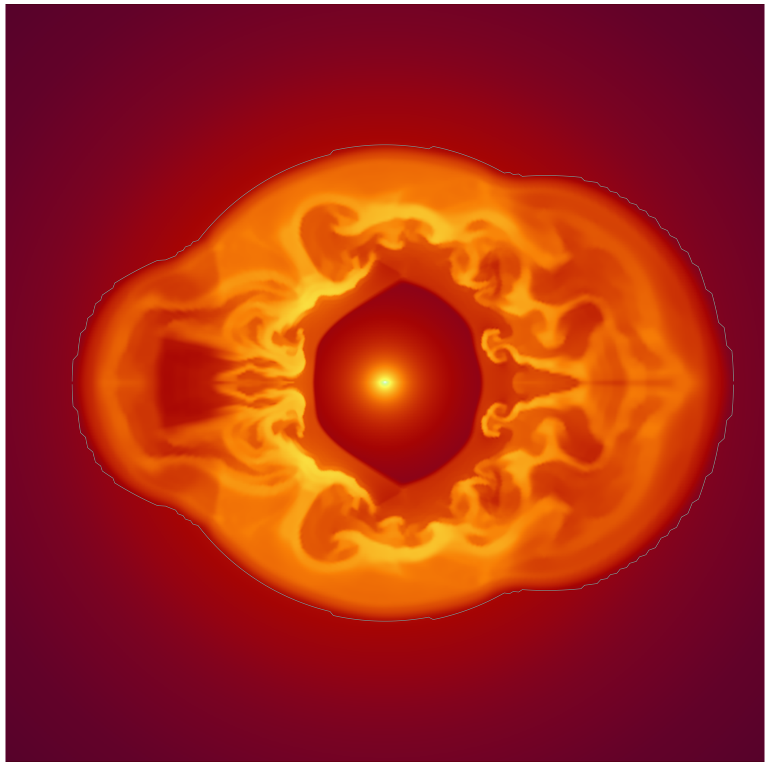
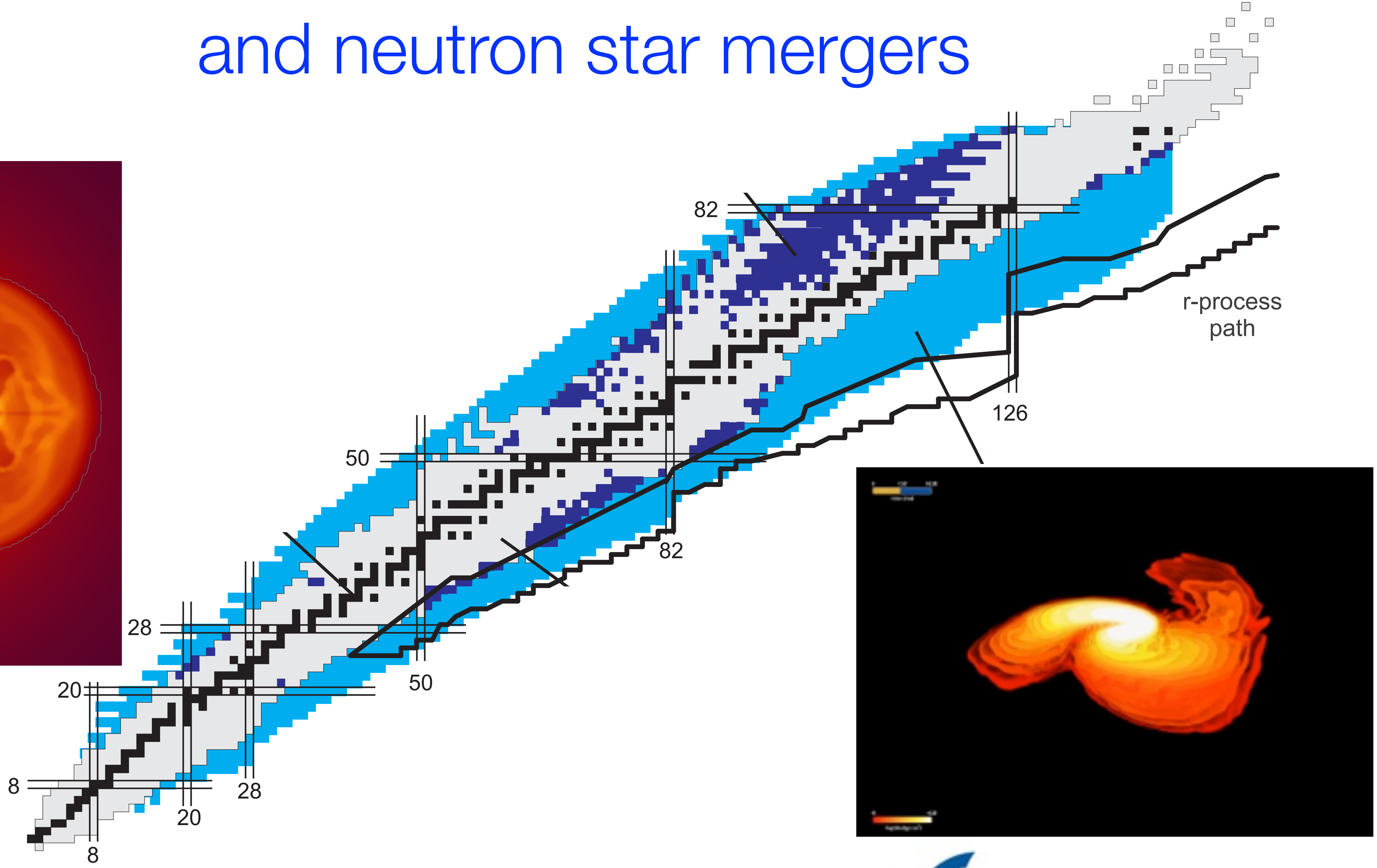
Neutrinos and Dark Matter in Nuclear Physics 2015
NDM '15

# Heavy element nucleosynthesis in core-collapse supernovae and neutron star mergers





TECHNISCHE
UNIVERSITÄT
DARMSTADT

GSI

Almudena Arcones
Helmholtz Young Investigator Group

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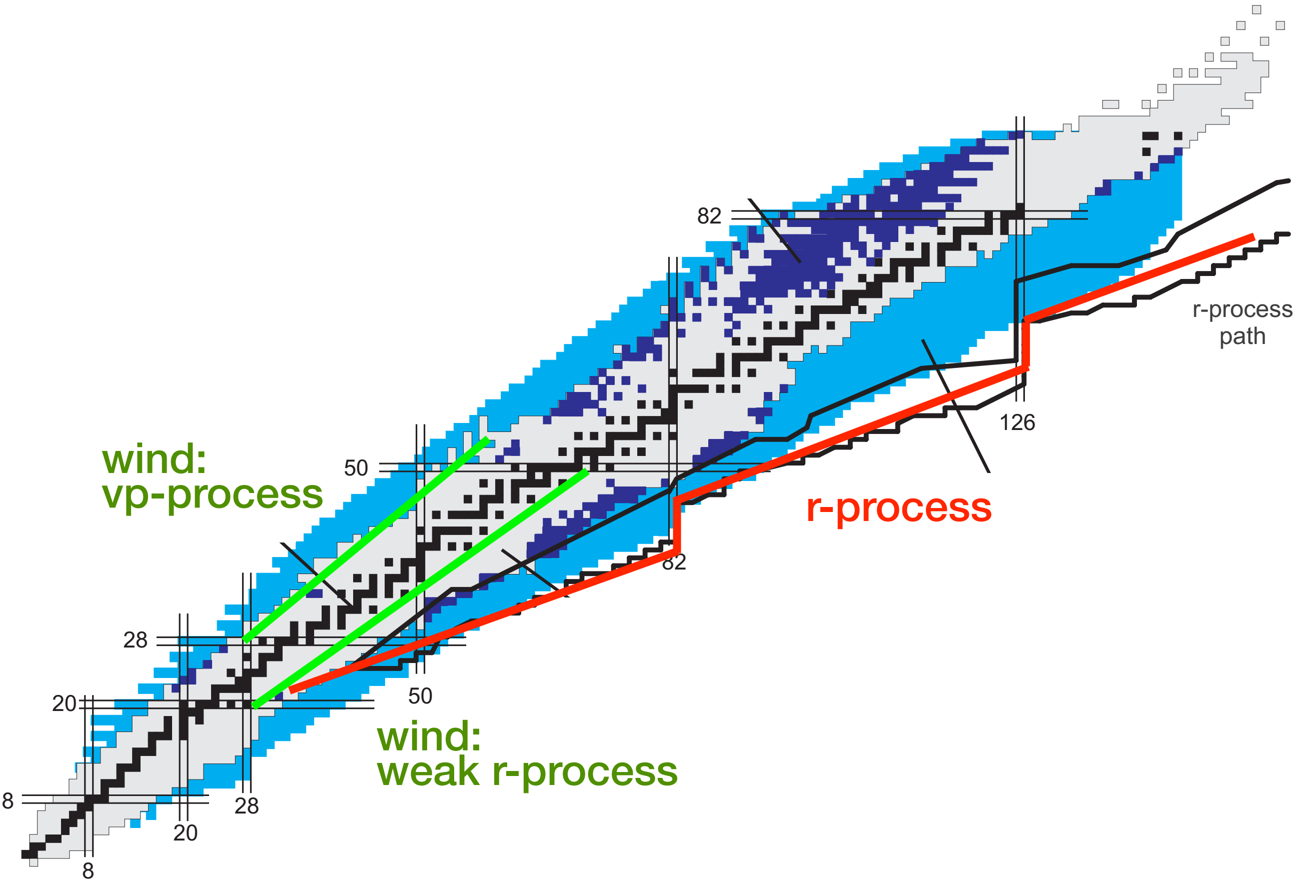
# Nucleosynthesis of heavy elements

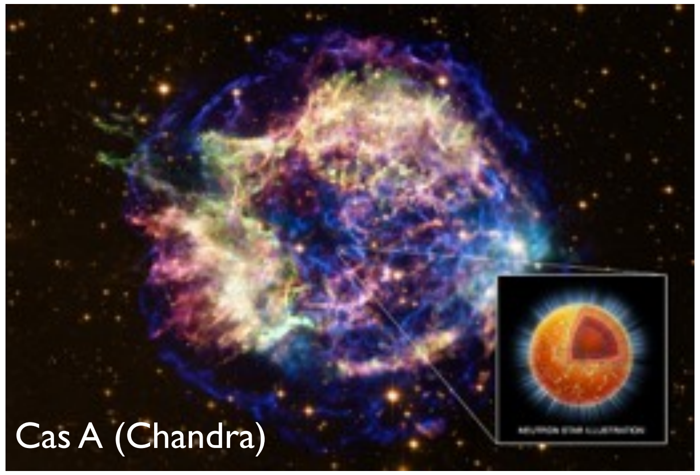


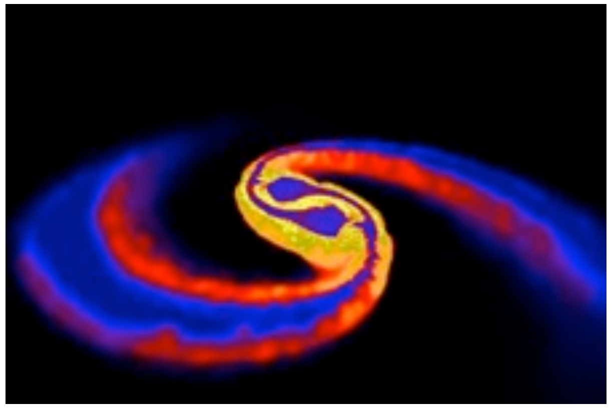
**Core-collapse supernovae:**

explosive: up to Fe

wind: up to ~Ag

jets: r-process





**Neutron star mergers:**

r-process

weak r-process

Nucleosynthesis based on simulations

Uncertainties from
astrophysics and nuclear physics

Long-time hydrodynamic simulations
nucleosynthesis relevant conditions

**Compare to observations and chemical evolution**

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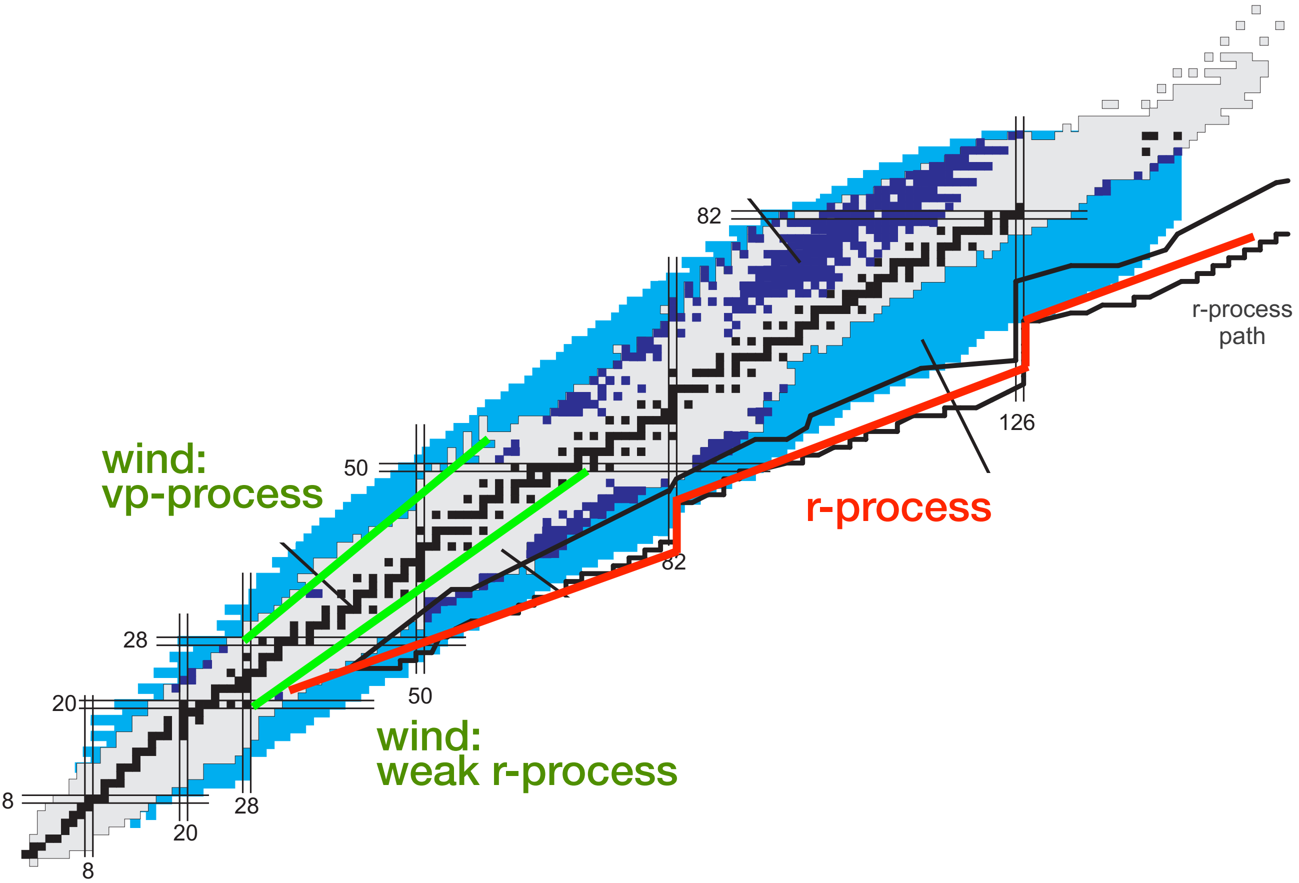

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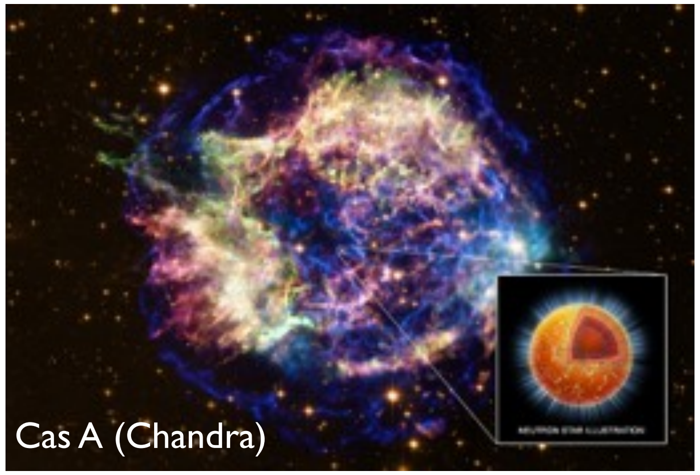

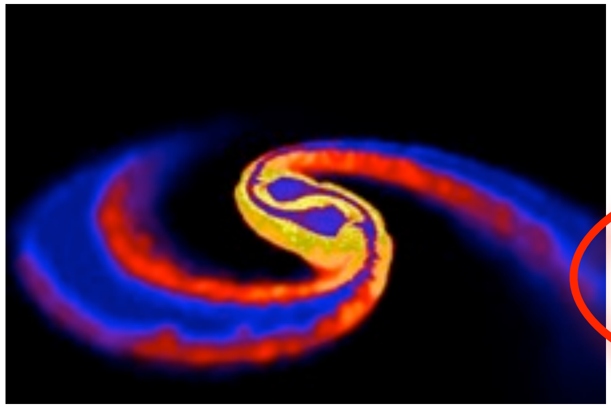

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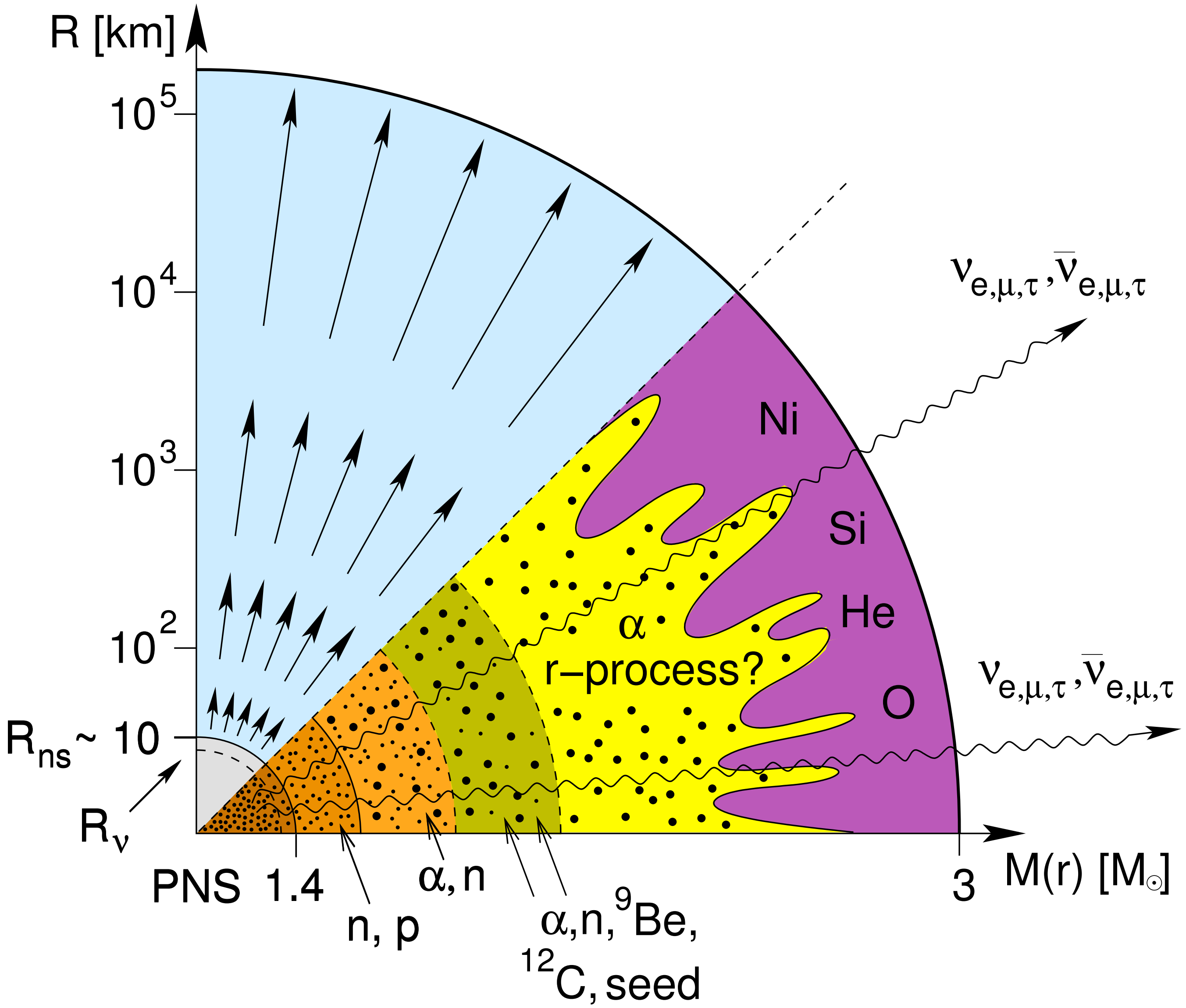
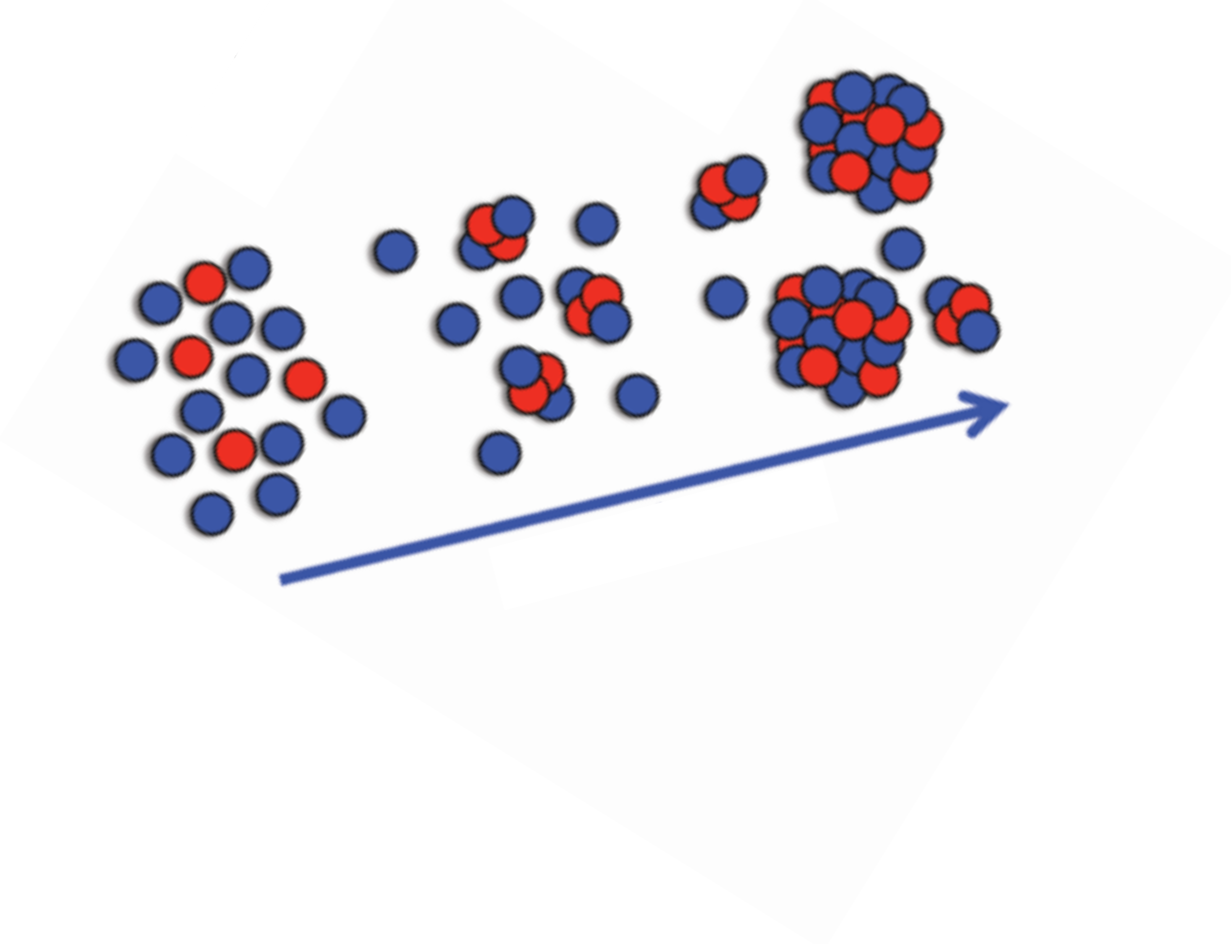
# Neutrino-driven winds



neutrons and protons form α-particles
α-particles recombine into seed nuclei



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

T = 10 - 8 GK 8 - 2 GK

weak r-process
vp-process

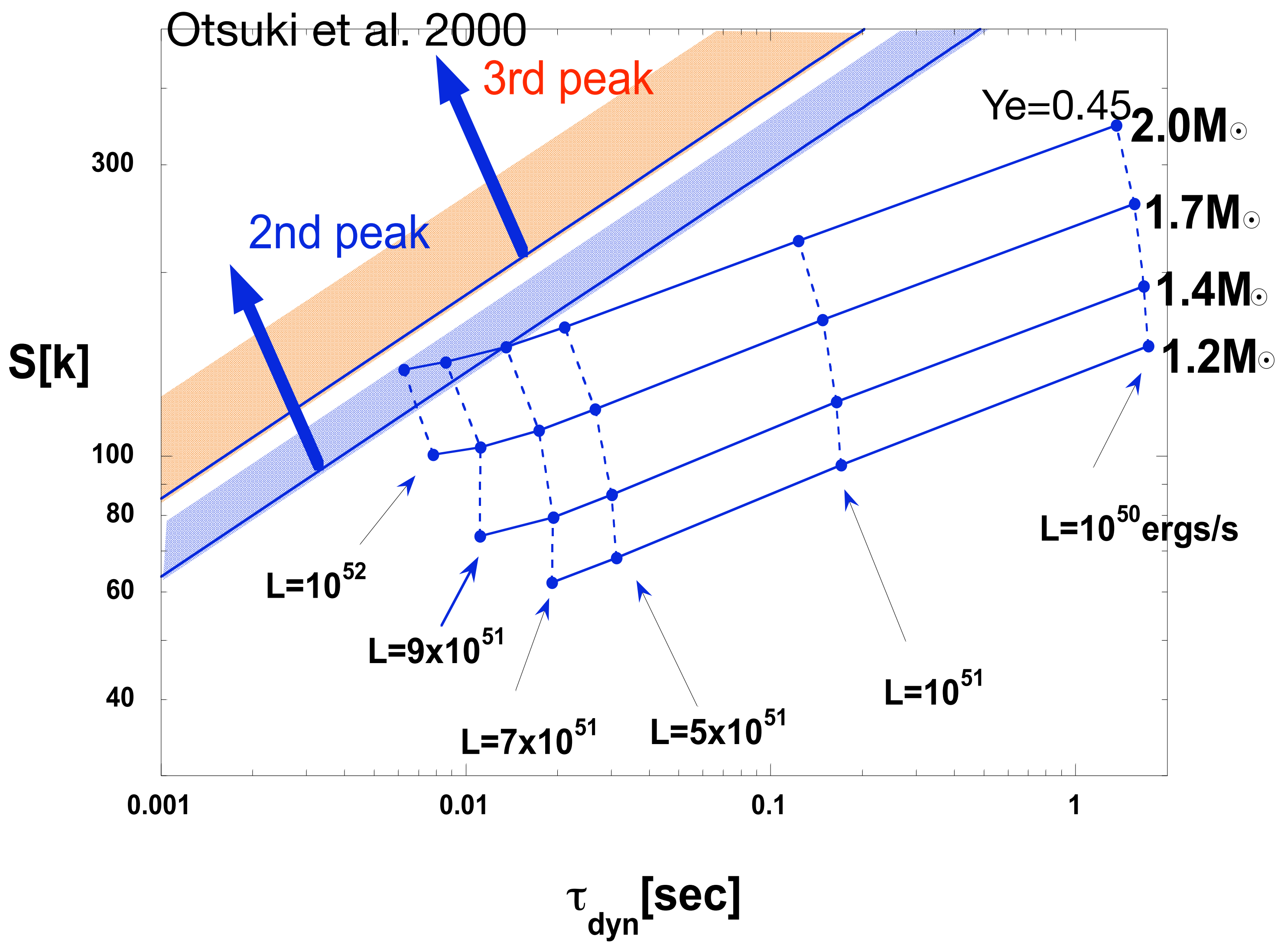
T < 3 GK

for a review see Arcones & Thielemann (2013)

# Neutrino-driven wind parameters

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

- Short expansion time scale: inhibit α-process and formation of seed nuclei
- High entropy: photons dissociate seed nuclei into nucleons
- Electron fraction: $Y_e<0.5$



Otsuki et al. 2000

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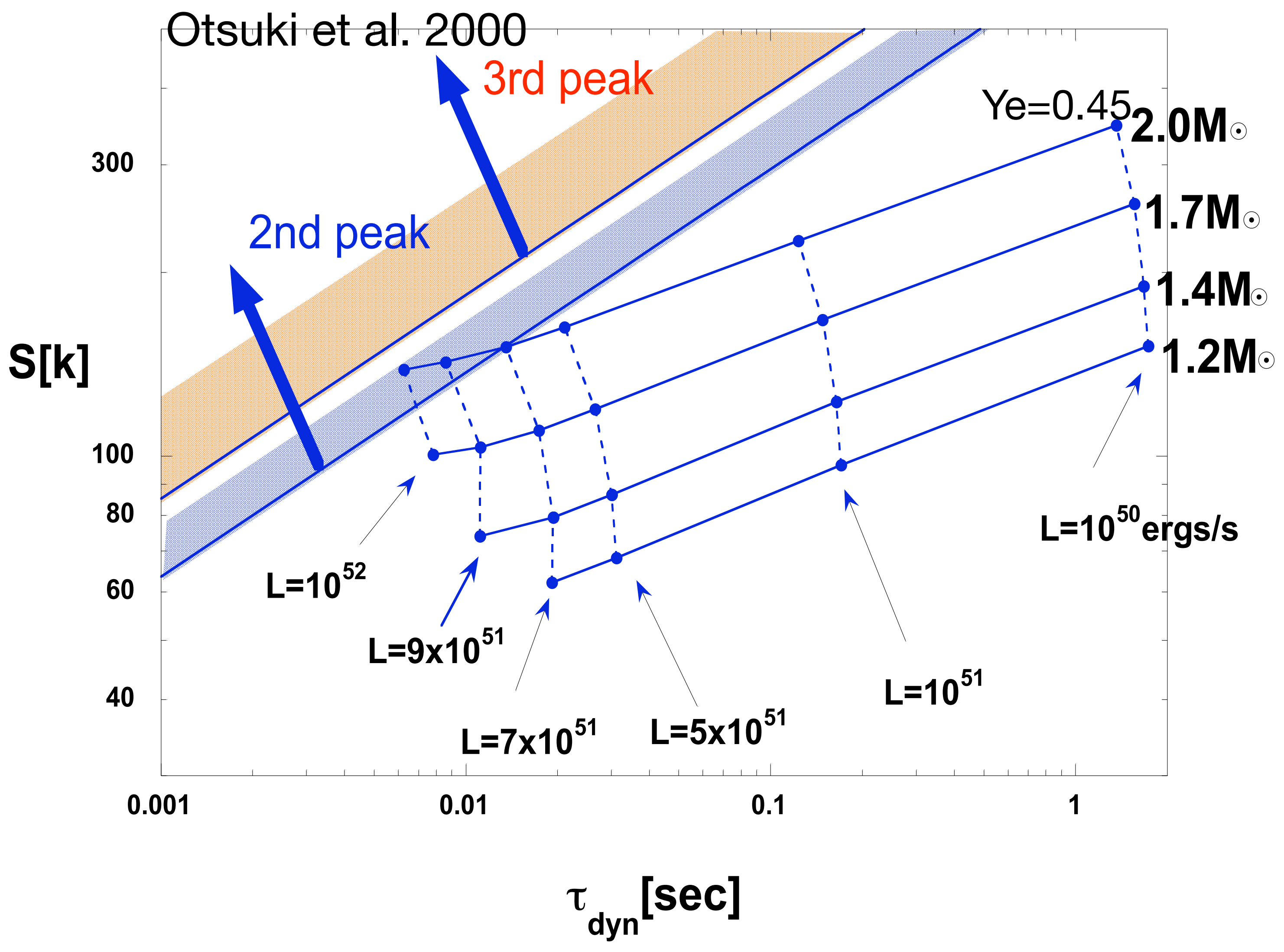


Otsuki et al. 2000

Conditions are not realized in hydrodynamic simulations

(Arcones et al. 2007, Fischer et al. 2010, Hüdepohl et al. 2010, Roberts et al. 2010, Arcones & Janka 2011, ...)

$S_{wind}$ = 50 - 120 $k_B$/nuc

τ = few ms

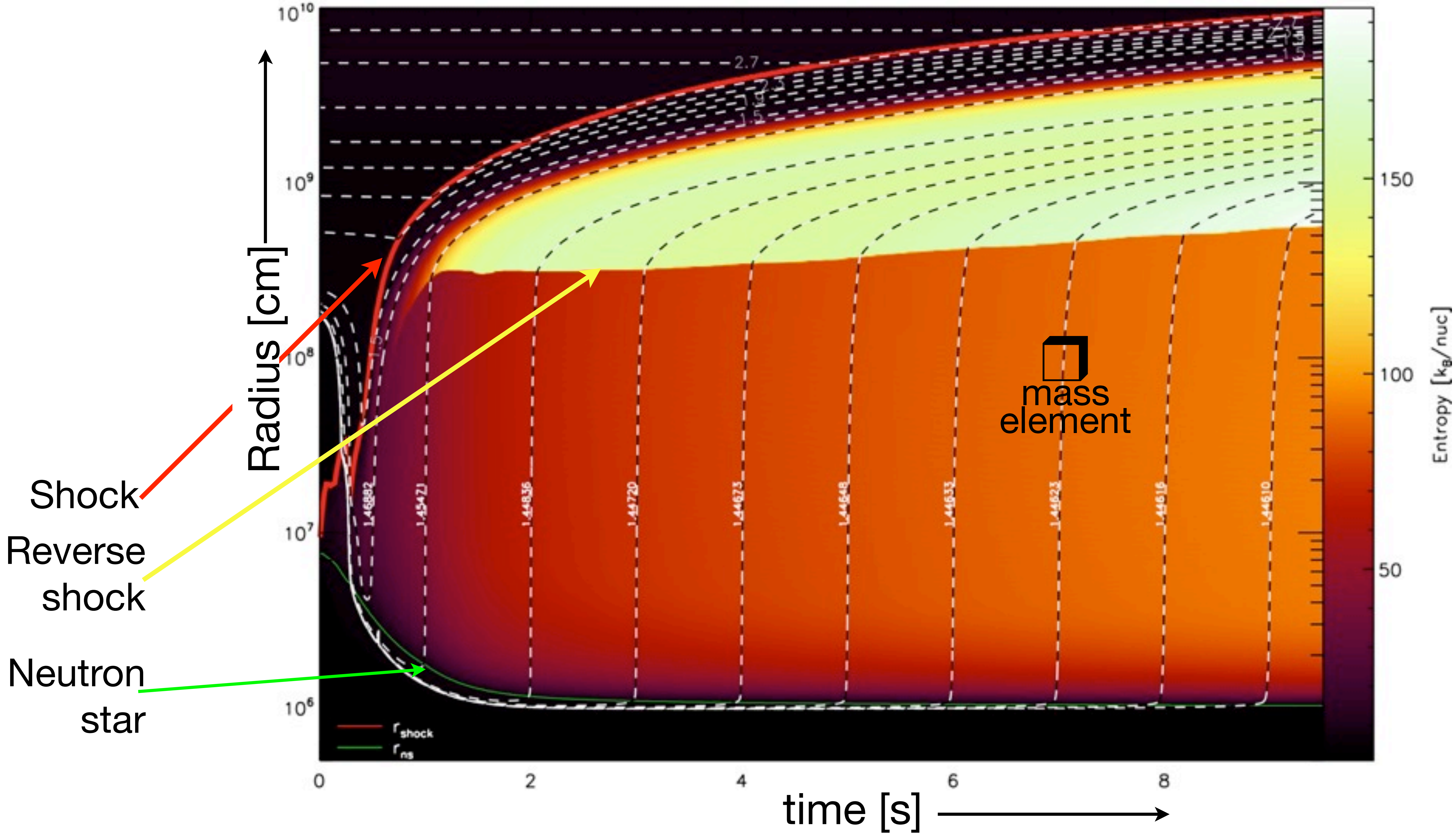
$Y_e$ ≈ 0.4 - 0.6?

Additional aspects:

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

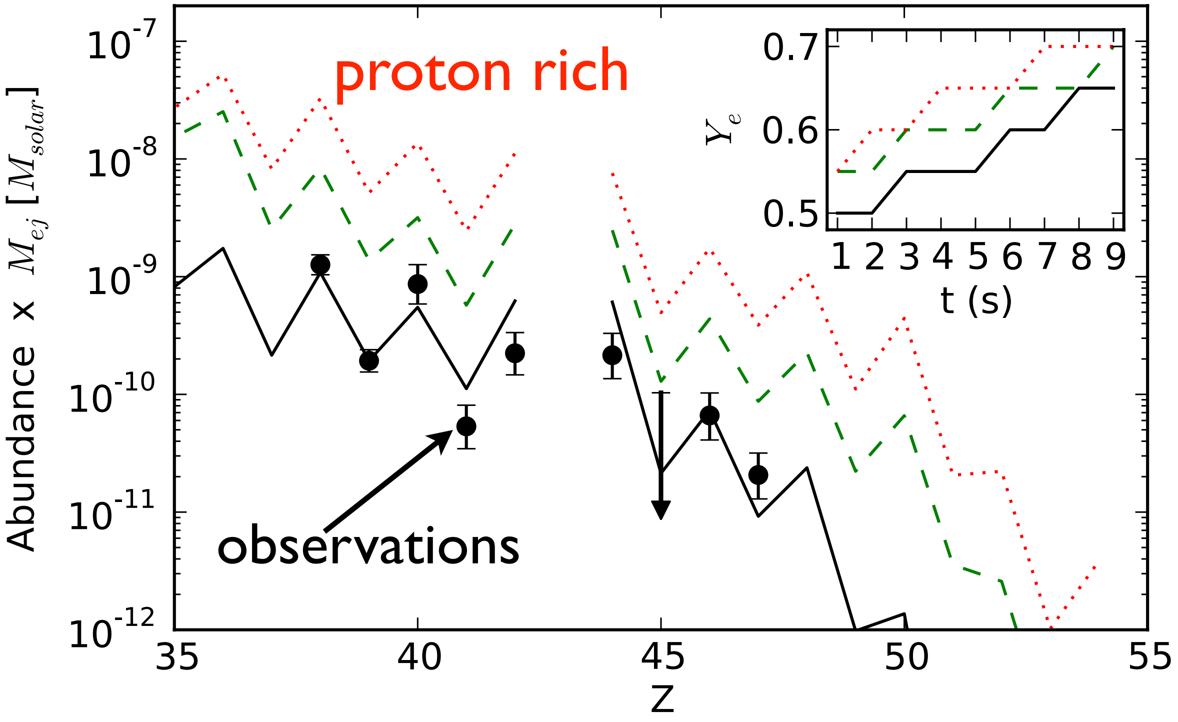
# Nucleosynthesis in neutrino winds

Arcones et al. 2007

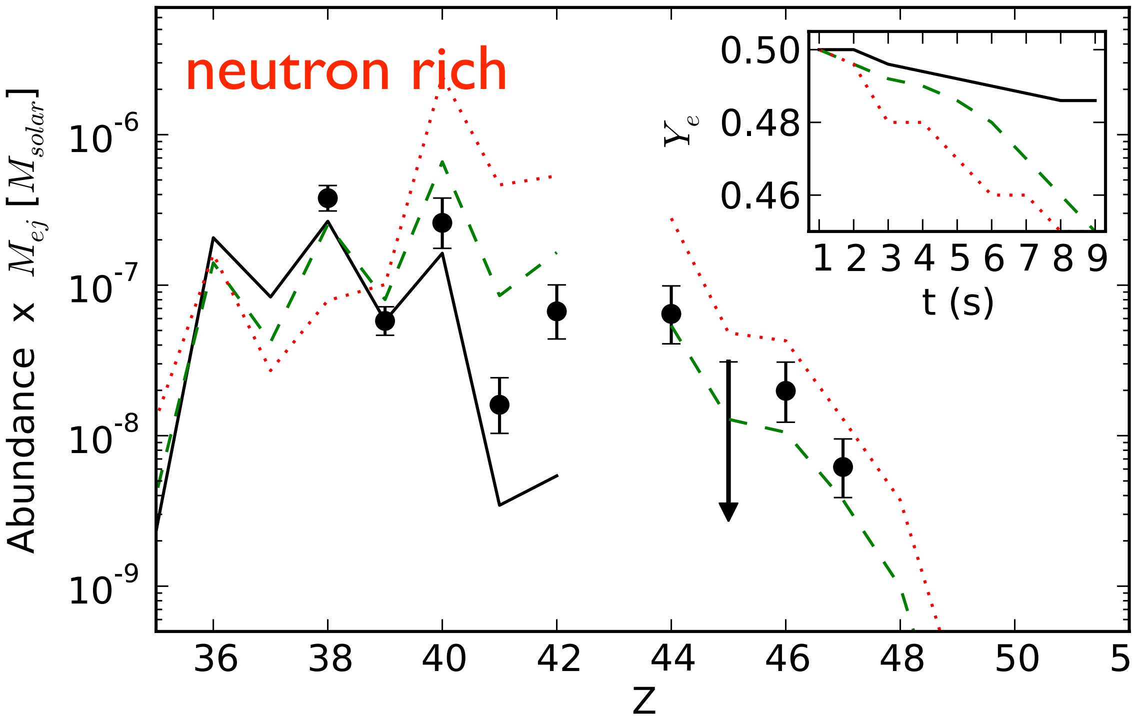


# Lighter heavy elements in neutrino-driven winds

vp-process



weak r-process



Observation pattern reproduced!

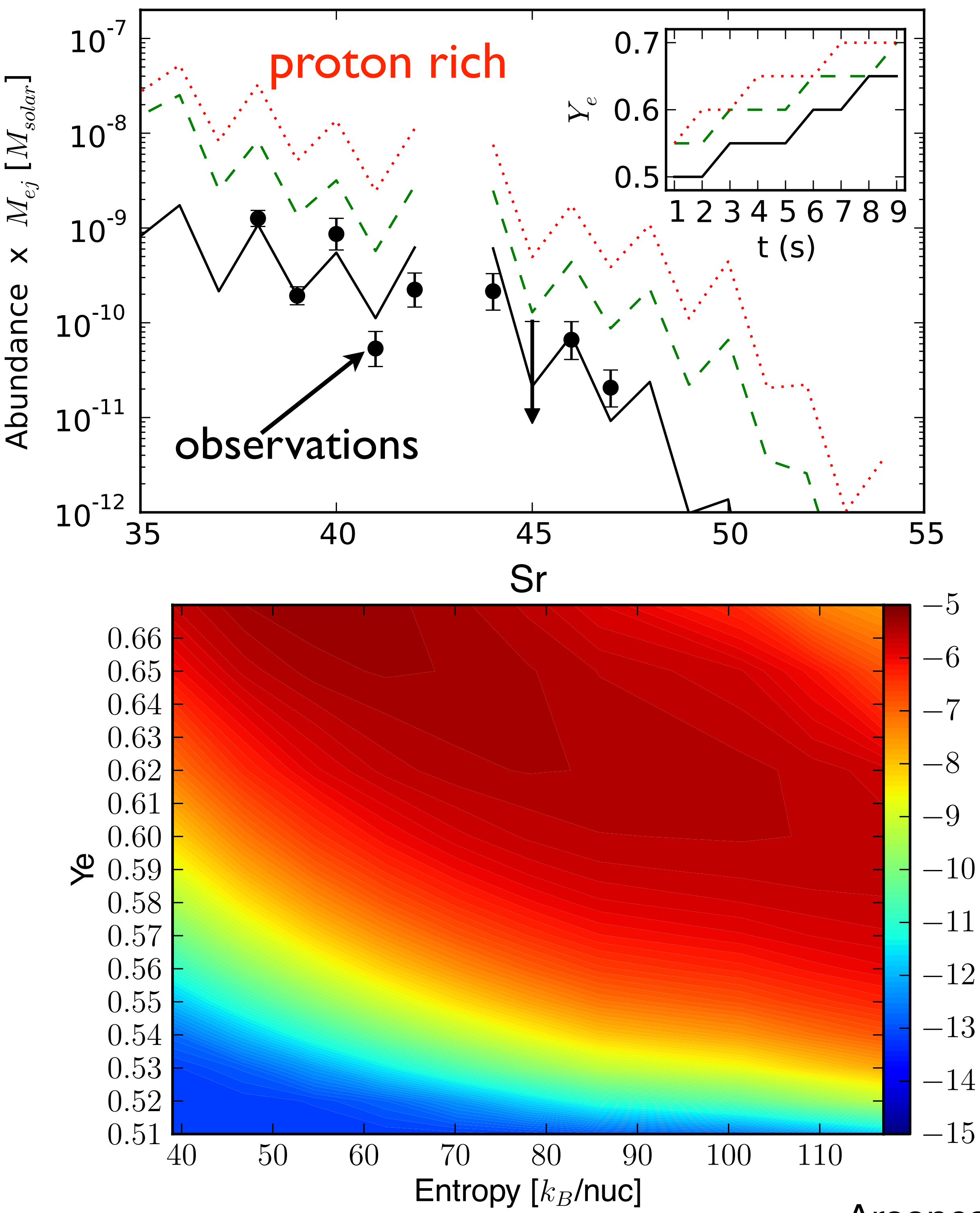
Production of p-nuclei

Overproduction at A=90, magic neutron number N=50 (Hoffman et al. 1996) suggests: only a fraction of neutron-rich ejecta (Wanajo et al. 2011)

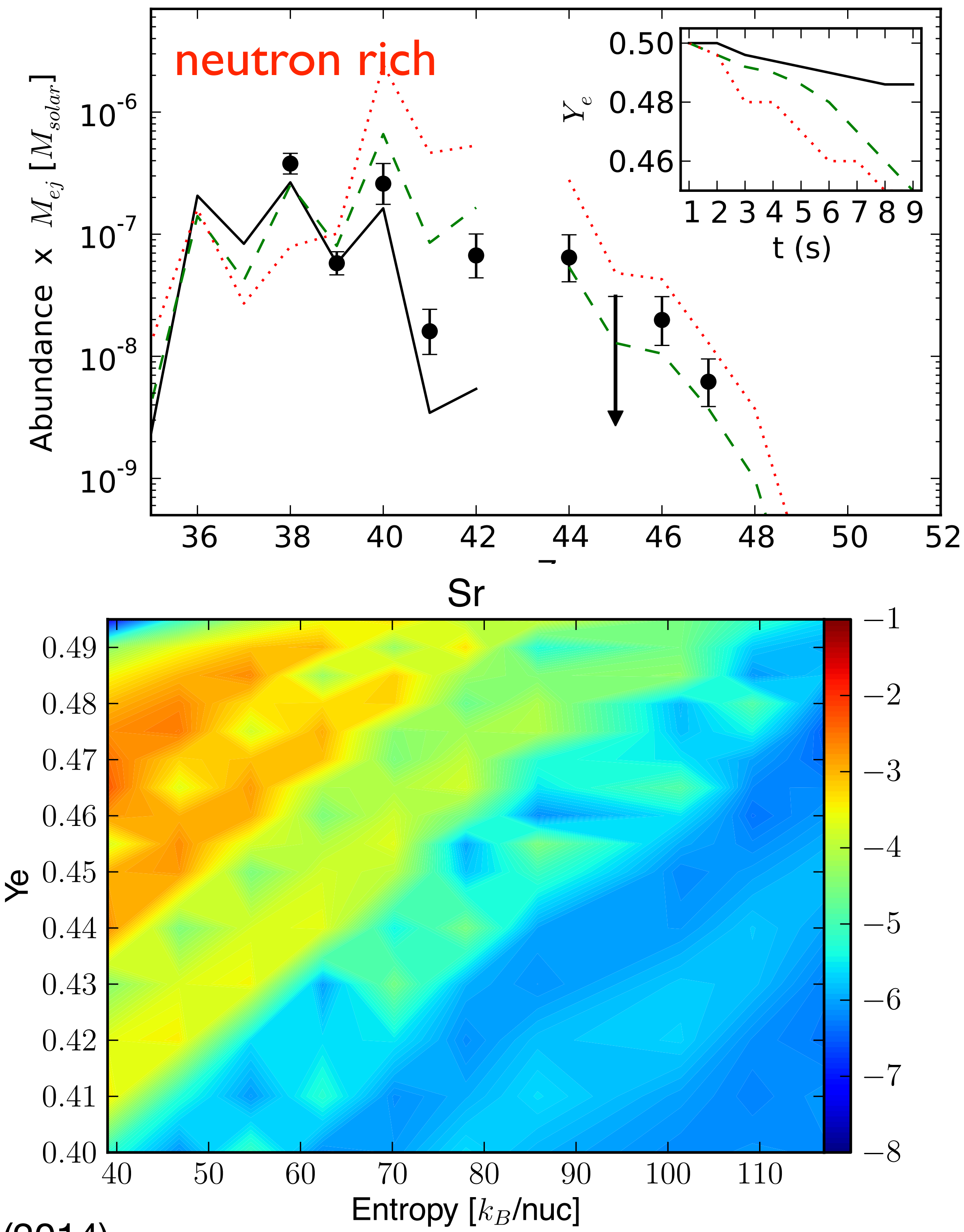
(Arcones & Montes, 2011, based on simulations Arcones et al. 2007)

# Lighter heavy elements in neutrino-driven winds

## vp-process



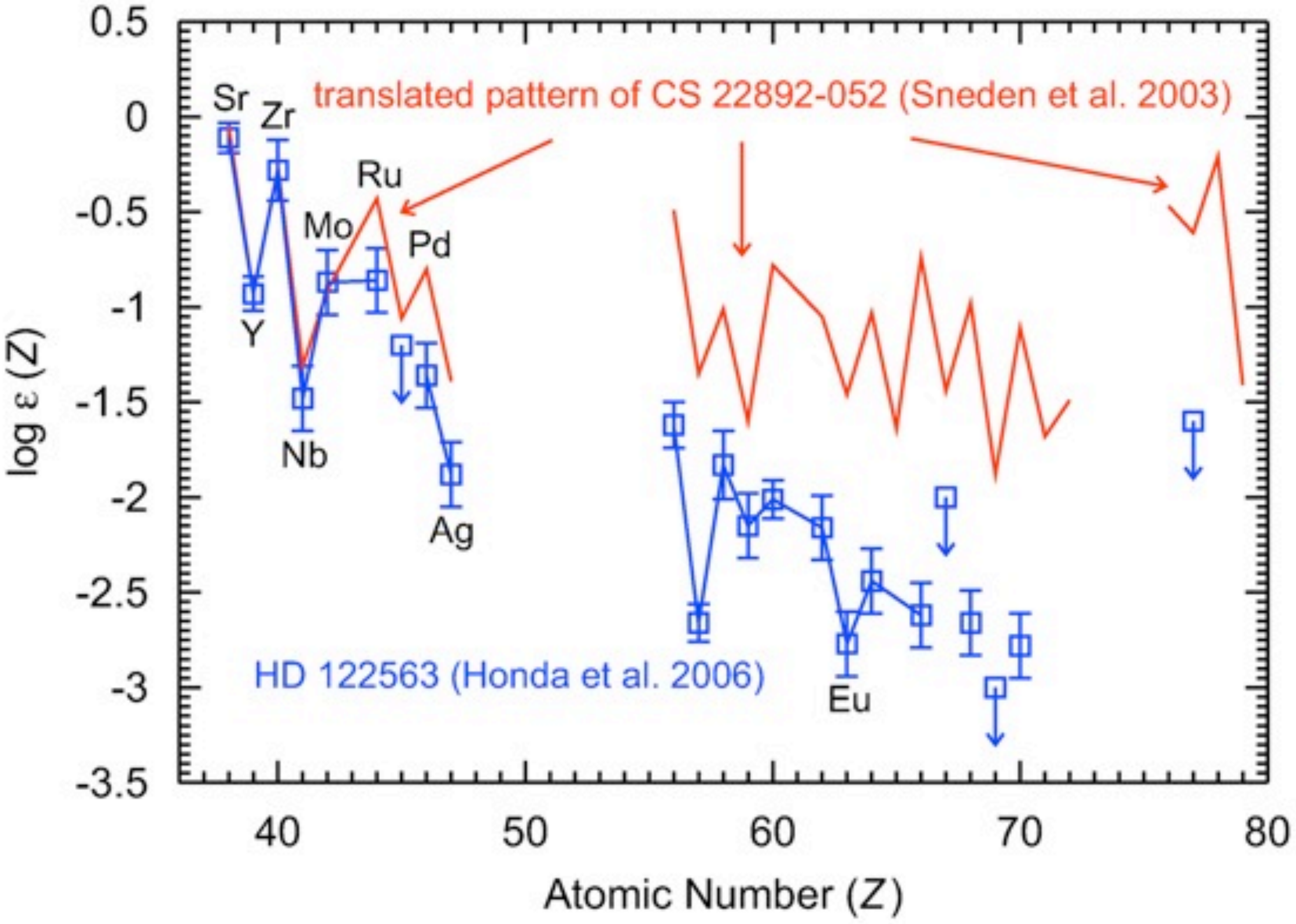
## weak r-process



Arcones & Bliss (2014)

# Lighter heavy elements: Sr - Ag

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



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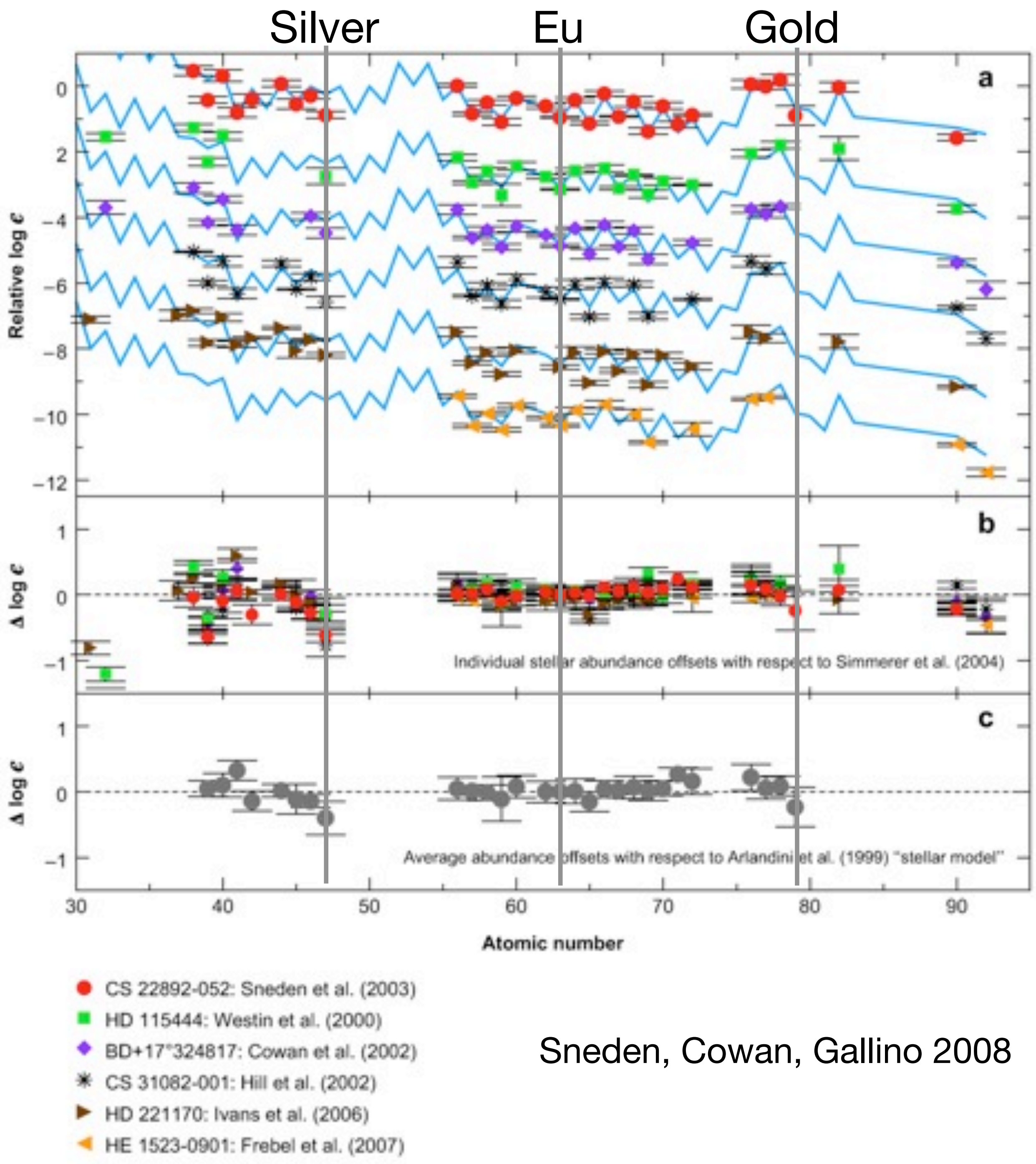
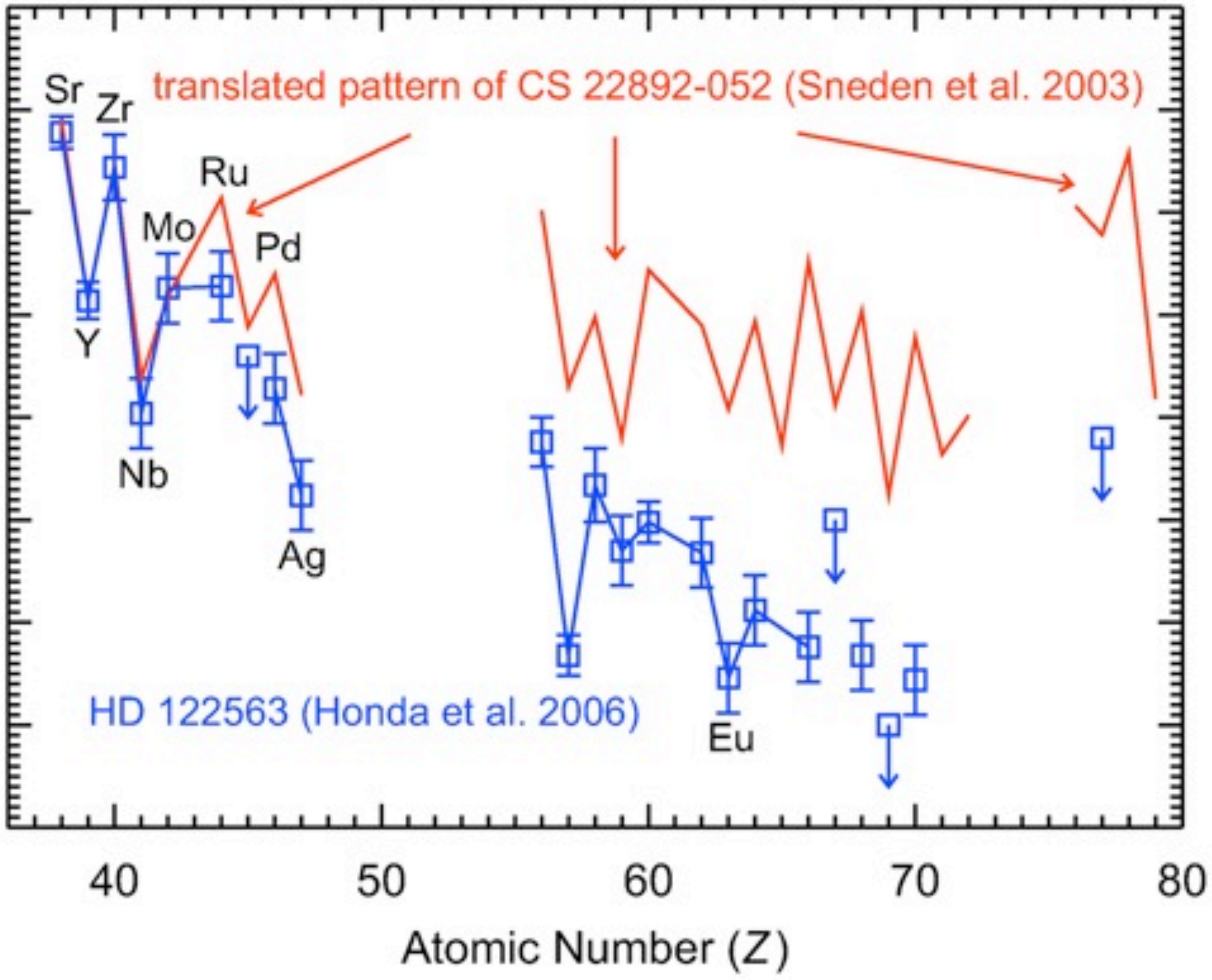


Sneden, Cowan, Gallino 2008



PP

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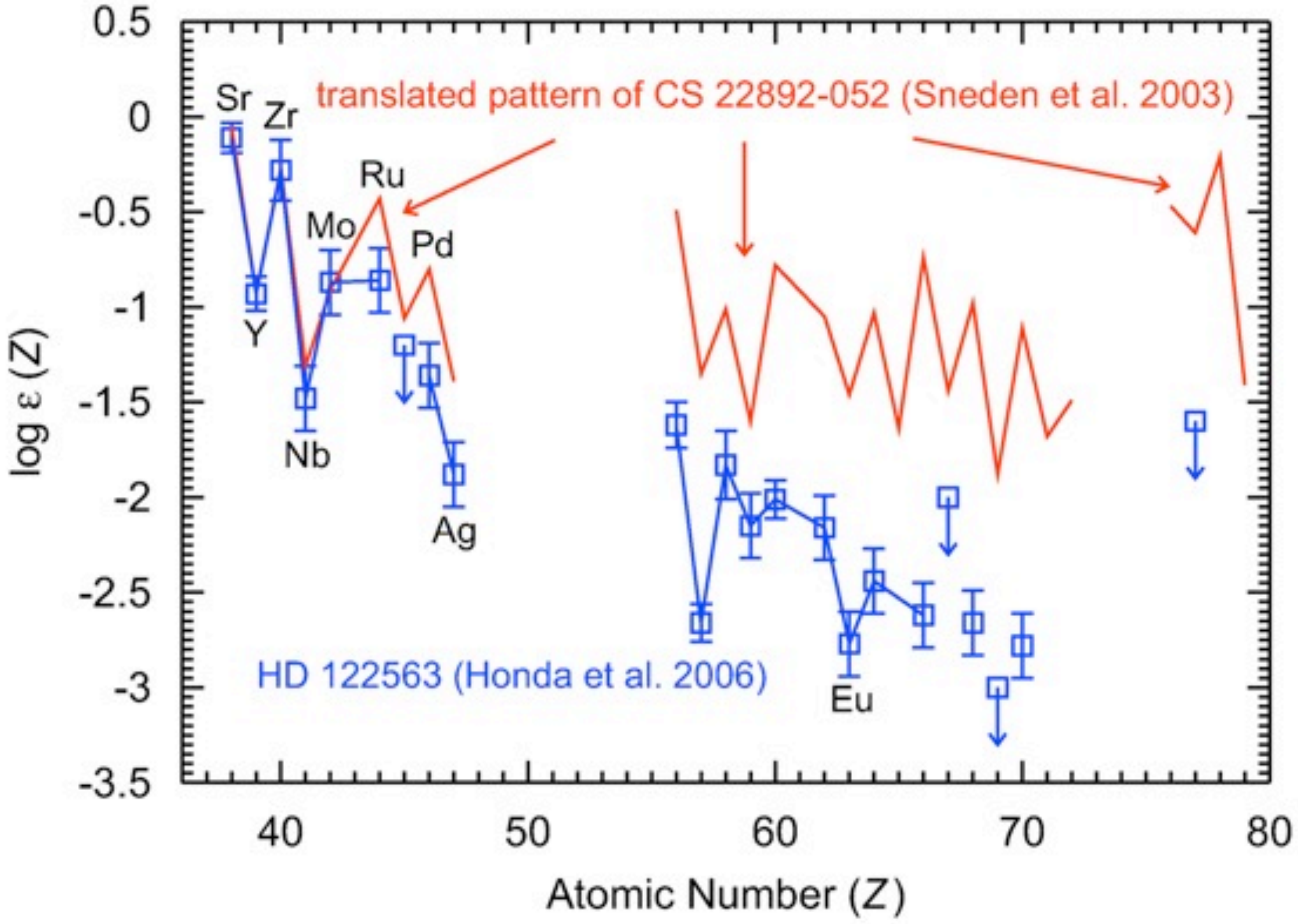

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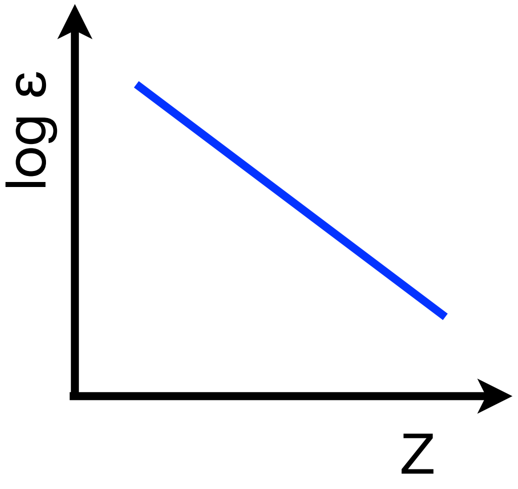
Are Honda-like stars the outcome of one nucleosynthesis event or the combination of several?



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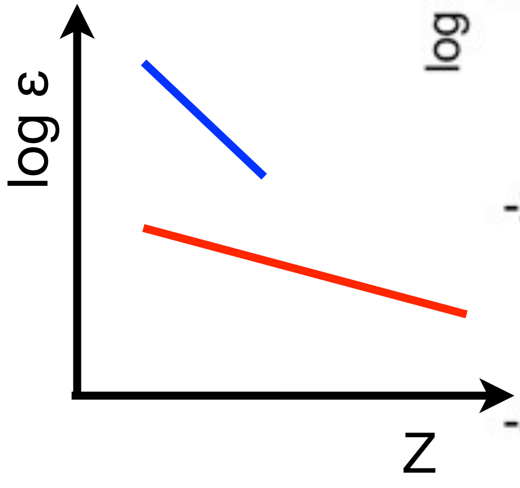

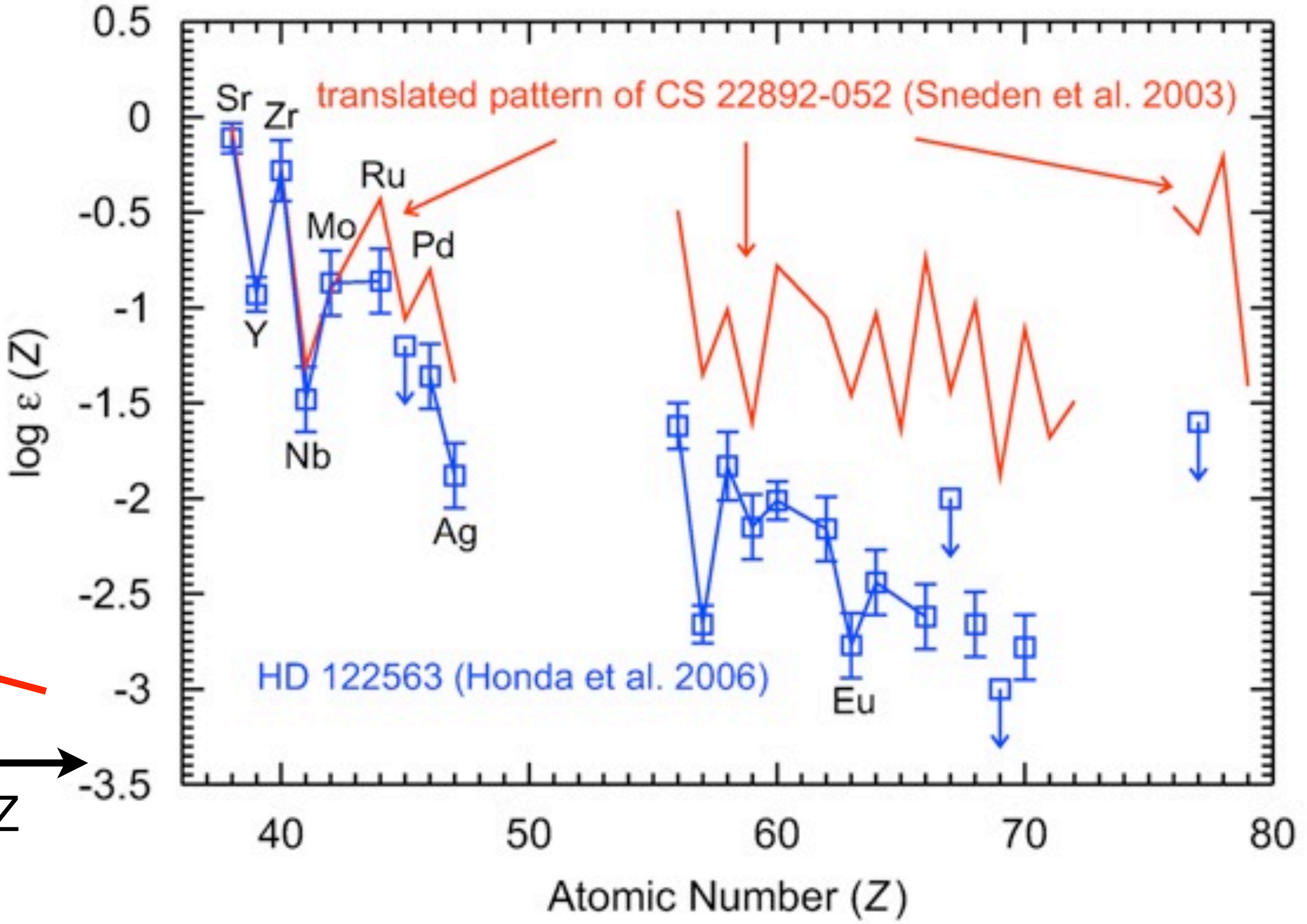

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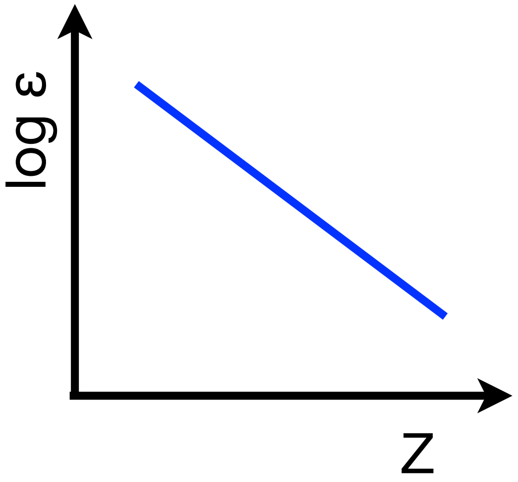

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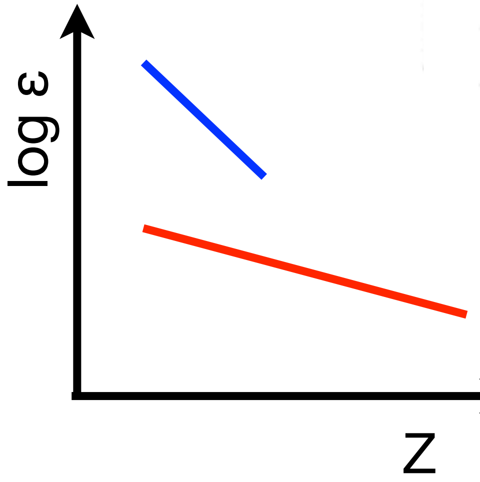

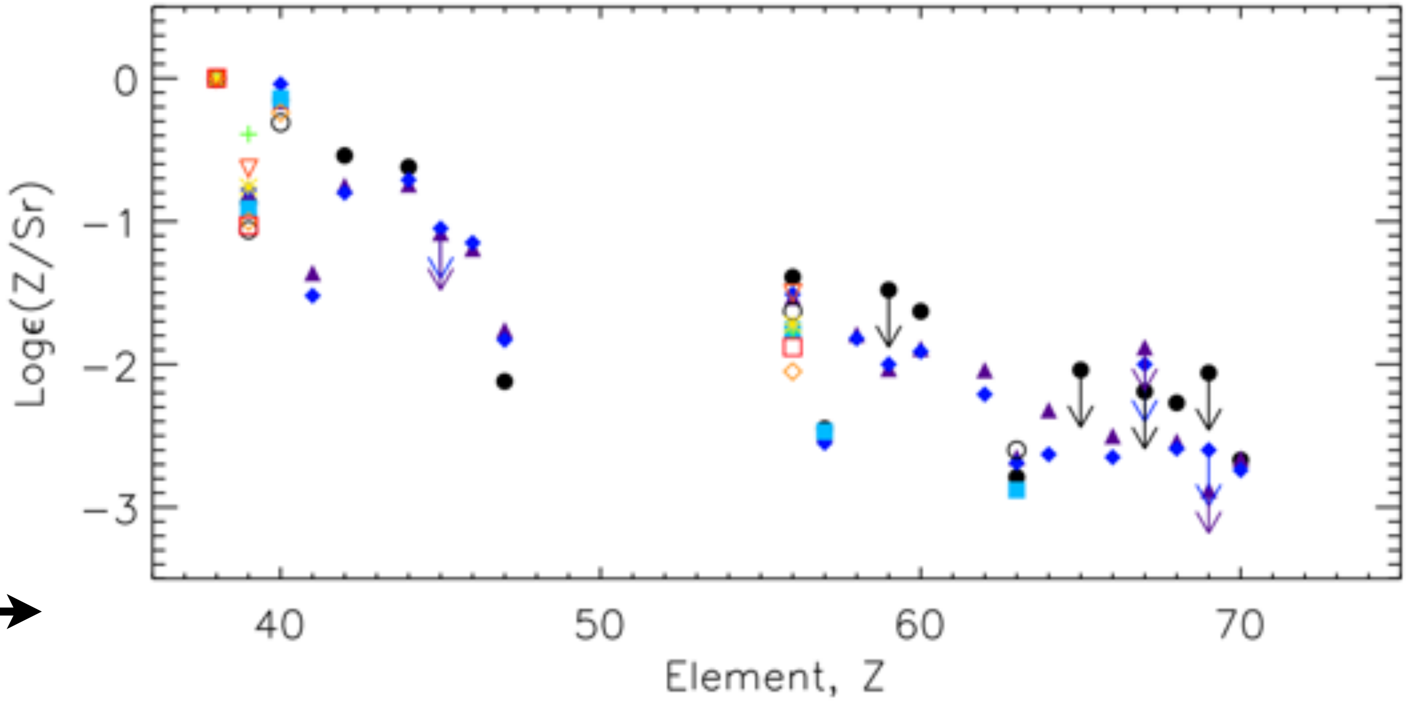

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# Nucleosynthesis components

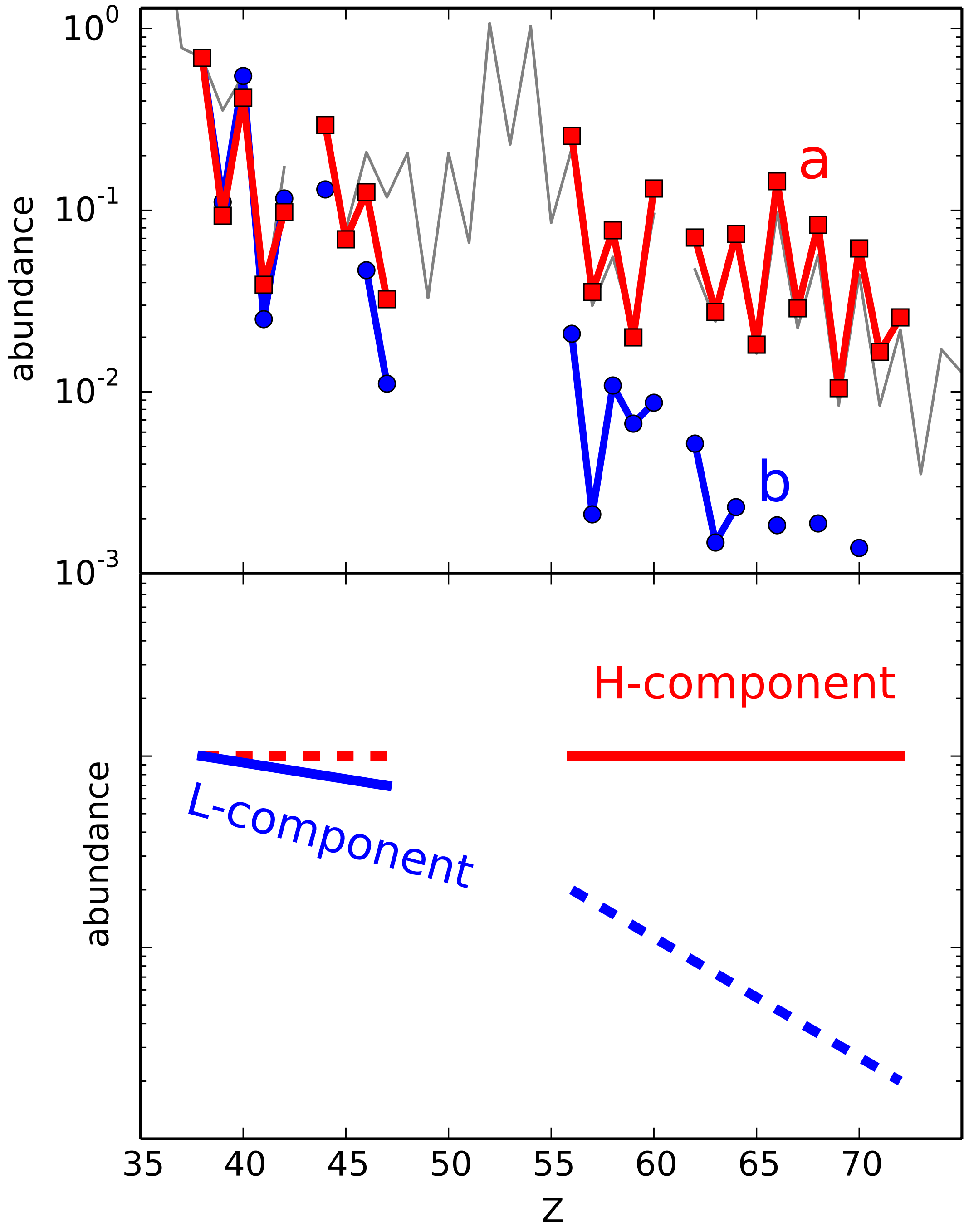
C.J. Hansen, Montes, Arcones 2014

L and H-components based on 3 methods:

M1: L-component = Honda star (b)
H-component= Sneden star (a)

M2: L-component = Honda - Sneden
H-component = Sneden

M3: iterative method (Li et al. 2013)
L-component = L - H
H-component = H - L

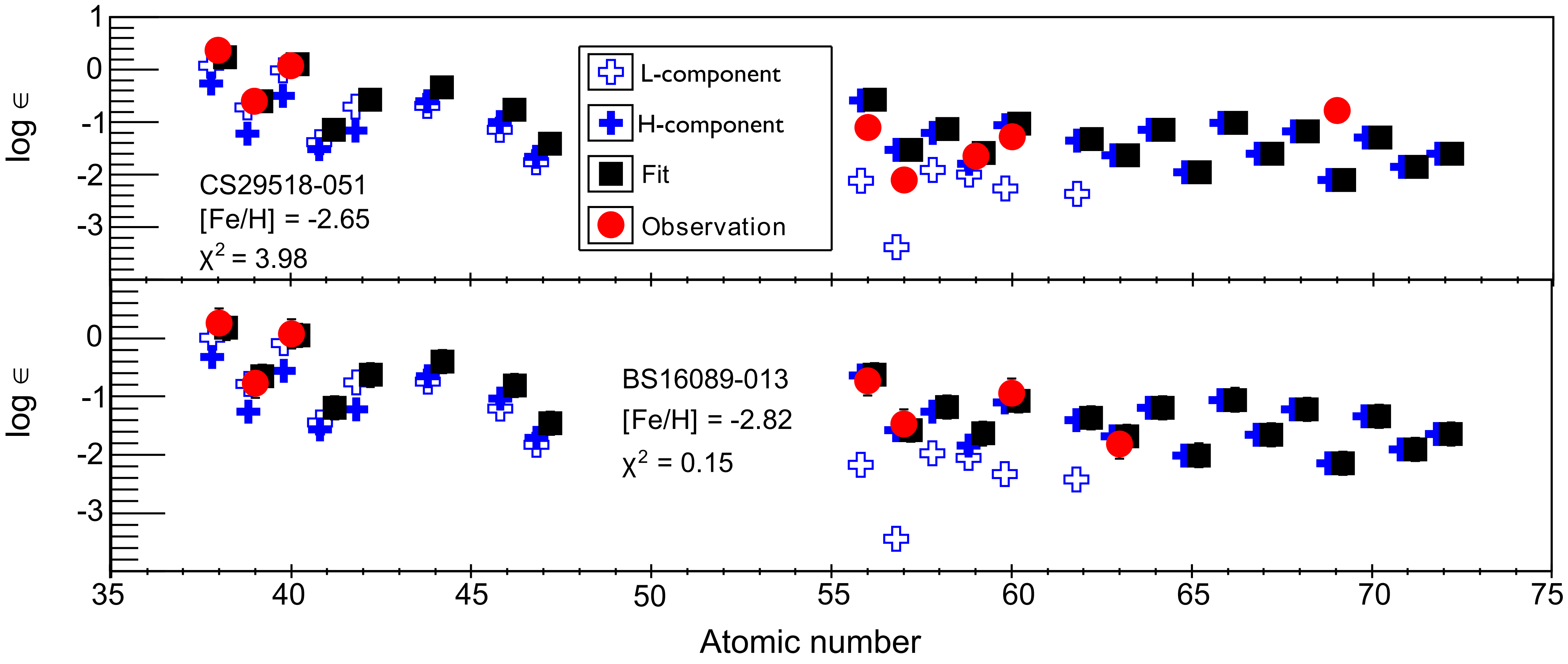


→ Component abundance pattern: $Y_H$ and $Y_L$
Assumptions: Z range for components
robust pattern within uncertainties (0.32 dex= $10^{0.32}$)

# Abundance deconvolution

Fit abundance as combination of components:

$$Y_{\text{calc}}(Z) = (C_H Y_H(Z) + C_L Y_L(Z)) \cdot 10^{[\text{Fe/H}]}$$



From big sample of stars (Frebel et al. 2010)
remove s-process, carbon enhanced, and stars with internal mixing

# Abundance deconvolution

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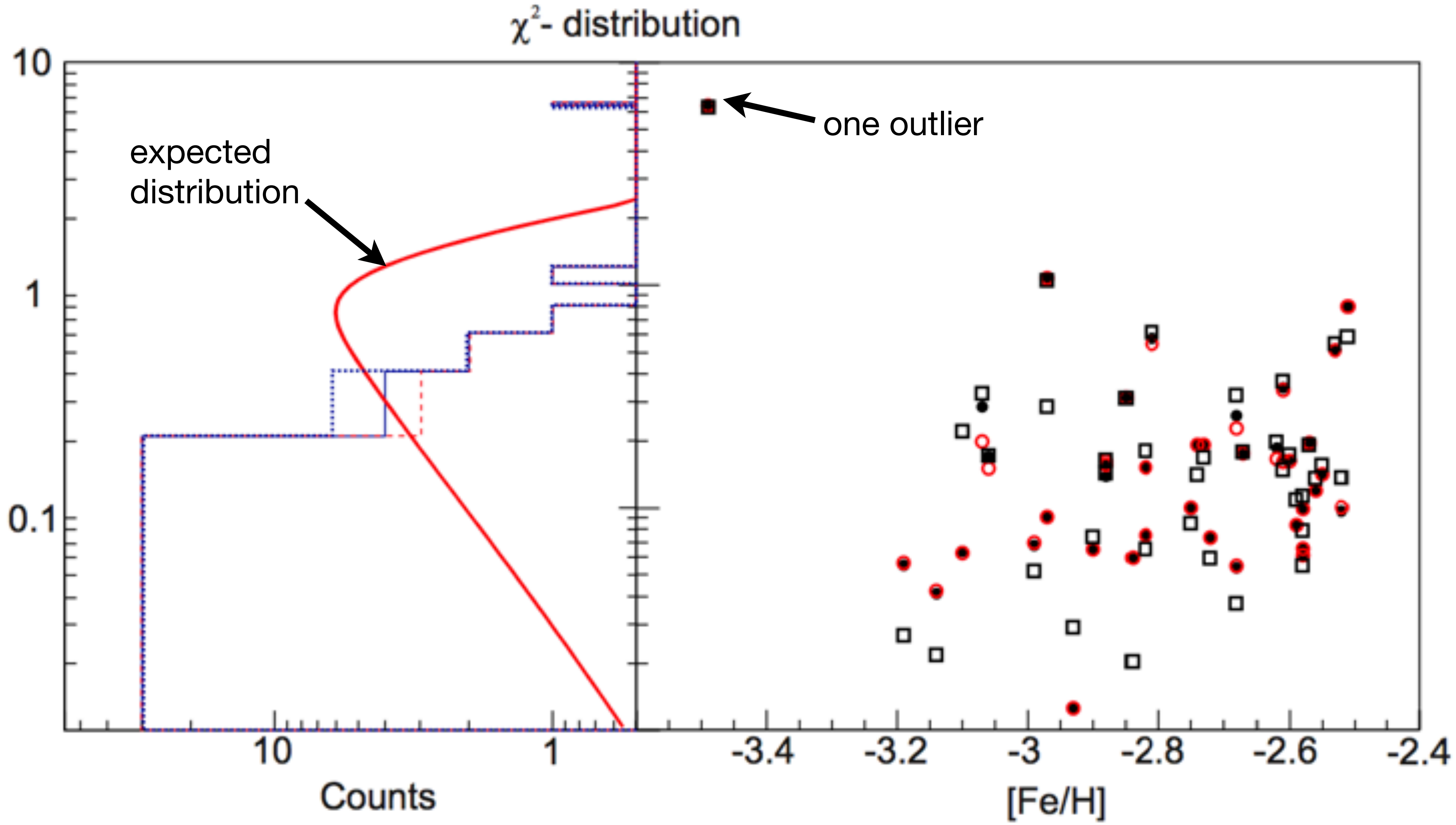
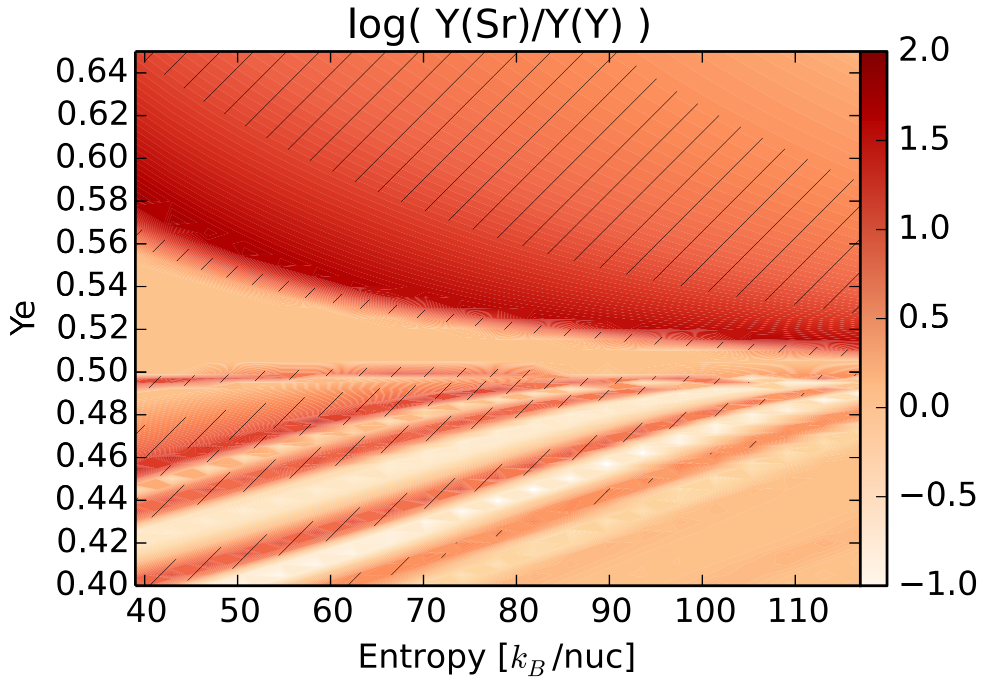


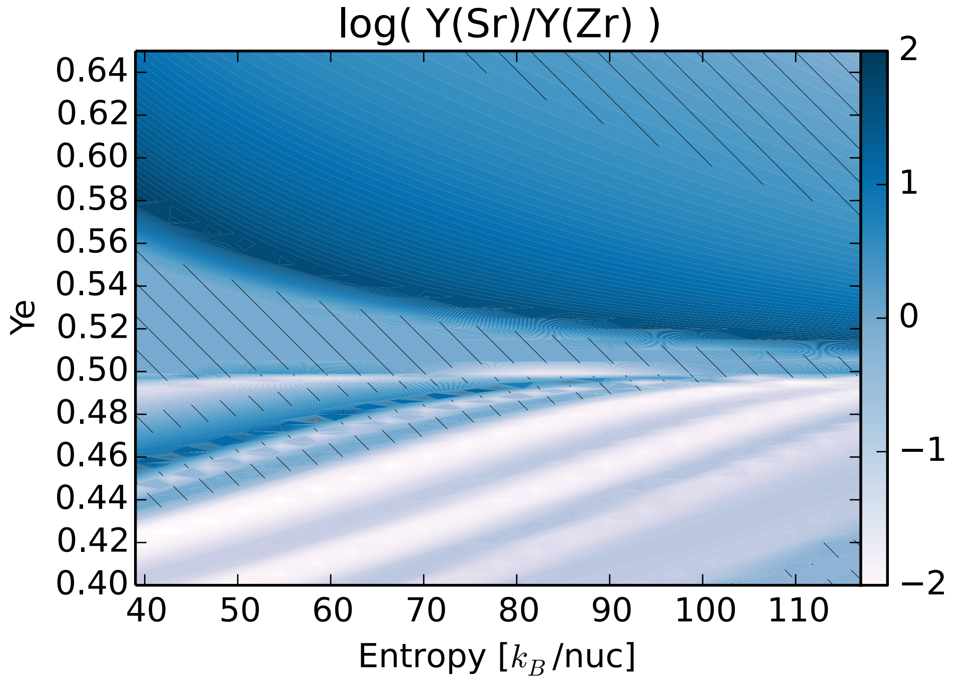
$$\chi^2 = \frac{1}{\nu} \sum_{Z_{\mathrm{range}}} \left( \log Y_{\mathrm{observed}}(Z) - \log Y_{\mathrm{calc}}(Z) \right)^2 / \Delta(Z)^2 \xrightarrow{} \text{0.32 dex (obs. + method)}$$

# L-component: constraining conditions

L-component abundance ratios:

- Sr/Y = 6.13 (//)
- Sr/Zr = 1.22 (\\)
- Sr/Ag = 48.2





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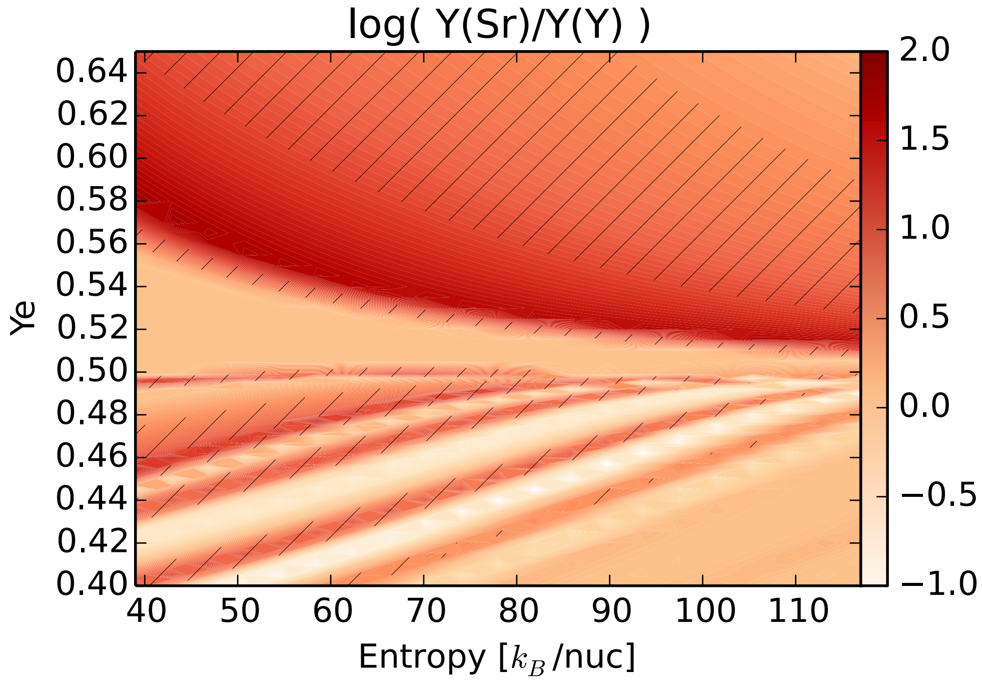
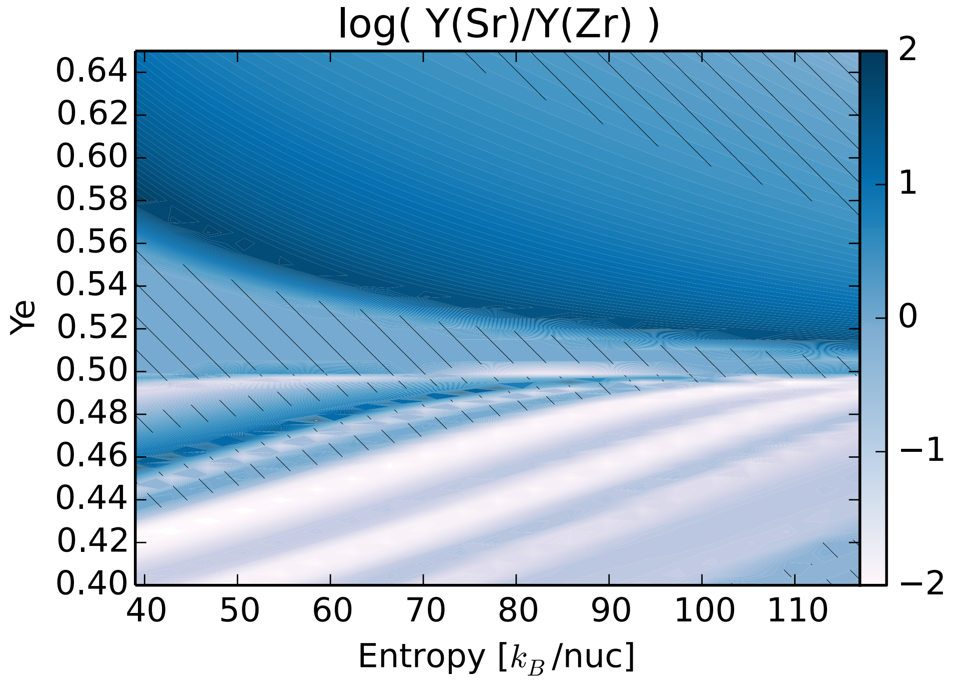

log( Y(Sr)/Y(Y) )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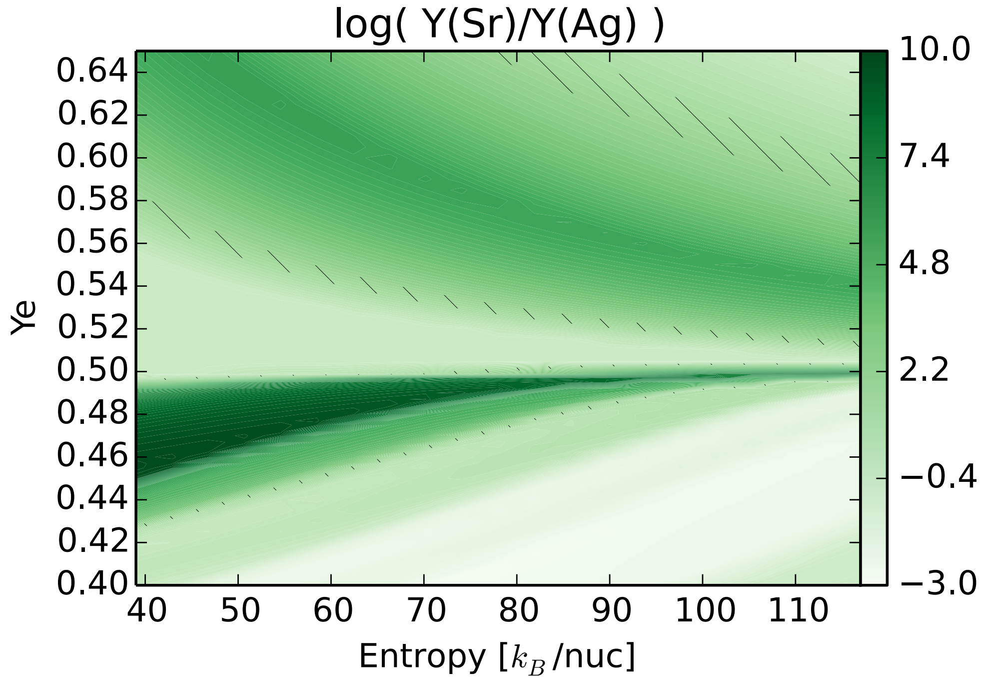
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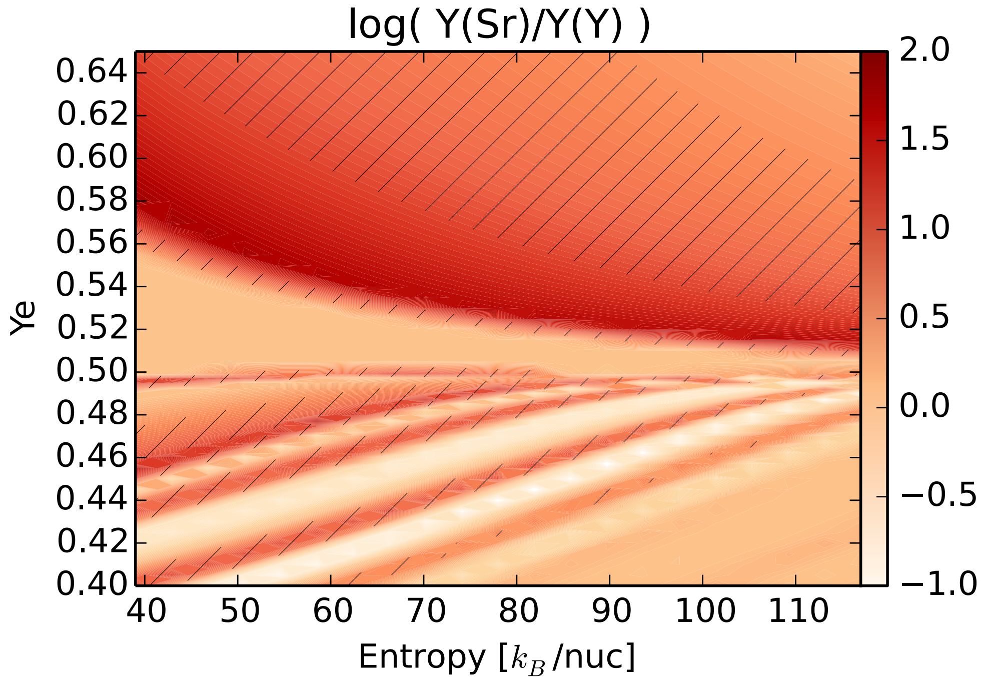
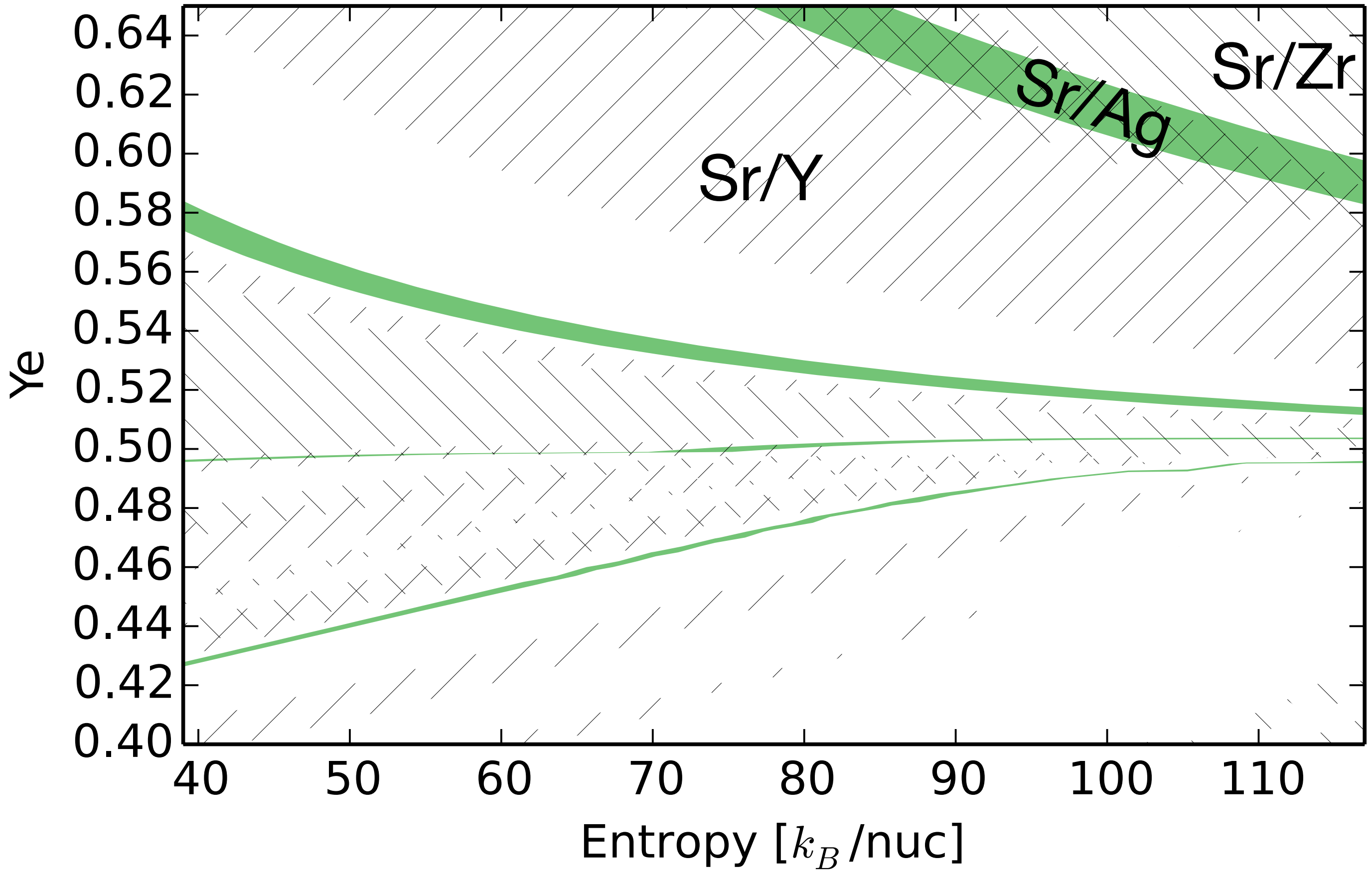
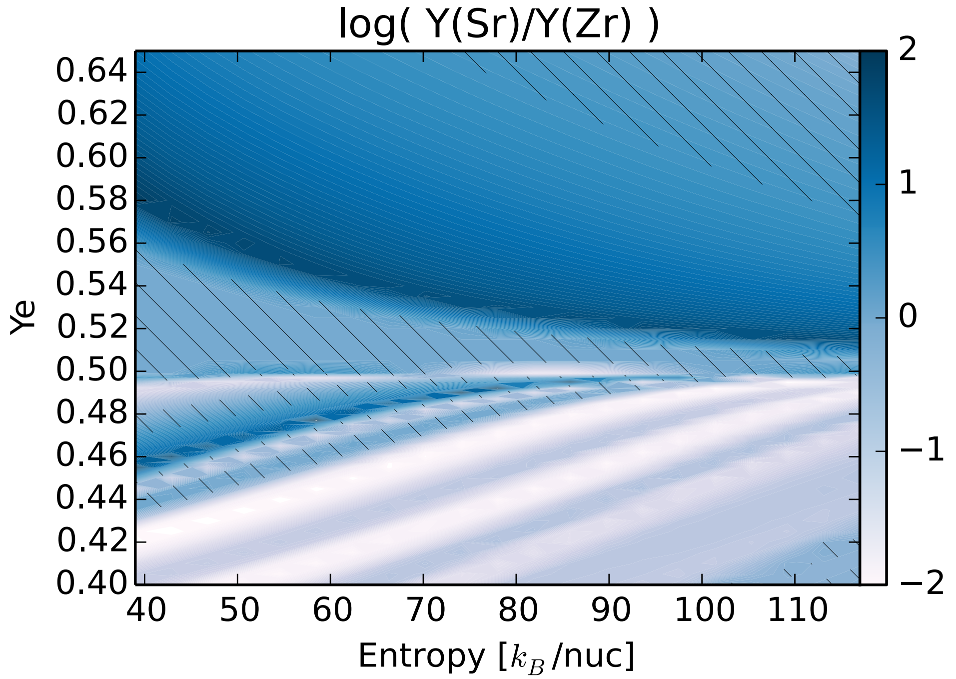
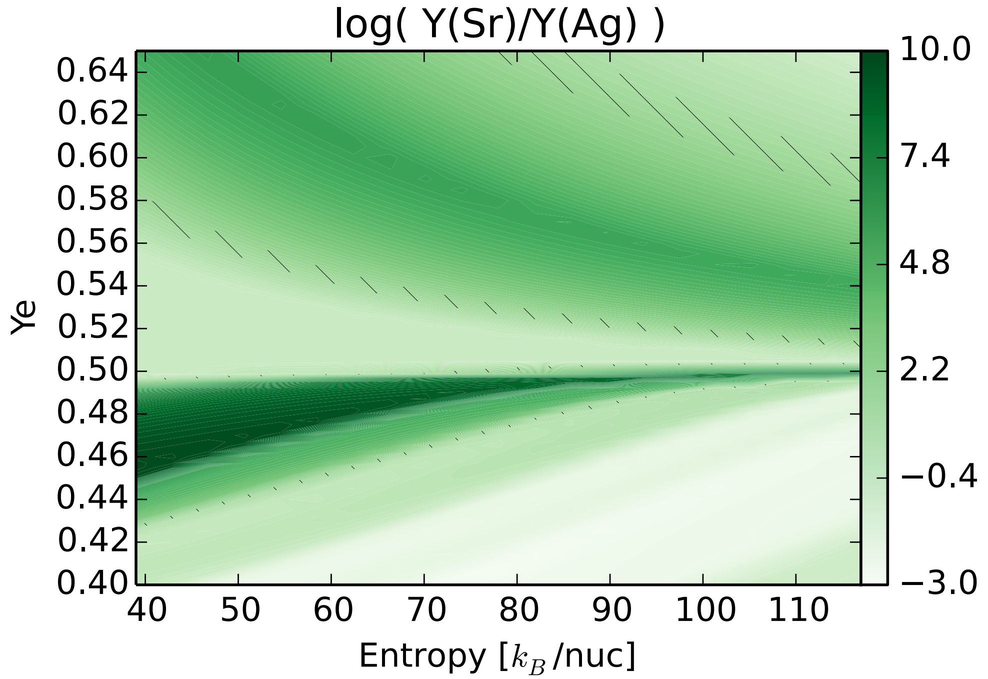


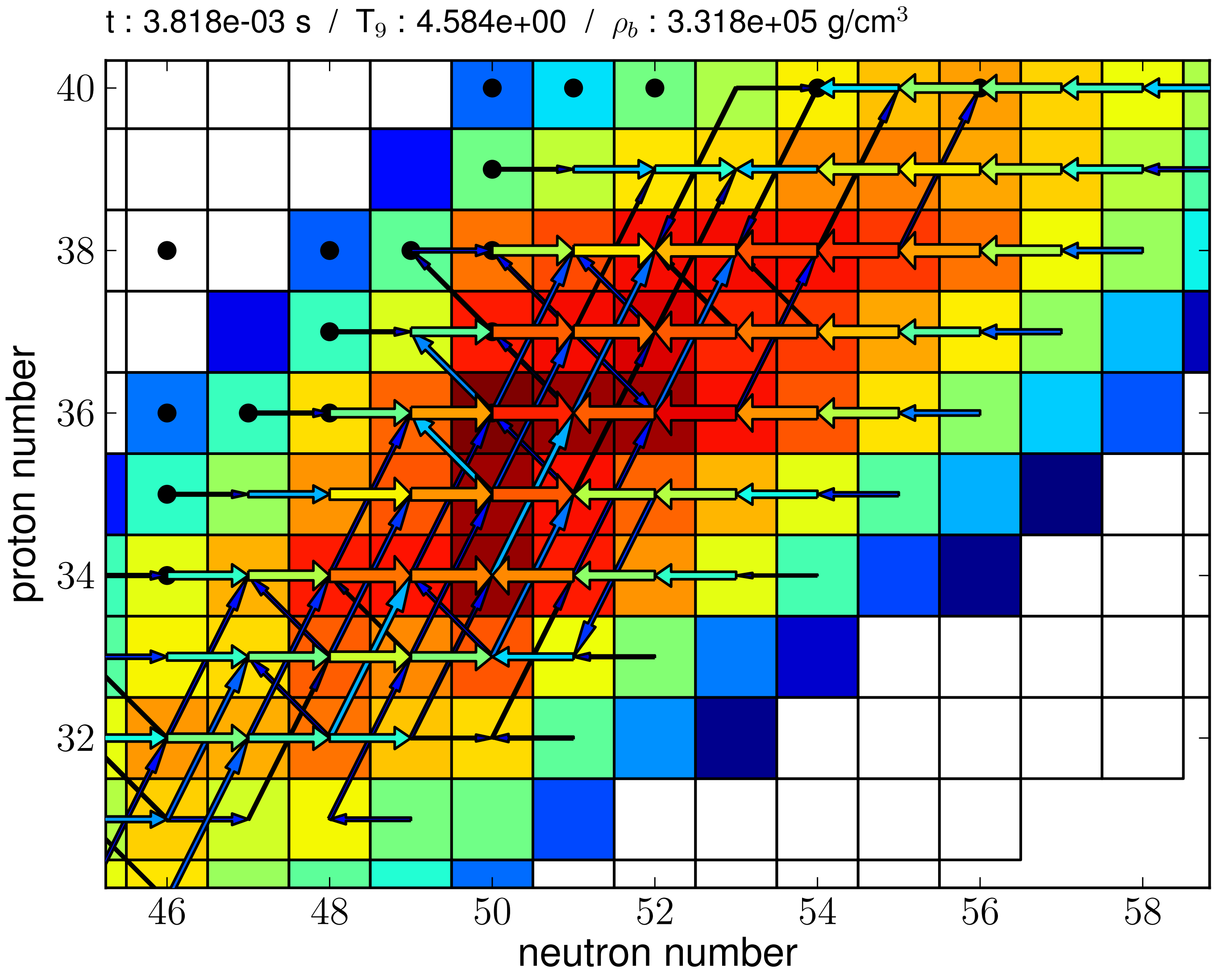


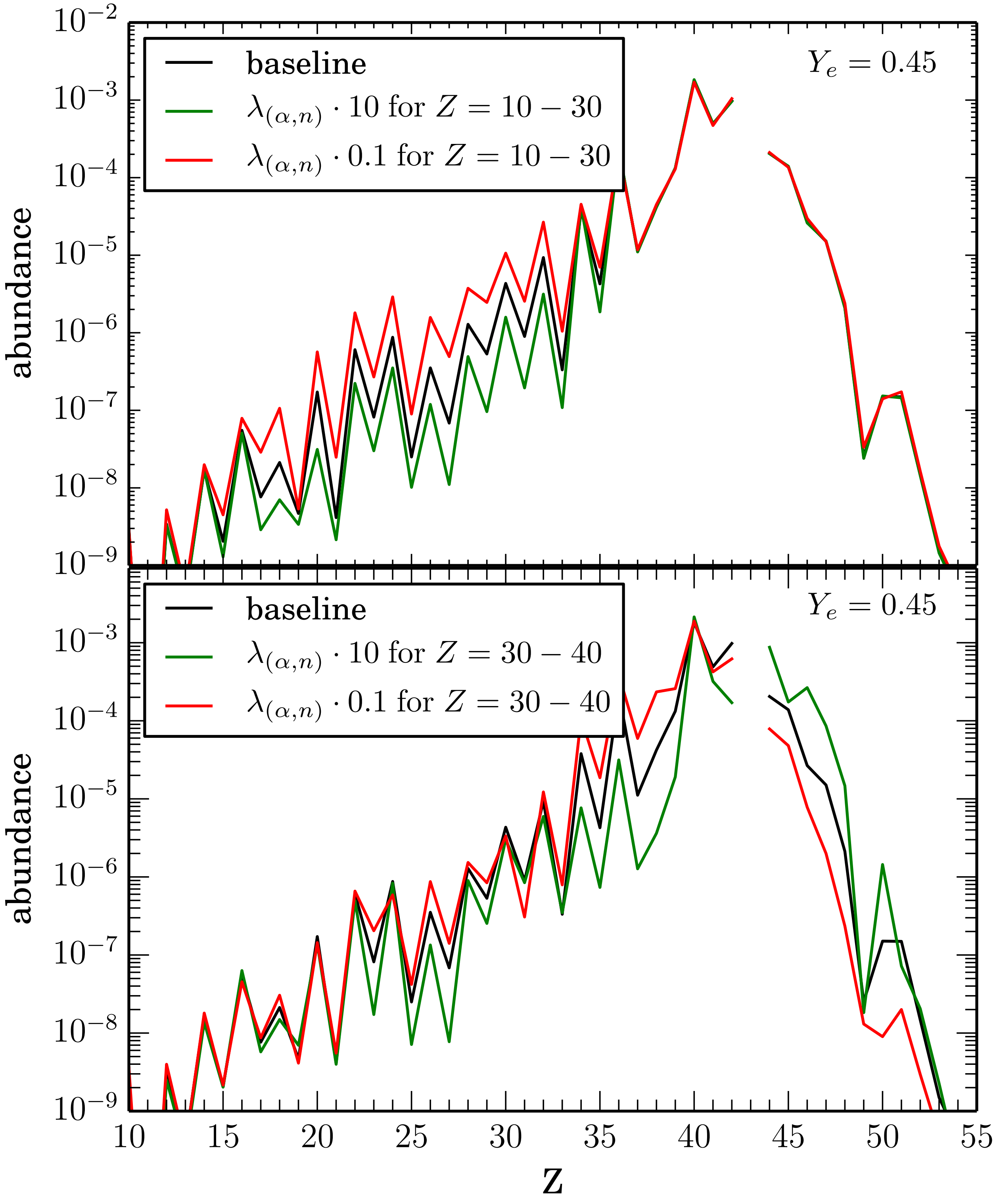




# Key reactions: weak r-process

## (α,n)

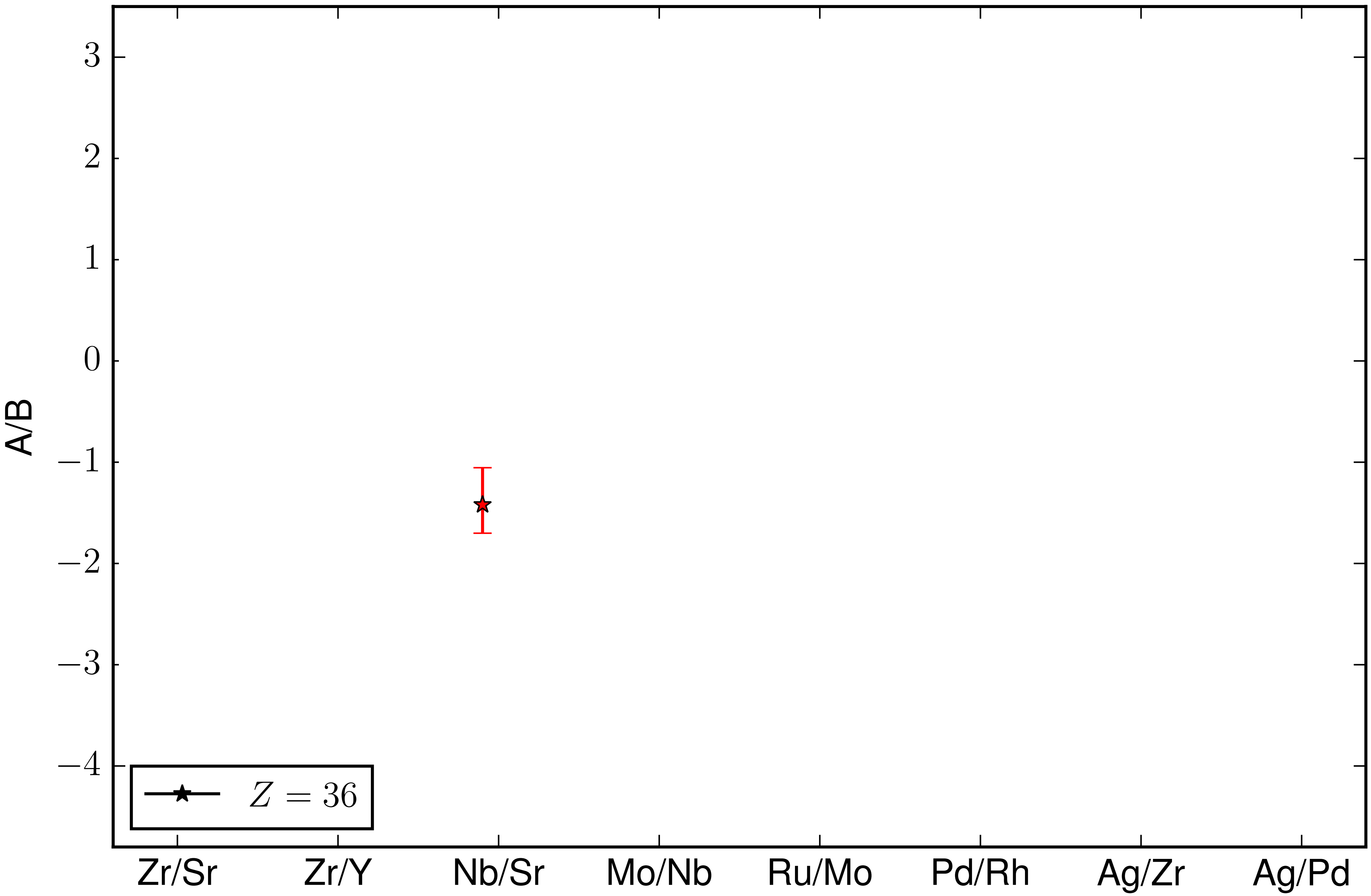




Bliss, Arcones, Montes, Pereira (in prep.)

# Astrophysics and nuclear physics uncertainties

Error bar: variation of (α,n) by factors 10 and 0.1 for all isotopic chain



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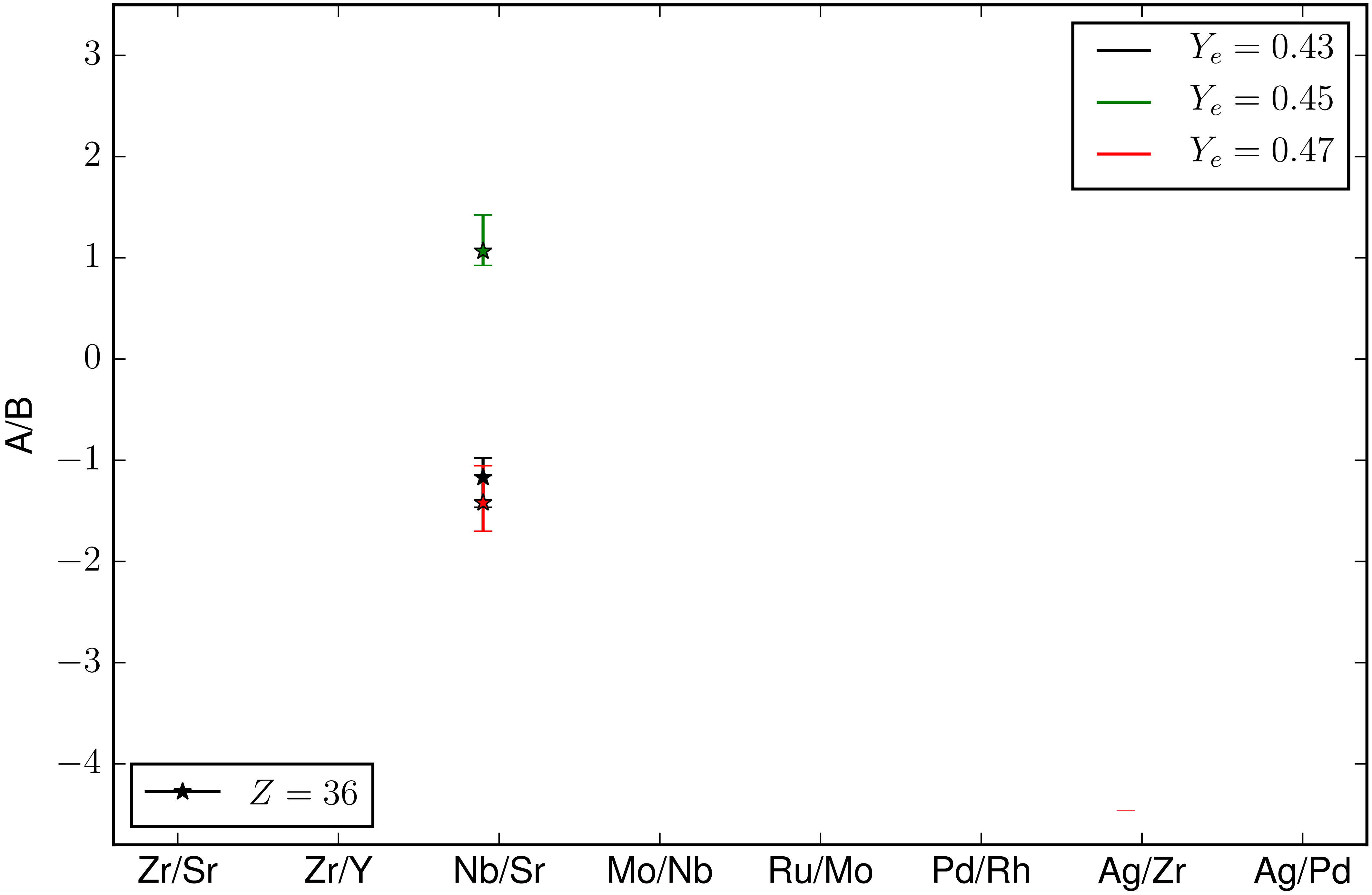

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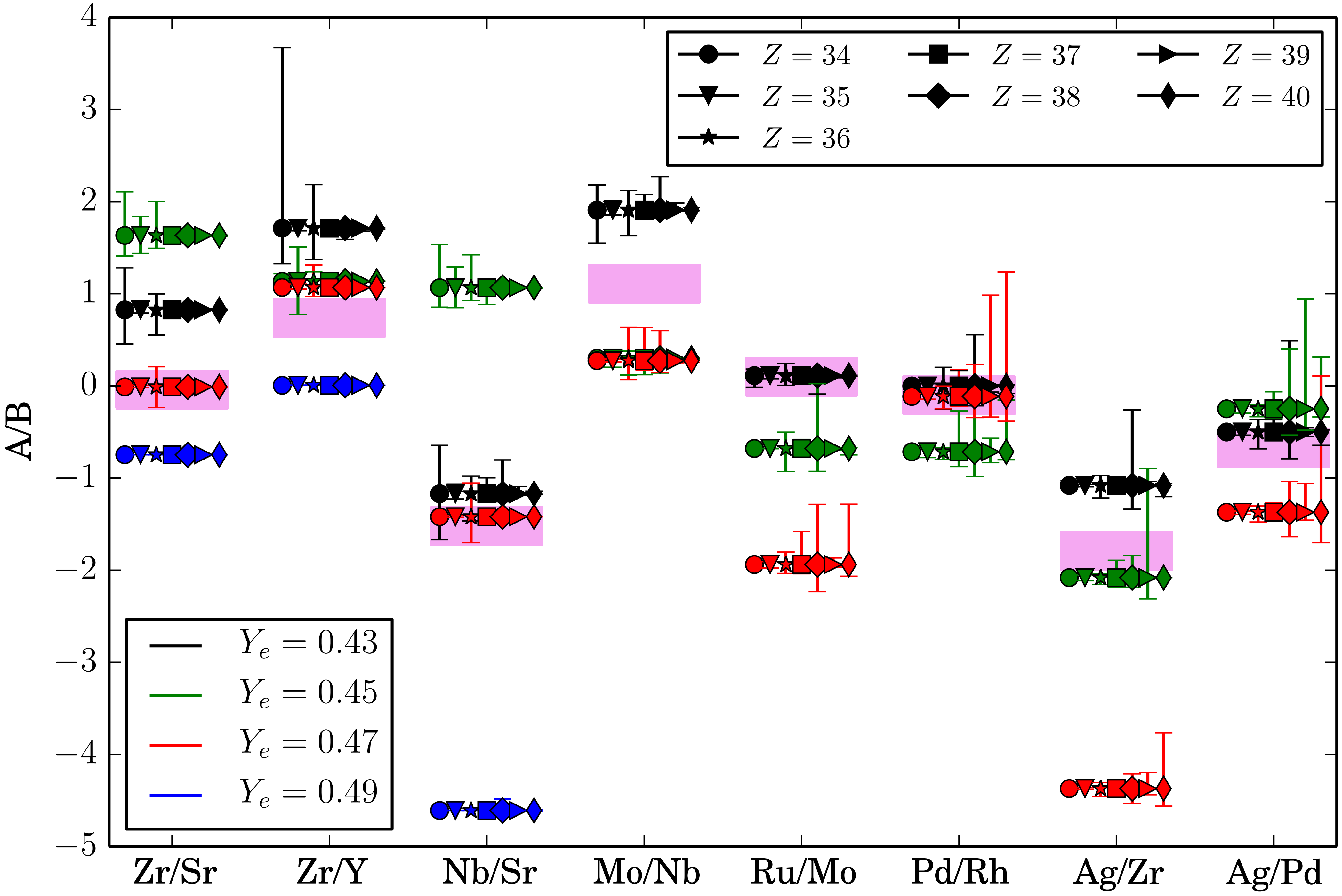

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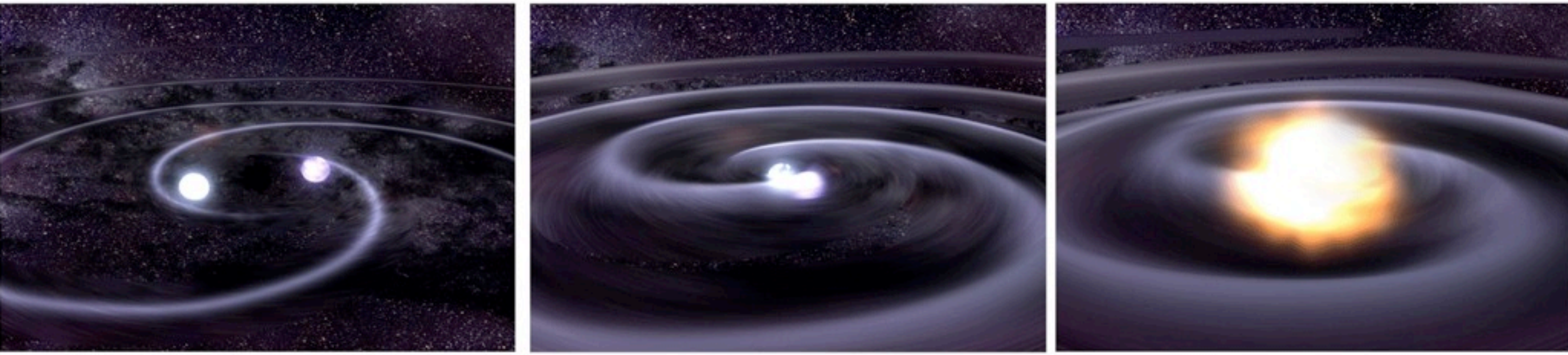
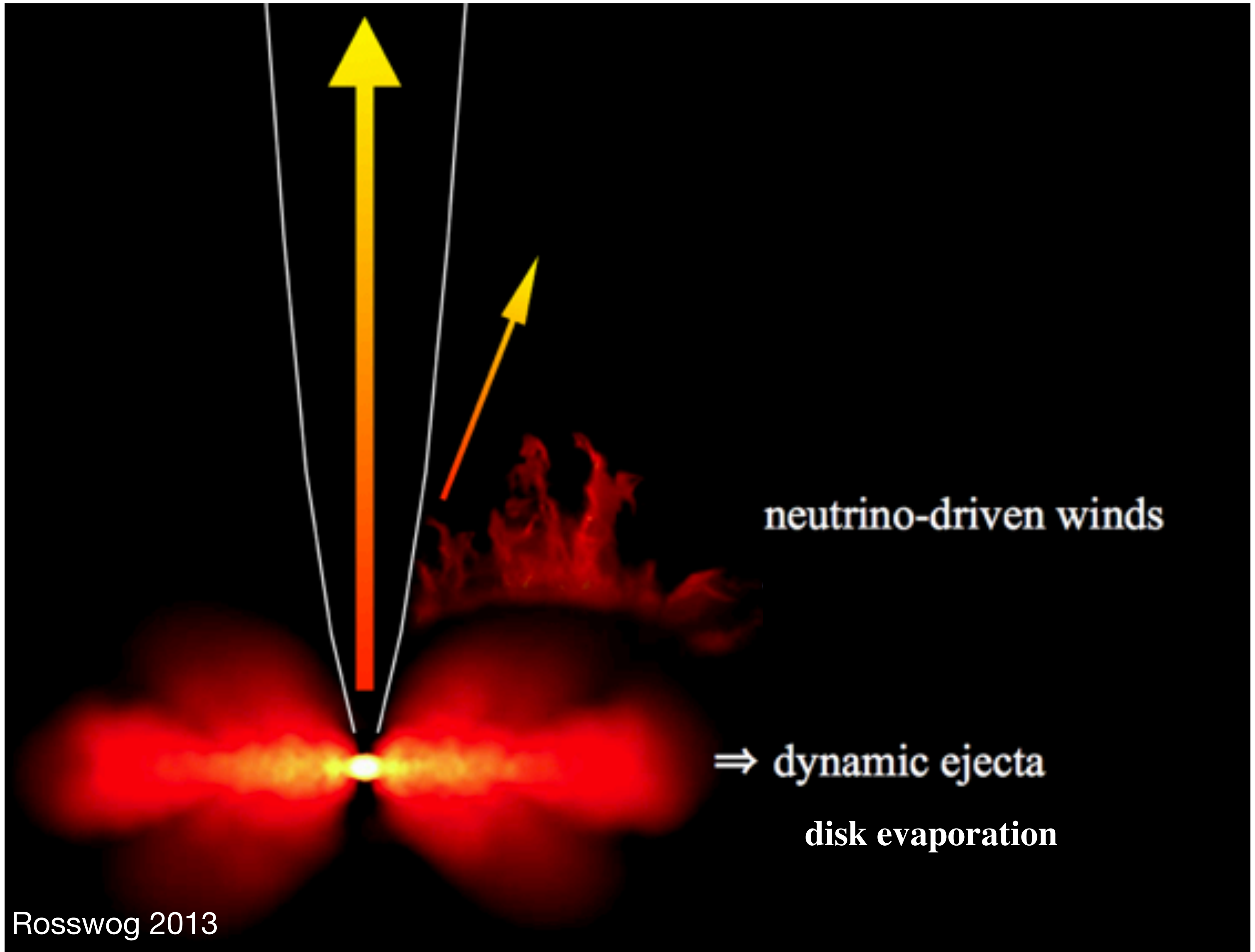
# Neutron star mergers



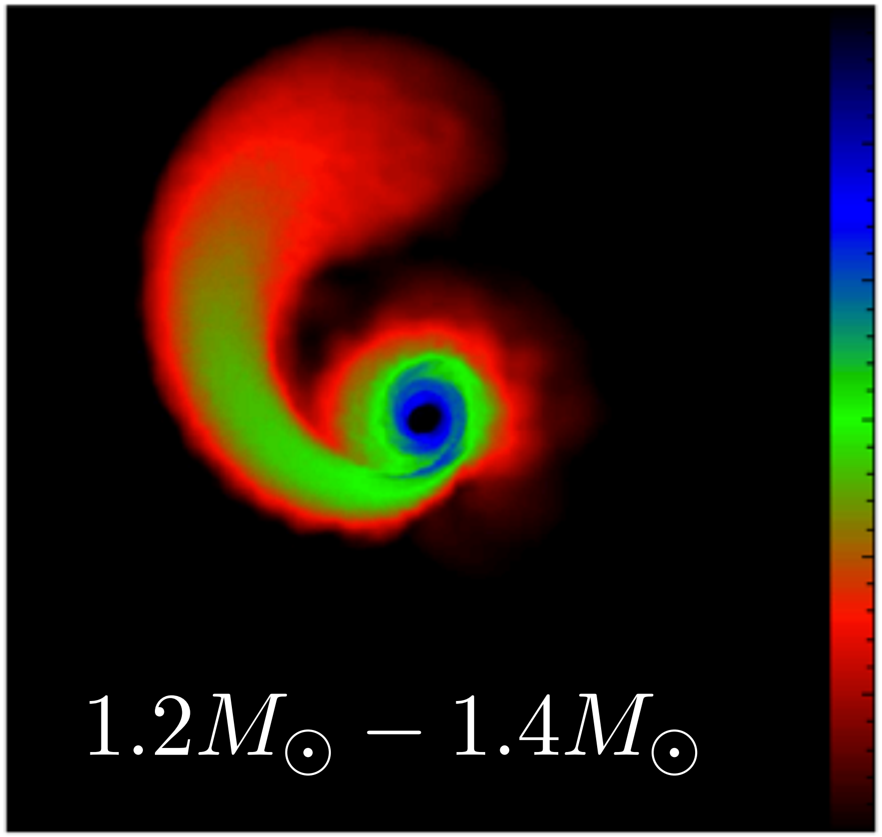
Ejecta from three regions:

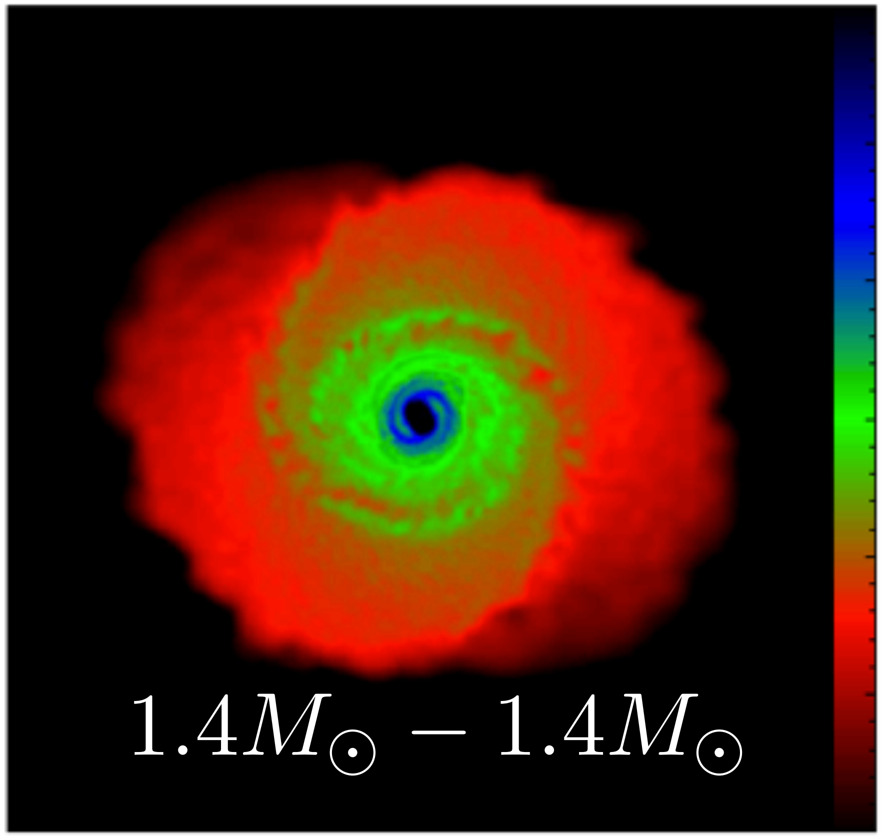
- dynamical ejecta
- neutrino-driven wind
- disk evaporation

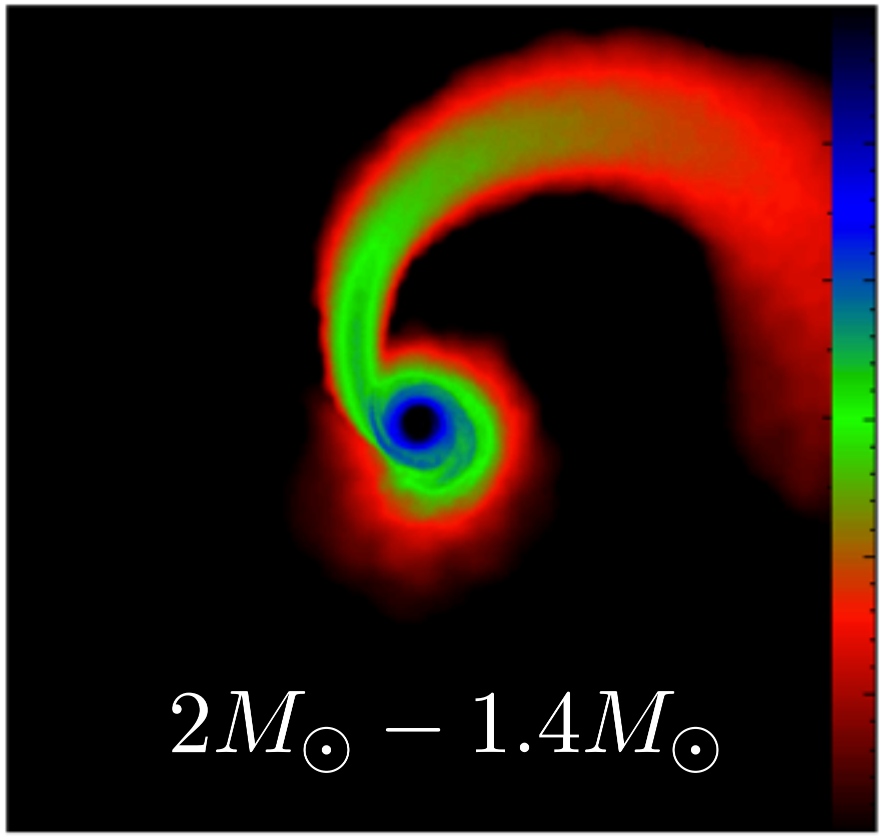


Rosswog 2013

# Neutron star mergers: robust r-process



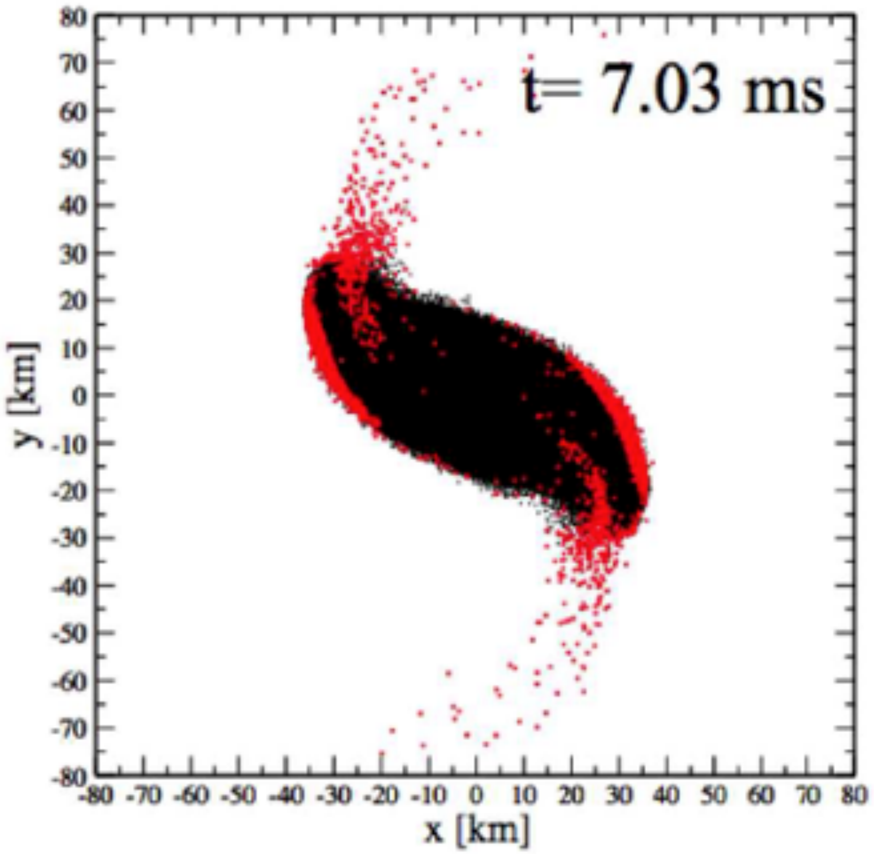




Right conditions for a successful r-process
(Lattimer & Schramm 1974, Freiburghaus et al. 1999)

nucleosynthesis of dynamical ejecta
robust r-process:

- extreme neutron-rich conditions ($Y_e$ =0.04)
- several fission cycles



Korobkin, Rosswog, Arcones, Winteler (2012)
see also Bauswein, Goriely, and Janka
Hotokezaka, Kiuchi, Kyutoku, Sekiguchi, Shibata, Tanaka, Wanajo
Ramirez-Ruiz, Roberts, ...

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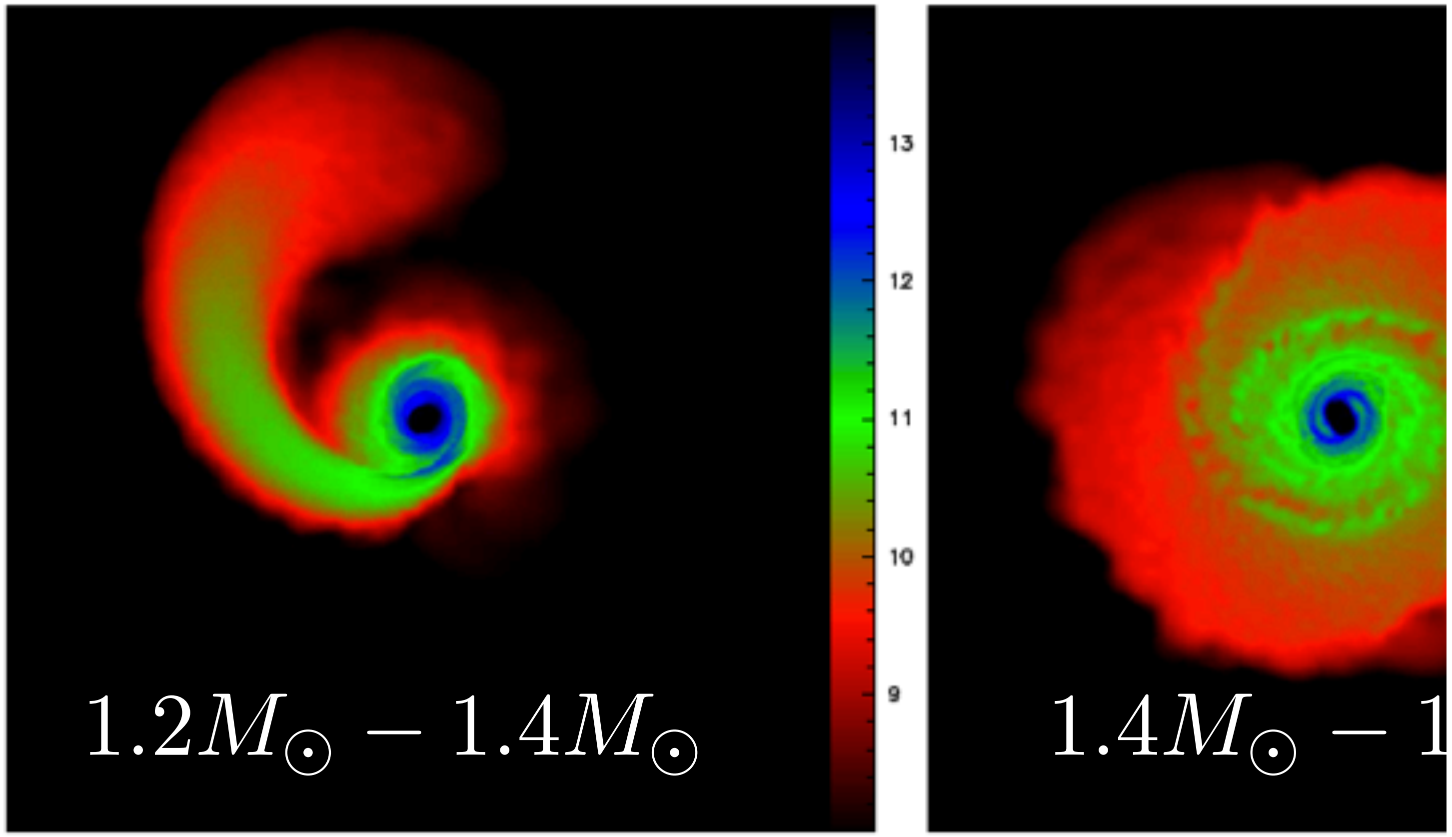

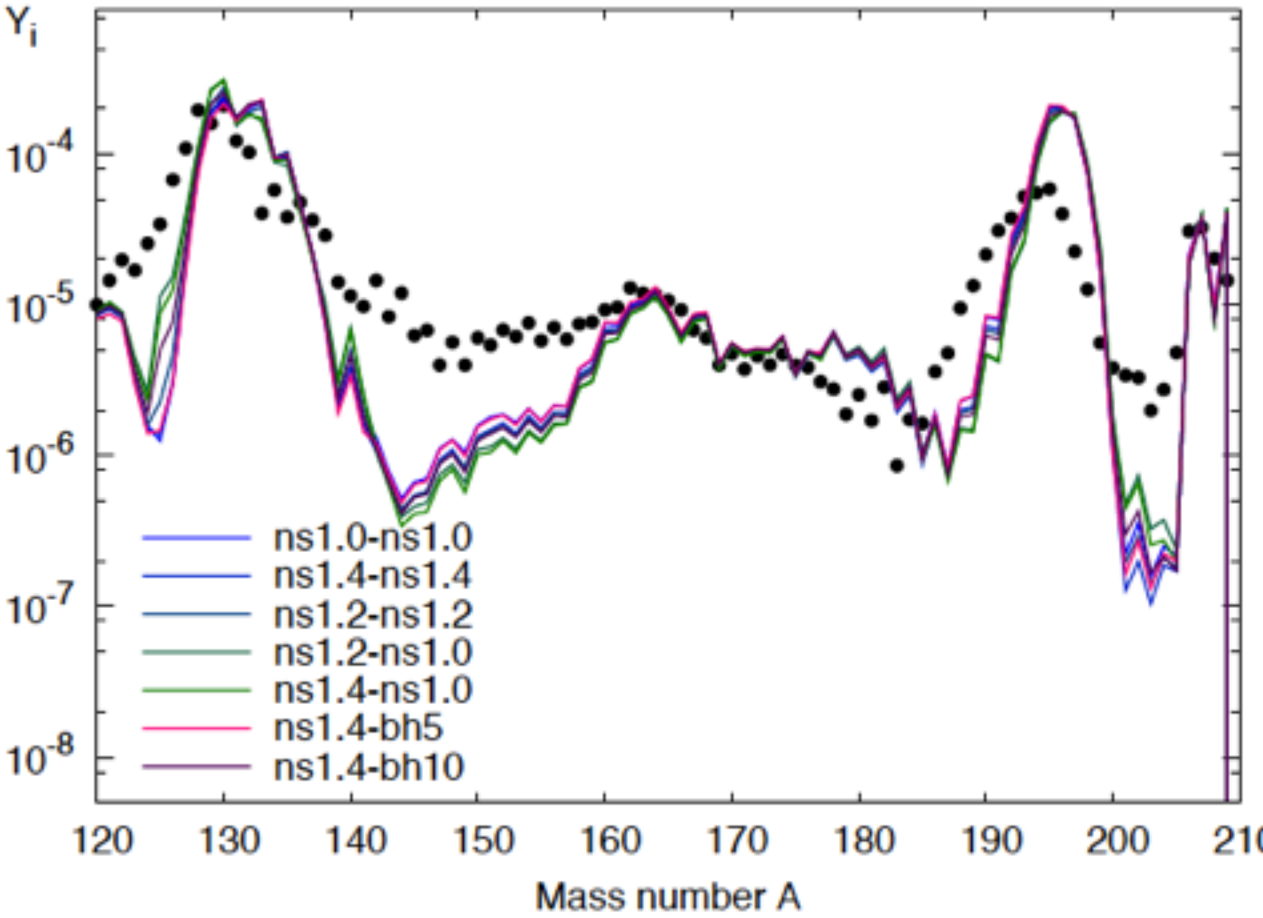

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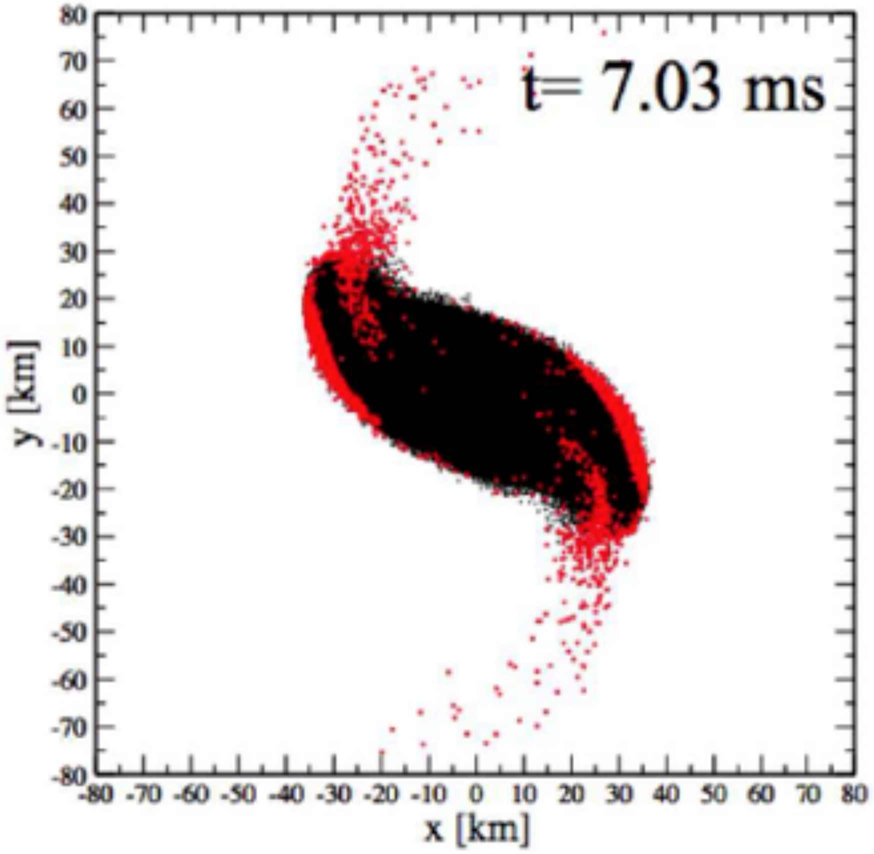

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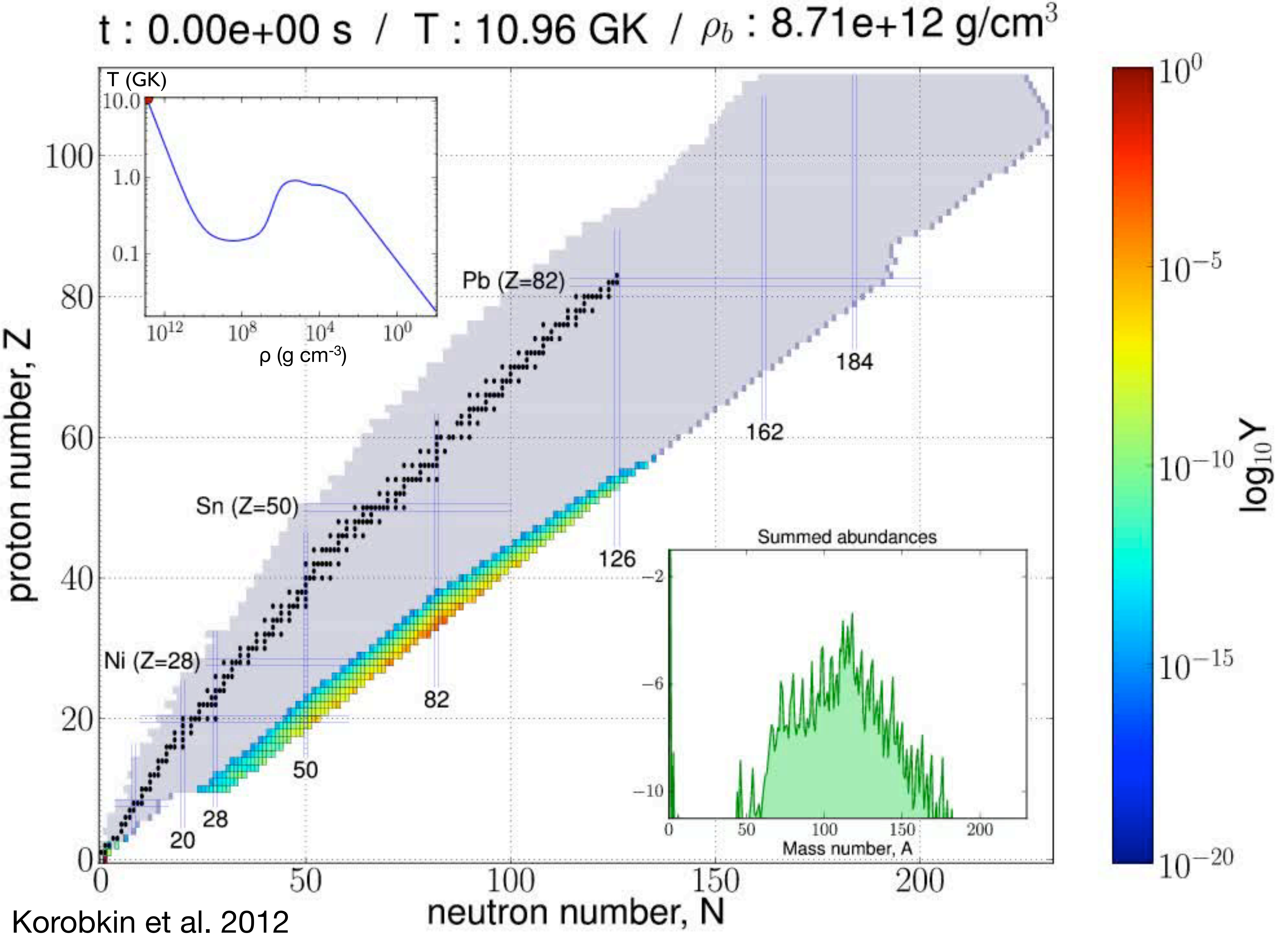
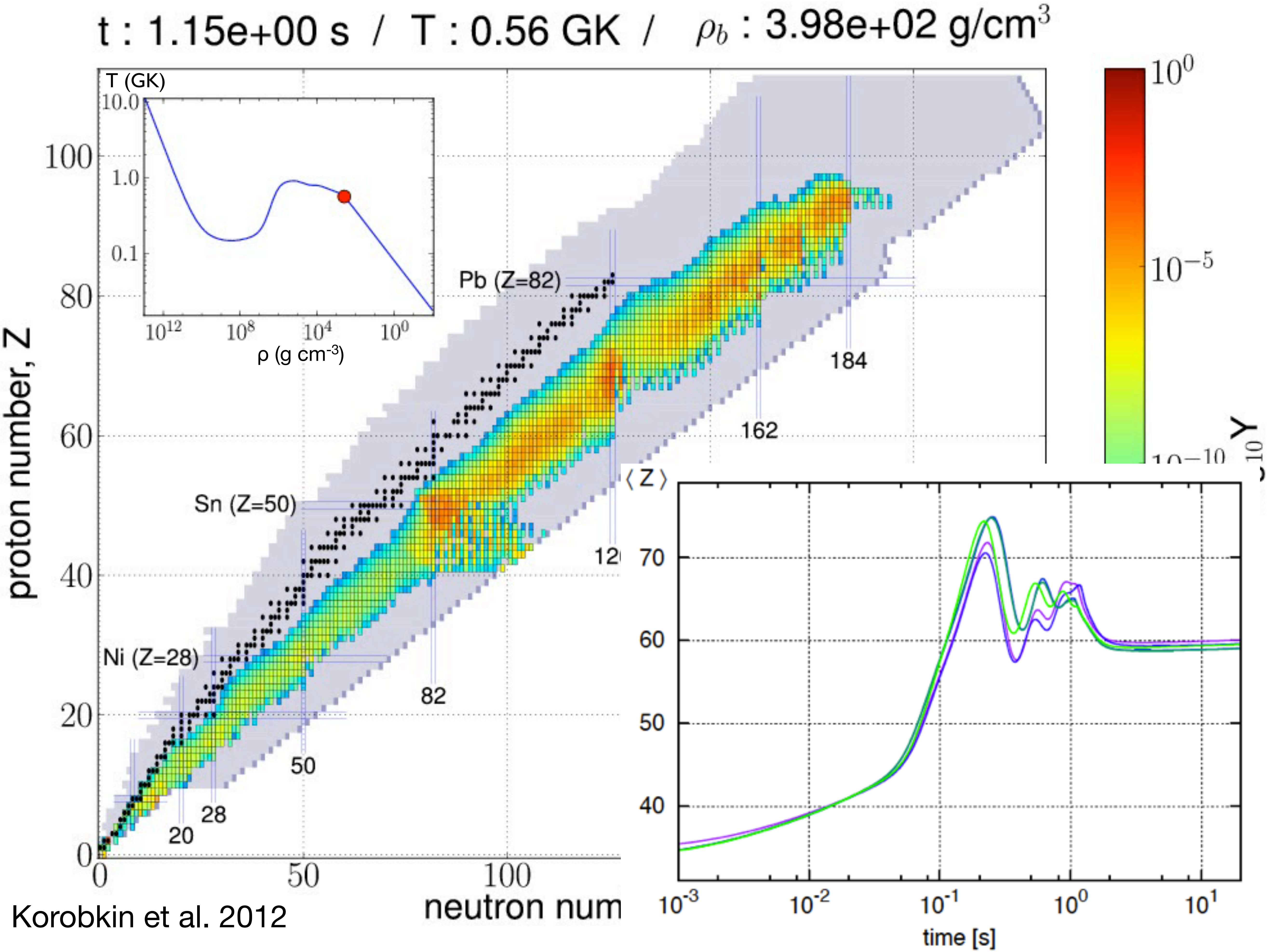
T (GK)

ρ (g $cm^{-3}$)

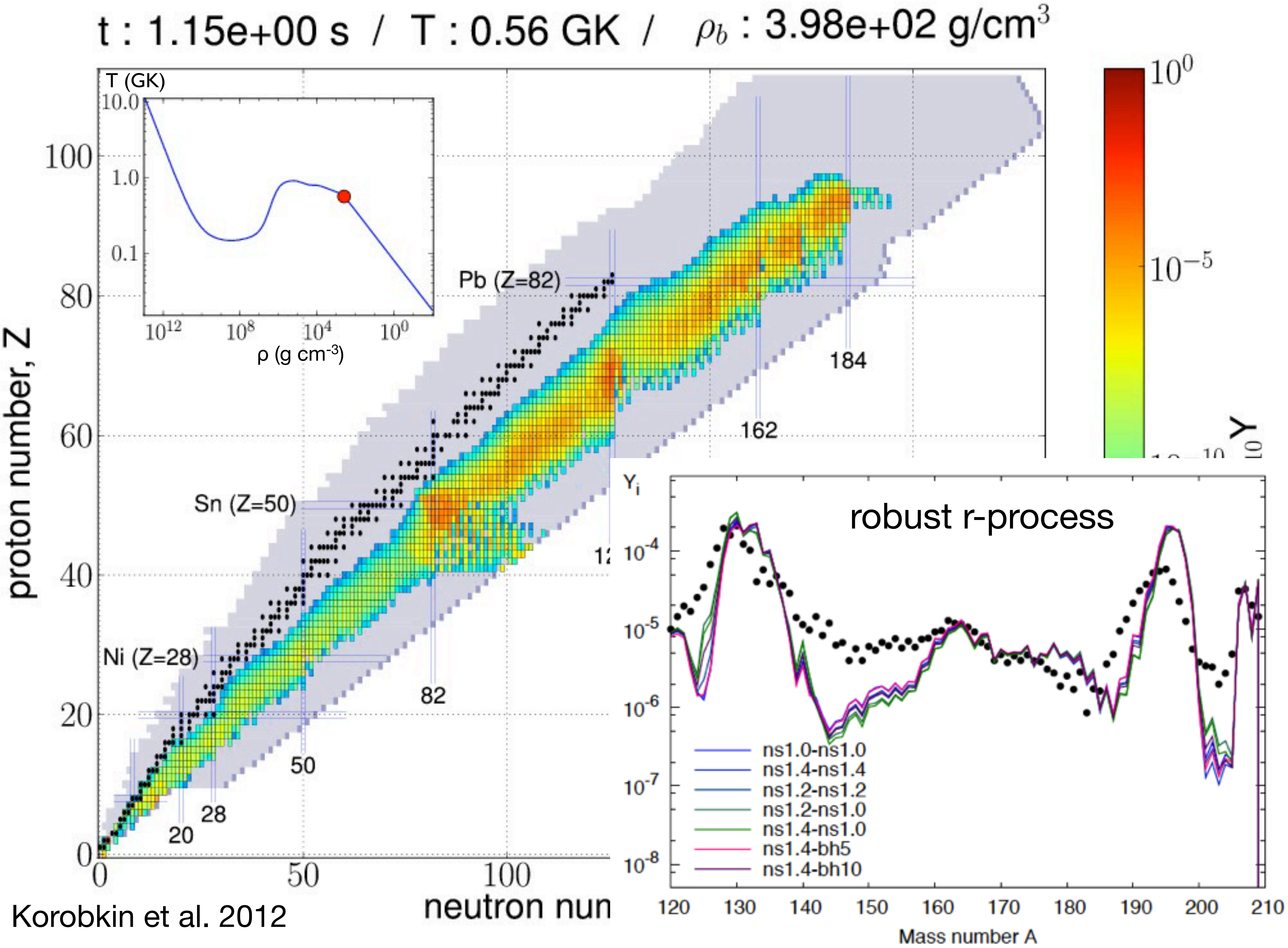
Korobkin et al. 2012



Korobkin et al. 2012



Korobkin et al. 2012

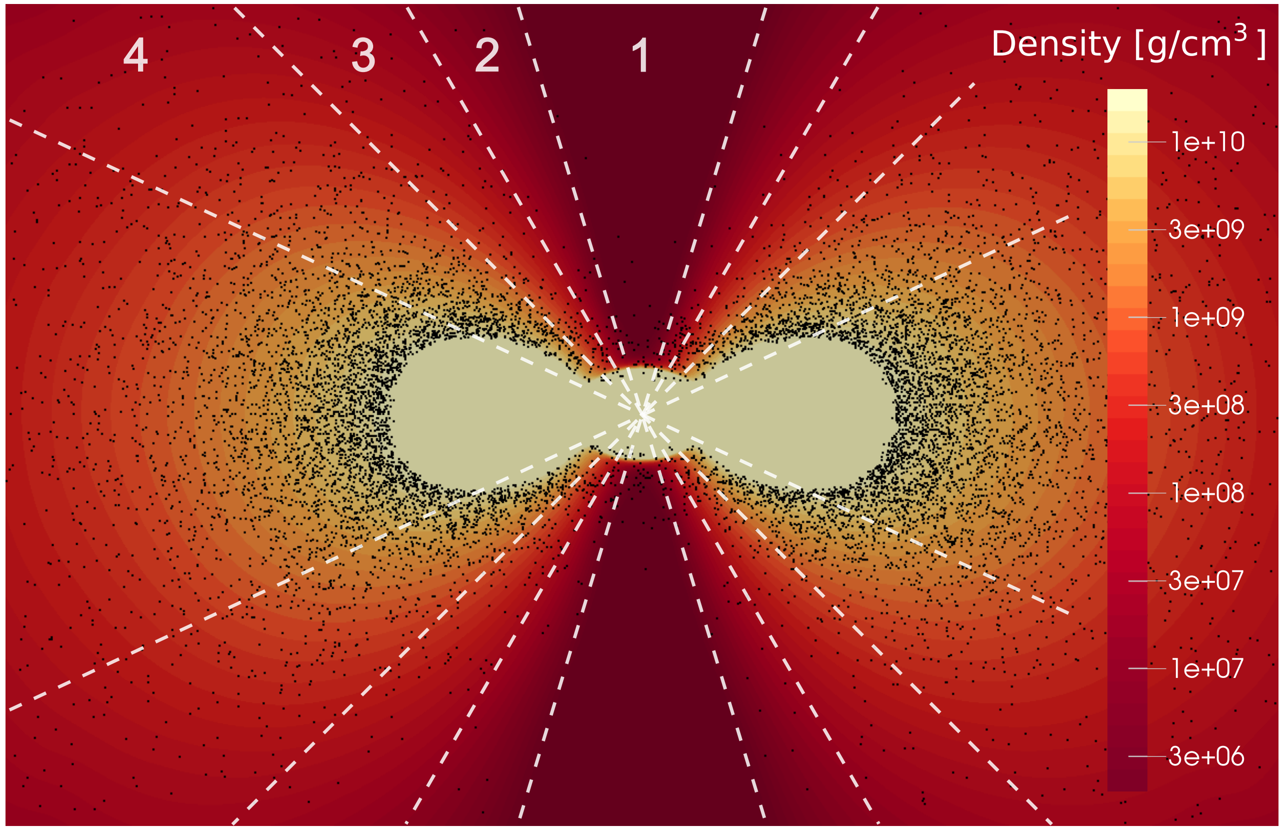


robust r-process

Korobkin et al. 2012

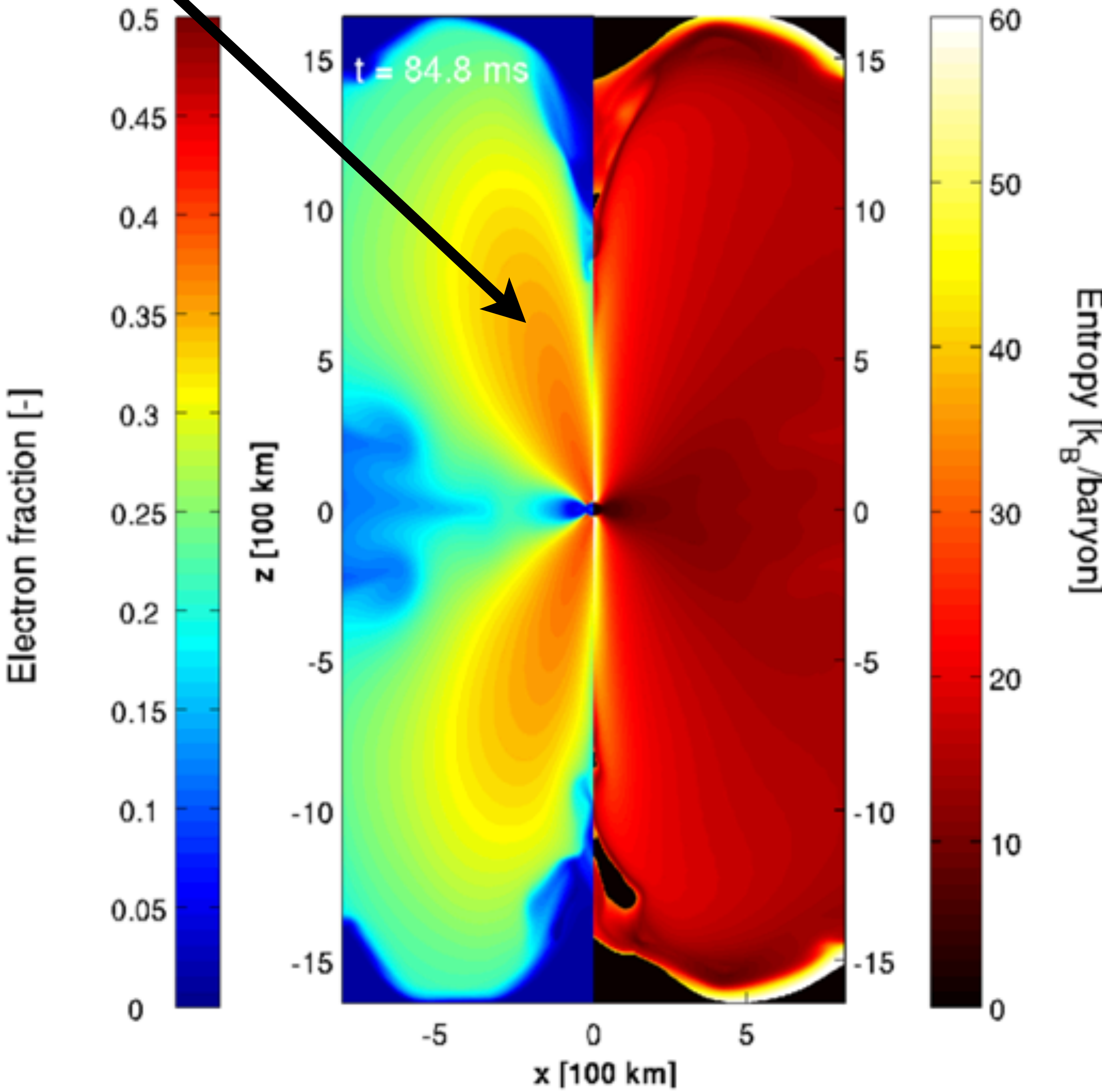
# Neutron star mergers: neutrino-driven wind

3D simulations after merger
disk and neutrino-wind evolution
neutrino emission and absorption
Nucleosynthesis: 17 000 tracers



Martin et al. (in prep)

Perego et al. (2014)



see also
Fernandez & Metzger 2013, Metzger Fernandez 2014,
Just et al. 2014, Sekiguchi et al.

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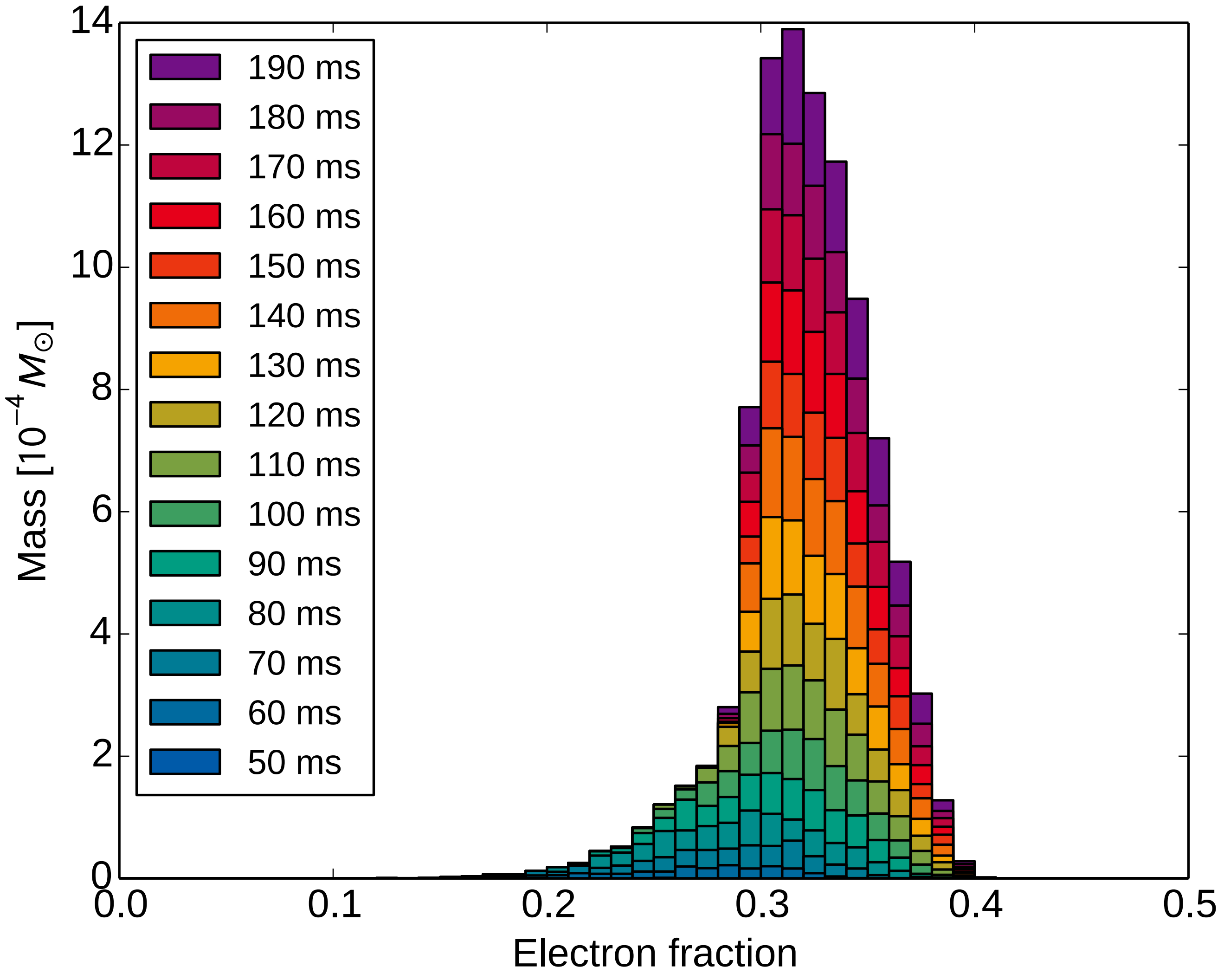

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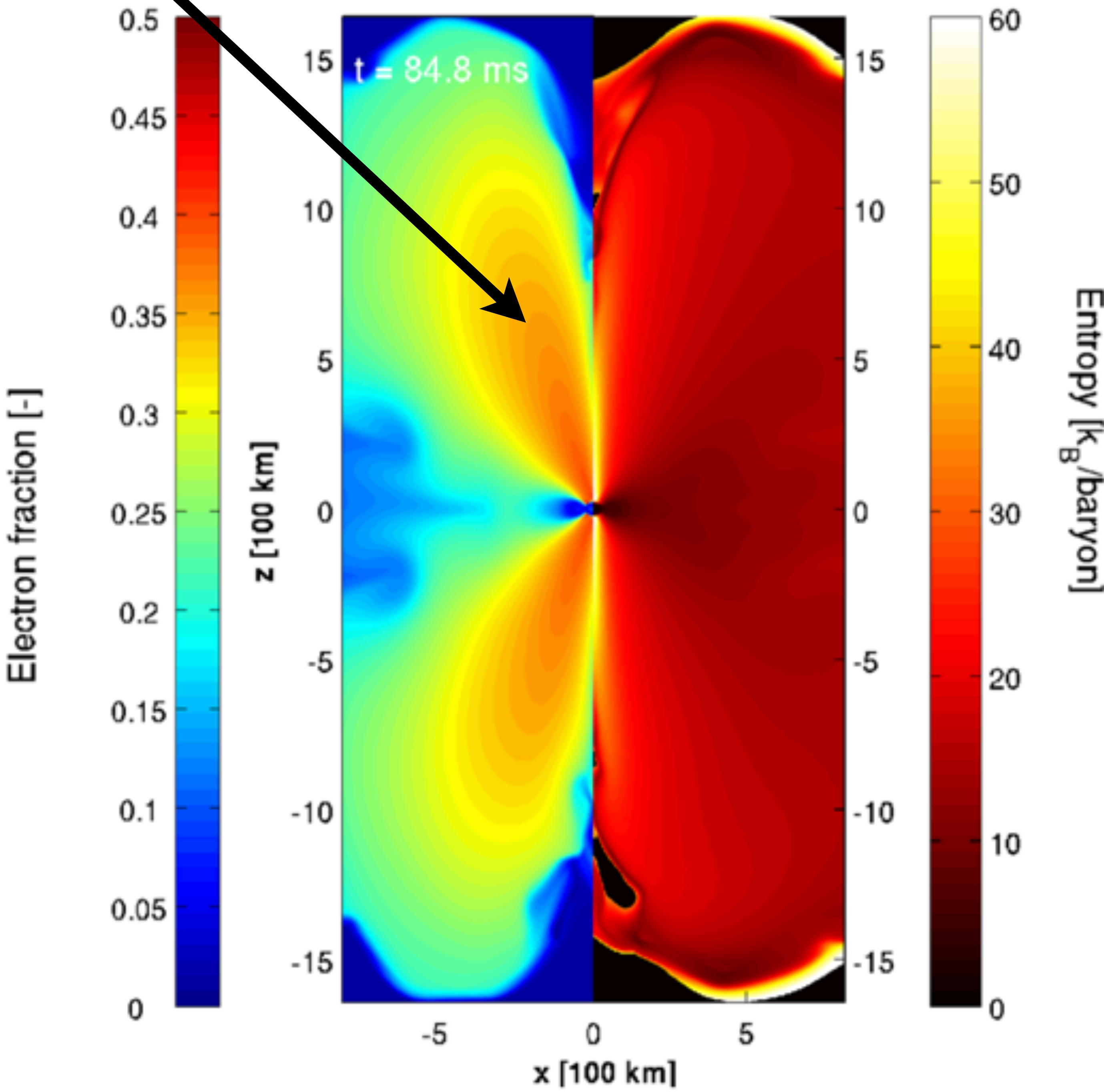

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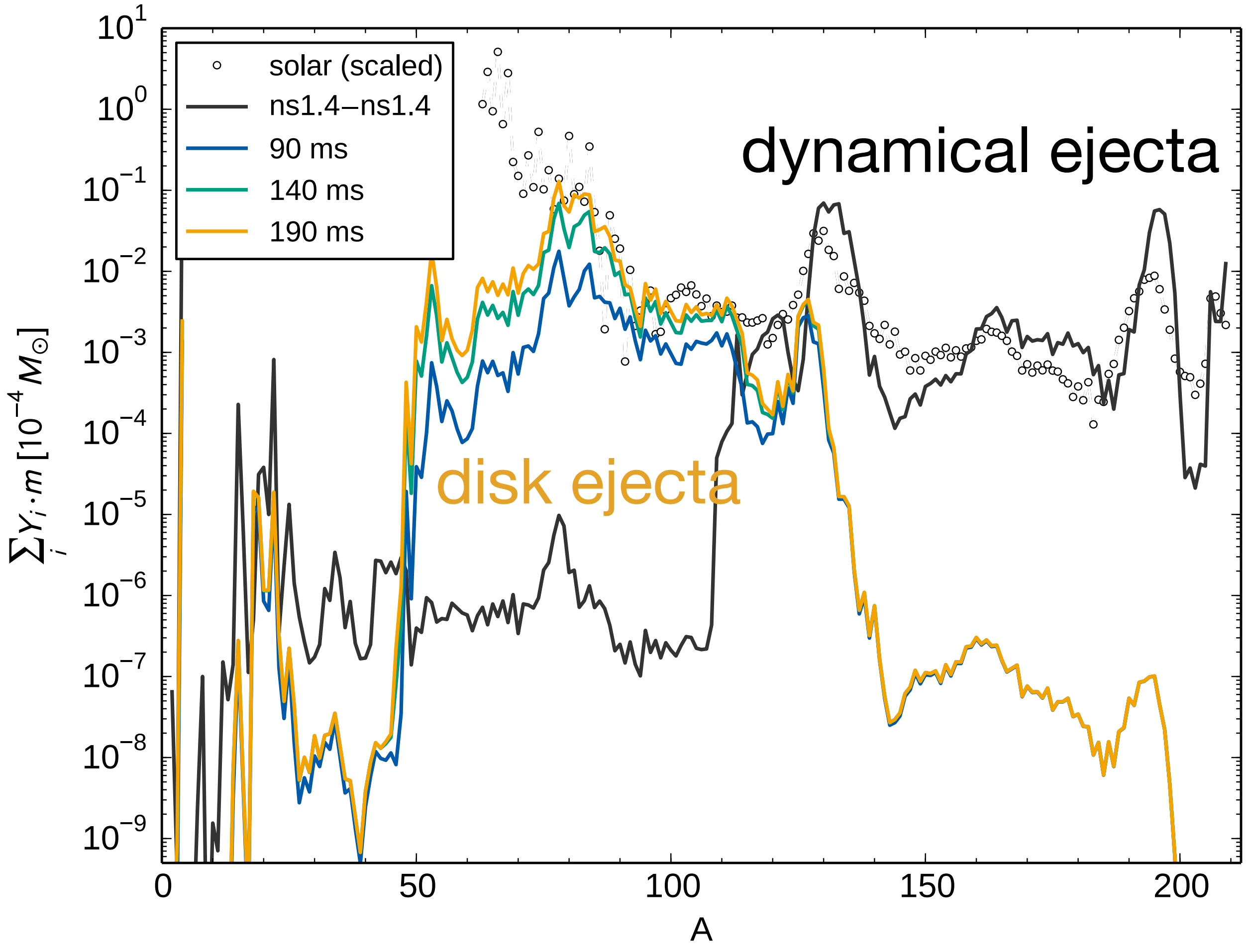

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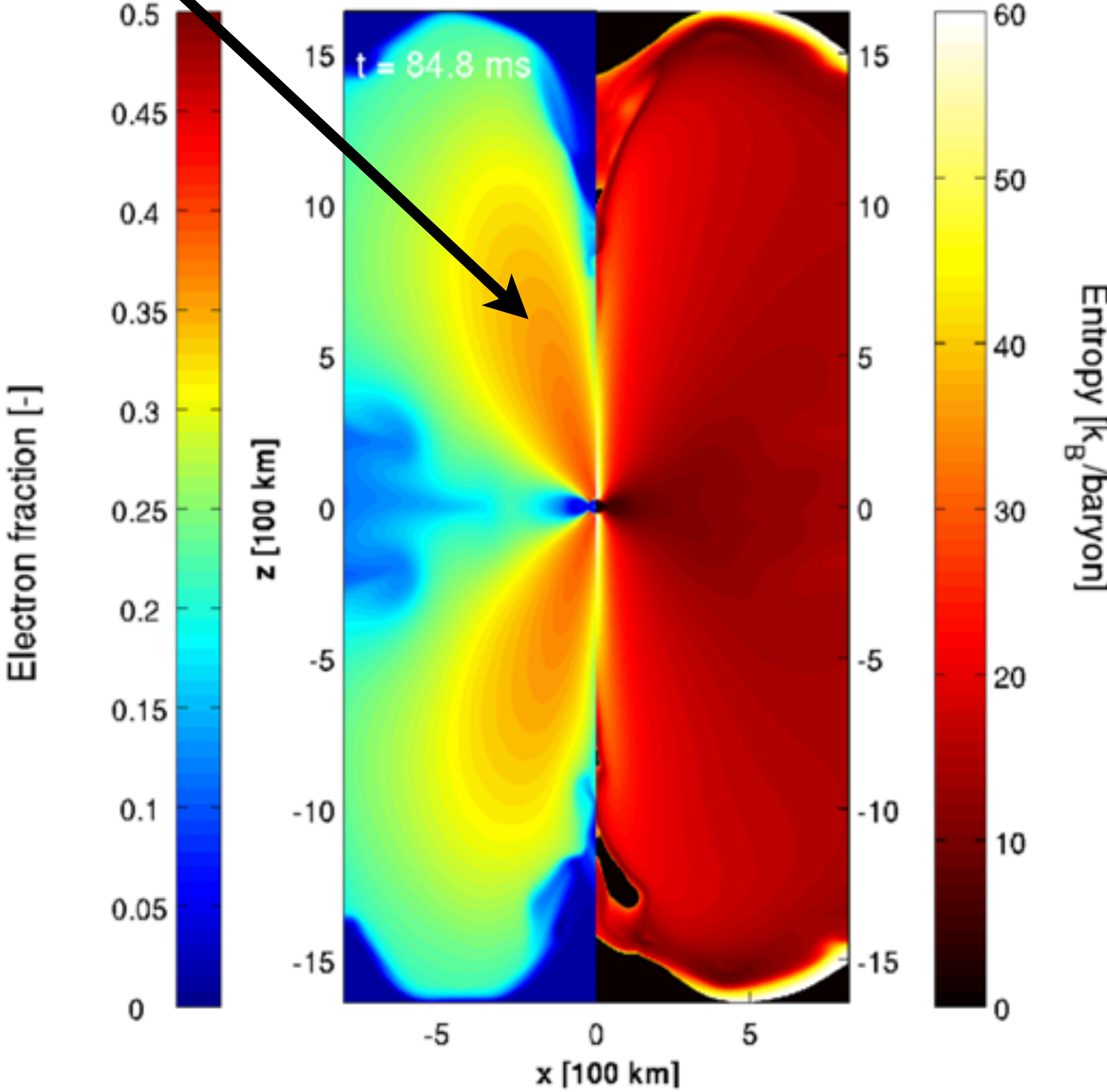

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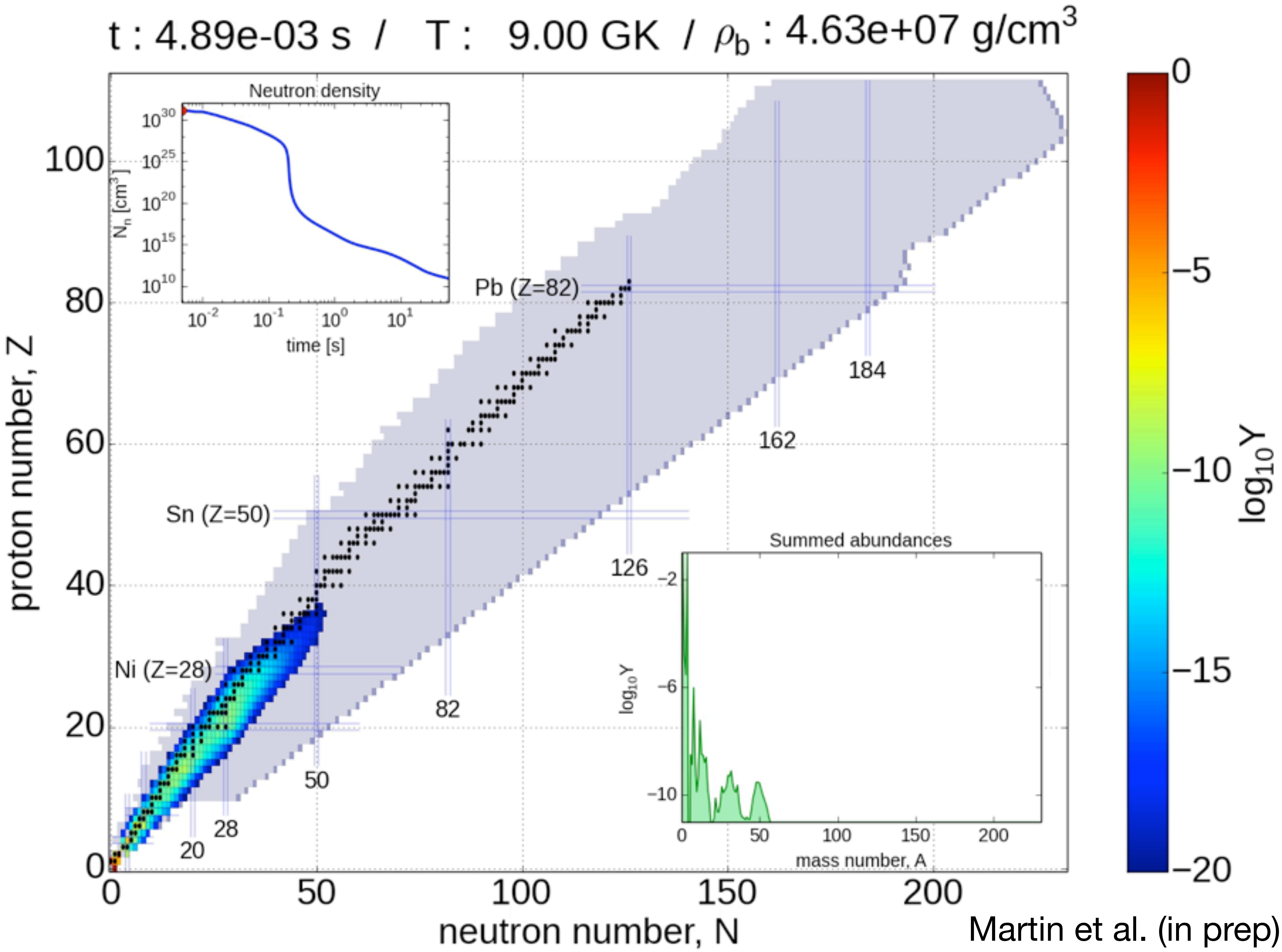
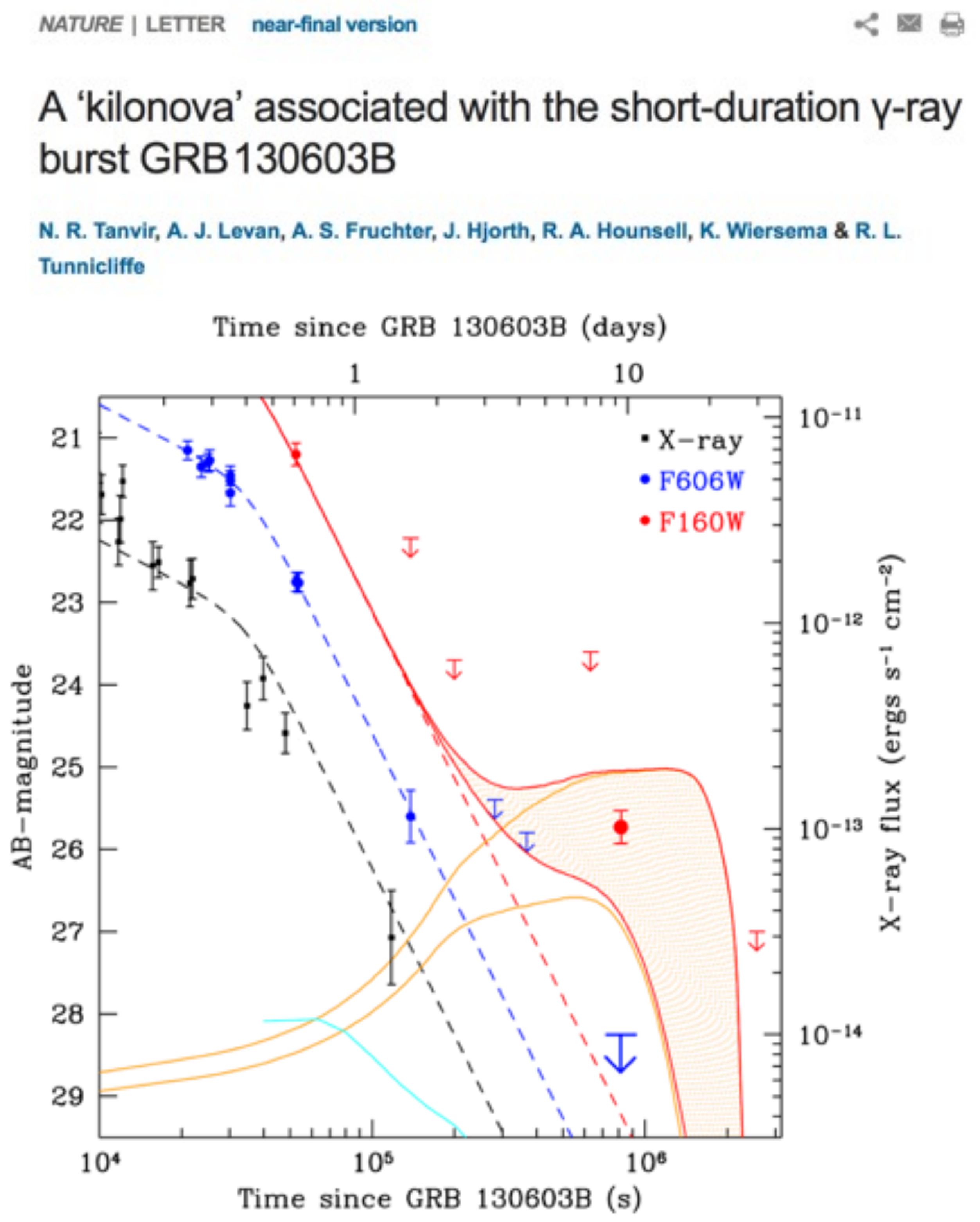


Martin et al. (in prep)

# Radioactive decay in neutron star mergers



*NATURE* | LETTER near-final version

A ‘kilonova’ associated with the short-duration γ-ray burst GRB 130603B

N. R. Tanvir, A. J. Levan, A. S. Fruchter, J. Hjorth, R. A. Hounsell, K. Wiersema & R. L. Tunnicliffe

Berger, Fong & Chornock, 2013
Hotokezaka et al. 2013

Transient with kilo-nova luminosity (Metzger et al. 2010, Roberts et al. 2011, Goriely et al. 2011):
direct observation of r-process,
EM counter part to GW

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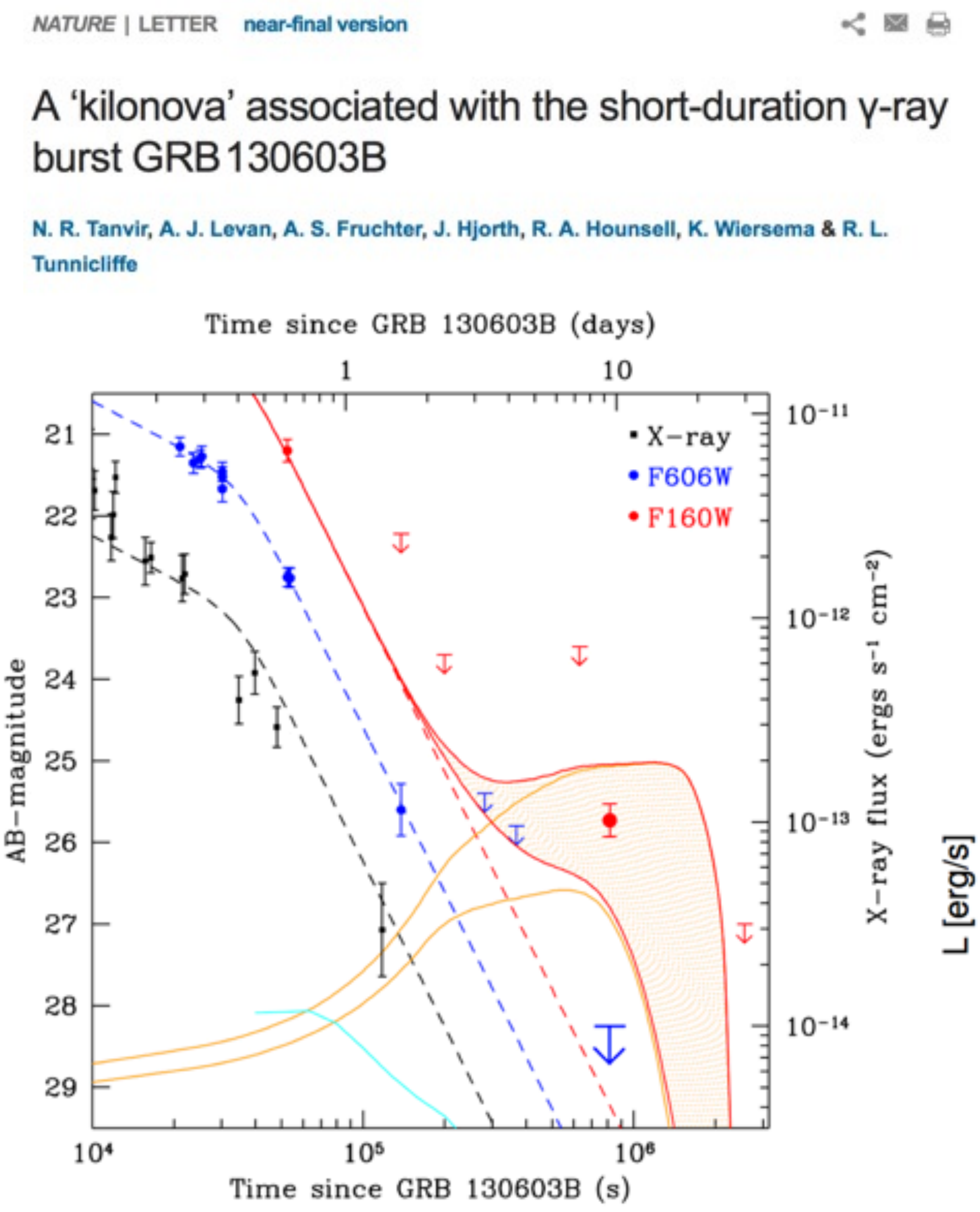

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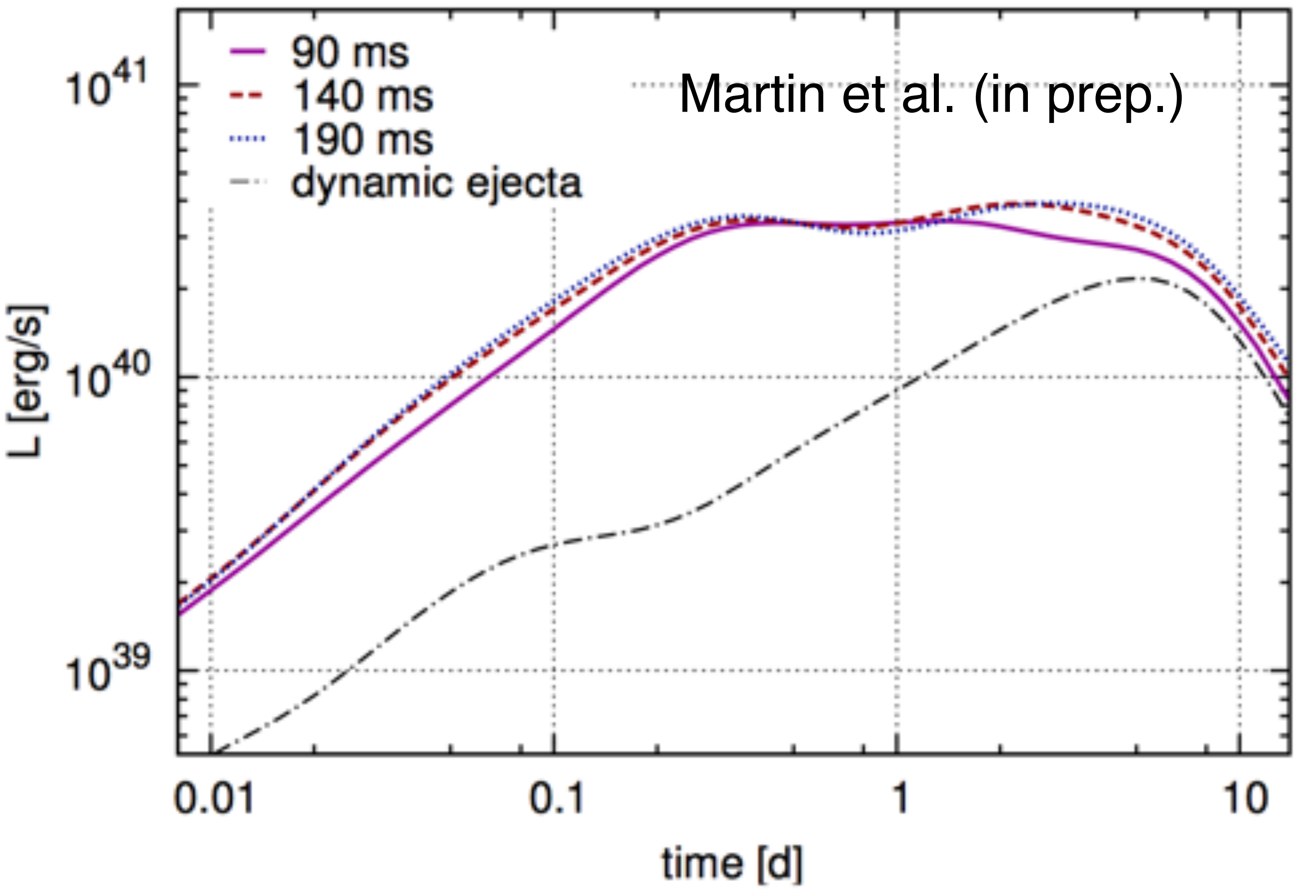
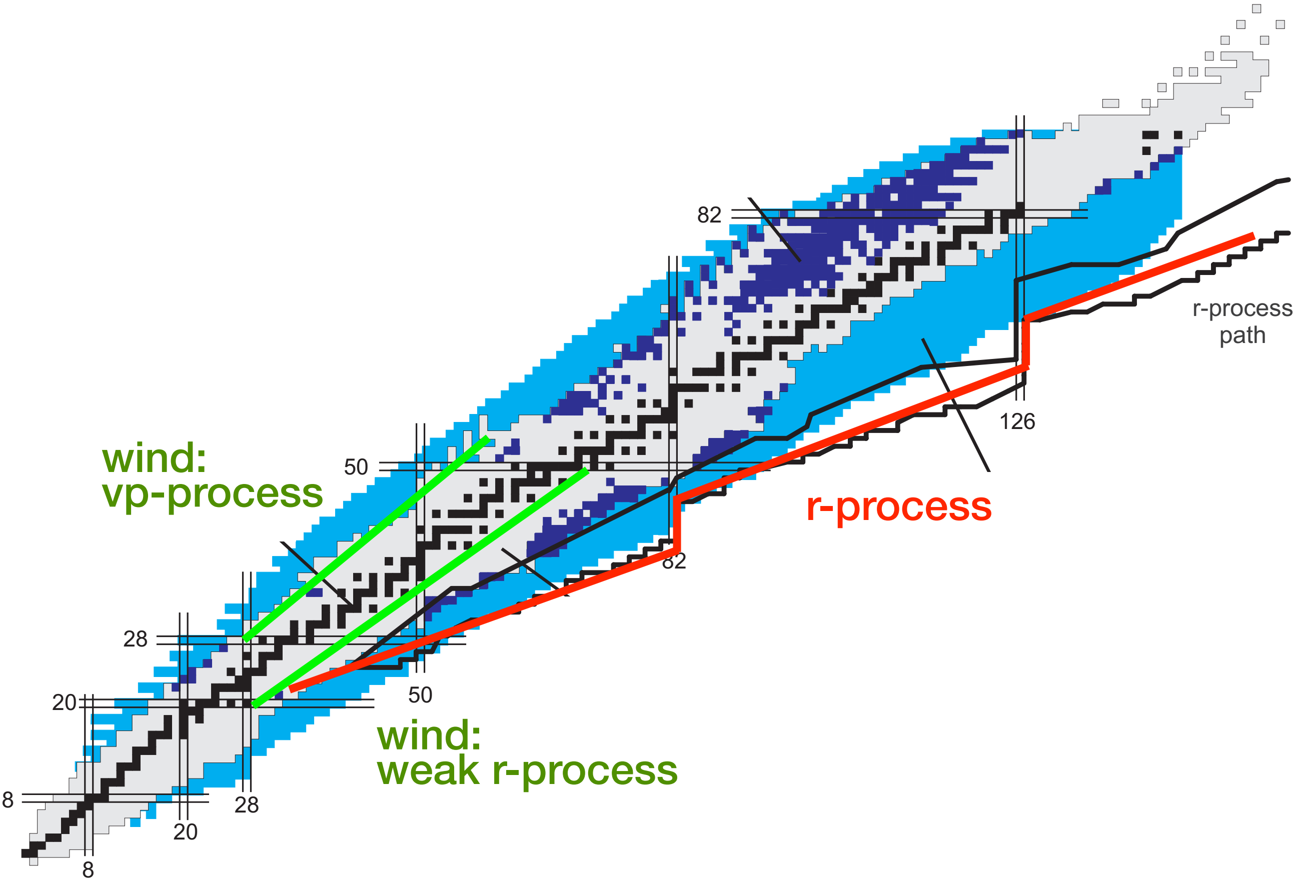
## Light curve wind + dyn. ejecta



# Conclusions

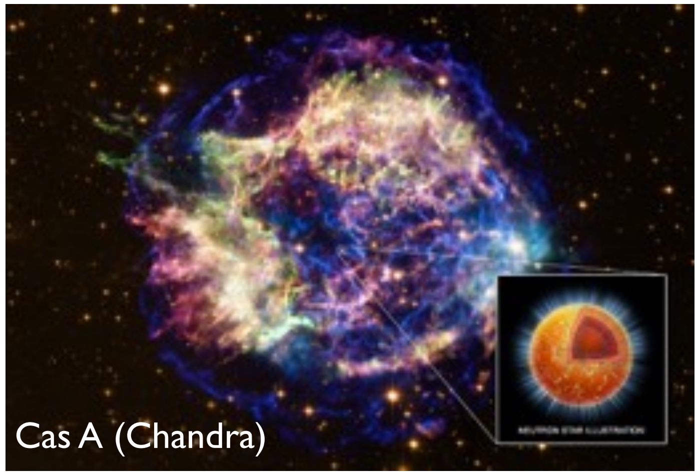


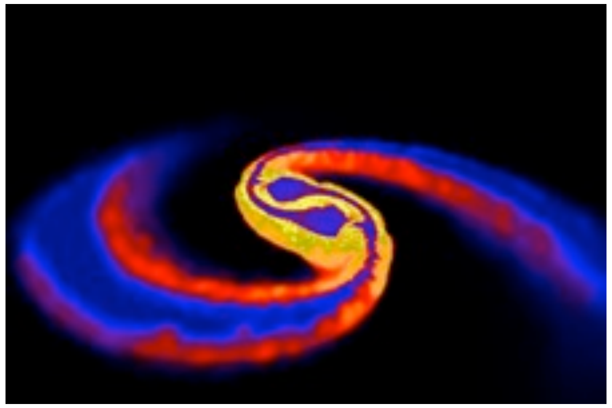
Core-collapse supernovae:

explosive: up to Fe

**wind: up to ~Ag**

jets: r-process


Cas A (Chandra)



Neutron star mergers:

r-process

**weak r-process**

Impact of nuclear physics and astrophysics: (α,n) and $Y_e$

Observations to constrain astrophysics