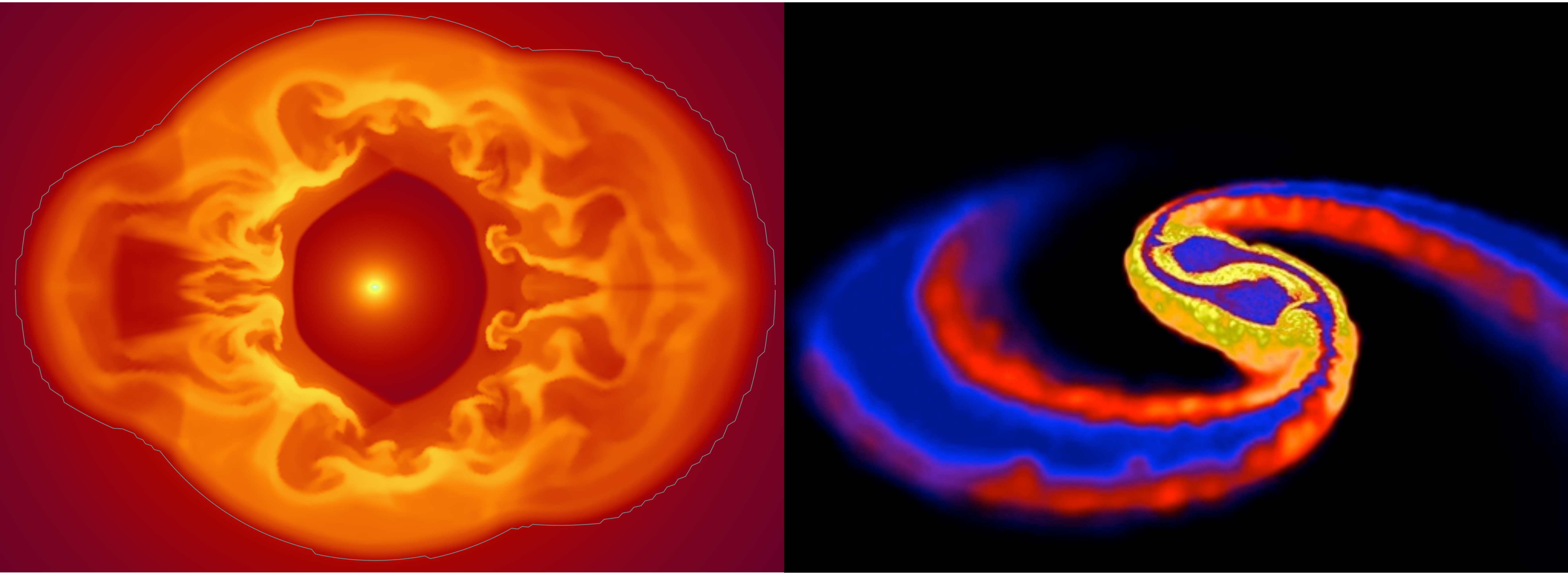
Nucleosynthesis in core-collapse supernovae and neutron star mergers



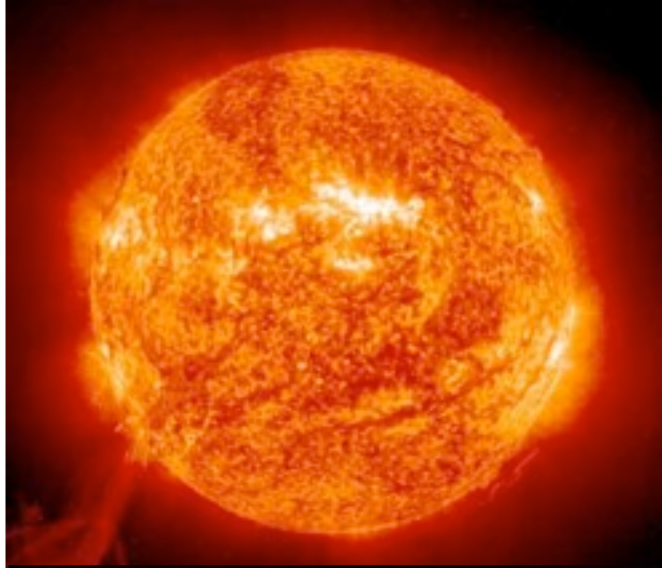
TECHNISCHE UNIVERSITÄT DARMSTADT

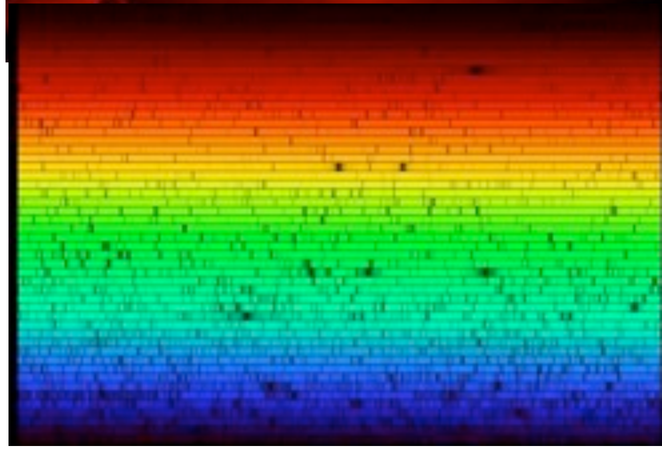
Almudena Arcones

HELMHOLTZ GEMEINSCHAFT

GSI

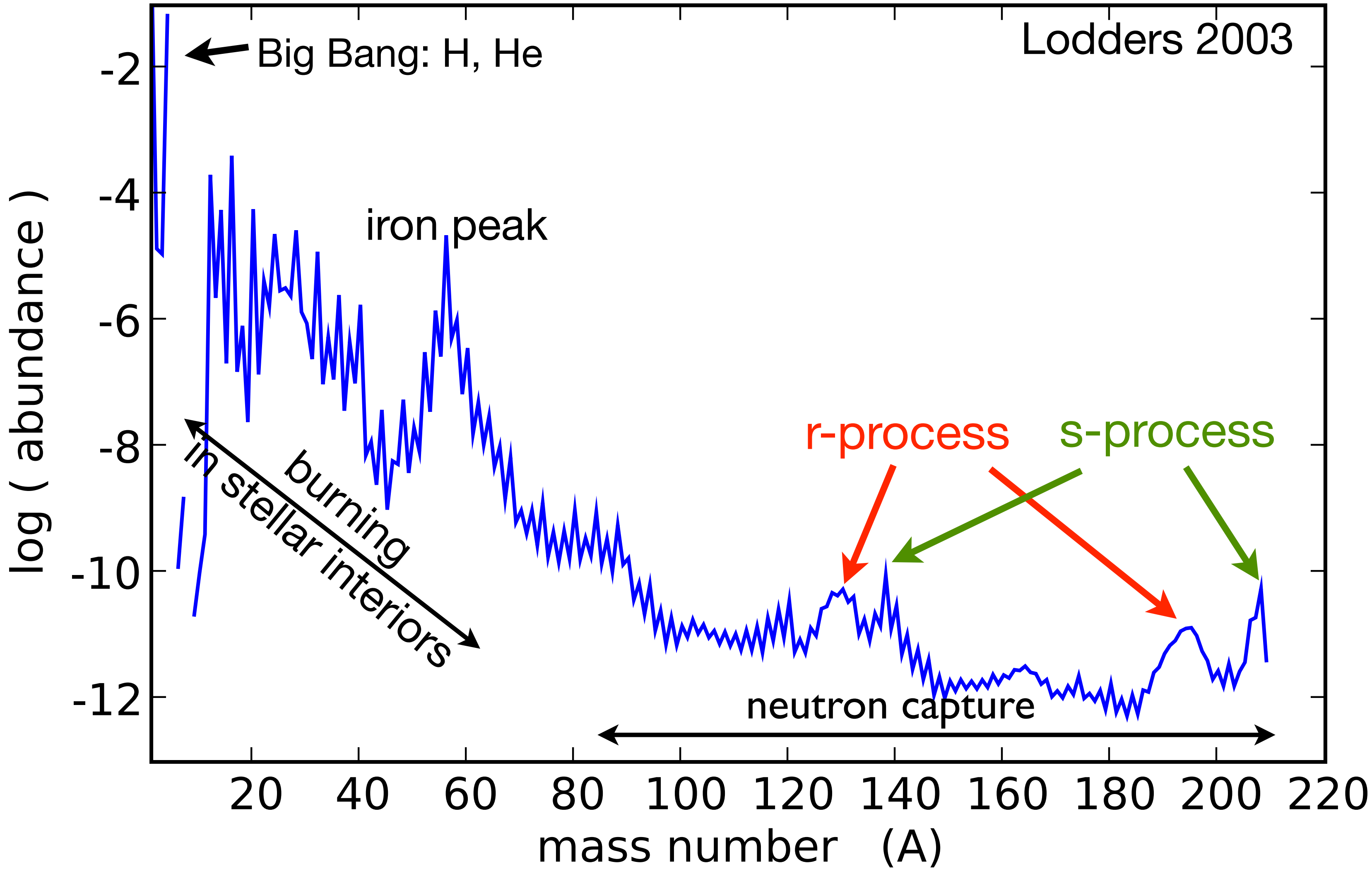
Solar system abundances





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

Contribution of all nucleosynthesis processes

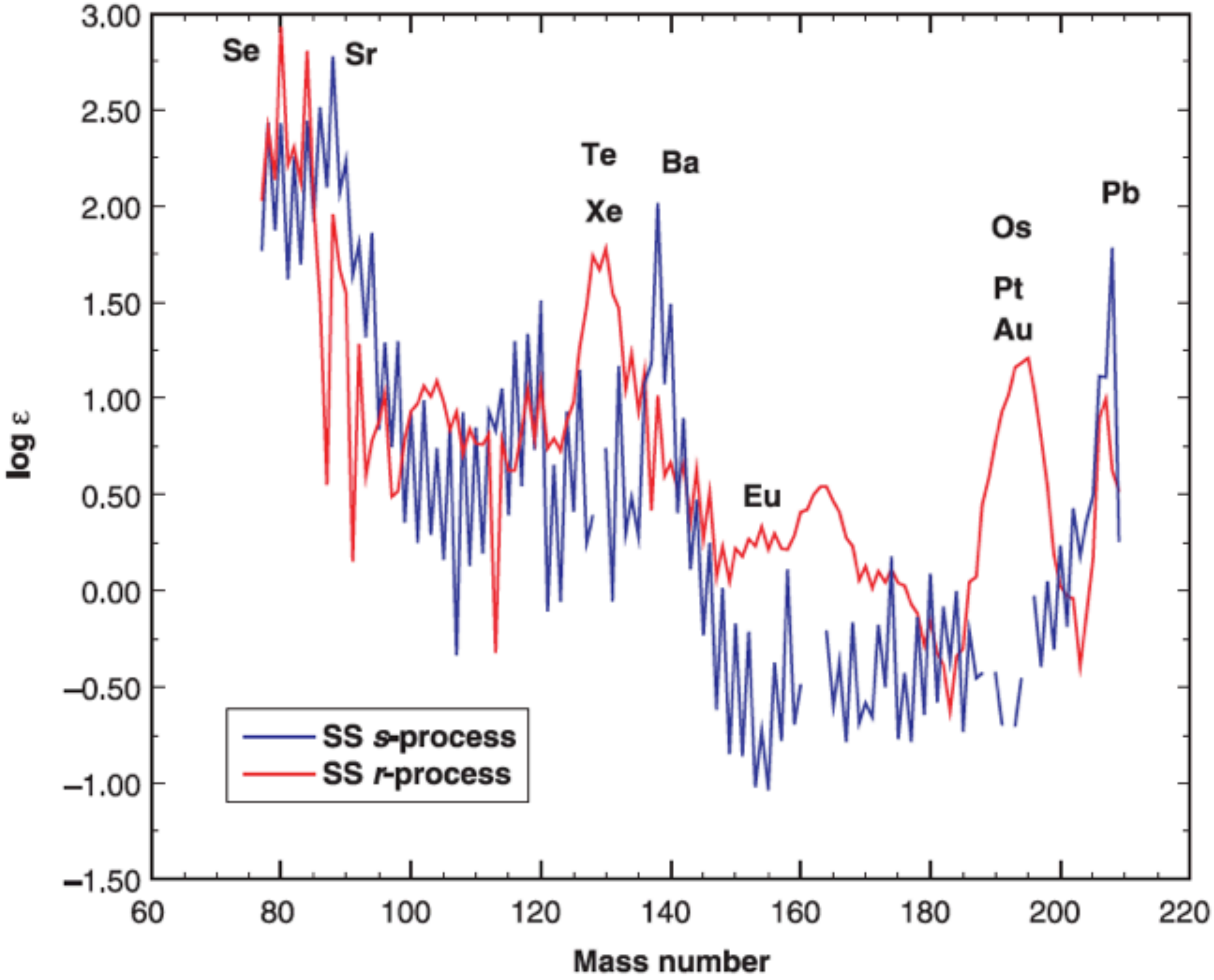


s-process:
slow neutron capture
r-process:
rapid neutron capture

abundance = mass fraction / mass number

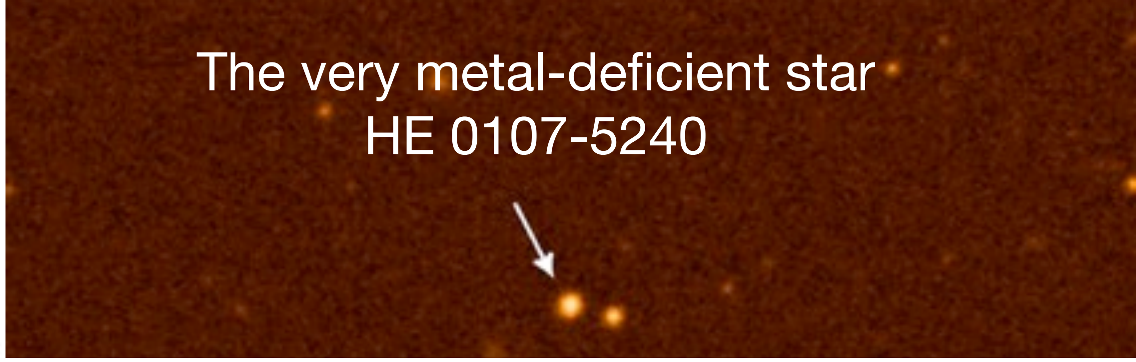
Solar system abundance

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

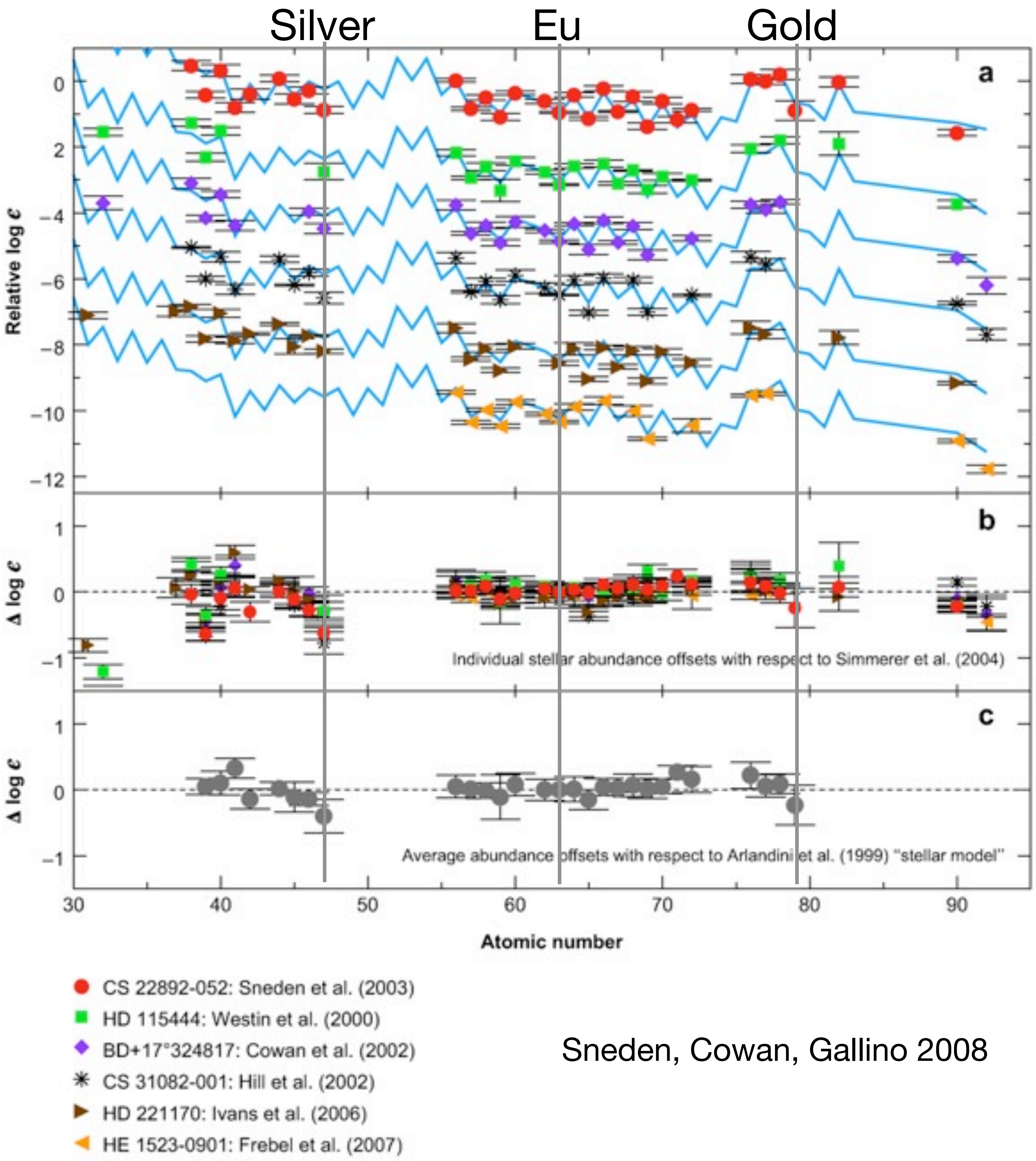


Sneden & Cowan 2003

Oldest observed stars



The very metal-deficient star
HE 0107-5240



Sneden, Cowan, Gallino 2008

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

‣Robust r-process for $56<Z<83$

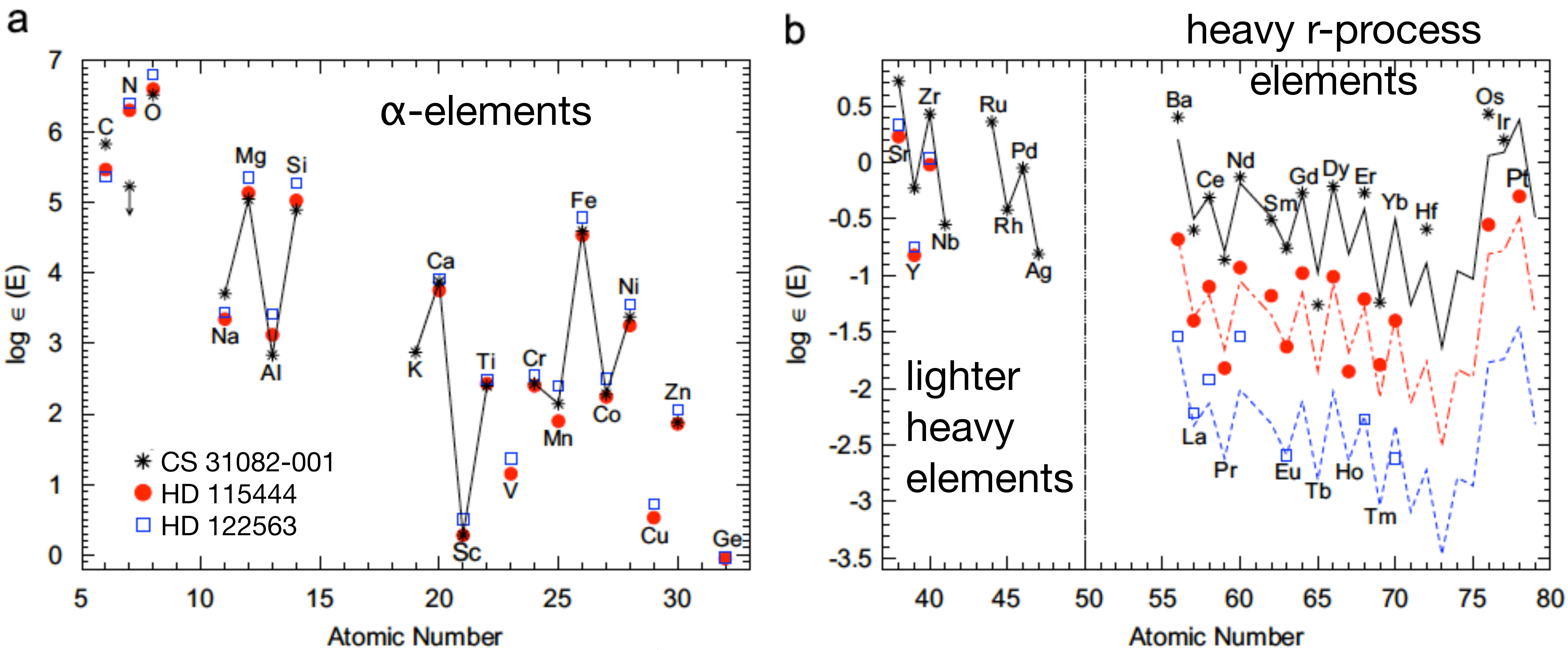
‣Scatter for lighter heavy elements, Z~40

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

Elemental abundances in ultra metal-poor stars

Following Qian & Wasserburg 2007 three groups:

- Fe-like elements (A ~ 23 to 70): Na, Mg, Al, Si, ..., Fe, ..., Zn
- Sr-like elements (A ~ 88 to 110): Sr, Y, Zr, ..., Ag
- Eu-like elements (A > 130): Ba, ..., Eu, ..., Au, ..., Th, ..., U



α-elements

heavy r-process elements

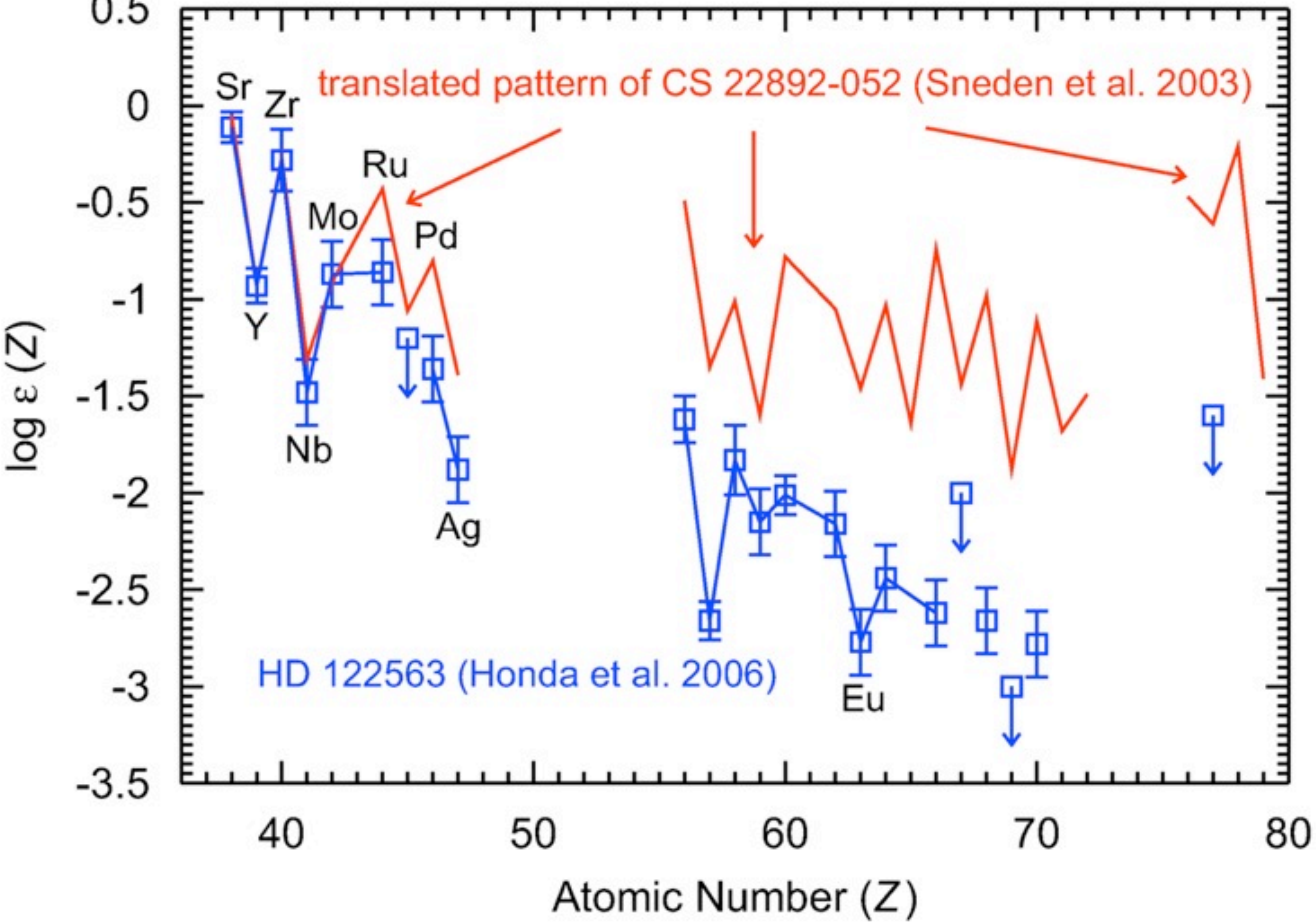
lighter heavy elements

Qian & Wasserburg 2007

r-process**es**

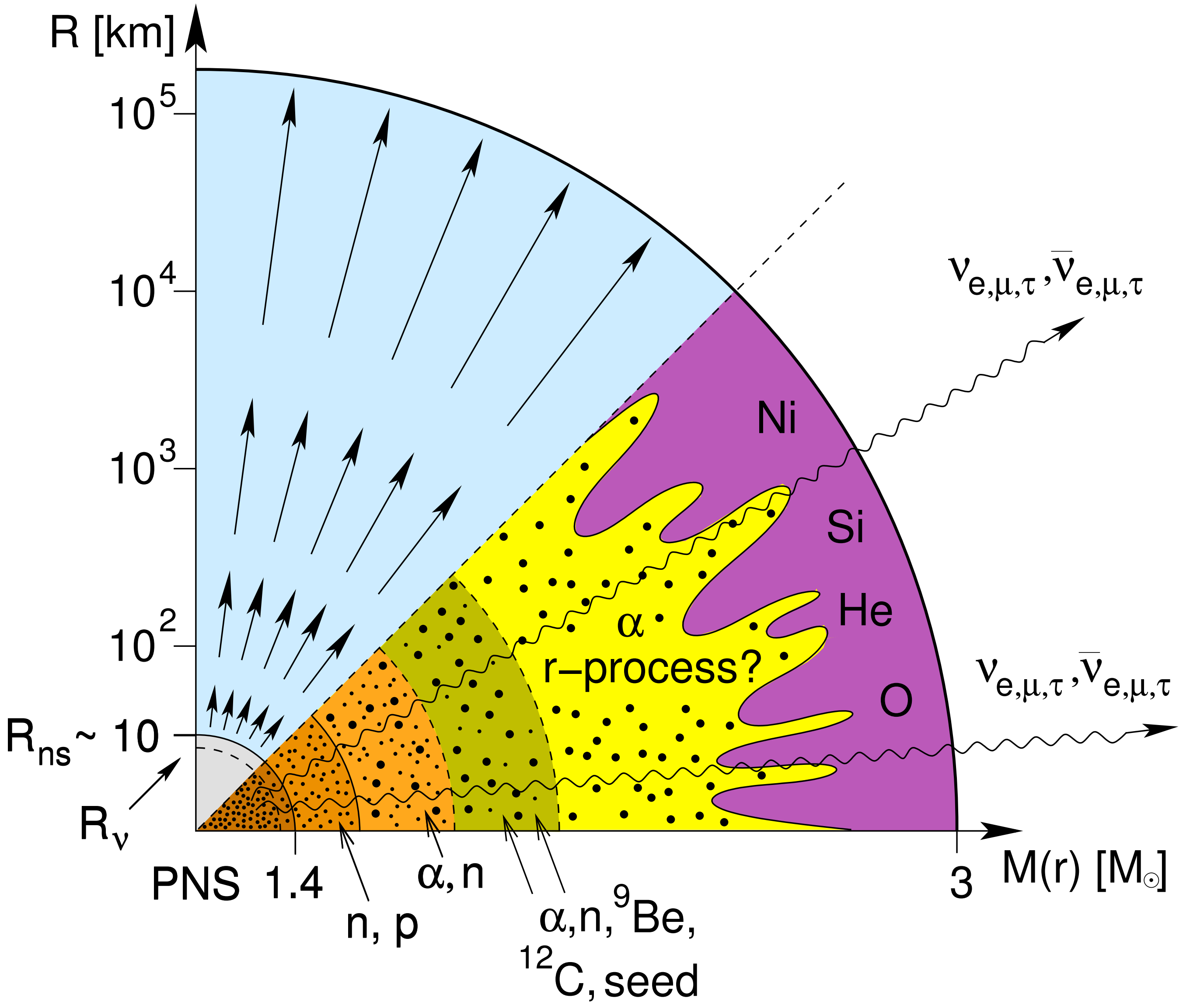
lighter heavy elements

heavy r-process elements



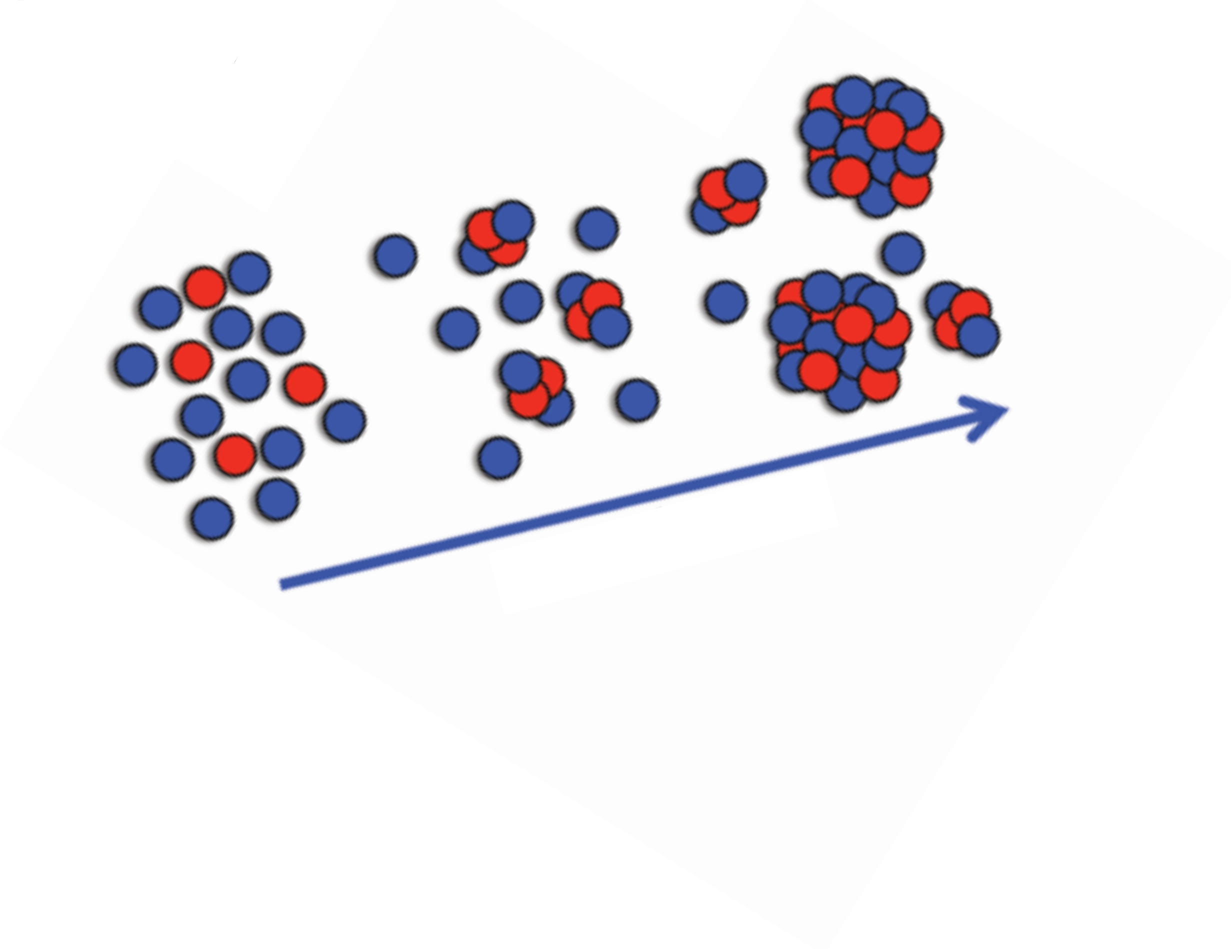
Lighter heavy elements (Sr to Ag) in neutrino-driven winds

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

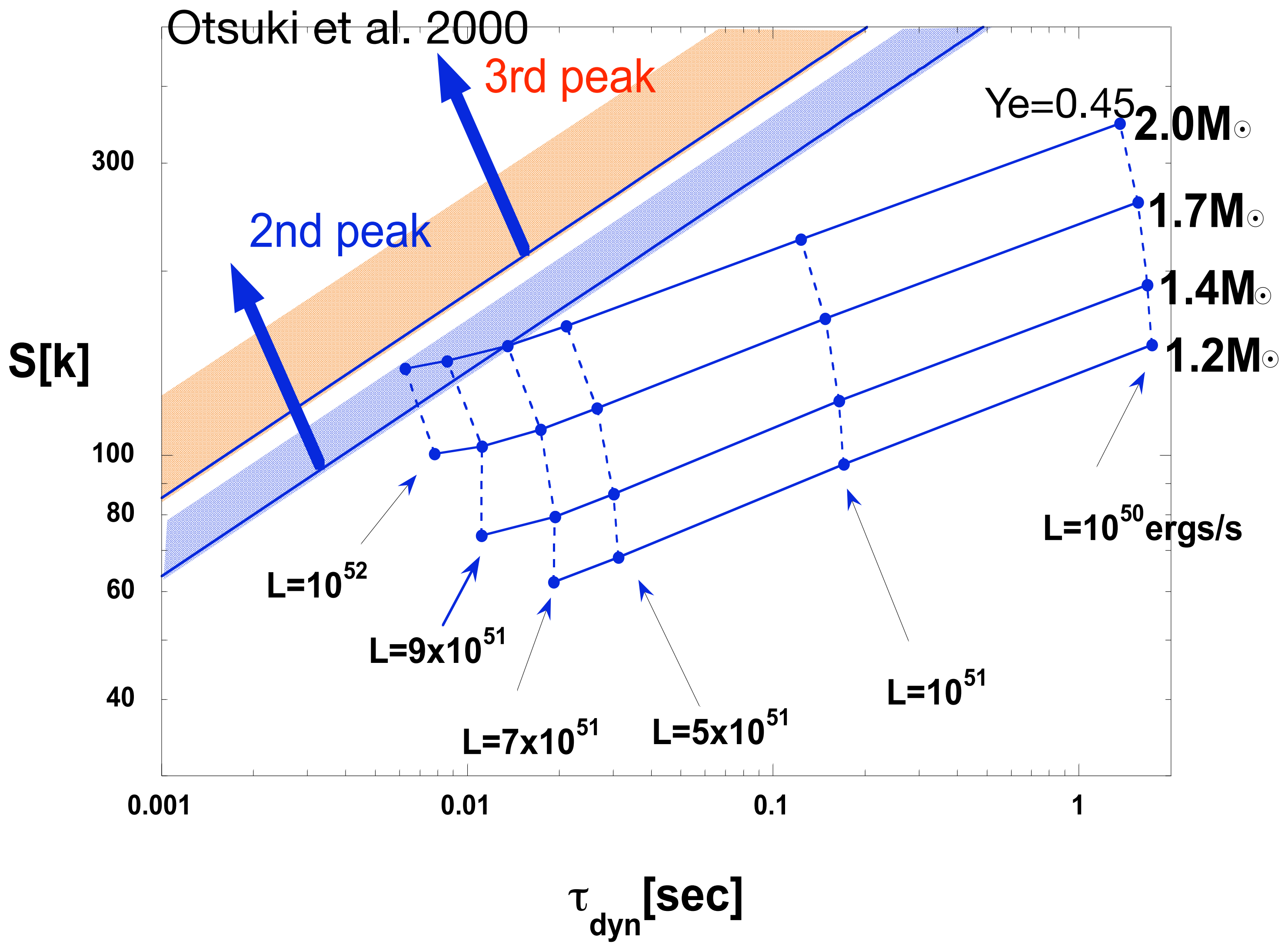
8 - 2 GK

T < 3 GK

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)

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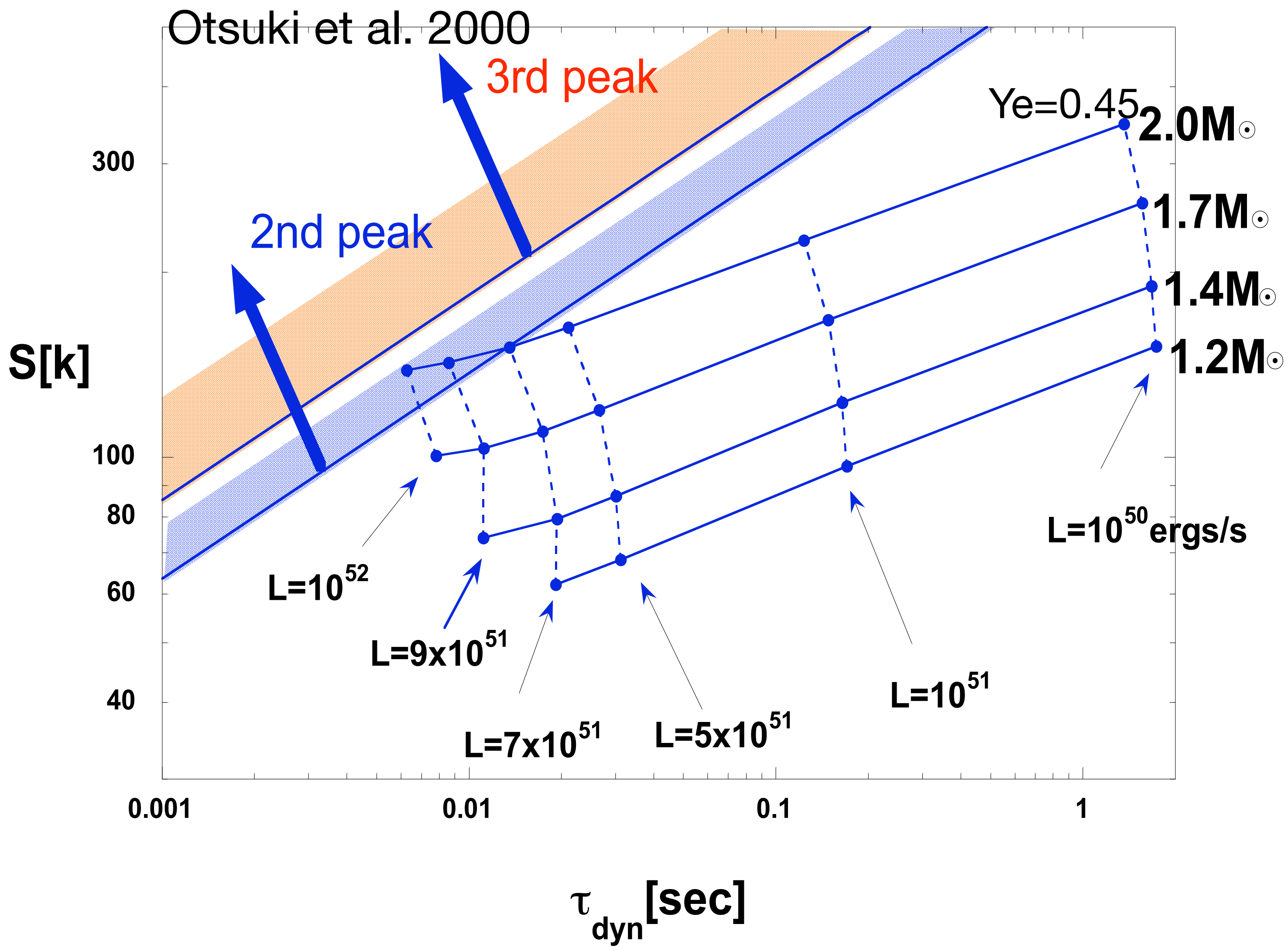


Otsuki et al. 2000

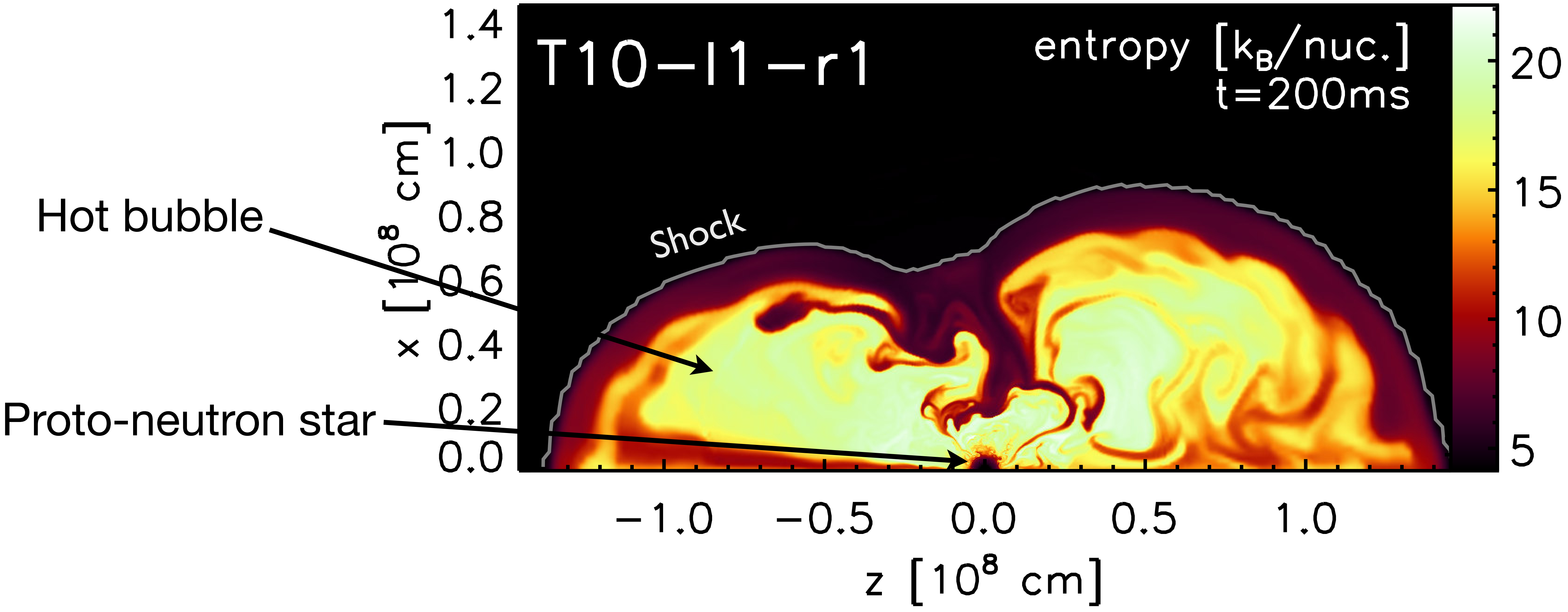
Review: Arcones & Thielemann (2013)

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

Core-collapse supernova simulations

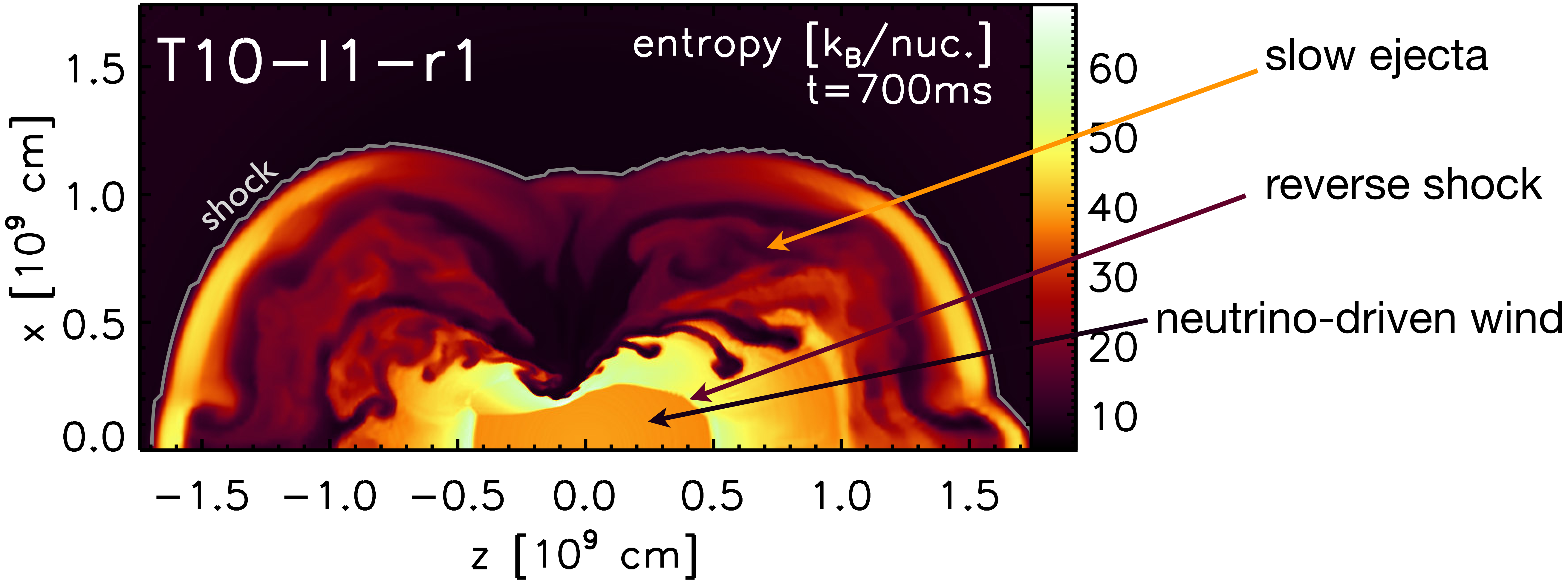

Hot bubble

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:

- ejecta evolution from ~5ms after bounce to ~3s in 2D (Arcones & Janka 2011)
  and ~10s in 1D (Arcones et al. 2007)
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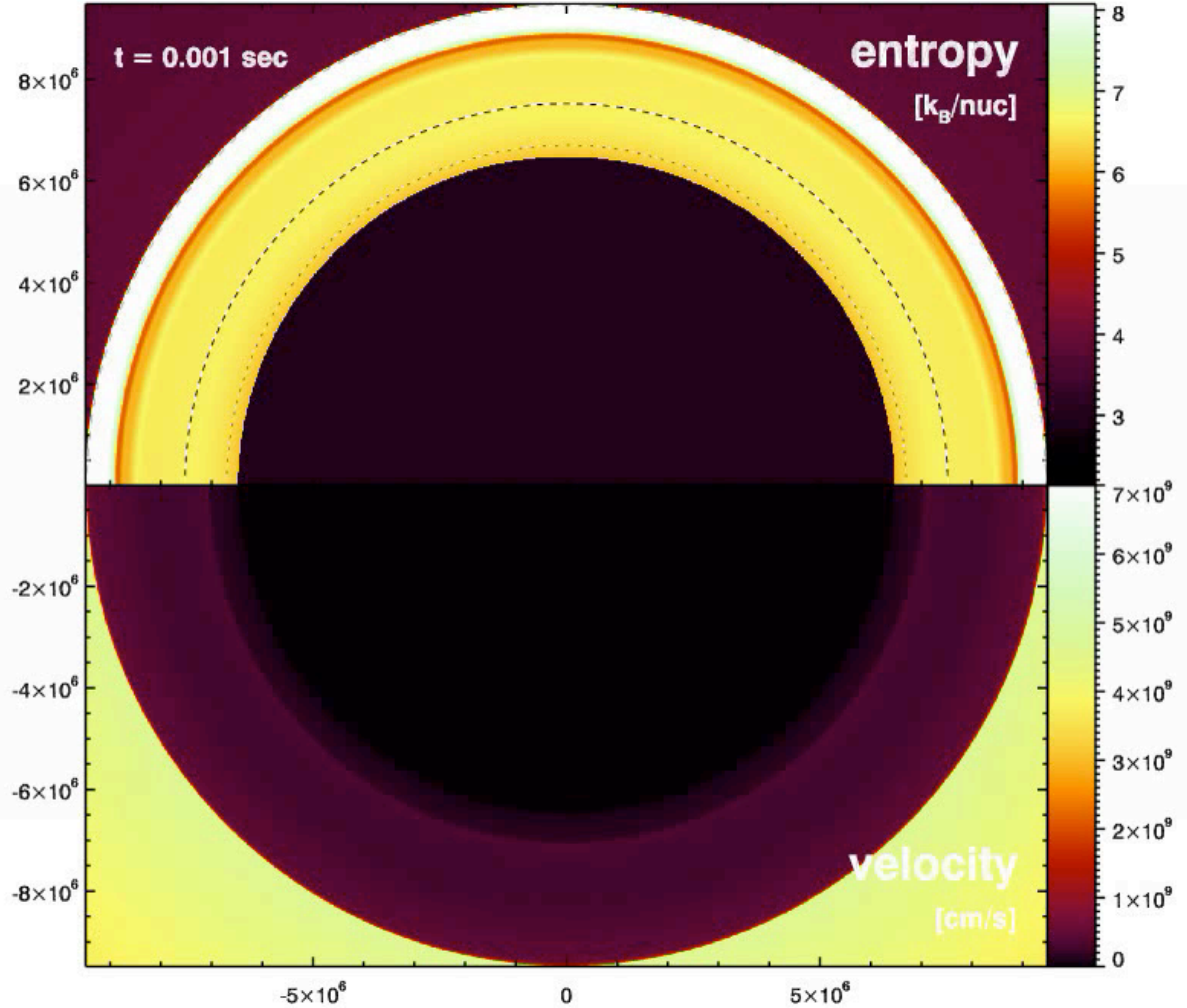
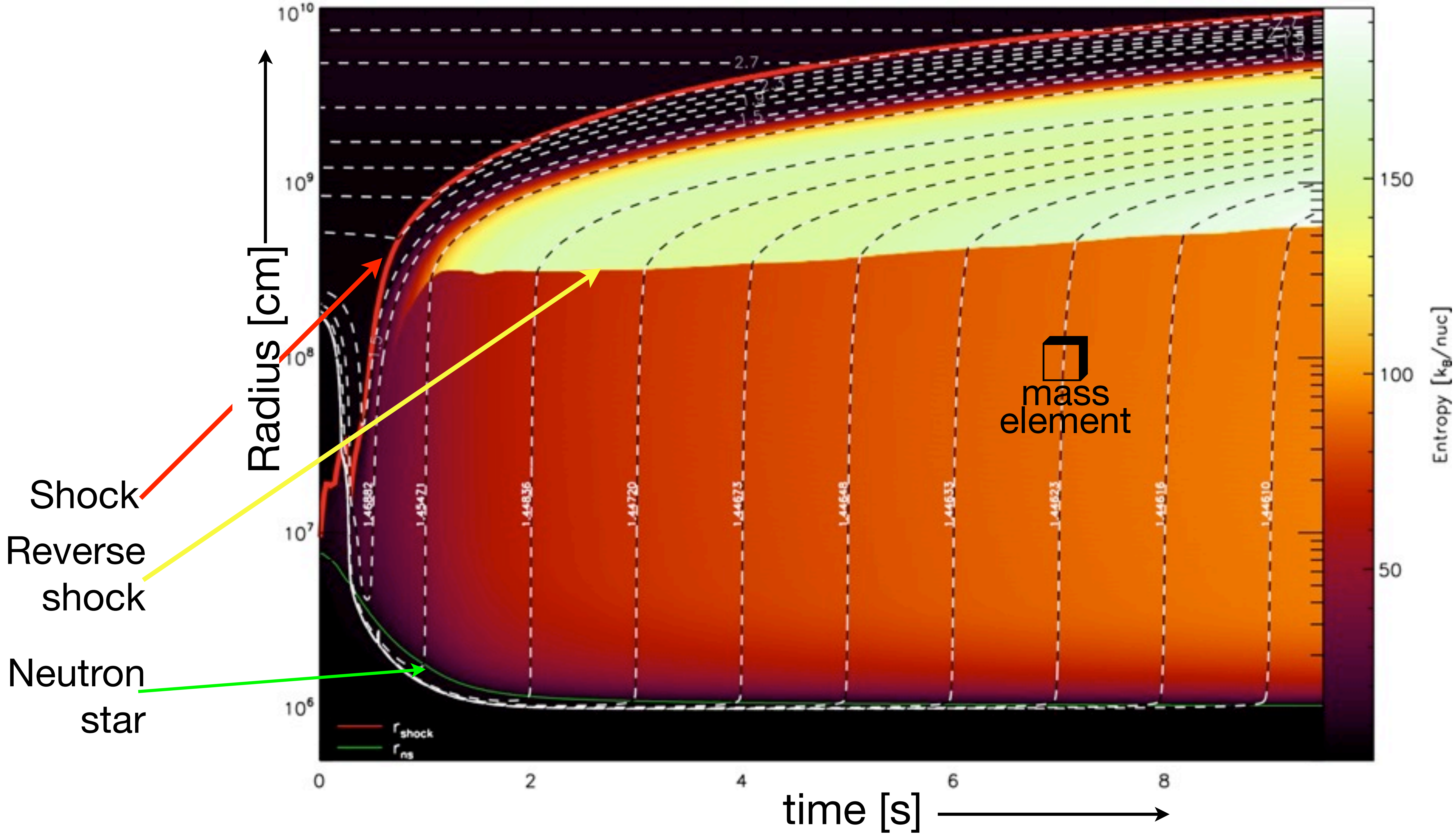
Arcones & Janka (2011)



1D simulations for nucleosynthesis studies

Arcones et al 2007



Radius [cm]

time [s]

Shock

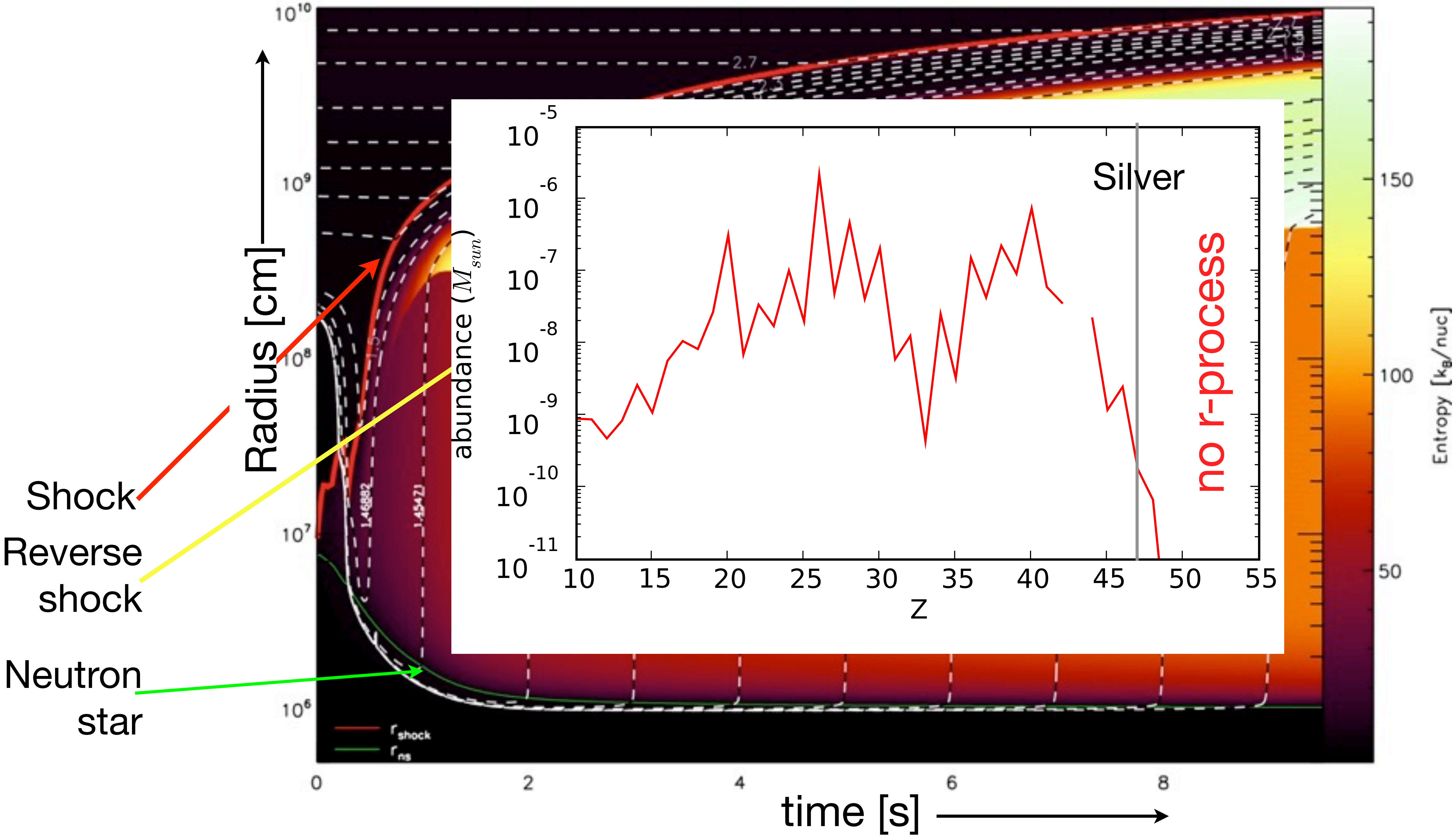
Reverse shock

Neutron star

mass element

1D simulations for nucleosynthesis studies

Arcones et al 2007



no r-process

Radius [cm]

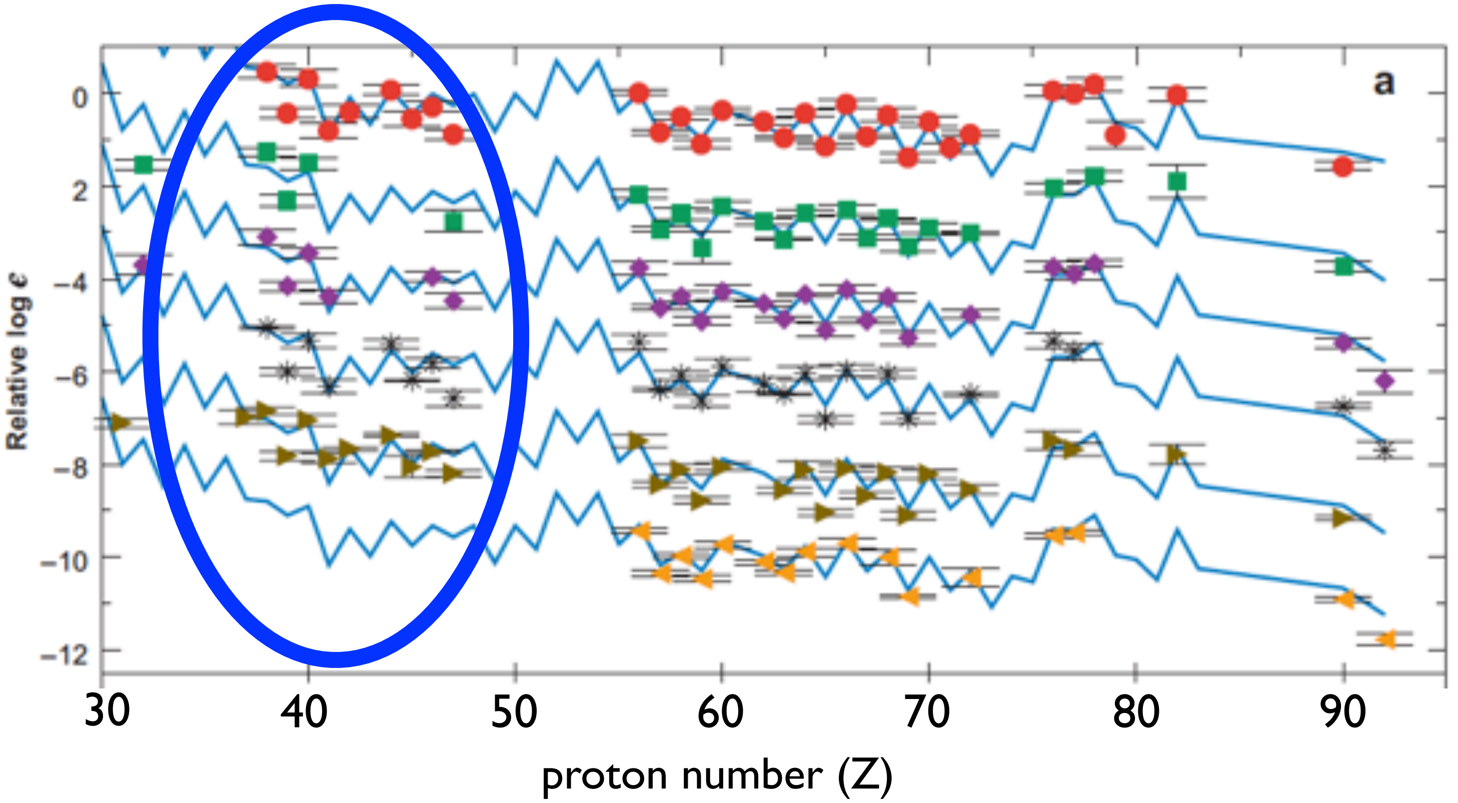
time [s]

Shock

Reverse shock

Neutron star

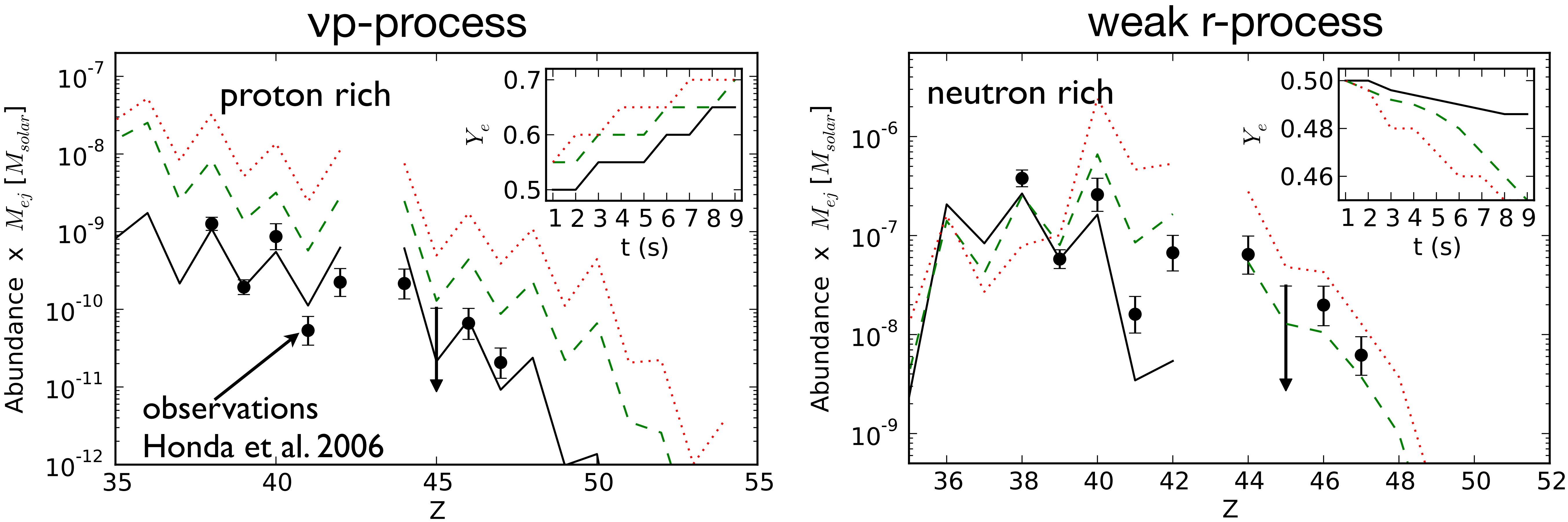
Lighter heavy elements in neutrino-driven winds



Lighter Element Primary Process

(Travaglio et al. 2004, Montes et al. 2007)

Charged-particle reactions (Qian & Wasserburg 2001) + ...


νp-process

weak r-process

Arcones & Montes (2011)

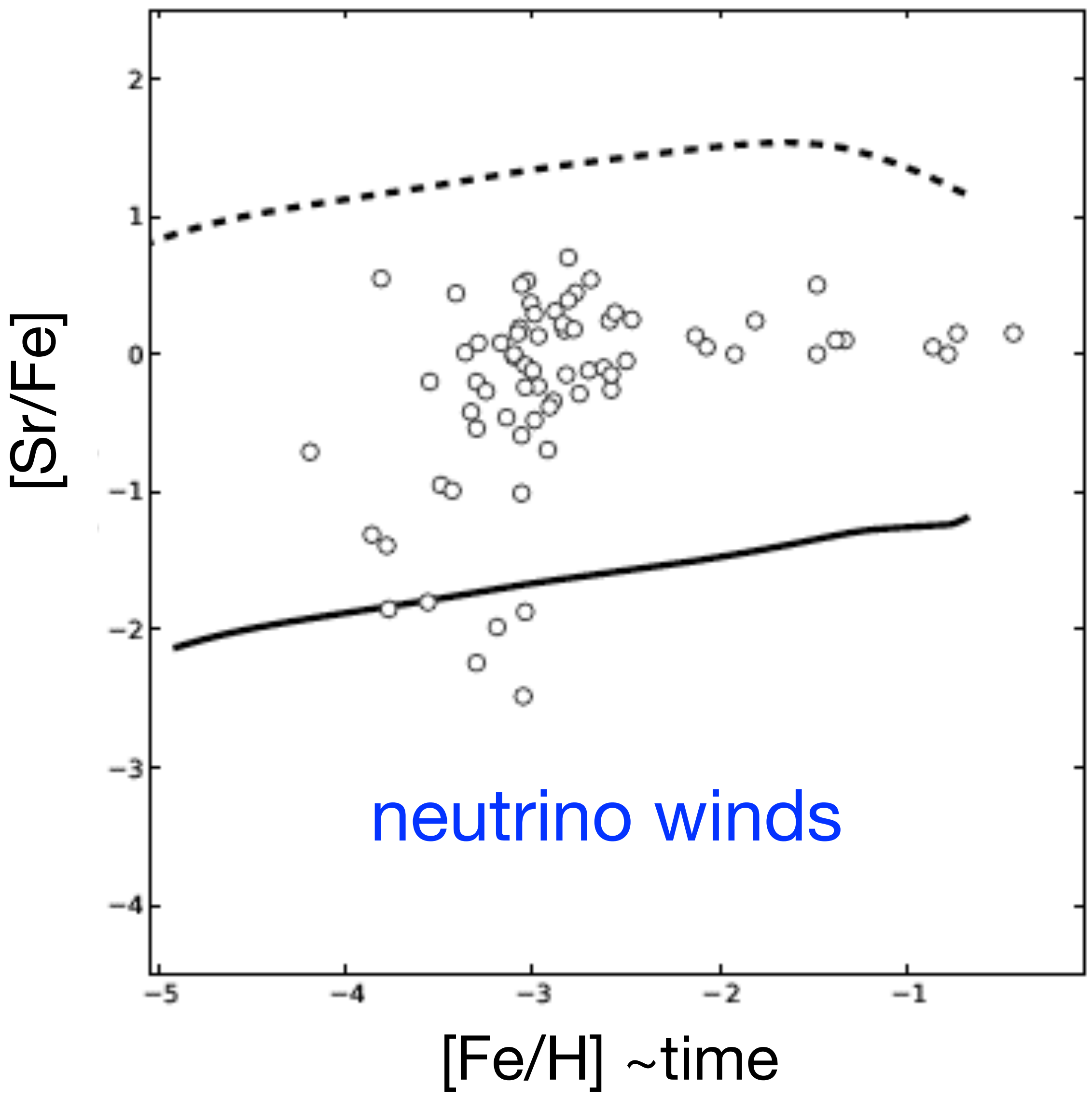
Lighter heavy elements from different sites

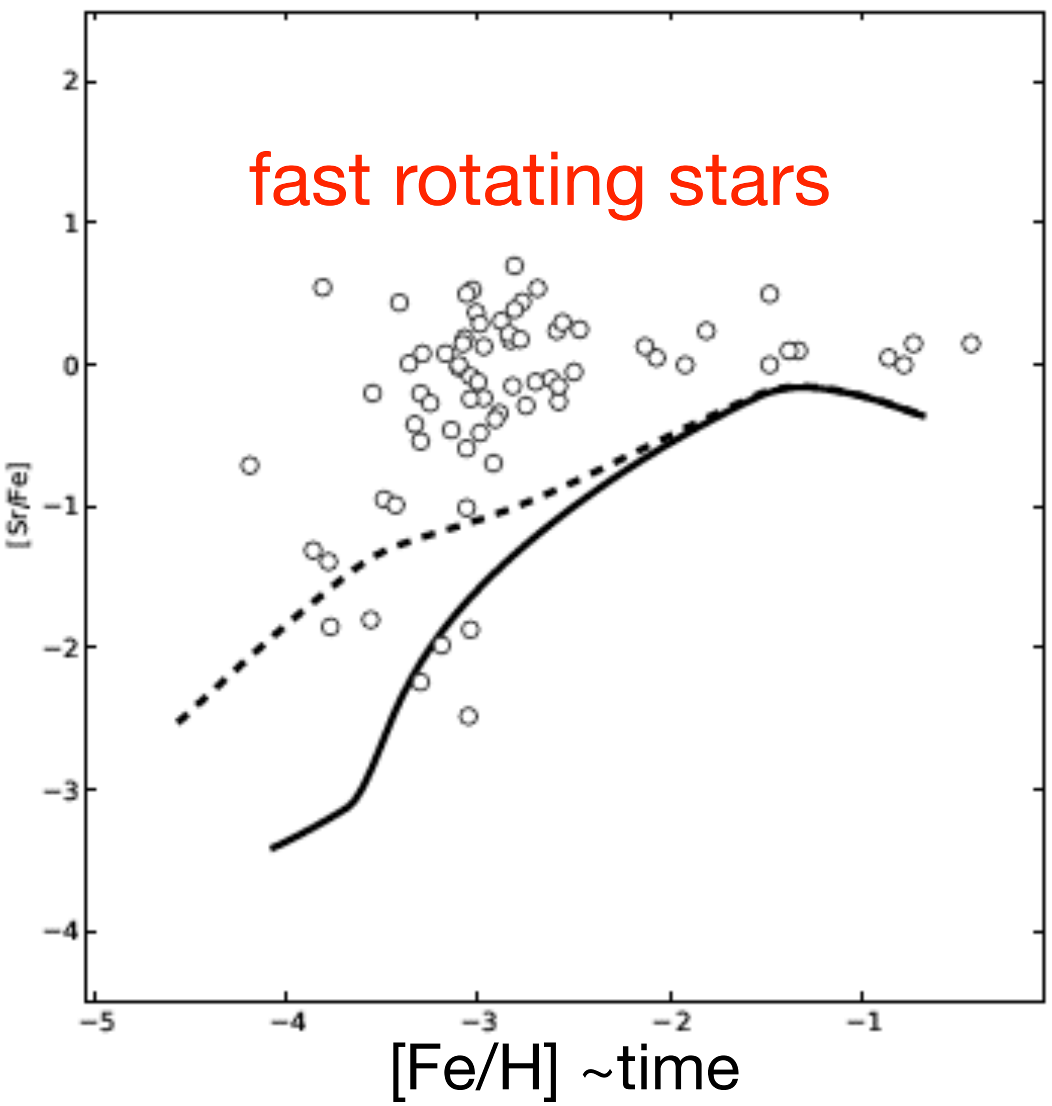
New observations and chemical evolution models

Different astrophysical scenarios:

neutrino-driven wind, fast rotating stars (Frischknecht et al., talk of G. Cescutti)

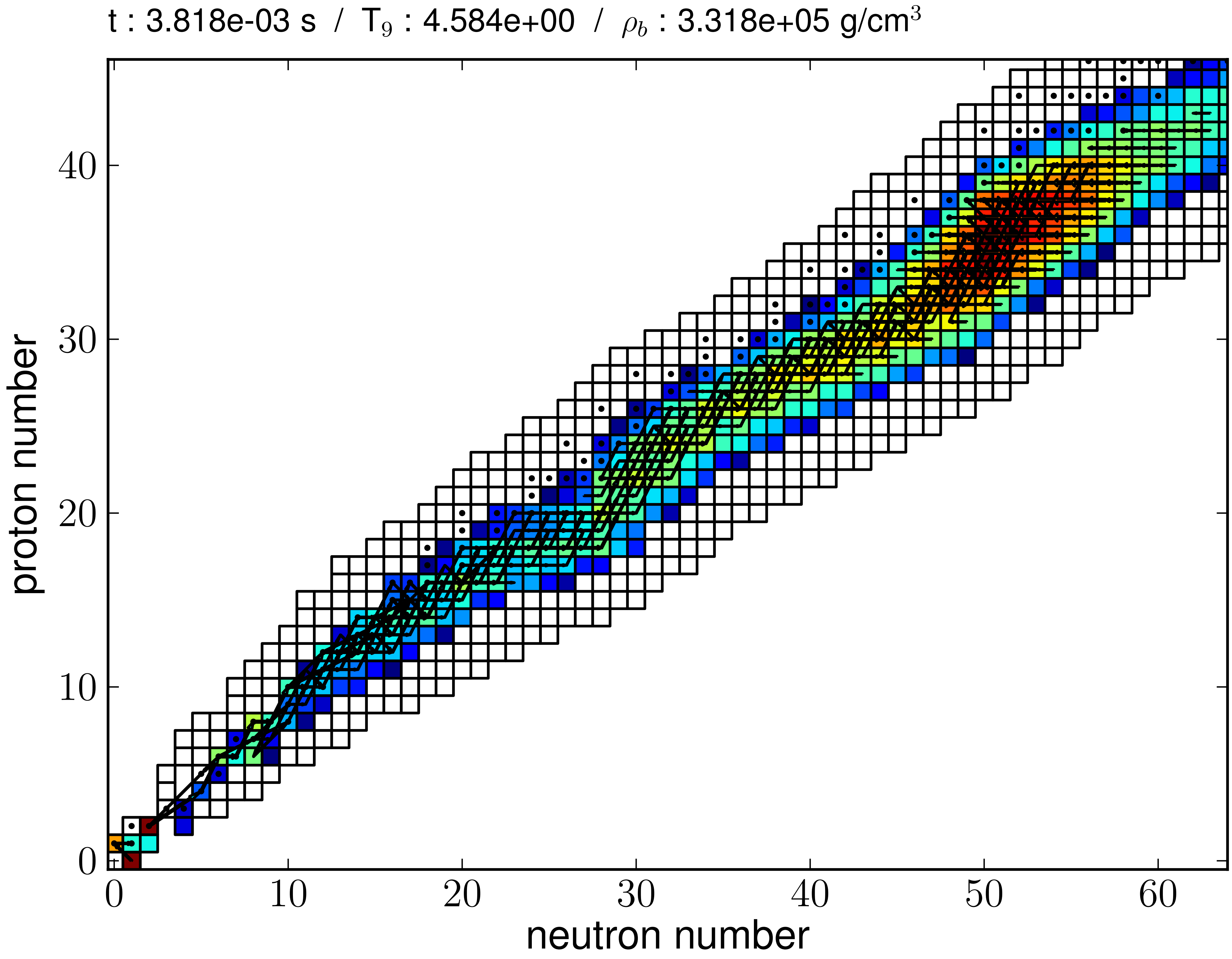
Nuclear reactions not very far from stability: identify key reactions



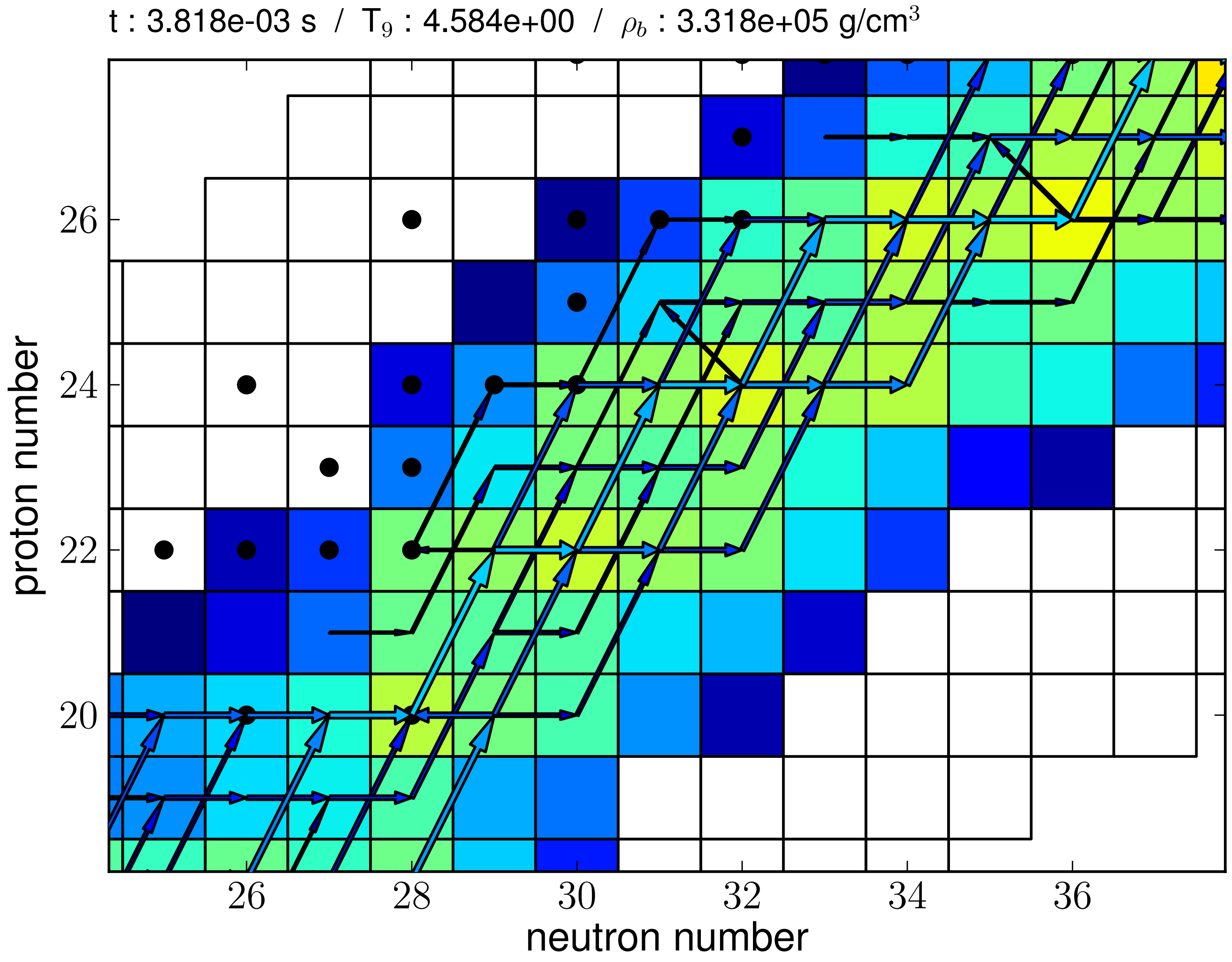


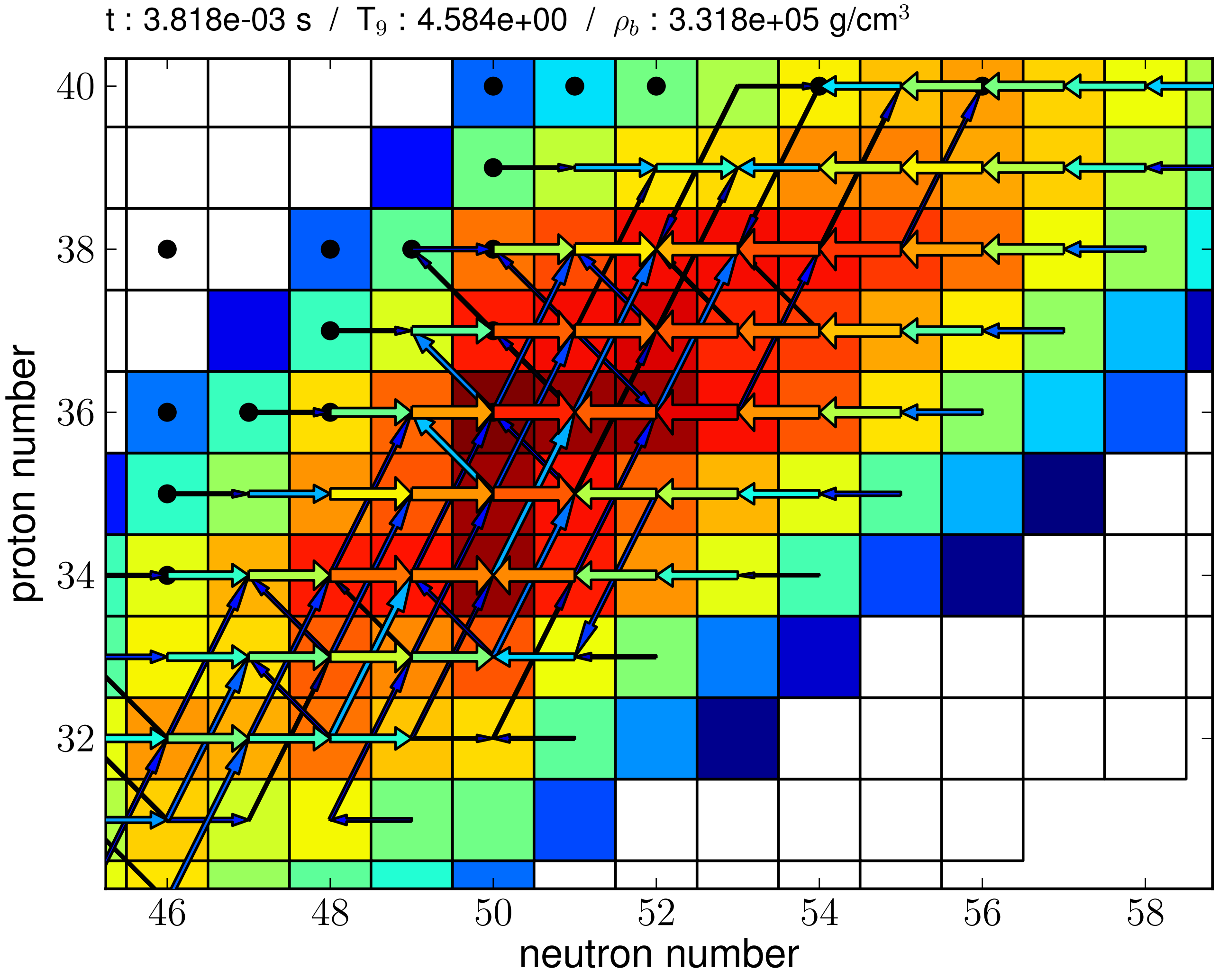
Hansen et al. 2013, arXiv:1212:4147

Key reactions

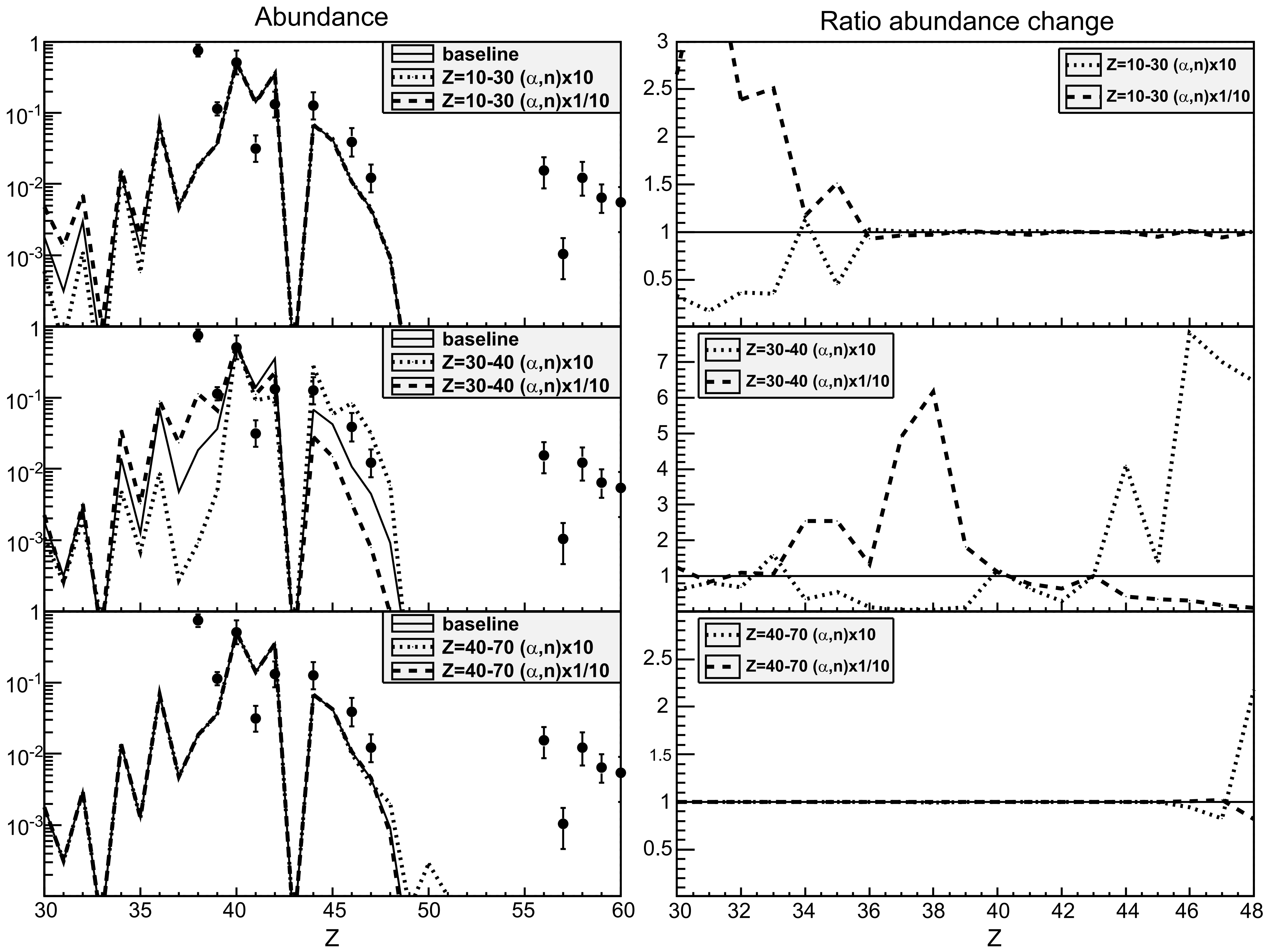


Key reactions





Key reactions: (α,n)



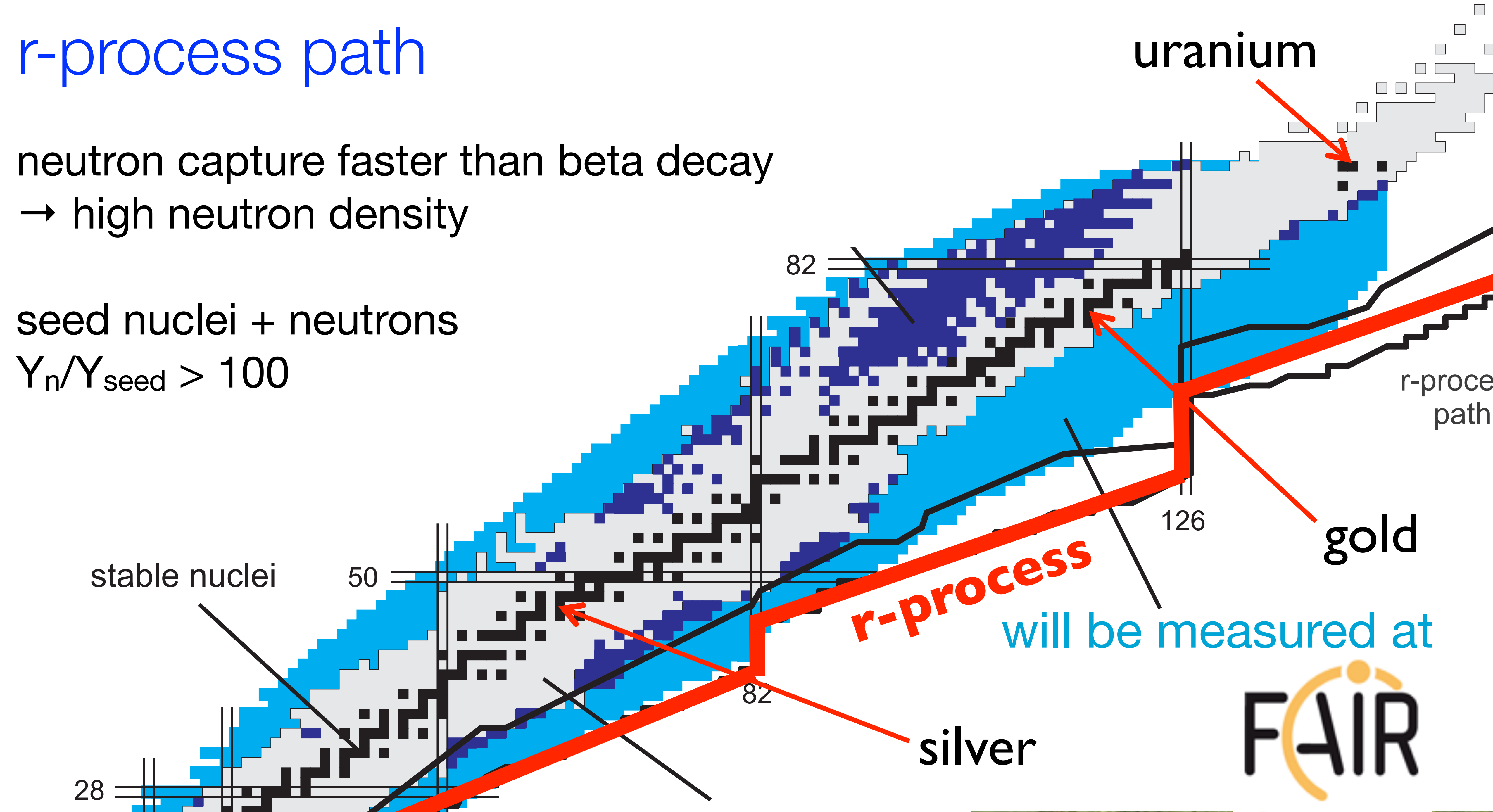
Montes, Arcones, Pereira (in prep.)

Heavy r-process ($Z \geq 50$)
where?

r-process path

neutron capture faster than beta decay
→ high neutron density

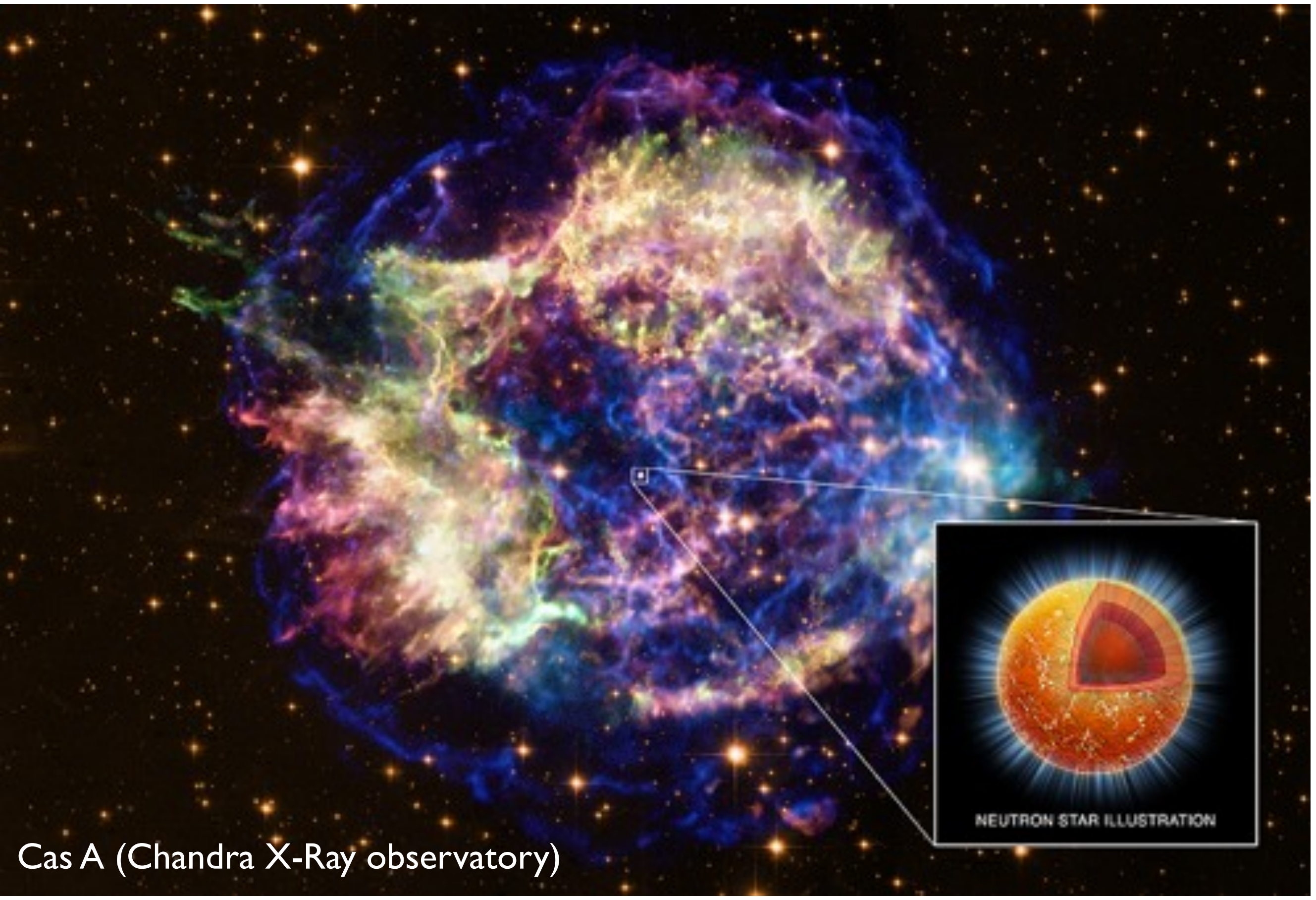
seed nuclei + neutrons
$Y_n/Y_{seed} > 100$



will be measured at FAIR

Where does the r-process occur?

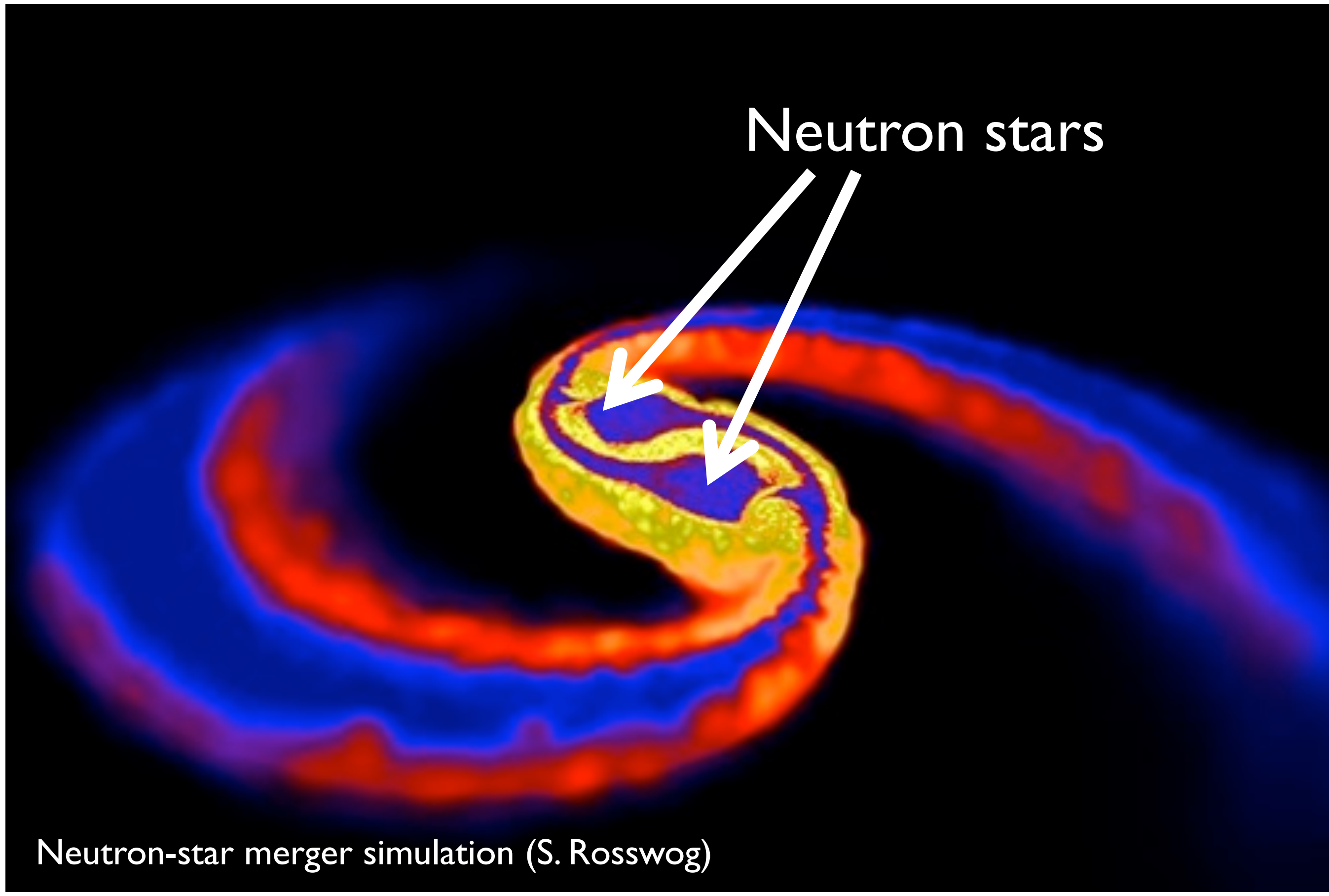
Core-collapse supernovae



Cas A (Chandra X-Ray observatory)

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

Neutron star mergers

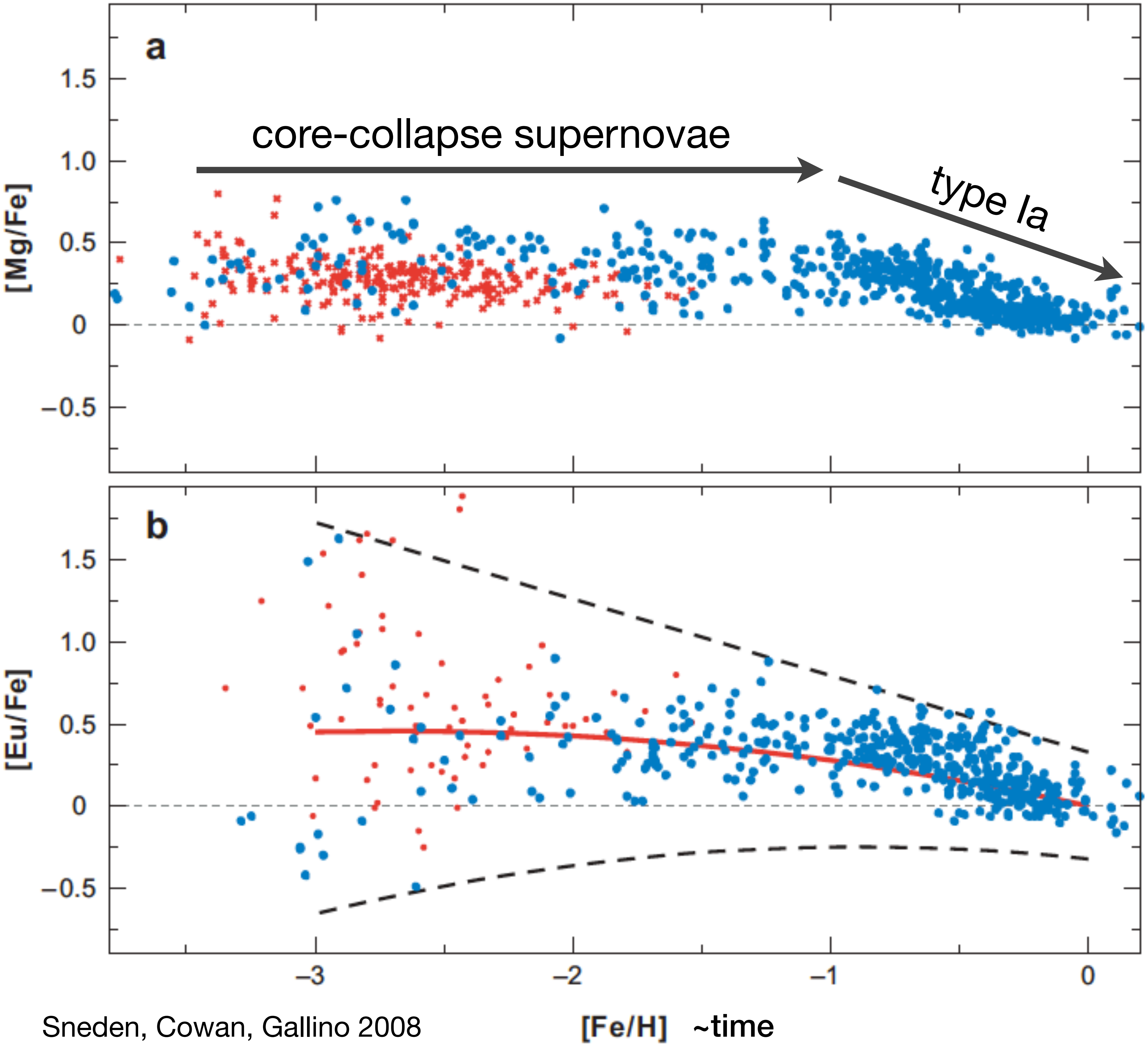


Neutron-star merger simulation (S. Rosswog)

- spiral arms
- neutrino-driven wind

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

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

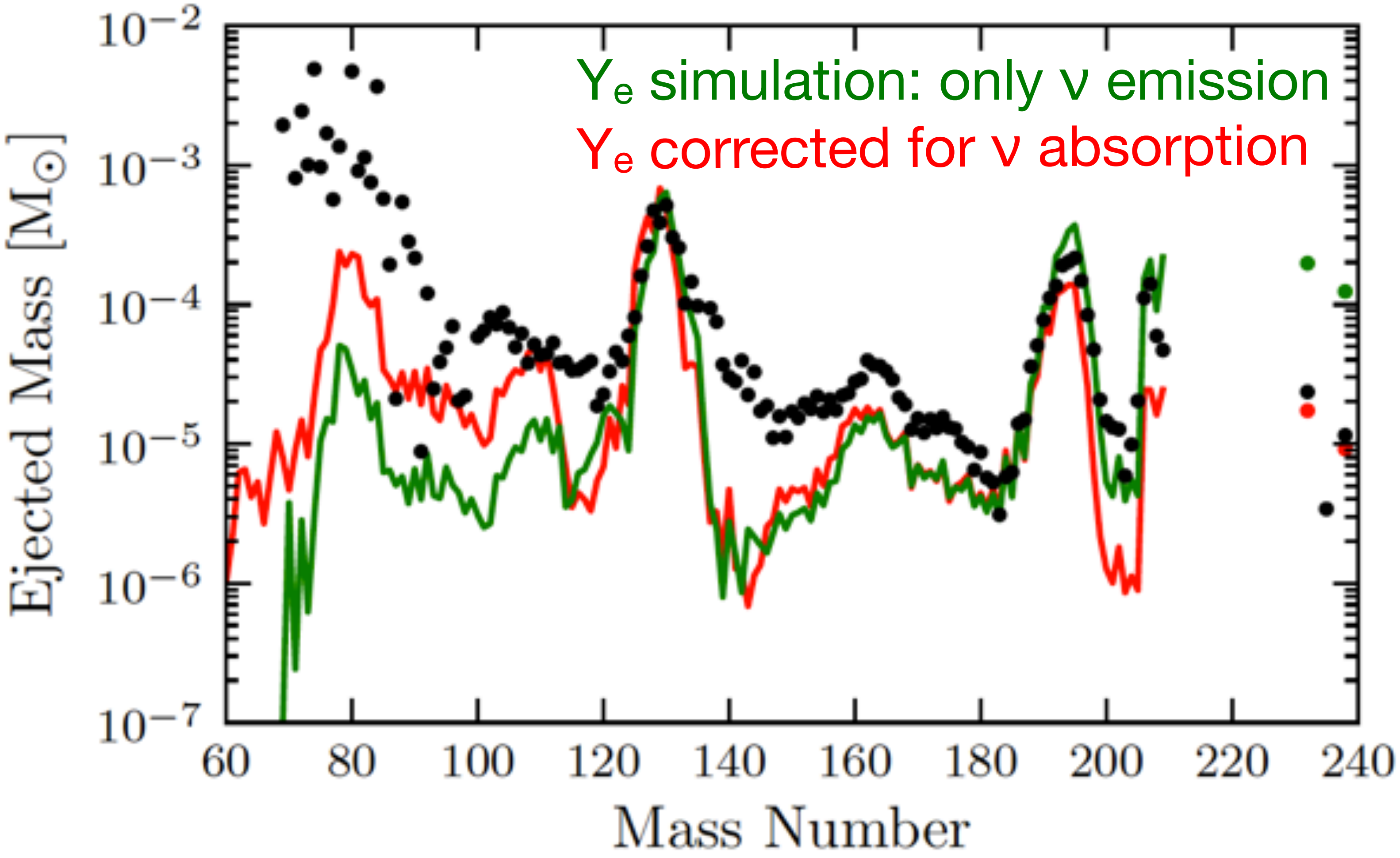
Mg and Fe production is not coupled to r-process production

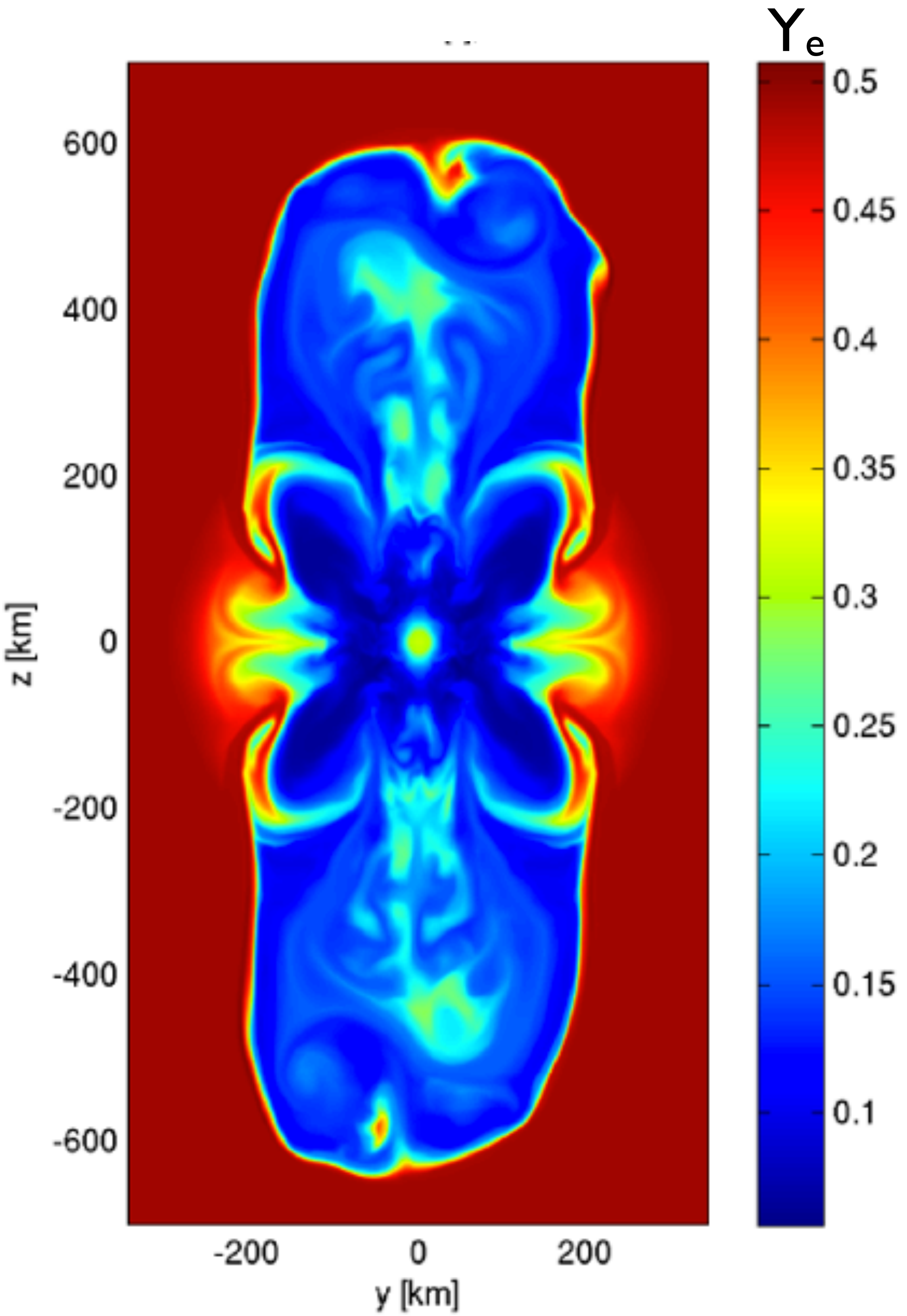
Supernova-jet-like explosion

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

matter collimates: neutron-rich jets

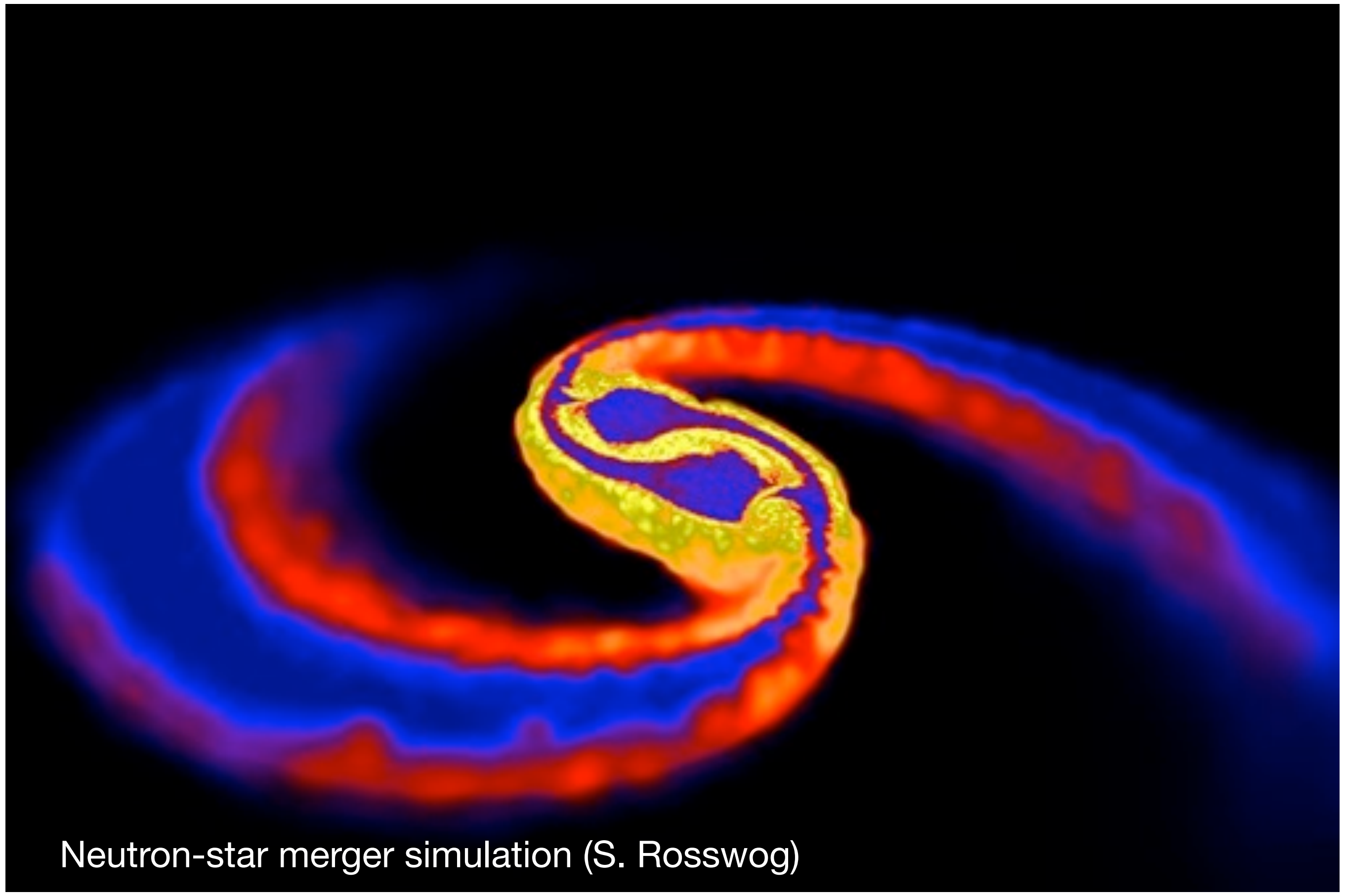
right r-process conditions



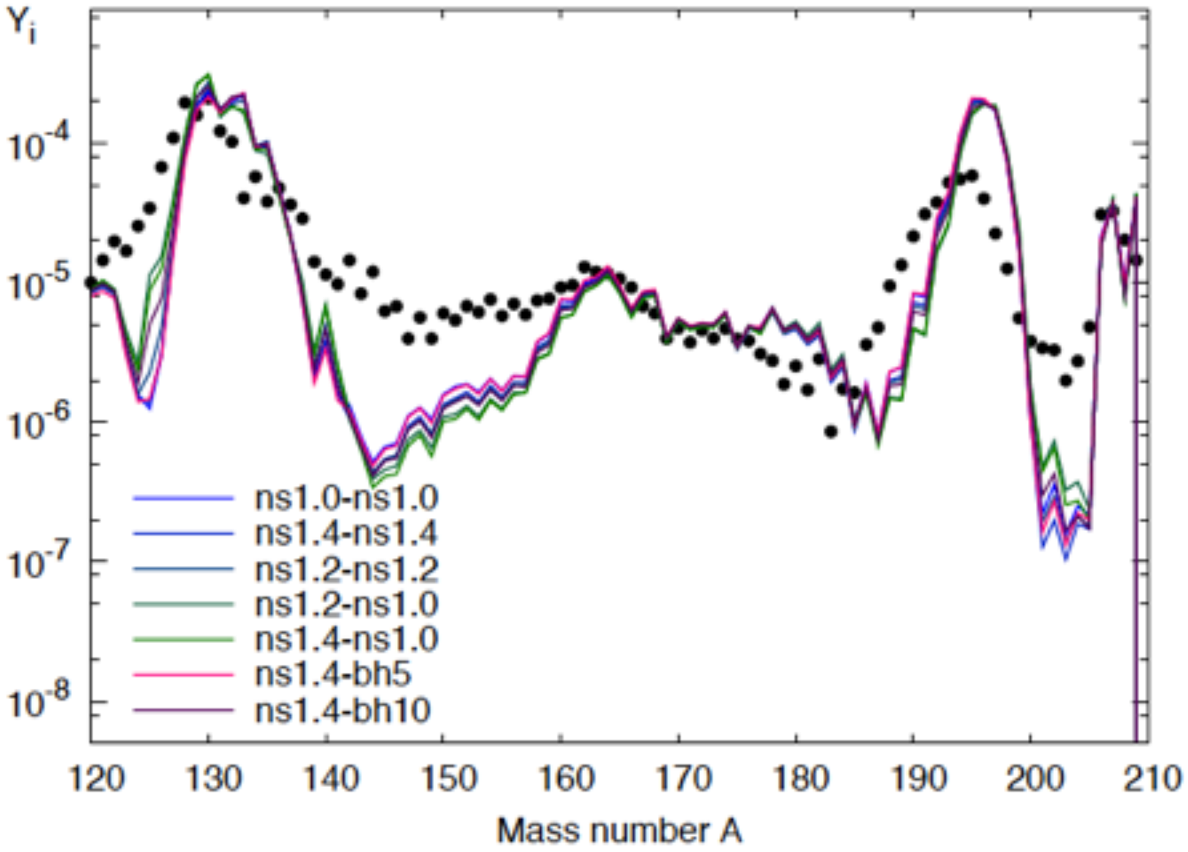


Winteler, Käppeli, Perego, et al. 2012

Neutron star mergers



Korobkin, Rosswog, Arcones, Winteler (2012)



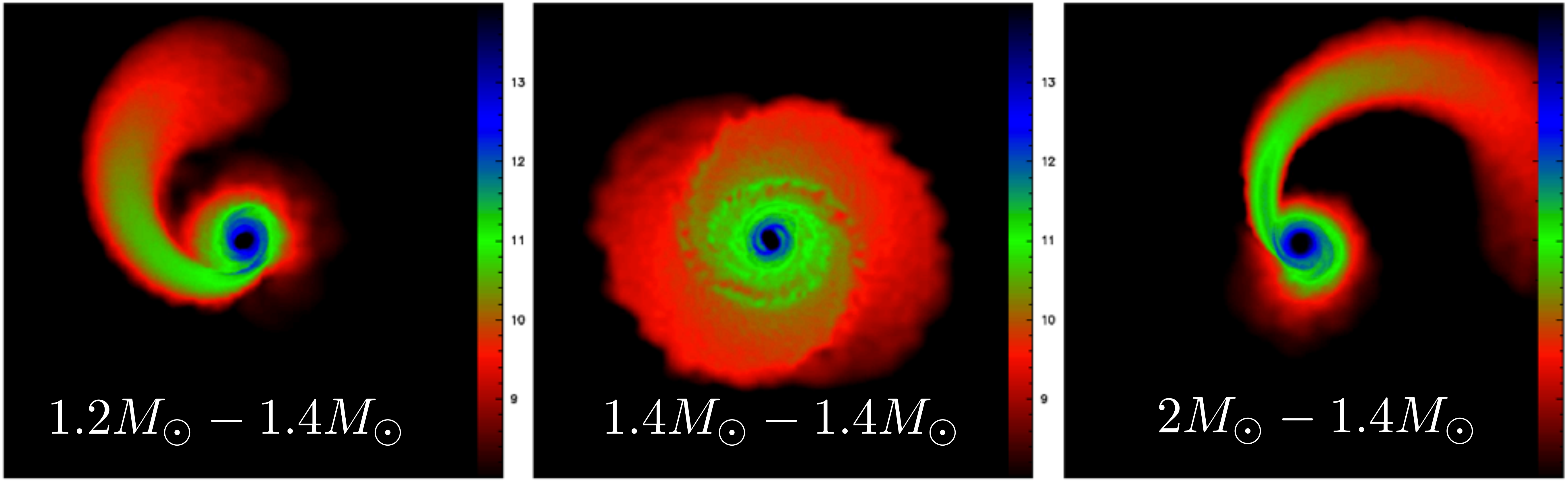
Right conditions for a successful r-process
(Lattimer & Schramm 1974, Freiburghaus et al. 1999, ..., Goriely et al. 2011)

Do they occur early enough to explain UMP star abundances (Argast et al. 2004)?

r-process heating affects merger dynamics: late X-ray emission in short GRBs (Metzger, Arcones, Quataert, Martinez-Pinedo 2010)

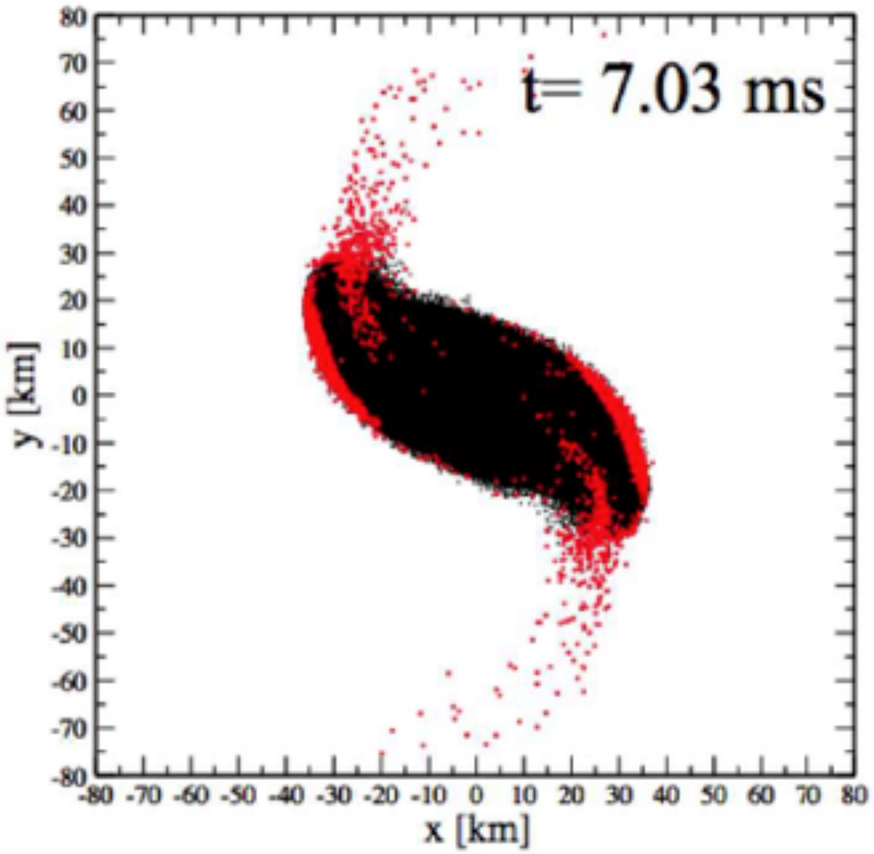
Transient with kilo-nova luminosity (Metzger et al. 2010, Roberts et al. 2011, Goriely et al. 2011): direct observation of r-process, EM counter part to WG

Neutron star mergers



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

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

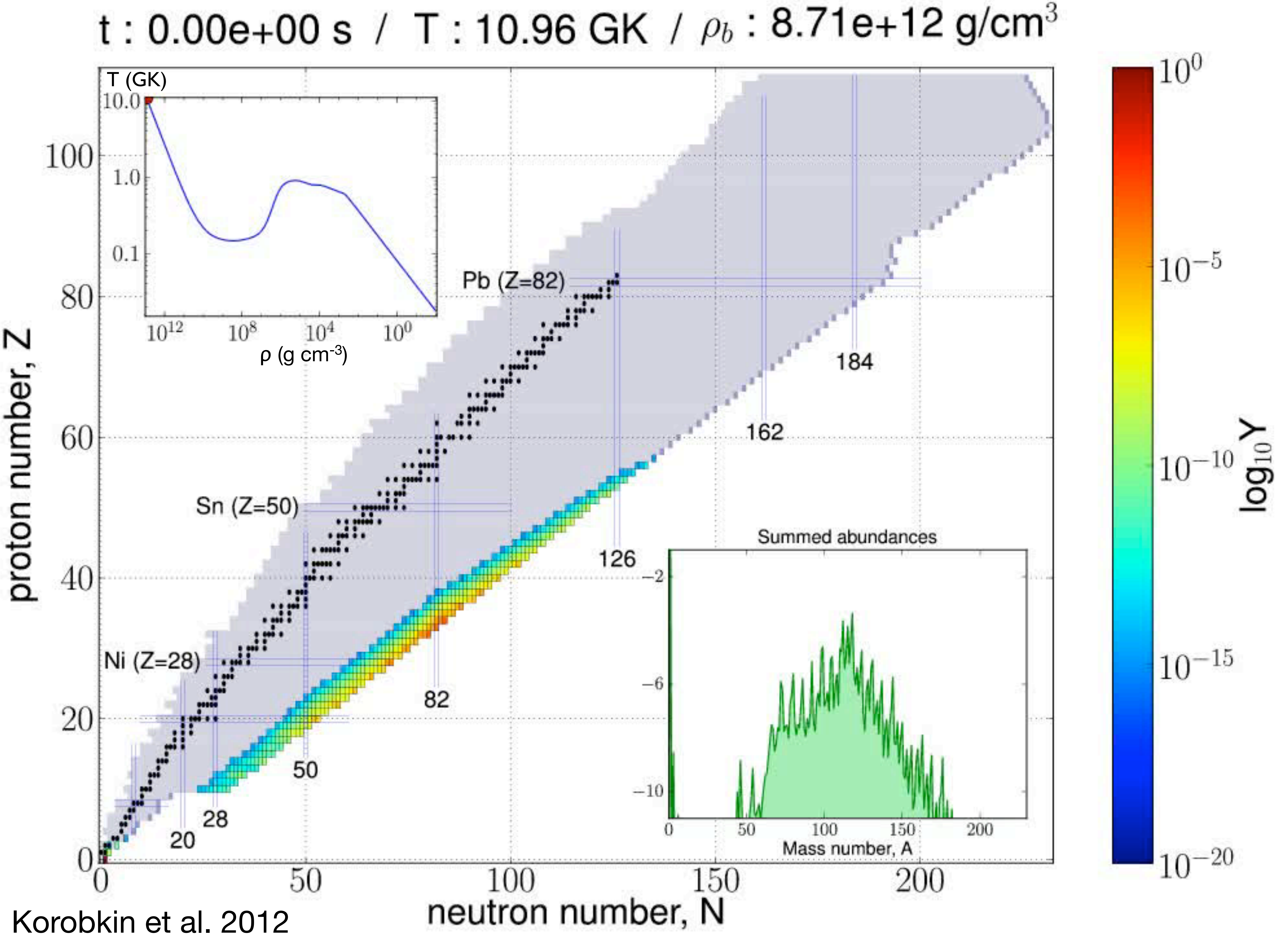


Korobkin, Rosswog, Arcones, Winteler (2012)

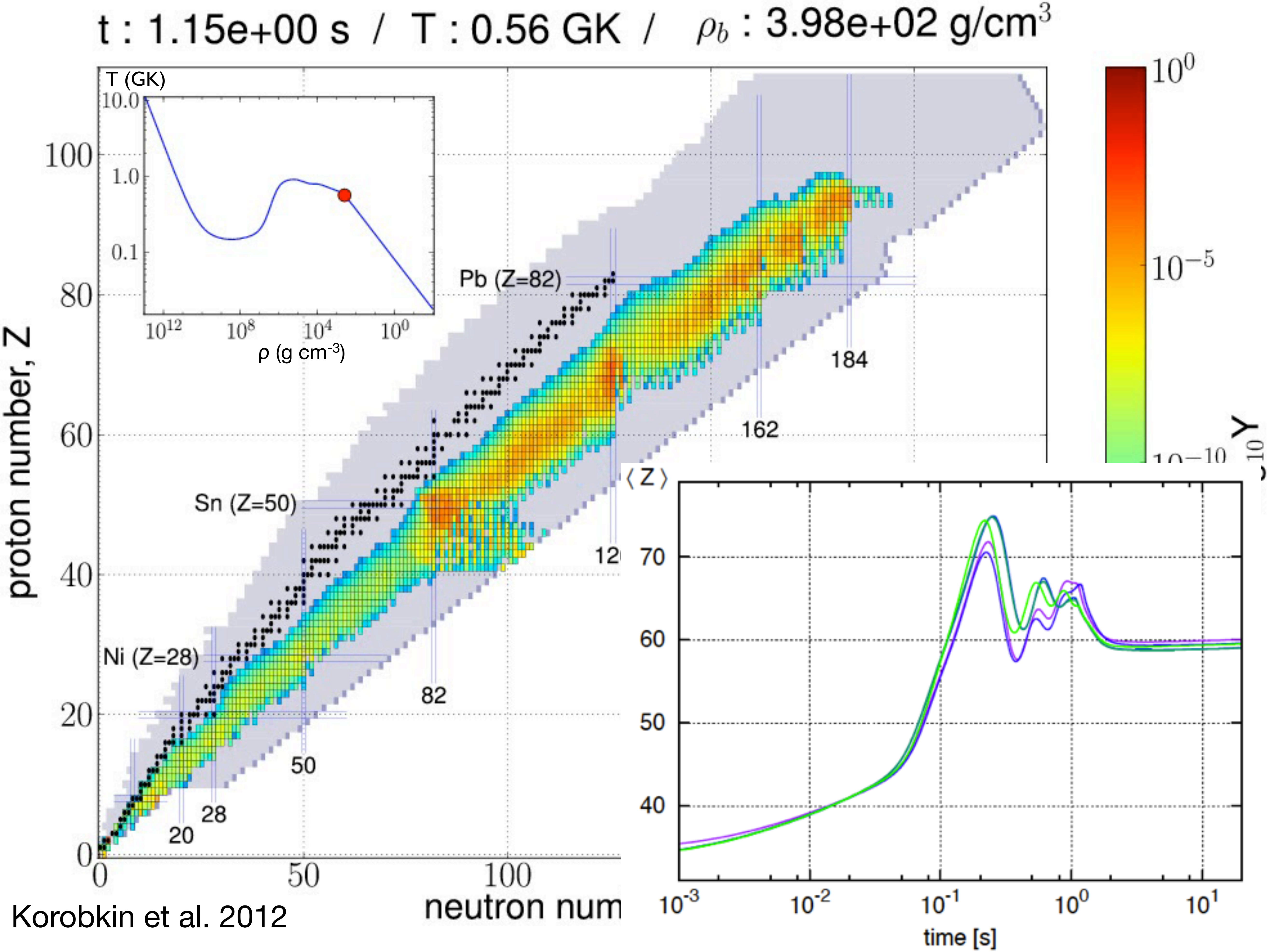
T (GK)

ρ (g cm^{-3})

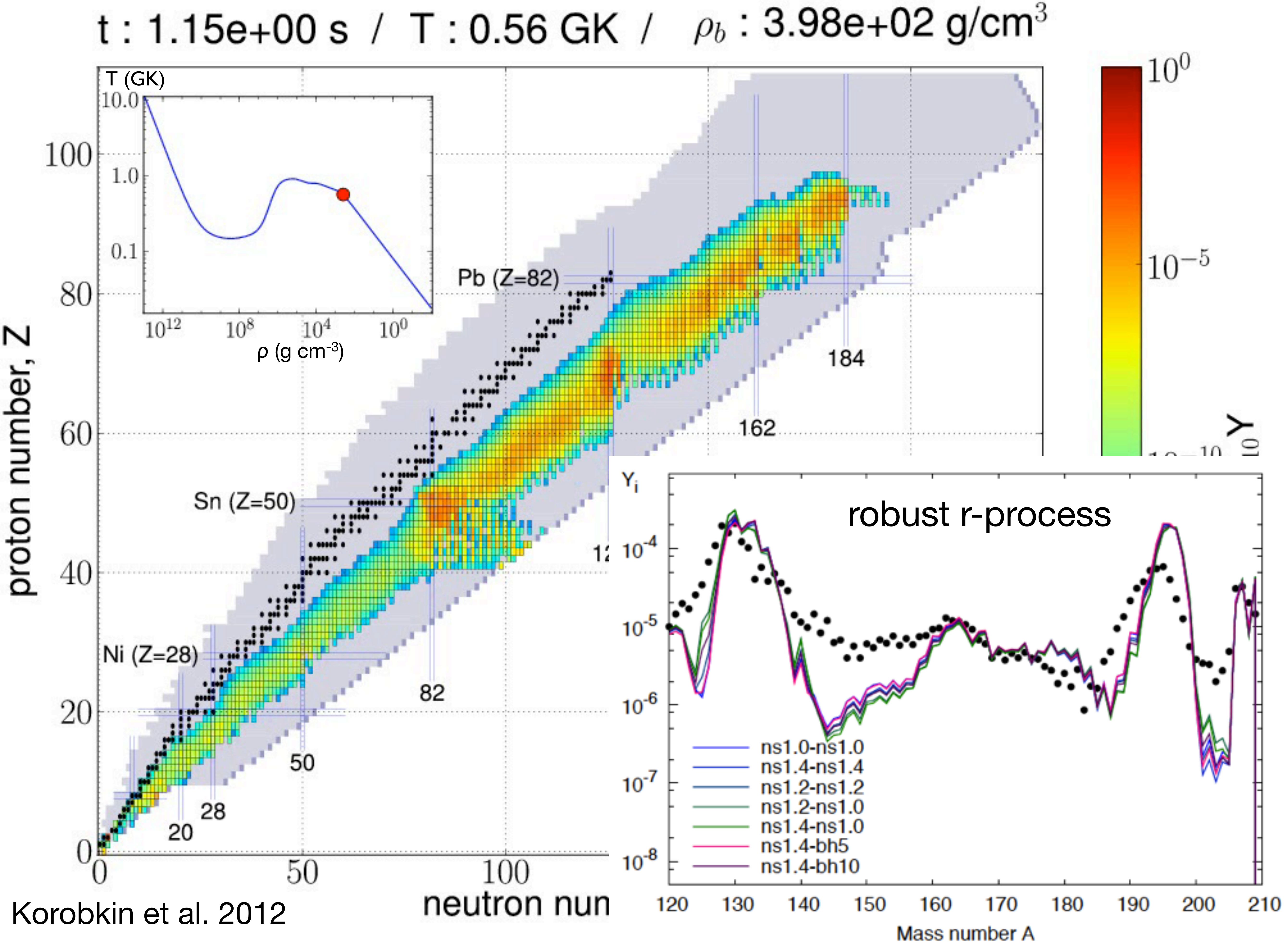
Korobkin et al. 2012



Korobkin et al. 2012



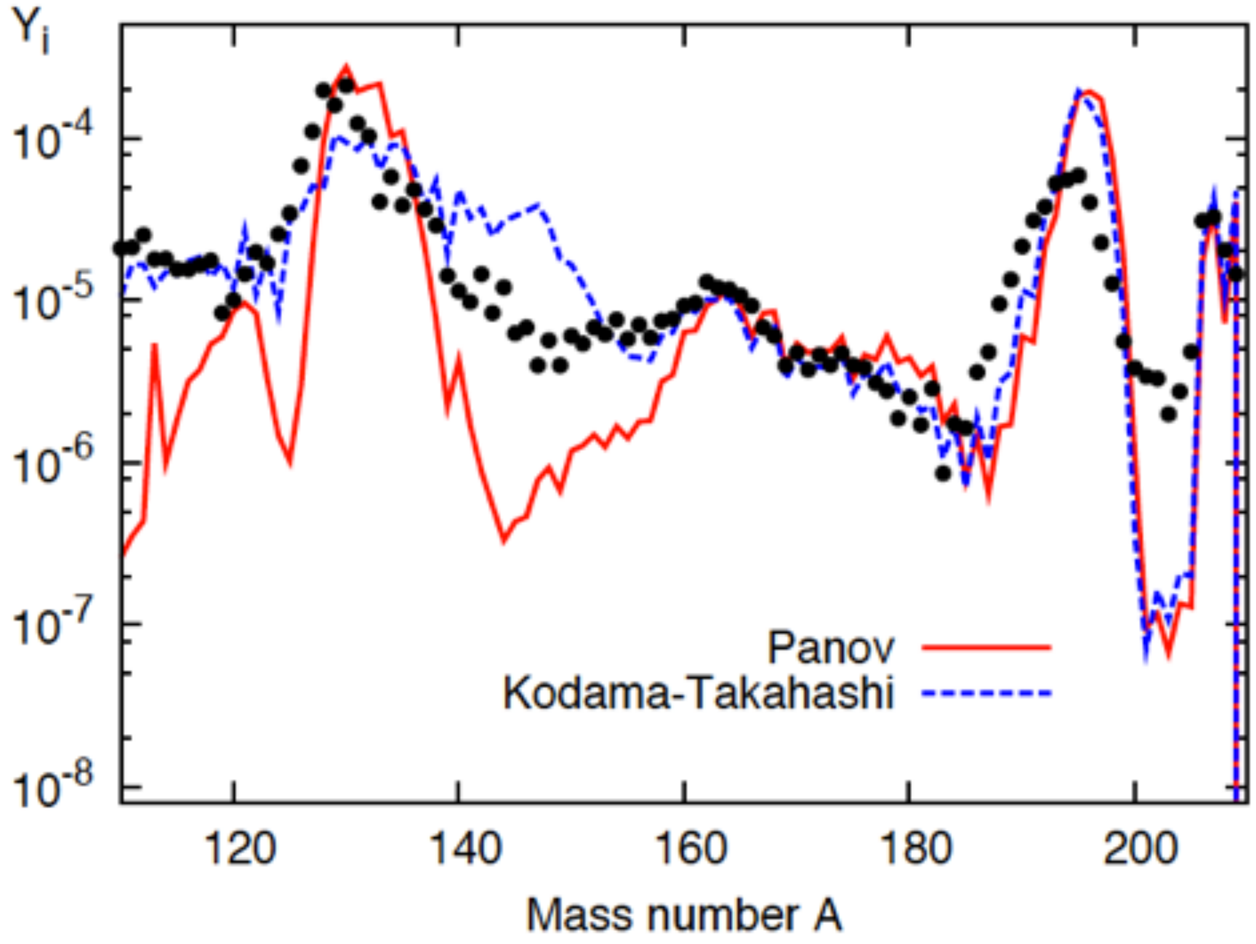
Korobkin et al. 2012



robust r-process

Korobkin et al. 2012

Fission: barriers and yield distributions

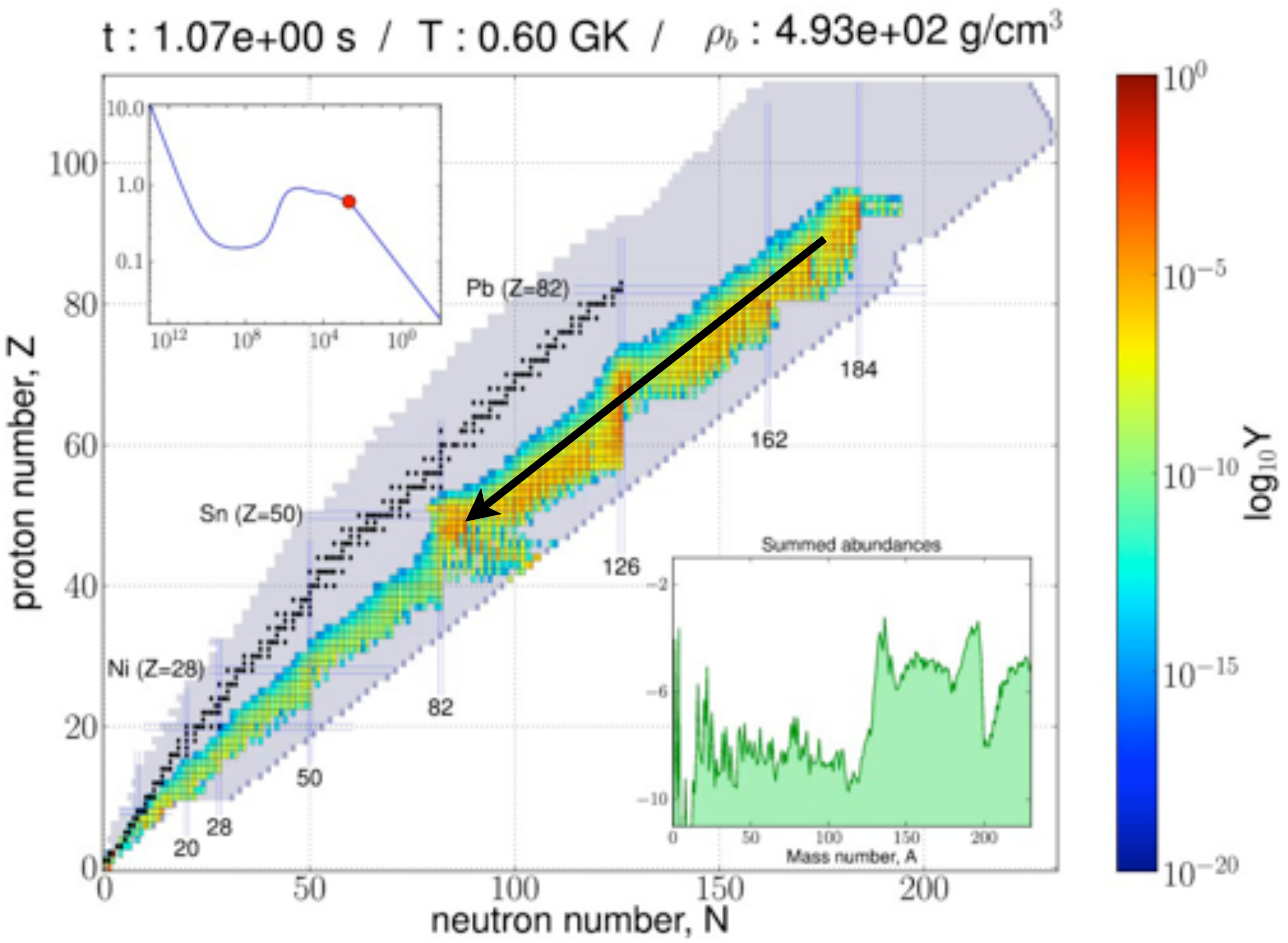


Korobkin, Rosswog, Arcones, Winteler (2012)

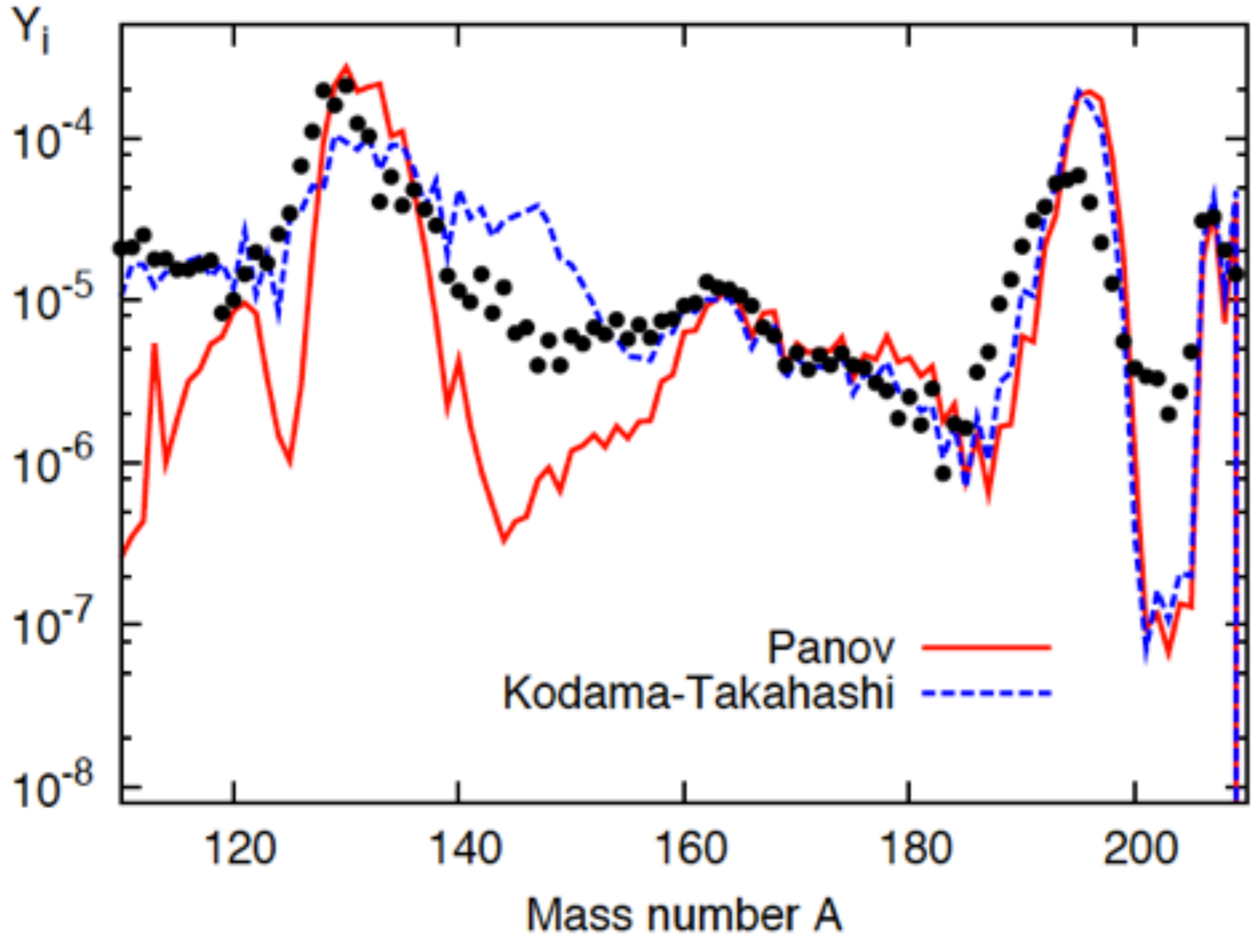
Neutron star mergers: r-process with two simple fission descriptions

2nd peak (A~130): fission yield distribution
3rd peak (A~195): mass model, neutron captures

Fission: barriers and yield distributions



Korobkin, Rosswog, Arcones, Winteler (2012)

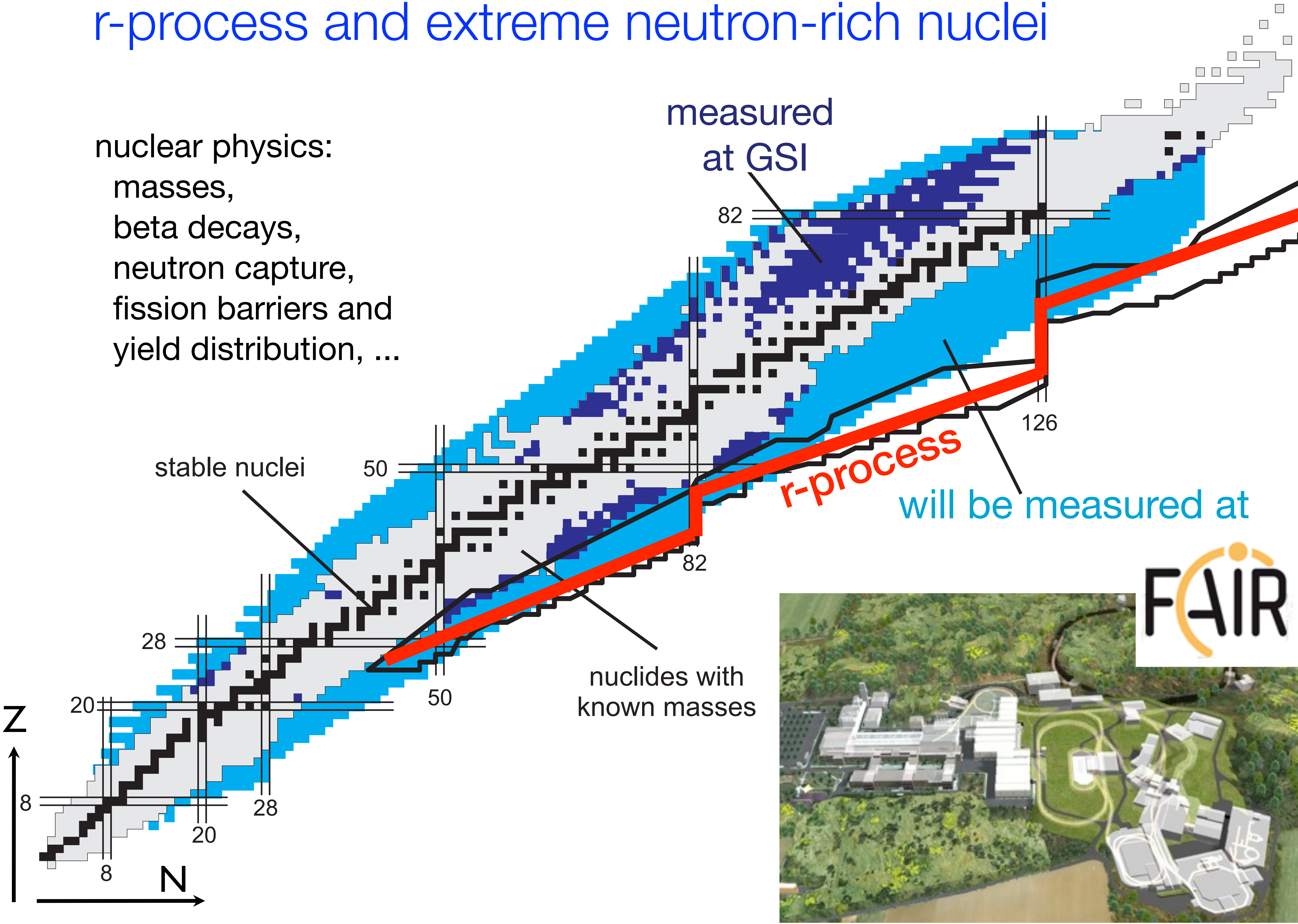


Neutron star mergers: r-process with two simple fission descriptions

2nd peak (A~130): fission yield distribution
3rd peak (A~195): mass model, neutron captures

r-process and extreme neutron-rich nuclei

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

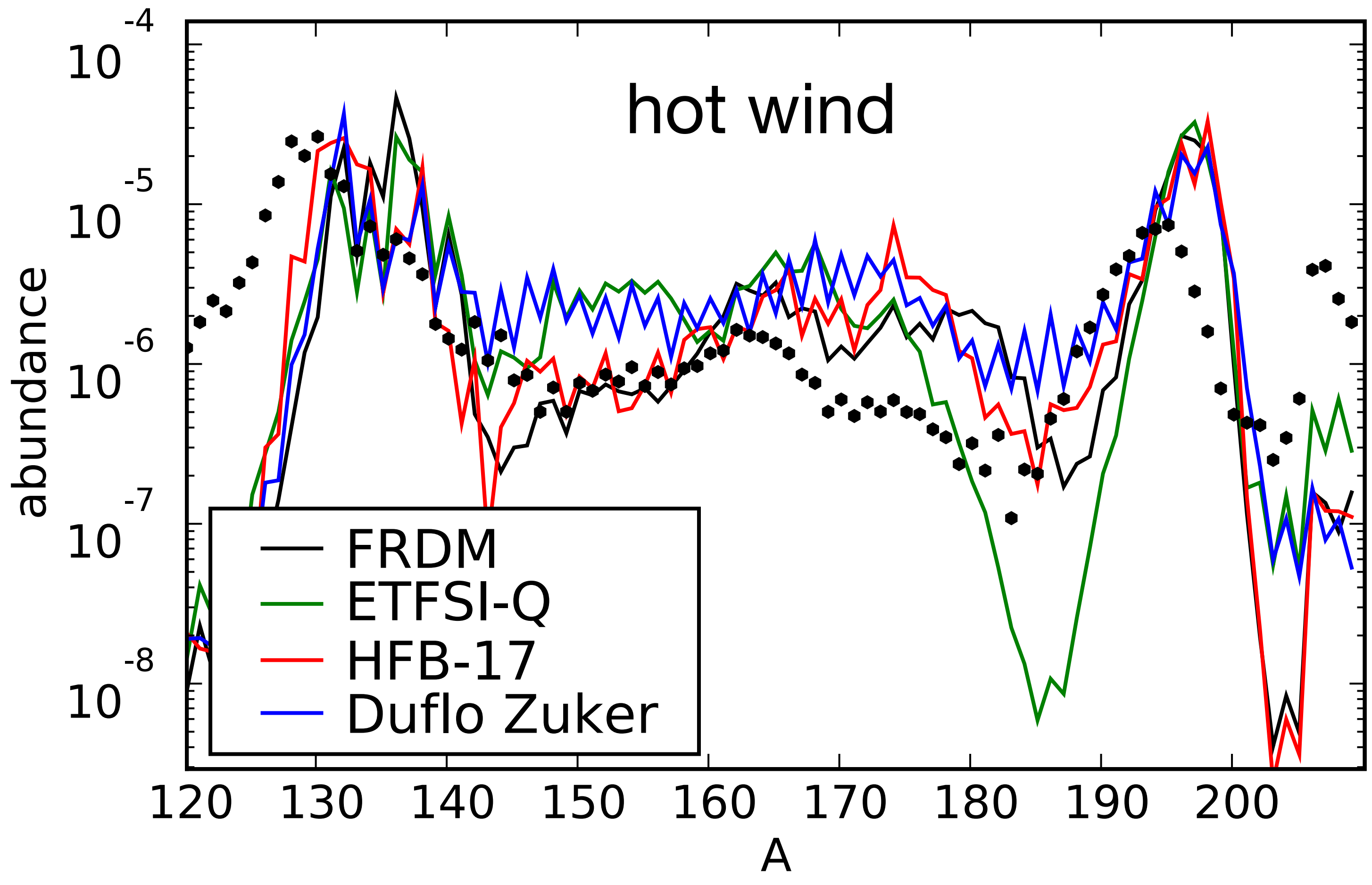


Nuclear masses

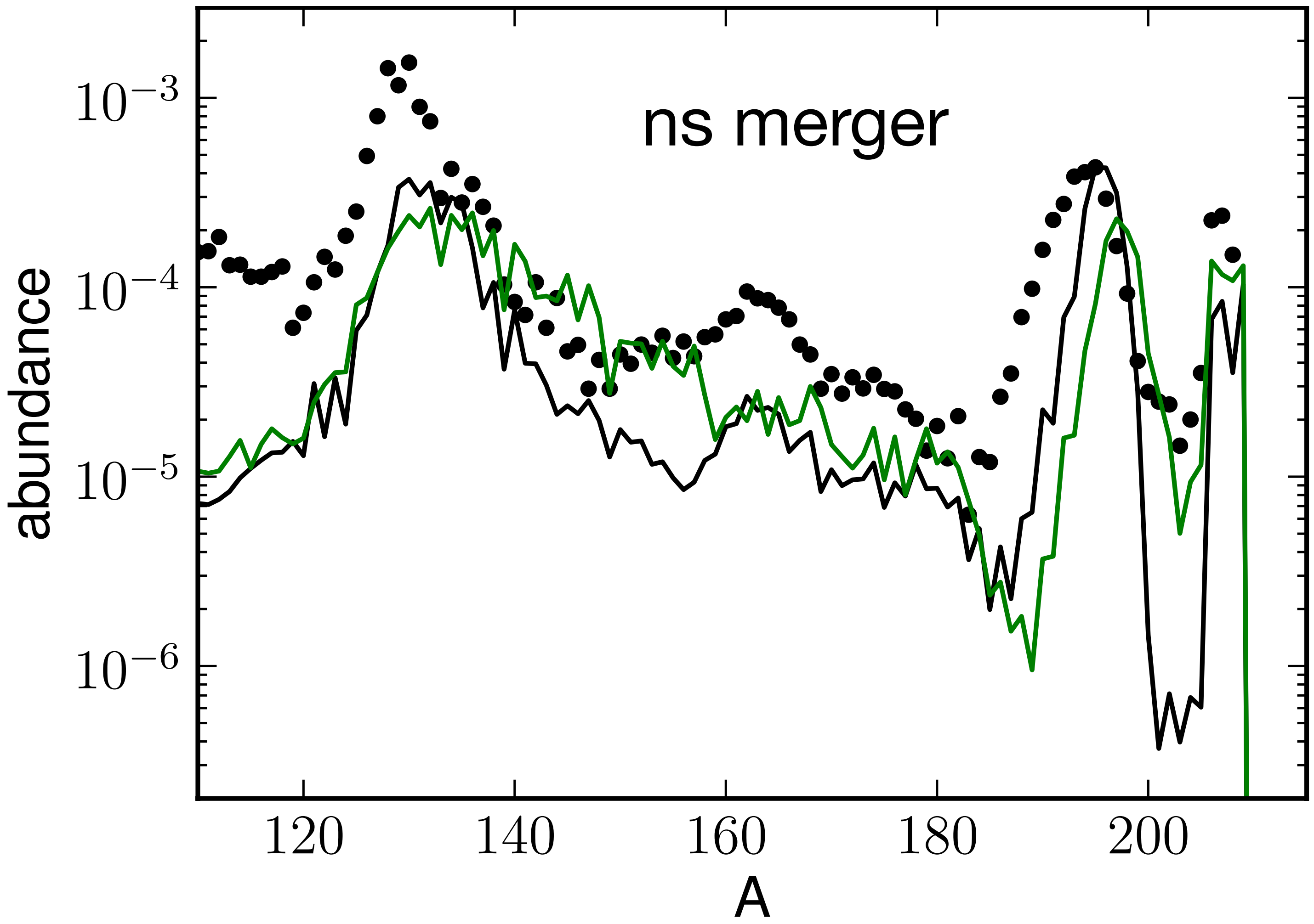
Given astrophysical conditions, comparison of abundances based different mass models

- 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

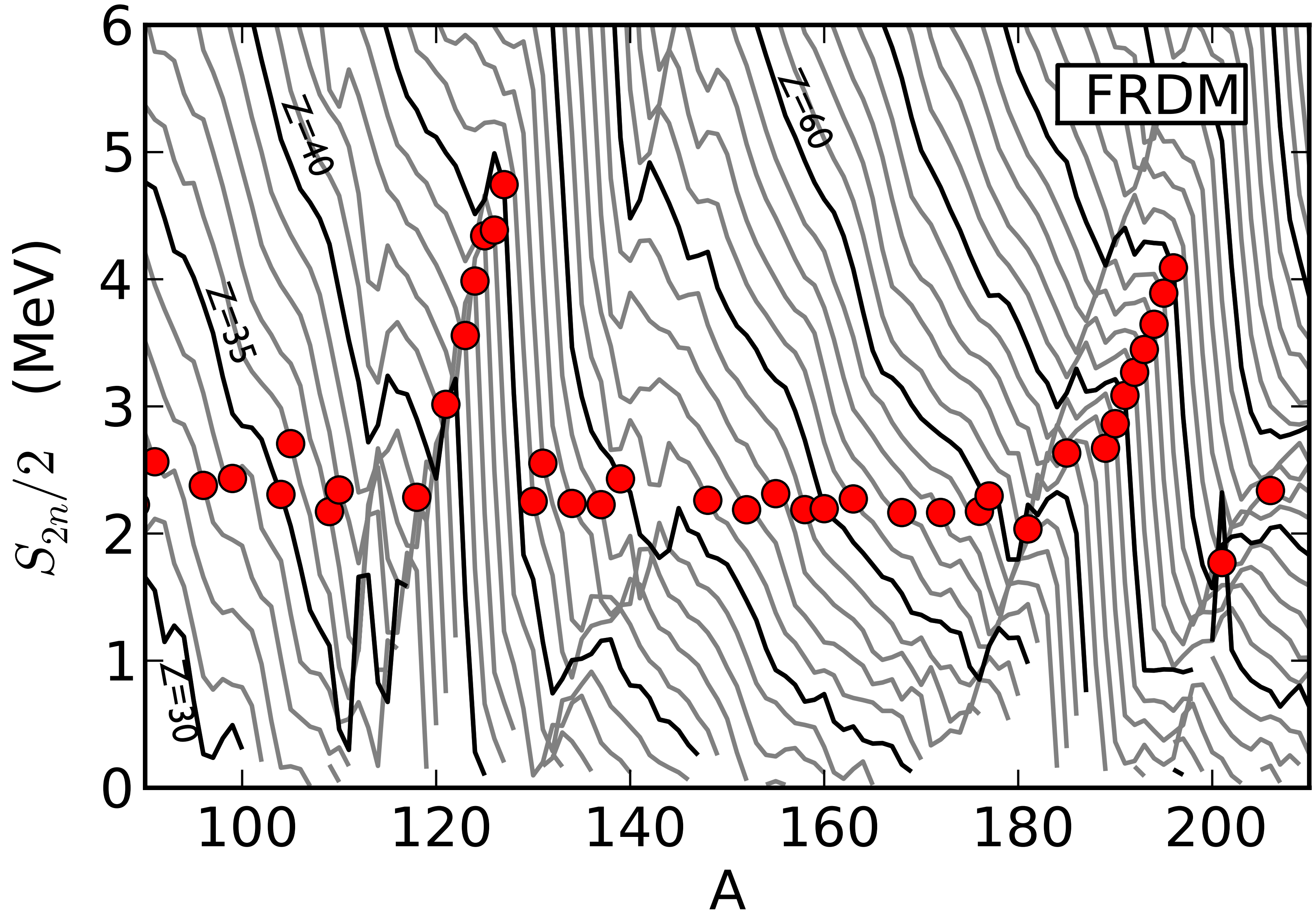


Two neutron separation energy

Abundances

S_{2n}

Nuclear properties



Two neutron separation energy

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S_{2n}

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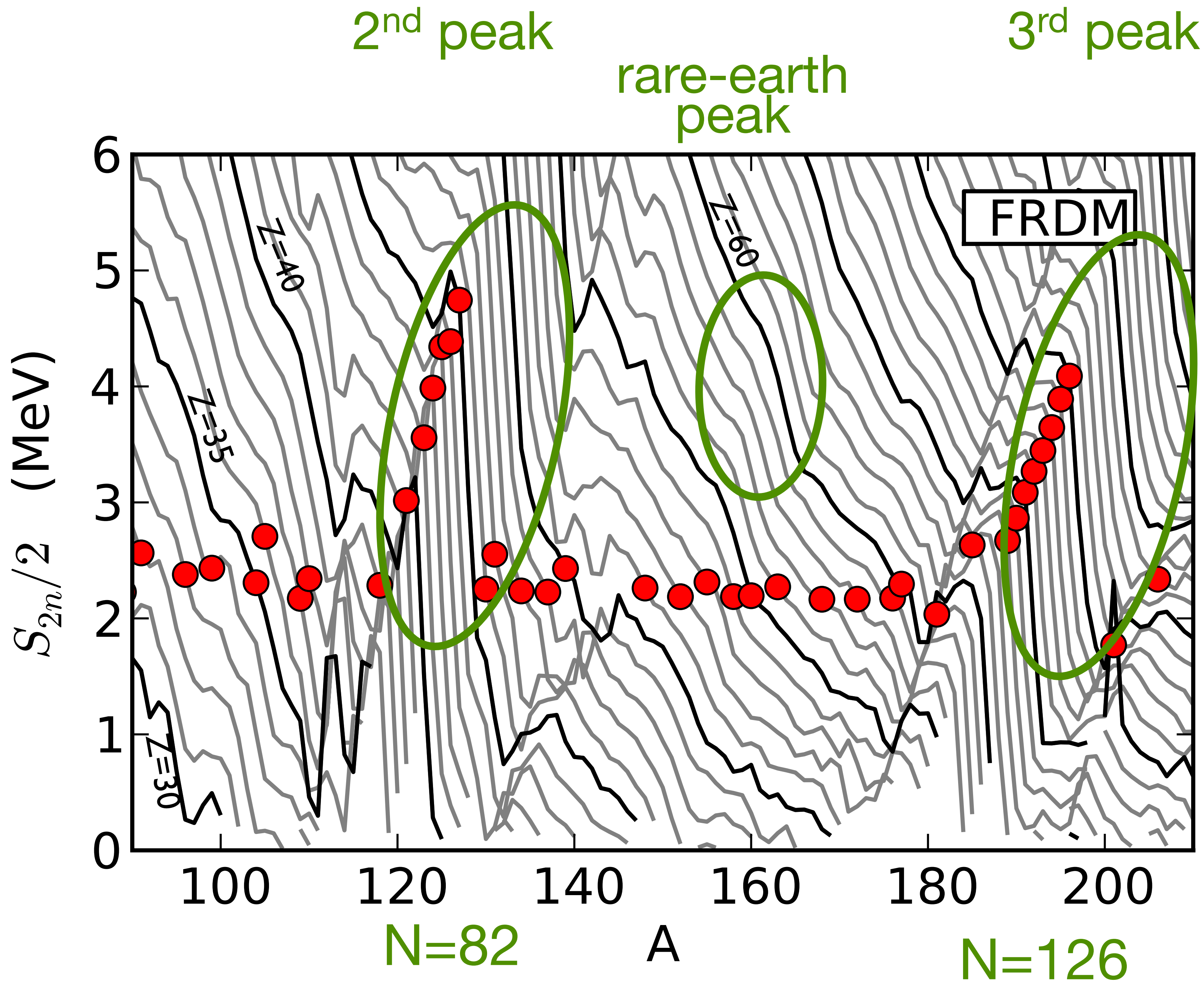


Two neutron separation energy

Abundances

S_{2n}

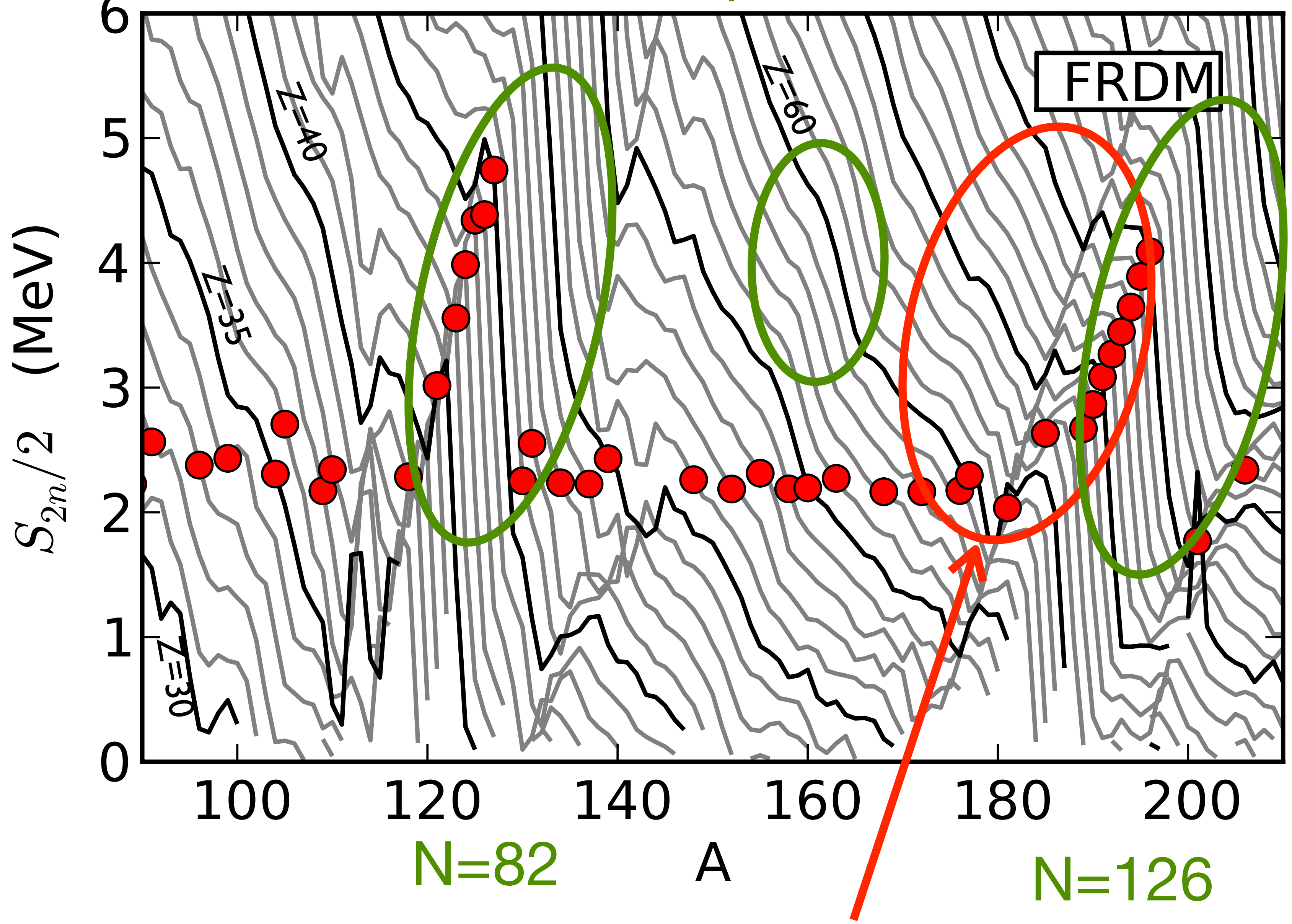
Nuclear properties

2nd peak

rare-earth peak

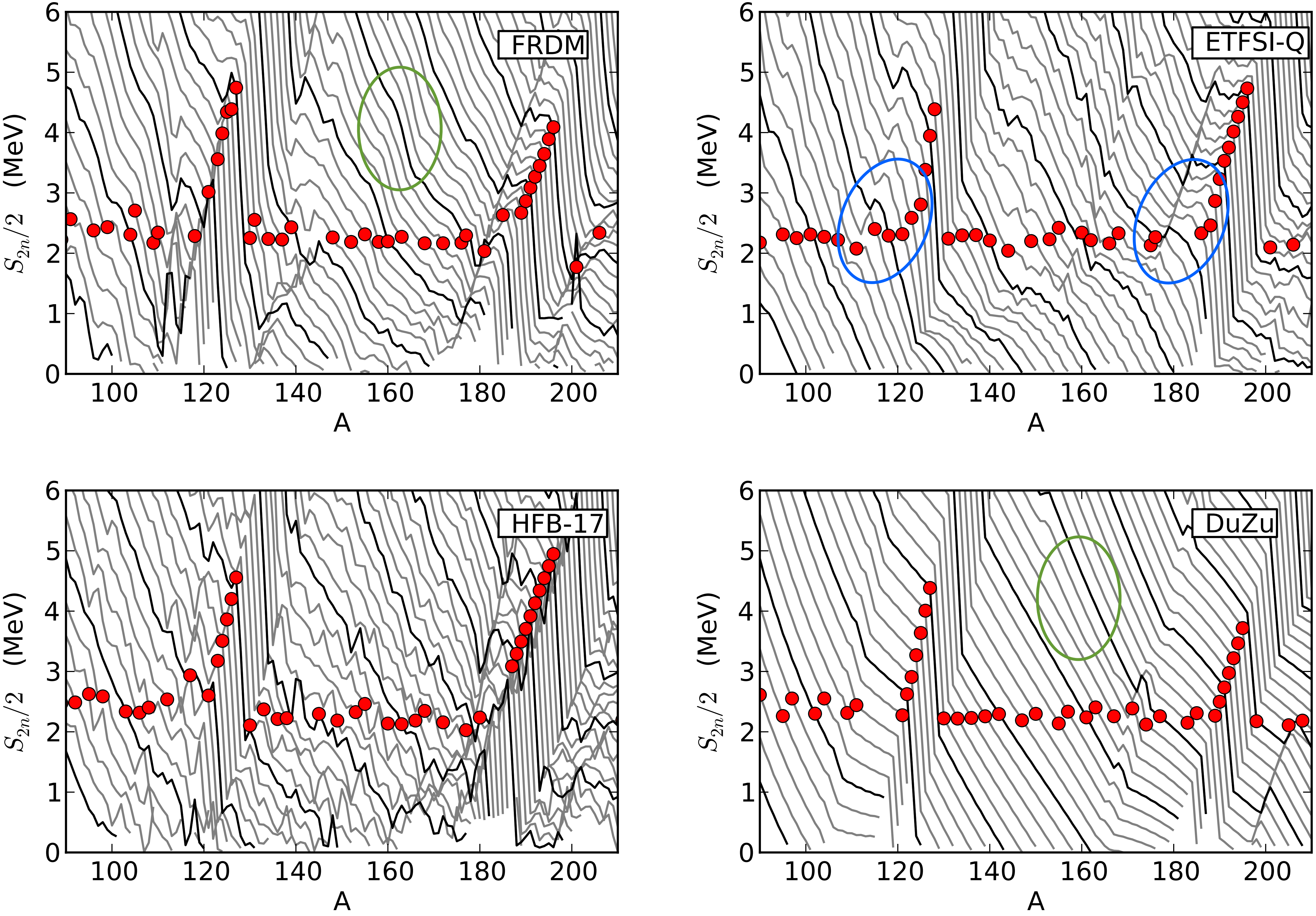
trough

3rd peak



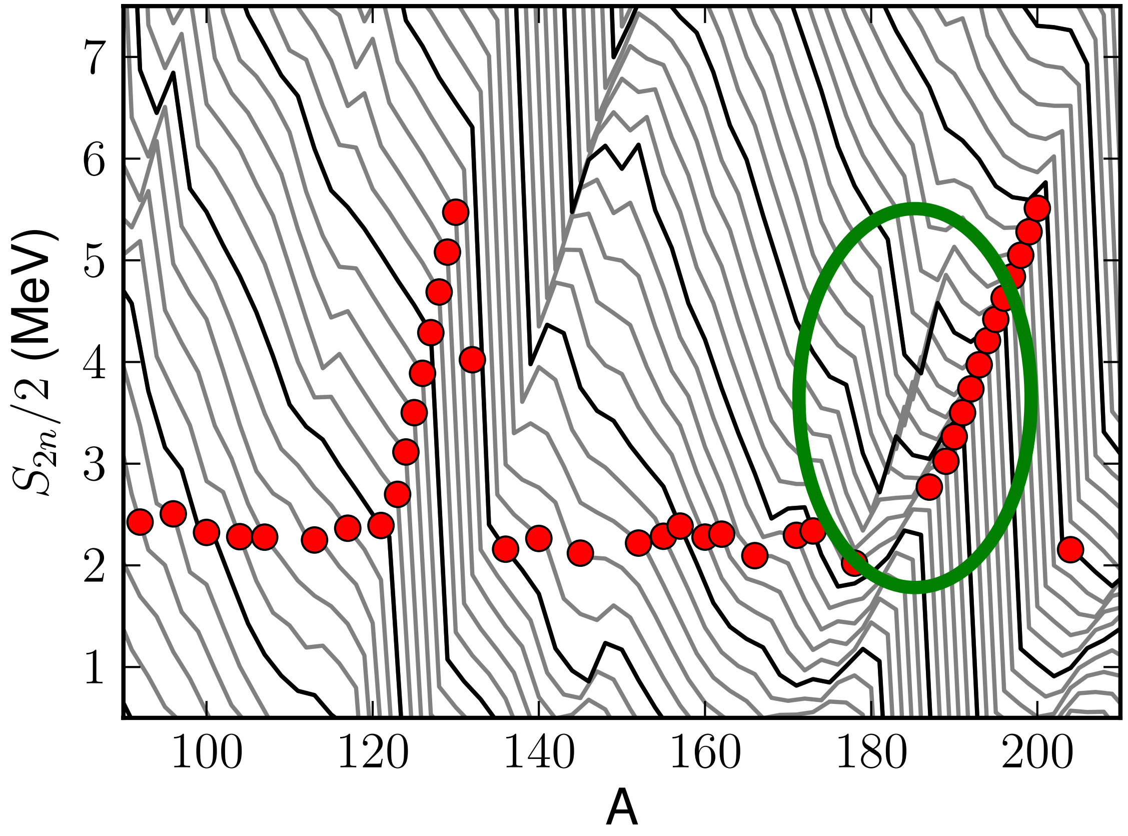
transition from deformed to spherical

Aspects of different mass models

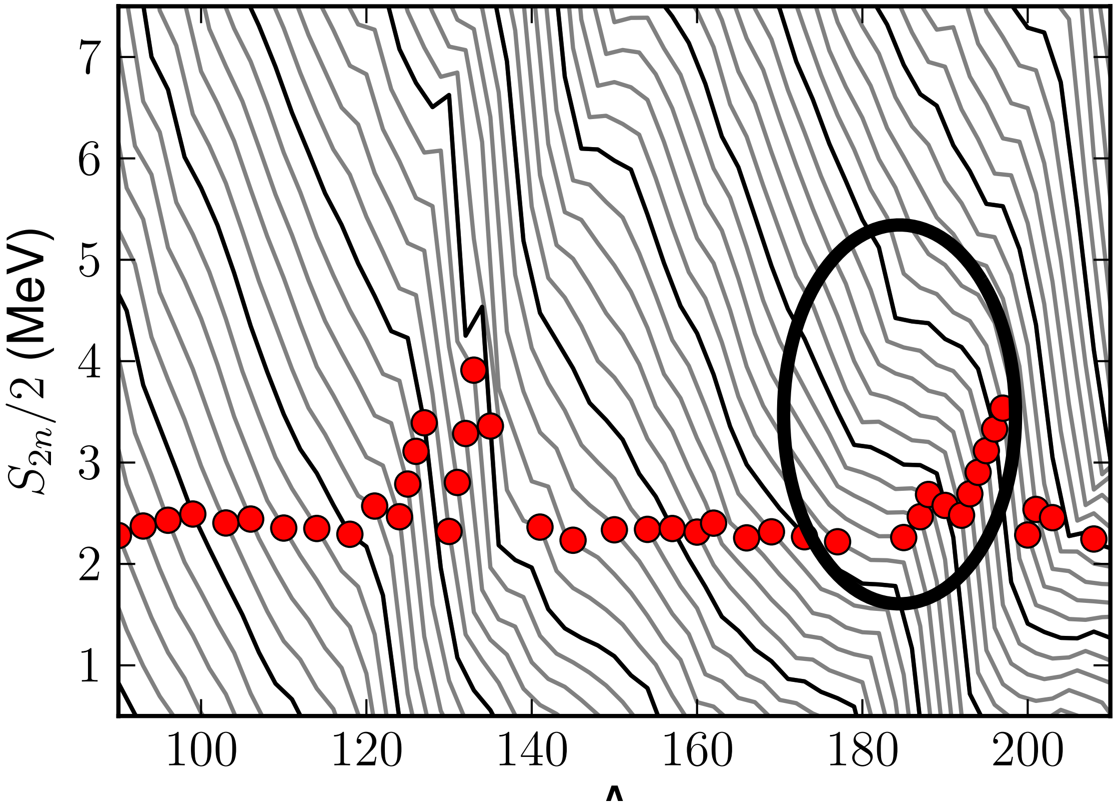


Nuclear correlations and r-process

without correlations

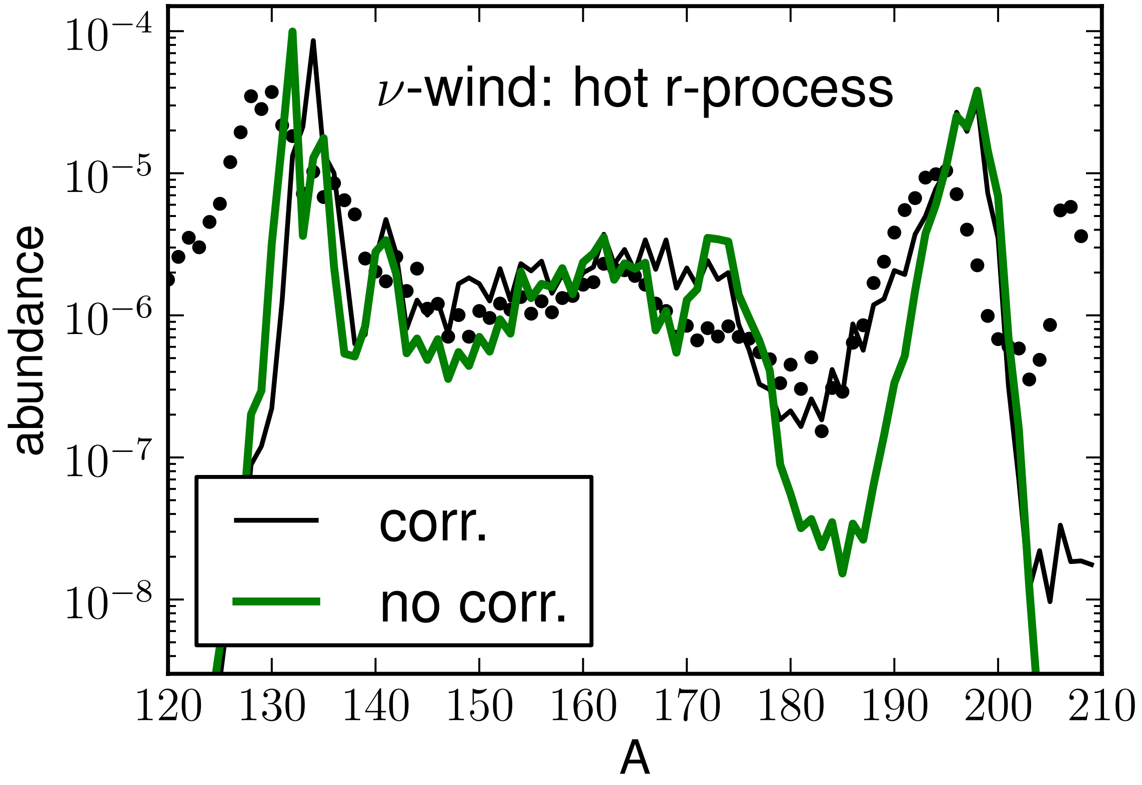


with correlations



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

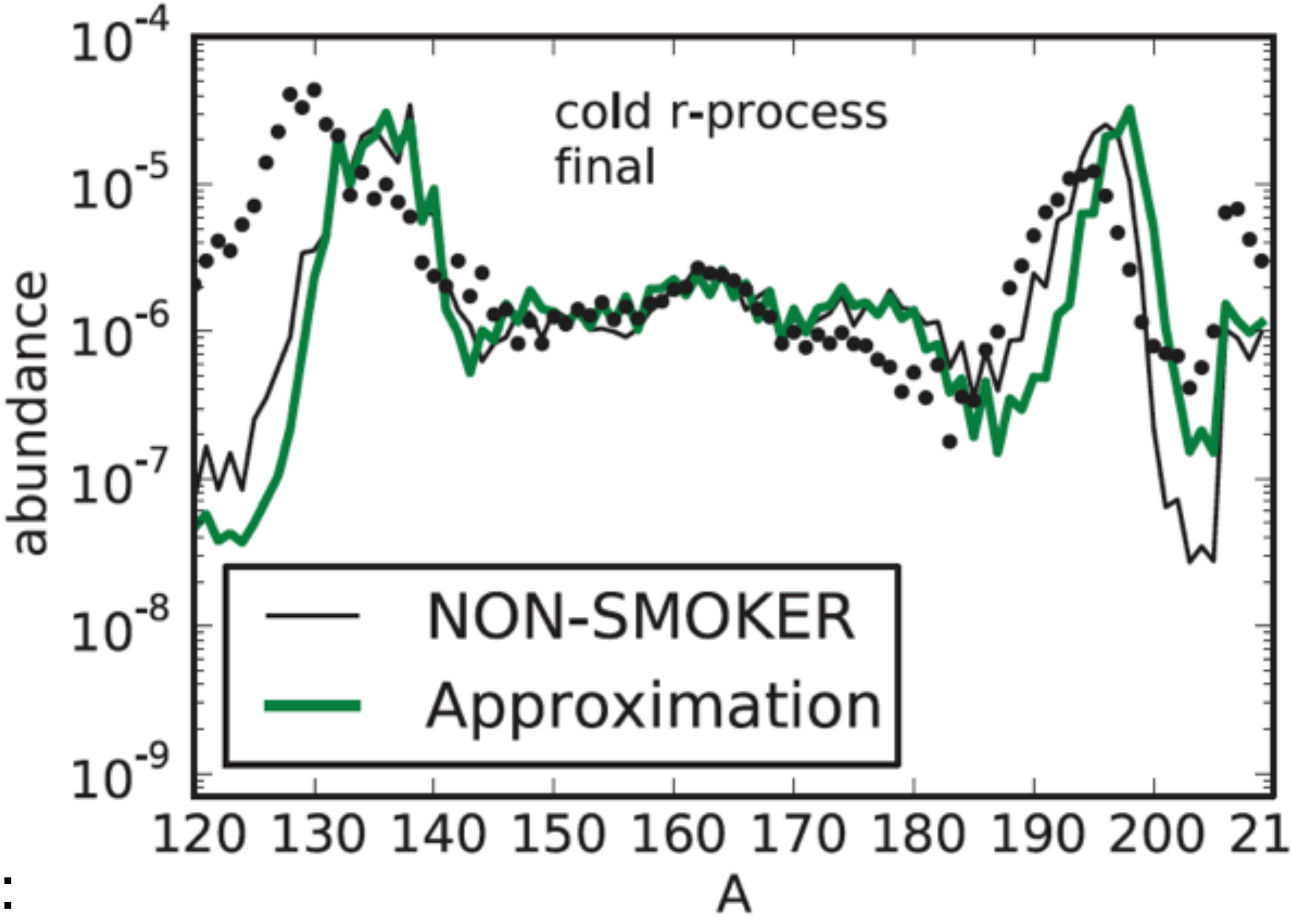
Nuclear correlations: strong impact on trough before third peak



Arcones & Bertsch (2012)

Neutron captures

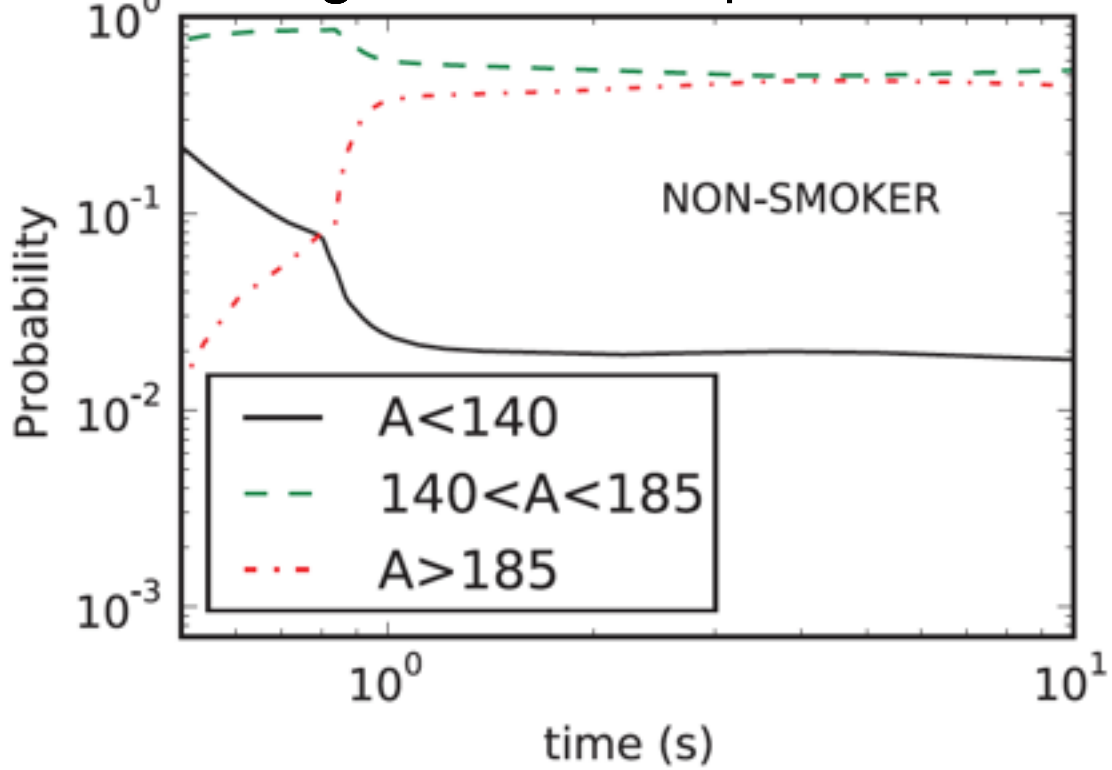
- -NON-SMOKER
  (Rauscher & Thielemann, 2000)
- -Approximation
  (Woosley, Fowler et al. 1975)



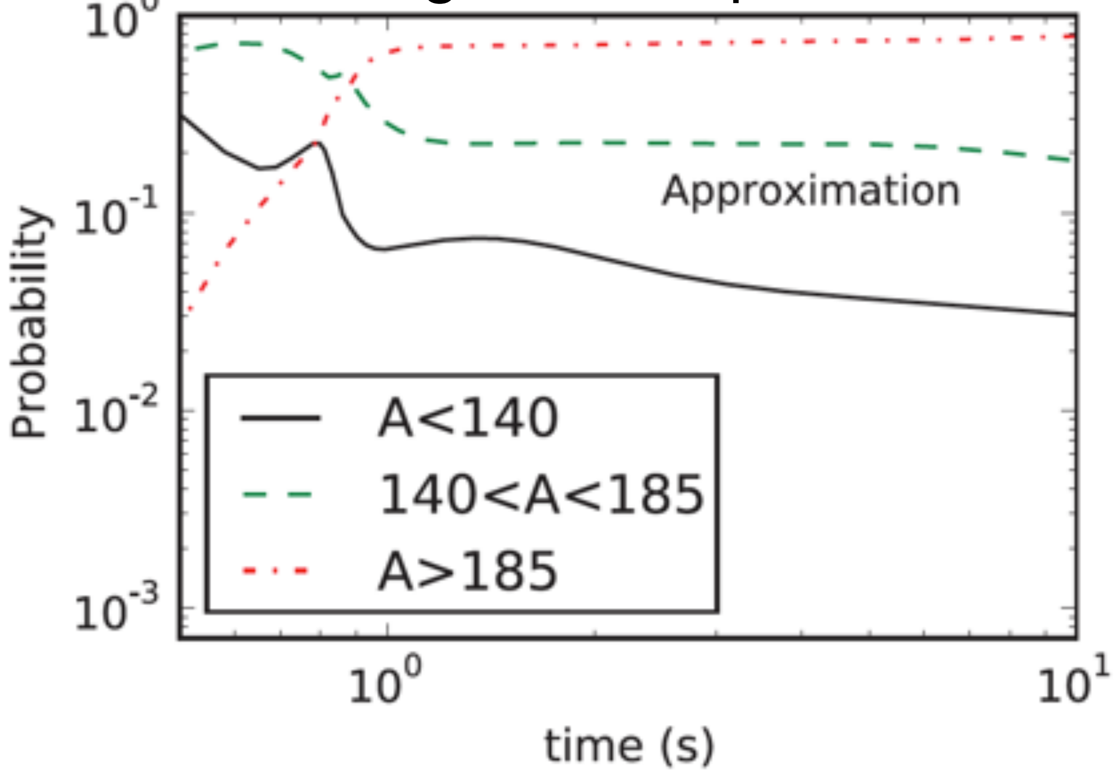
Arcones & Martinez-Pinedo, 2011

Neutron capture probability:

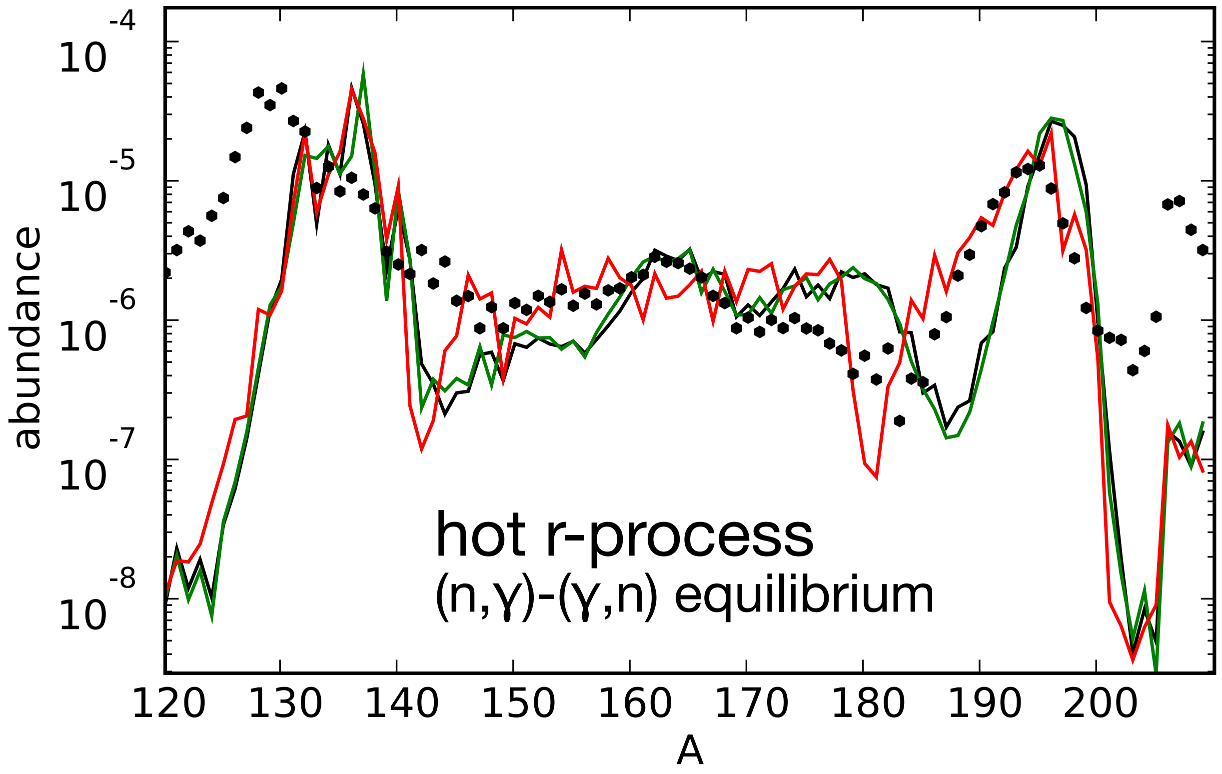
region between peaks



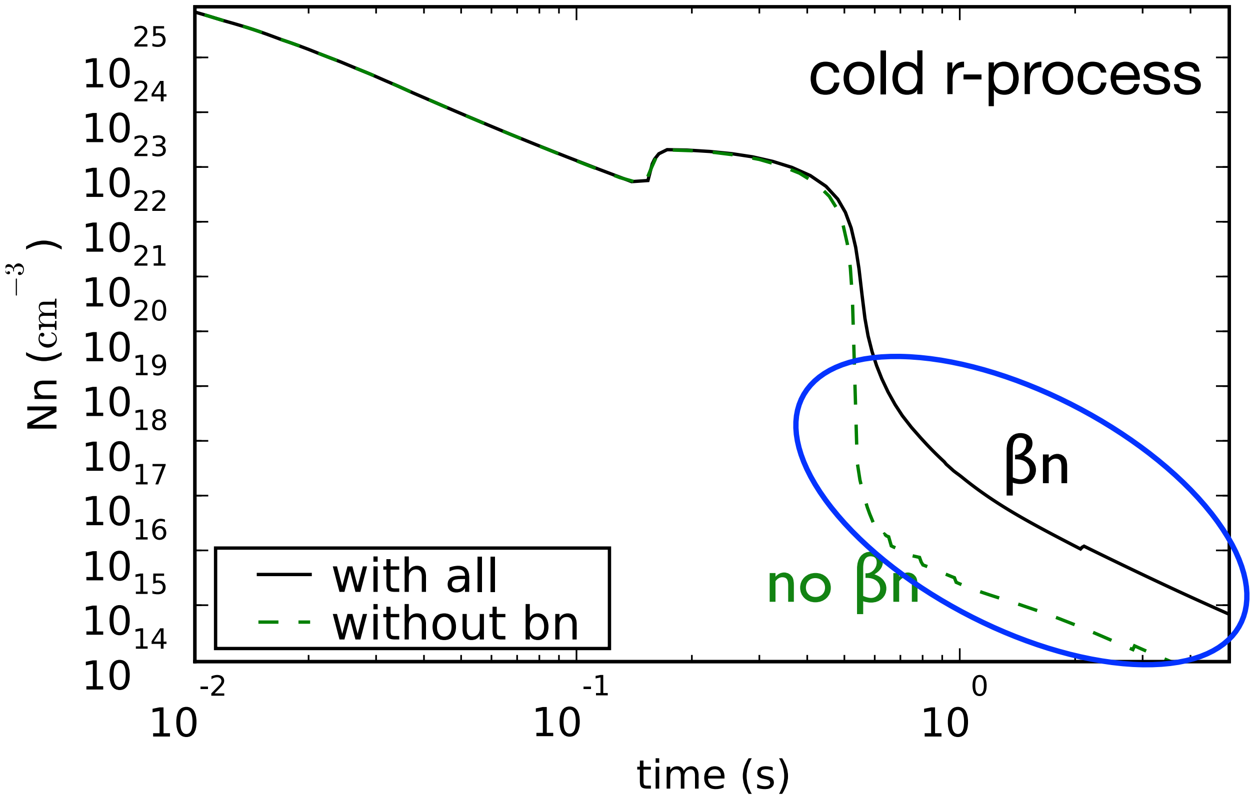
region of 3rd peak

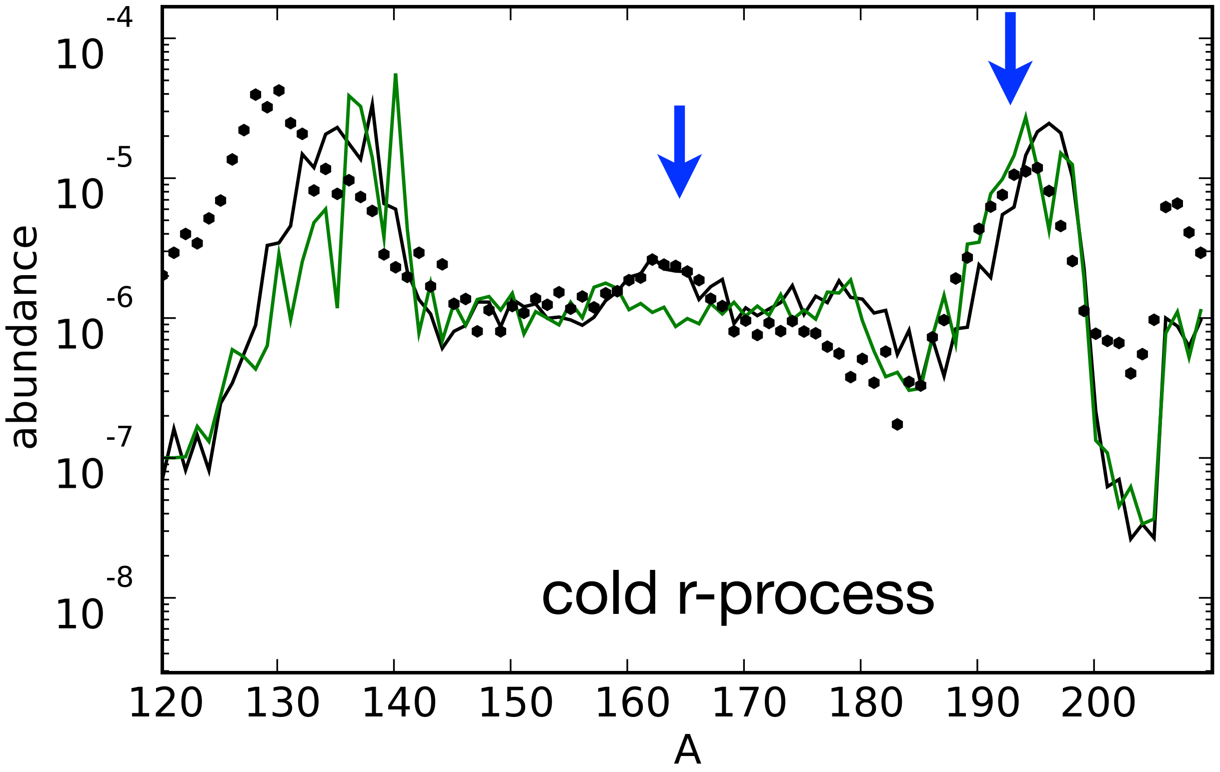


Decay to stability



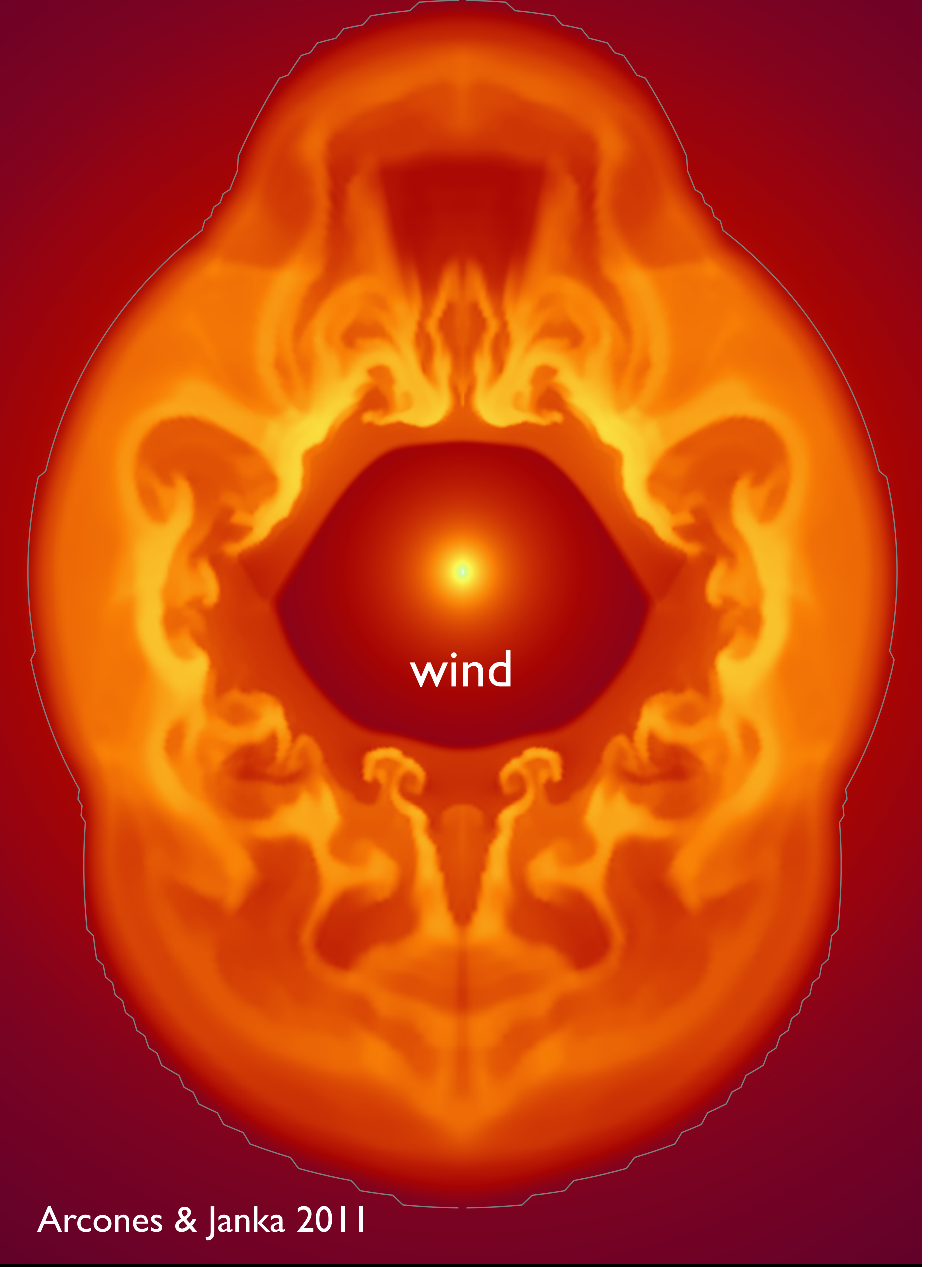
We compare final abundances with and without beta-delayed neutron emission and with and without neutron captures after freeze-out.



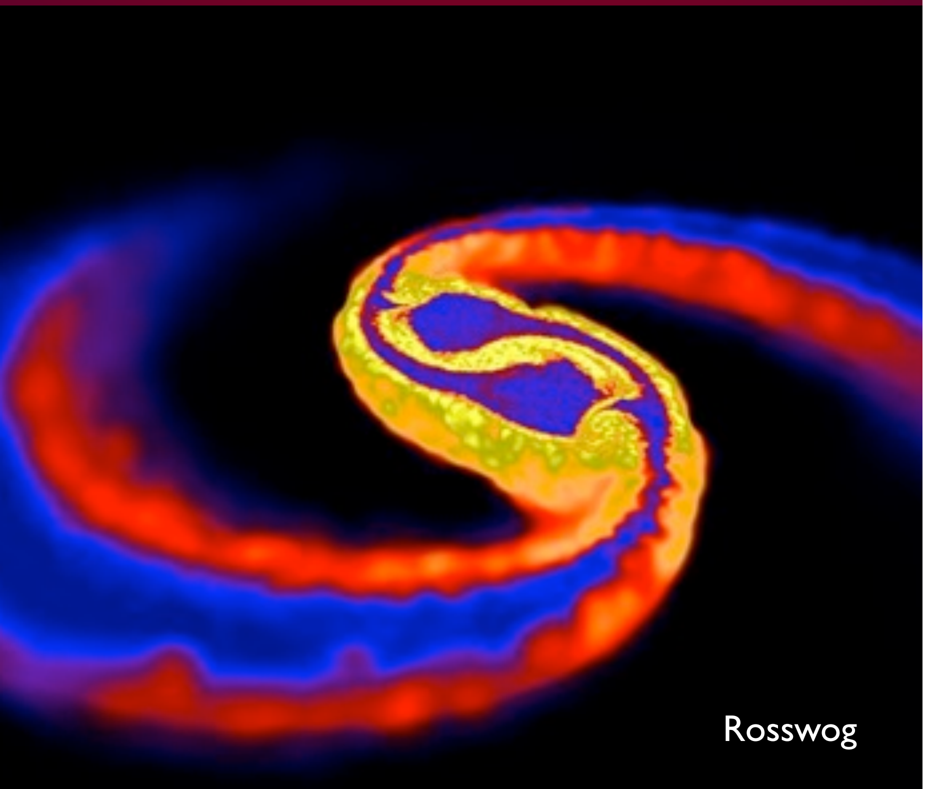


Arcones & Martinez-Pinedo, 2011

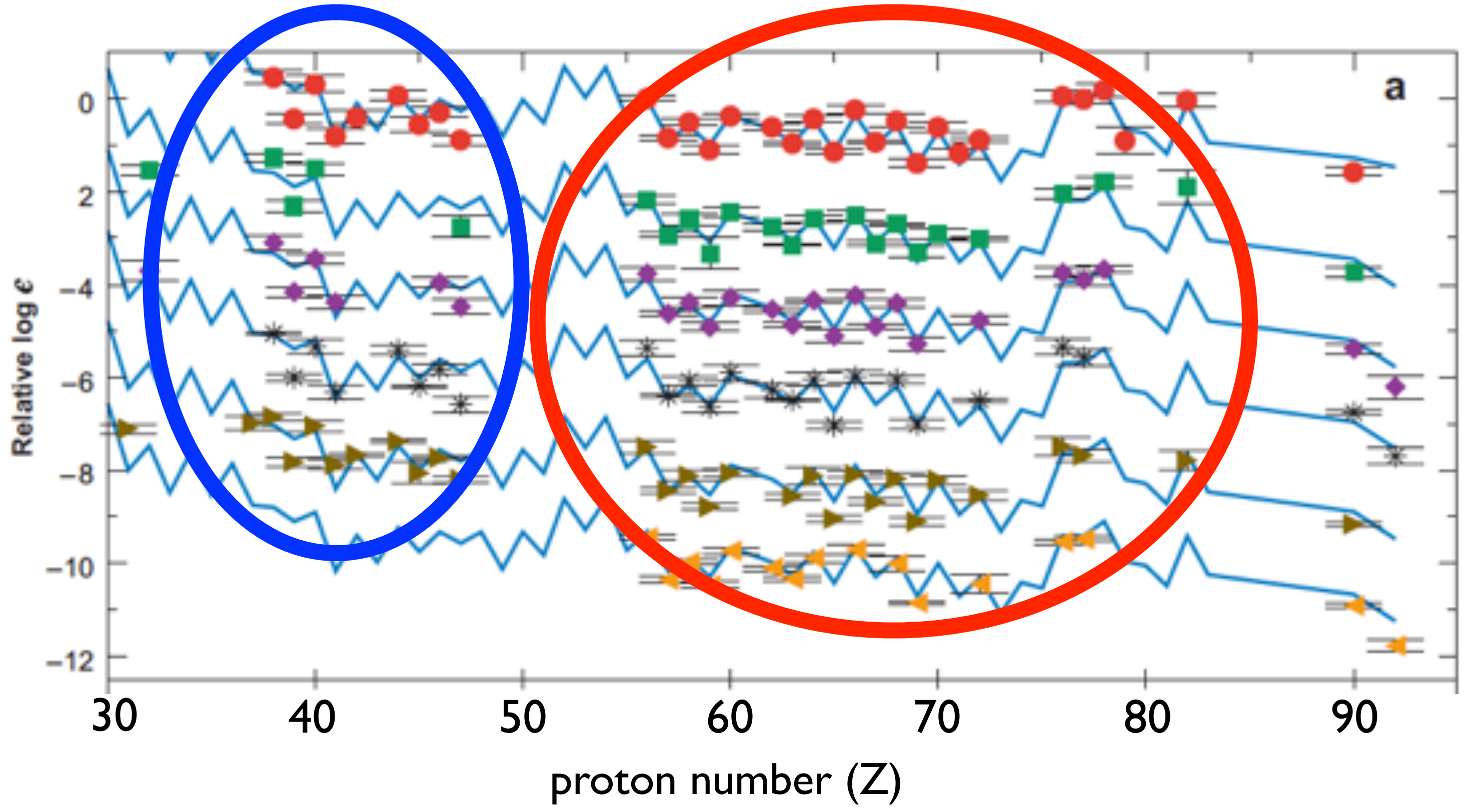
Conclusions



Arcones & Janka 2011



Rosswog



Lighter heavy elements (Sr, Y, Zr)
produced in neutrino-driven winds
key reactions: (α,n)

Heavy r-process elements
astrophysical site? sn, merger, ... → GCE
uncertainties on nuclear physics input