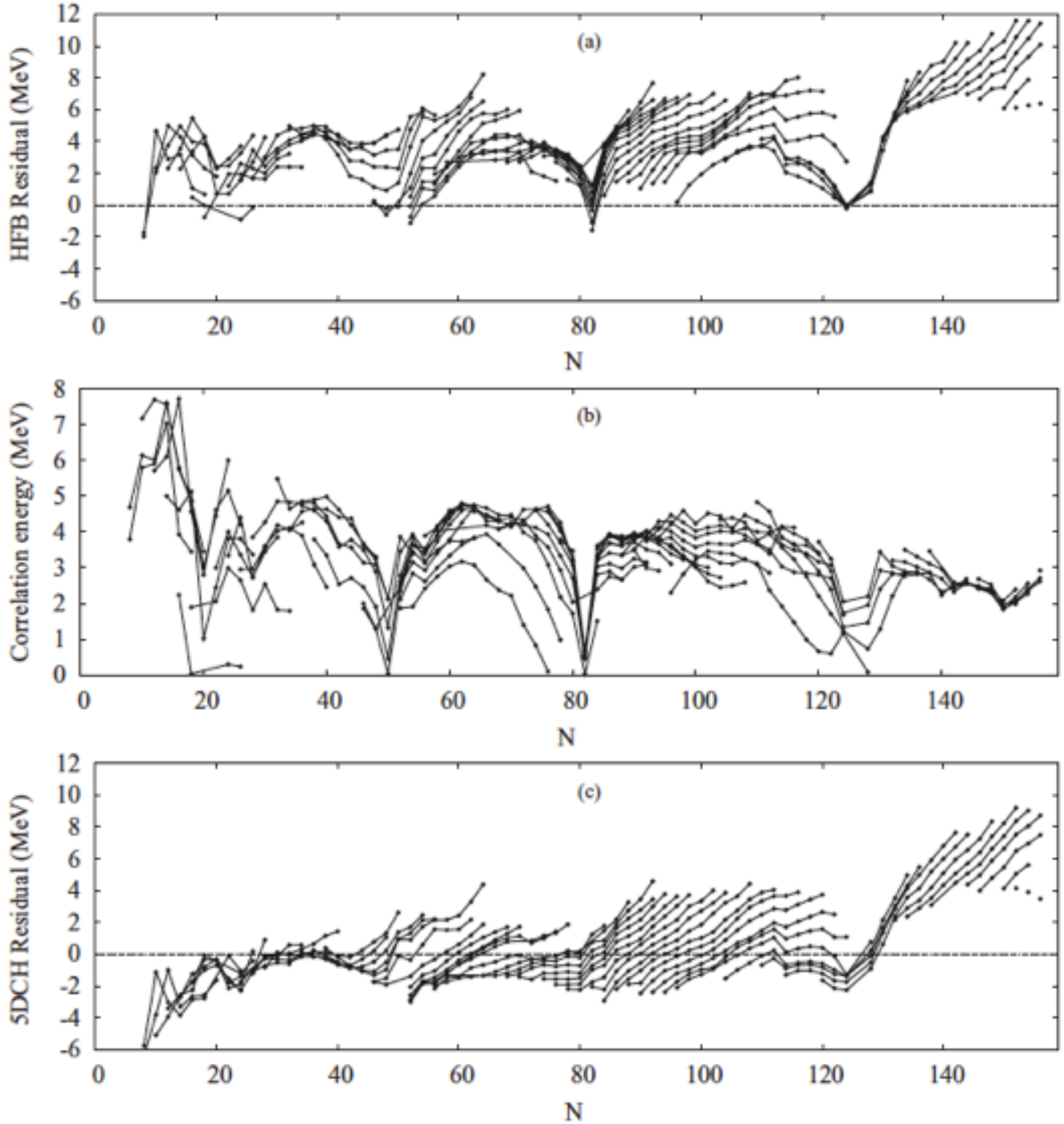


PHYSICAL REVIEW C 81, 014303 (2010)

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*

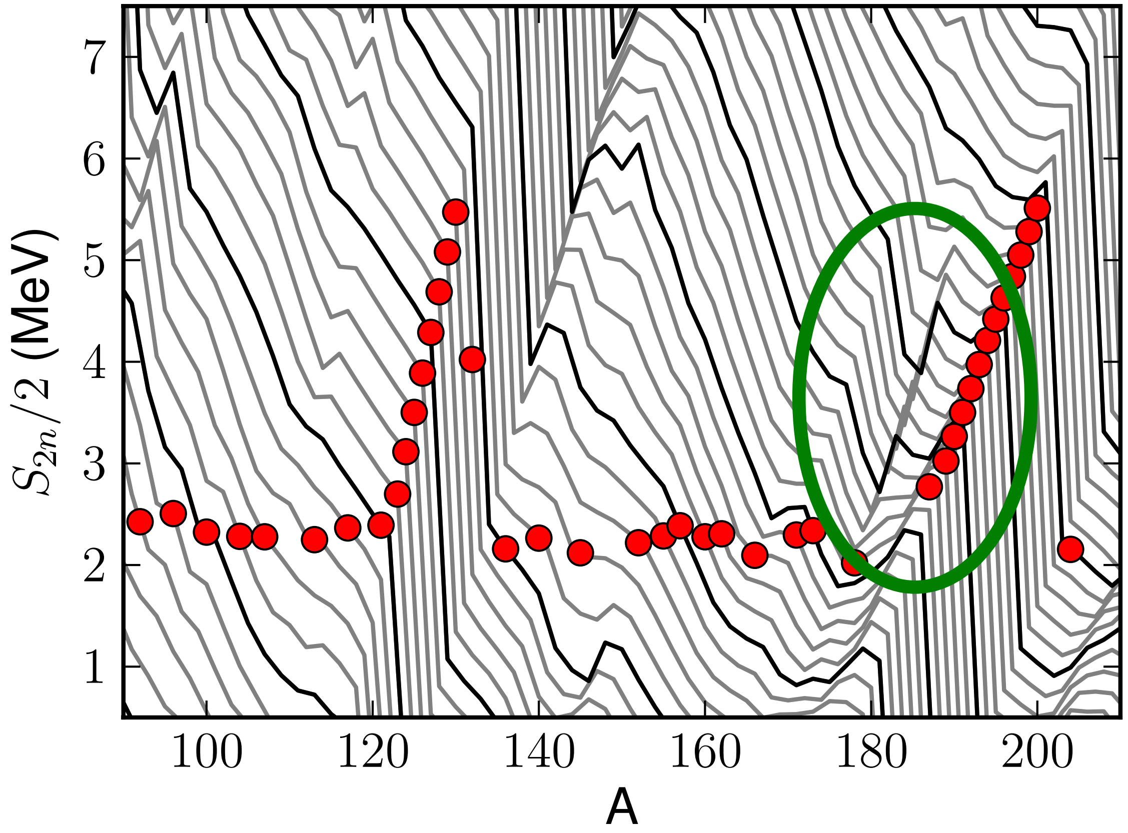
ry 2010)



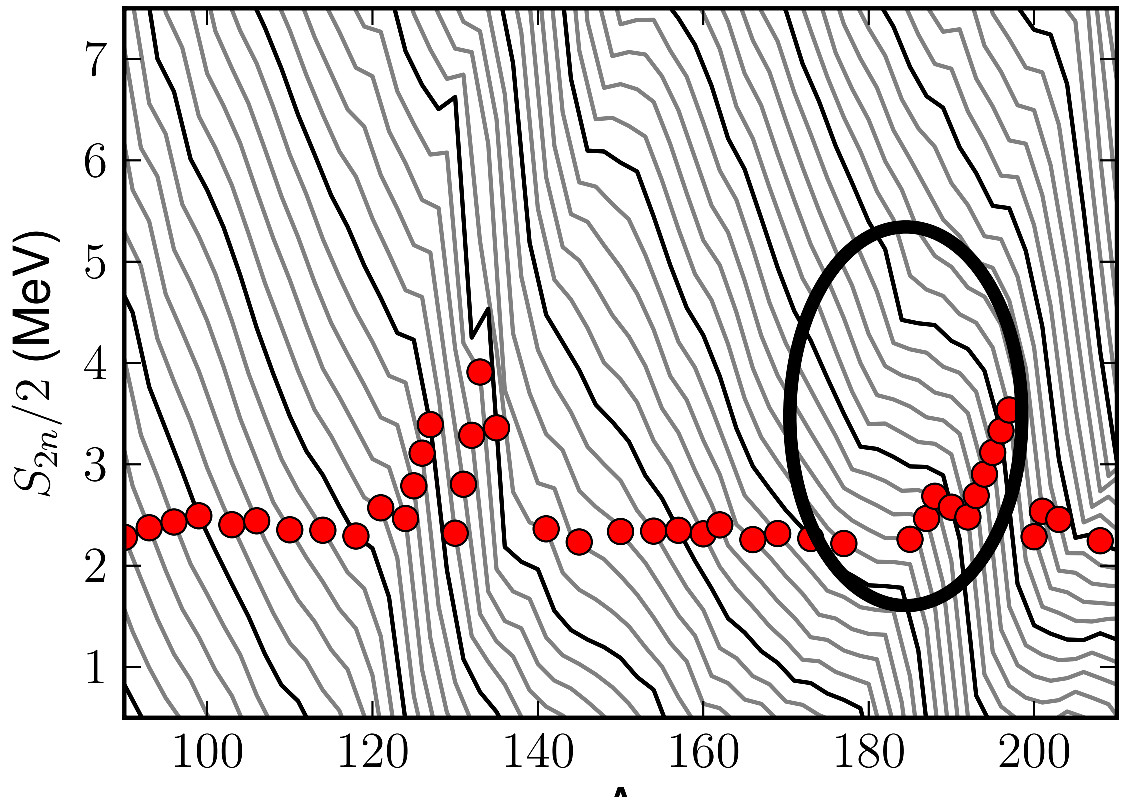
Impact of
nuclear correlations on
the r-process

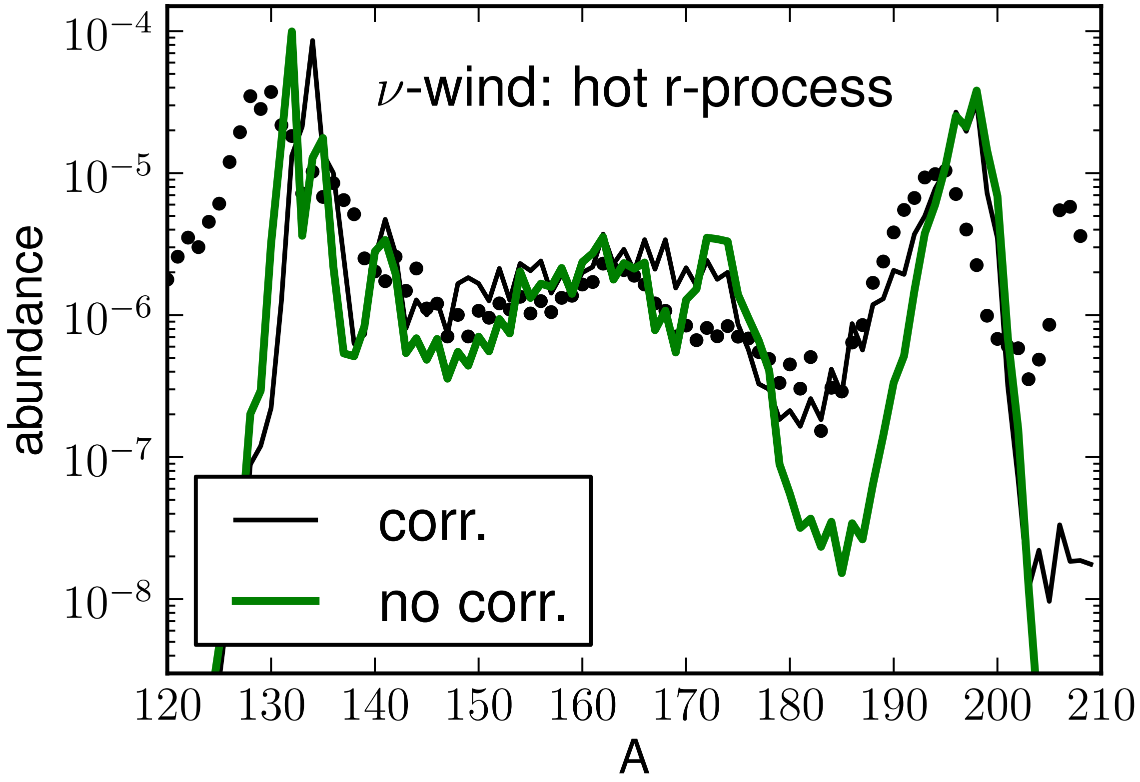
Nuclear correlations and r-process

without correlations



with correlations





nuclear correlations: strong impact on trough before third peak!

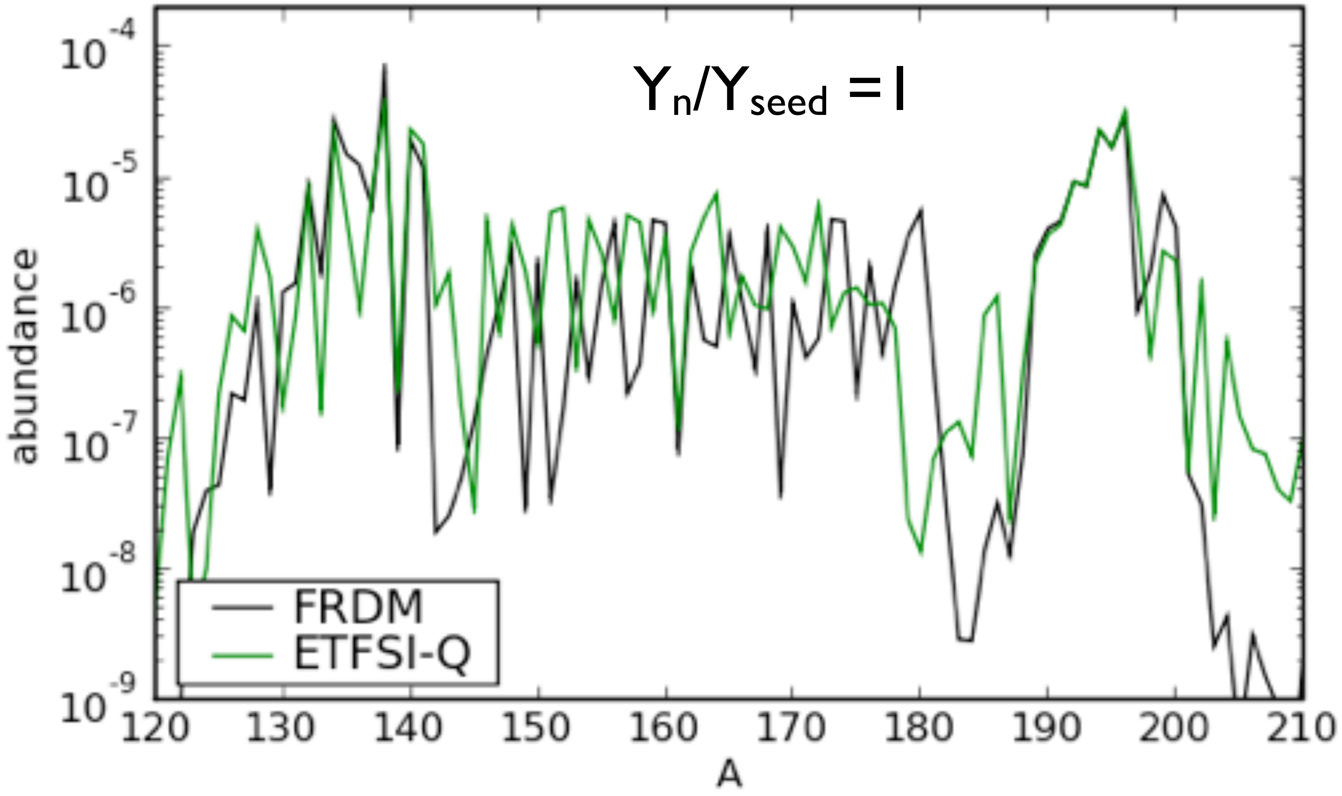
(Arcones & Bertsch, 2012)

Decay to stability

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

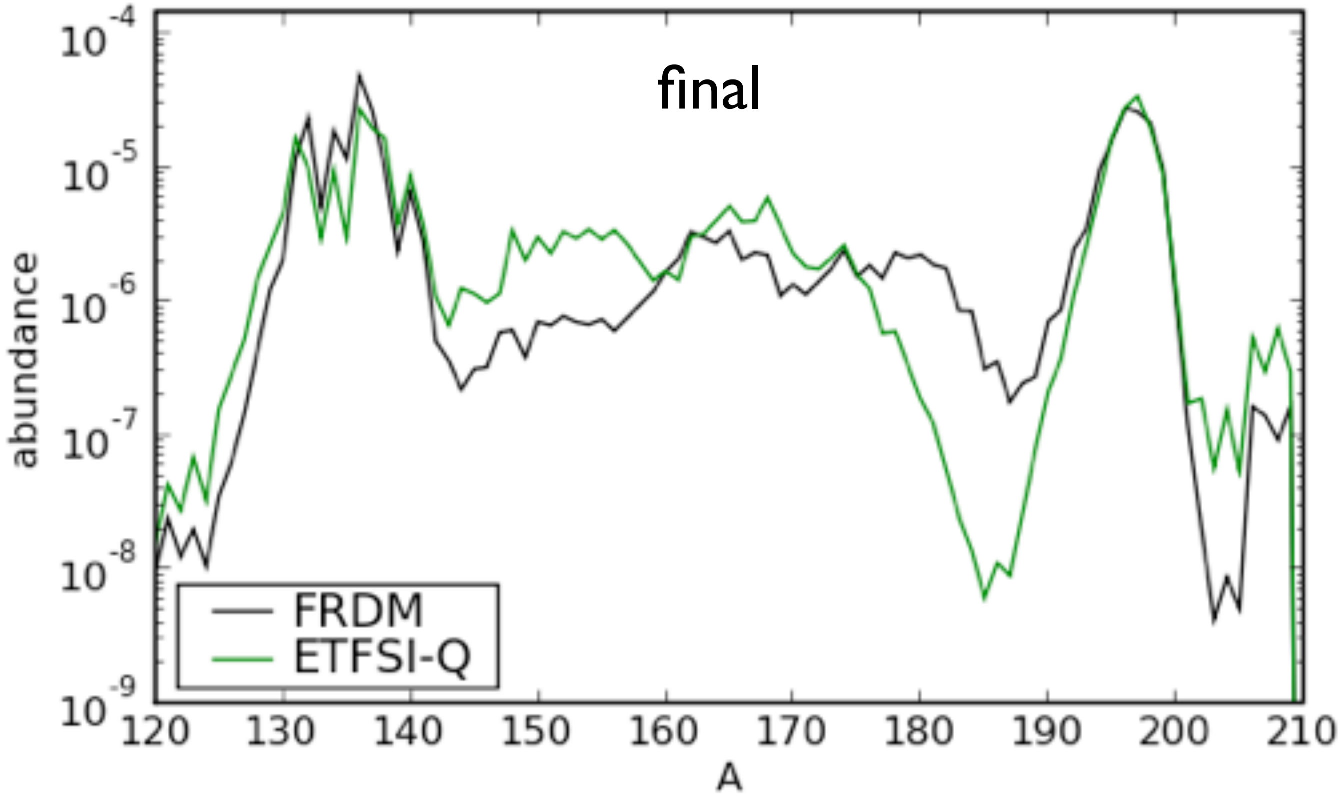
Final abundances are smoother like solar abundances.

Why does the abundance pattern change?



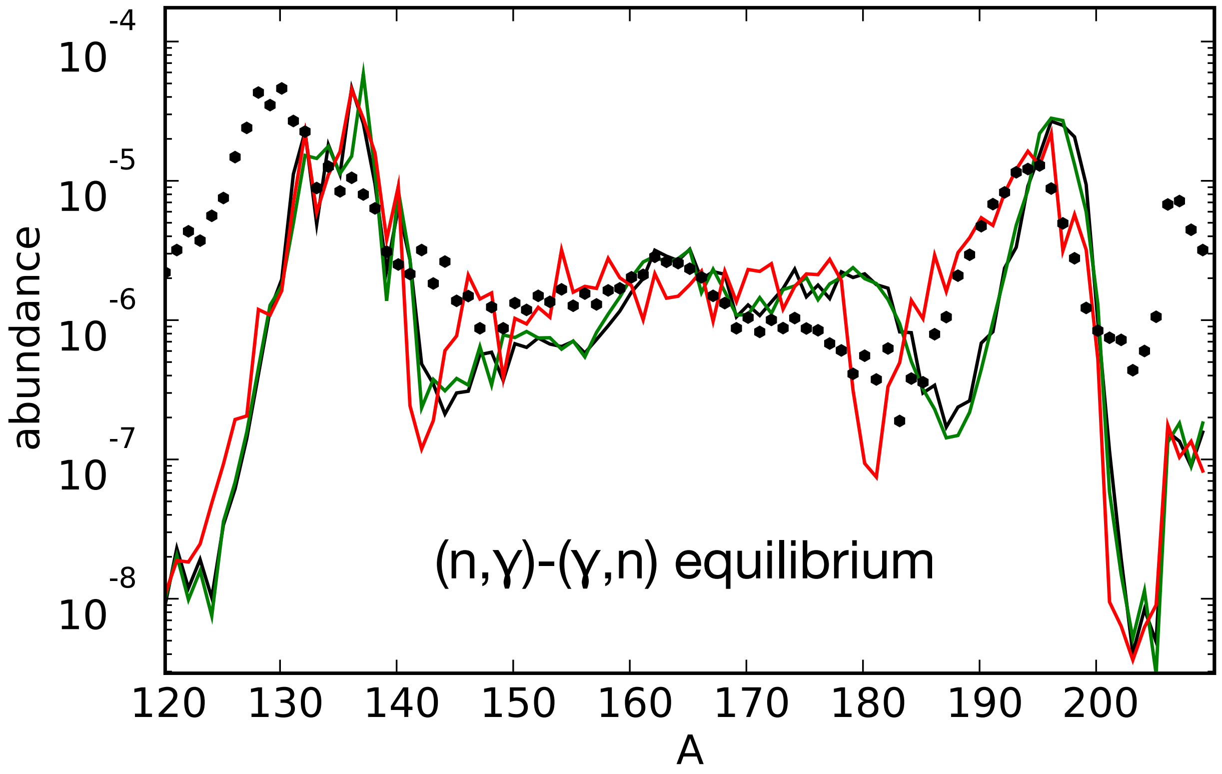
Classical r-process (waiting point approximation): beta-delayed neutron emission (Kodama & Takahashi 1973, Kratz et al. 1993)

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, Mumpower et al. 2011, 2012a,b)



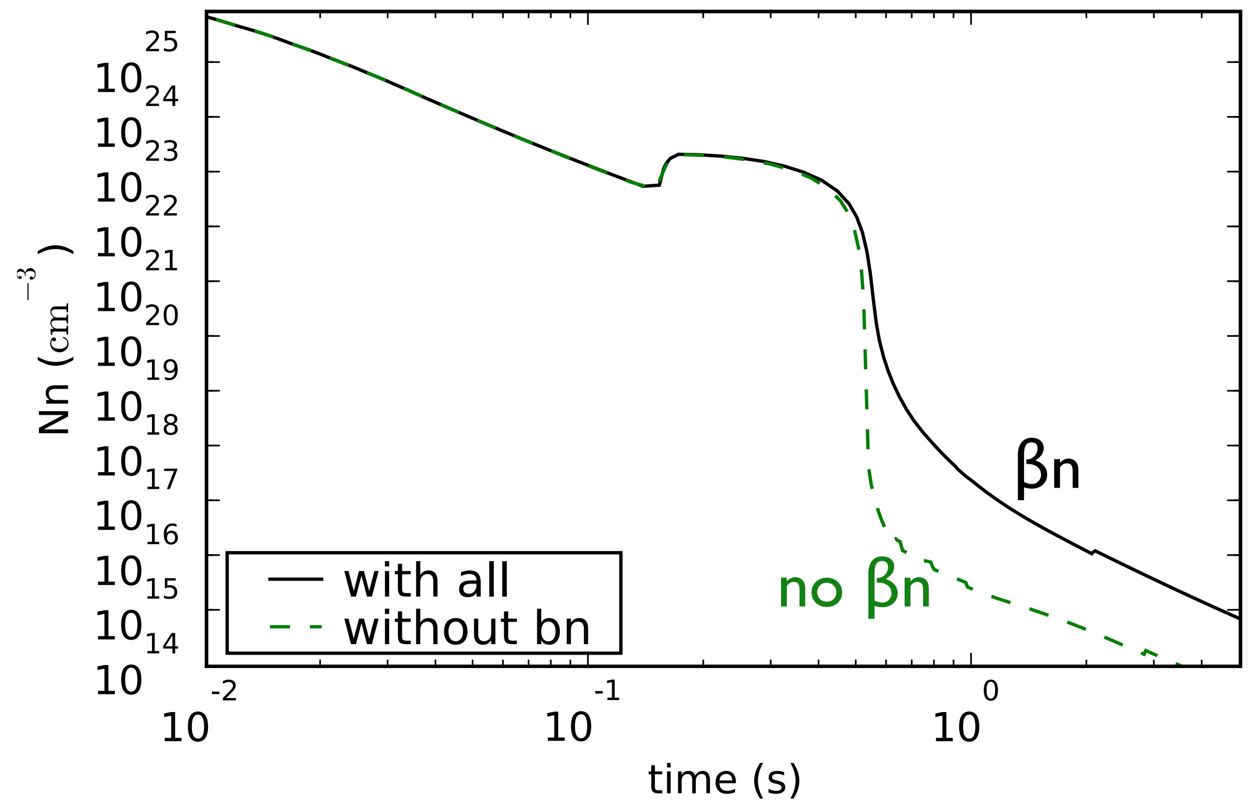
Arcones & Martinez-Pinedo, 2011

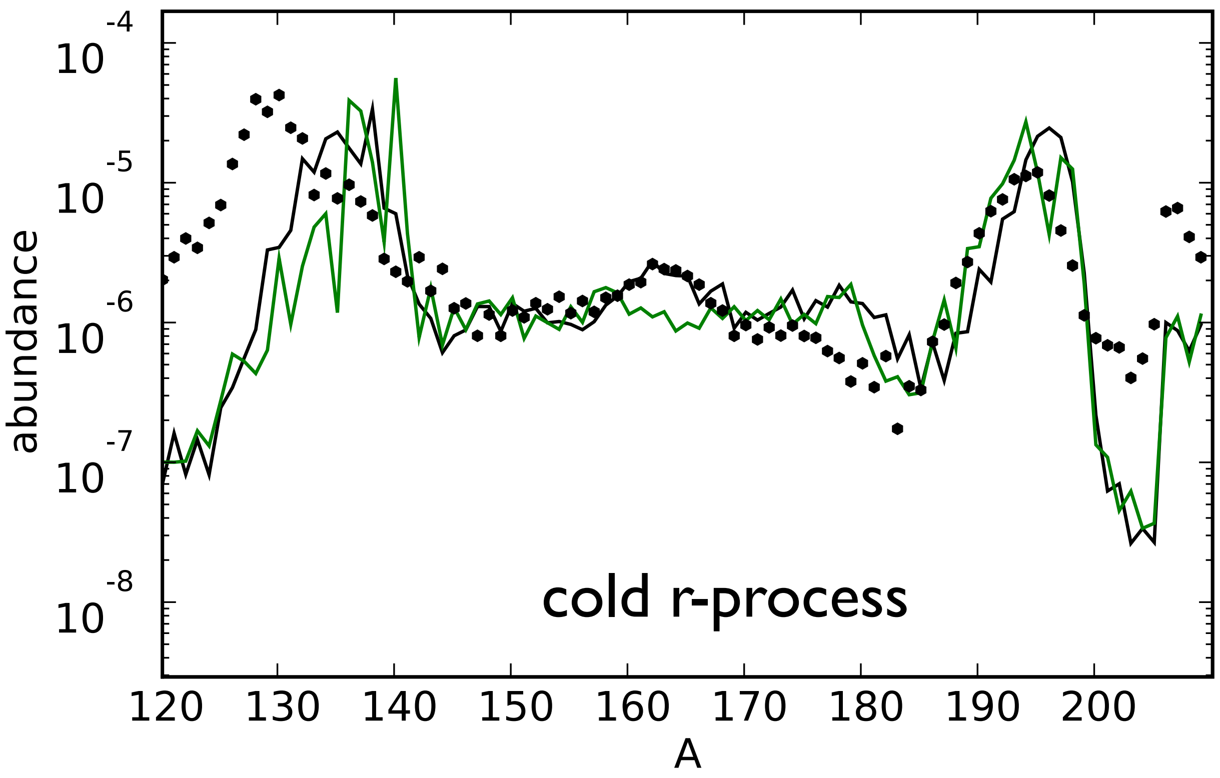
Neutron captures and beta-delayed neutron emission



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

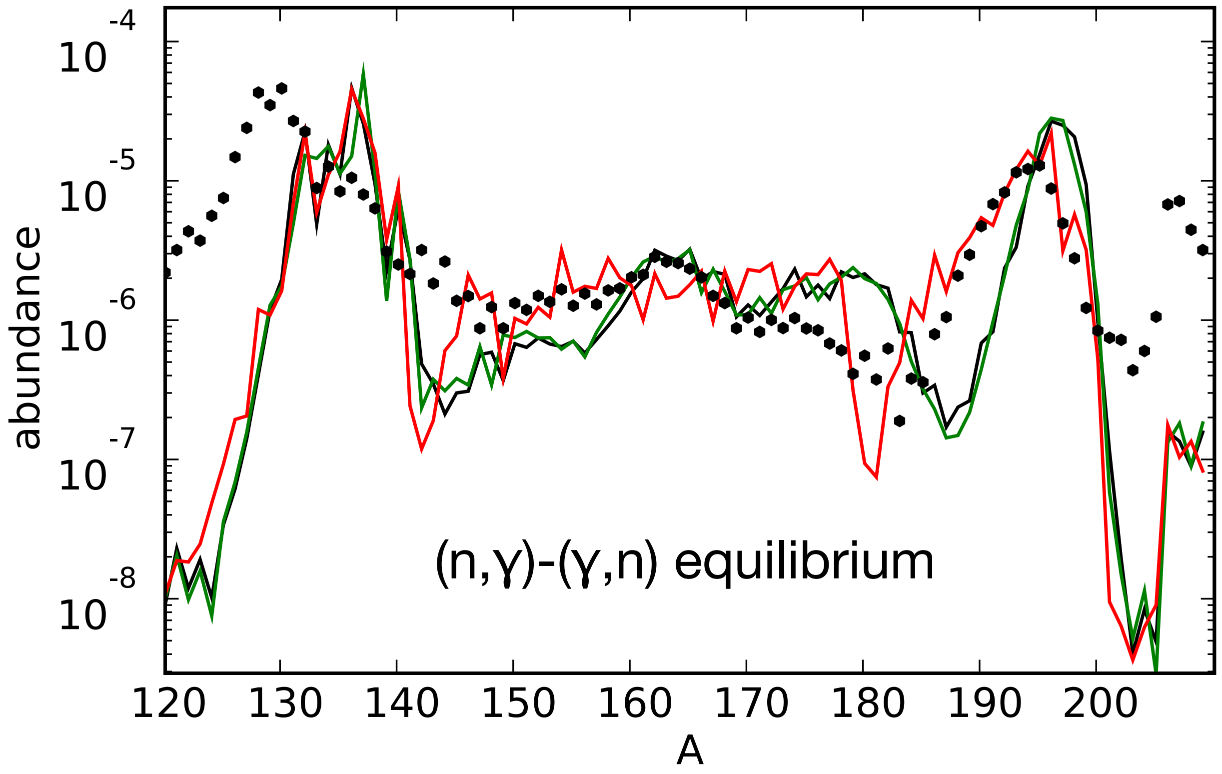
The main role of the beta-delayed neutron emission is to supply neutrons.





Arcones & Martinez-Pinedo, 2011

Neutron captures and beta-delayed neutron emission



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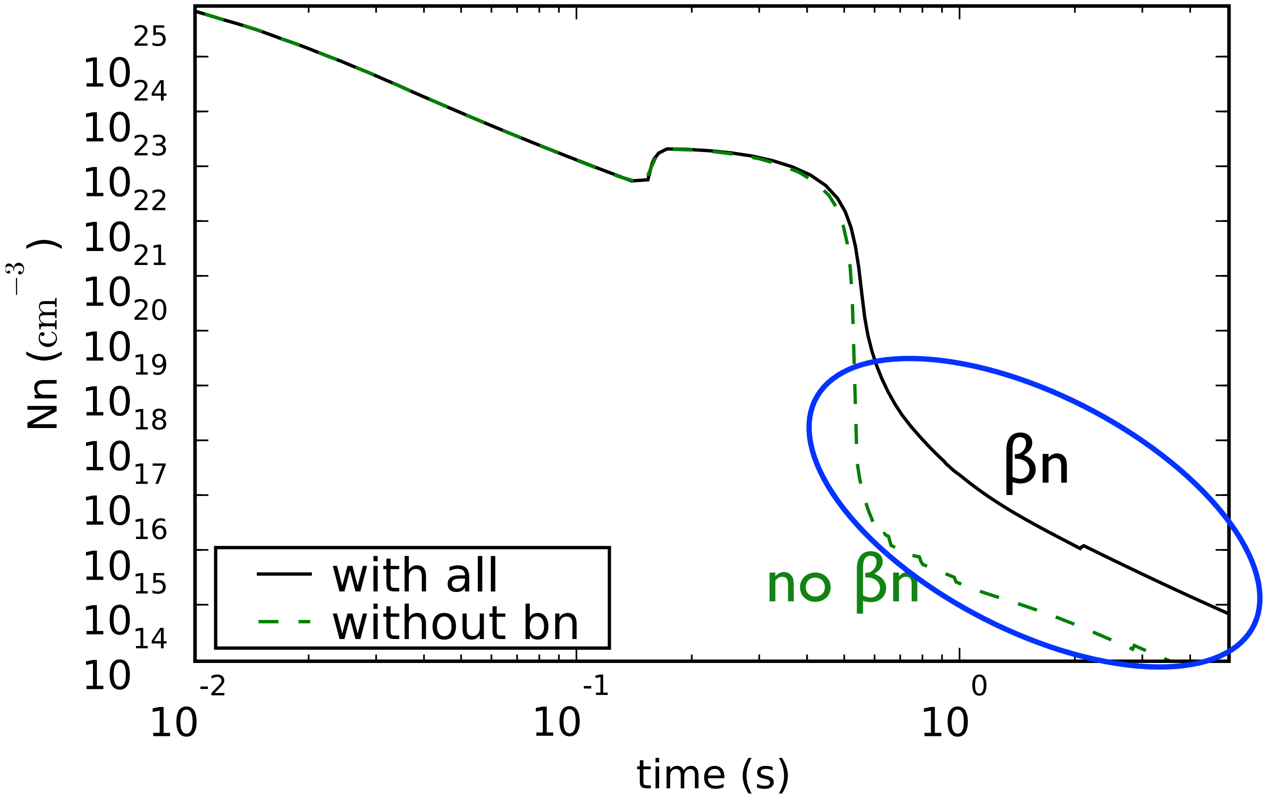
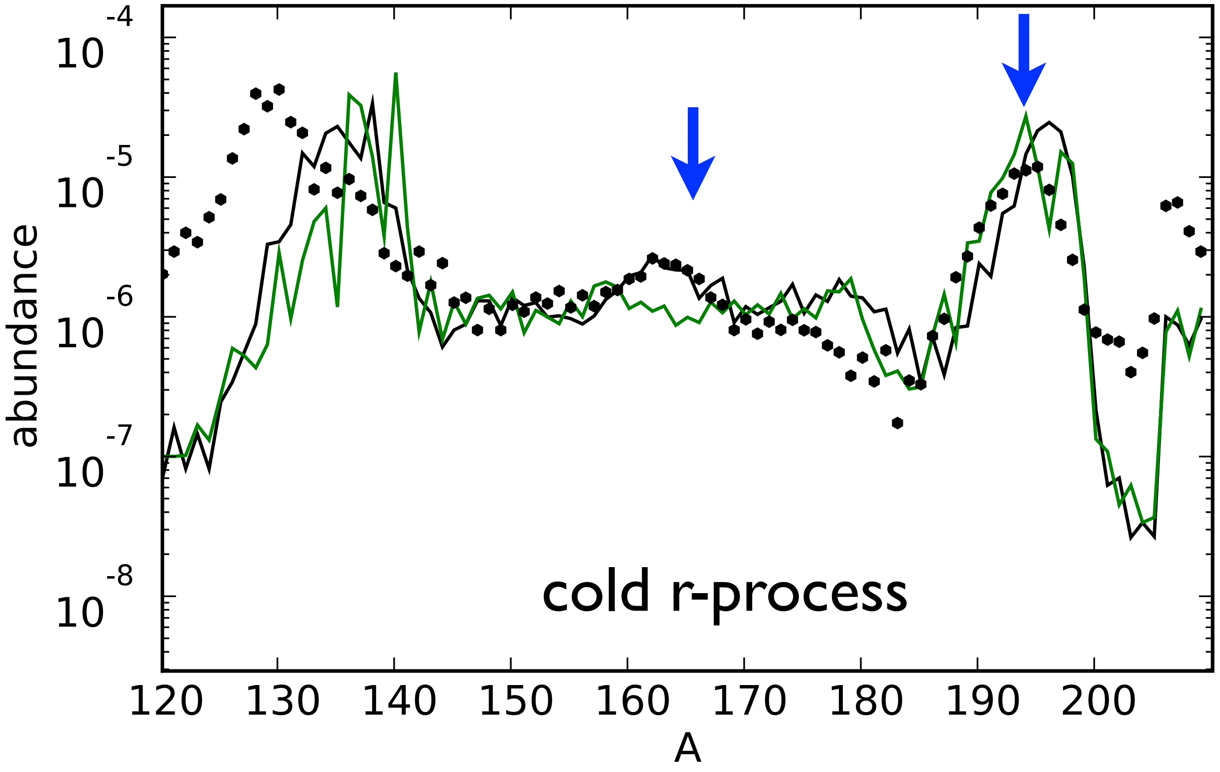


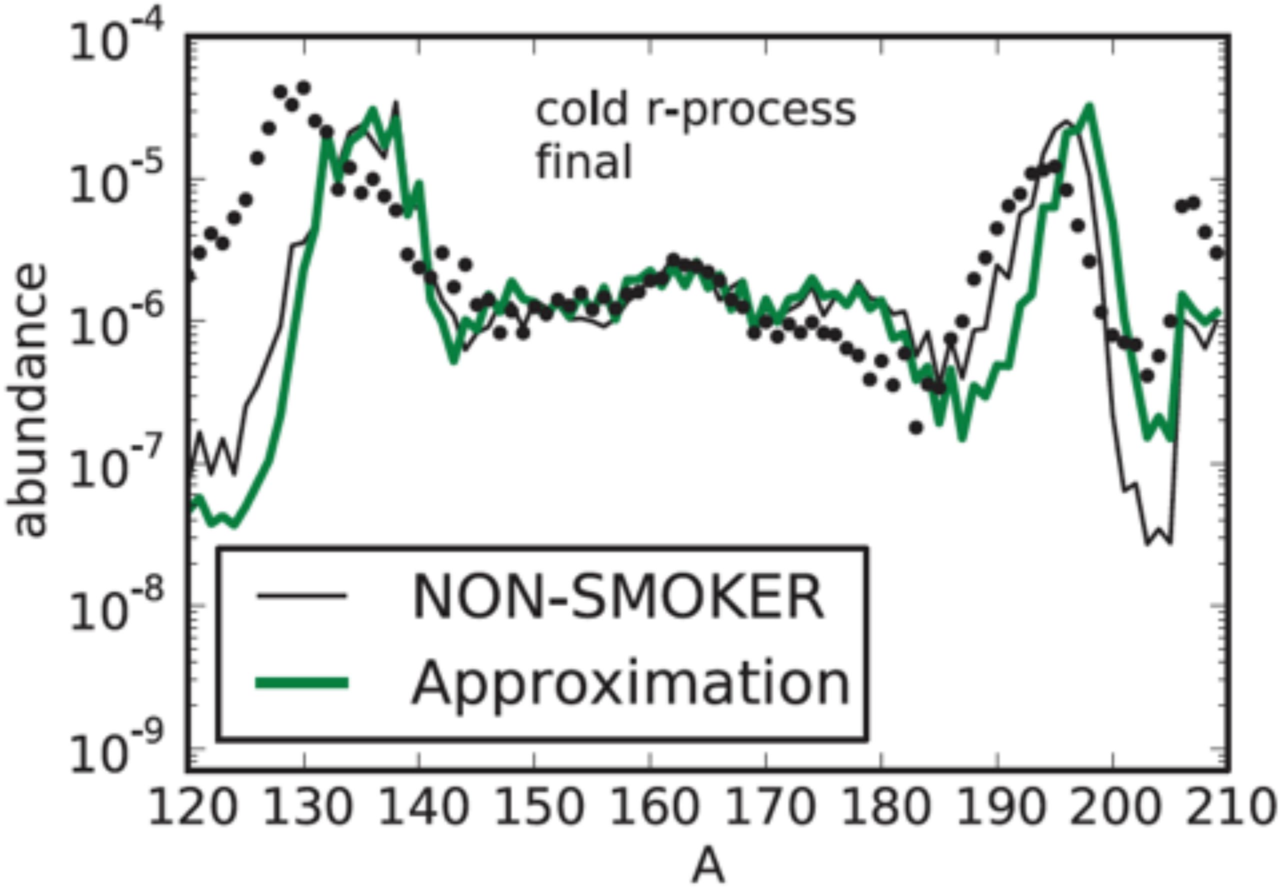


Arcones & Martinez-Pinedo, 2011

Neutron captures

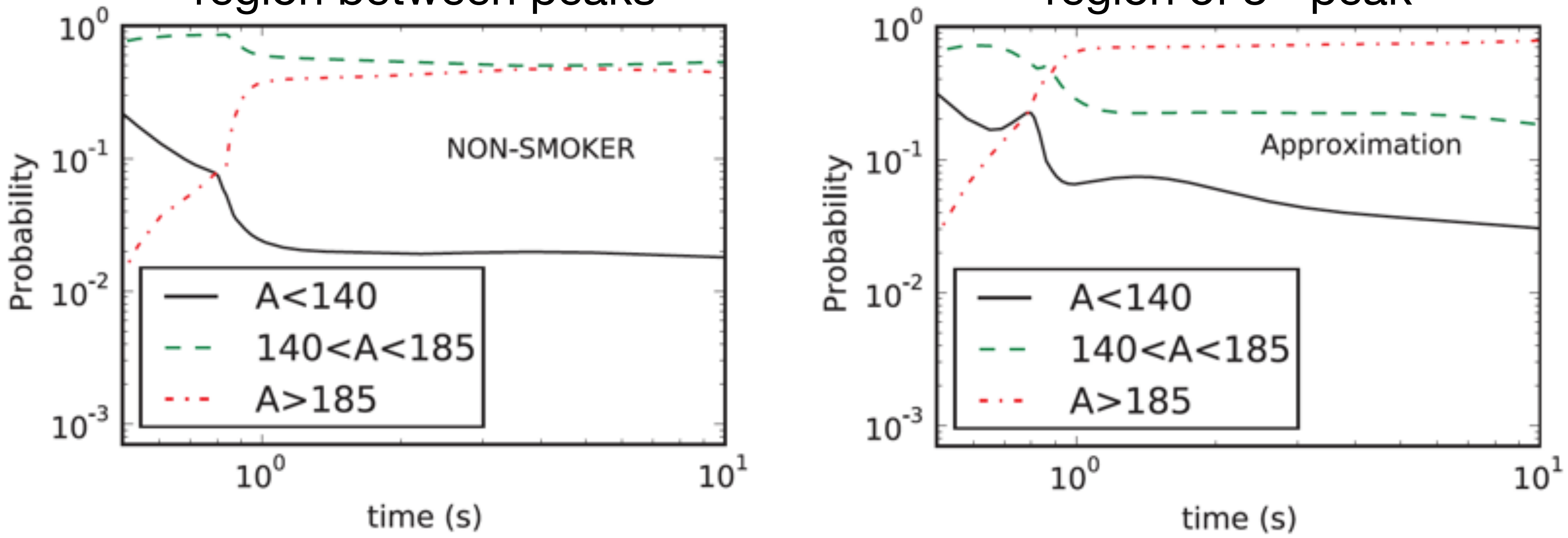
Compare neutron capture calculations:

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



Arcones & Martinez-Pinedo, 2011

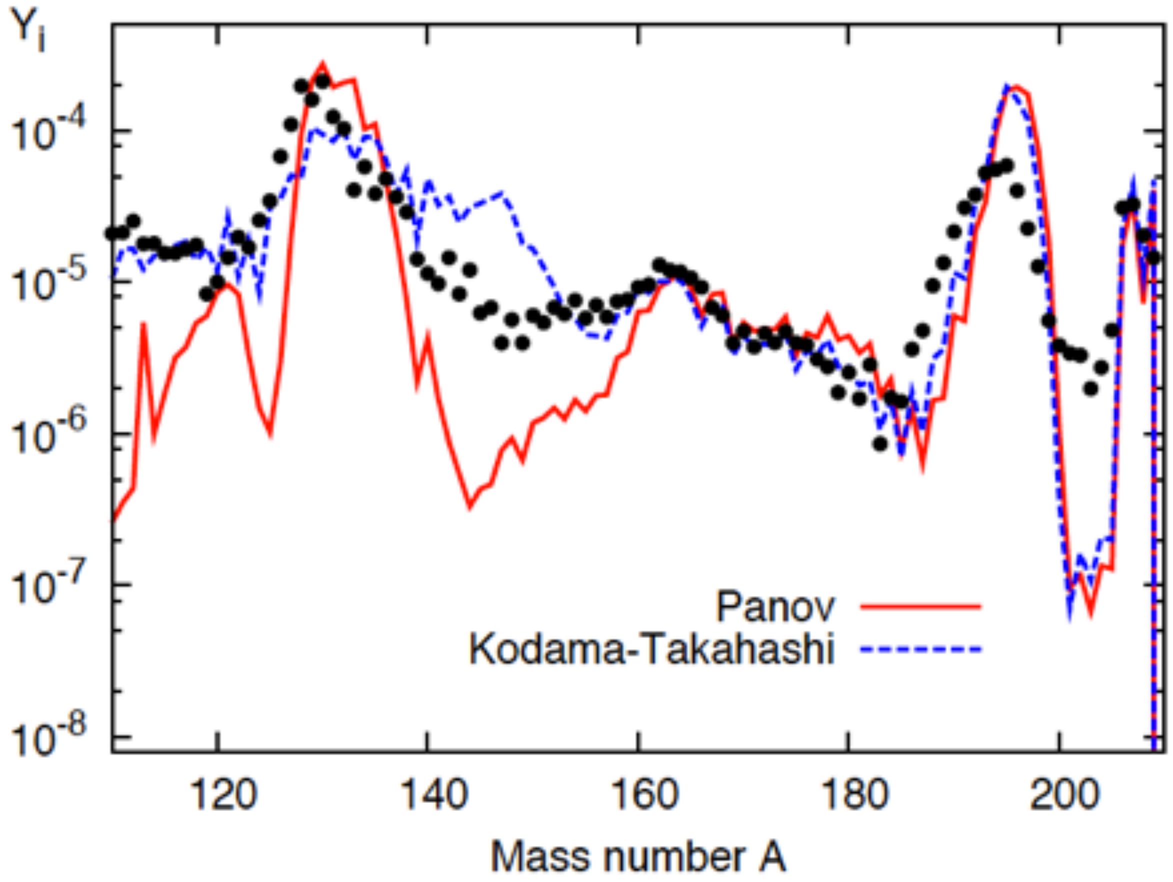
Neutron capture probability:



region between peaks

region of 3rd peak

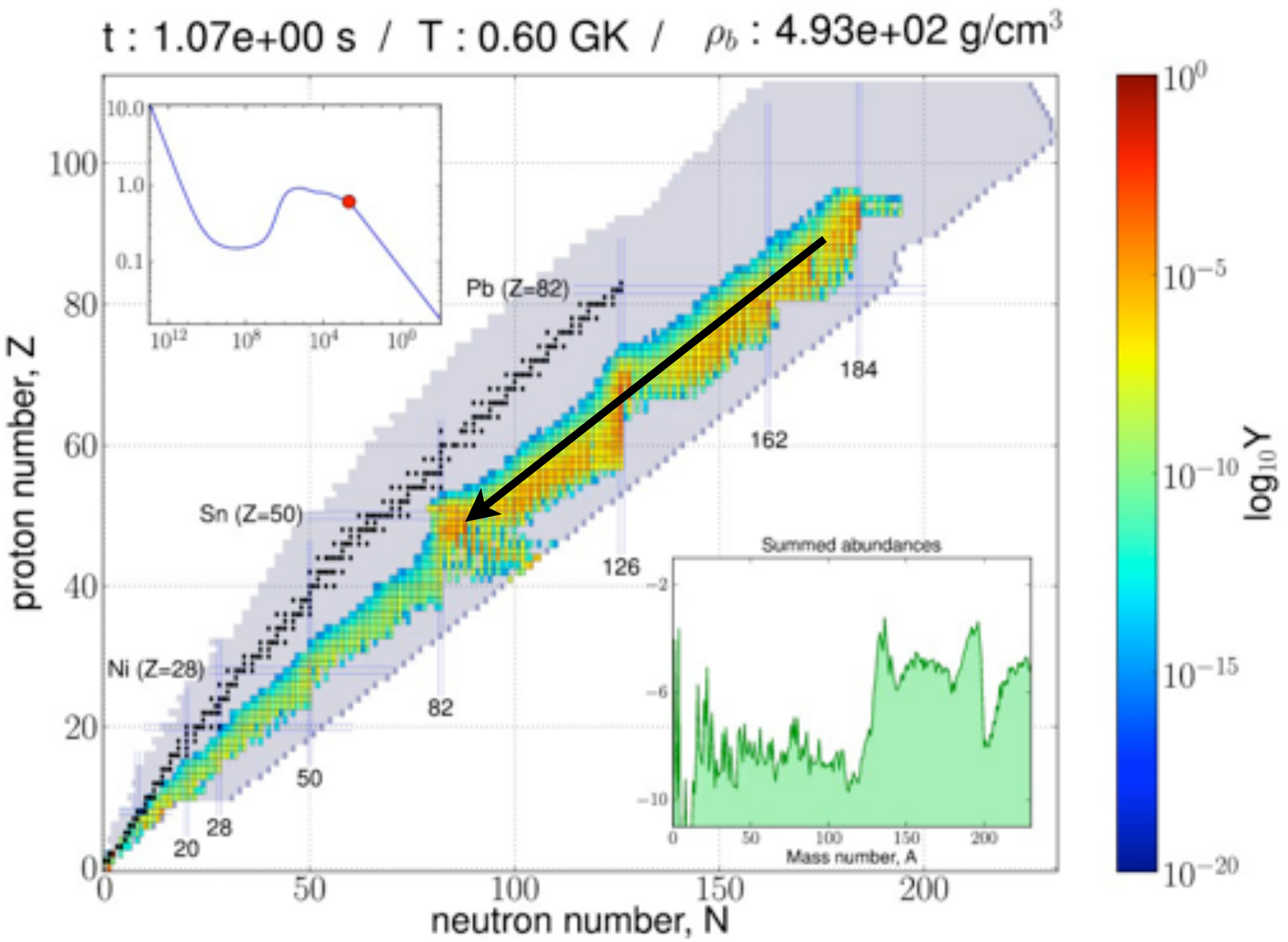
Fission: barriers and yield distributions


Korobkin, Rosswog, Arcones, Winteler (2012)

Neutron star mergers: r-process with two simple fission descriptions

2nd peak (A~130): fission yield distribution
3rd peak (A~195): mass model, drip line

Fission: barriers and yield distributions



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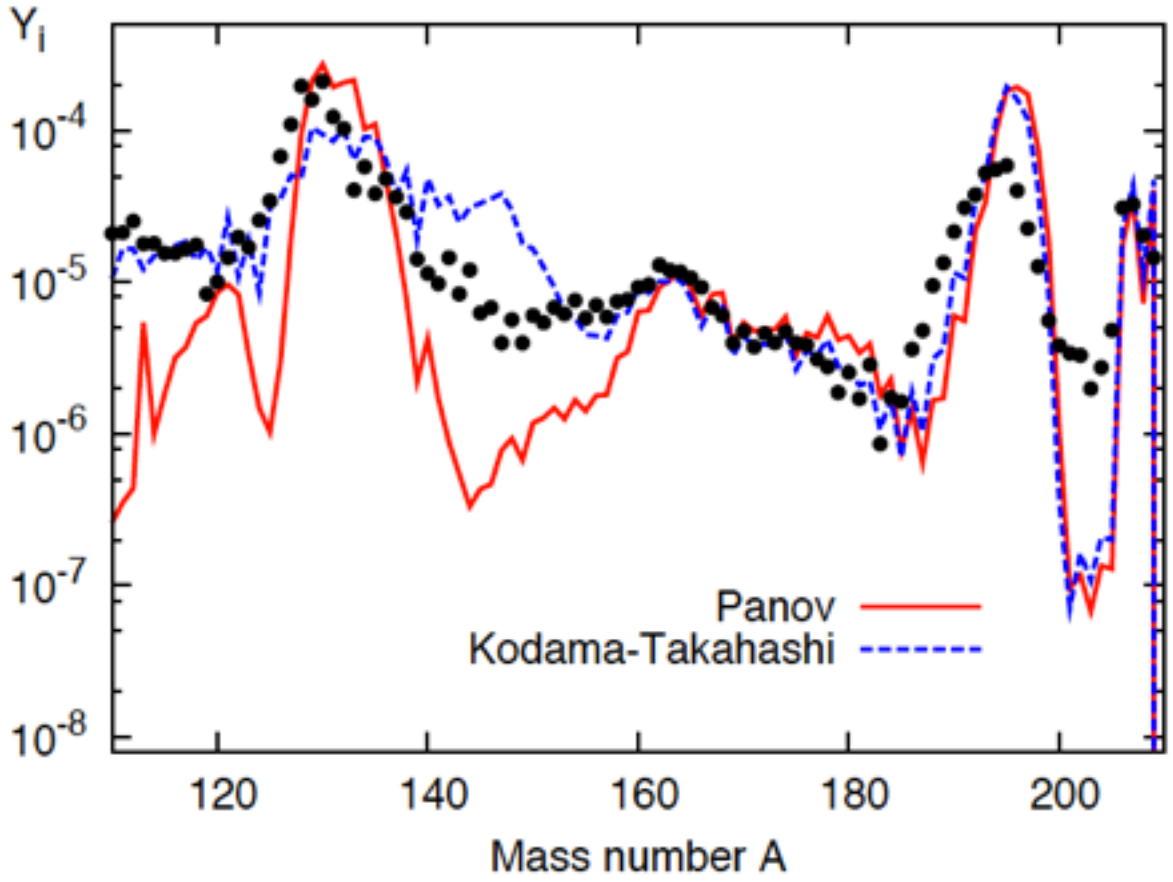

Neutron star mergers: r-process with two simple fission descriptions

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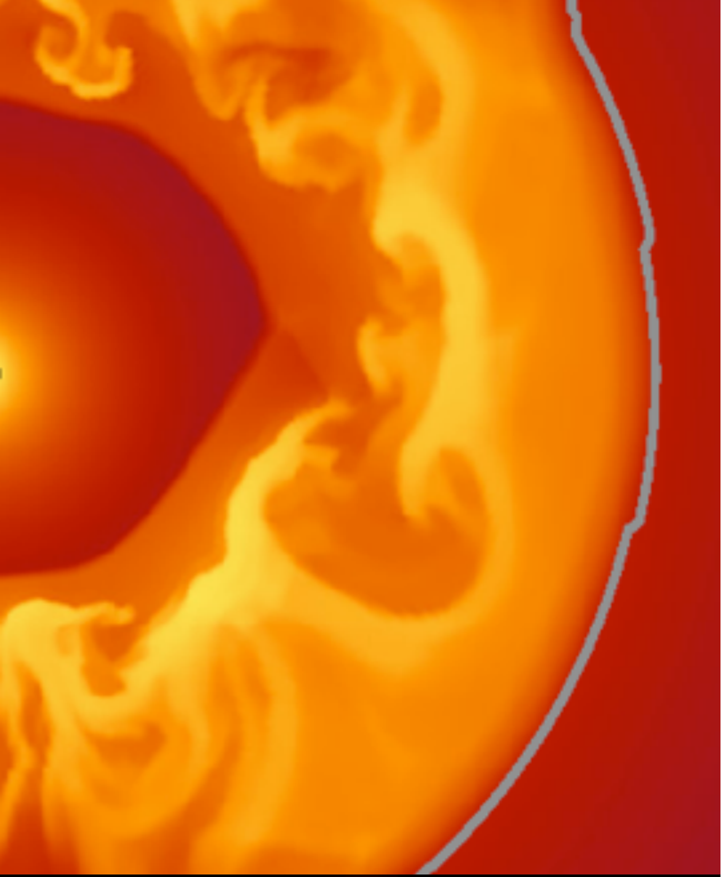
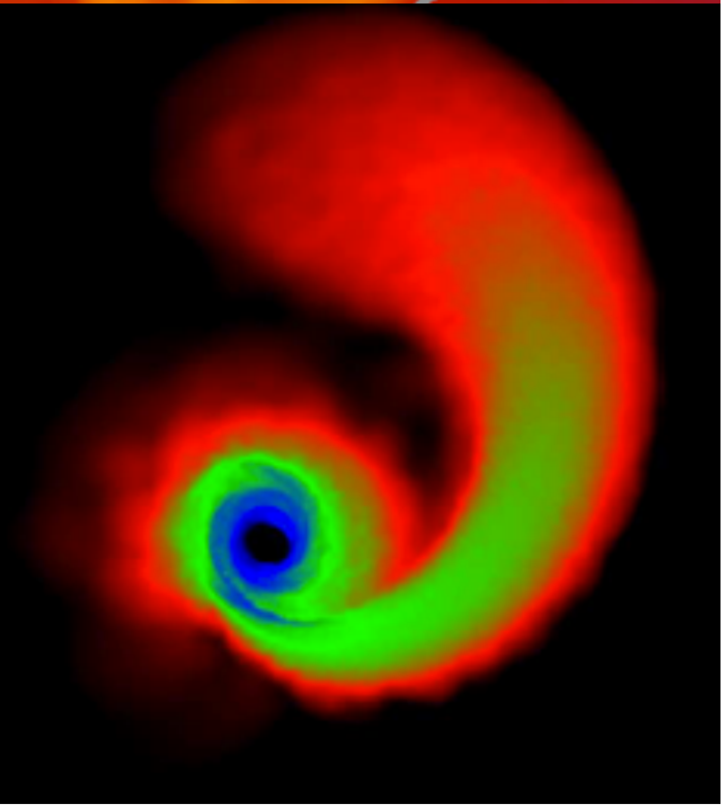
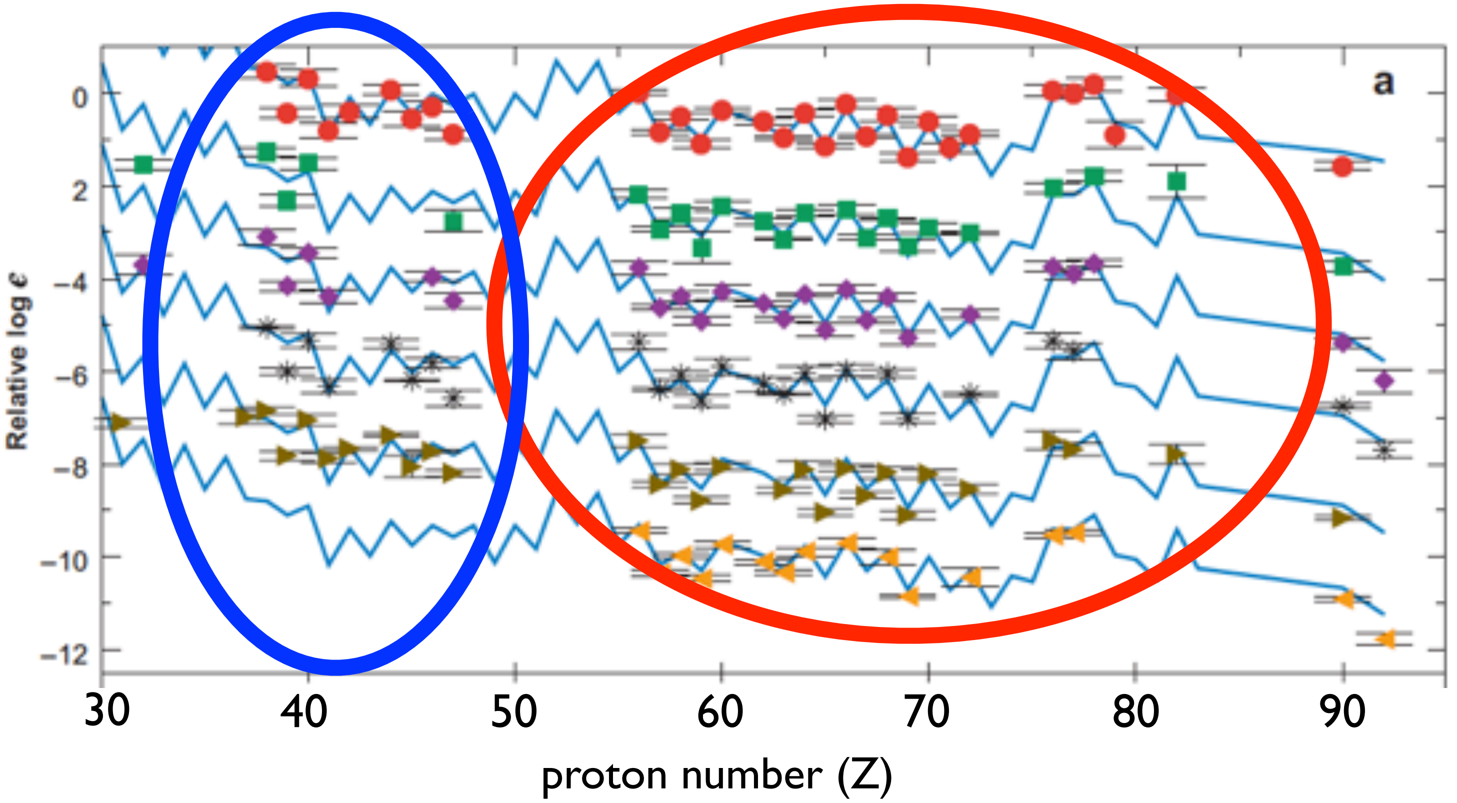
Conclusions





Lighter heavy elements (Sr, Y, Zr)

produced in neutrino-driven wind → Y_e



Heavy r-process elements

astrophysical site? neutron star mergers, jet-like supernovae

uncertainties on nuclear physics input:

nuclear masses, beta decays, neutron captures, fission