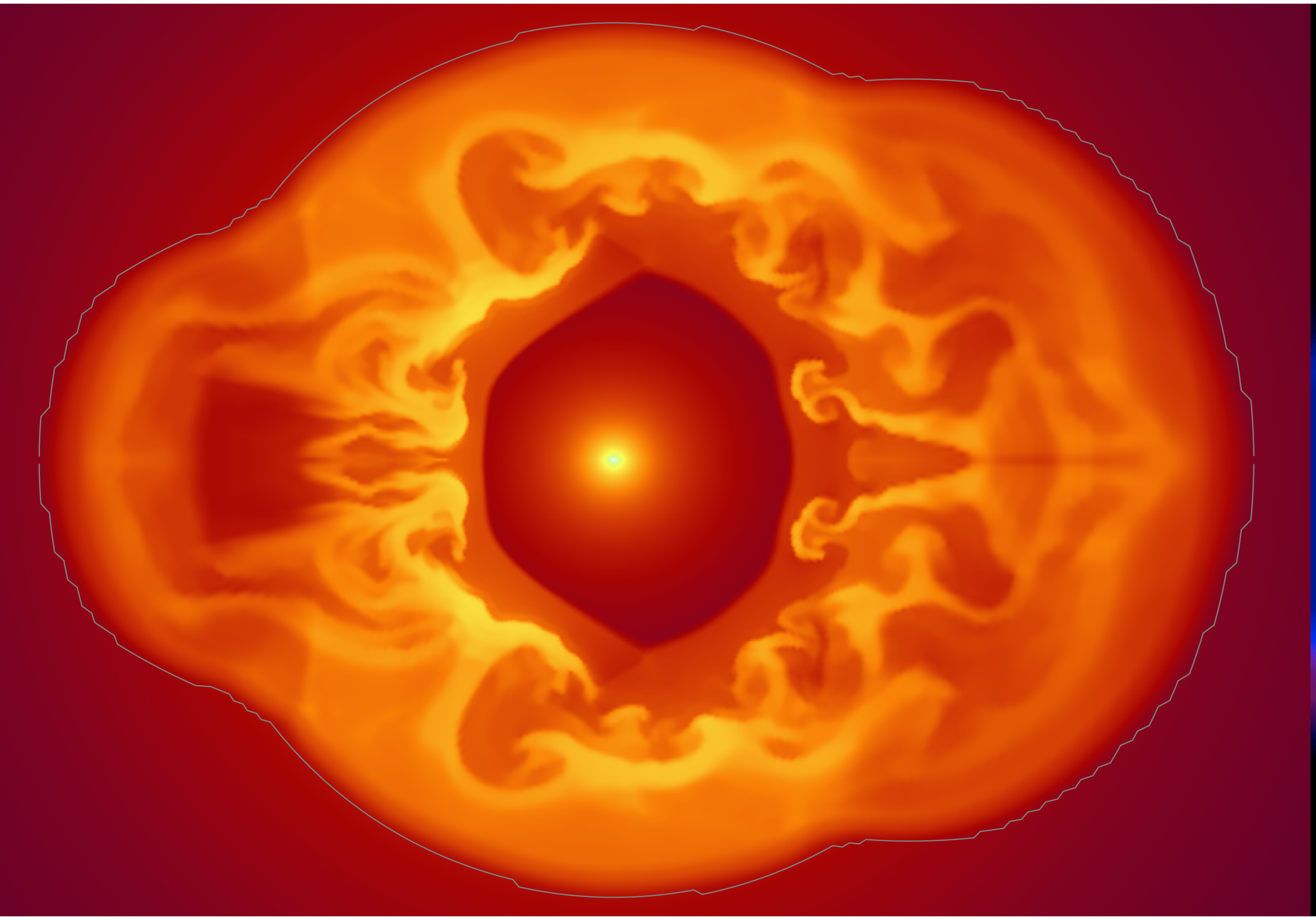
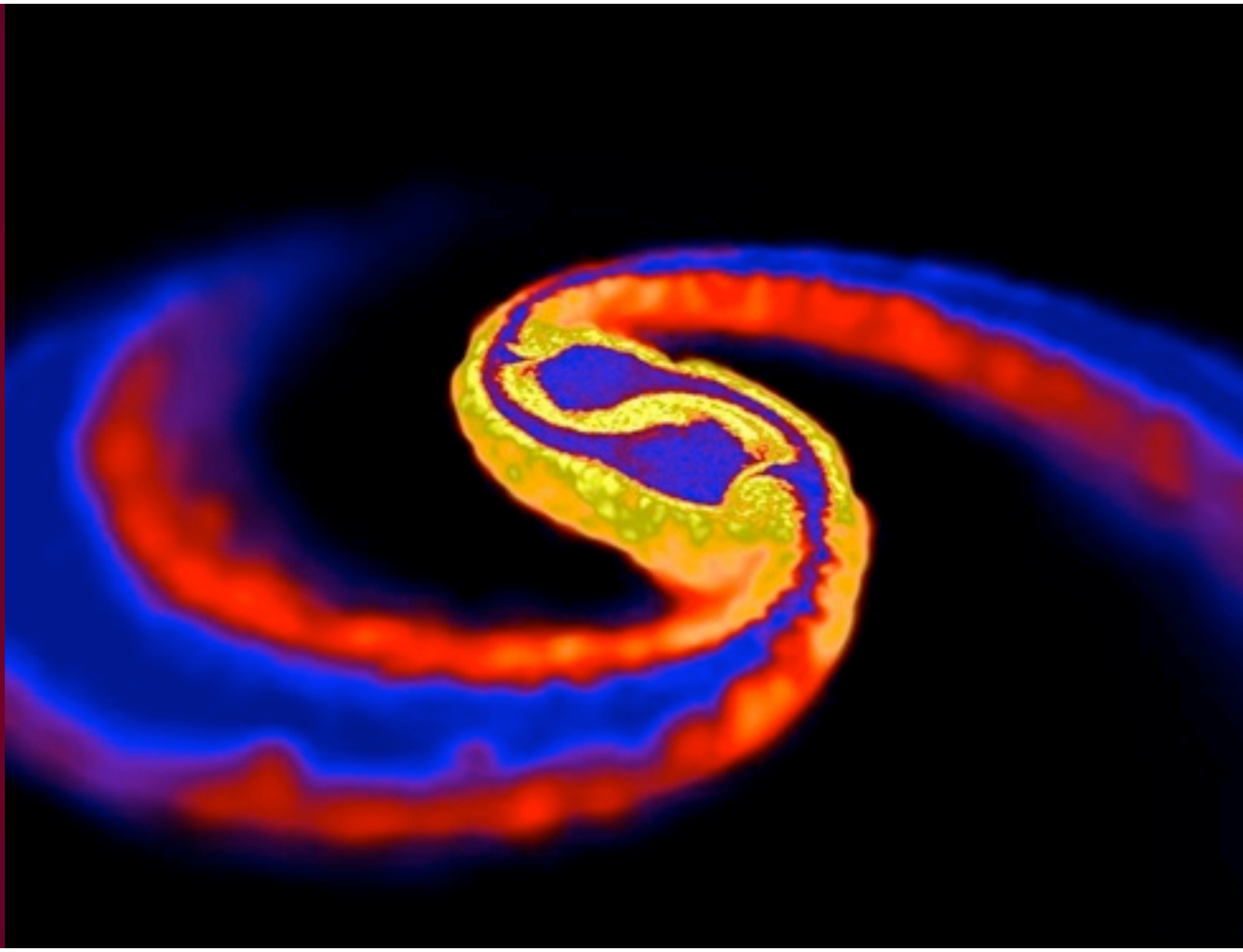
Nucleosynthesis in core-collapse supernovae and neutron star mergers





TECHNISCHE
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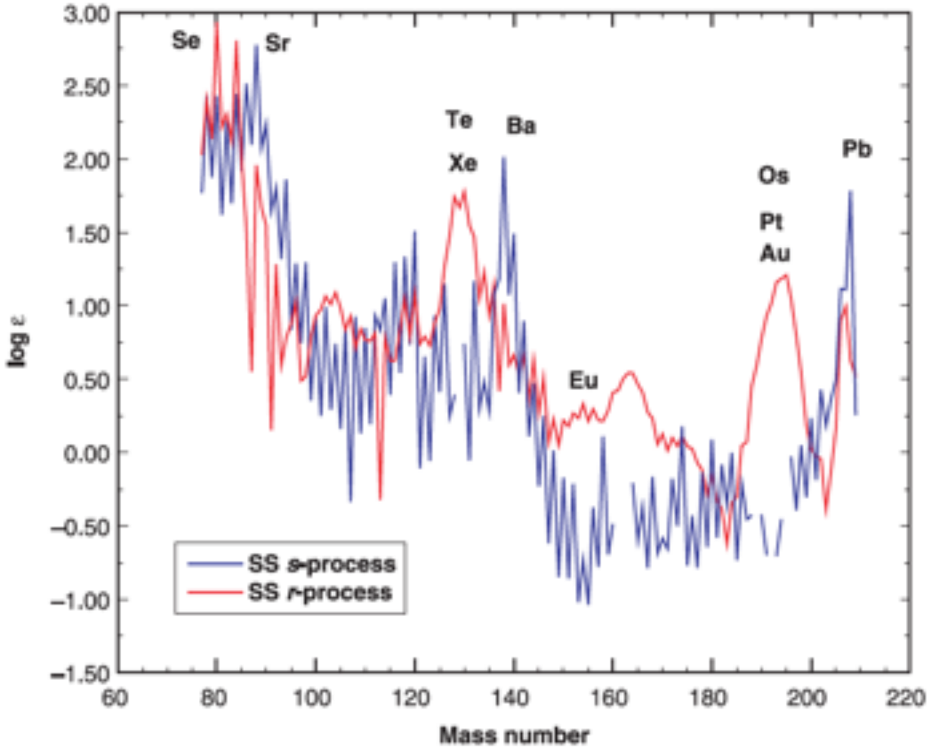
DARMSTADT

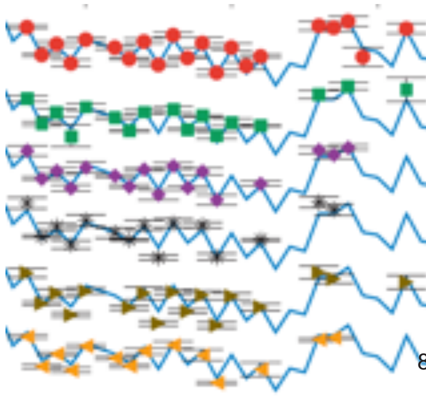
GSI

Almudena Arcones
Helmholtz Young Investigator Group

HELMHOLTZ
GEMEINSCHAFT

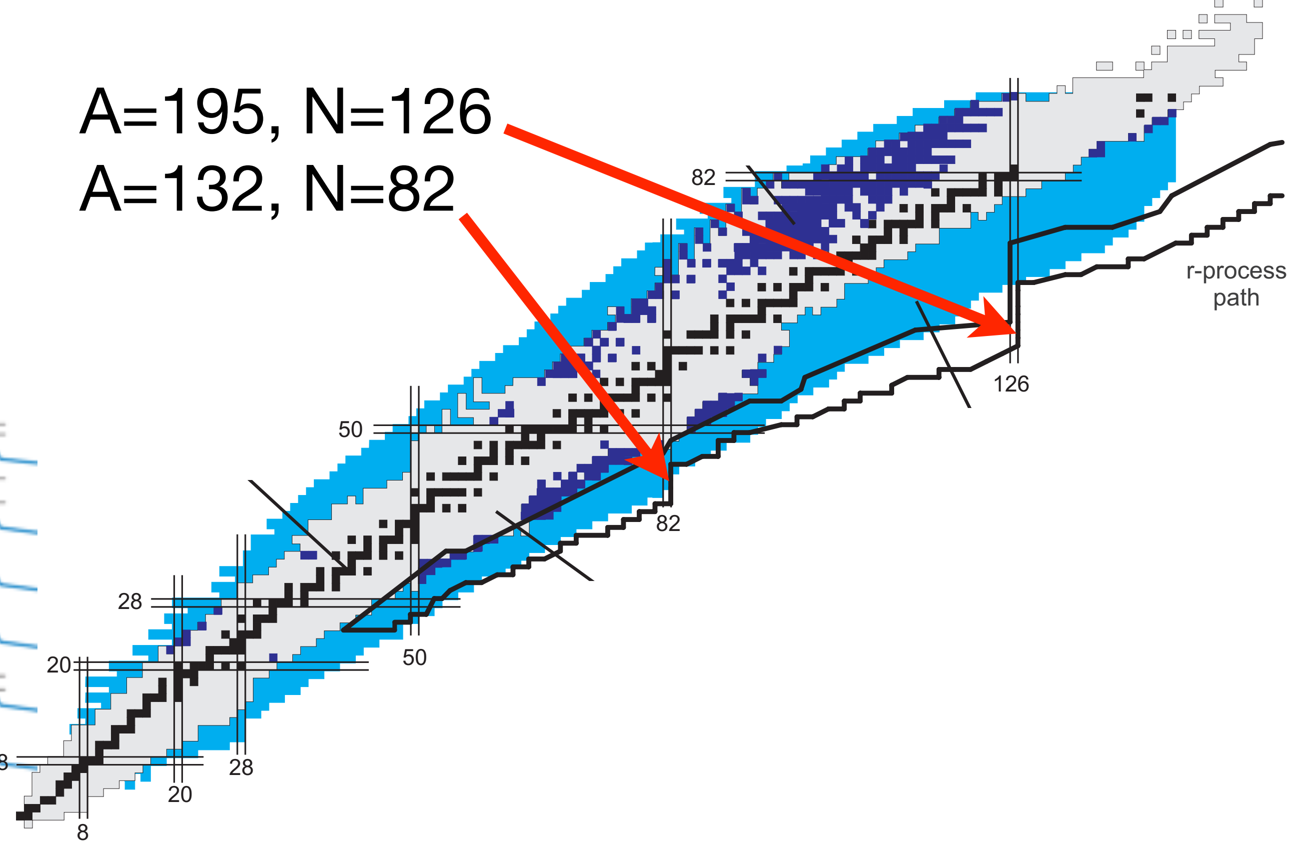
solar and UMP star abundances





A=195, N=126

A=132, N=82



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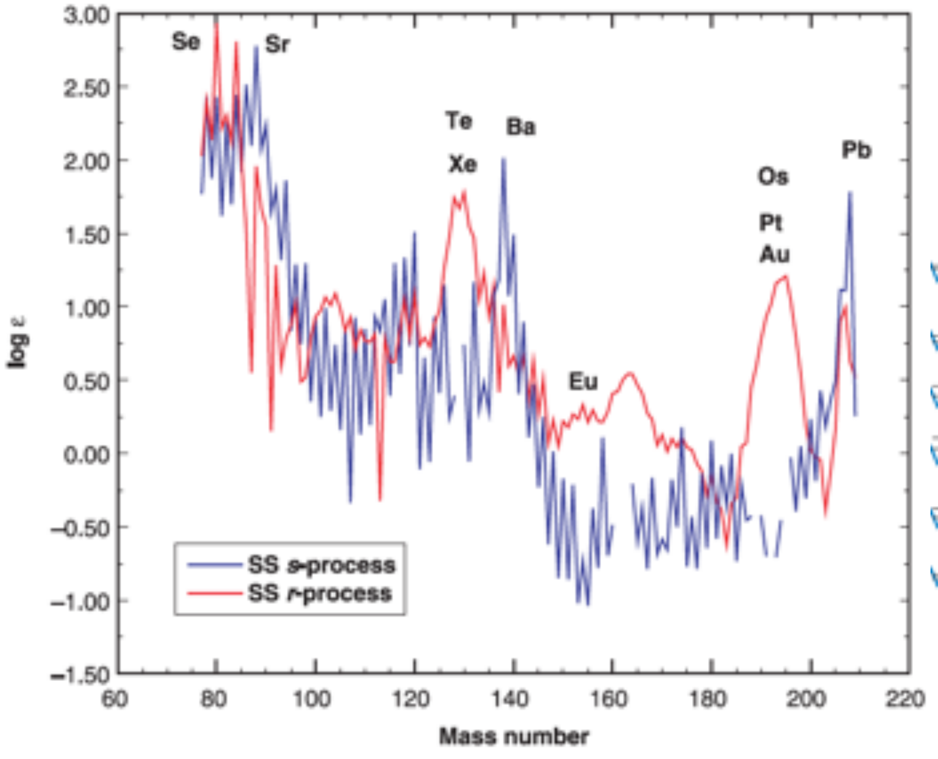

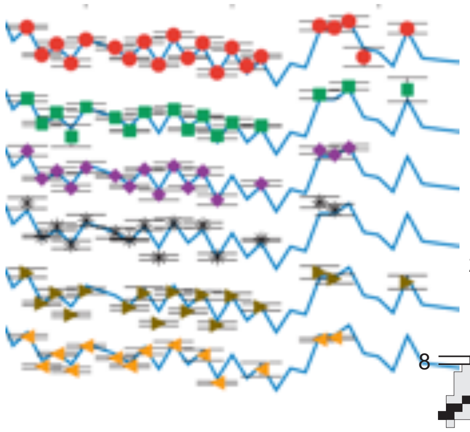

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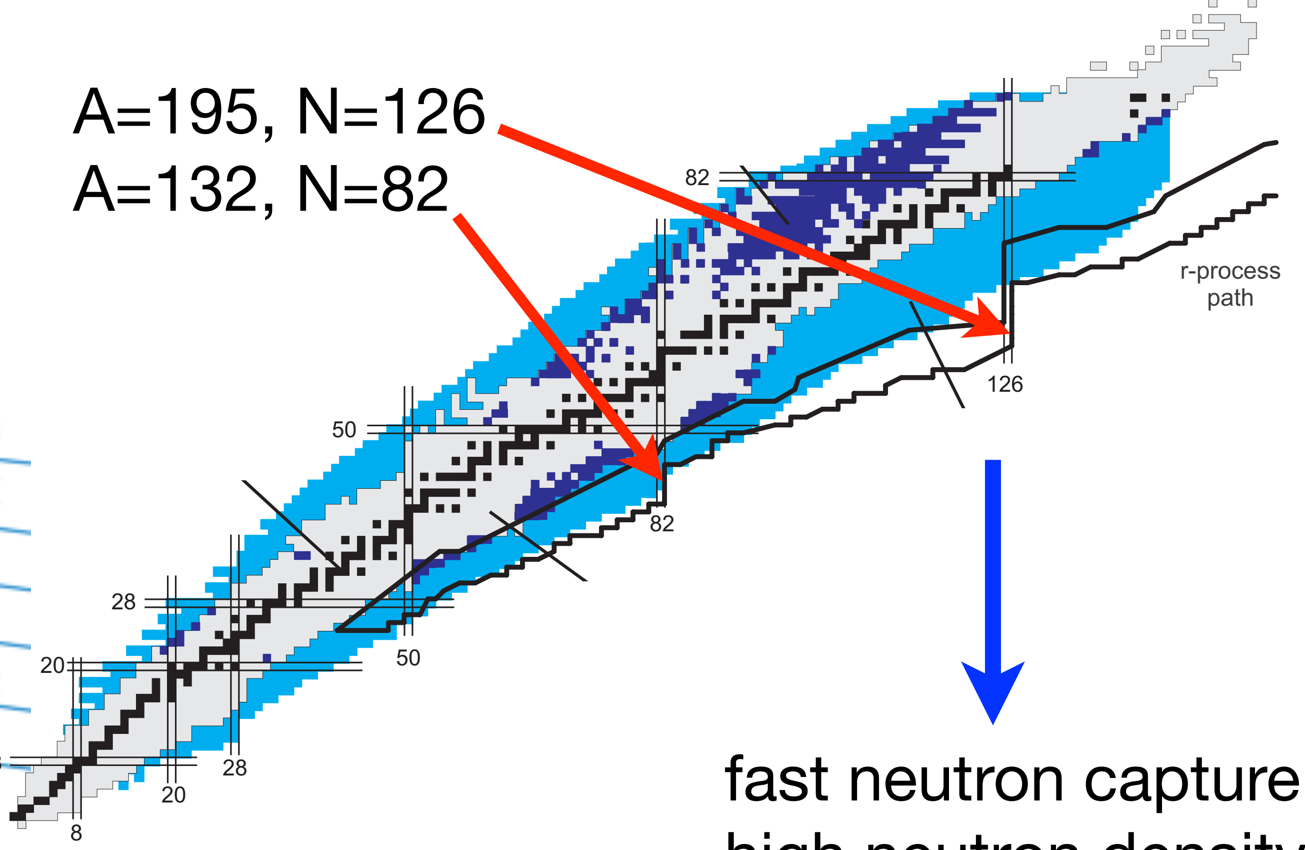
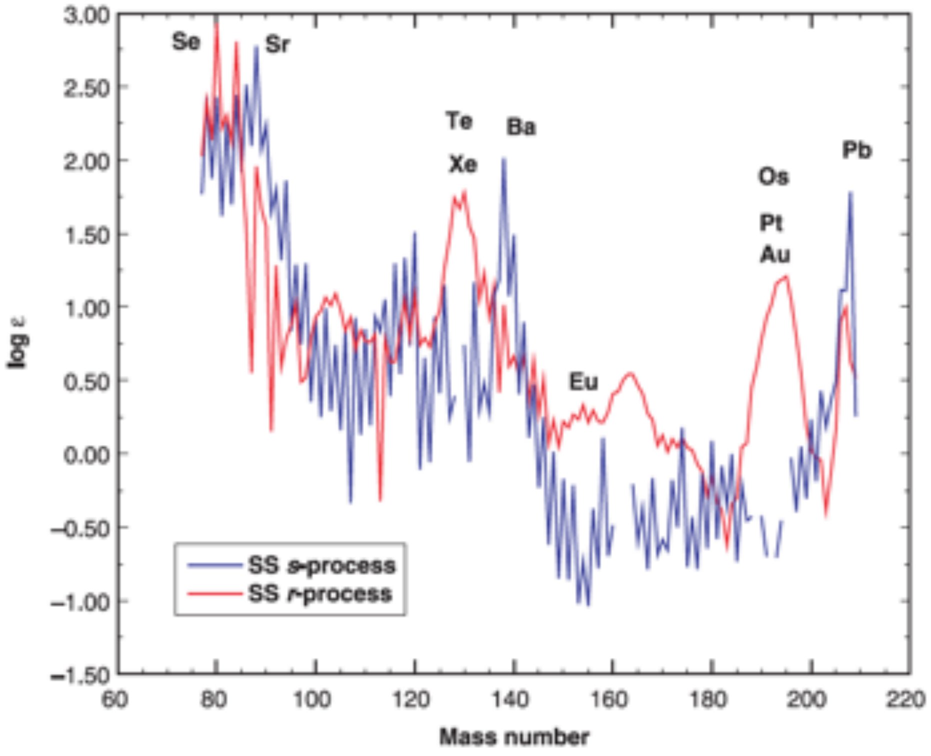
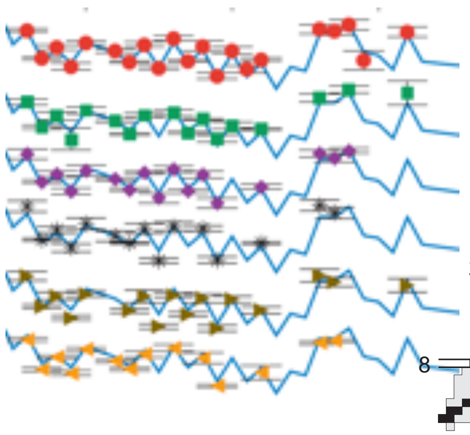


fast neutron capture
high neutron density

explosive environment
neutron rich

solar and UMP star abundances





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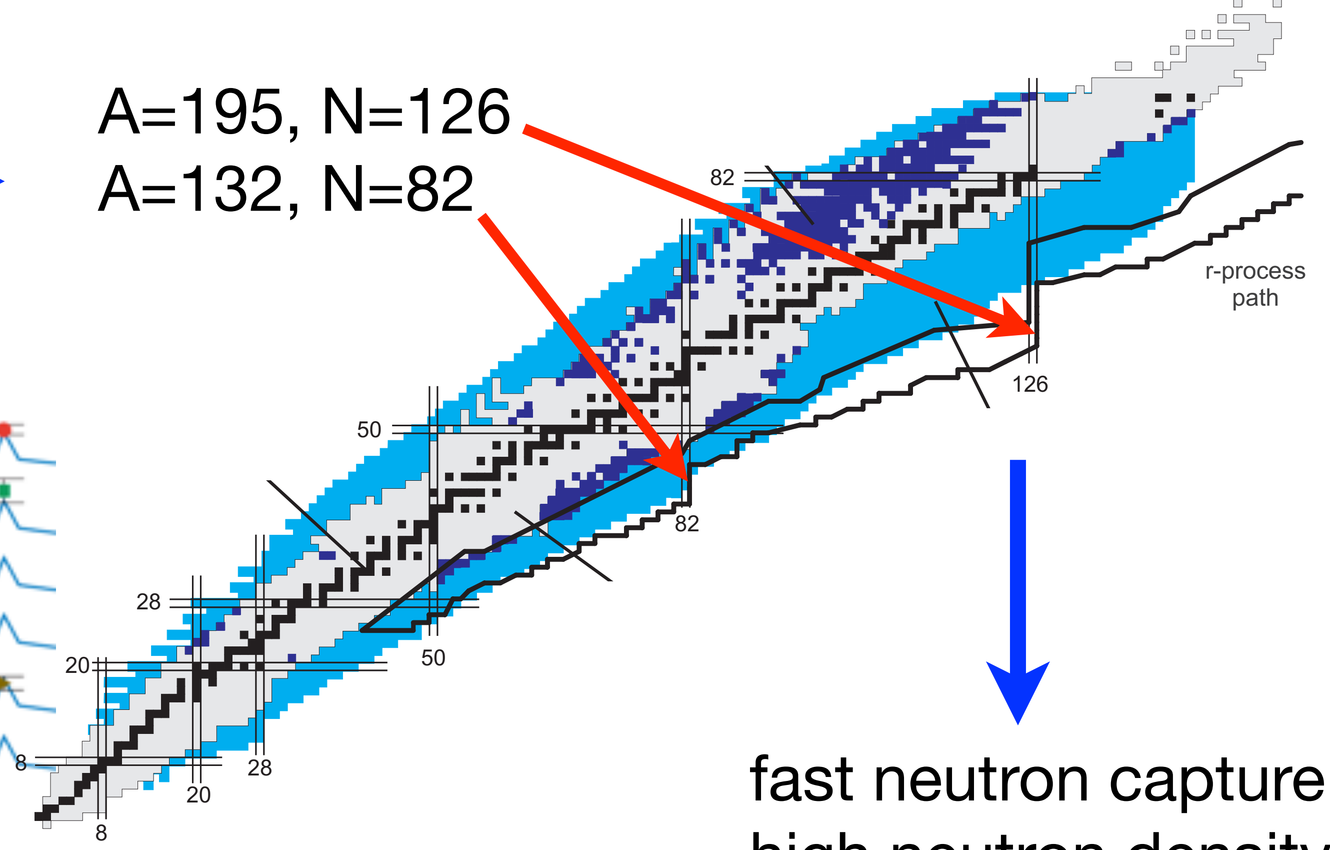

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high neutron density

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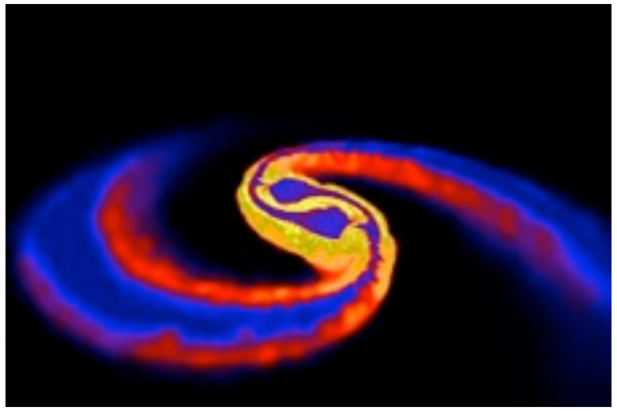
hydrodynamical simulations
high density EoS, neutrino transport



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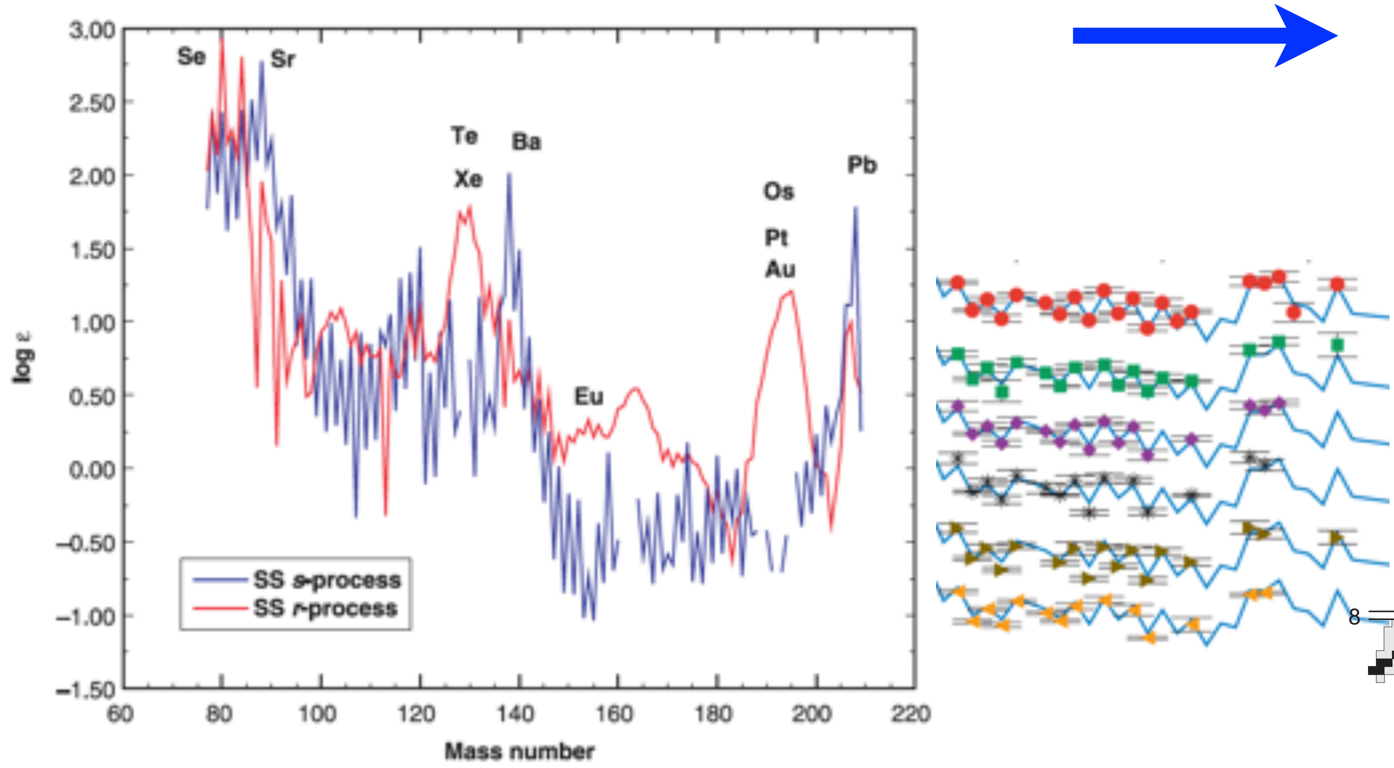

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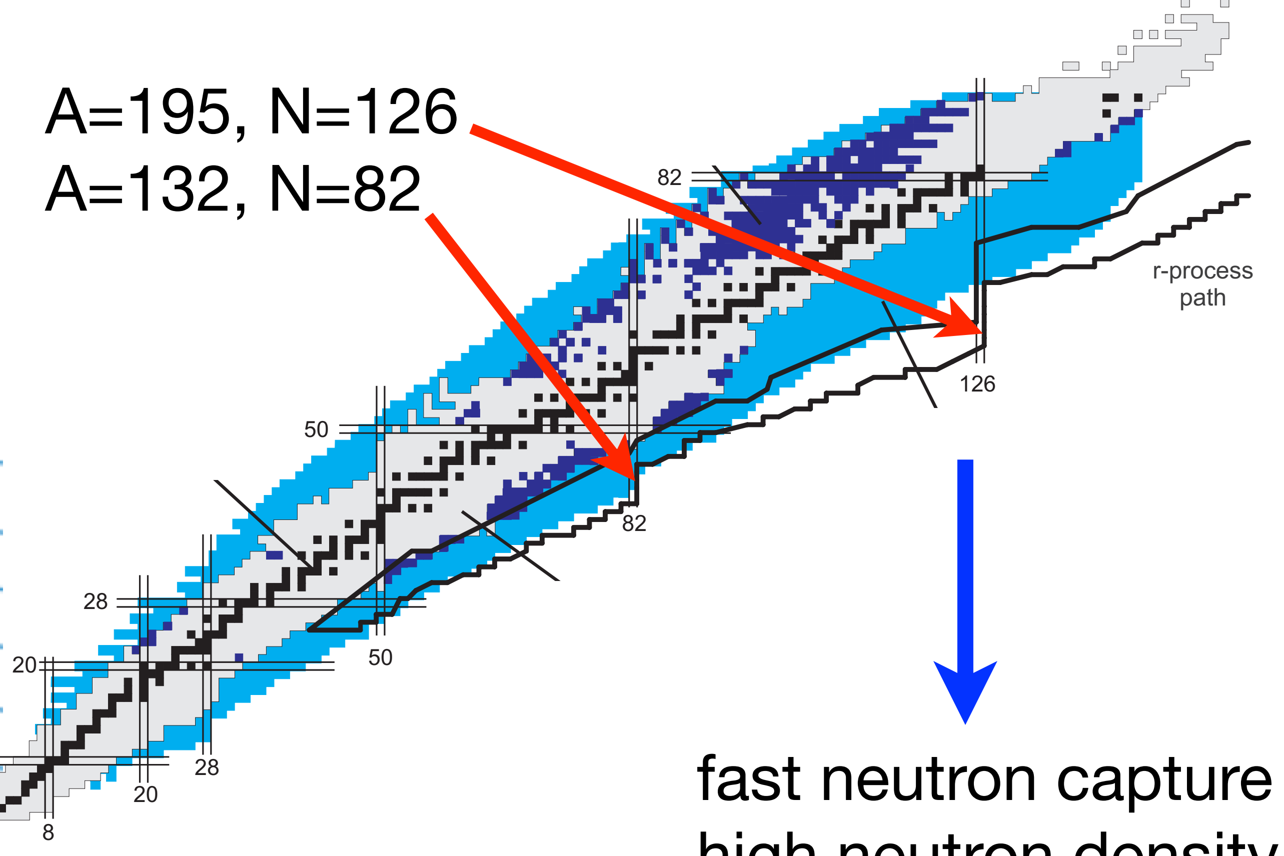

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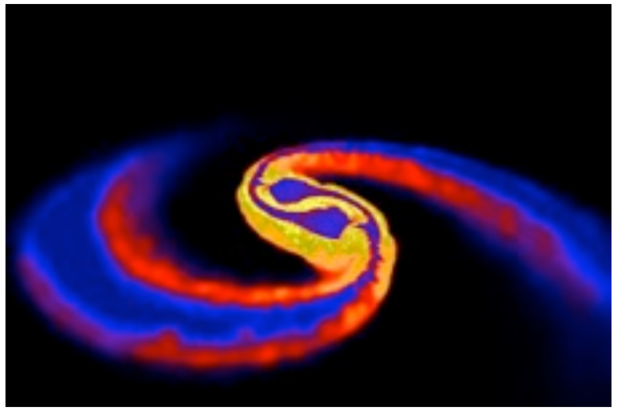
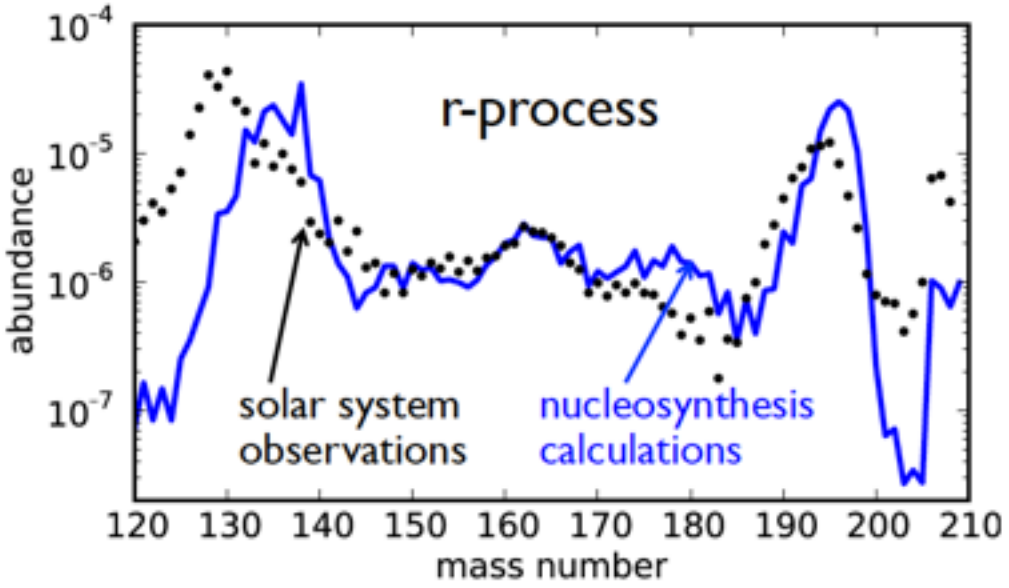
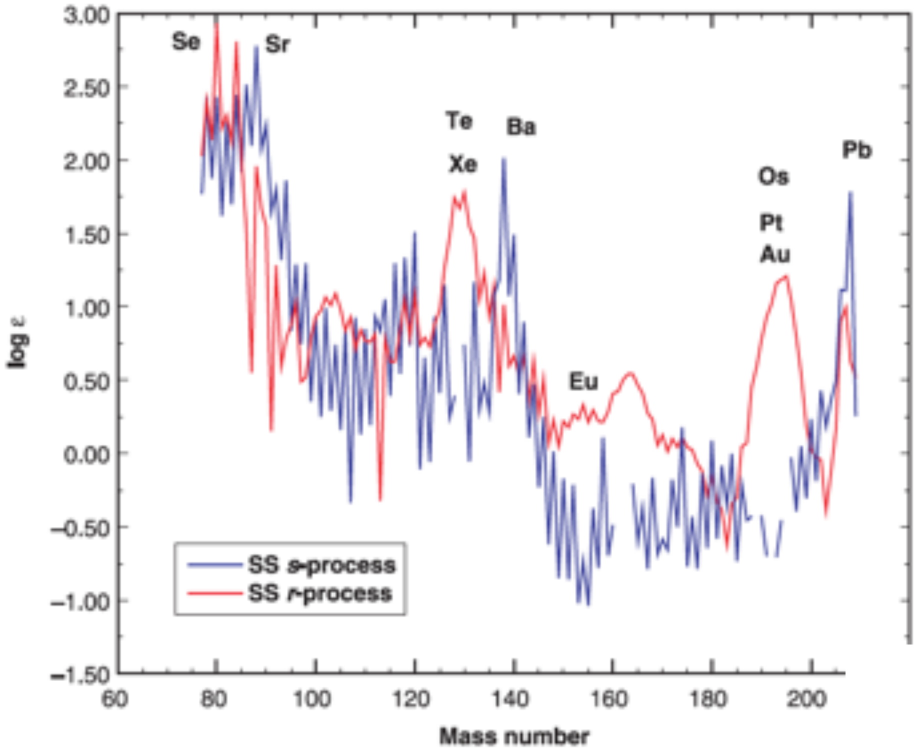
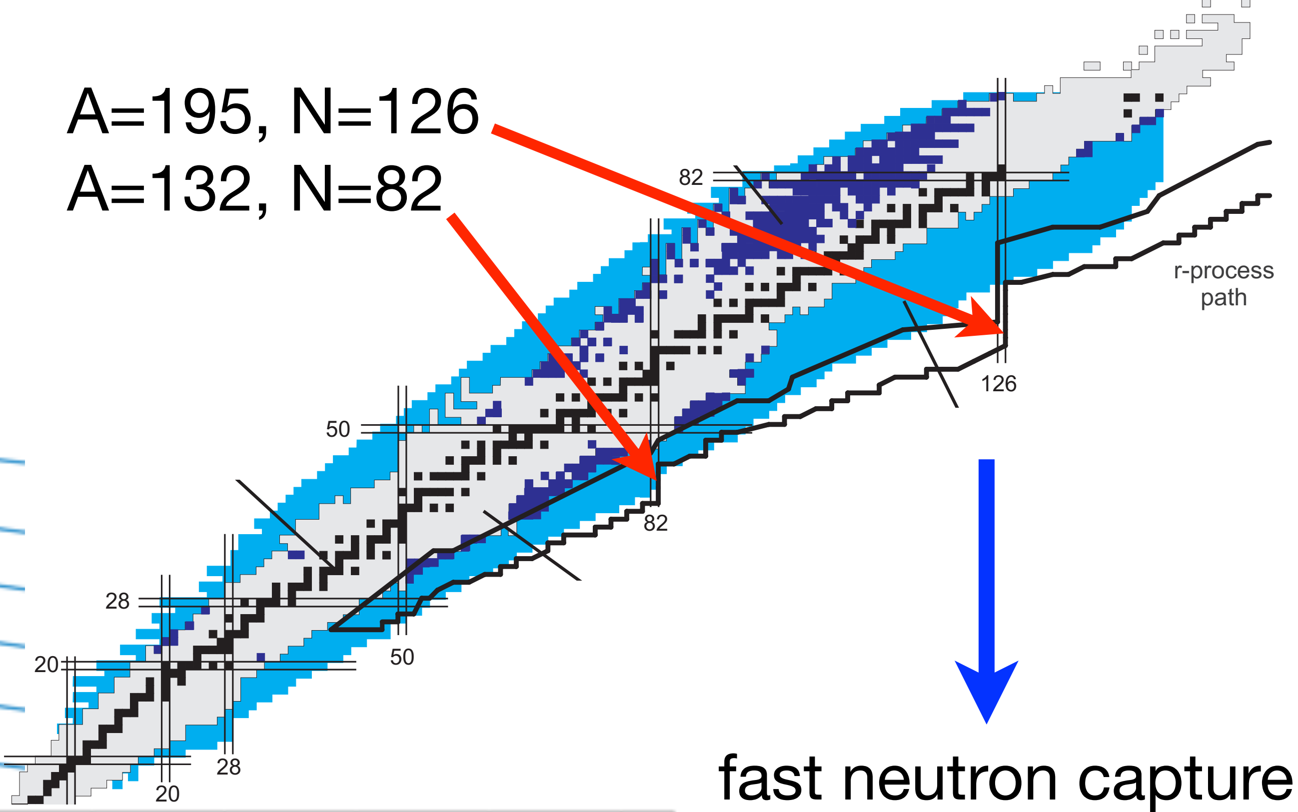




nucleosynthesis calculations
nuclear reaction network

solar and UMP star abundances





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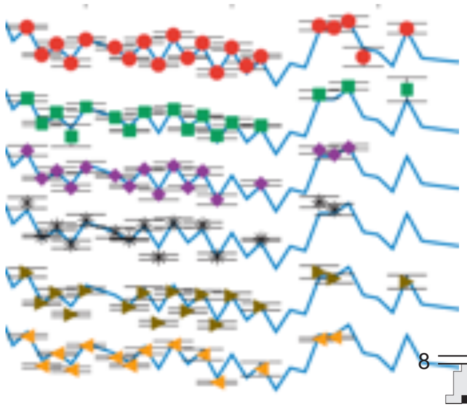
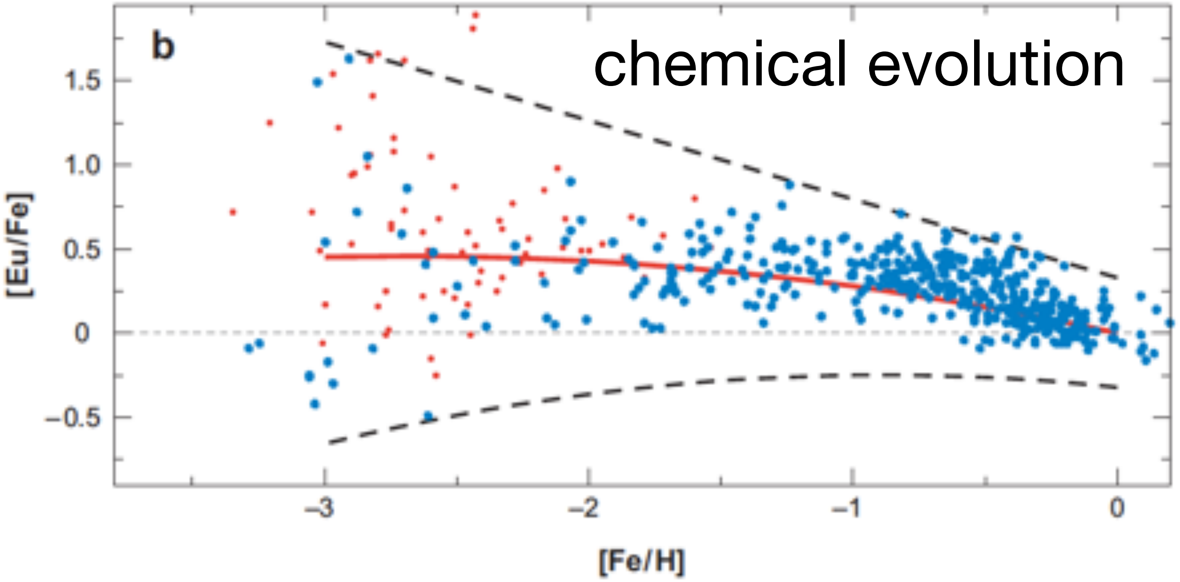


chemical evolution



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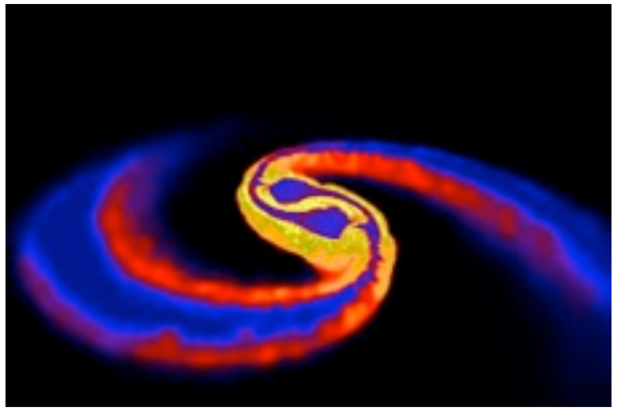

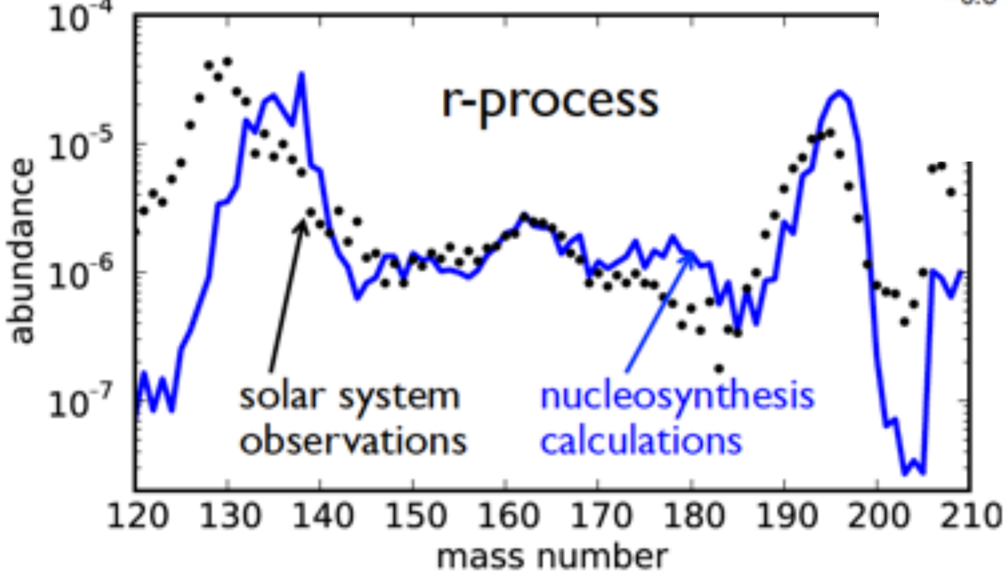

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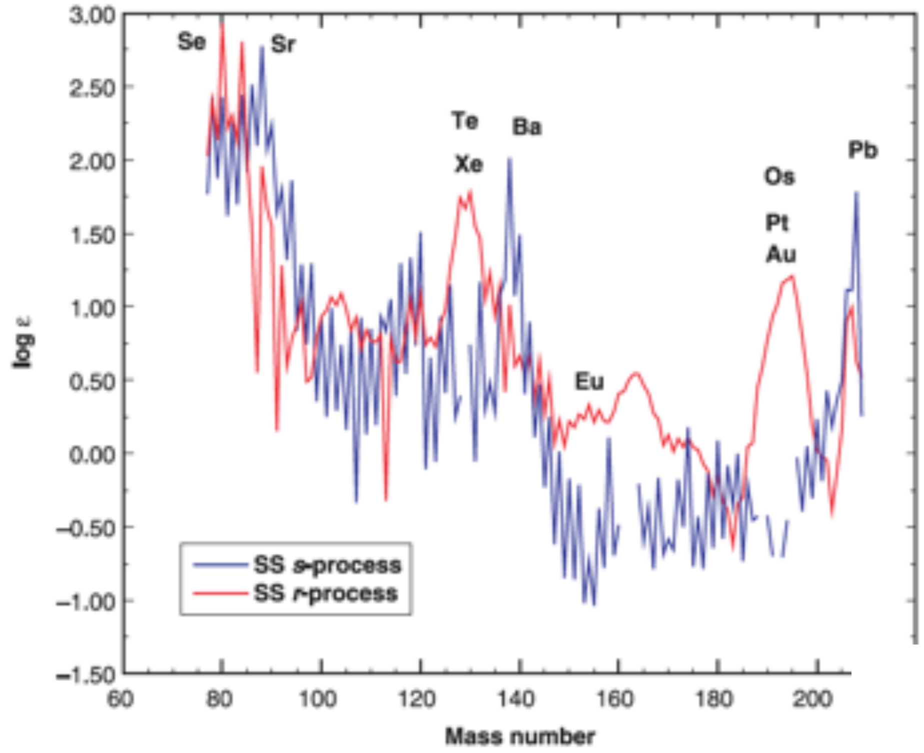

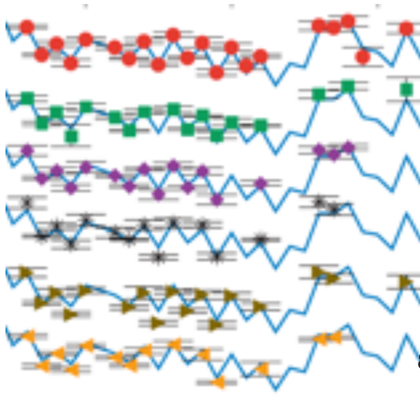

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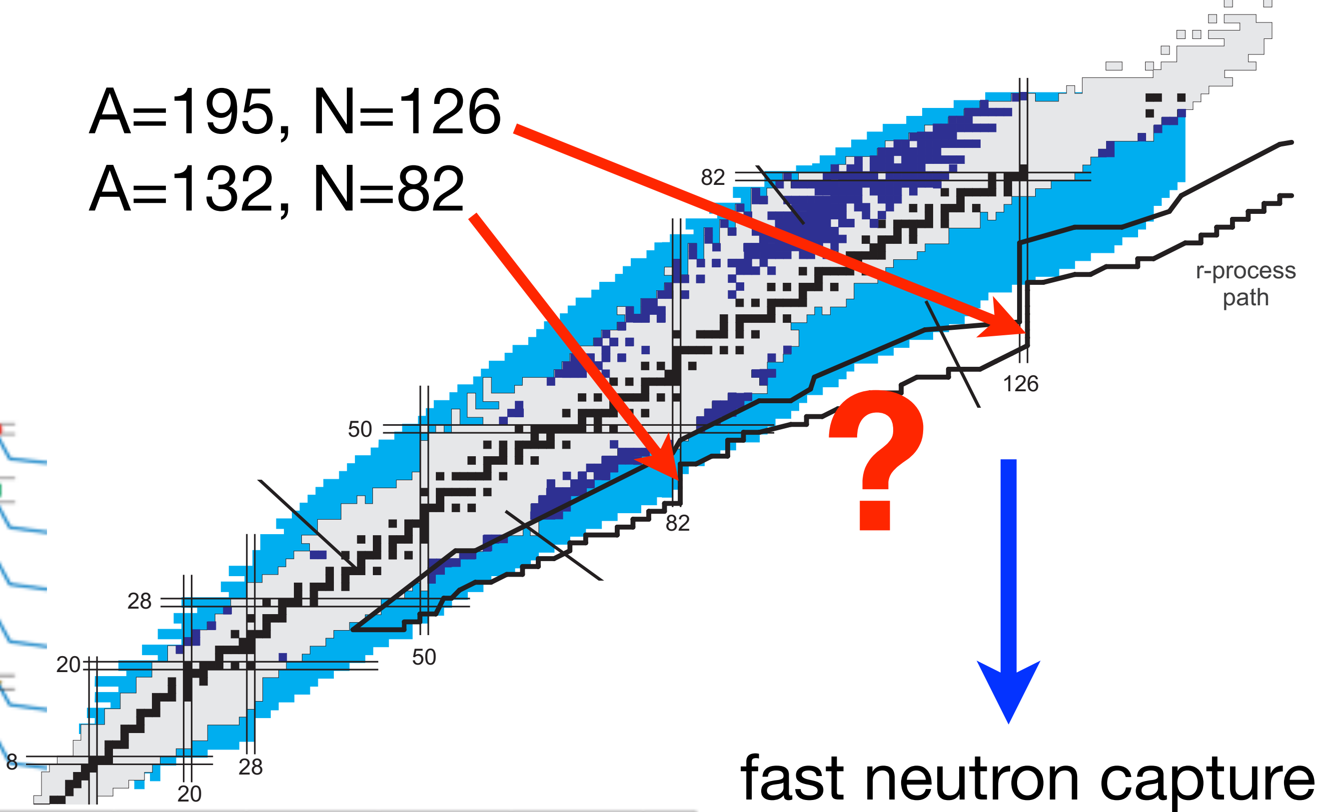
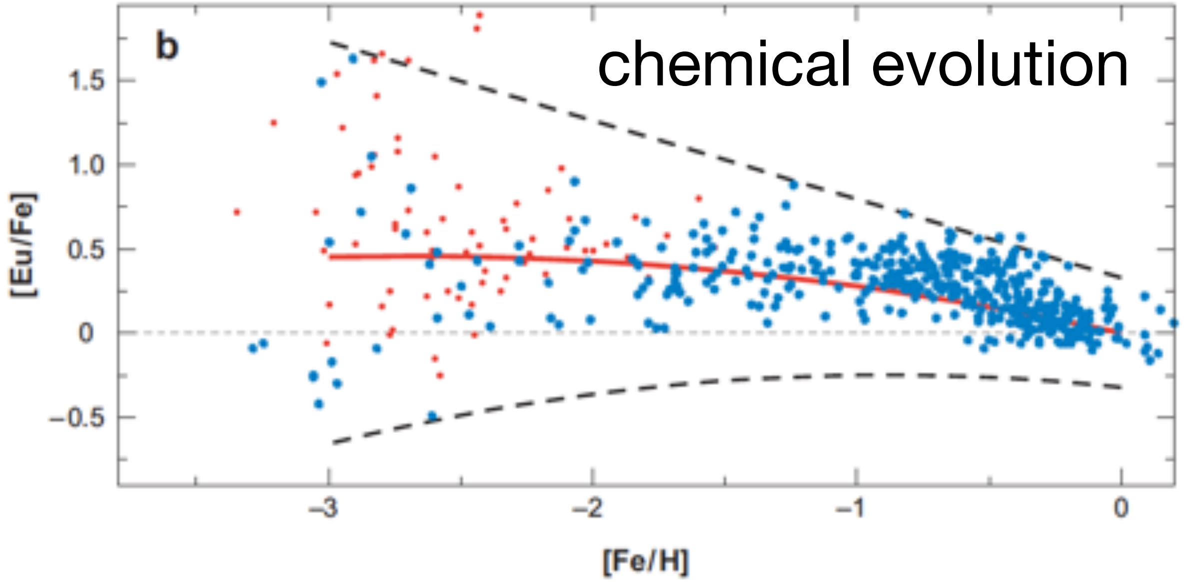


?

fast neutron capture
high neutron density

chemical evolution



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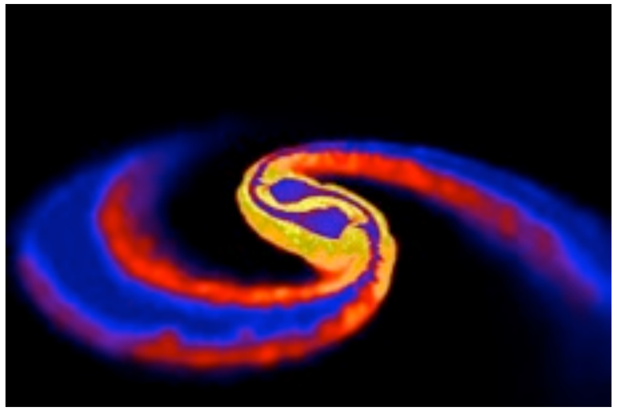

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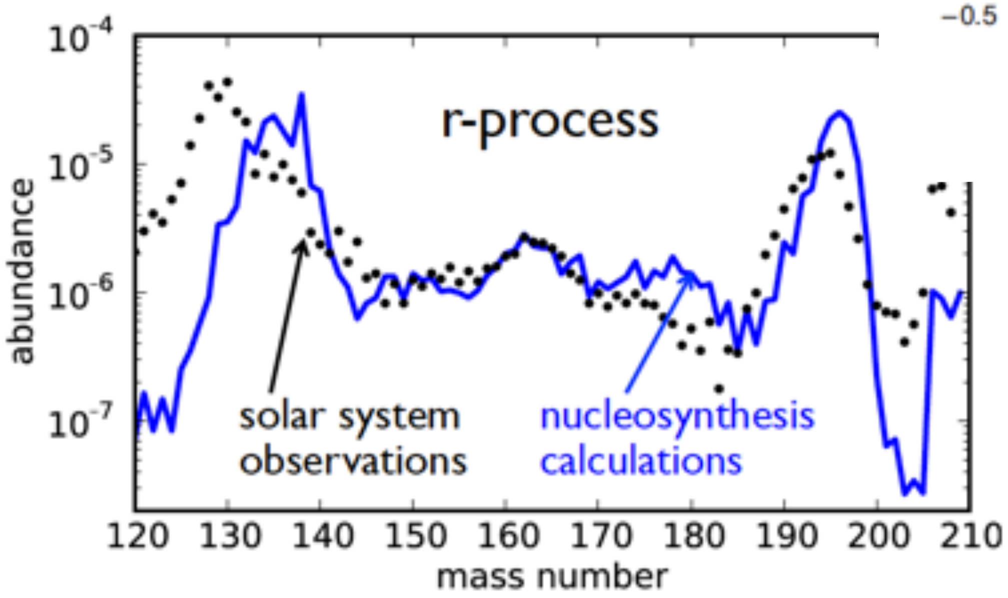
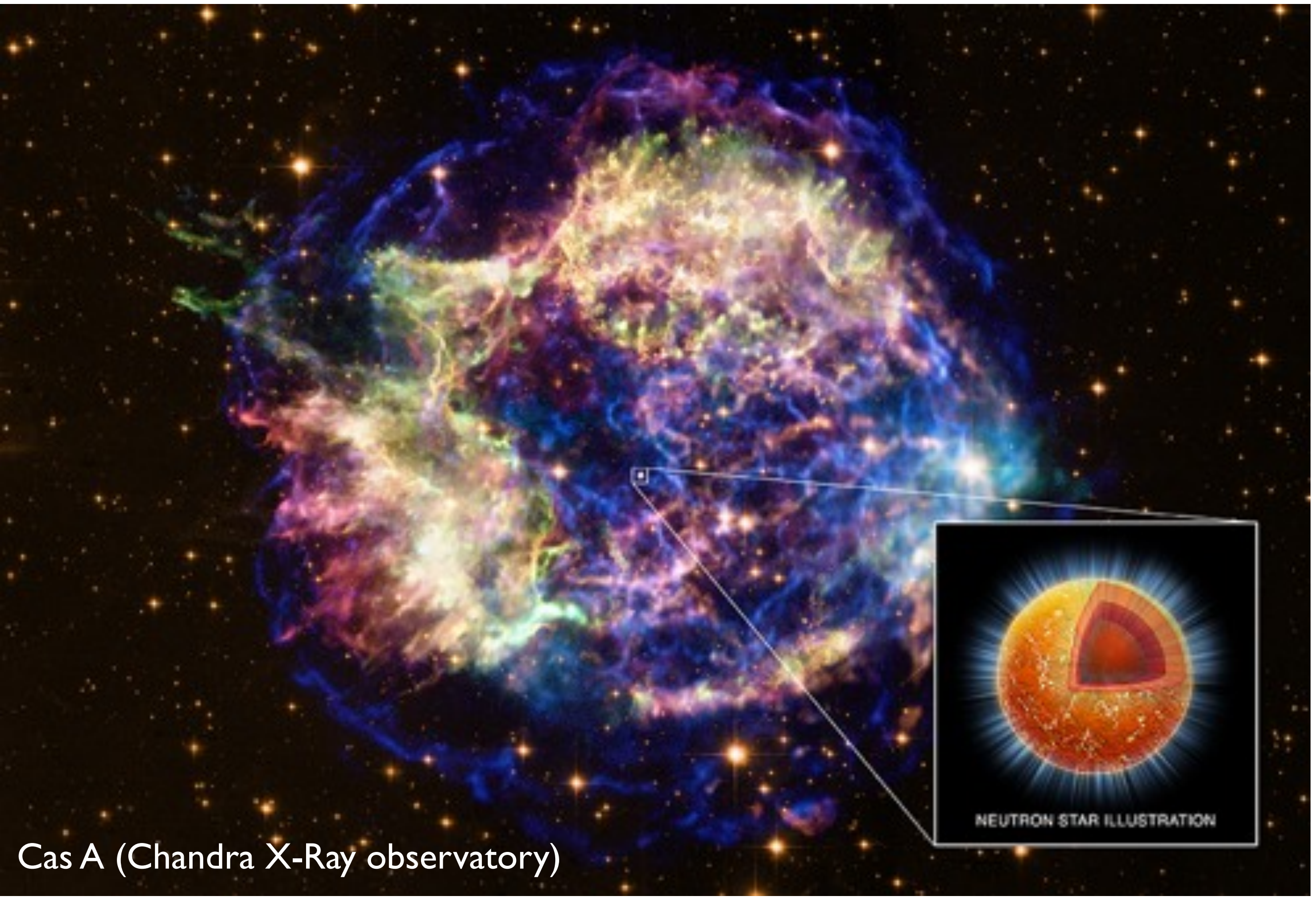


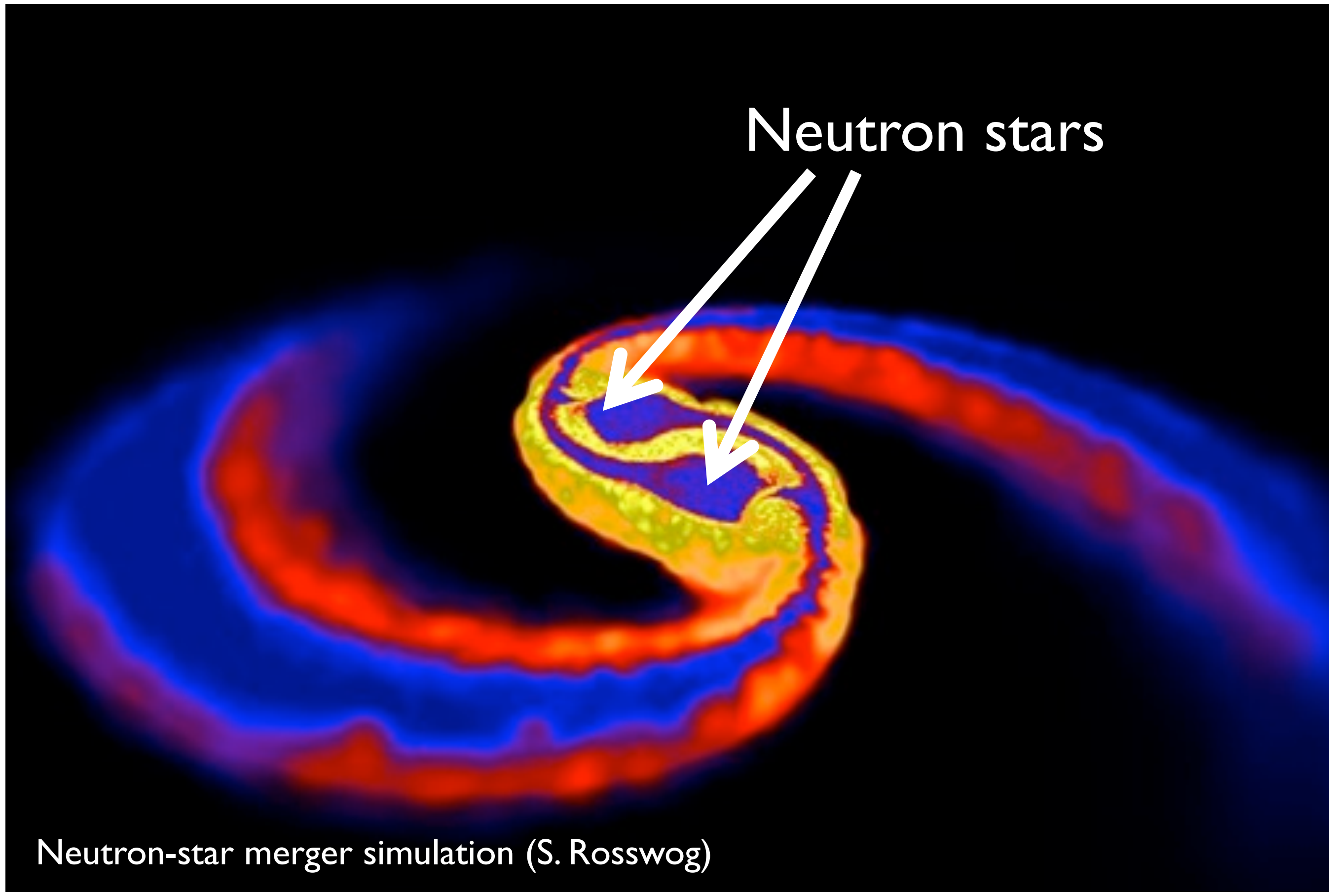
Where does the r-process occur?

Core-collapse supernovae



Cas A (Chandra X-Ray observatory)

Neutron star mergers



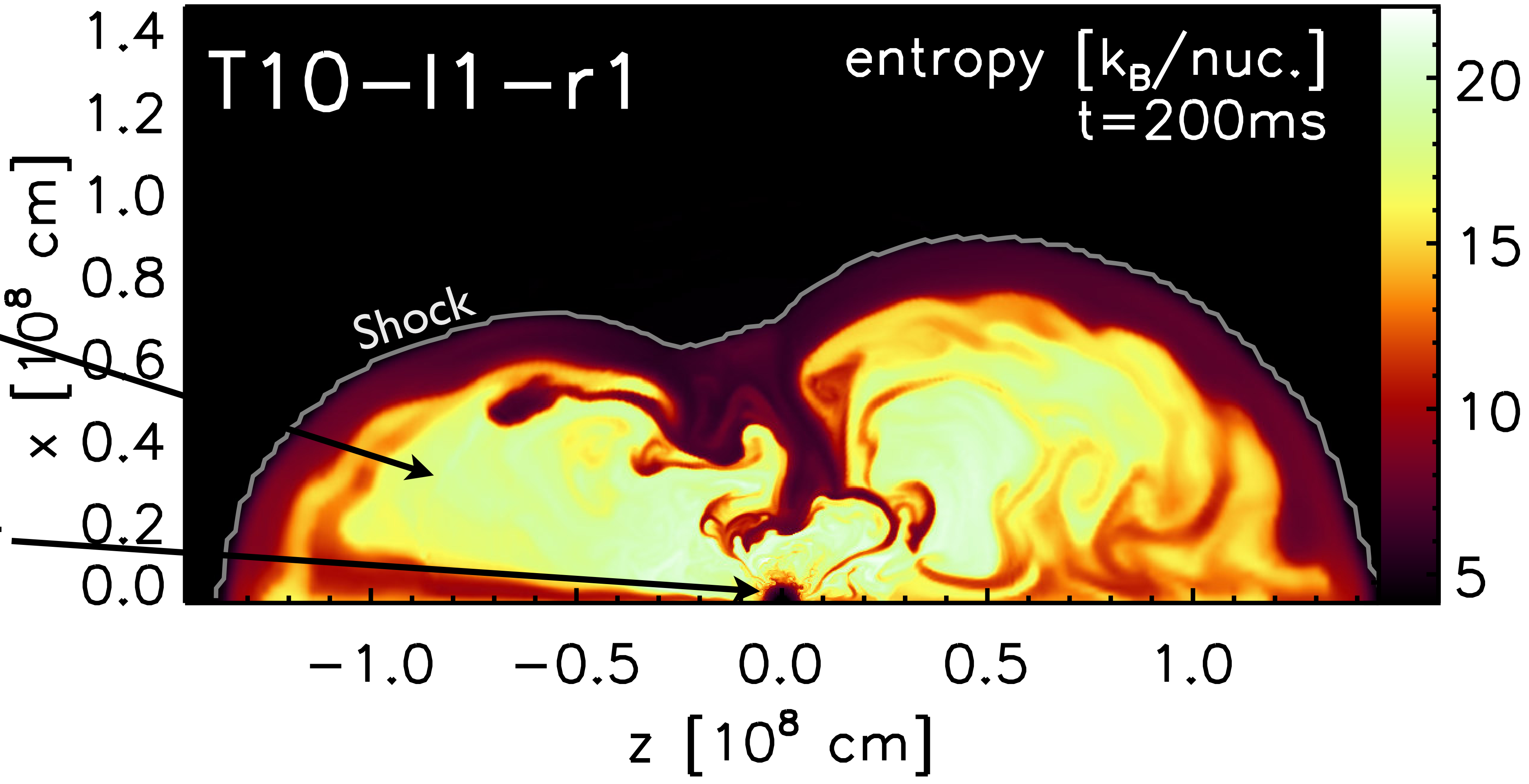
Neutron-star merger simulation (S. Rosswog)

- 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)

- spiral arms
- neutrino-driven winds
- evaporation disk

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

Core-collapse supernova simulations



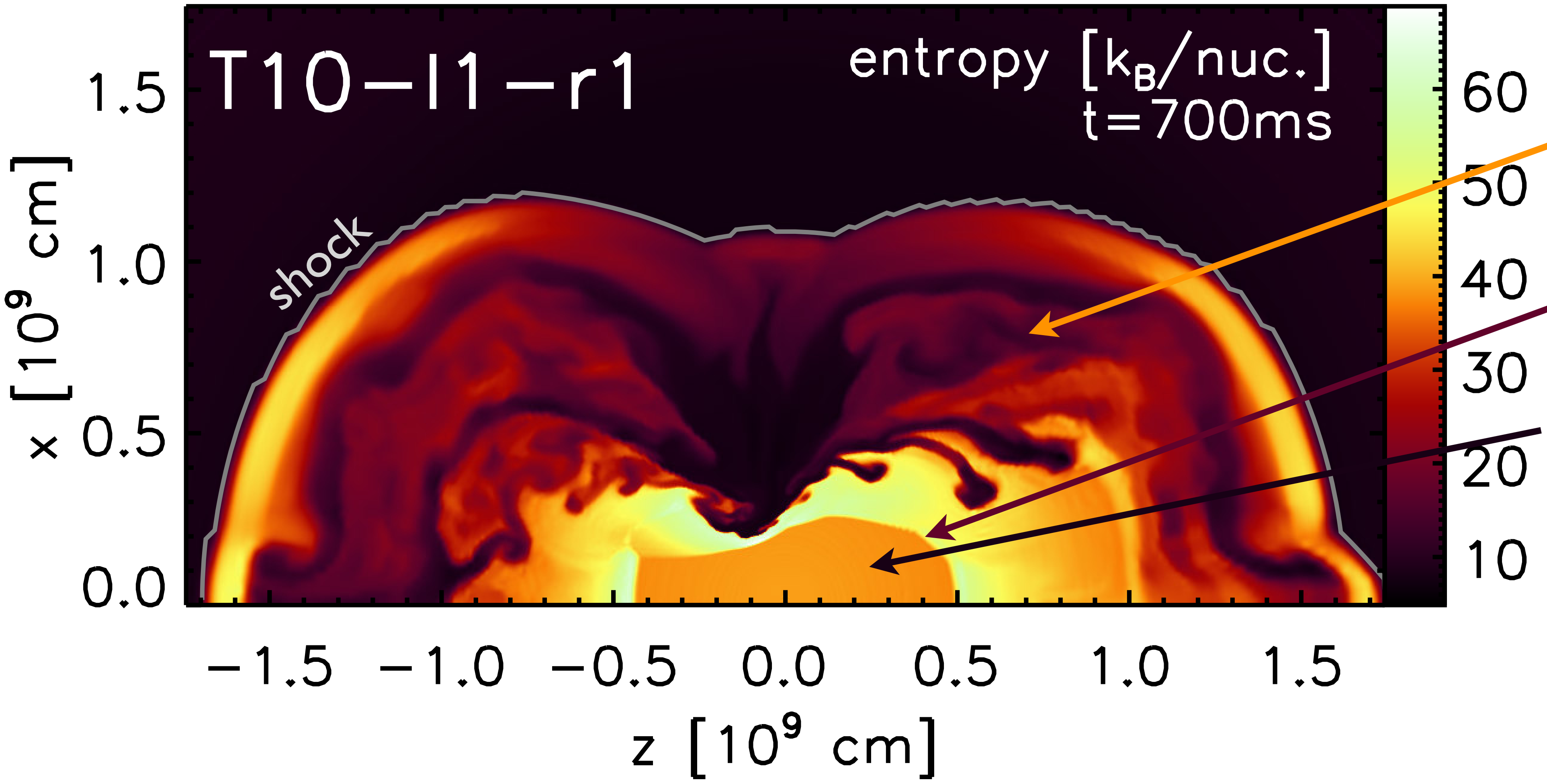
Hot bubble

Proto-neutron star

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

Long-time hydrodynamical simulations:

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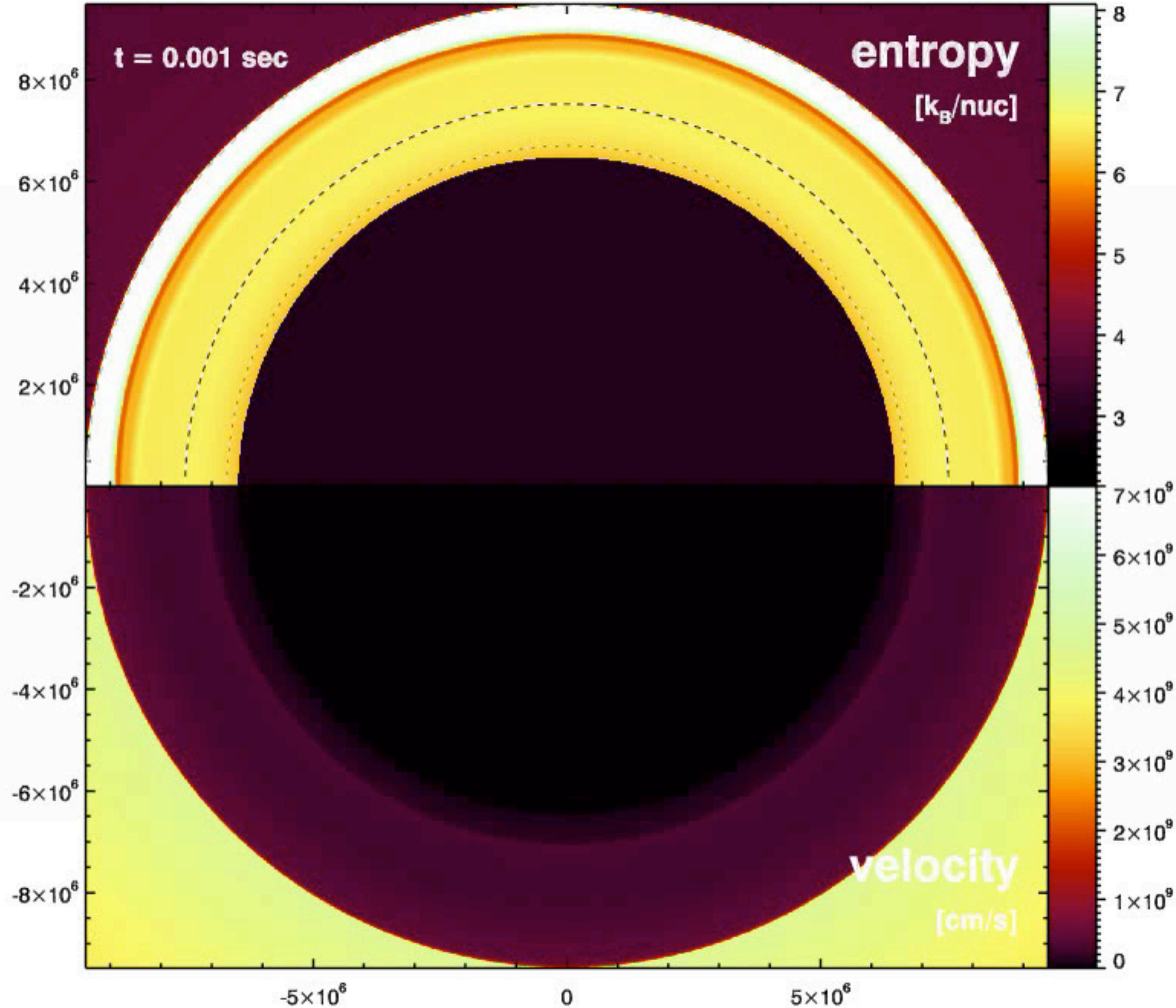
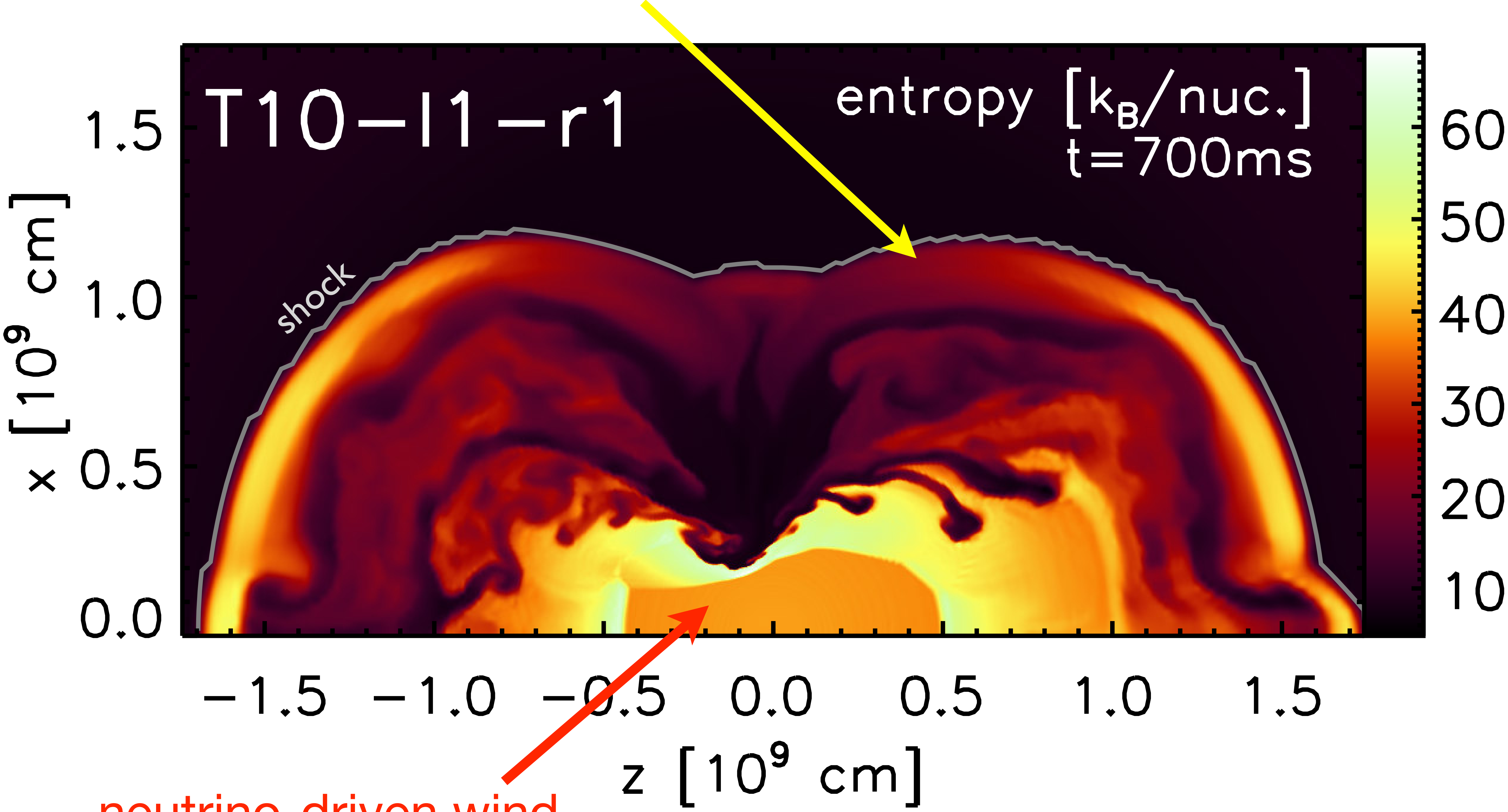
Arcones & Janka (2011)



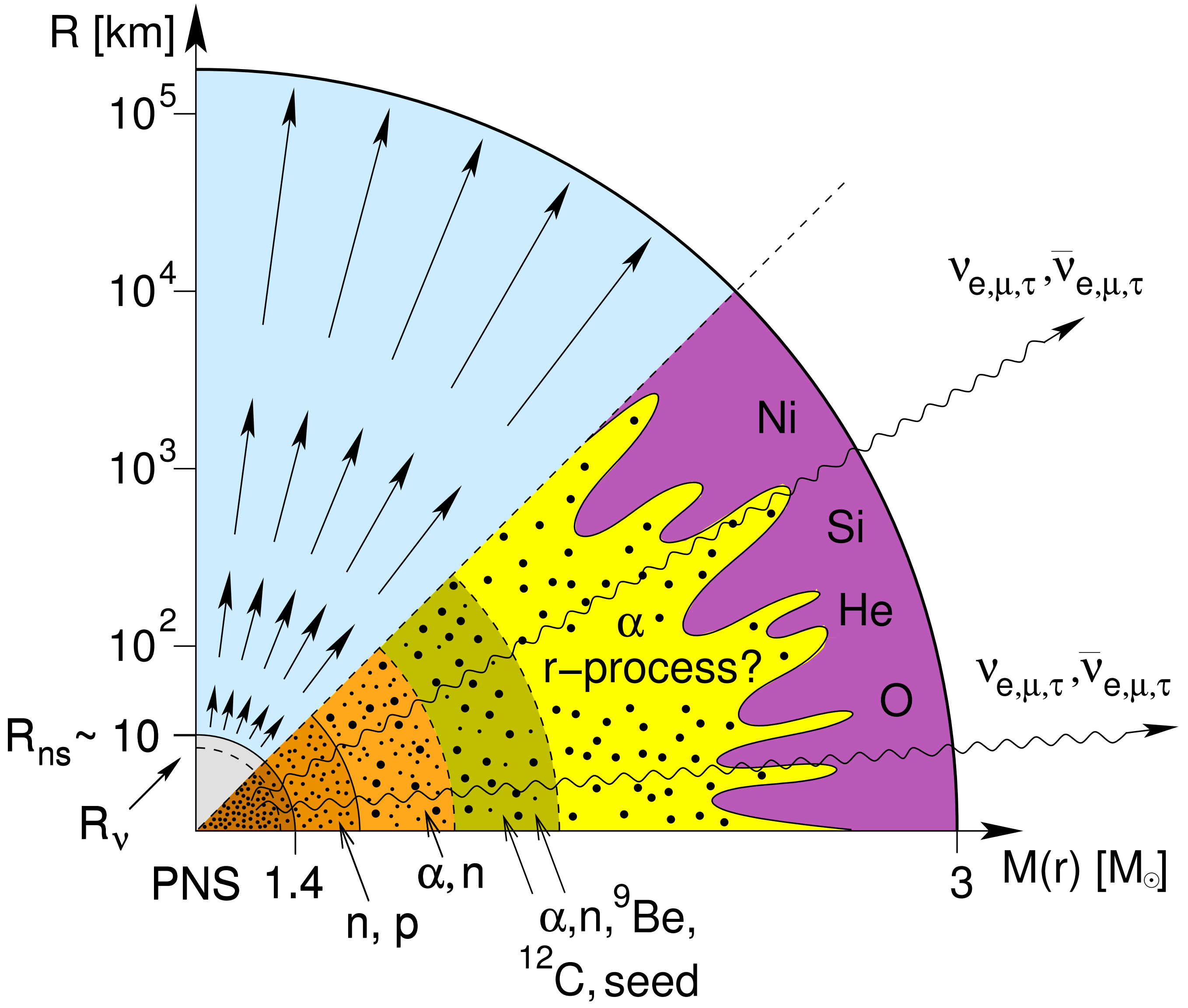
Nucleosynthesis in core-collapse supernovae

Explosive nucleosynthesis: O, Mg, Si, S, Ca, Ti, Fe
shock wave heats falling matter

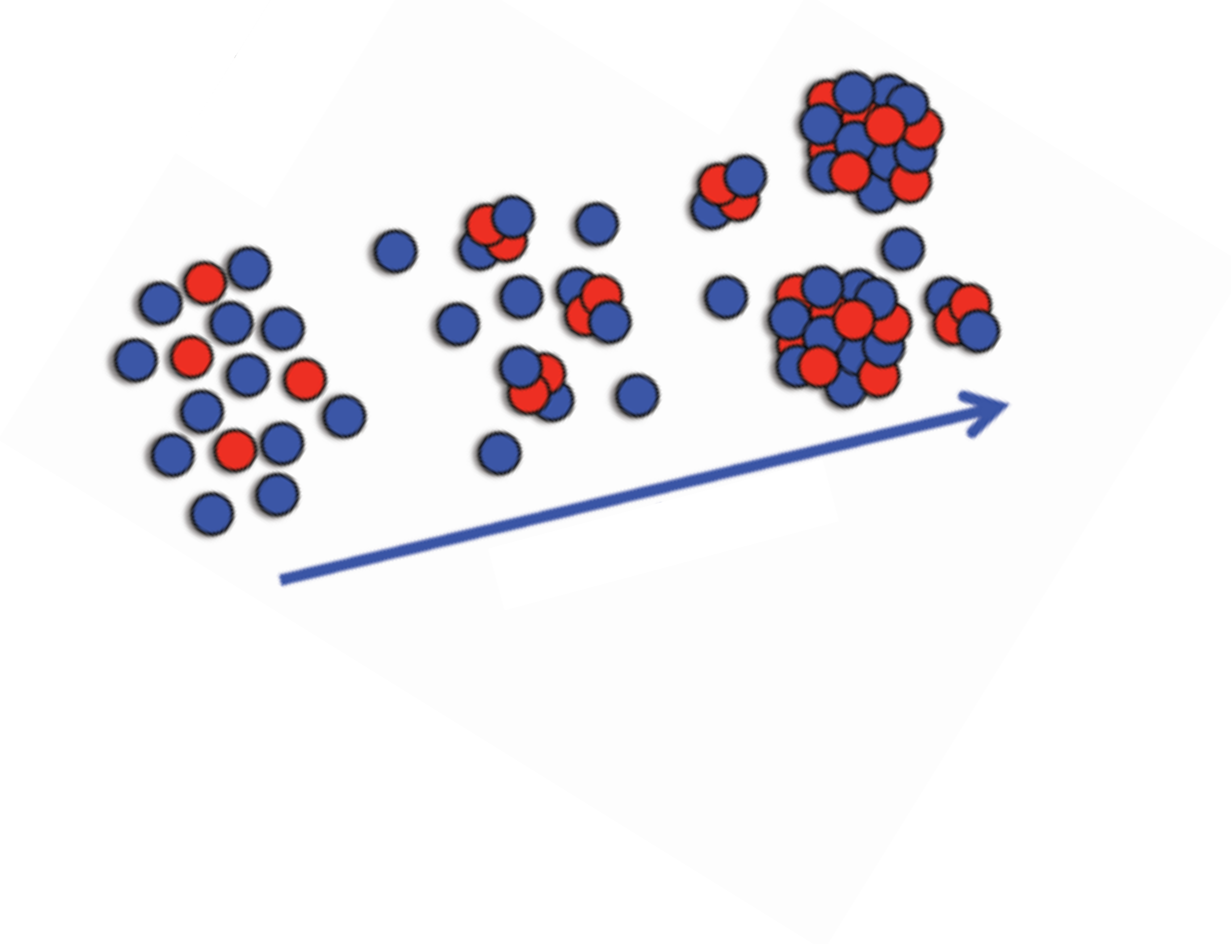


neutrino-driven wind

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

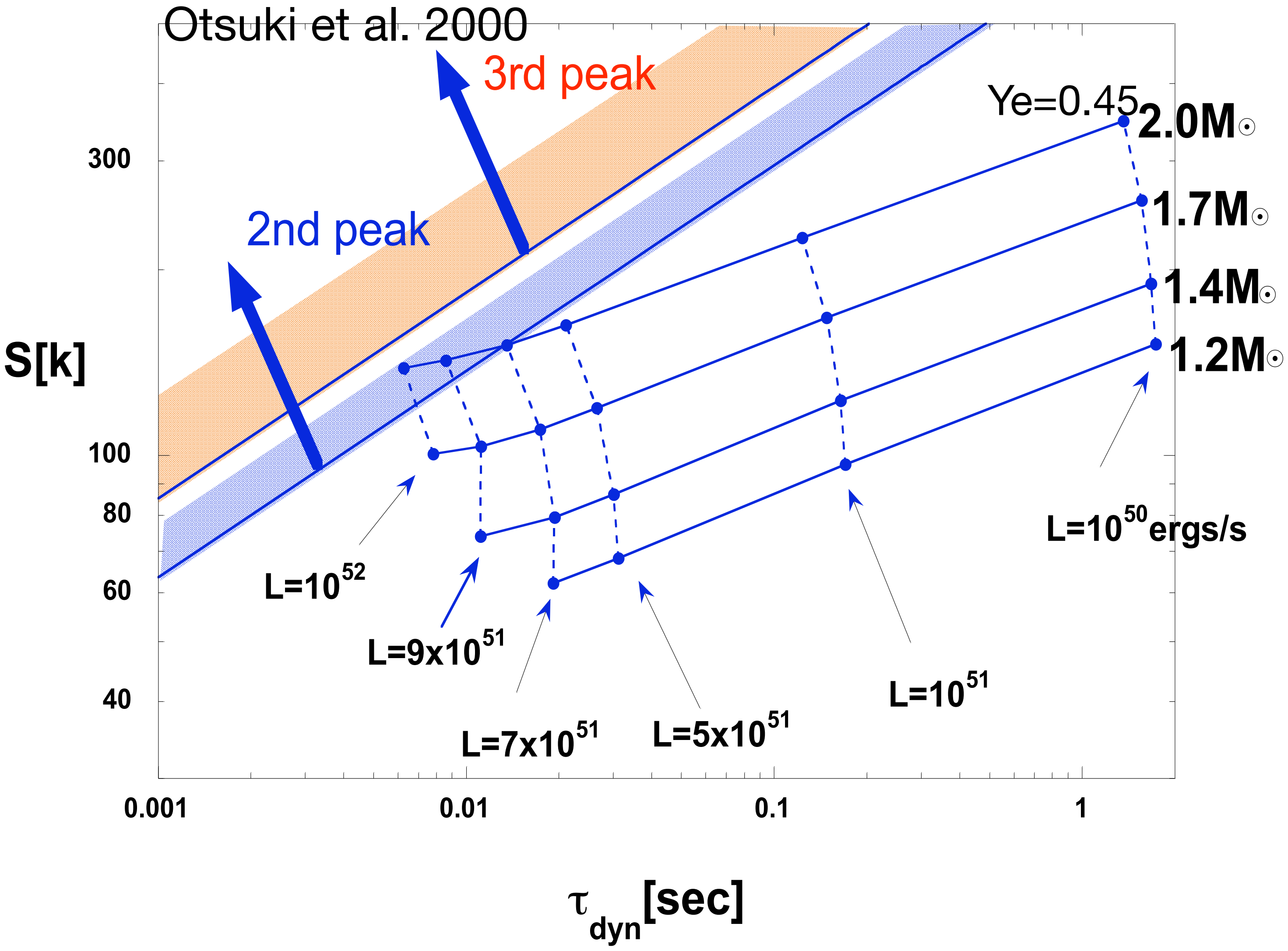
νp-process

T < 3 GK

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

Review: Arcones & Thielemann (2013)

Neutrino-driven wind parameters

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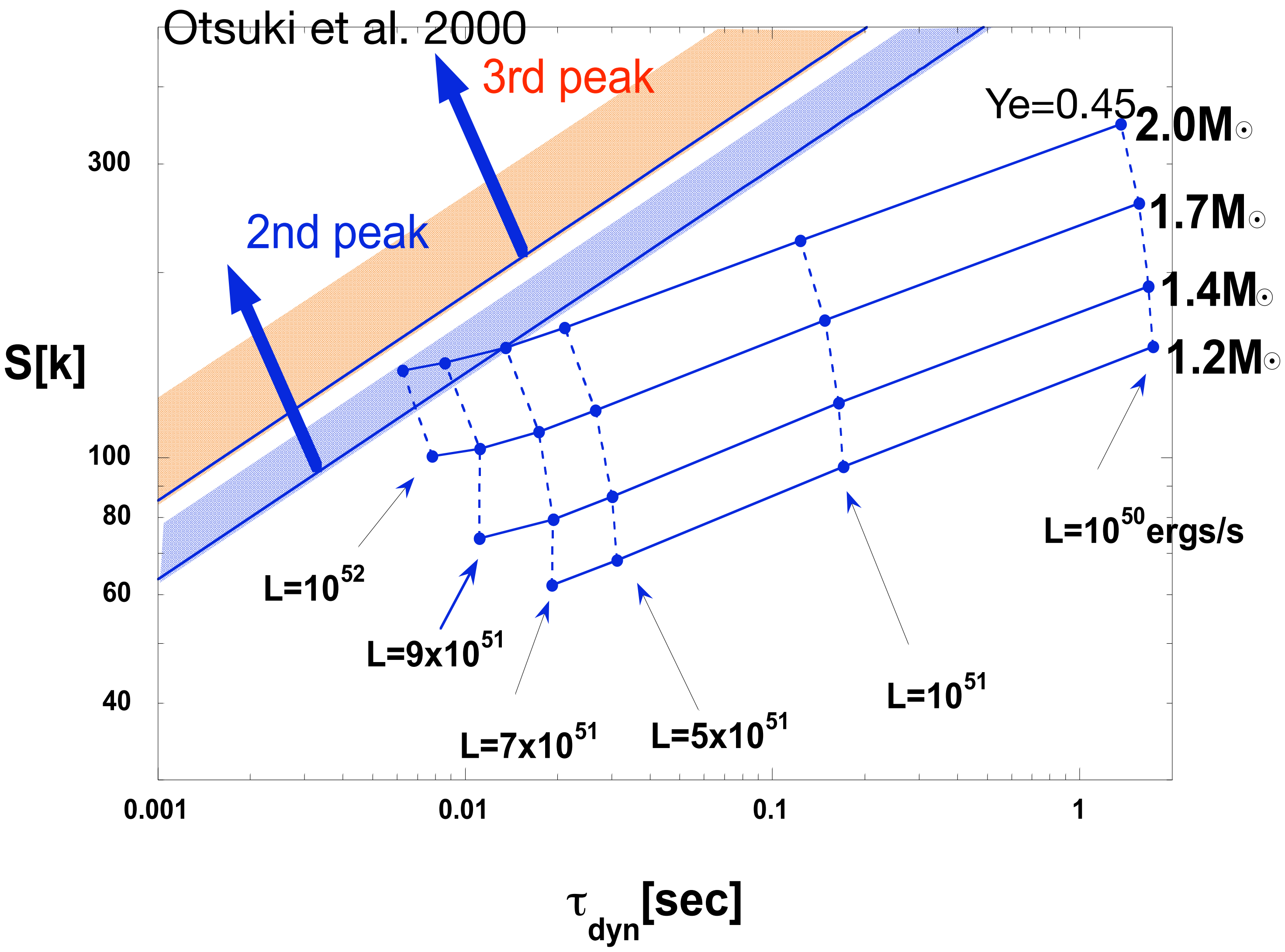


Review: Arcones & Thielemann (2013)

Conditions are not realized in recent 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

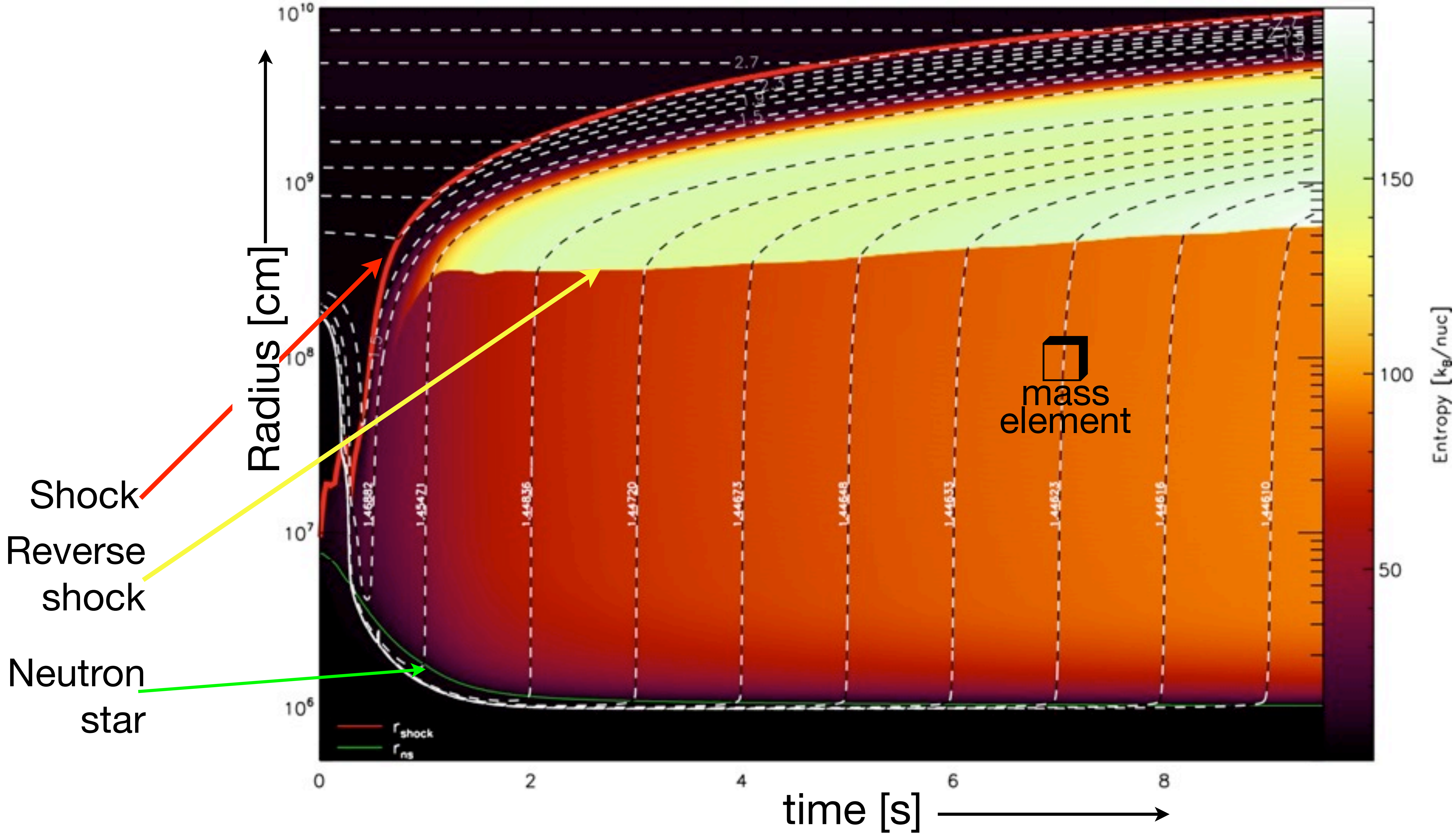
Y_e ≈ 0.4 - 0.6?

Additional ingredients:

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

Which elements are produced in neutrino winds?

Arcones et al 2007



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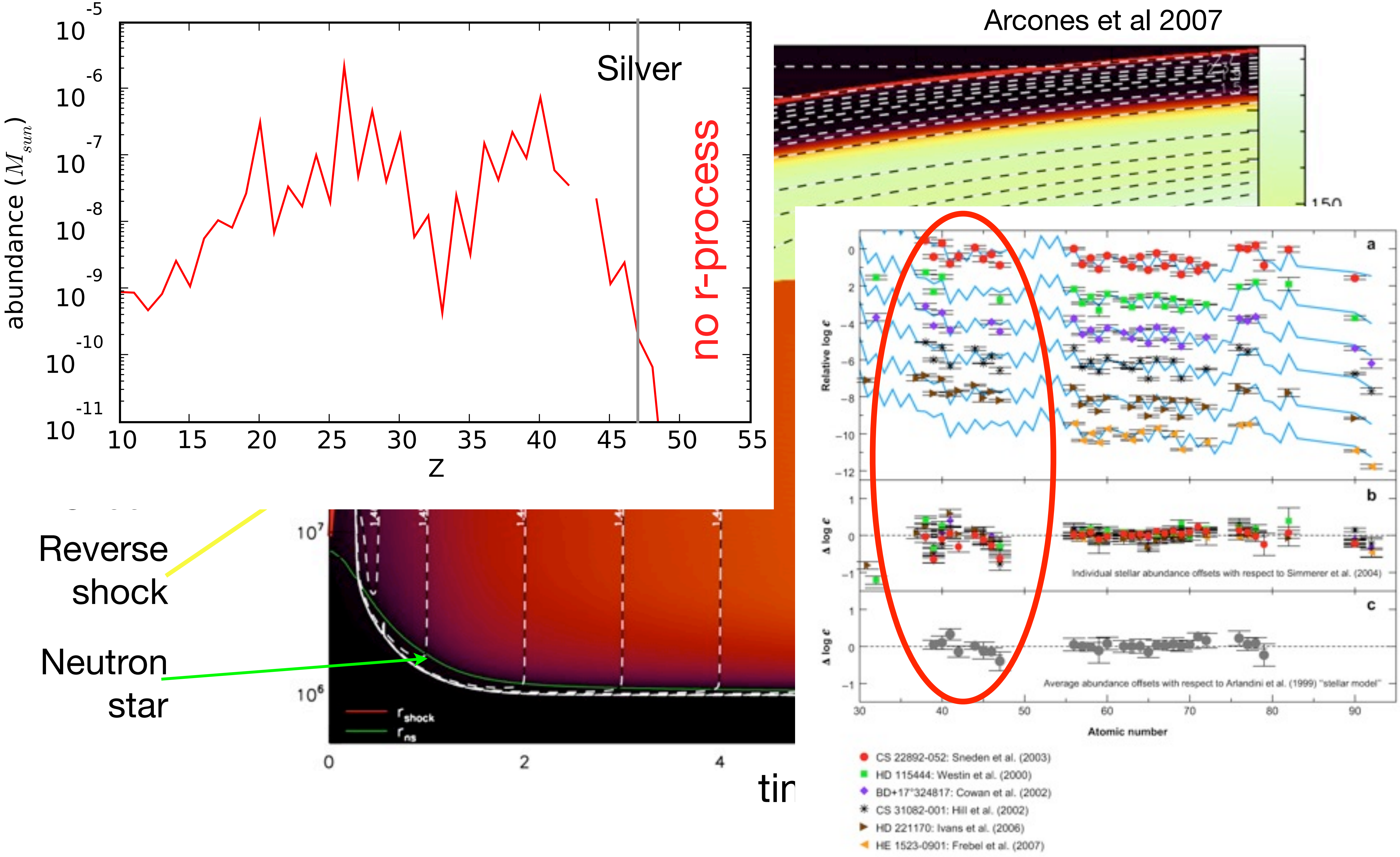
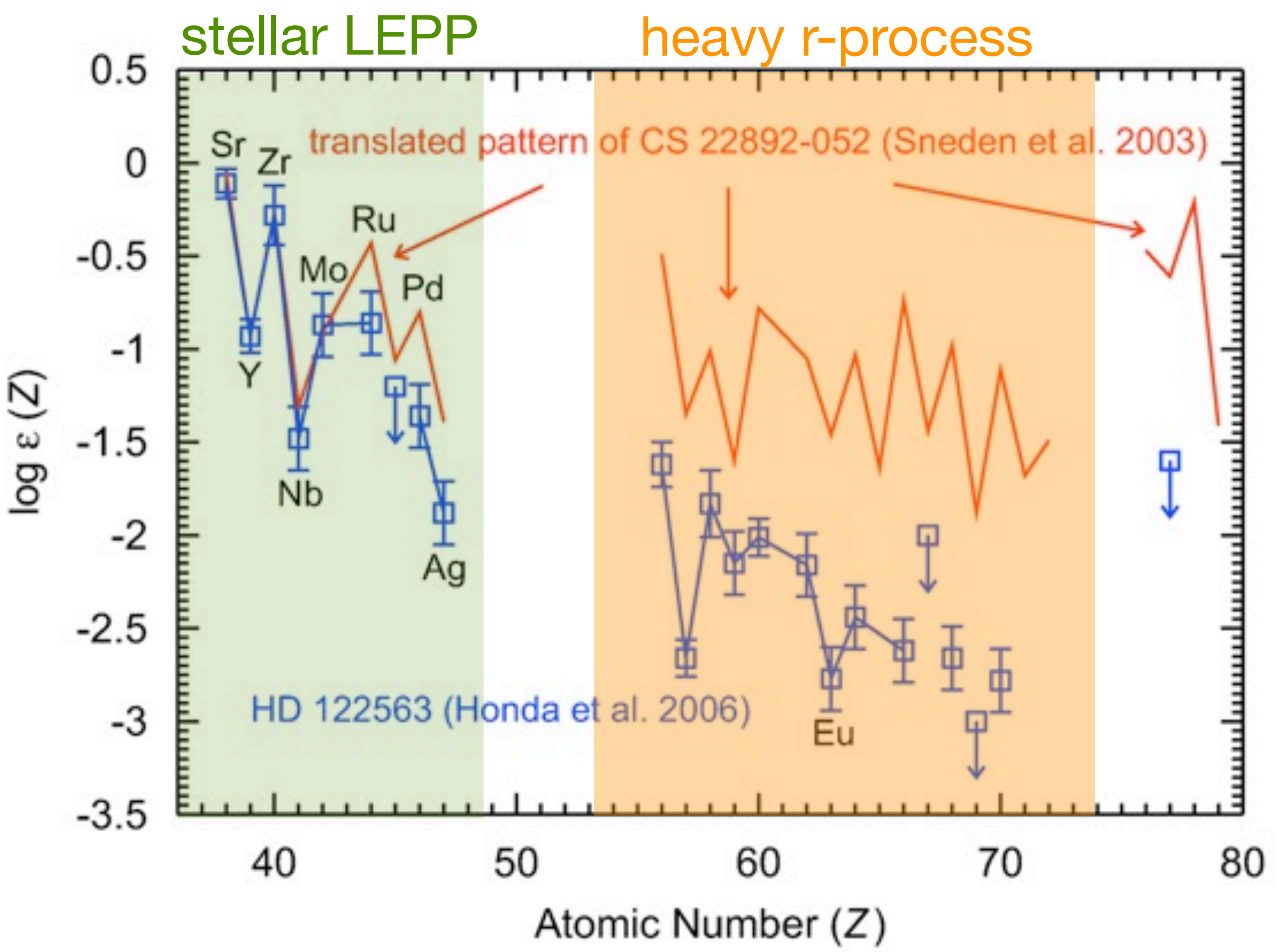


Reverse shock

Neutron star

LEPP: Lighter Element Primary Process

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



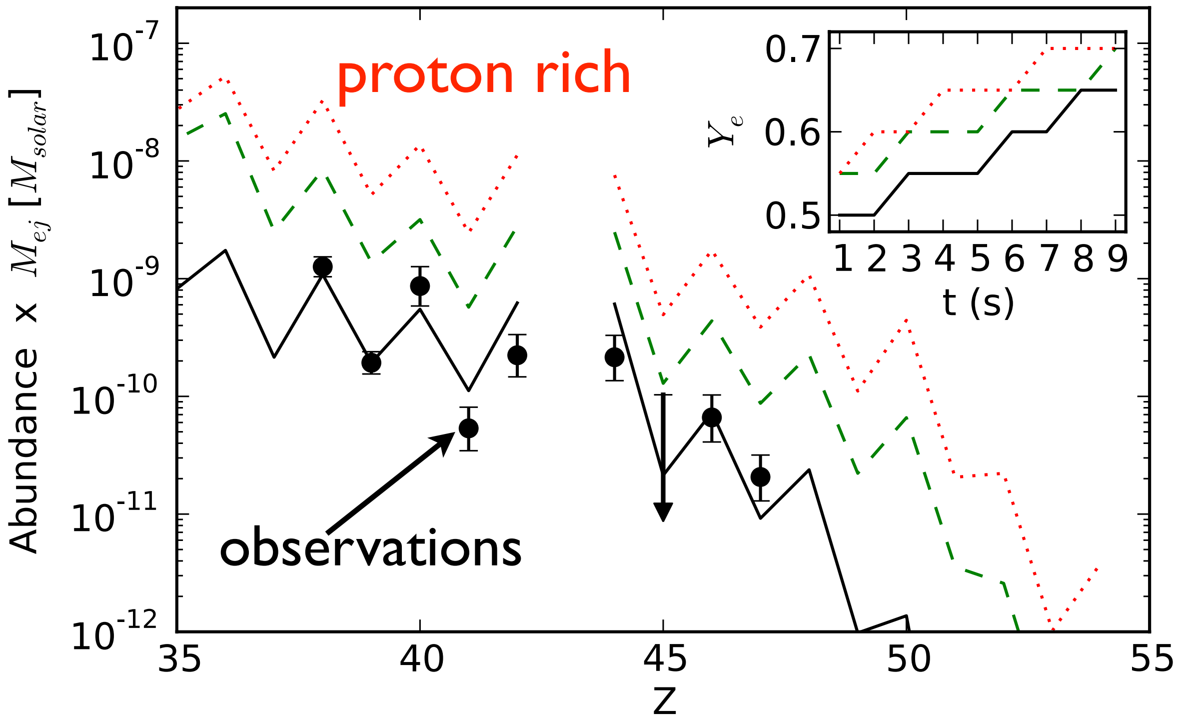
Travaglio et al. 2004: solar = r-process + s-process + solar LEPP

LEPP contributes 20-30% of solar Sr-Y-Zr and explains under-productions of “s-only” isotopes from ^{96}Mo to ^{130}Xe

Montes et al. 2007: solar LEPP ~ stellar LEPP → unique?

Lighter heavy elements in neutrino-driven winds

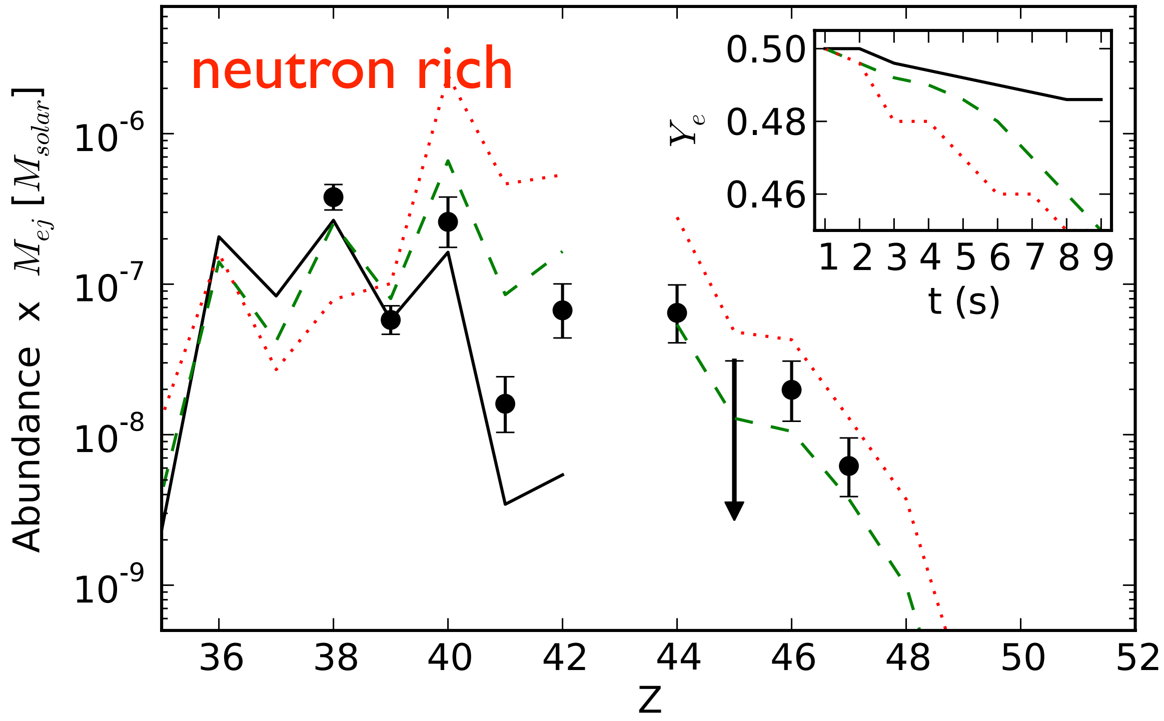
vp-process



Observation pattern reproduced!

Production of p-nuclei

weak r-process

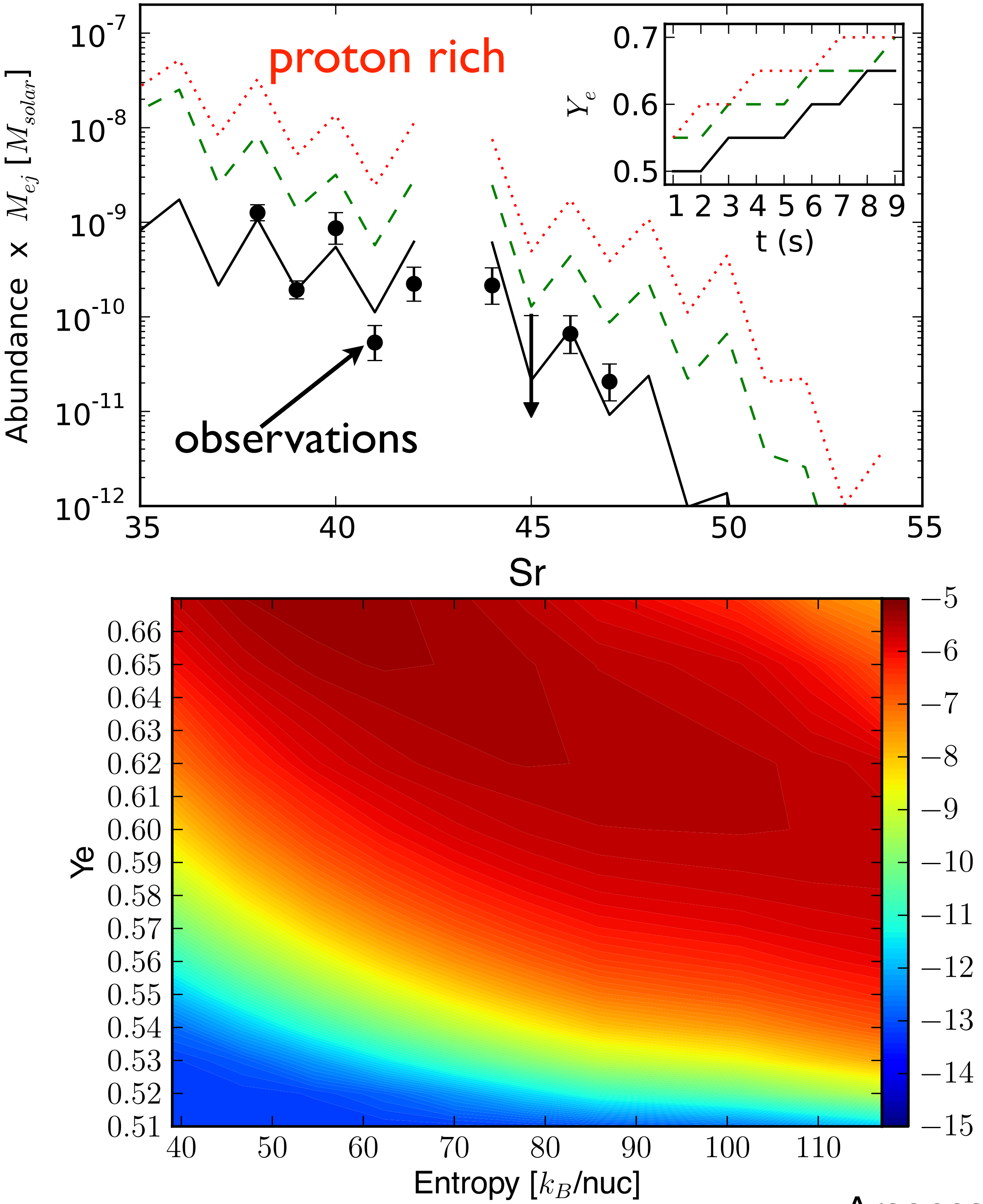


Overproduction at A=90, magic neutron number N=50 (Hoffman et al. 1996) suggests: only a fraction of neutron-rich ejecta

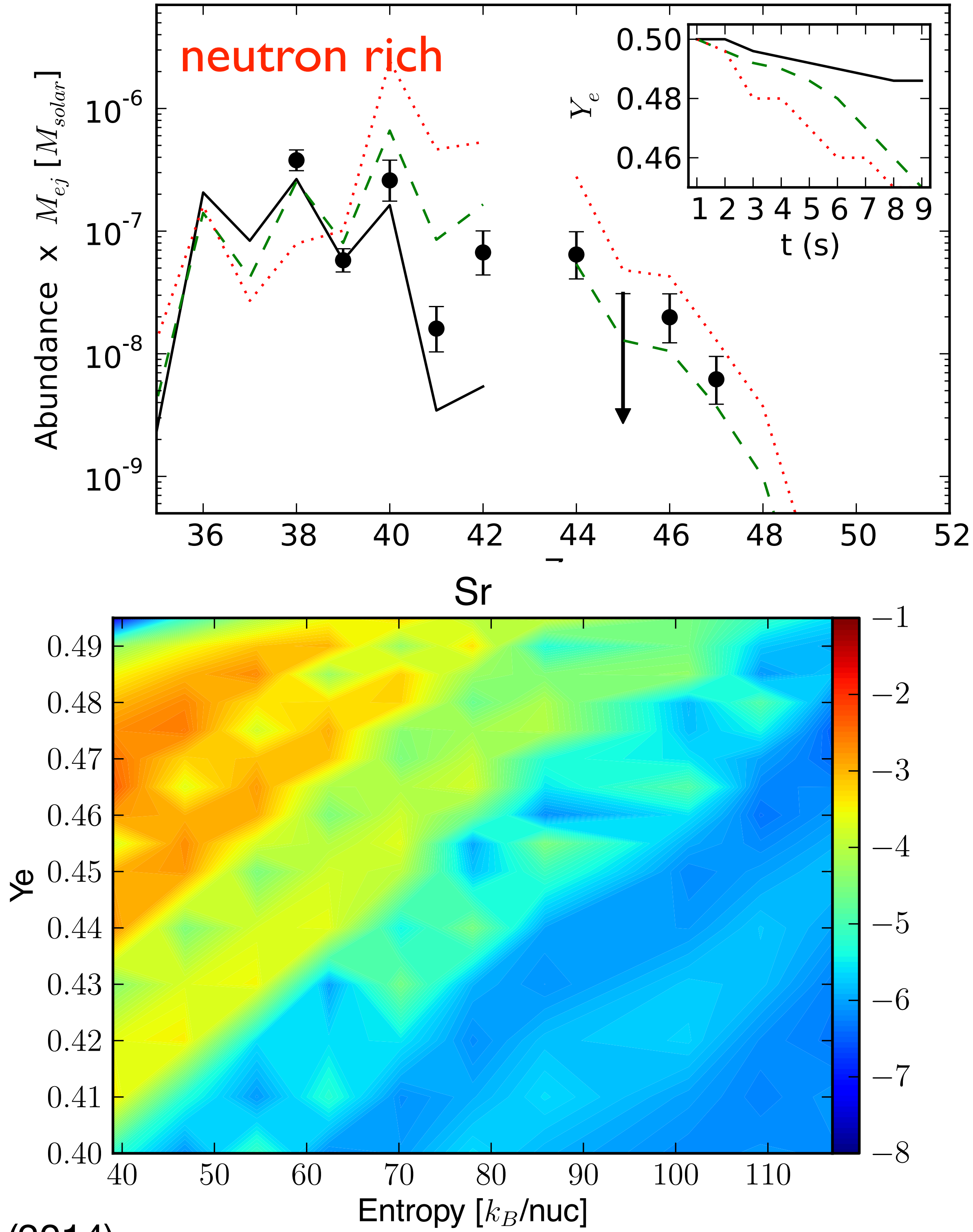
(Arcones & Montes, 2011)

Lighter heavy elements in neutrino-driven winds

vp-process



weak r-process

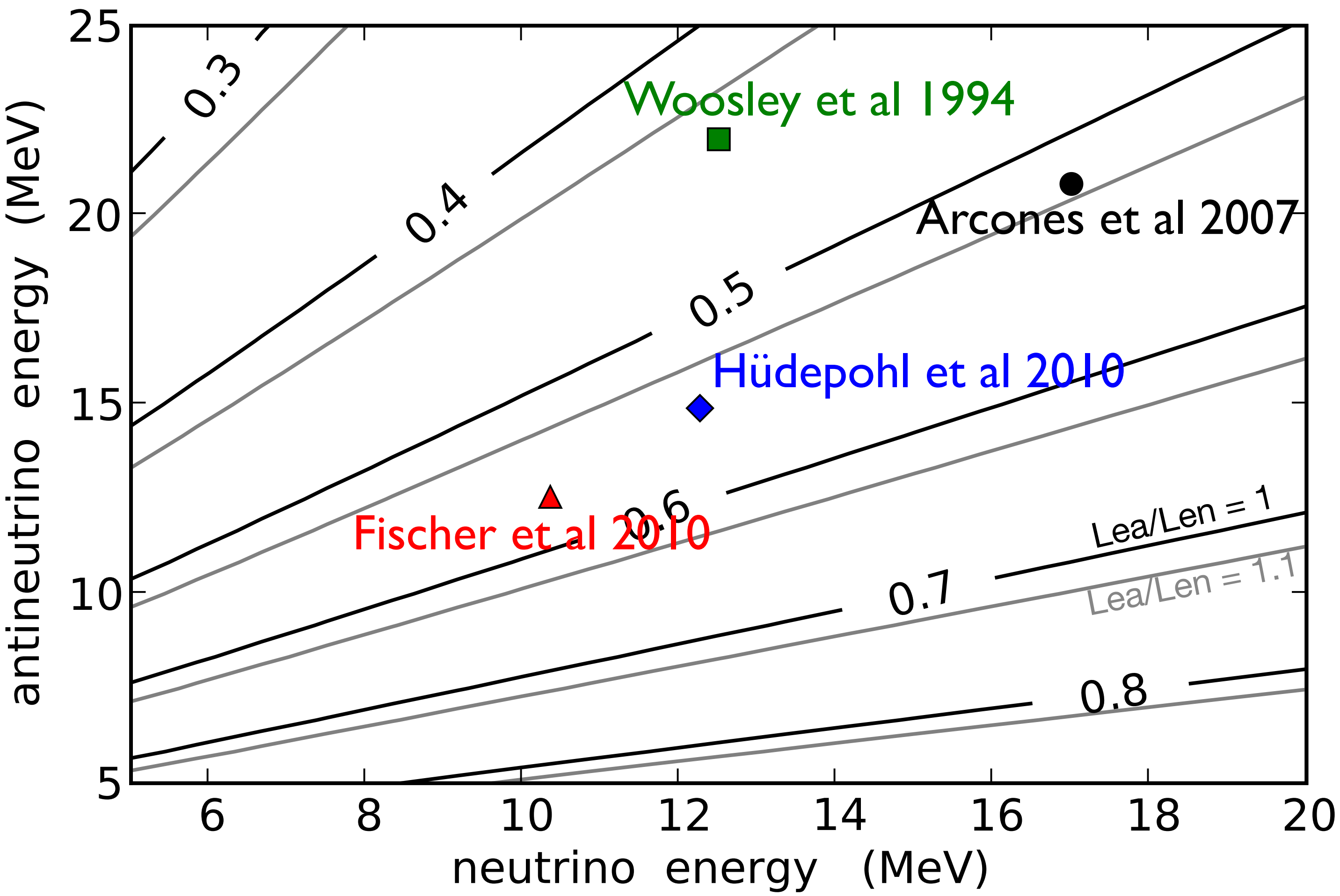


Arcones & Bliss (2014)

Neutron or proton rich?

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

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

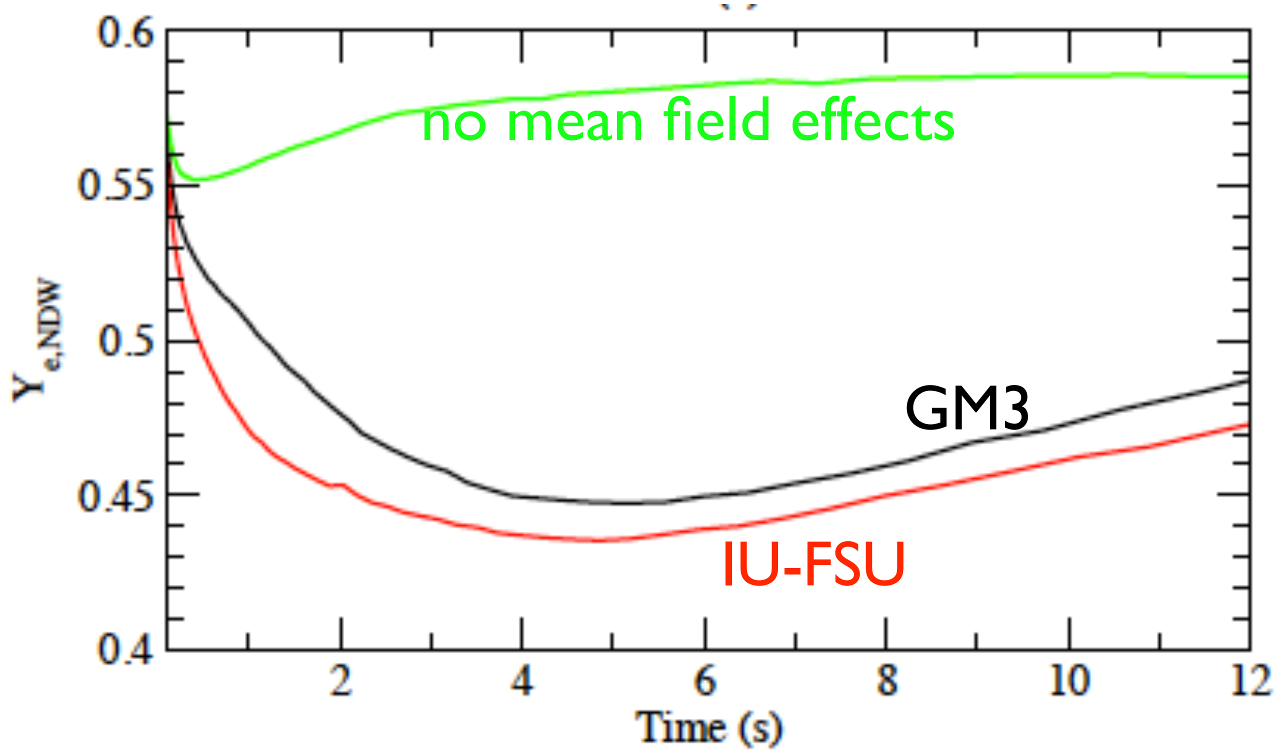


neutron rich:

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

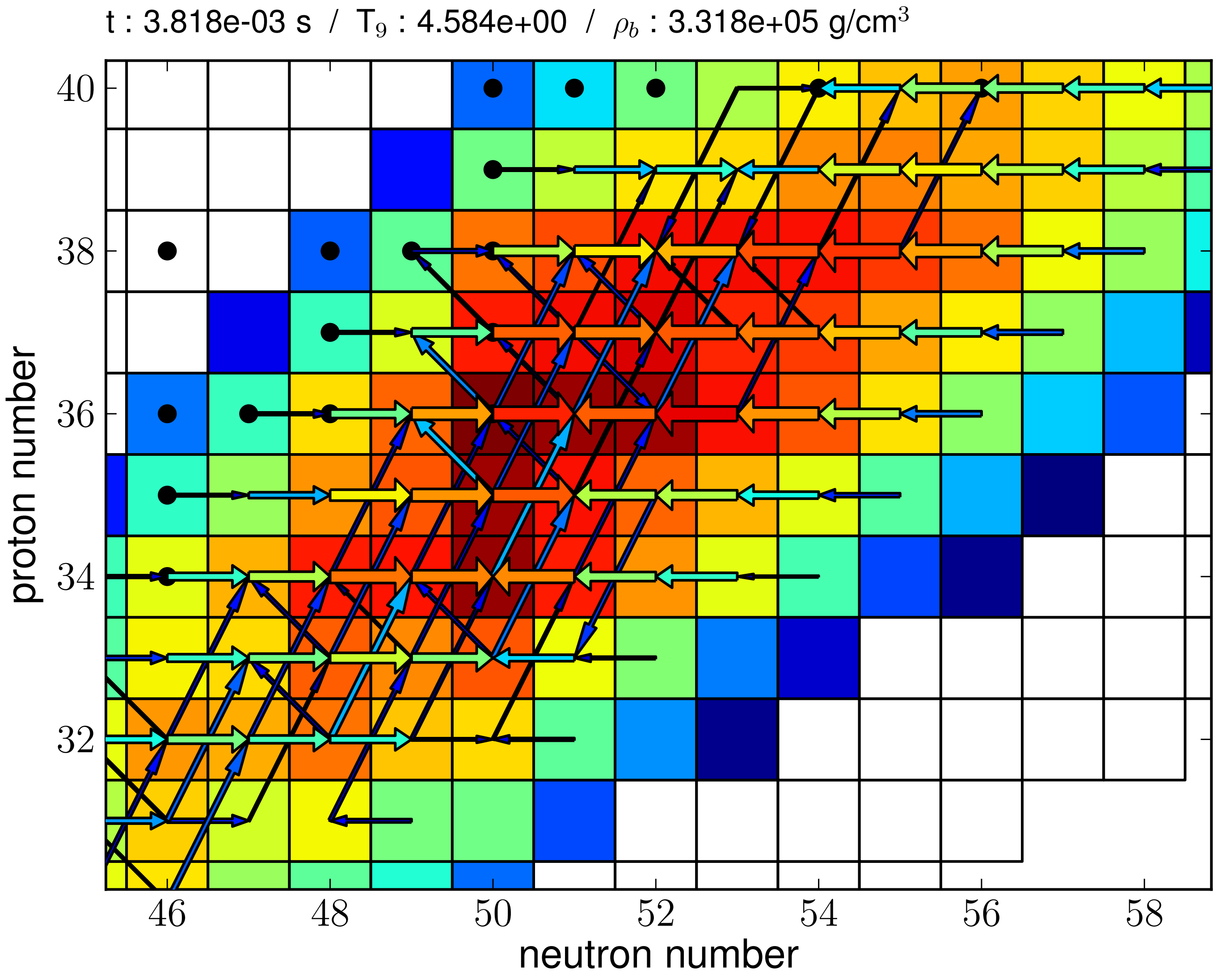
Wind electron fraction still uncertain due to neutrino-matter interactions at high densities

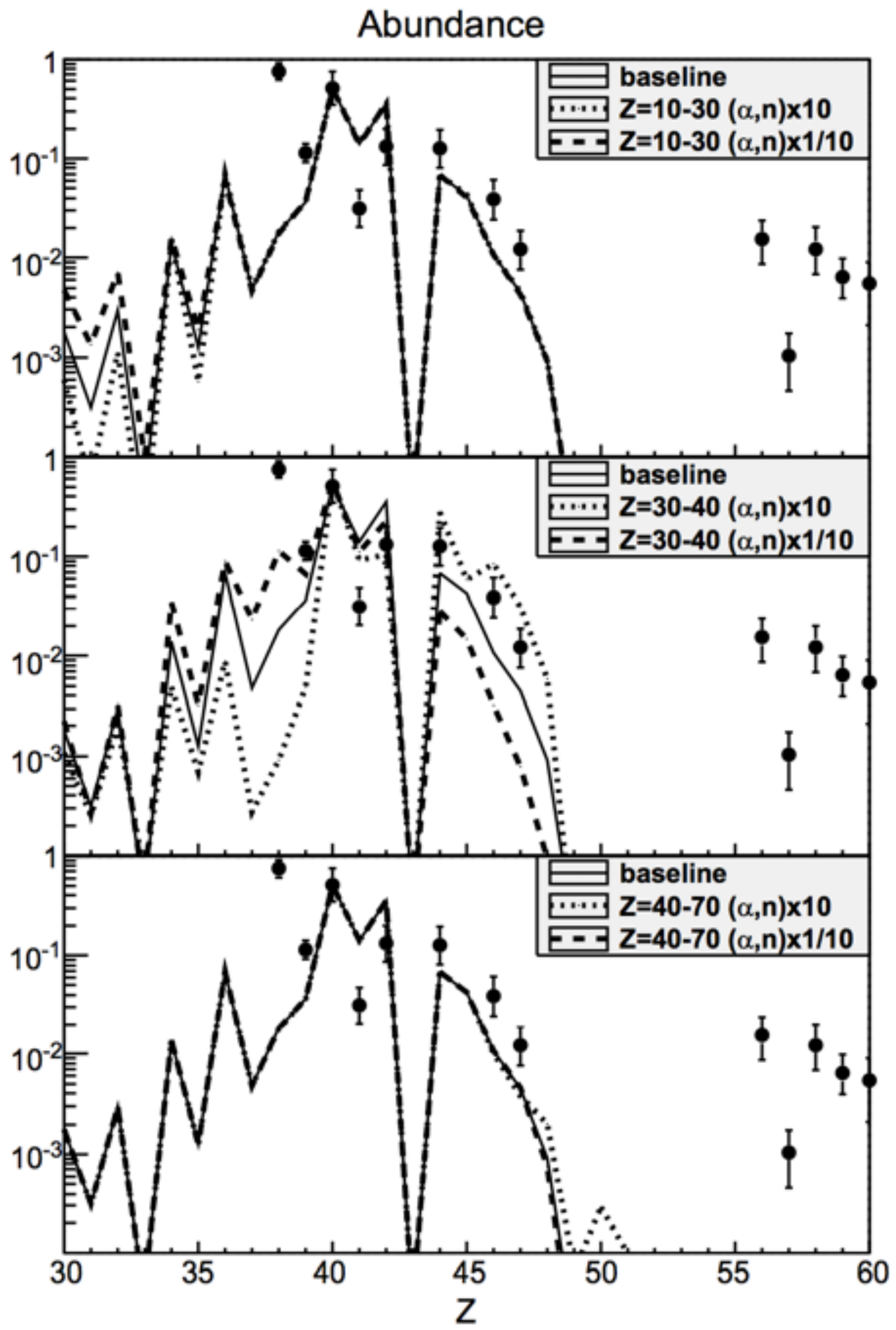
Roberts et al. 2012,
Martinez-Pinedo et al. 2012



Key reactions: weak r-process

(α,n)

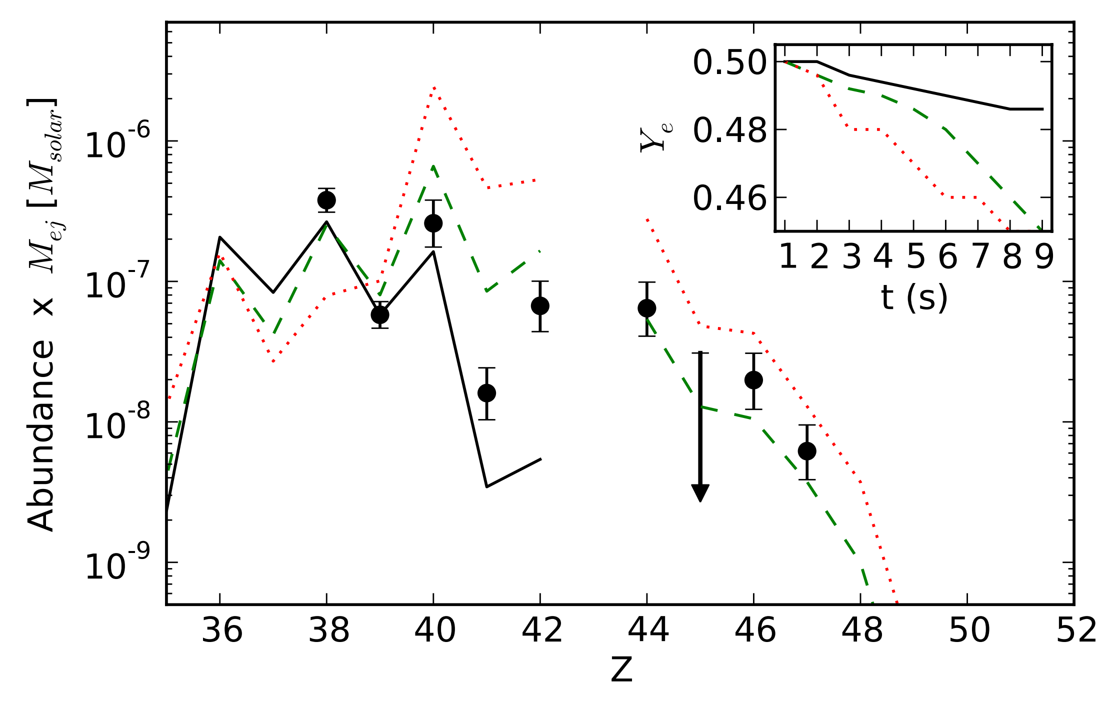




Montes, Arcones, Pereira (in prep.)

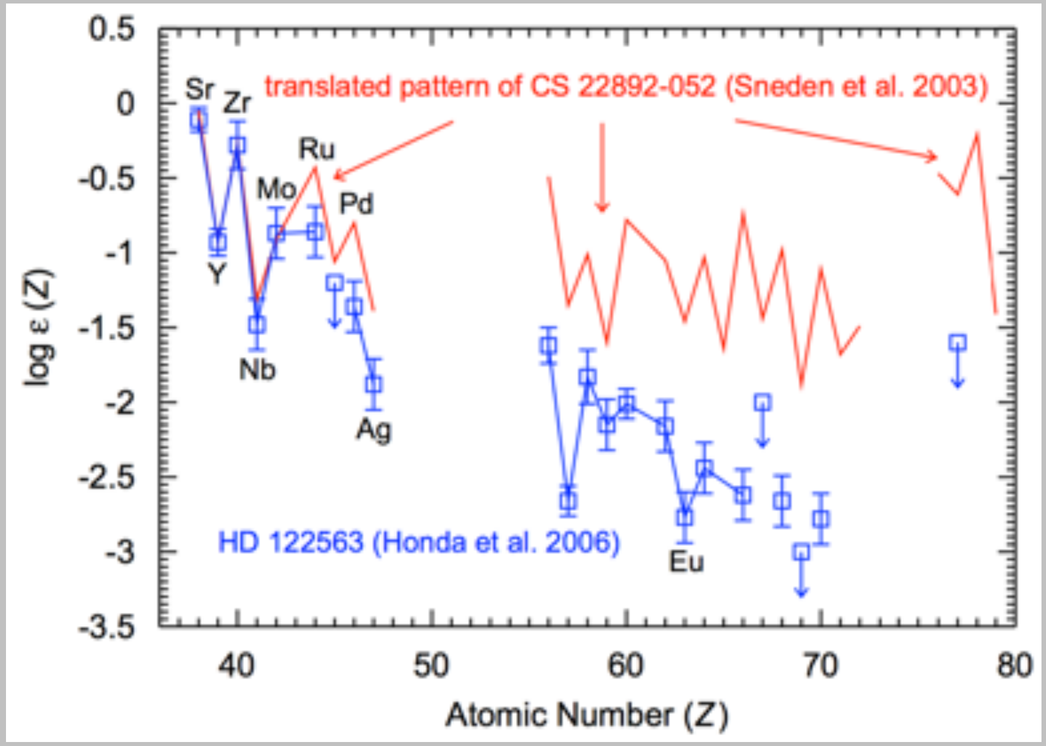
Origin of elements from Sr to Ag

Astrophysical site

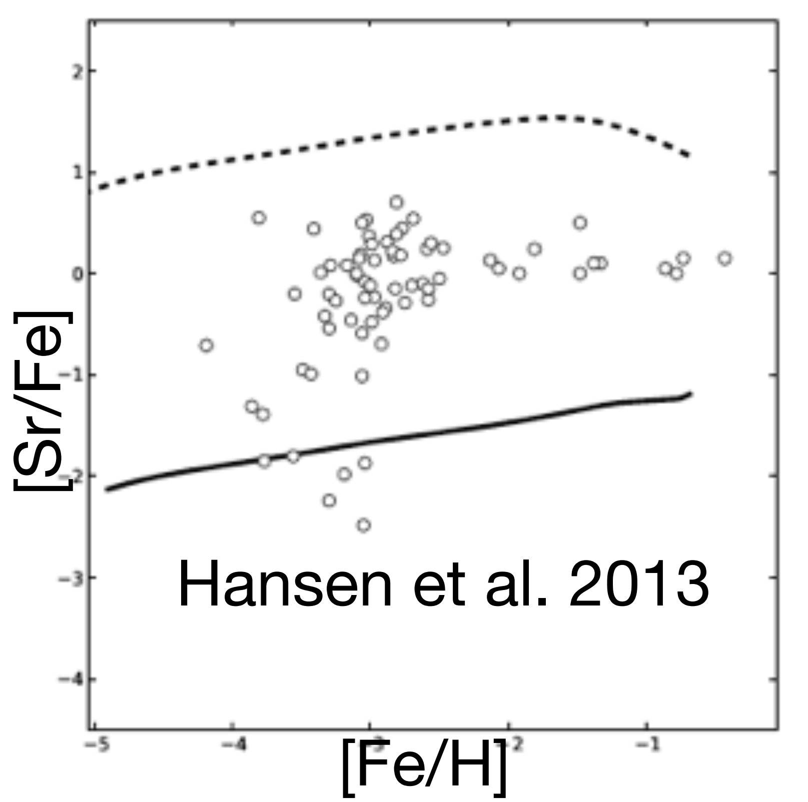


Nucleosynthesis:
identify key reactions

Observations



Chemical evolution

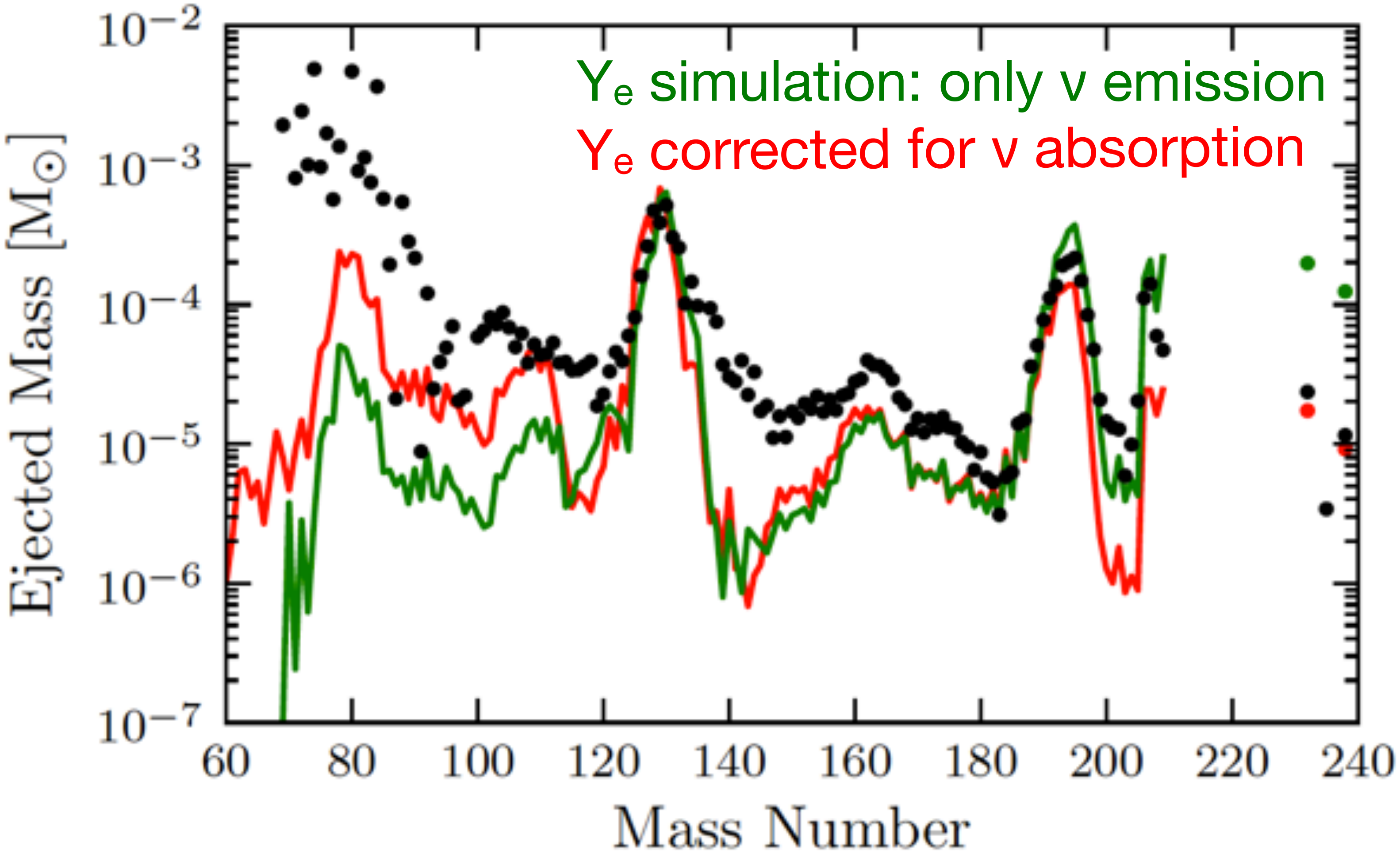


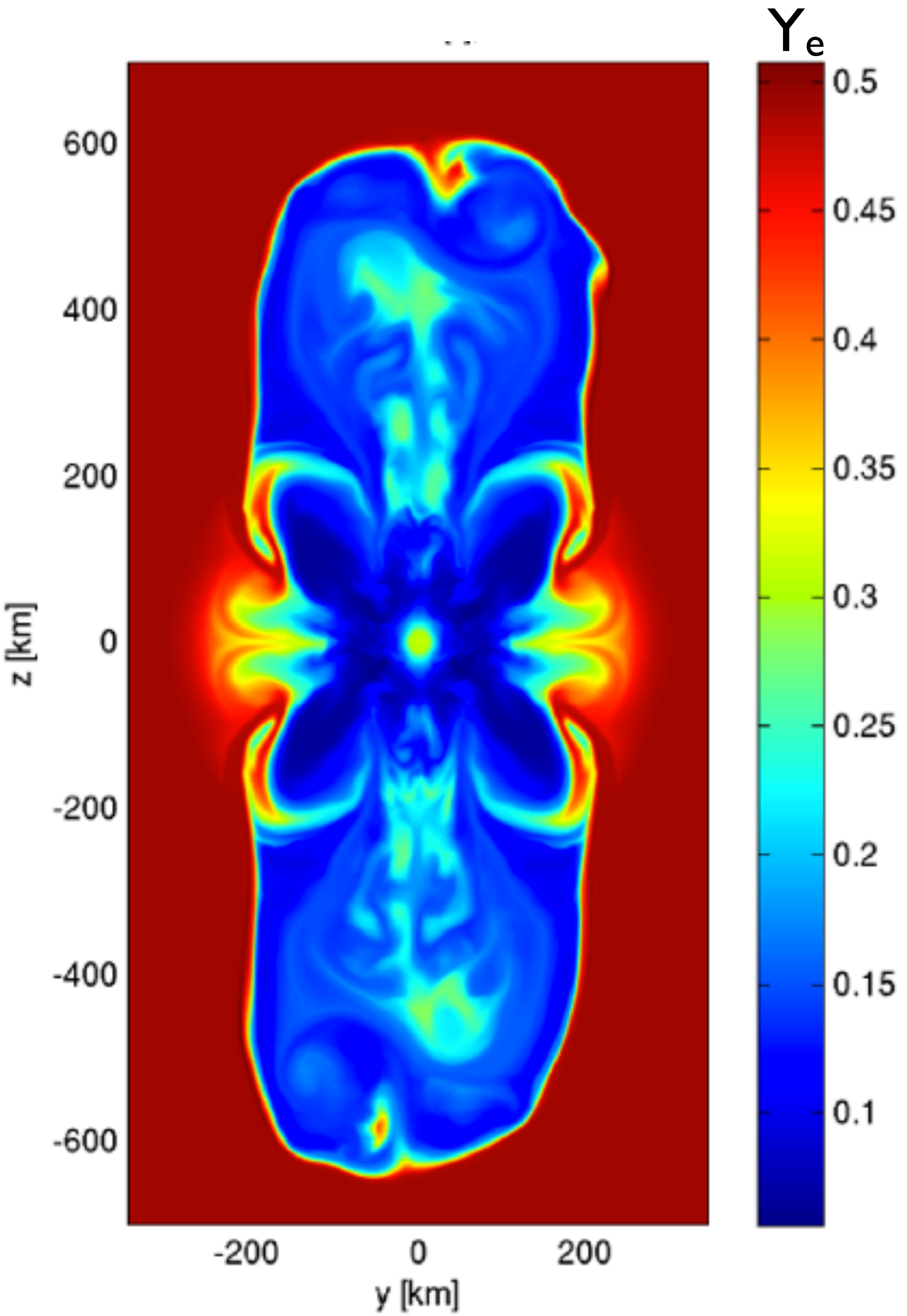
Supernova-jet-like explosion

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

matter collimates: neutron-rich jets

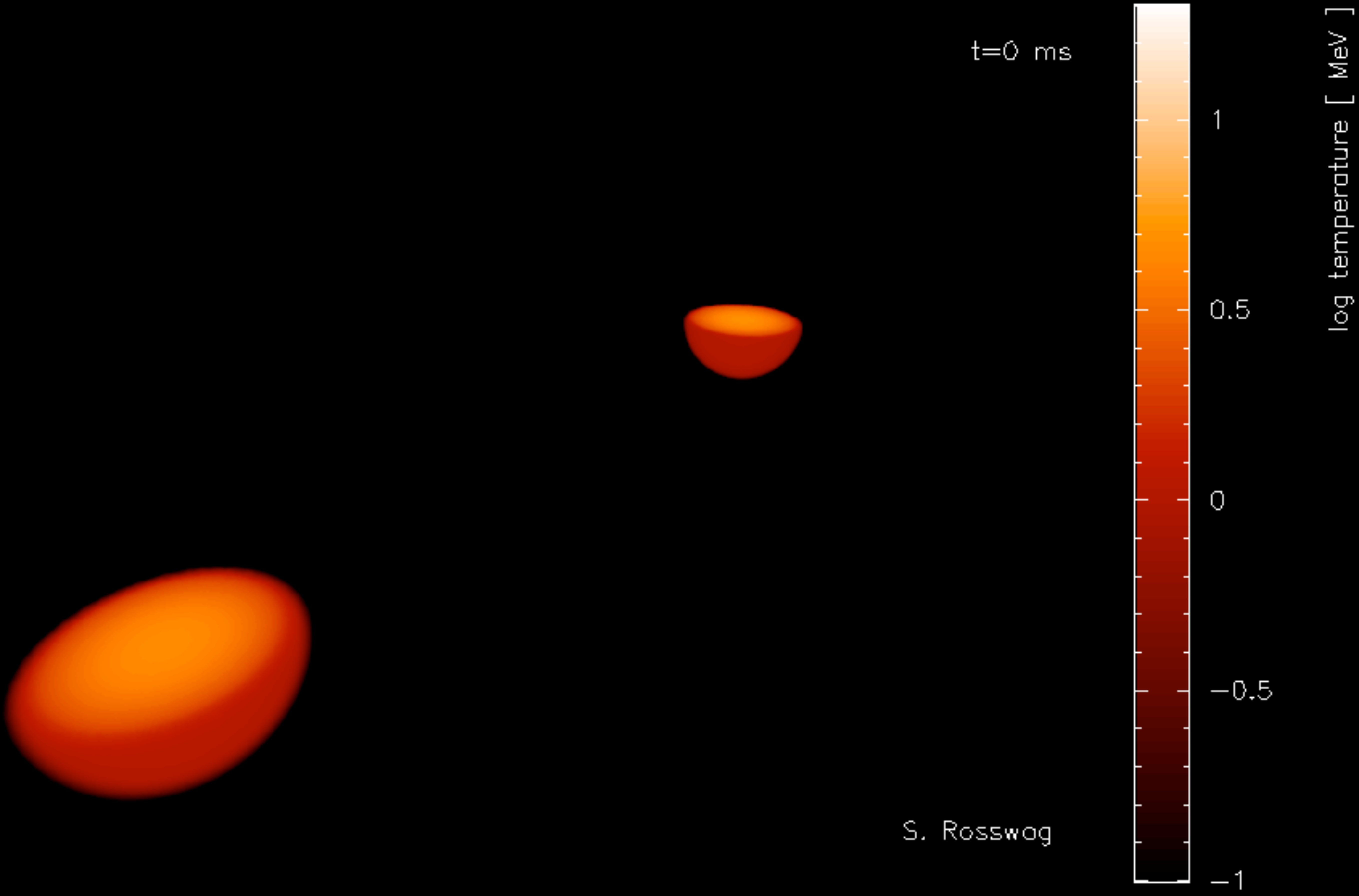
right r-process conditions



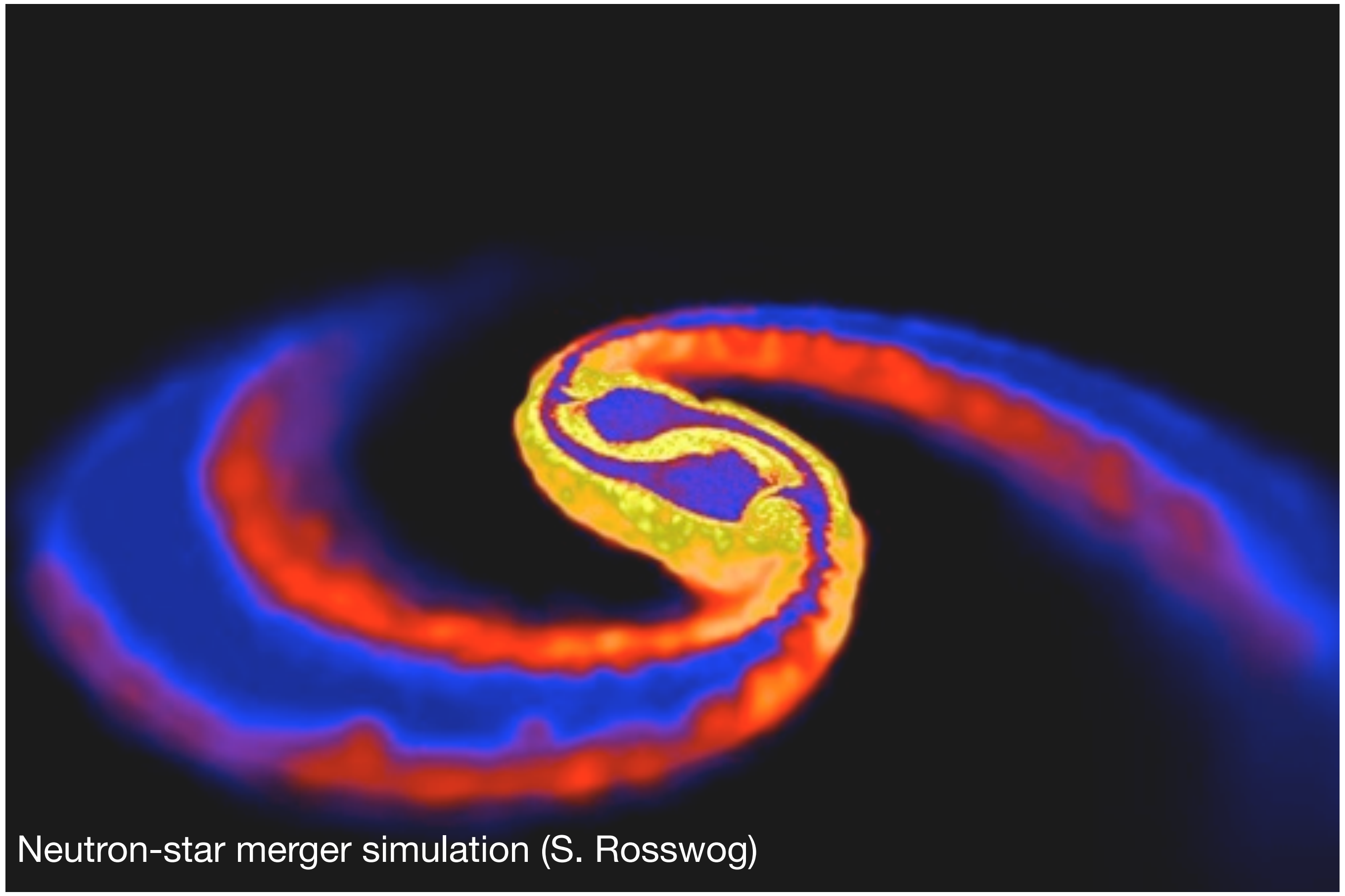


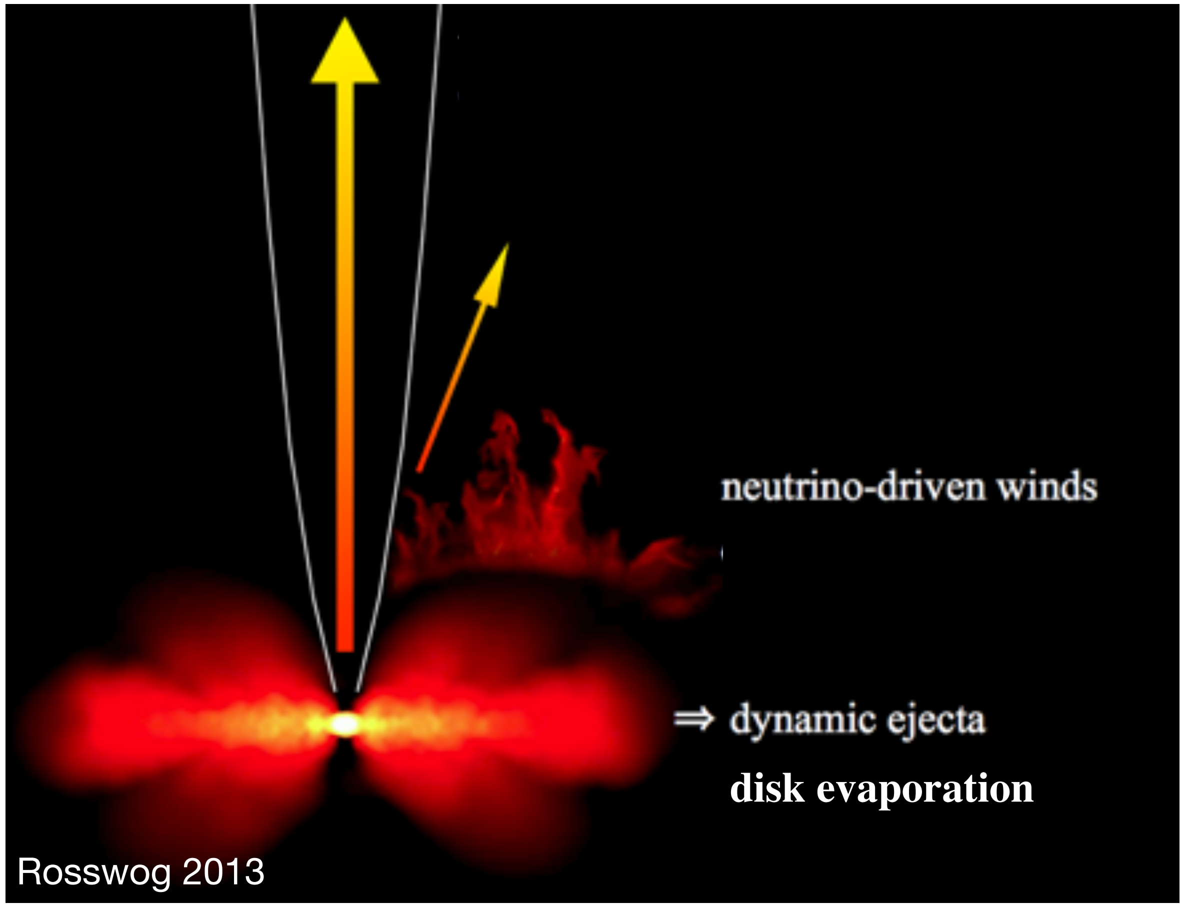
Winteler, Käppeli, Perego et al. 2012

Neutron star mergers



Heavy r-process and neutron star mergers


Neutron-star merger simulation (S. Rosswog)

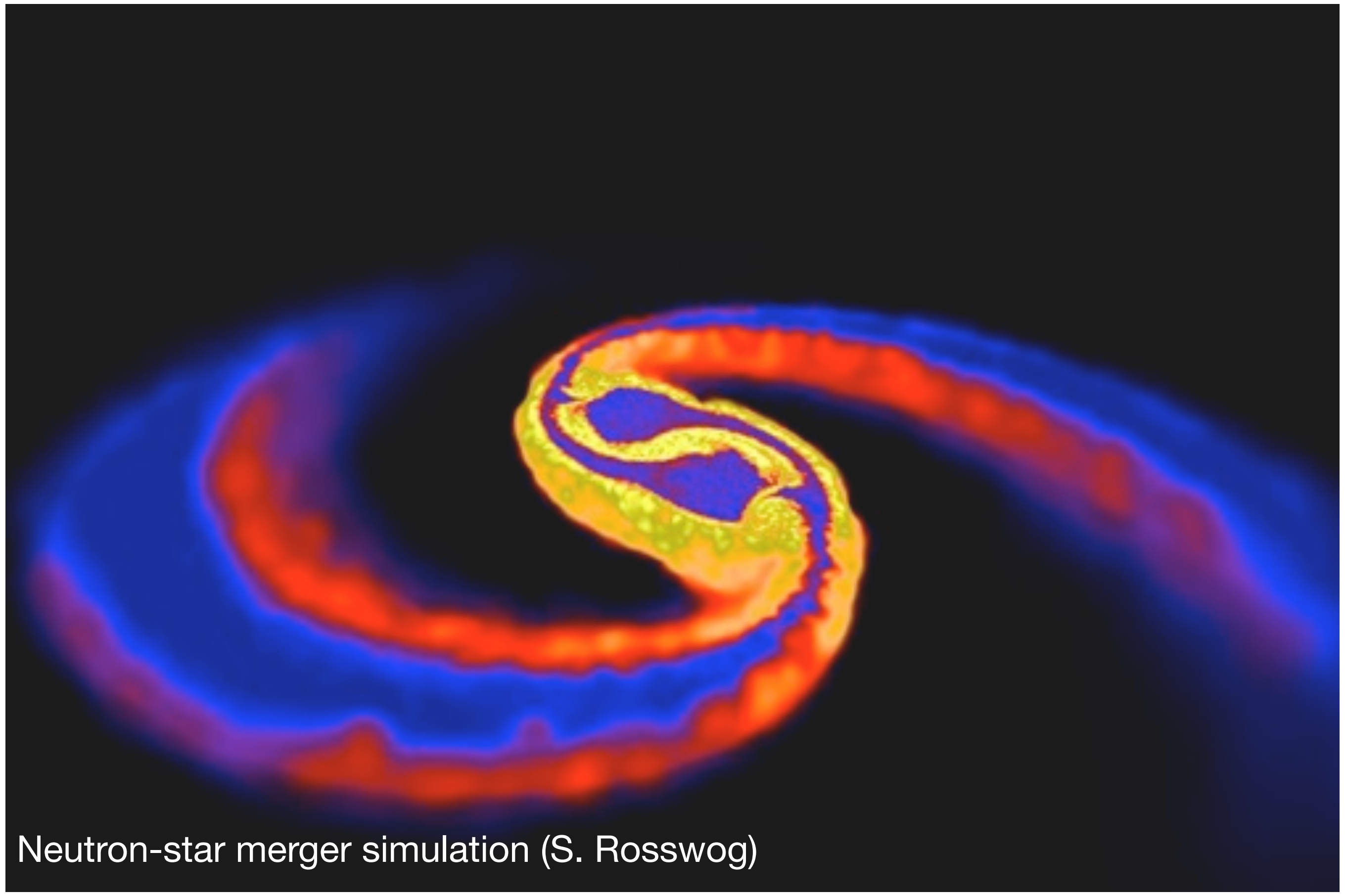


Rosswog 2013

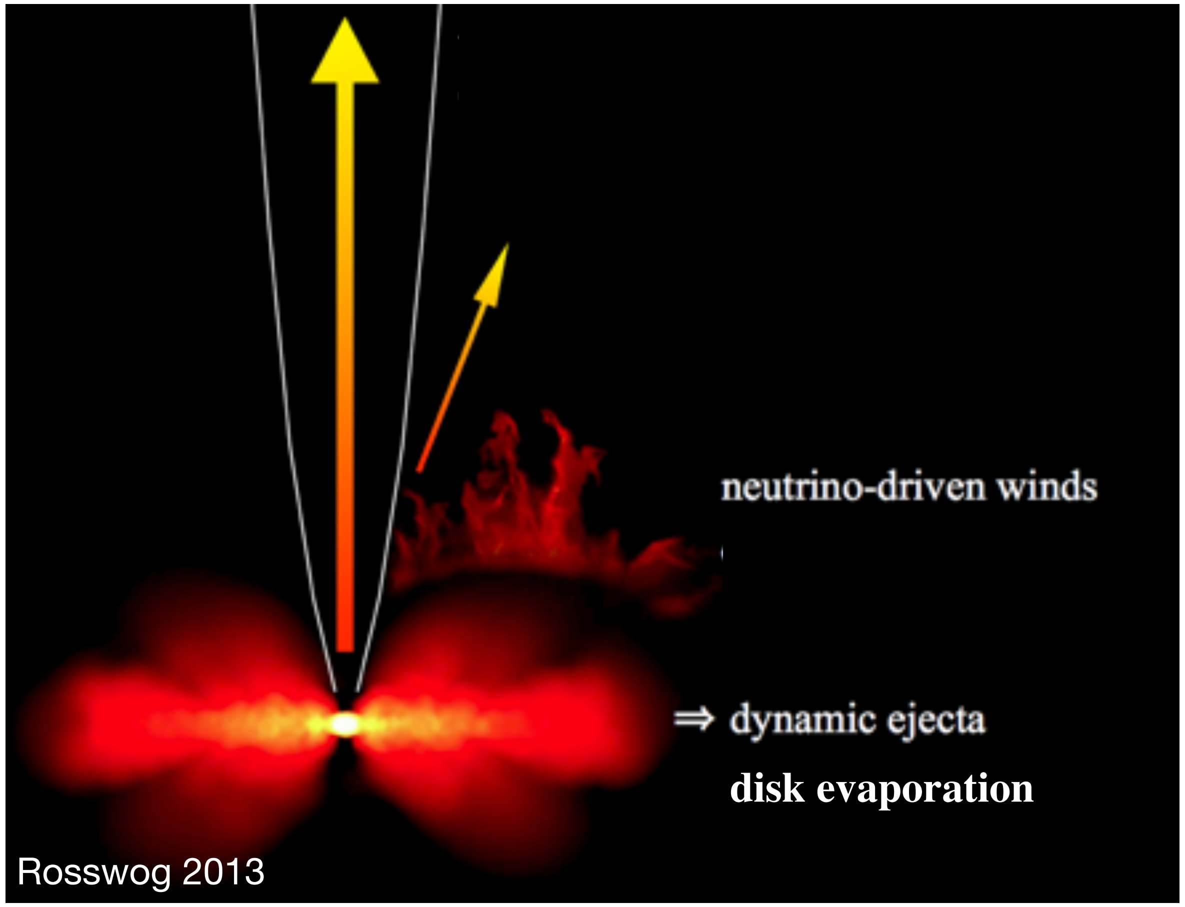
Right conditions for a successful r-process

(Lattimer & Schramm 1974, Freiburghaus et al. 1999, ..., Goriely et al. 2011, Roberts et al. 2011, ...)

Heavy r-process and neutron star mergers



Neutron-star merger simulation (S. Rosswog)



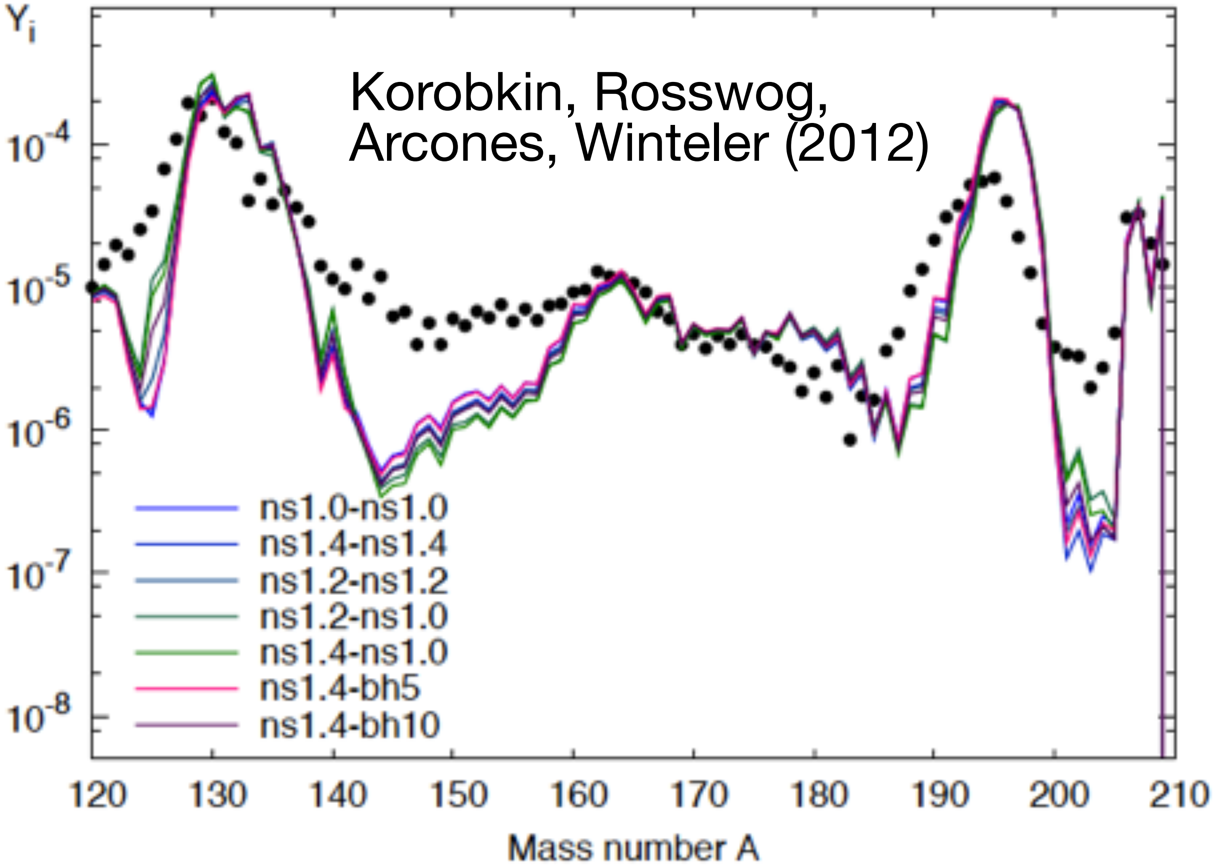
Rosswog 2013

Right conditions for a successful r-process

(Lattimer & Schramm 1974, Freiburghaus et al. 1999, ..., Goriely et al. 2011, Roberts et al. 2011, ...)

Robust r-process:

- extreme neutron-rich conditions
- several fission cycles

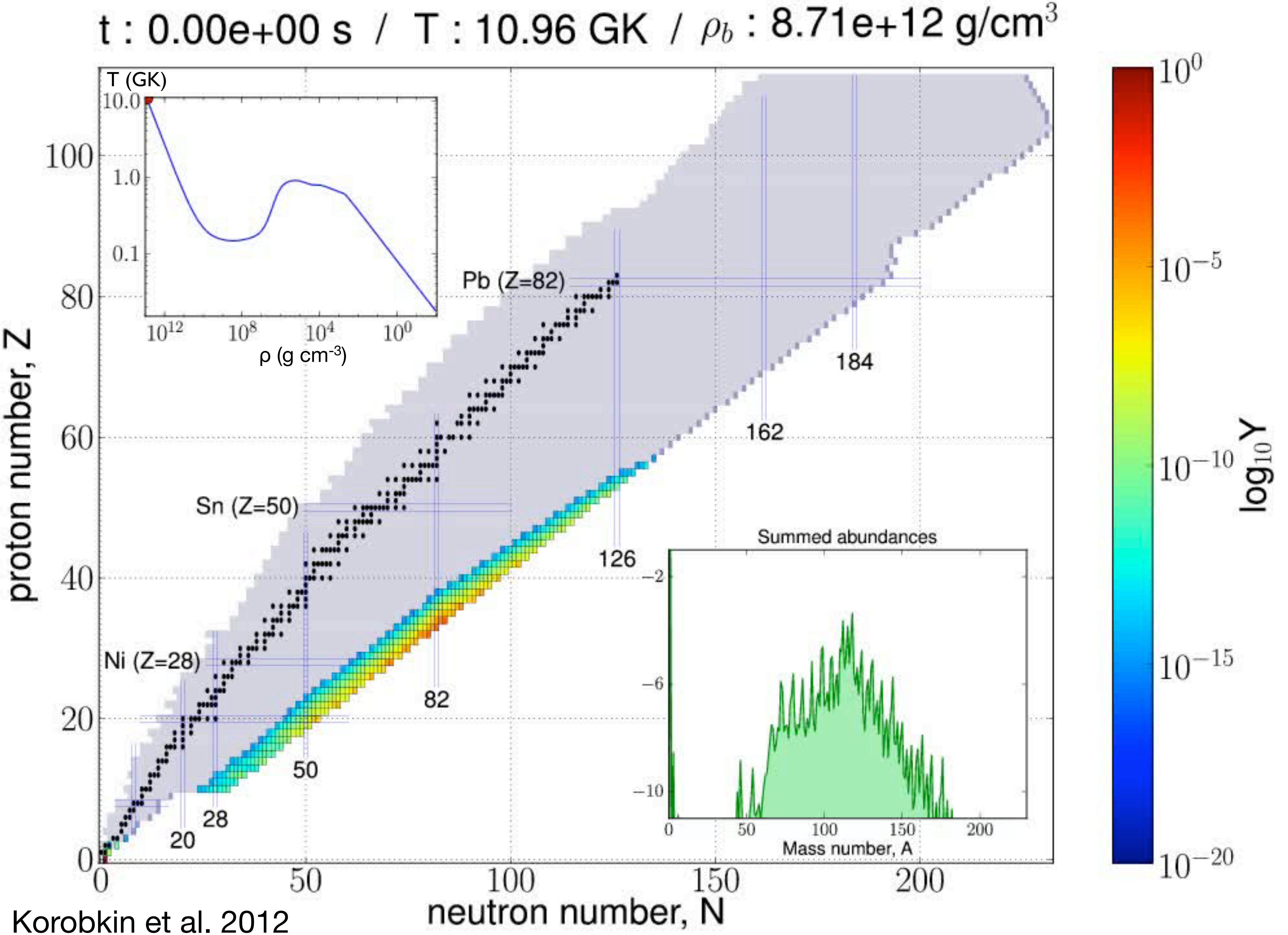


Korobkin, Rosswog, Arcones, Winteler (2012)

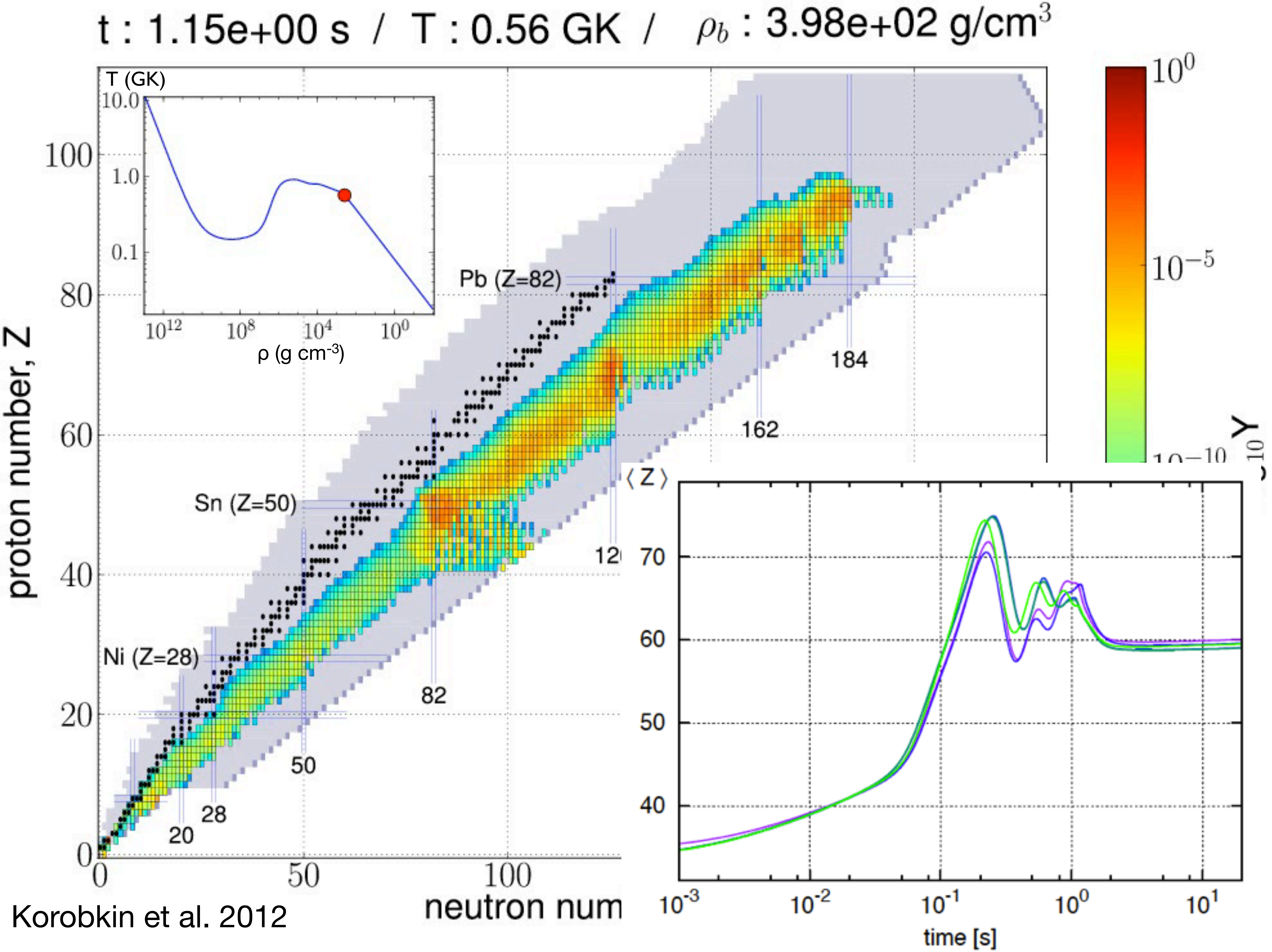
T (GK)

ρ (g cm^{-3})

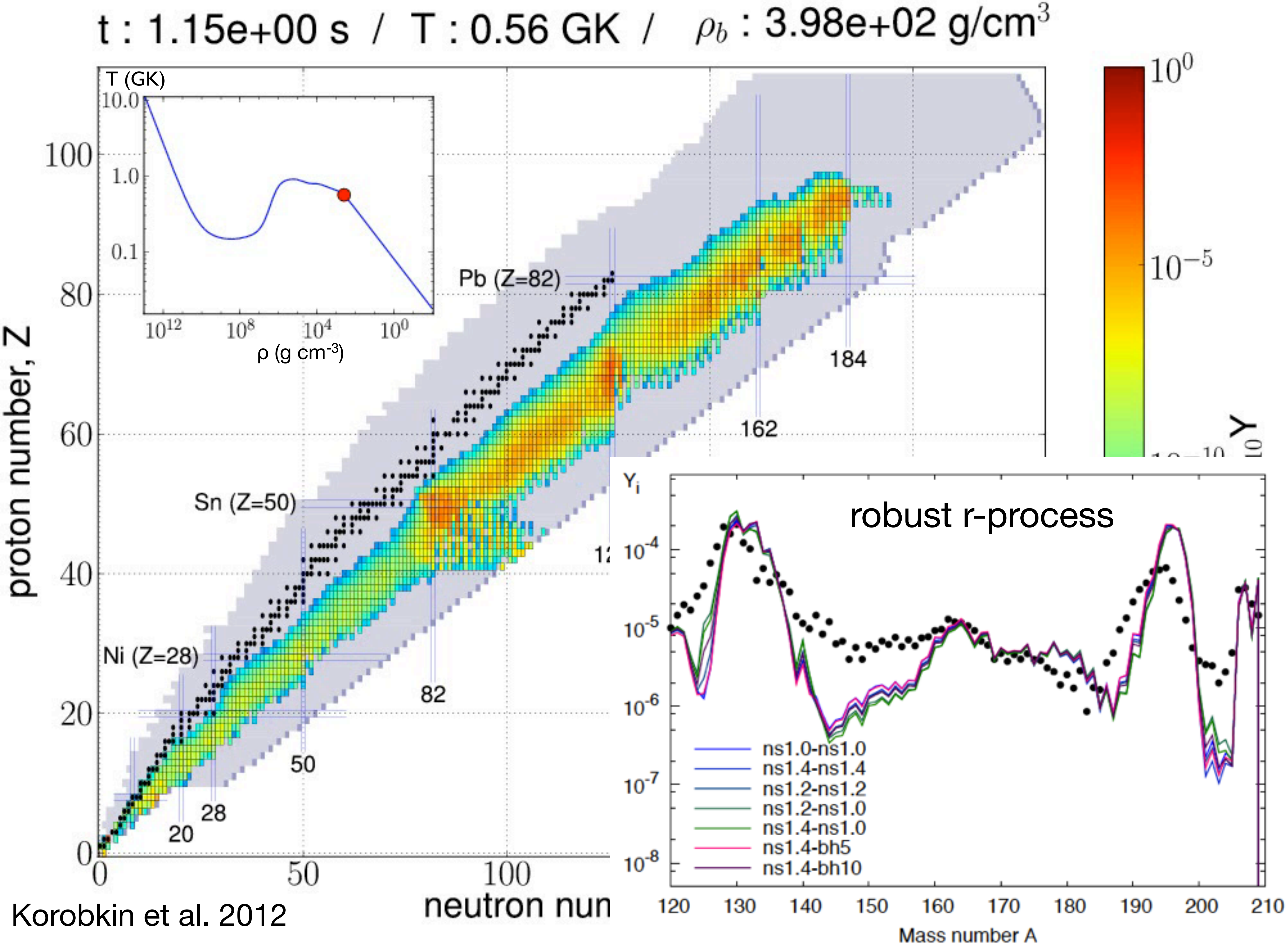
Korobkin et al. 2012



Korobkin et al. 2012



Korobkin et al. 2012



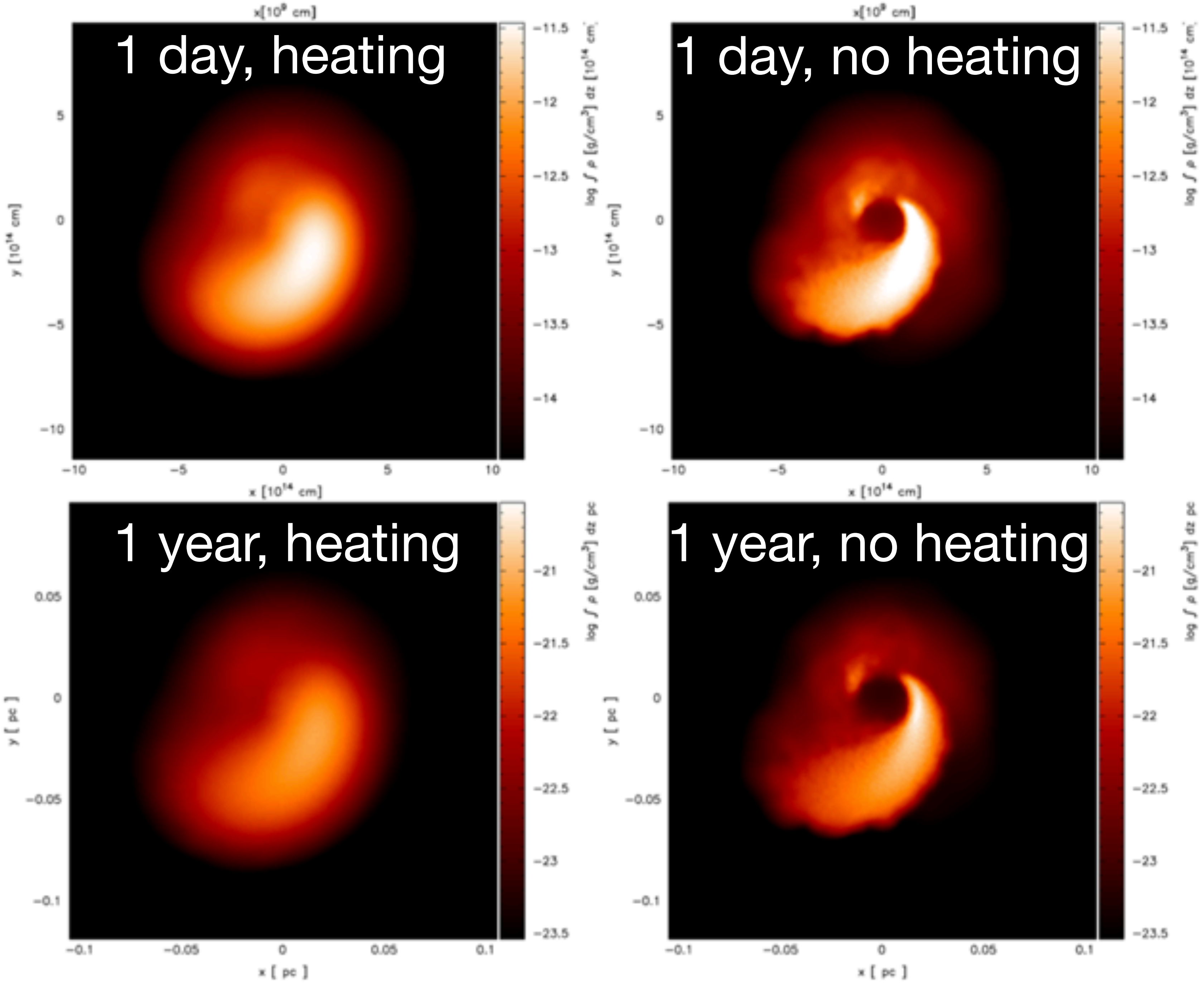
robust r-process

Korobkin et al. 2012

Radioactive decay in neutron star mergers

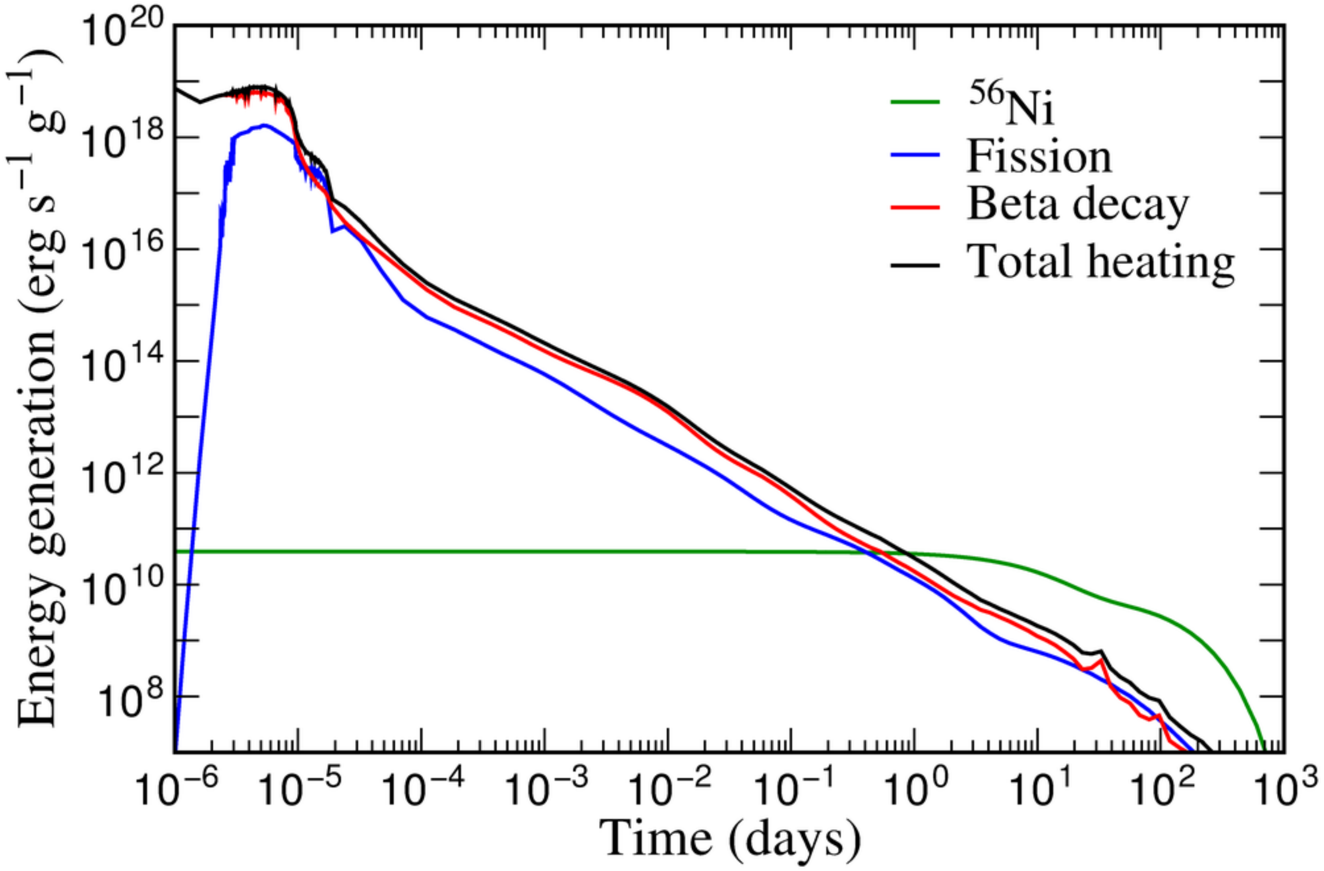
r-process heating affects:

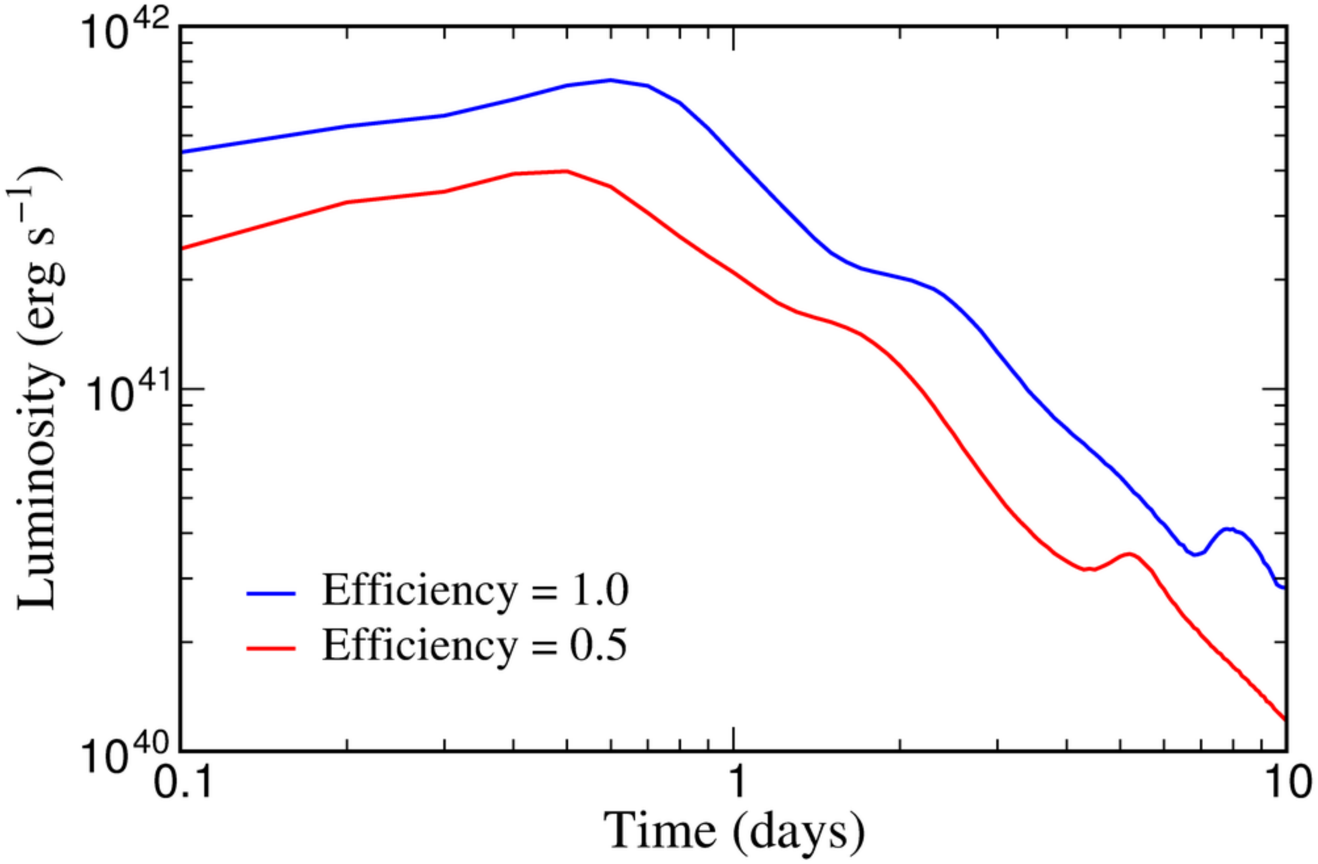
- merger dynamics: late X-ray emission in short GRBs
  (Metzger, Arcones, Quataert,Martinez-Pinedo 2010)
- remnant evolution (Rosswog, Korobkin, Arcones, Thielemann, Piran 2013)



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



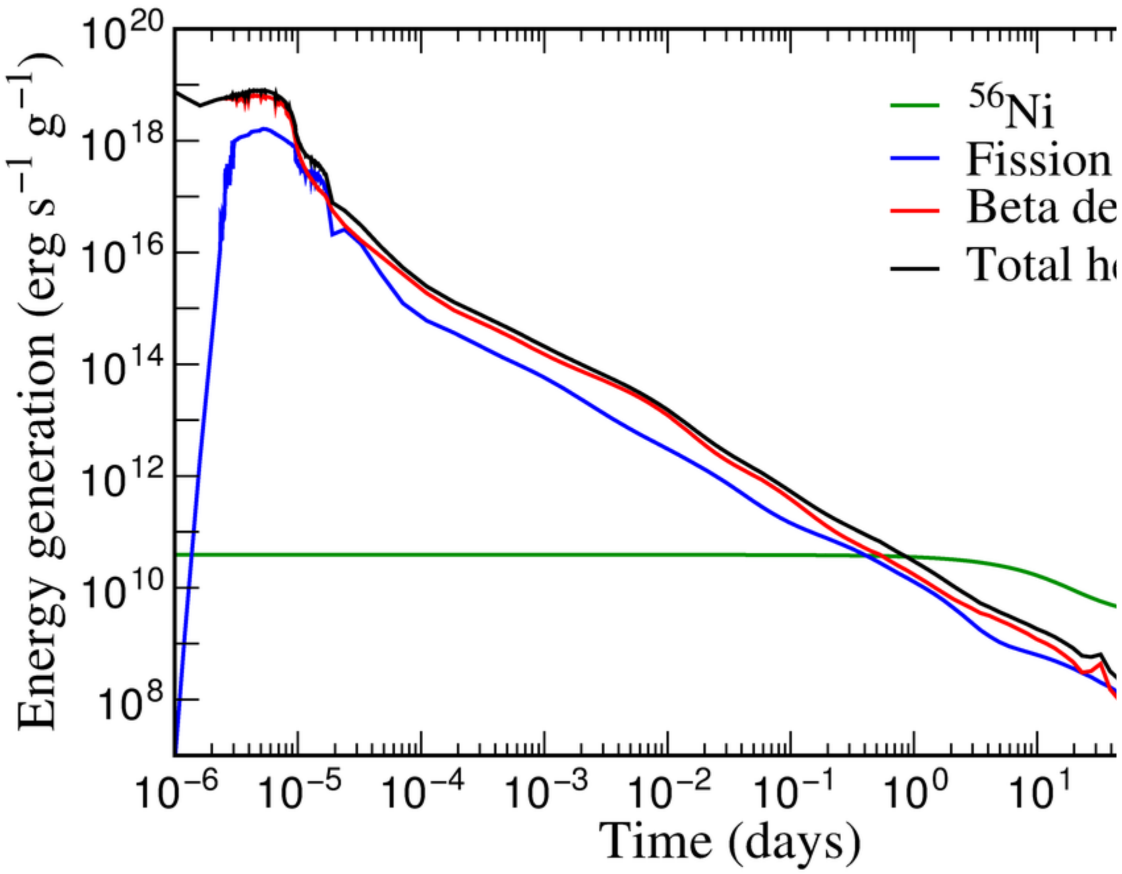


Multi messenger (e.g. Metzger & Berger 2012, Rosswog 2012, Bauswein et al. 2013)

Radioactive decay in r

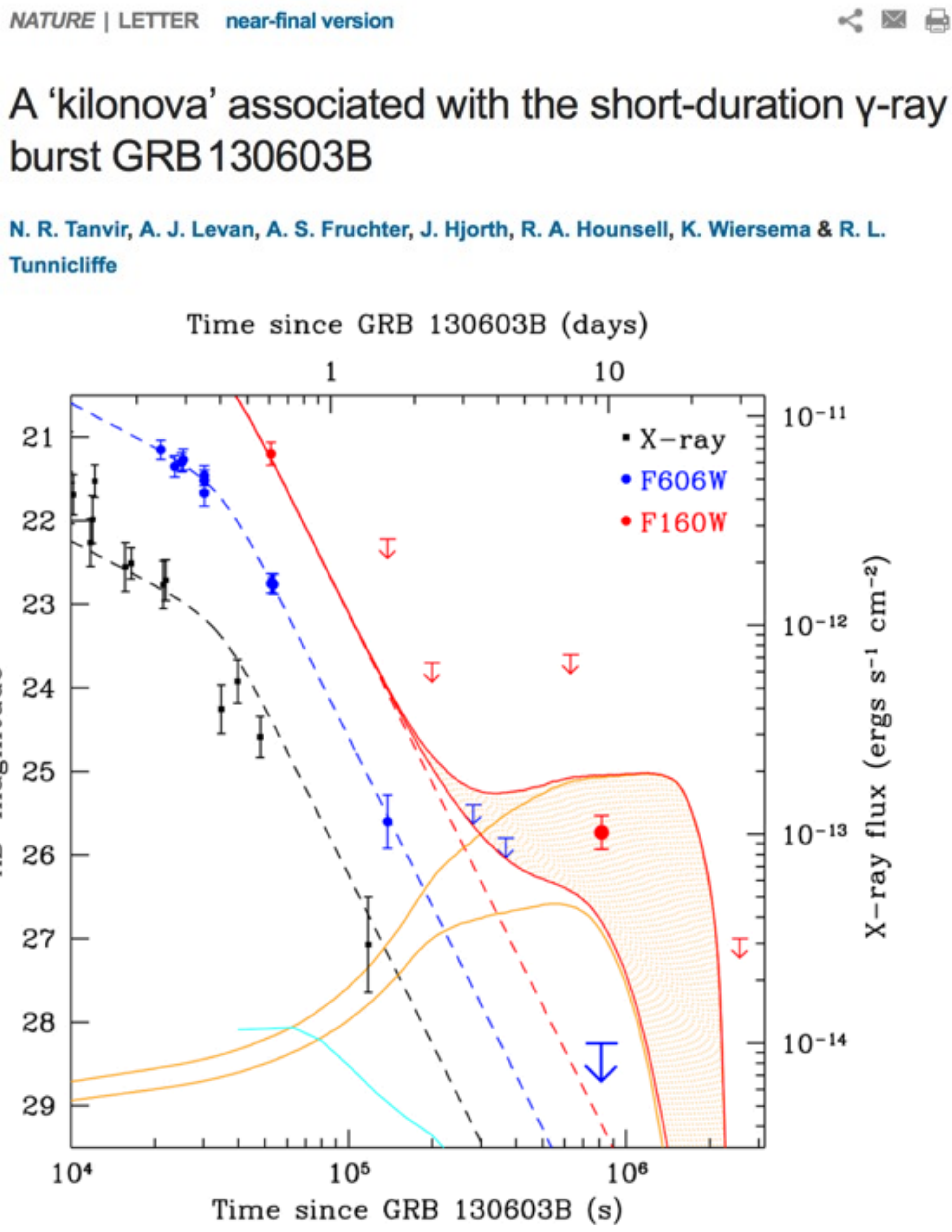
Transient with kilo-nova luminos

Goriely et al. 2011): direct observatio



Multi messenger (e.g. Metzger

Berger, Fong & Chornock, 2013
Tanaka & Hotokezaka, 2013
Grossman, Korobkin, Rosswog,Piran, 2013



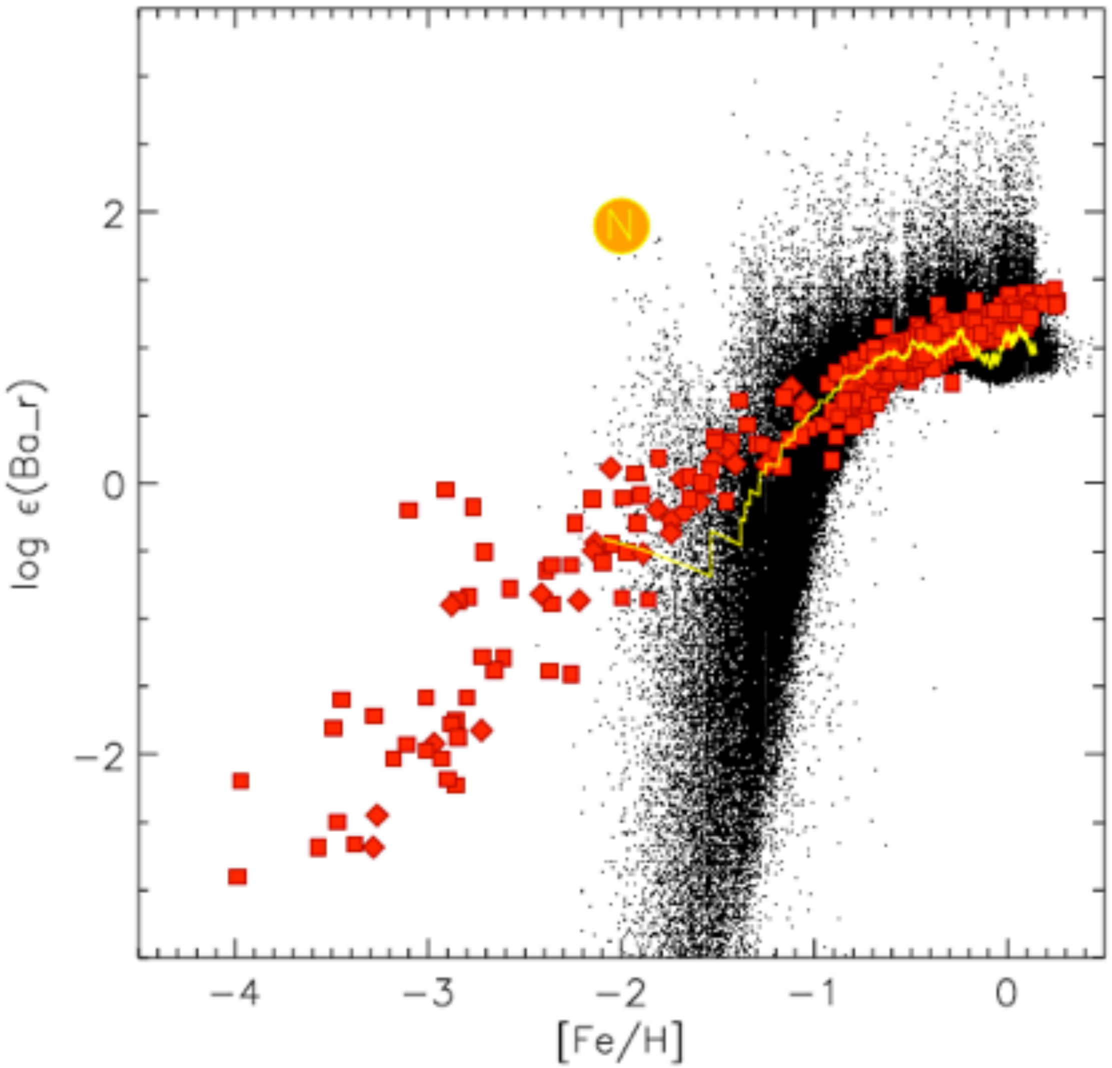
NATURE | LETTER **near-final version**

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

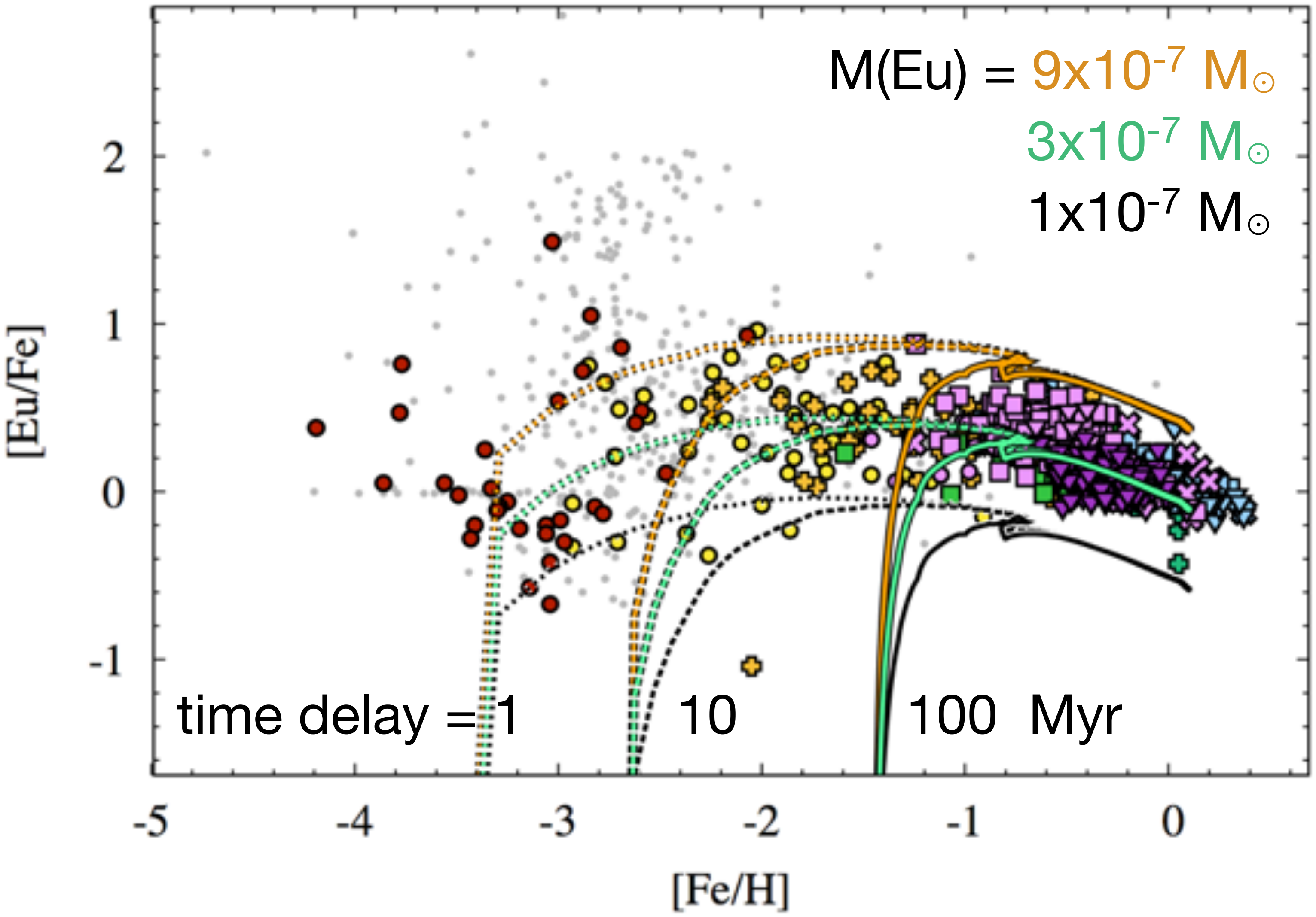
Neutron star mergers and GCE

Argast, Samland,
Thielemann, Qian (2004)



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

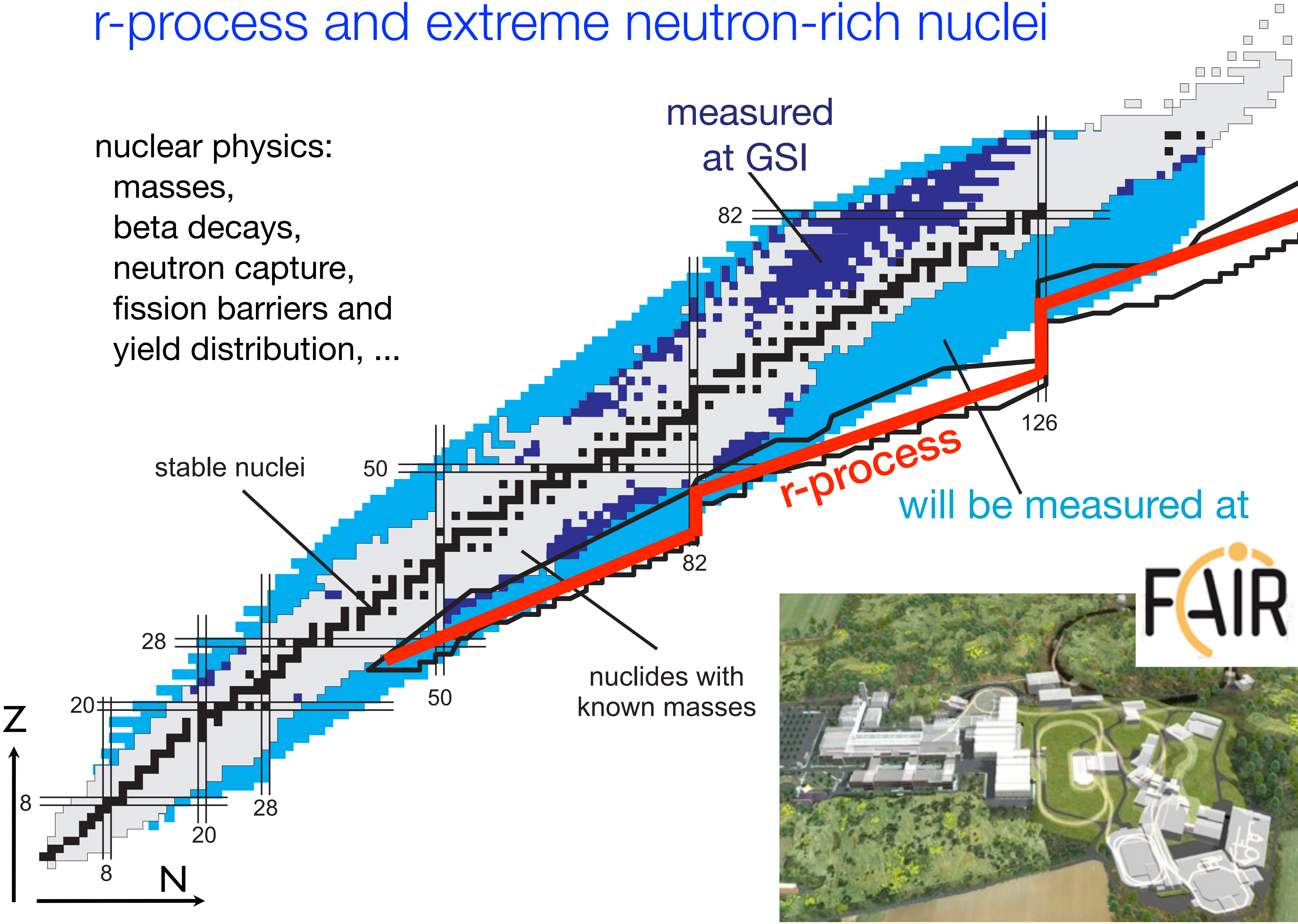
Matteucci, Romano,
Arcones, Korobkin, Rosswog (2013)



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

r-process and extreme neutron-rich nuclei

nuclear physics:
- masses,
- beta decays,
- neutron capture,
- fission barriers and
- yield distribution, ...

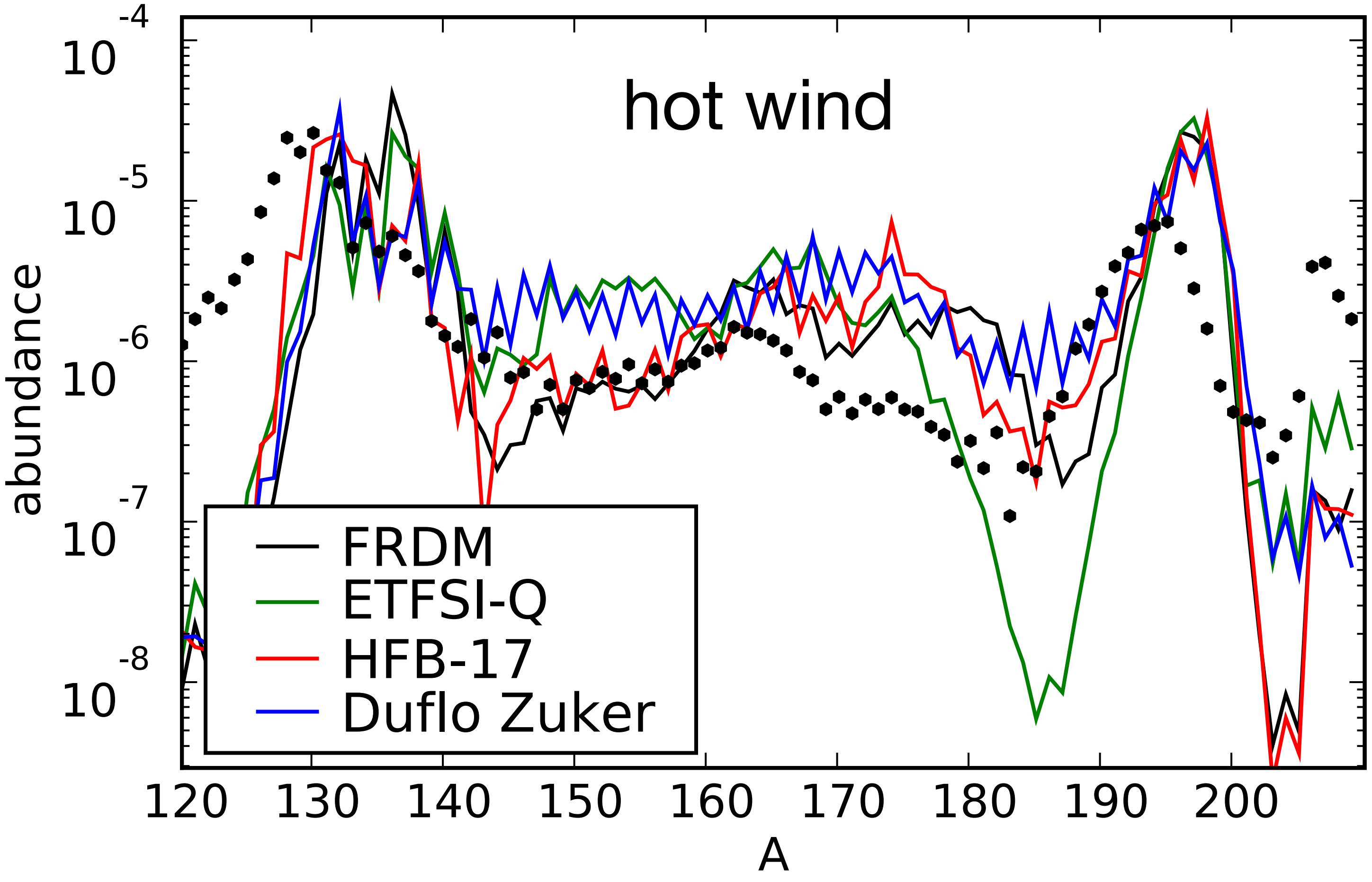


Nuclear masses

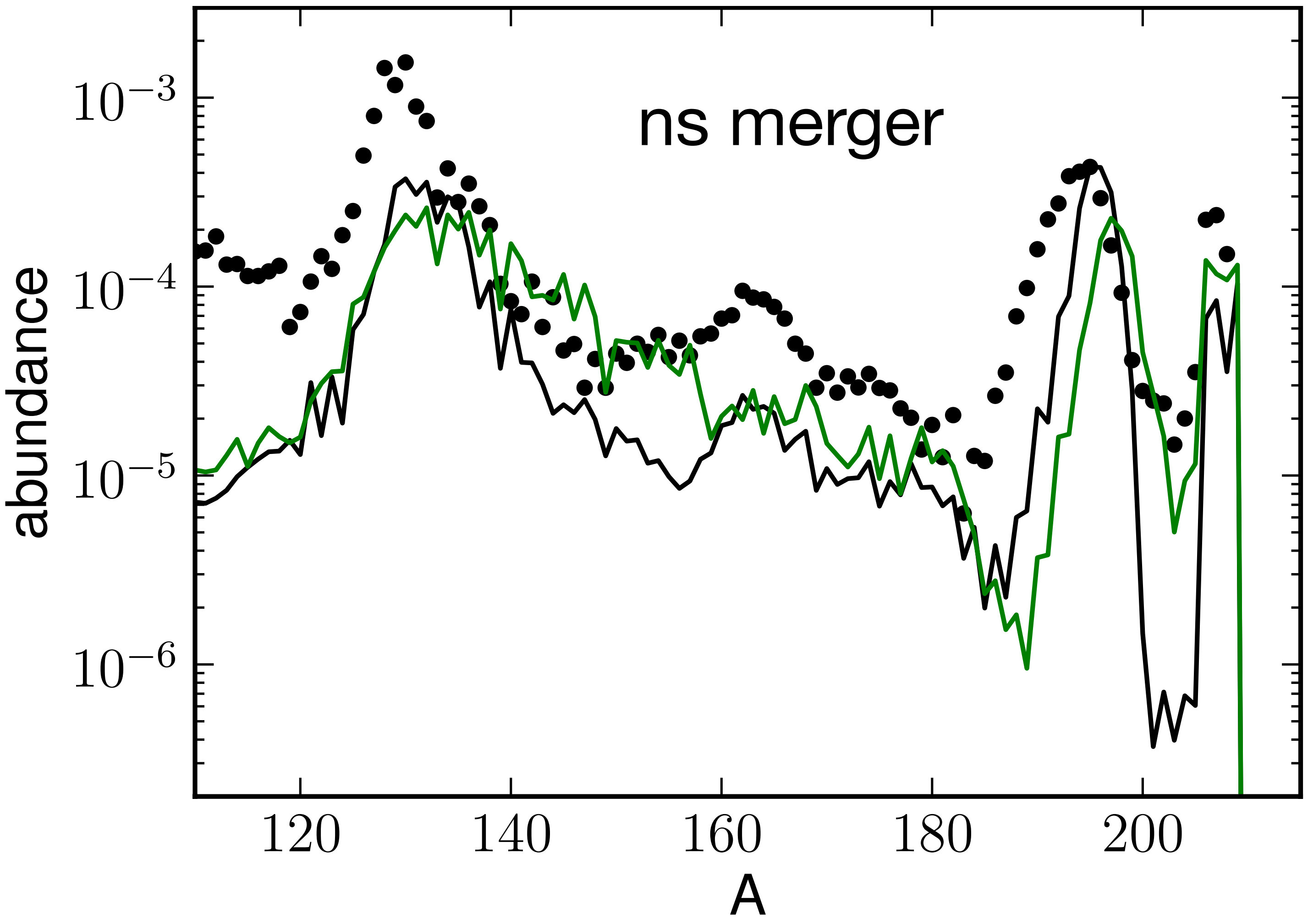
Given astrophysical conditions, comparison of abundances based different mass models

- FRDM (Möller et al. 1995)
- ETFSI-Q (Pearson et al. 1996)
- HFB-17 (Goriely et al. 2009)
- Duflo&Zuker

Can we link masses (neutron separation energies) to the final r-process abundances?



Arcones & Martinez-Pinedo, 2011

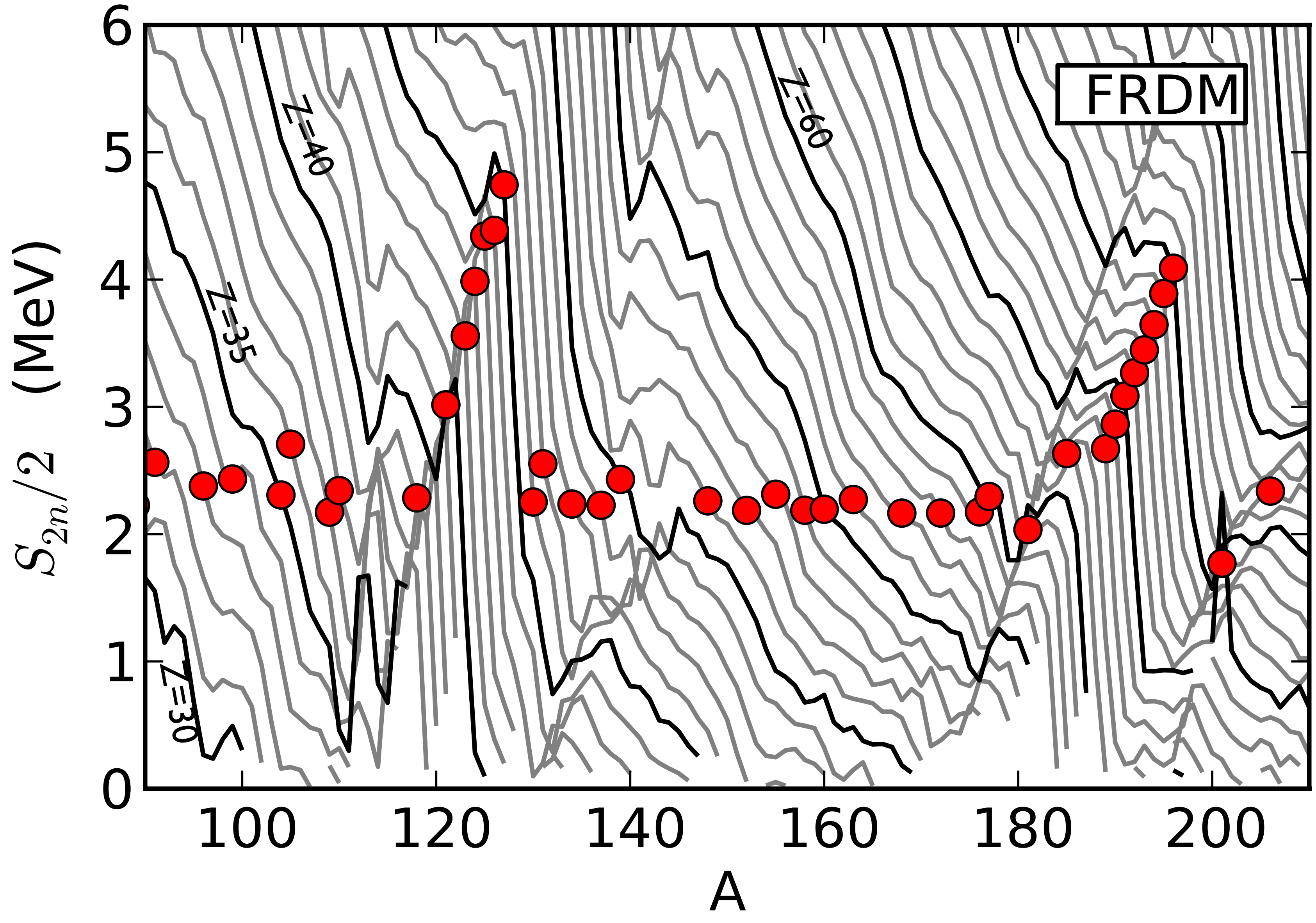


Two neutron separation energy

Abundances

S_{2n}

Nuclear properties



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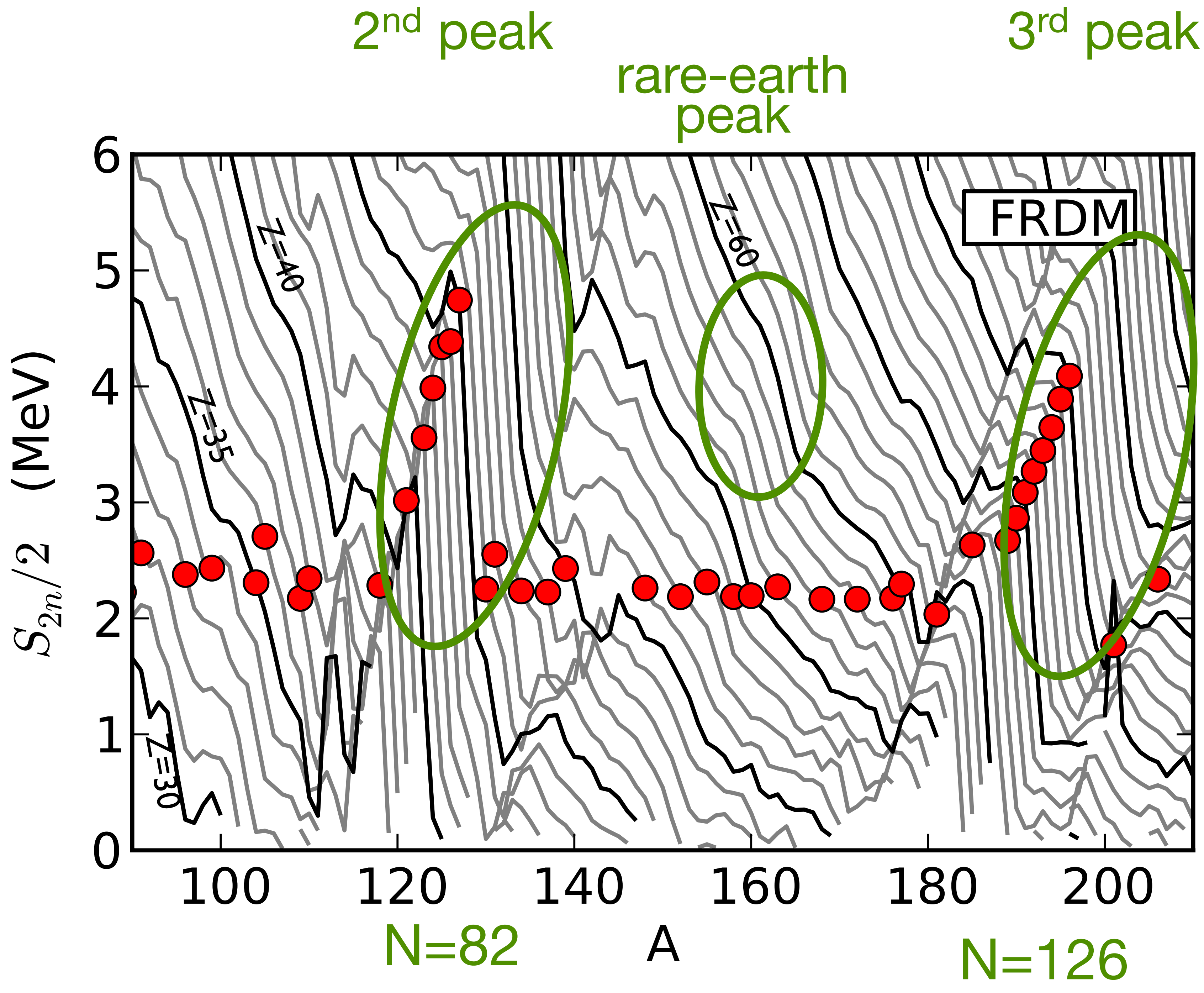


Two neutron separation energy

Abundances

S_{2n}

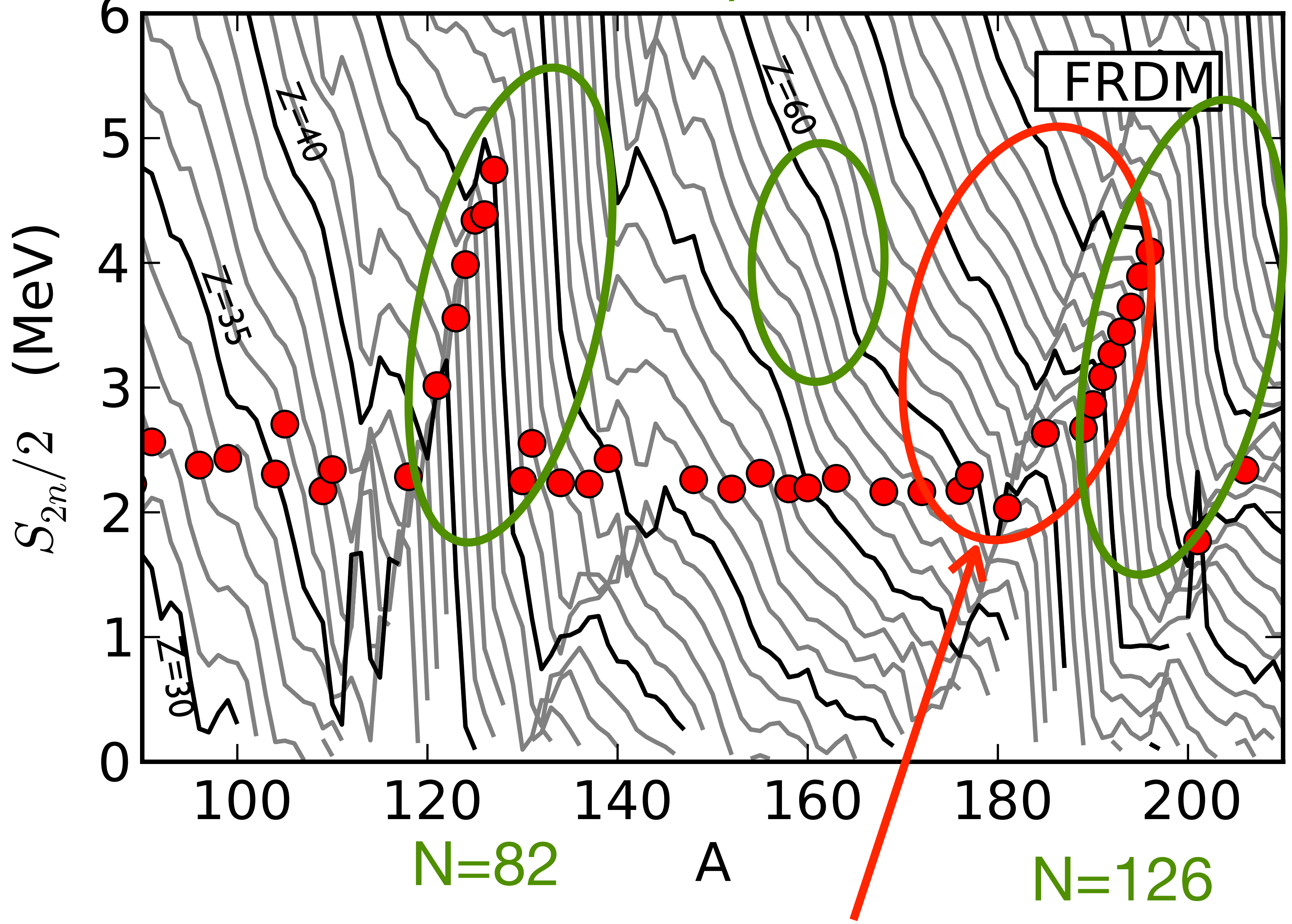
Nuclear properties

2^{nd} peak

rare-earth peak

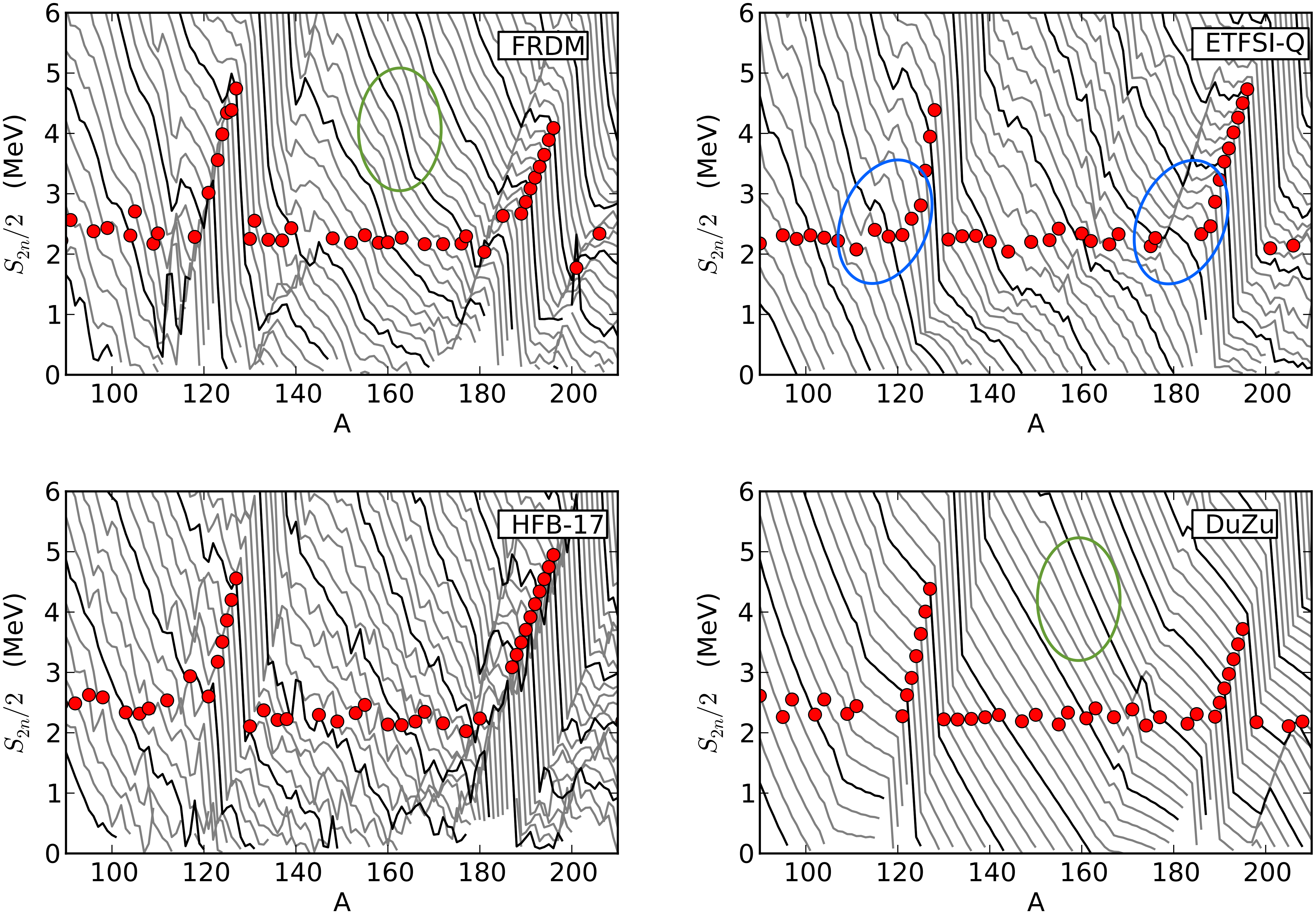
trough

3^{rd} peak



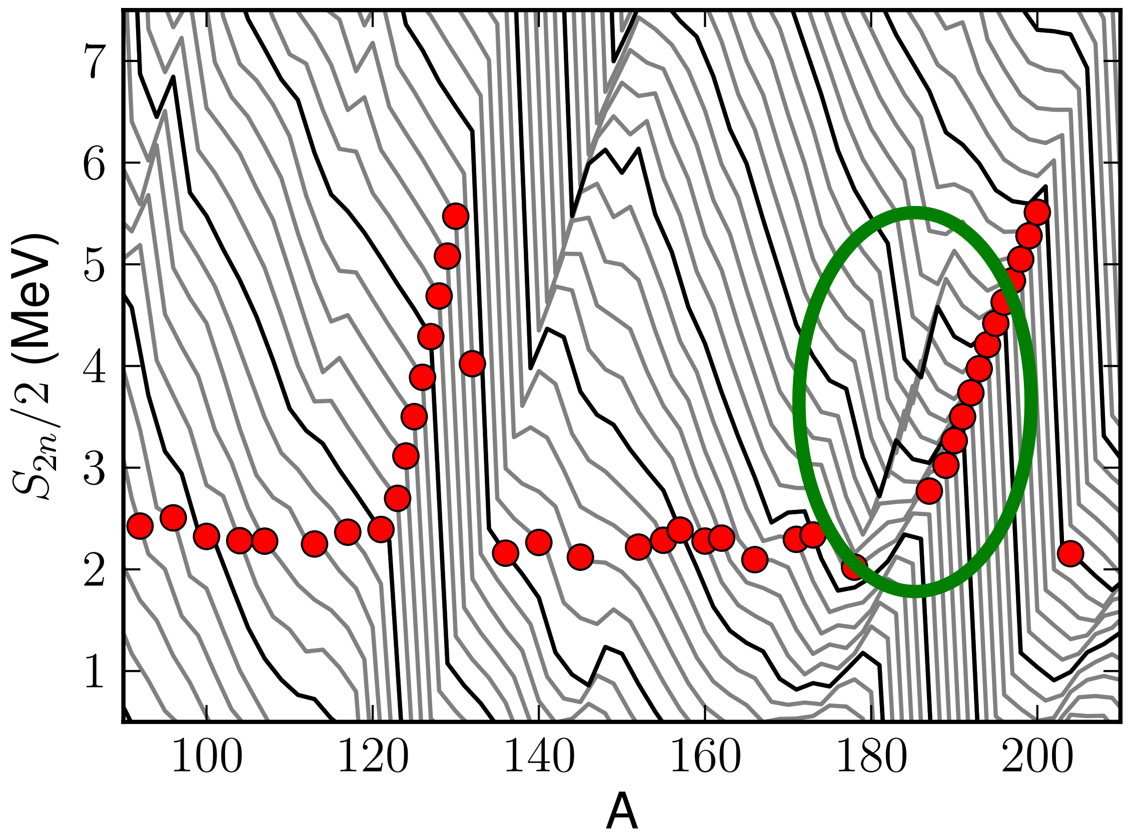
transition from deformed to spherical

Aspects of different mass models

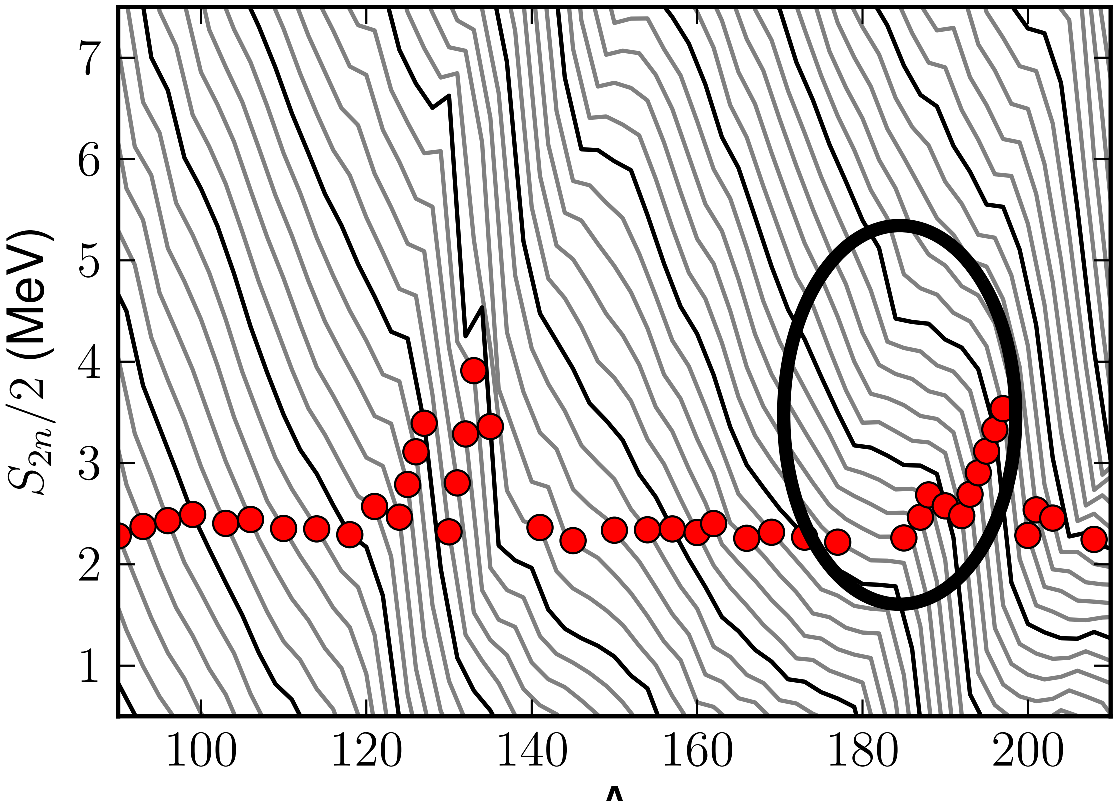


Nuclear correlations and r-process

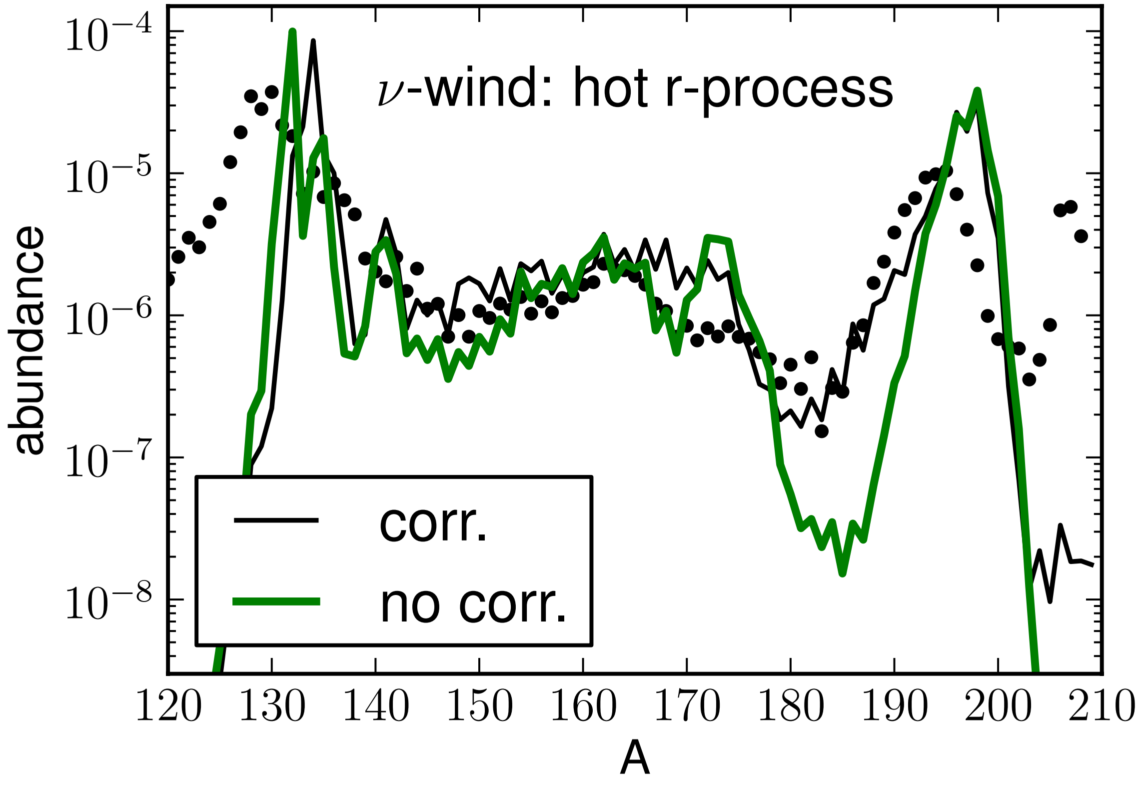
without correlations



with correlations



Delaroche et al. 2010: microscopic nuclear mass calculations including quadrupole correlations

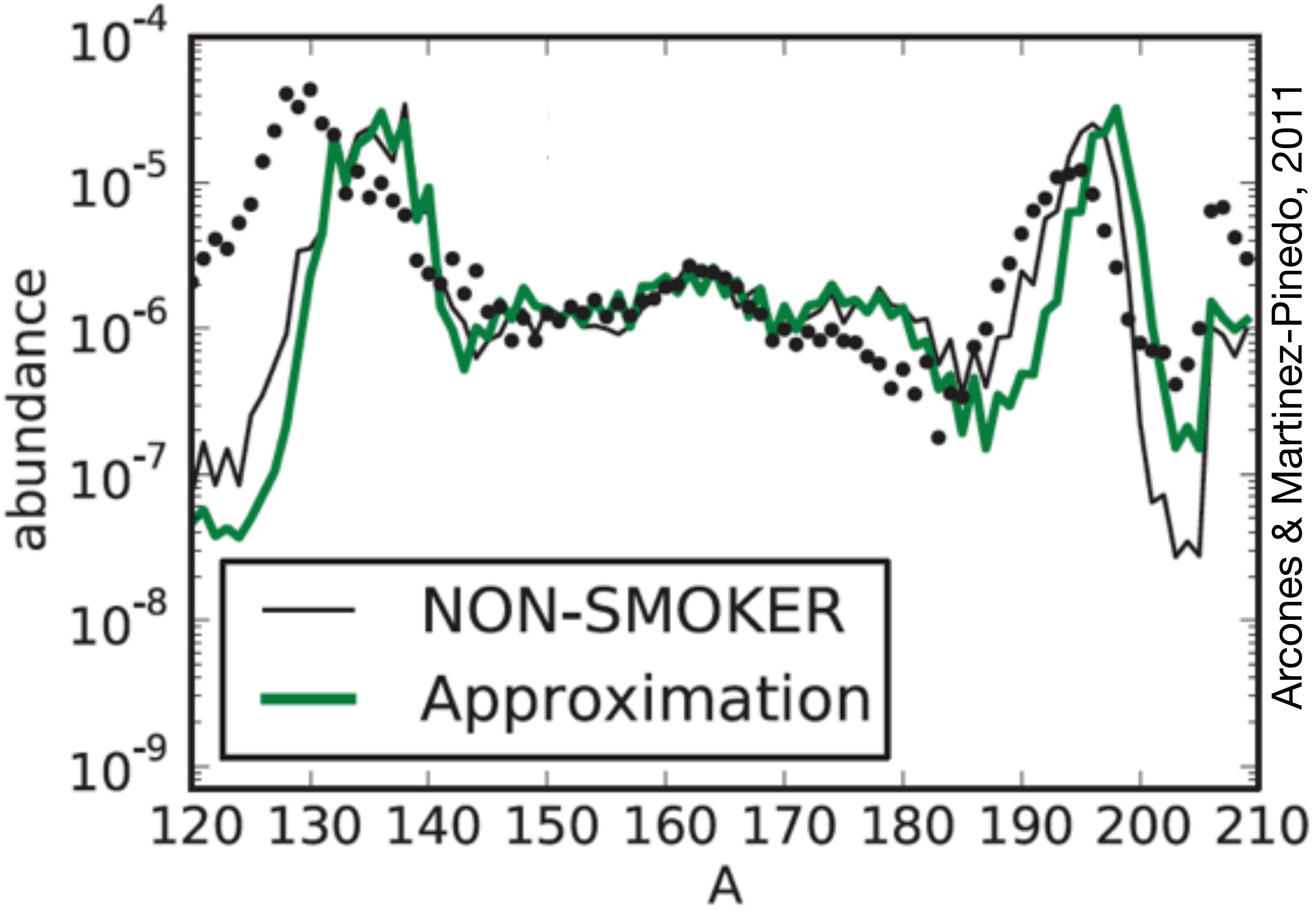


Nuclear correlations: strong impact on trough before third peak!

Arcones & Bertsch (2012)

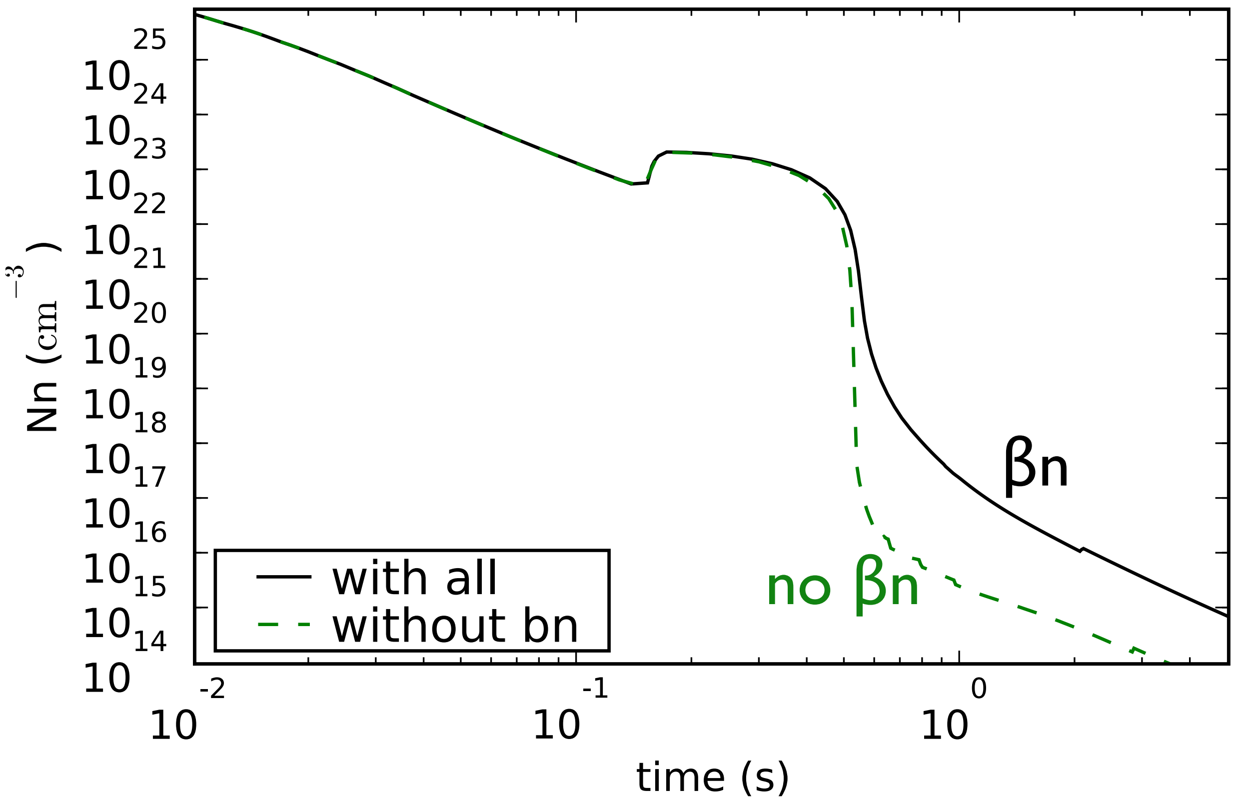
Neutron captures

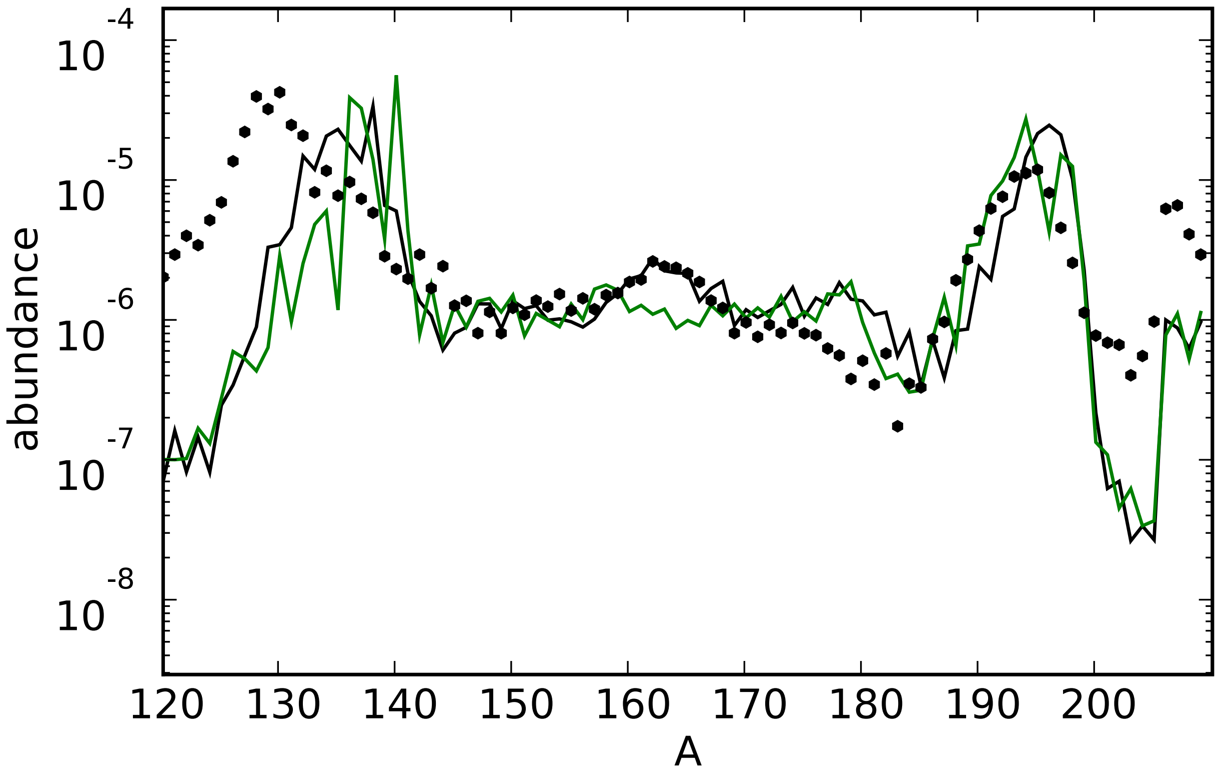
- -NON-SMOKER
  (Rauscher & Thielemann, 2000)
- -Approximation
  (Woosley, Fowler et al. 1975)



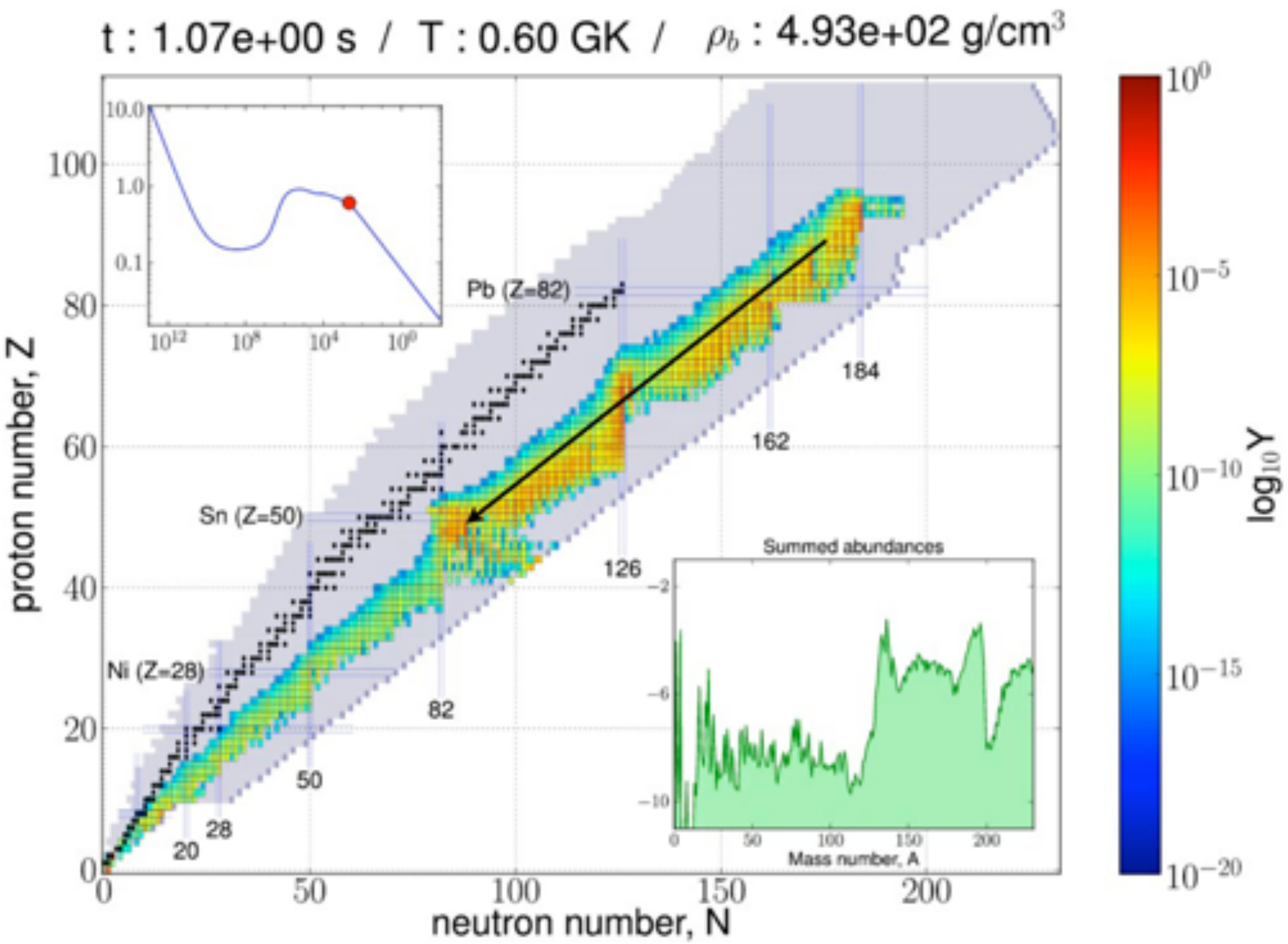
Arcones & Martinez-Pinedo, 2011

and beta-delayed neutron emission

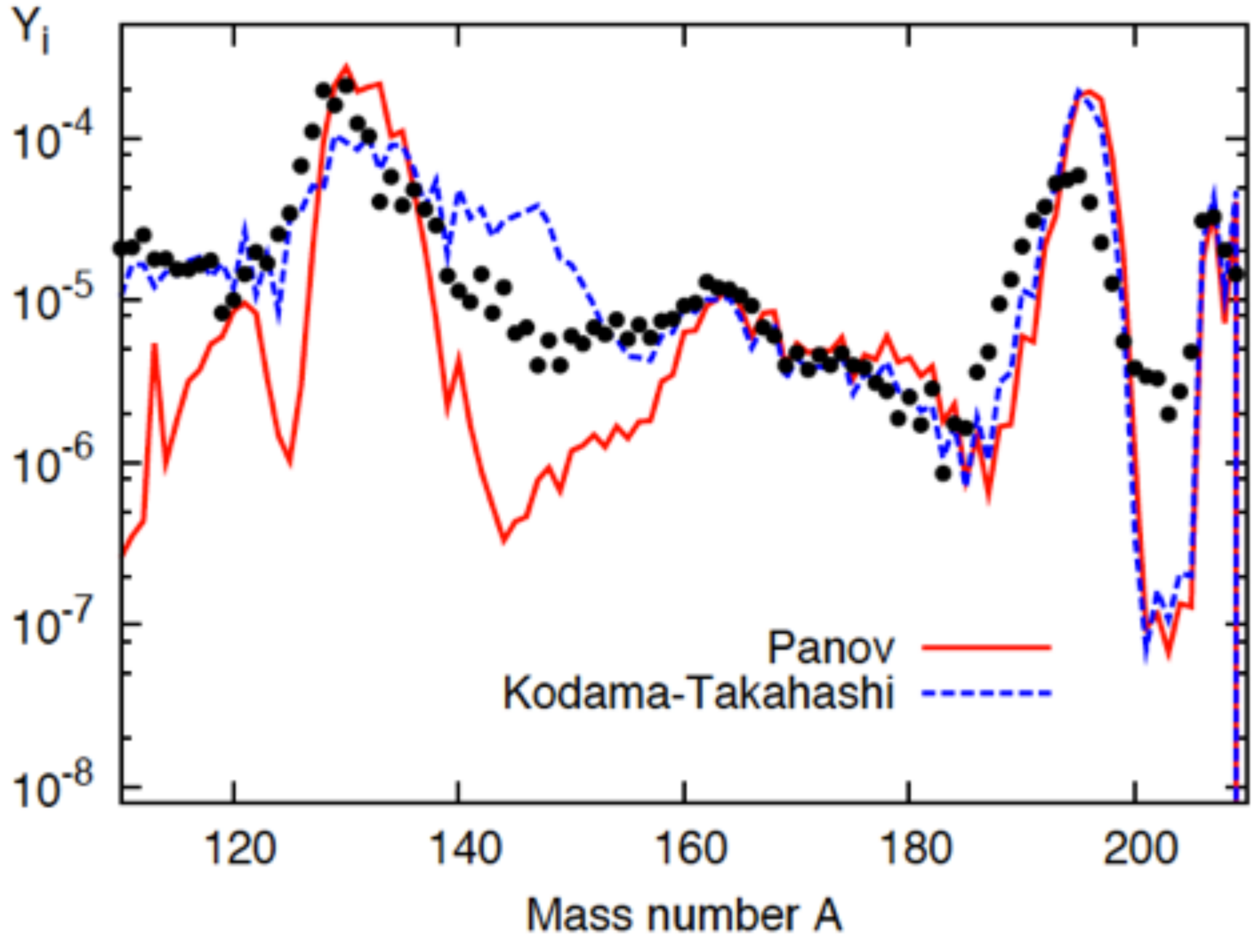




Fission: barriers and yield distributions



Korobkin, Rosswog, Arcones, Winteler (2012)



Neutron star mergers: r-process with two simple fission descriptions

2nd peak (A~130): fission yield distribution (see Goriely et al. 2013)
3rd peak (A~195): mass model, neutron captures

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

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INT Program (Seattle, July 28 - August 29):
Nucleosynthesis and Chemical Evolution
W. Aoki, A. Arcones, J. Dalcanton, F. Montes, Y.-Z. Qian