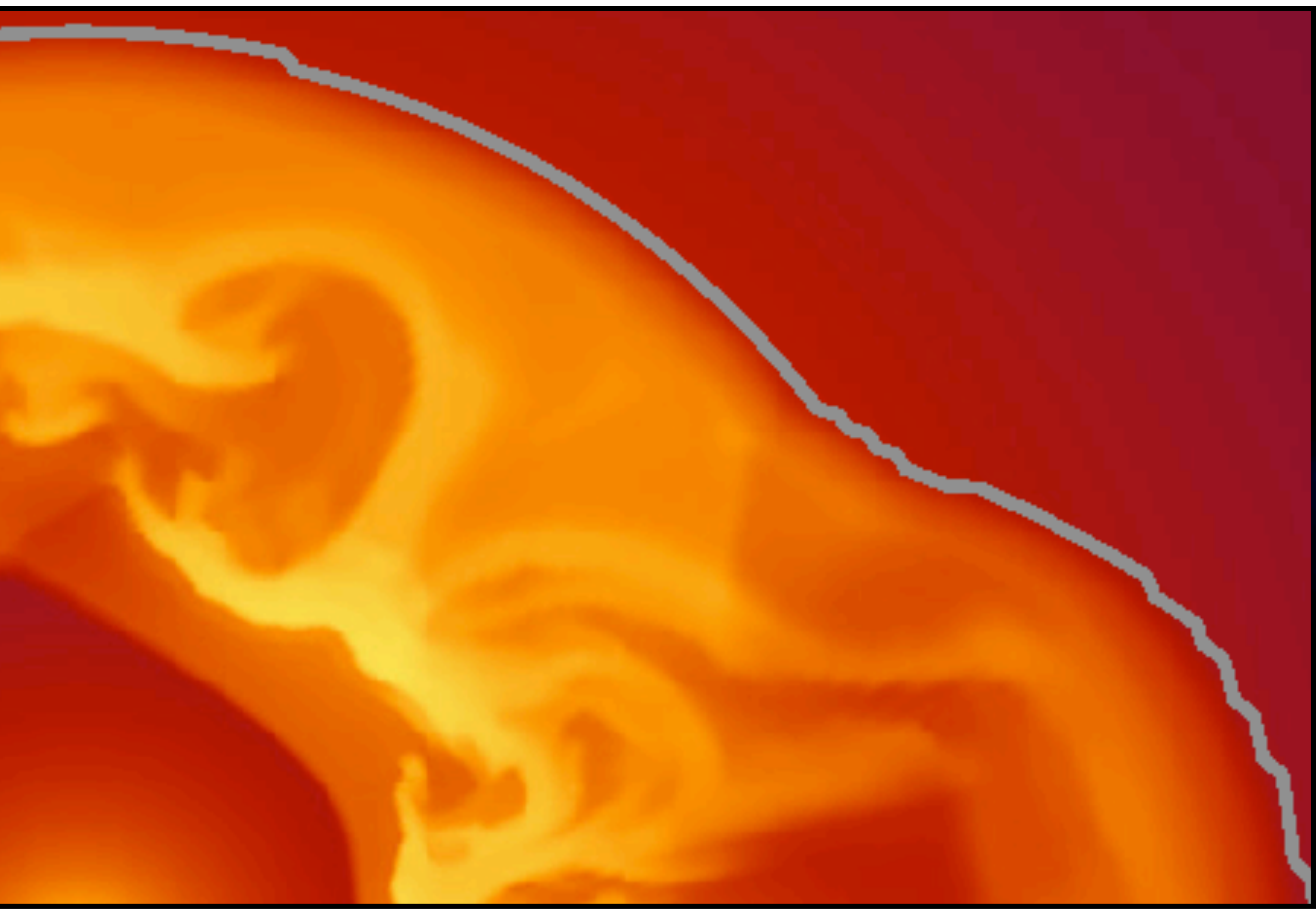
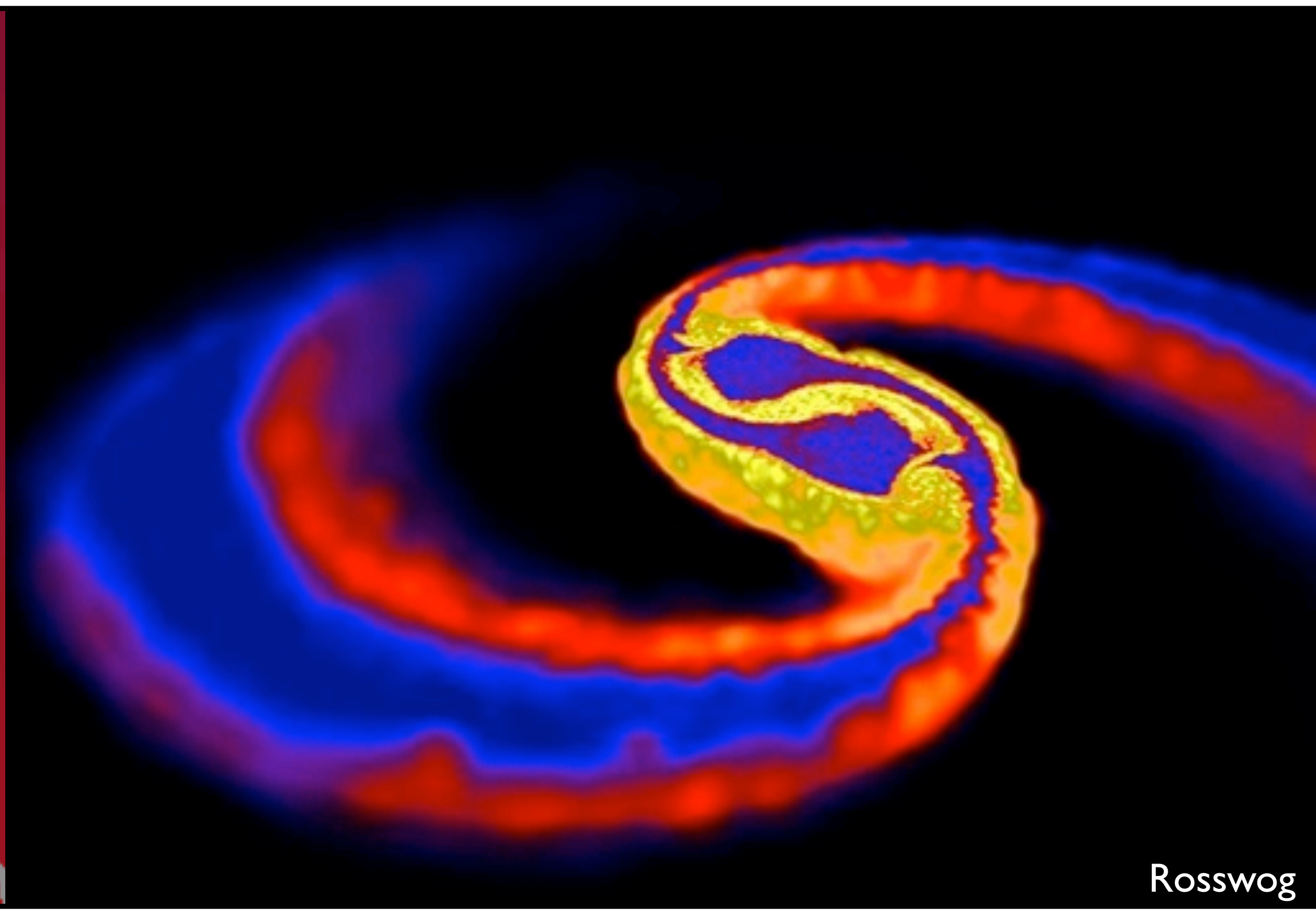
The r-process as a source of new elements, energy and optical transients





Almudena Arcones

Feodor Lynen Fellow at the University of Basel

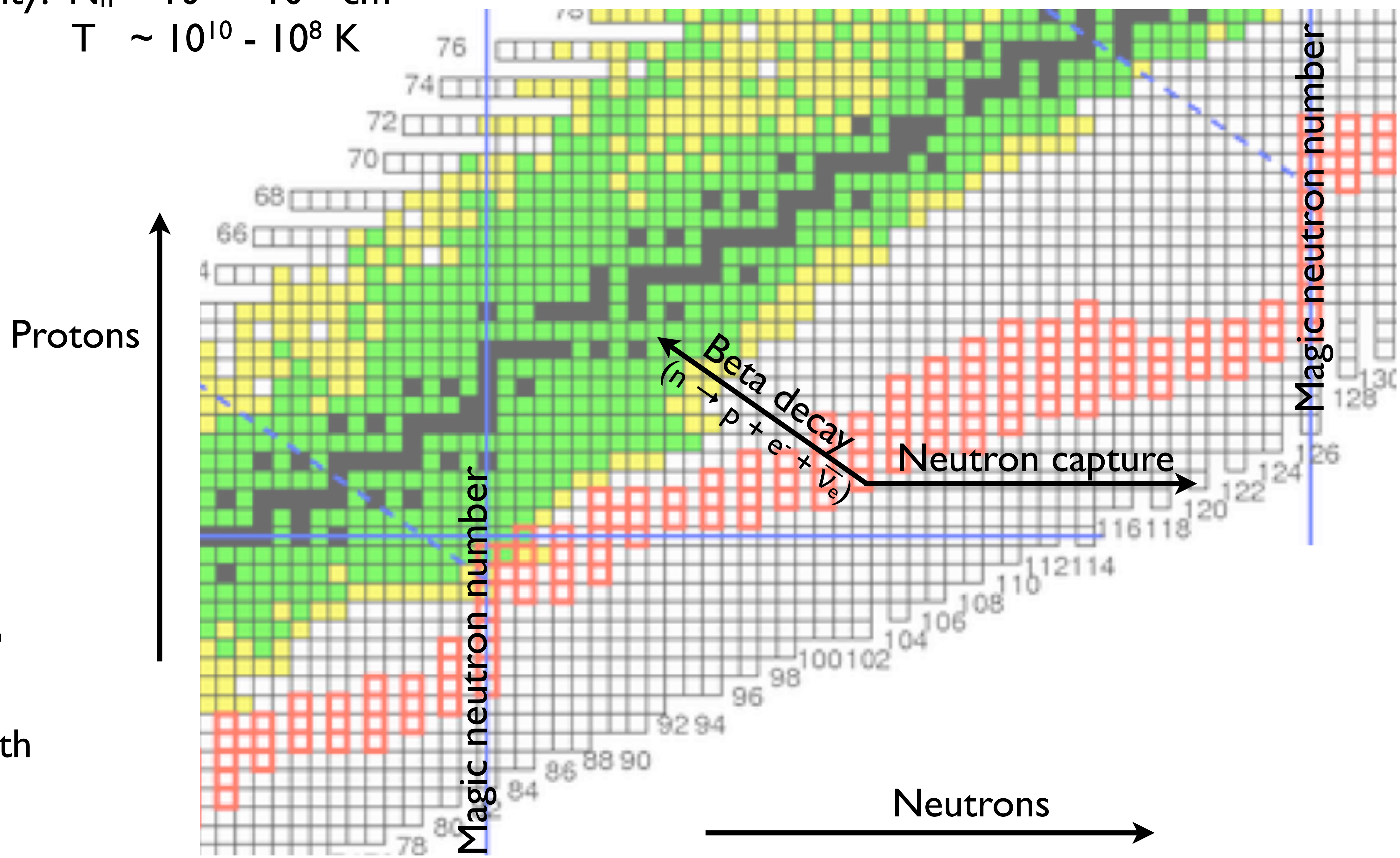
Alexander von Humboldt Stiftung/Foundation

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



Stable nuclei

nuclei in lab

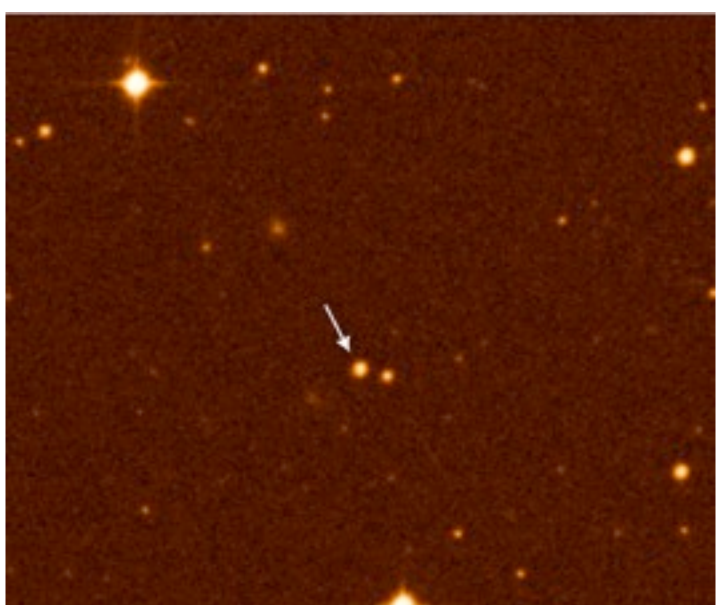
r-process path

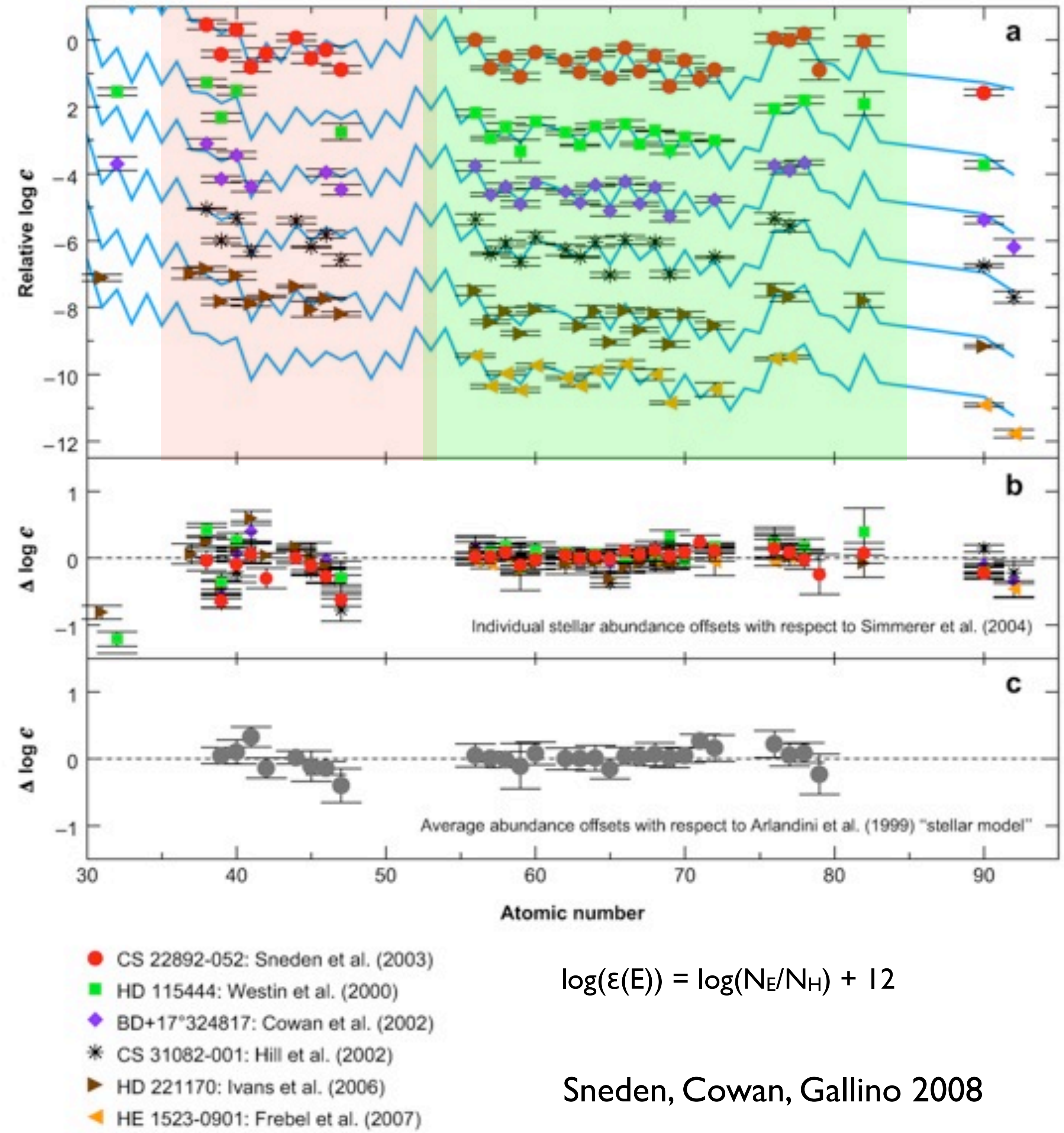
Ultra metal-poor stars = very old stars

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

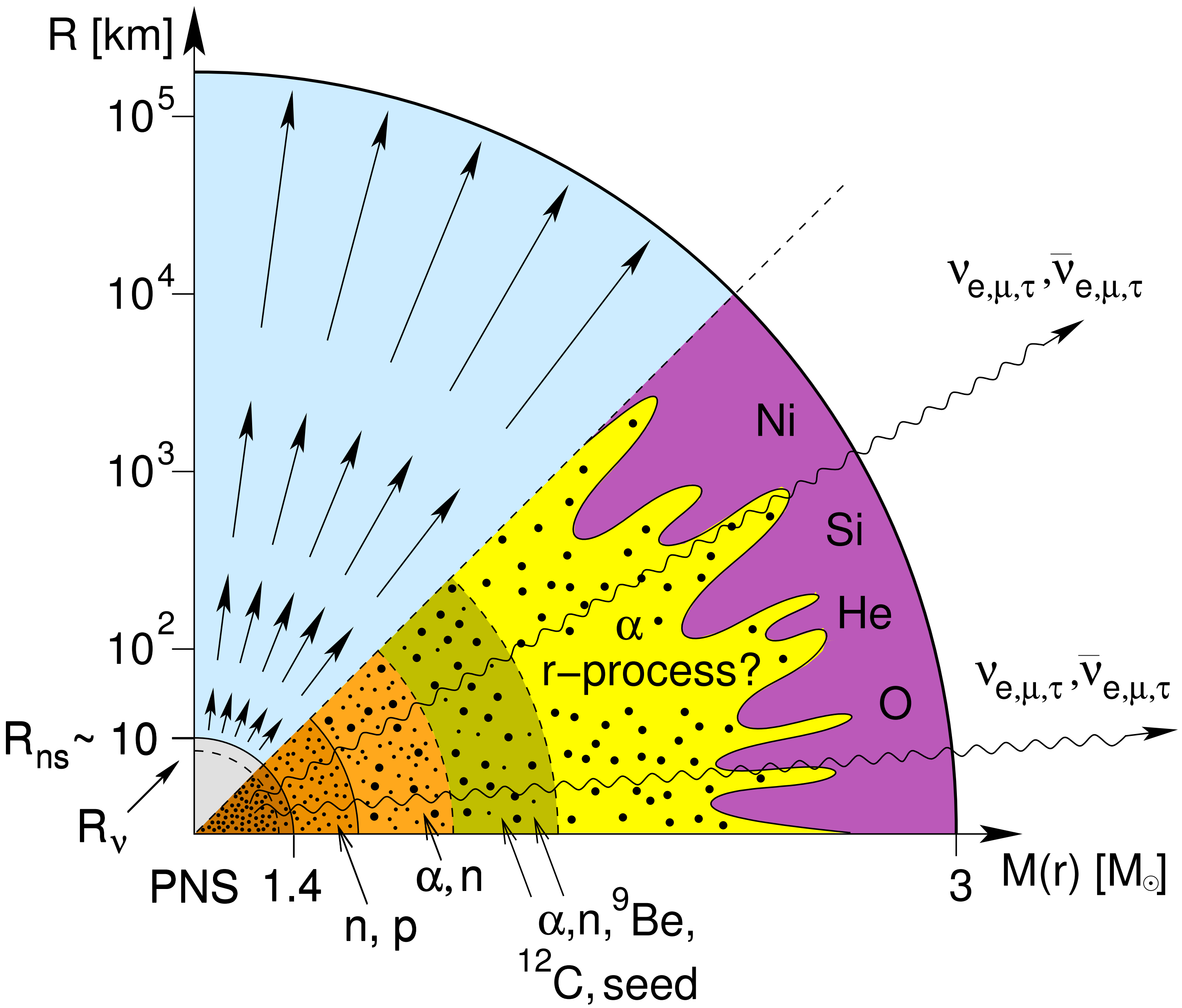
Astrophysical site(s) of the r-process

core-collapse supernovae

(B²FH 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)

Nucleosynthesis in neutrino-driven winds



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

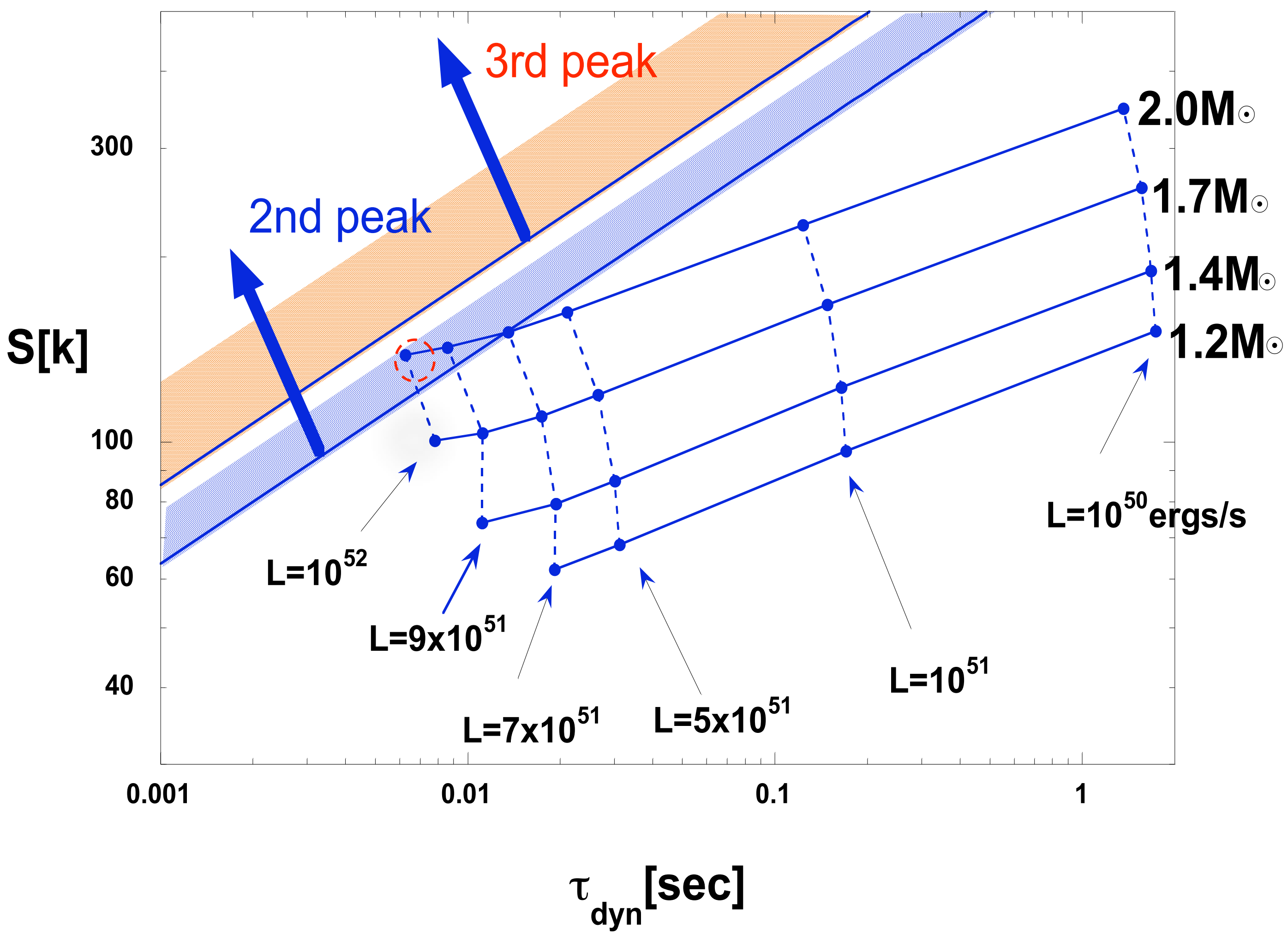
Necessary conditions for the r-process:

- 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...)

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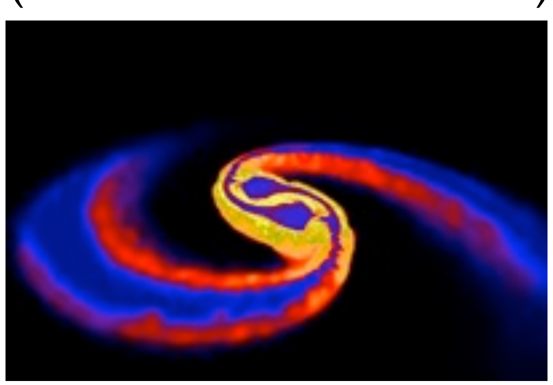
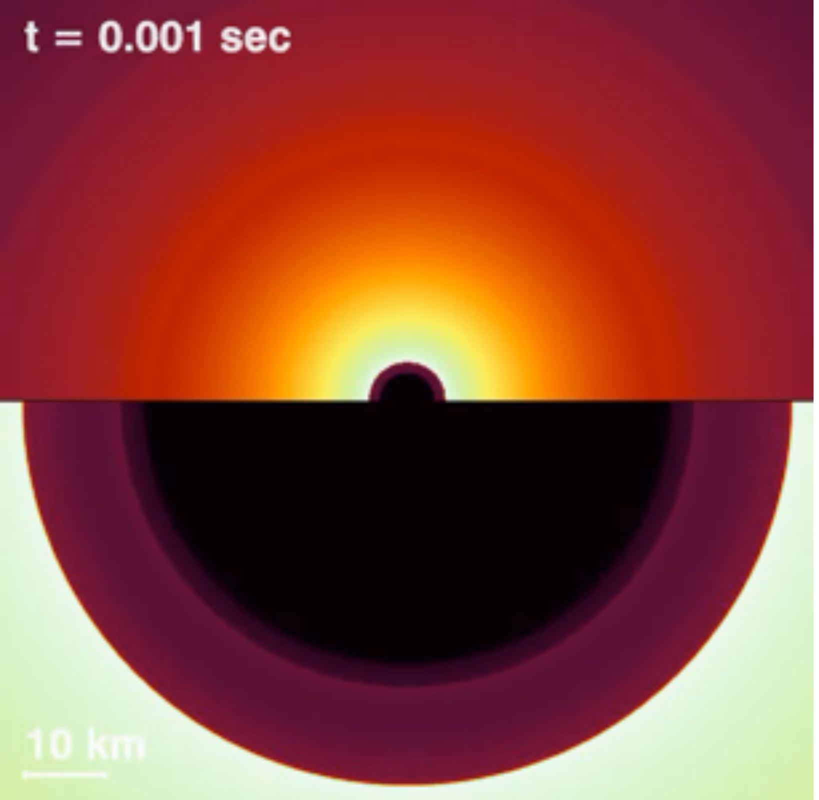
neutron star mergers

(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)



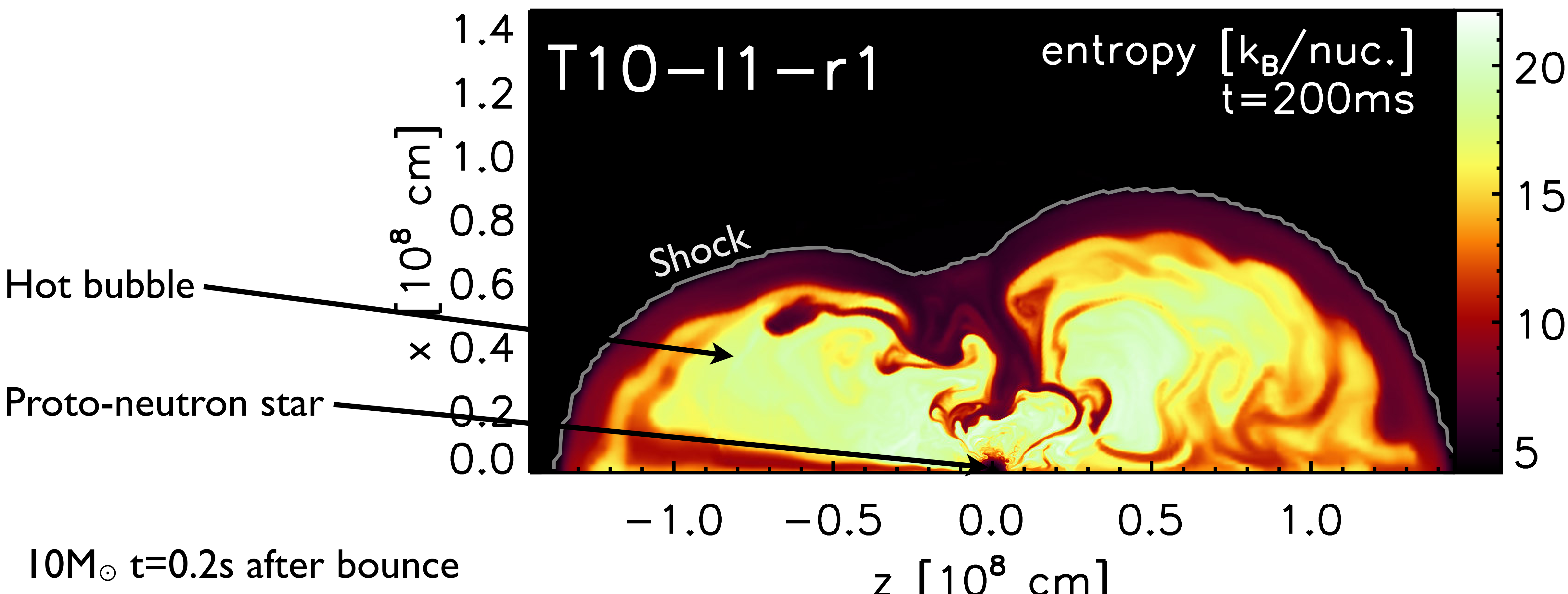
Hydrodynamical simulations

Long-time hydrodynamical simulations following the ejecta from ~5ms after bounce to ~3s in 2D (Arcones & Janka 2011) and ~10s in 1D (Arcones et al. 2007).

Explosion by increasing the neutrino luminosities to obtain typical explosion energies ~10^{51}erg.

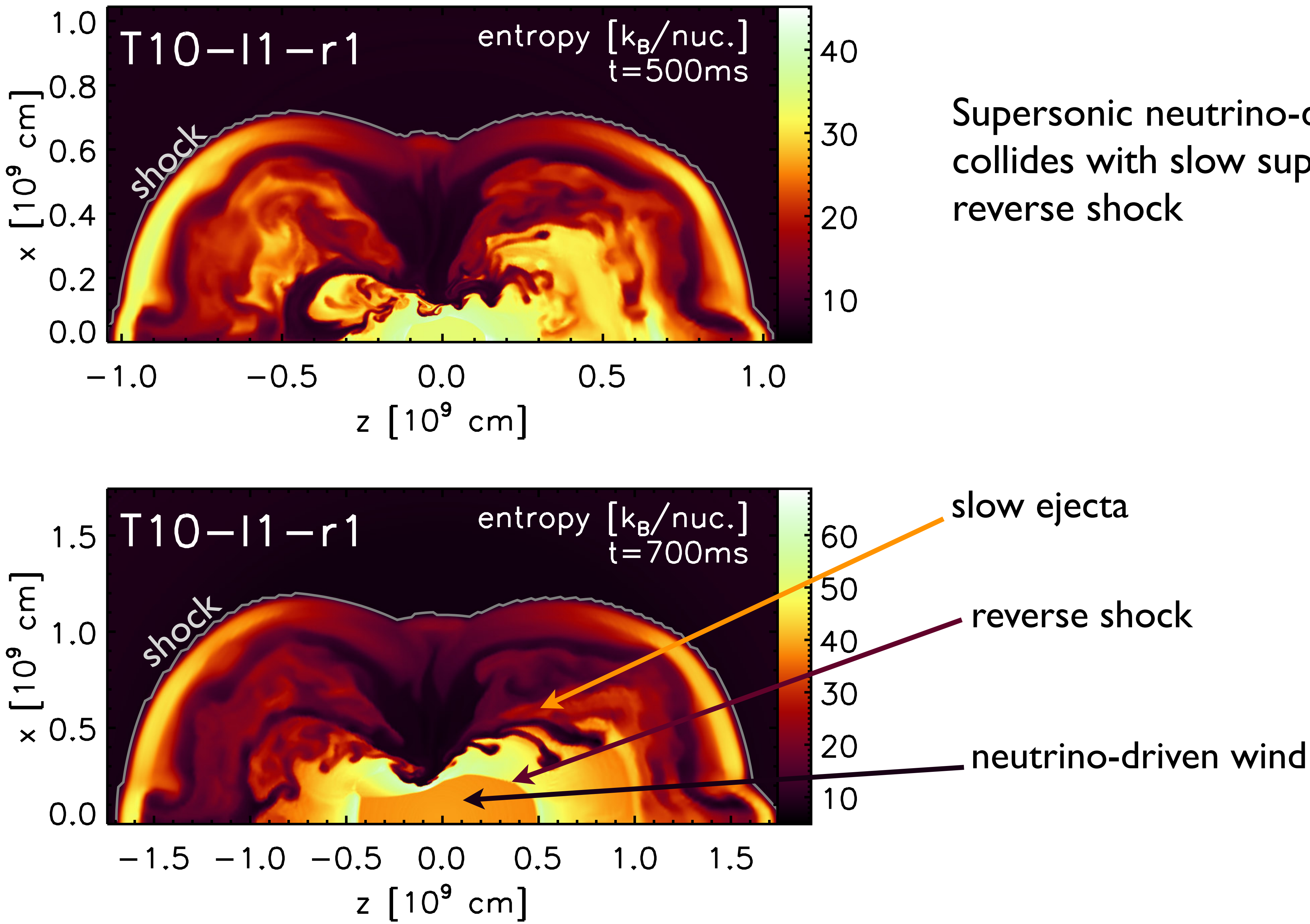
Detailed study of nucleosynthesis-relevant conditions: interaction of the neutrino-driven wind and the slow supernova ejecta.

Variations of explosion energy, proto-neutron star cooling, and progenitor.



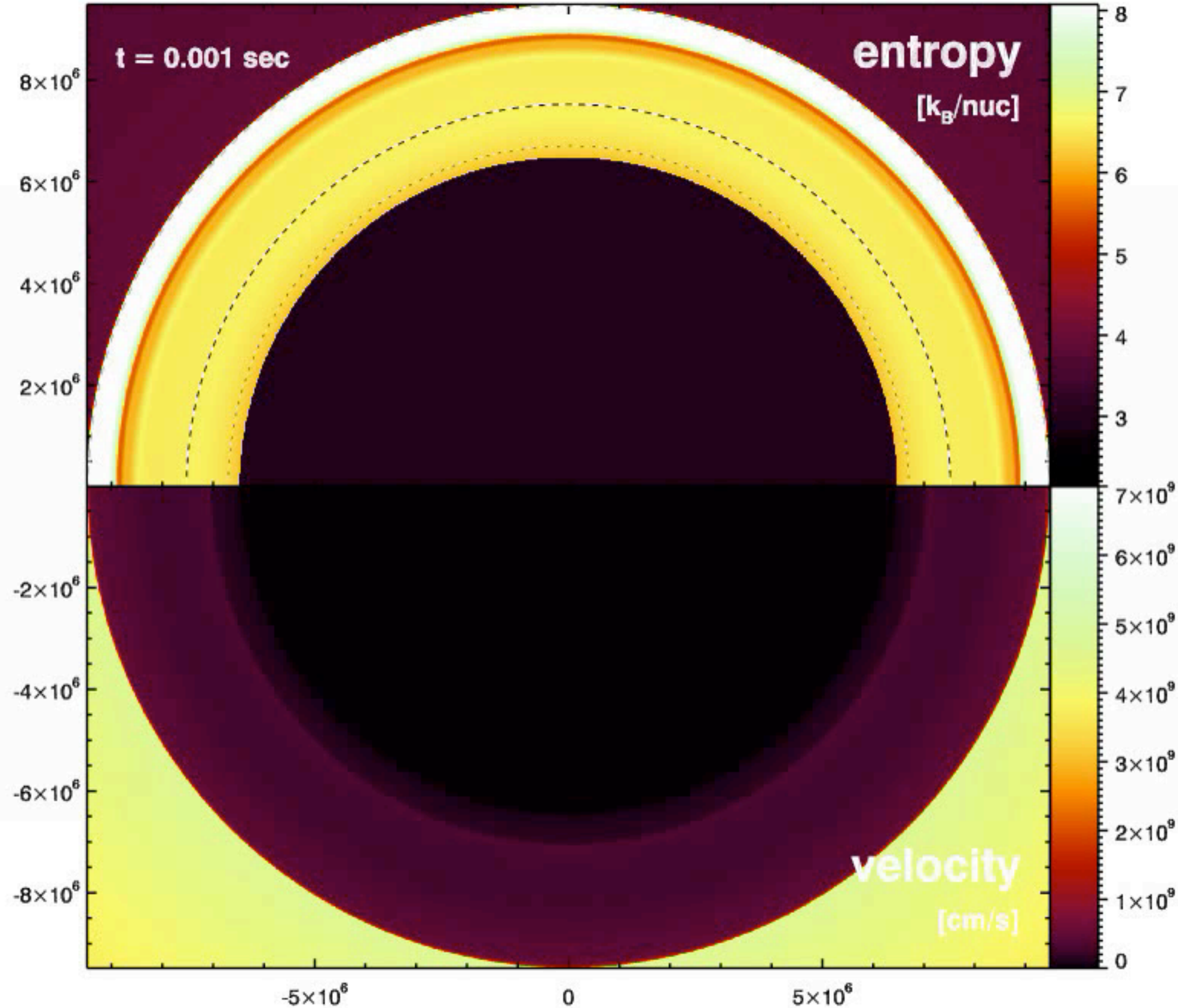
$10M_\odot$ t=0.2s after bounce

Neutrino-driven wind in 2D



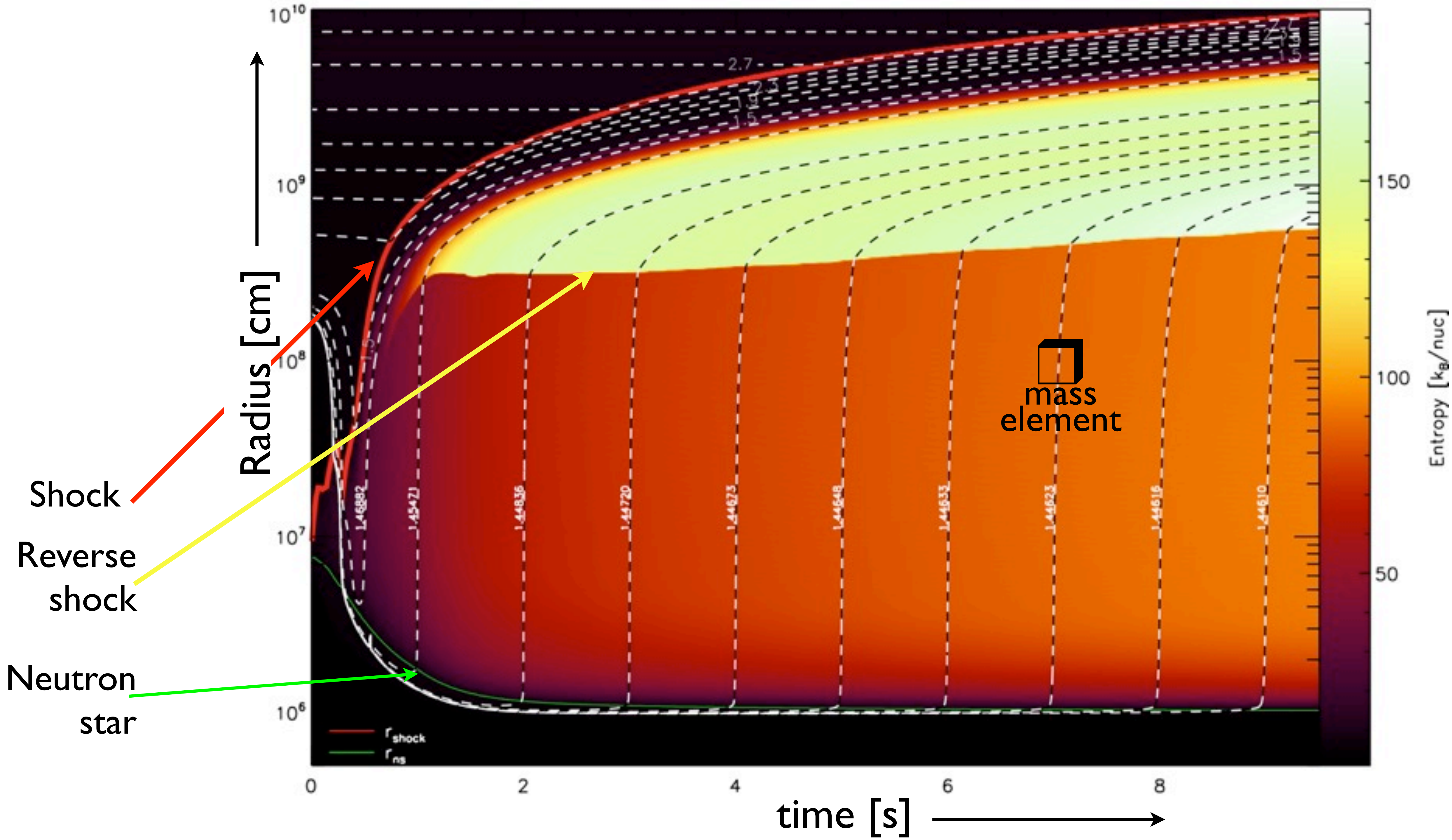
Supersonic neutrino-driven wind collides with slow supernova ejecta: reverse shock

Arcones & Janka (2011)



1D simulations for nucleosynthesis studies

Arcones et al. 2007



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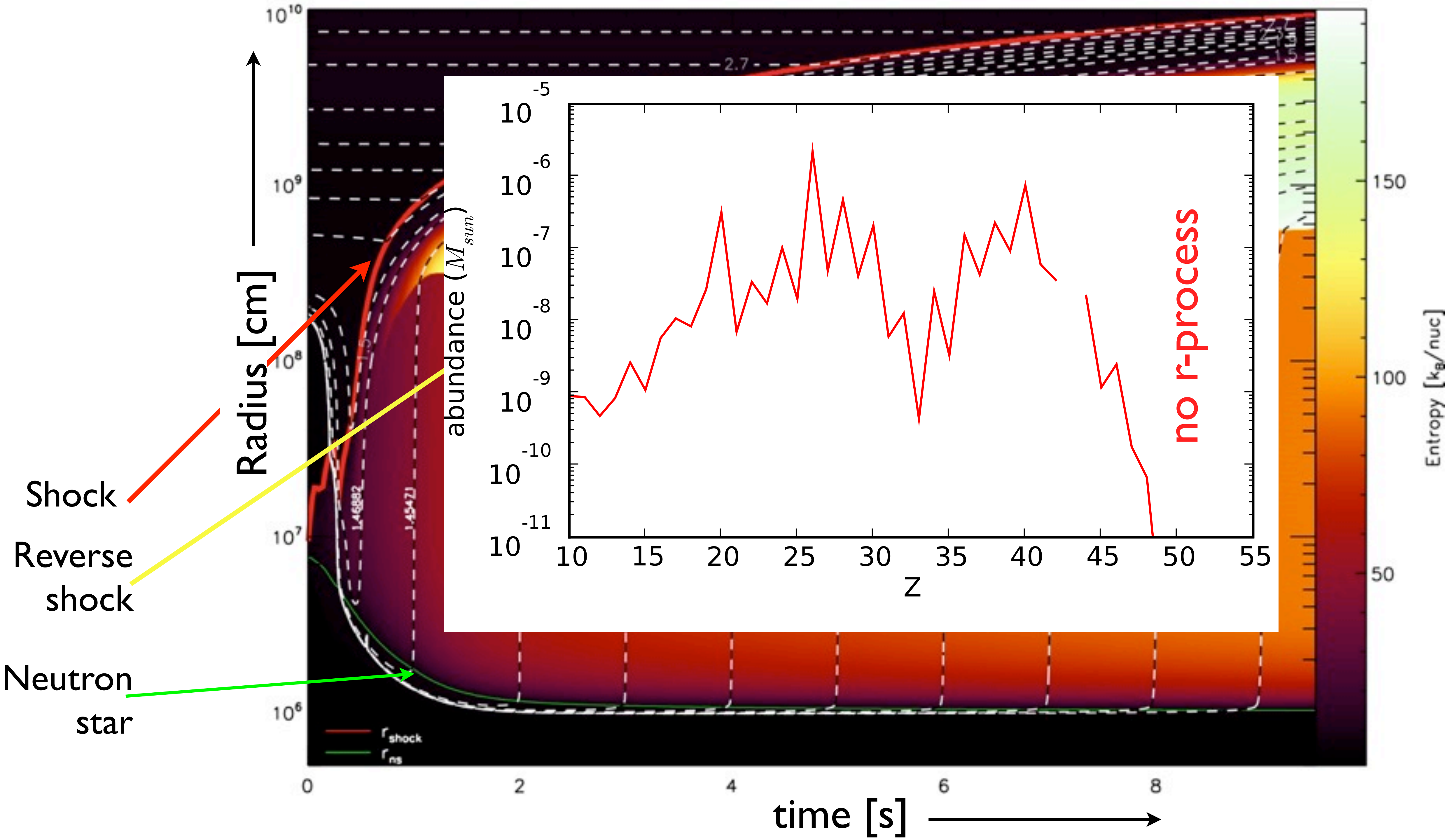

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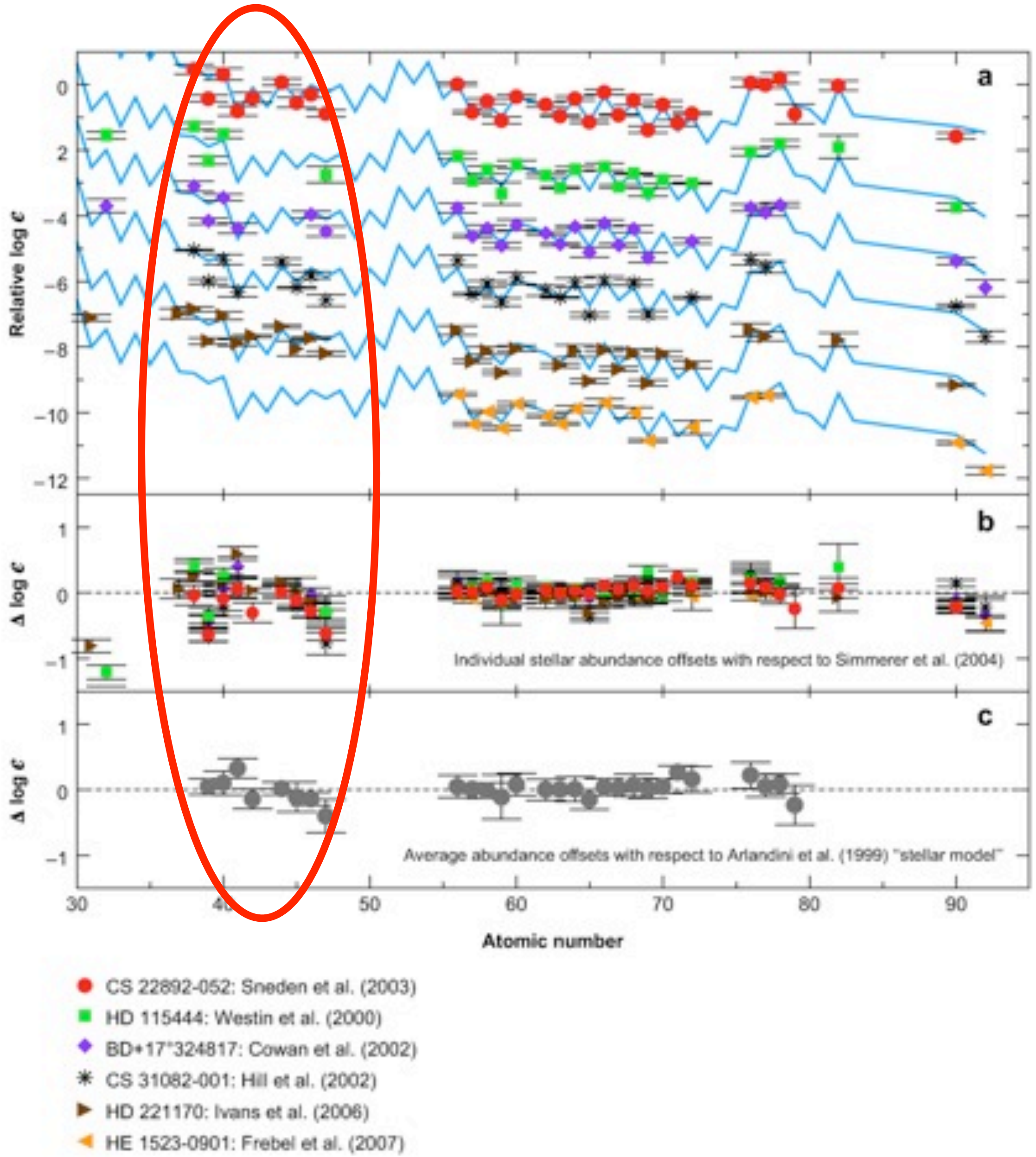
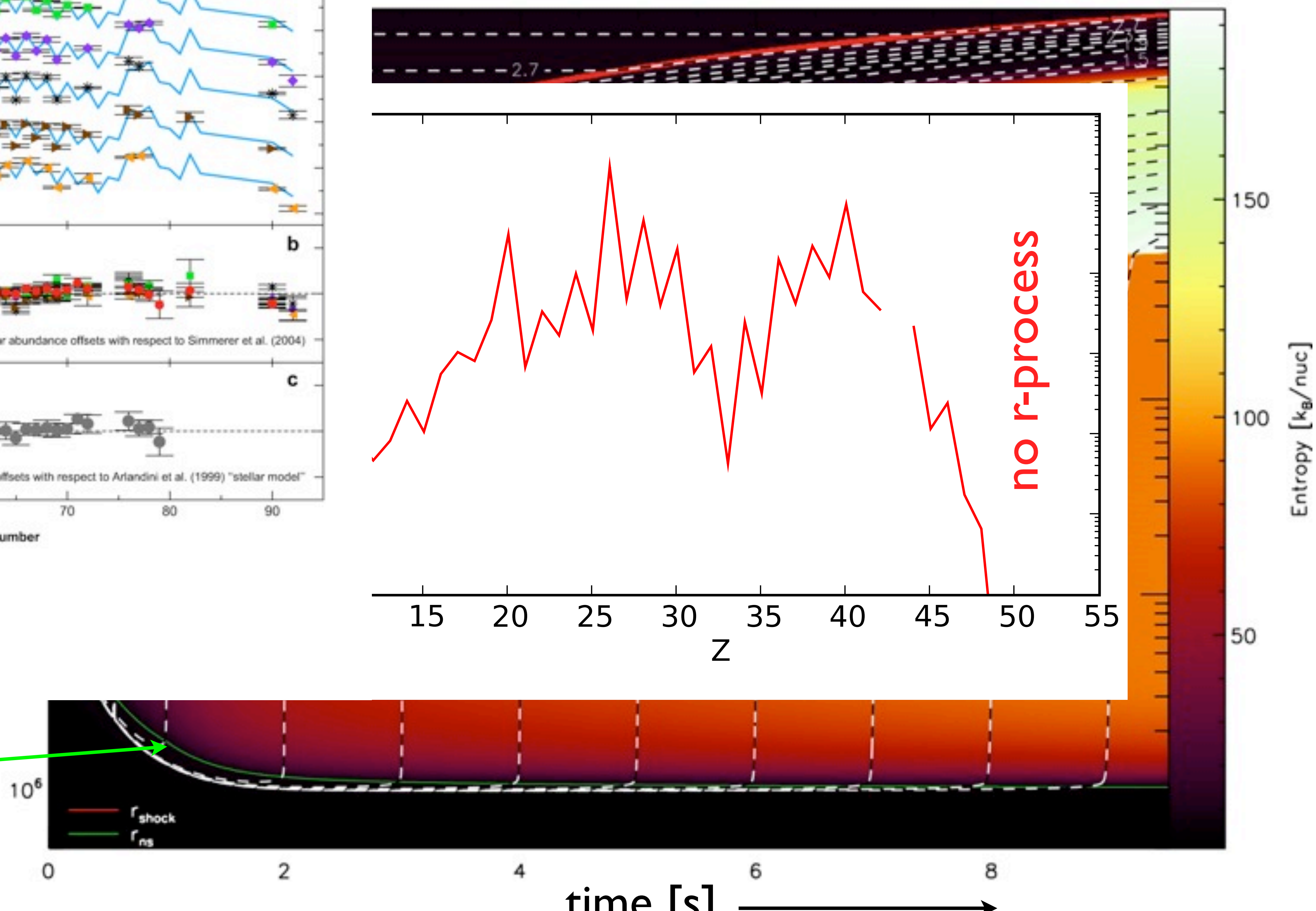


Arcones et al. 2007



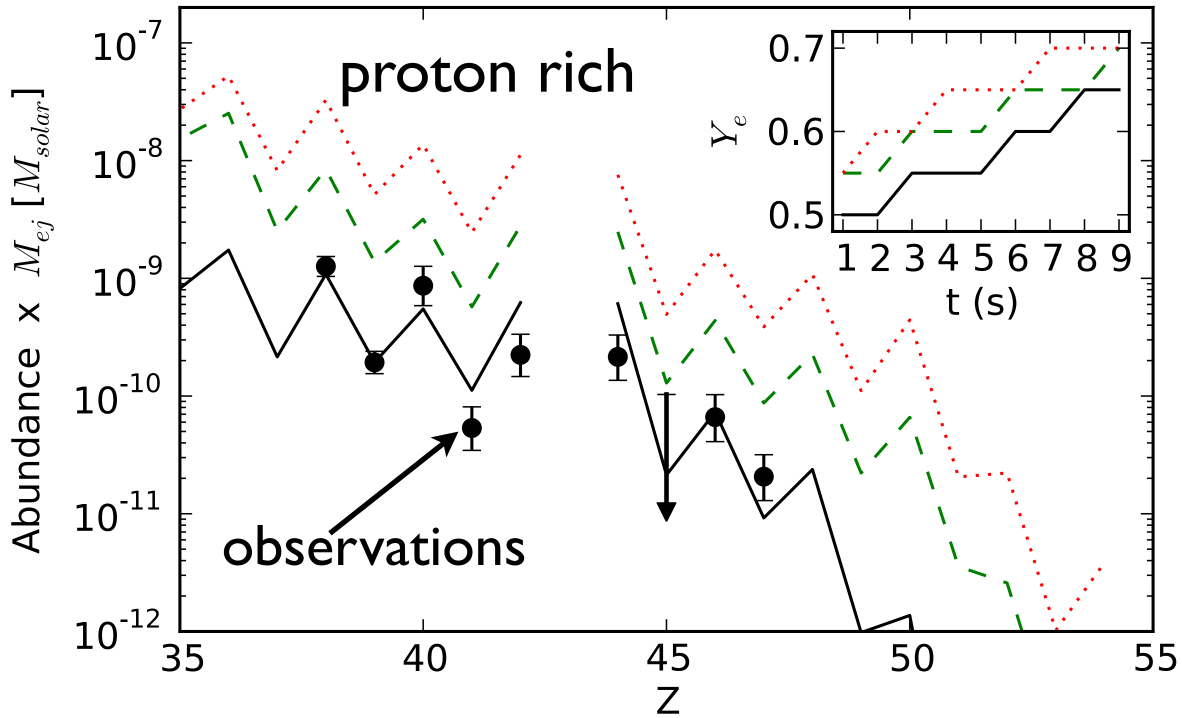
Neutron star

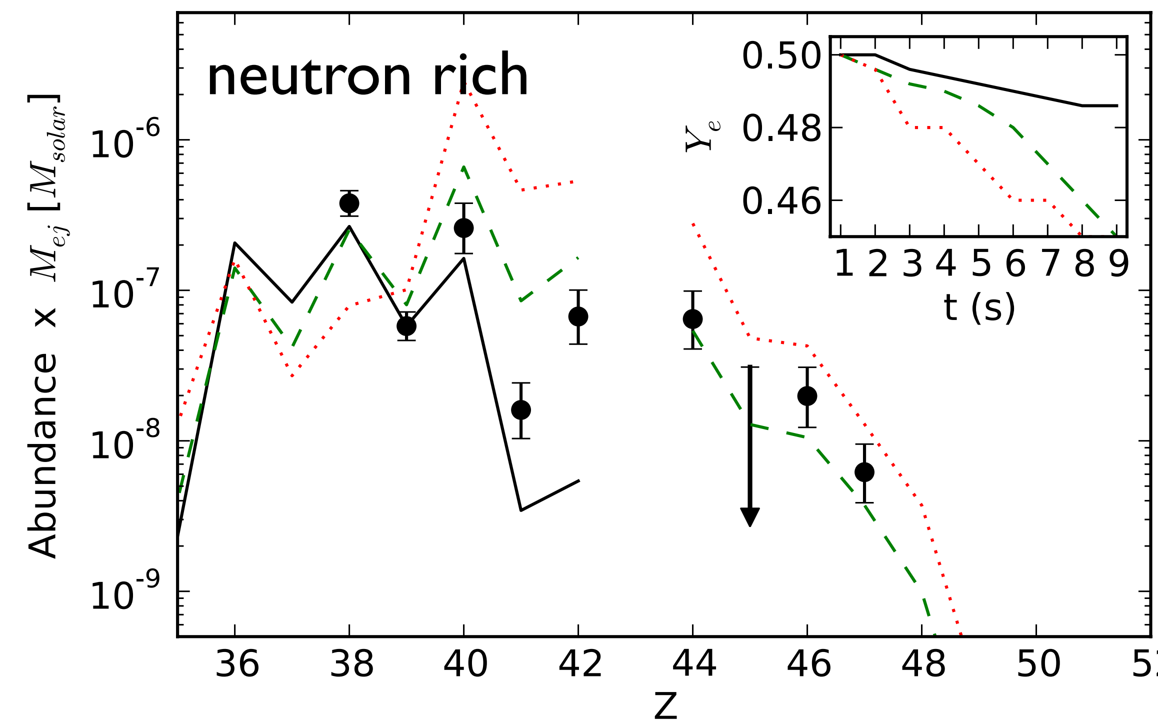
Lighter heavy elements in neutrino-driven winds

(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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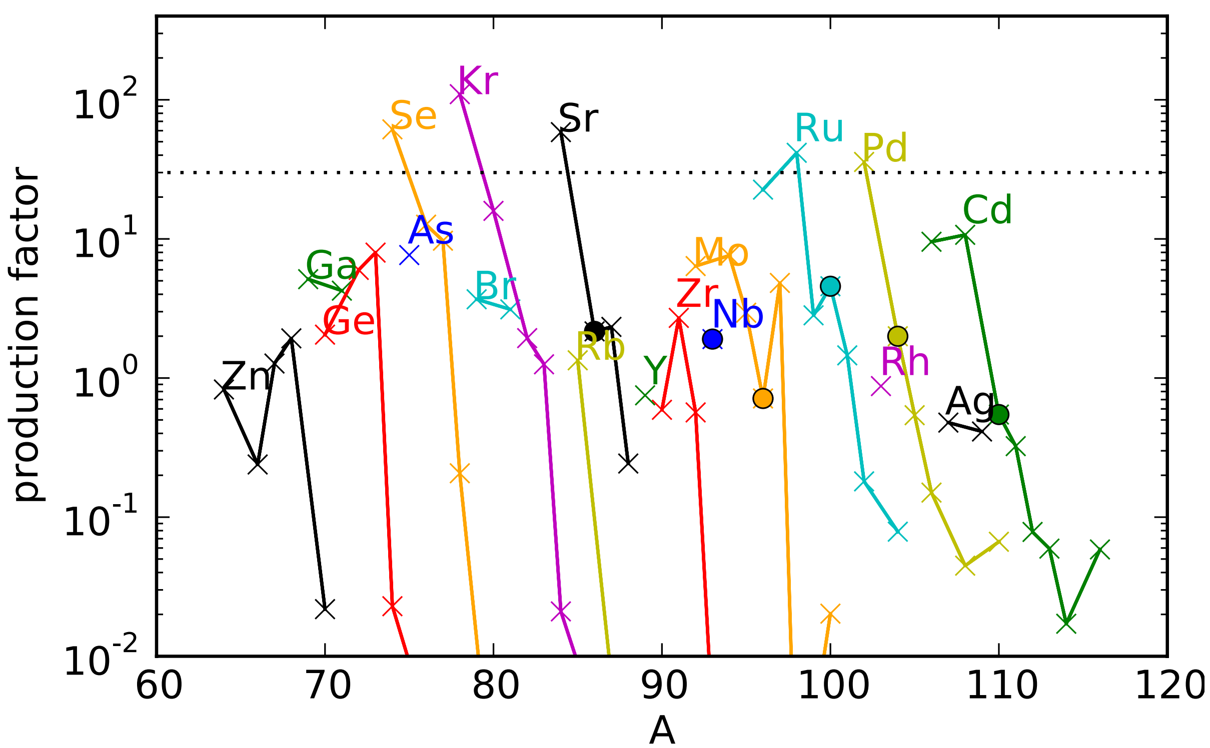

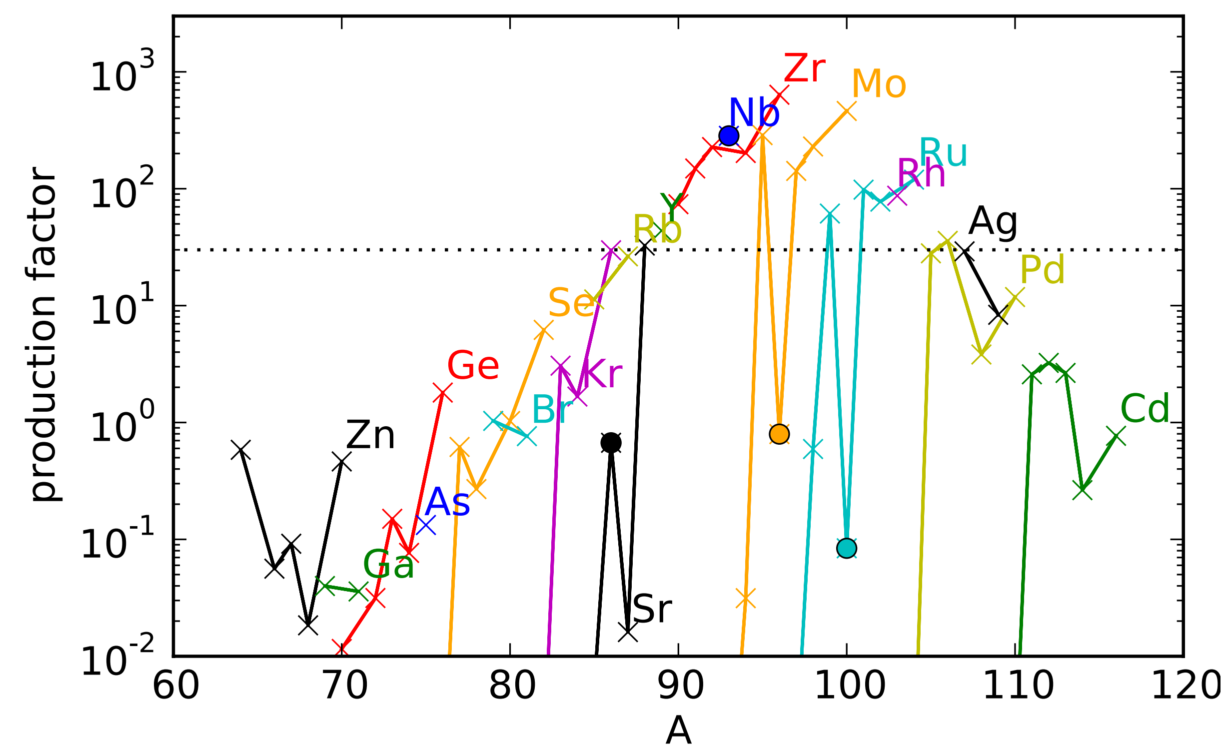

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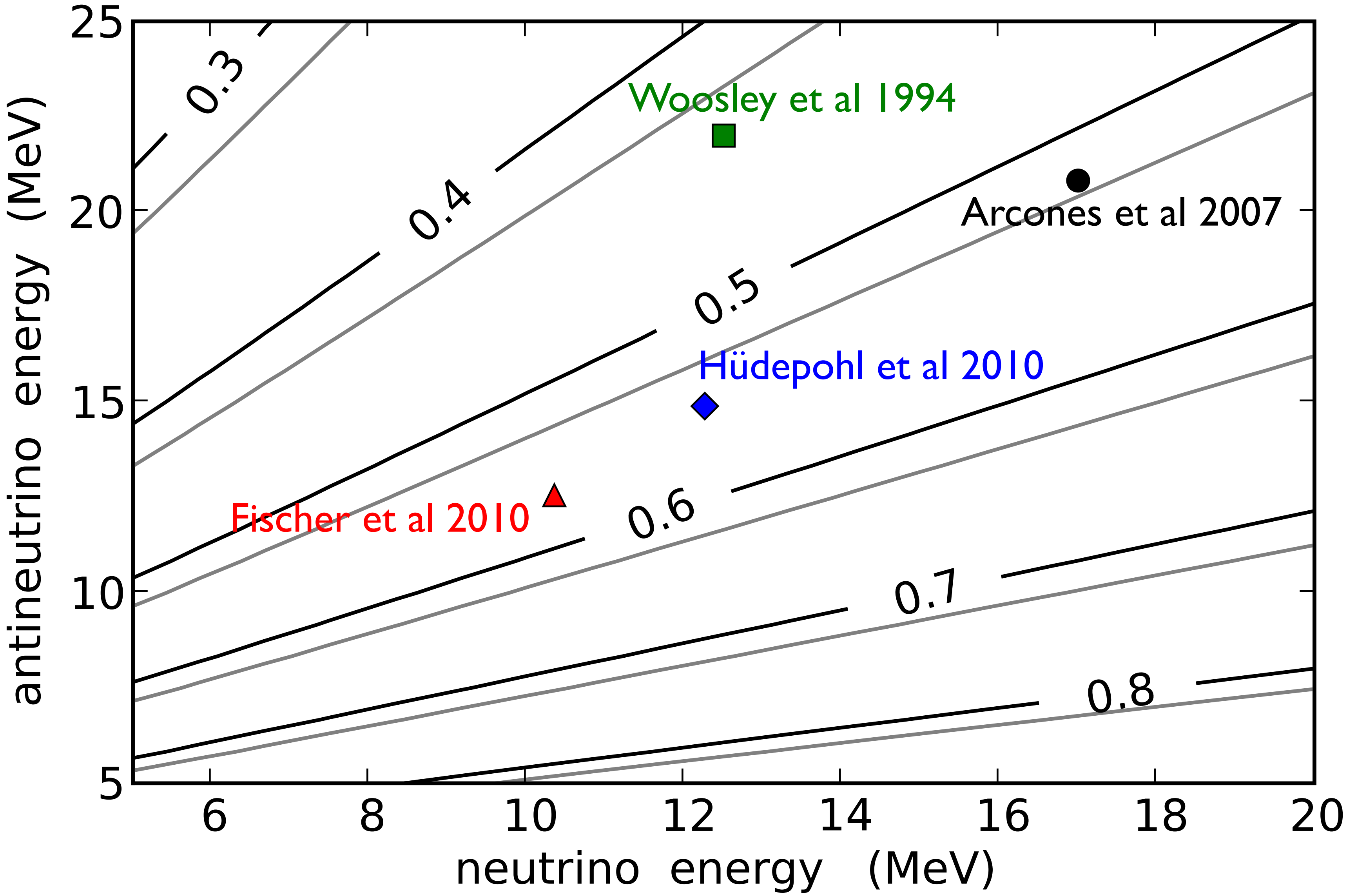
Wind models and electron fraction

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



Qian & Woosley 1996

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

$Y_e > 0.5$: $\varepsilon_{\bar{\nu}} - \varepsilon_{\nu} < 4\Delta$

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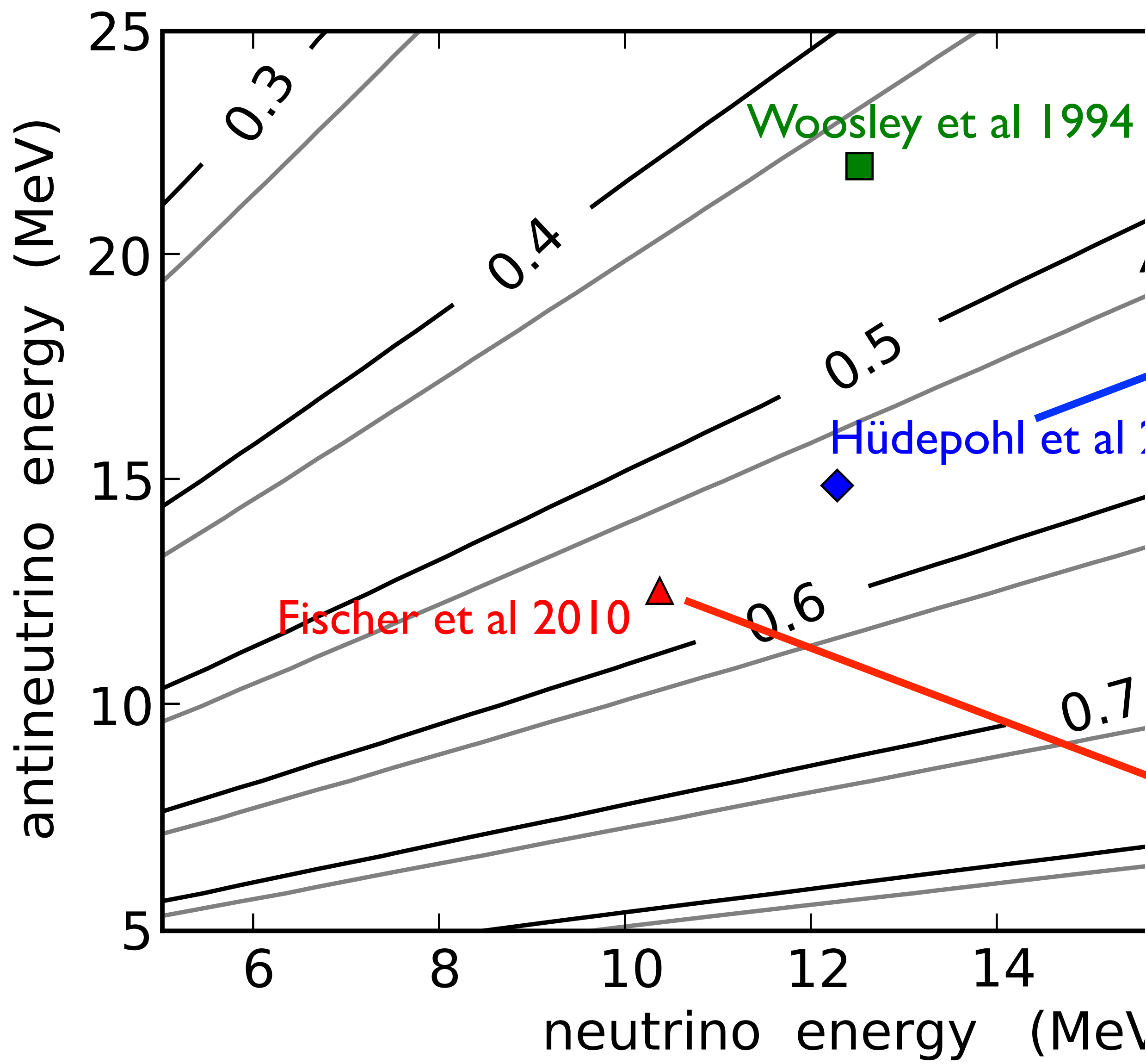
More recent simulations obtain lower antineutrinc



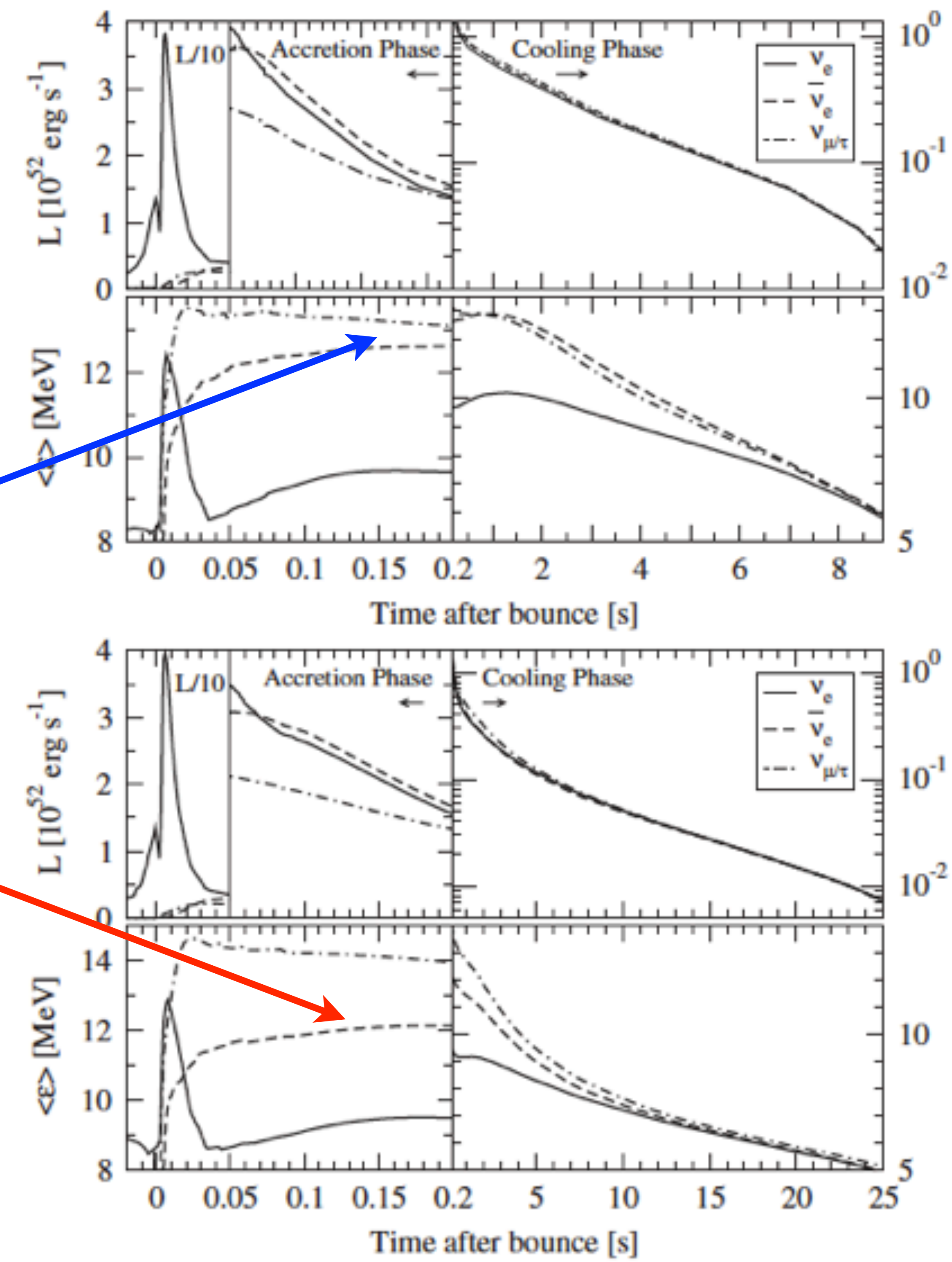


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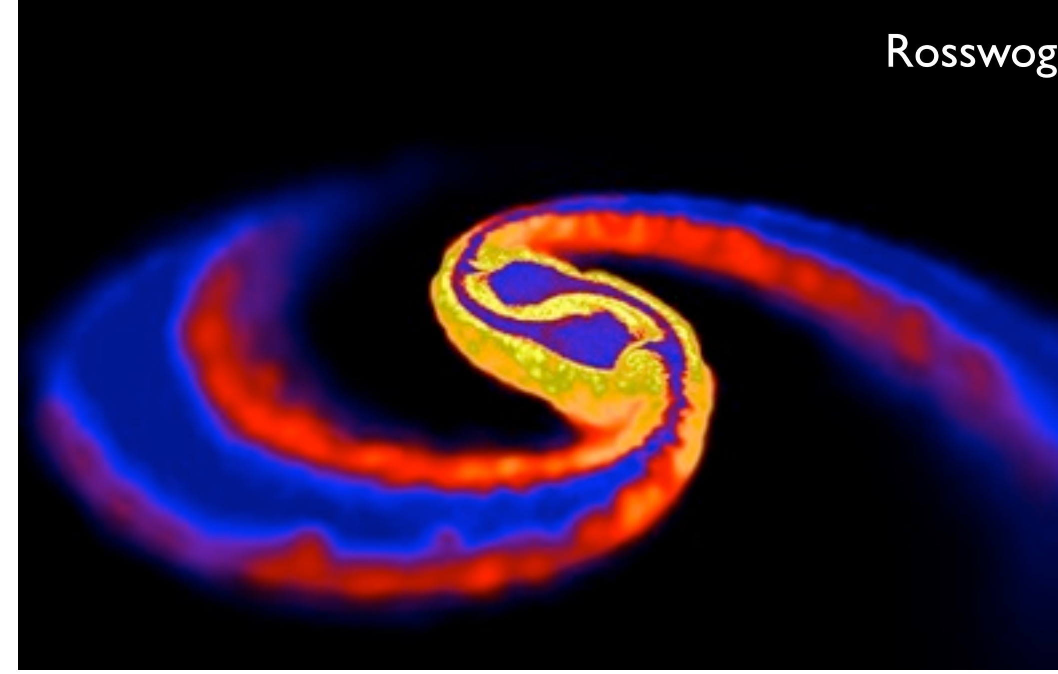
FIG. 1. Neutrino luminosities and mean energies observed at infinity. Top: Full set of neutrino opacities (model Sf). Bottom: Reduced set (model Sr).

r-process in neutron star mergers

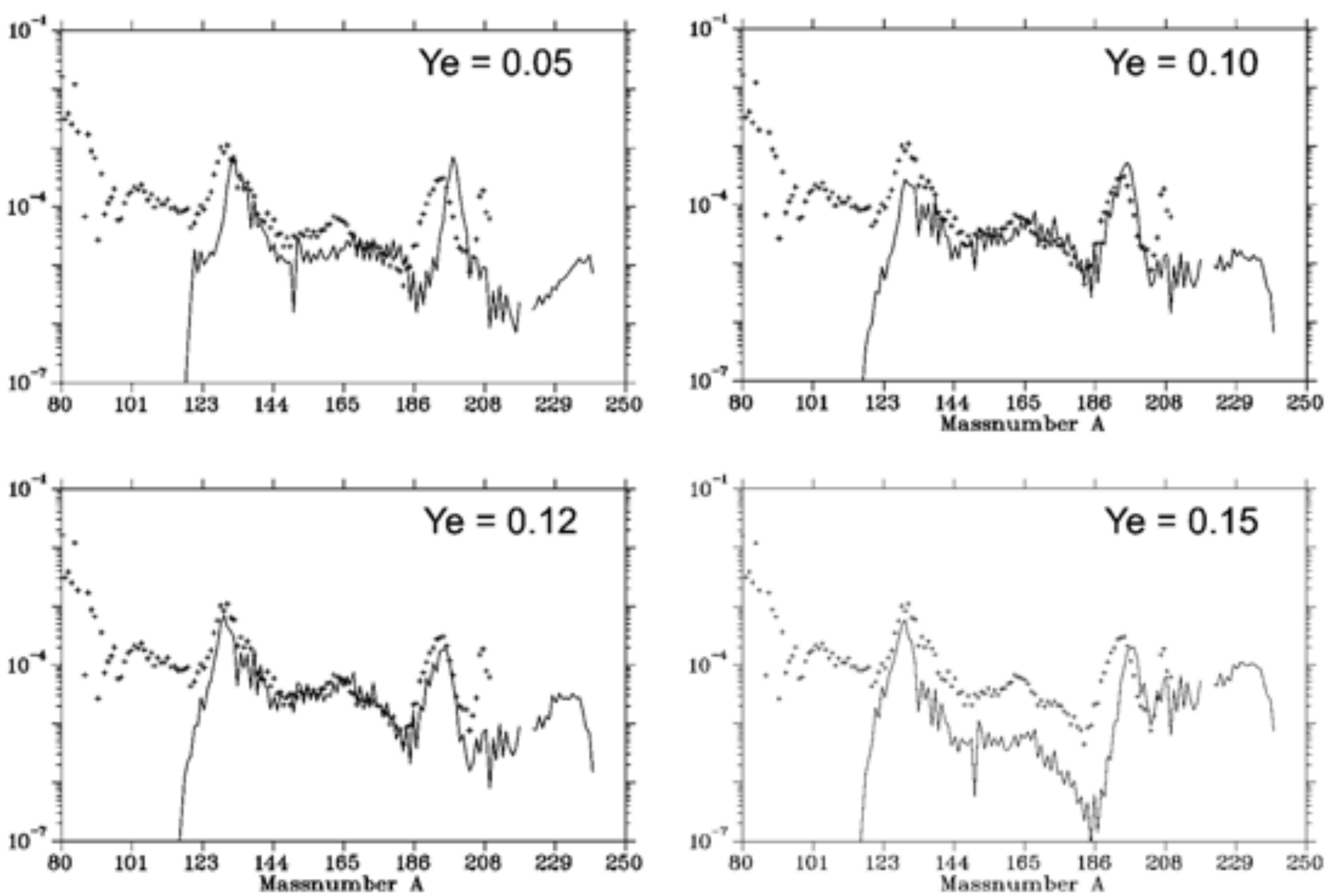


contribution to chemical history of our galaxy
(Freiburghaus et al. 1999, ...).

r-process heating affects merger dynamics
(Freiburghaus et al. 1999, Metzger et al. 2010).

transient with kilo-nova luminosity (Metzger et al. 2010): detection of r-process in neutron-star mergers (complementary to gravitational wave detection).

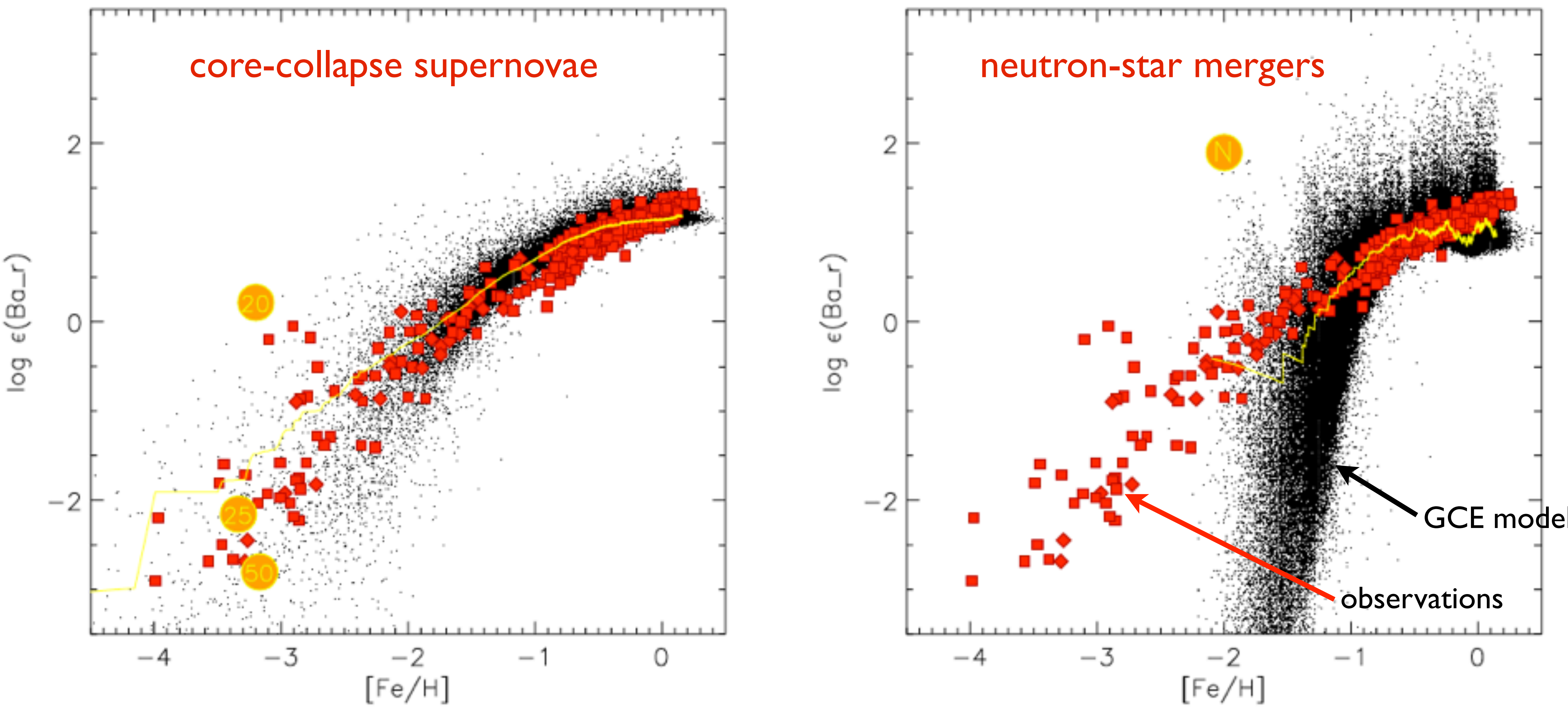
Freiburghaus, Rosswog, Thielemann 1999



low entropy,
high neutron densities,
no alpha particles,
neutron-rich seed nuclei

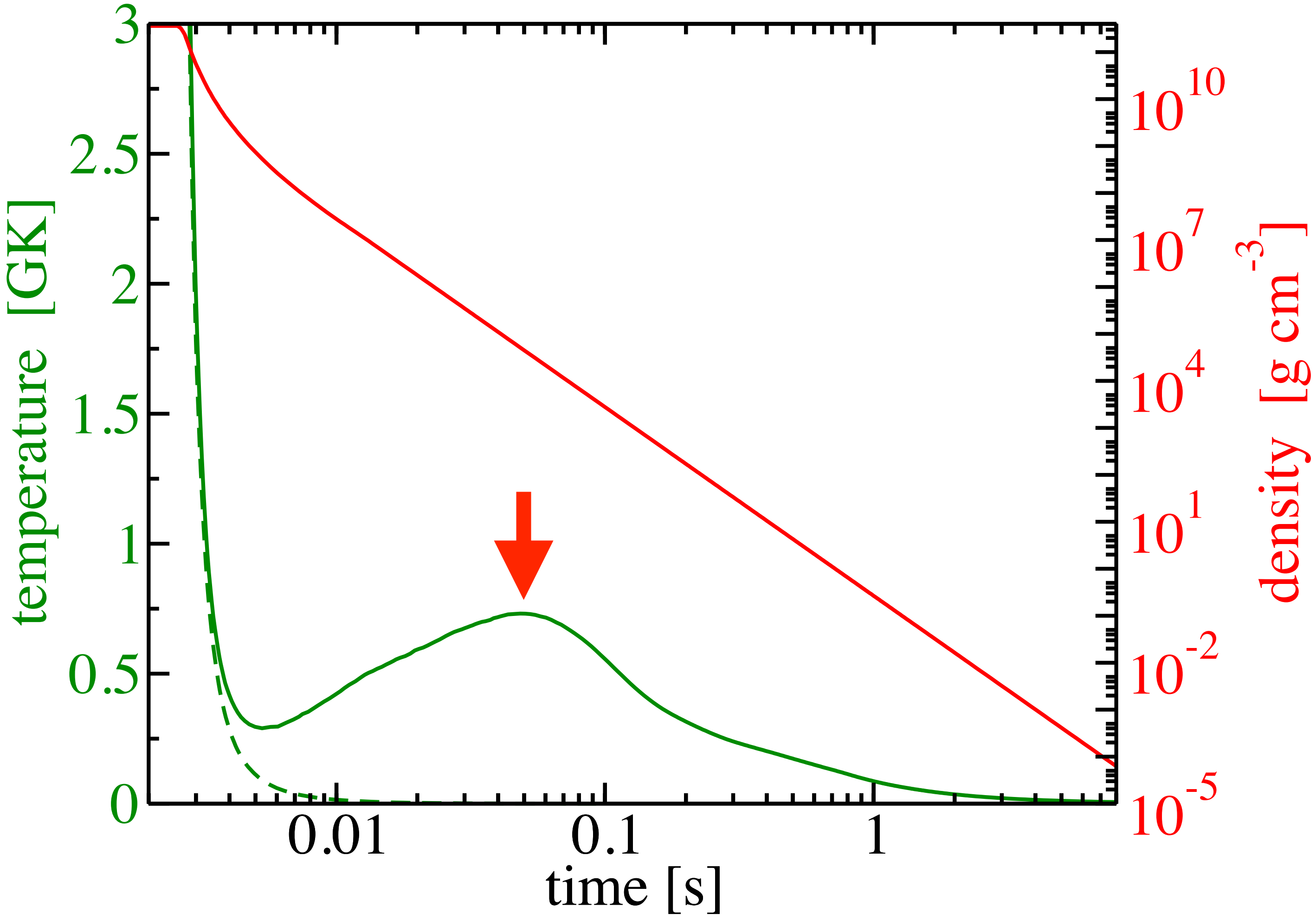
Chemical history of our galaxy

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



Open questions: amount of mass ejected
event rate

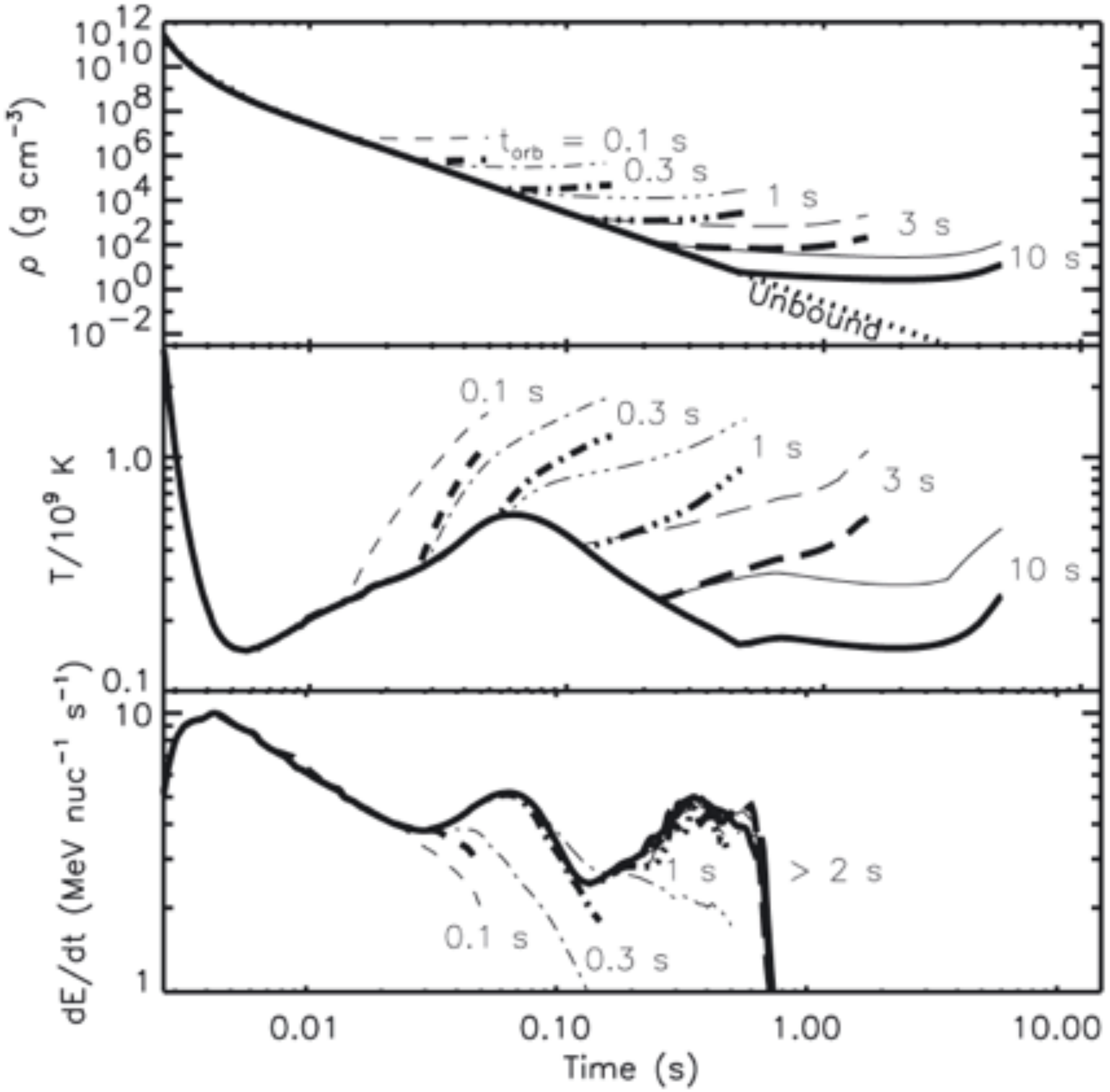
r-process heating



Freiburghaus, Rosswog, Thielemann 1999

r-process heating: effect on fall-back accretion

Metzger, Arcones, Quataert, Martinez-Pinedo 2010



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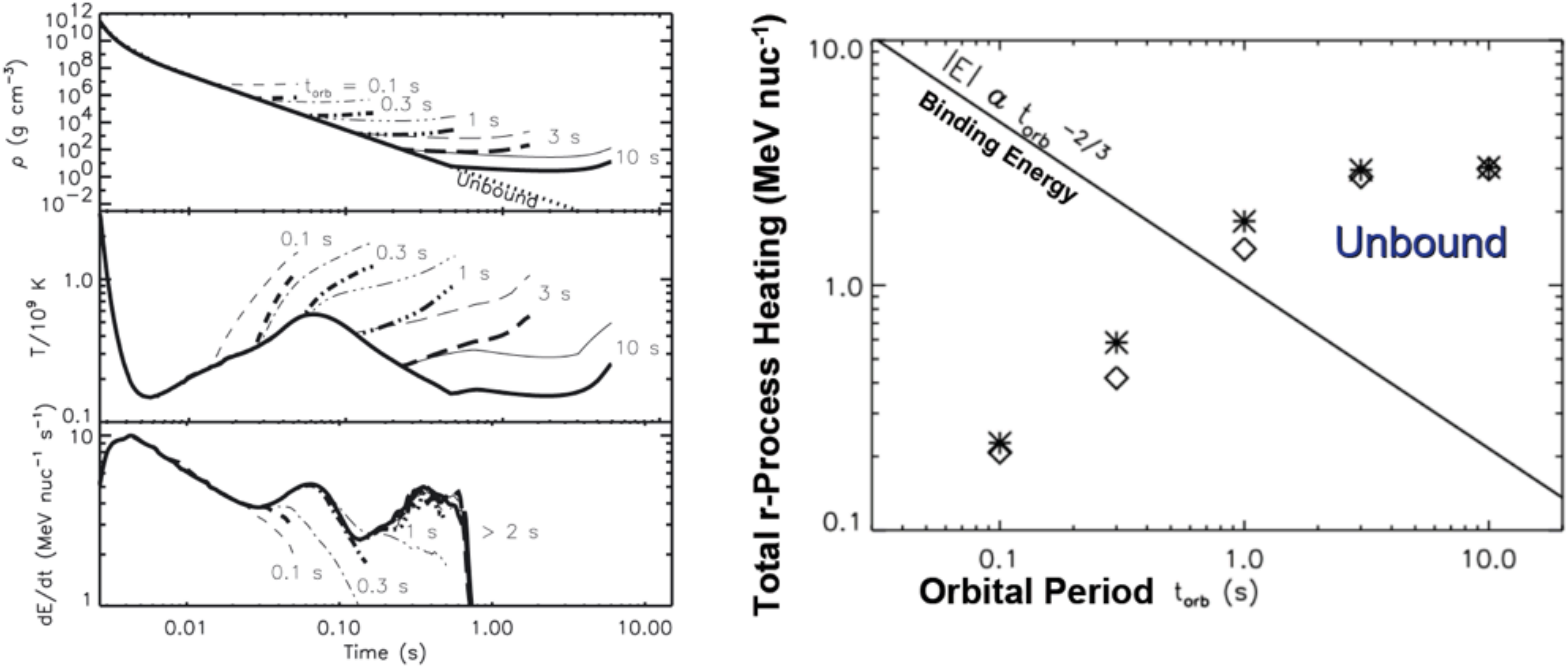

Binding energy of merger ejecta

$$|E| = \frac{GMm_n}{2a} \simeq 1.0 \left(\frac{M}{3M_\odot}\right)^{2/3} \left(\frac{t_{orb}}{1\,s}\right)^{-2/3} \frac{\text{MeV}}{\text{nucleon}}$$

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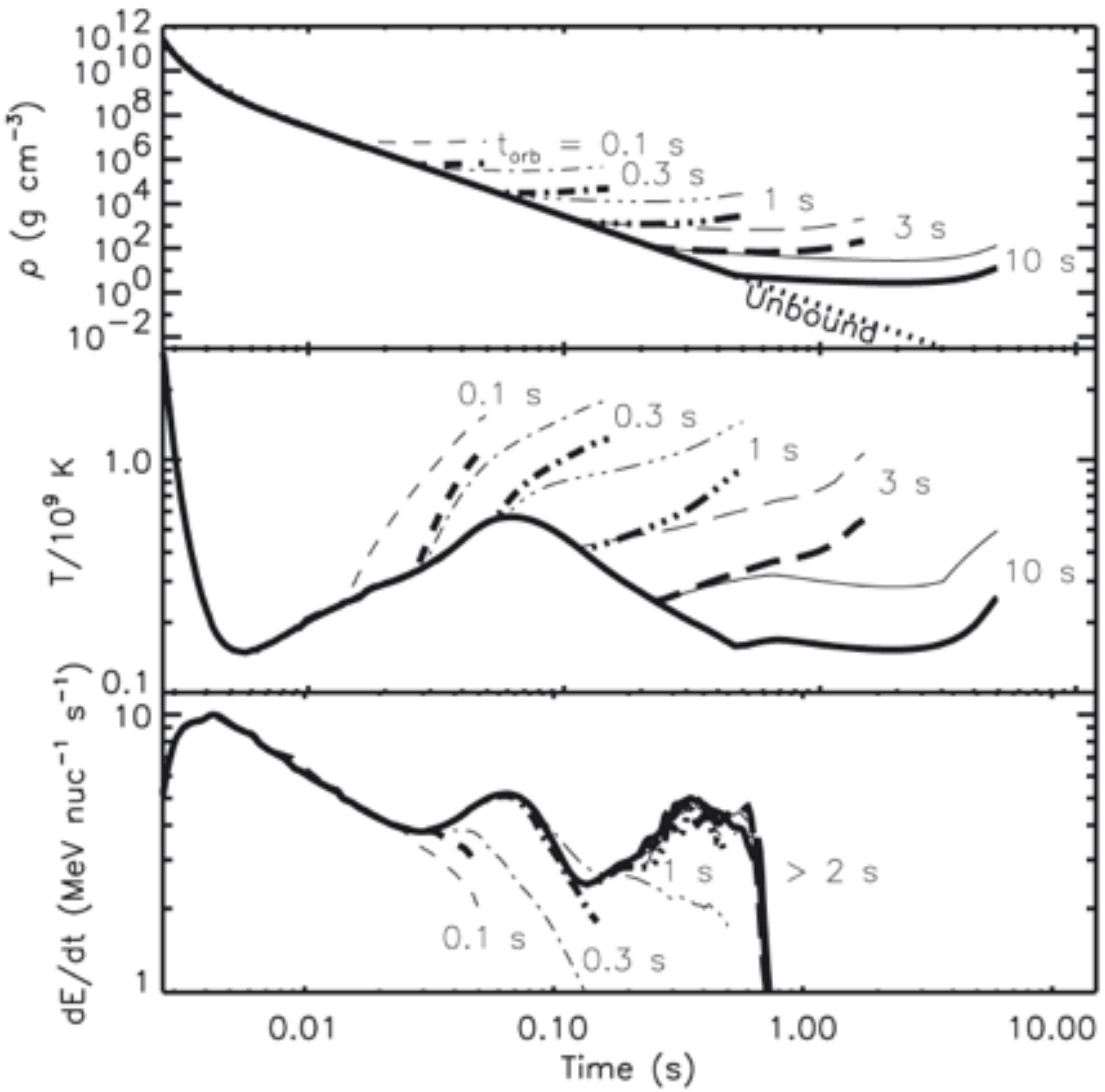

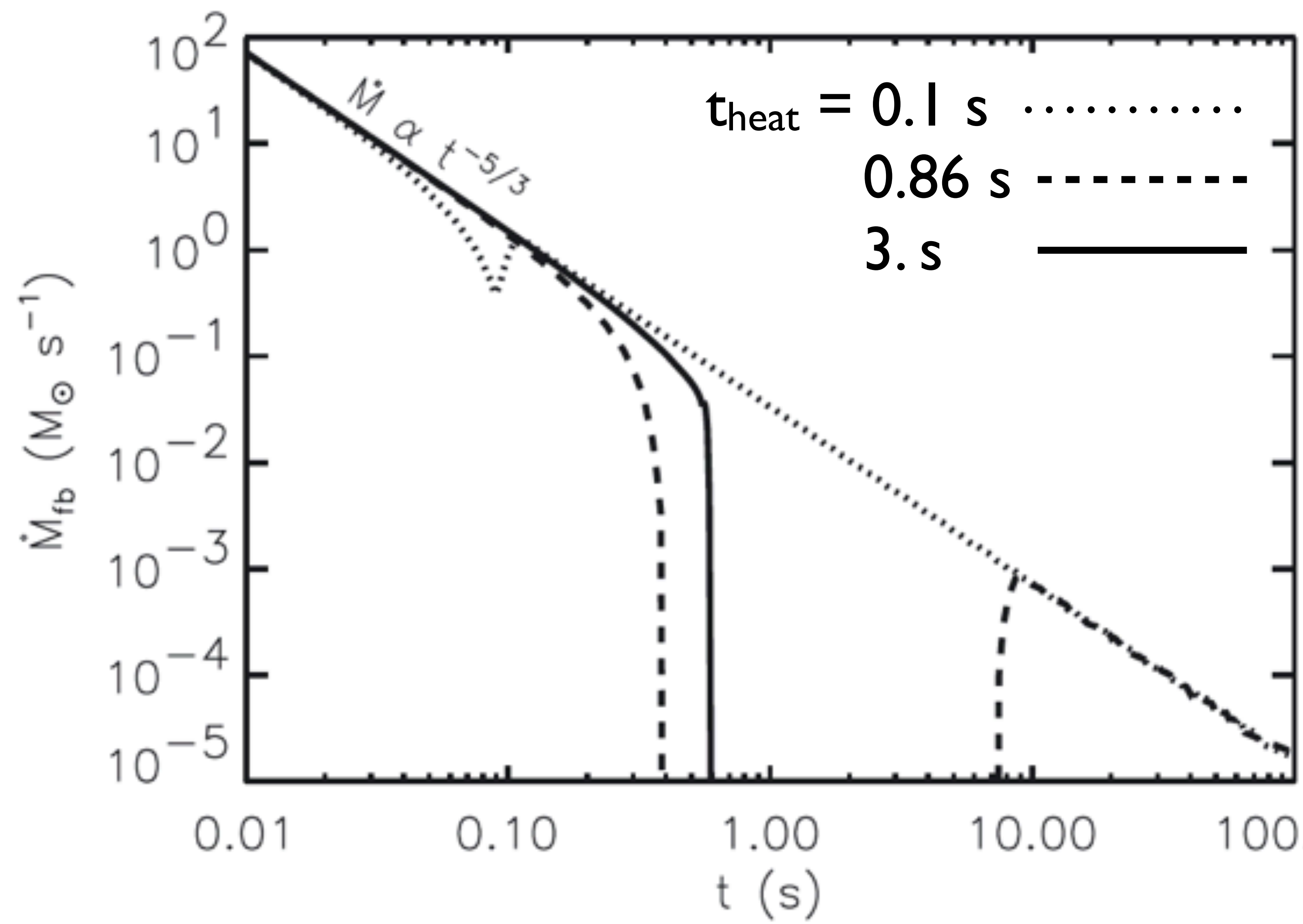

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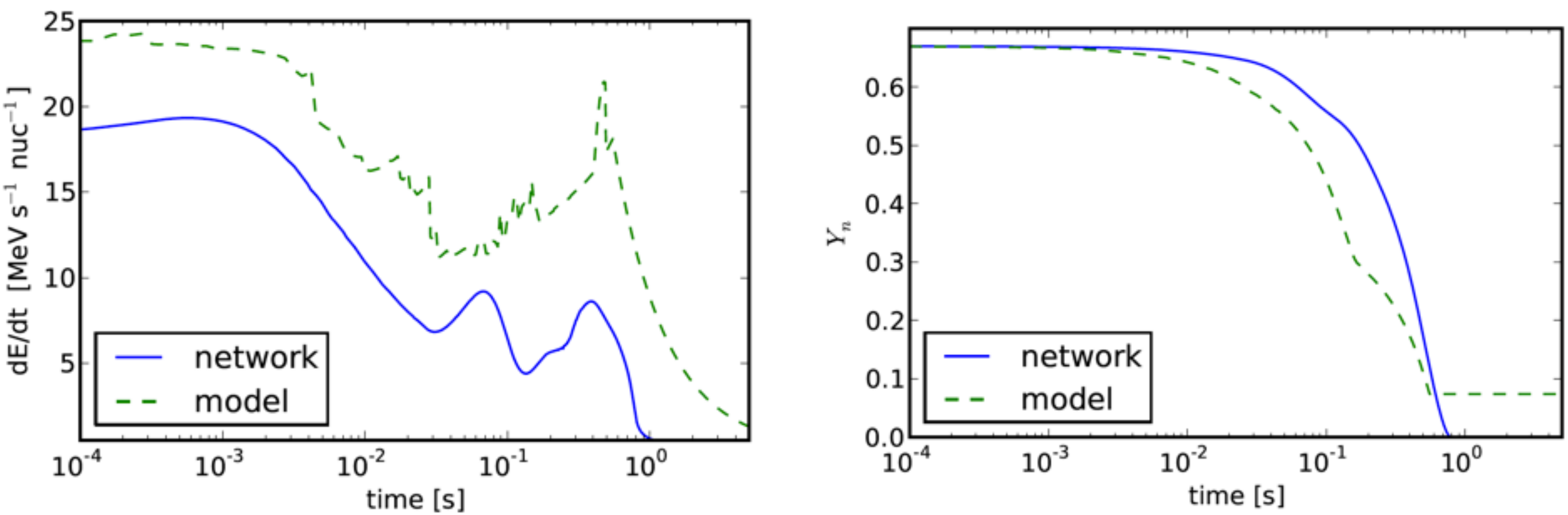
r-process heating model

to account for the r-process energy generation in merger simulations

assumptions: (n,γ)-(γ,n) equilibrium
energy from beta decay

input: T, N_n, $\langle Z \rangle$

output: $\dot{E}$, $\dot{Y}_n$, $\langle \dot{Z} \rangle$



Arcones, Martinez-Pinedo, Thielemann, in prep.

r-process: direct observation

(Metzger et al. 2010)

PHYSICAL REVIEW VOLUME 103, NUMBER 5 SEPTEMBER 1, 1956

Californium-254 and Supernovae*

G. R. Burbidge and F. Hoyle,† *Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California*

AND

E. M. Burbidge, R. F. Christy, and W. A. Fowler, *Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California*

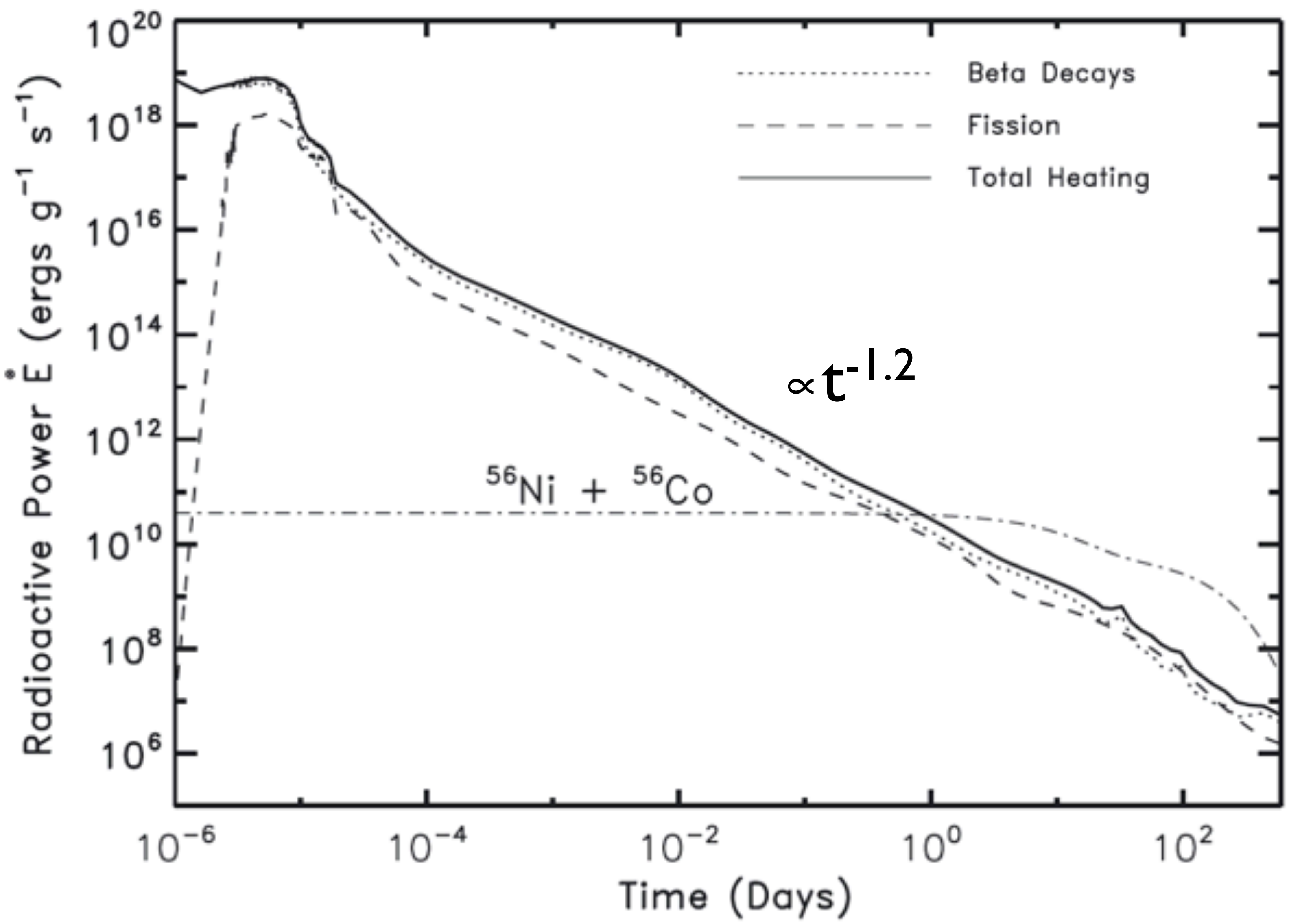
(Received May 17, 1956)

It is suggested that the spontaneous fission of Cf^{254} with a half-life of 55 days is responsible for the form of the decay light-curves of supernovae of Type I which have an exponential form with a half-life of 55 nights. The way in which Cf^{254} may be synthesized in a supernova outburst, and reasons why the energy

r-process: direct observation

(Metzger et al. 2010)

Radioactive heating of NS merger ejecta

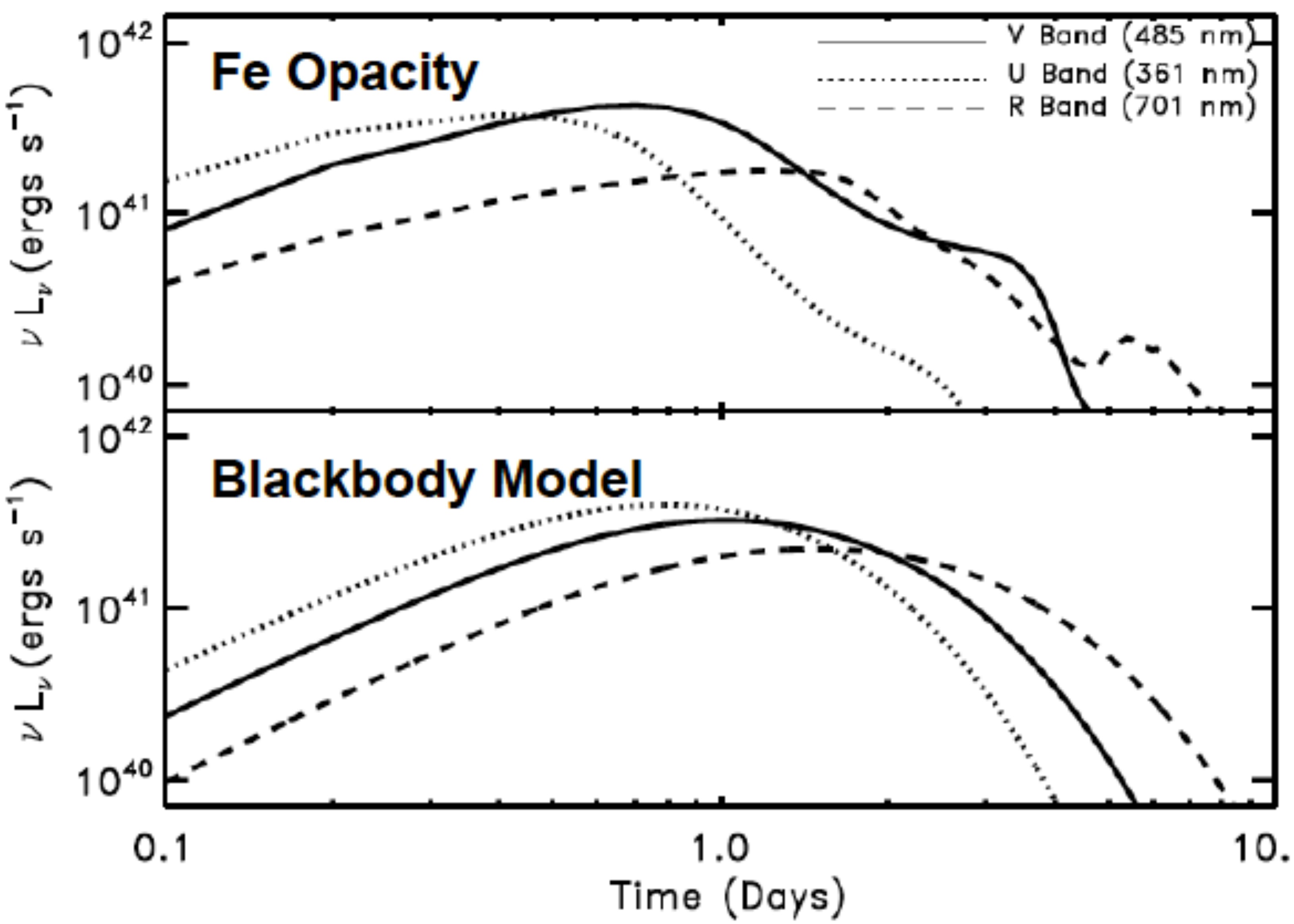


Electromagnetic counterparts of NS-NS/NS-BH mergers

Thermal transient (Li & Paczynski) powered by radioactive ejecta

r-process: direct observation
(Metzger et al. 2010)

Light curves



SEDONA, Kasen et al. 2006

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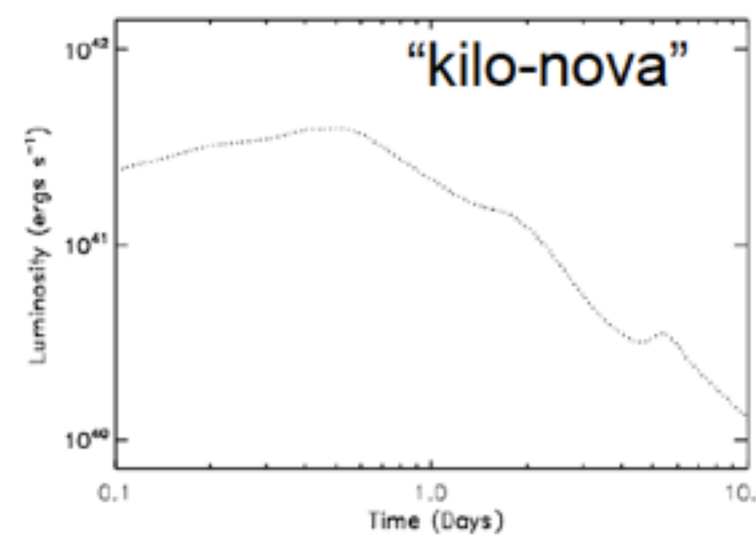
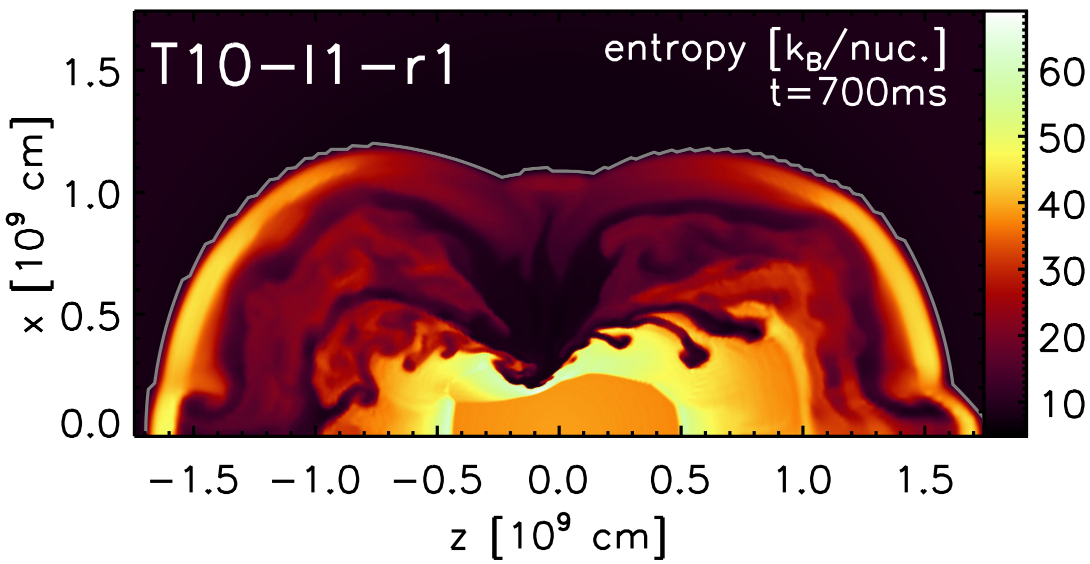


see also Roberts et al. 2011

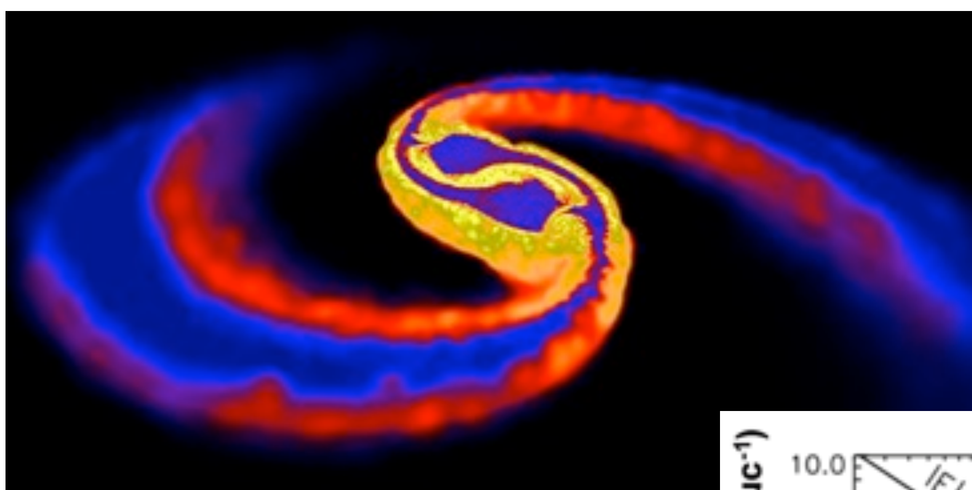
Conclusions

The r-process is a source of new elements, energy and transients



Neutrino-driven winds:

- no r-process
- lighter heavy elements (Sr,Y,Zr)
- nucleosynthesis depends on Y_e



Neutron-star mergers:

- heavy r-process elements
- energy generation affects fall-back dynamics
- thermal transient powered by radioactive ejecta