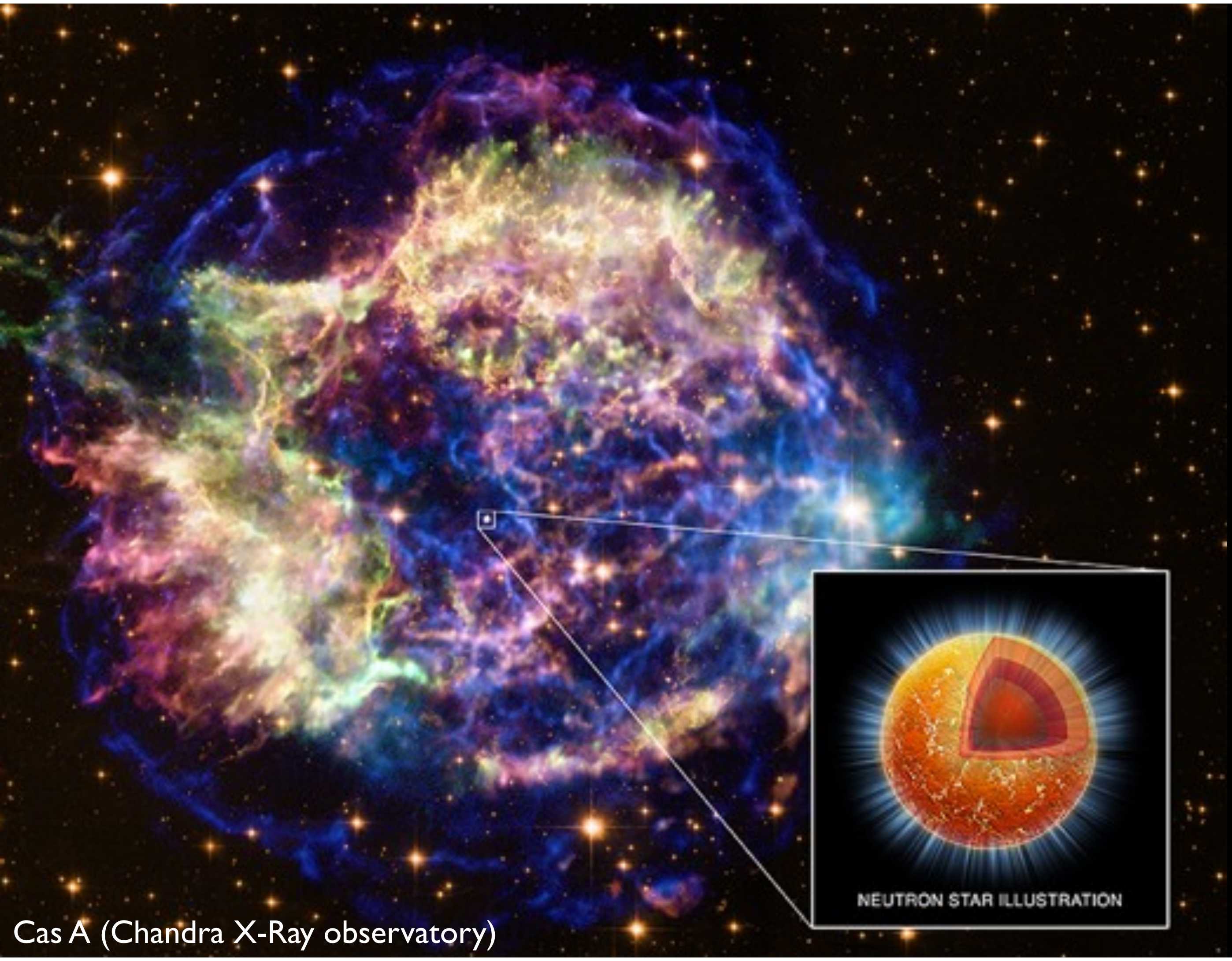
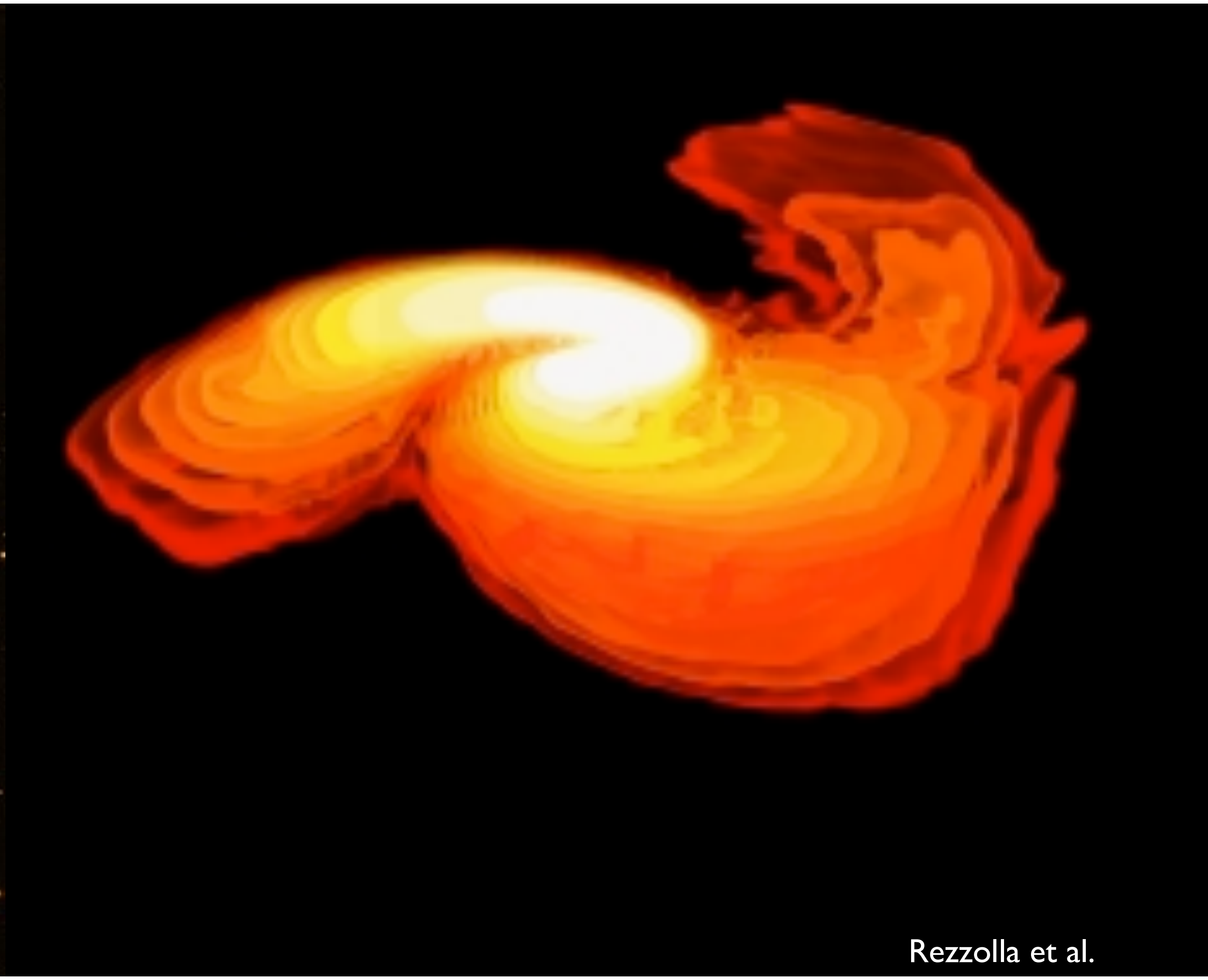
INT Workshop: The r-process: status and challenges
July 28 - August 1, 2014

Nucleosynthesis of heavy elements: r-process and its astrophysical site



Cas A (Chandra X-Ray observatory)


Rezzolla et al.

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Almudena Arcones
Helmholtz Young Investigator Group

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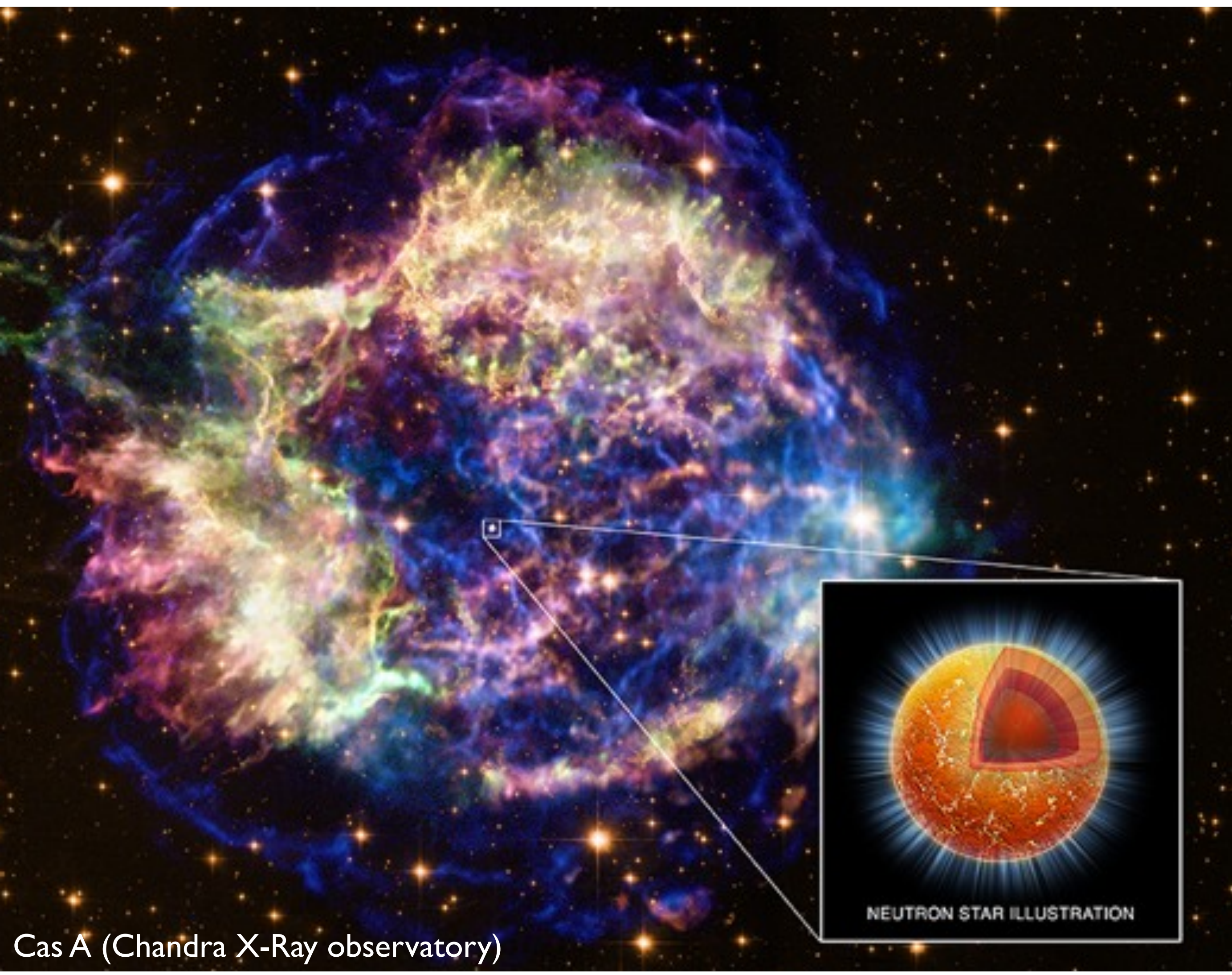

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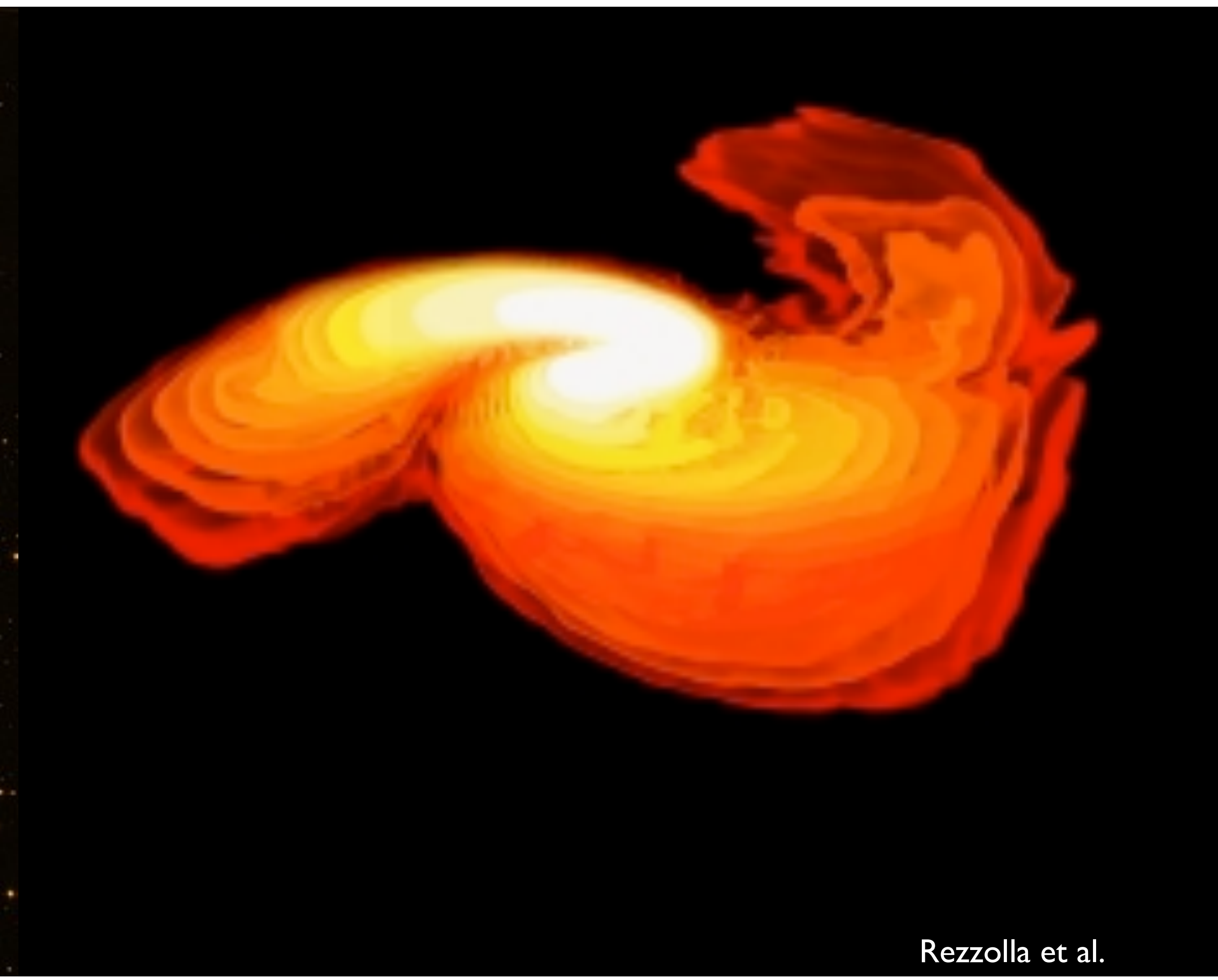
Rezzolla et al.

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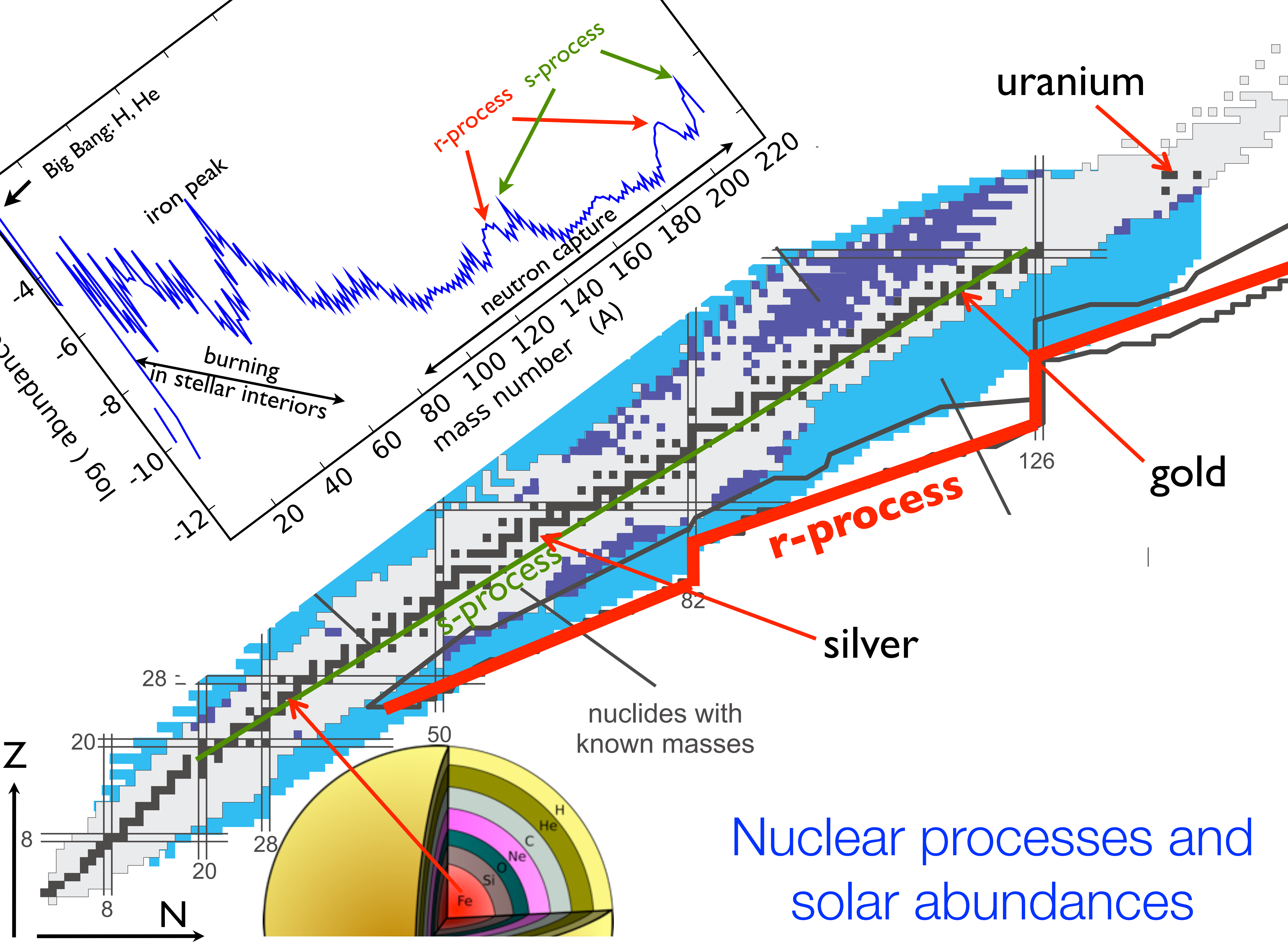
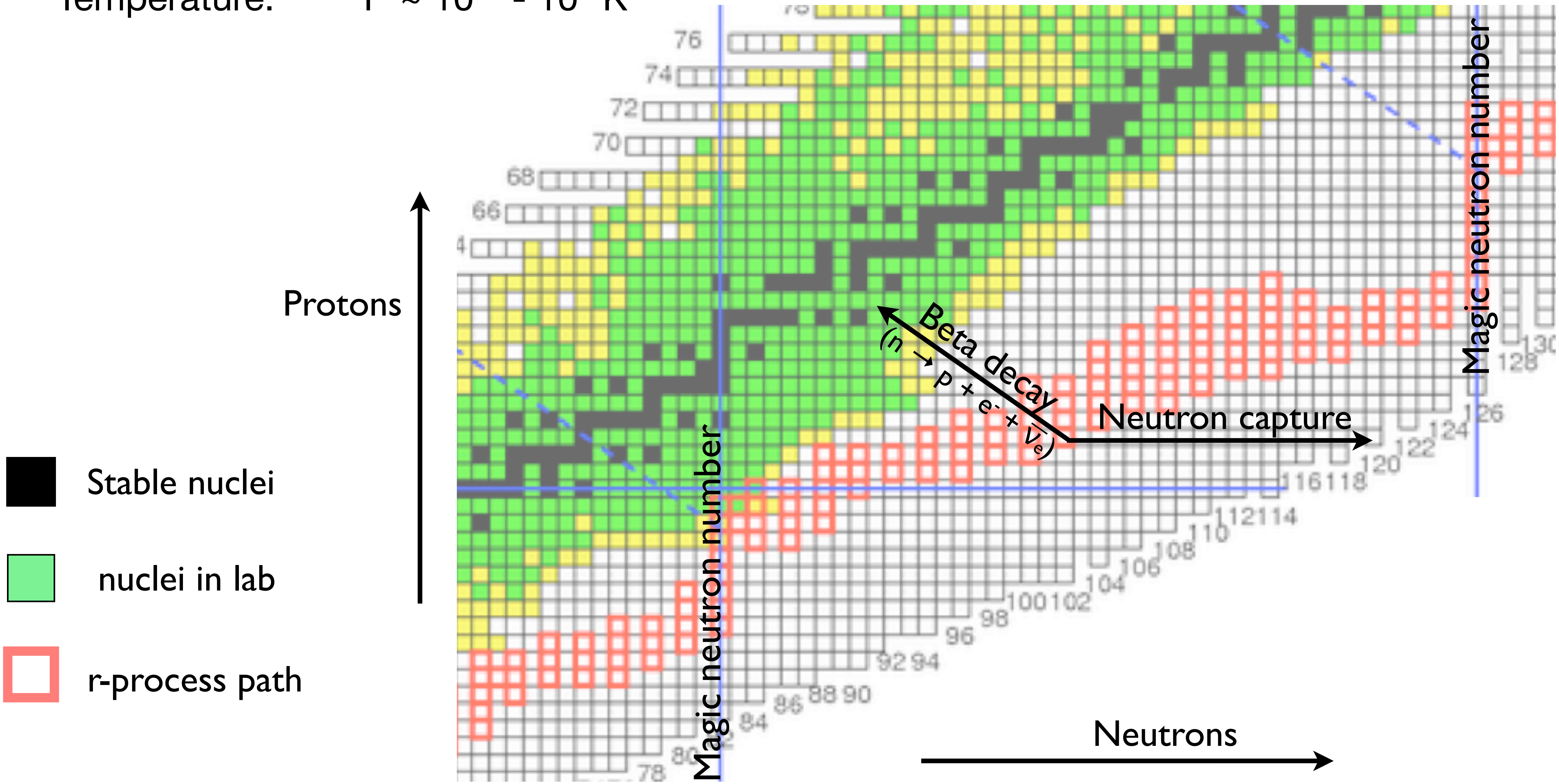
Nuclear processes and solar abundances



r-process

Rapid neutron capture compared to beta decay

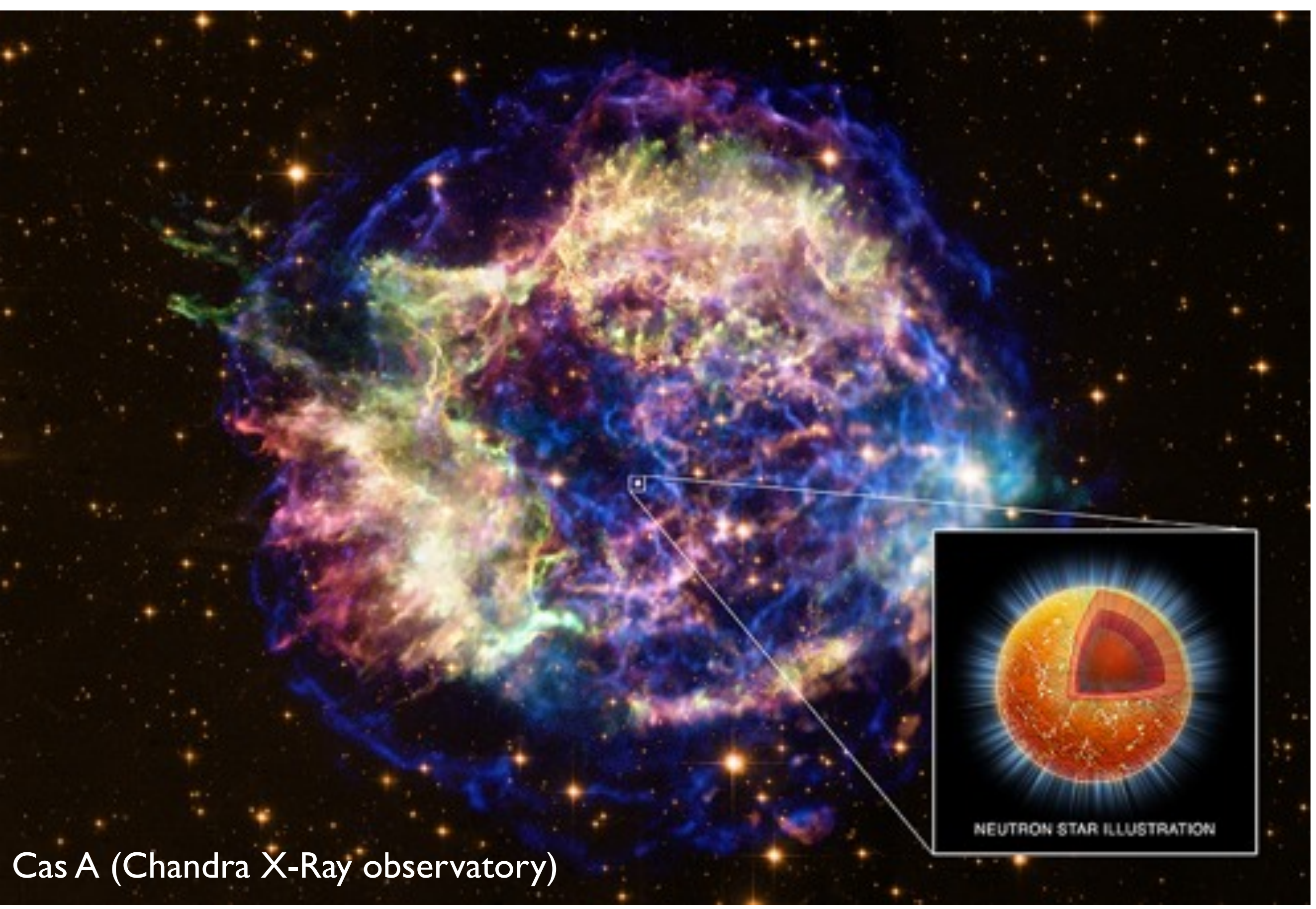
Neutron density: $N_n \sim 10^{27} - 10^{20}\ cm^{-3}$
Temperature: $T \sim 10^{10} - 10^{8}$ K



Where does the r-process occur?

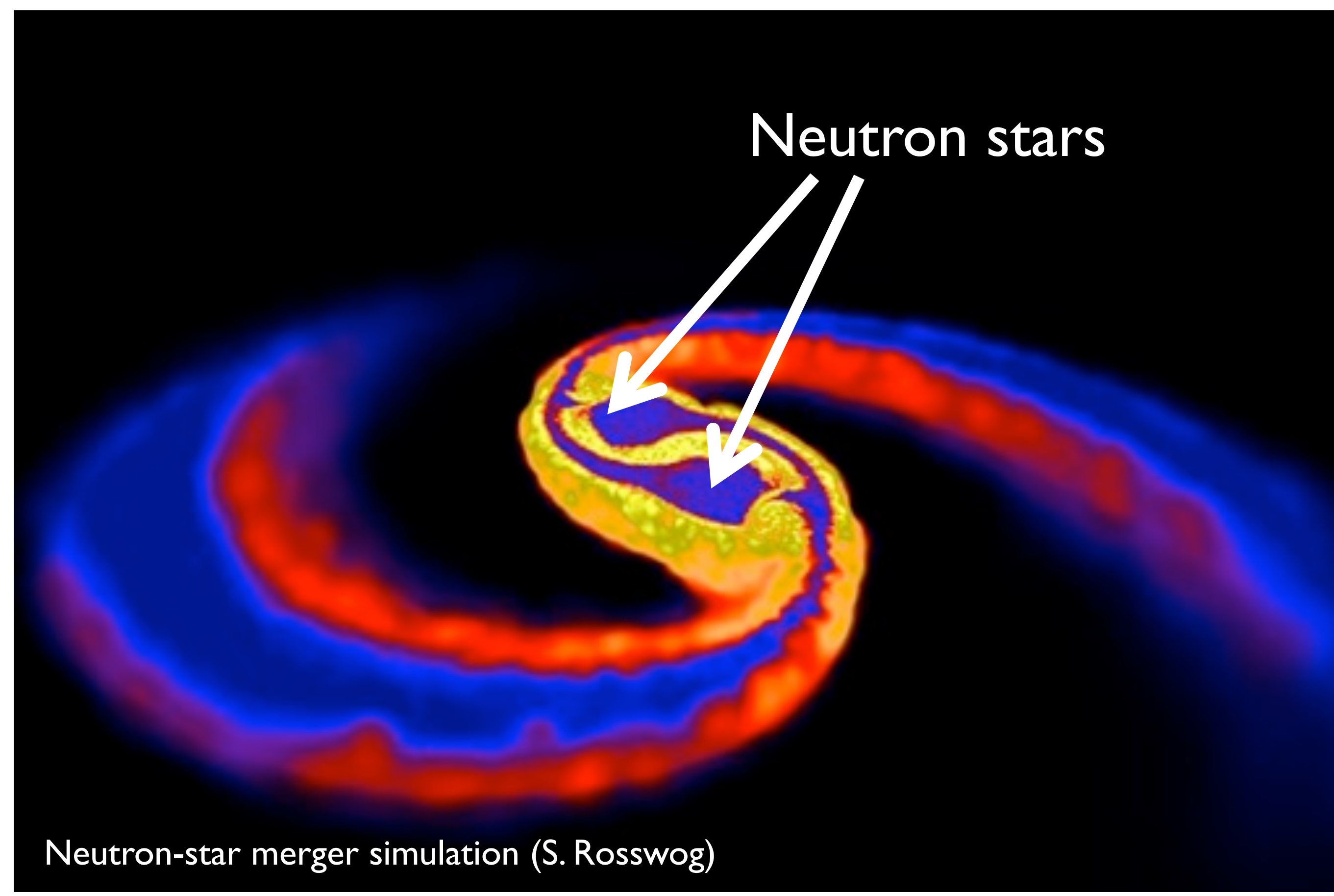
rapid process → explosions
high neutron densities → neutron stars

Core-collapse supernovae



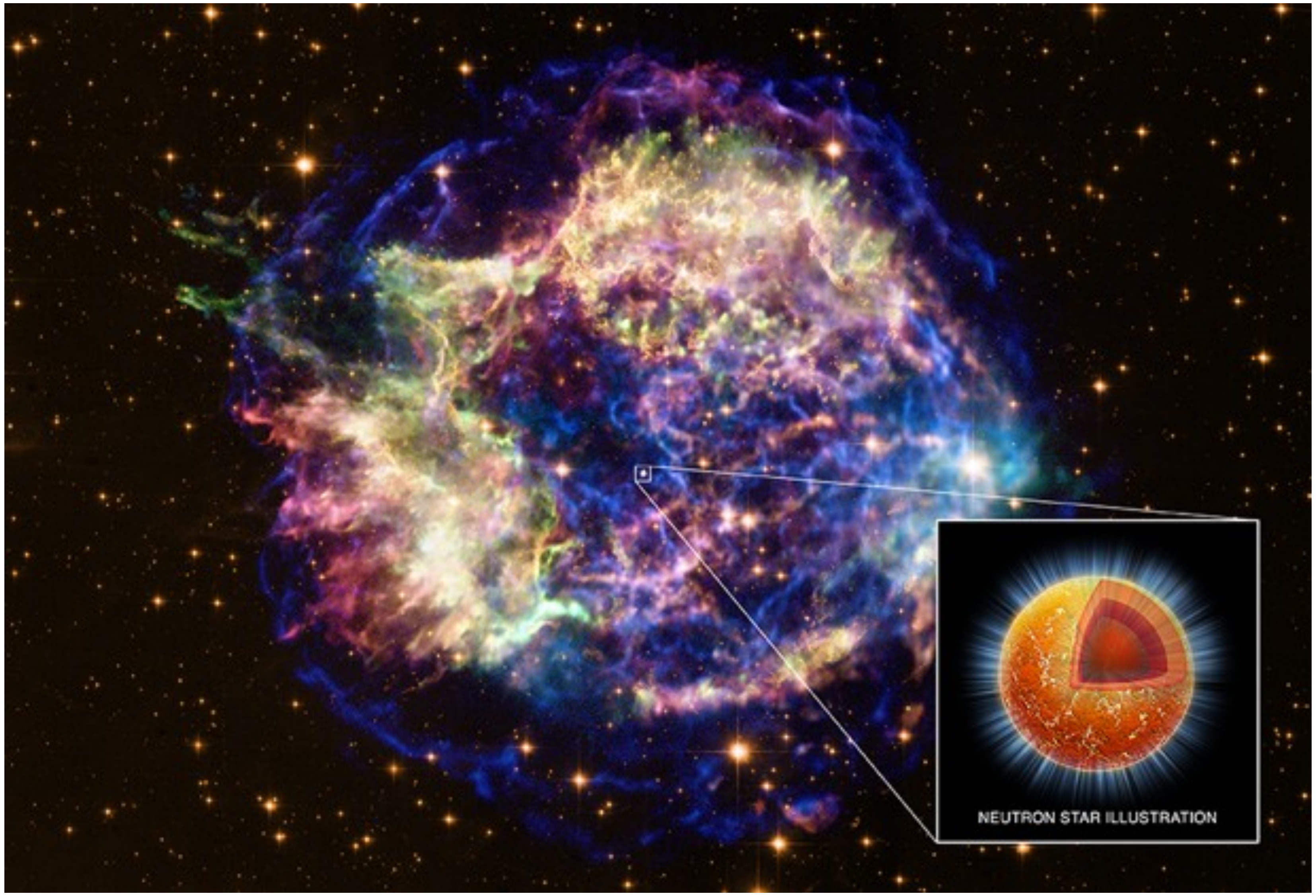
Cas A (Chandra X-Ray observatory)

Neutron star mergers



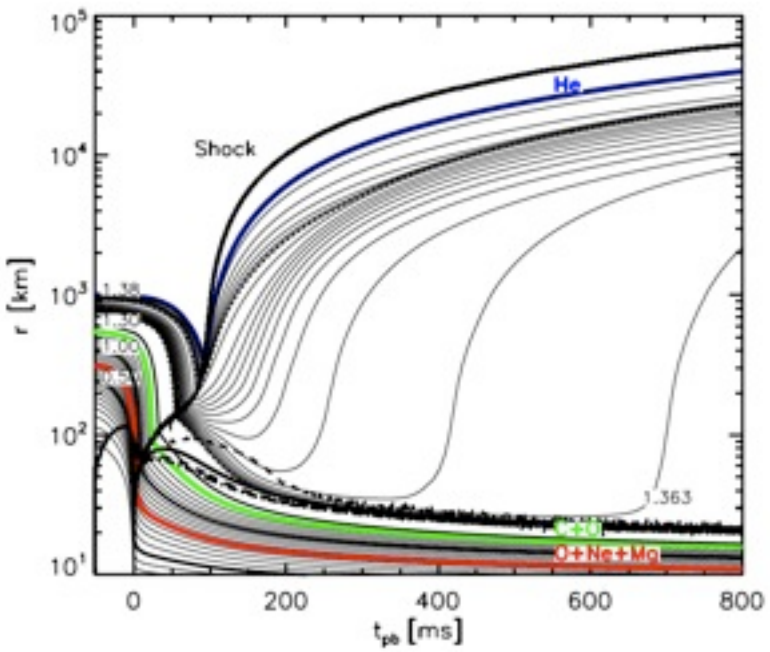
Neutron-star merger simulation (S. Rosswog)

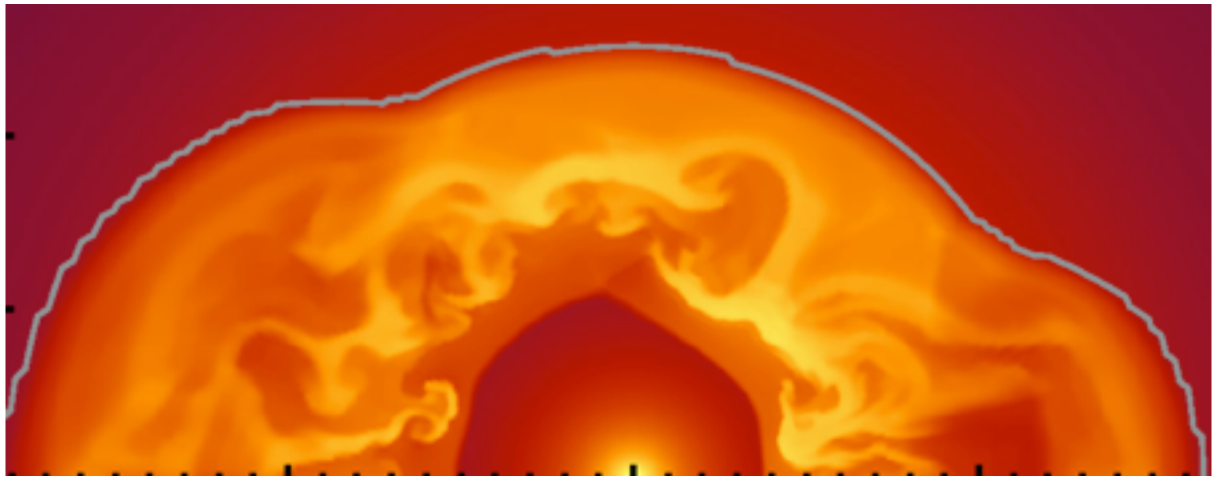
core-collapse supernovae



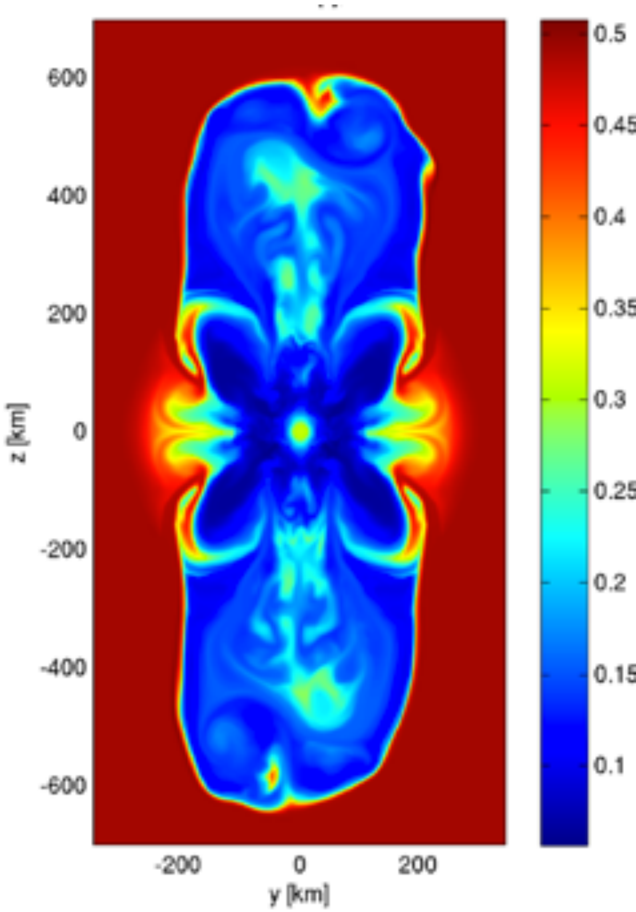
r-process in core-collapse supernovae? (B^{2}FH 1957)

- prompt explosion (Hillebrandt 1978, Hillebrandt et al. 1984)
- neutrino-driven wind (Meyer et al. 1992, Woosley et al. 1994)
- shocked surface layers (Ning, Qian, Meyer 2007)
- neutrino-induced in He shells (Banerjee, Haxton, Qian 2011)
- jets (e.g., Winteler et al. 2012)





wind



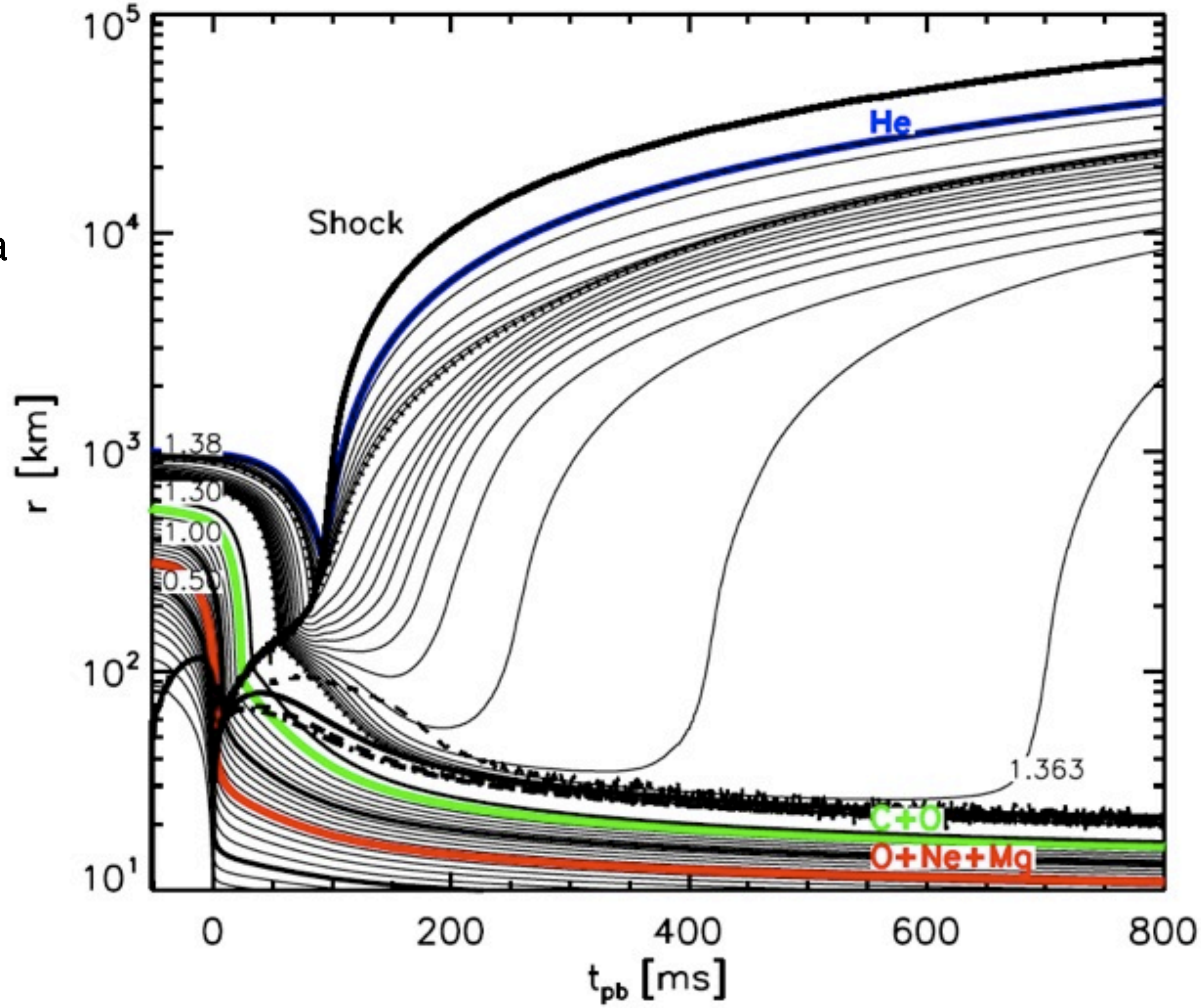
Core-collapse supernova: ONeMg

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)

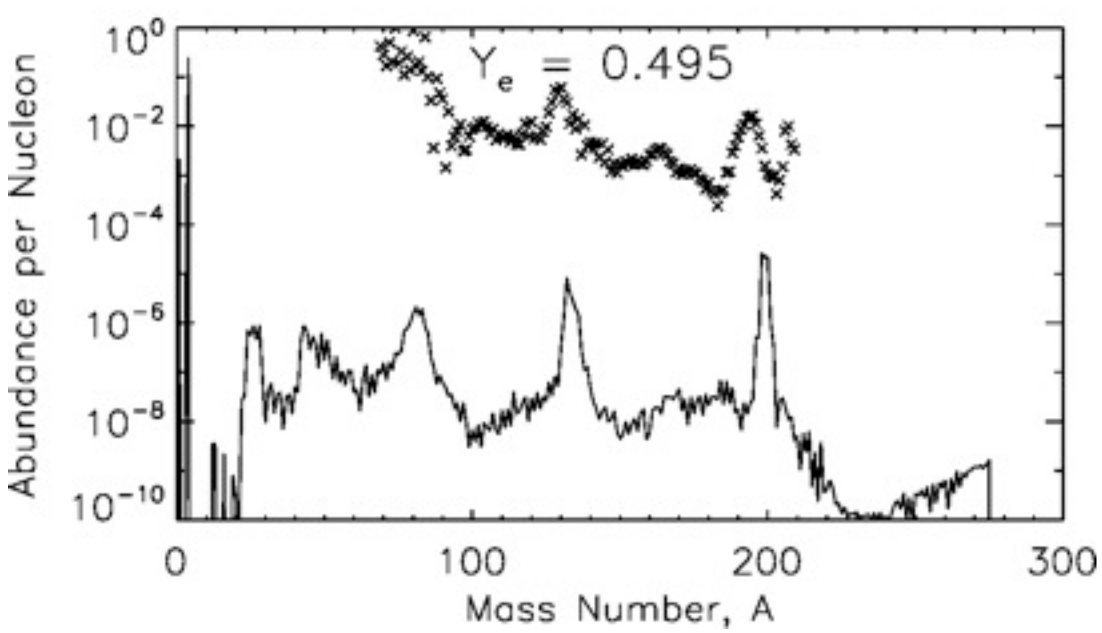
Prompt explosion excluded as r-process site

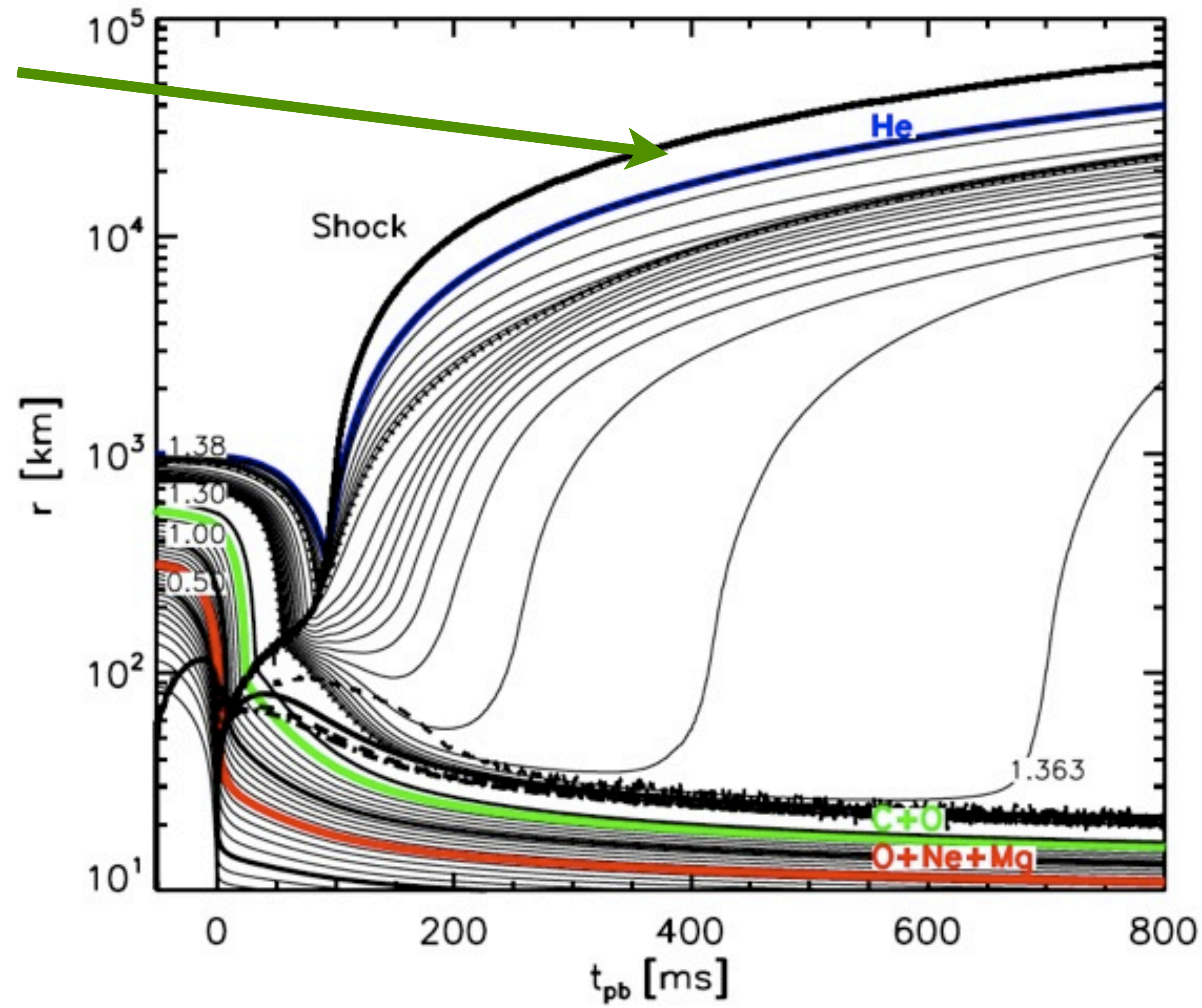


Core-collapse supernova: ONeMg

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

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





Core-collapse supernova: ONeMg

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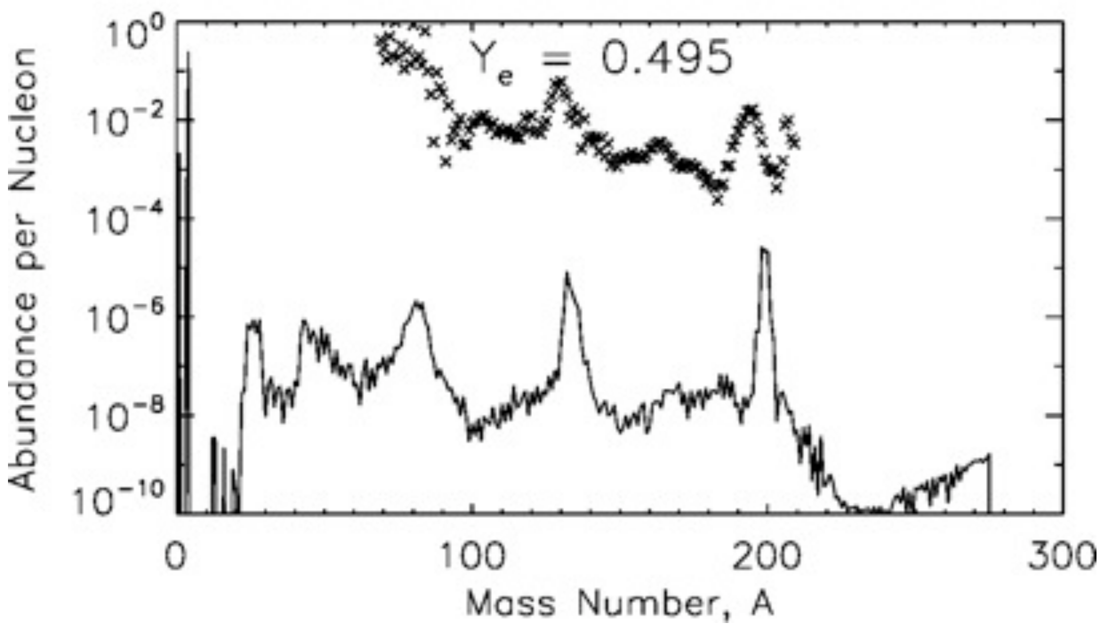
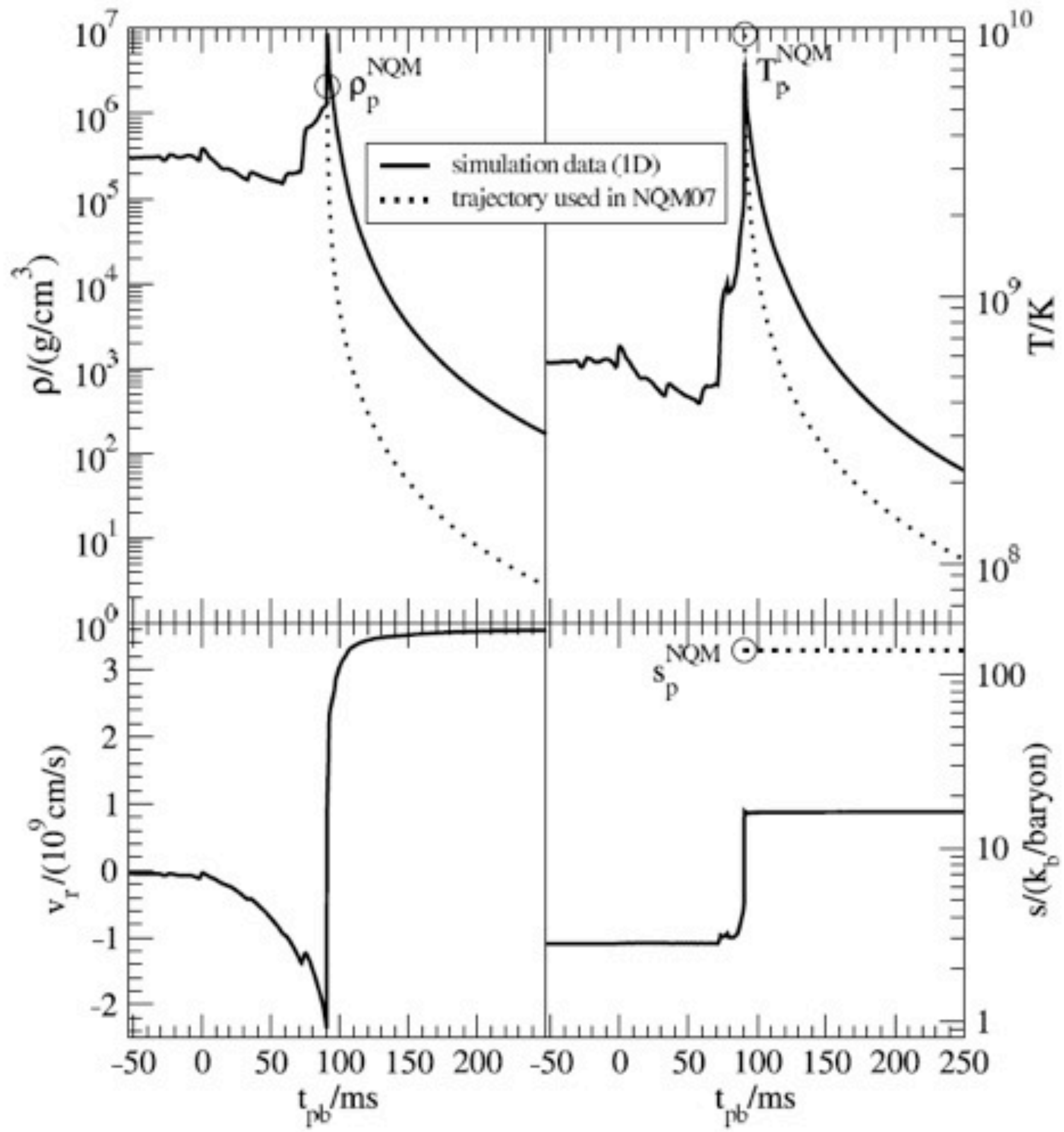
not found in simulations





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

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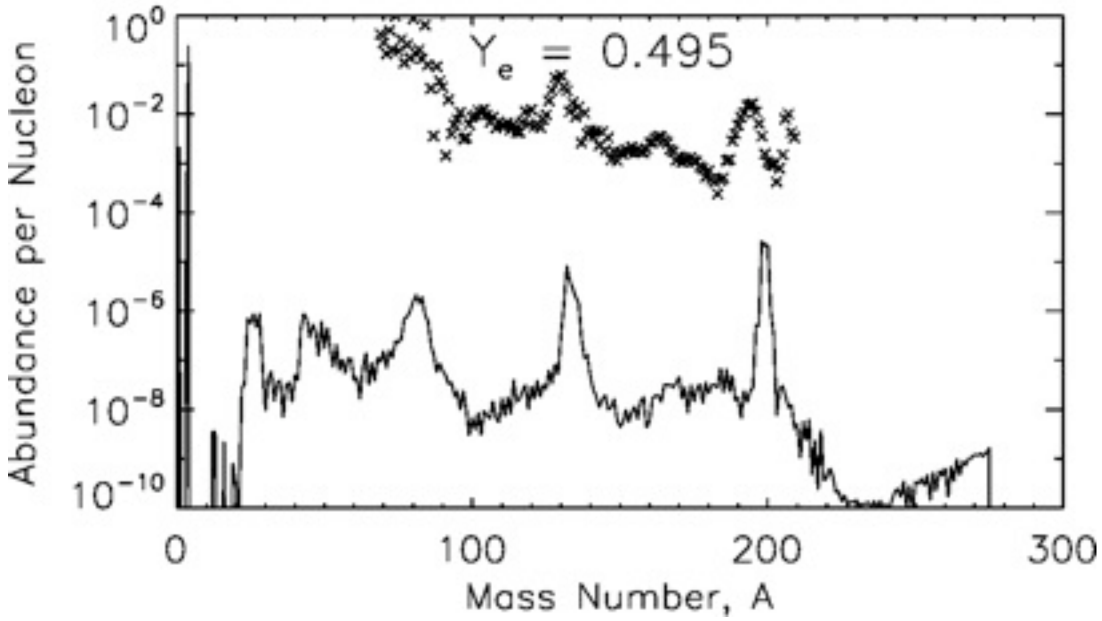
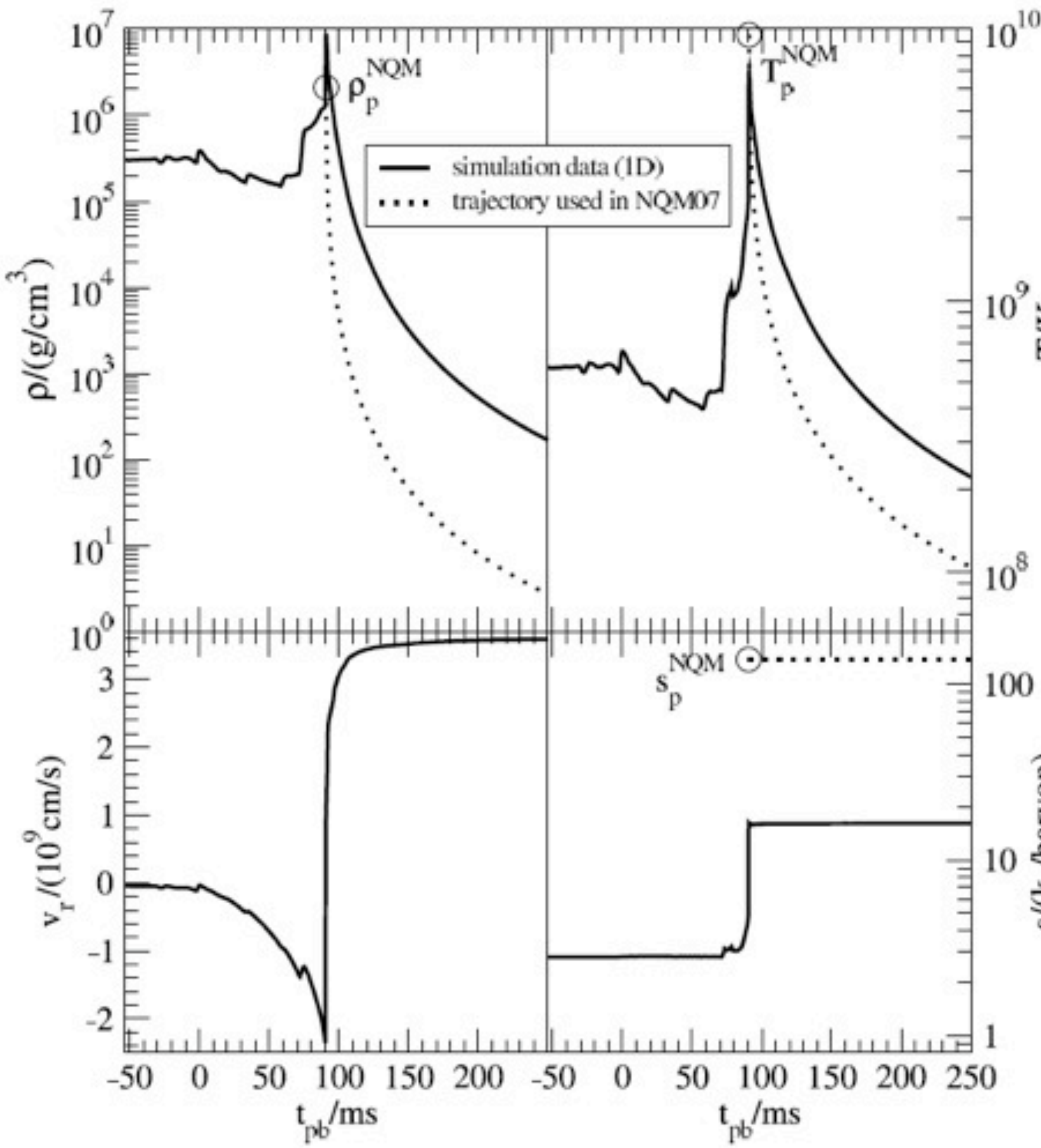




Janka et al. 2008, Hoffman et al. 2008, Wanajo et al. 2009

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

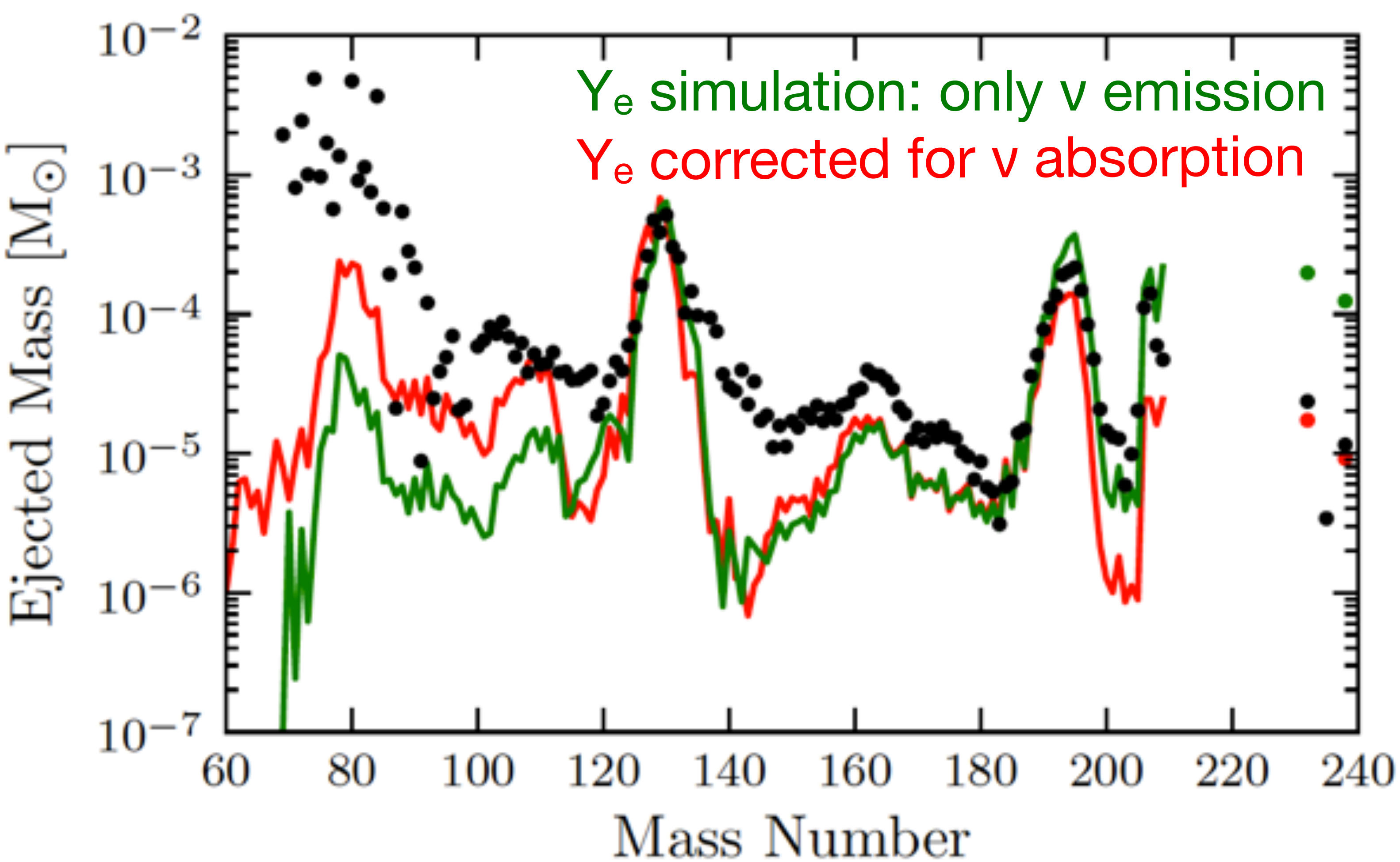
Promising scenario for the r-process, requires further investigation
Eichler, Arcones, Thielemann 2012

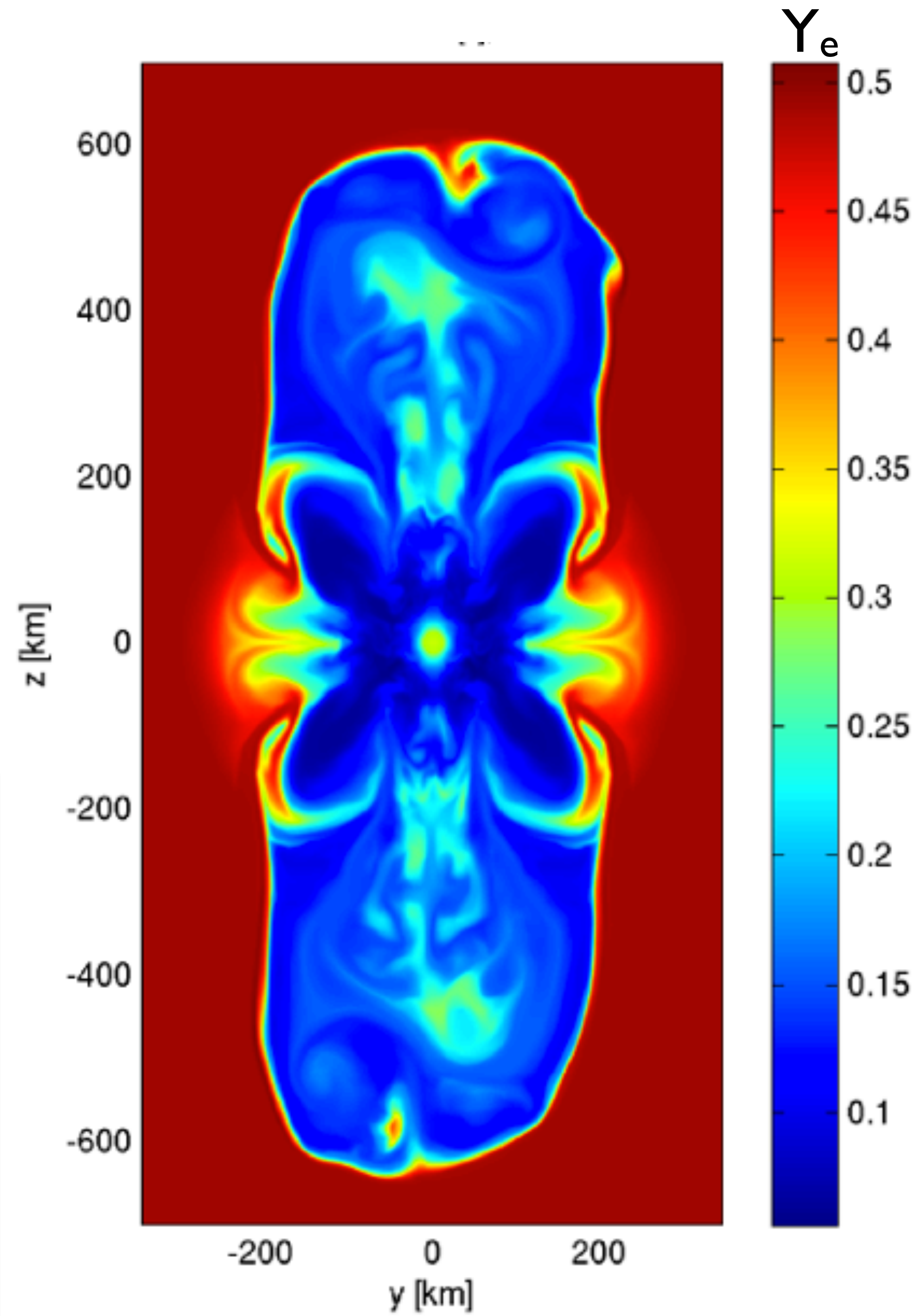
Supernova-jet-like explosion

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

matter collimates: neutron-rich jets

right r-process conditions



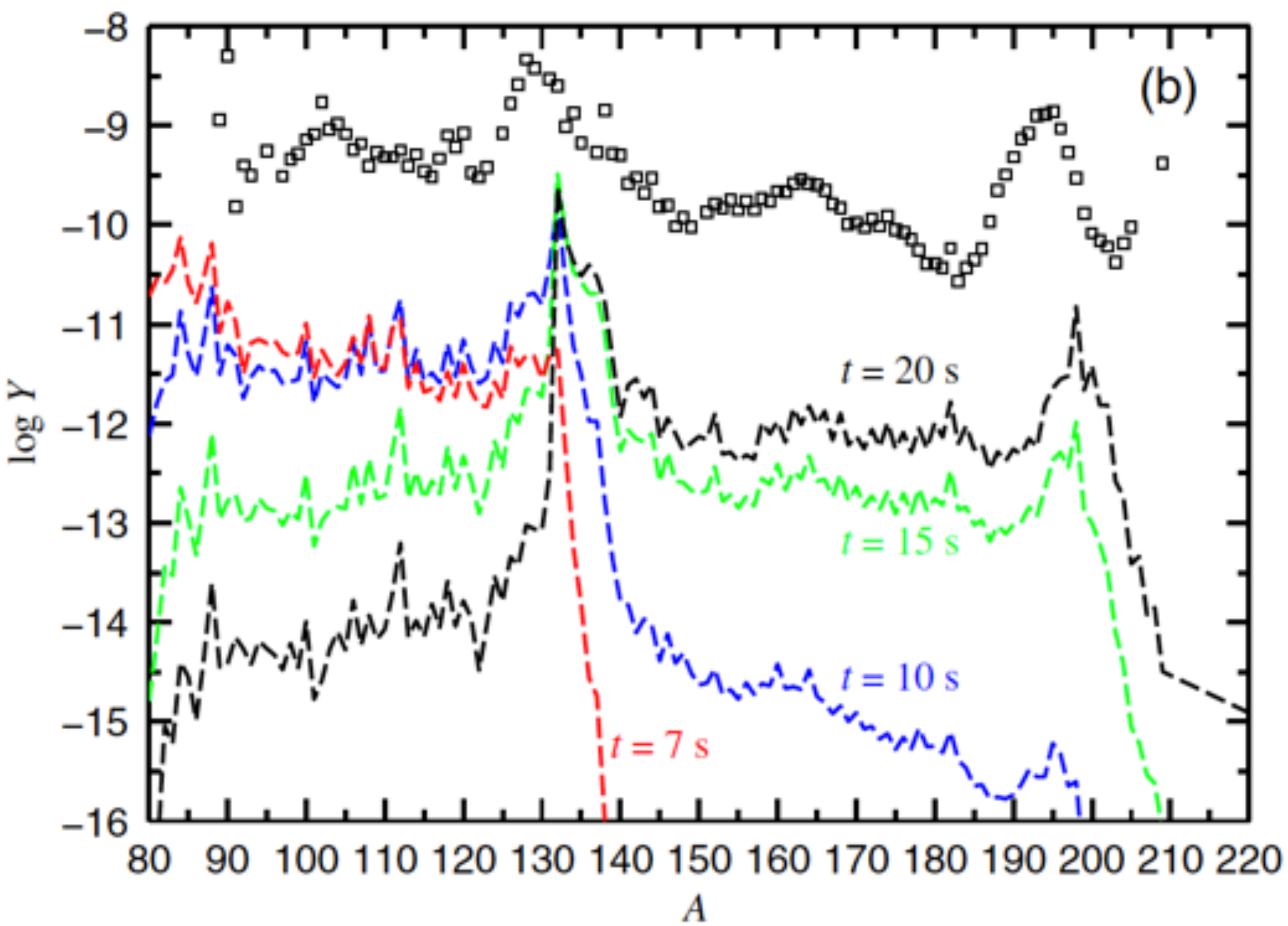


Winteler, Käppeli, Perego et al. 2012

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

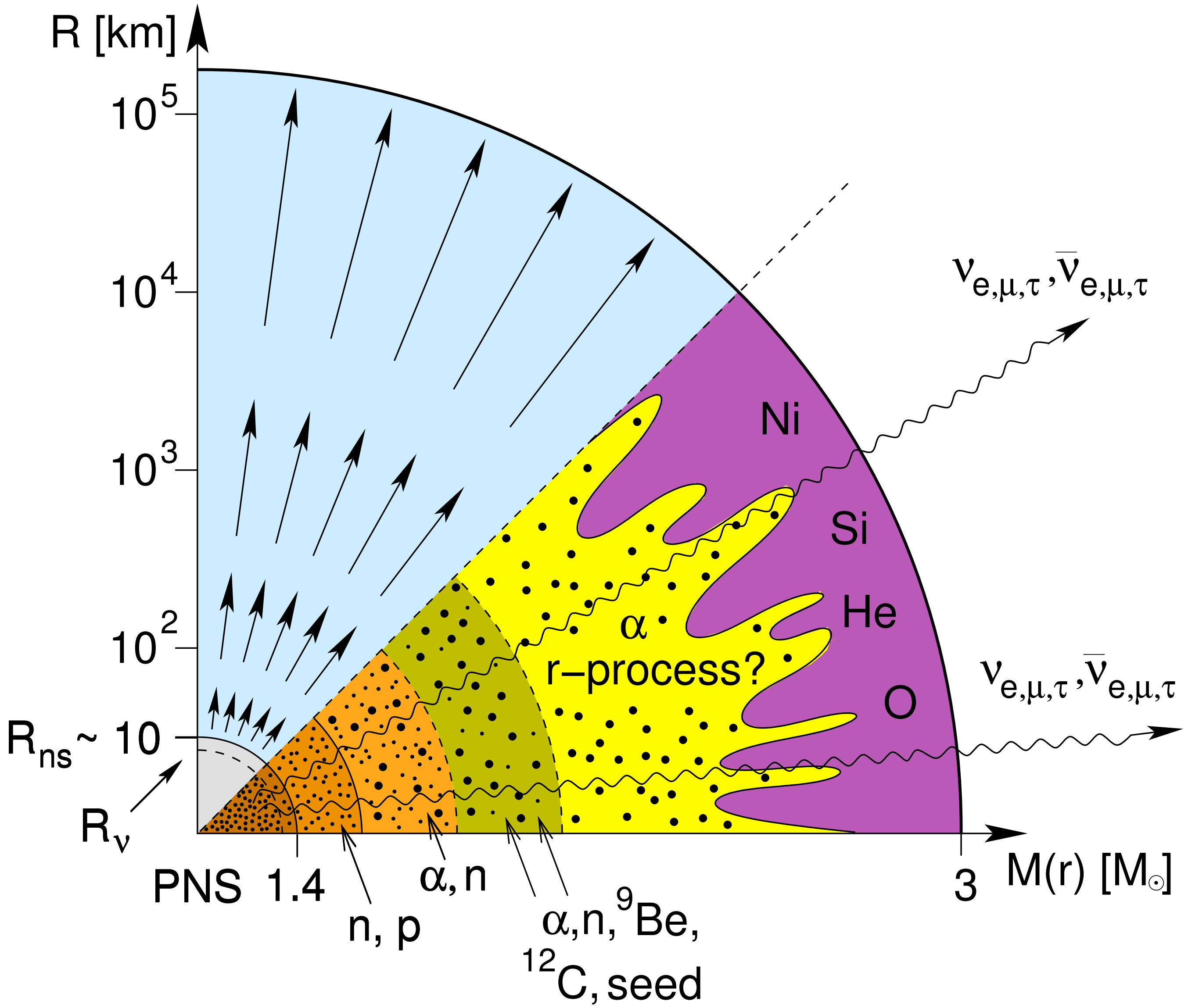
relative low neutron density

lasts ~20s

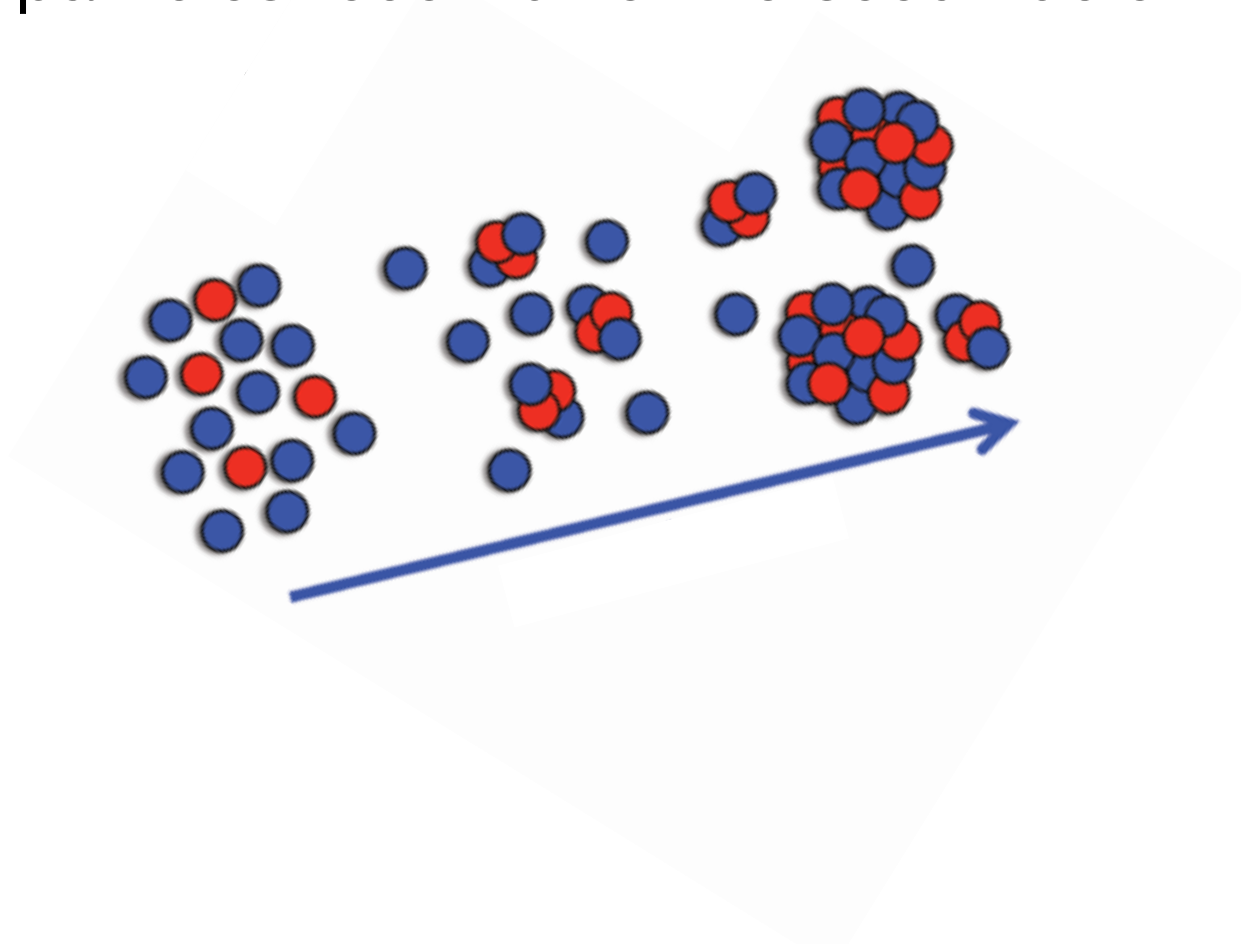
peaks shift to high A
(between r- and s-process)

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

Neutrino-driven winds



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



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

weak r-process

νp-process

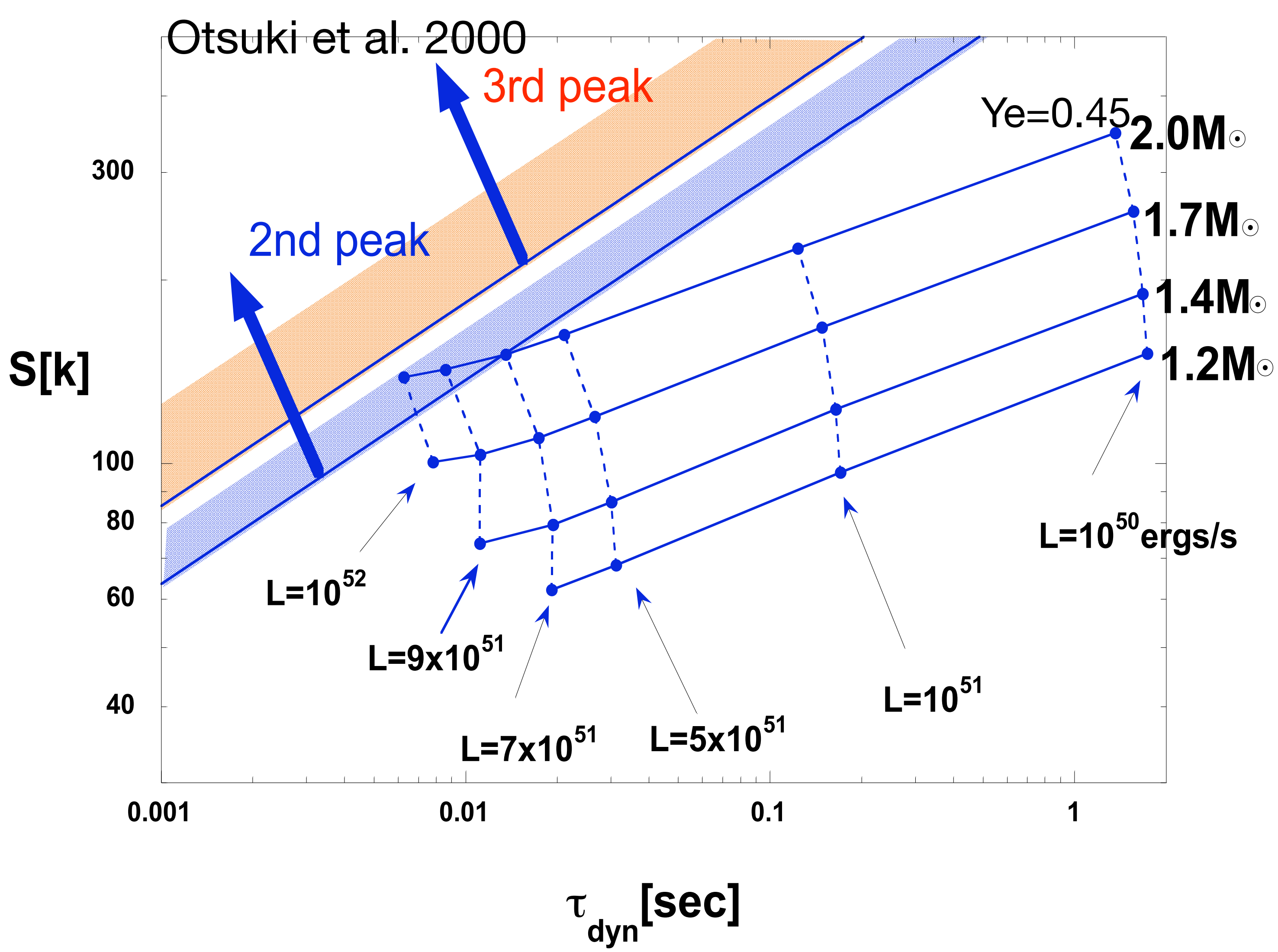
T = 10 - 8 GK   8 - 2 GK   T < 3 GK

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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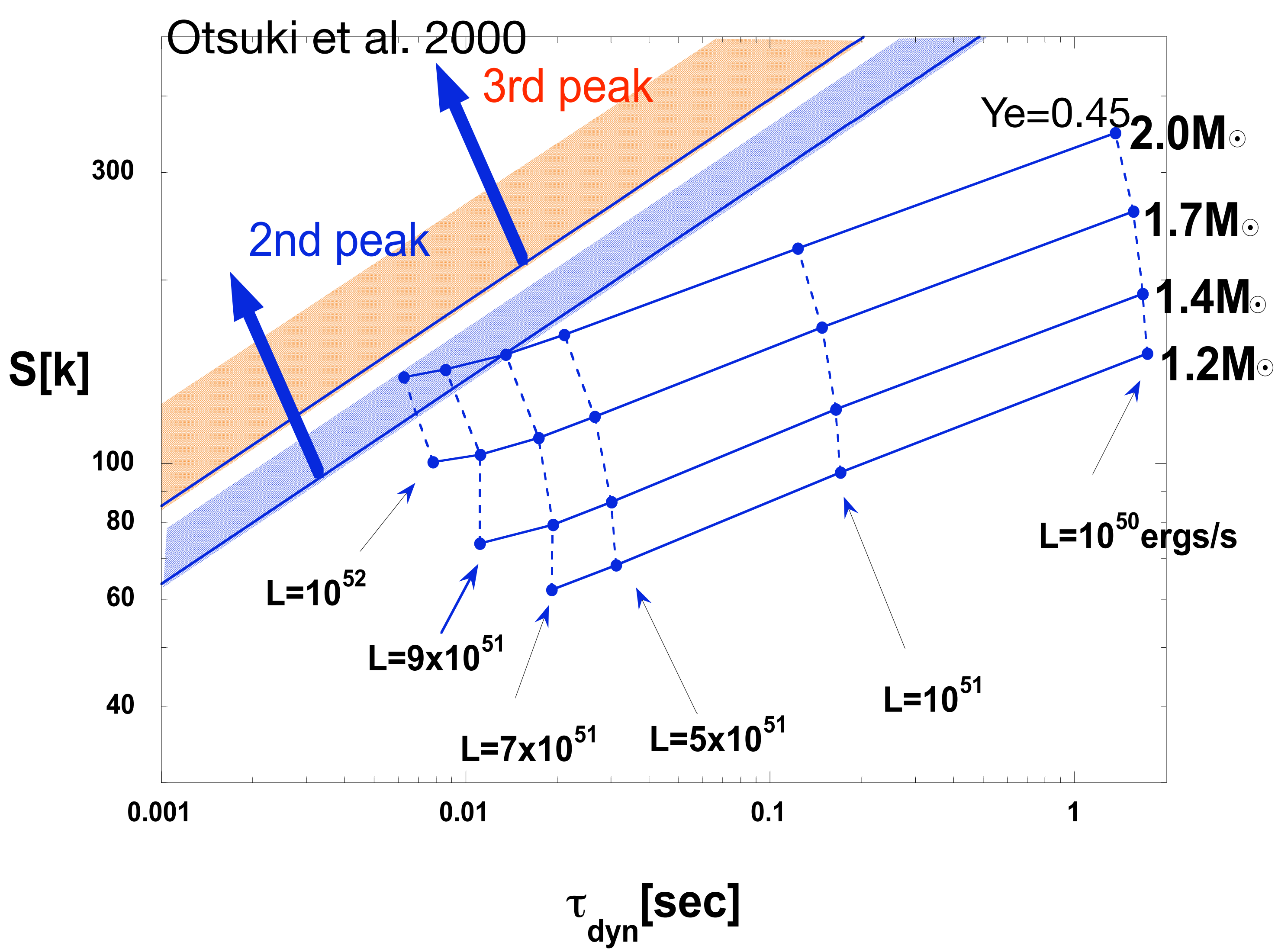
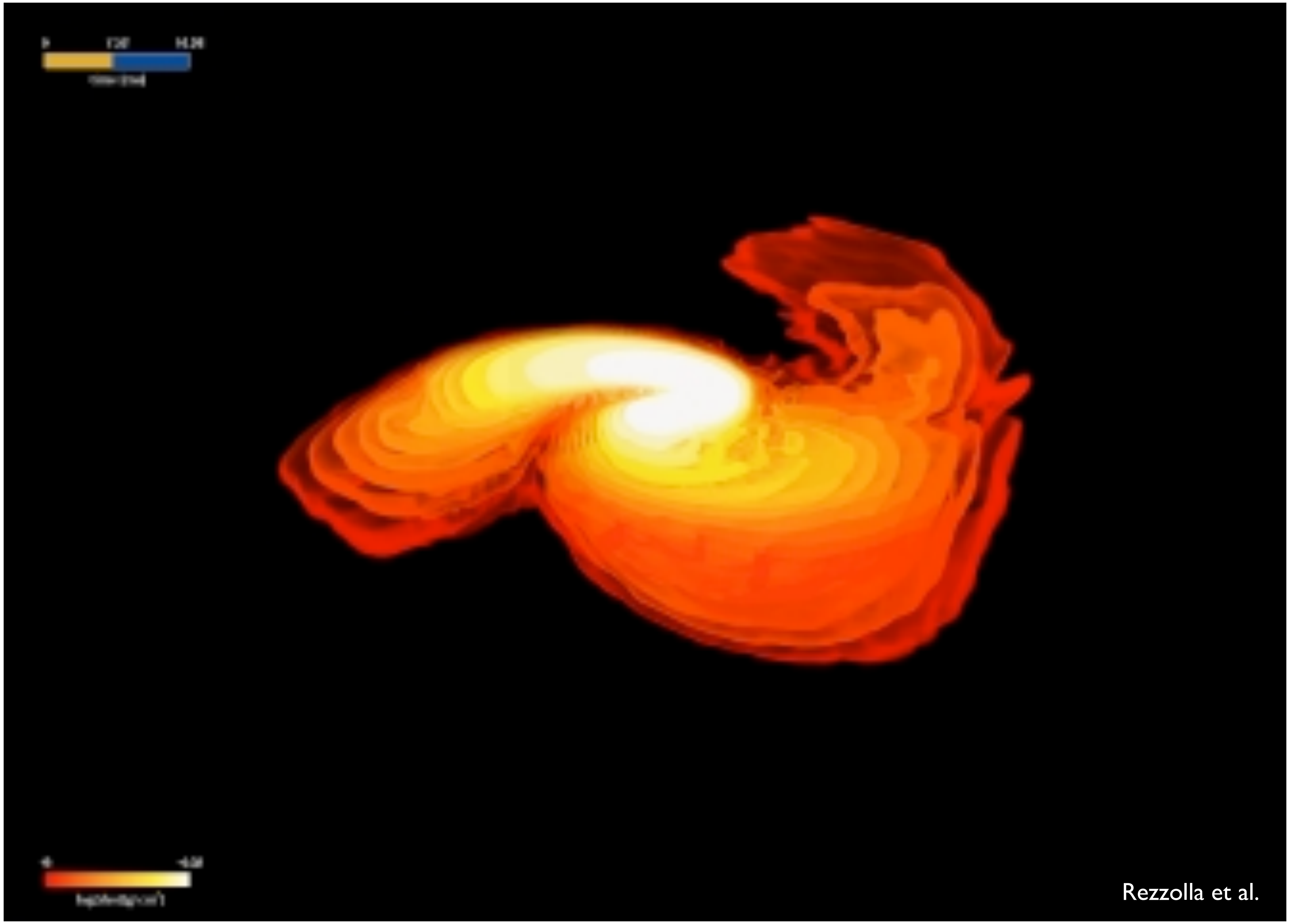


Conditions are not realized in hydrodynamic simulations
(Arcones et al. 2007, Fischer et al. 2010, Hüdepohl et al. 2010, Roberts et al. 2010, Arcones & Janka 2011, ...)

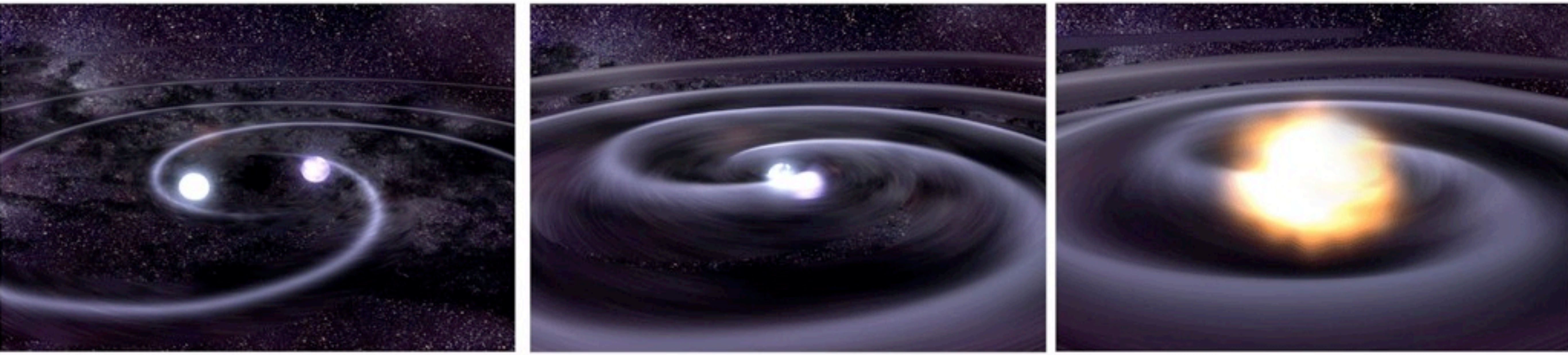
S_{wind} = 50 - 120 k_B/nuc
τ = few ms
Y_e ≈ 0.4 - 0.6?

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

neutron-star mergers

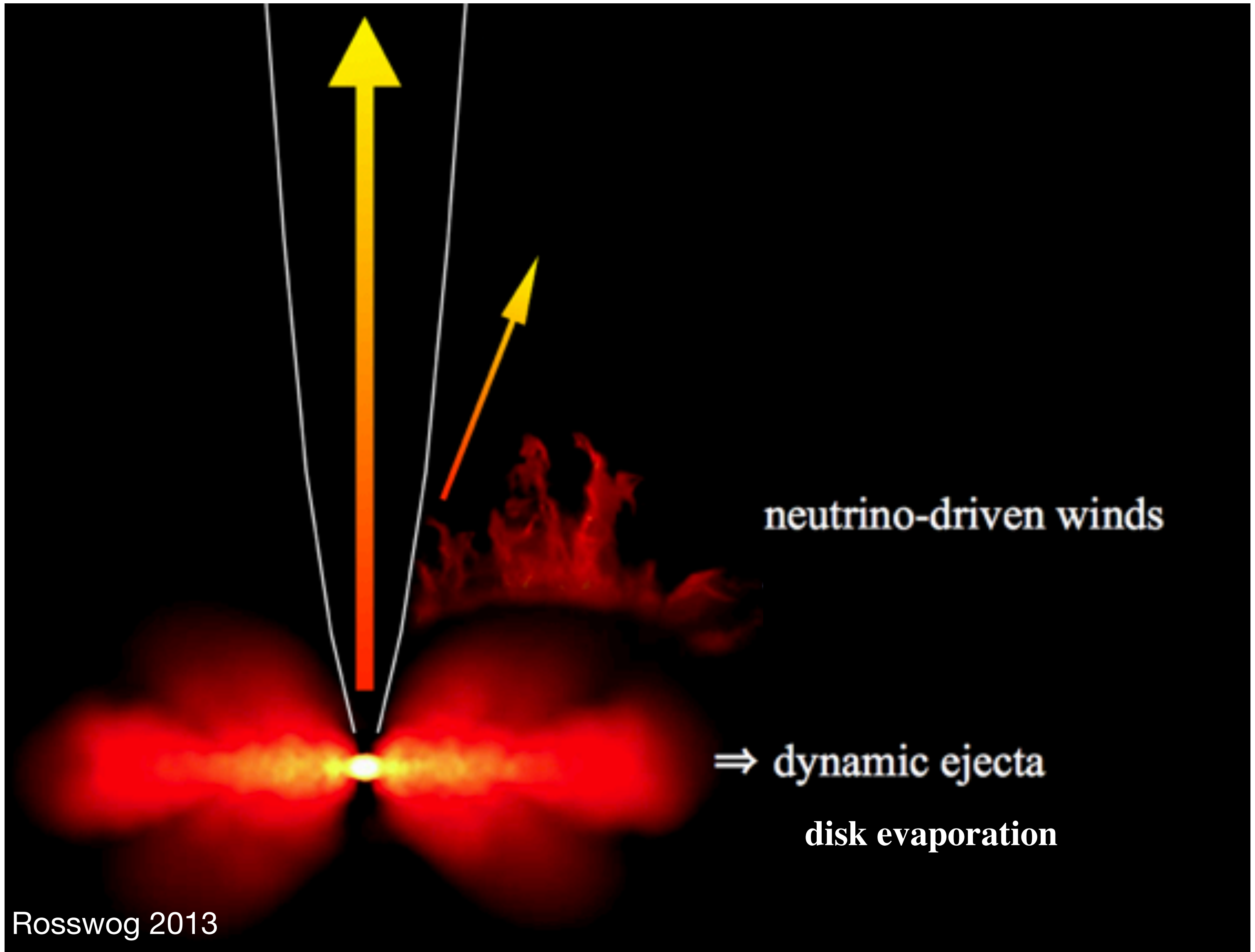


Neutron star mergers

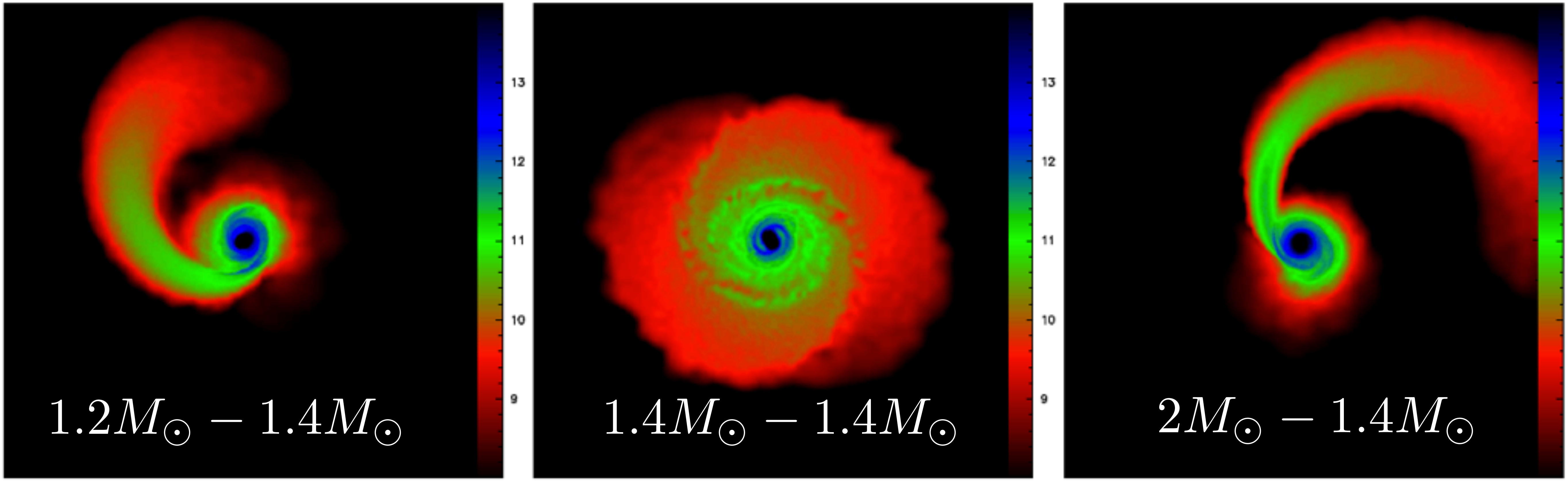


Ejecta from three regions:

- dynamical ejecta
- neutrino-driven wind
- disk evaporation

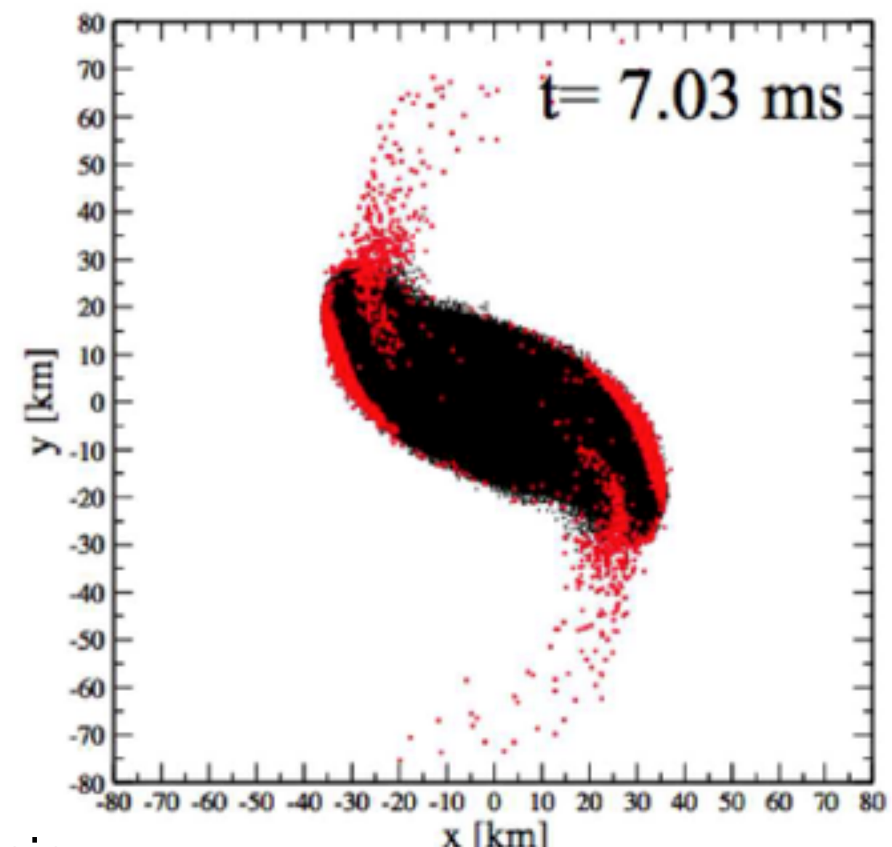


Neutron star mergers: robust r-process



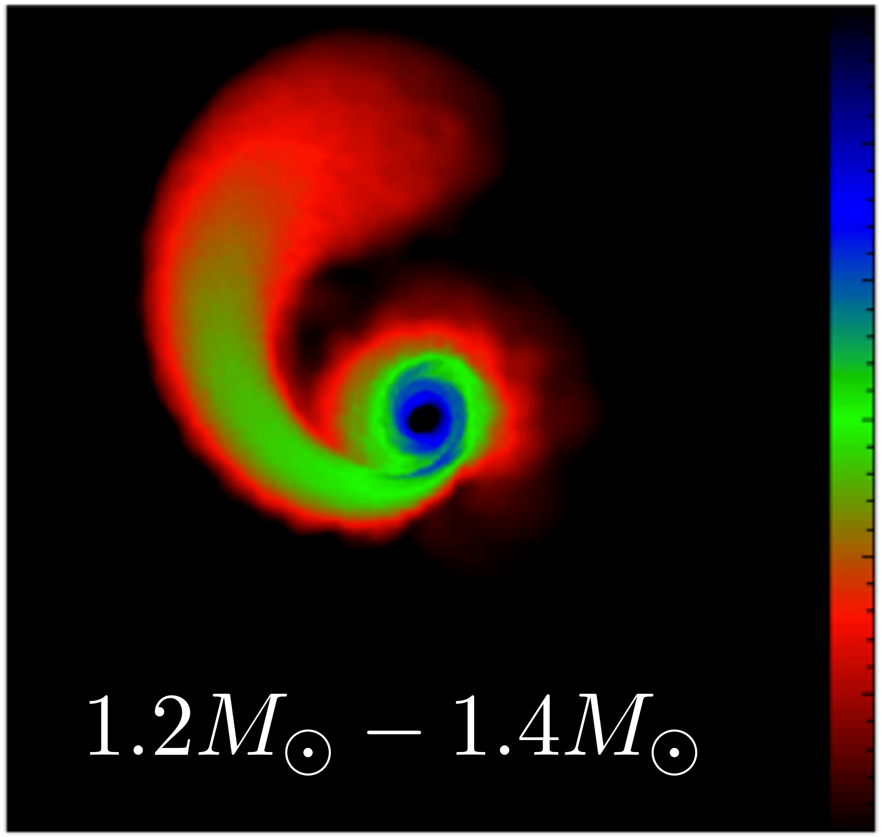
simulations: 21 mergers of 2 neutron stars
2 of neutron star black hole

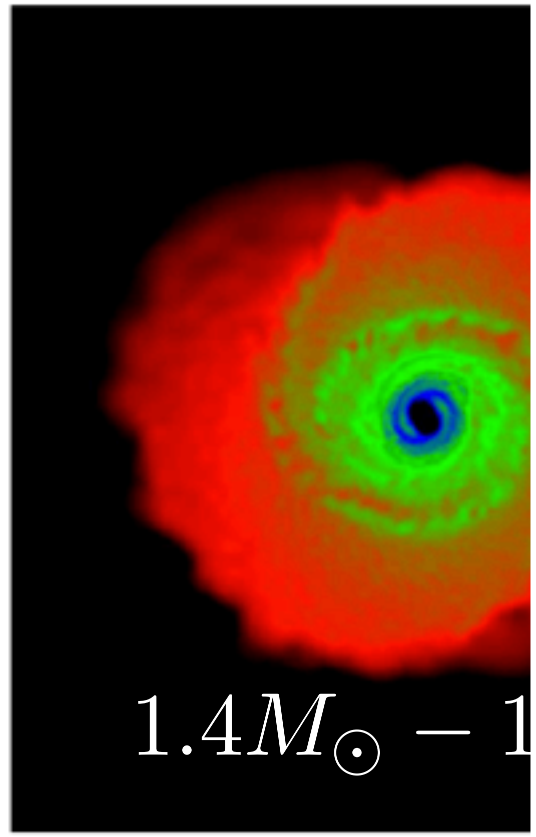
nucleosynthesis of dynamical ejecta
robust r-process:
- extreme neutron-rich conditions (Y_e =0.04)
- several fission cycles

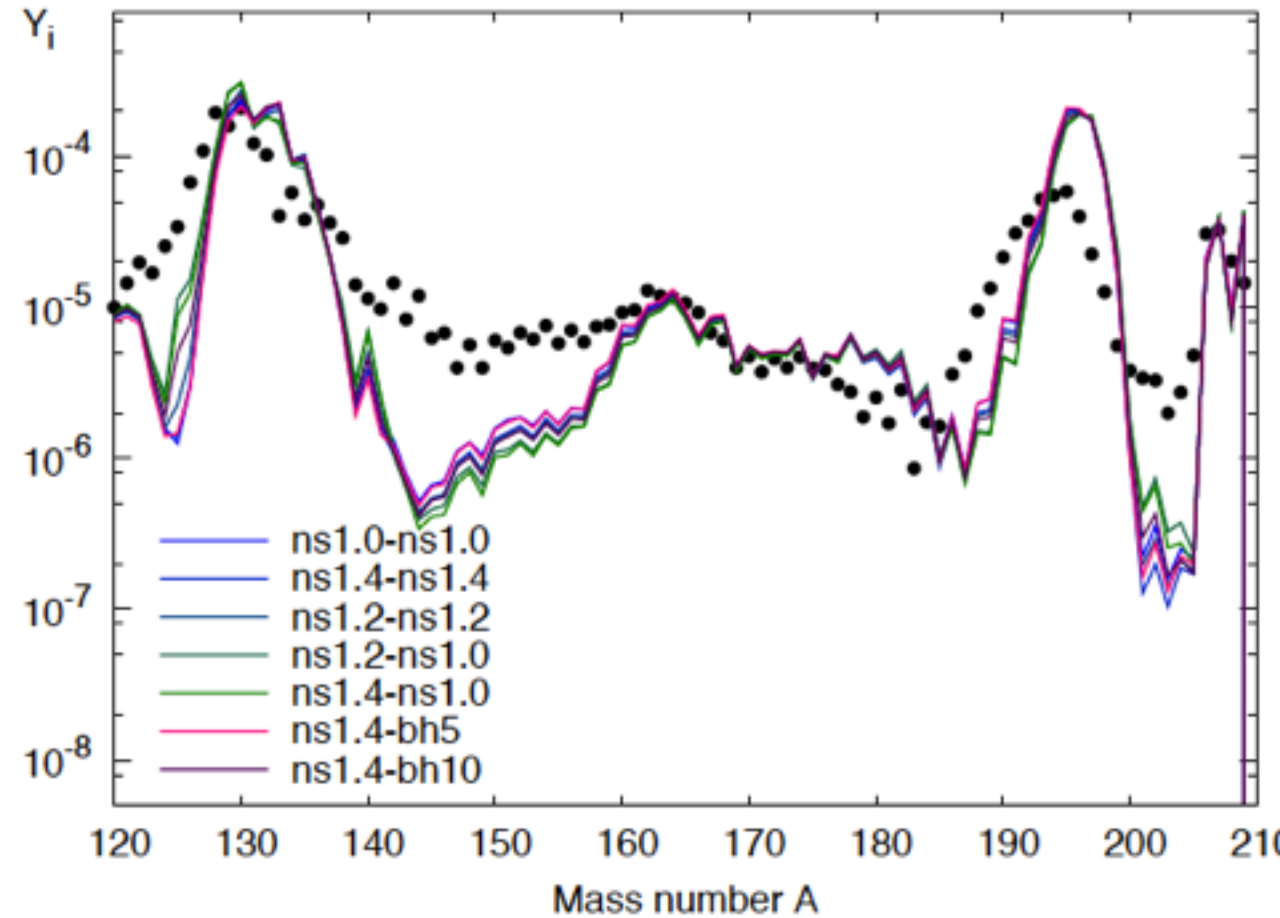


Korobkin, Rosswog, Arcones, Winteler (2012)
see also Bauswein, Goriely, and Janka
Hotokezaka, Kiuchi, Kyutoku, Sekiguchi, Shibata, Tanaka, Wanajo

Neutron star mergers: robust r-process







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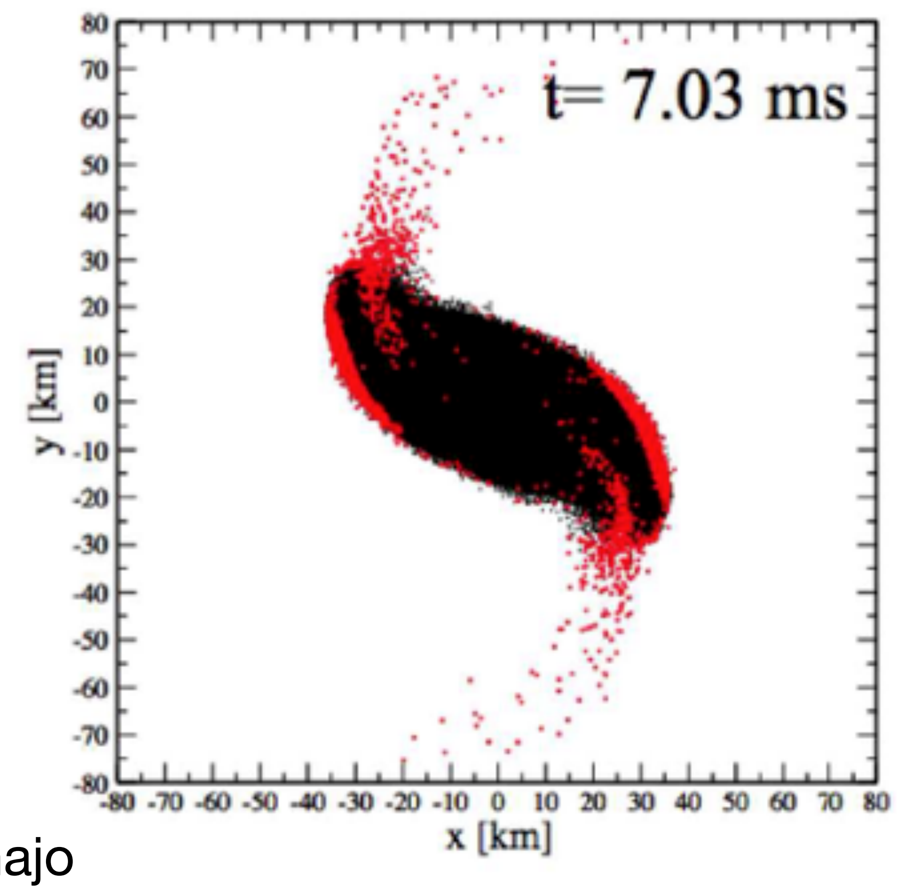

nucleosynthesis of dynamical ejecta

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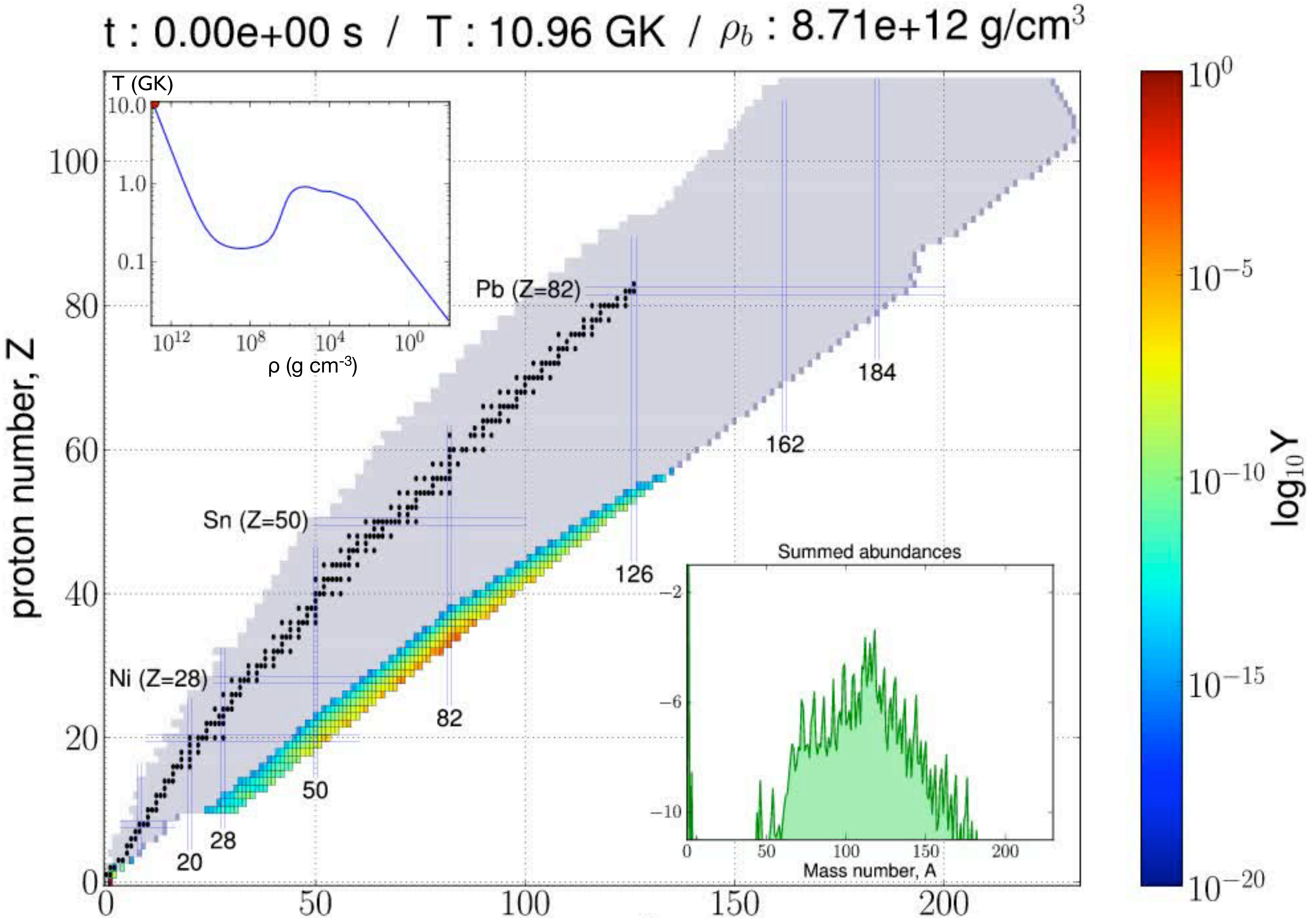
see also Bauswein, Goriely, and Janka

Hotokezaka, Kiuchi, Kyutoku, Sekiguchi, Shibata, Tanaka, Wanajo

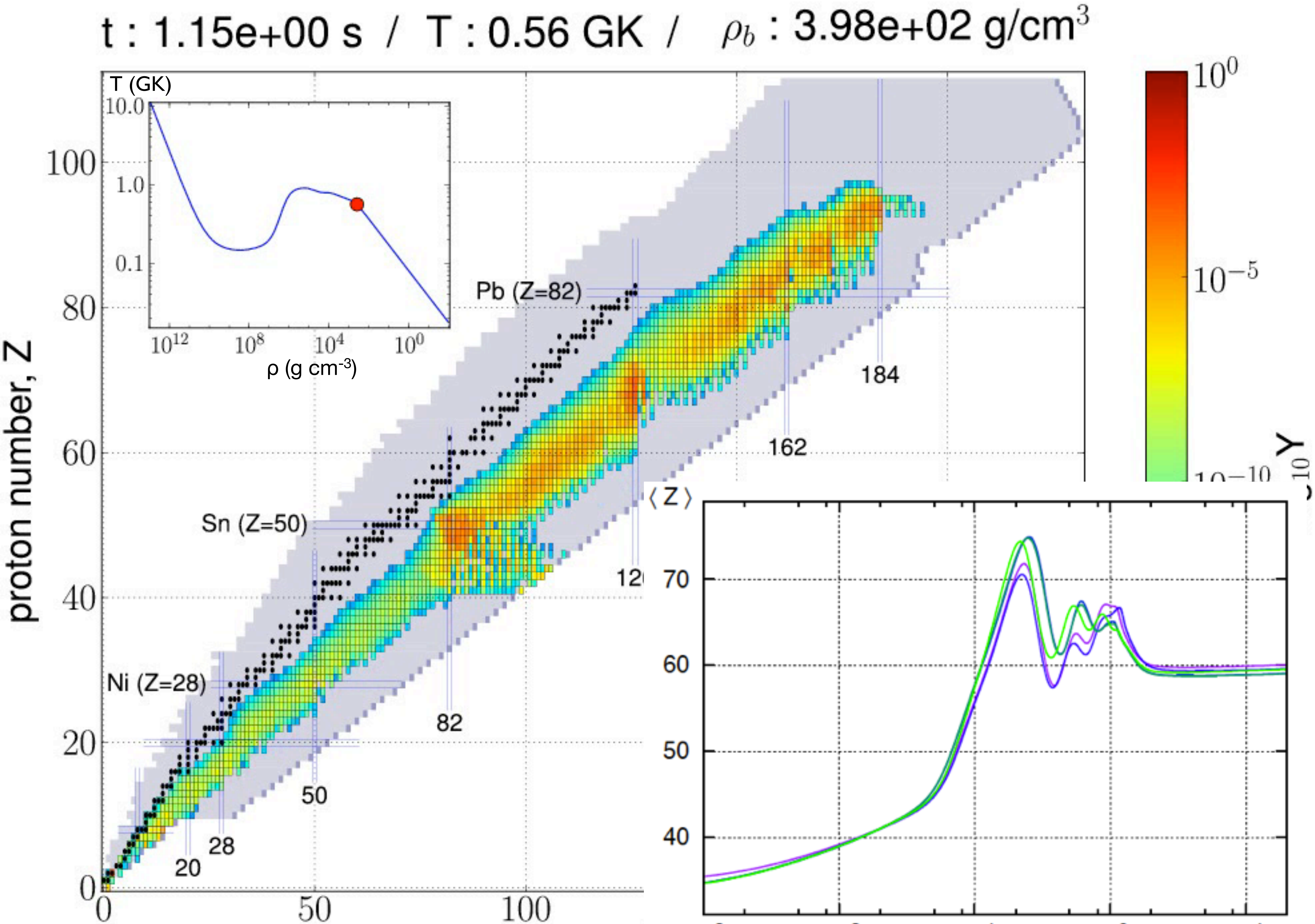
T (GK)

ρ (g cm^{-3})

Korobkin et al. 2012



Korobkin et al. 2012



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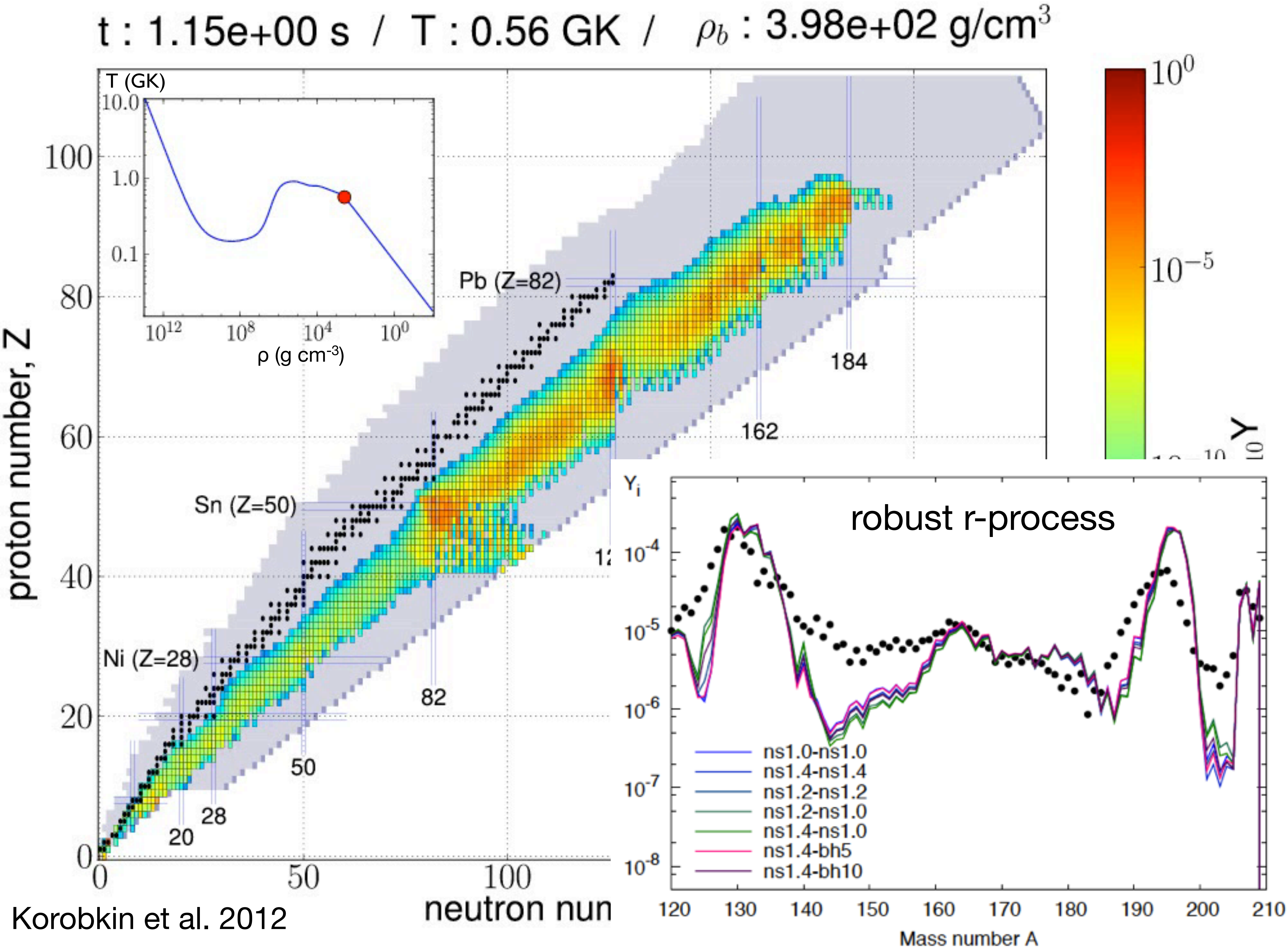
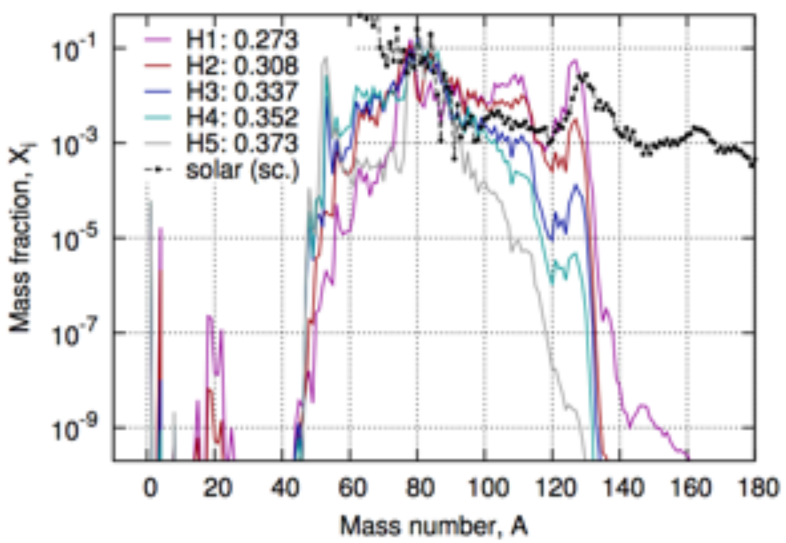


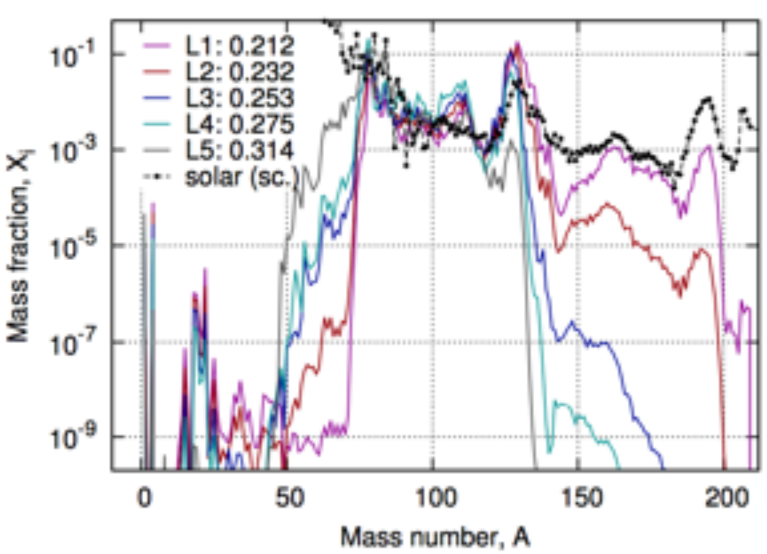
Korobkin et al. 2012

Neutron star mergers: neutrino-driven wind

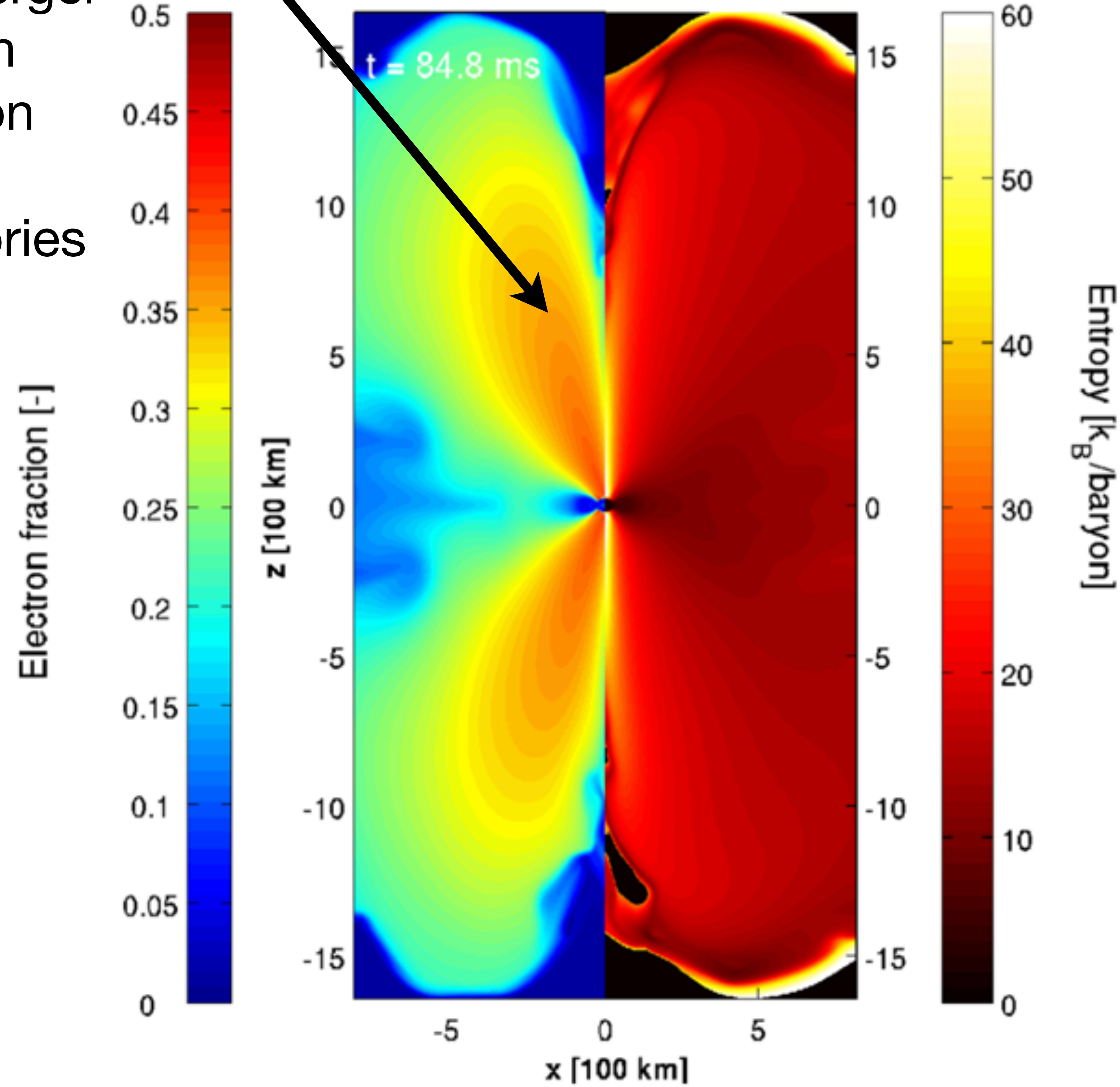
3D simulations ~100ms after merger
disk and neutrino-wind evolution
neutrino emission and absorption

Nucleosynthesis for few trajectories





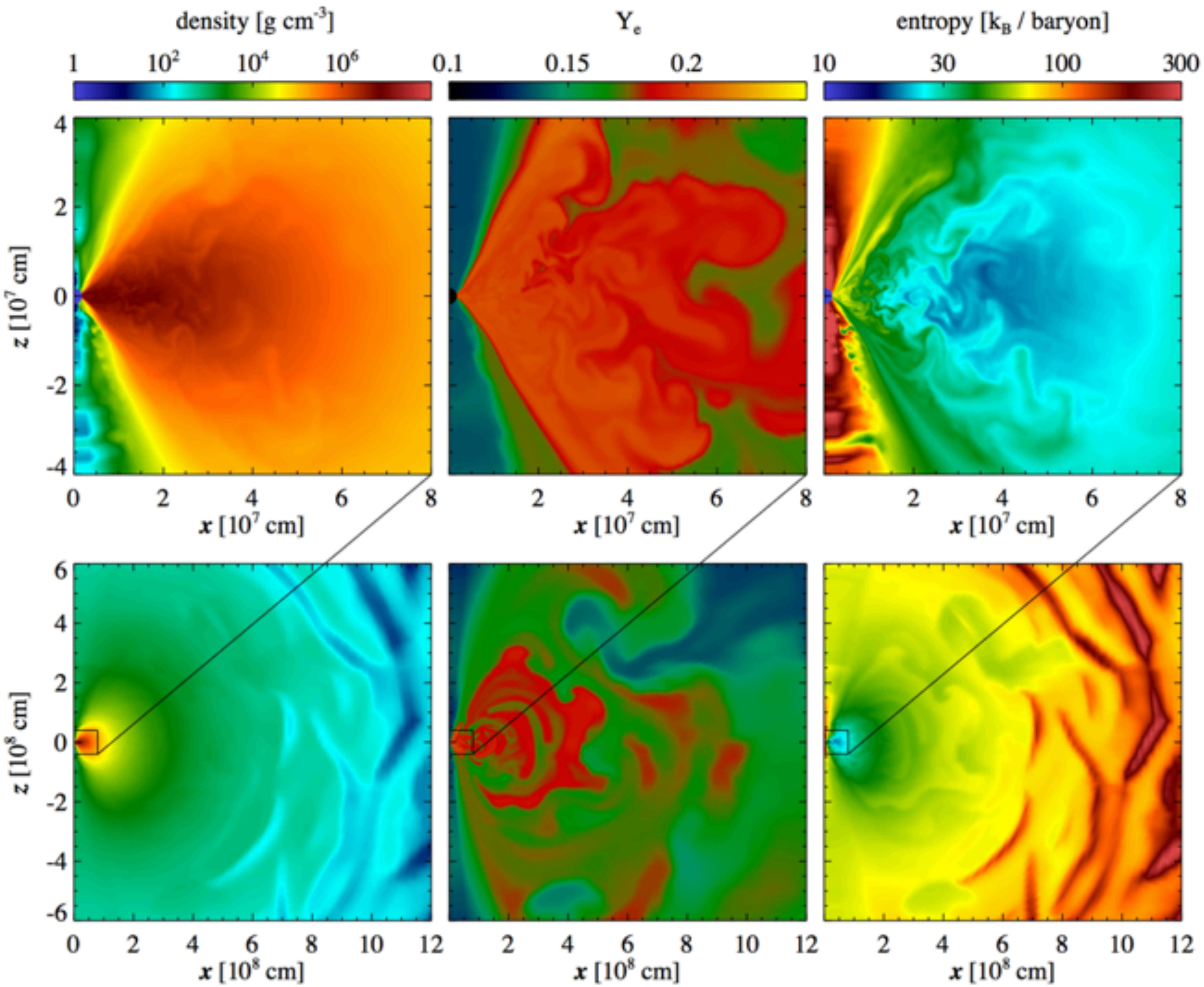
Perego et al. (2014)



see also Just et al. 2014, Sekiguchi et al.

Neutron star mergers: evaporation disk

2D simulations with simple neutrino treatment
outflows from accretion disk: black hole, super-massive neutron star
matter unbound: viscosity and alpha recombination



Fernandez & Metzger 2013

see also Just et al. 2014

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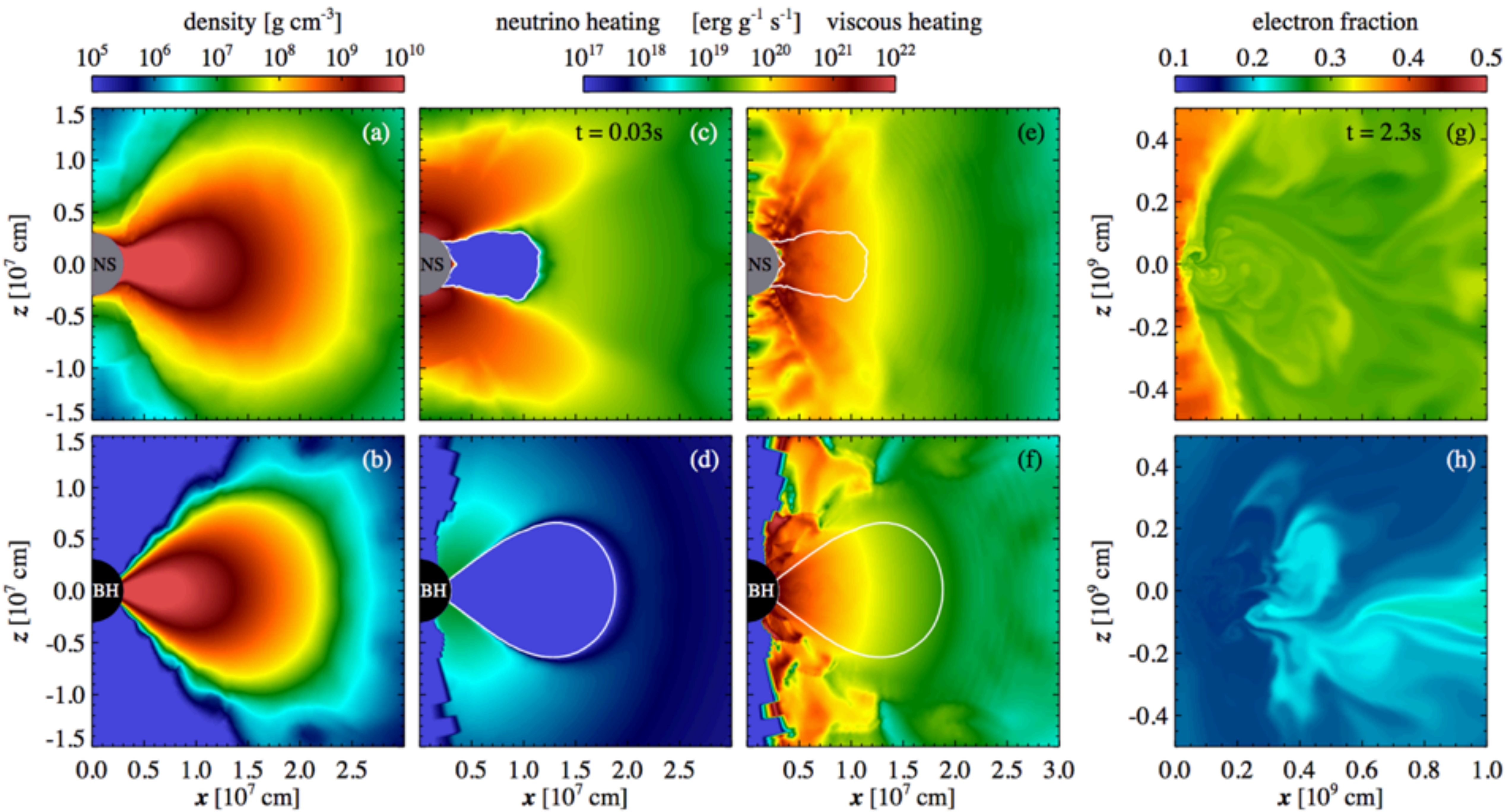
Metzger & Fernandez 2014

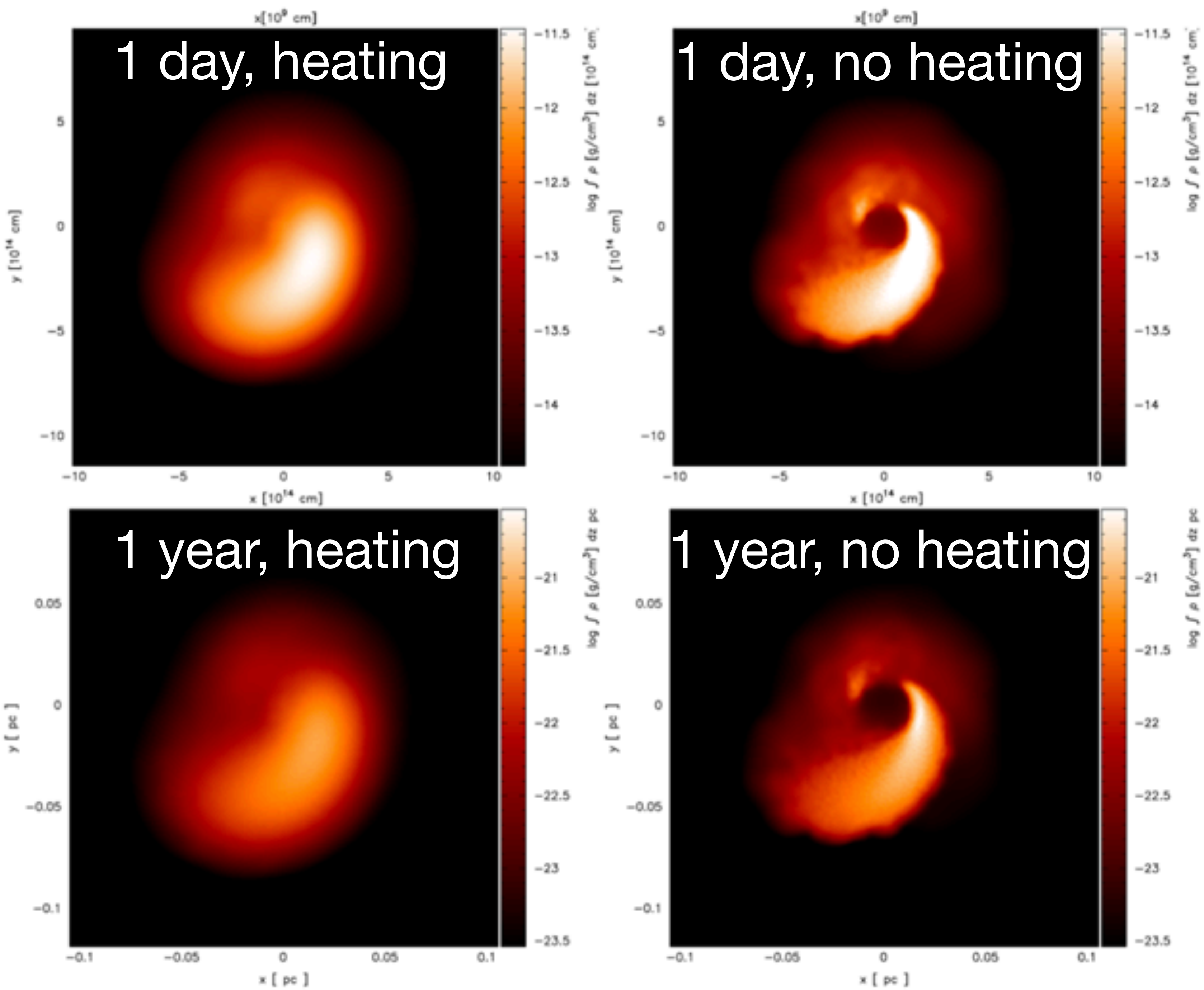


see also Just et al. 2014

Radioactive decay in neutron star mergers

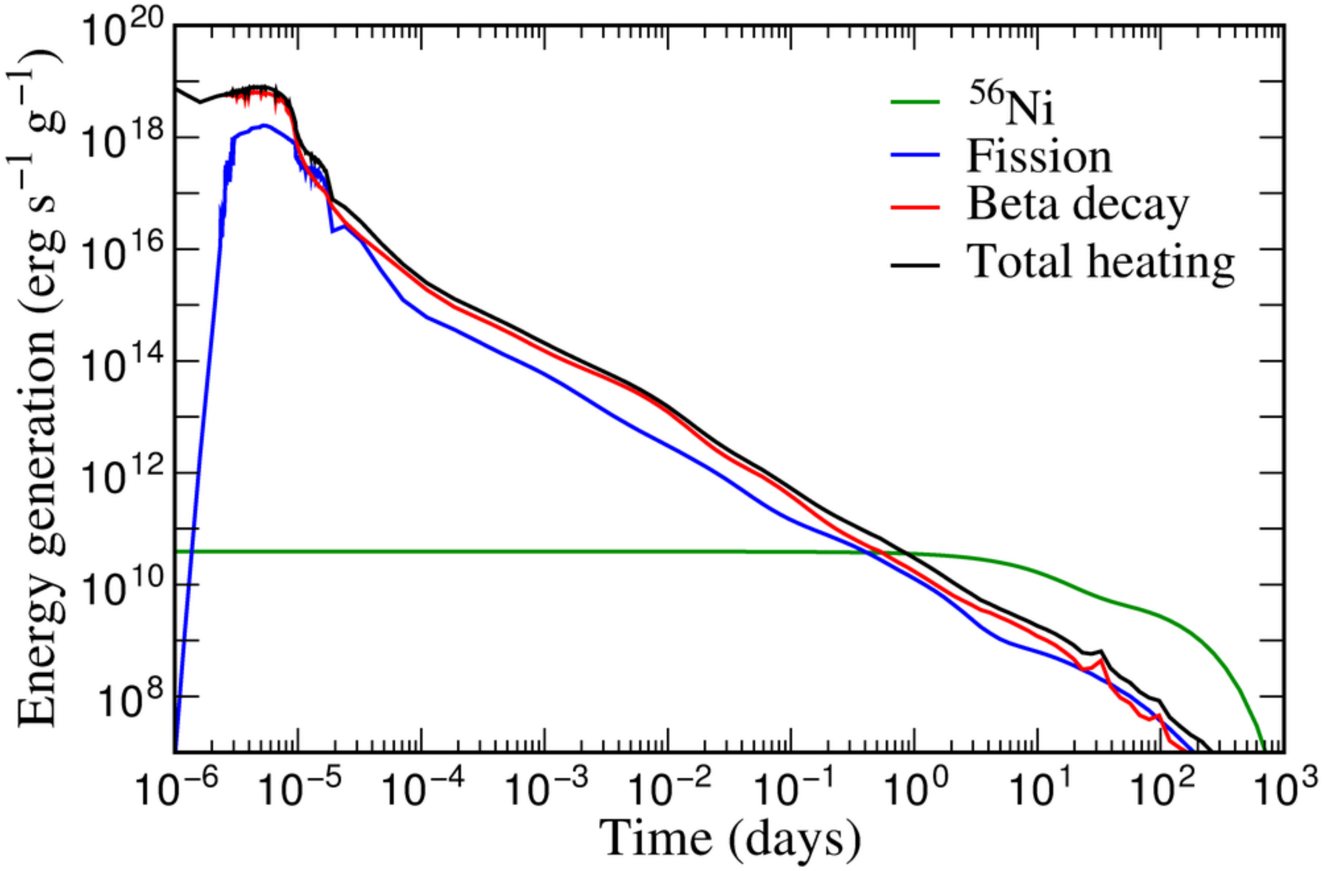
r-process heating affects:

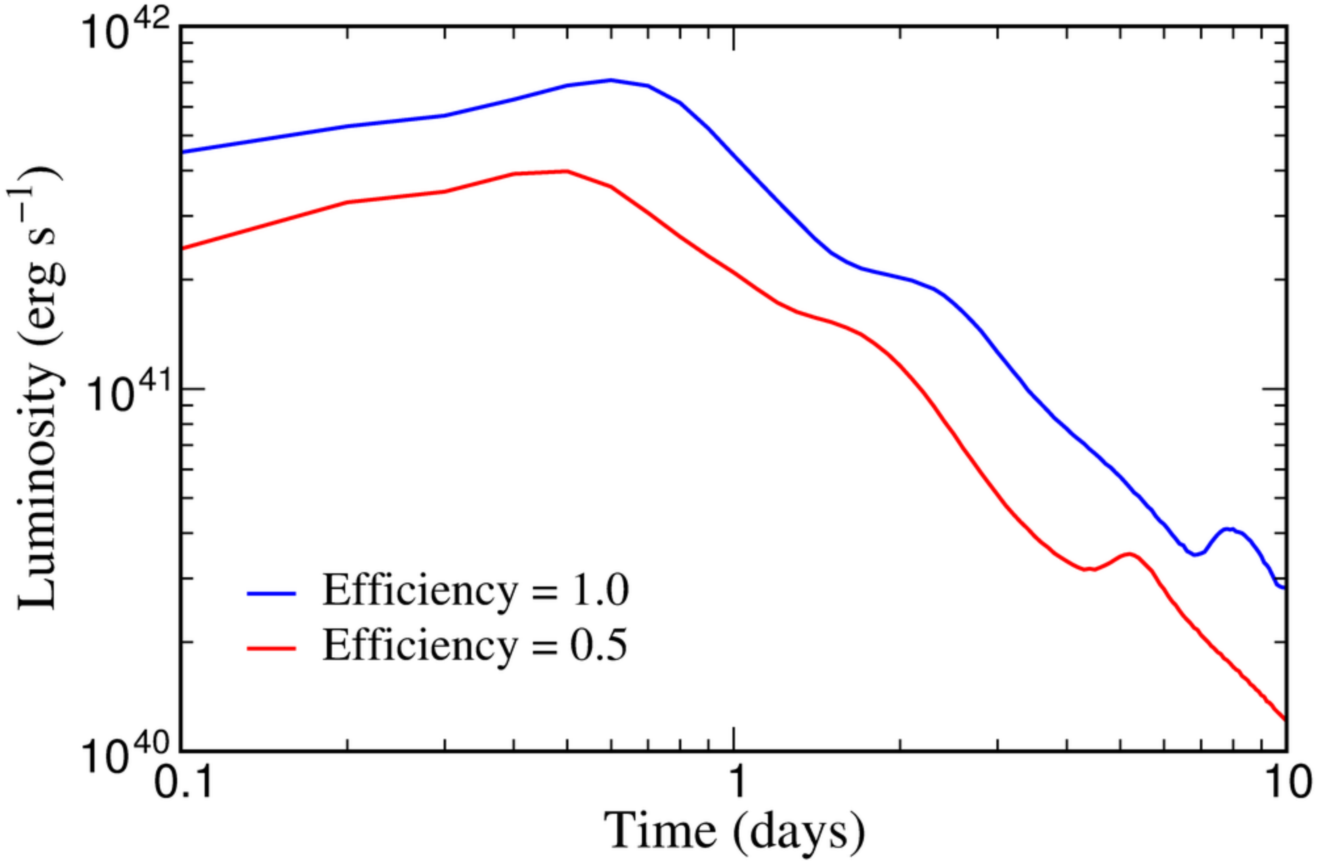
- merger dynamics: late X-ray emission in short GRBs
  (Metzger, Arcones, Quataert,Martinez-Pinedo 2010)
- remnant evolution (Rosswog, Korobkin, Arcones, Thielemann, Piran 2014)



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





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

NATURE | LETTER near-final version

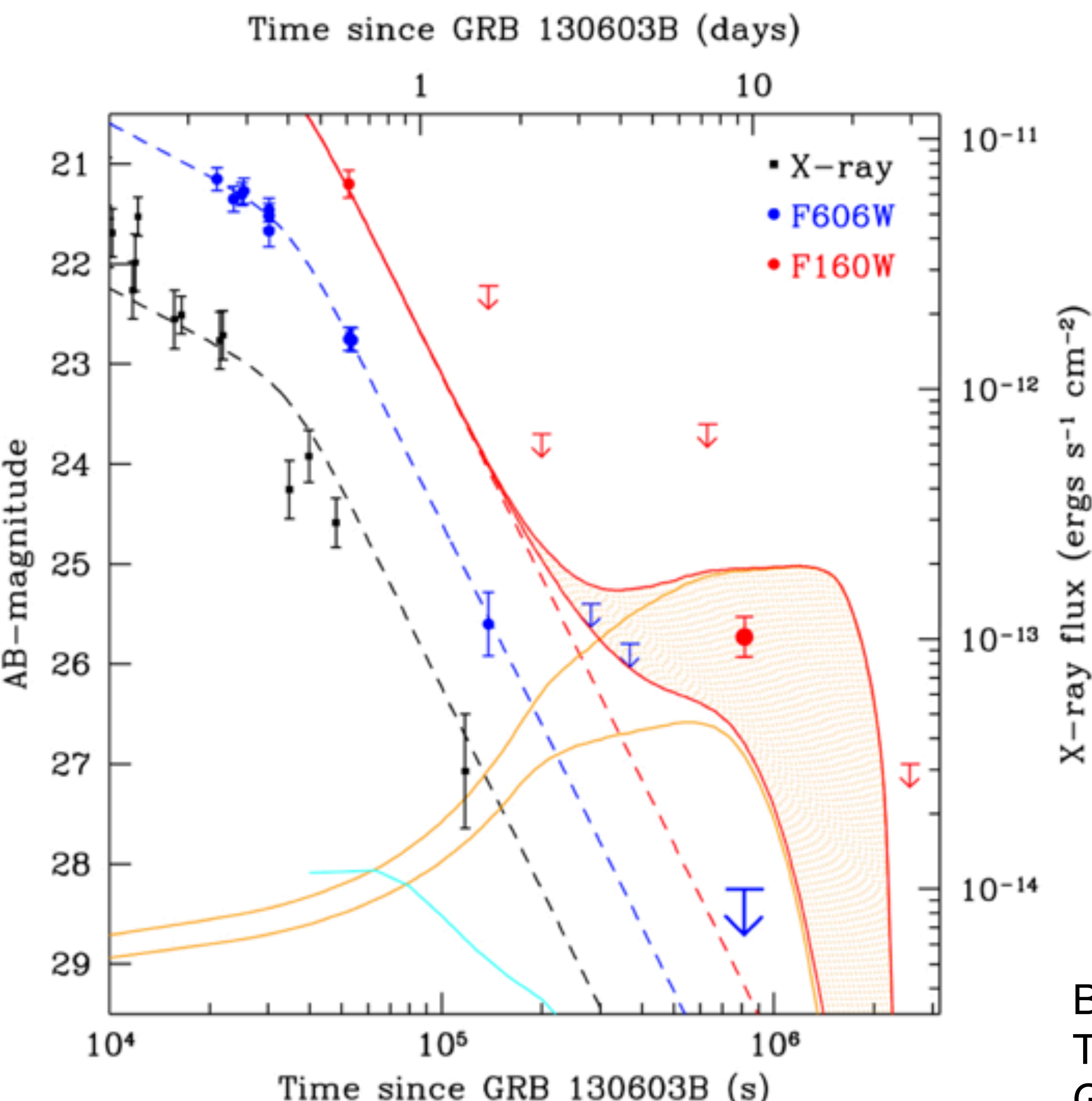
A ‘kilonova’ associated with the short-duration γ-ray burst GRB 130603B

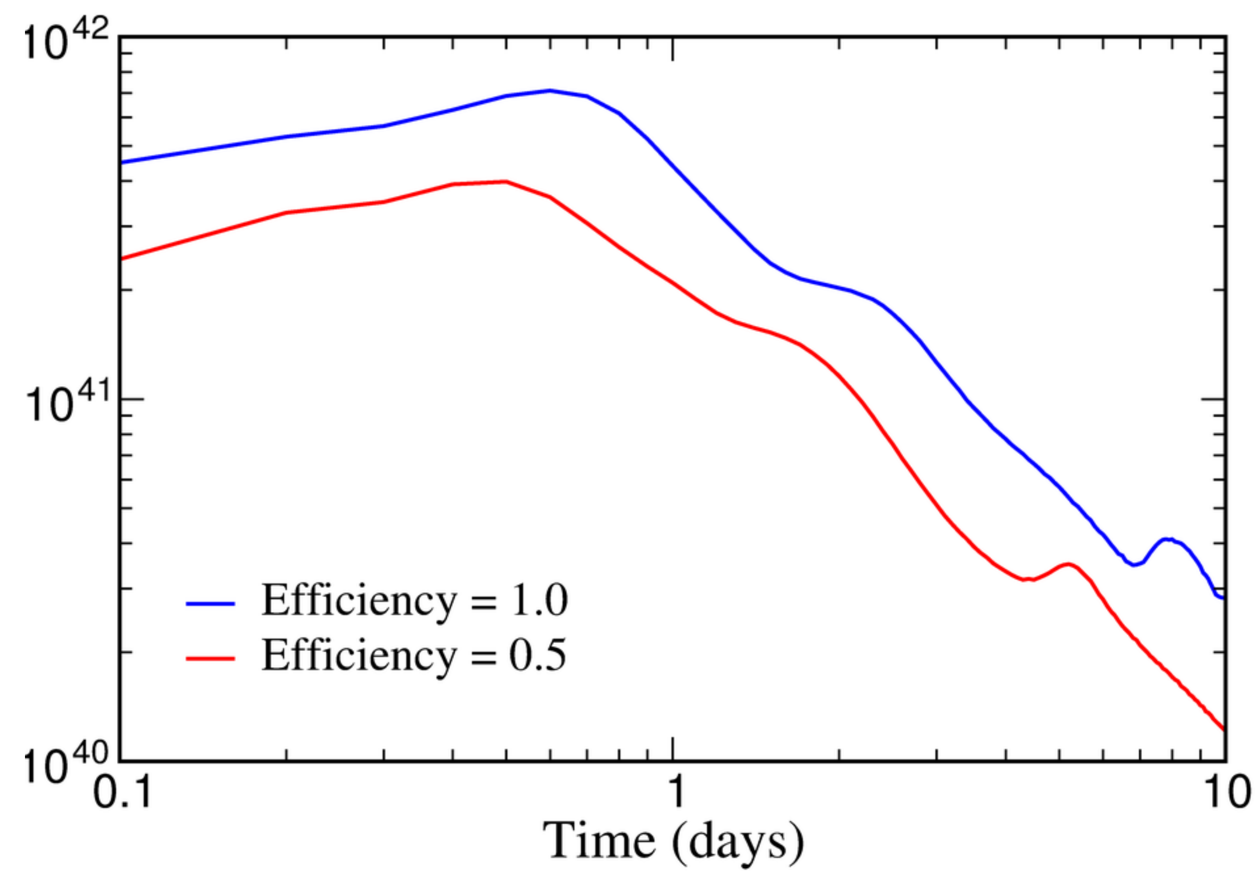
N. R. Tanvir, A. J. Levan, A. S. Fruchter, J. Hjorth, R. A. Hounsell, K. Wiersema & R. L. Tunnicliffe

on star mergers

ger et al. 2010, Roberts et al. 2011,

rocess, EM counter part to GW



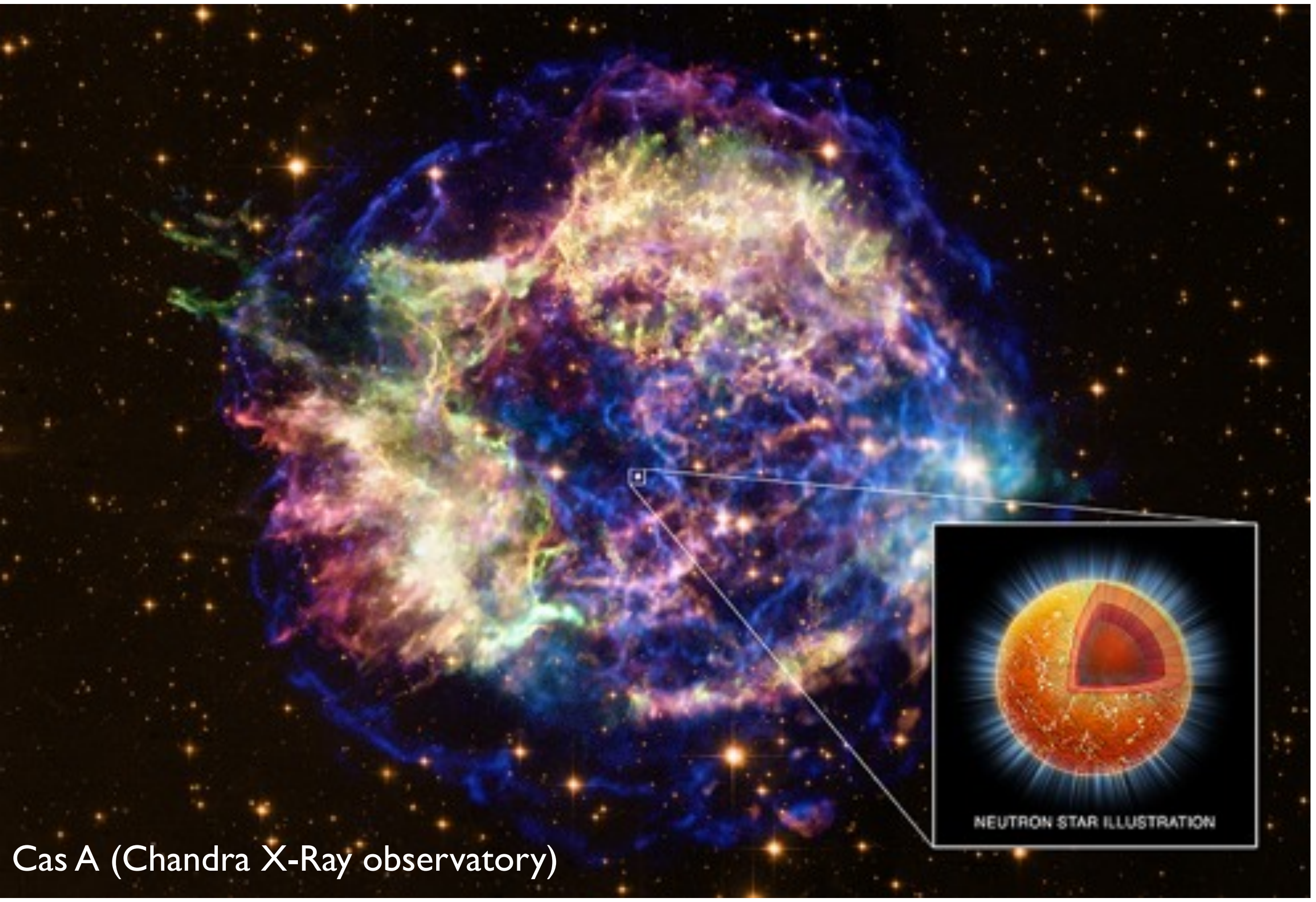


l2, Rosswog 2012, Bauswein et al. 2013)

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

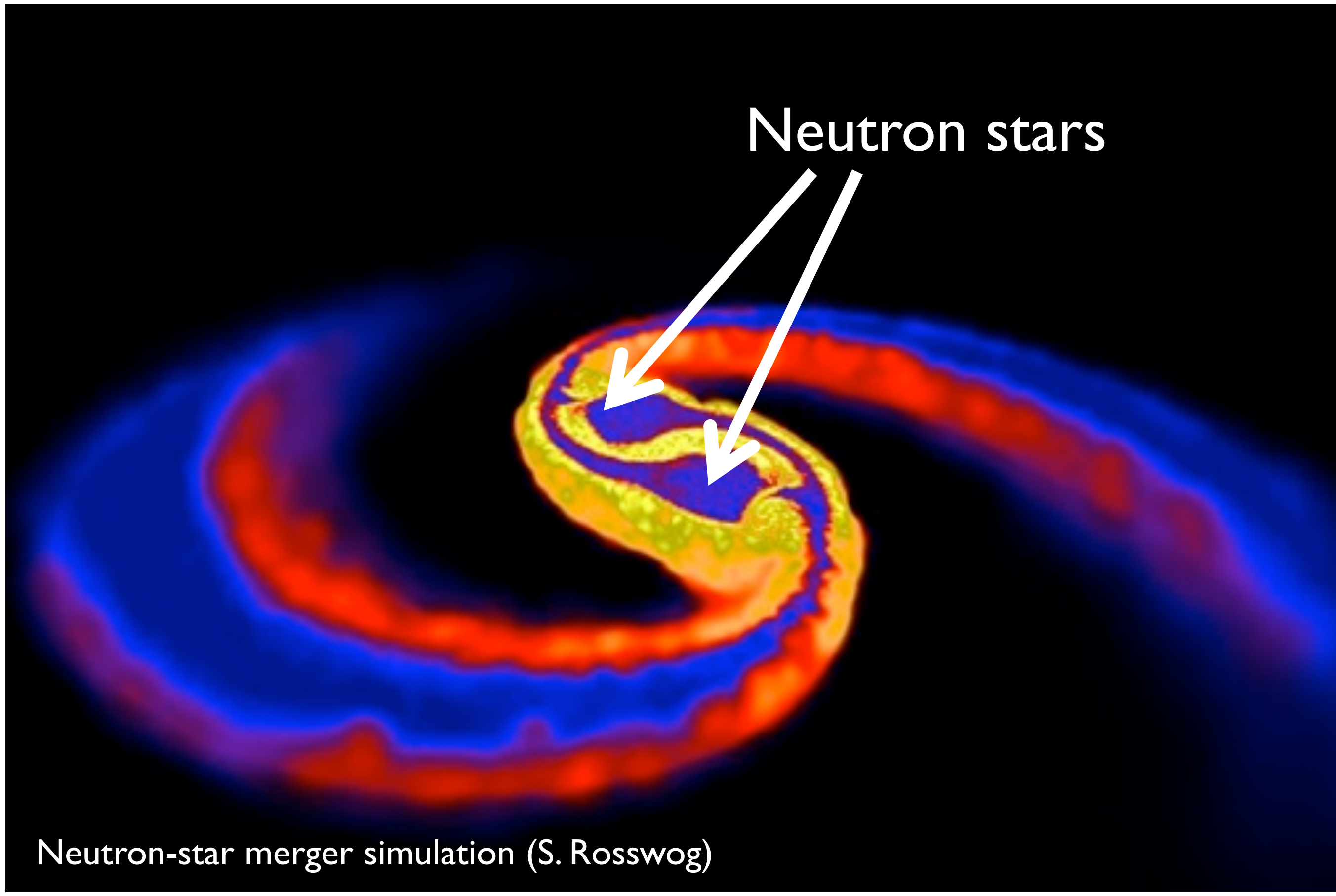
Where does the r-process occur?

Rare core-collapse supernovae



Cas A (Chandra X-Ray observatory)

Neutron star mergers

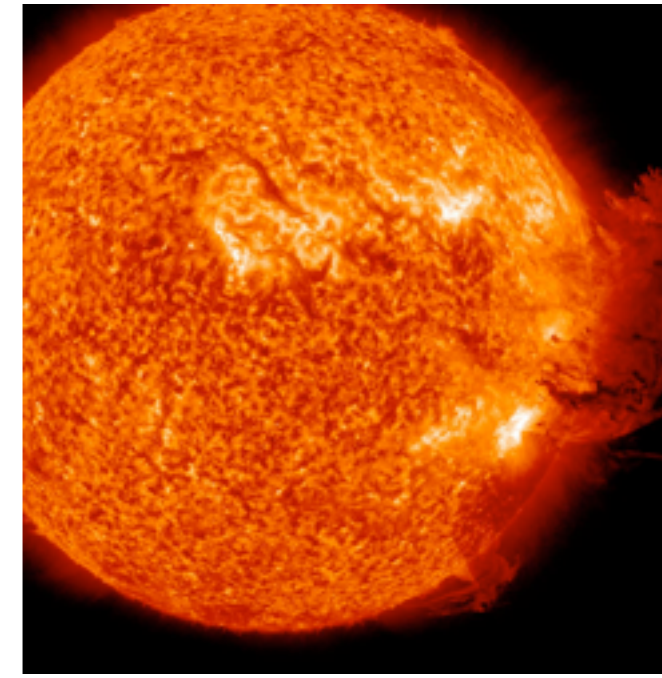


Neutron-star merger simulation (S. Rosswog)

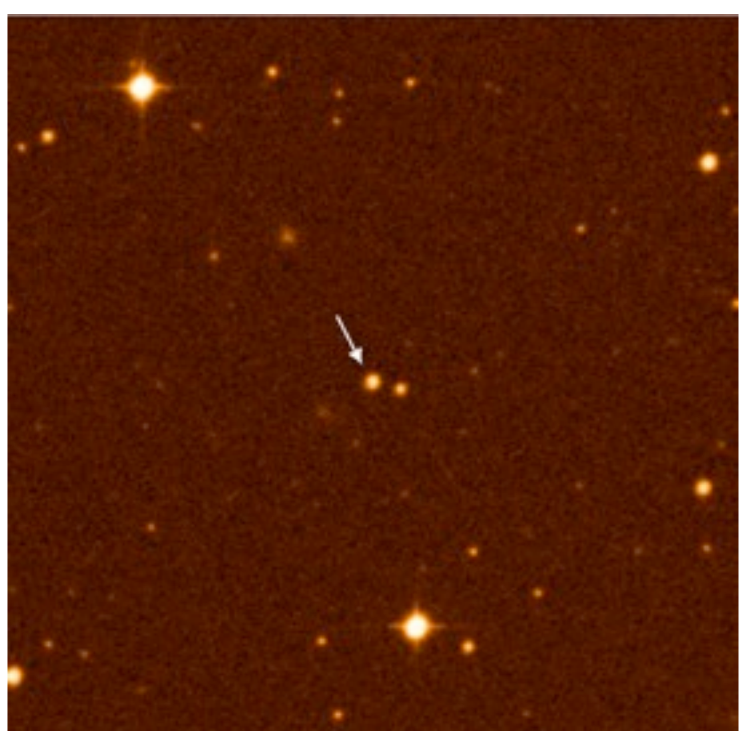
Galactic chemical evolution

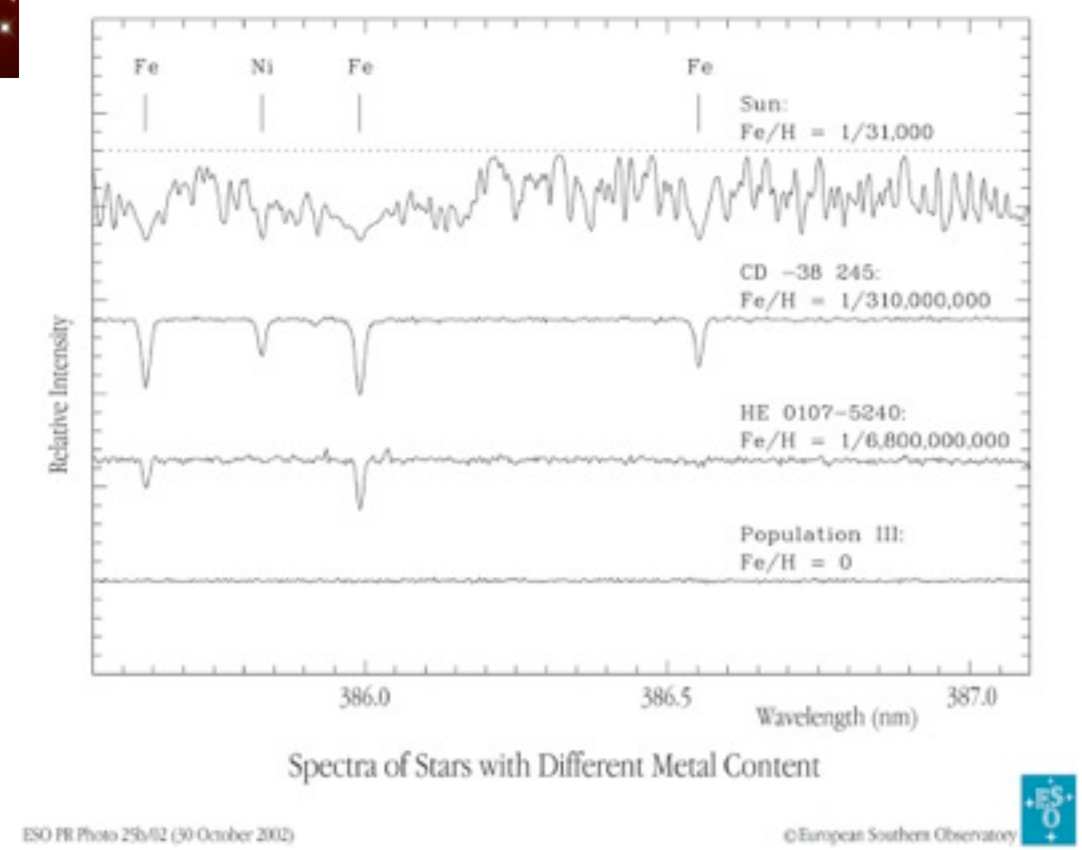
First stars: H, He → Heavy elements ← New generation of stars

Interstellar medium (ISM)

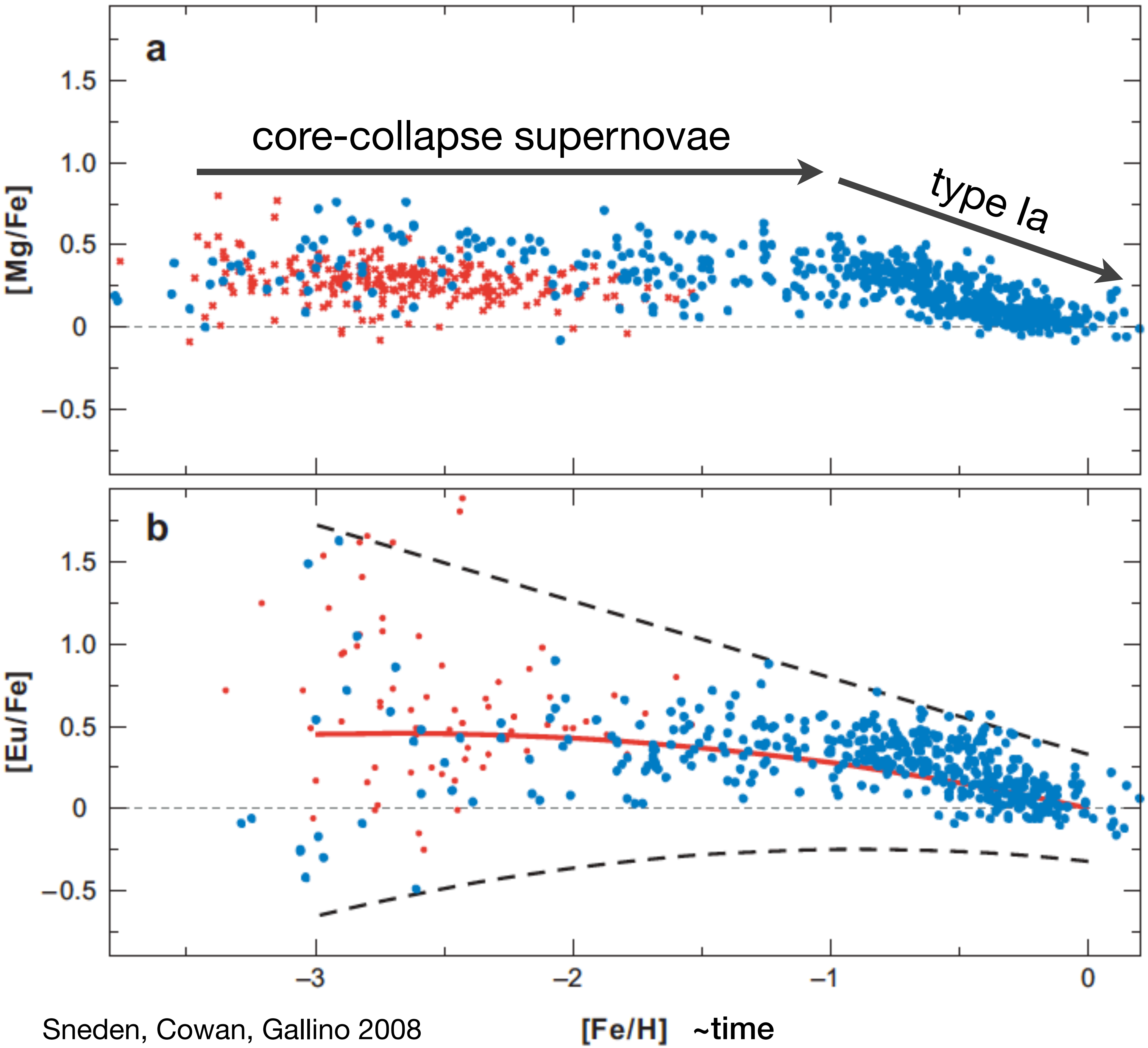


The very metal-deficient star
HE 0107-5240
(Hamburg-ESO survey)





Trends with metallicity



Sneden, Cowan, Gallino 2008

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

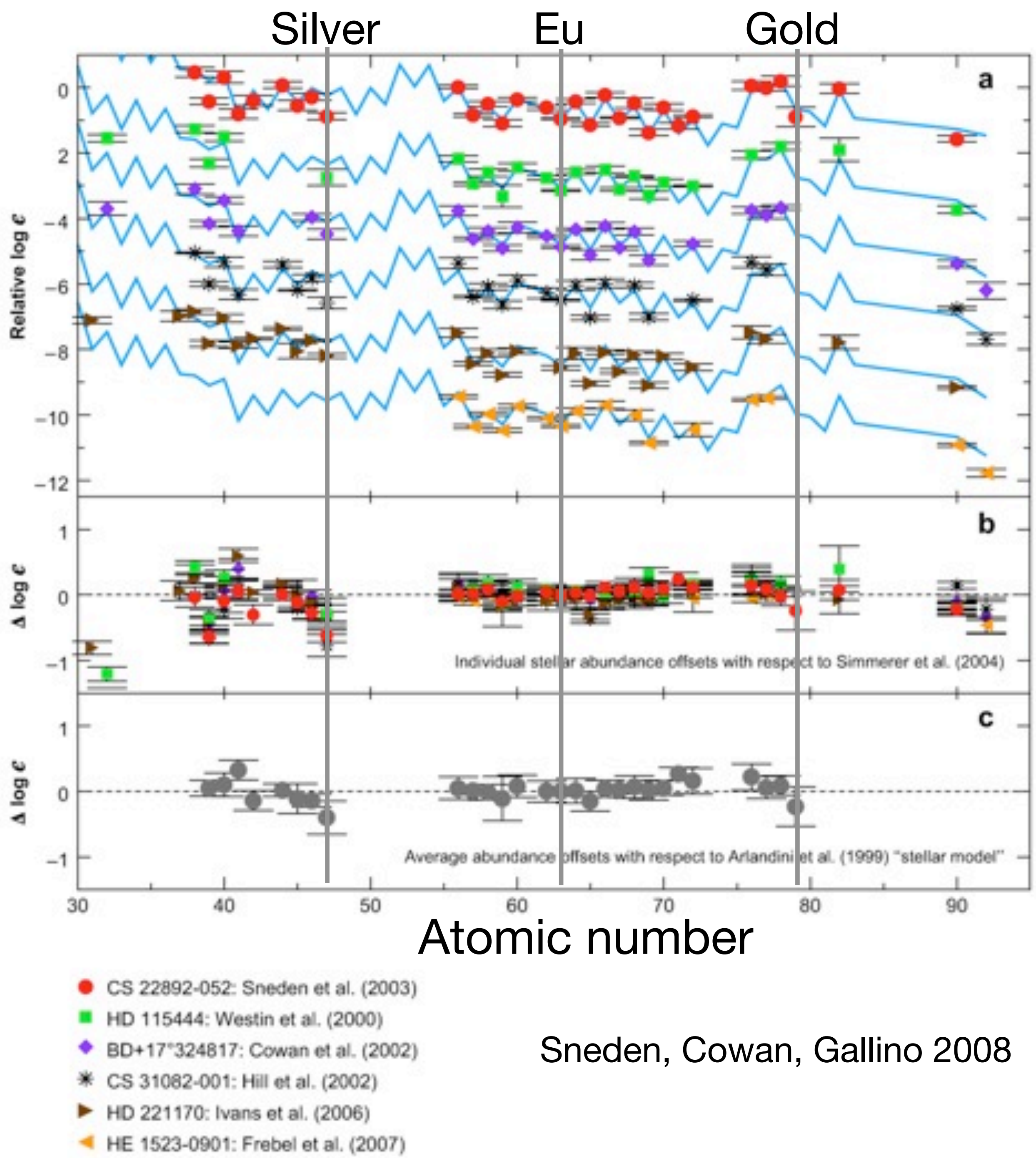
Significant scatter at low metallicities

r-process production rare in the early Galaxy

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

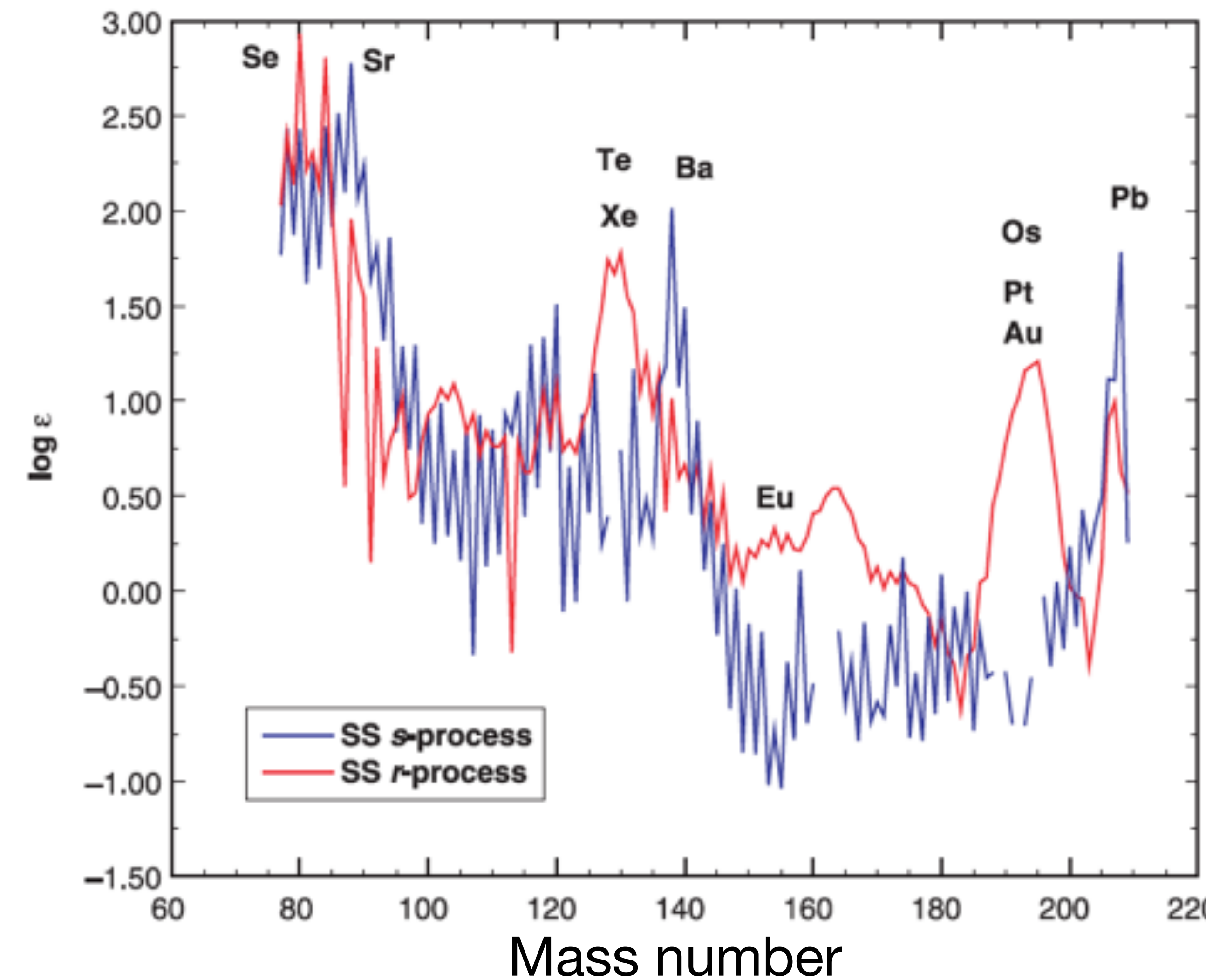
Fingerprint of the r-process

Oldest observed stars



Sneden, Cowan, Gallino 2008

Solar system abundances

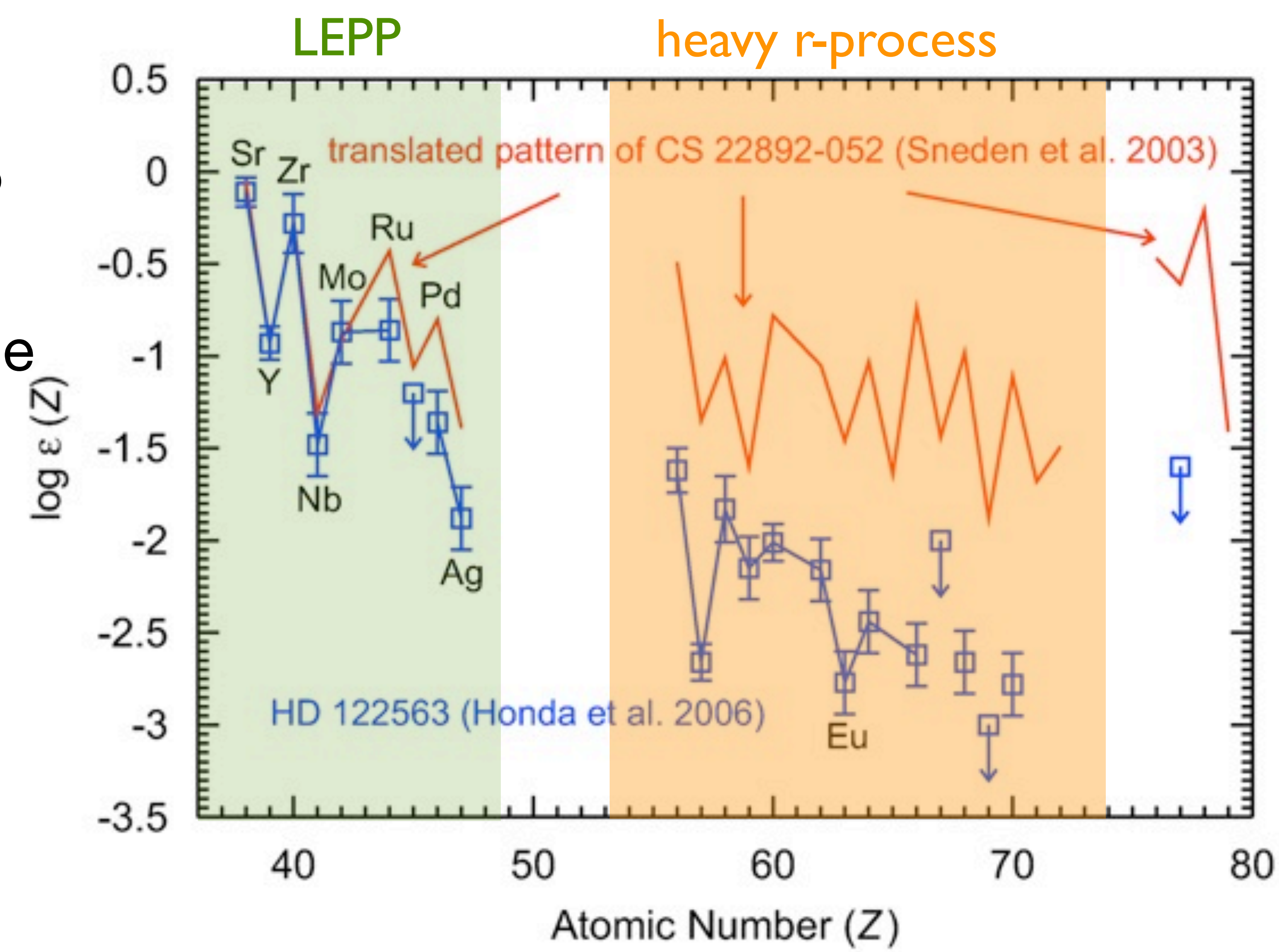


LEPP: Lighter Element Primary Process

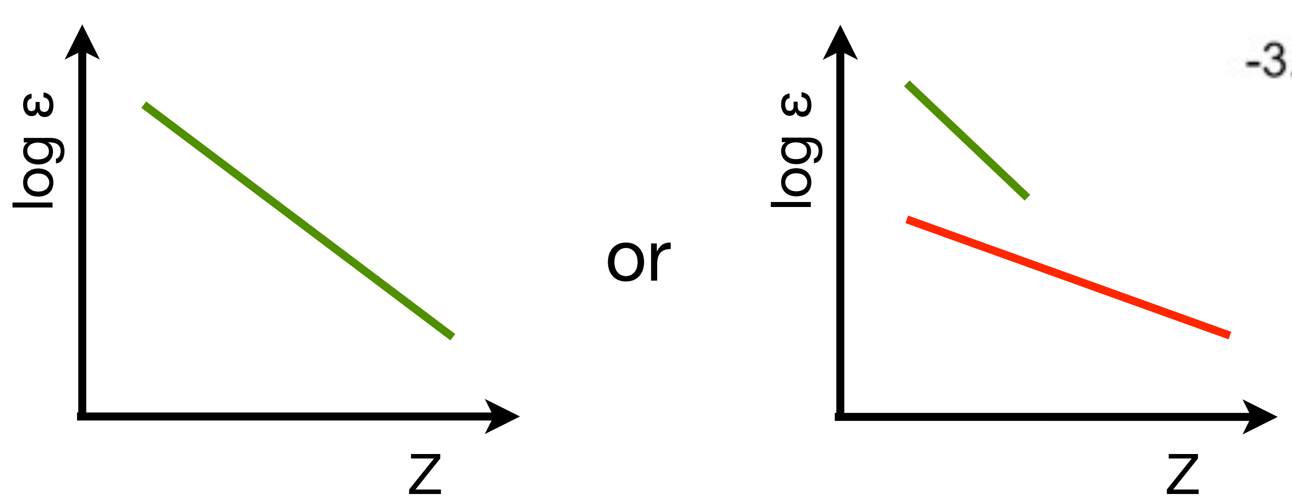
Ultra metal-poor stars with high and low enrichment of heavy r-process nuclei suggest: at least two components or sites (Qian & Wasserburg):

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

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



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



Nucleosynthesis components

C.J. Hansen, Montes, Arcones 2014

LEPP and r-process components
based on 3 methods:

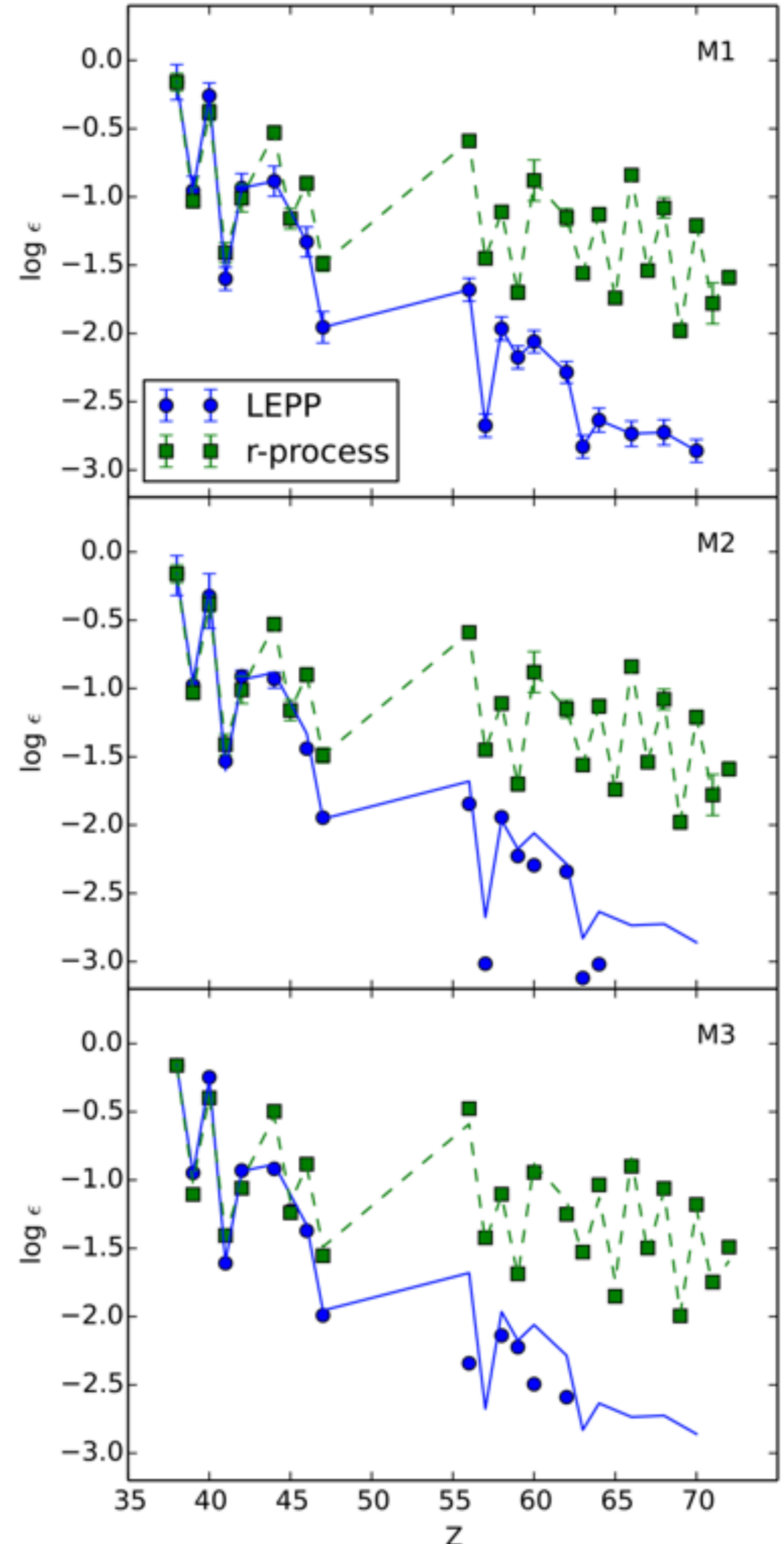
M1: LEPP = Honda star
r-process = Sneden star

M2: LEPP = Honda - Sneden
r-process = Sneden

M3: iterative method (Li et al. 2013)
LEPP = LEPP - r-process
r-process = r-process - LEPP

→ Component abundance pattern: Y_r and Y_L
Assumptions: Z range for components
robust pattern

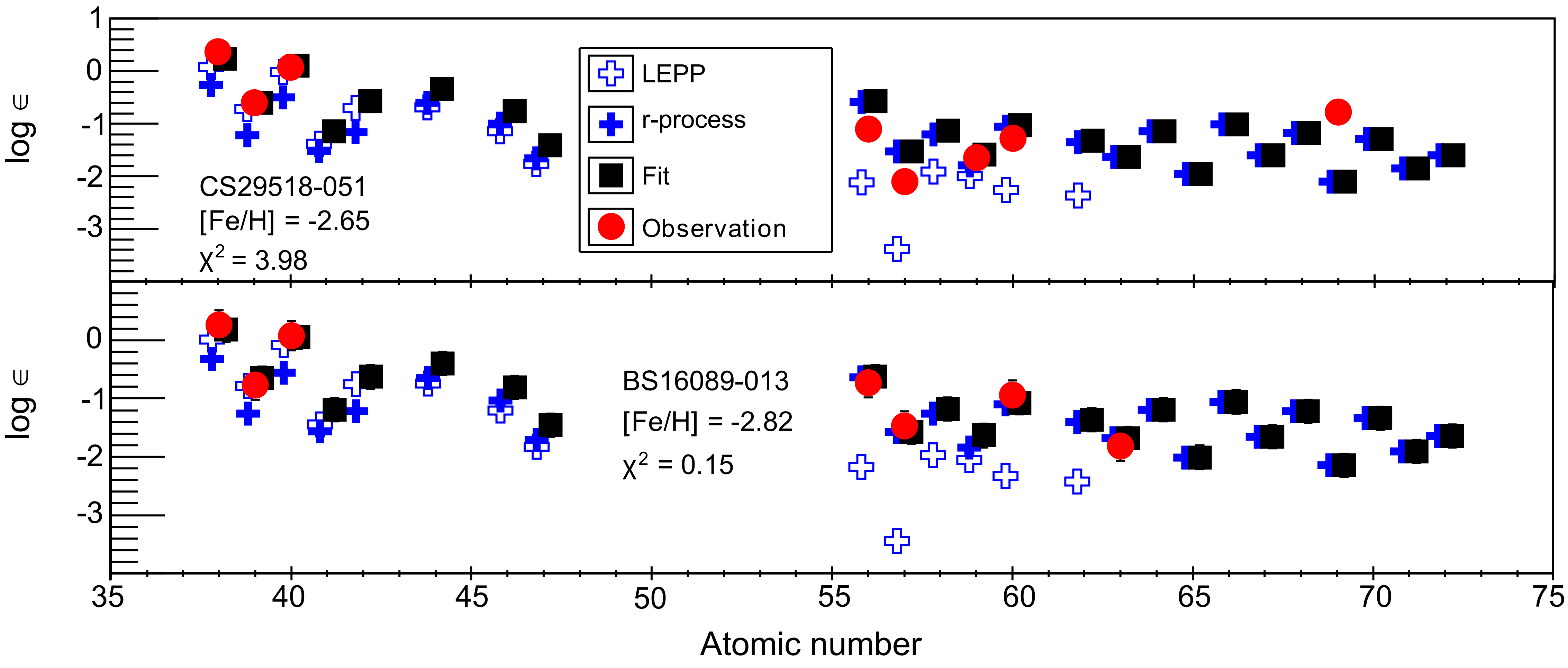
lines = M1



Abundance deconvolution

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

fit abundance as combination of components: $Y_{\mathrm{calc}}(Z) = (C_r Y_r(Z) + C_L Y_L(Z)) \cdot 10^{[\mathrm{Fe/H}]}$



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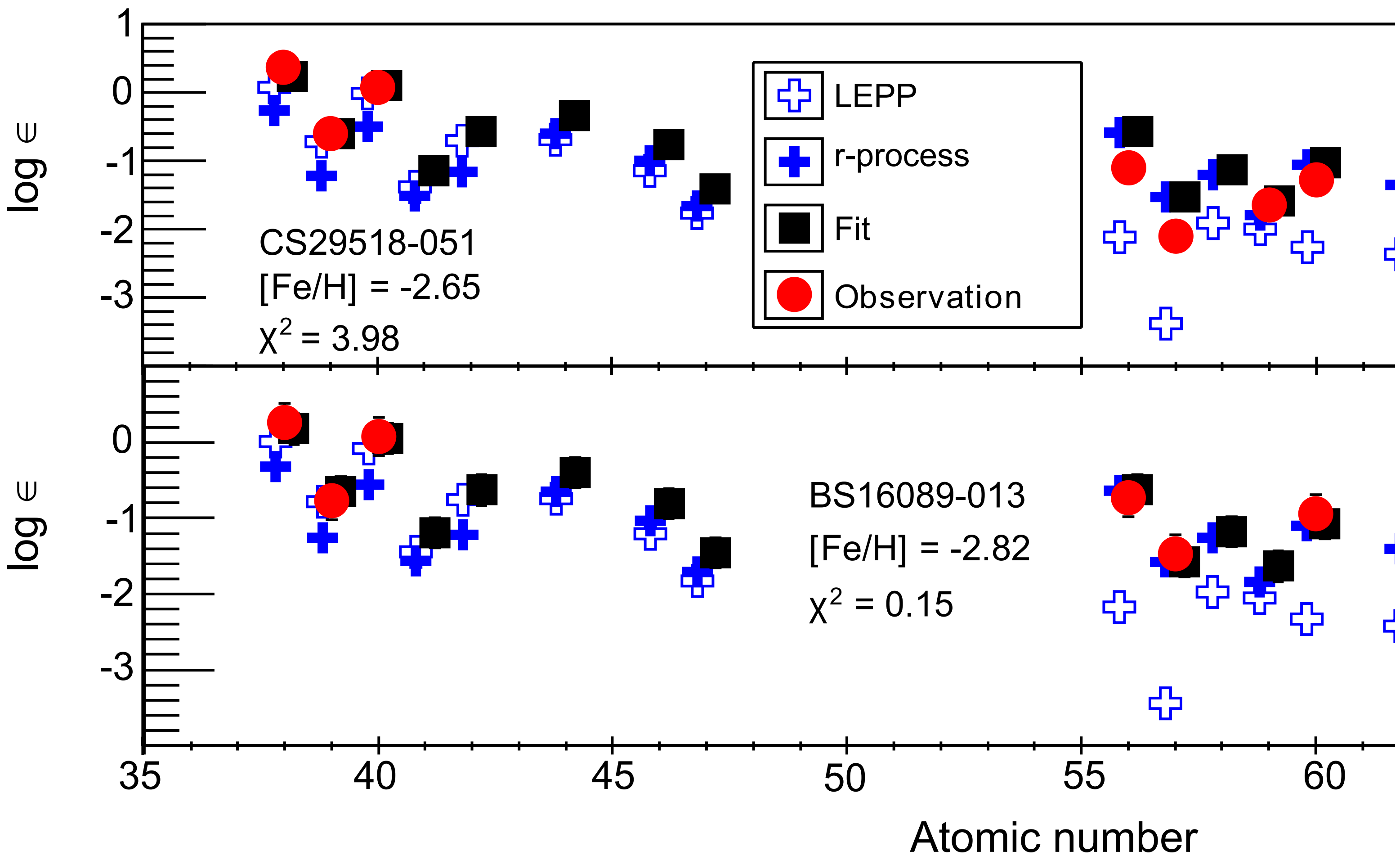

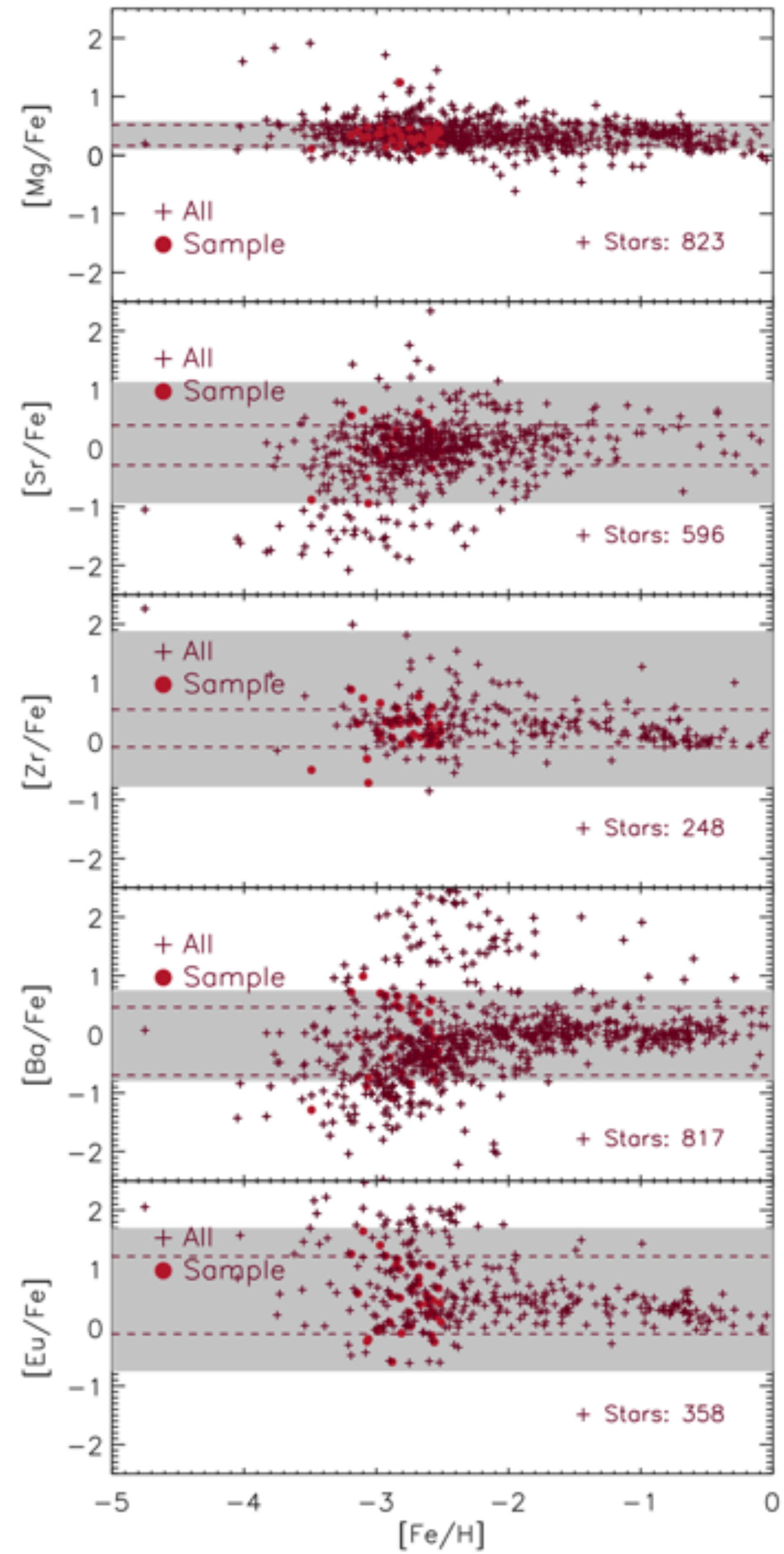

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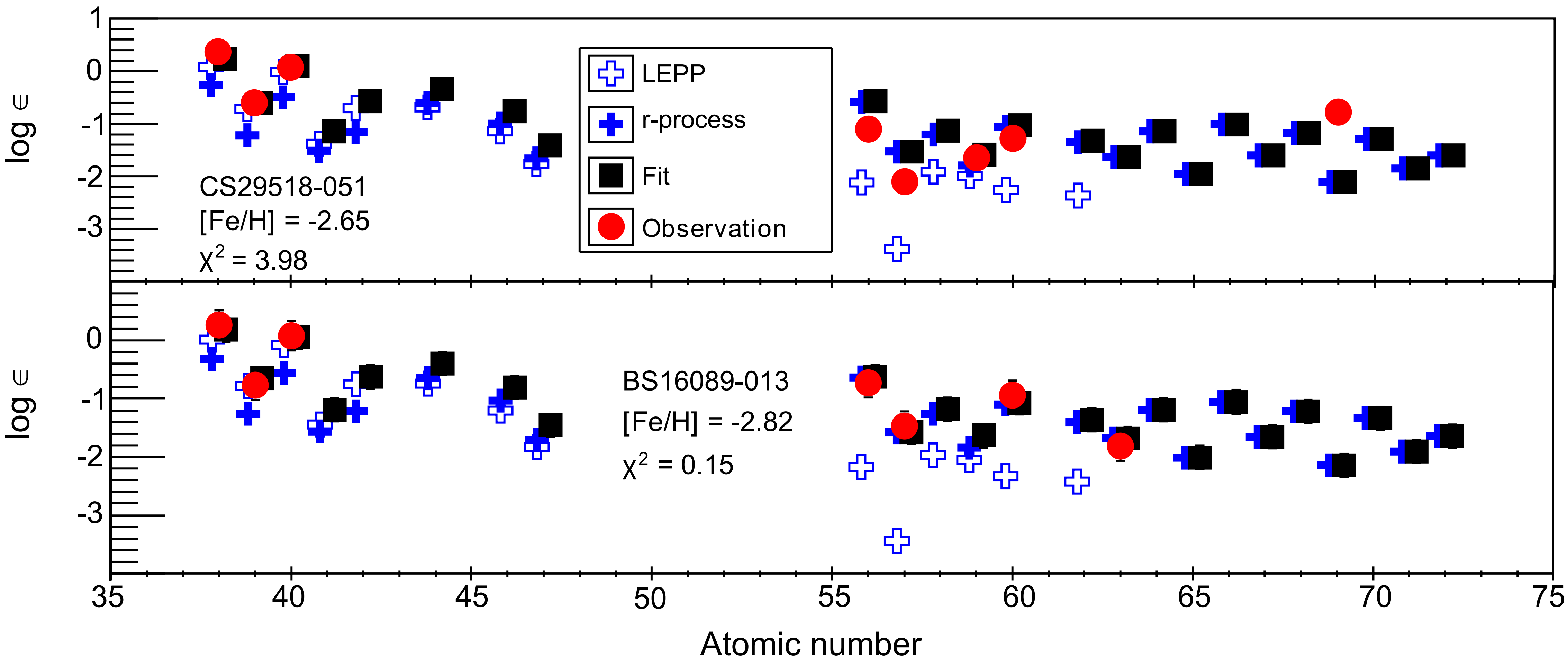

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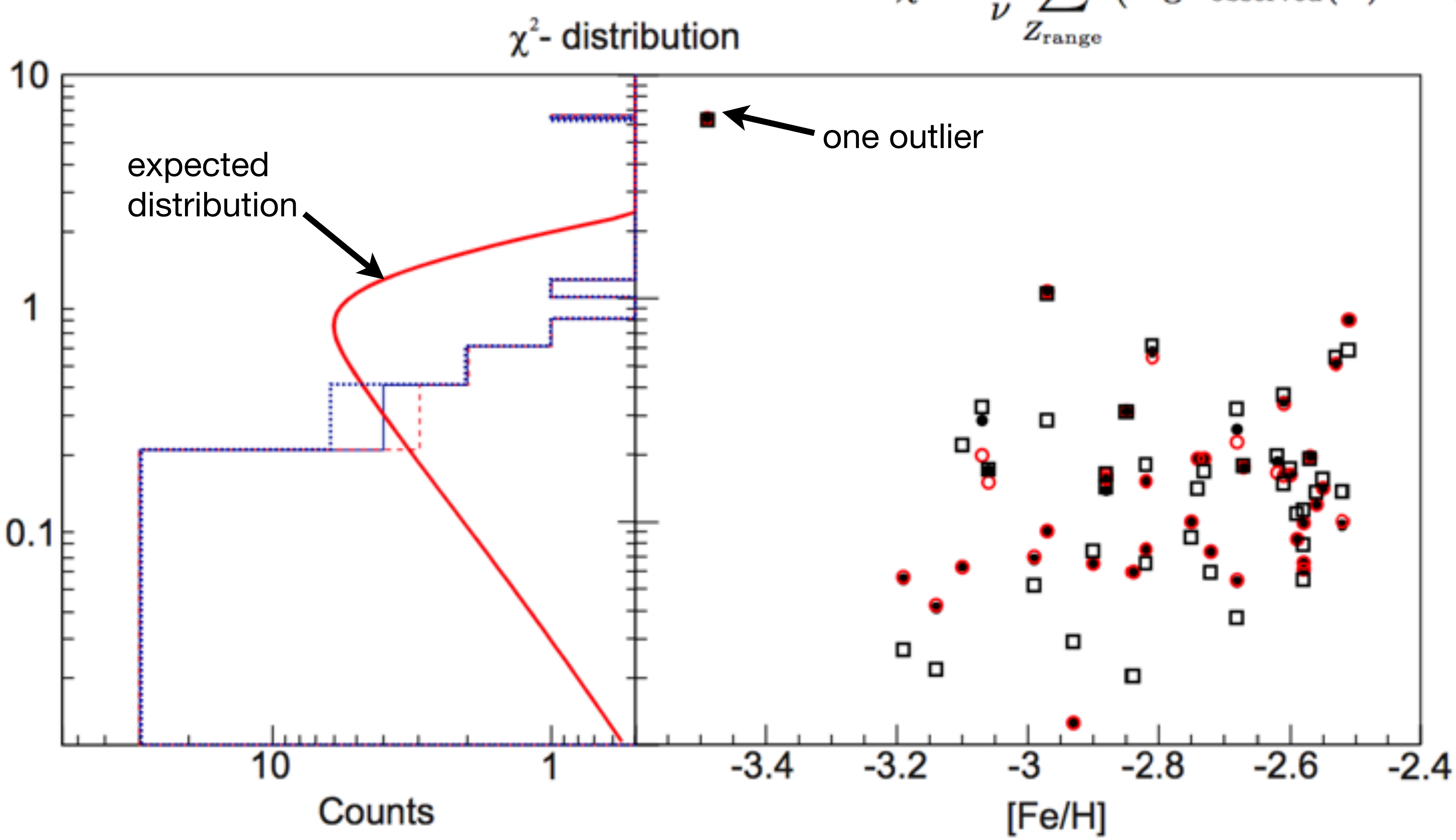
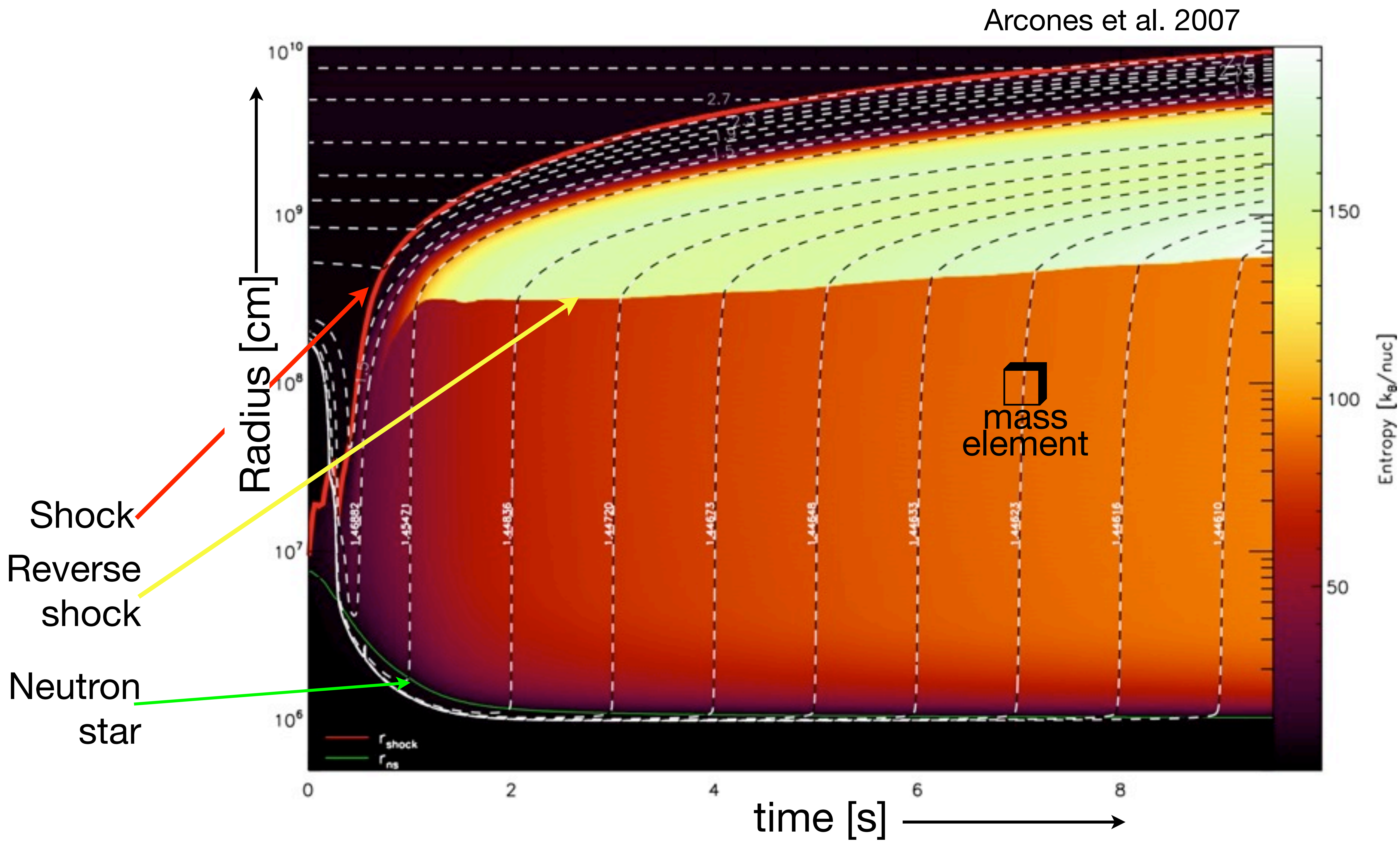
$$\chi^2 = \frac{1}{\nu} \sum_{Z_{\rm range}} \left(\log Y_{\rm observed}(Z) - \log Y_{\rm calc}(Z)\right)^2 / \Delta(Z)^2,$$

0.32 dex
(obs. + method)

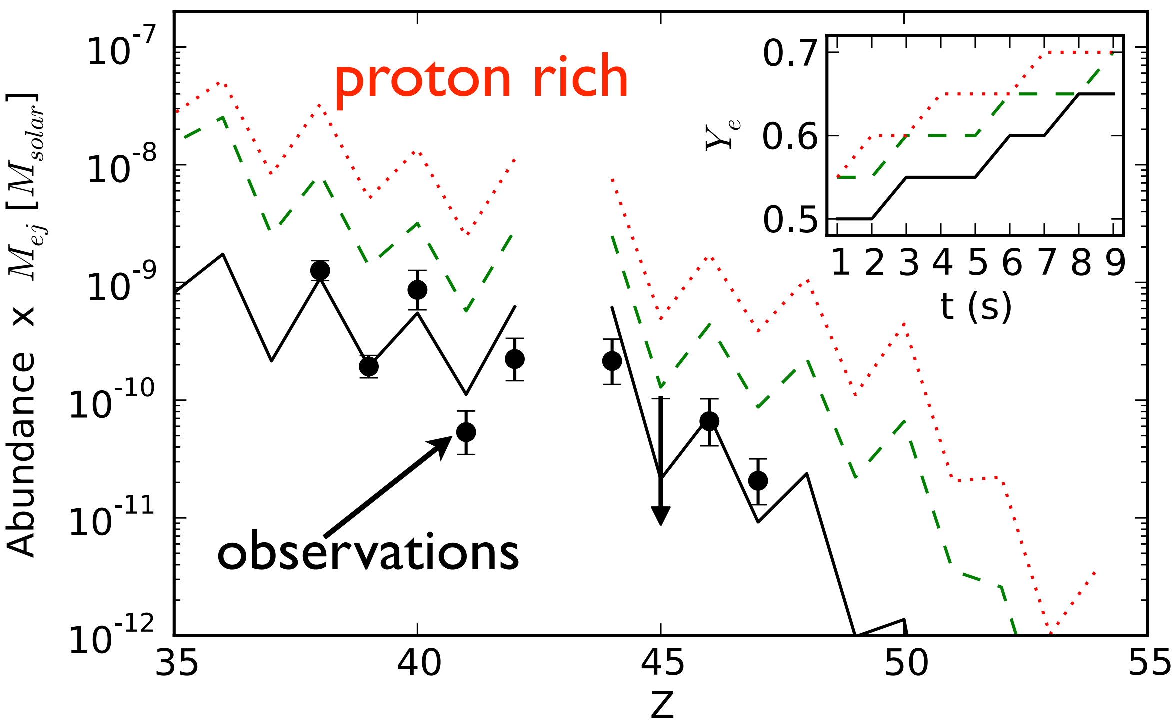


LEPP in neutrino winds?

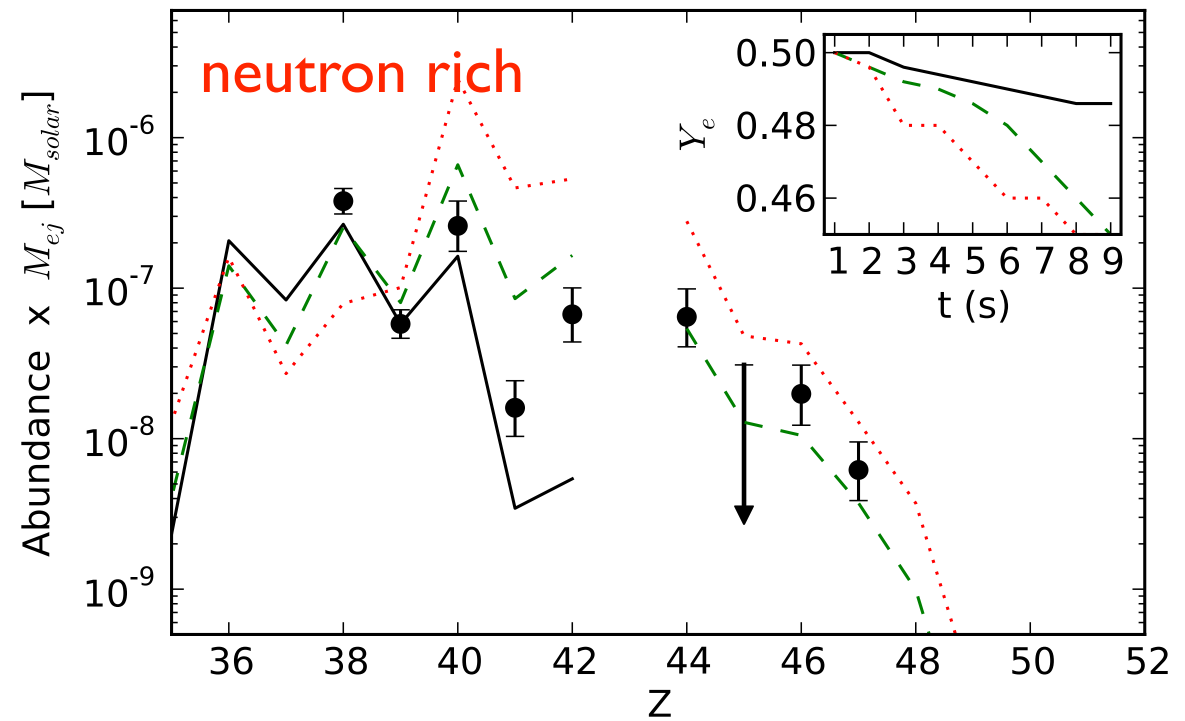


Lighter heavy elements in neutrino-driven winds

vp-process



weak r-process



Observation pattern reproduced!

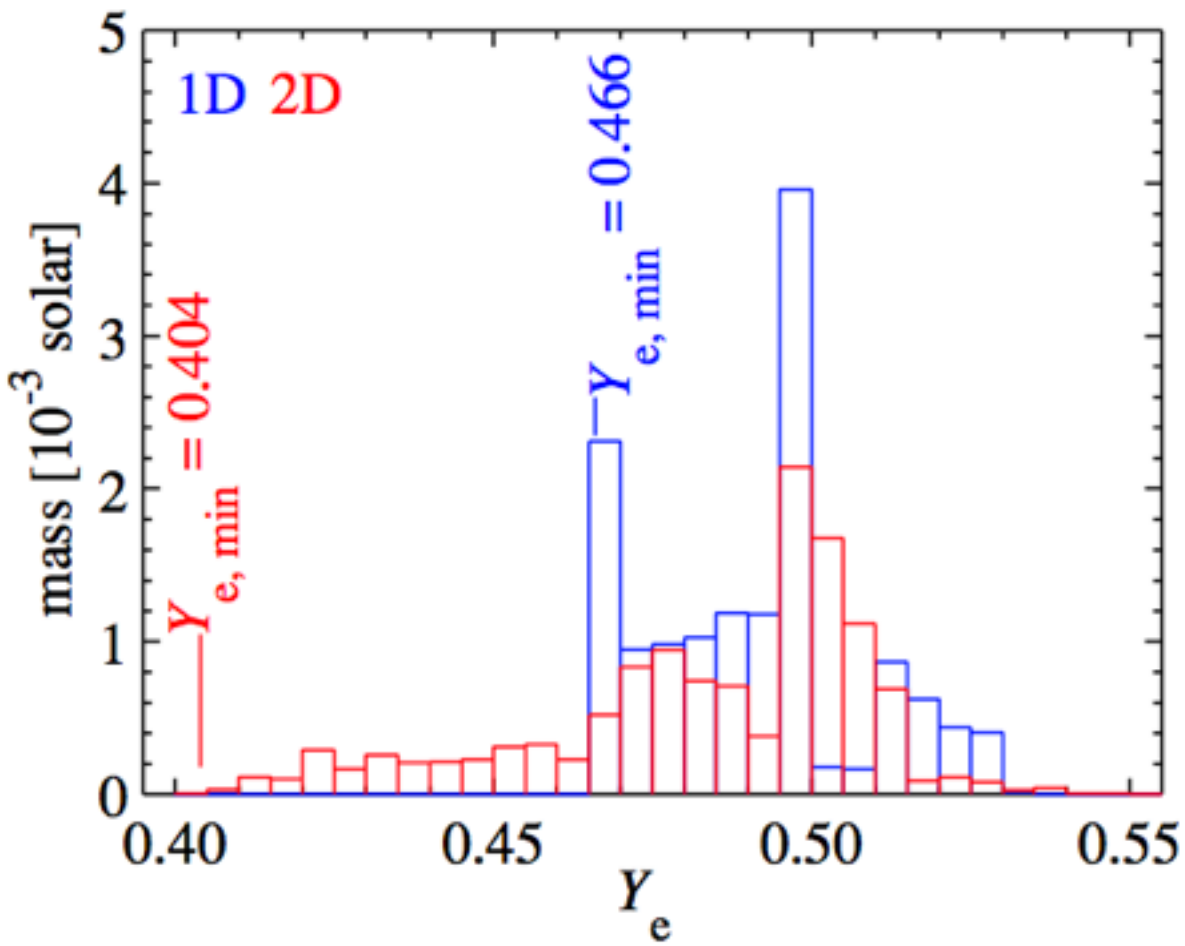
Production of p-nuclei

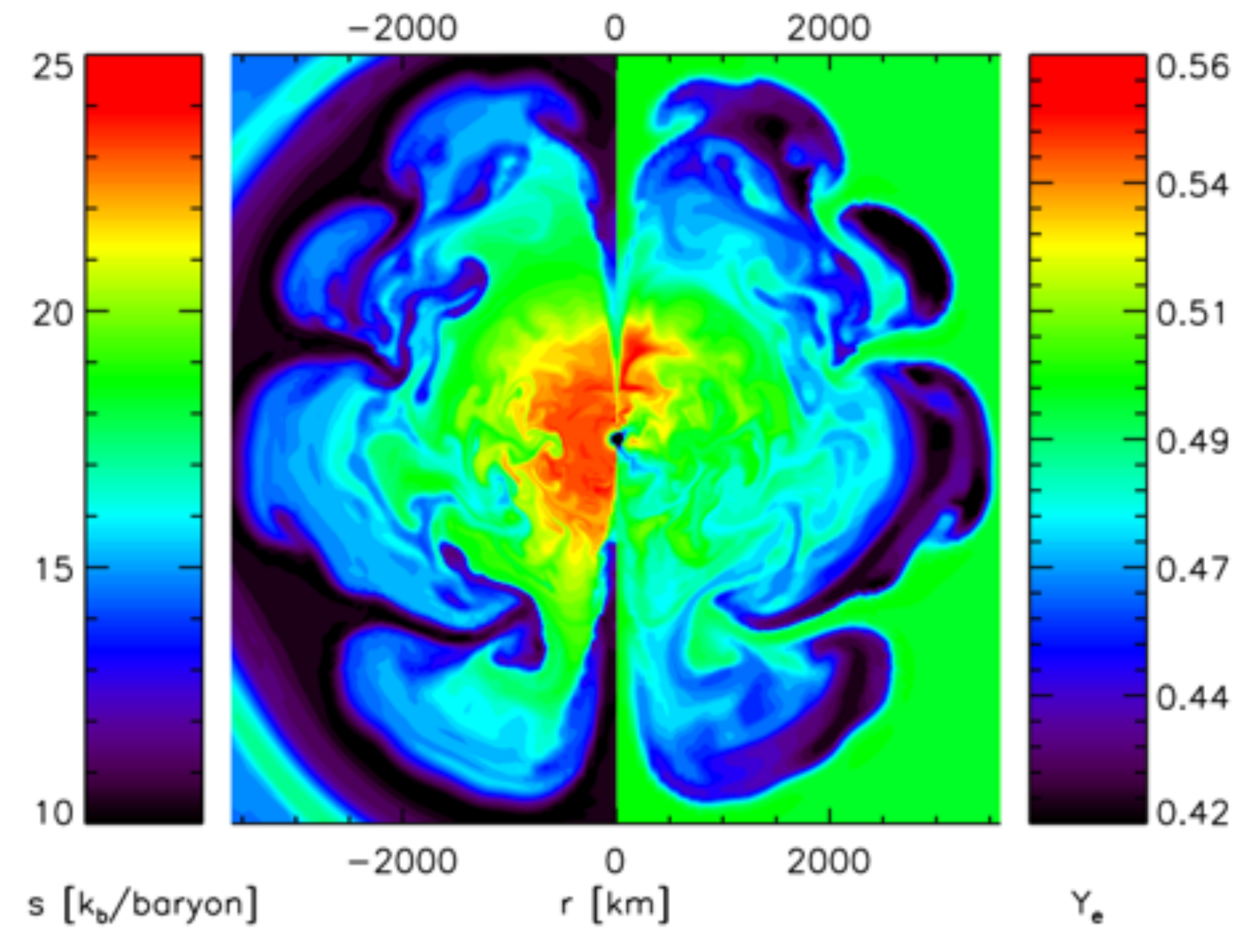
Overproduction at A=90, magic neutron number N=50 (Hoffman et al. 1996) suggests: only a fraction of neutron-rich ejecta (Wanajo et al. 2011)

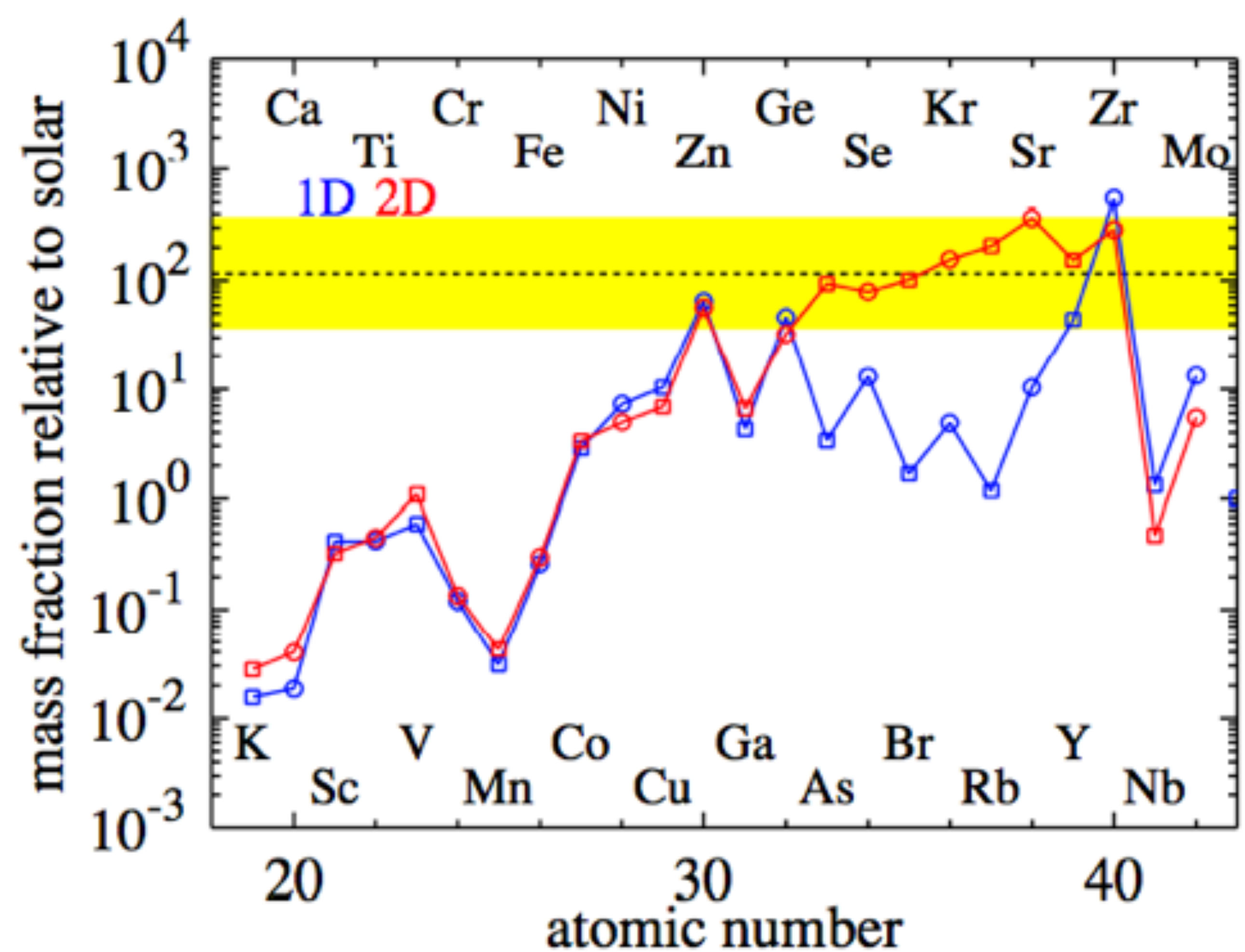
(Arcones & Montes, 2011)

Electron capture supernova

Wanajo, Janka, Müller (2011):
small neutron-rich pockets
in 2D simulations

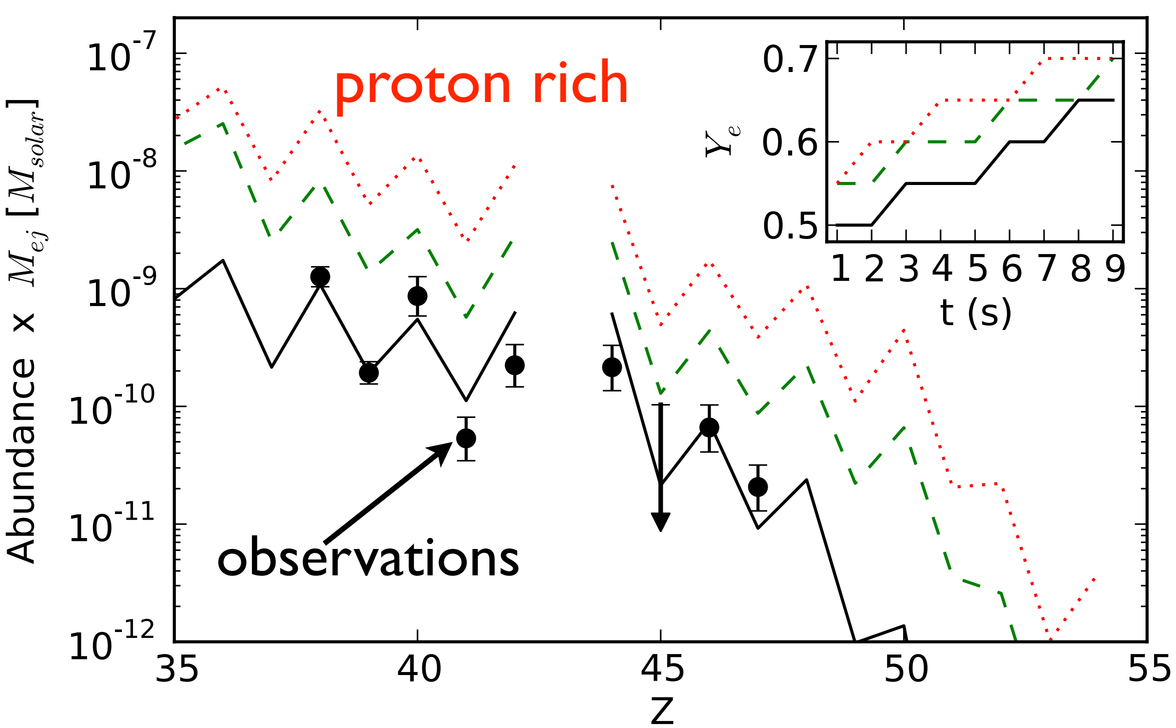






Lighter heavy elements in neutrino-driven winds

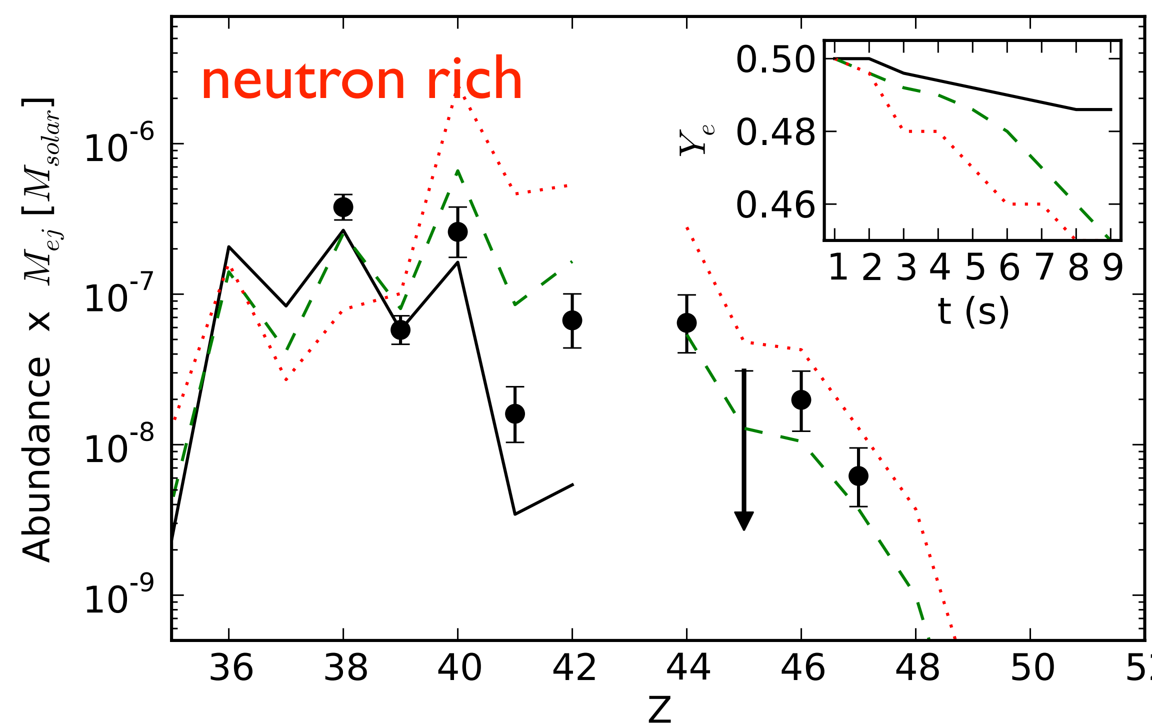
vp-process



Observation pattern reproduced!

Production of p-nuclei

weak r-process



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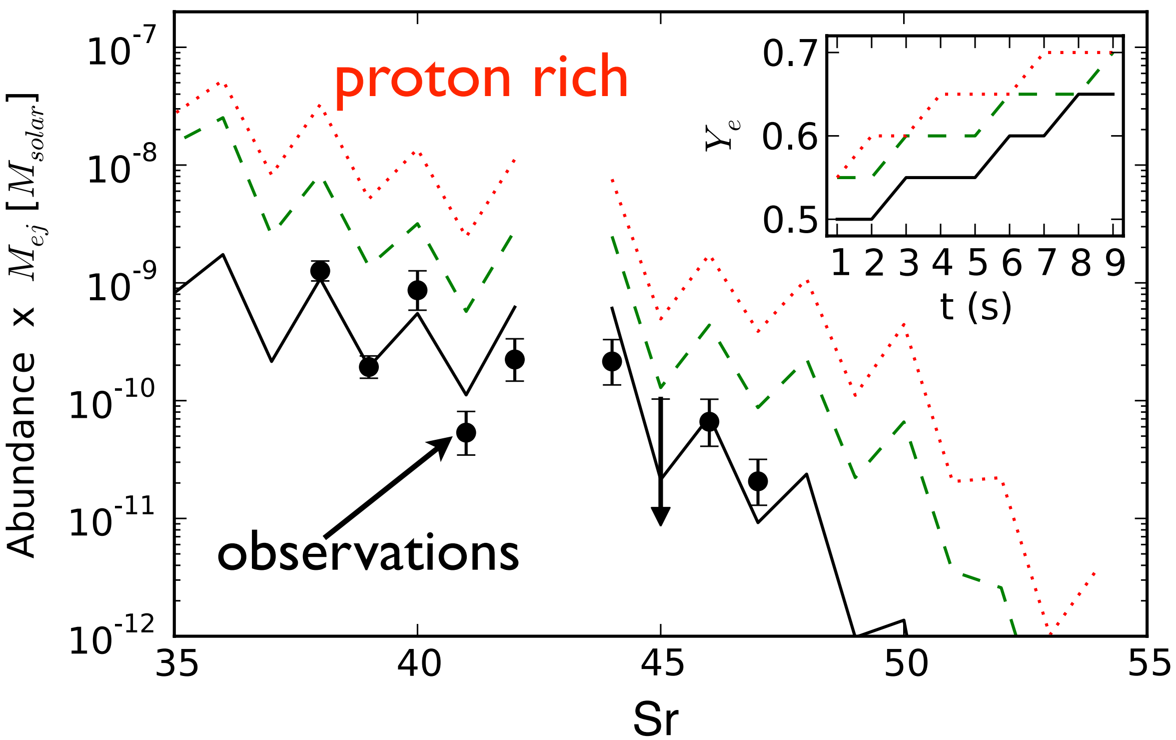
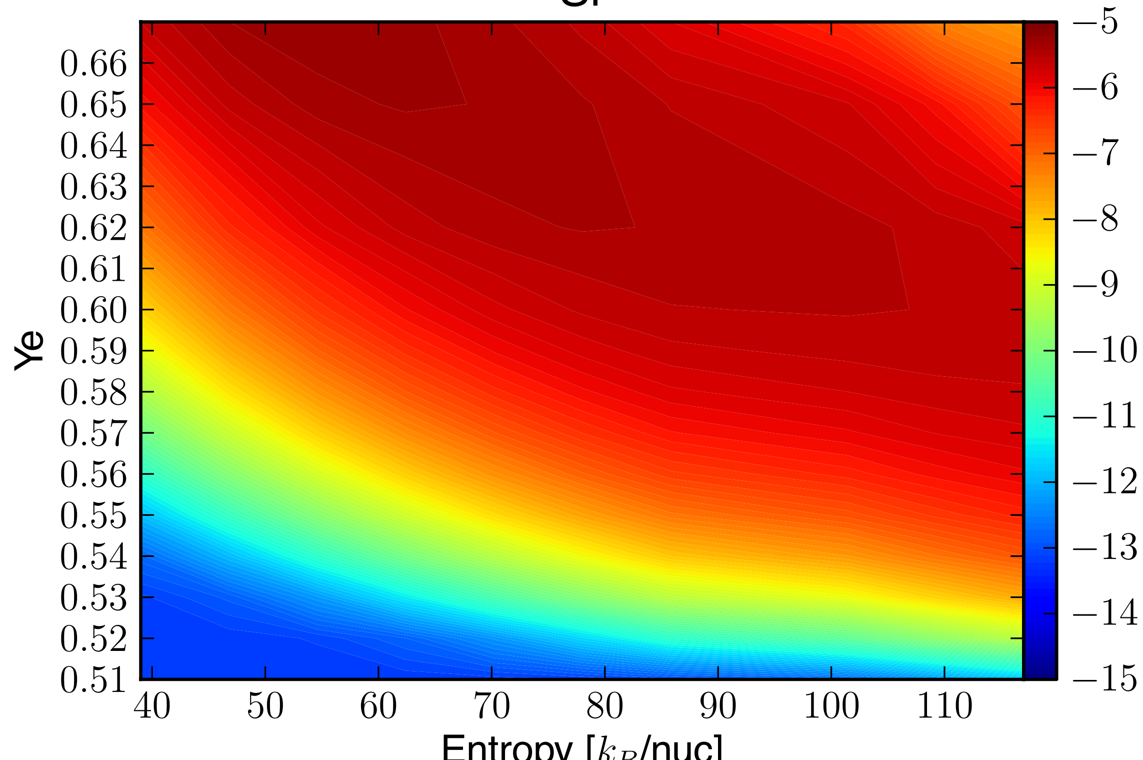
Lighter heavy elements in neutrino-driven winds

vp-process





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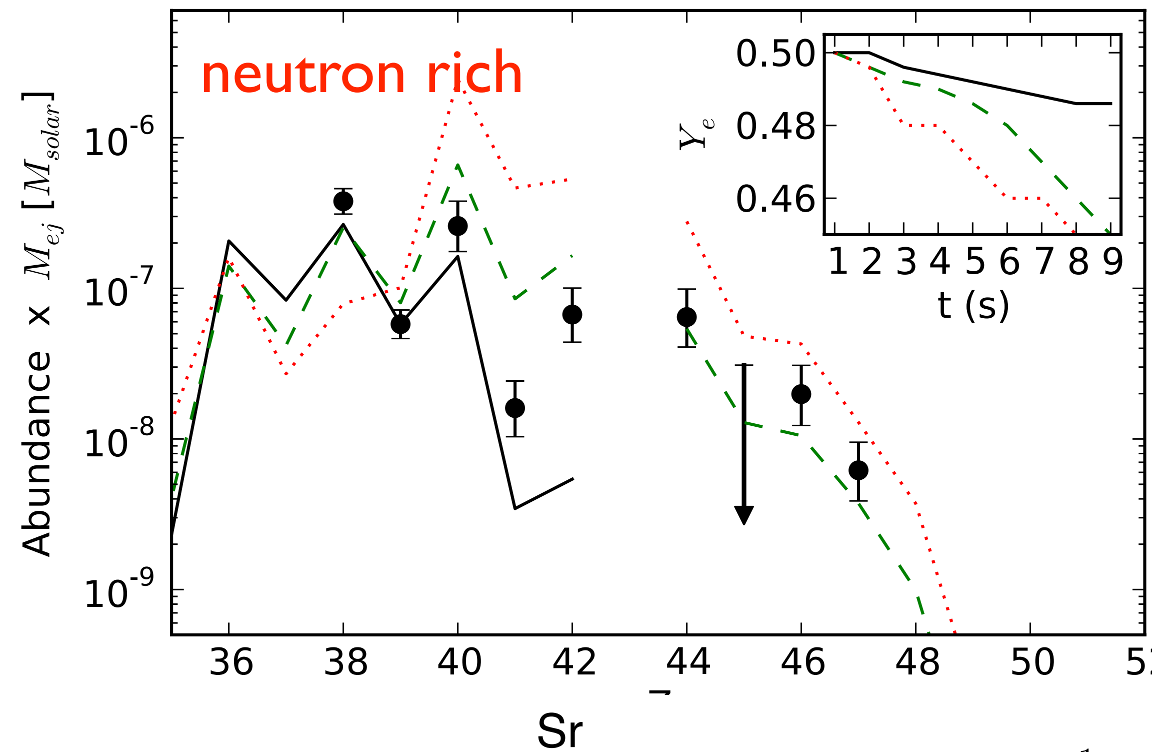
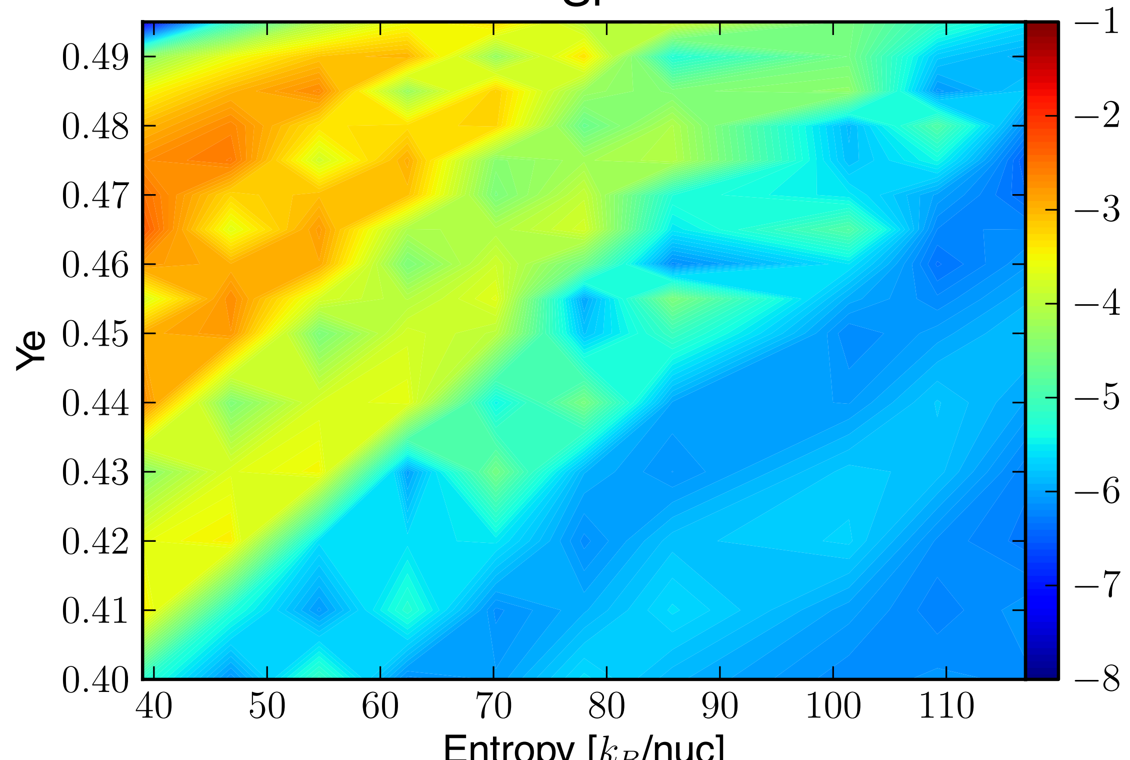




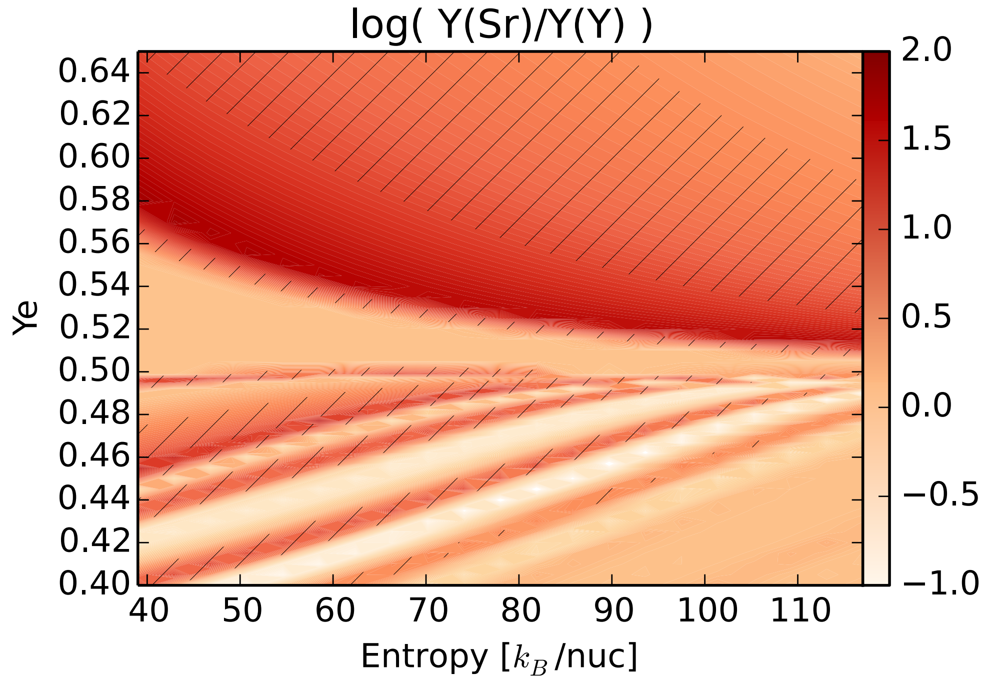
Arcones & Bliss (2014)

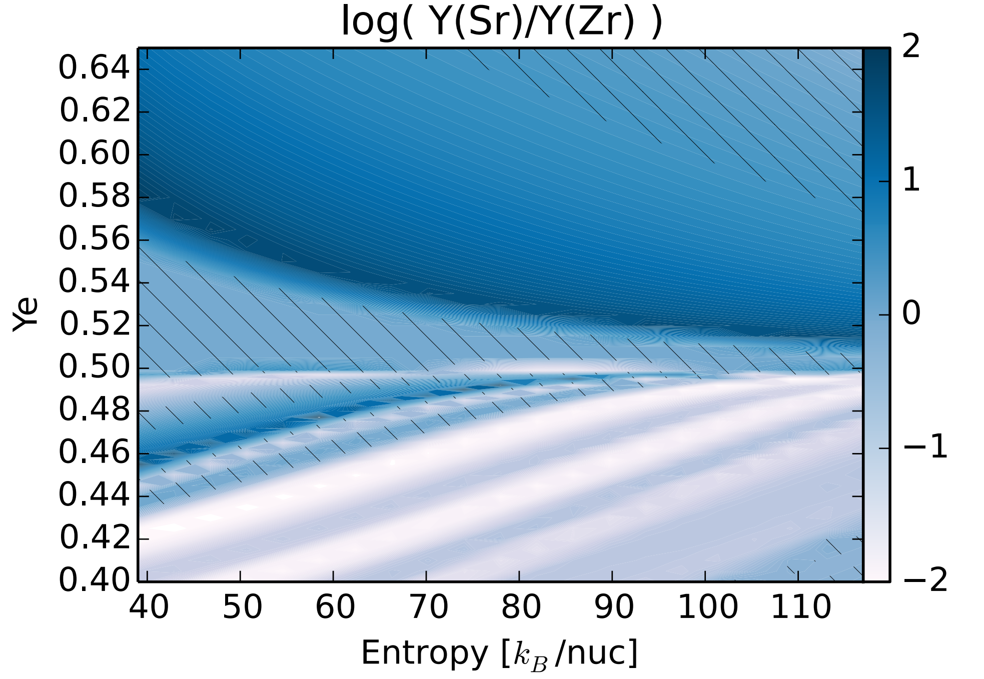
LEPP components: constraining conditions

LEPP abundance ratios: Sr/Y = 6.13 (//)

Sr/Zr = 1.22 (\\)

Sr/Ag = 48.2





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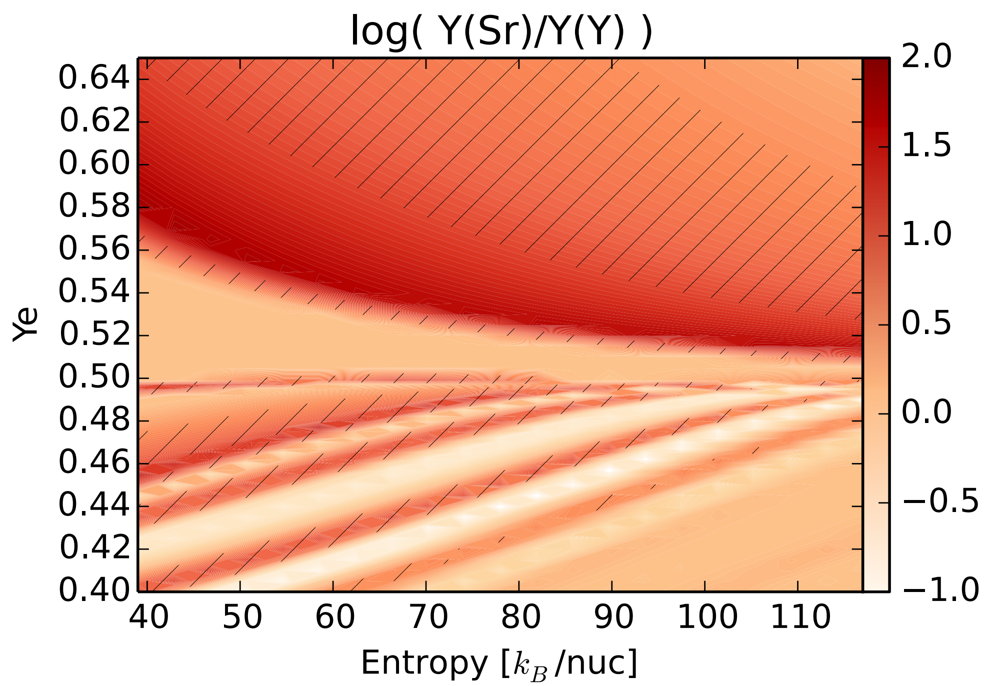

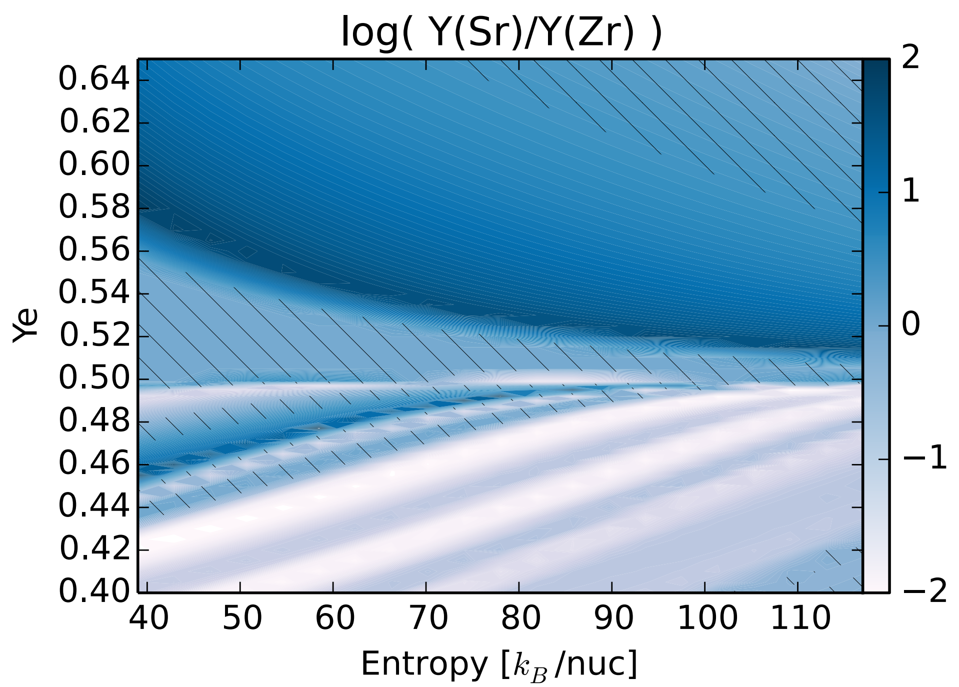

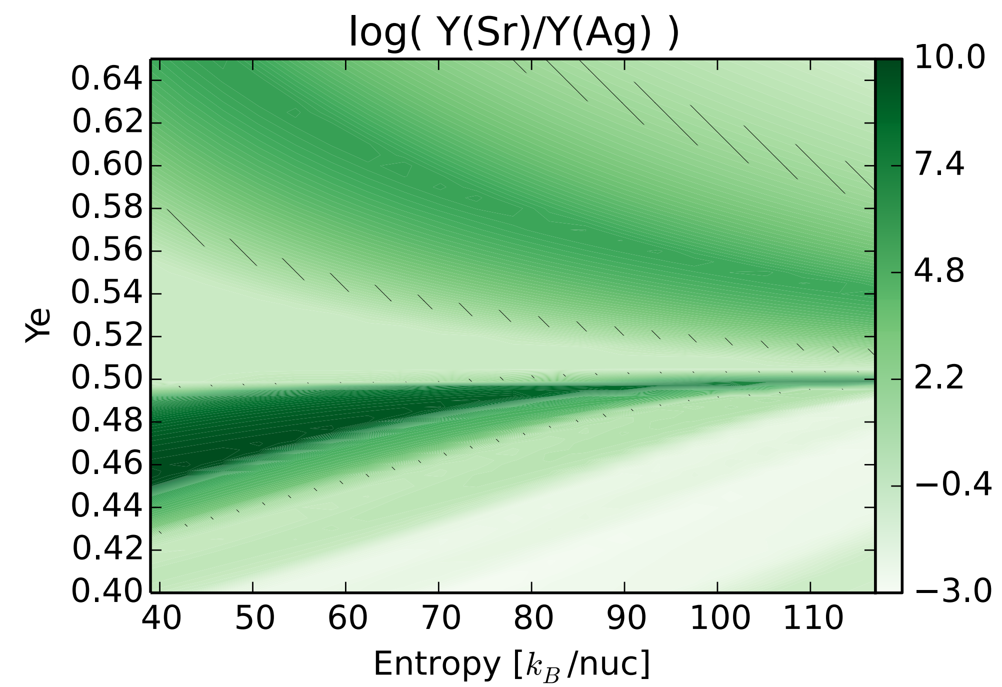

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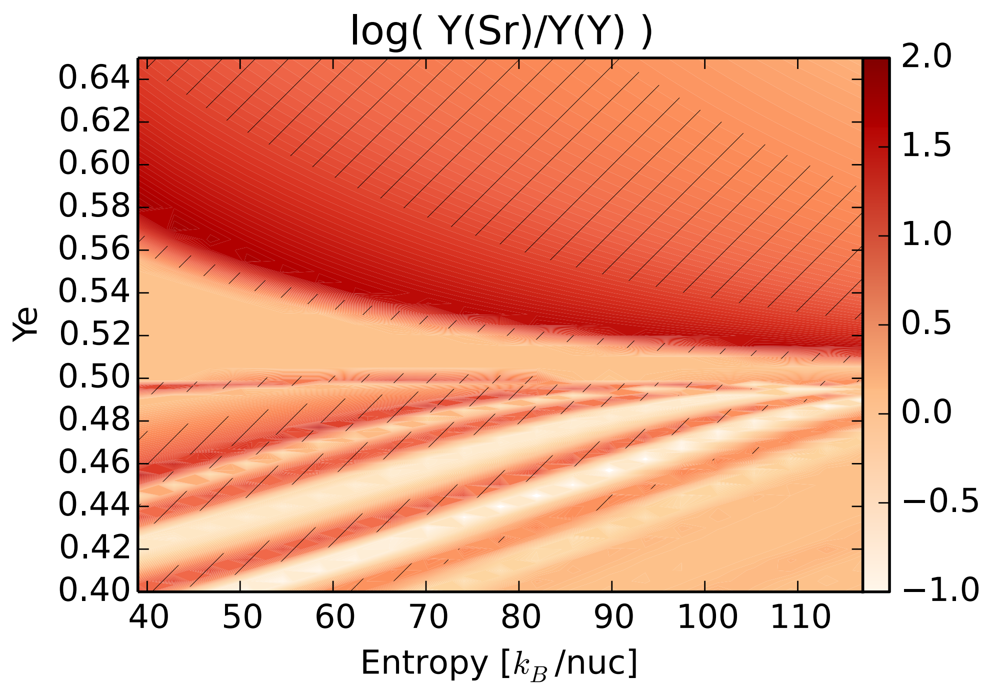

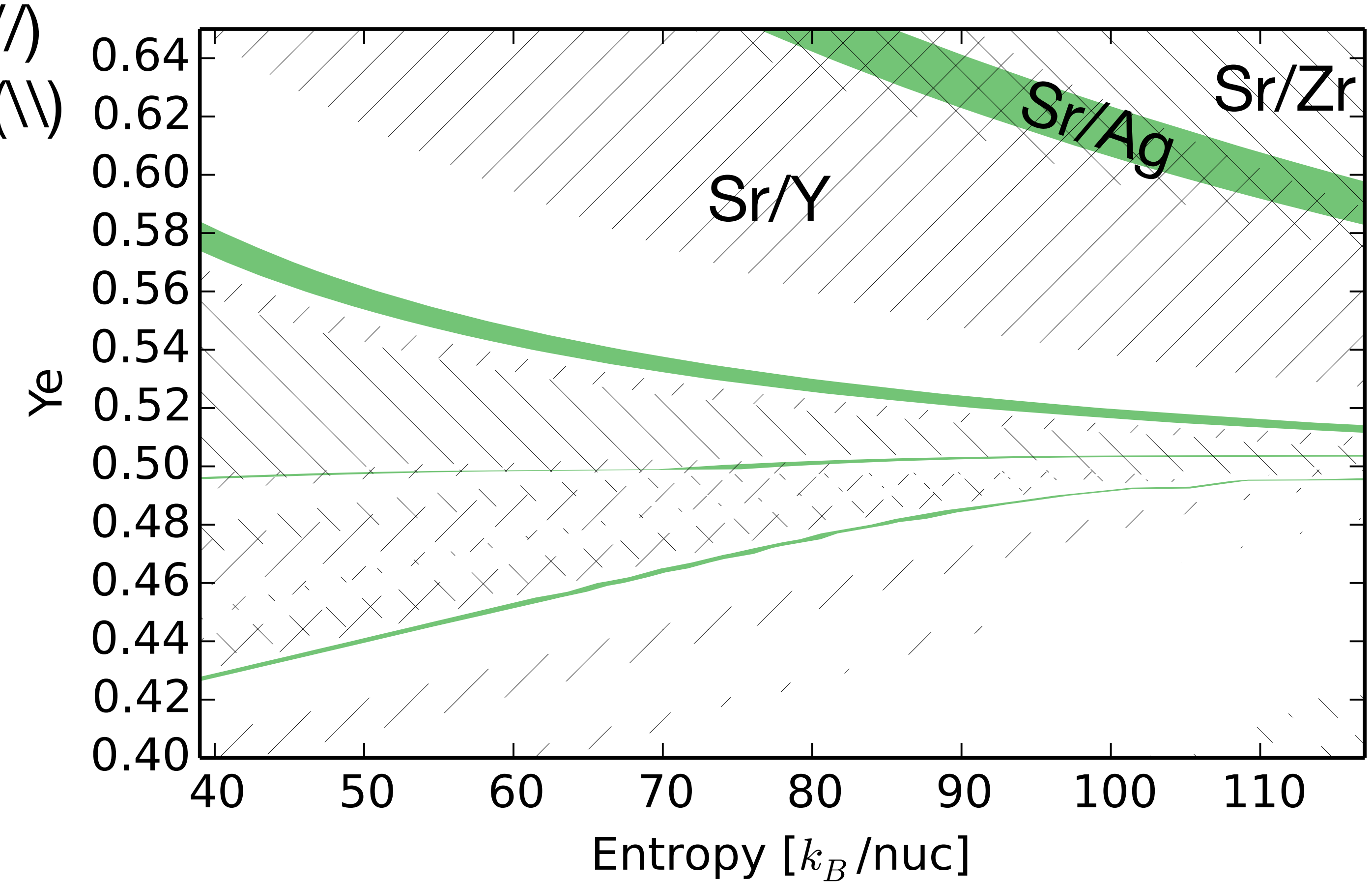

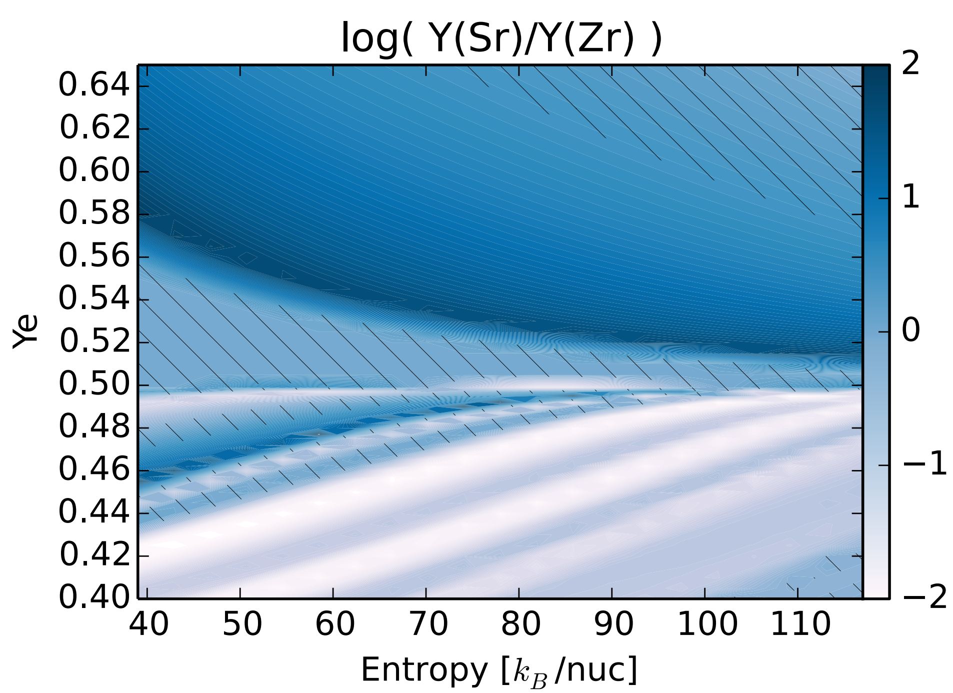

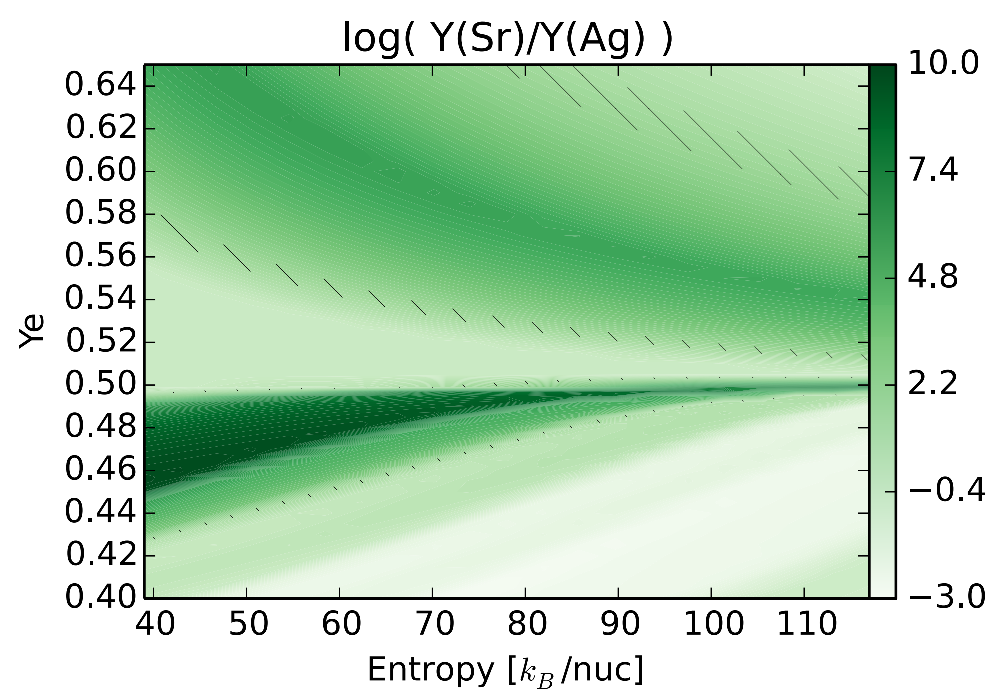

Conclusions

How many r-processes? How many astrophysical sites?

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

lighter heavy elements: neutrino-driven winds
mergers: wind, disk evaporation
constraints from observations: LEPP component

Needs

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

Neutron-rich nuclei: experiments with radioactive beams, theory

Improved supernova and merger simulations

Chemical evolution models