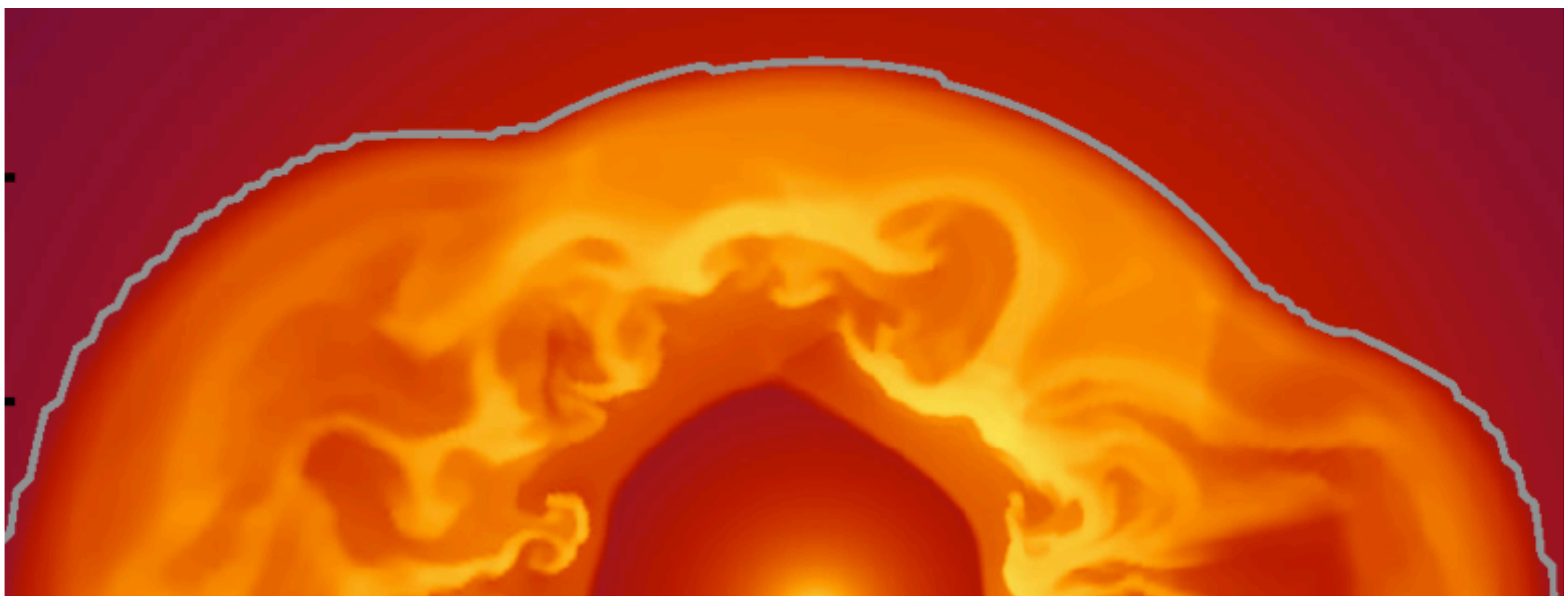
Nucleosynthesis in core-collapse supernovae



HELMHOLTZ GEMEINSCHAFT

Almudena Arcones

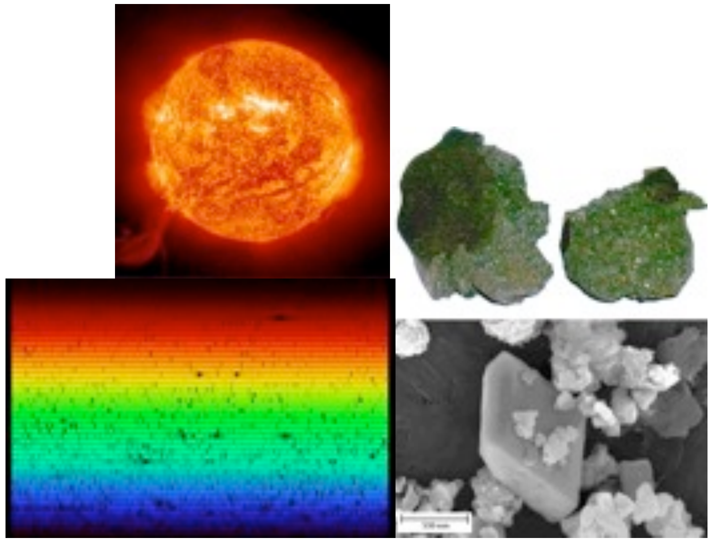
TECHNISCHE UNIVERSITÄT DARMSTADT

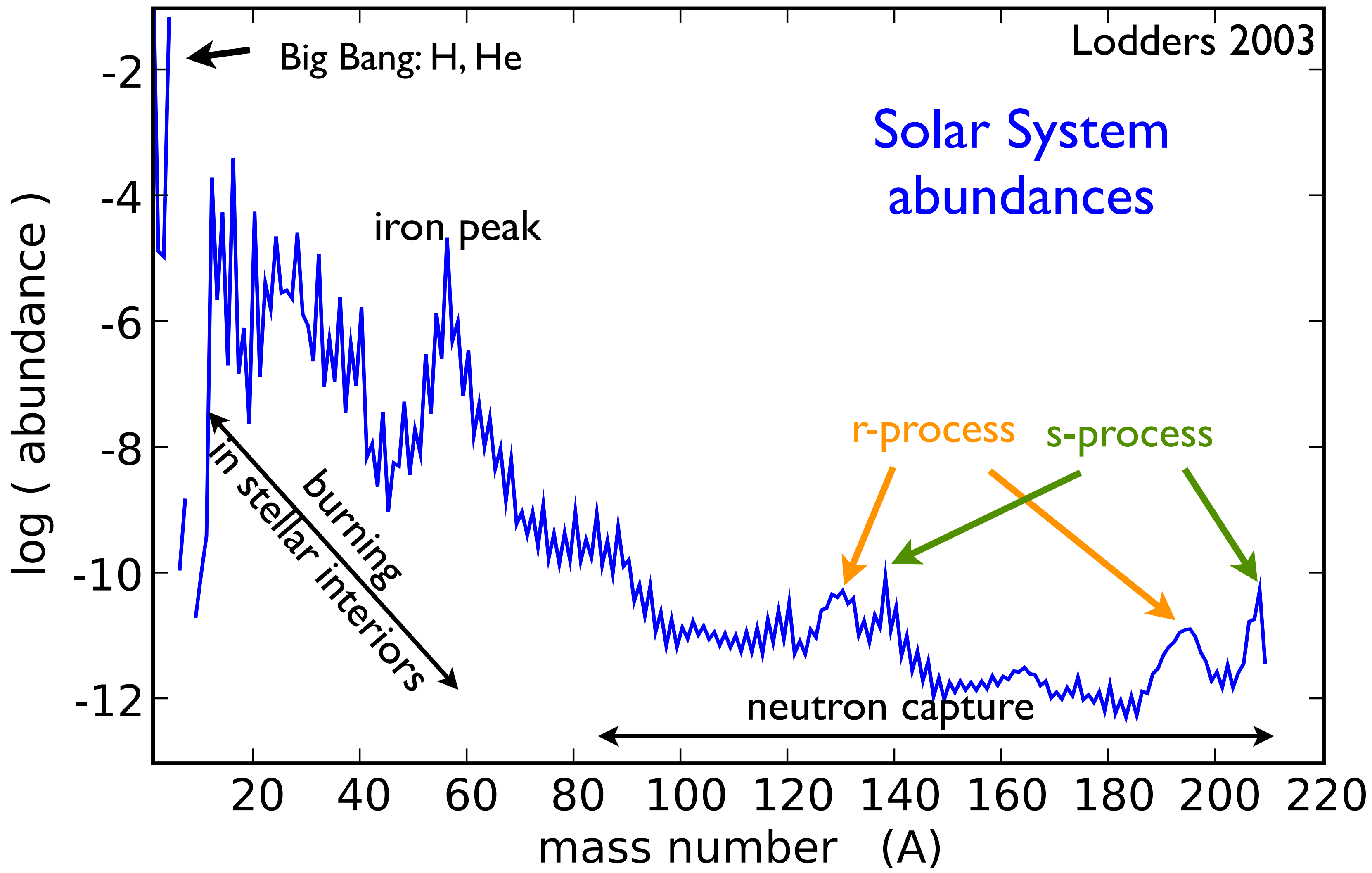
GSI

Solar system abundances

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

Contribution of all nucleosynthesis processes.

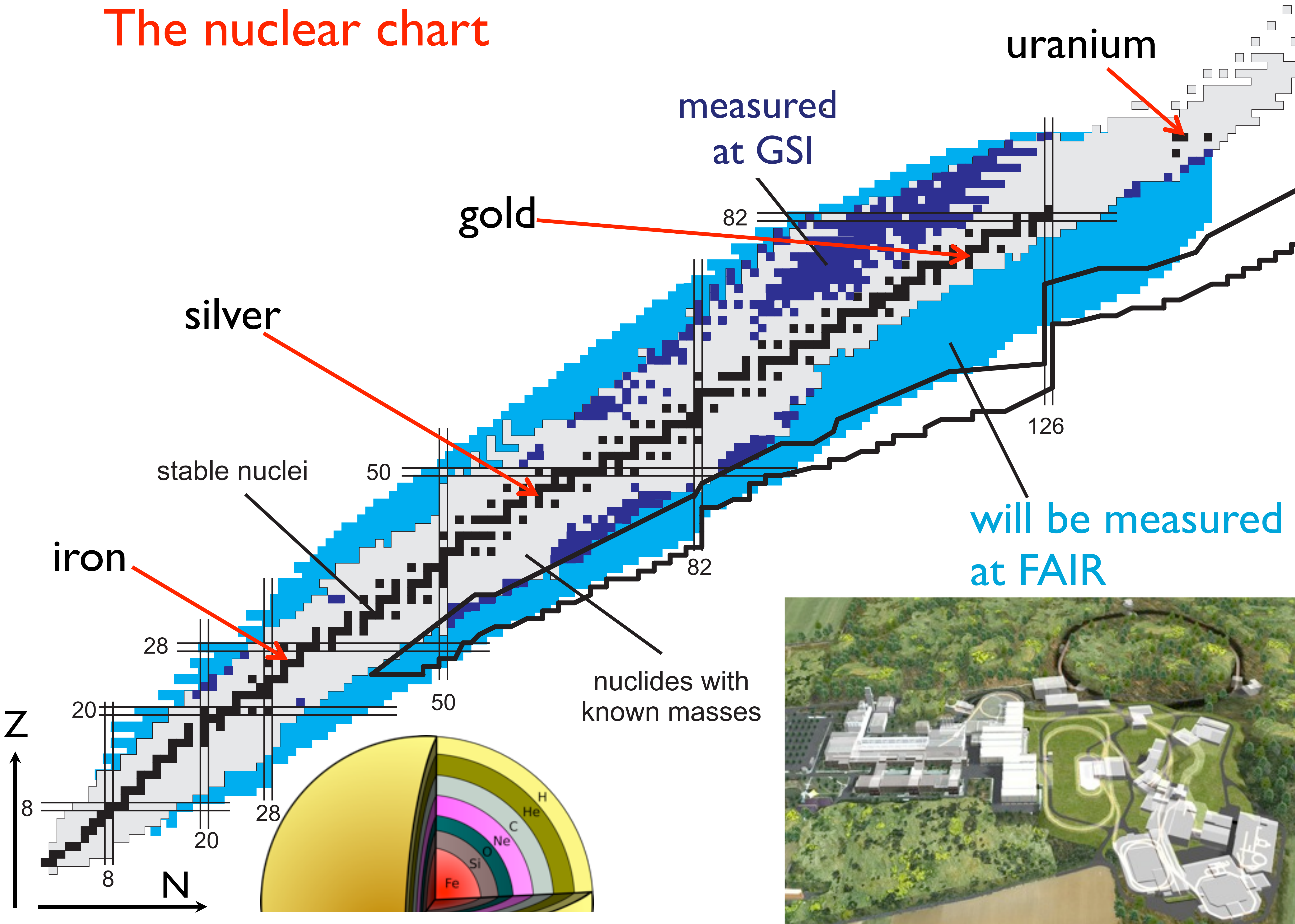




s-process: slow neutron capture in stellar envelopes.

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

The nuclear chart



Nucleosynthesis in ccsn

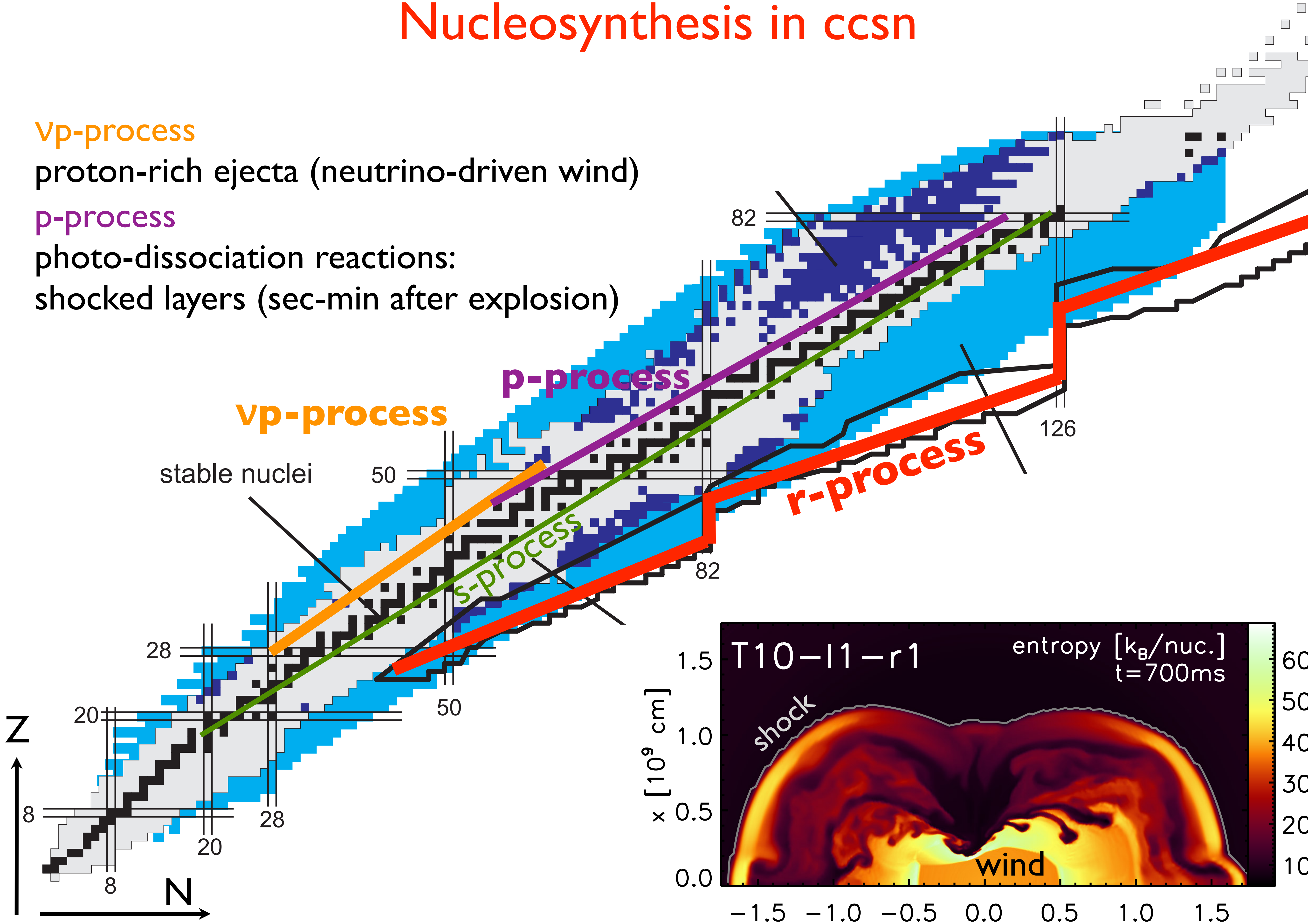
νp-process

proton-rich ejecta (neutrino-driven wind)

p-process

photo-dissociation reactions:

shocked layers (sec-min after explosion)



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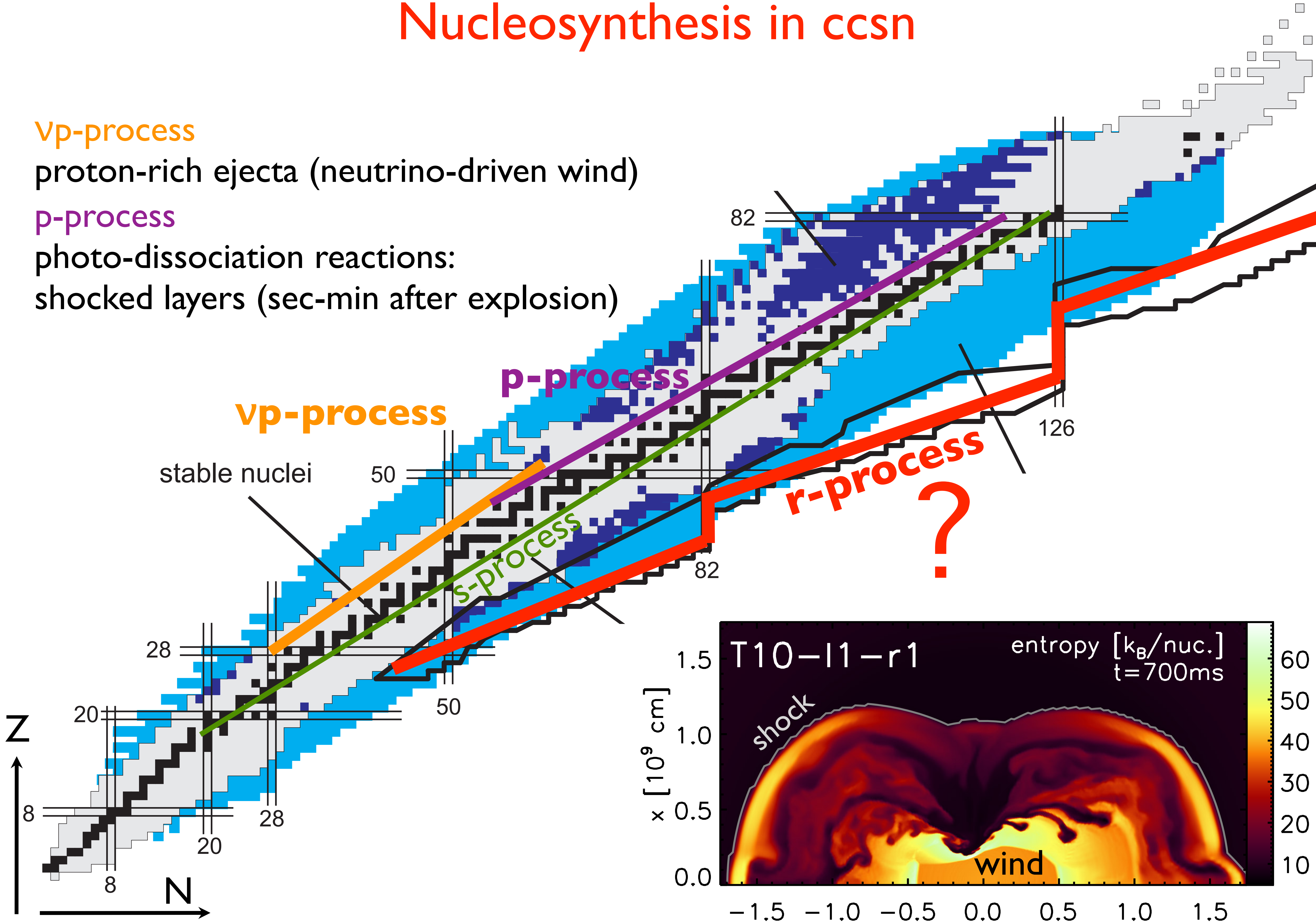
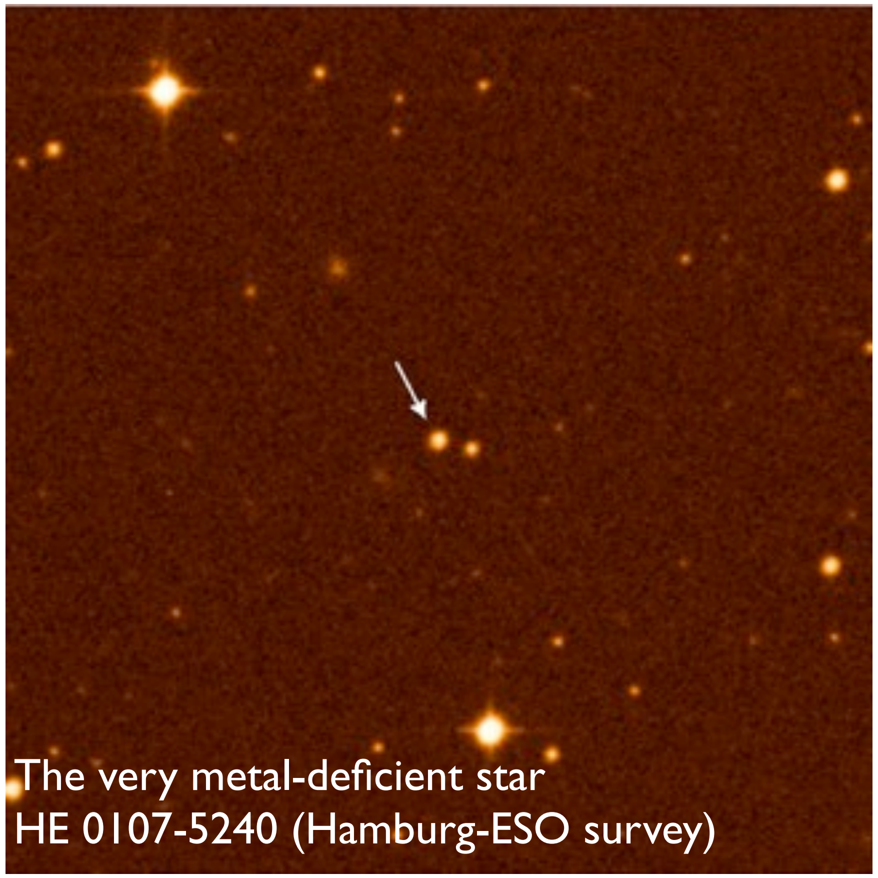


Ultra metal-poor stars

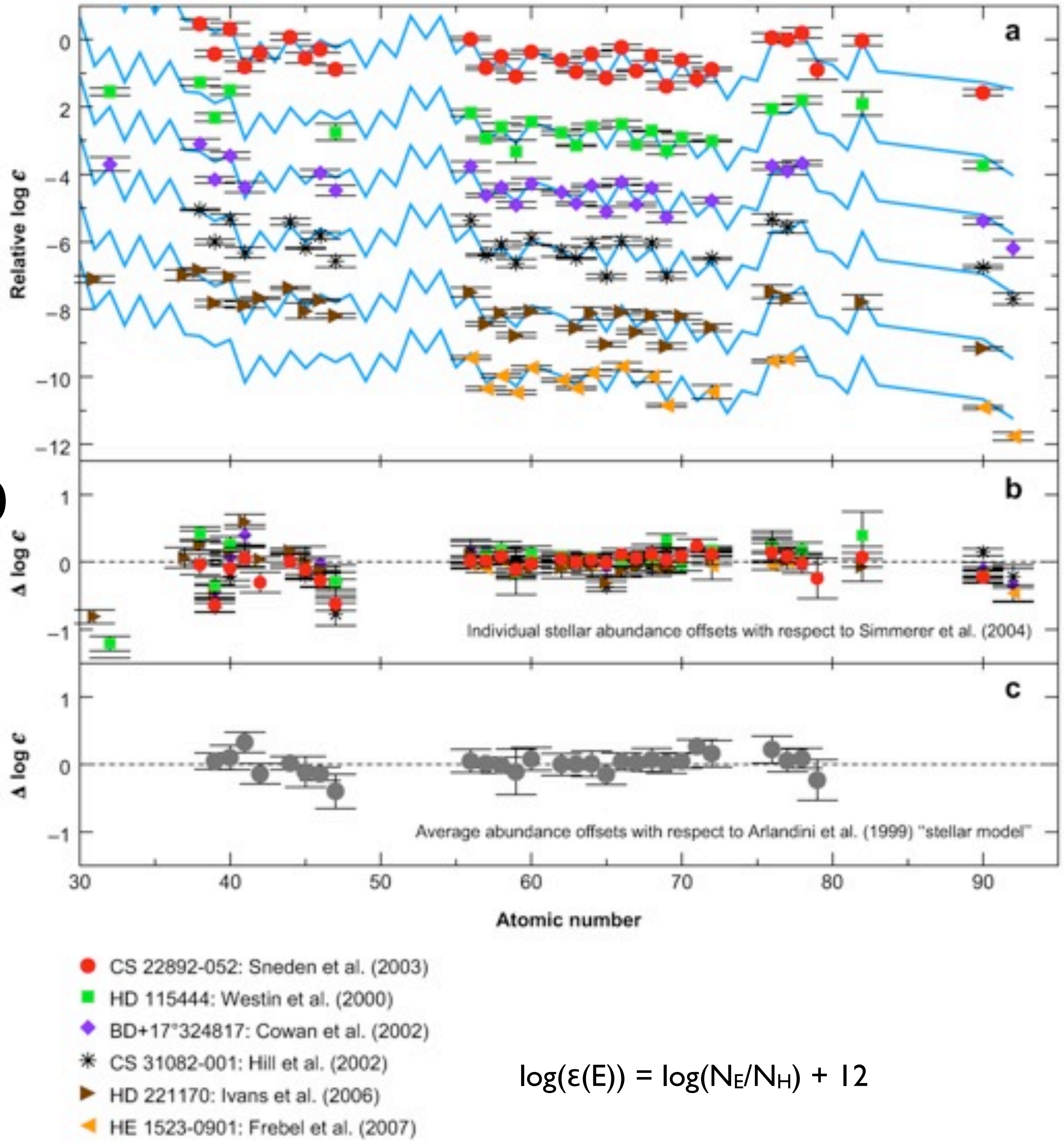
Abundances of r-process elements in:
- ultra metal-poor stars and
- solar system

Robust r-process for 56<Z<83

Scatter for lighter heavy elements, Z~40



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 in core-collapse supernovae? (B^{2}FH 1957)

- prompt explosion (Hillebrandt 1978, Hillebrandt et al. 1984)
- neutrino-driven wind (Meyer et al. 1992, Woosley et al. 1994)
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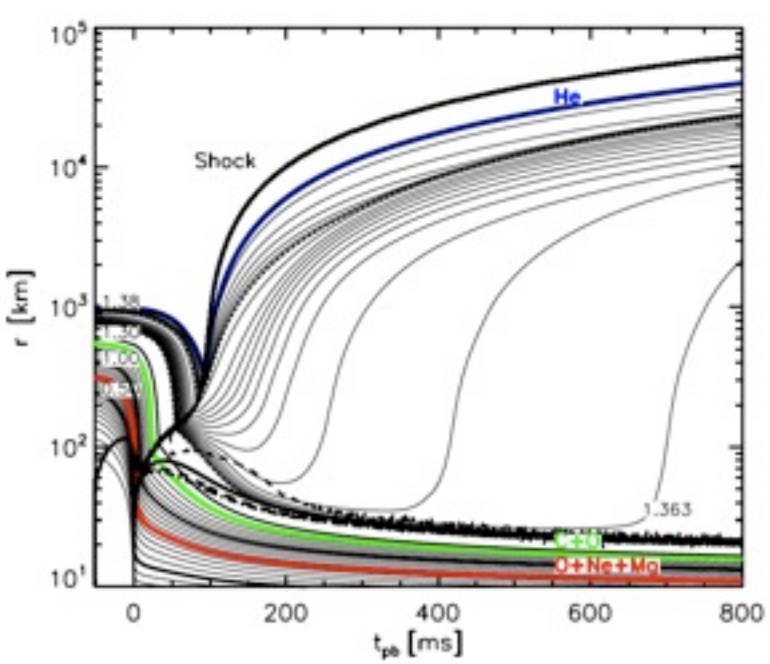
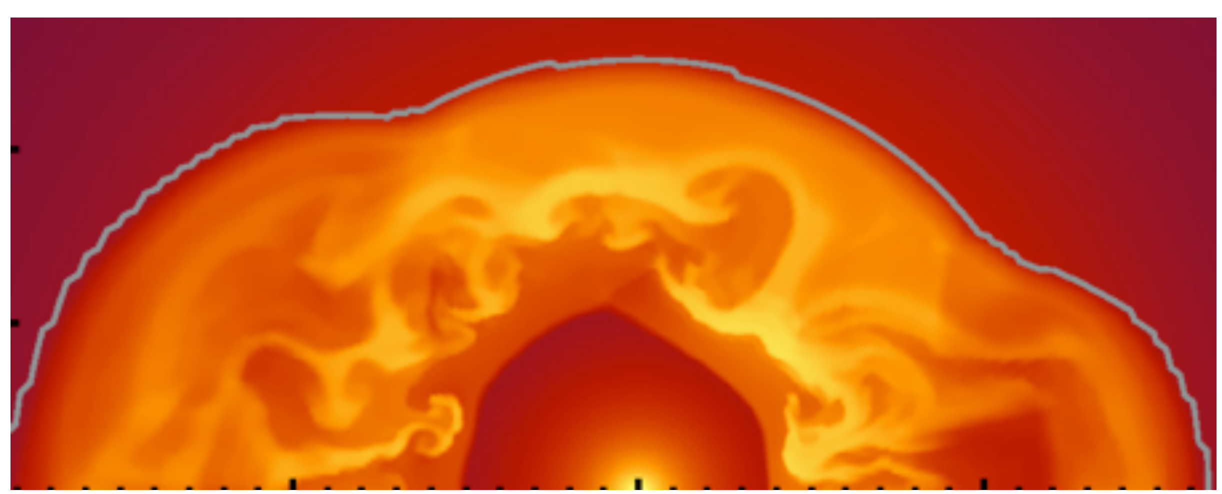
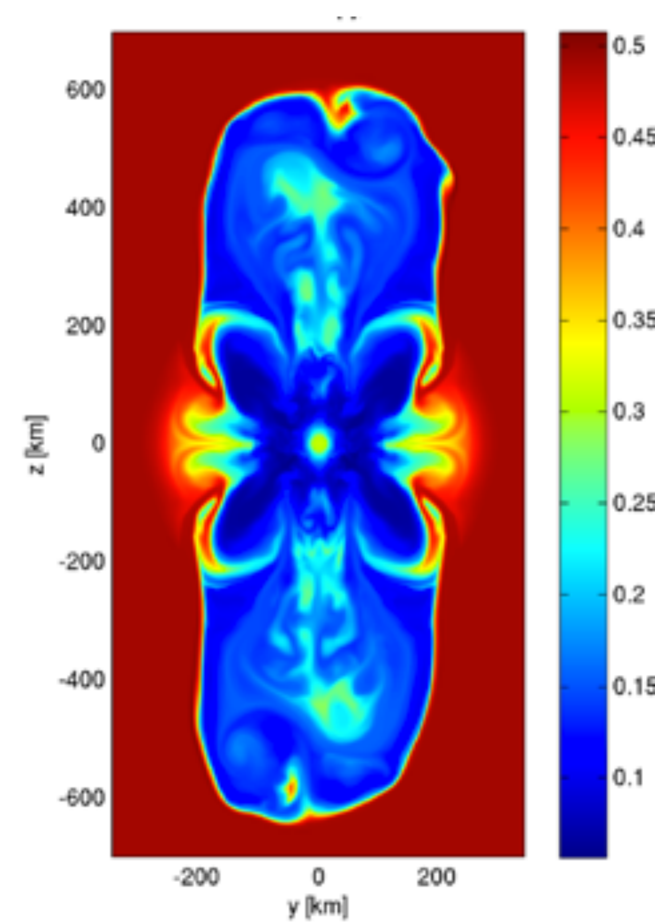




wind



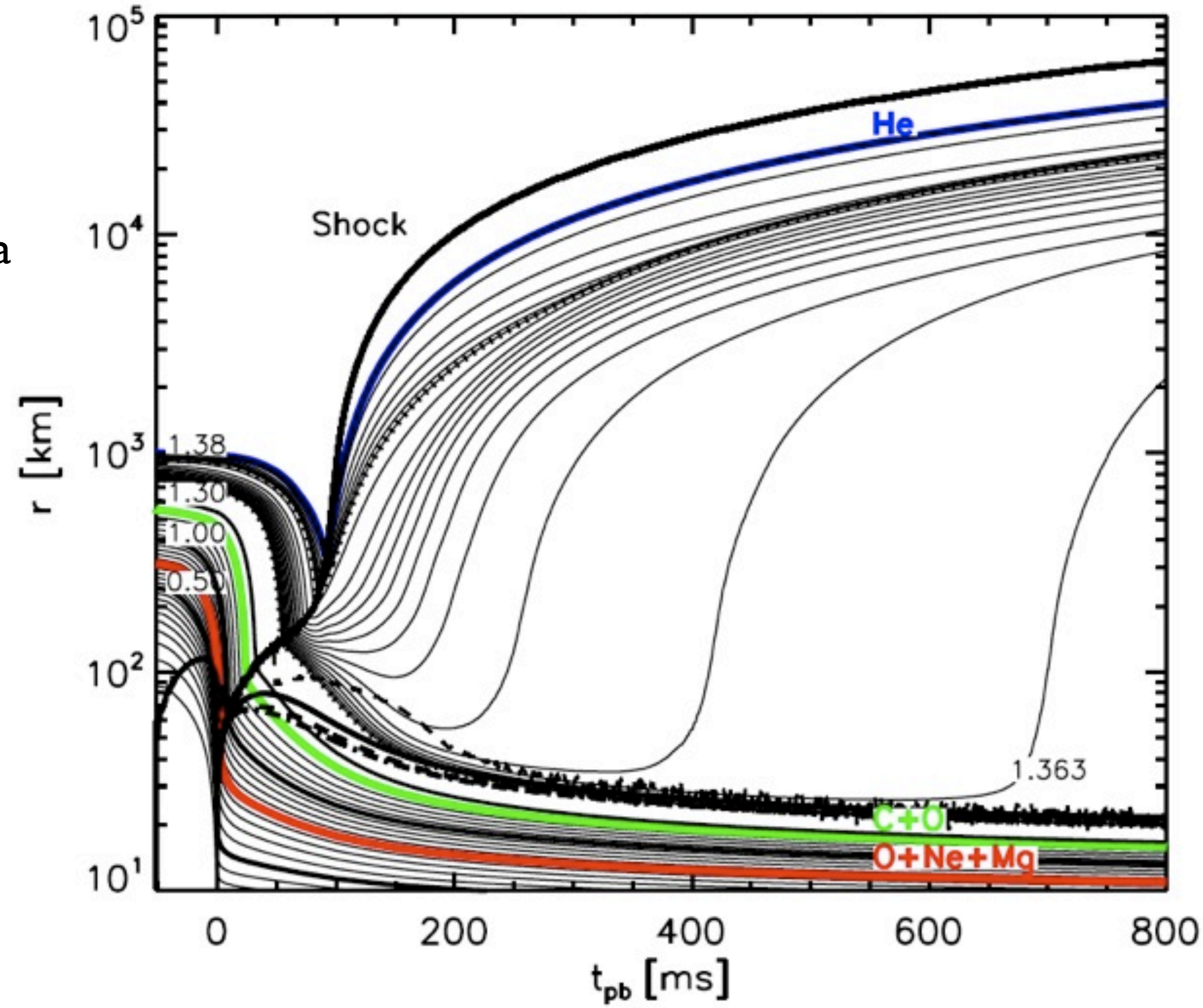
Core-collapse supernova: ONeMg

ONeMg core: P_e reduced as e^- captured ⟶ collapse (electron-capture supernova)

Prompt explosion (Hillebrandt 1978, Hillebrandt et al. 1984)
not confirmed by modern supernova simulations (Kitaura, Janka, Hillebrandt 2006)

Delayed neutrino-driven explosion works for this progenitor even in 1D (Kitaura et al. 2006, Fischer et al. 2010)

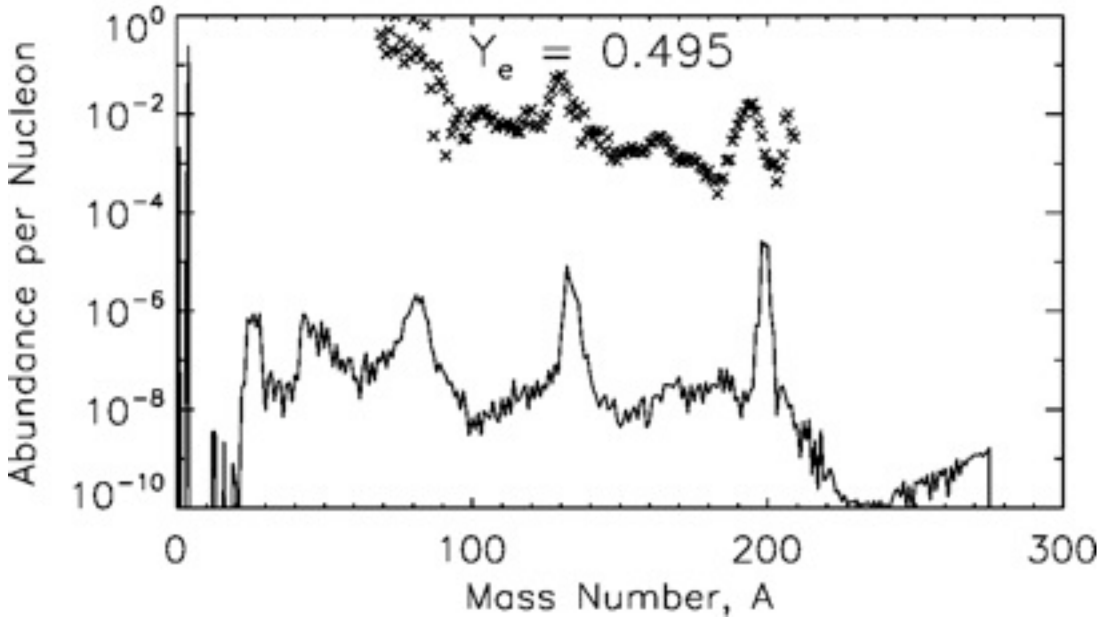
Prompt explosion excluded as r-process site

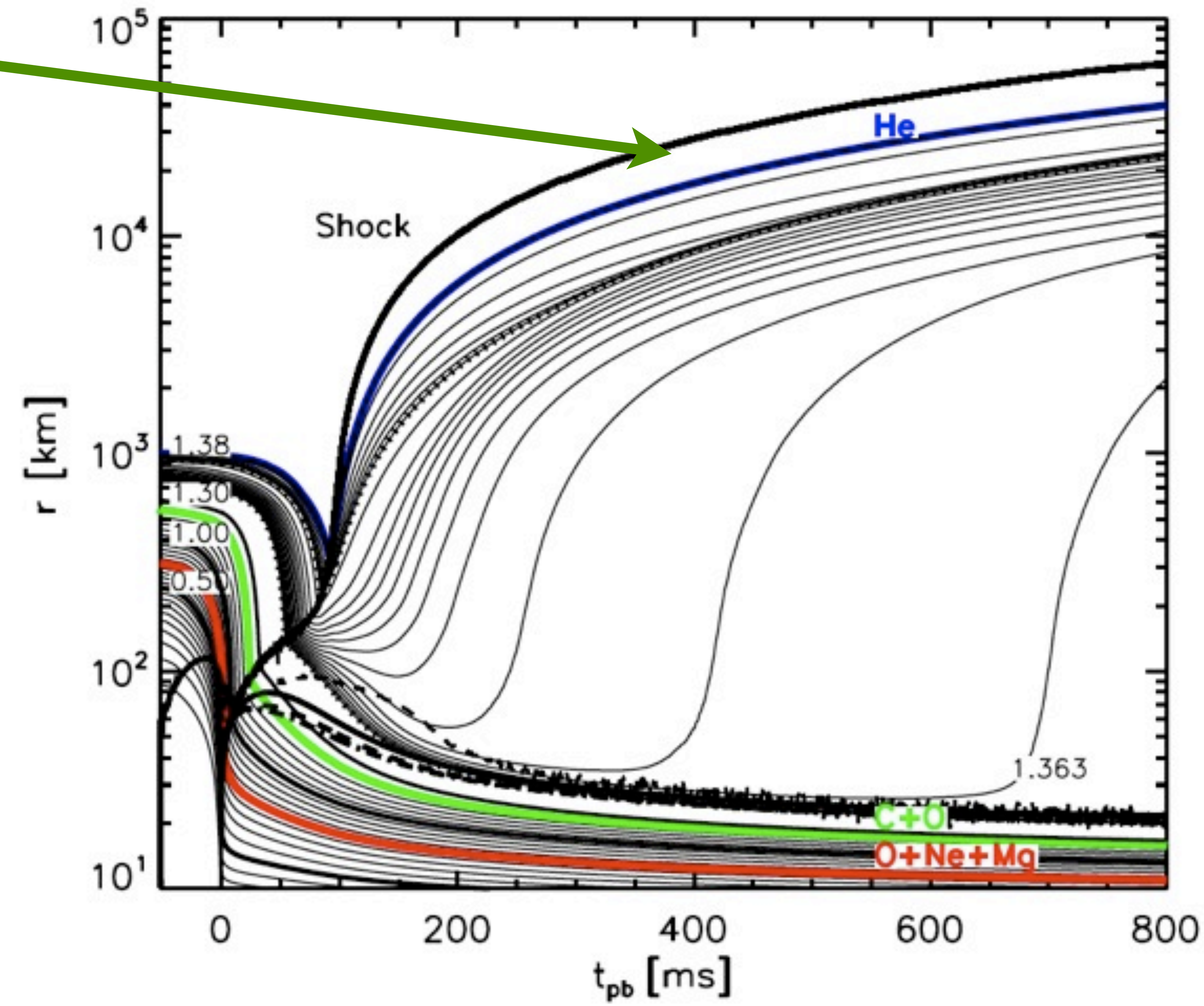


Core-collapse supernova: ONeMg

r-process in the shocked surface layers
(Ning, Qian, Meyer 2007):

- very high velocity (c/3)
- high entropy
- slightly neutron rich is sufficient





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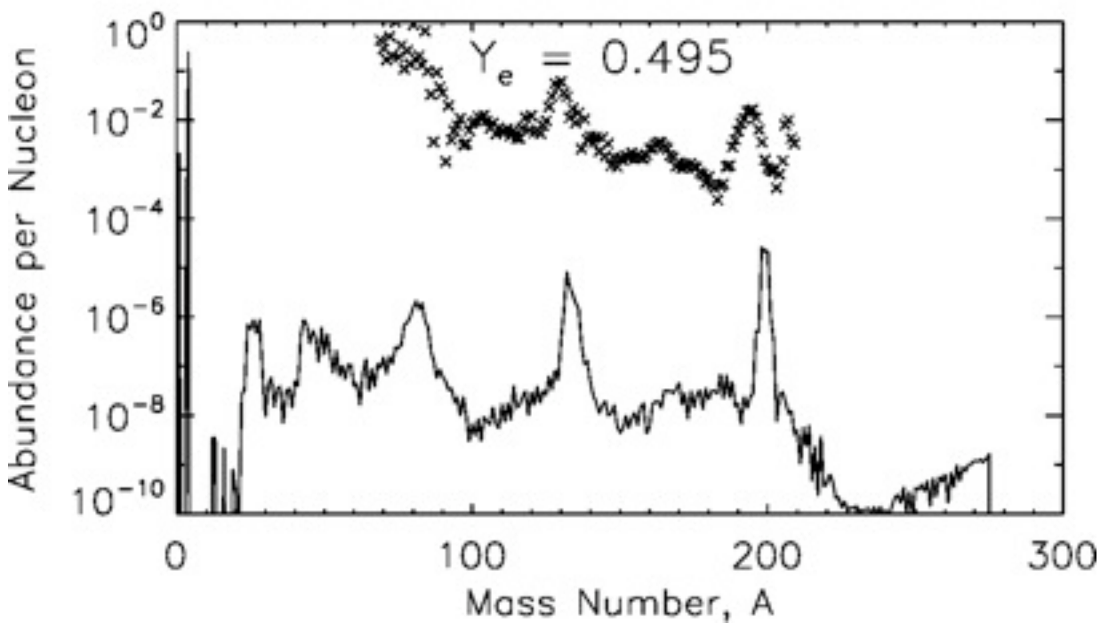

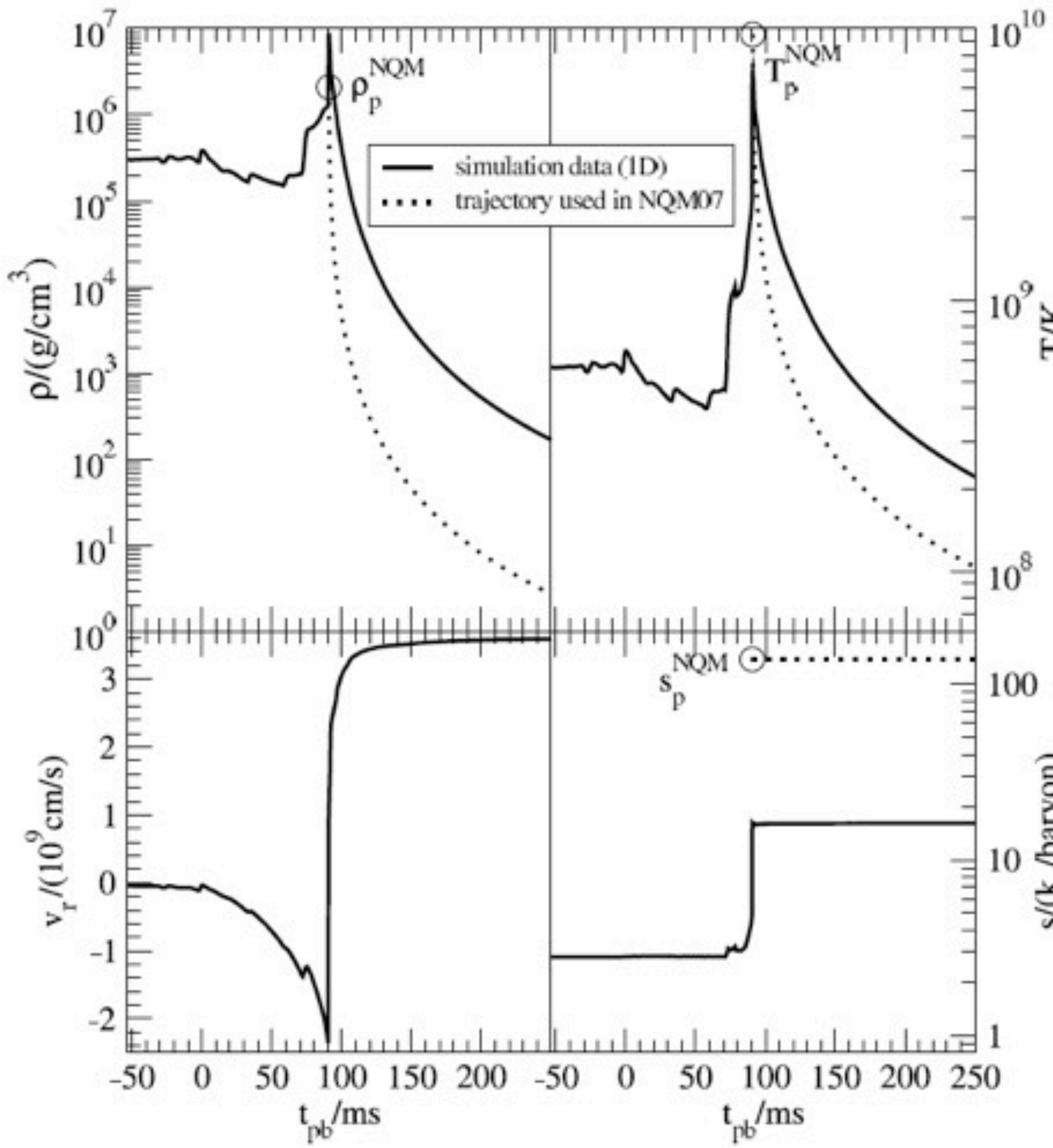

Janka et al. 2008, Hoffman et al. 2008, Wanajo et al. 2009

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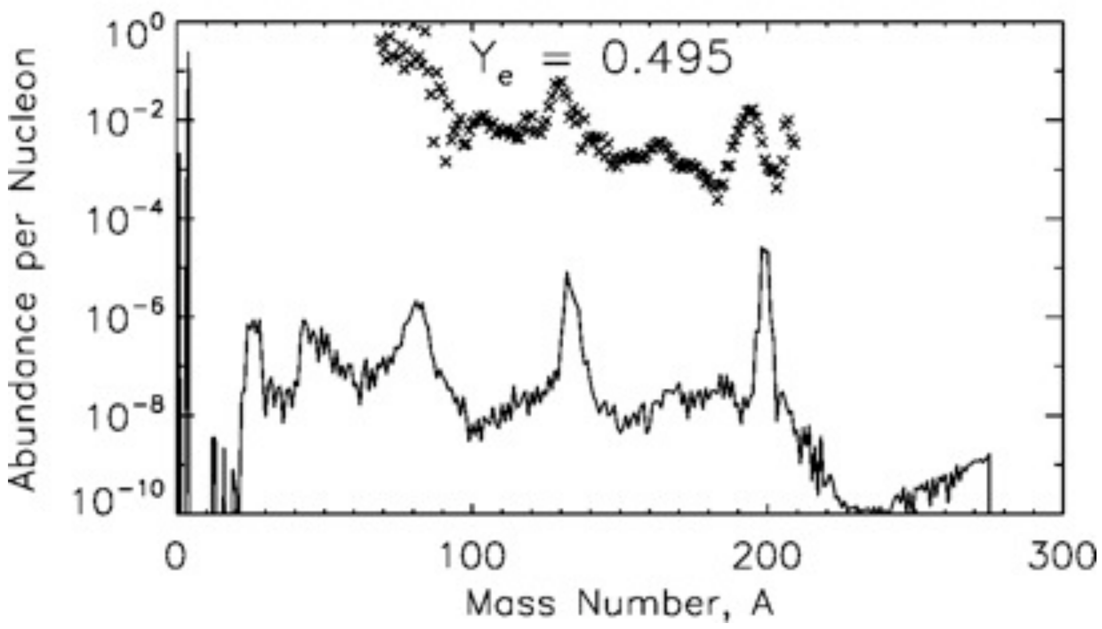
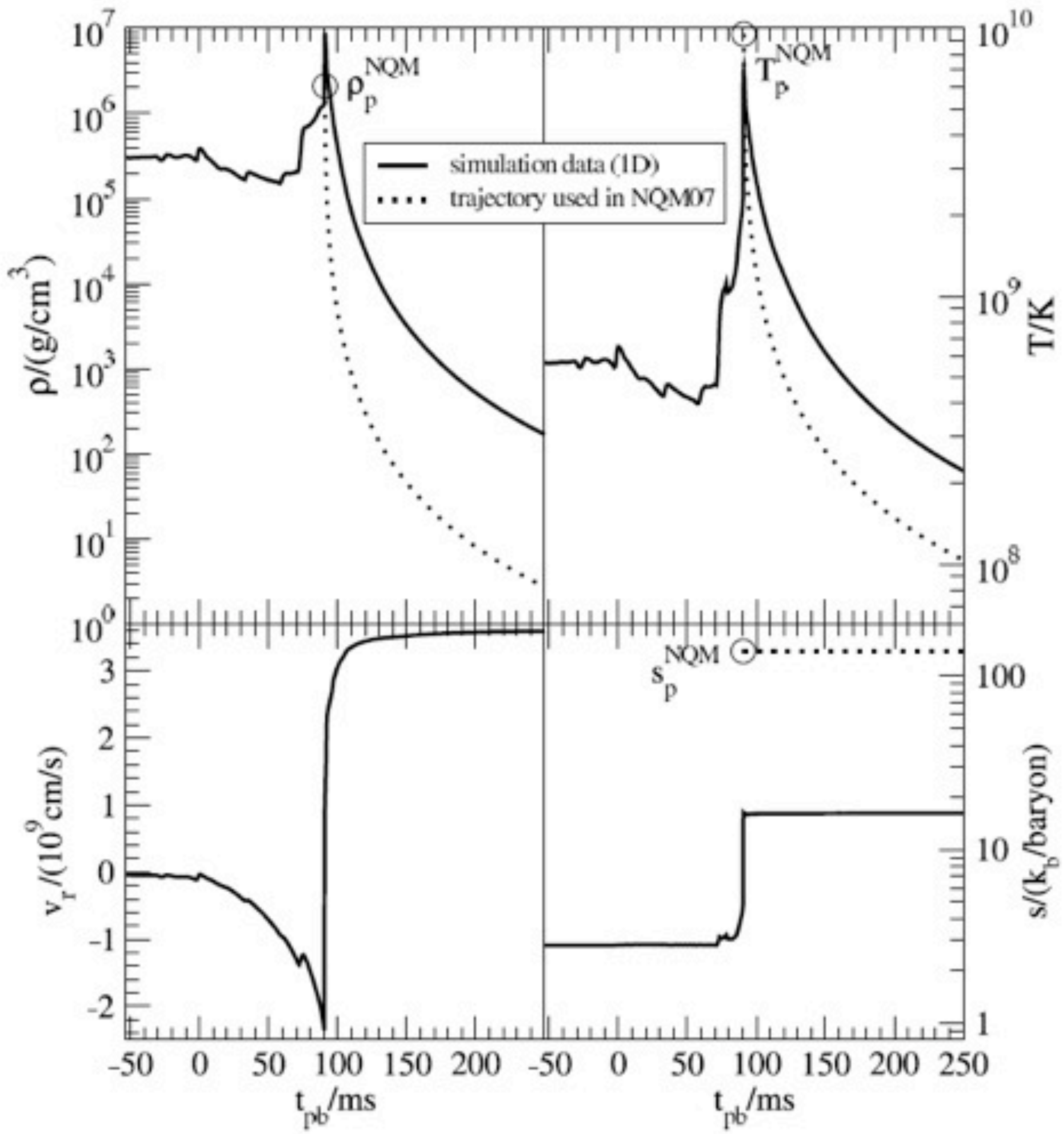




Janka et al. 2008, Hoffman et al. 2008, Wanajo et al. 2009

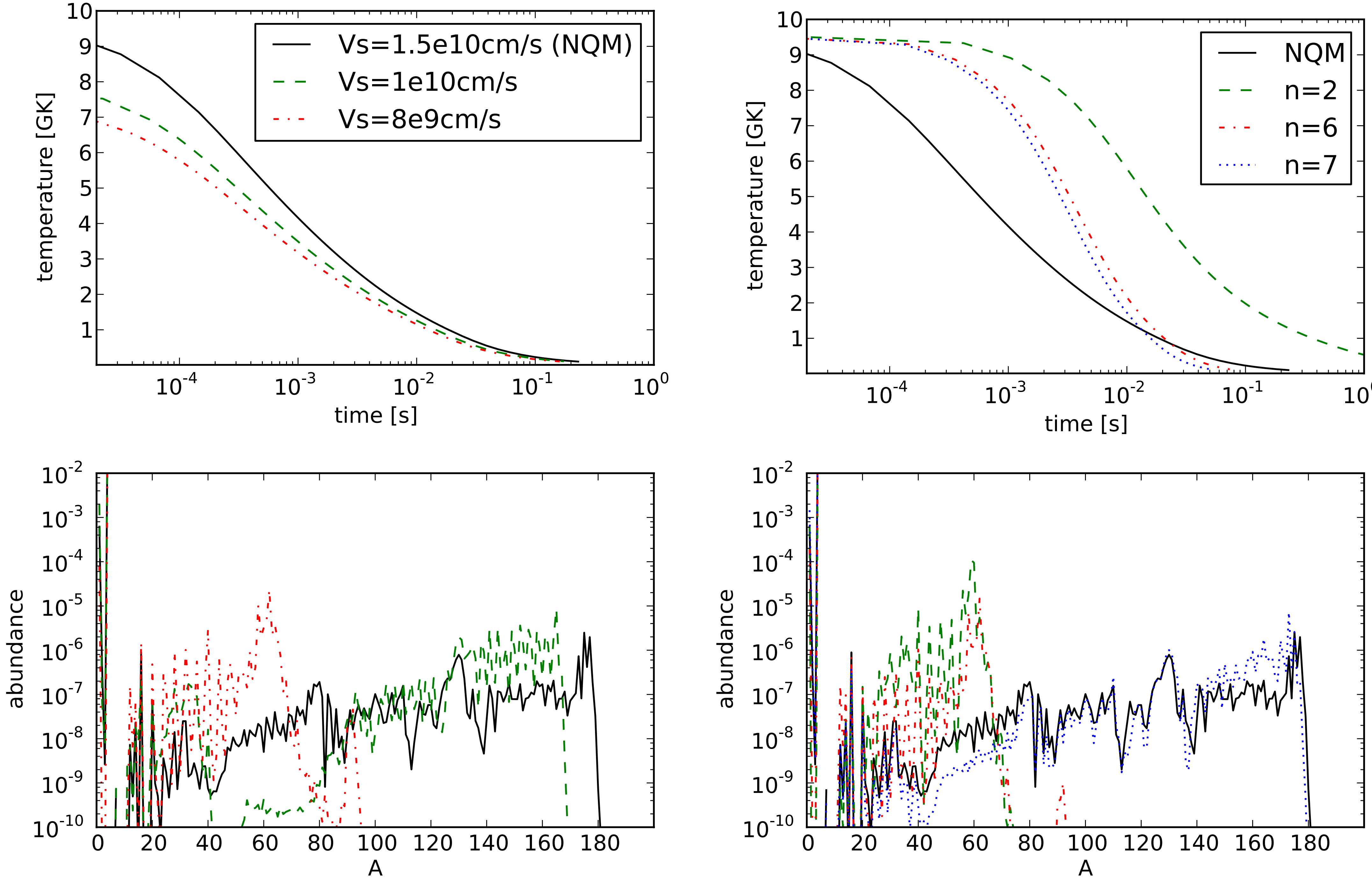
One model for low mass progenitors: $8.8M_{sun}$ (Nomoto 1984, 1987)

Promising scenario for the r-process, requires further investigation

r-process in shocked surface layers

parametric study: shock velocity

expansion ($\rho \sim t^{-n}$)



Preliminary results by M. Eichler

r-process in core-collapse supernovae? (B^{2}FH 1957)

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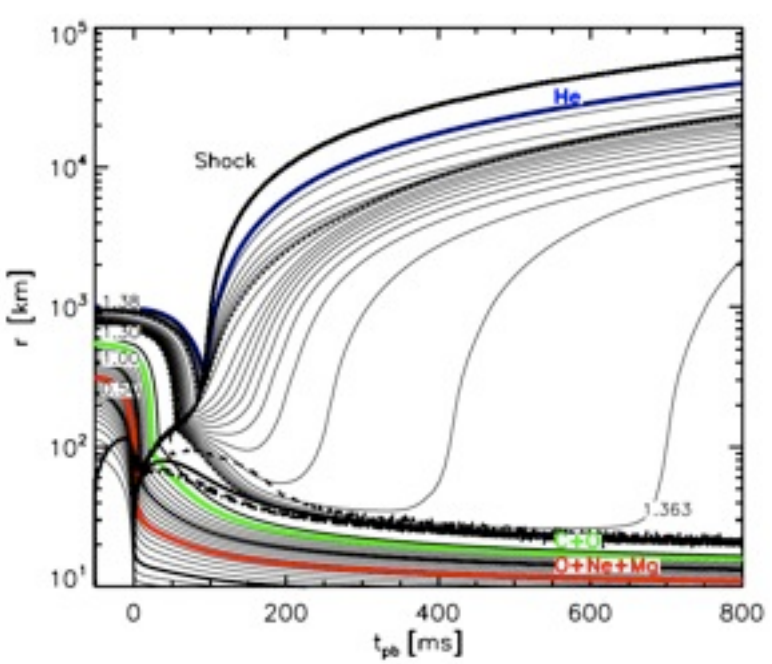

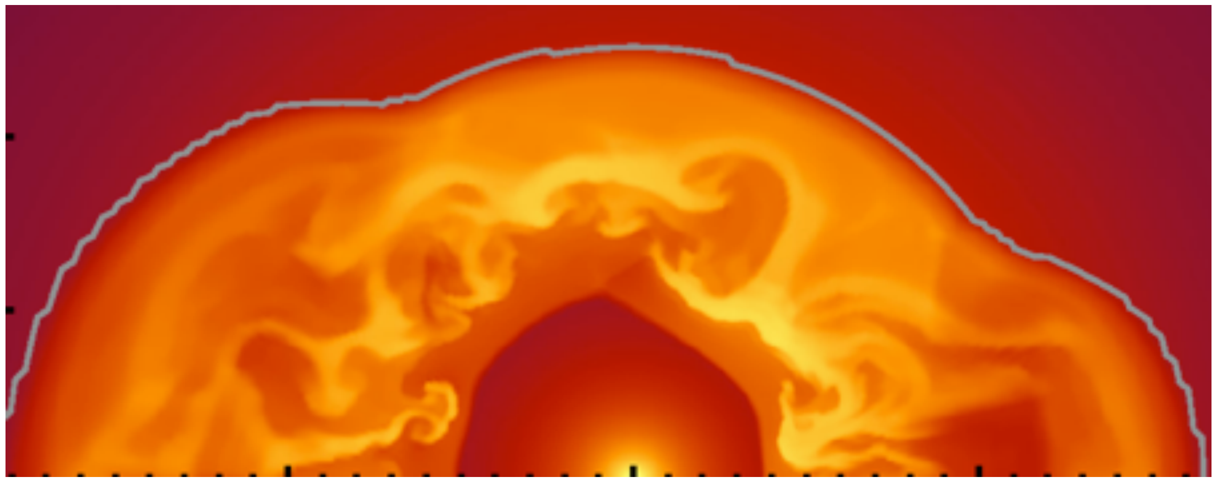

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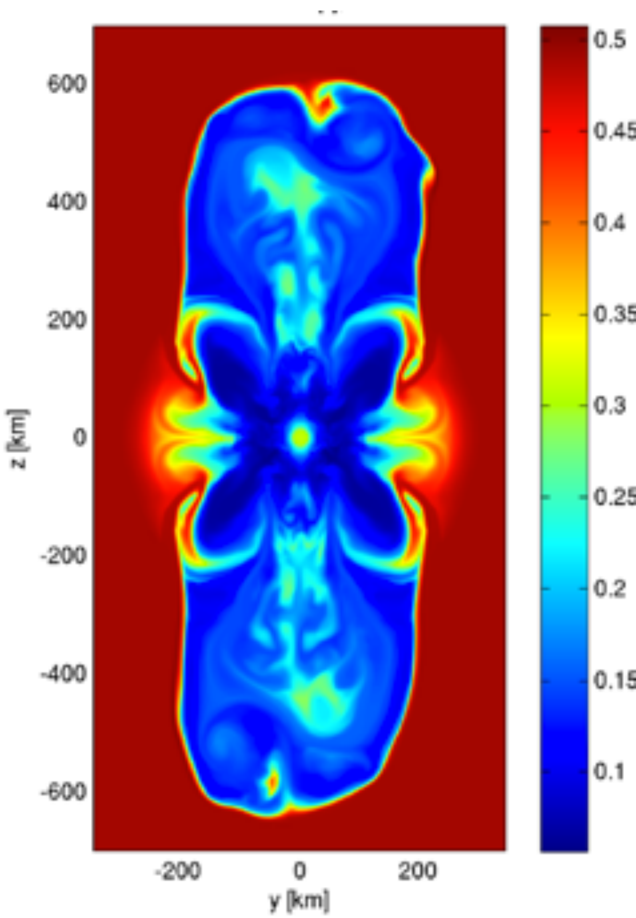
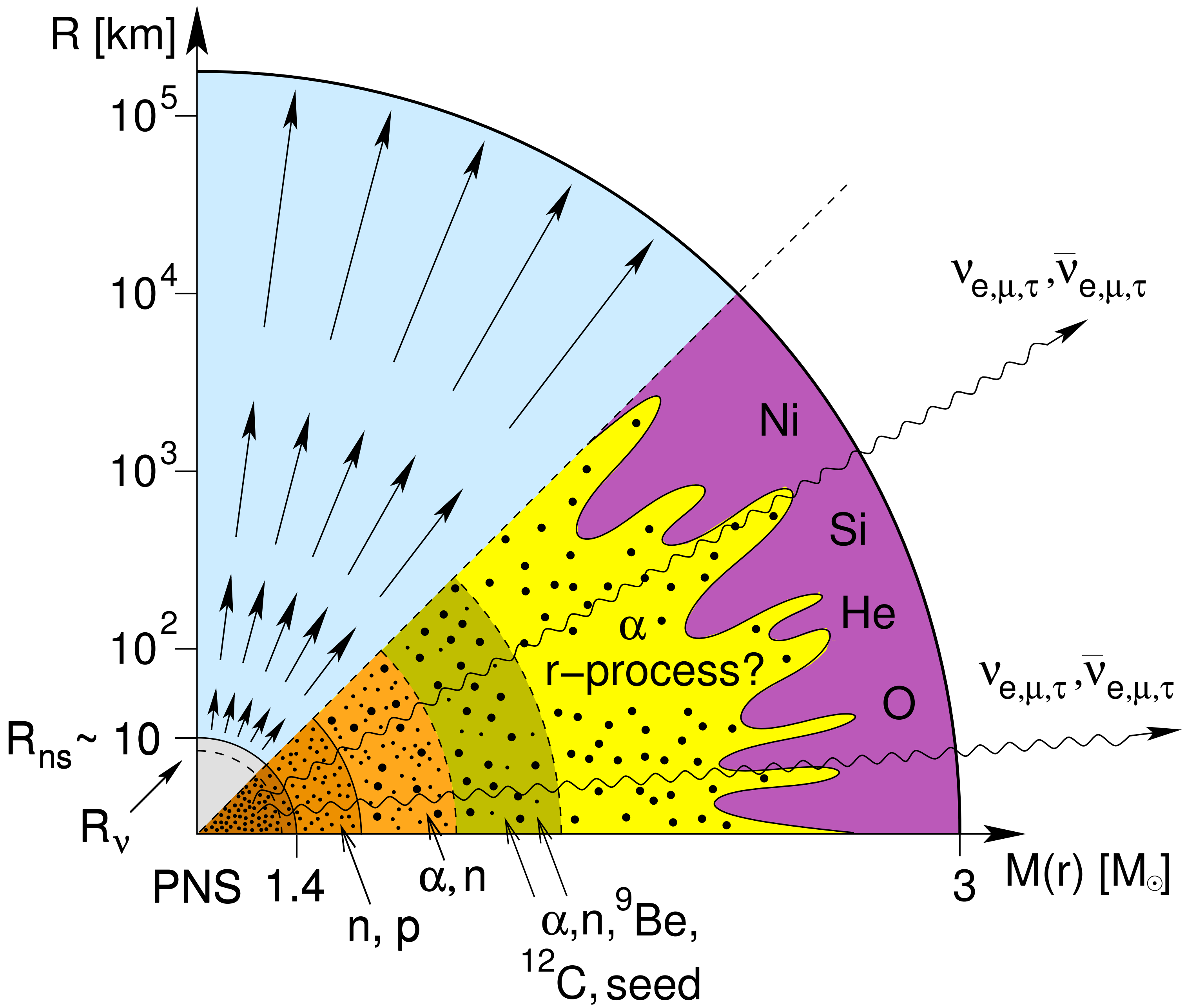


Nucleosynthesis in neutrino-driven winds



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

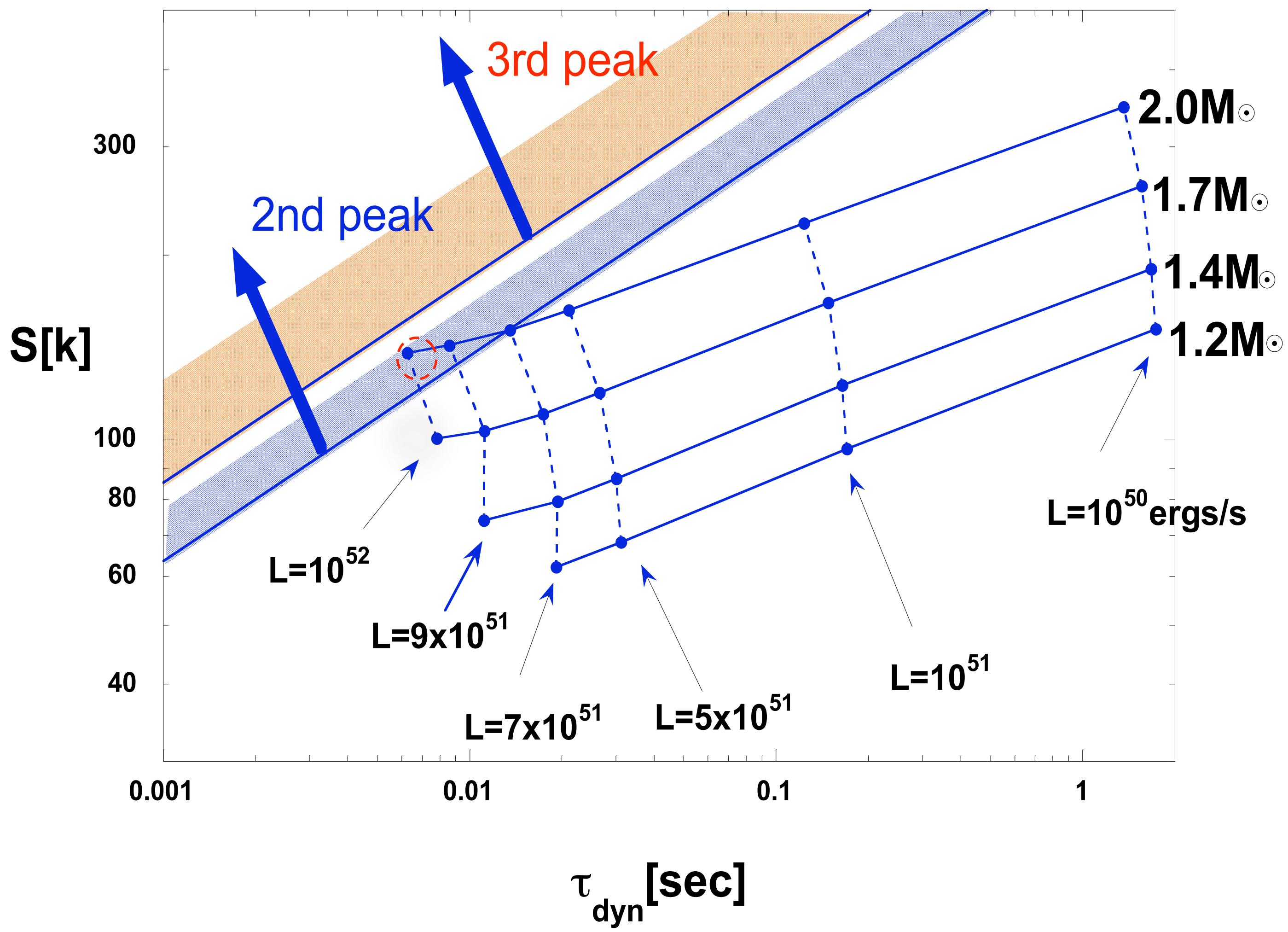
Necessary conditions for the r-process:

- 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



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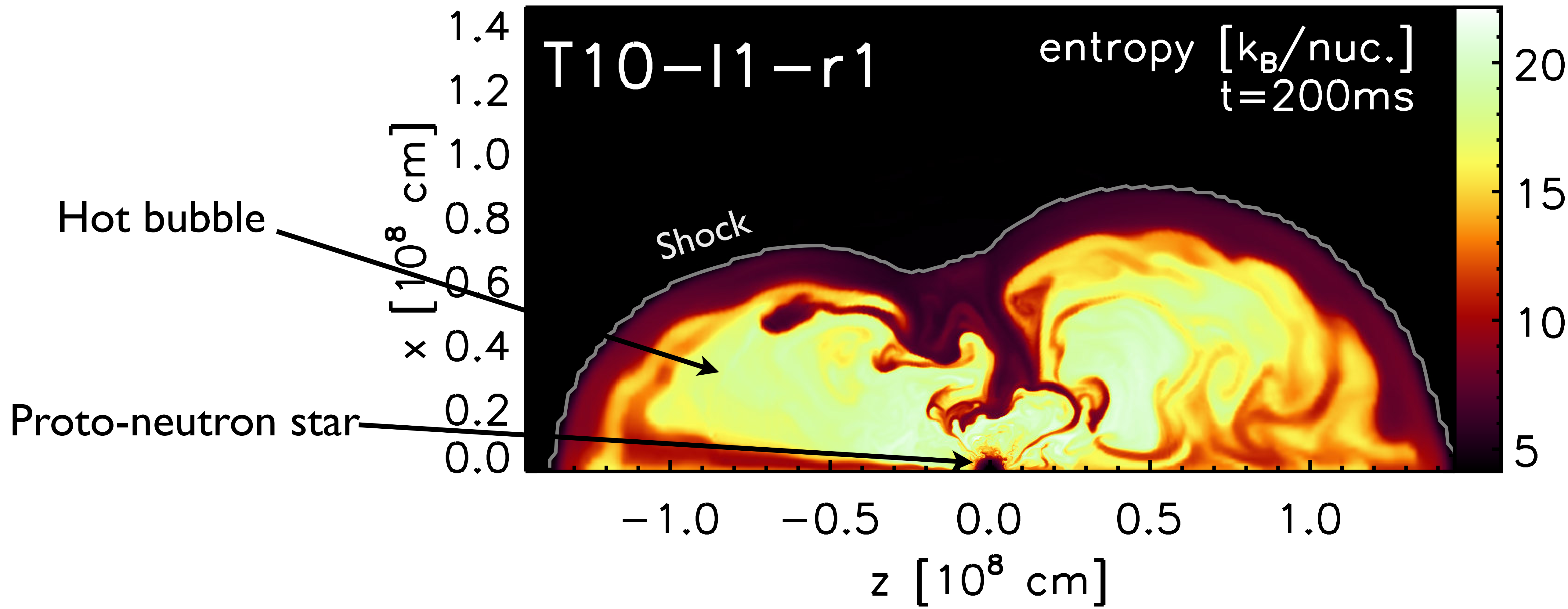
Necessary conditions identified by steady-state models (e.g. Otsuki et al. 2000, Thompson et al. 2001) are not realized in recent simulations (Arcones et al. 2007, Fischer et al. 2010, Hüdepohl et al. 2010, Roberts et al. 2010)

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

Core-collapse supernova simulations

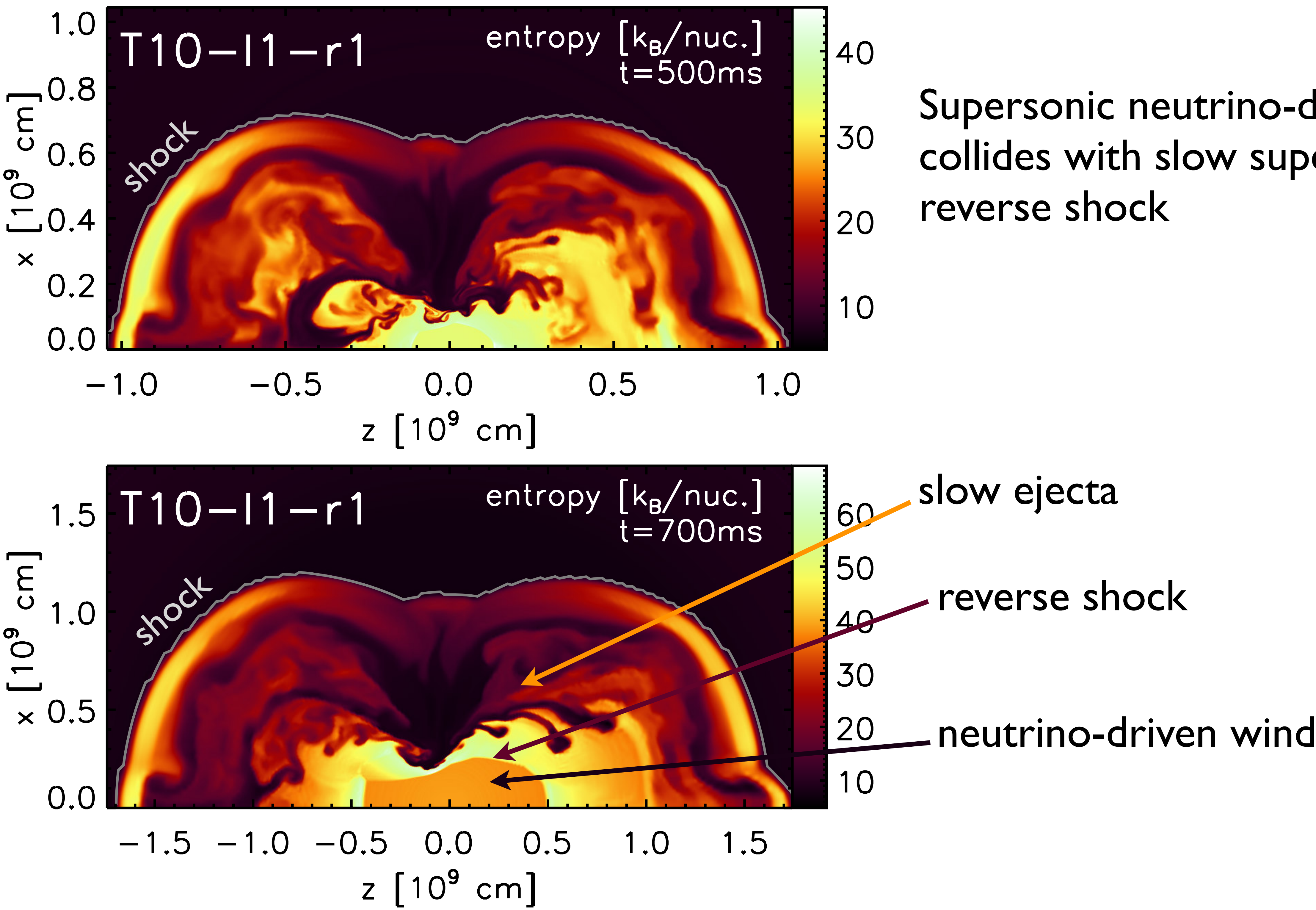


Long-time hydrodynamical simulations:

- 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

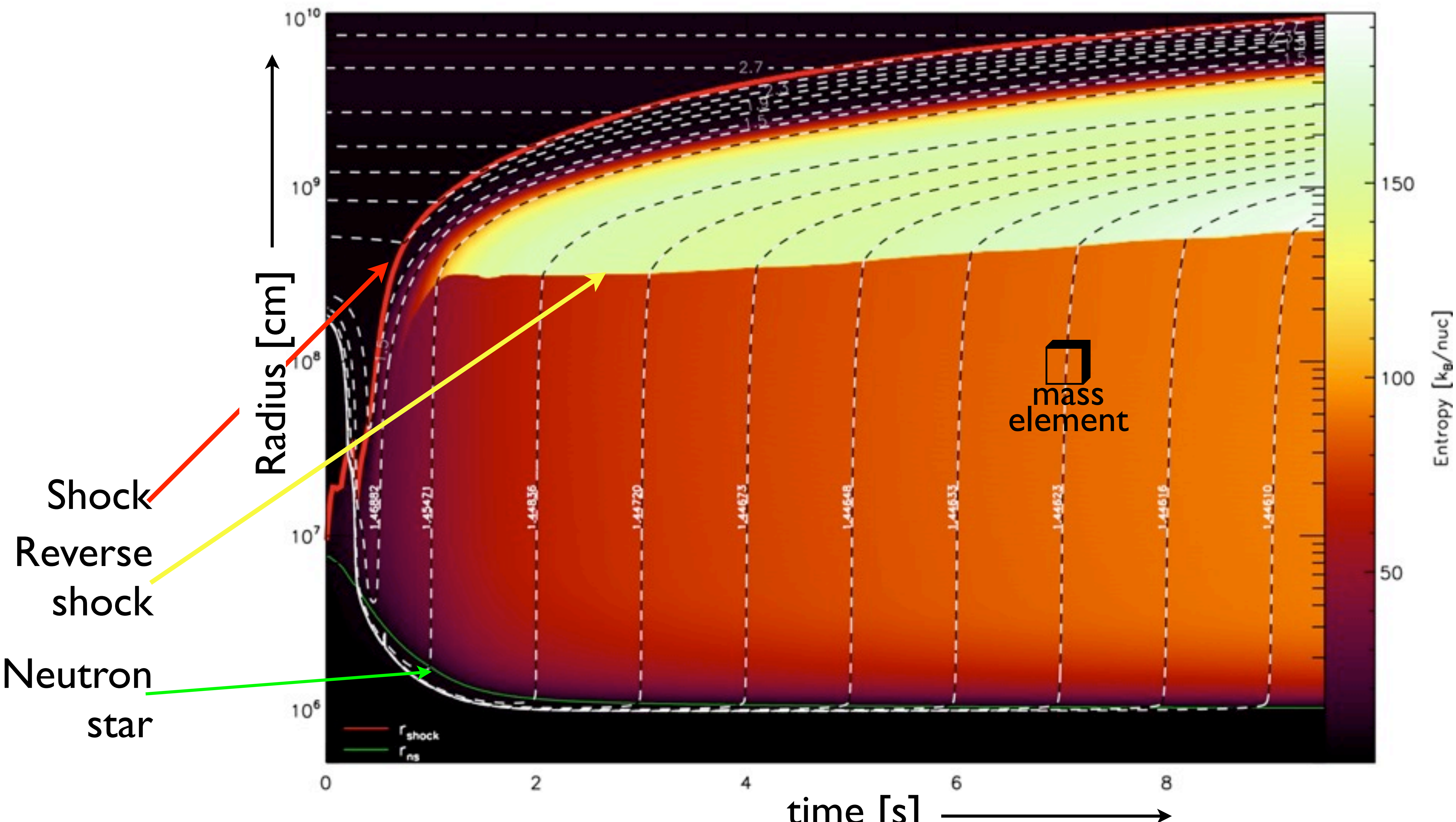
Neutrino-driven wind in 2D

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



1D simulations for nucleosynthesis studies

Arcones et al 2007



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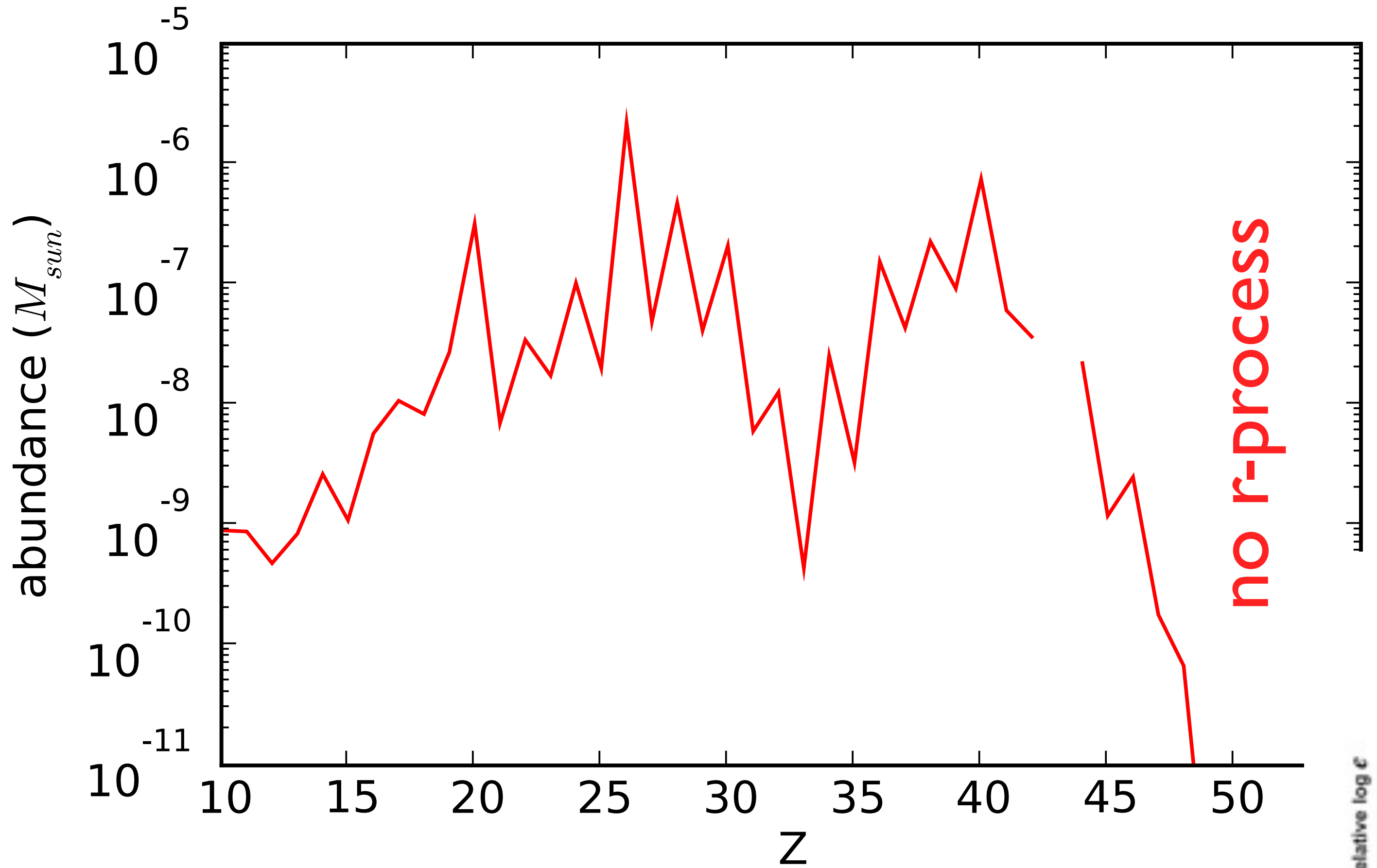

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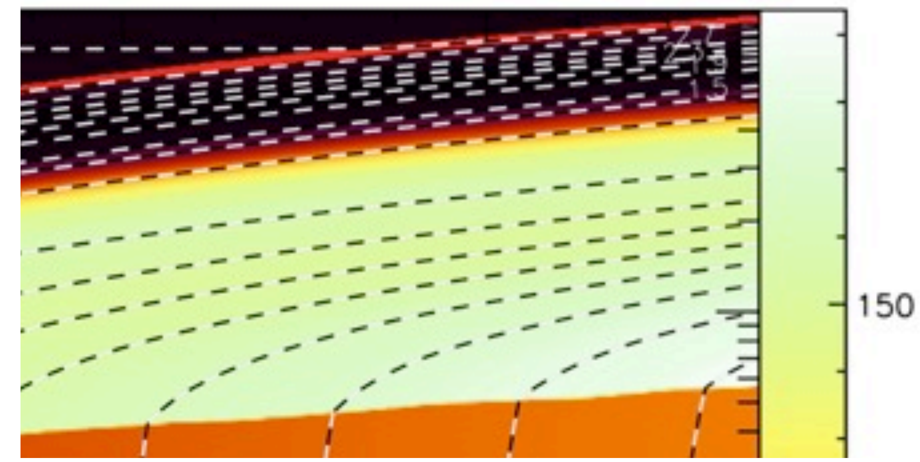
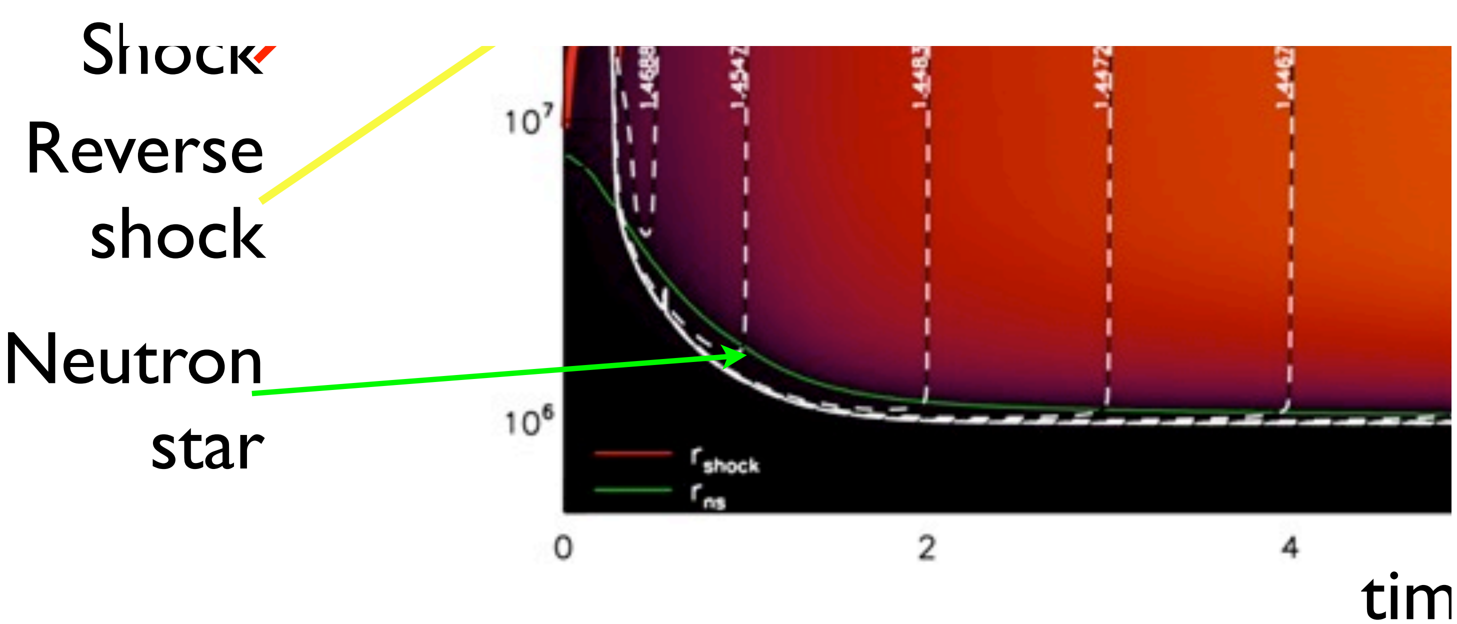
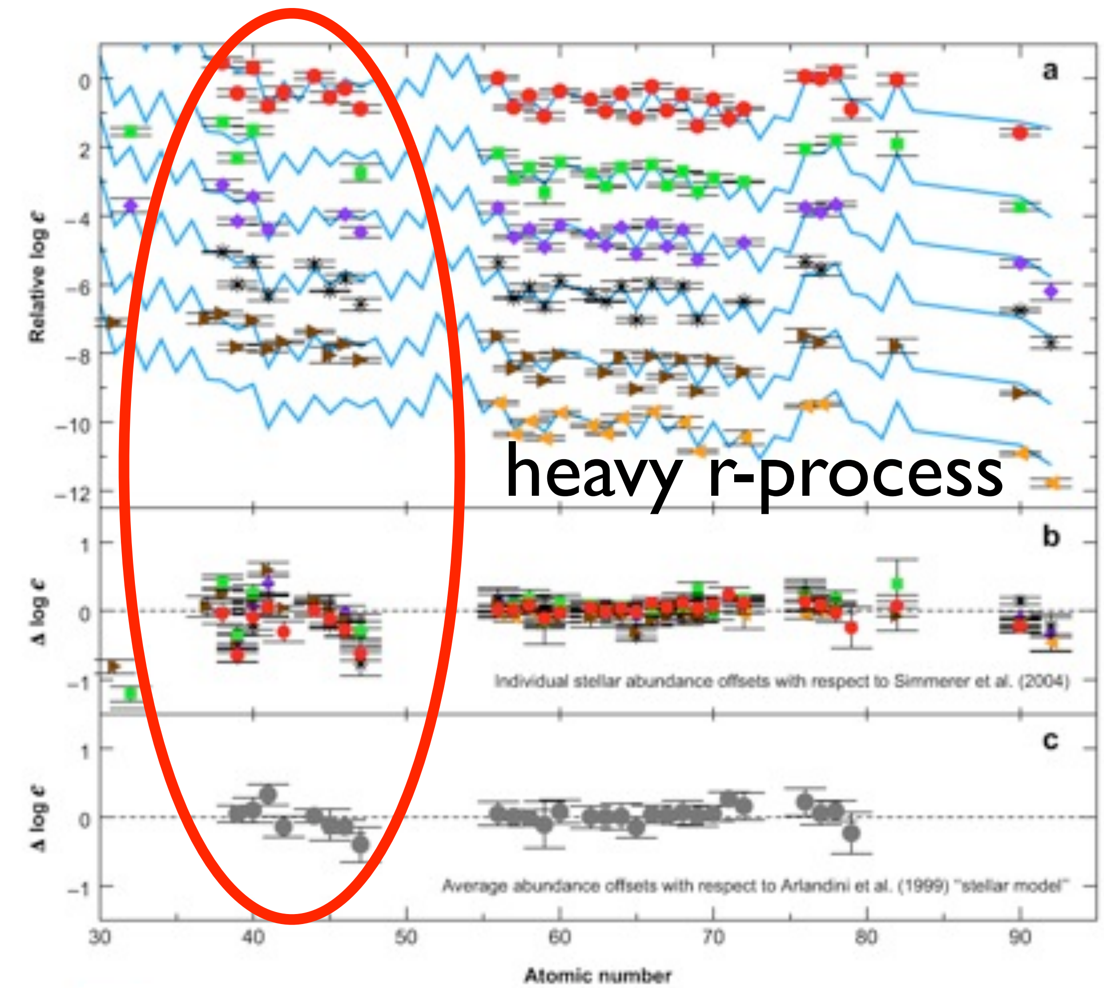




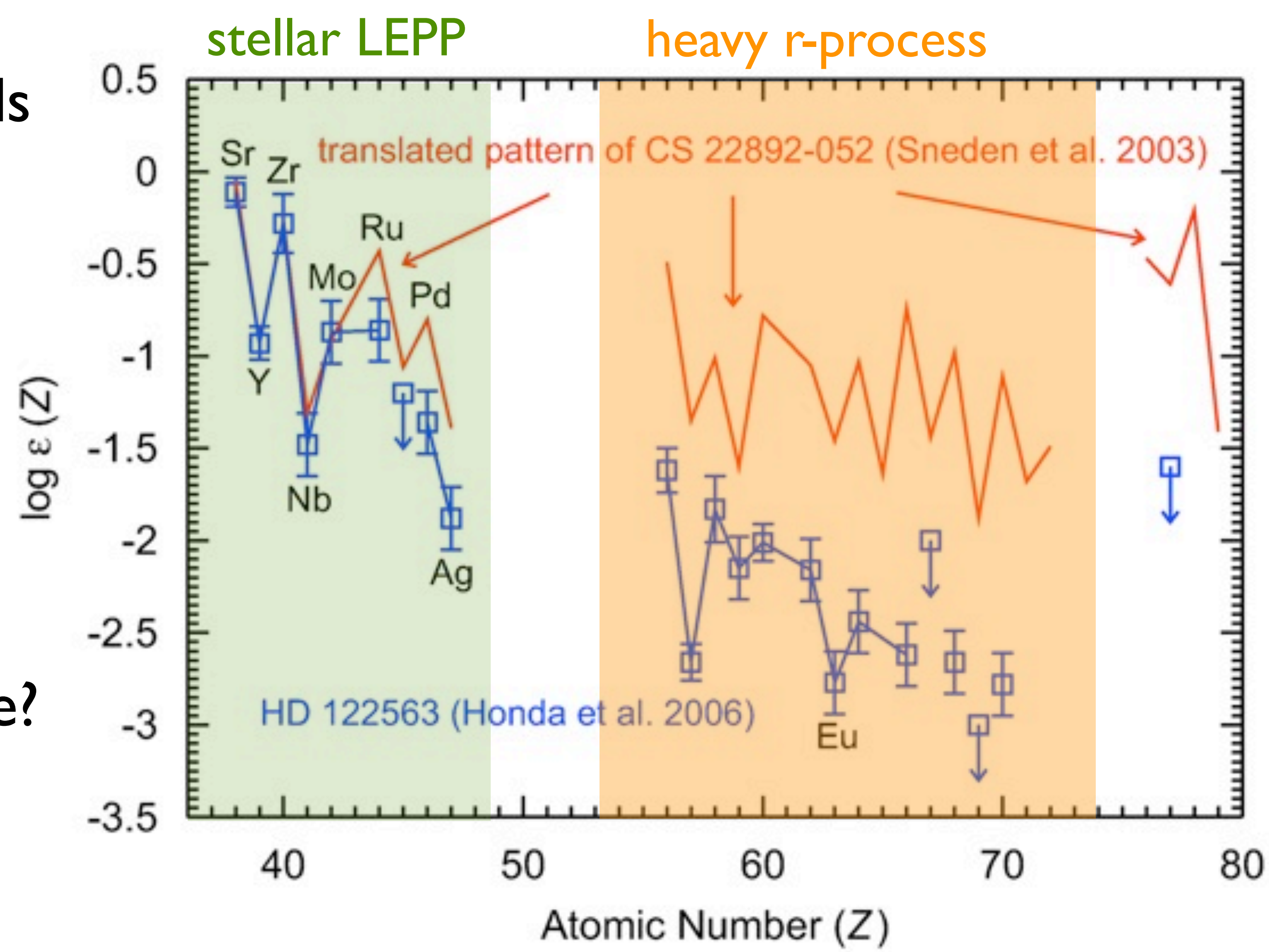


Sneden, Cowan, Gallino 2008

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):

- 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?

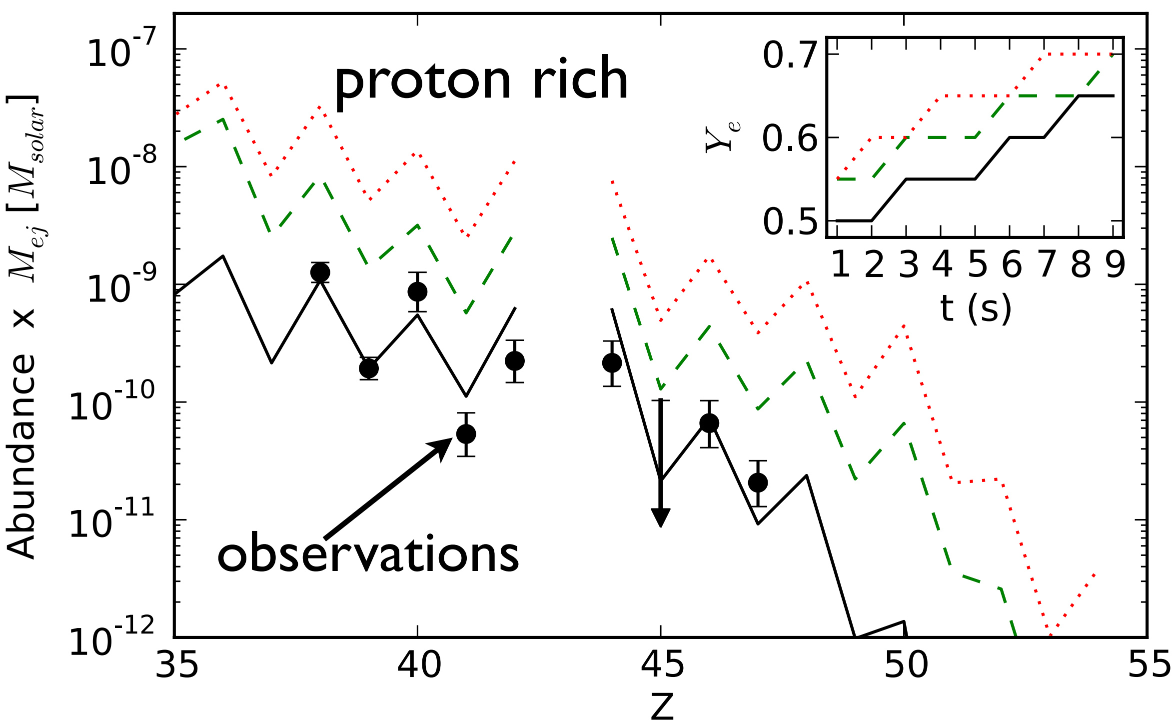
Can the LEPP pattern be produced in neutrino-driven wind simulations?

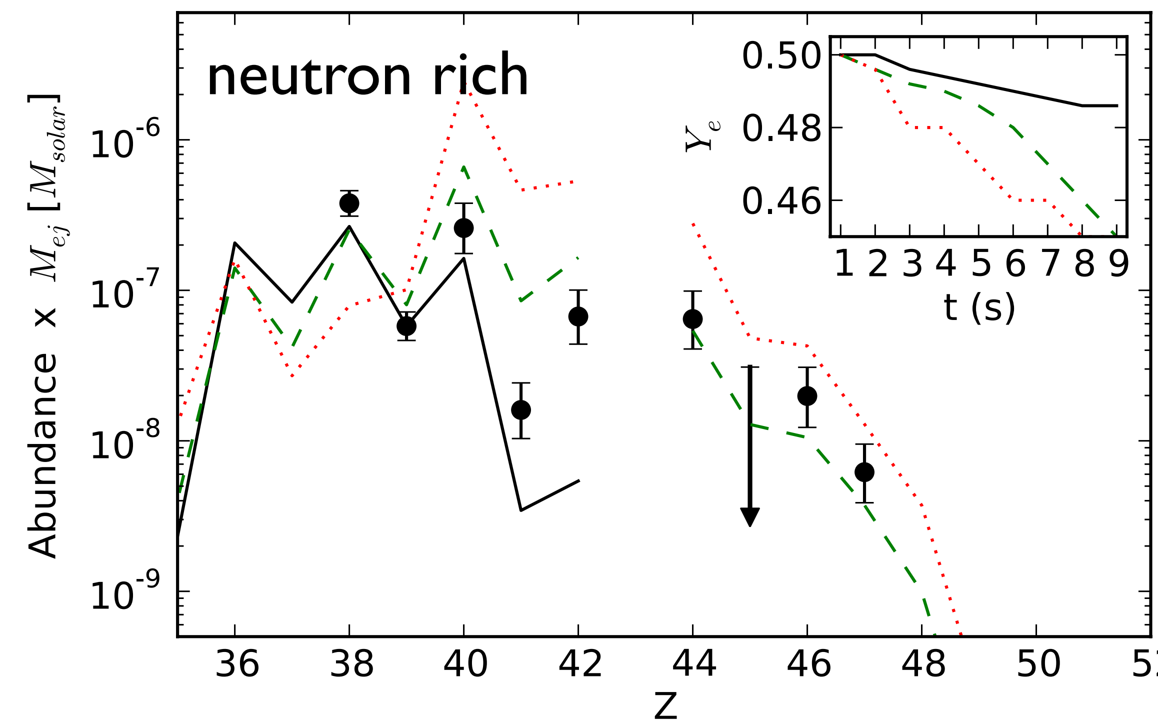
Lighter heavy elements in neutrino-driven winds

(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!

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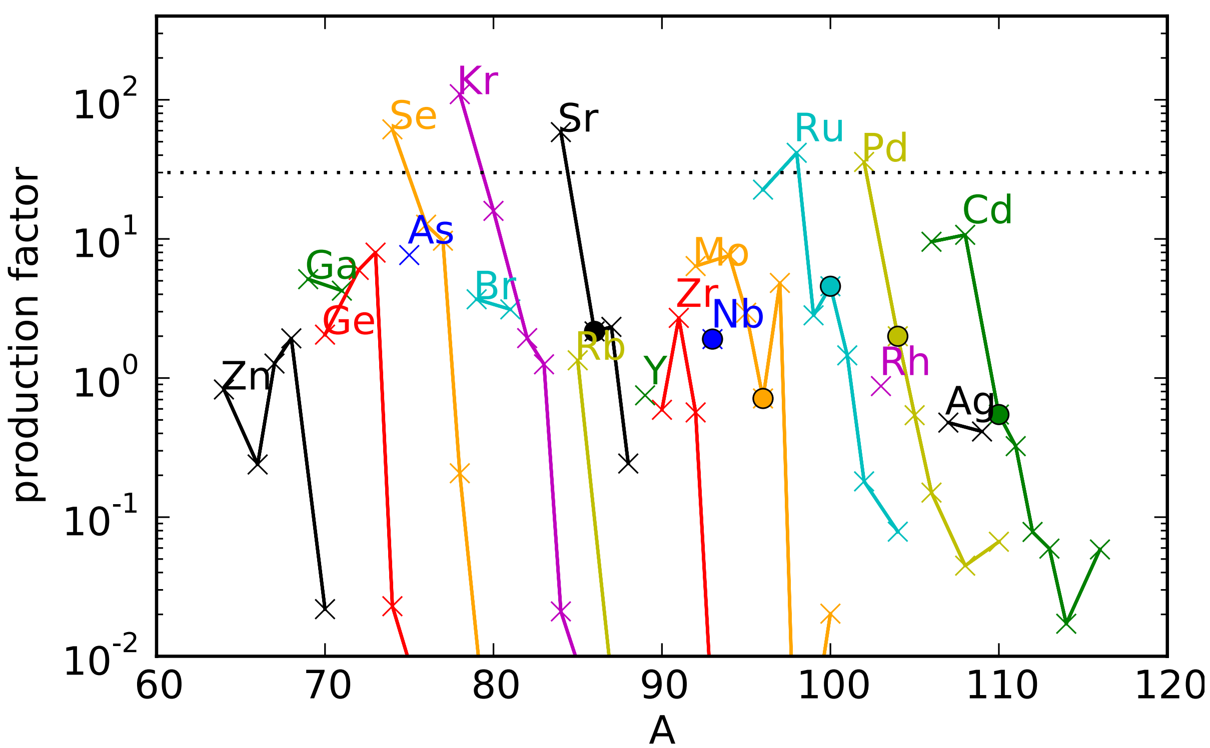

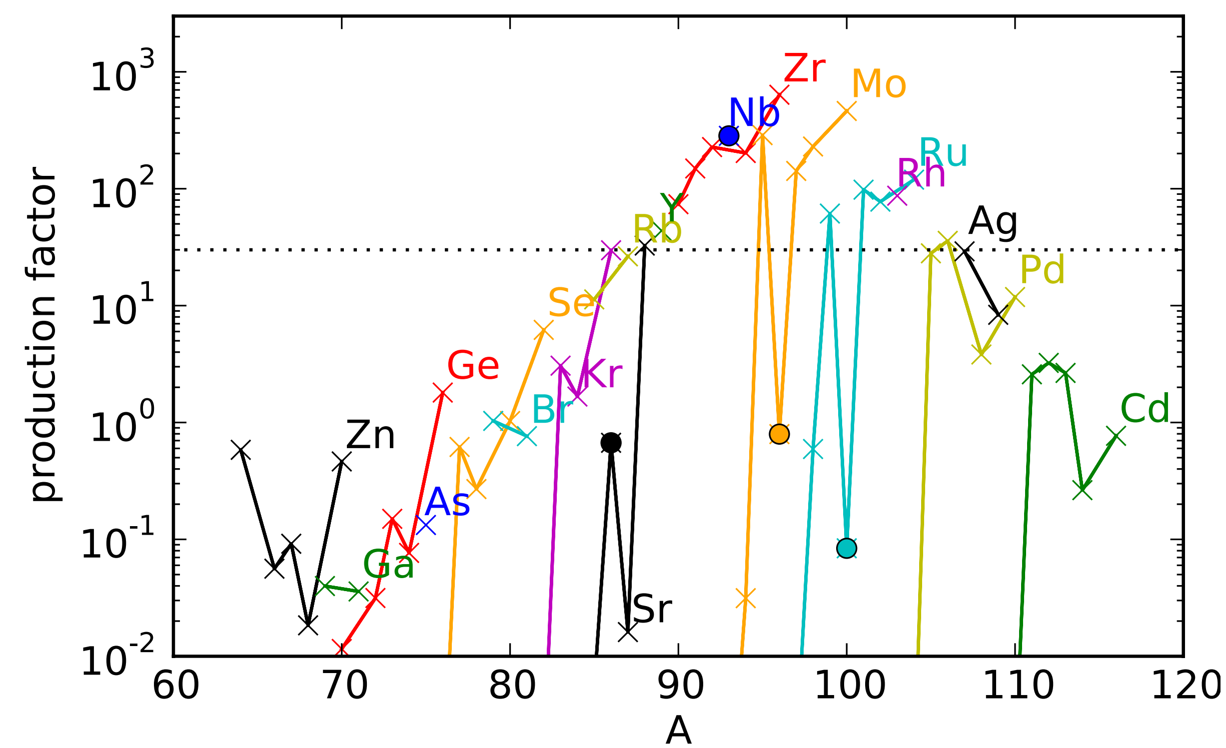

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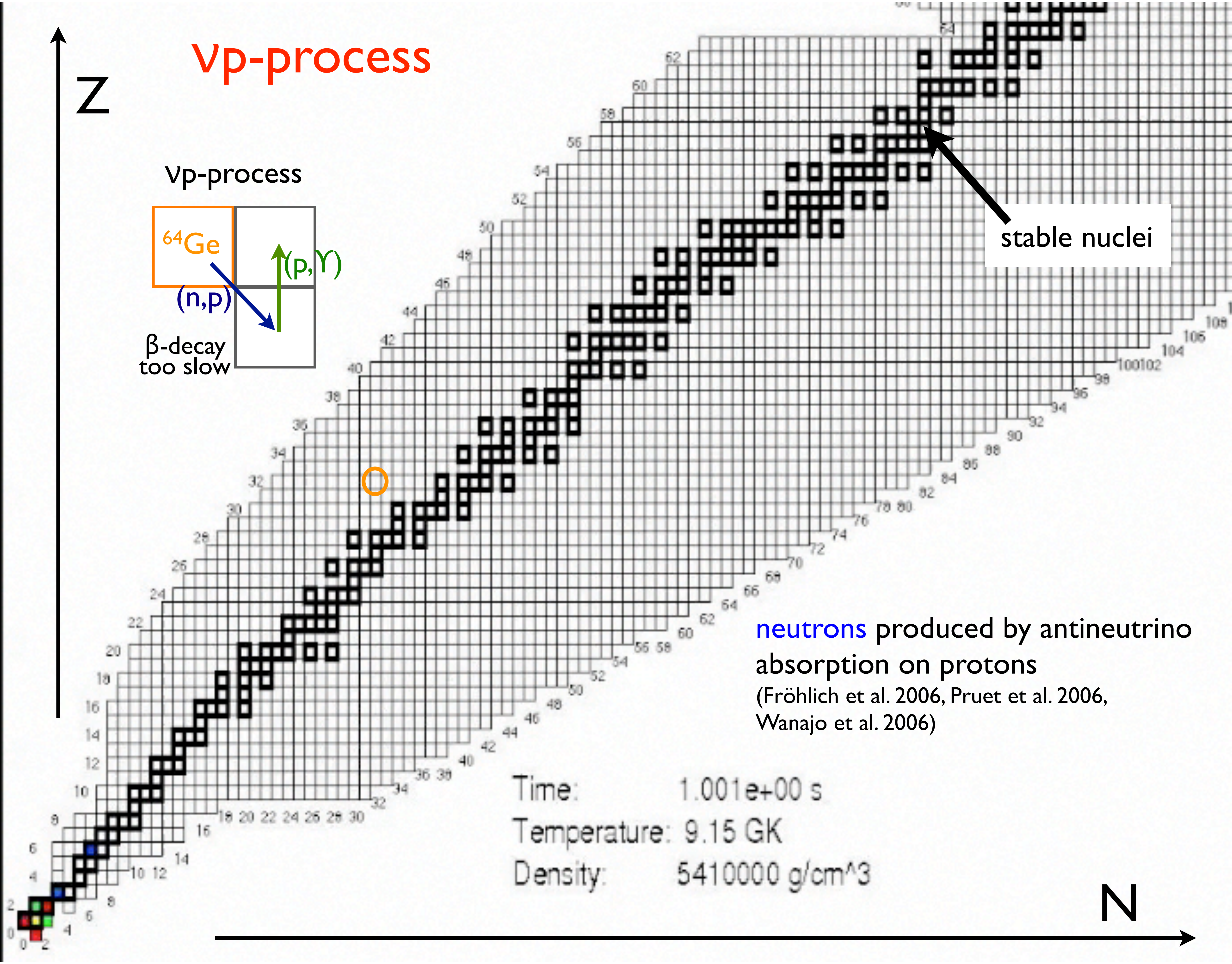


νp-process
Z
νp-process
64Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
neutrons produced by antineutrino absorption on protons
(Fröhlich et al. 2006, Pruet et al. 2006, Wanajo et al. 2006)
Time: 1.001e+00 s
Temperature: 9.15 GK
Density: 5410000 g/cm^3
N

Is the neutrino-driven wind proton rich?

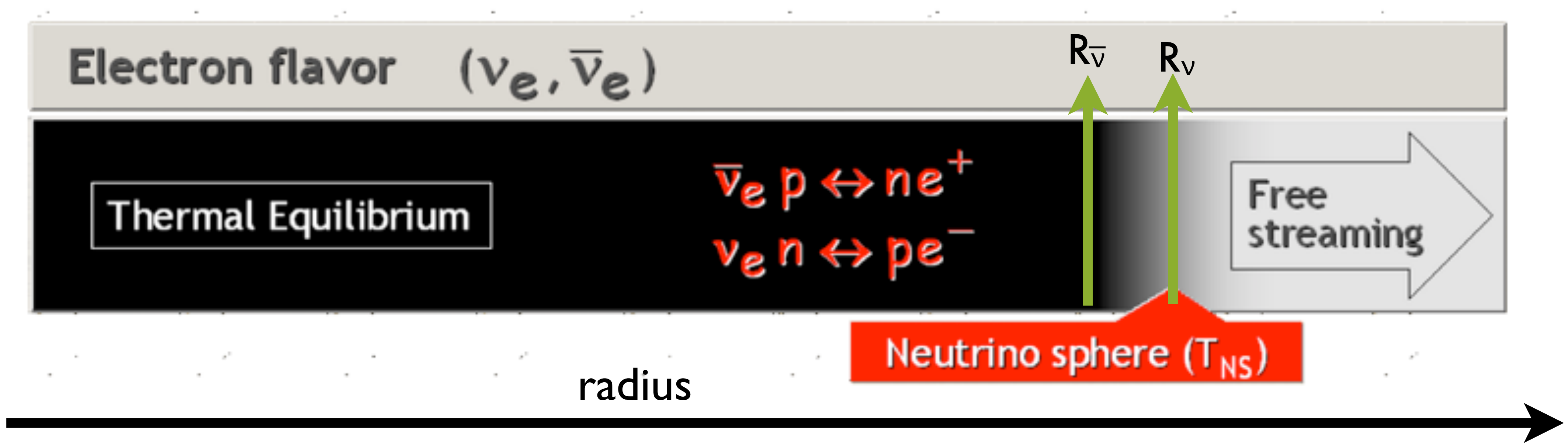
Electron fraction and uncertainties

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

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

($\Delta = m_n - m_p$)

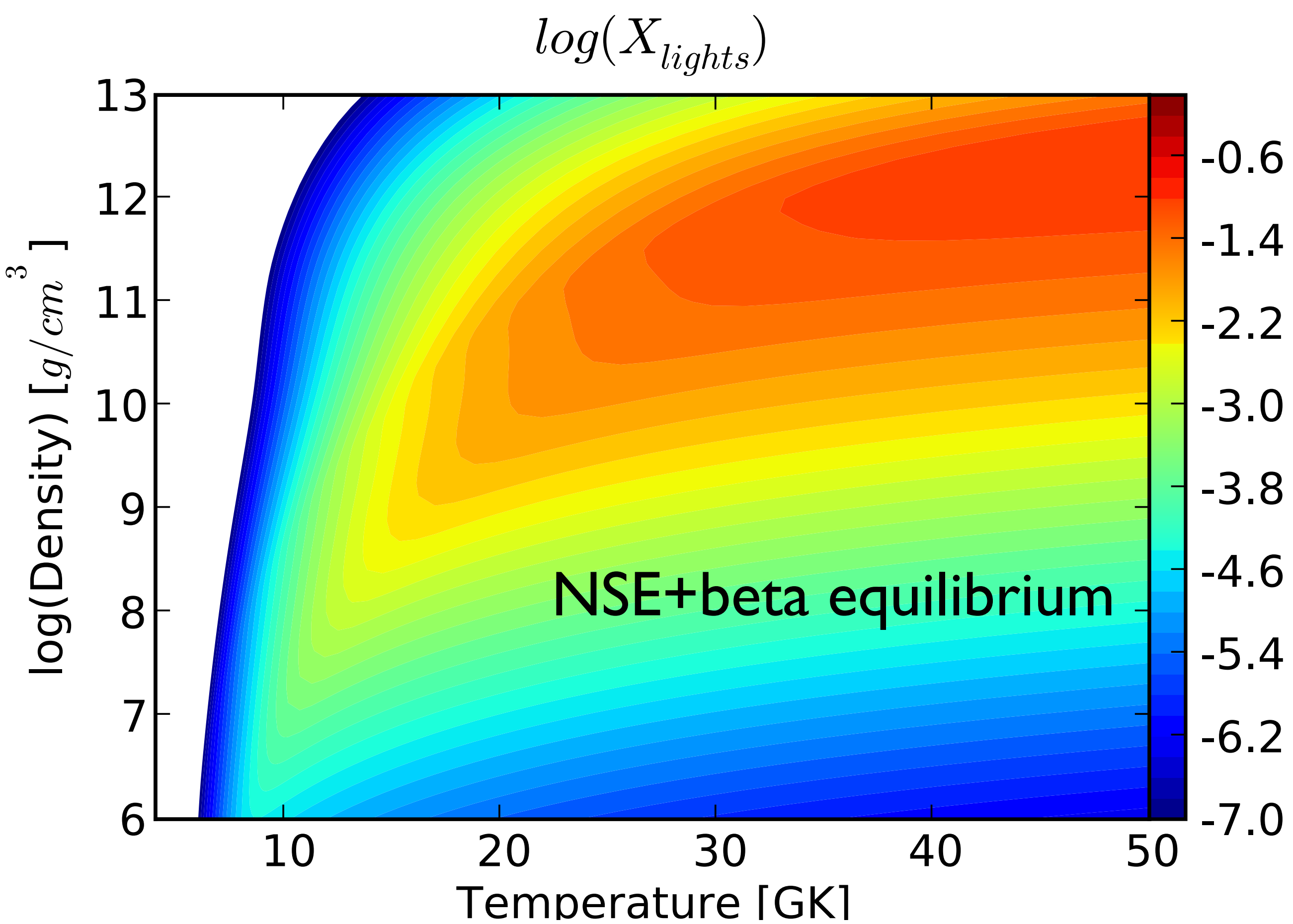
The neutrino energies are determined by the position (temperature) where neutrinos decouple from matter: neutrinosphere



Raffelt 2001, ApJ, 561,890

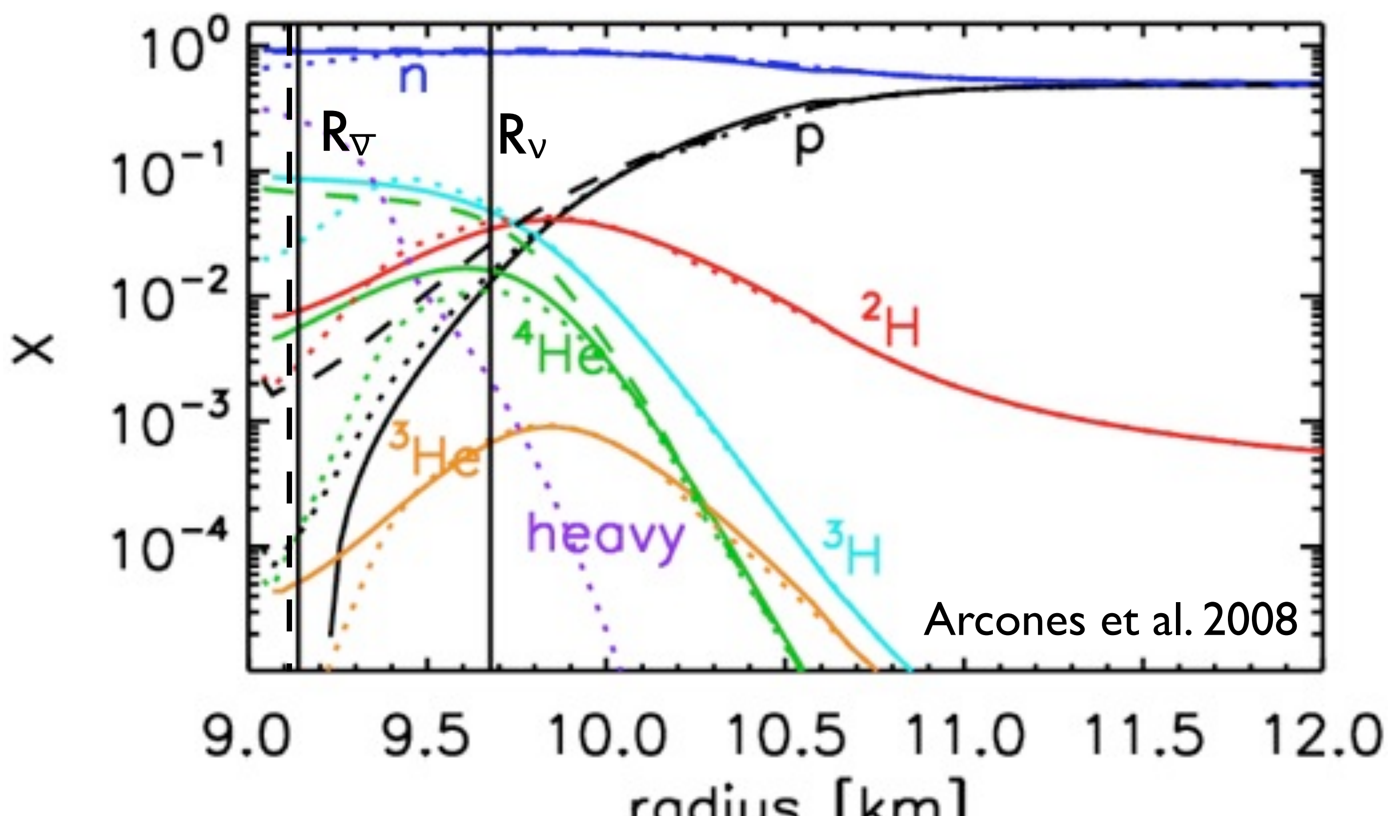
Light clusters

Light nuclei ($A \leq 4$) present at $\rho \approx 10^{12}$g/cm^3
(O'Connor et al. 2007, Sumiyoshi & Ropke 2008).



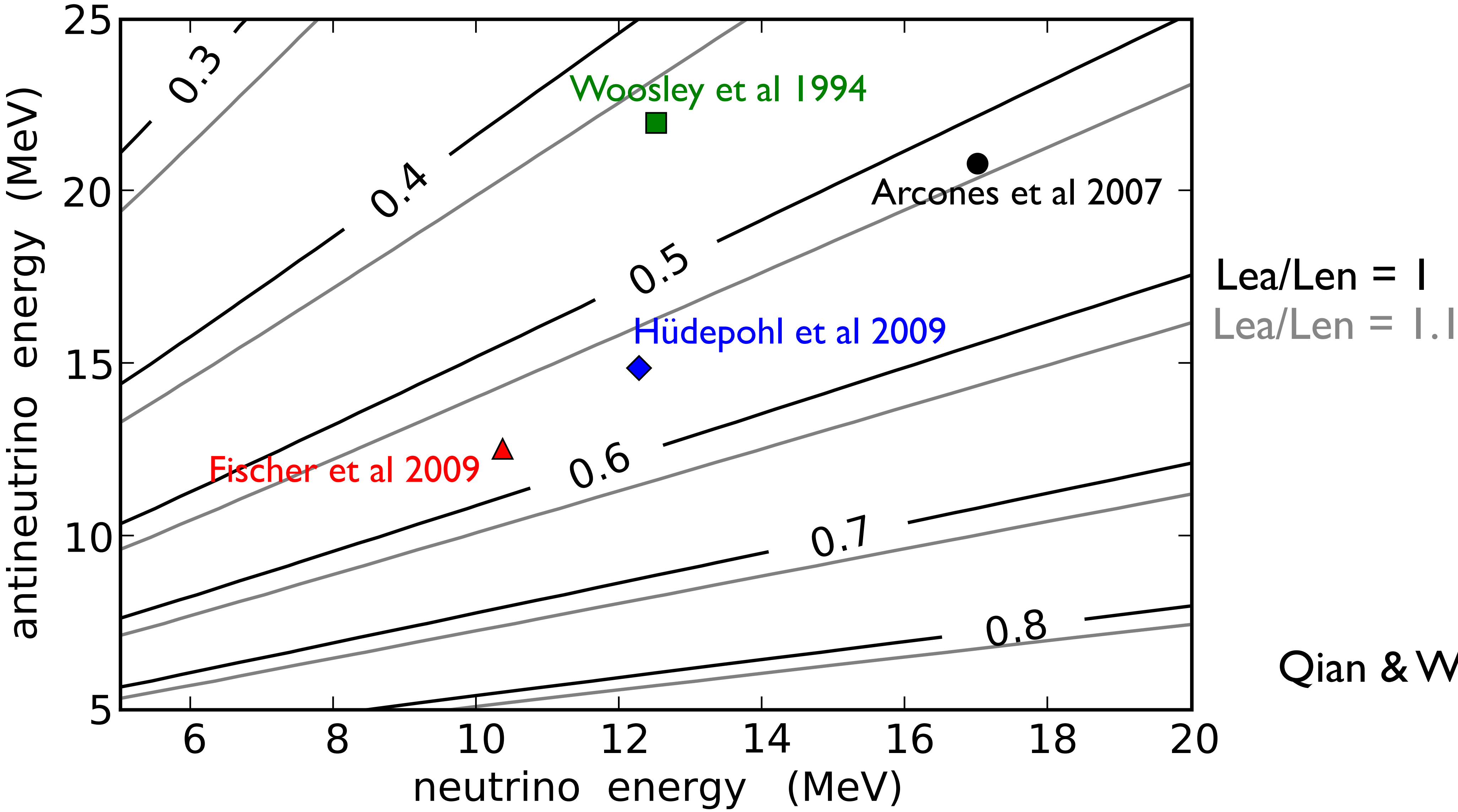
Arcones et al. 2010

- non-interaction ideal gas of n,p,α (dashed lines)
- Virial (Horowitz & Schwenk 2006): nuclei with $A \leq 4$ and interactions (solid lines)
- NSE (dotted lines)



Wind models and electron fraction

Neutrino energies change with more realistic neutrino physics input
More recent simulations obtain lower antineutrino energies and therefore proton-rich conditions



Qian & Woosley 1996

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

Charged-current weak interaction processes in hot and dense matter and its impact on the spectra of neutrinos emitted from proto-neutron star cooling

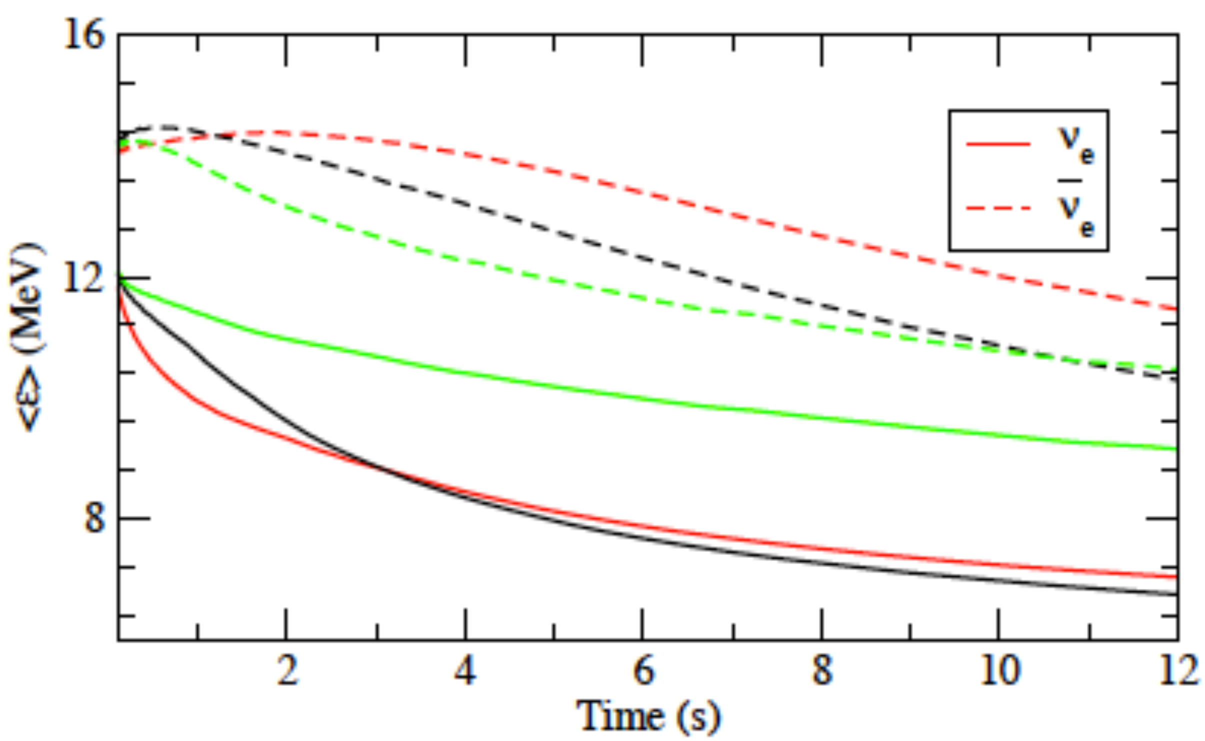
G. Martínez-Pinedo,[1,2] T. Fischer,[2,1] A. Lohs,[1] and L. Huther[1]

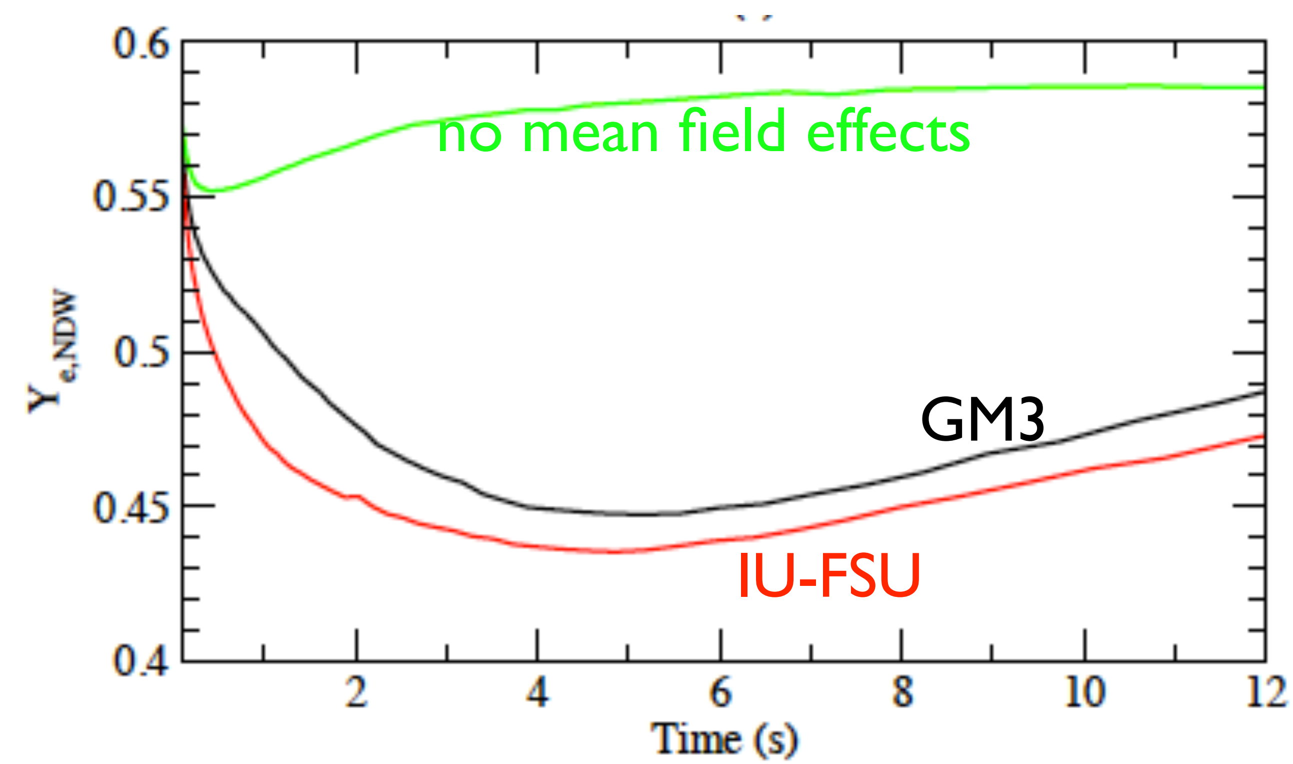
A NEW CODE FOR PROTO-NEUTRON STAR EVOLUTION

L. F. Roberts†

Medium modification of the charged current neutrino opacity and its implications

L. F. Roberts[1] and Sanjay Reddy[2]



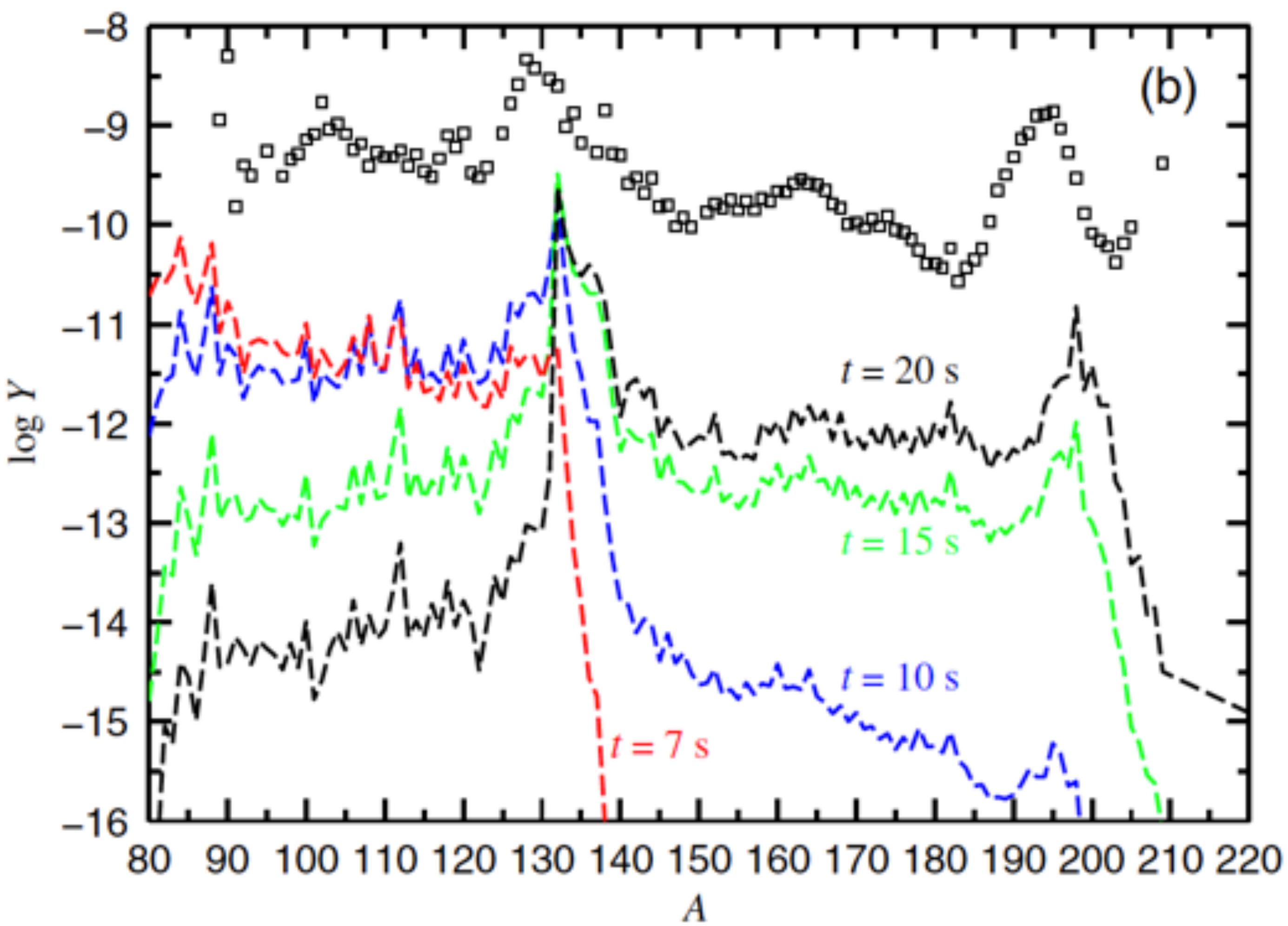


Where is the r-process?

Neutrino-induced r-process in He shell

at low metallicity $Z<10^{-3}Z_{sun}$ → low seed abundance

neutral- and charged-current neutrino reactions on He → few neutrons



cold r-process

relative low neutron density

lasts ~20s

peaks shift to high A
(between r- and s-process)

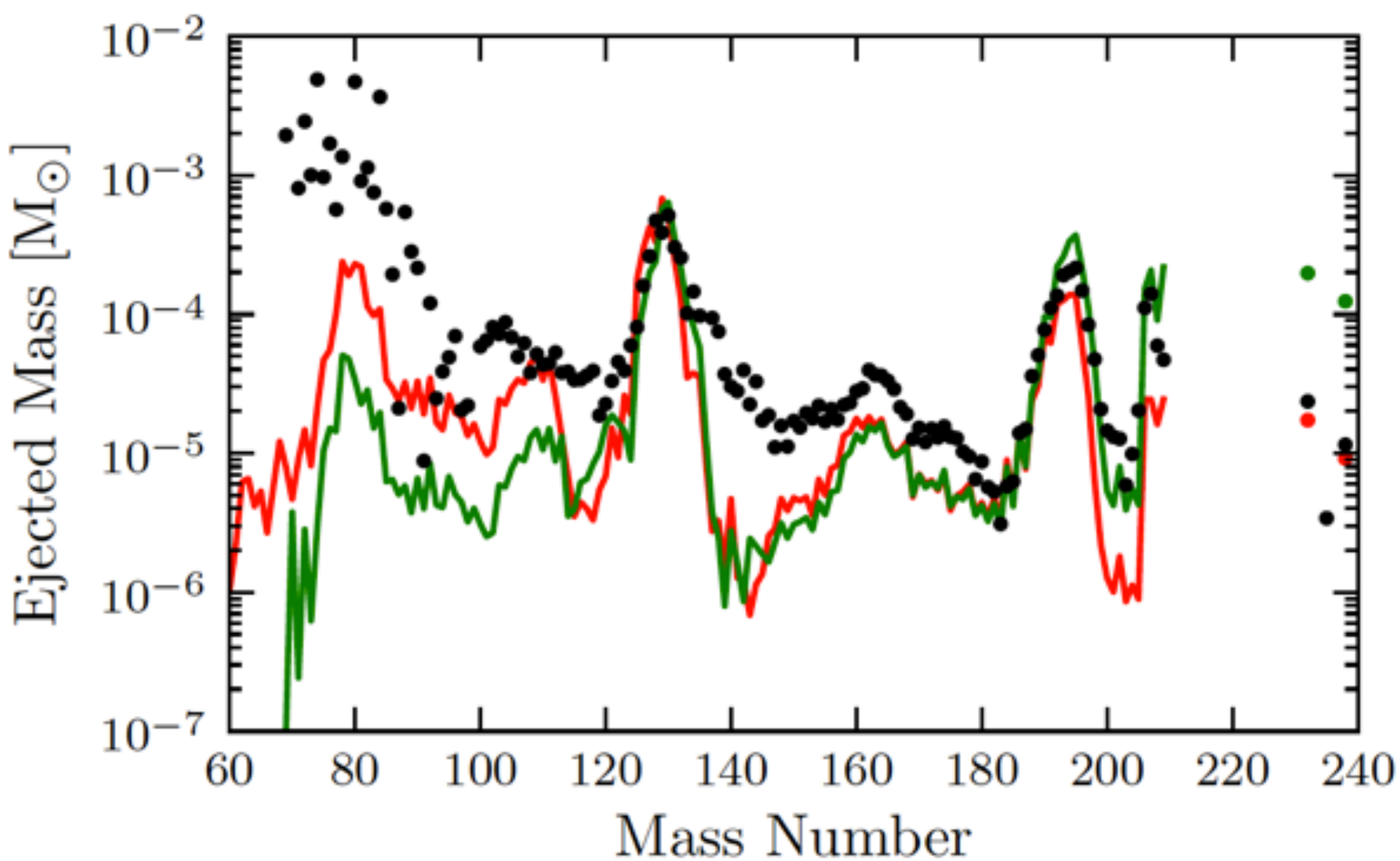
Banerjee, Haxton, Qian 2011
Epstein, Colgate, Haxton 1988, Woosley, Hartmann, Hoffman, Haxton 1990
Nadyozhin, Panov, Blinnikov 1998

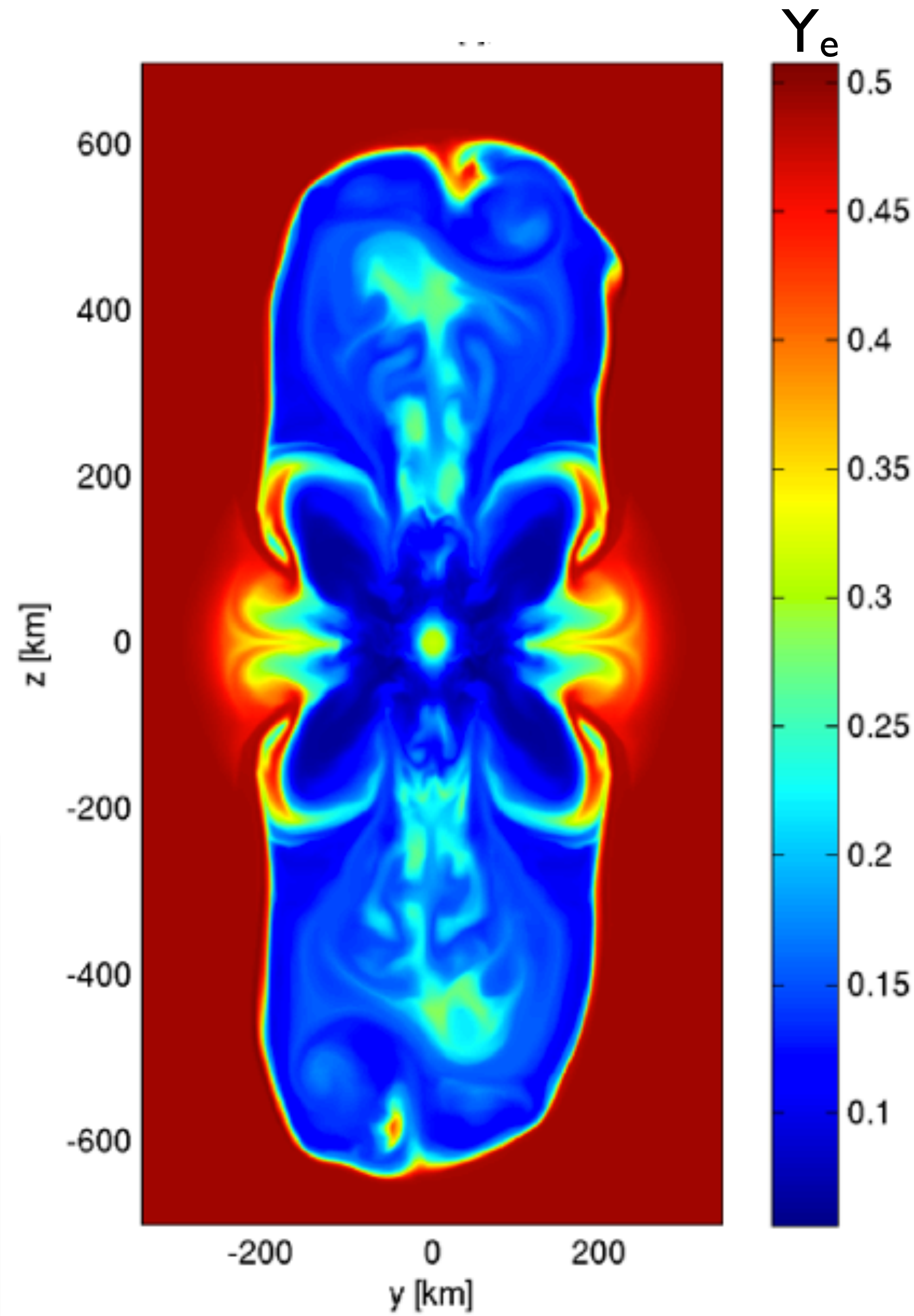
Supernova-jet-like explosion

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

matter collimates: neutron-rich jets

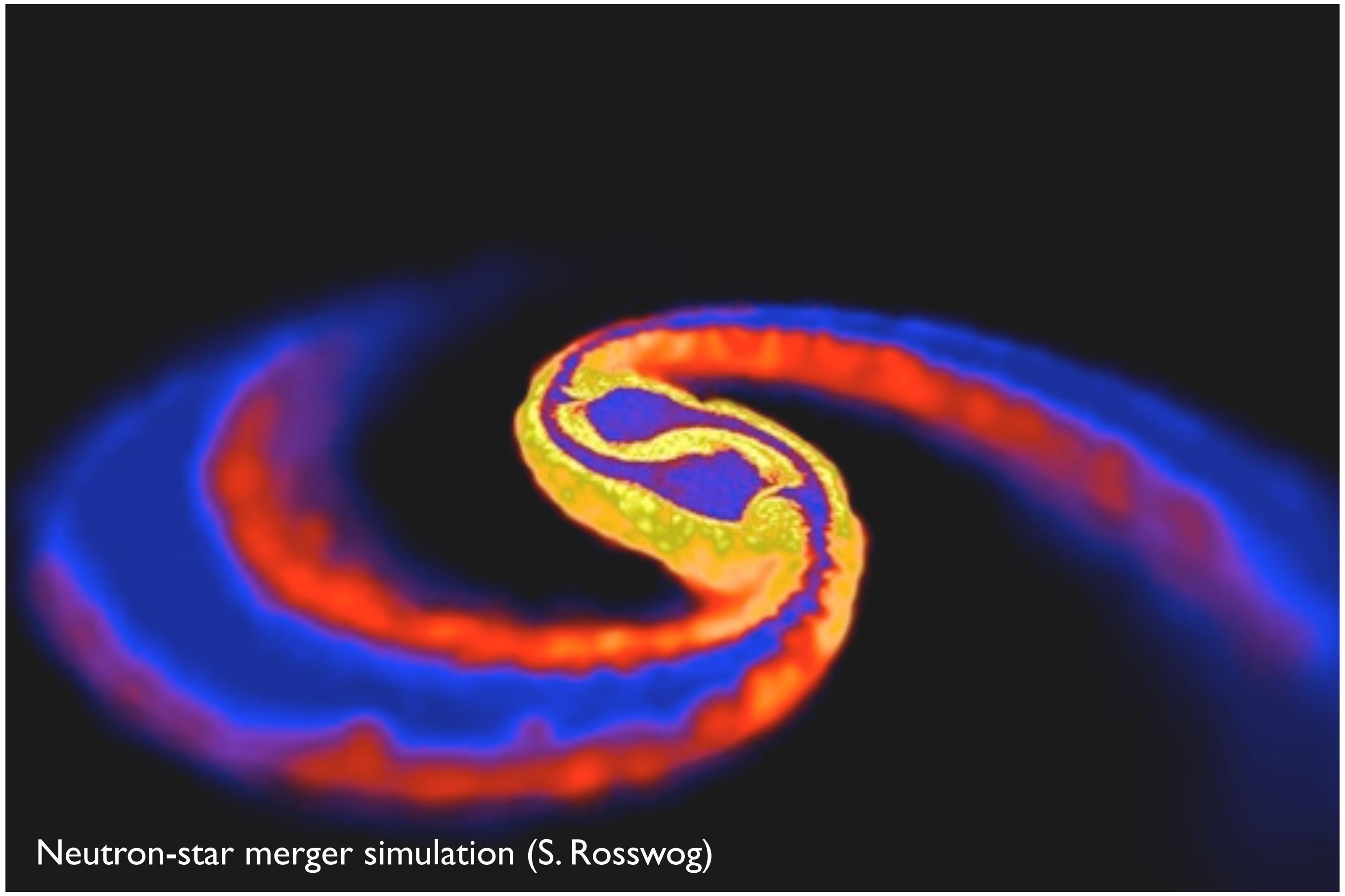
right r-process conditions

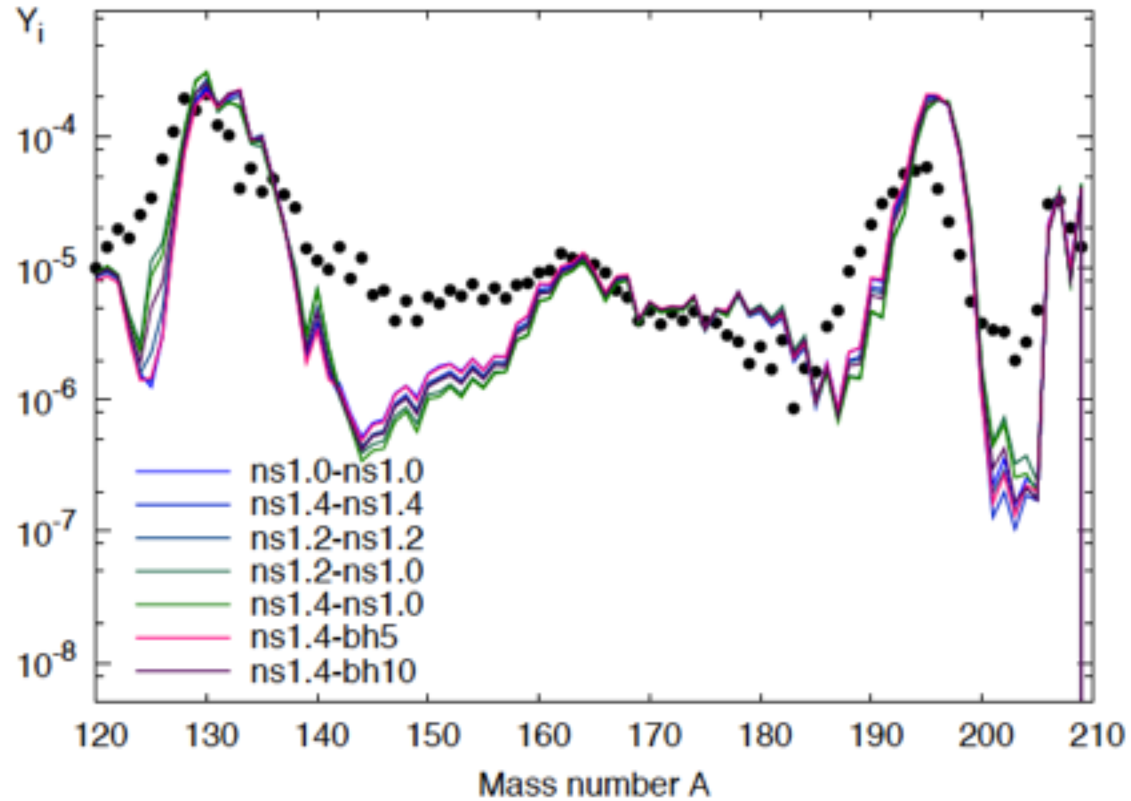




Winteler, Käppeli, Perego, et al. 2012

Neutron star mergers





Korobkin, Rosswog, Arcones, Winteler (submitted MNRAS)

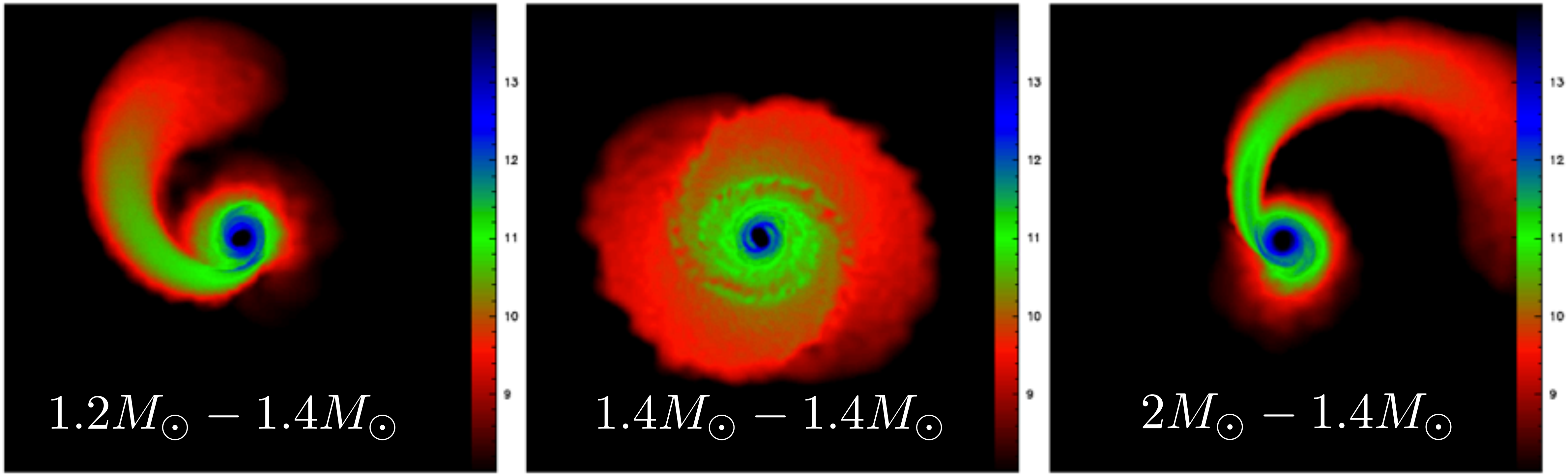
Right conditions for a successful r-process
(Lattimer & Schramm 1974, Freiburghaus et al. 1999, ..., Goriely et al. 2011)

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)

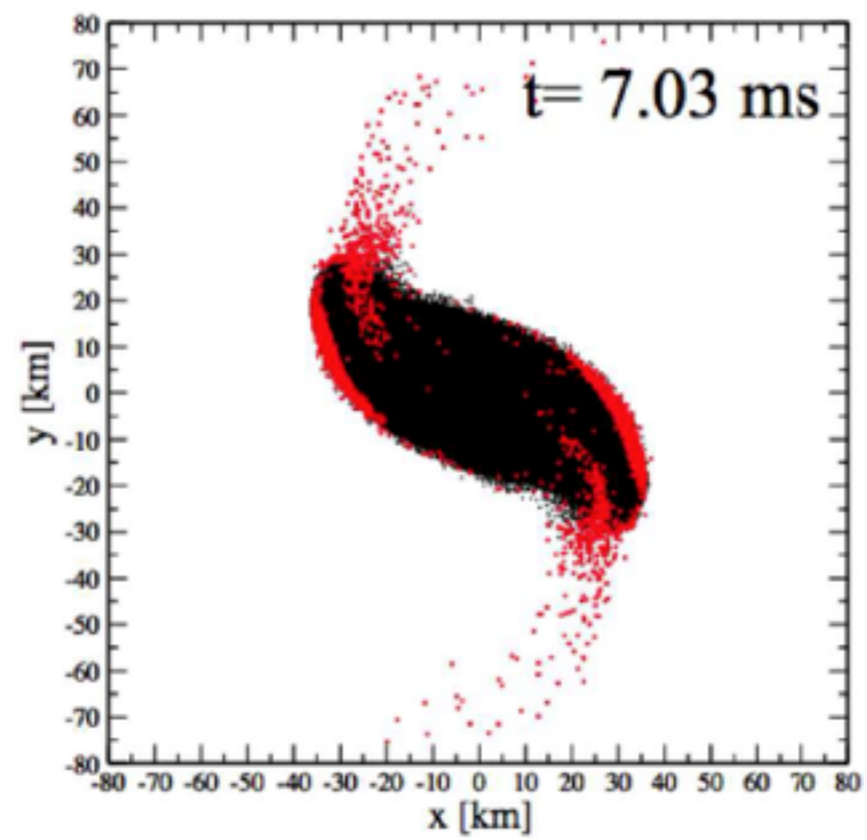
Transient with kilo-nova luminosity (Metzger et al. 2010): direct observation of r-process, EM counter part to WG

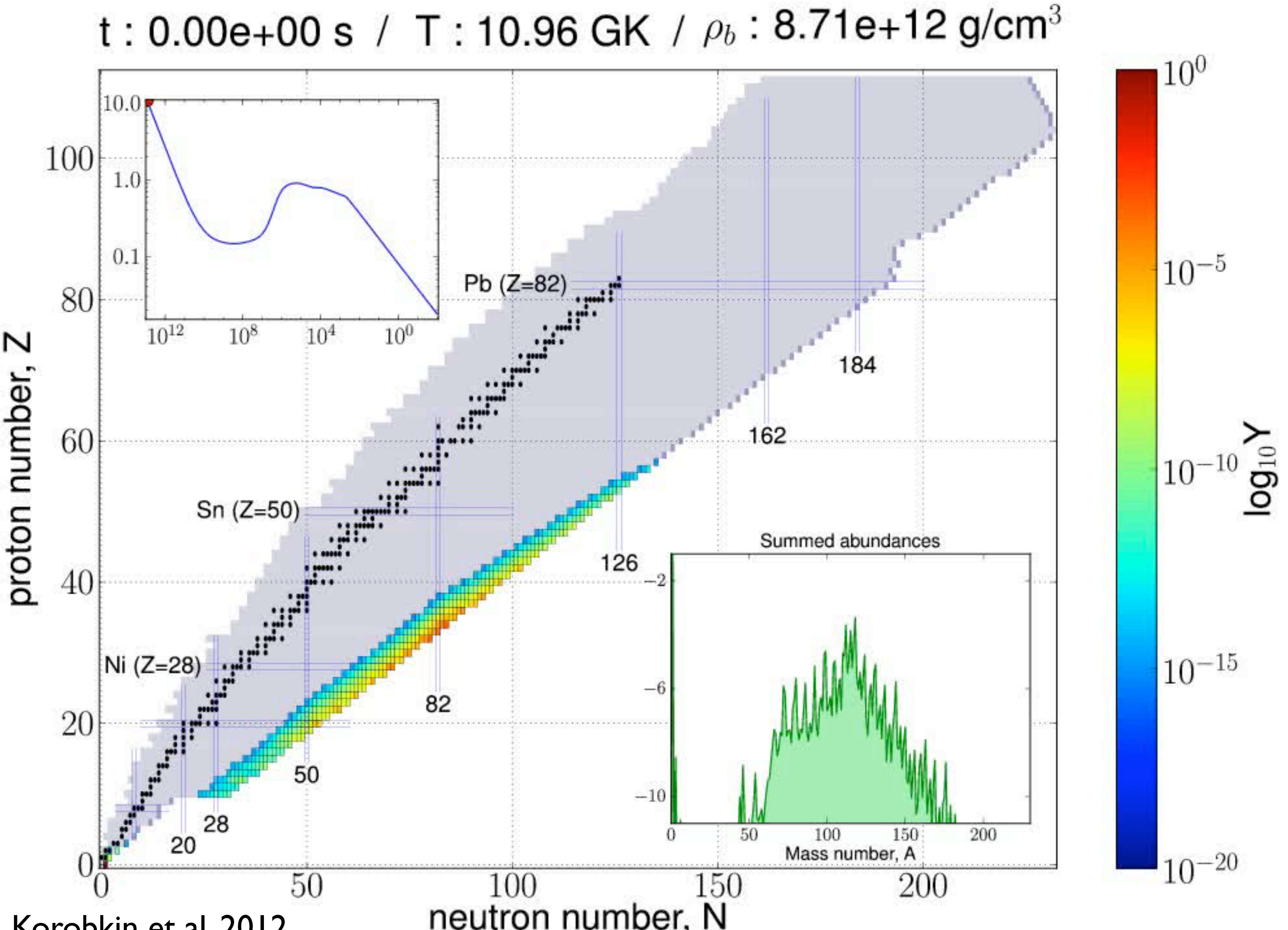
Neutron star mergers



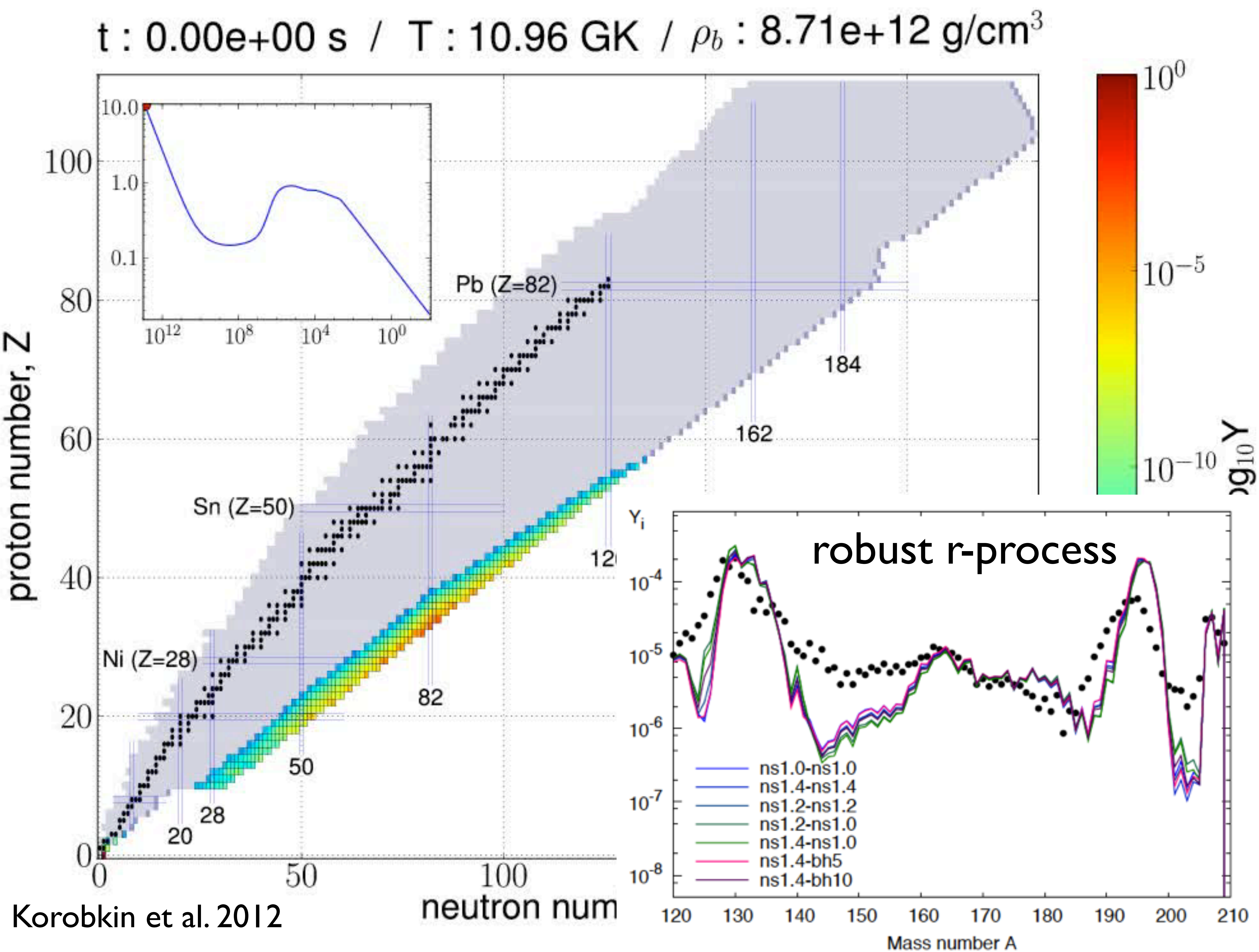
simulations: 21 mergers of 2 neutron stars
2 of neutron star black hole

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

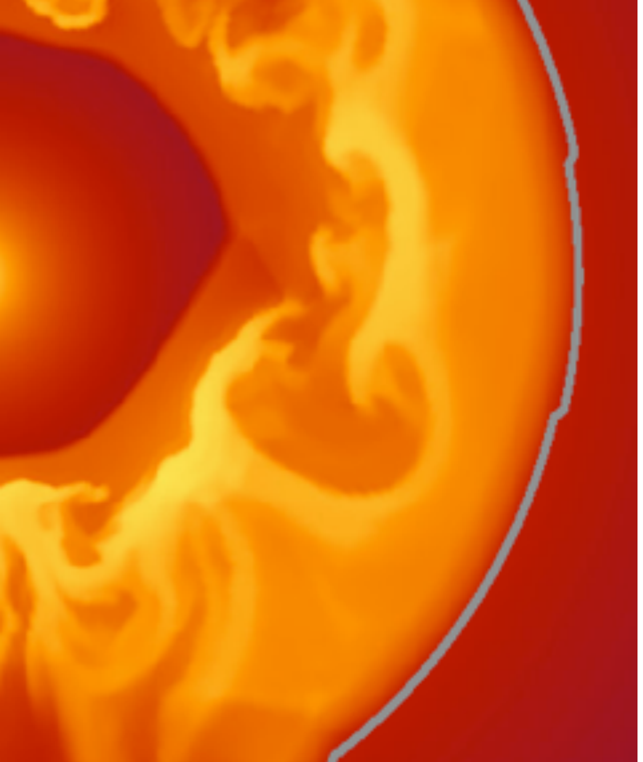


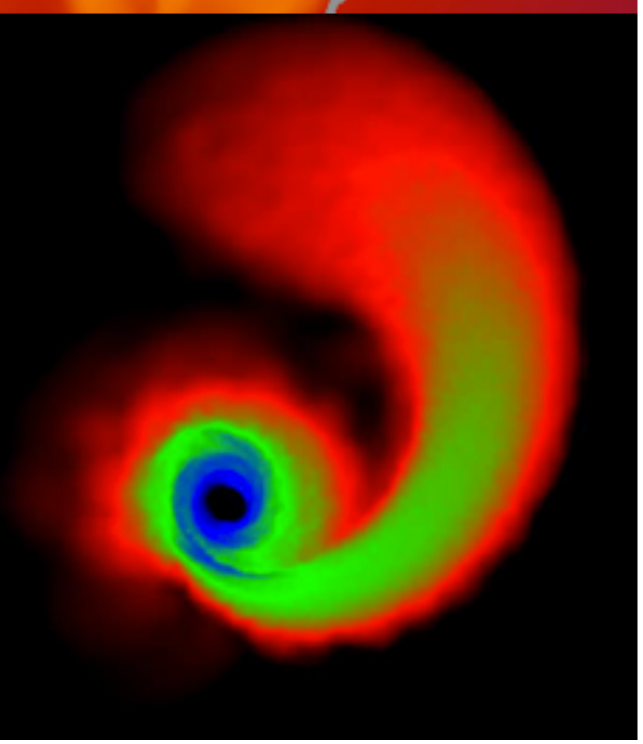


Korobkin et al. 2012



Korobkin et al. 2012

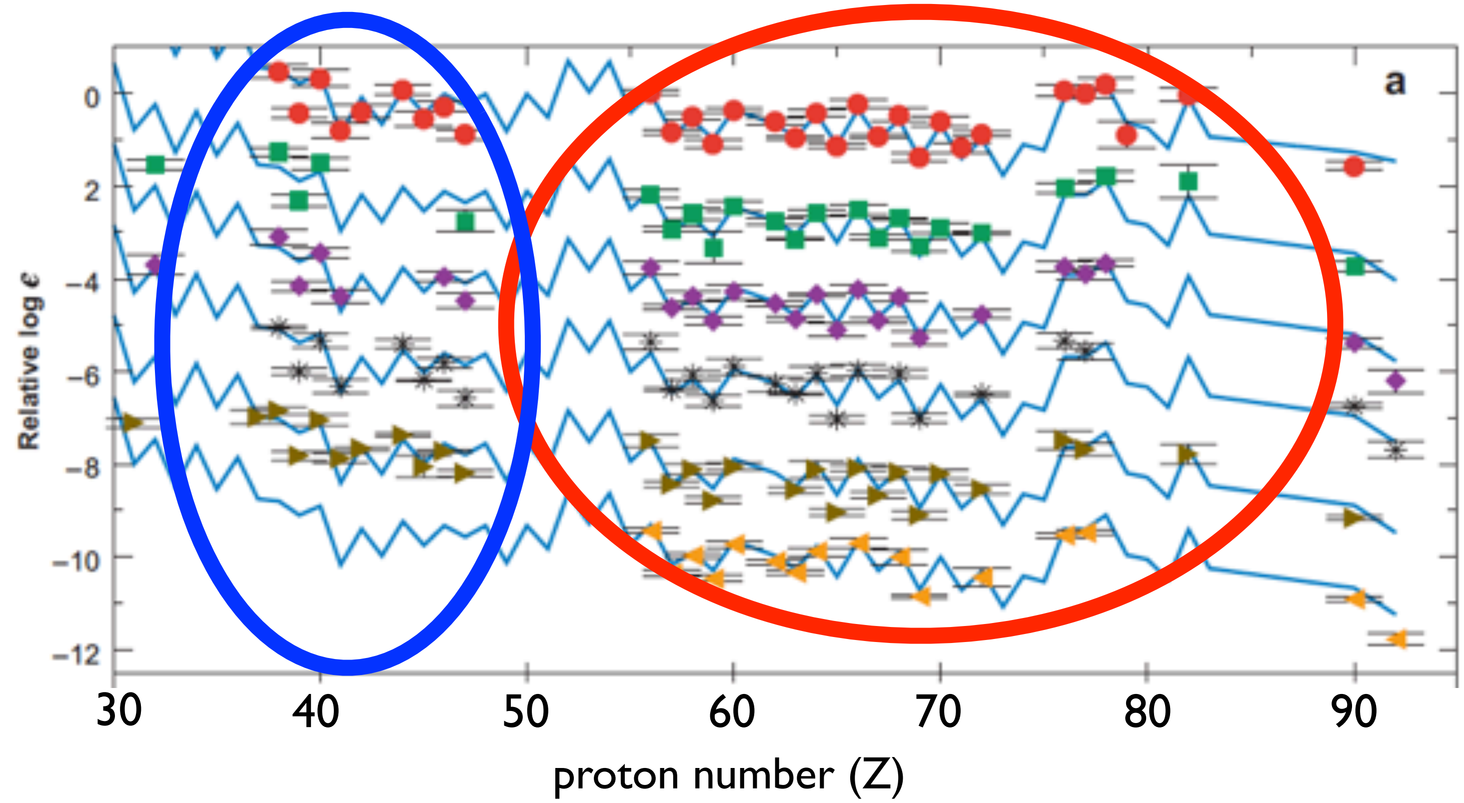




Conclusions

Lighter heavy elements (Sr, Y, Zr)

produced in neutrino-driven wind → Y_e

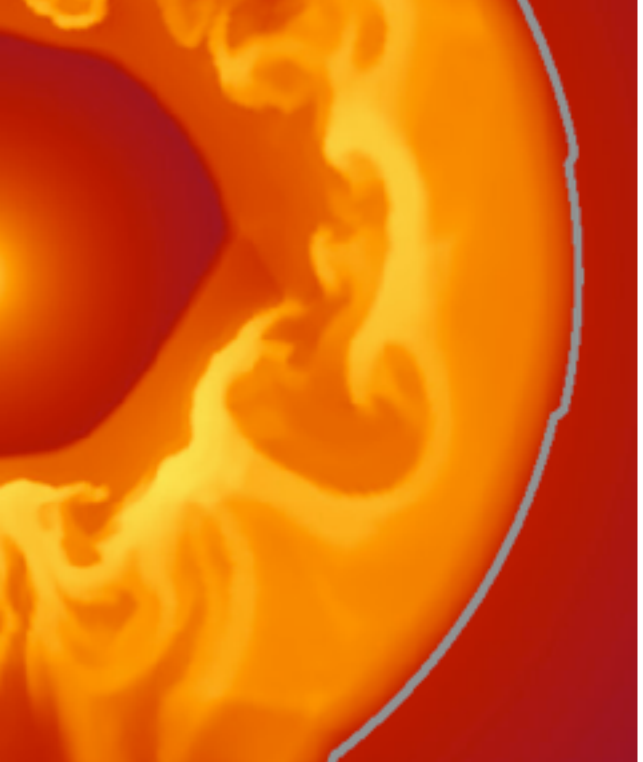


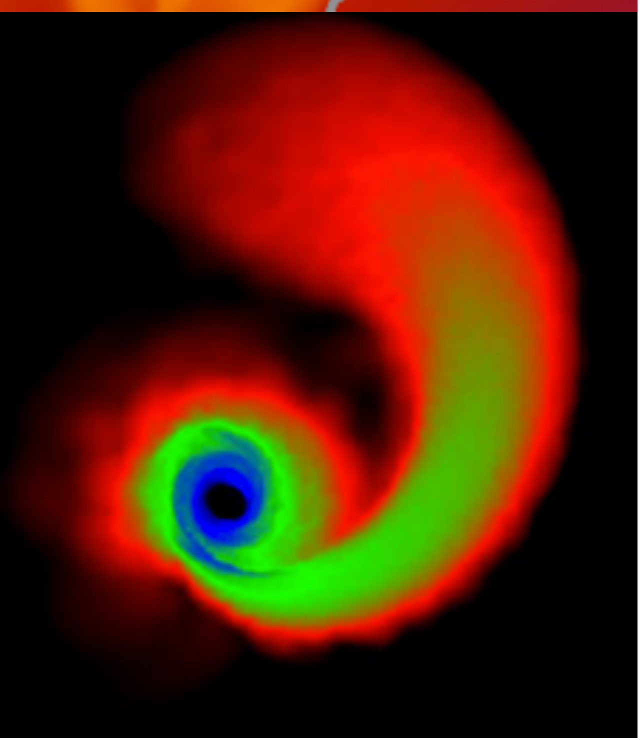
Heavy r-process elements

astrophysical site? neutron star mergers, jet-like supernovae

uncertainties on nuclear physics input:

nuclear masses, beta decays, neutron captures, fission





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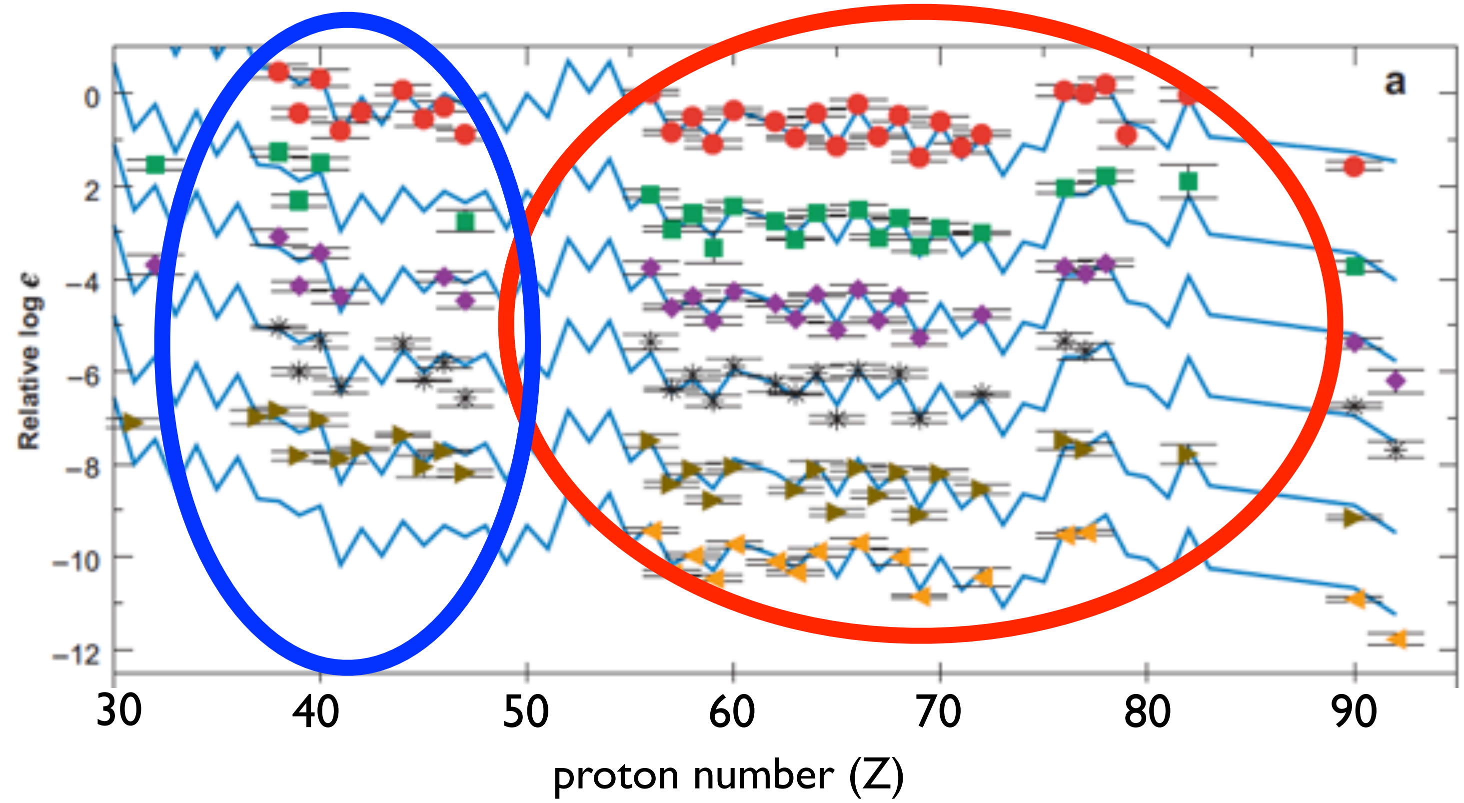

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