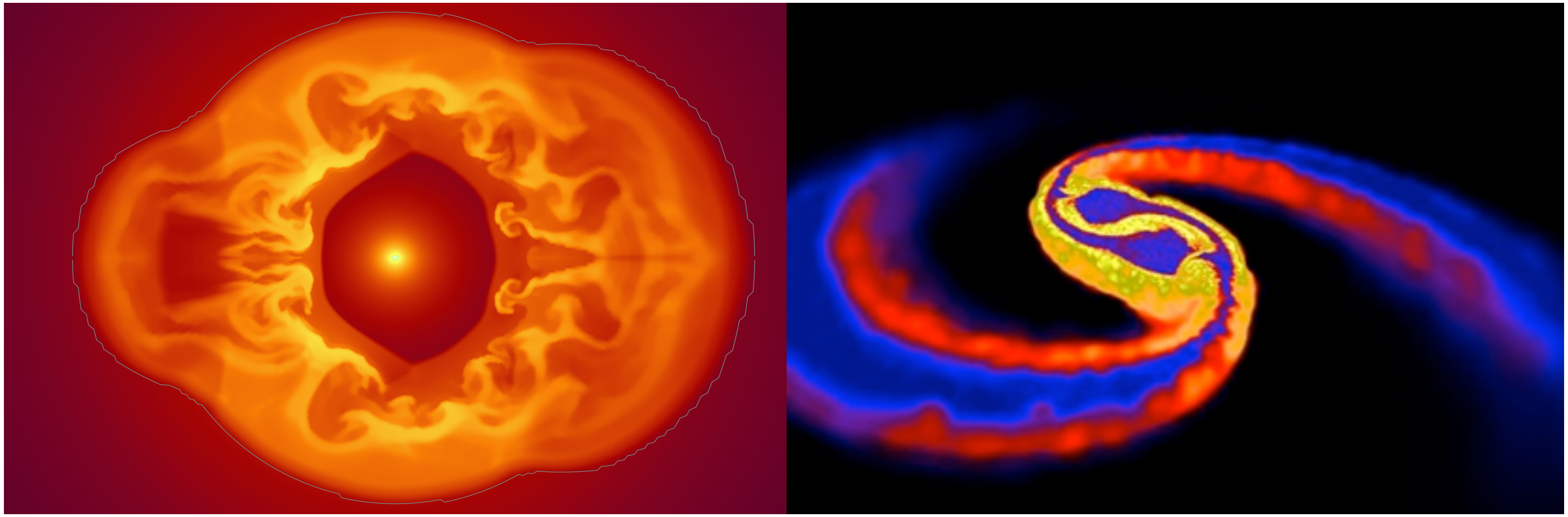
Annual NewCompStar Conference 2015

Nucleosynthesis of heavy elements in core-collapse supernovae & neutron star mergers

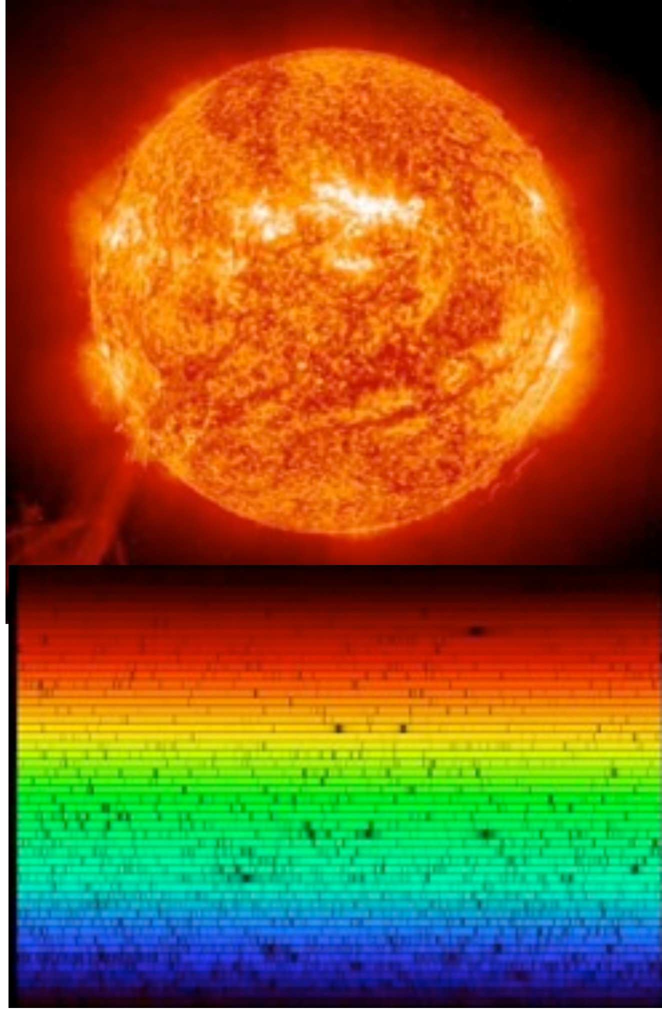


TECHNISCHE UNIVERSITÄT DARMSTADT

Almudena Arcones
Helmholtz Young Investigator Group

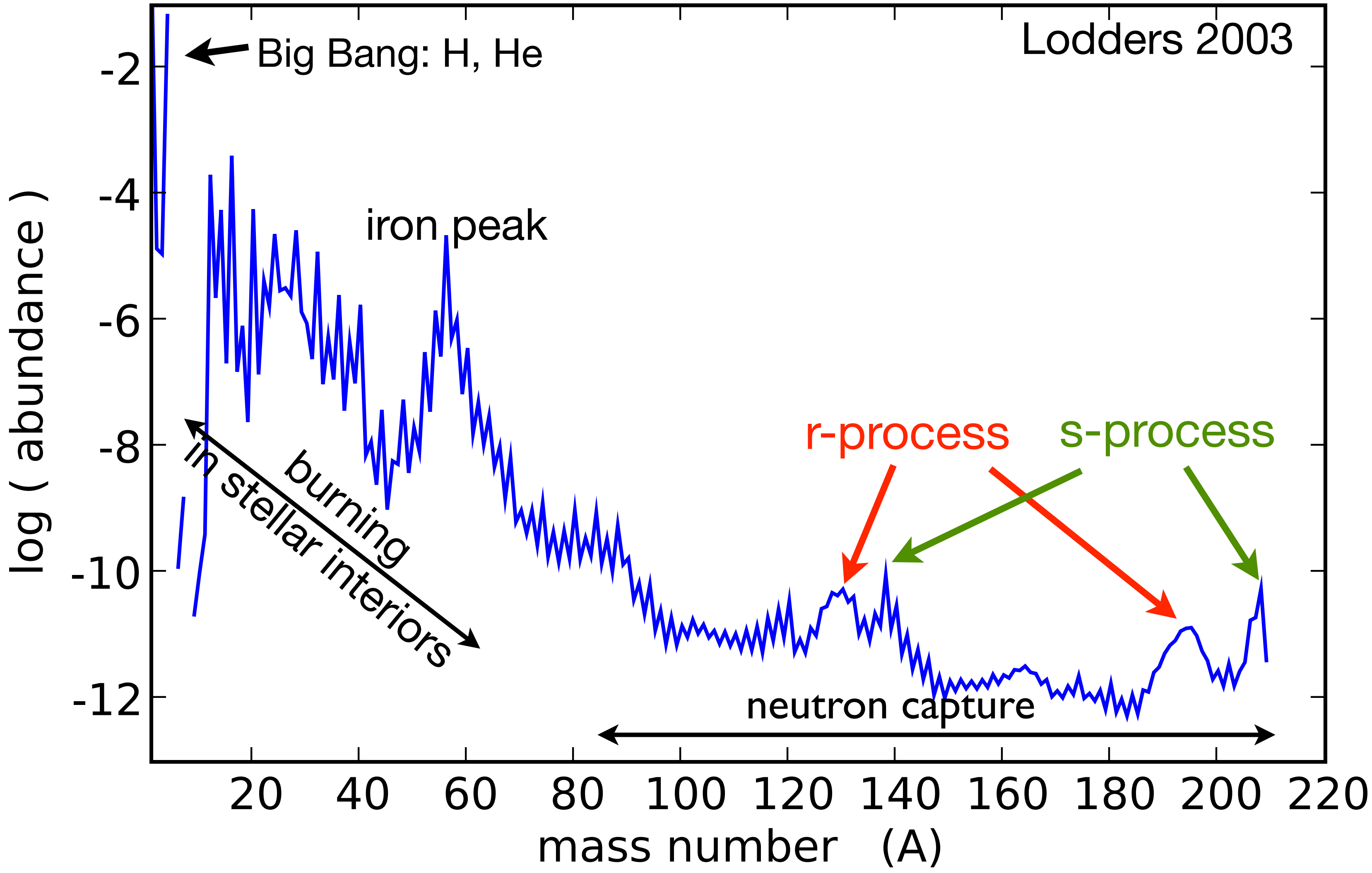
HELMHOLTZ GEMEINSCHAFT

Solar system abundances



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

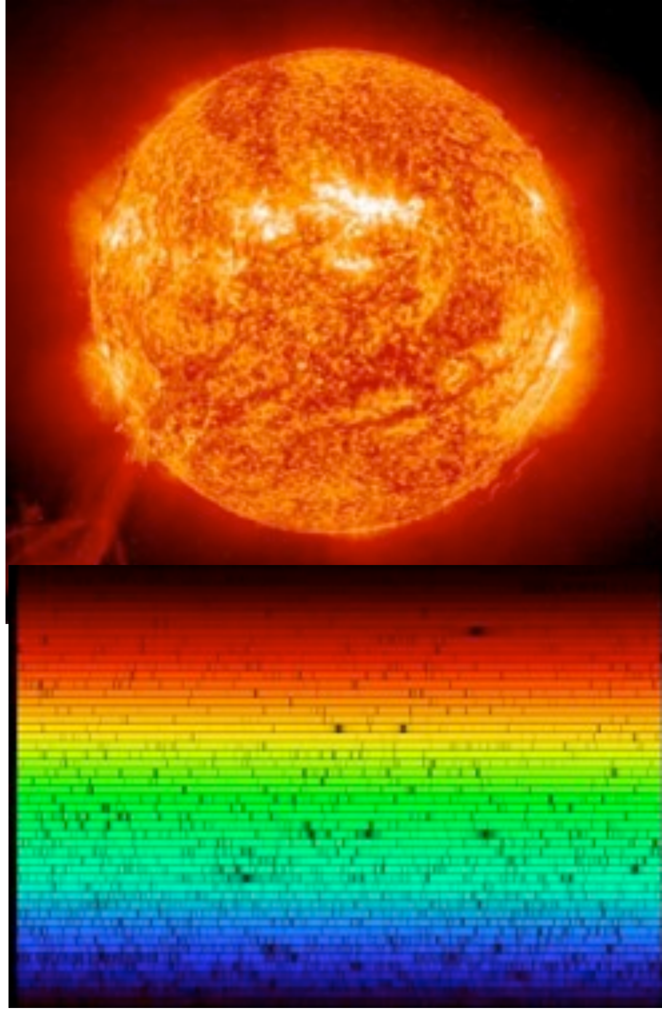
Contribution of all nucleosynthesis processes



s-process:
slow neutron capture
r-process:
rapid neutron capture

abundance = mass fraction / mass number

Solar system abundances



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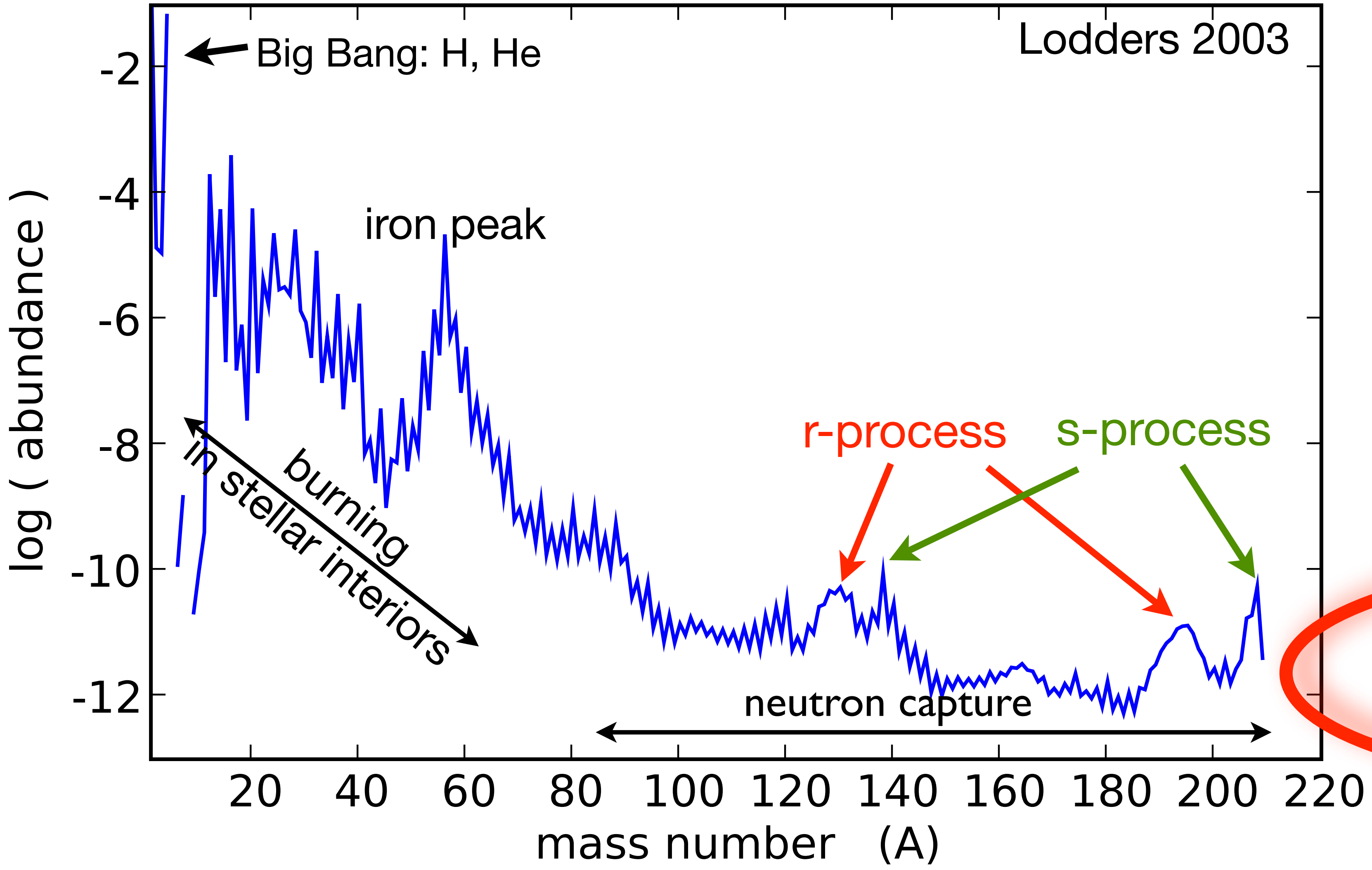

s-process:
slow neutron capture
r-process:
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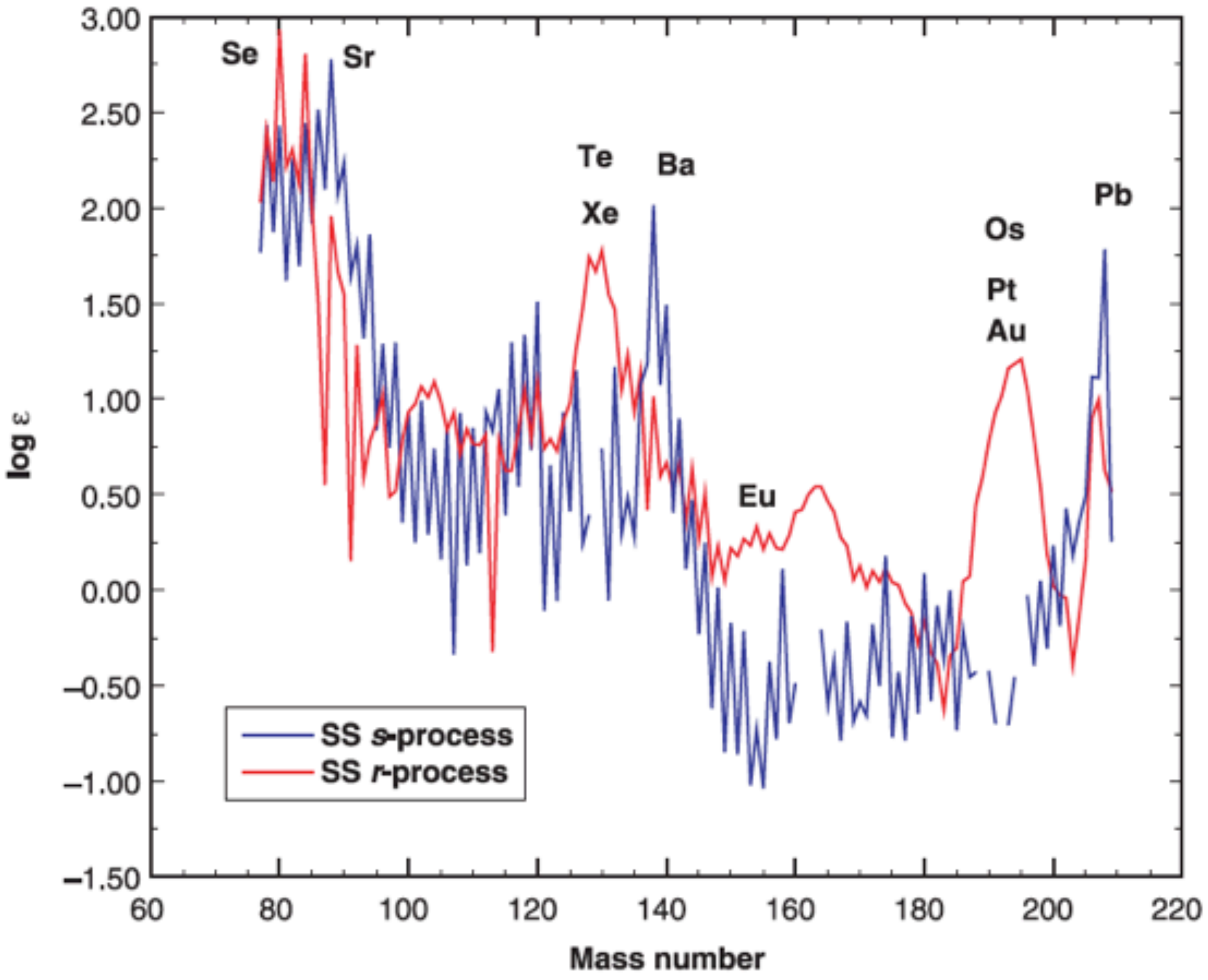
abundance = mass fraction / mass number

Solar system abundance

solar r-process = total - s-process - p-process = residual abundances



Sneden & Cowan 2003

r-process peaks:

1st peak: A≈80 → N=50

2nd peak: A≈130 → N=82

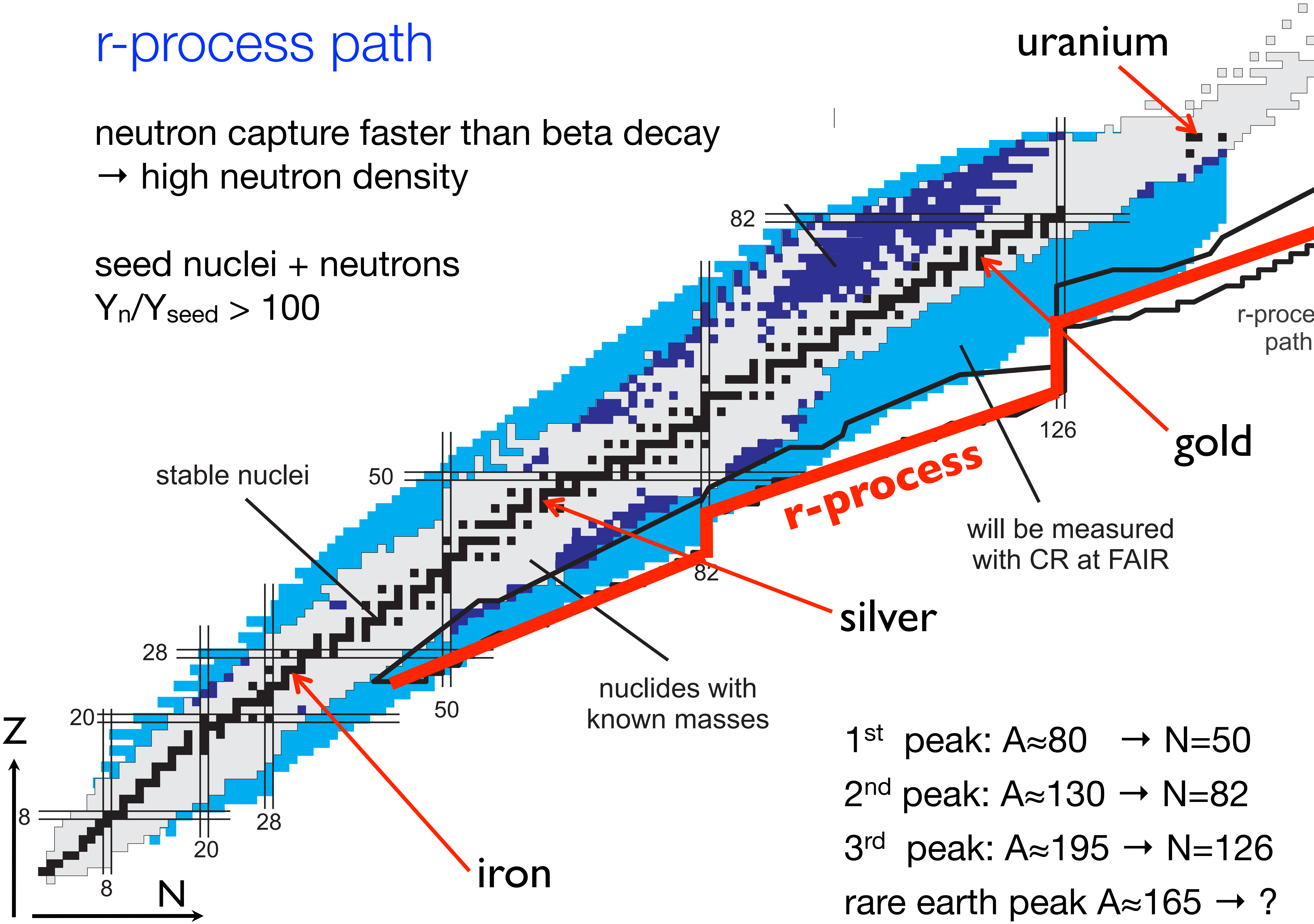
3rd peak: A≈195 → N=126

rare earth peak A≈165 → ?

r-process path

neutron capture faster than beta decay
→ high neutron density

seed nuclei + neutrons
$Y_n/Y_{seed} > 100$



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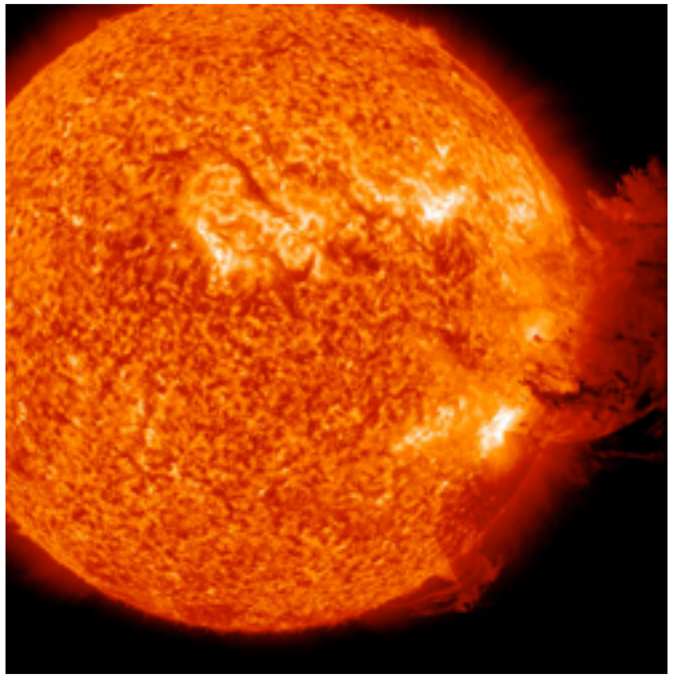
rare earth peak A≈165 → ?

Galactic chemical evolution

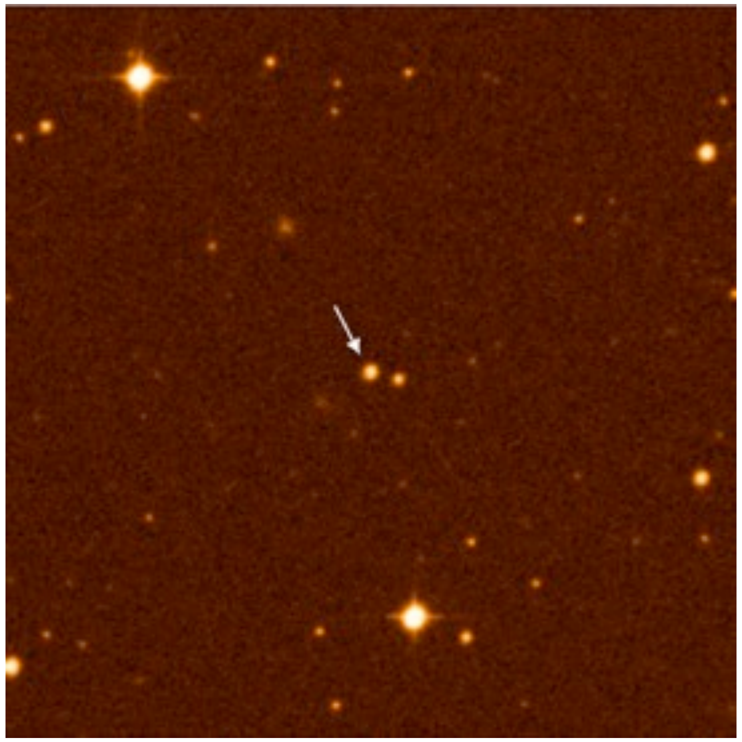
First stars: H, He → Heavy elements ← New generation of stars

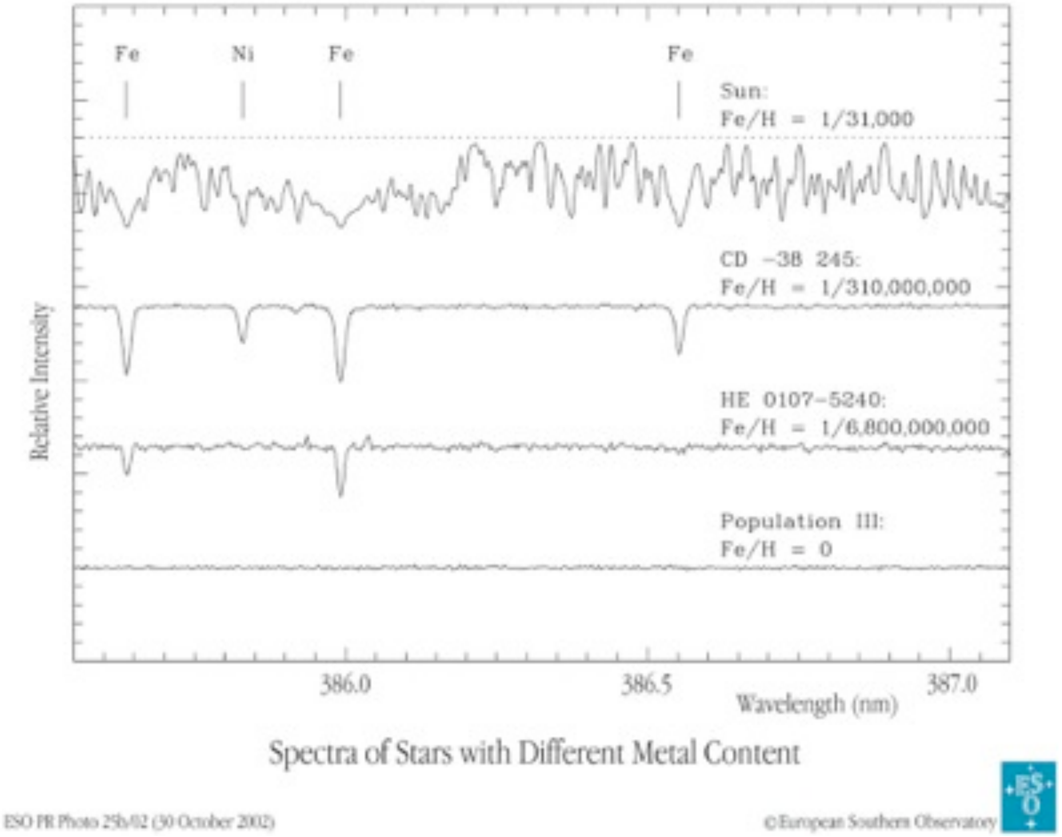
Heavy elements → Interstellar medium (ISM) → New generation of stars

Artist's View of Star Formation in the Early Universe
Painting by Adolf Schaller • STScI-PRC02-02



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



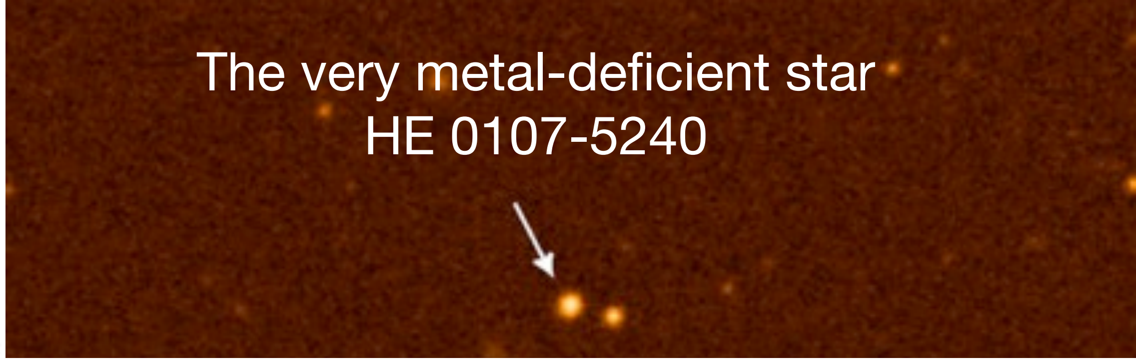


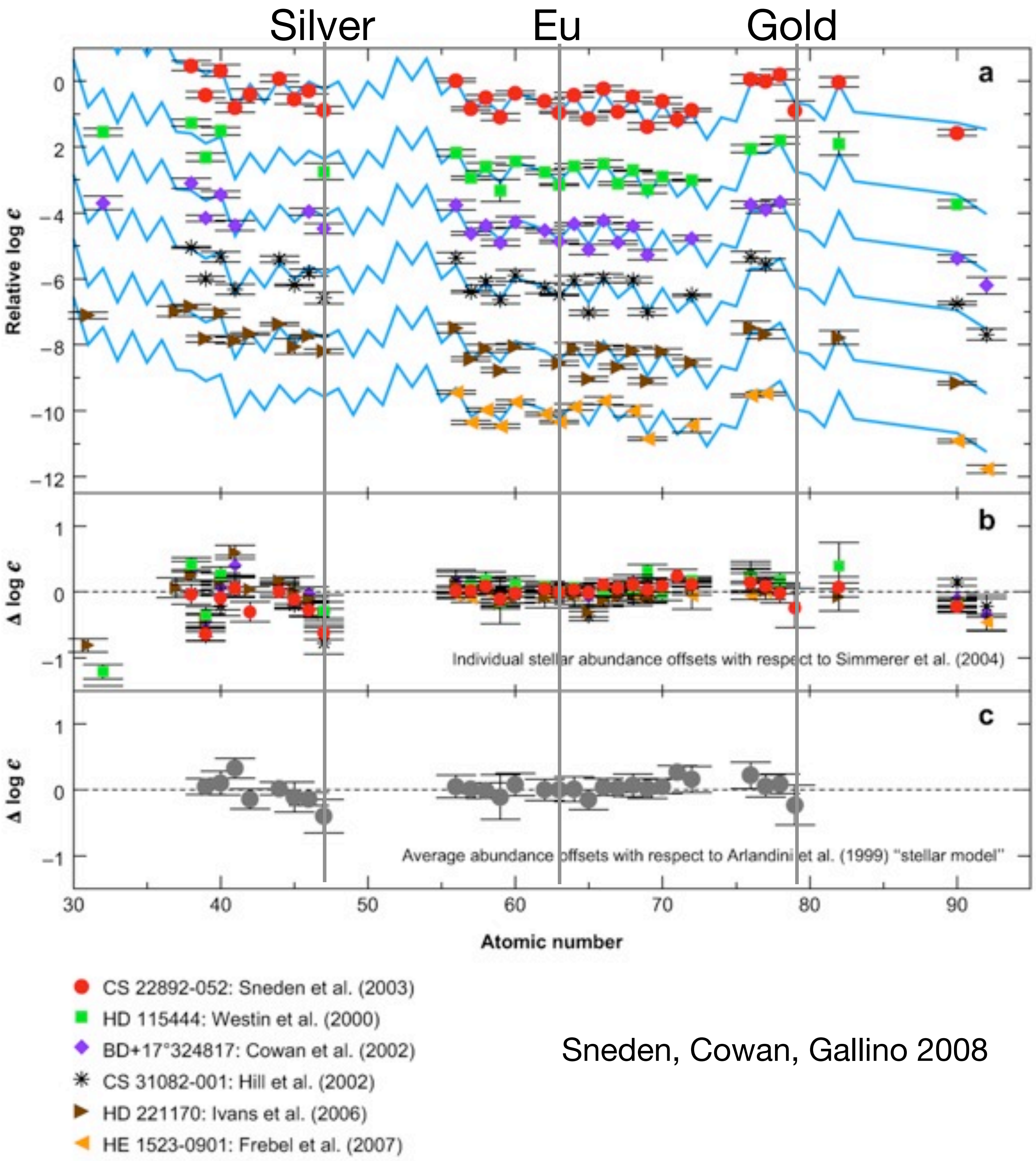
Spectra of Stars with Different Metal Content

ESO PR Photo 25b/02 (30 October 2002)

©European Southern Observatory

Oldest observed stars





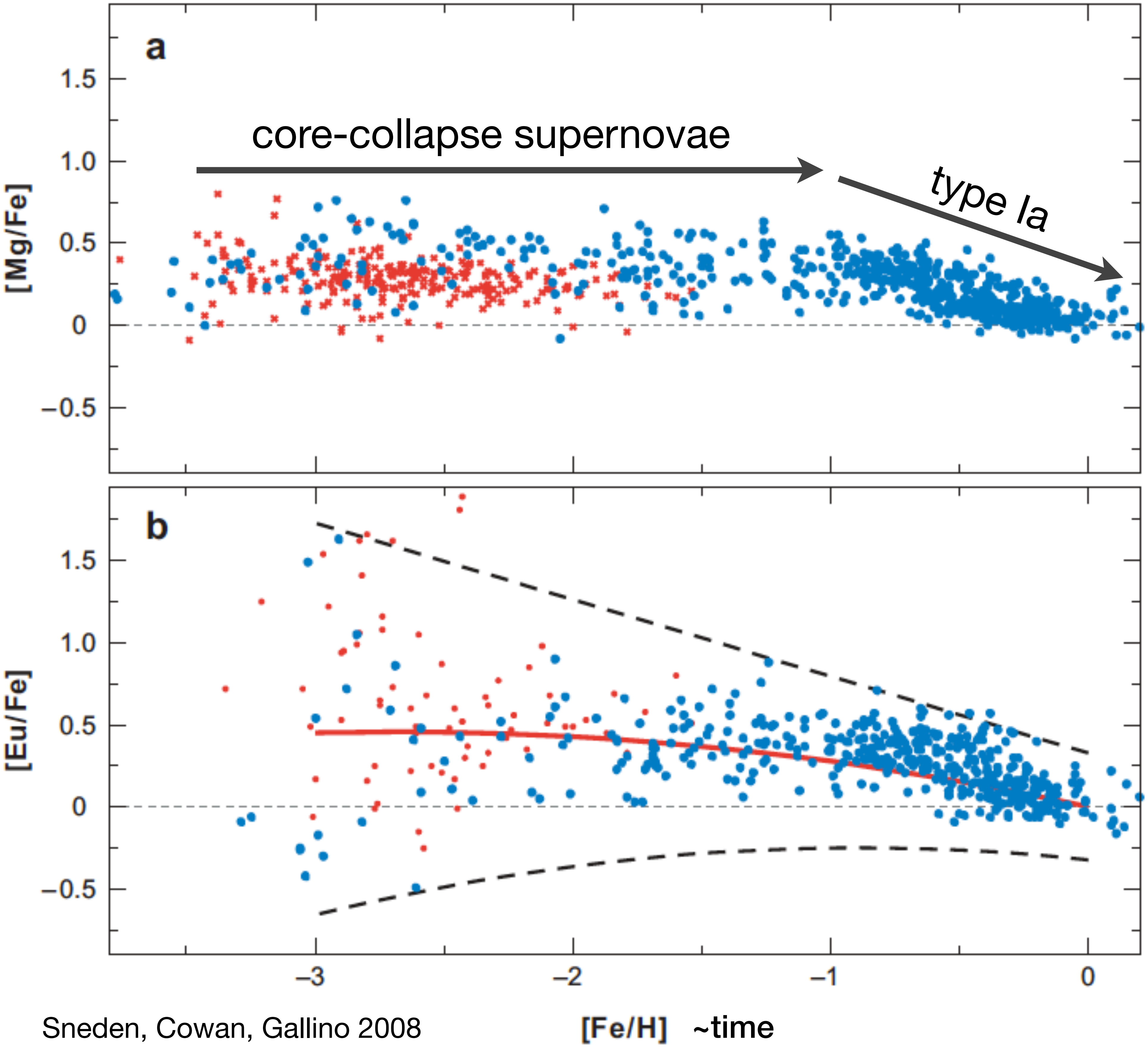
Sneden, Cowan, Gallino 2008

Elemental abundances in:
- ultra metal-poor stars and
- solar system

- Robust r-process for 56<Z<83
- Scatter for lighter heavy elements, Z~40

How many "r-processes" contribute to solar system and UMP stars abundances?

Trends with metallicity



Sneden, Cowan, Gallino 2008

Fe and Mg produced in same site:
core-collapse supernovae

Significant scatter at low metallicities

r-process production rare in the early Galaxy

Mg and Fe production is not coupled to r-process production

The r-process: what do we know?

- Solar system: residual r-process
  r-process peaks and path → fast neutron capture
- Astrophysical environment: explosive and high neutron density
- UMP stars: robust process from 2nd to 3rd peak
  contribution from other process(es) below 2nd peak
- Chemical evolution: r-process does not occur in every
  core-collapse supernovae

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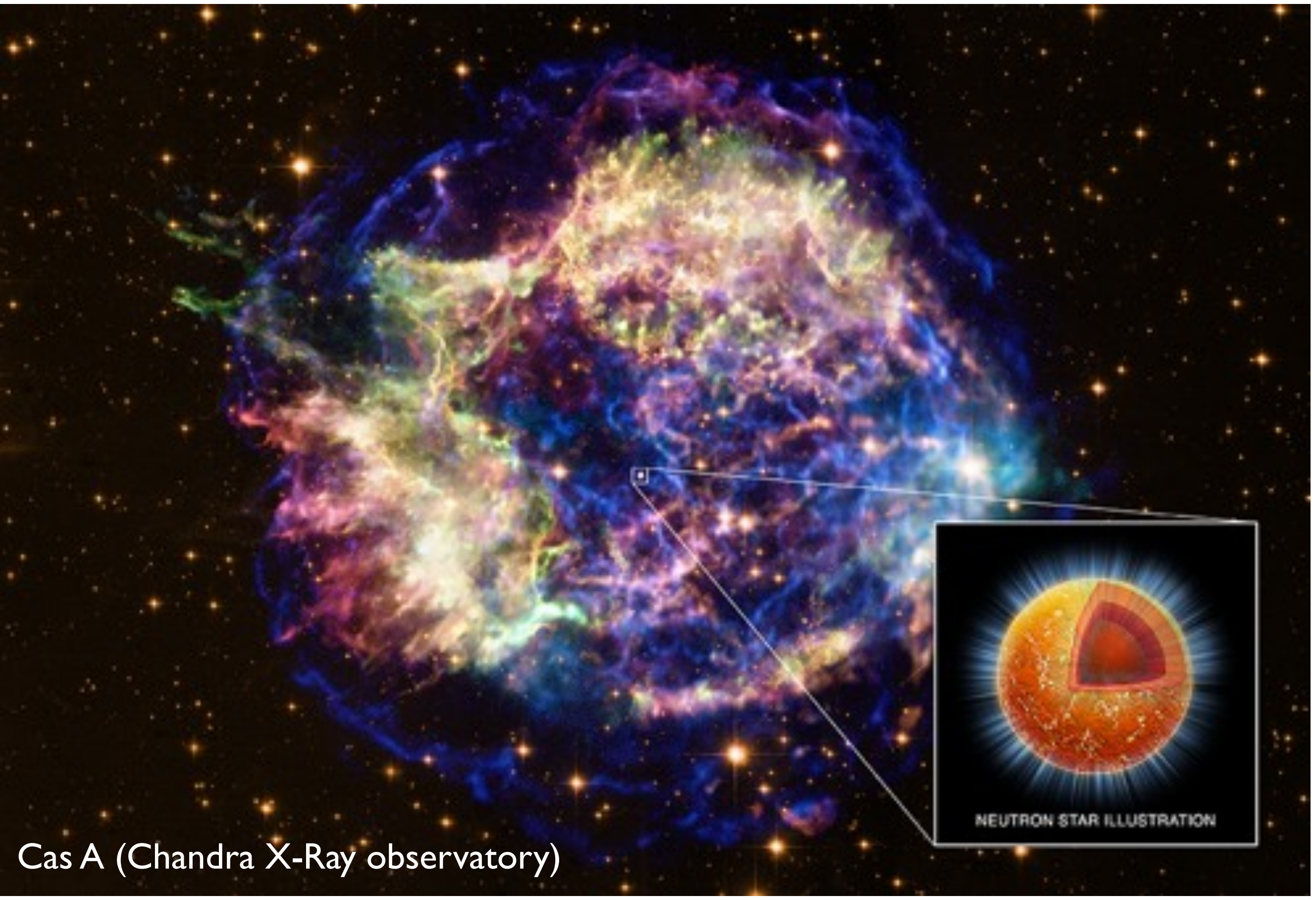
What do we need to know better?

- Astrophysical site(s)
- Nuclear physics

Where does the r-process occur?

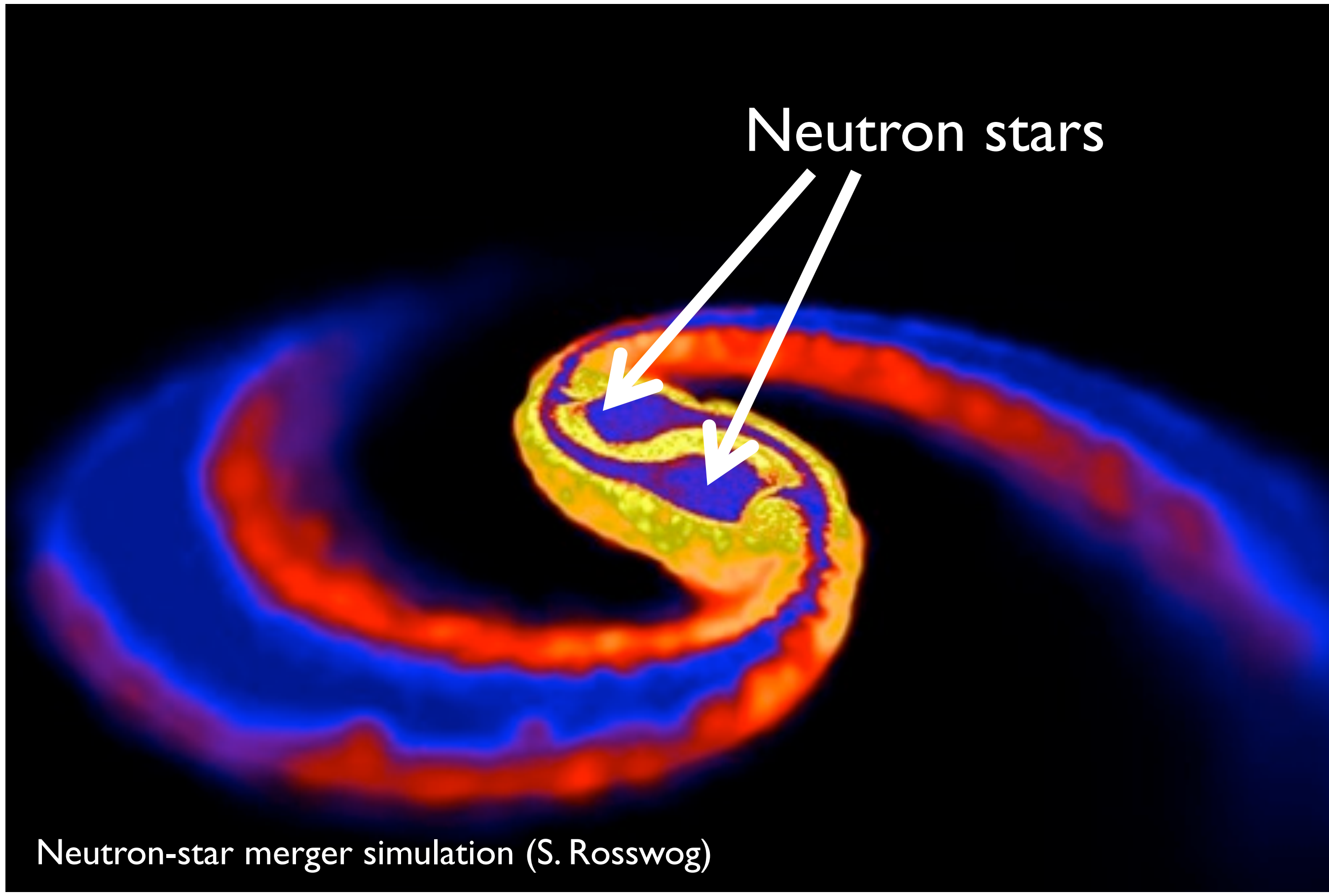
Core-collapse supernovae



Cas A (Chandra X-Ray observatory)

- neutrino-driven winds (Woosley et al. 1994,...)
- shocked surface layers (Ning, Qian, Meyer 2007)
- jets (Winteler et al. 2012)
- neutrino-induced in He shell (Banerjee, Haxton, Qian 2011)

Neutron star mergers

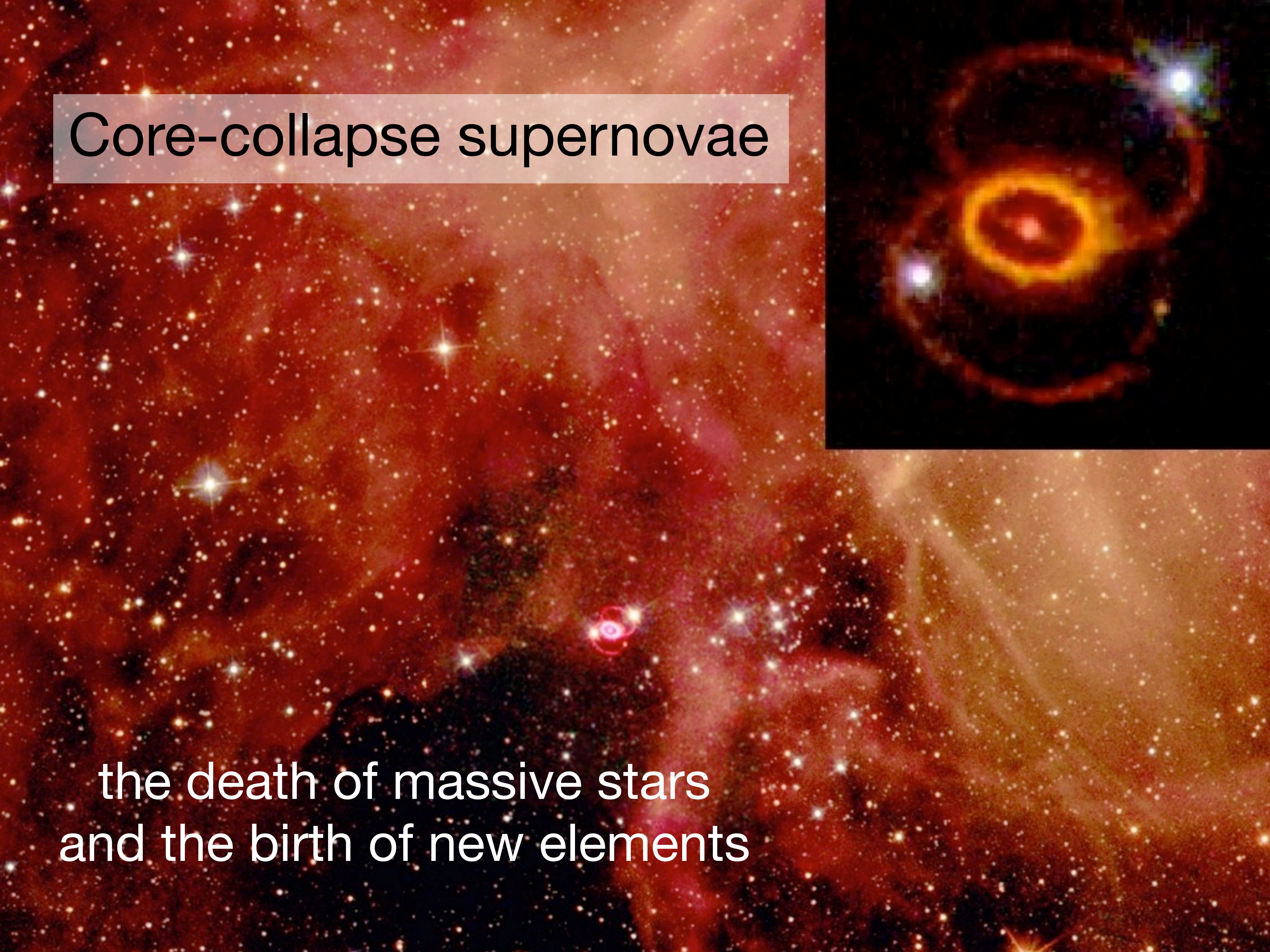


Neutron-star merger simulation (S. Rosswog)

- dynamic ejecta
- neutrino-driven winds
- evaporation disk

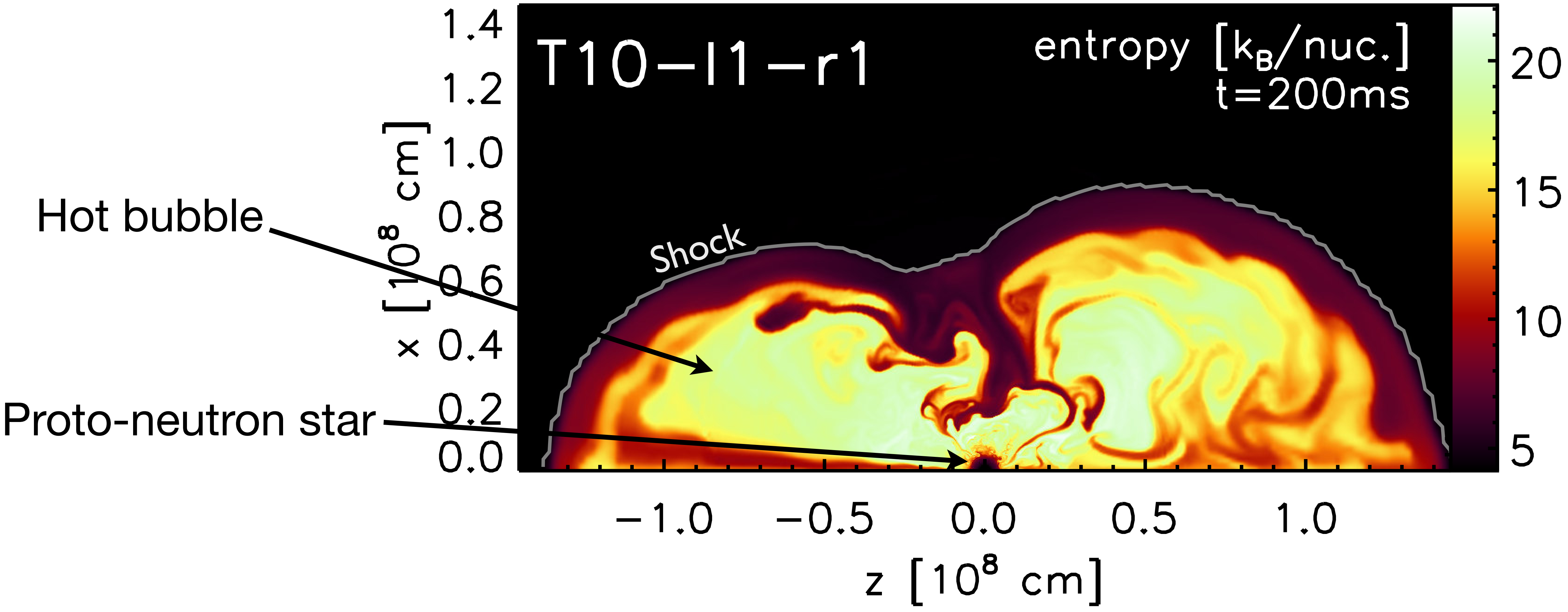
(Lattimer & Schramm 1974, Freiburghaus et al. 1999, ...)

Core-collapse supernovae



the death of massive stars
and the birth of new elements

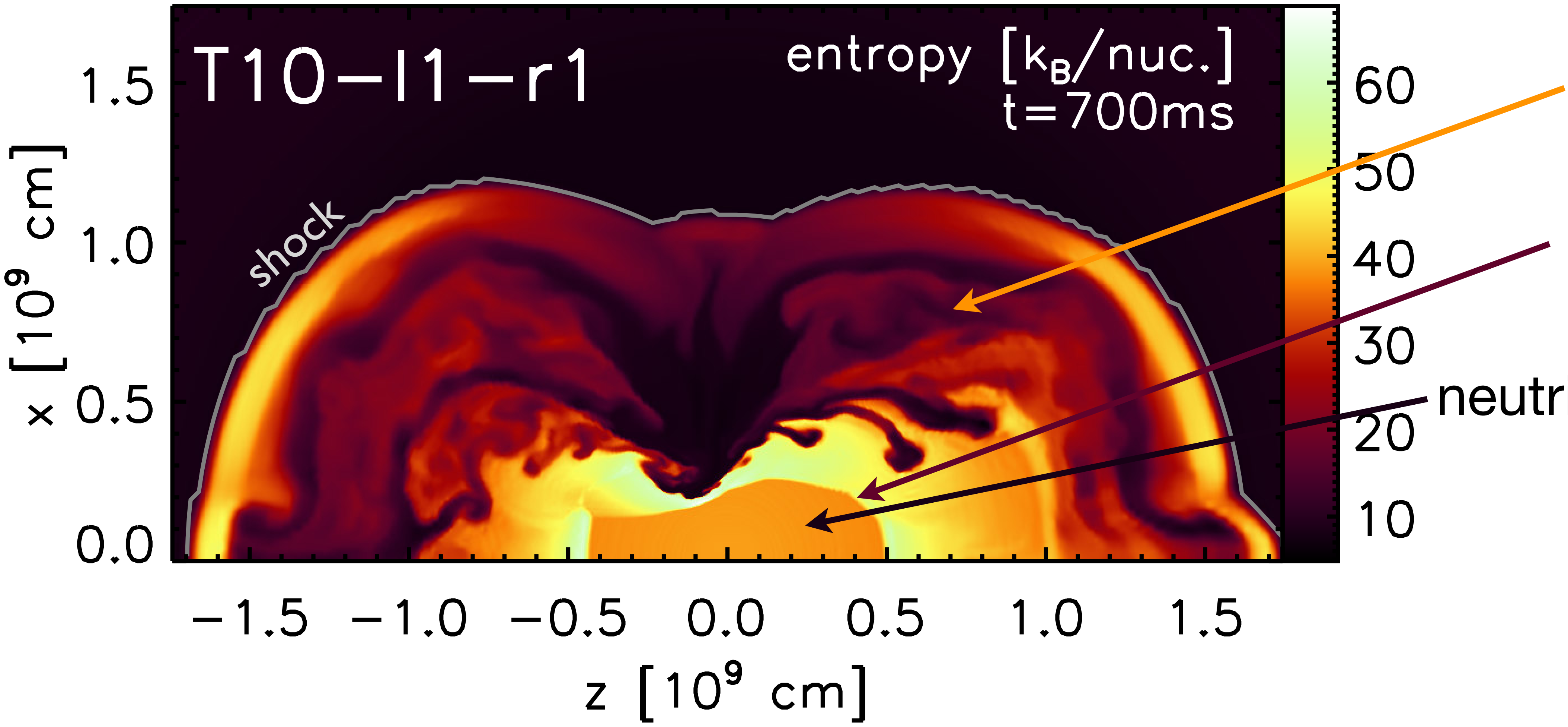
Core-collapse supernova simulations



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

Core-collapse supernova simulations



slow ejecta

reverse shock

neutrino-driven wind

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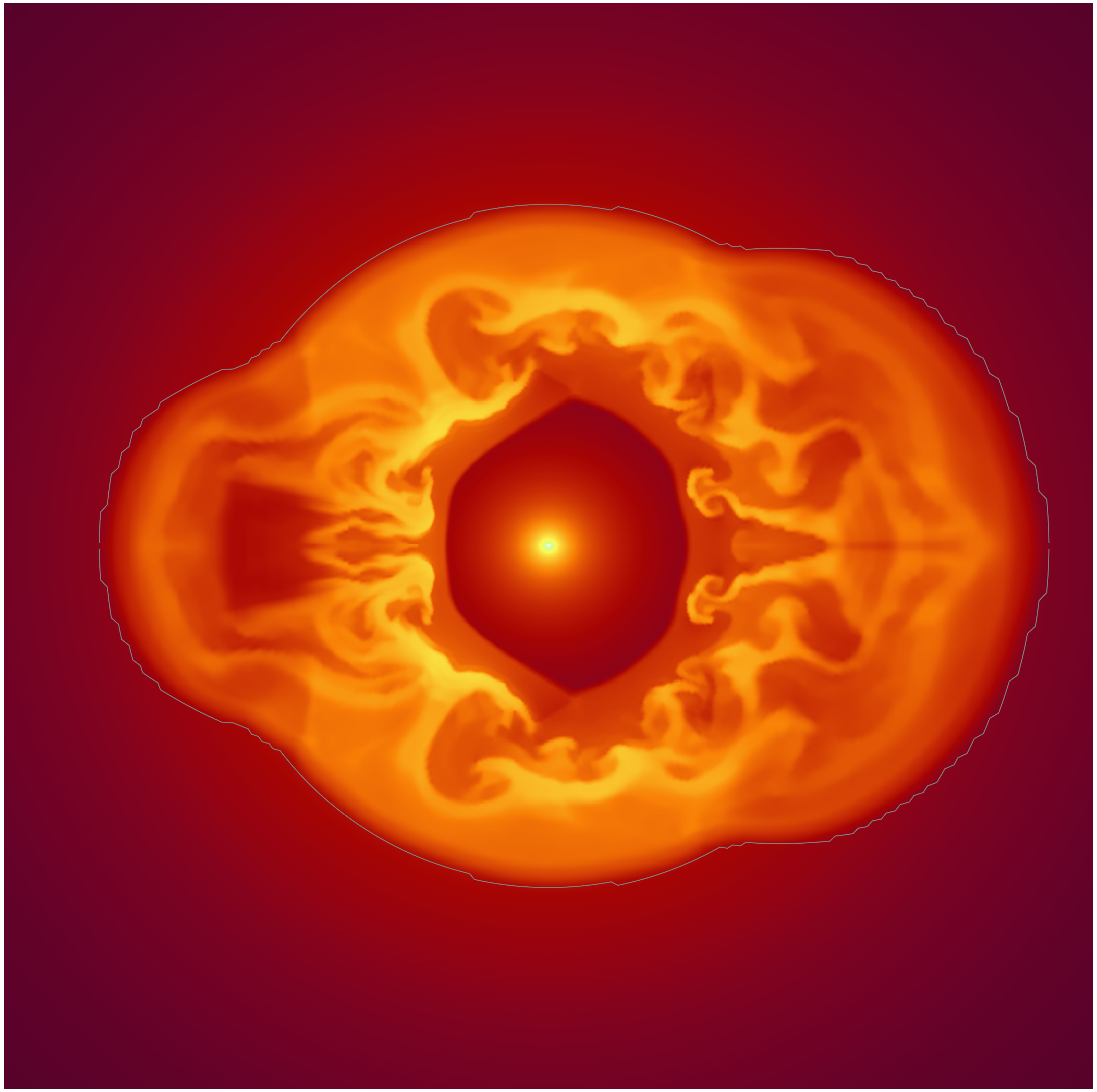
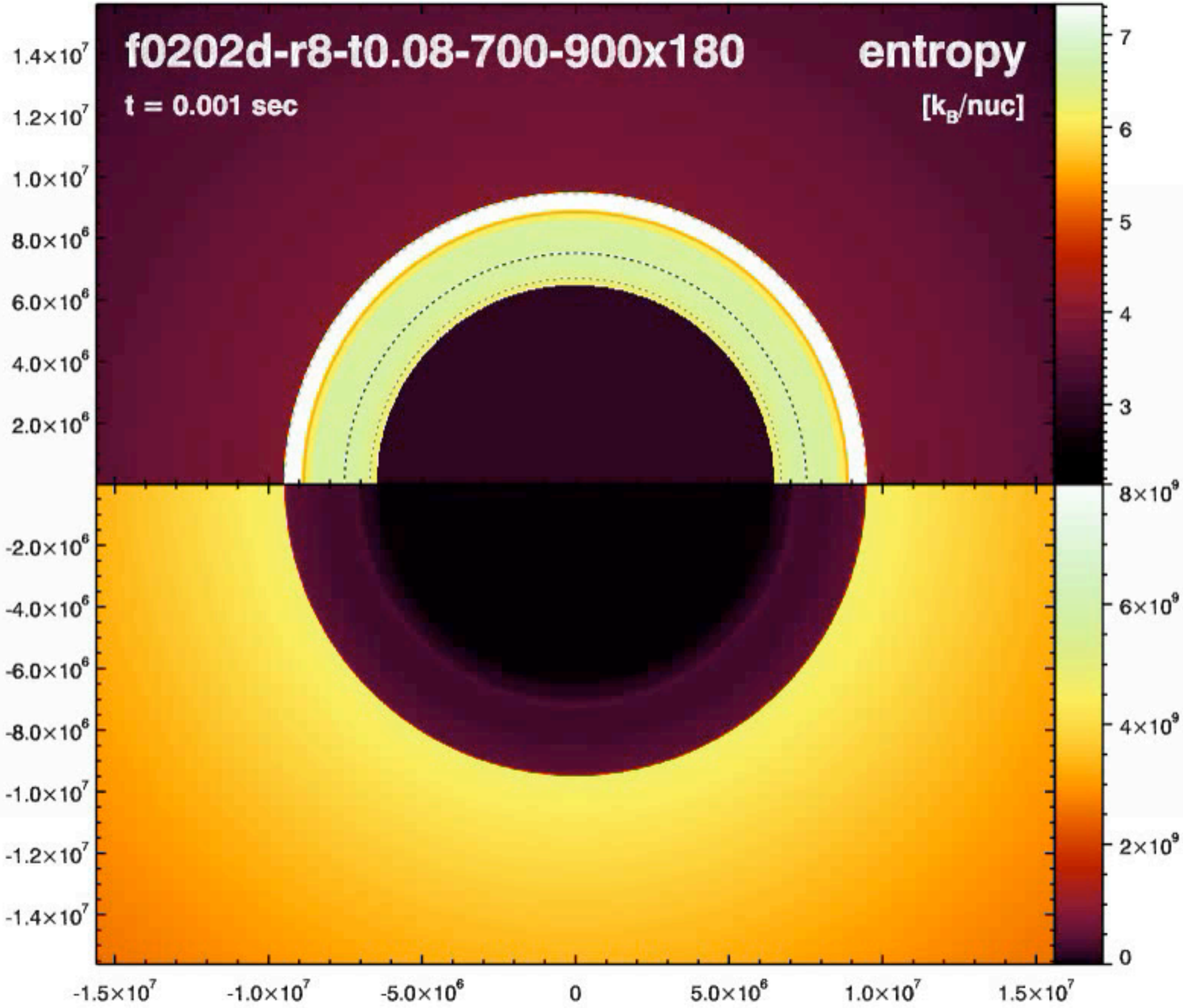
Neutrino-driven winds



Arcones & Janka (2011)

Neutrino-driven winds



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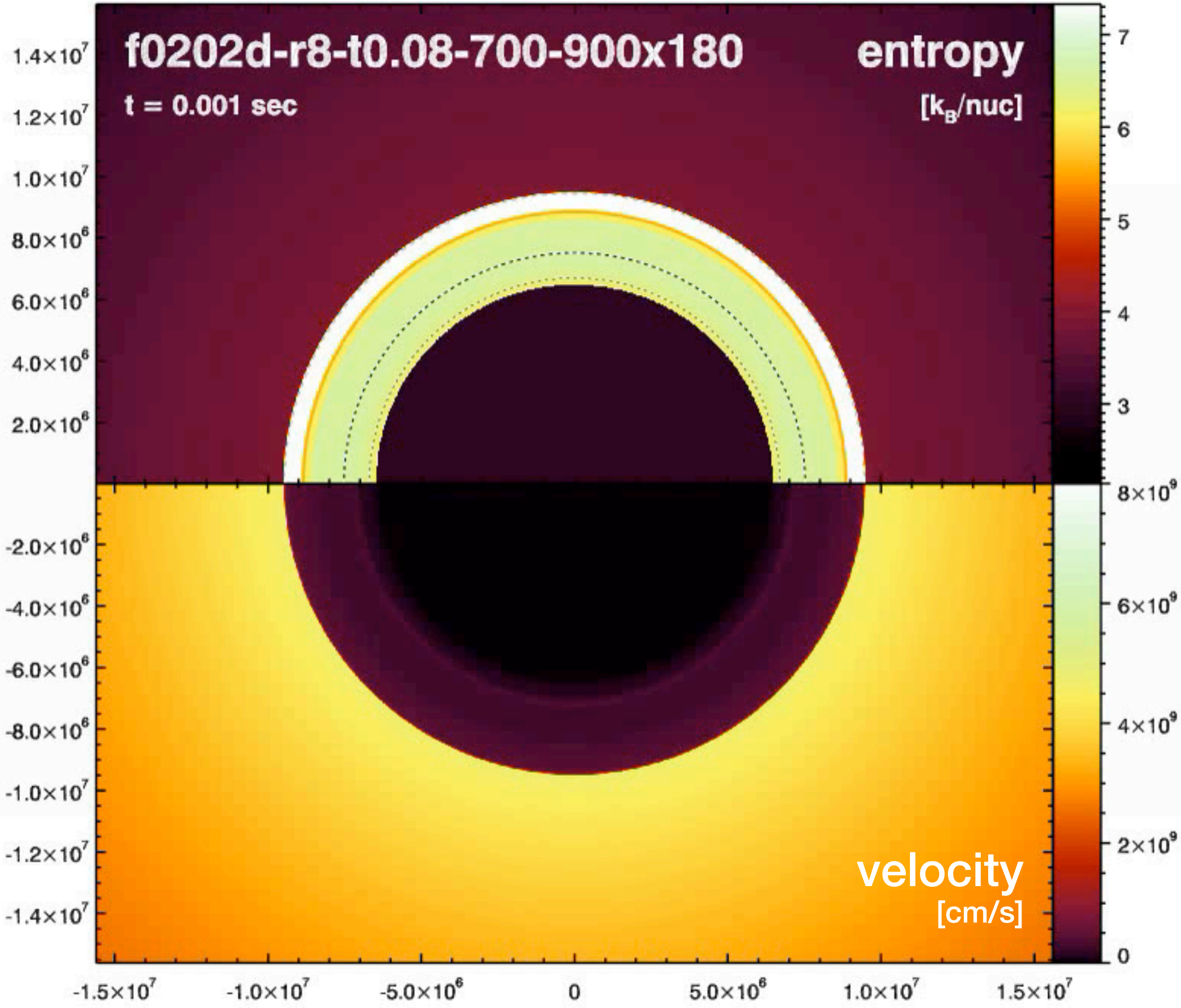

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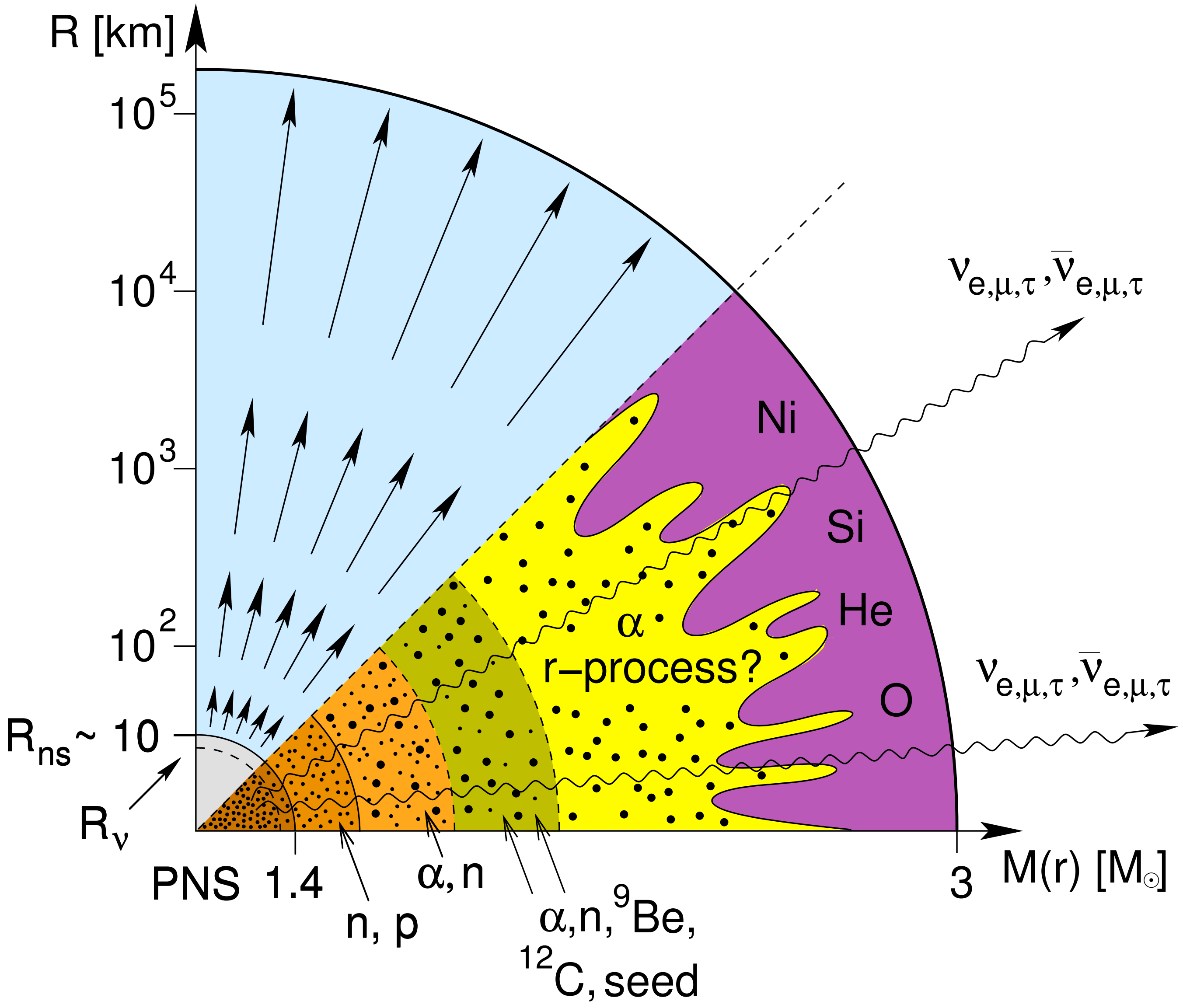
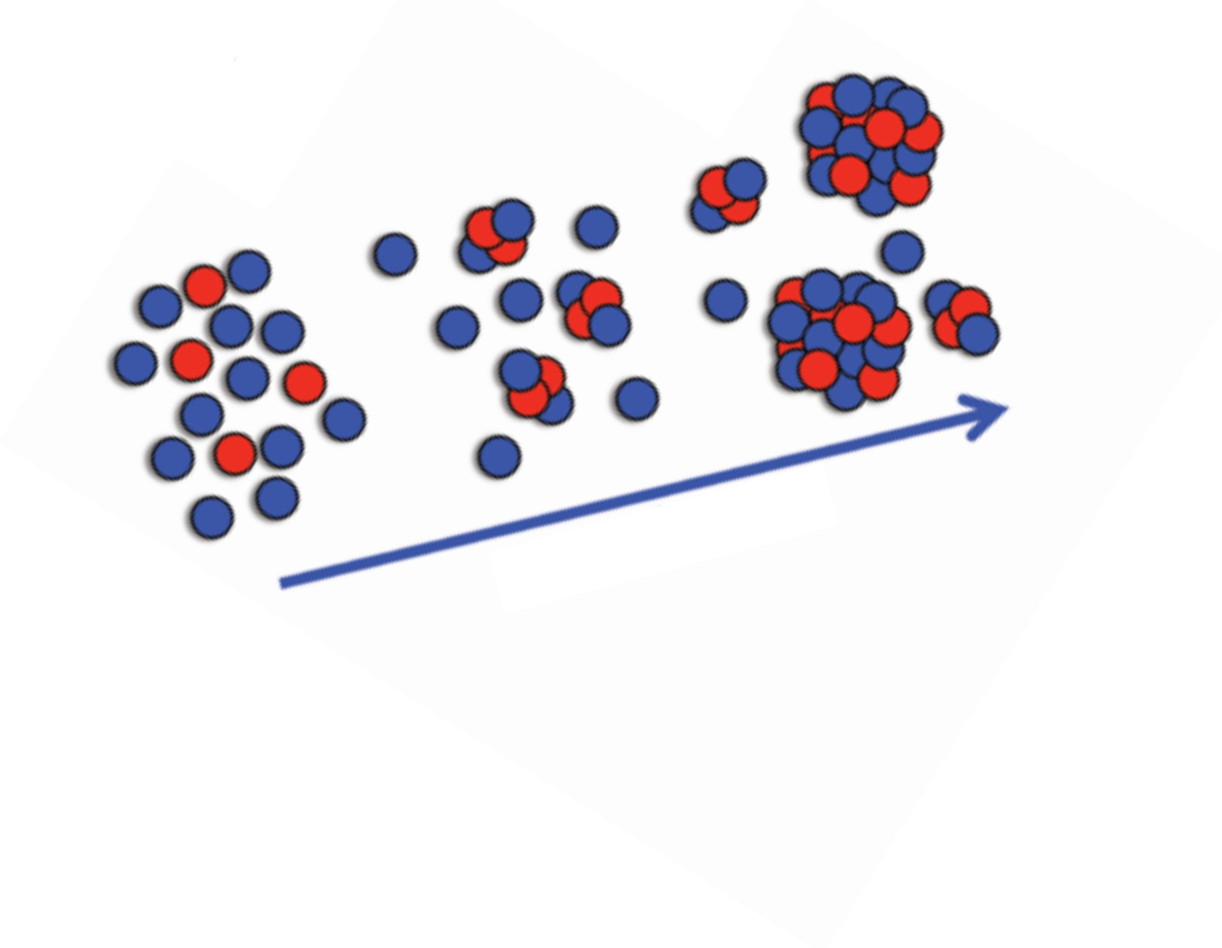


neutrons and protons form α-particles
α-particles recombine into seed nuclei



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

T = 10 - 8 GK

8 - 2 GK

weak r-process

νp-process

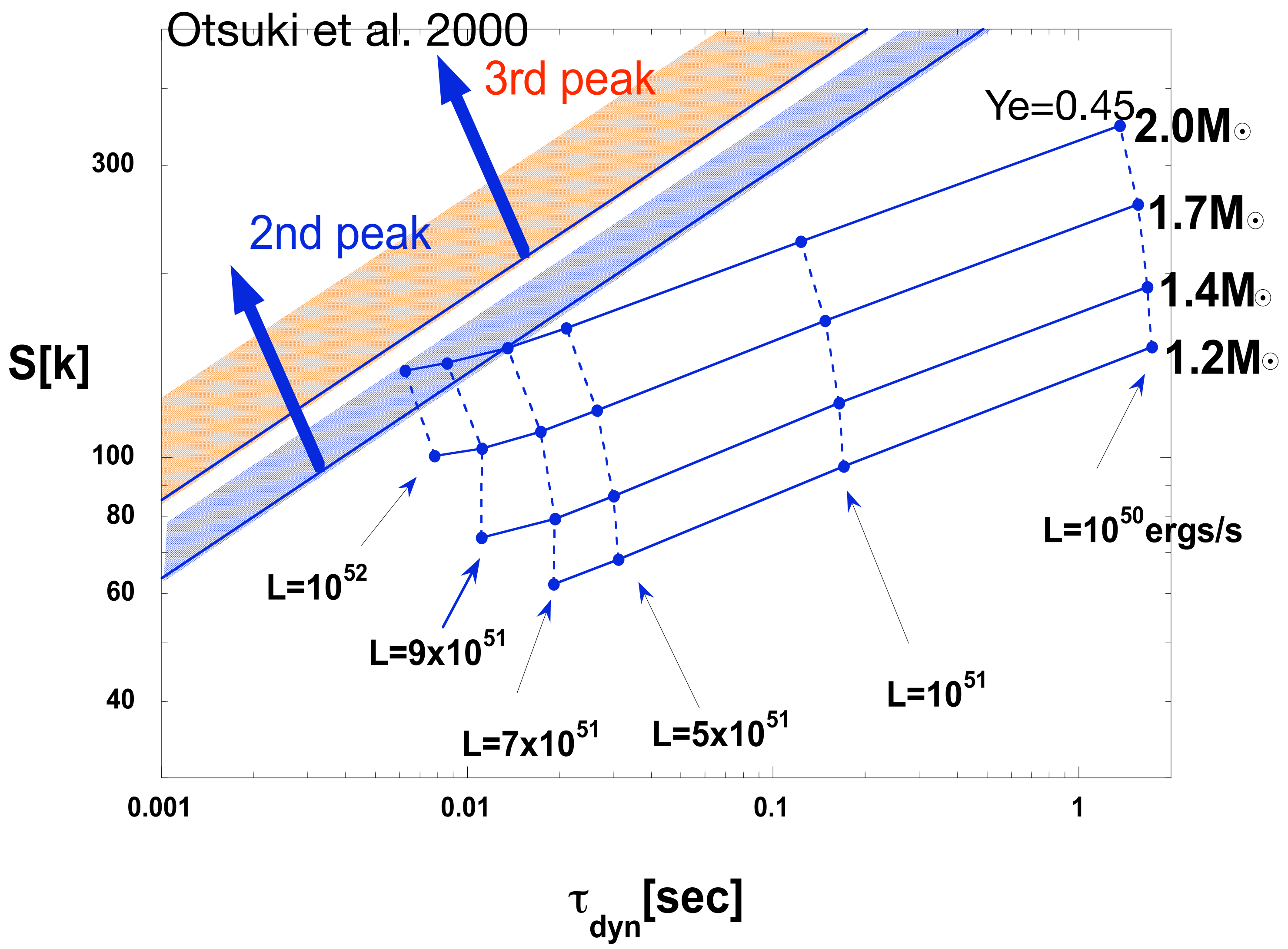
T < 3 GK

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: $Y_e<0.5$



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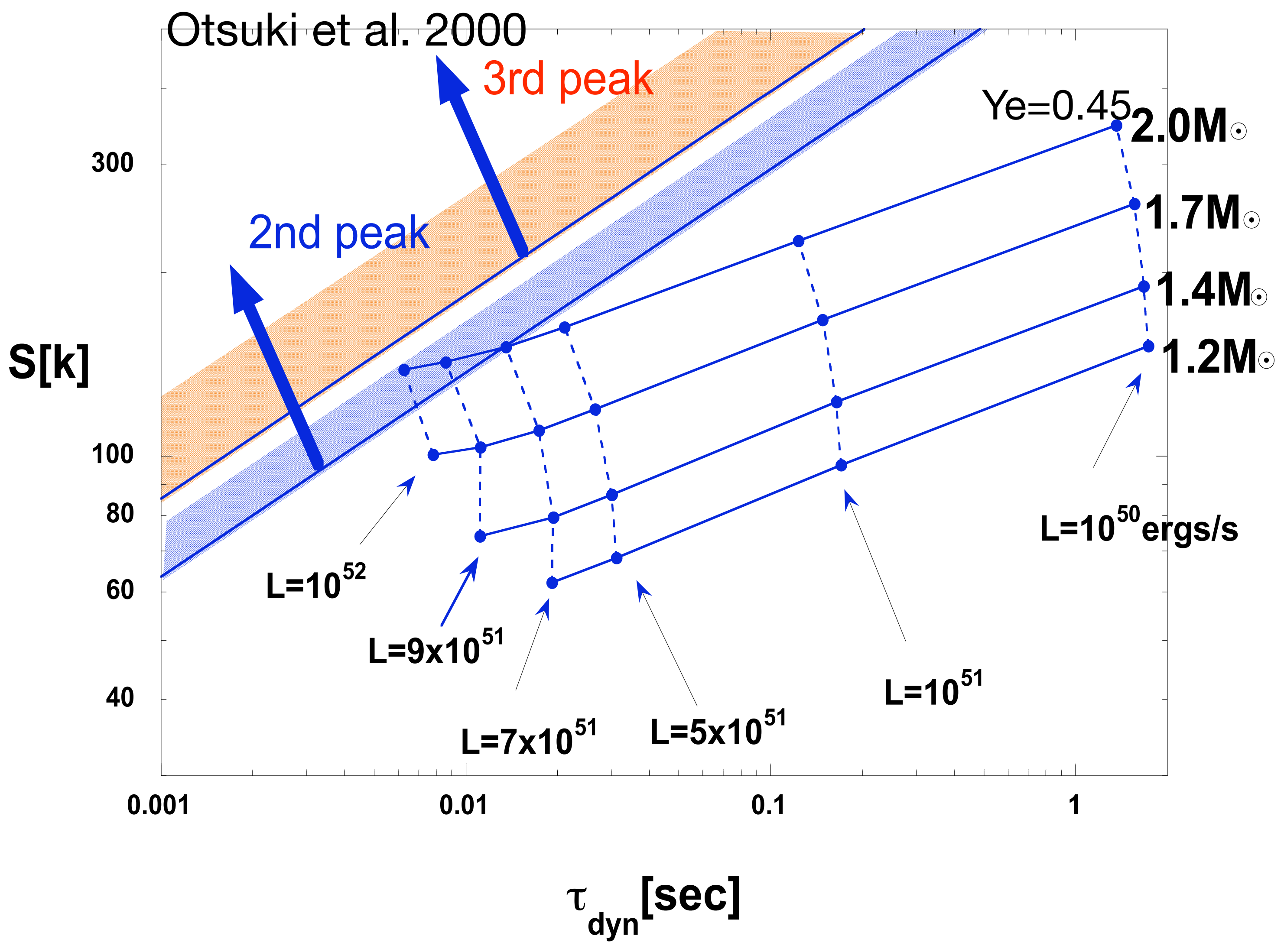

Otsuki et al. 2000

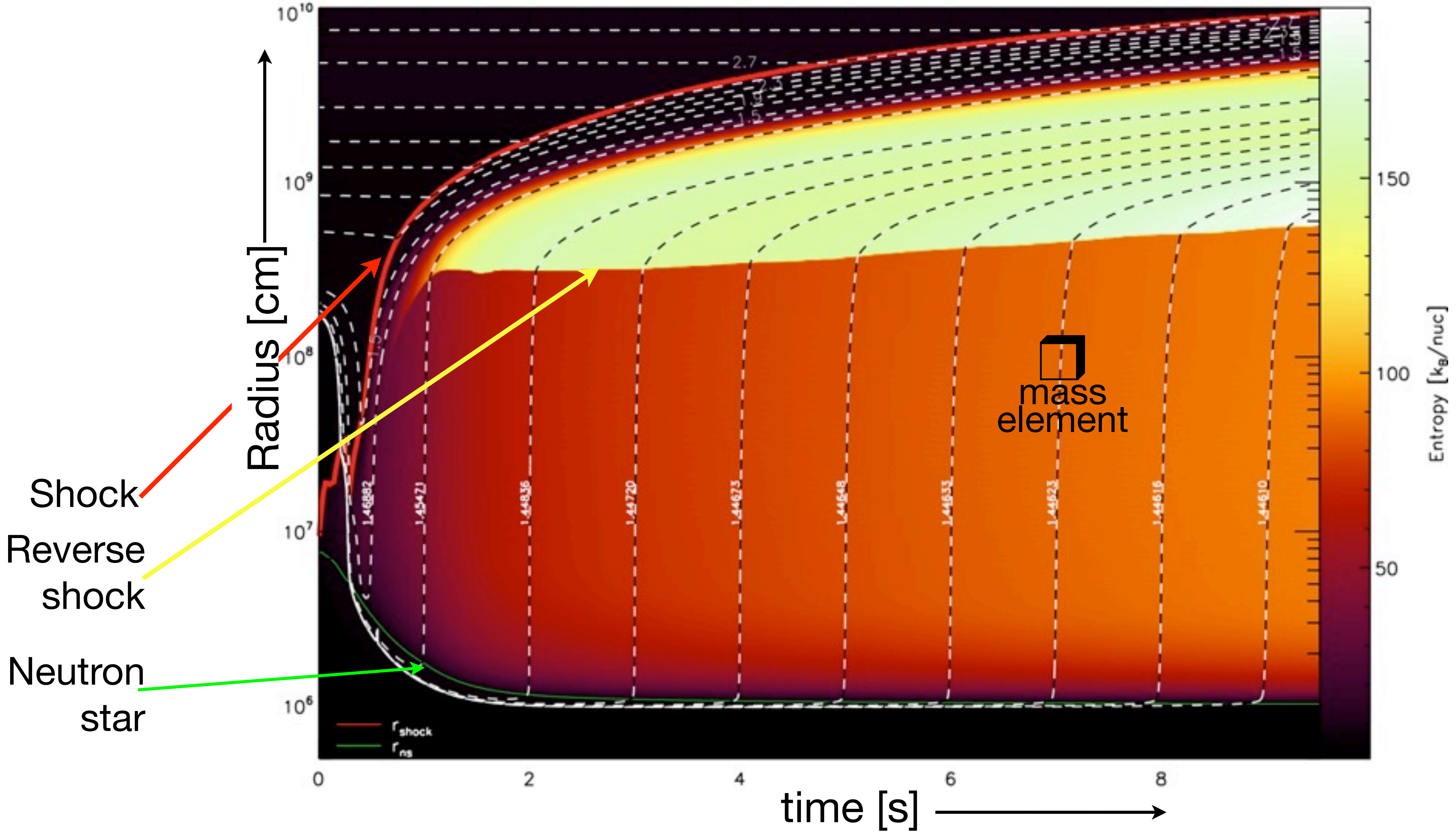
Conditions are not realized in hydrodynamic simulations
(Arcones et al. 2007, Fischer et al. 2010, Hüdepohl et al. 2010, Roberts et al. 2010, Arcones & Janka 2011, ...)

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

Which elements are produced in neutrino winds?

Arcones et al 2007



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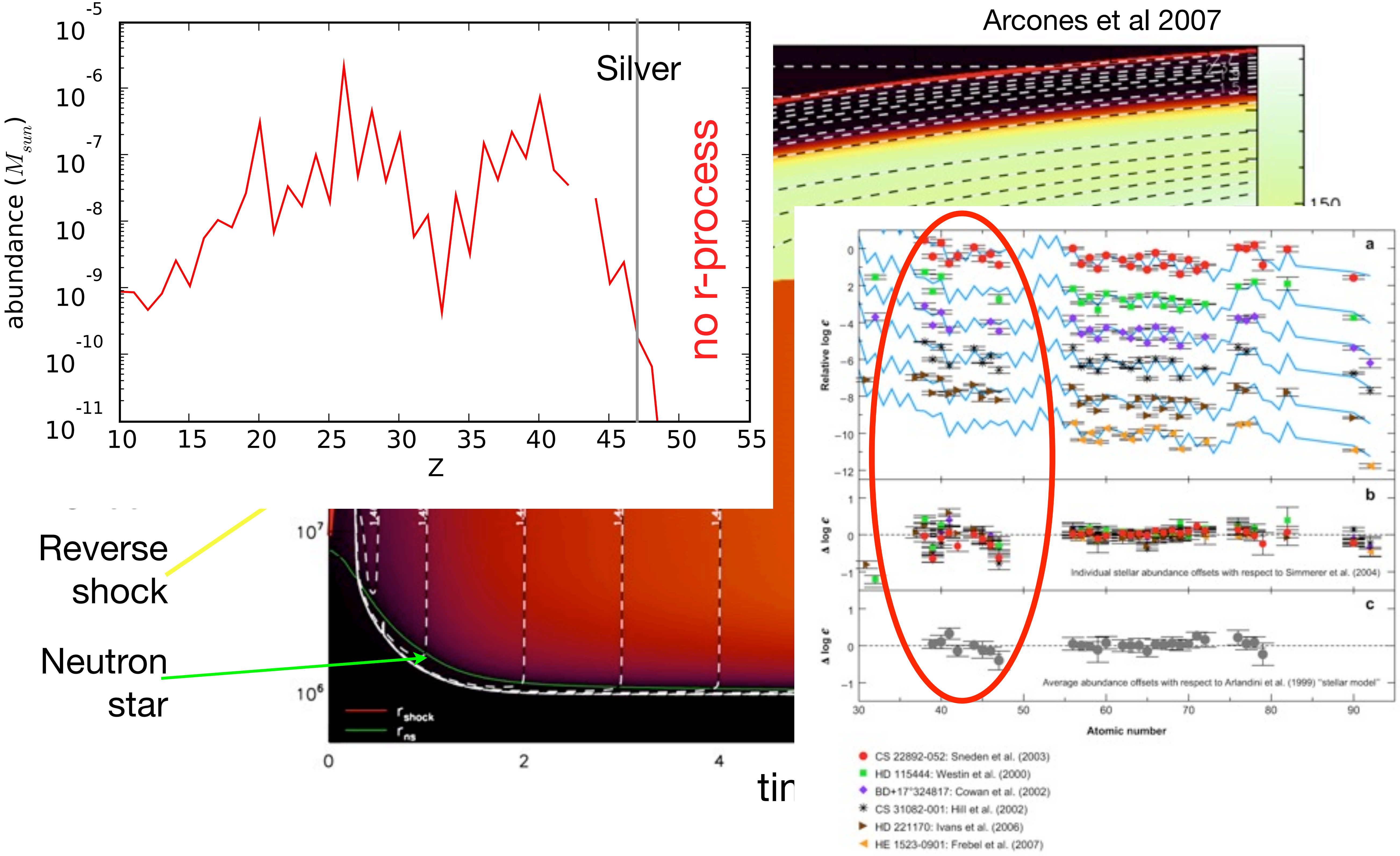

Arcones et al 2007

Neutron or proton rich?

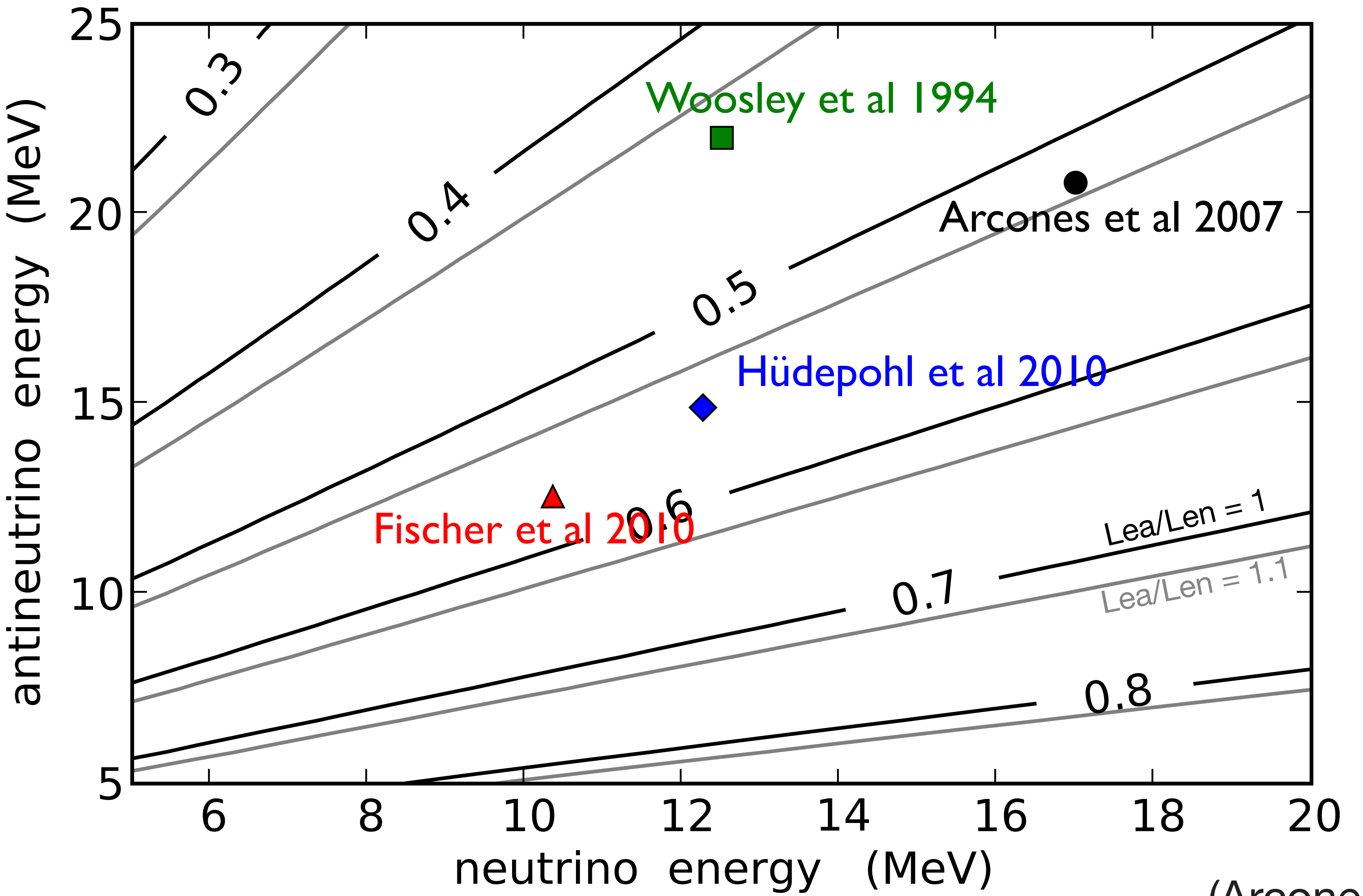
Wind Y_e still uncertain due to neutrino-matter interactions at high densities

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

Qian & Woosley 1996 ($\Delta = m_n - m_p$)

see also Roberts et al. 2012, Martinez-Pinedo et al. 2012

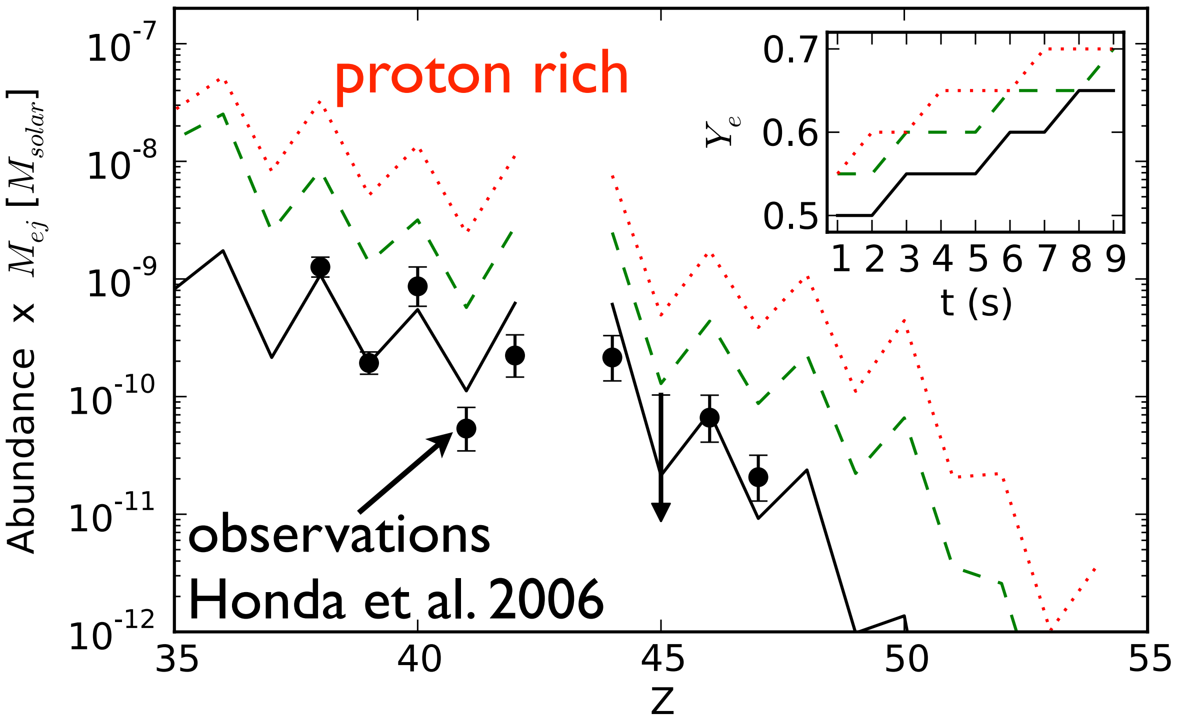
neutron rich: $\epsilon_{\bar{\nu}_e} - \epsilon_{\nu_e} \gtrsim 4\Delta \approx 5$ MeV



(Arcones & Montes, 2011)

Lighter heavy elements in neutrino-driven winds

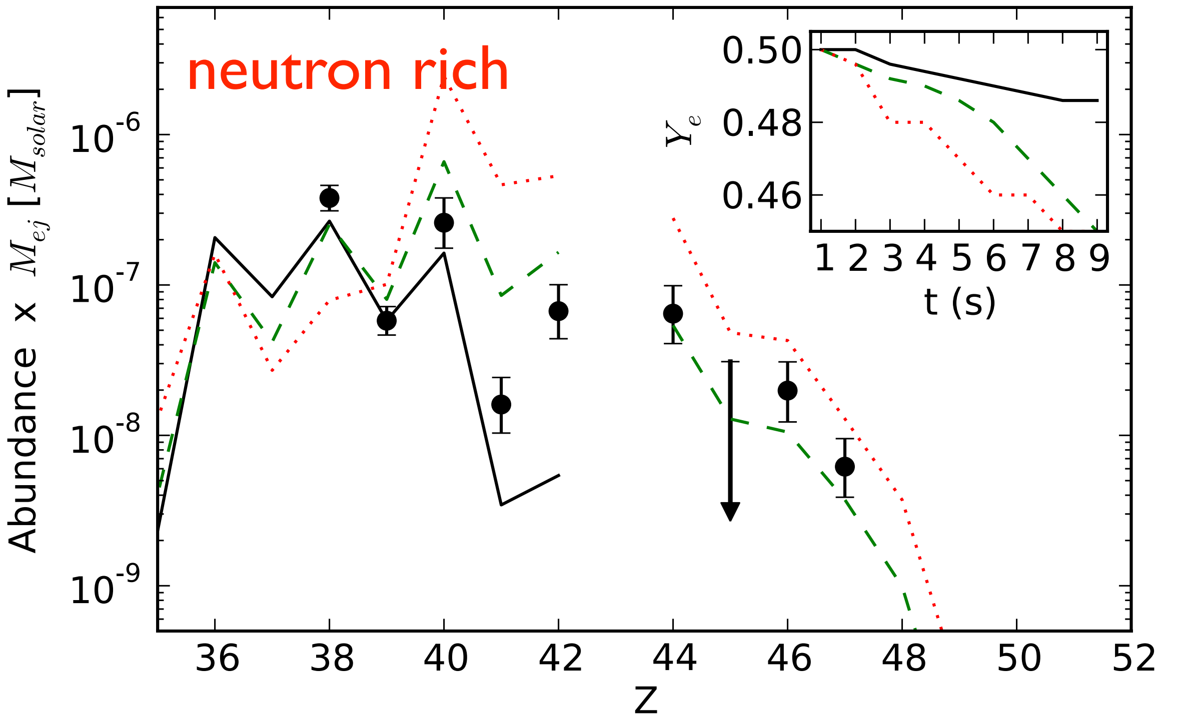
vp-process



Observation pattern reproduced!

Production of p-nuclei

weak r-process

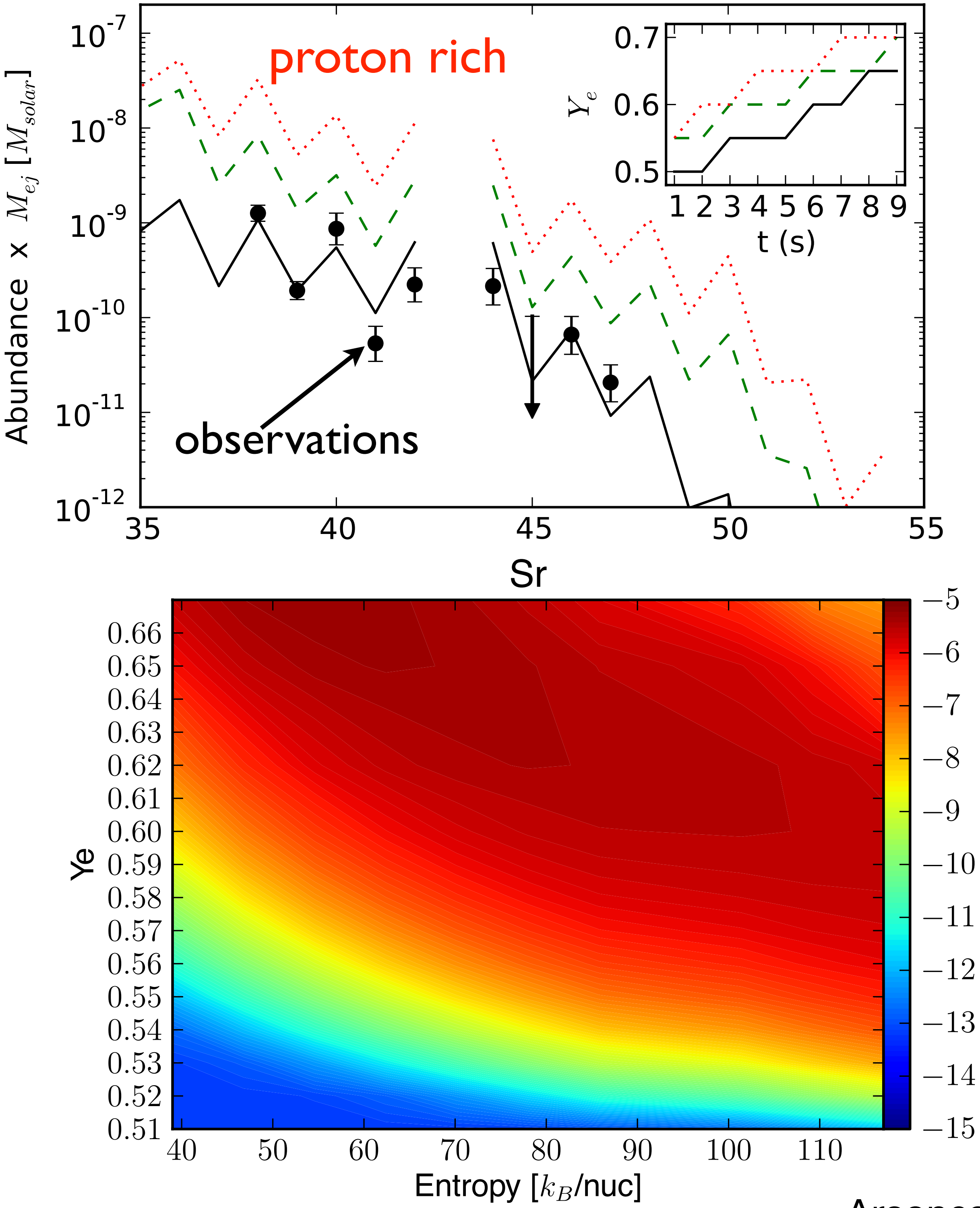


Overproduction at A=90, magic neutron number N=50 (Hoffman et al. 1996) suggests: only a fraction of neutron-rich ejecta (Wanajo et al. 2011)

(Arcones & Montes, 2011)

Lighter heavy elements in neutrino-driven winds

vp-process



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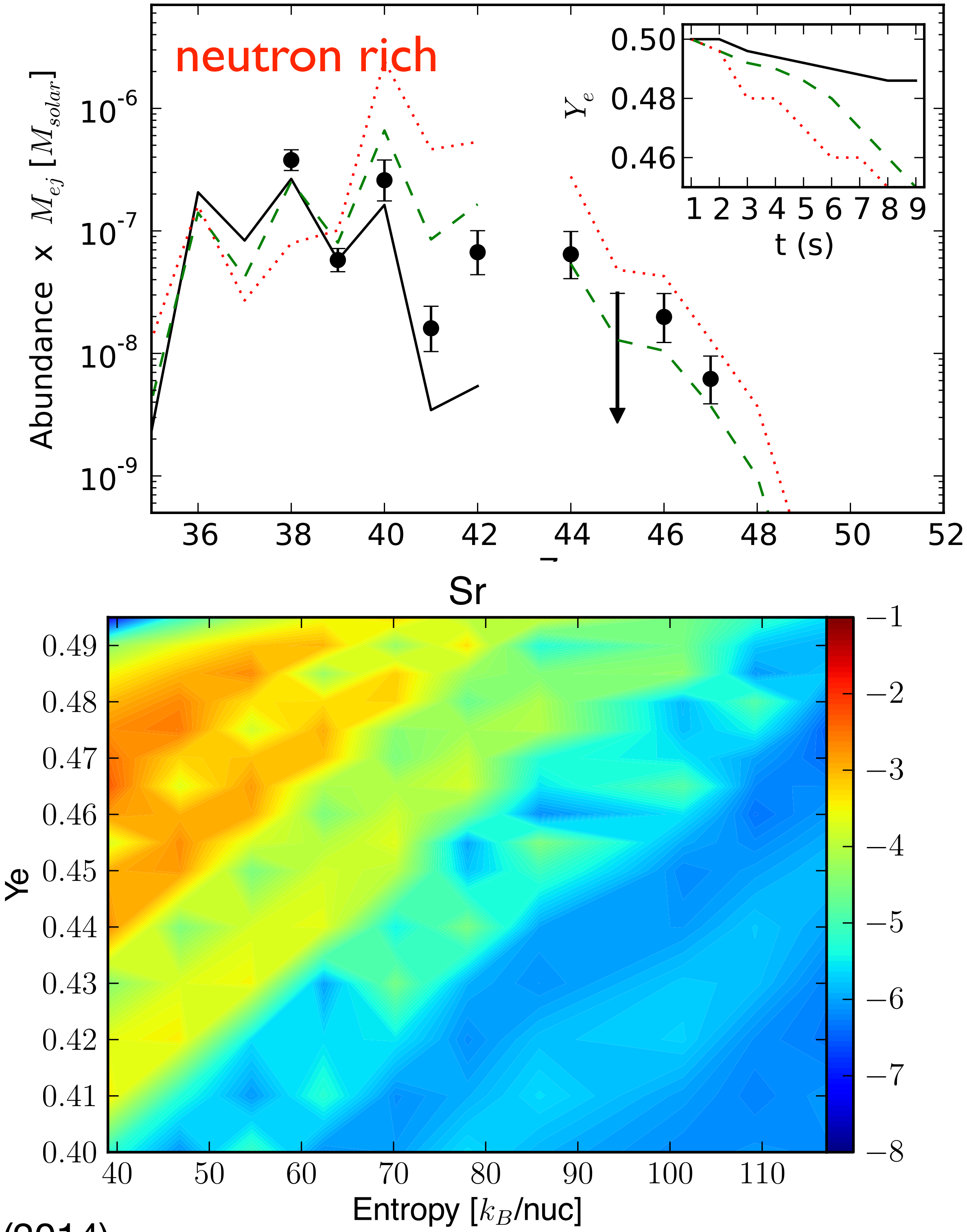
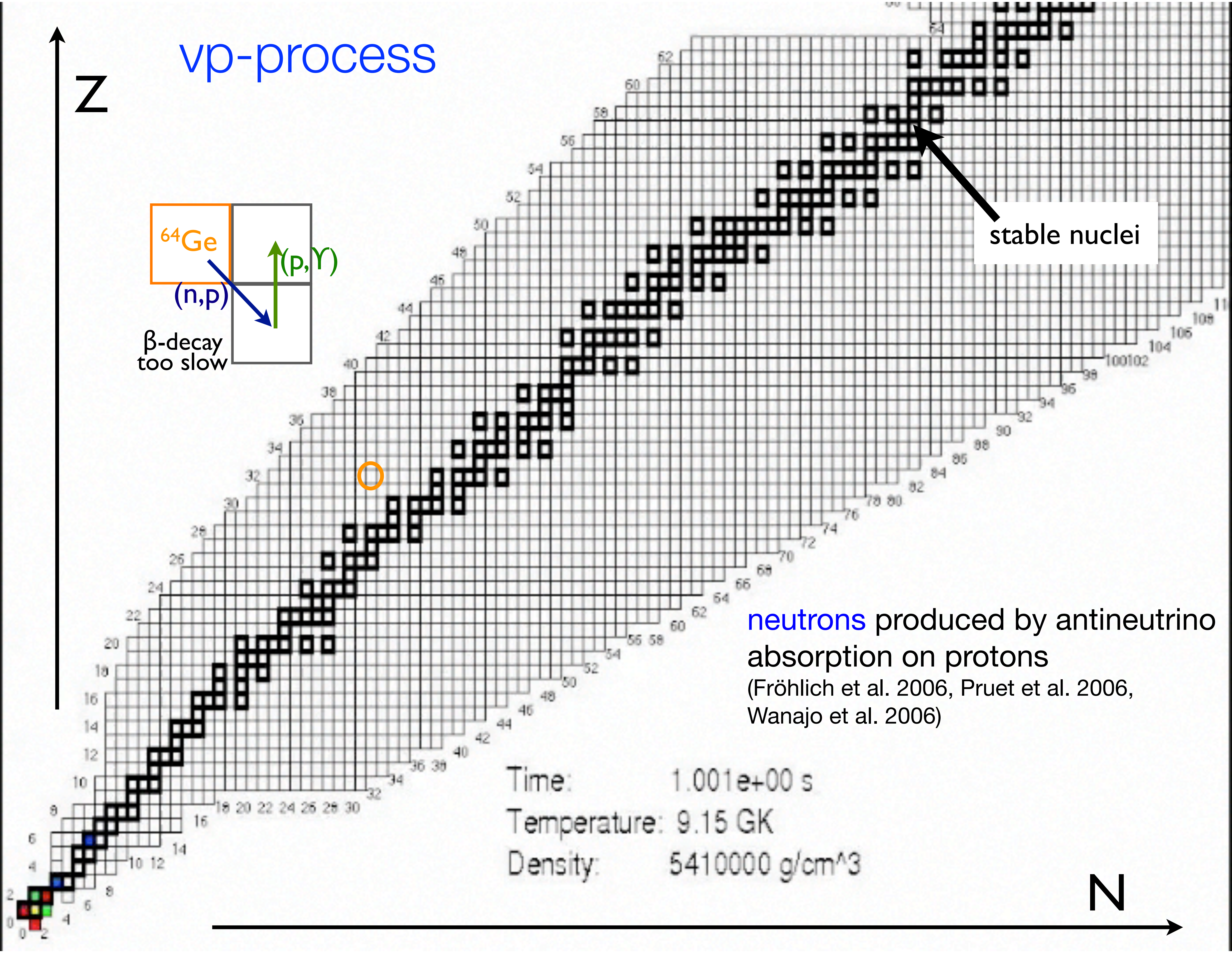


Arcones & Bliss (2014)

νp-process



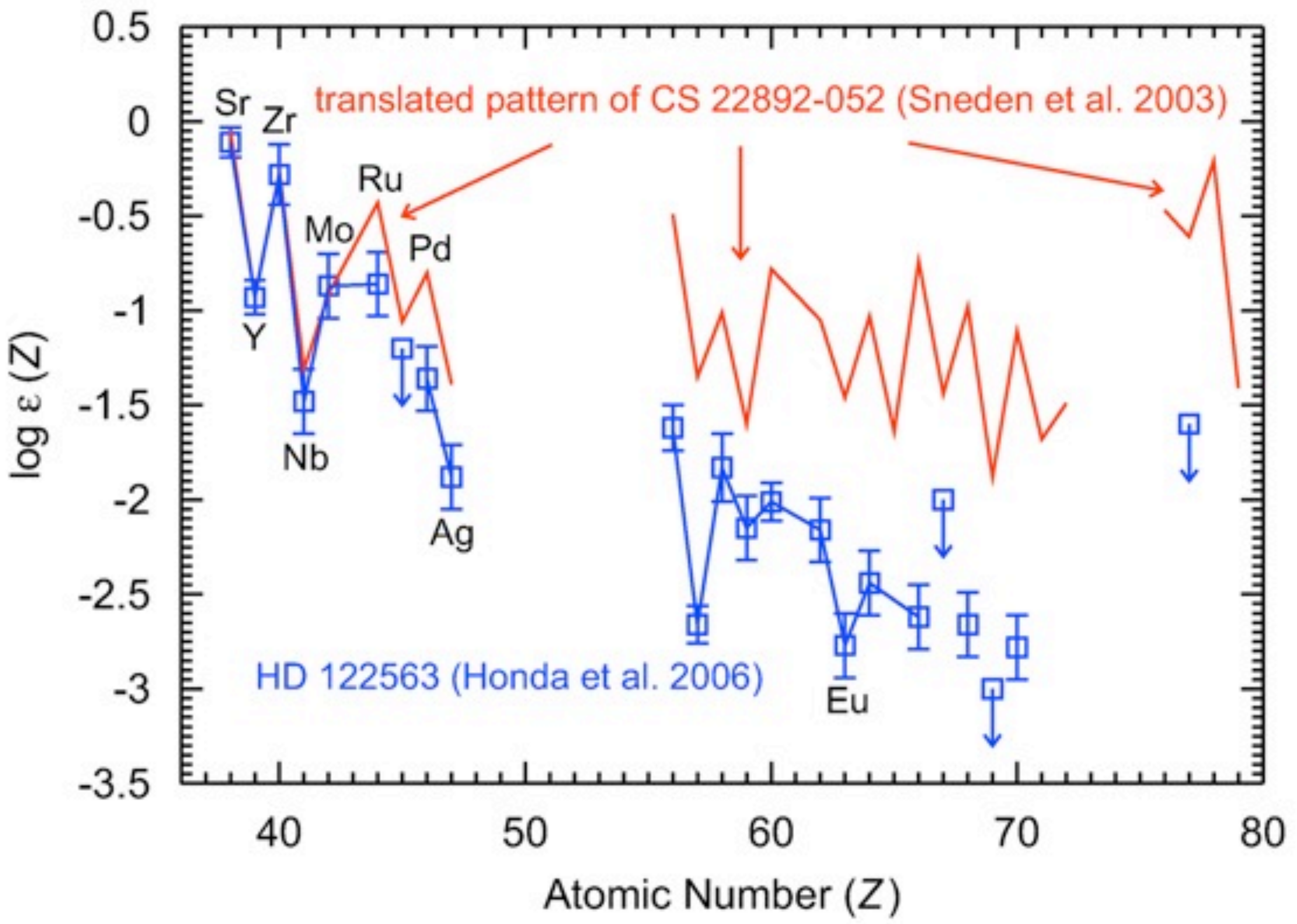
stable nuclei

neutrons produced by antineutrino absorption on protons

(Fröhlich et al. 2006, Pruet et al. 2006, Wanajo et al. 2006)

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

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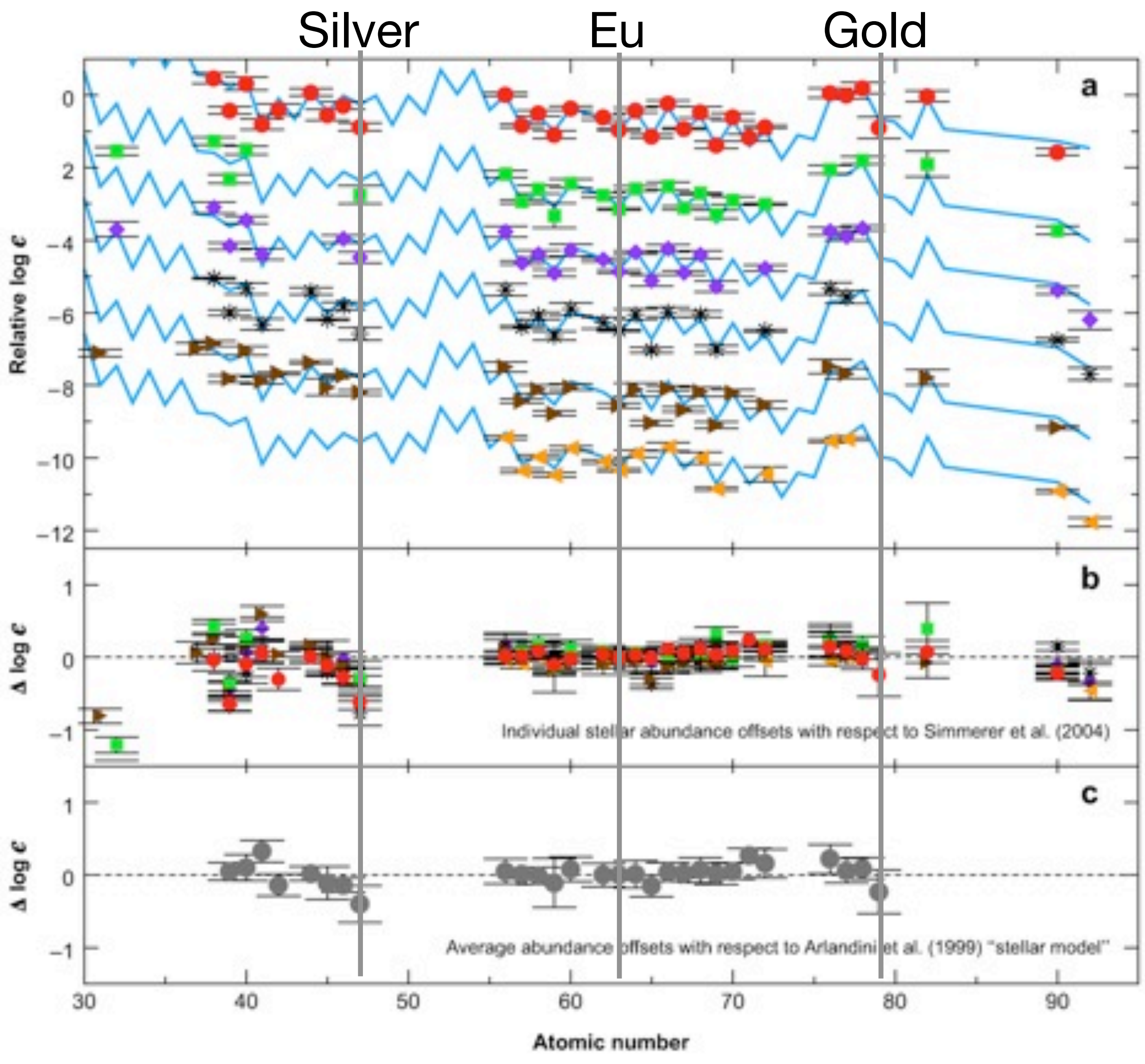

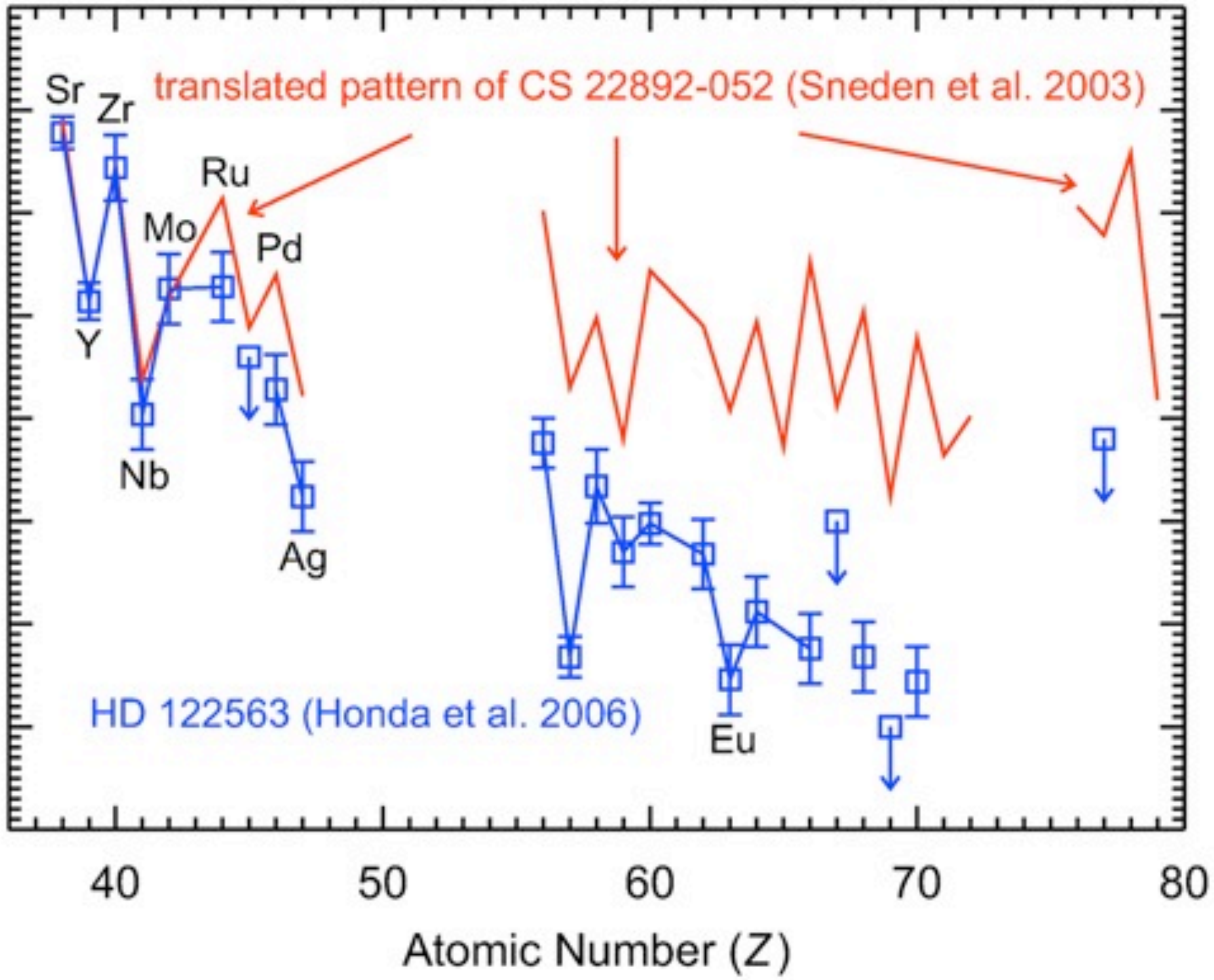

Sneden, Cowan, Gallino 2008

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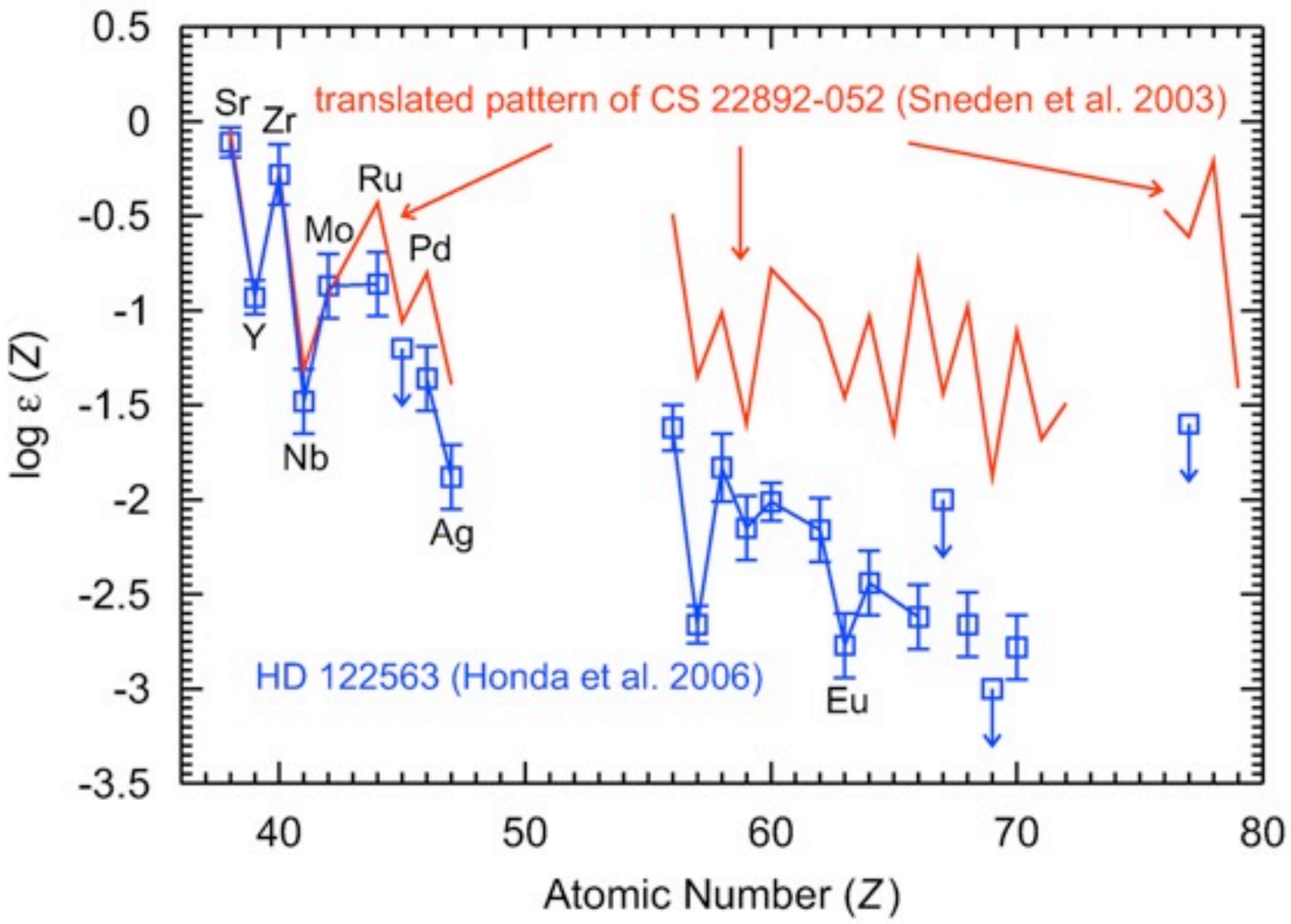

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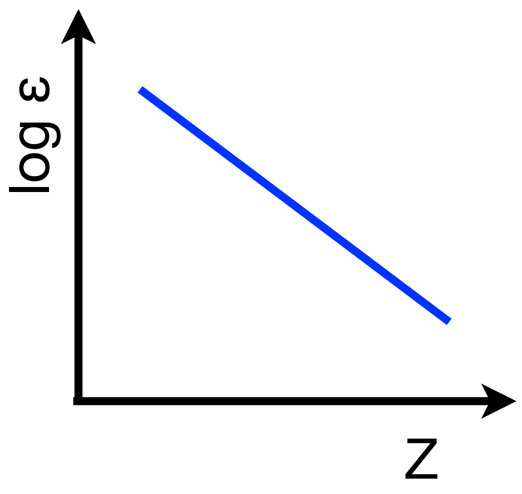
Are Honda-like stars the outcome of one nucleosynthesis event or the combination of several?



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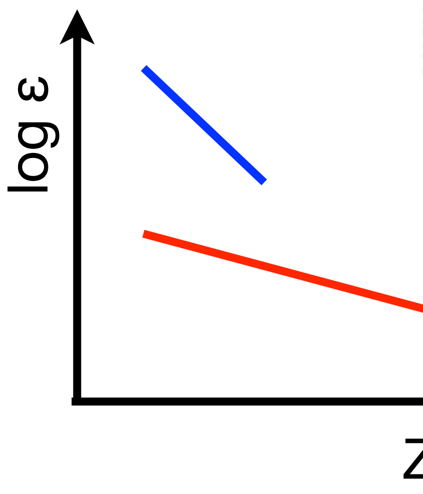

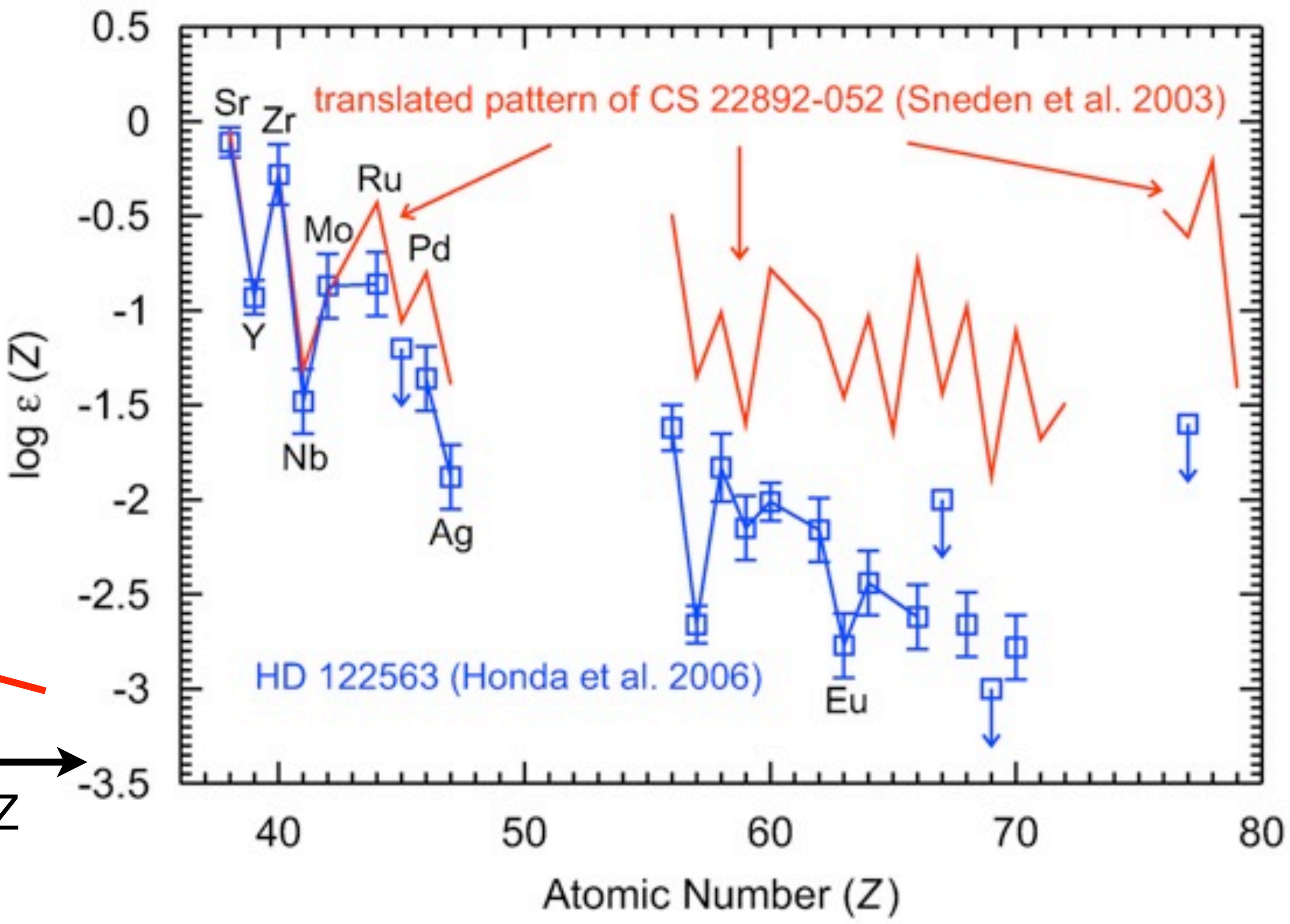

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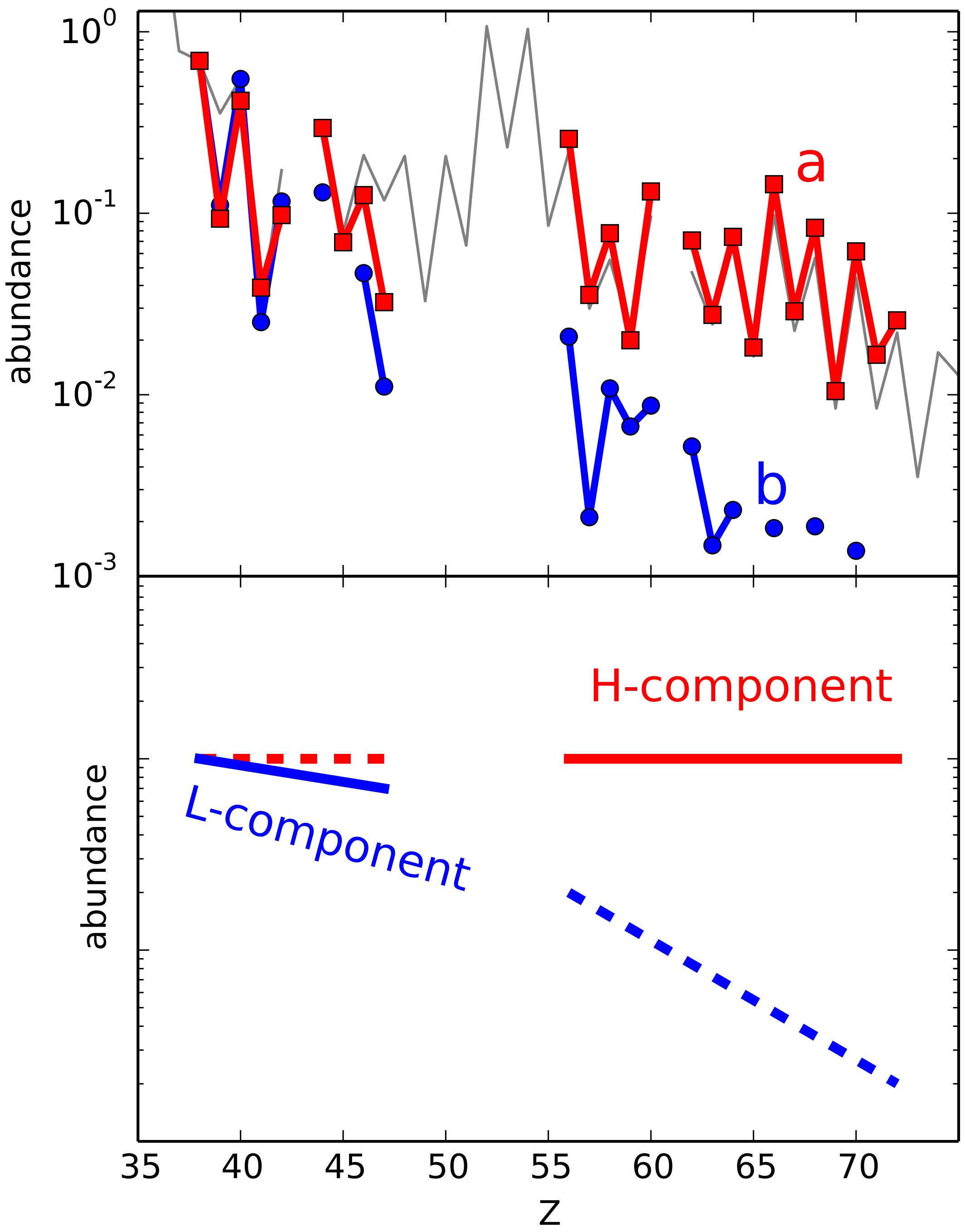
Nucleosynthesis components

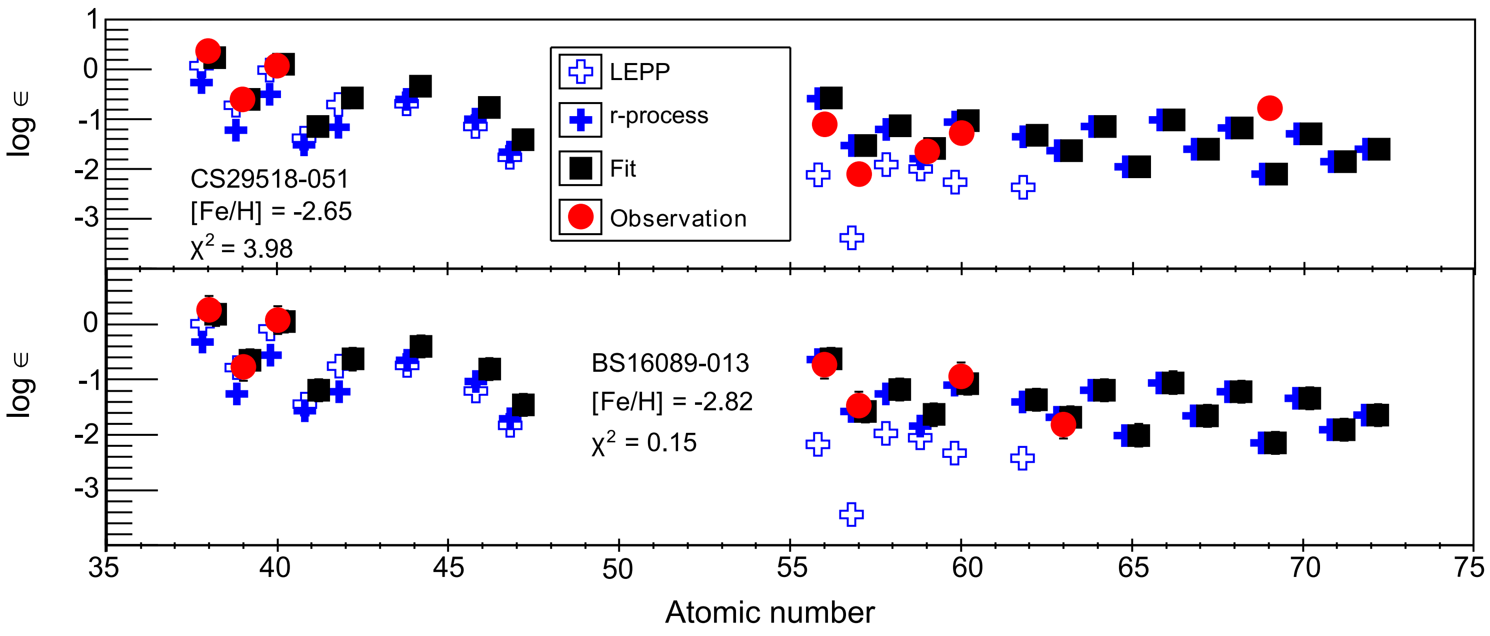
Abundance of many UMP stars can be explained by two components:



Component abundance pattern: Y_H and Y_L

Fit abundance as combination of components:

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



C.J. Hansen, Montes, Arcones (2014)

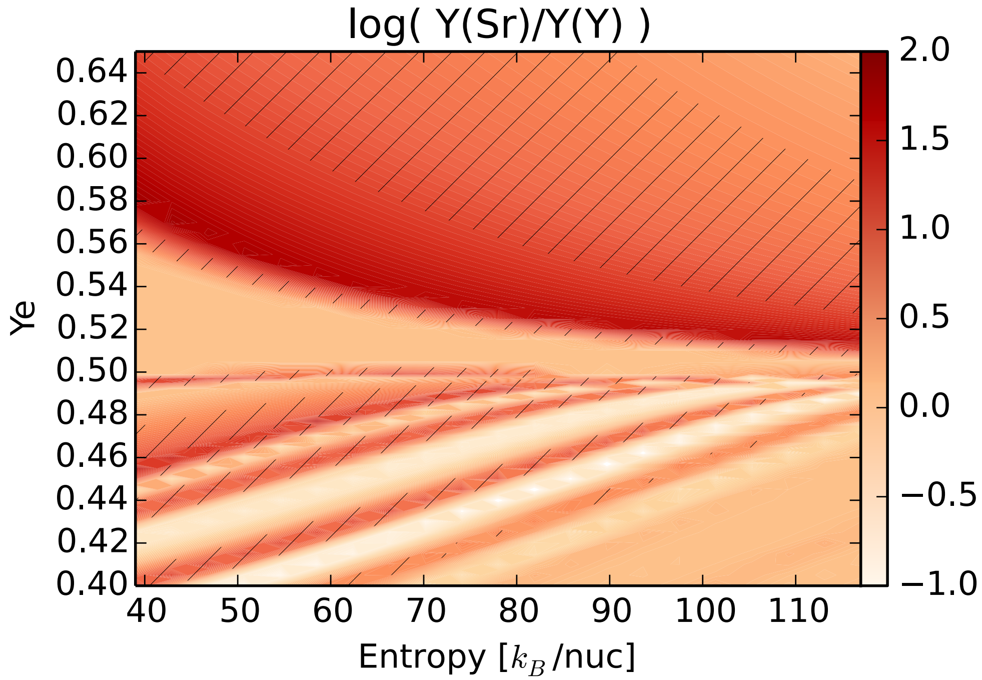
L-component: constraining conditions

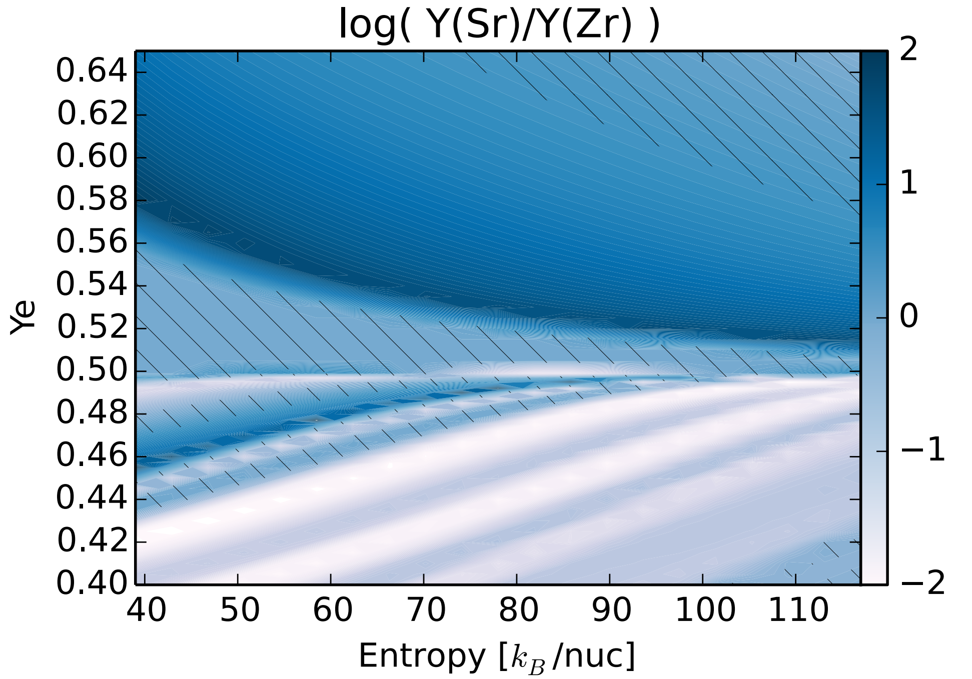
L-component abundance ratios:

Sr/Y = 6.13 (//)

Sr/Zr = 1.22 (\\)

Sr/Ag = 48.2





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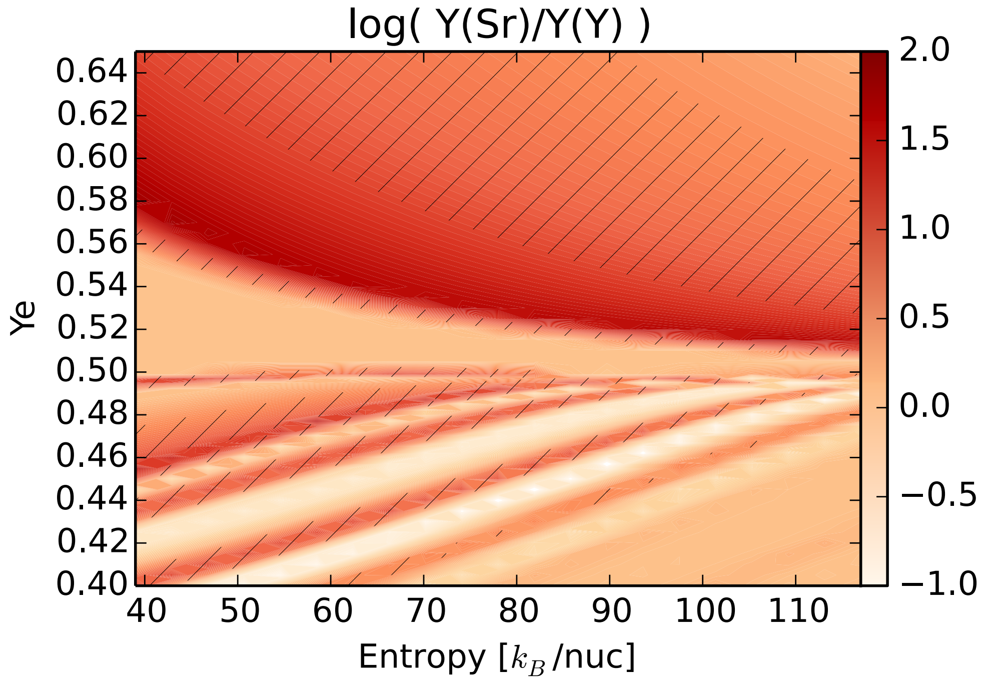
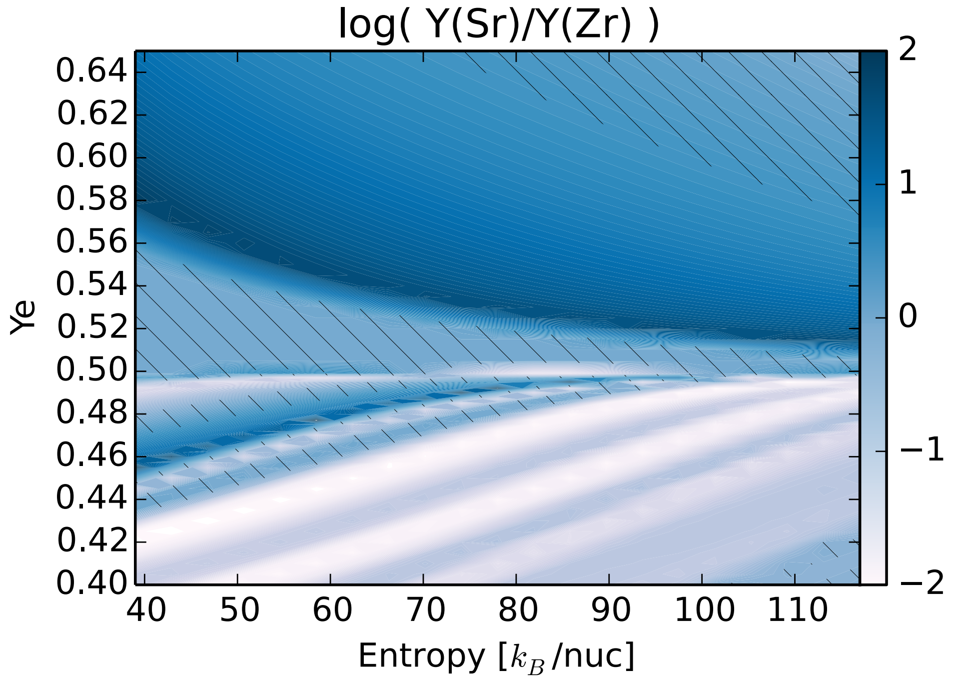

log(Y(Sr)/Y(Y))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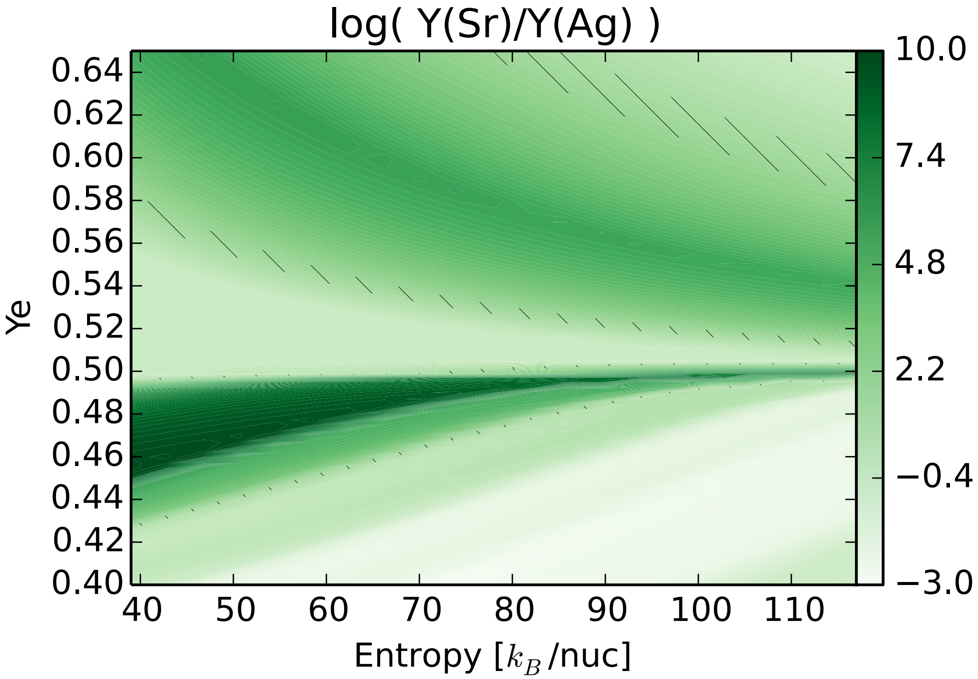
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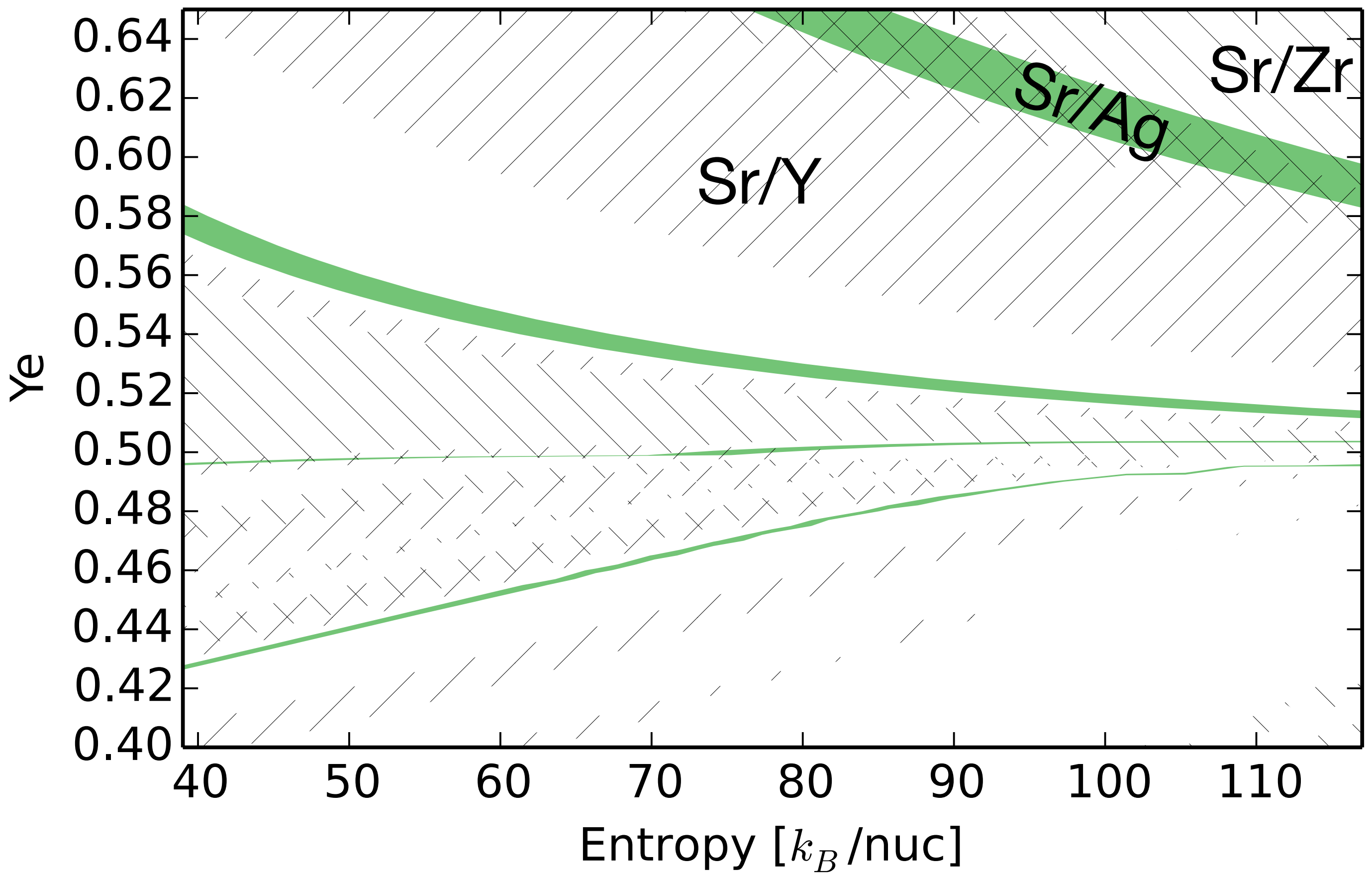

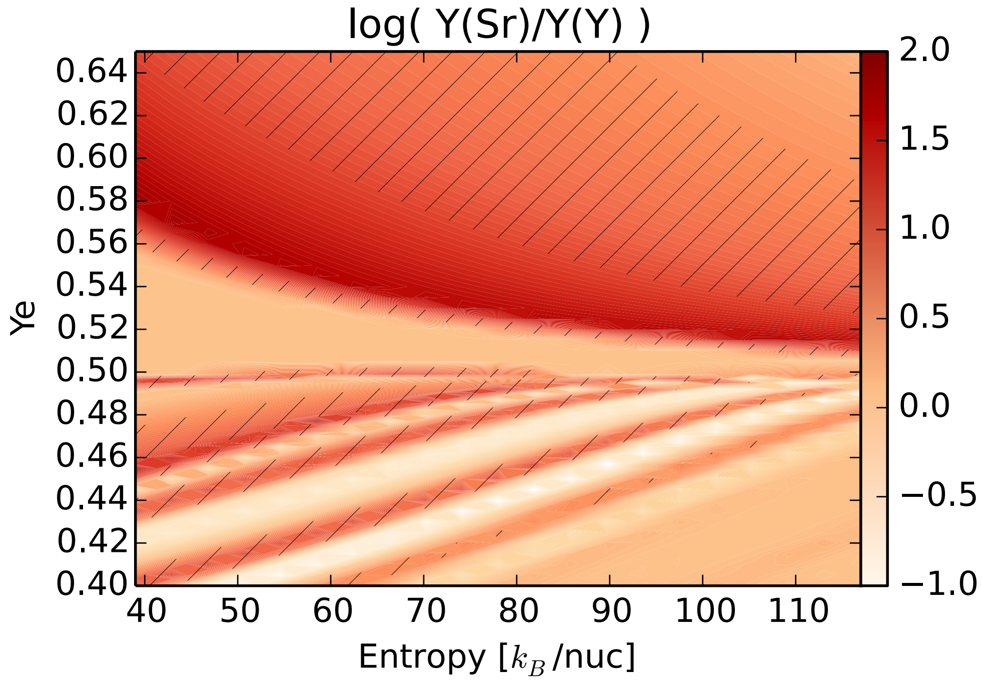
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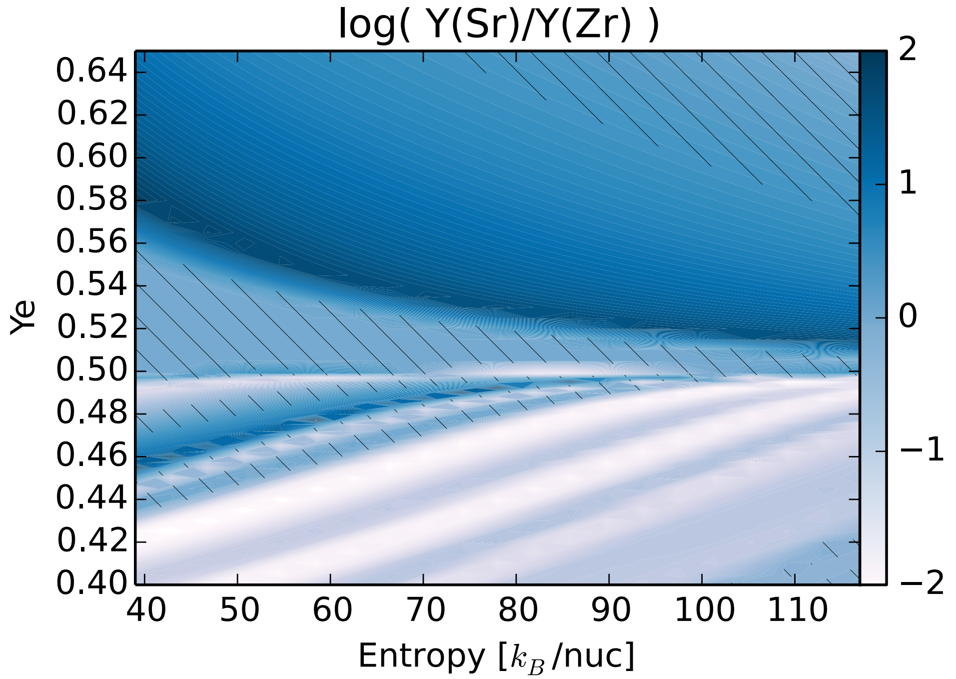
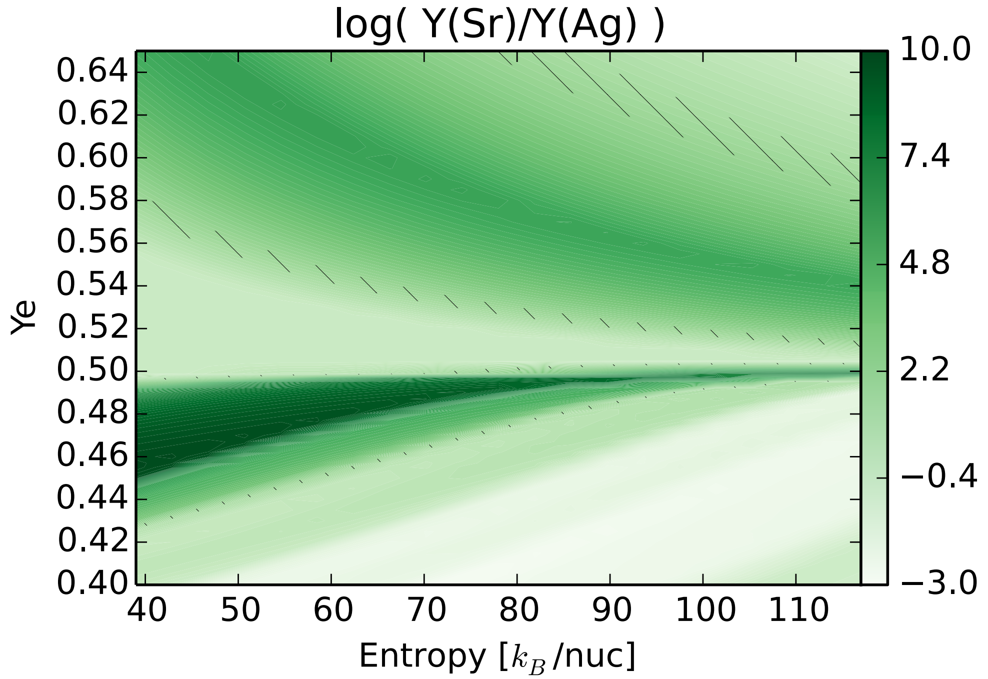
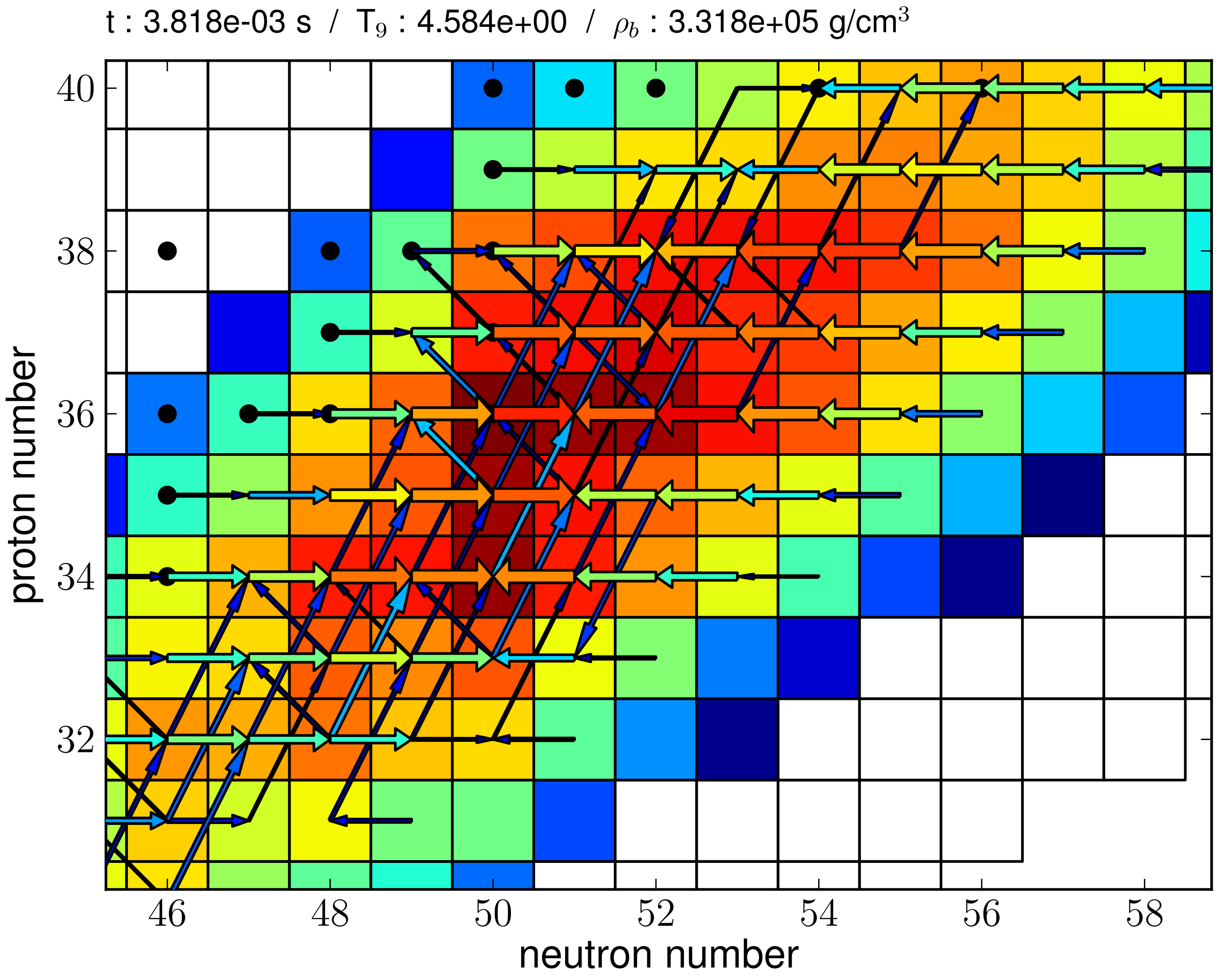
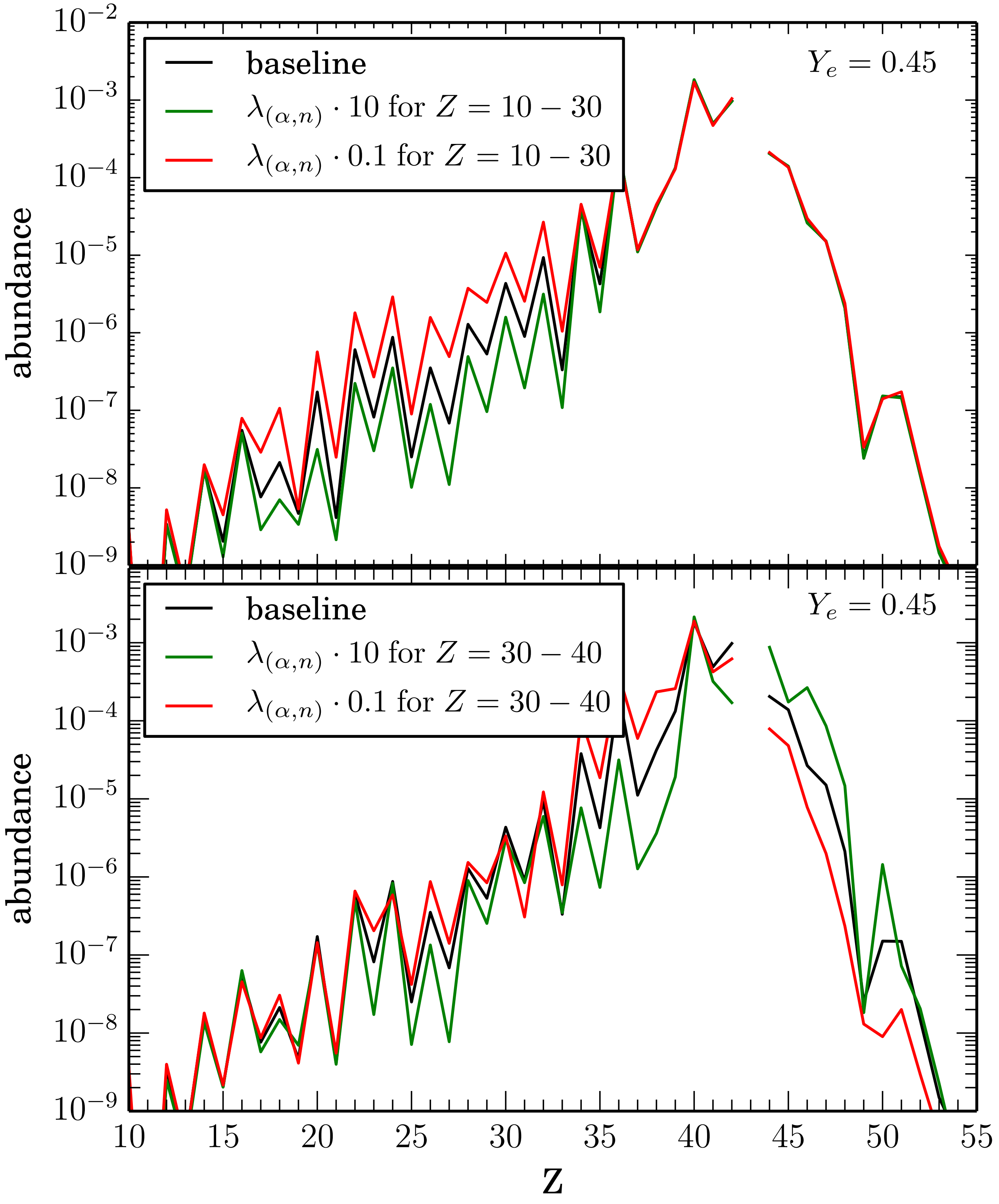

log(Y(Sr)/Y(Zr))


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

Key reactions: weak r-process

(α,n)

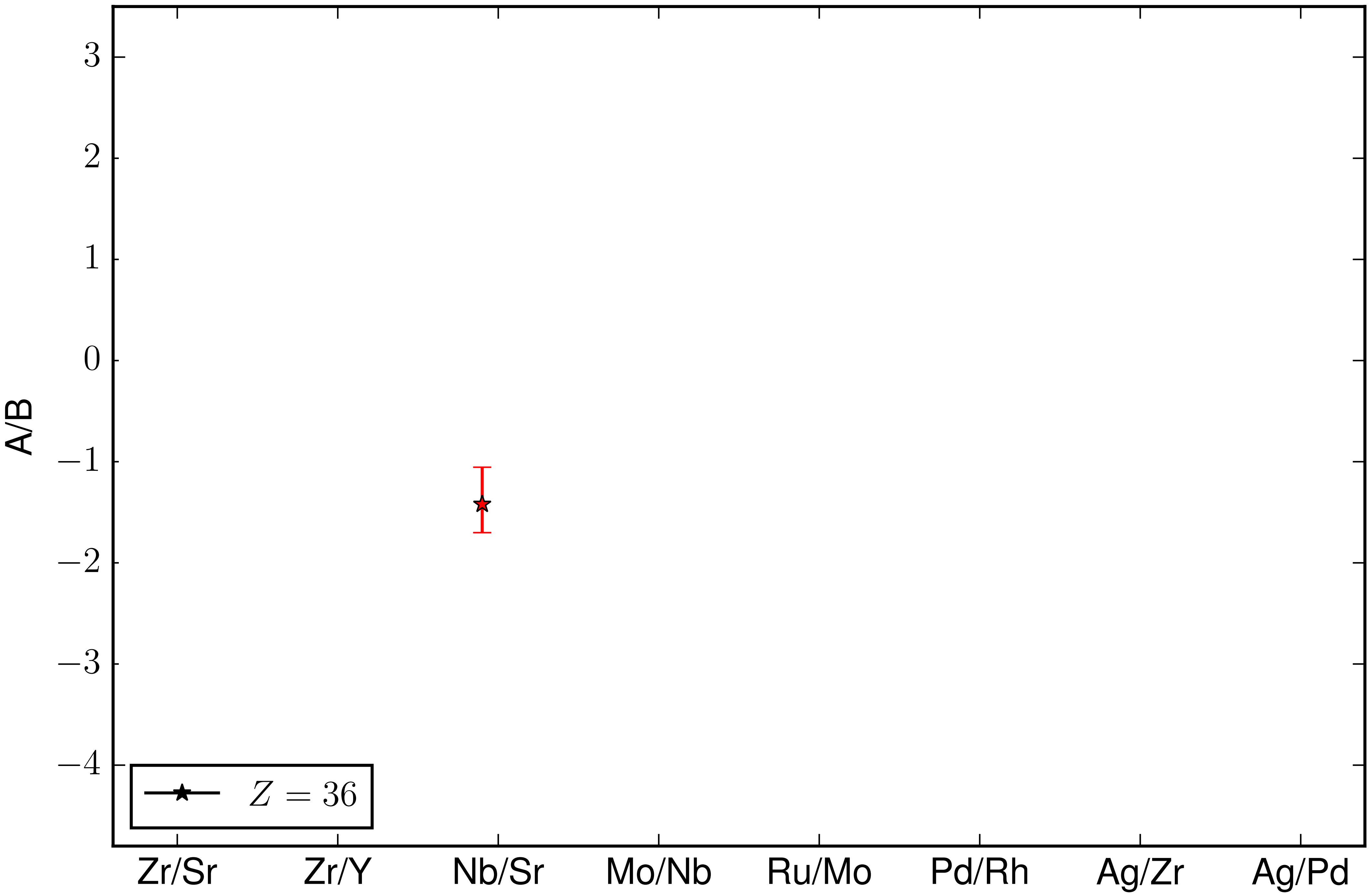




Bliss, Arcones, Montes, Pereira (in prep.)

Astrophysics and nuclear physics uncertainties

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



Astrophysics and nuclear physics uncertainties

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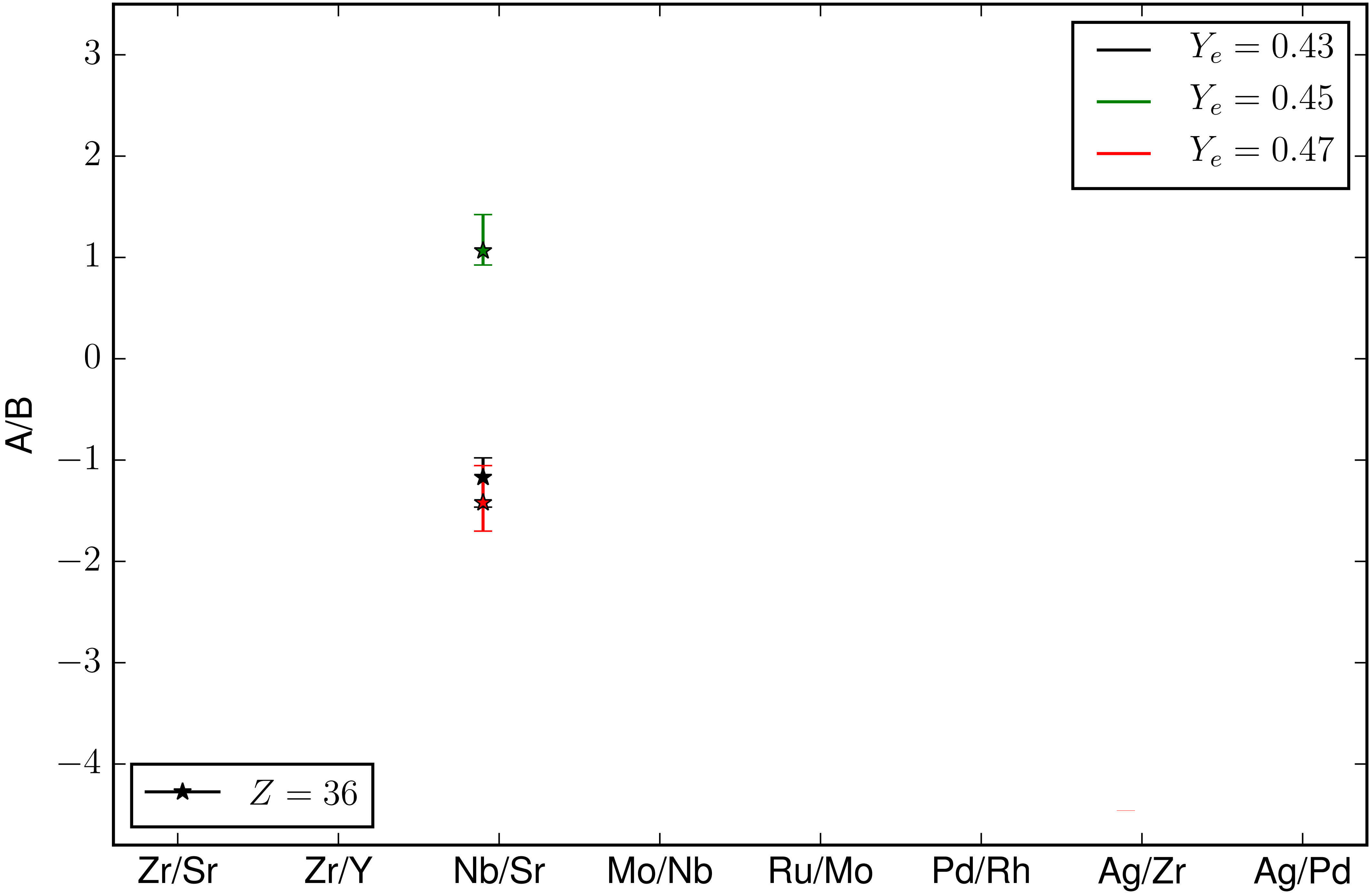
Color: variation of astrophysical conditions (Y_e)



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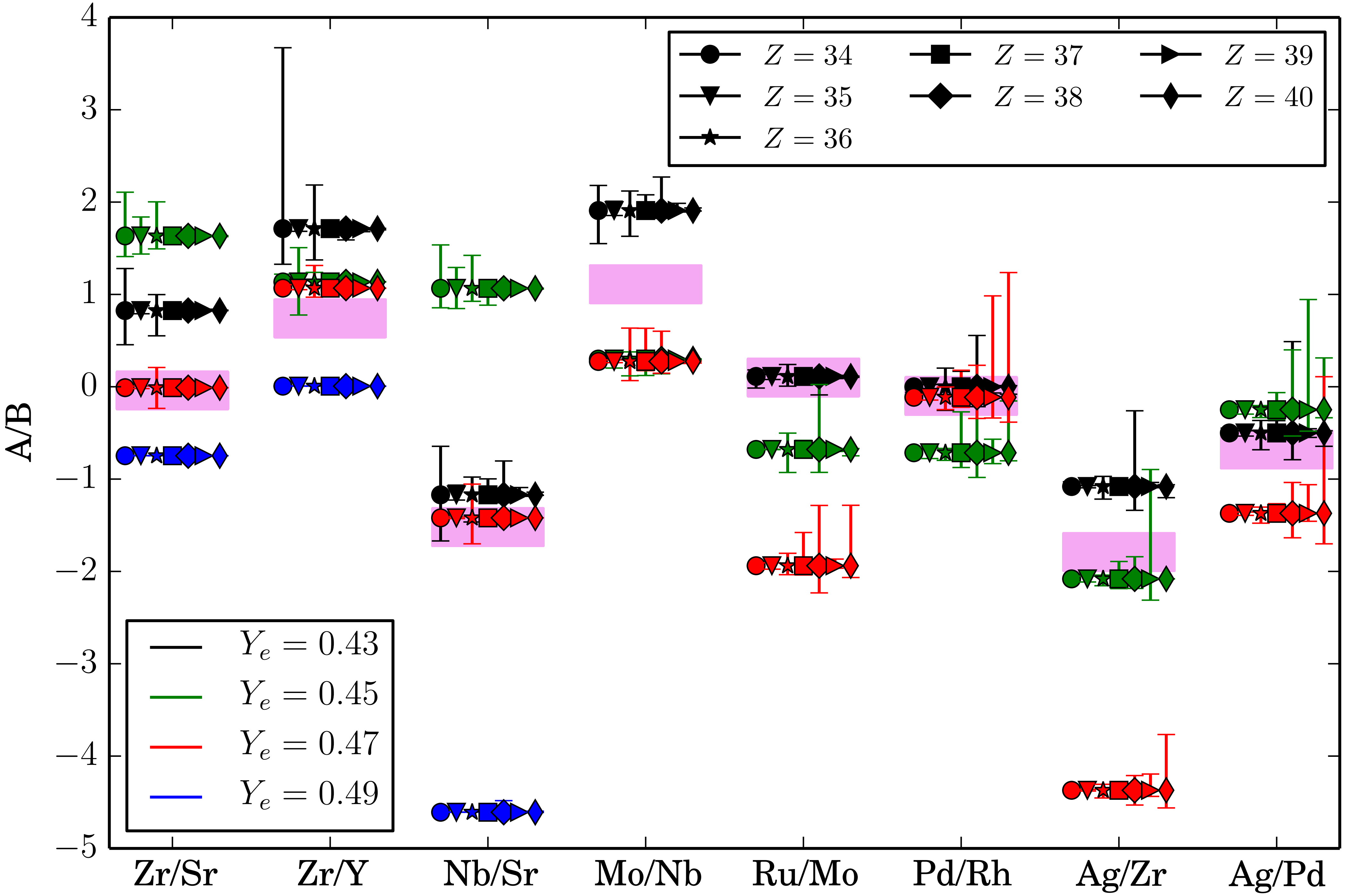
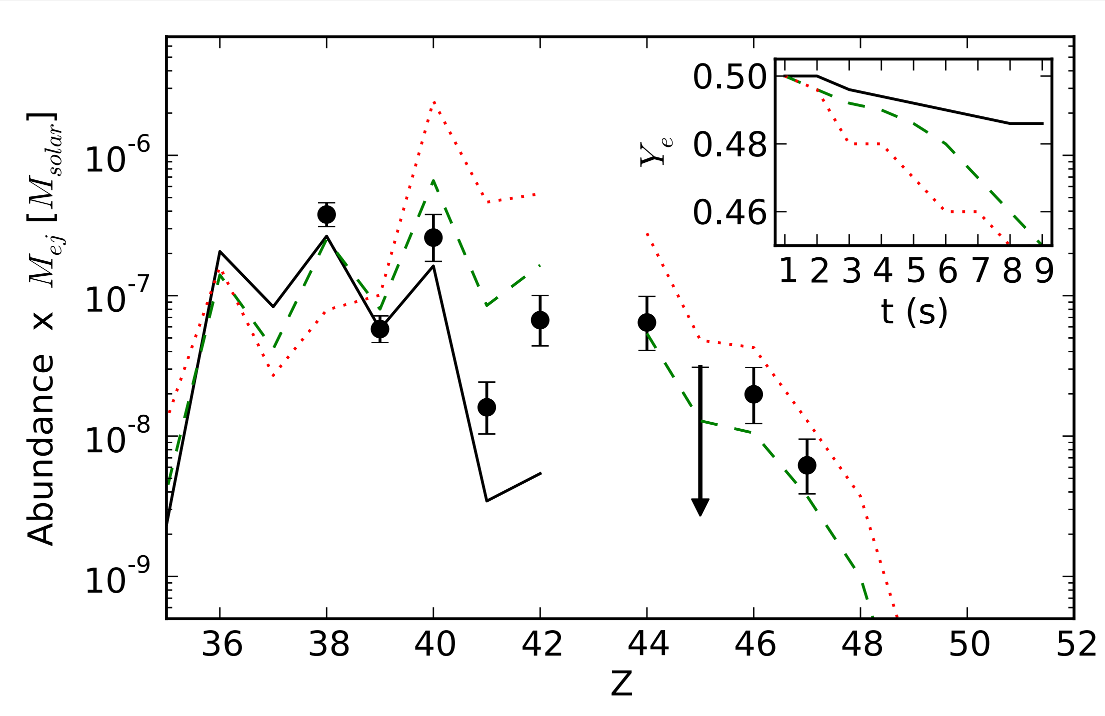


Bliss, Arcones, Montes, Pereira (in prep.)

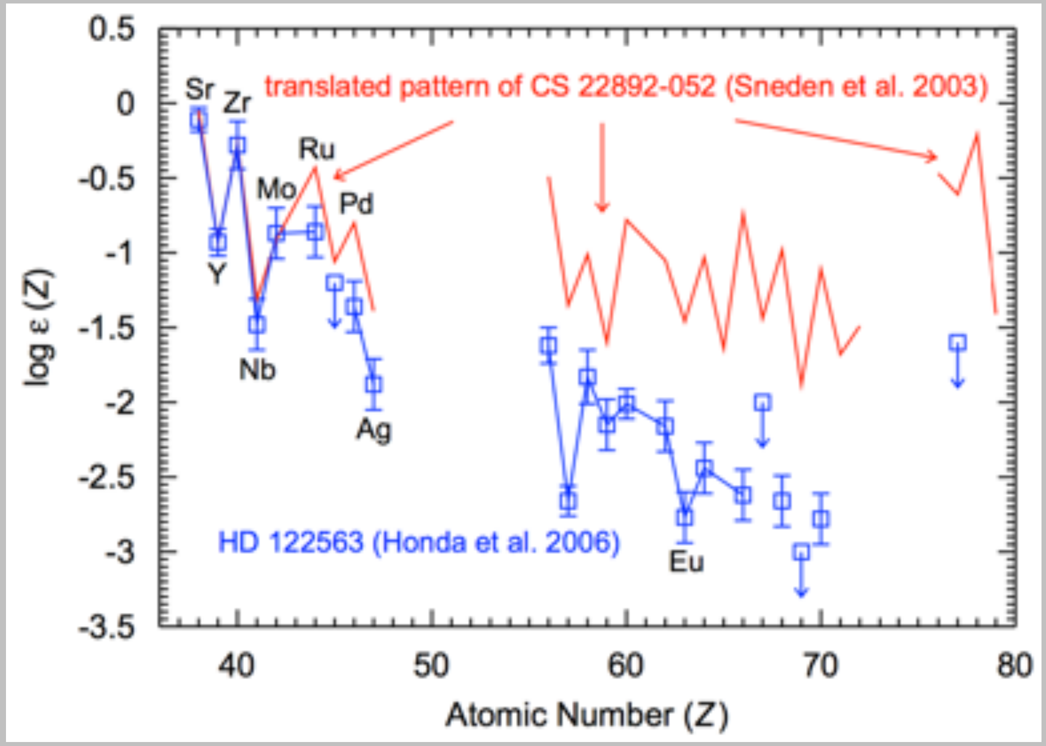
Origin of elements from Sr to Ag

Astrophysical site

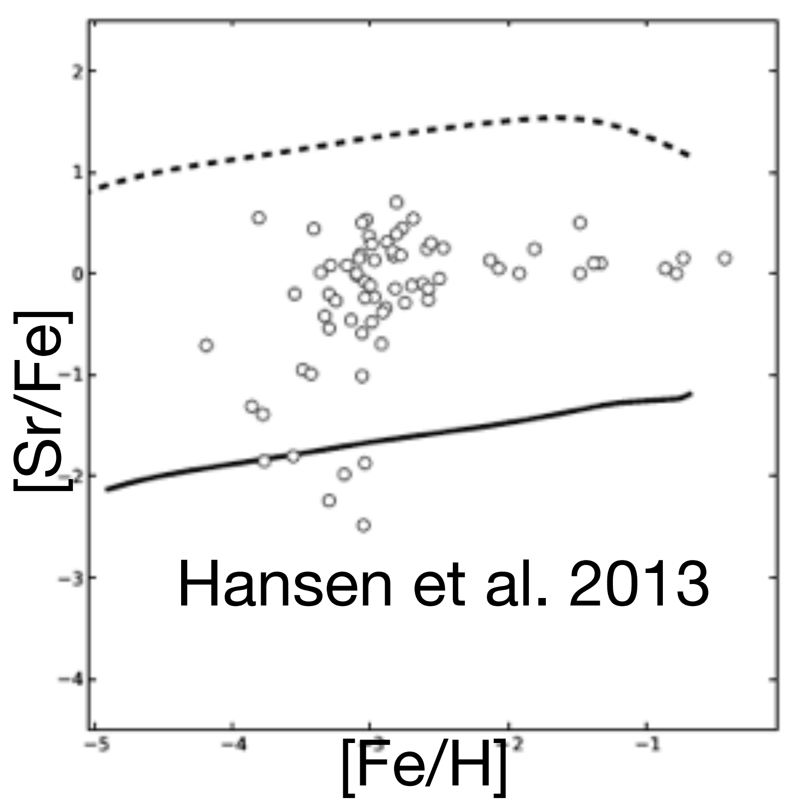


Nucleosynthesis:
identify key reactions

Observations

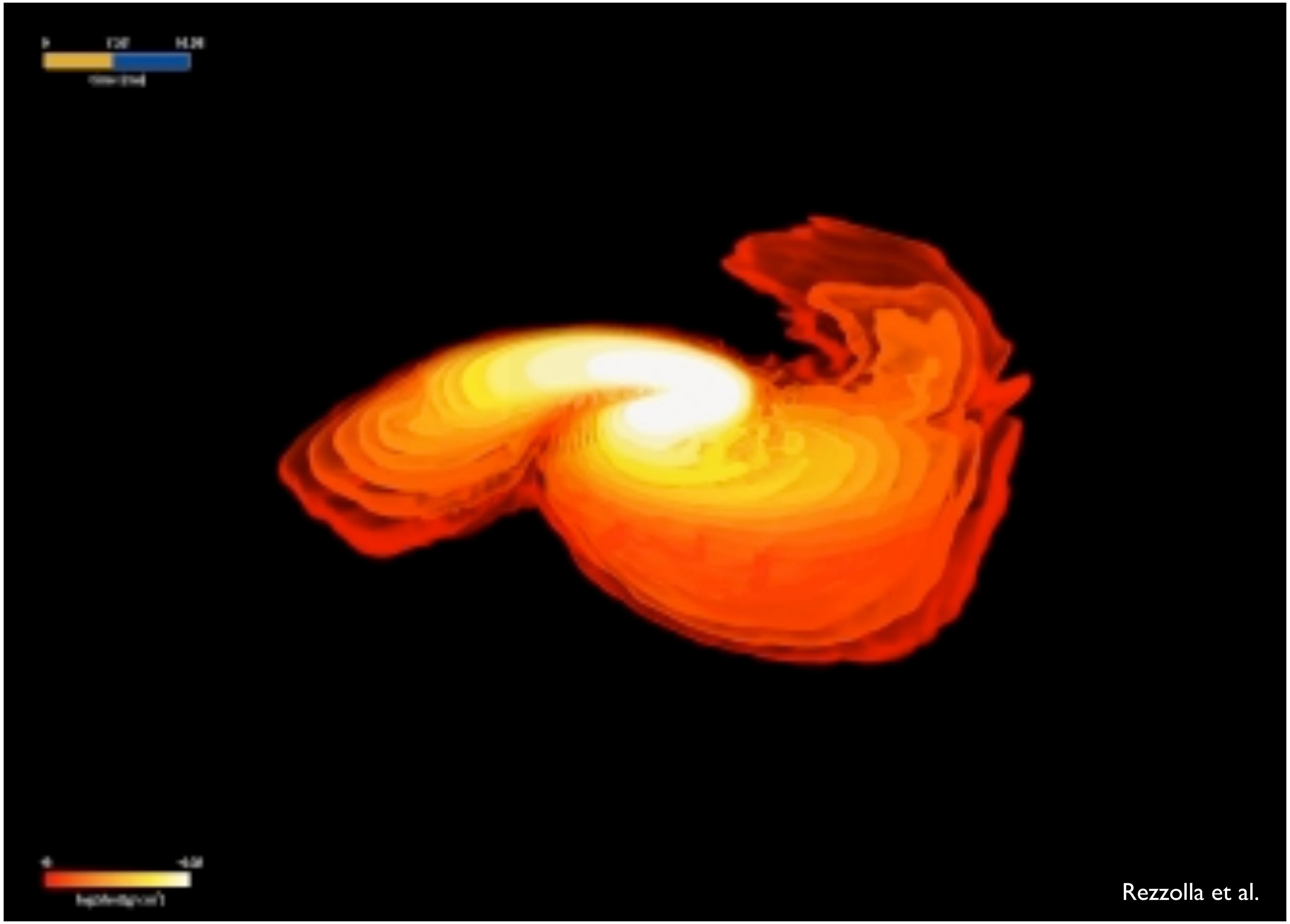


Chemical
evolution



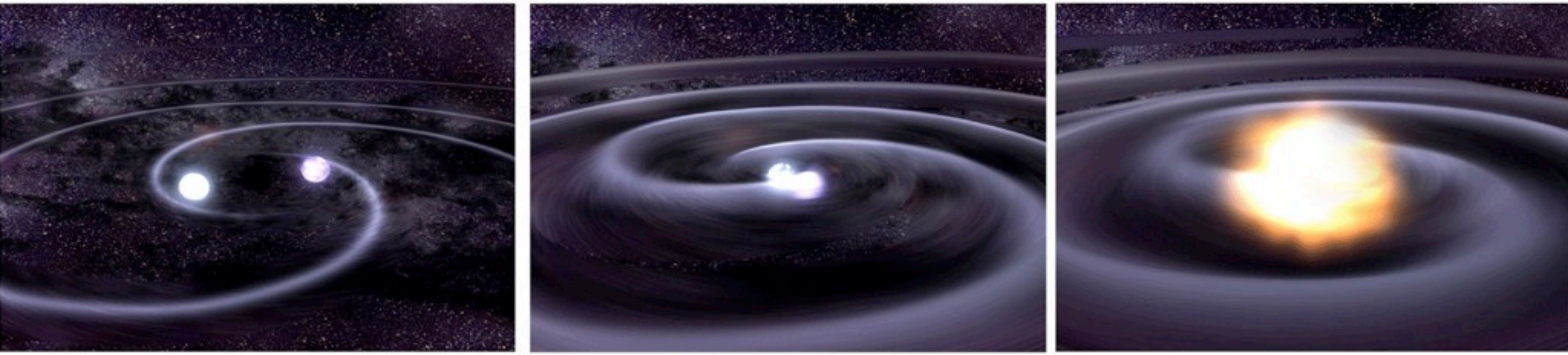
Hansen et al. 2013

Neutron-star mergers



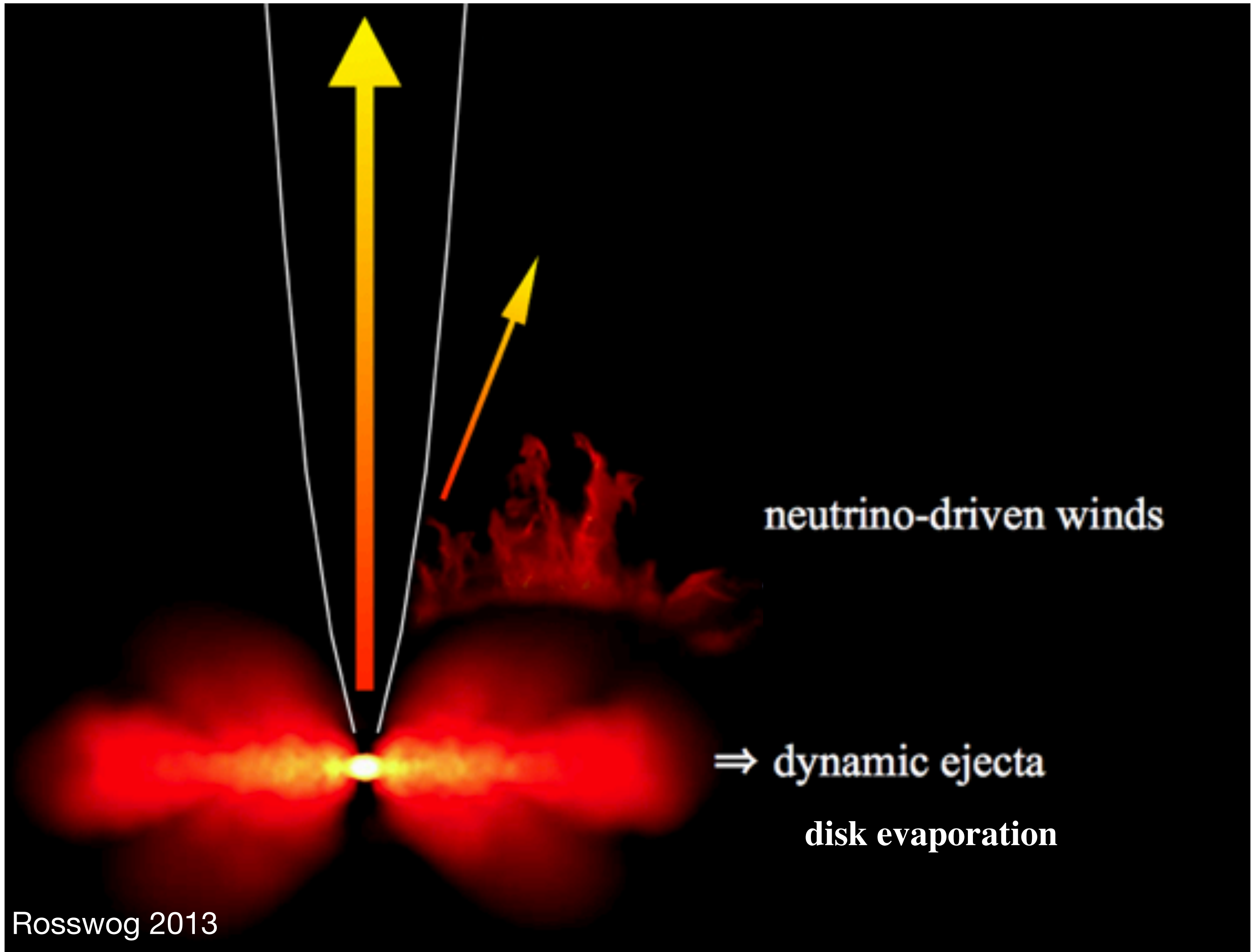
Rezzolla et al.

Neutron star mergers



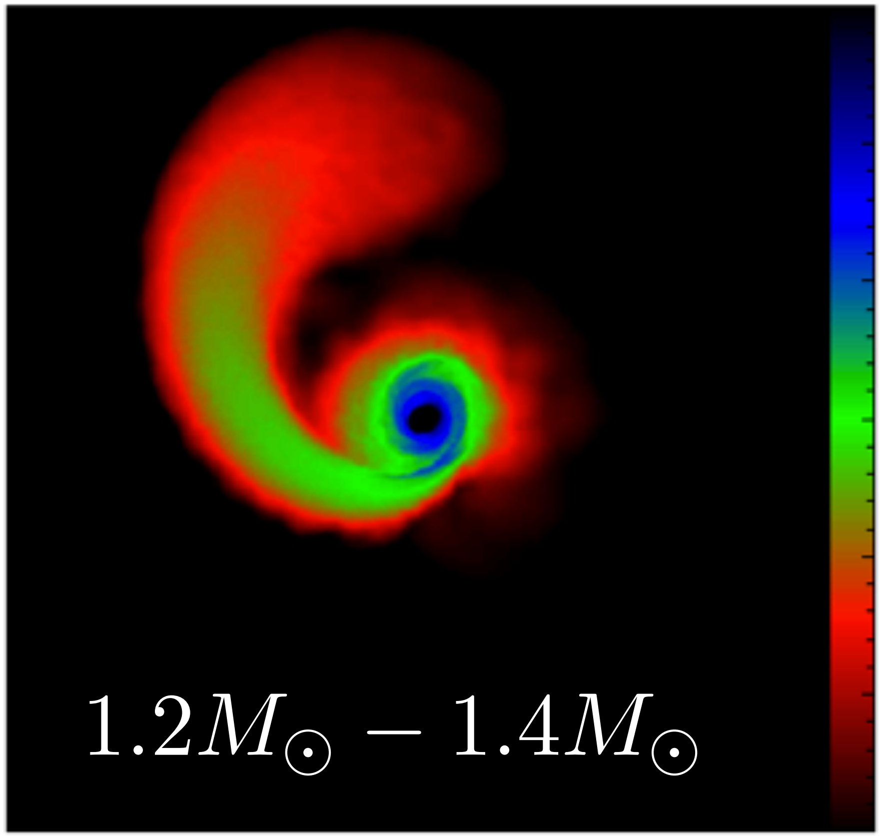
Ejecta from three regions:

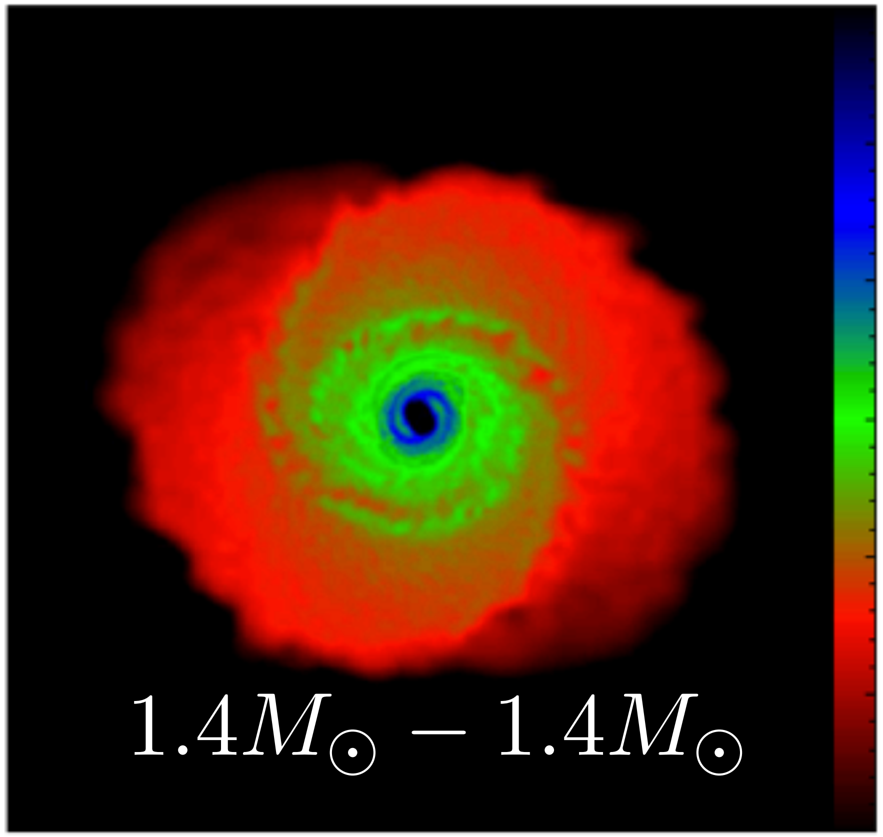
- dynamical ejecta
- neutrino-driven wind
- disk evaporation

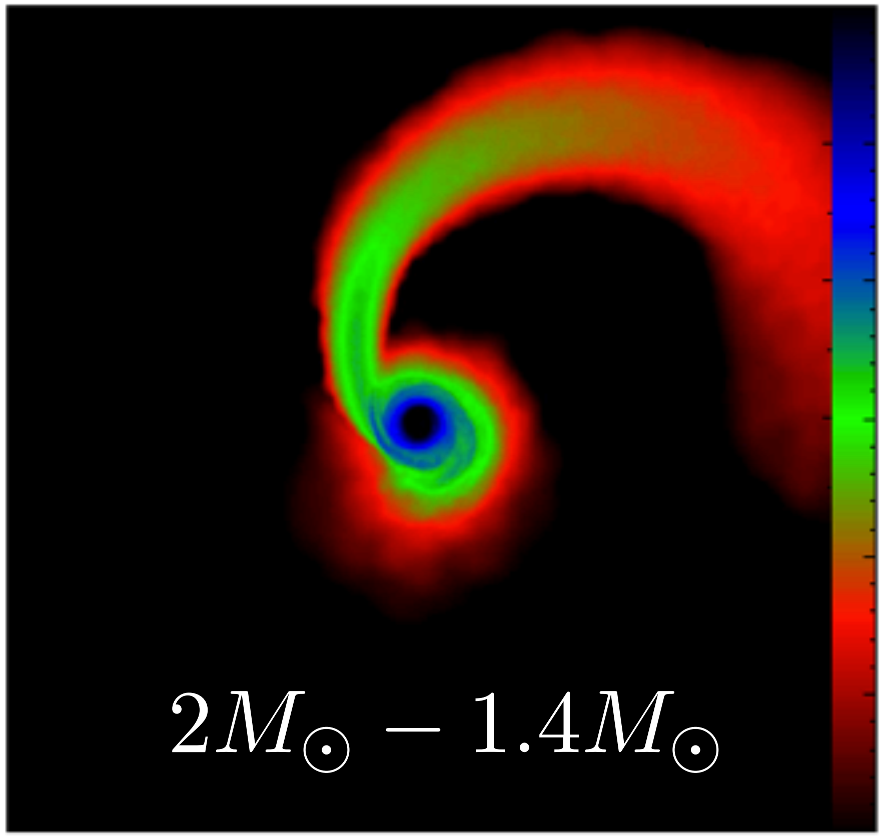


Rosswog 2013

Neutron star mergers: robust r-process





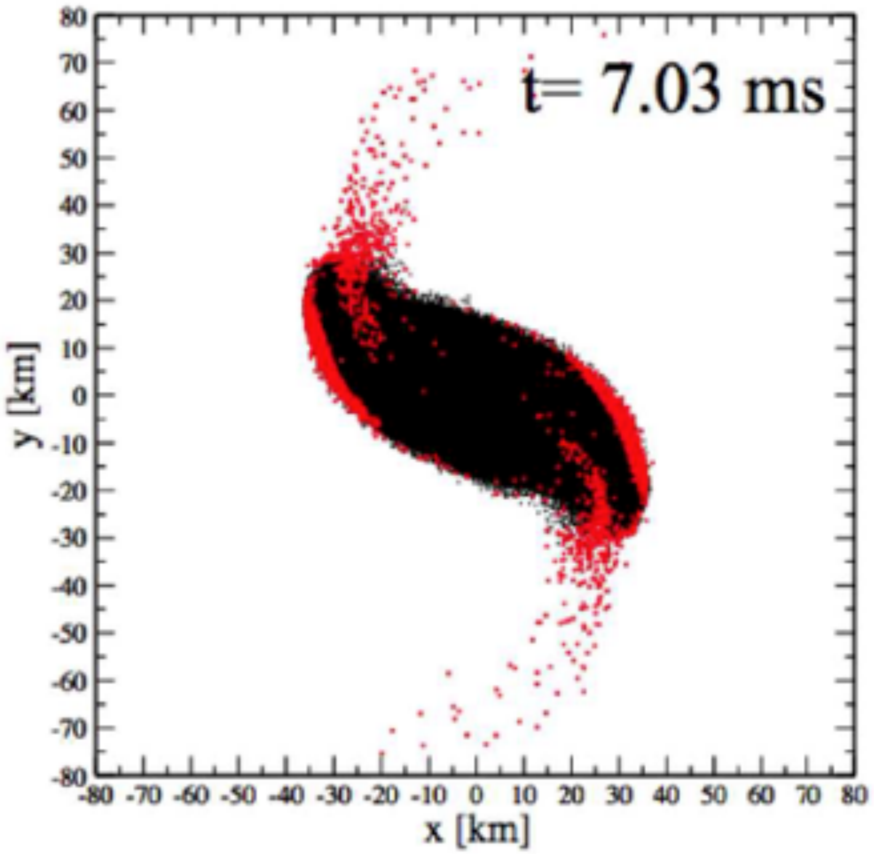


Right conditions for a successful r-process
(Lattimer & Schramm 1974, Freiburghaus et al. 1999)

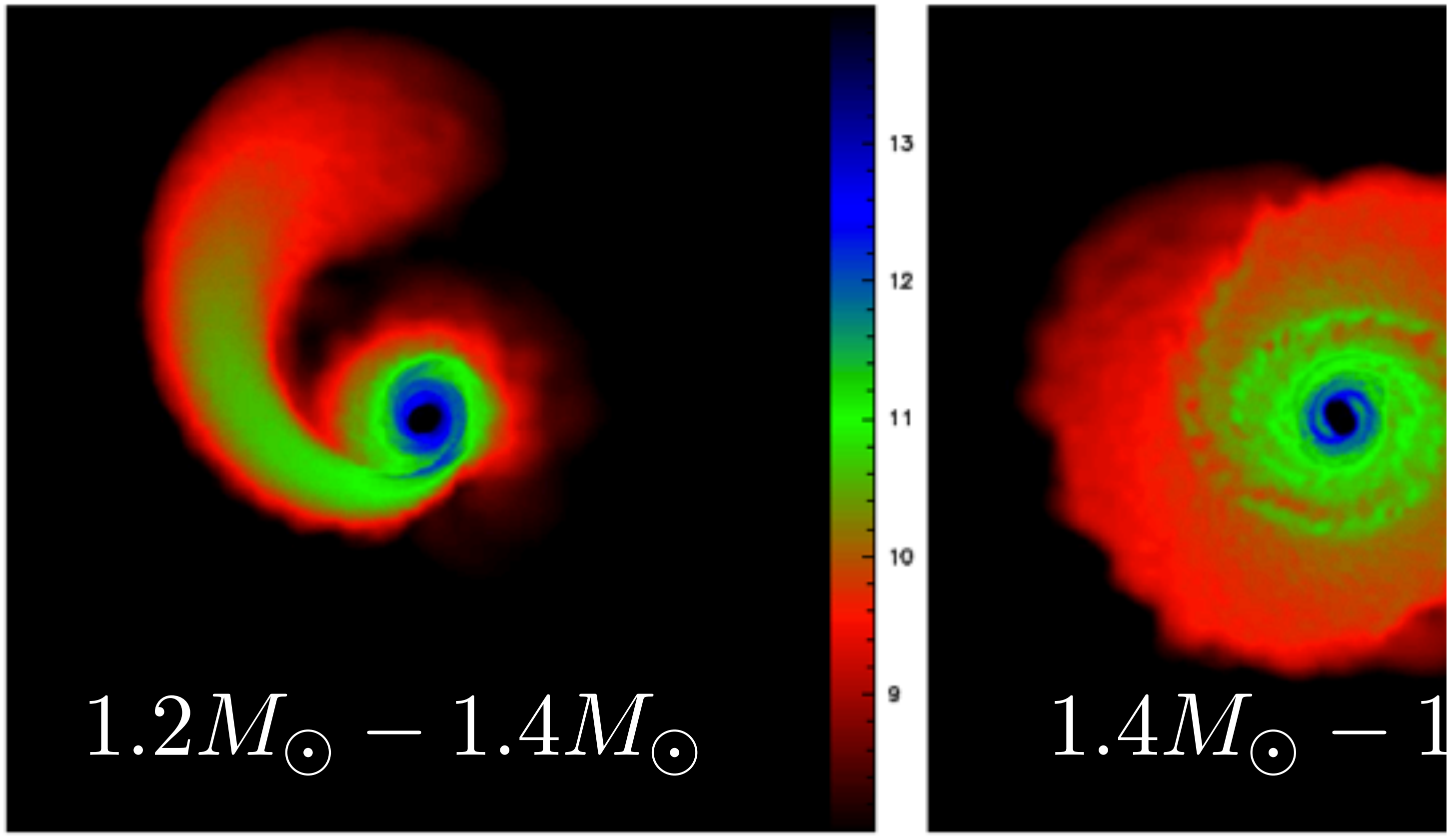
nucleosynthesis of dynamical ejecta
robust r-process:

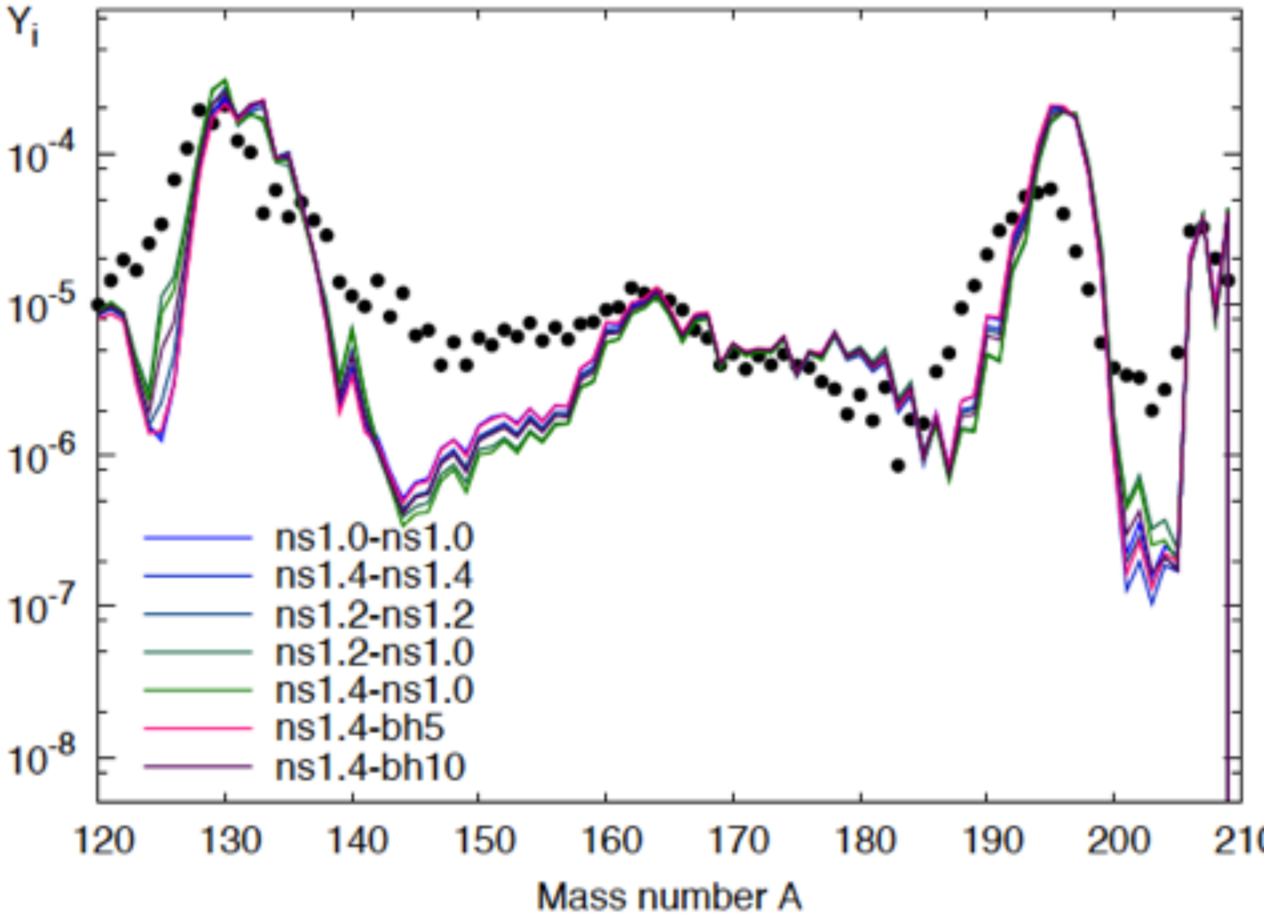
- extreme neutron-rich conditions (Y_e =0.04)
- several fission cycles

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



Neutron star mergers: robust r-process





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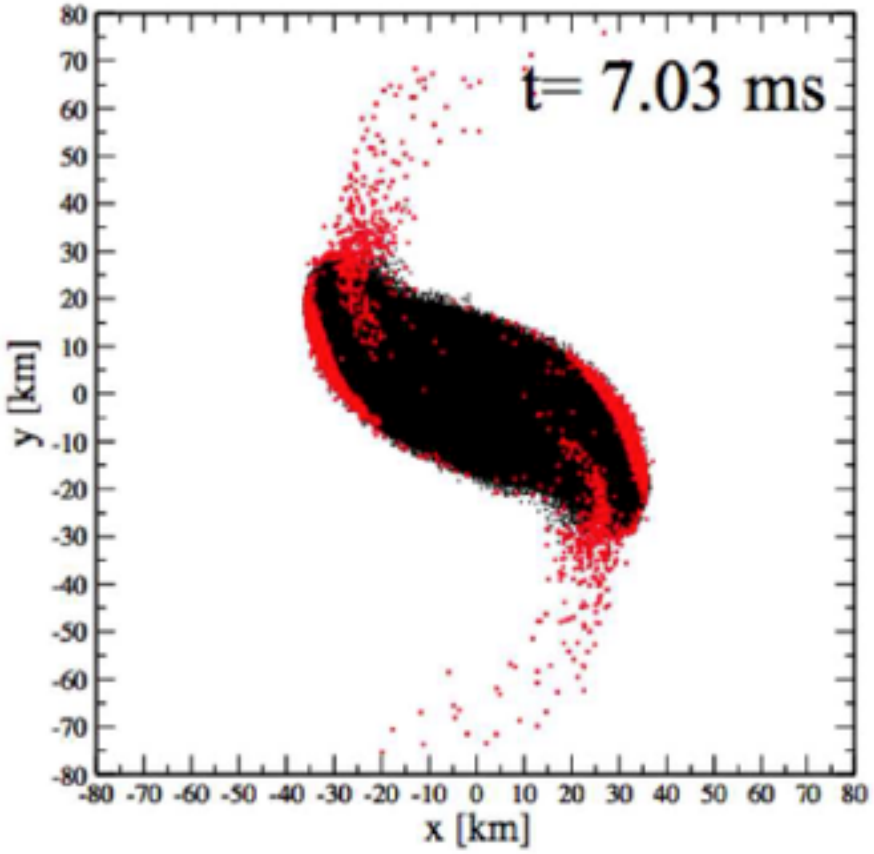
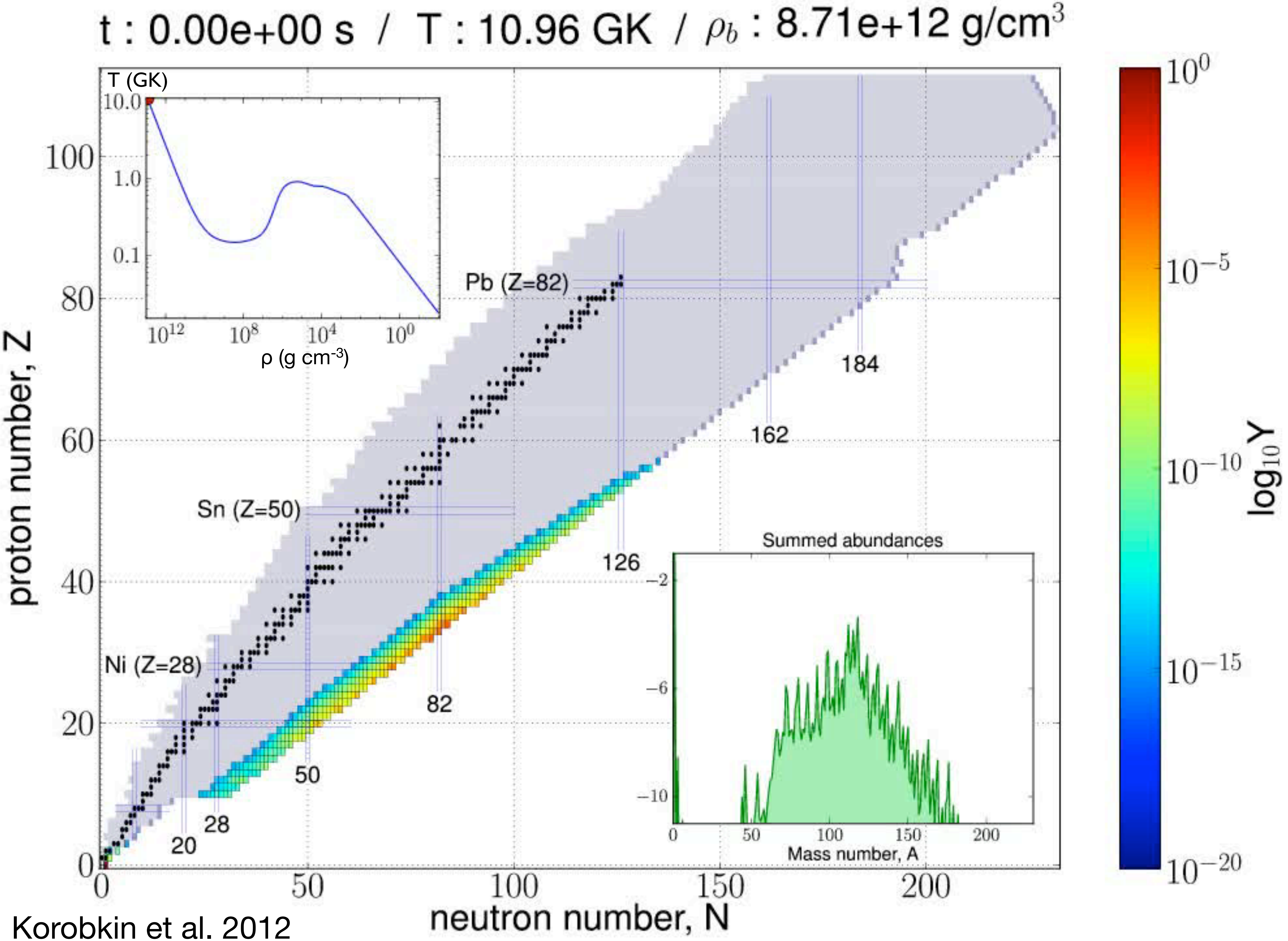


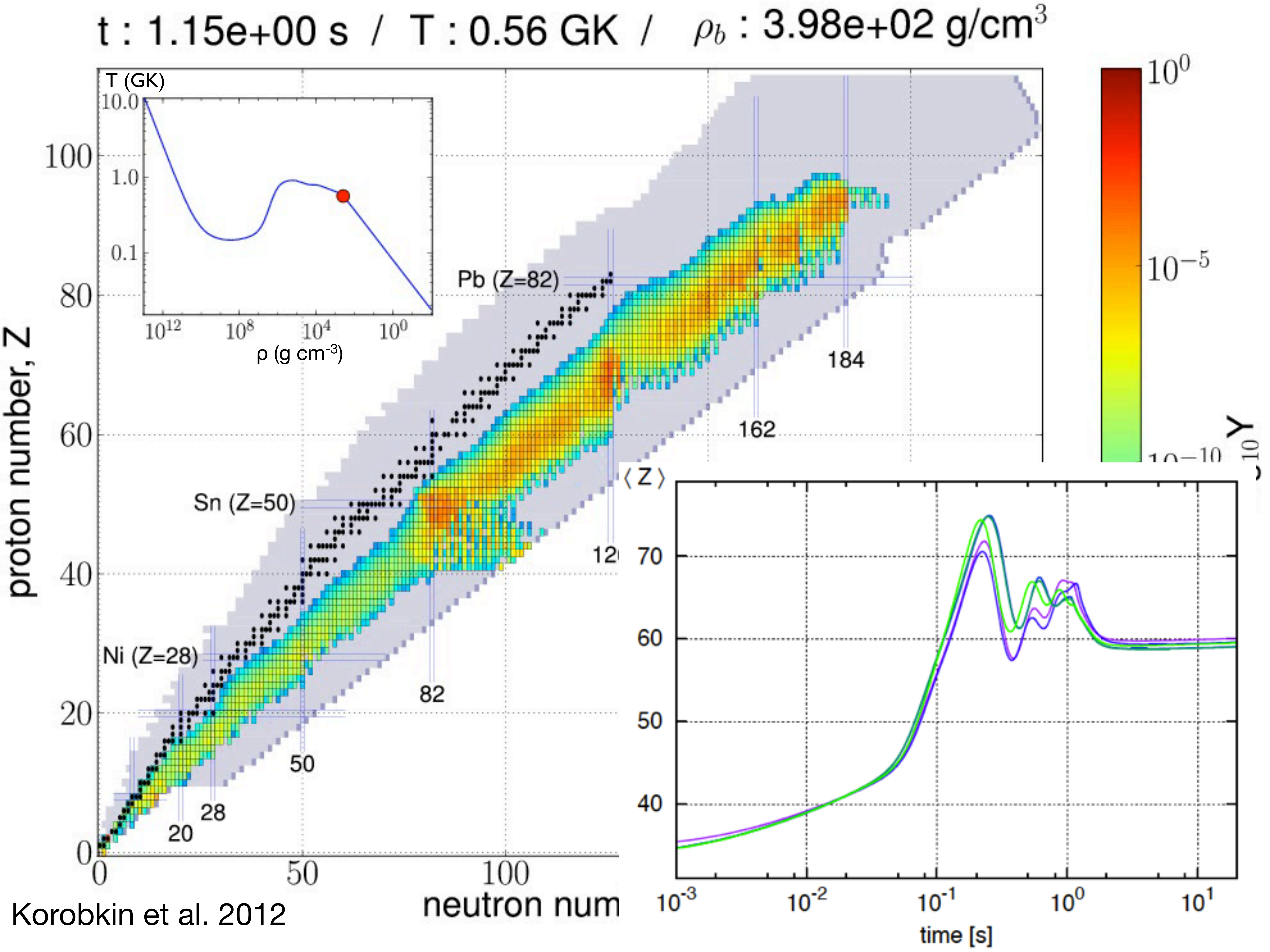
T (GK)

ρ (g cm^{-3})

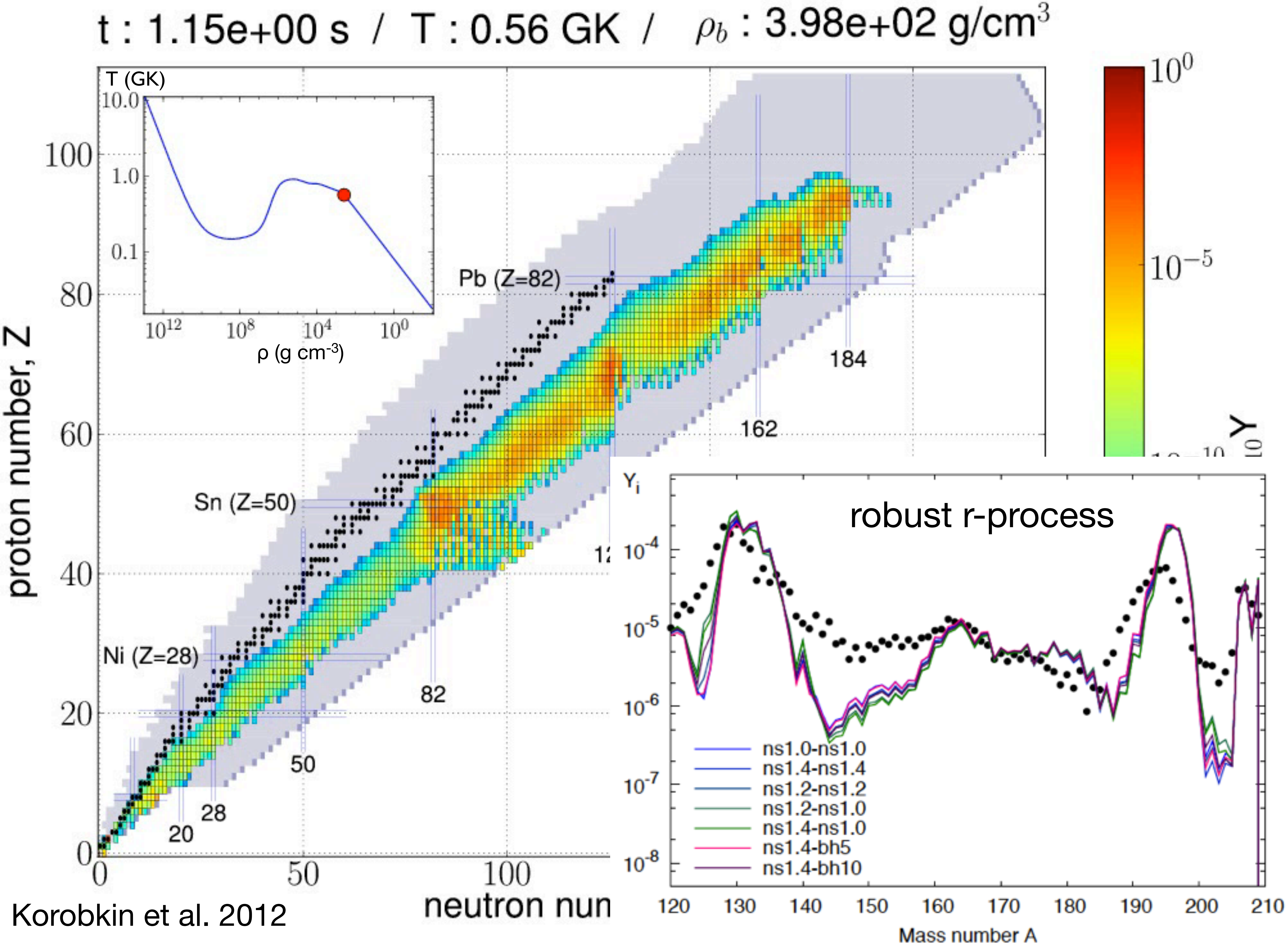
Korobkin et al. 2012



Korobkin et al. 2012



Korobkin et al. 2012



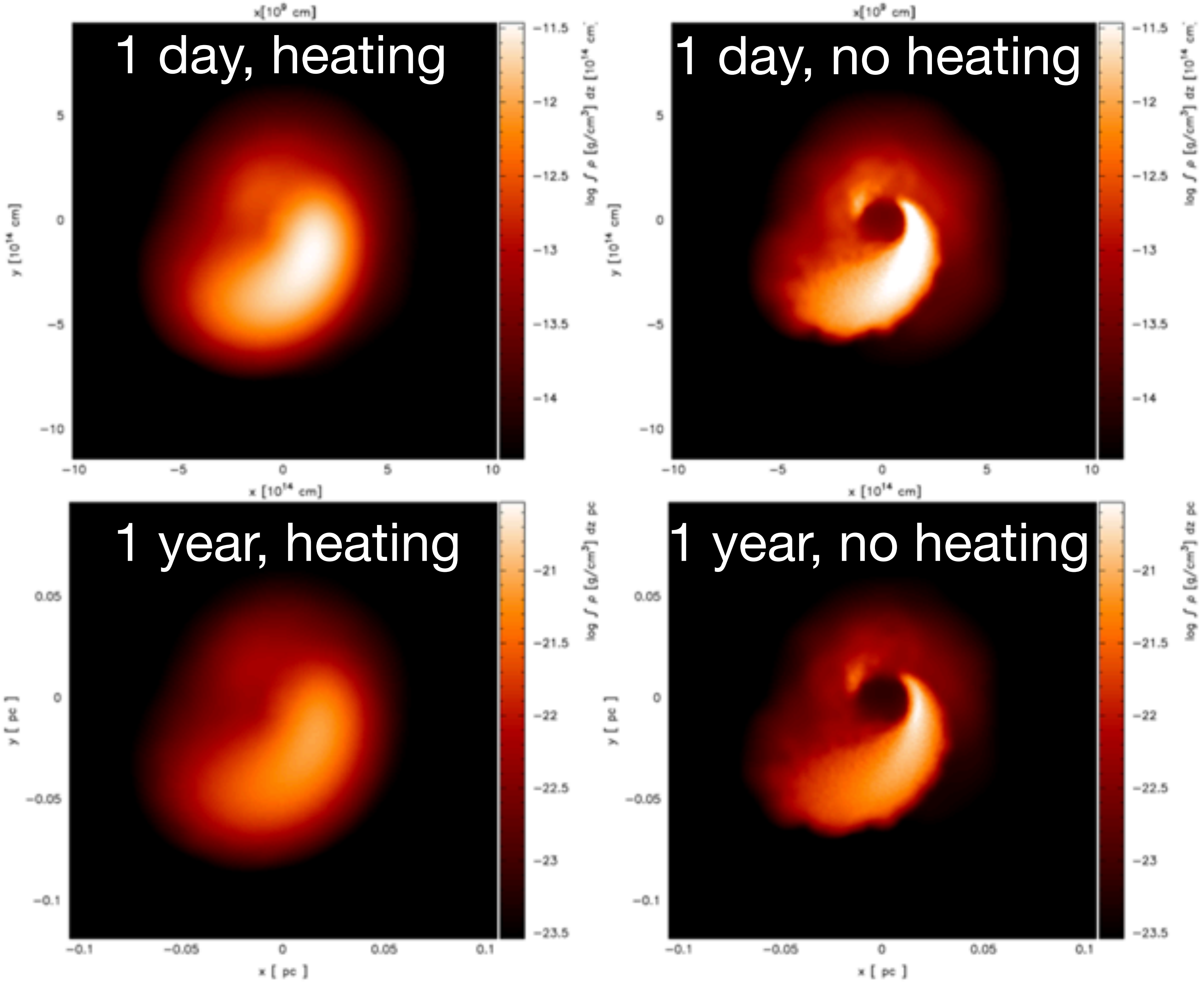
robust r-process

Korobkin et al. 2012

Radioactive decay in neutron star mergers

r-process heating affects:

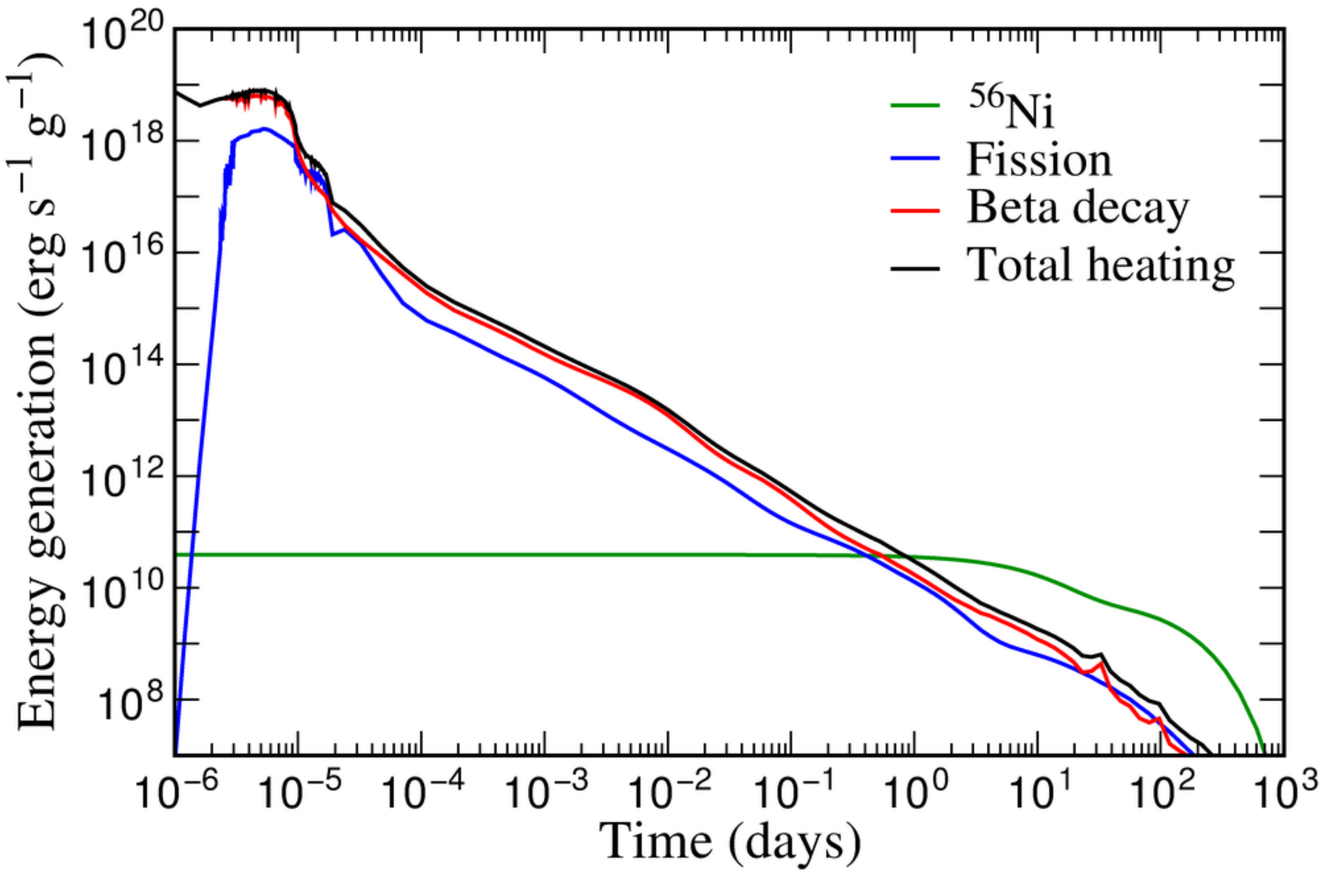
- merger dynamics: late X-ray emission in short GRBs
  (Metzger, Arcones, Quataert,Martinez-Pinedo 2010)
- remnant evolution (Rosswog, Korobkin, Arcones, Thielemann, Piran 2014)

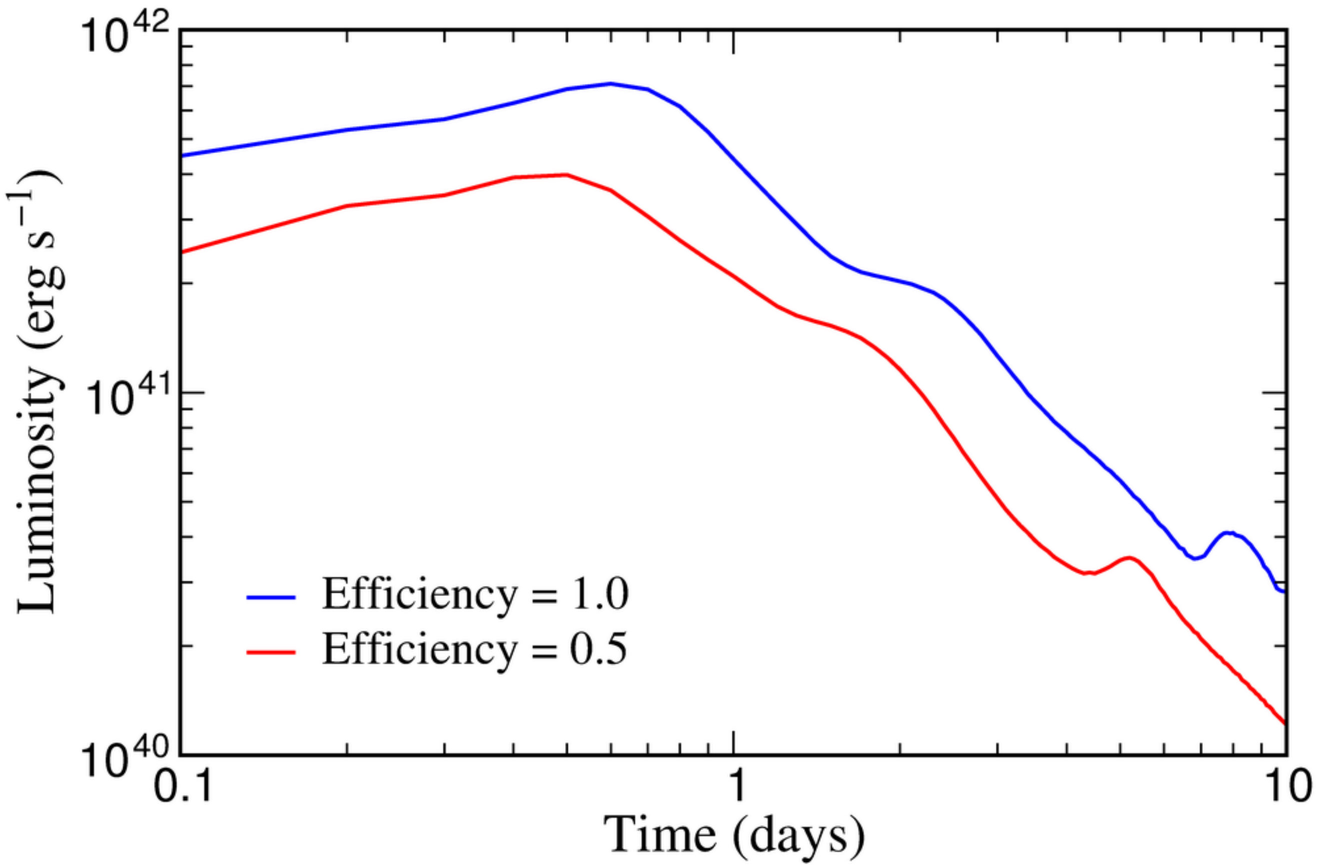


Radioactive decay in neutron star mergers

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

(see also Kulkarni 2005: macronova)





Multi messenger (e.g. Metzger & Berger 2012, Rosswog 2012, 2013, Bauswein et al. 2013)

on star mergers

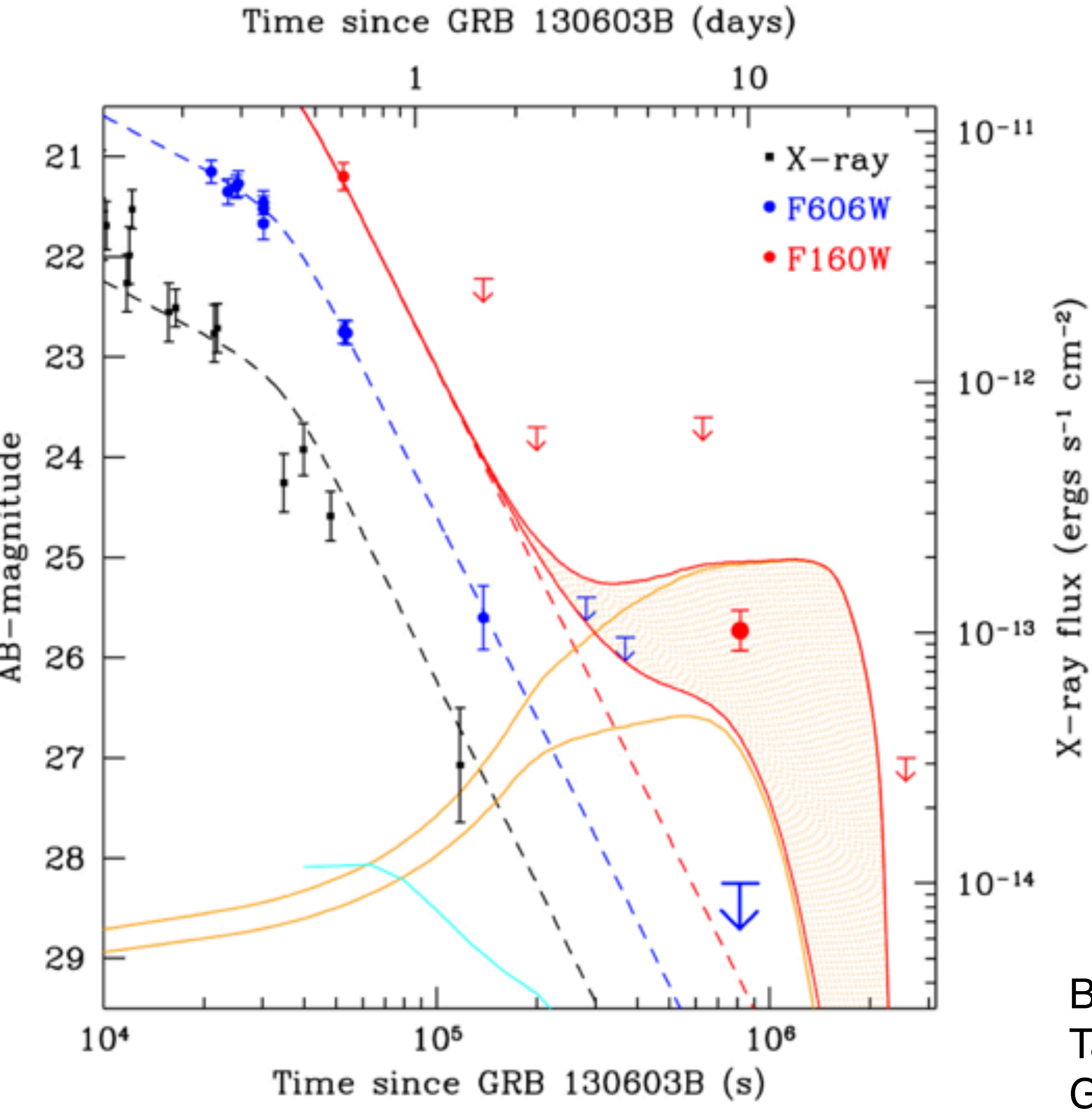
zger et al. 2010, Roberts et al. 2011,

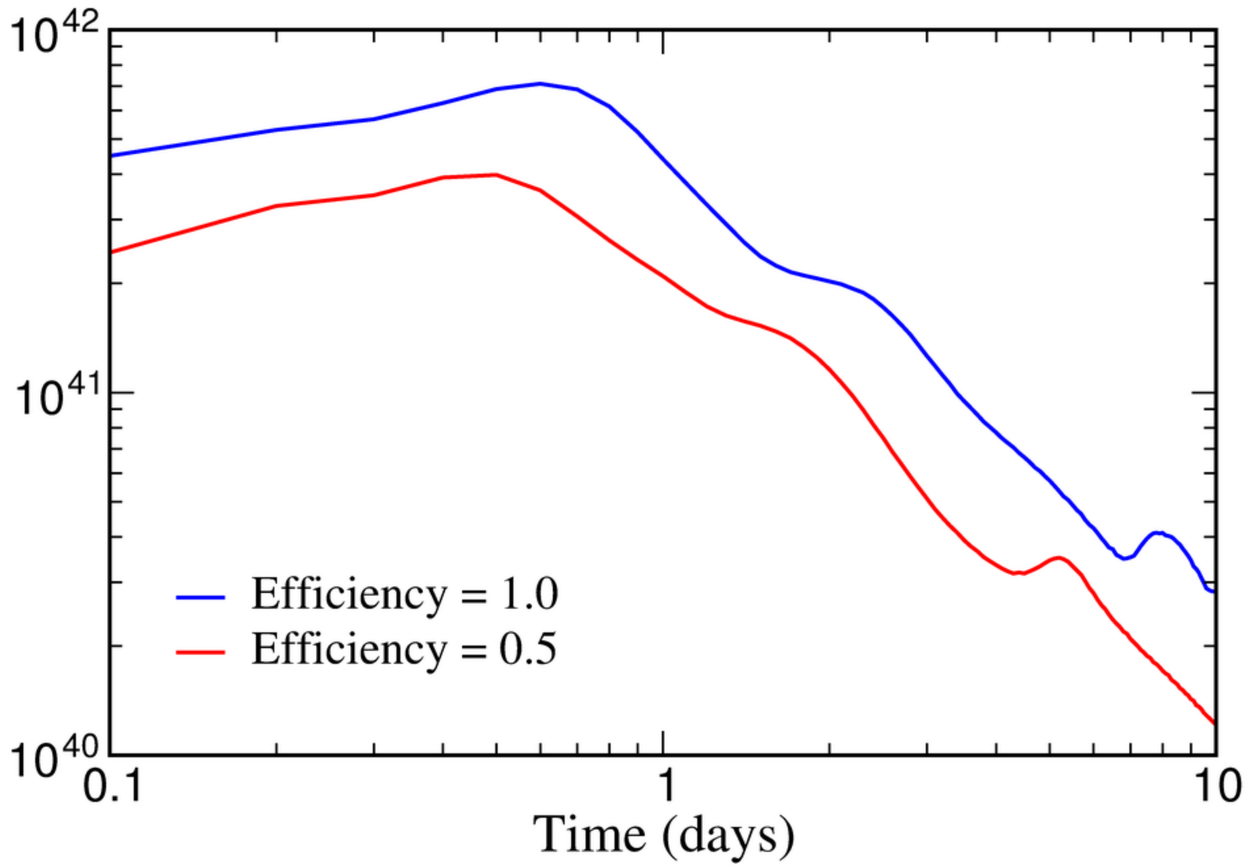
rocess, EM counter part to GW

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





12, Rosswog 2012, 2013, Bauswein et al. 2013)

Berger, Fong & Chornock, 2013
Tanaka & Hotokezaka, 2013, Hotokezaka et al. 2013
Grossman, Korobkin, Rosswog, Piran, 2014

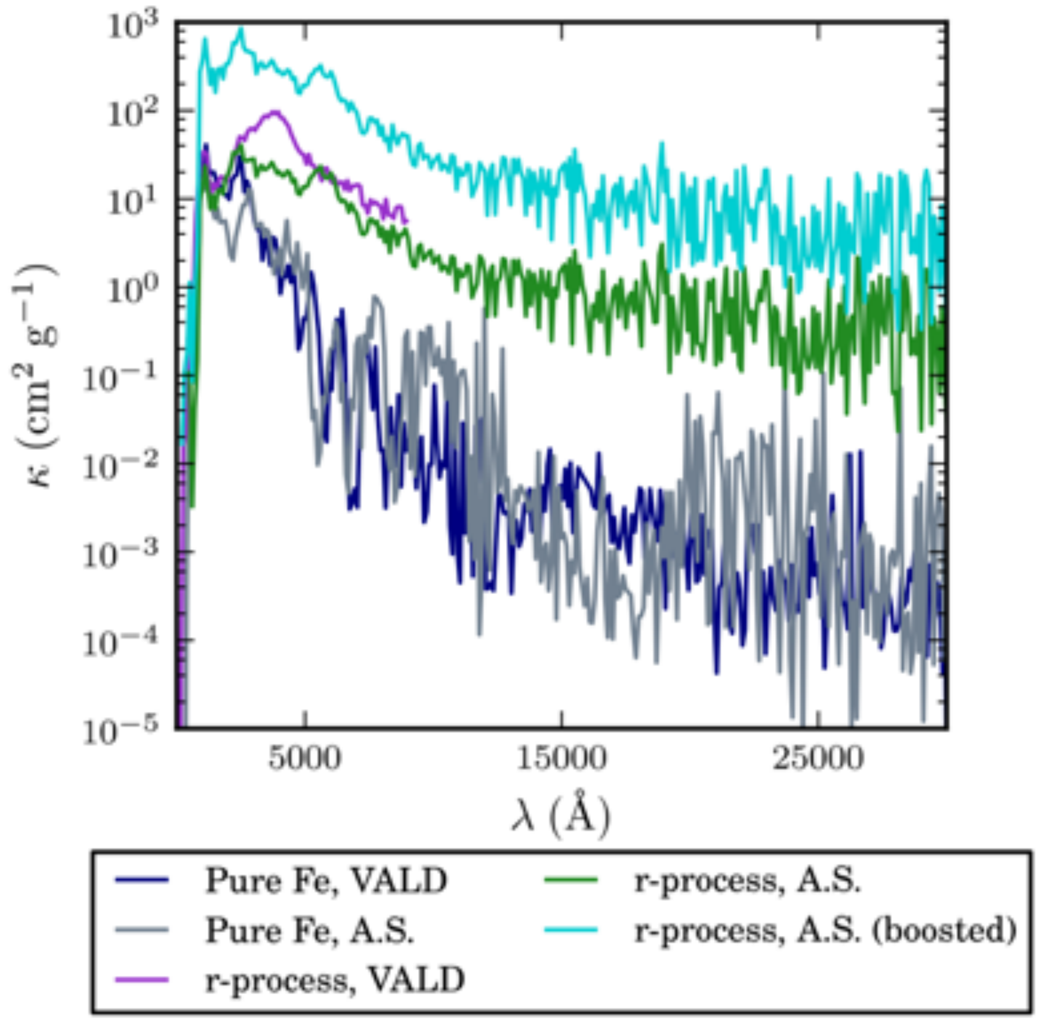
Opacities of r-process elements

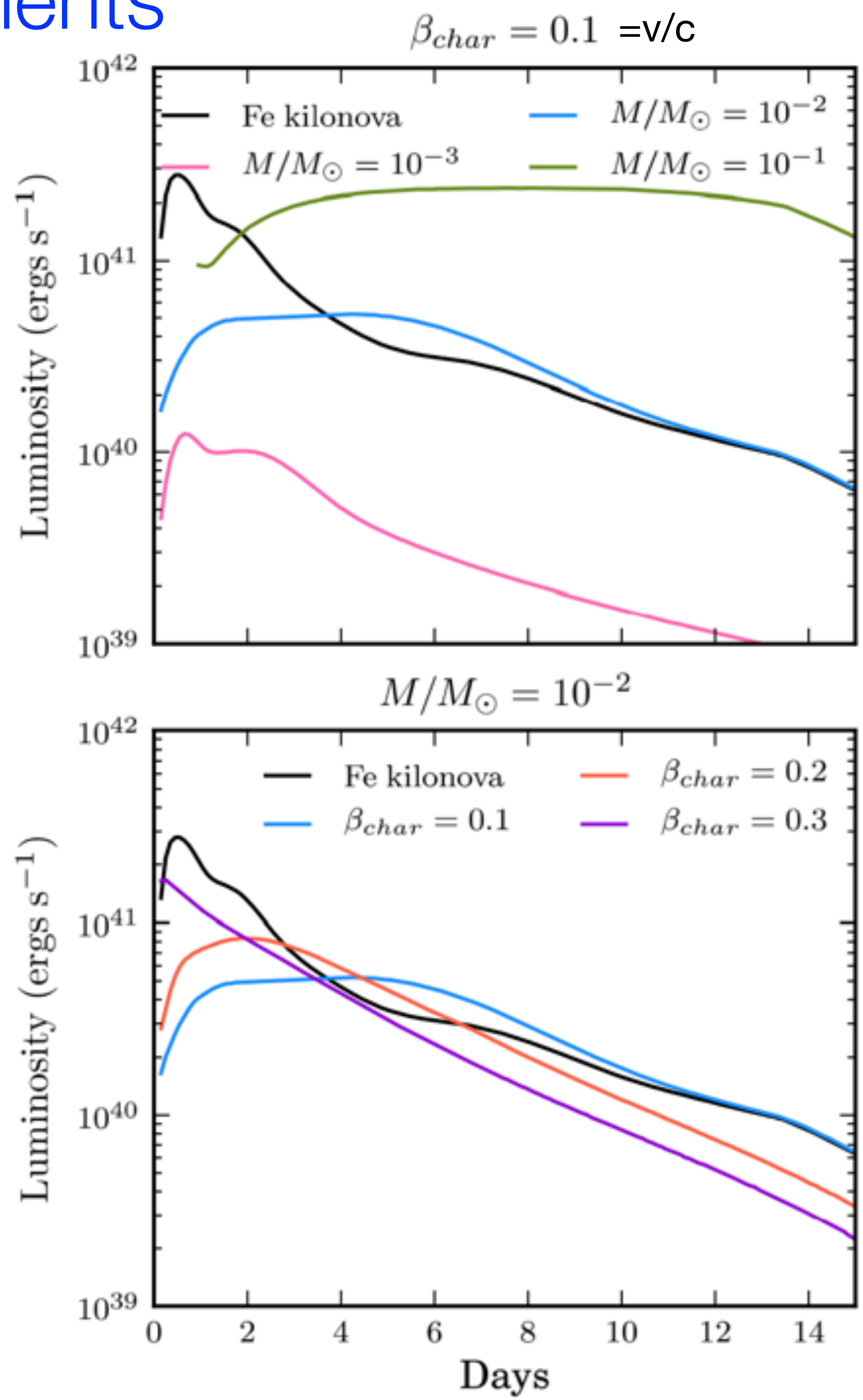
Initial models: iron opacities

(Metzger et al. 2010, Roberts et al. 2011, Goriely et al. 2011)

Barnes & Kasen 2013: r-process elements have higher opacities

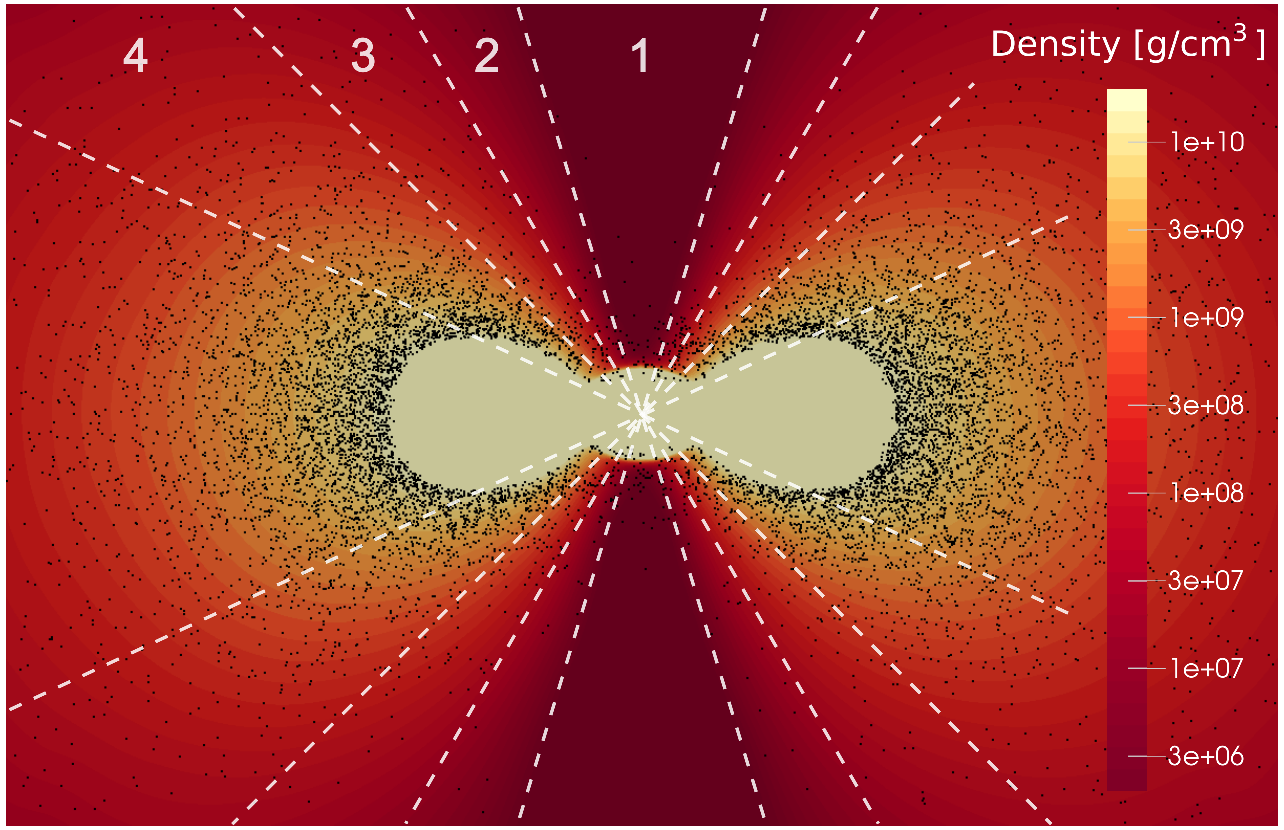
(Kasen, Badnell, Barnes 2013)





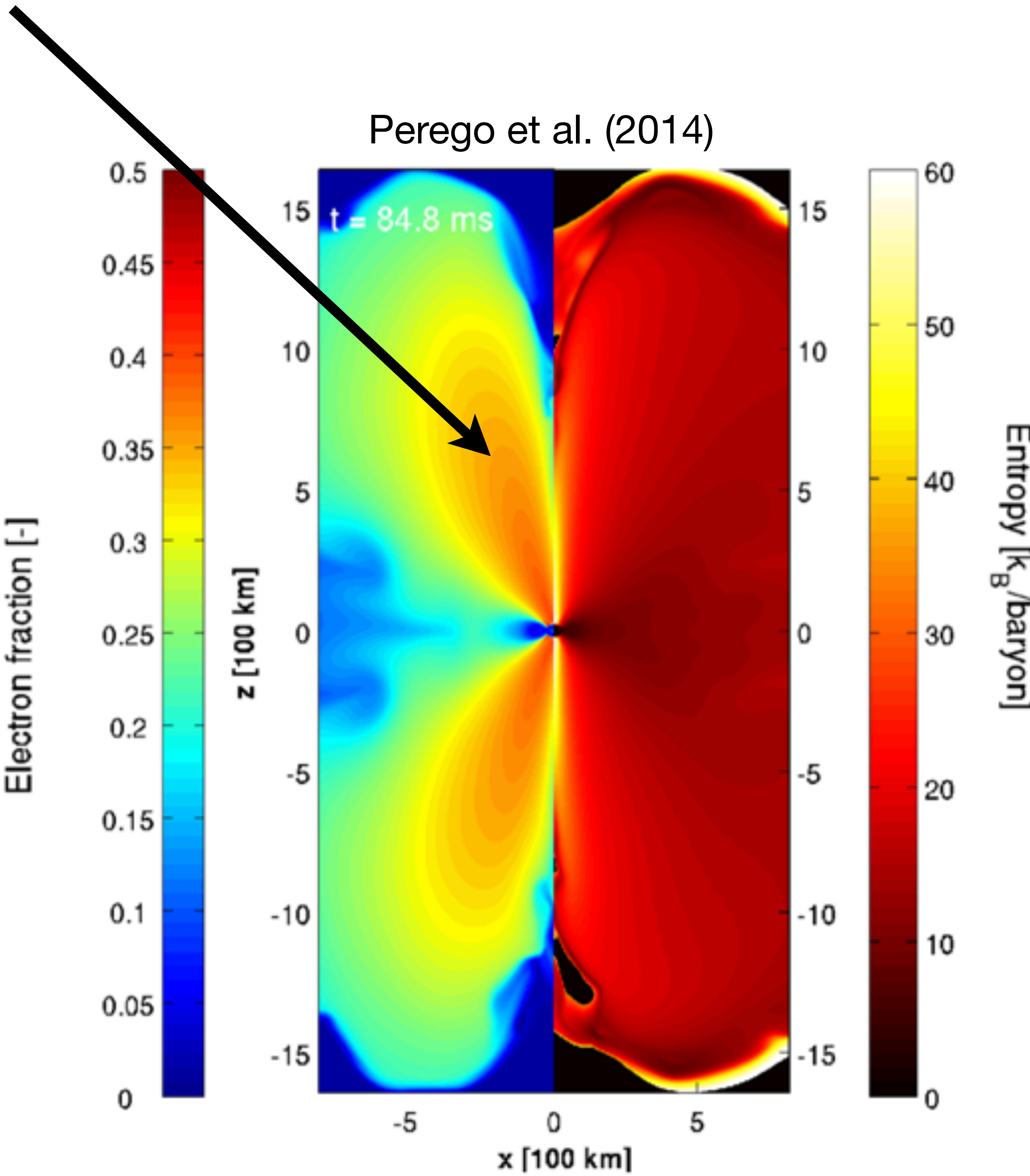
Neutron star mergers: neutrino-driven wind

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



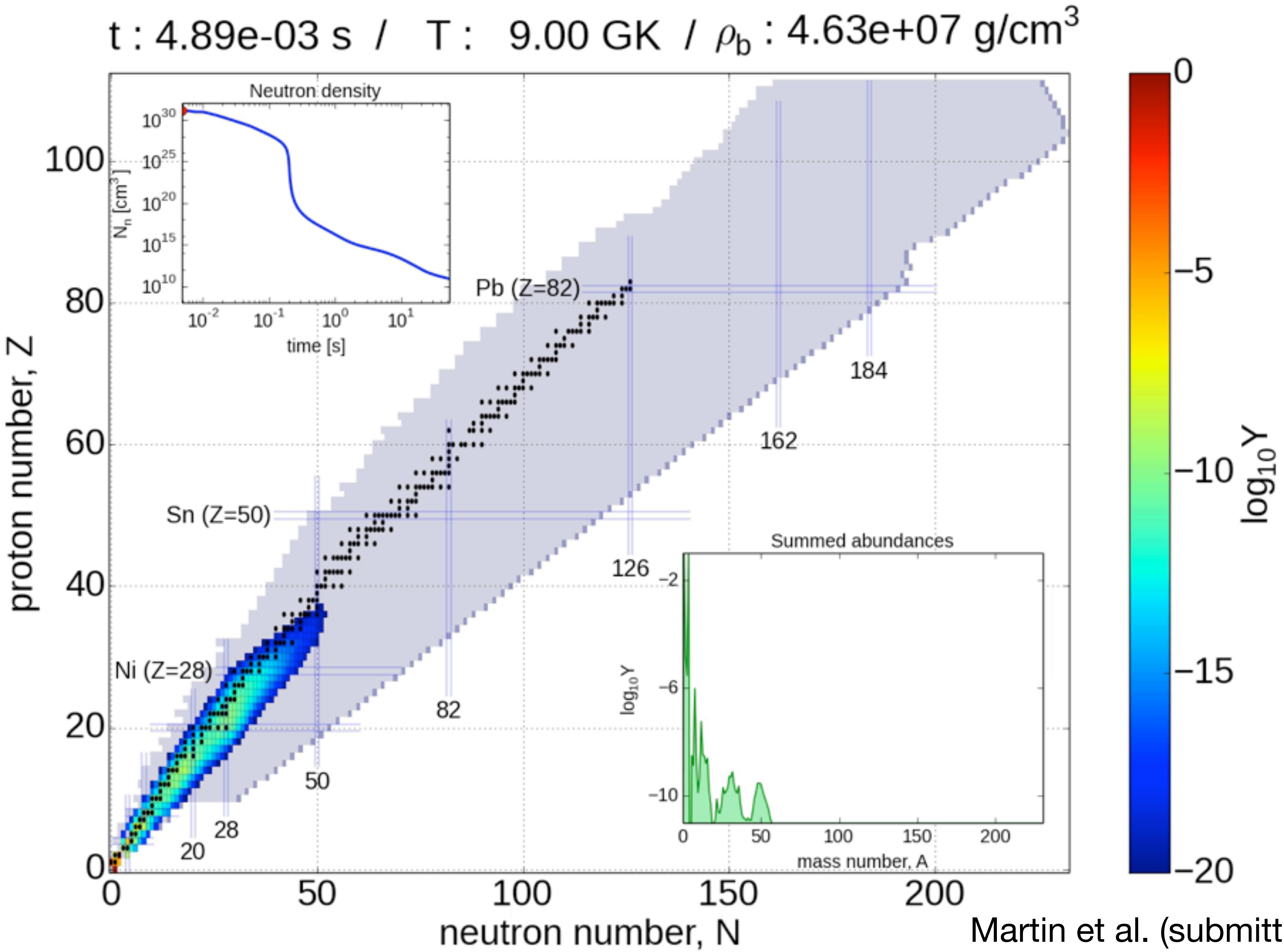
Martin et al. (submitted)

Perego et al. (2014)



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

Neutron star mergers: neutrino-driven wind

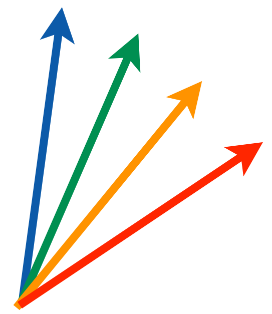


Martin et al. (submitted)

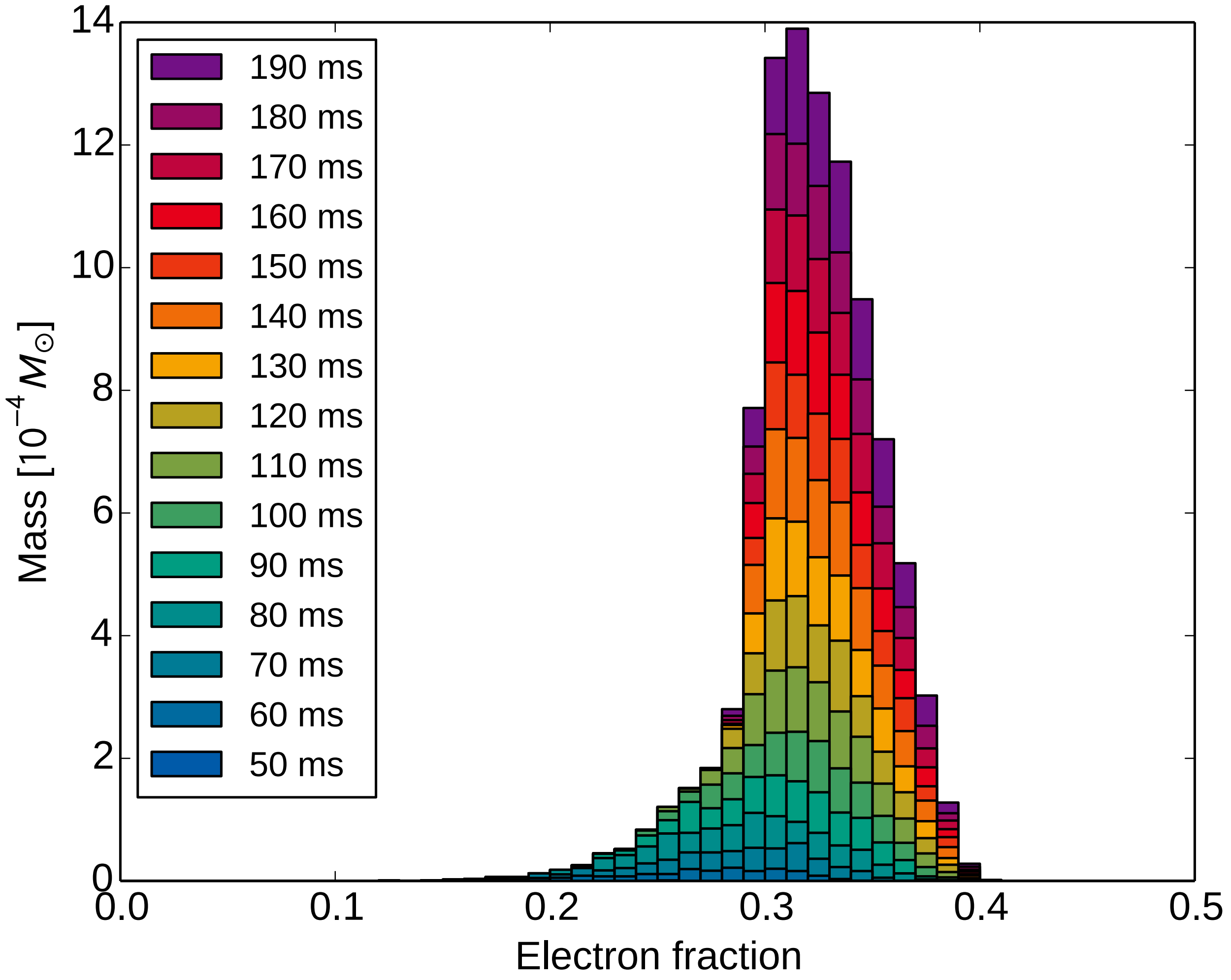
Time and angle dependency

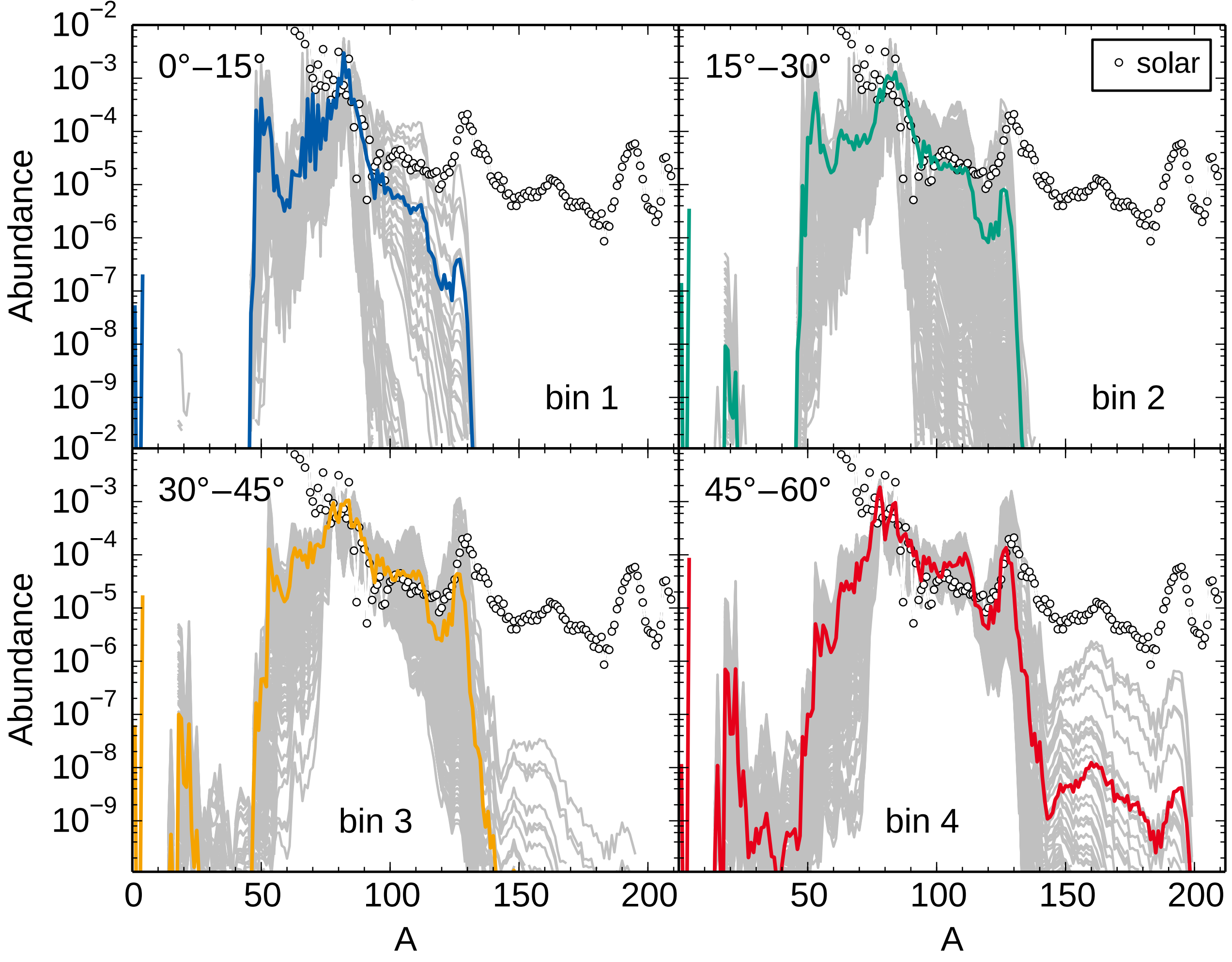
Black hole formation determines time for wind nucleosynthesis
(Fernandez & Metzger 2013, Kasen et al. 2015)

Early times: low Y_e: heavy elements
Late times: Y_e ~0.35: lighter heavy elements



angle dependency



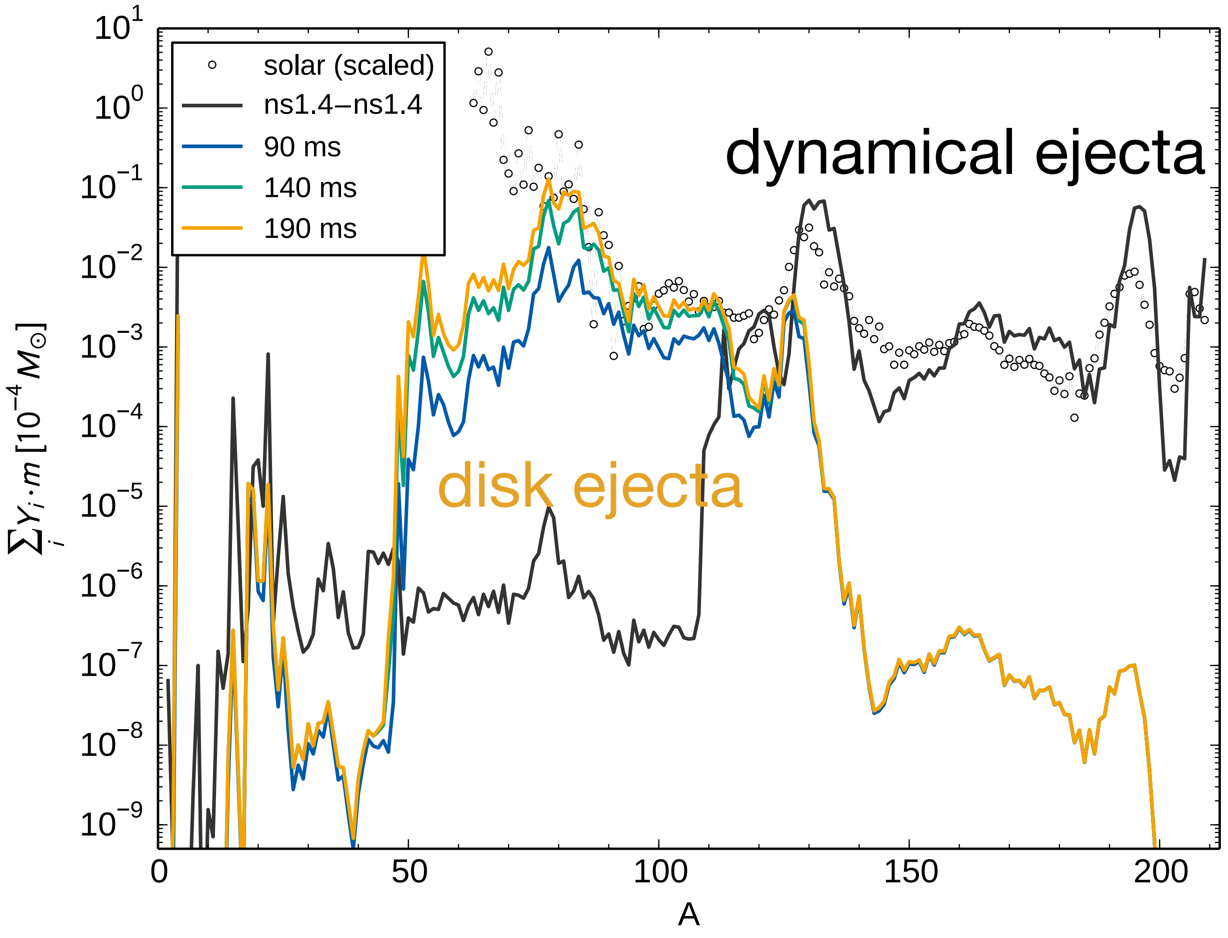


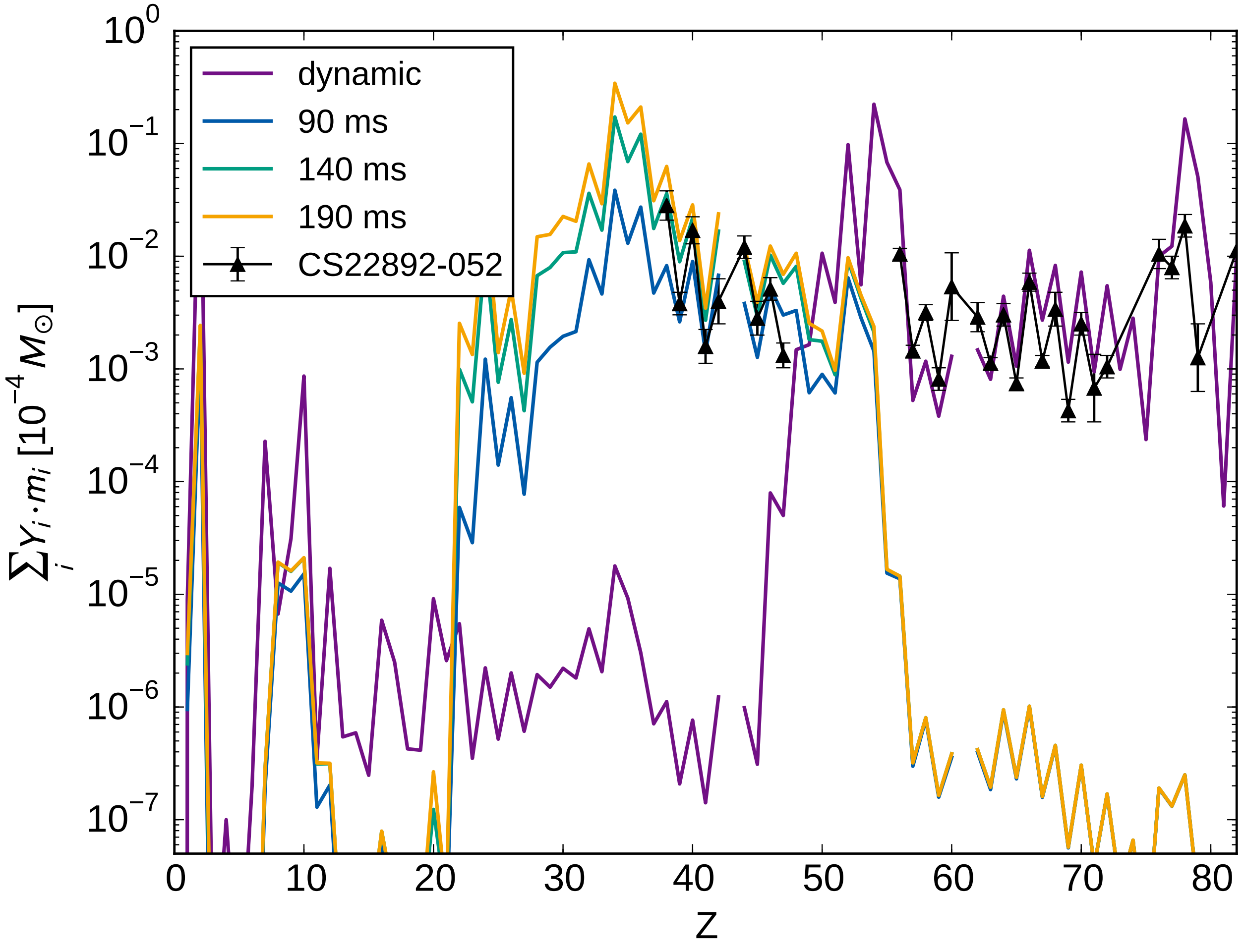
Martin et al. (submitted)

Wind and dynamic ejecta

Wind ejecta complement dynamic ejecta

Complete mixing: solar system abundances and UMP stars





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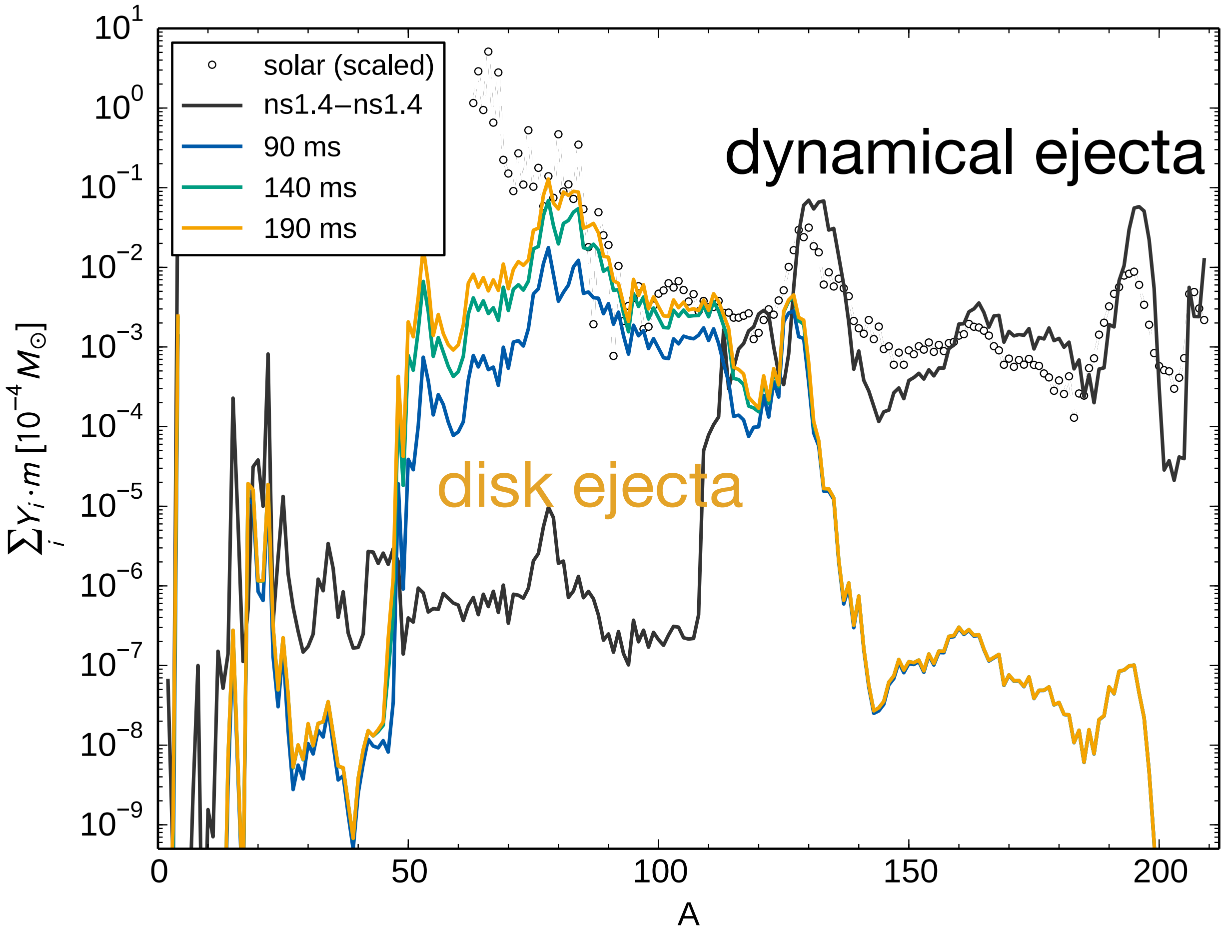
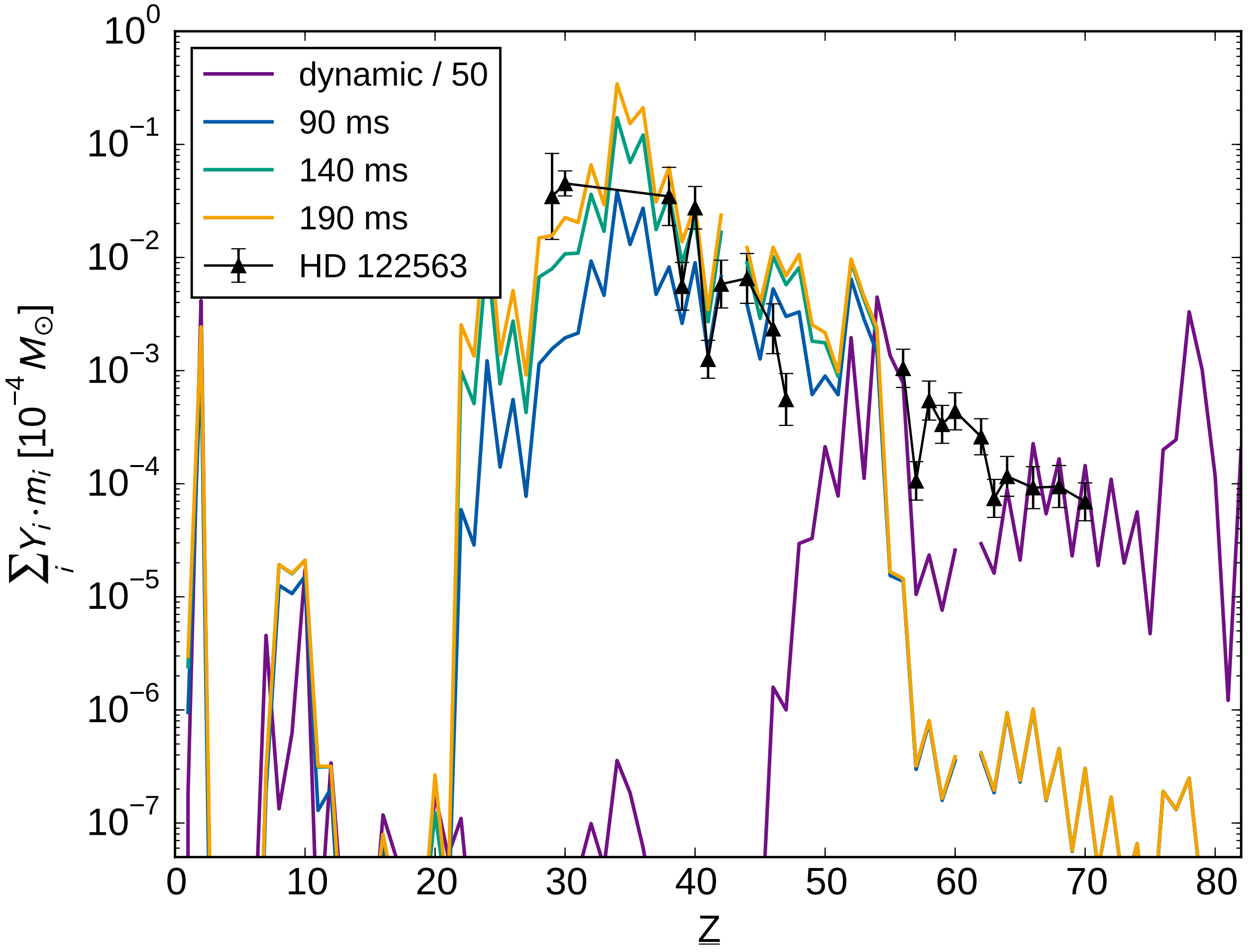


Partial mixing: Honda-like star?

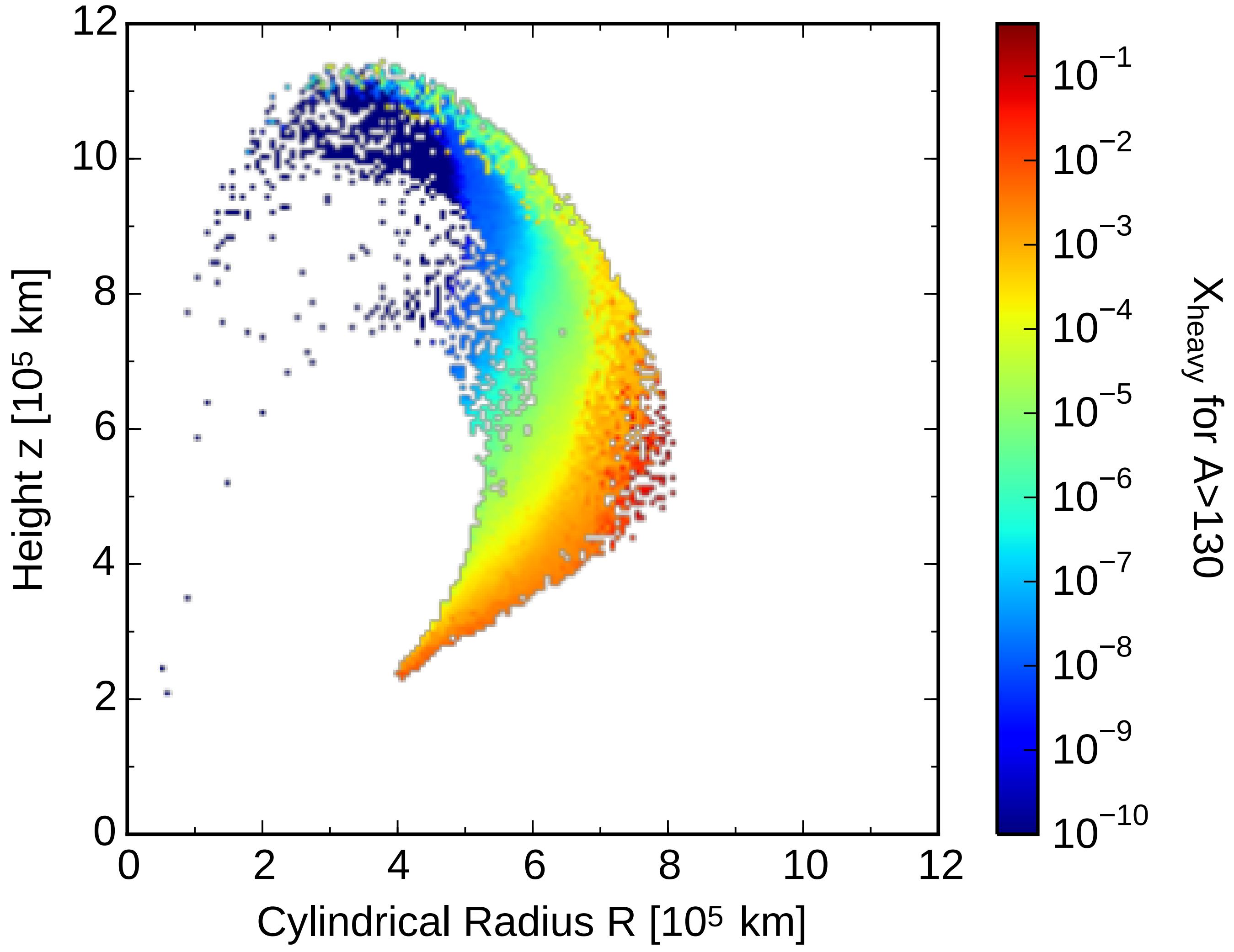


Martin et al. (submitted)

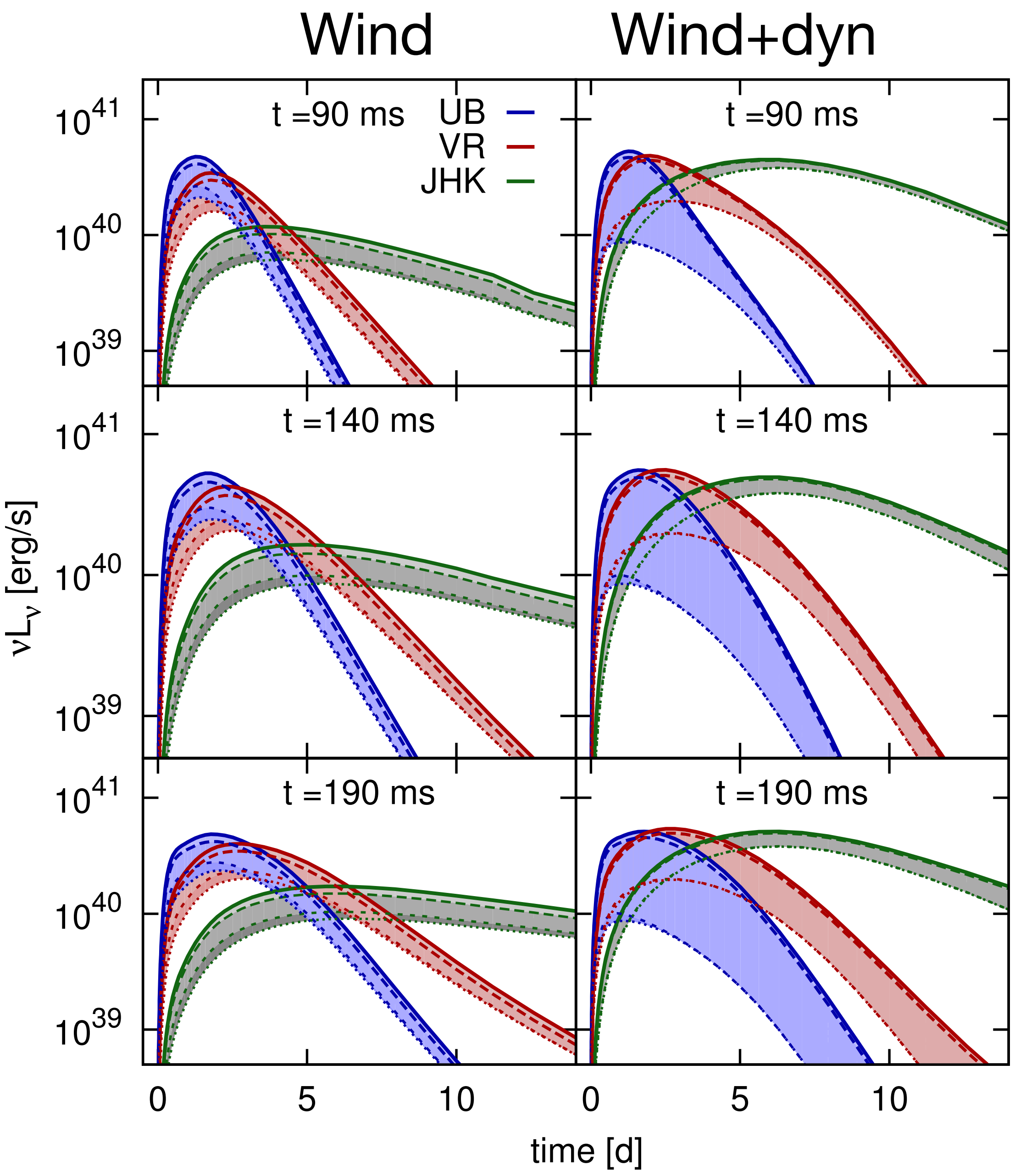
Wind kilonova

Less or no heavy r-process depending on angle → lower opacities

- Wind kilonova peaks on blue after ~4 hours
- Dynamic ejecta kilonova peaks on IR after 4-5 days



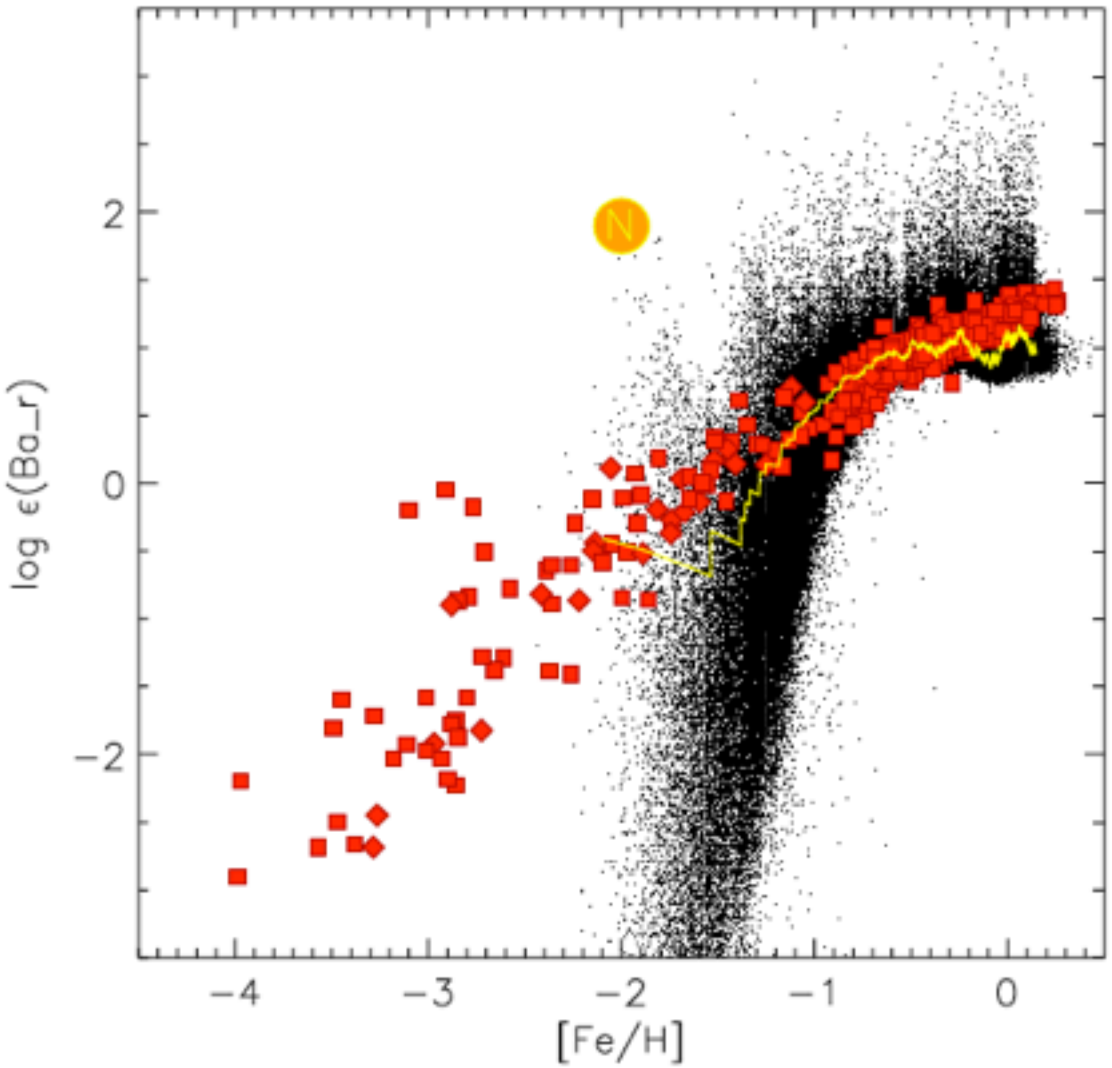
Martin et al. (submitted)



Three times for ns collapse: t=90, 140 and 190 ms

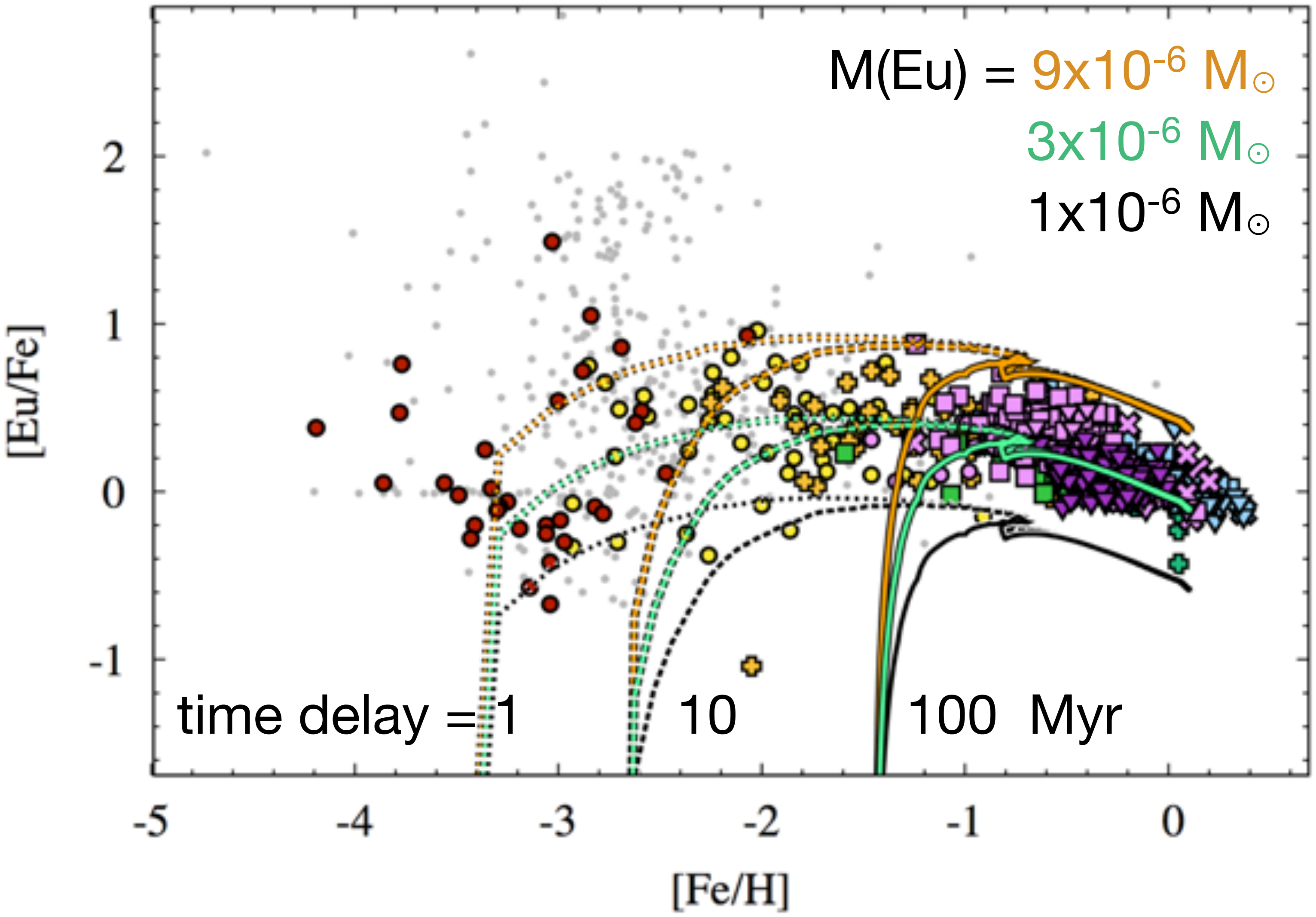
Neutron star mergers and GCE

Argast, Samland,
Thielemann, Qian (2004)



merger contribution always [Fe/H]>-2
inefficient mixing

Matteucci, Romano,
Arcones, Korobkin, Rosswog (2014)



merger rate = $83^{+209.1}_{-66.1}$ Myr^{-1} (Kalogera et al. 2004)
stars with M>30 M$_\odot$: black hole

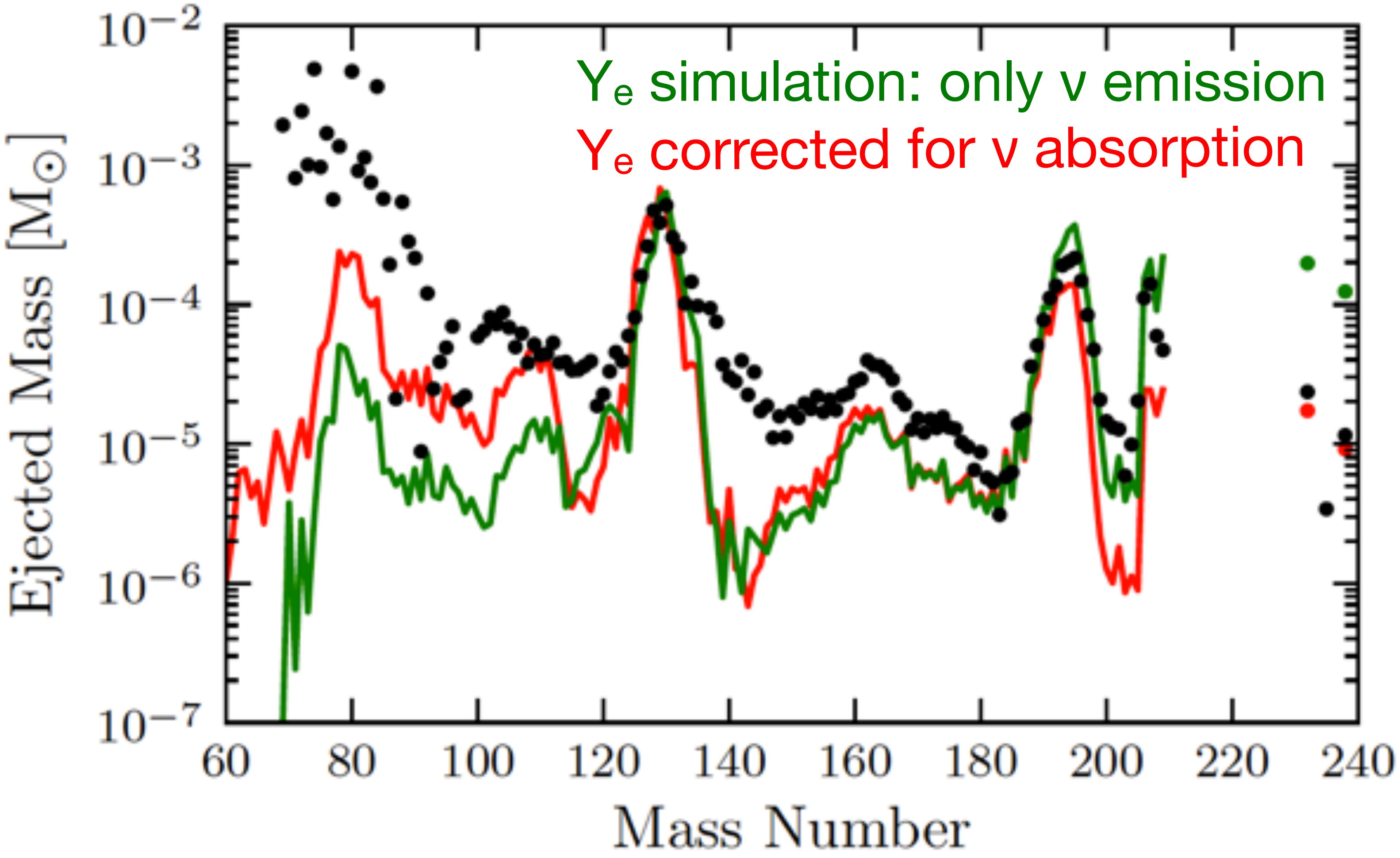
ns merger: Mennekens & Vanbeveren (2014), van de Voort et al. (2015), Ishimaru et al. (2015), ...
ns merger + ccsn (jets): Cescutti & Chiappini (2015), Wehmeyer et al. 2015

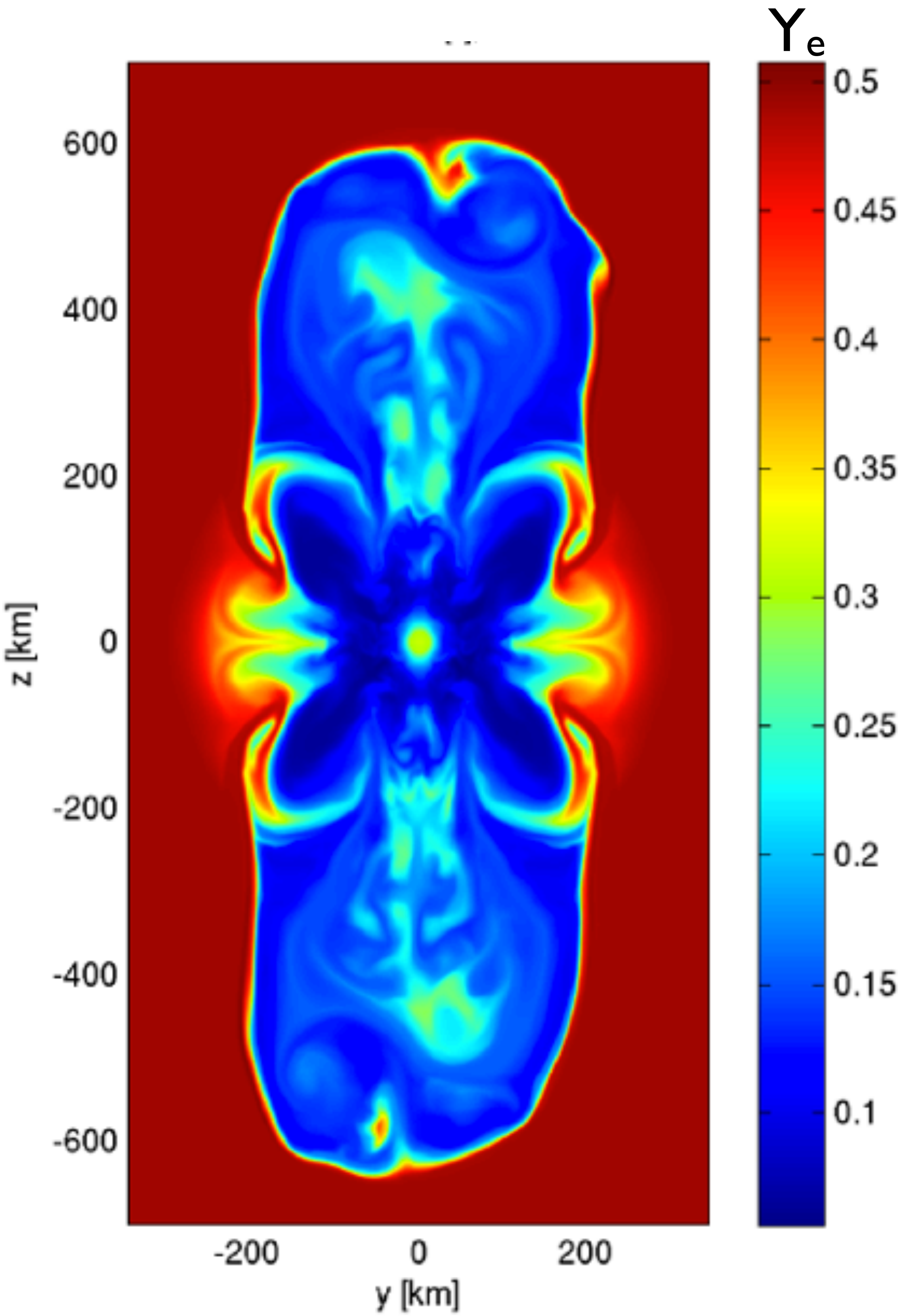
Supernova-jet-like explosion

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

Conclusions

How many r-processes? How many astrophysical sites?

lighter heavy elements (Sr-Y-Zr-...-Ag): neutrino-driven winds

heavy r-process: mergers: dynamical, wind, disk evaporation
jet-like supernovae

Needs

Observations: oldest stars, kilo/macronovae,
neutrinos, gravitational waves, ...

Neutron-rich nuclei: experiments with radioactive beams, theory

Improved supernova and merger simulations: EoS, neutrino rates

Chemical evolution models