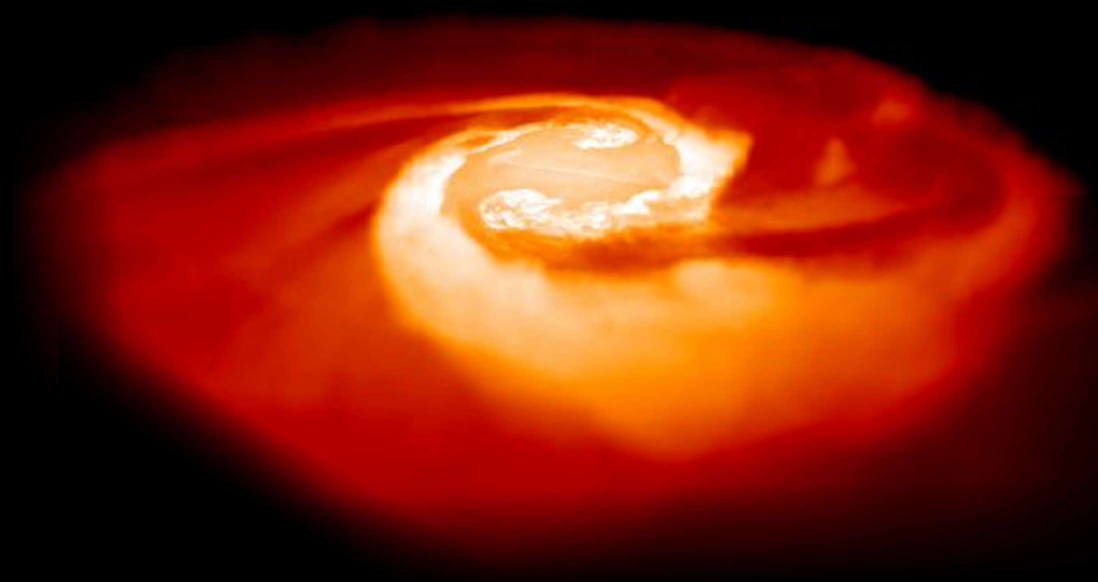


R-process nucleosynthesis: nuclear physics and astrophysics challenges

Almudena Arcones

European Research Council
SFB 1245
DFG
Bundesministerium für Bildung und Forschung
GSI
TECHNISCHE UNIVERSITÄT DARMSTADT

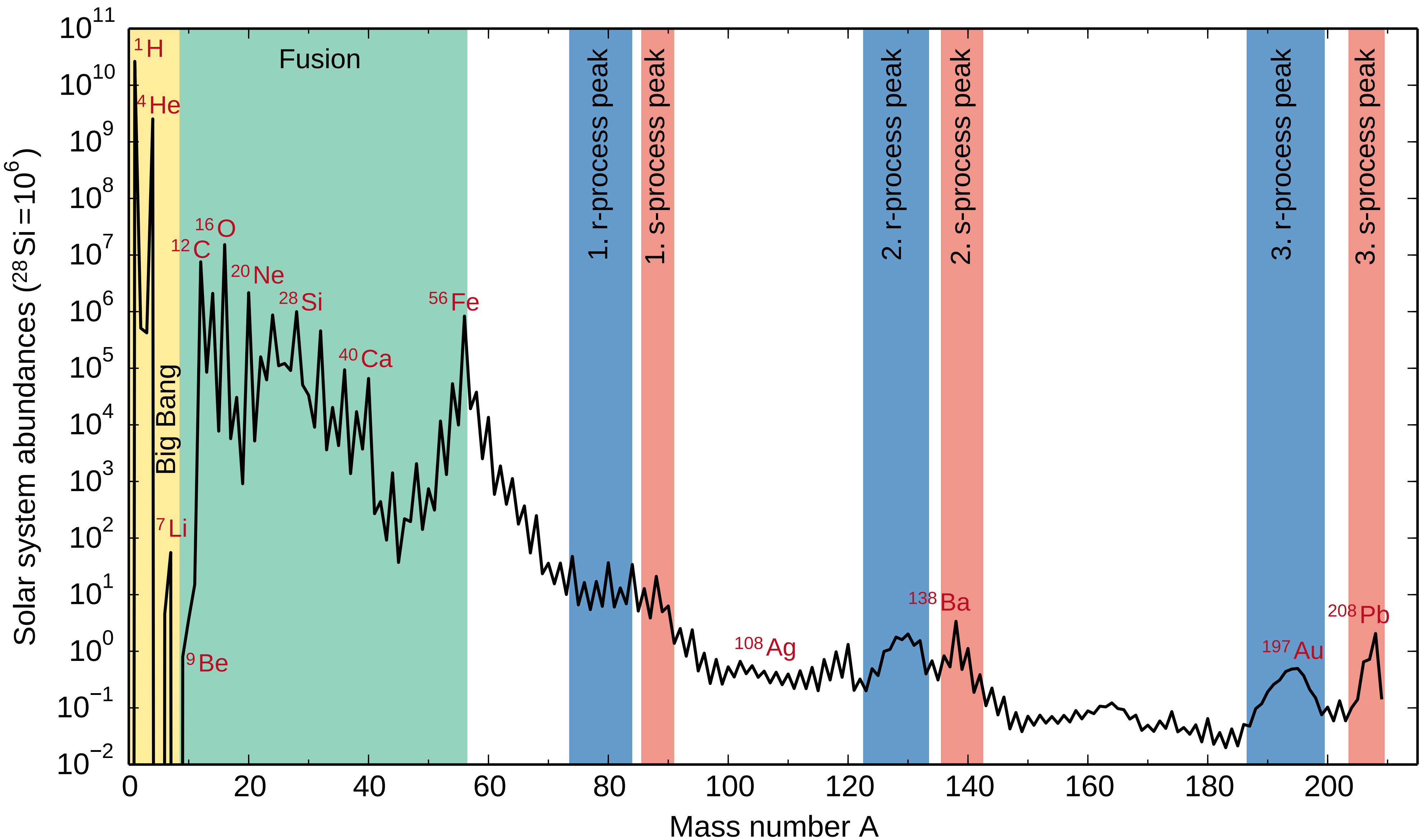
EMMI Rapid Reaction Task Force: The physics of neutron star mergers at GSI/FAIR

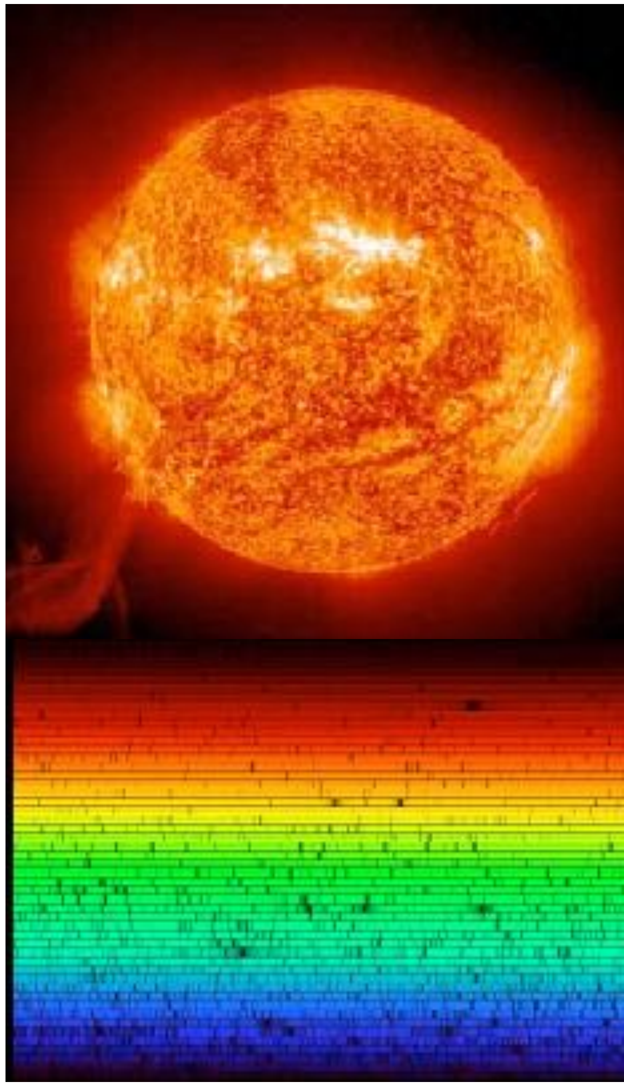
4-15 June 2018
GSI Helmholtzzentrum fuer Schwerionenforschung GmbH

Solar system abundances

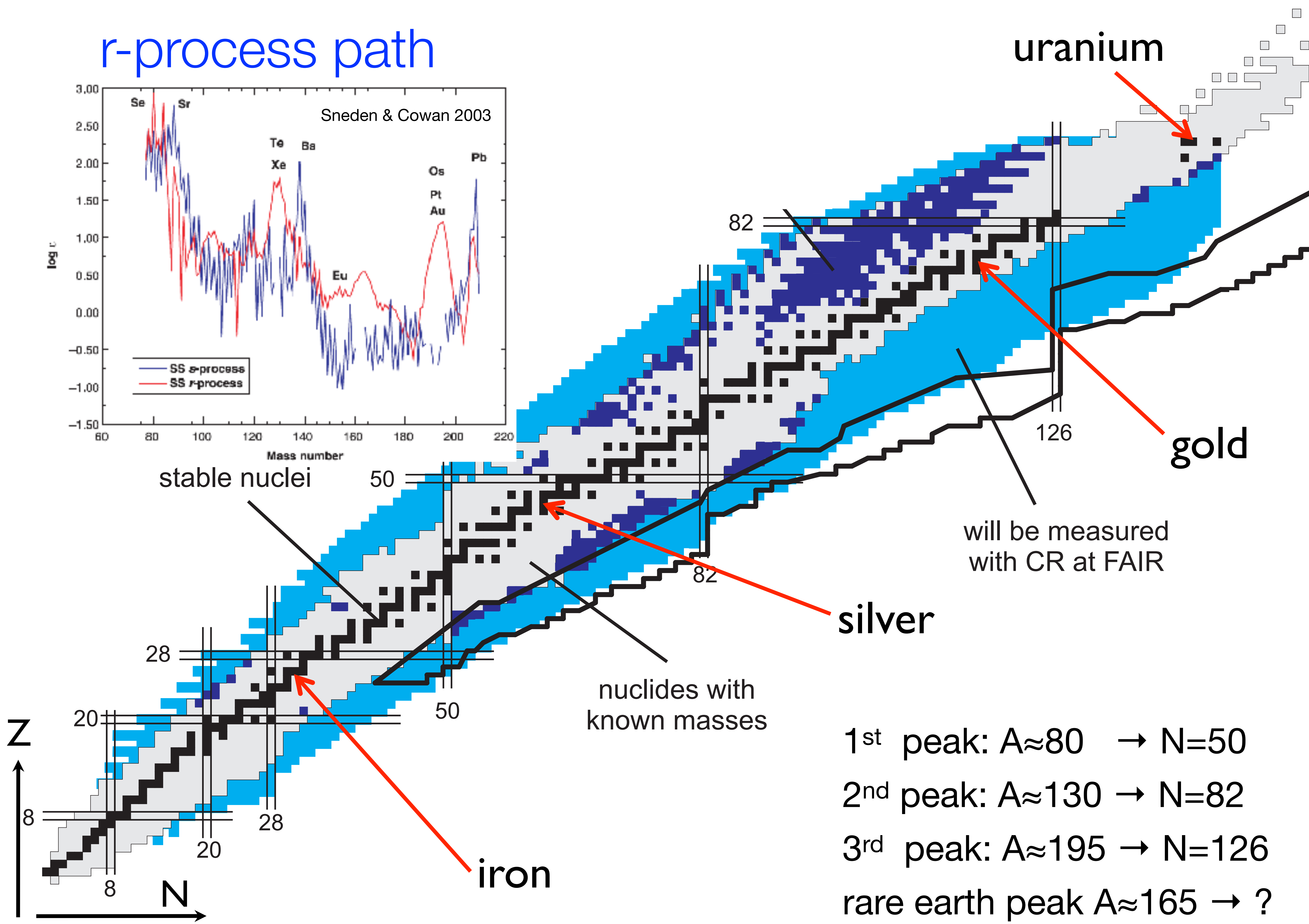
Solar photosphere and meteorites:
chemical signature of gas cloud where the Sun formed

Contribution of all nucleosynthesis processes





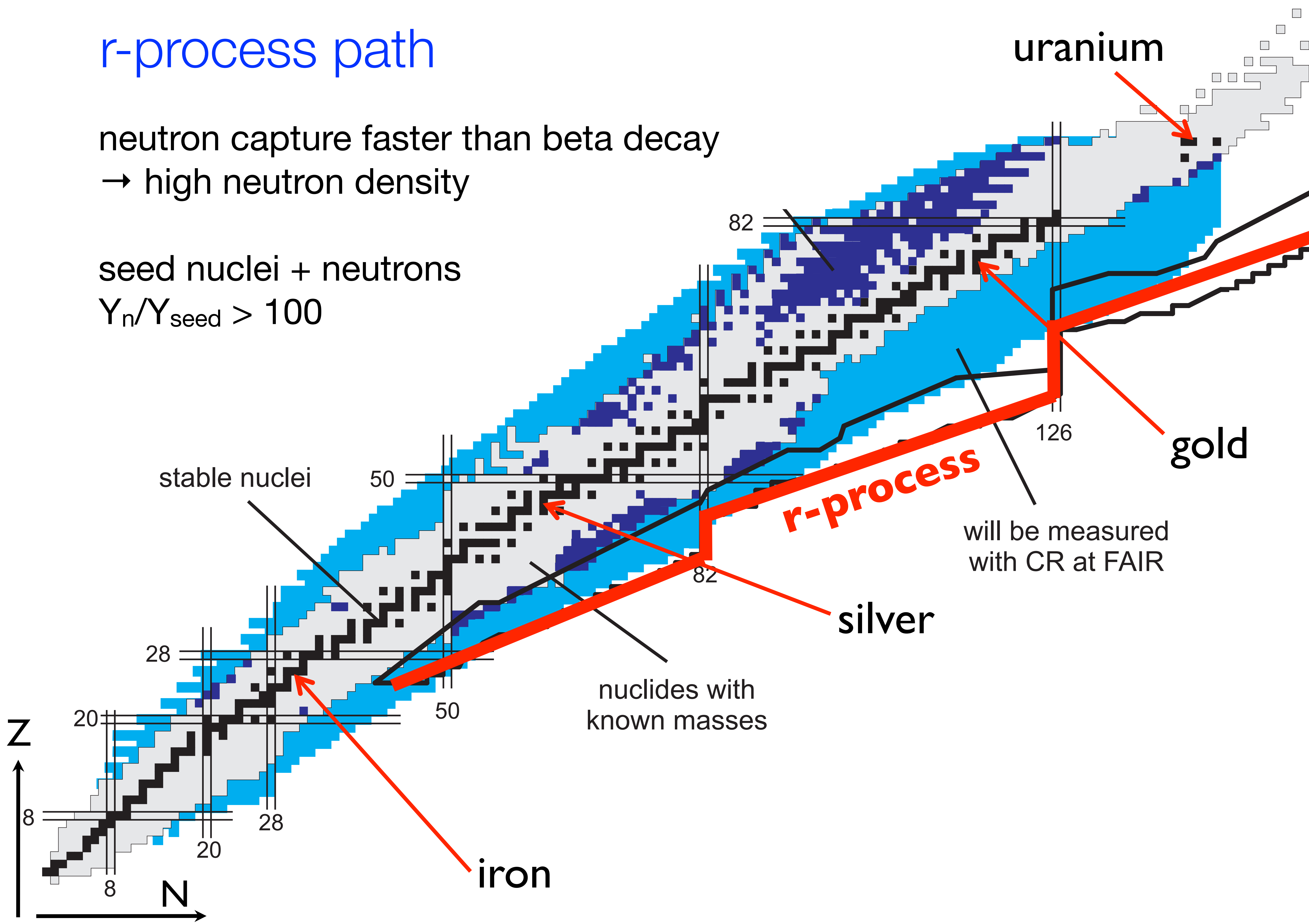
r-process path



r-process path

neutron capture faster than beta decay
→ high neutron density

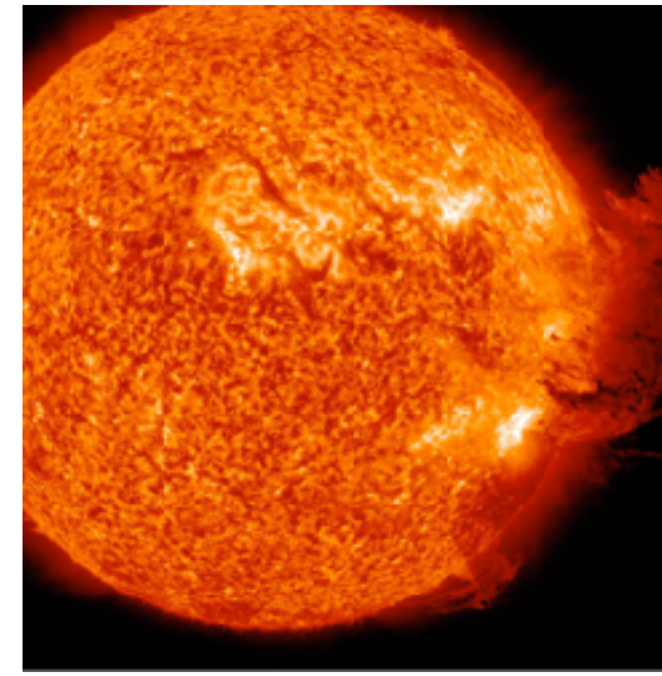
seed nuclei + neutrons
$Y_n/Y_{seed} > 100$



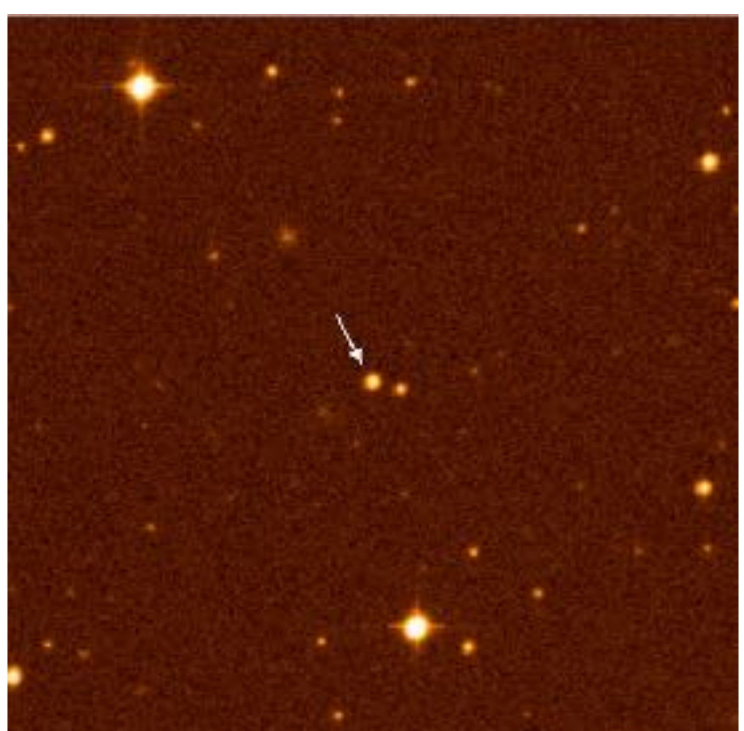
Galactic chemical evolution

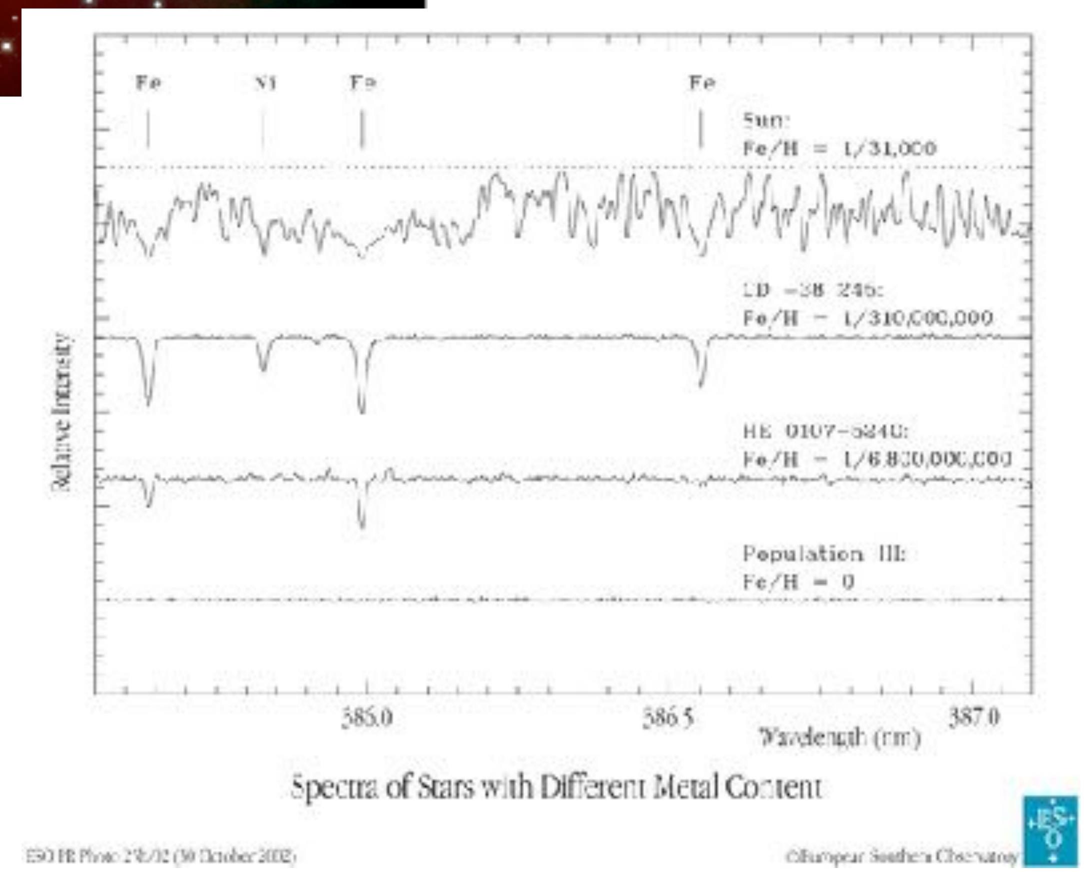
First stars: H, He → Heavy elements ← New generation of stars

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

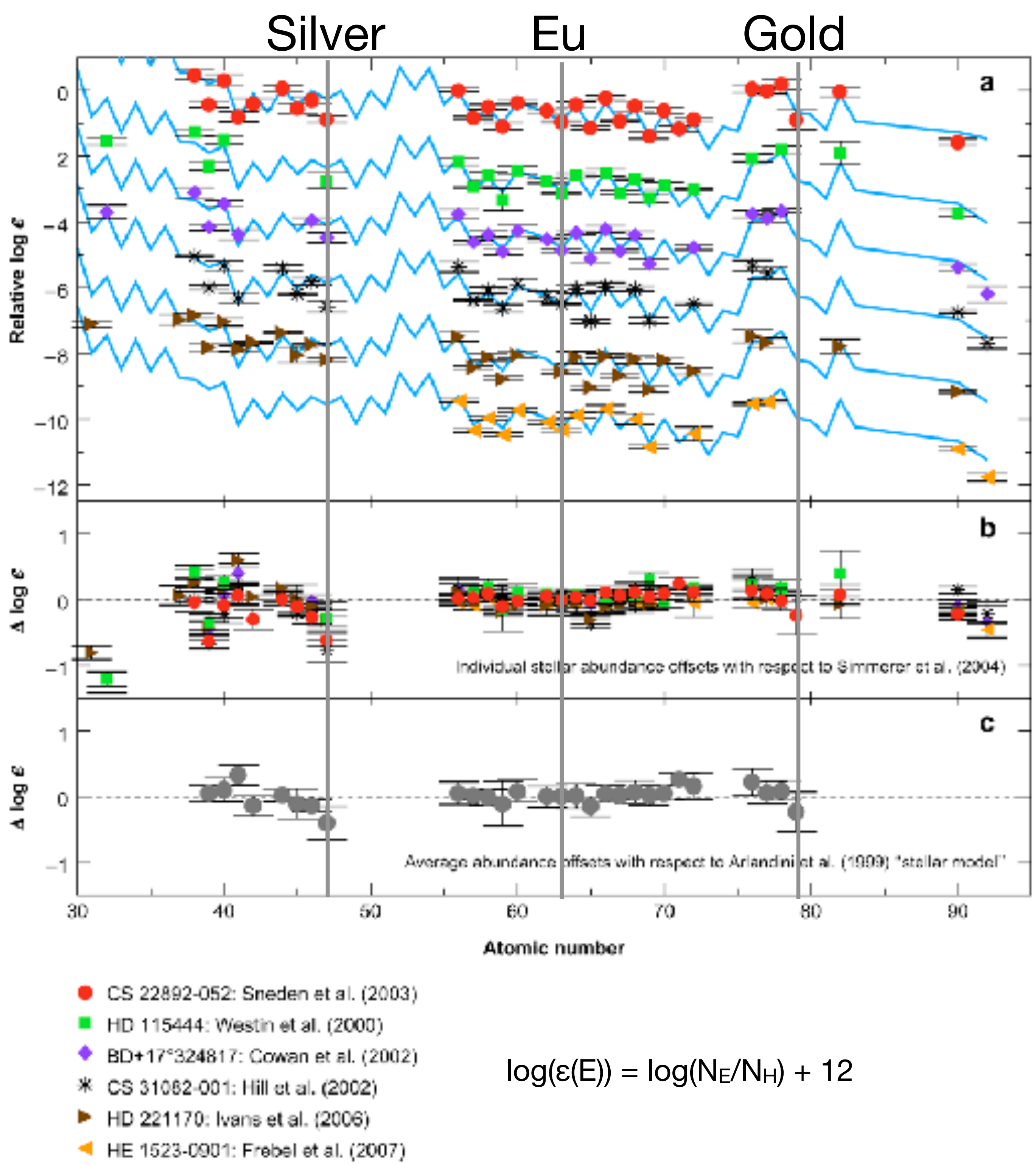


The very metal-deficient star
HE 0107-5240
(Hamburg-ESO survey)





r-process in ultra metal-poor stars



$\log(\varepsilon(E)) = \log(N_E/N_H) + 12$

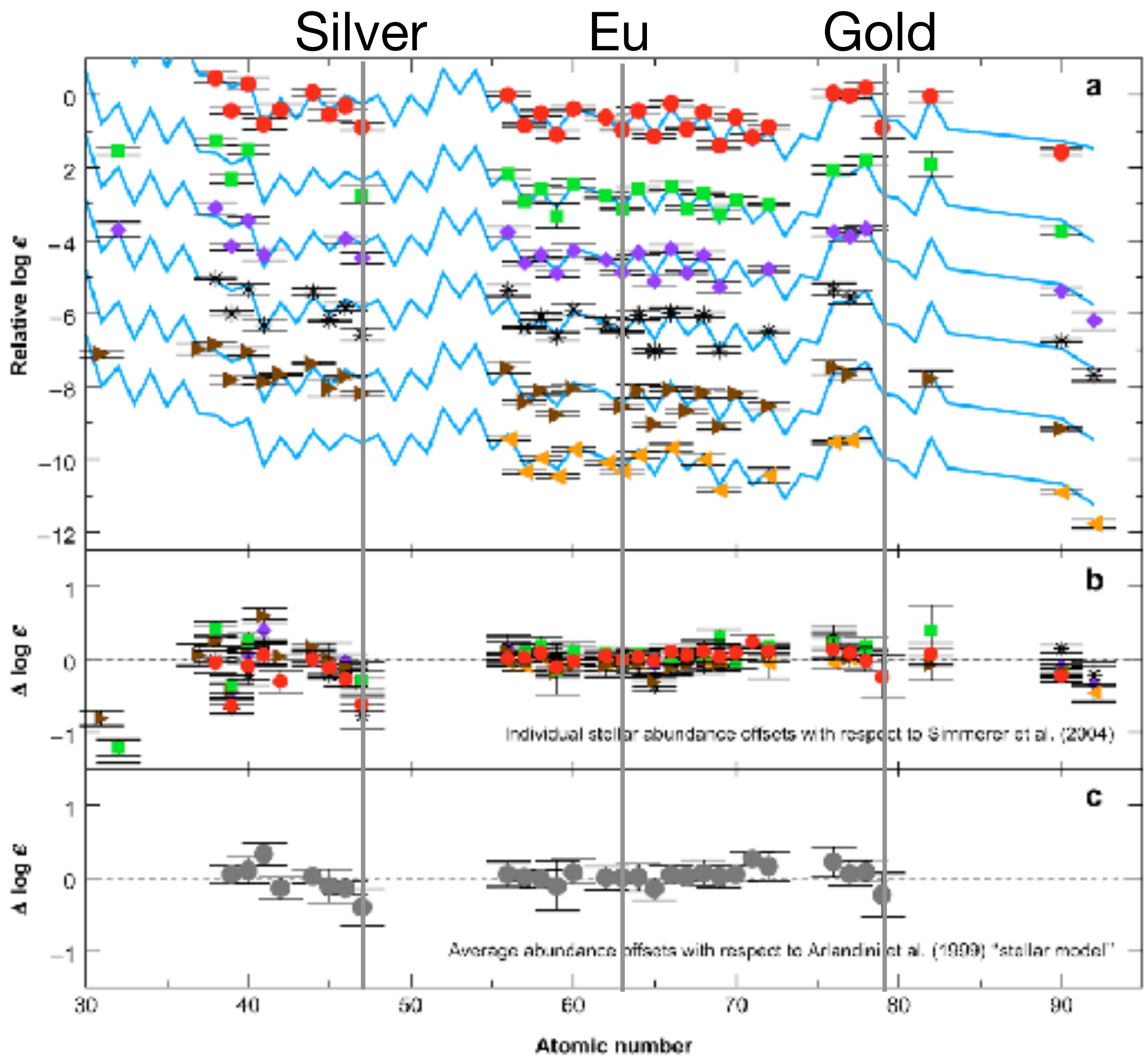
Sneden, Cowan, Gallino 2008

Abundances of r-process elements:
- ultra metal-poor stars and
- r-process solar system: $N_{solar} - N_s$

Robust r-process for 56<Z<83

Scatter for lighter heavy elements, Z~40

r-process in ultra metal-poor stars



- CS 22892-052: Sneden et al. (2003)
- HD 115444: Westin et al. (2000)
- BD+17°324817: Cowan et al. (2002)
- CS 31082-001: Hill et al. (2002)
- HD 221170: Ivans et al. (2006)
- HE 1523-0901: Frebel et al. (2007)

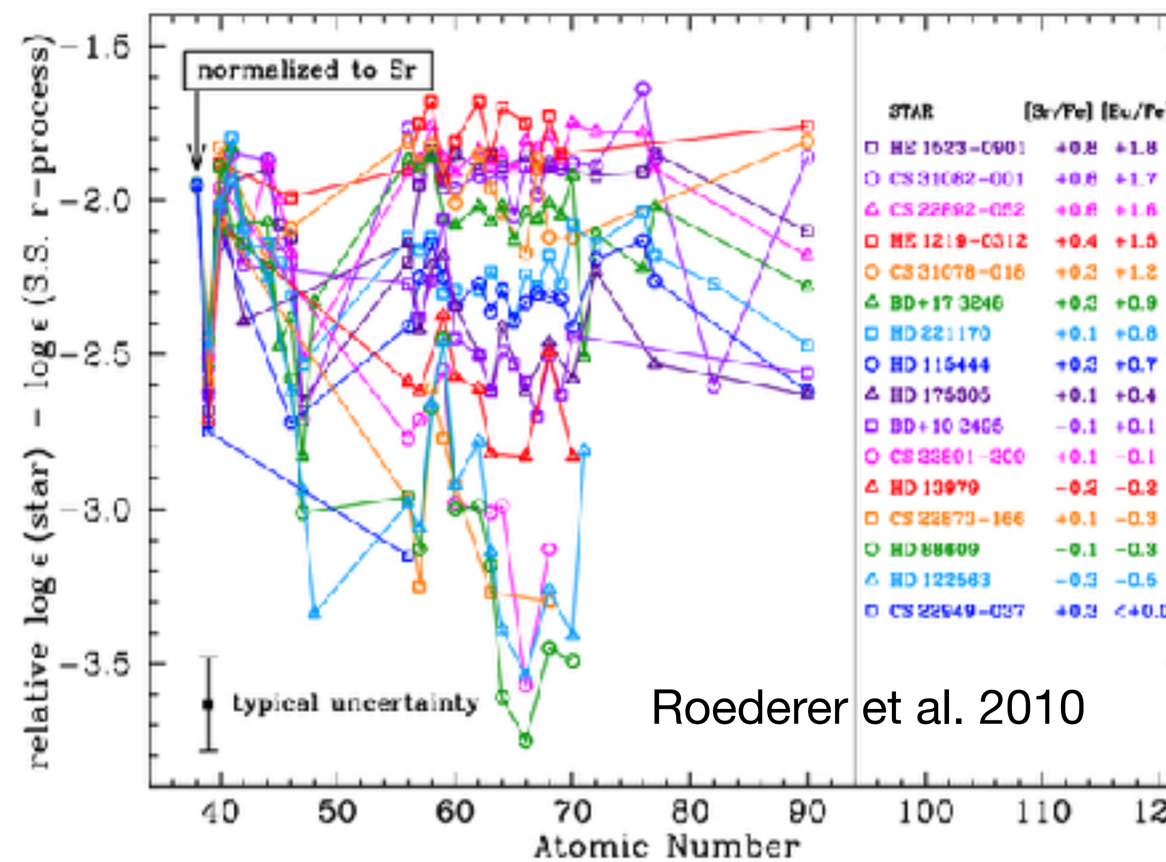
Sneden, Cowan, Gallino 2008

$\log(\varepsilon(E)) = \log(N_E/N_H) + 12$

Abundances of r-process elements:
- ultra metal-poor stars and
- r-process solar system: $N_{solar} - N_s$

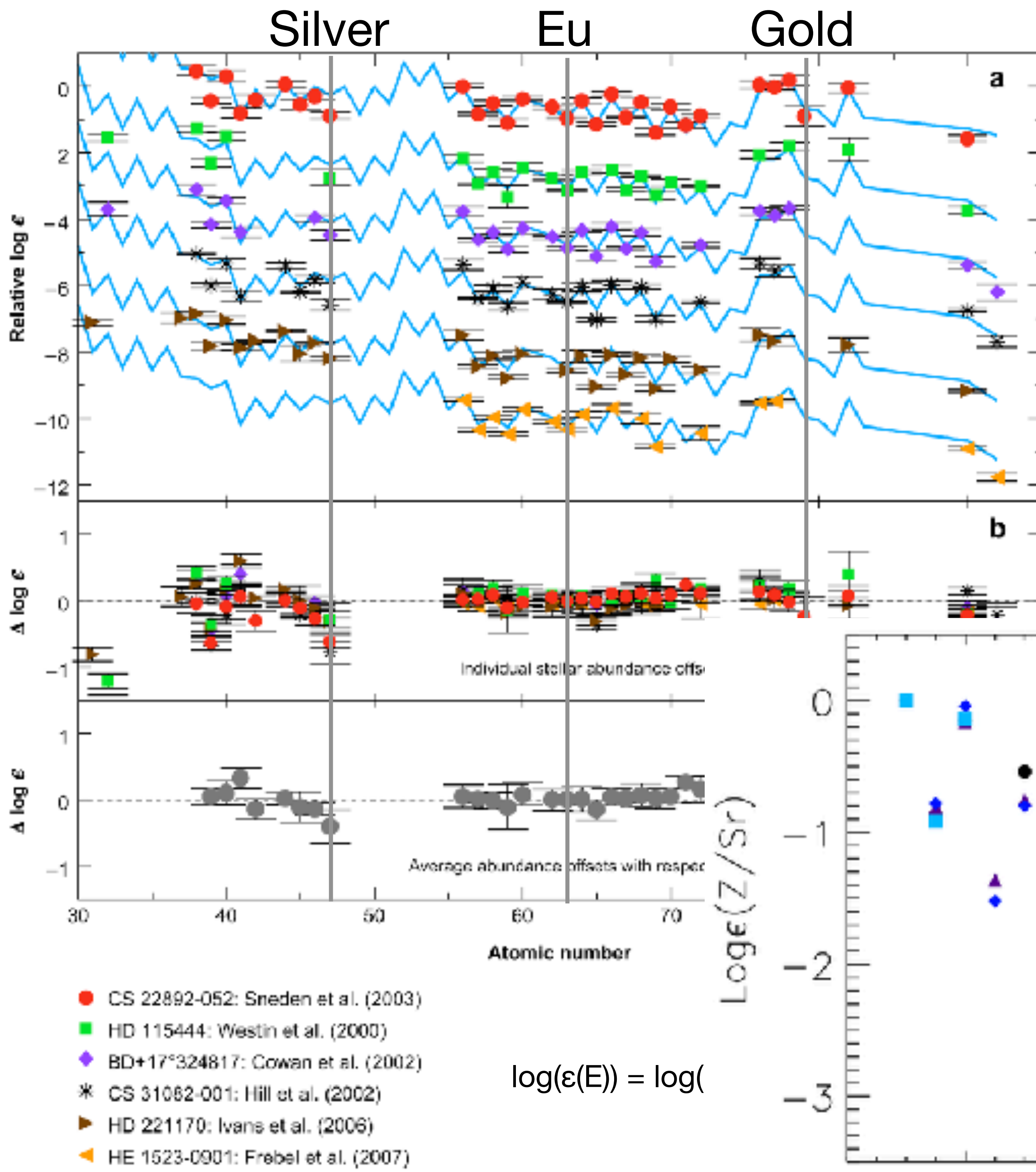
Robust r-process for 56<Z<83

Scatter for lighter heavy elements, Z~40



Roederer et al. 2010

r-process in ultra metal-poor stars

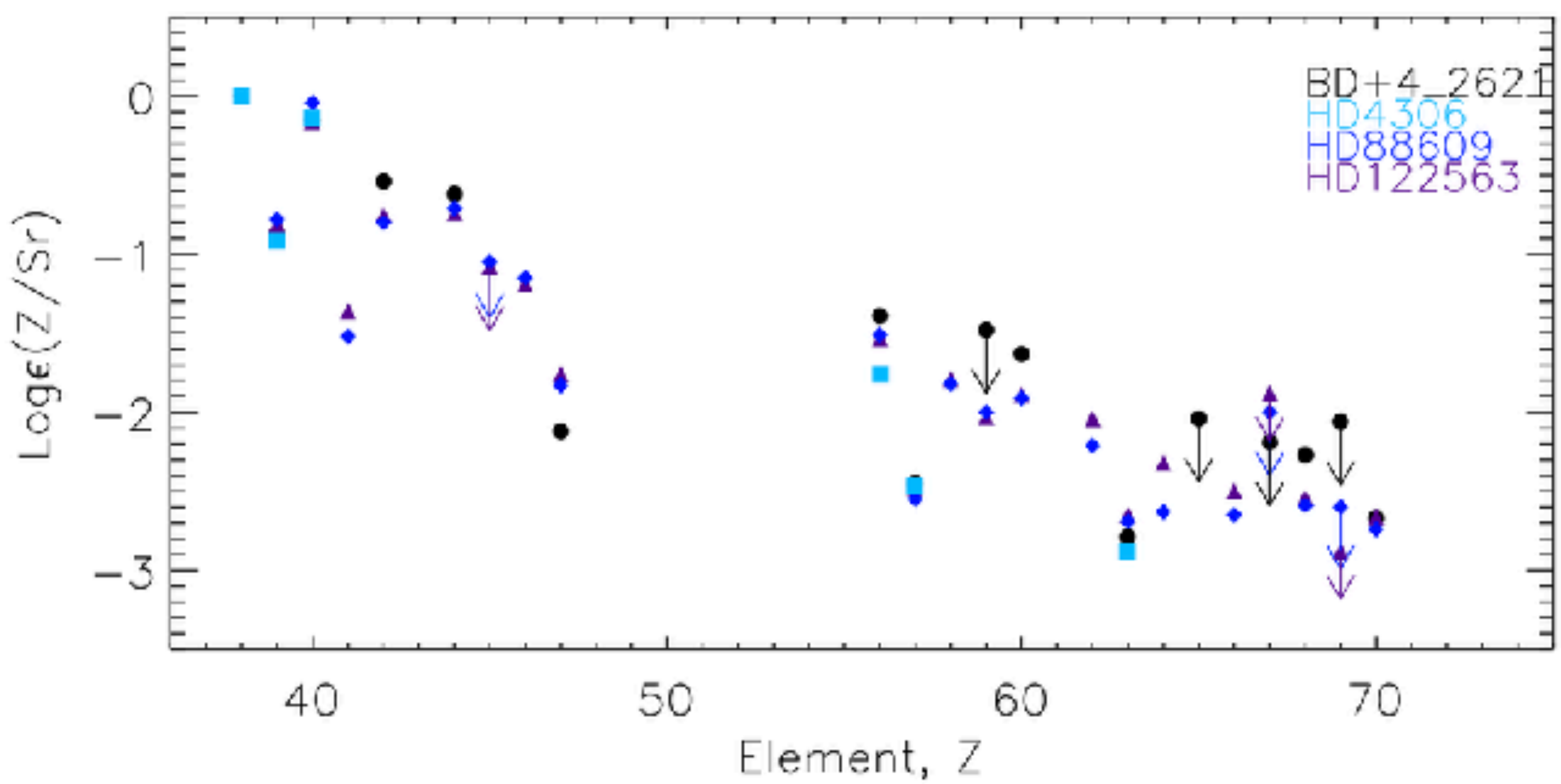


Sneden, Cowan, Gallino 2008

Abundances of r-process elements:
- ultra metal-poor stars and
- r-process solar system: N_{solar} - N_s

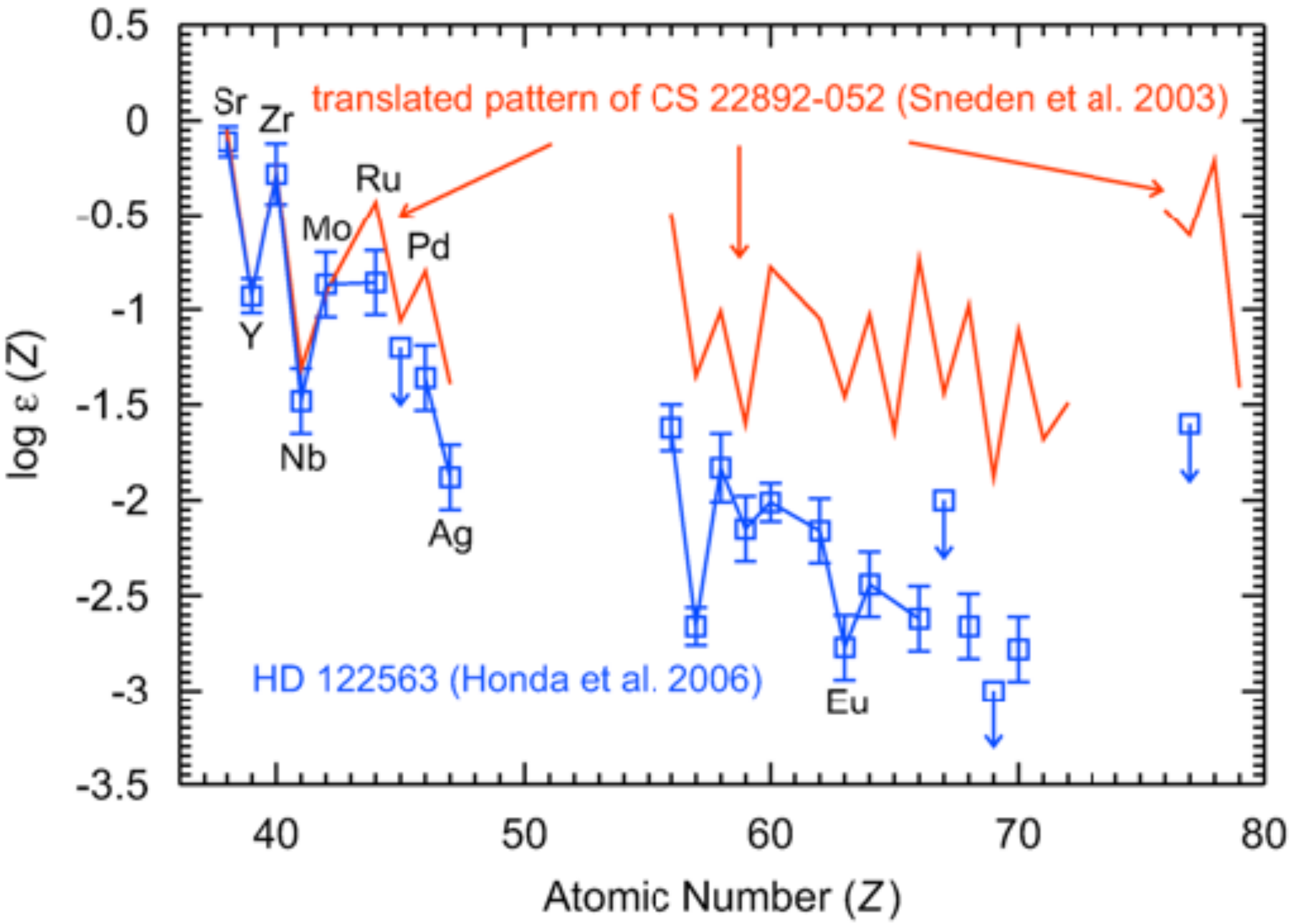
Robust r-process for 56<Z<83

Scatter for lighter heavy elements, Z~40

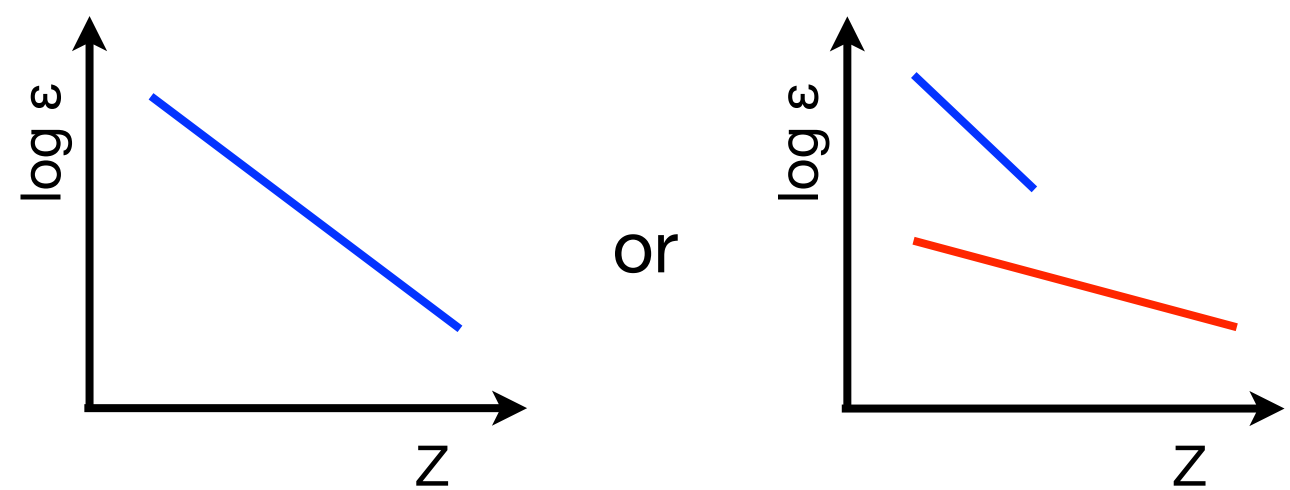


Lighter heavy elements: Sr - Ag

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



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

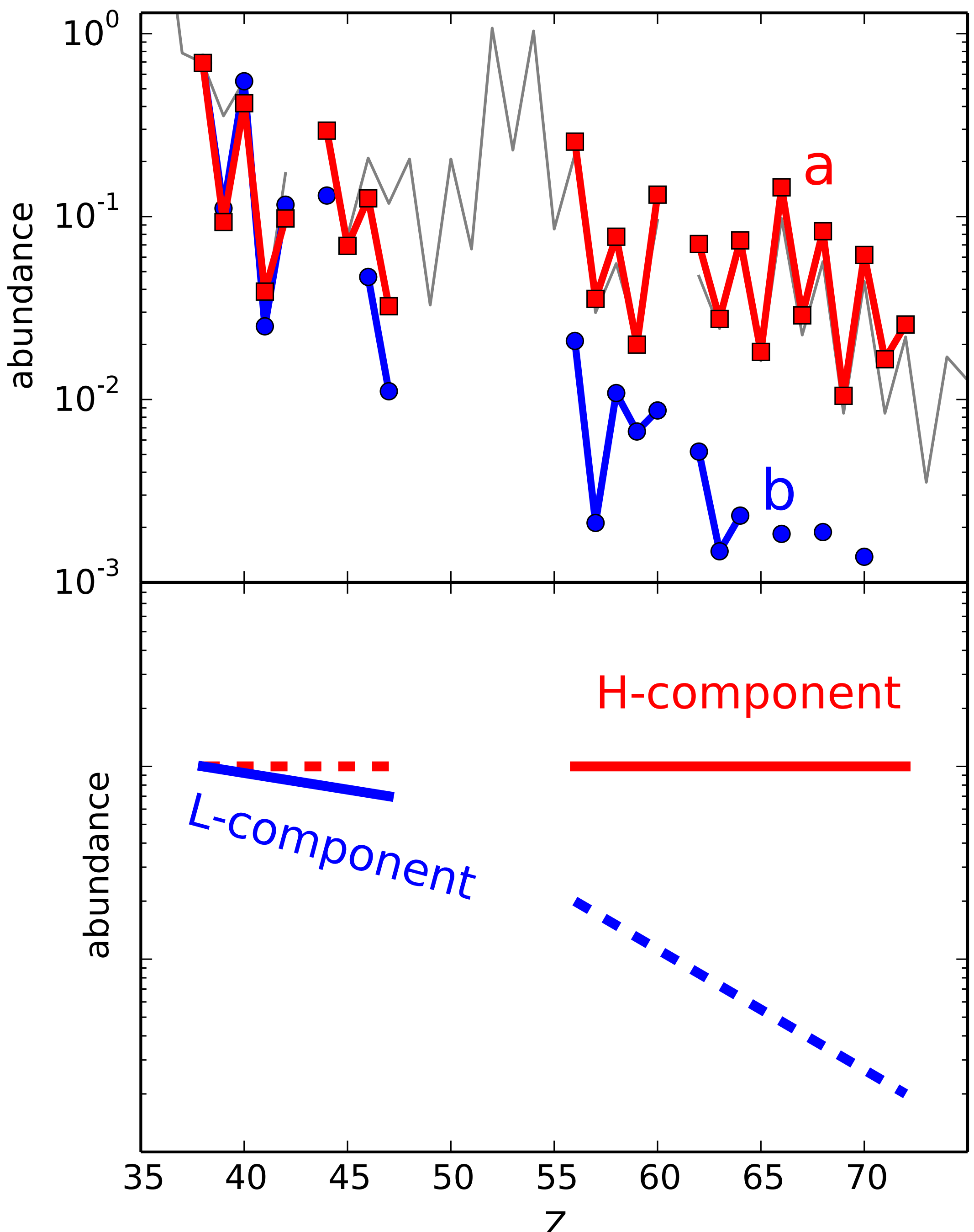


Honda-like = limited r-process

Travaglio et al. 2004: solar=r-process+s-process+LEPP
Montes et al. 2007: solar LEPP ~ UMP LEPP → unique

Nucleosynthesis components

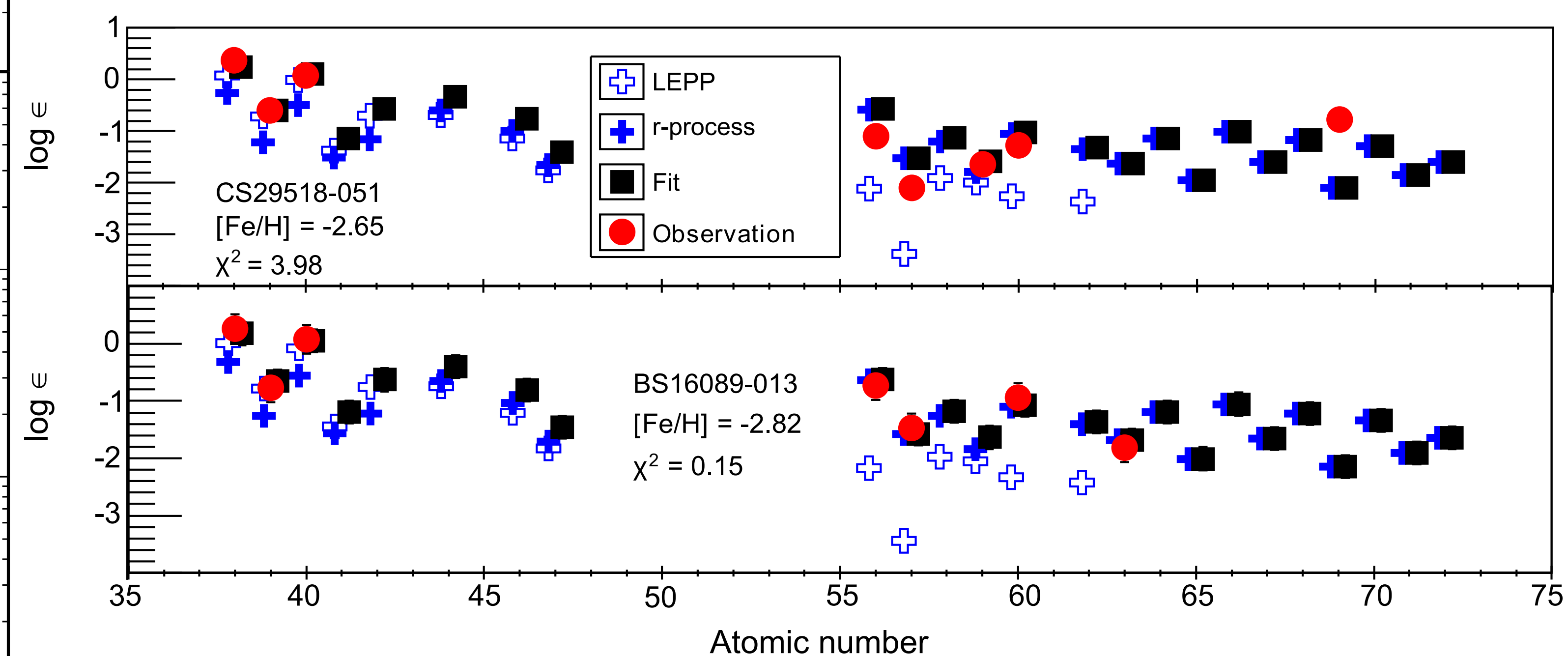
Abundance of many UMP stars can be explained by two components:



Component abundance pattern: Y_H and Y_L

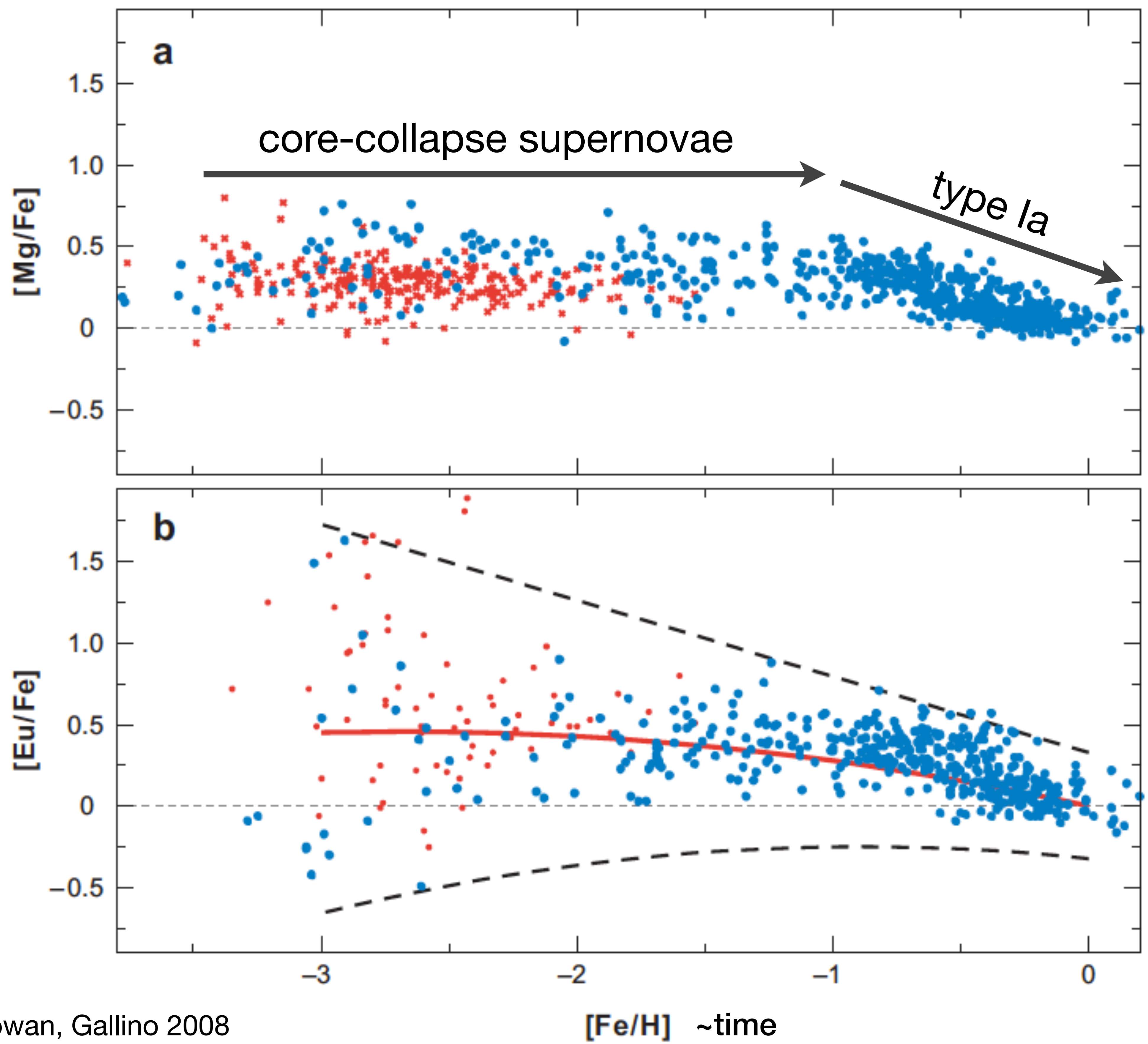
Fit abundance as combination of components:

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



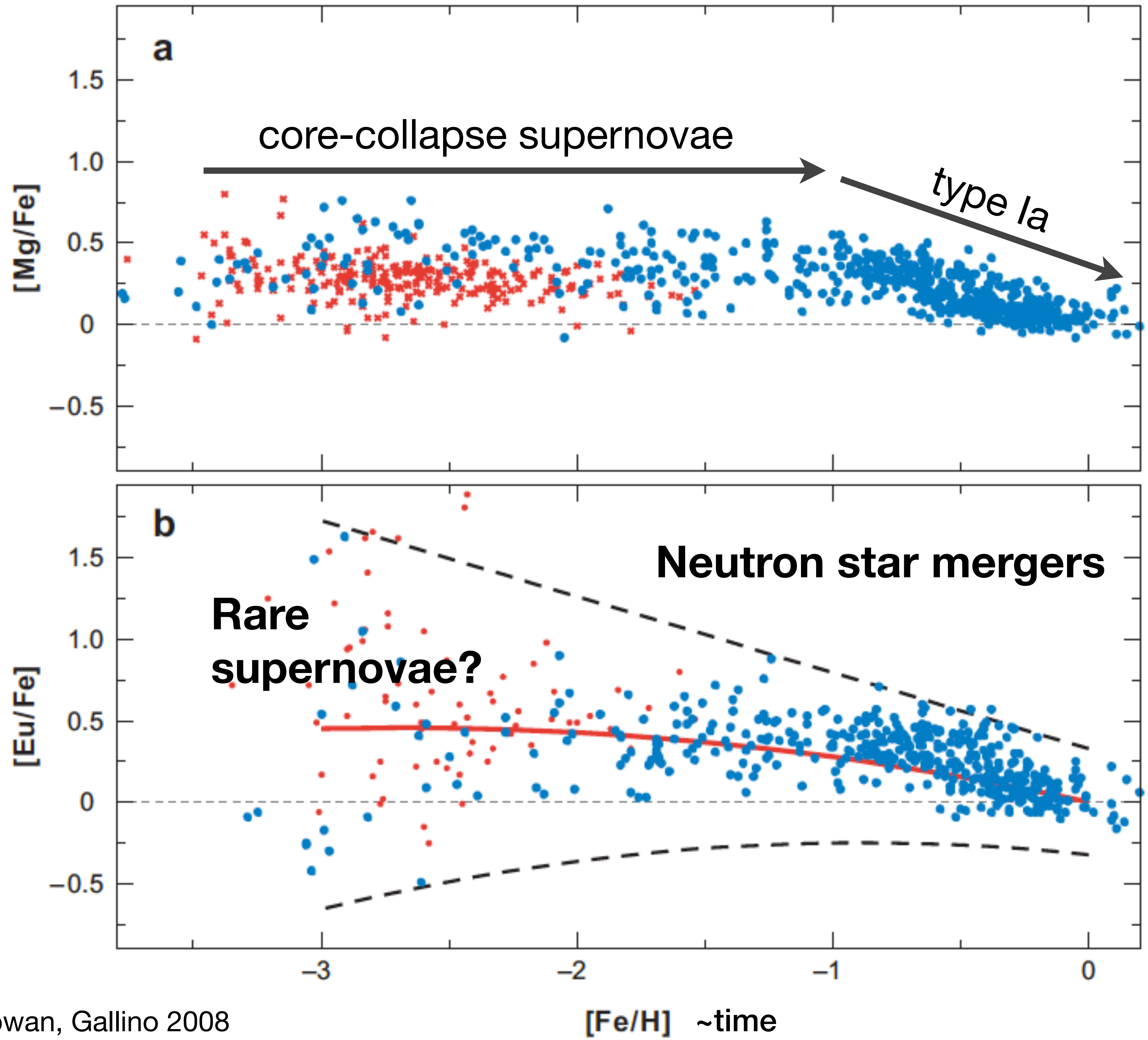
C.J. Hansen, Montes, Arcones (2014)

Trends with metallicity



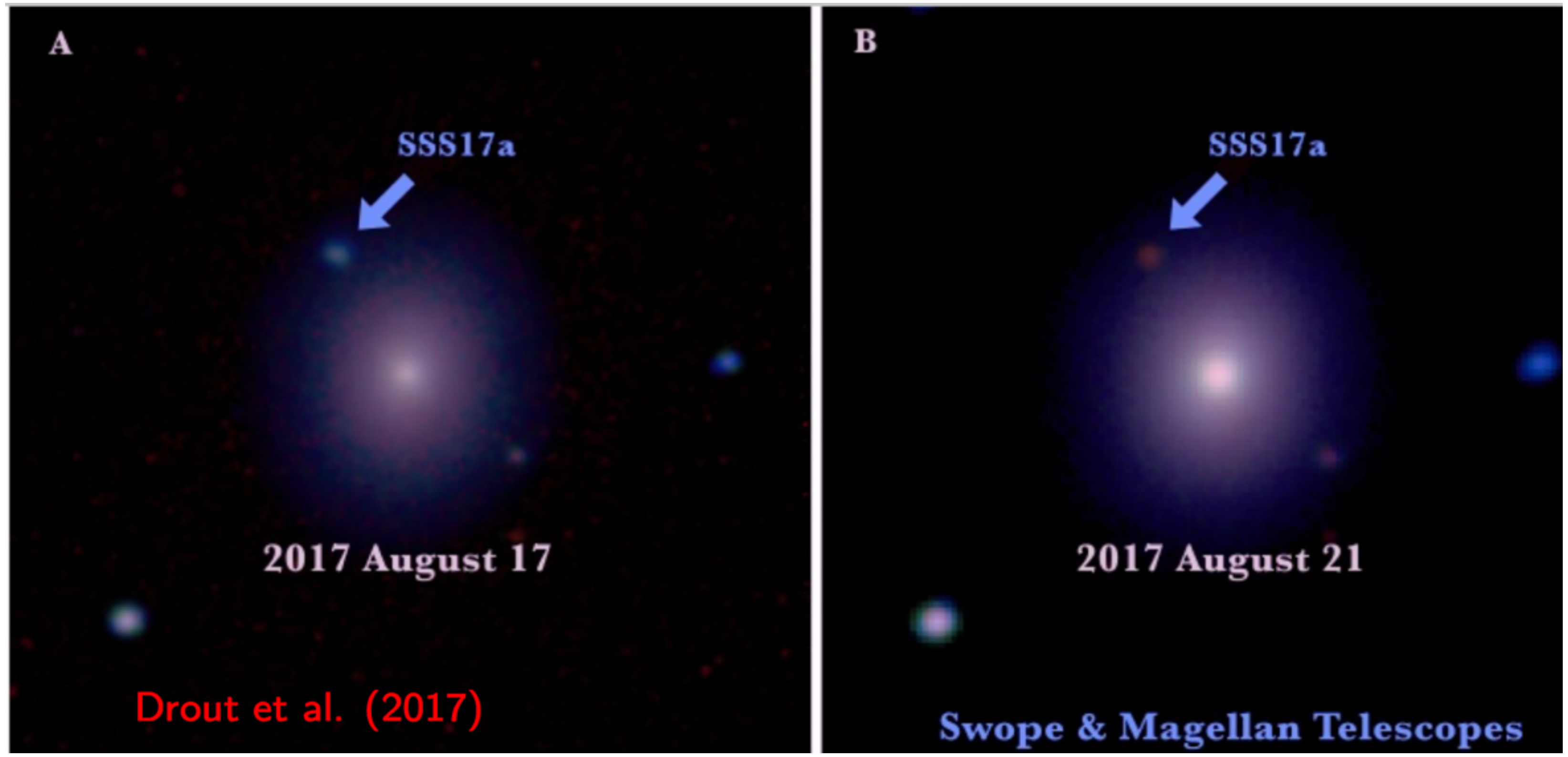
Sneden, Cowan, Gallino 2008

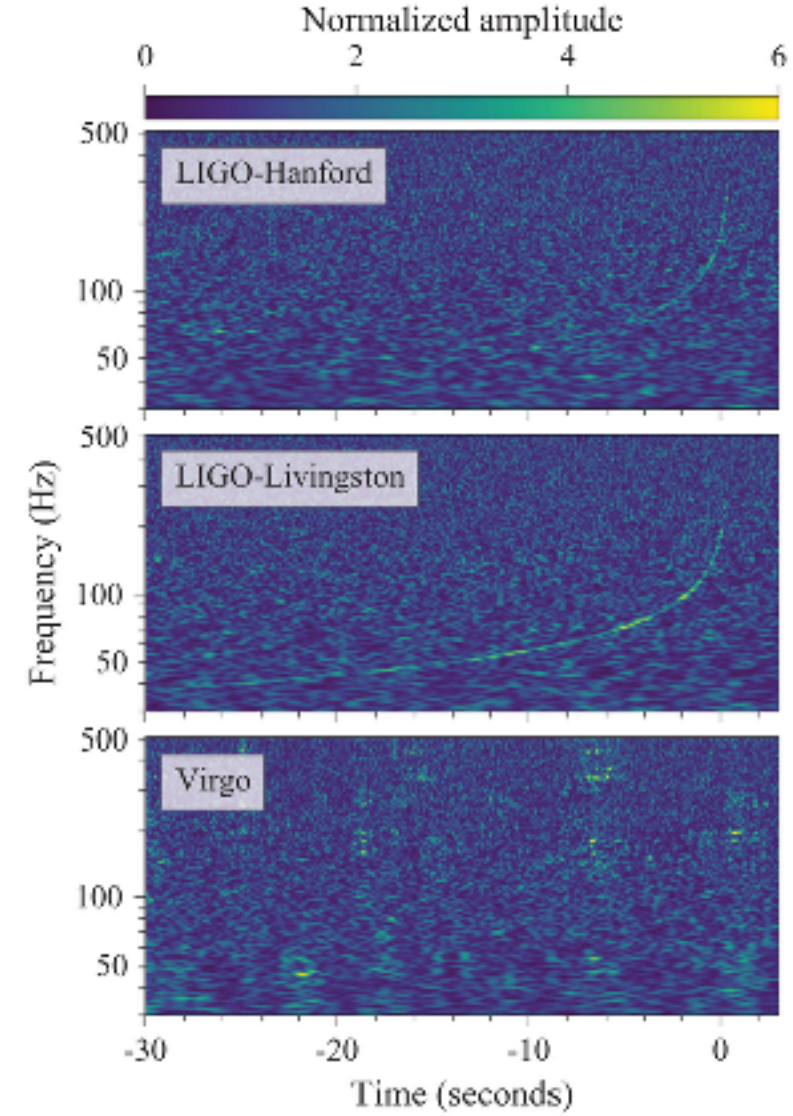
Trends with metallicity



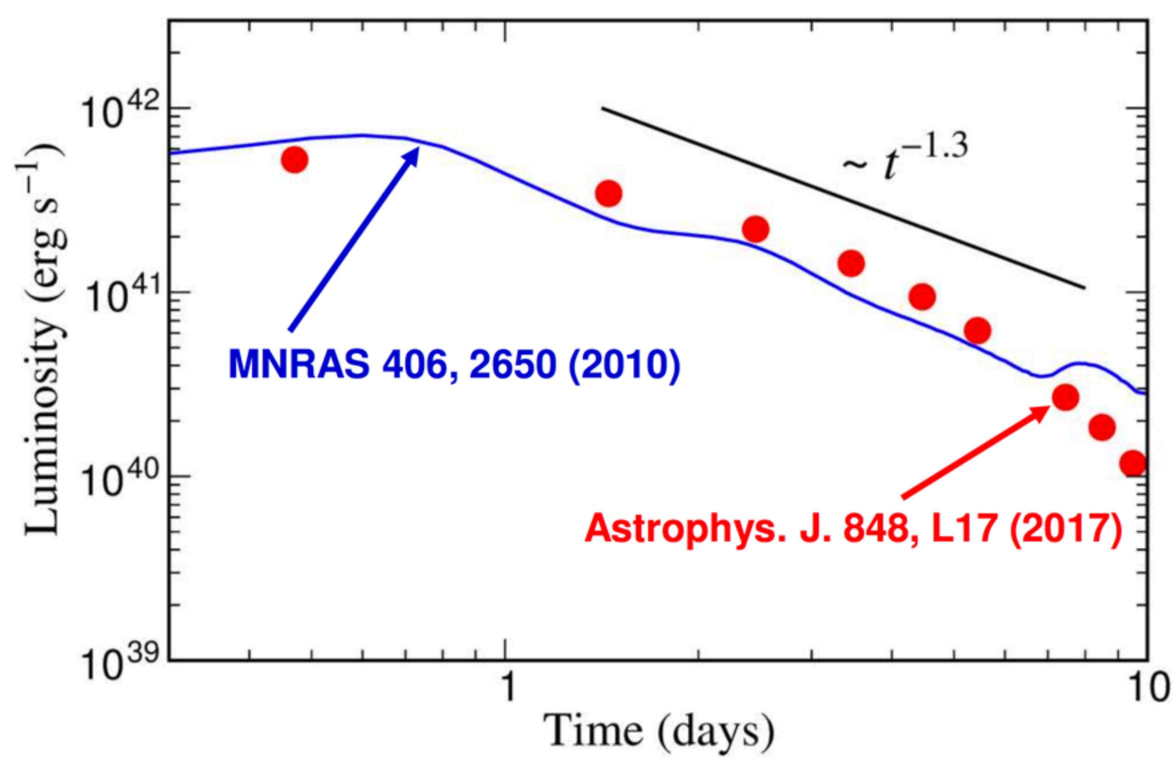
Sneden, Cowan, Gallino 2008

Neutron star mergers

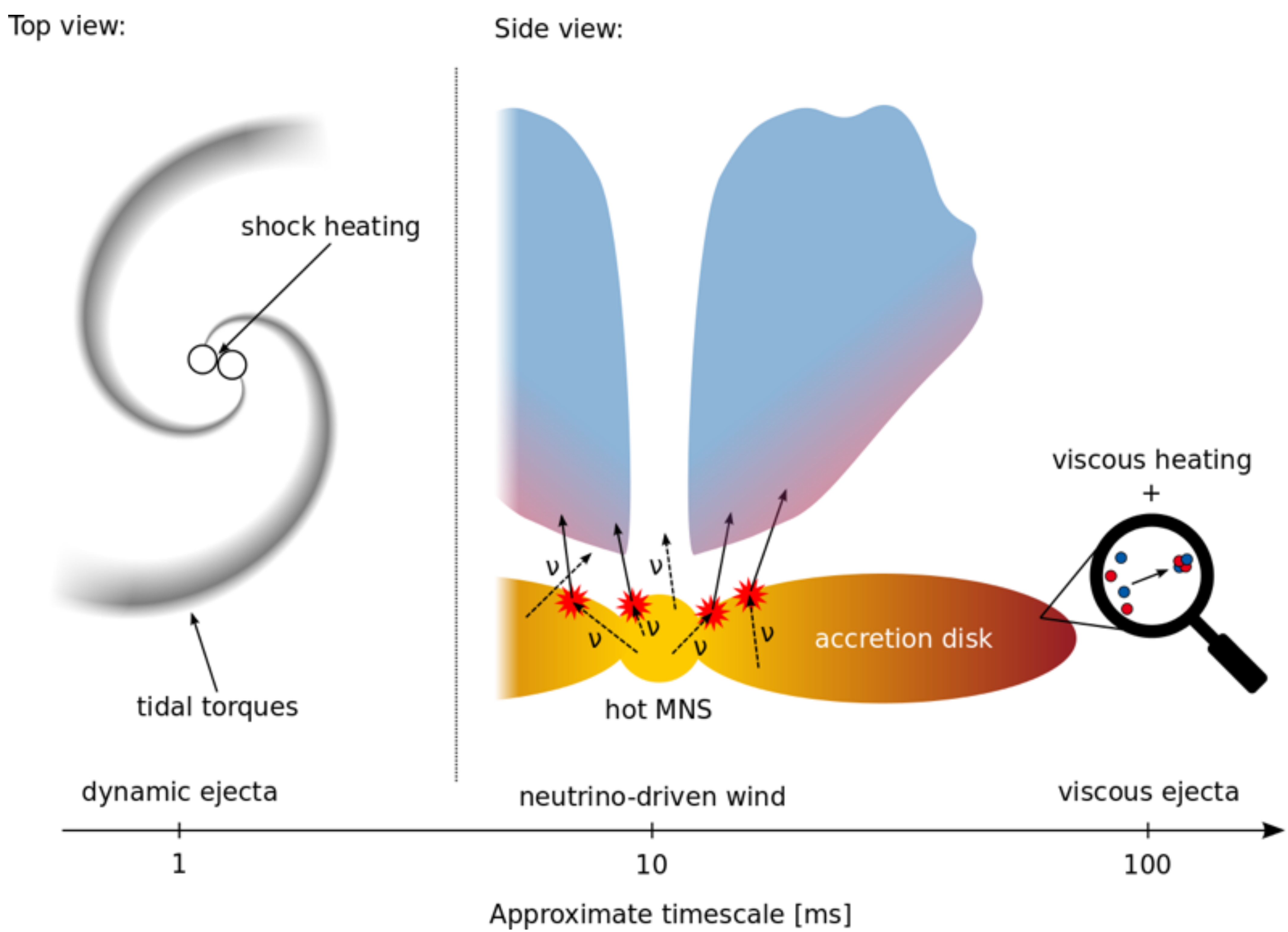


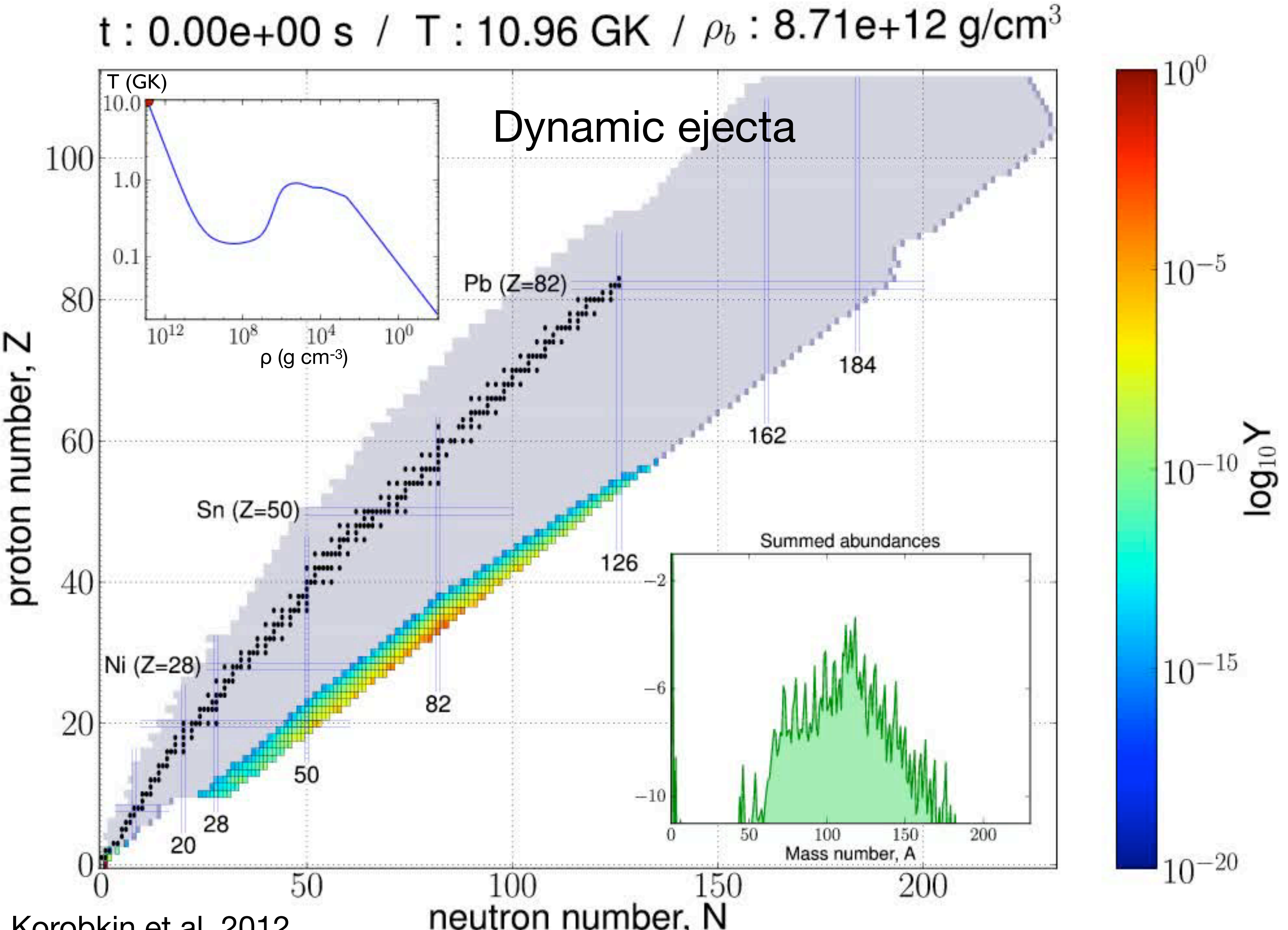


R-process in neutron star mergers confirmed by kilonova (radioactive decay of n-rich nuclei) after gravitational wave detection from GW170817

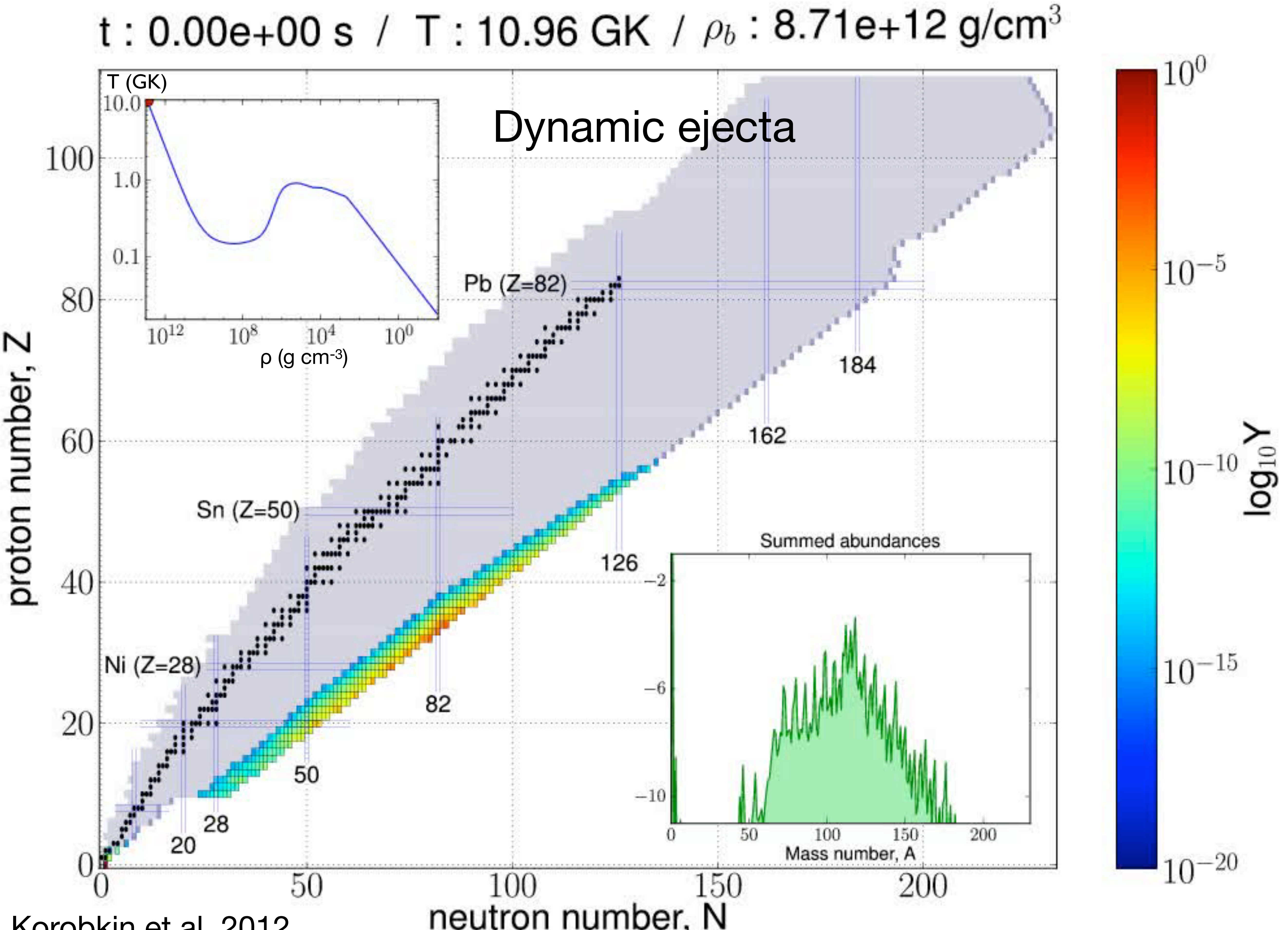


Ejecta and nucleosynthesis

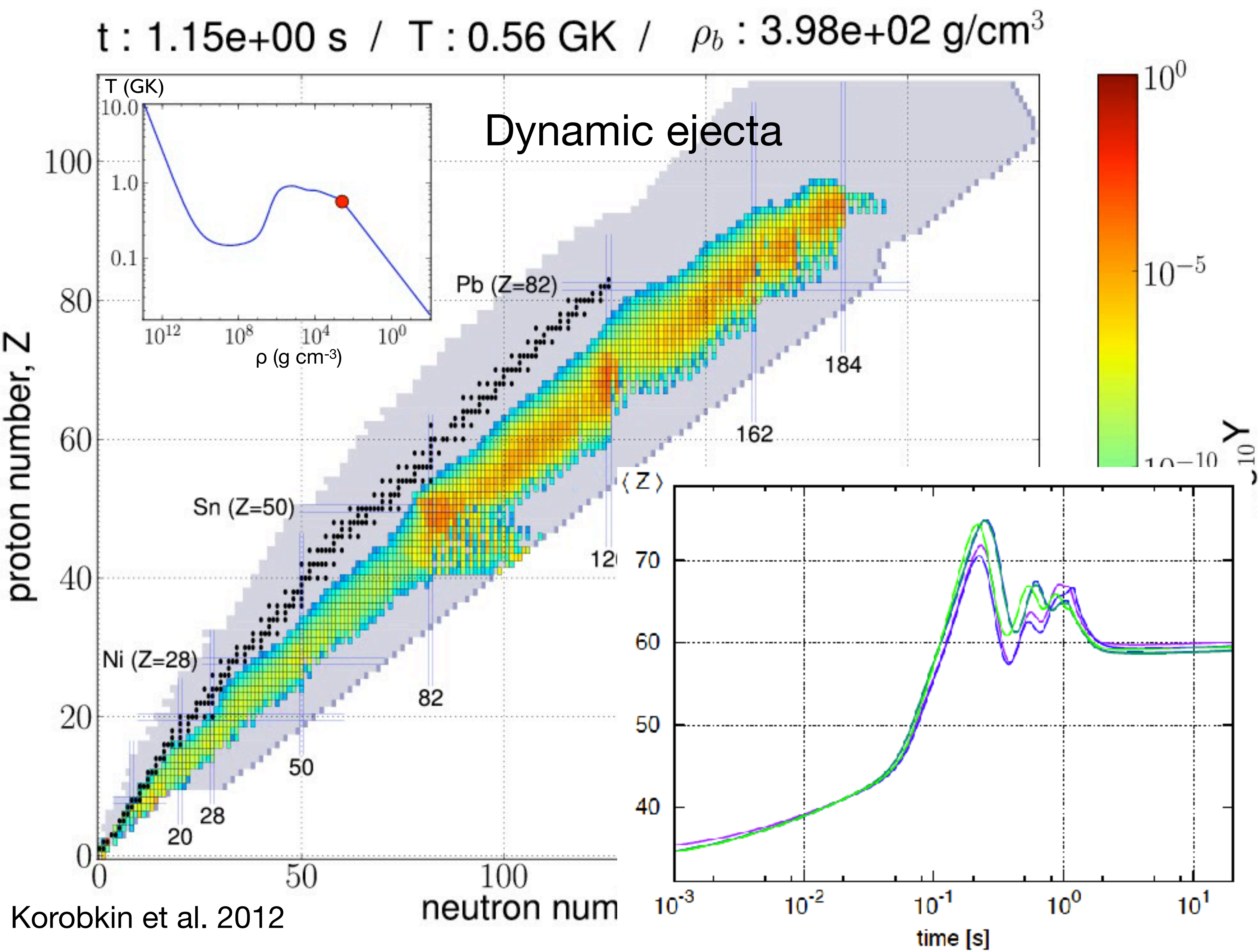




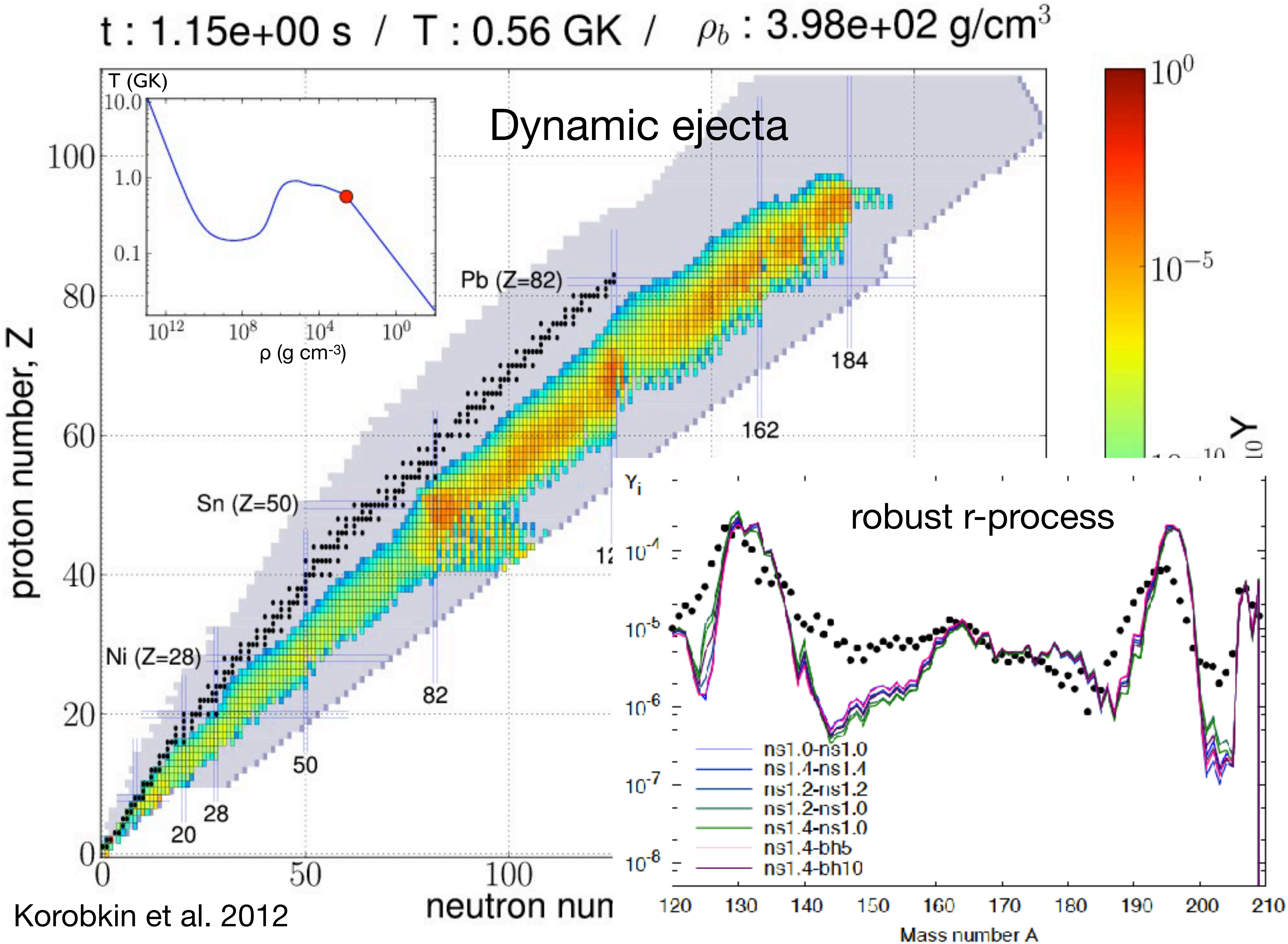
Korobkin et al. 2012



Korobkin et al. 2012



Korobkin et al. 2012

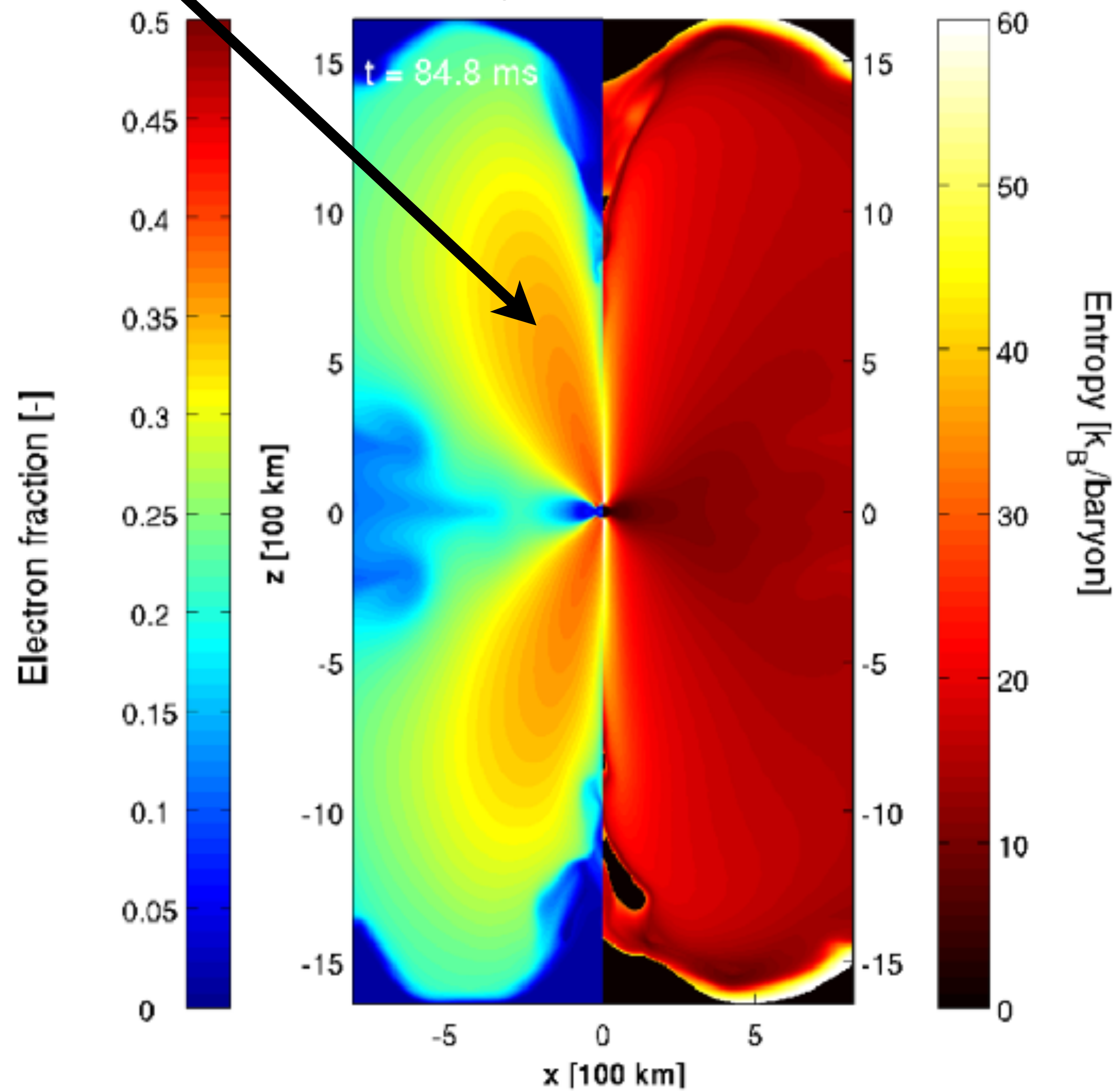


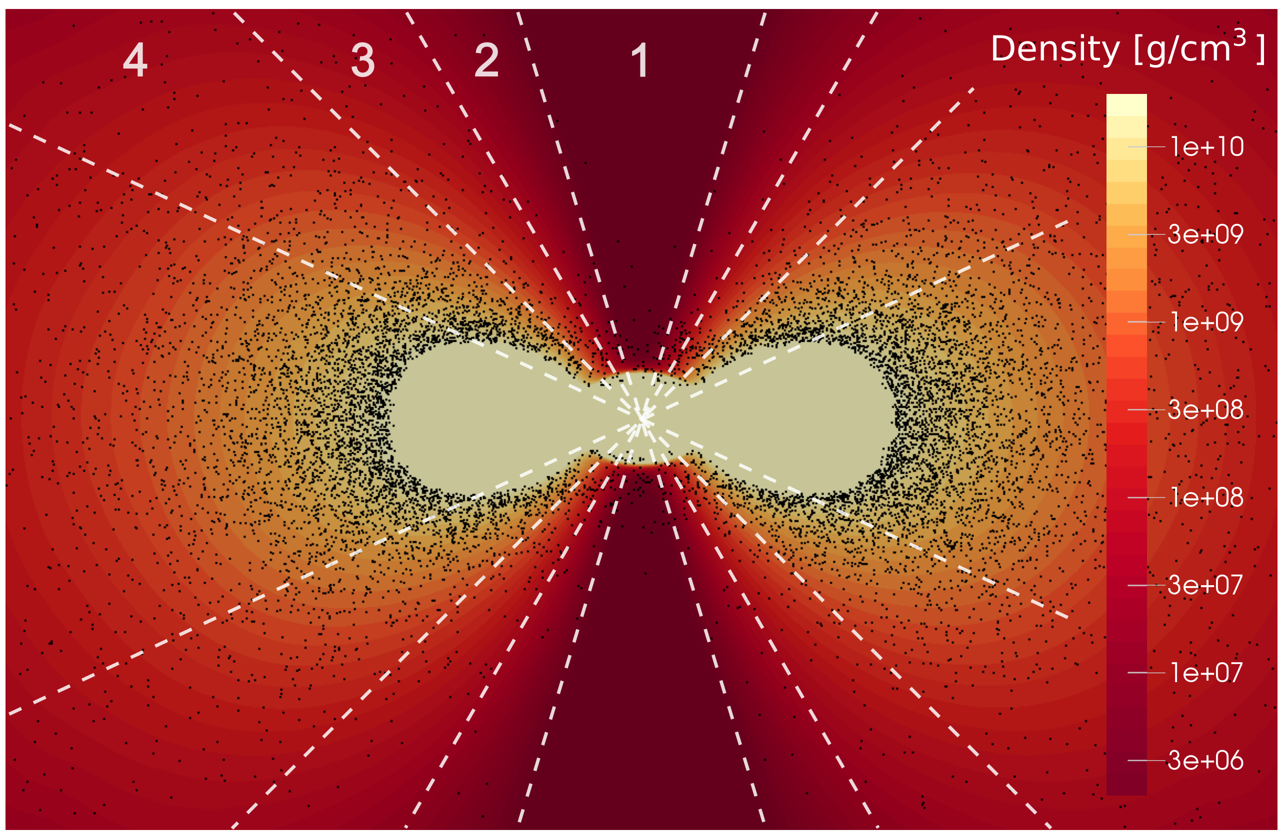
Korobkin et al. 2012

Neutron star mergers: neutrino-driven wind

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

Perego et al. (2014)

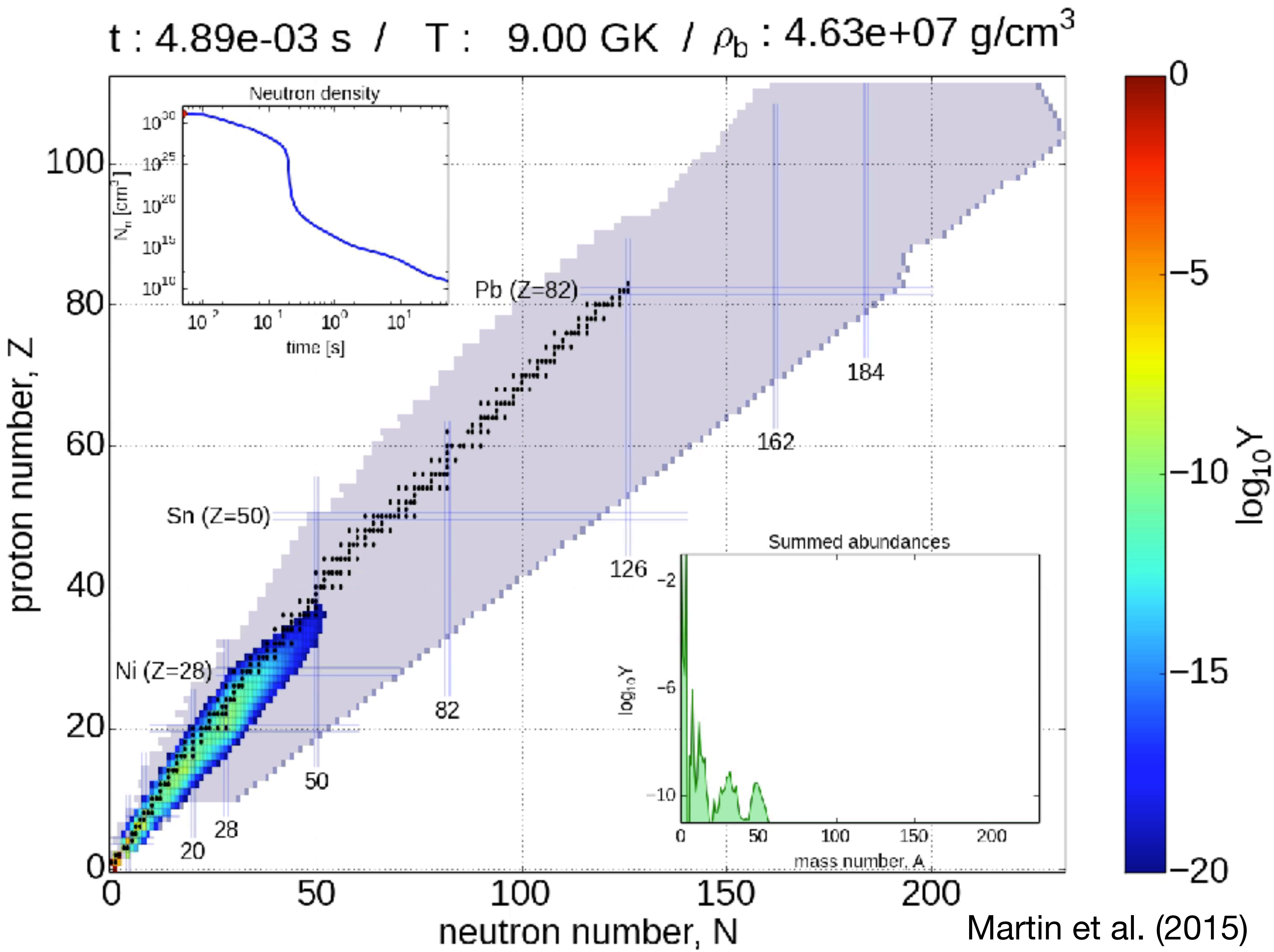




Martin et al. (2015)

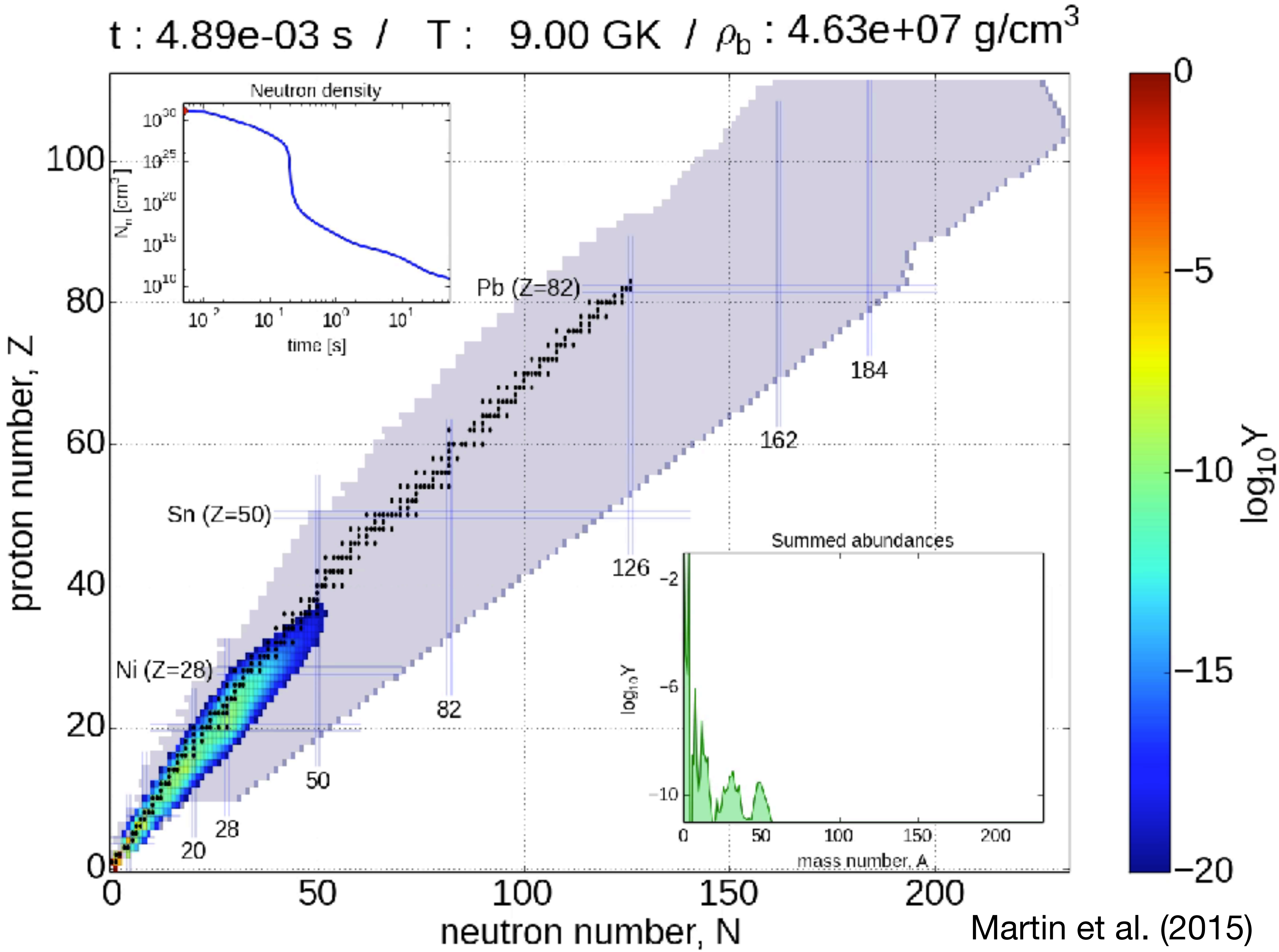
see also
Fernandez & Metzger 2013, Metzger & Fernandez 2014,
Just et al. 2014, Sekiguchi et al. 2016

Neutron star mergers: neutrino-driven wind



Martin et al. (2015)

Neutron star mergers: neutrino-driven wind

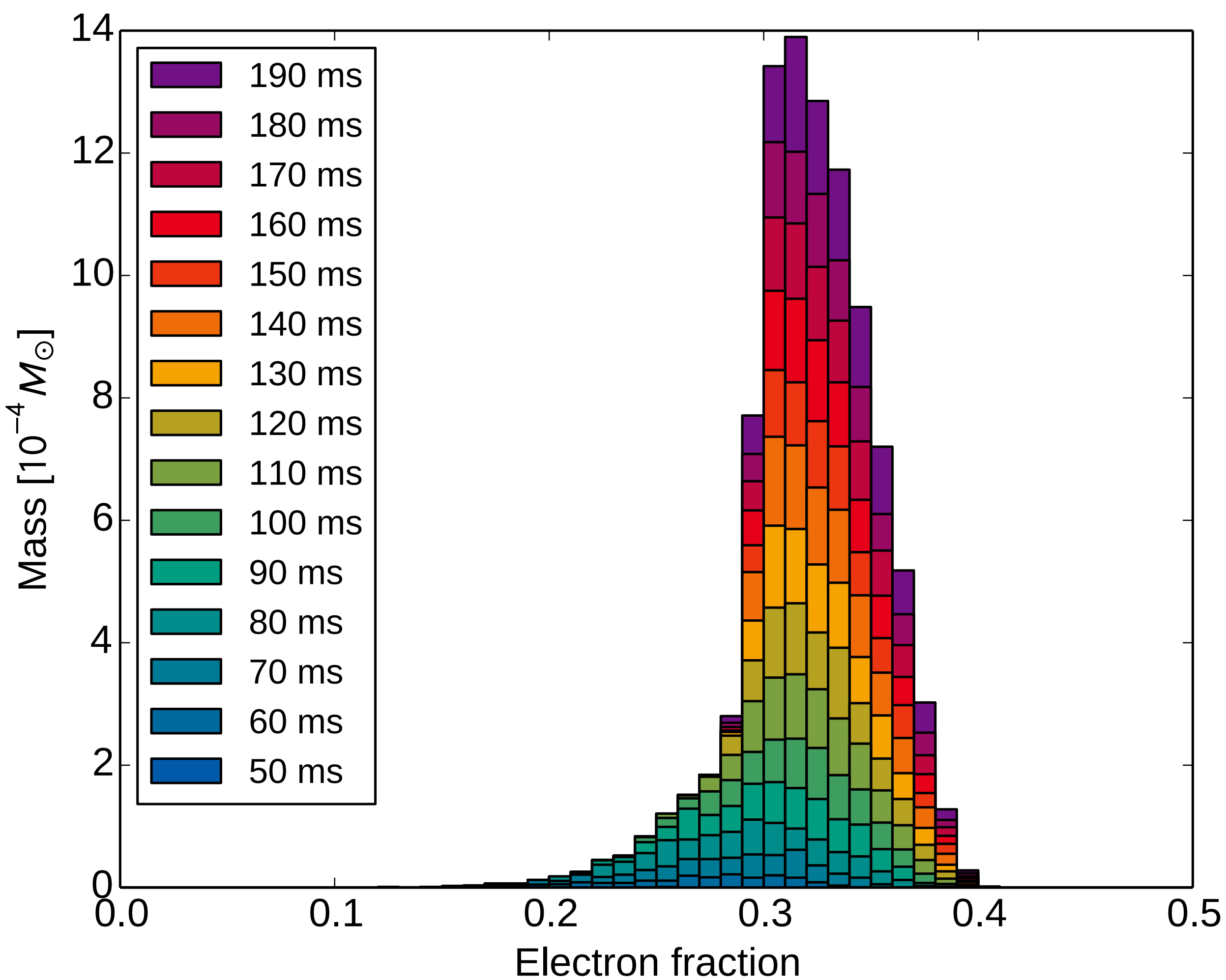


Martin et al. (2015)

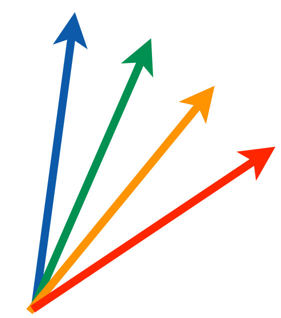
Time and angle dependency

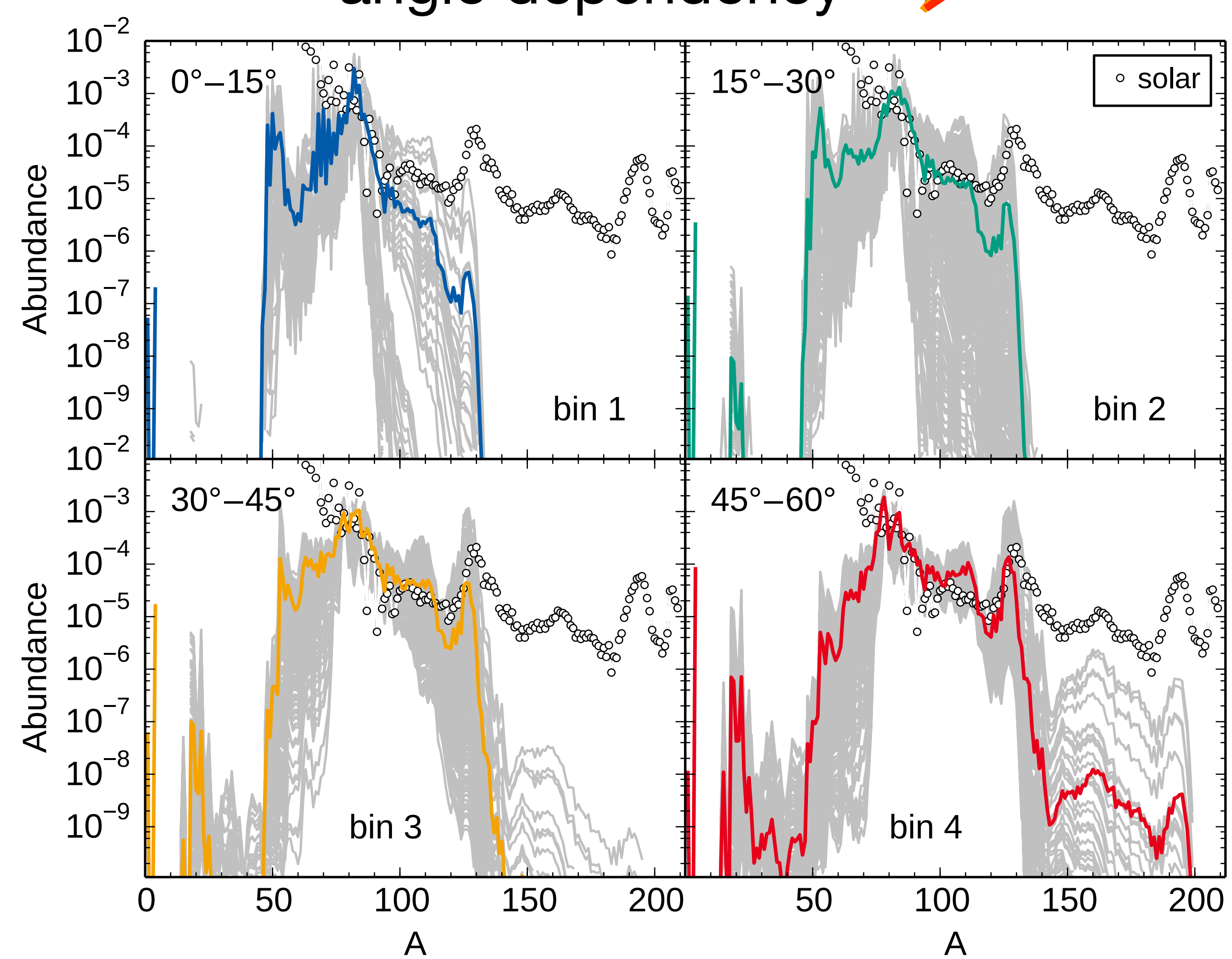
Black hole formation determines time for wind nucleosynthesis (Fernandez & Metzger 2013, Kasen et al. 2015)

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



angle dependency





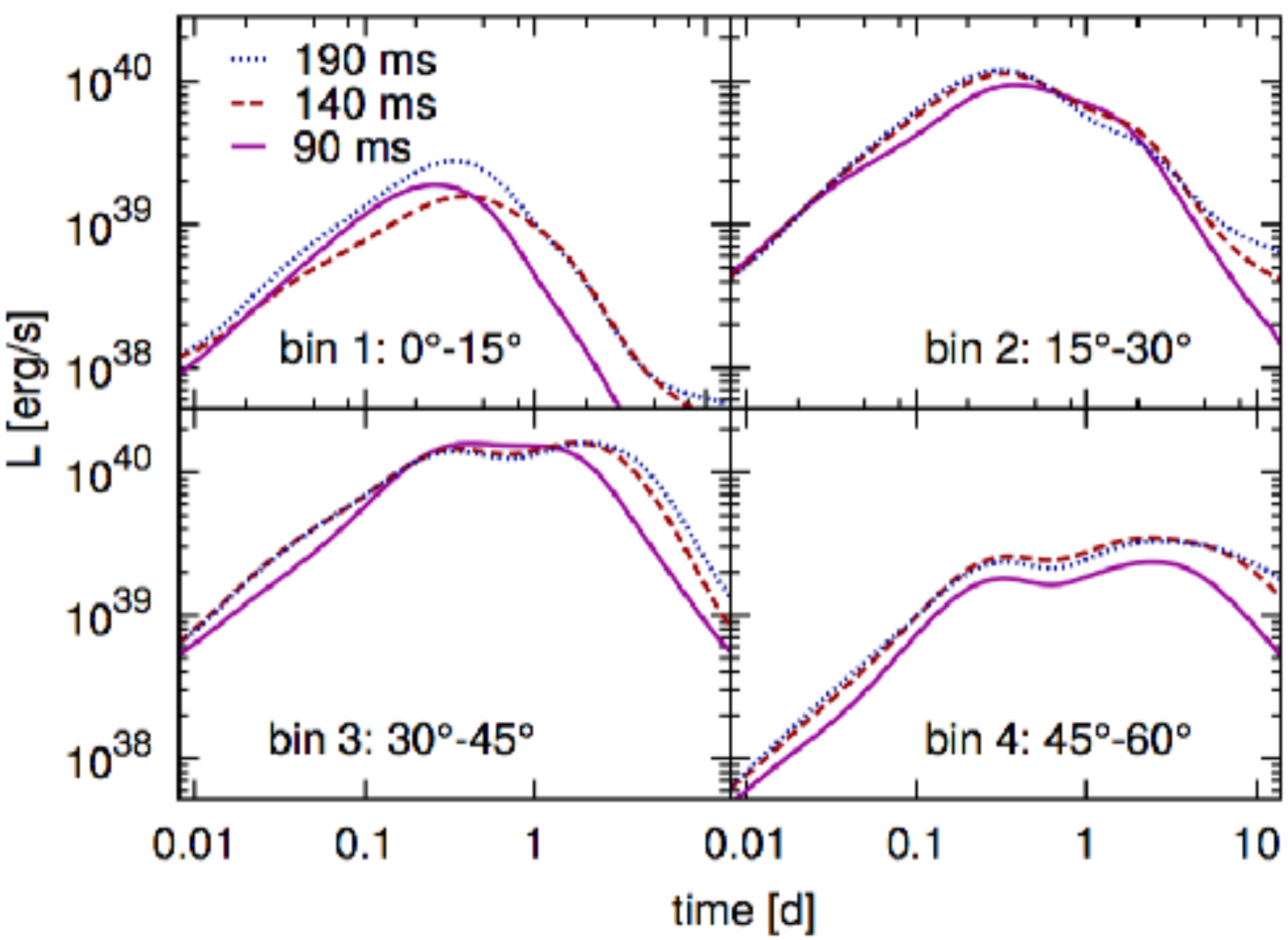
Martin et al. (2015)

Time and angle dependency

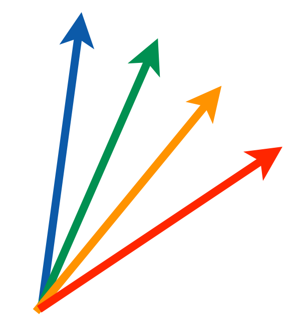
Black hole formation determines time for wind nucleosynthesis (Fernandez & Metzger 2013, Kasen et al. 2015)

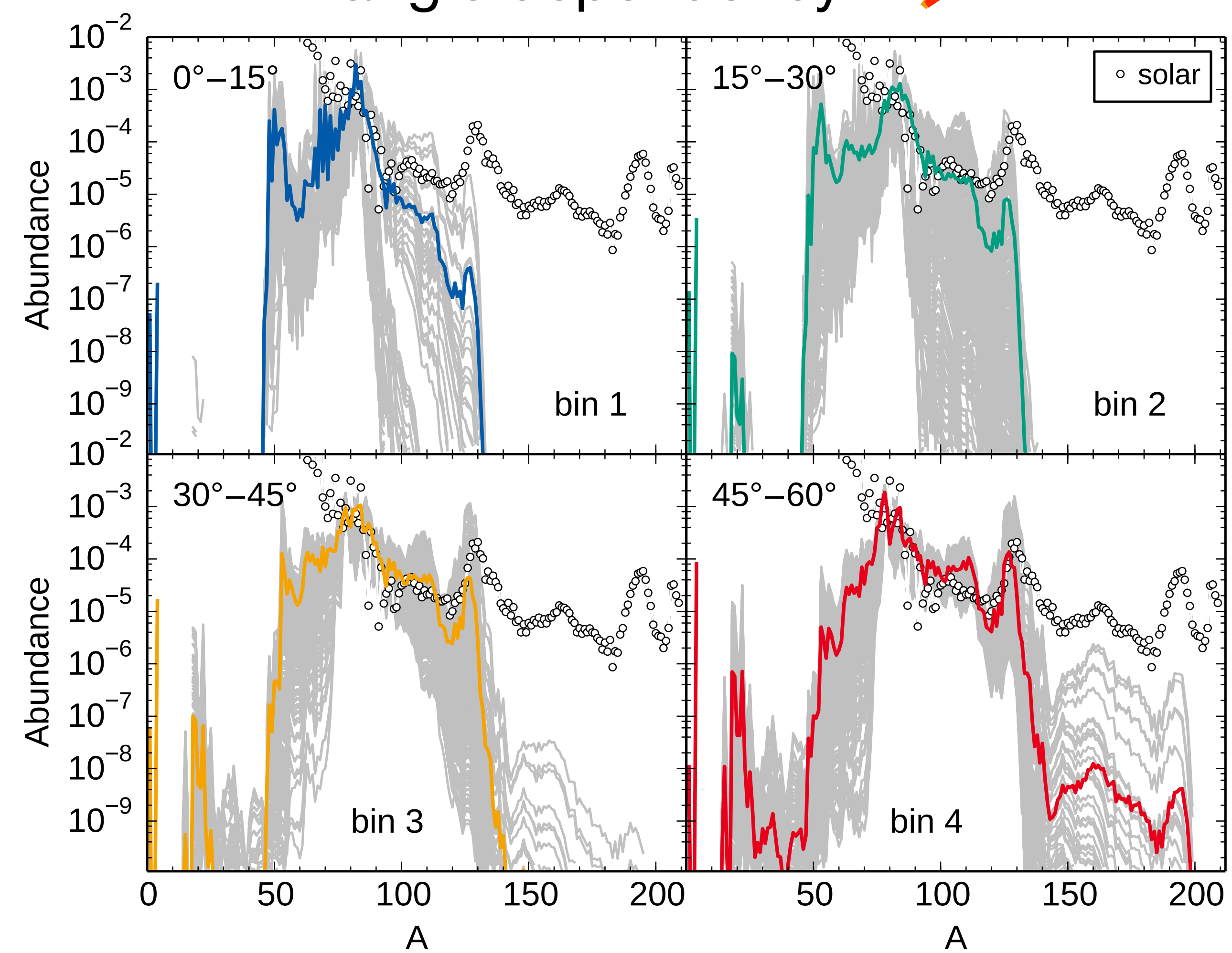
Early times: low Y_e: heavy elements

Late times: Y_e ~0.35: lighter heavy elements



angle dependency



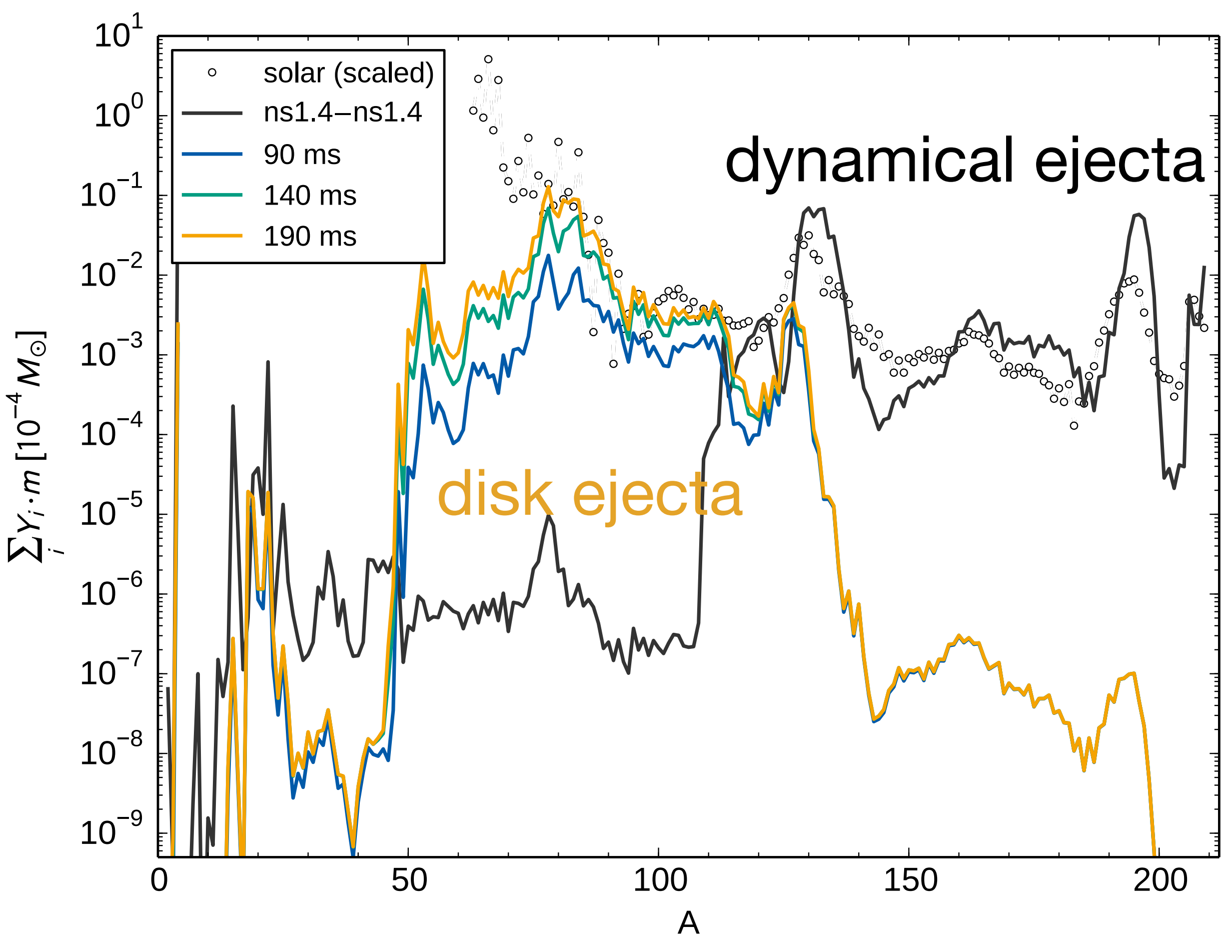


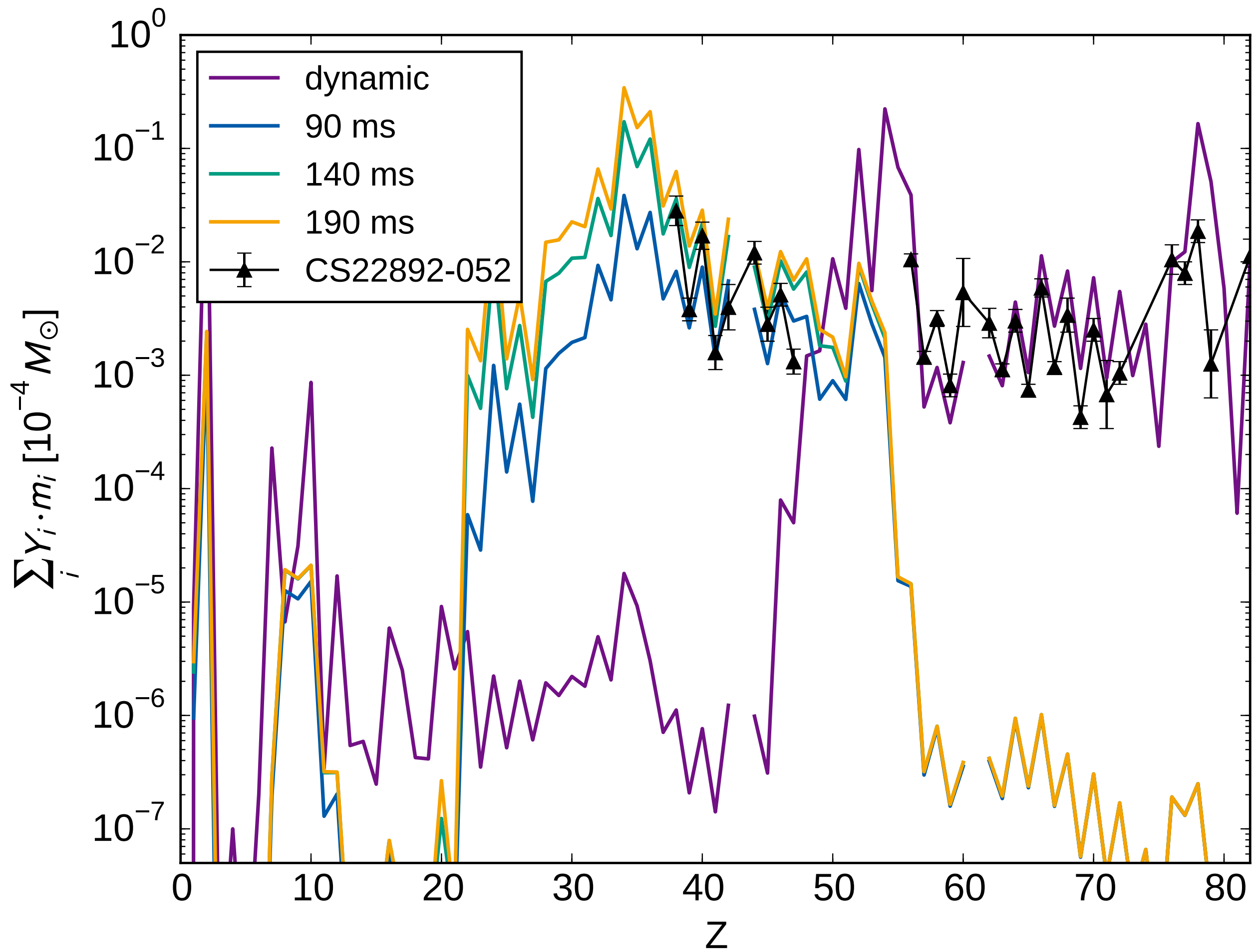
Martin et al. (2015)

Wind and dynamic ejecta

Wind ejecta complement dynamic ejecta

Complete mixing: solar system abundances and UMP stars





Martin et al. (2015)

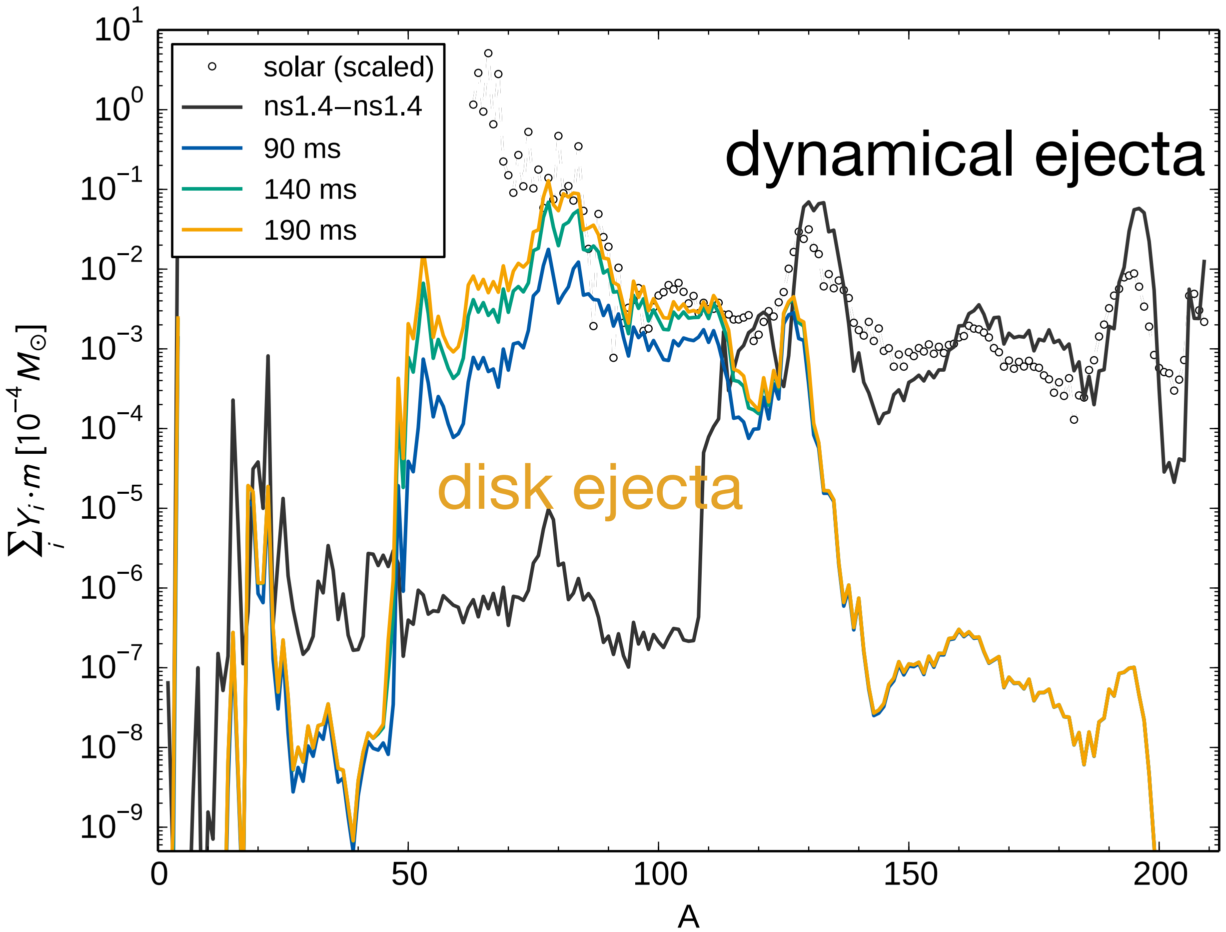
Two components: Hansen et al. 2014

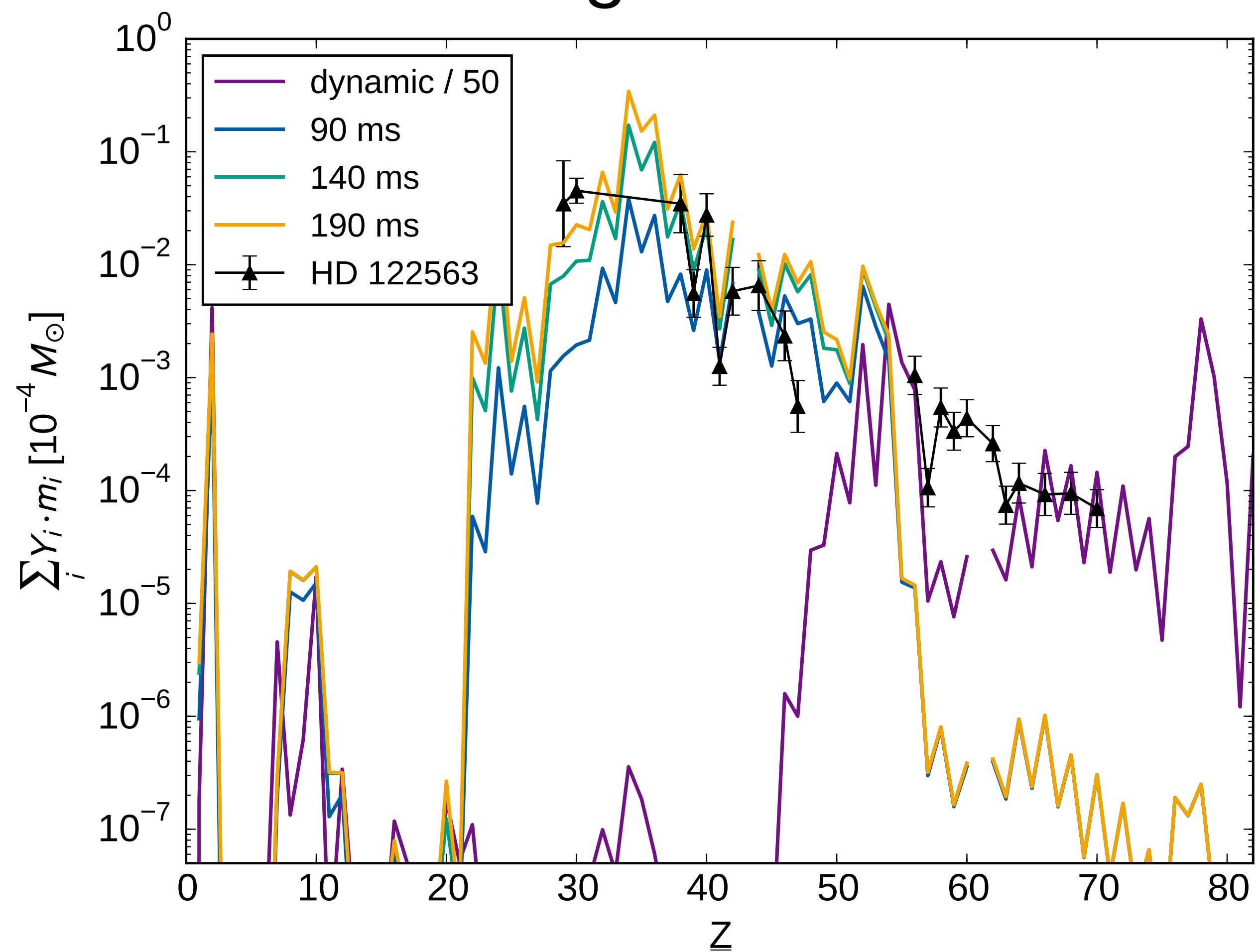
Wind and dynamic ejecta

Wind ejecta complement dynamic ejecta

Complete mixing: solar system abundances and UMP stars

Partial mixing: Honda-like star?



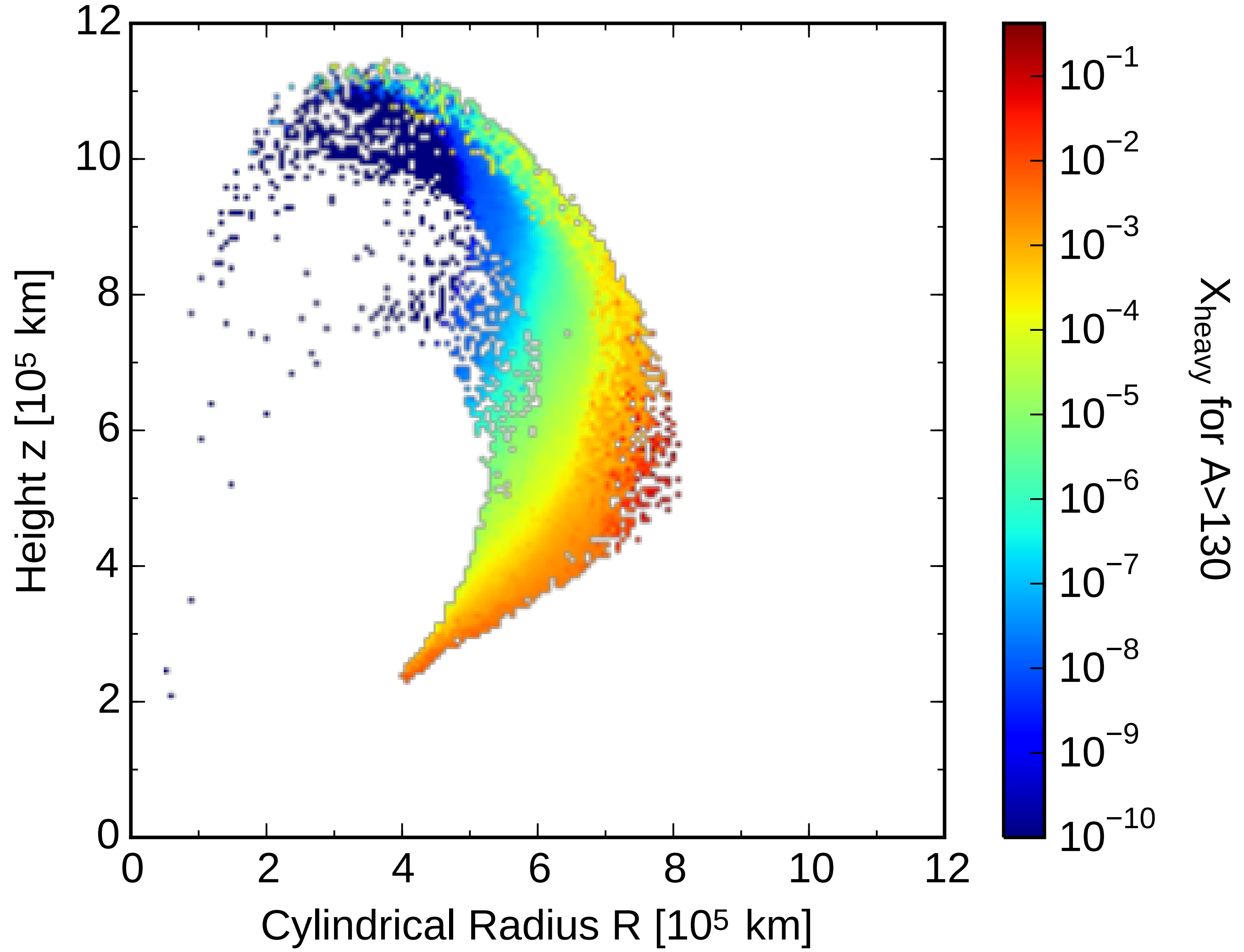


Martin et al. (2015)

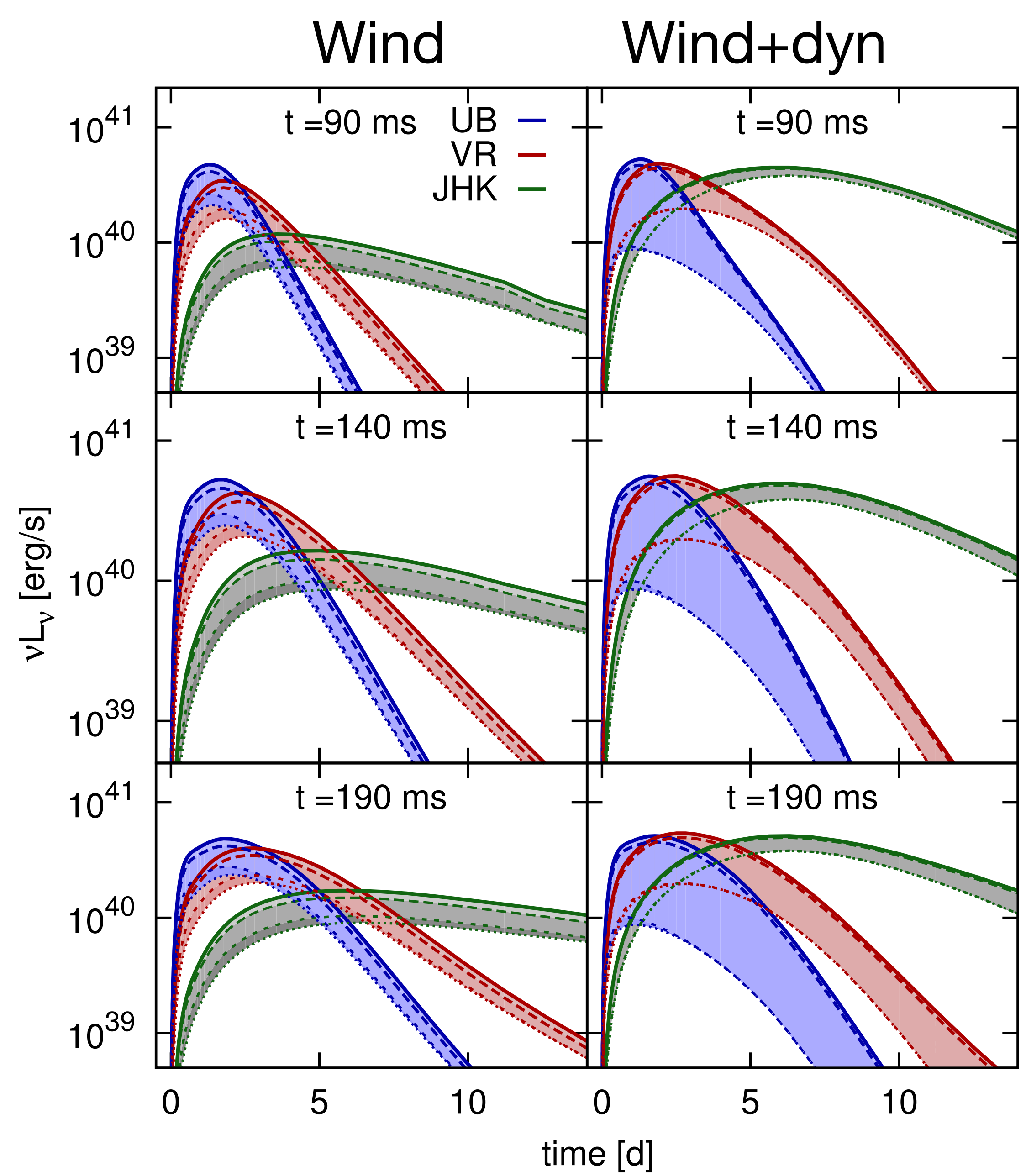
Two components: Hansen et al. 2014

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



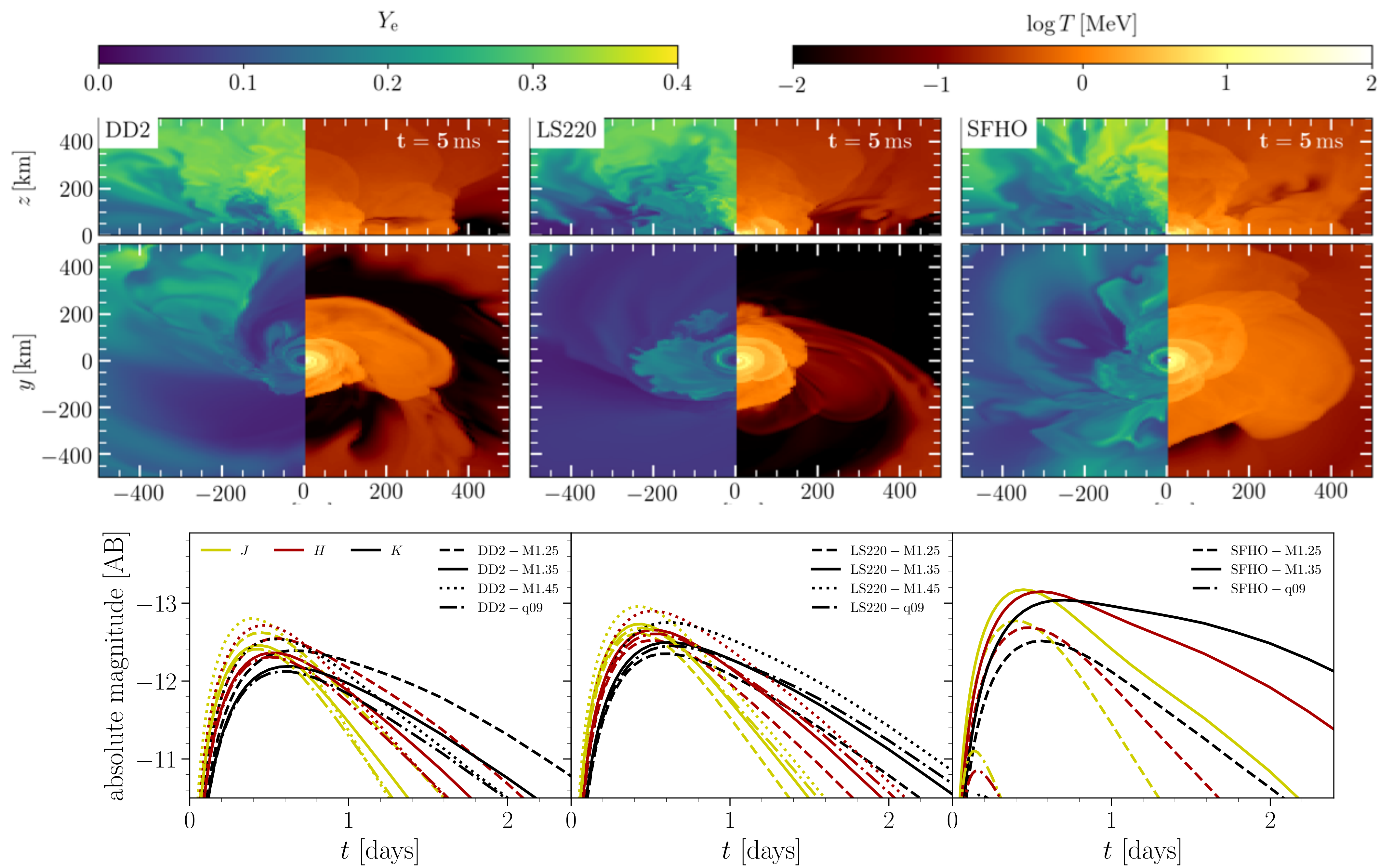
Martin et al. (2015)



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

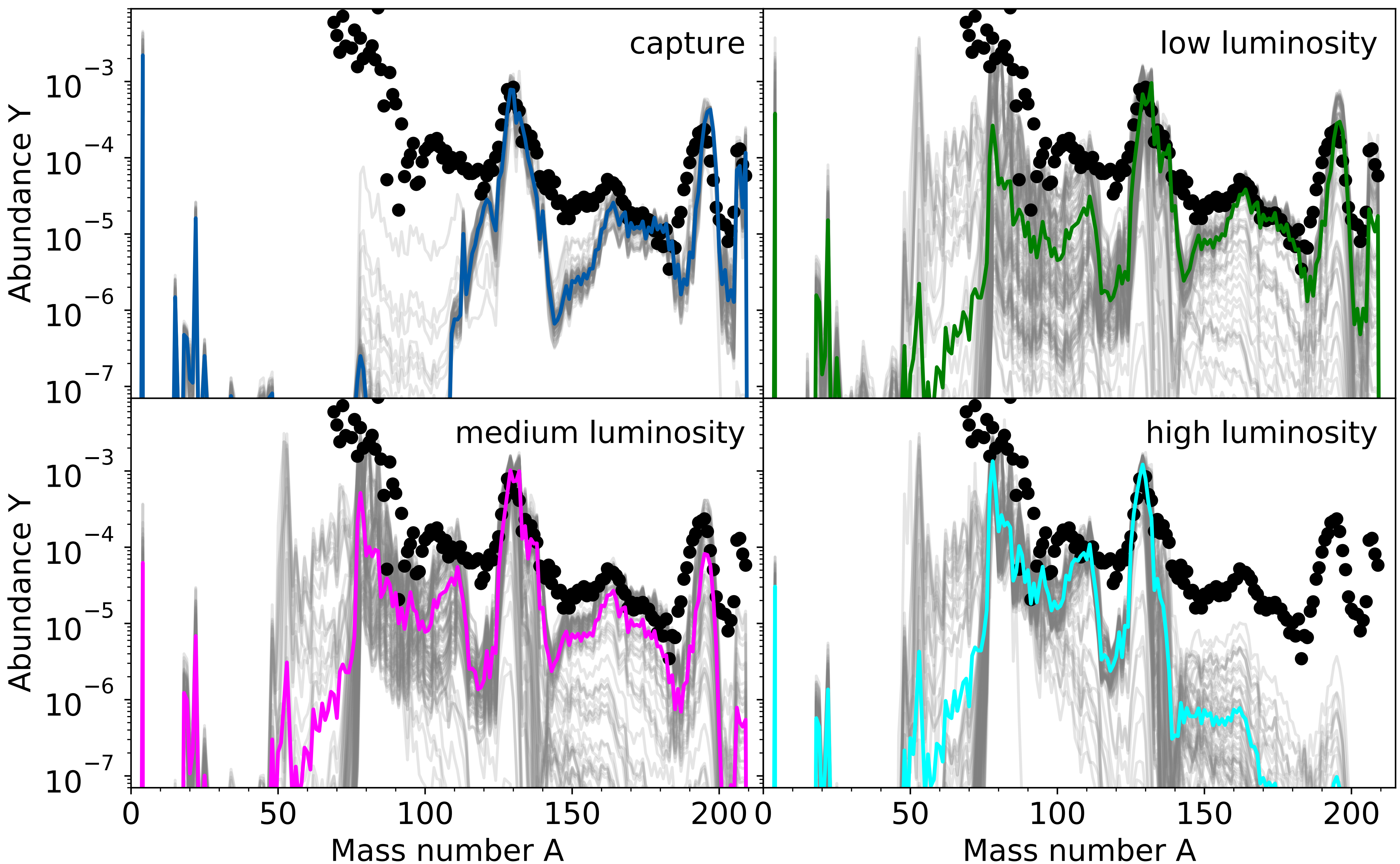
Equation of state and neutrinos

GR simulations: different EoS (Bovard et al. 2017)
impact of neutrinos (Martin et al. 2018)

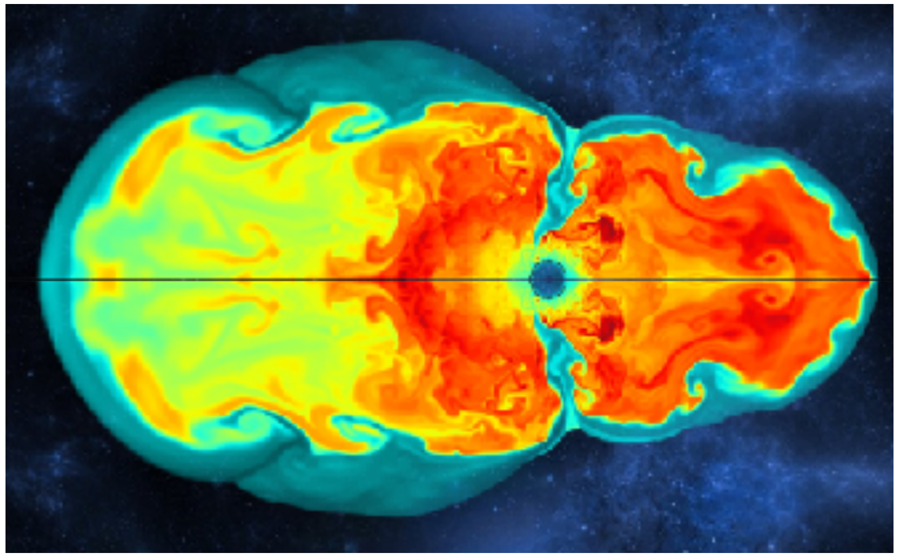


Equation of state and neutrinos

GR simulations: different EoS (Bovard et al. 2017)
impact of neutrinos (Martin et al. 2018)



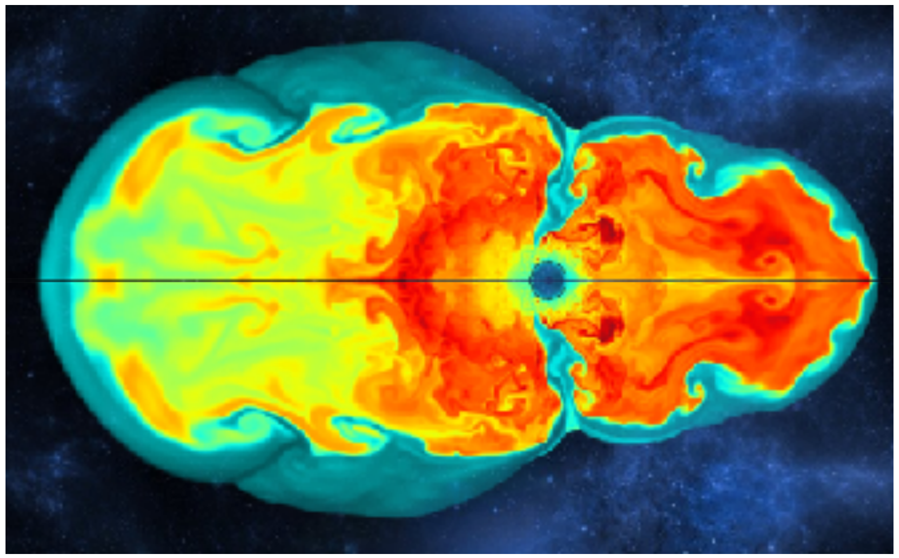
Core-collapse supernovae



Standard **neutrino-driven supernova**:
Weak r-process and νp-process
Elements up to ~Ag

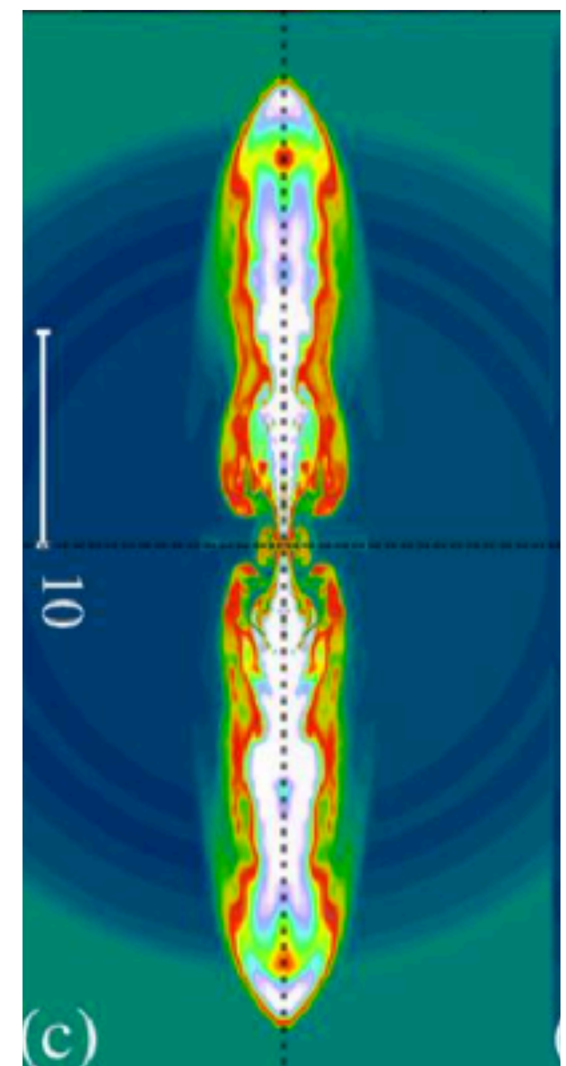
Bliss et al. 2018: astro uncertainties

Core-collapse supernovae



Standard **neutrino-driven supernova**:
Weak r-process and νp-process
Elements up to ~Ag

Bliss et al. 2018: astro uncertainties



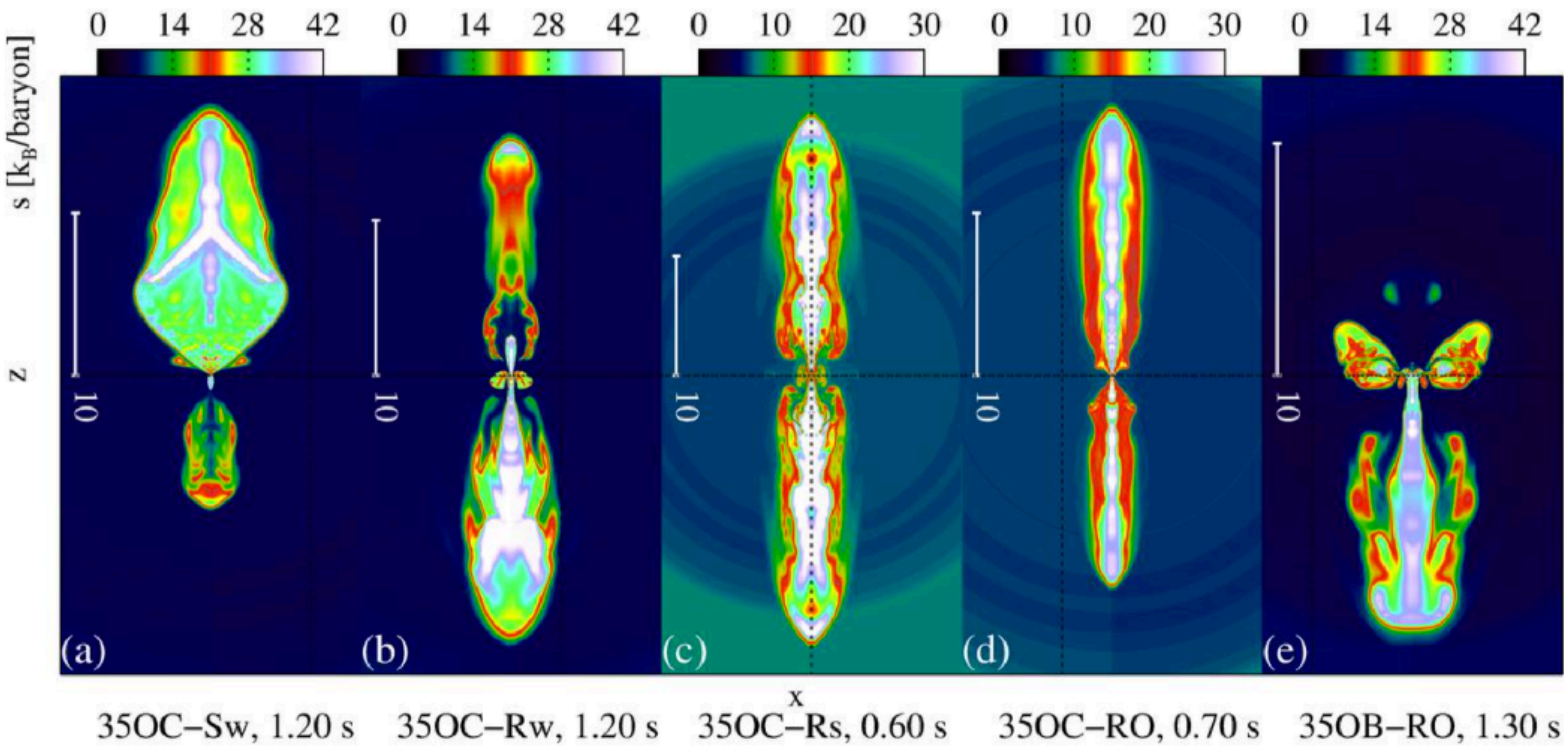
Magneto-rotational supernovae
Neutron-rich matter ejected by strong magnetic field
(Cameron 2003, Nishimura et al. 2006)

2D and 3D + parametric neutrino treatment :
- jet-like explosion: heavy r-process
- magnetic field vs. neutrinos: weak r-process

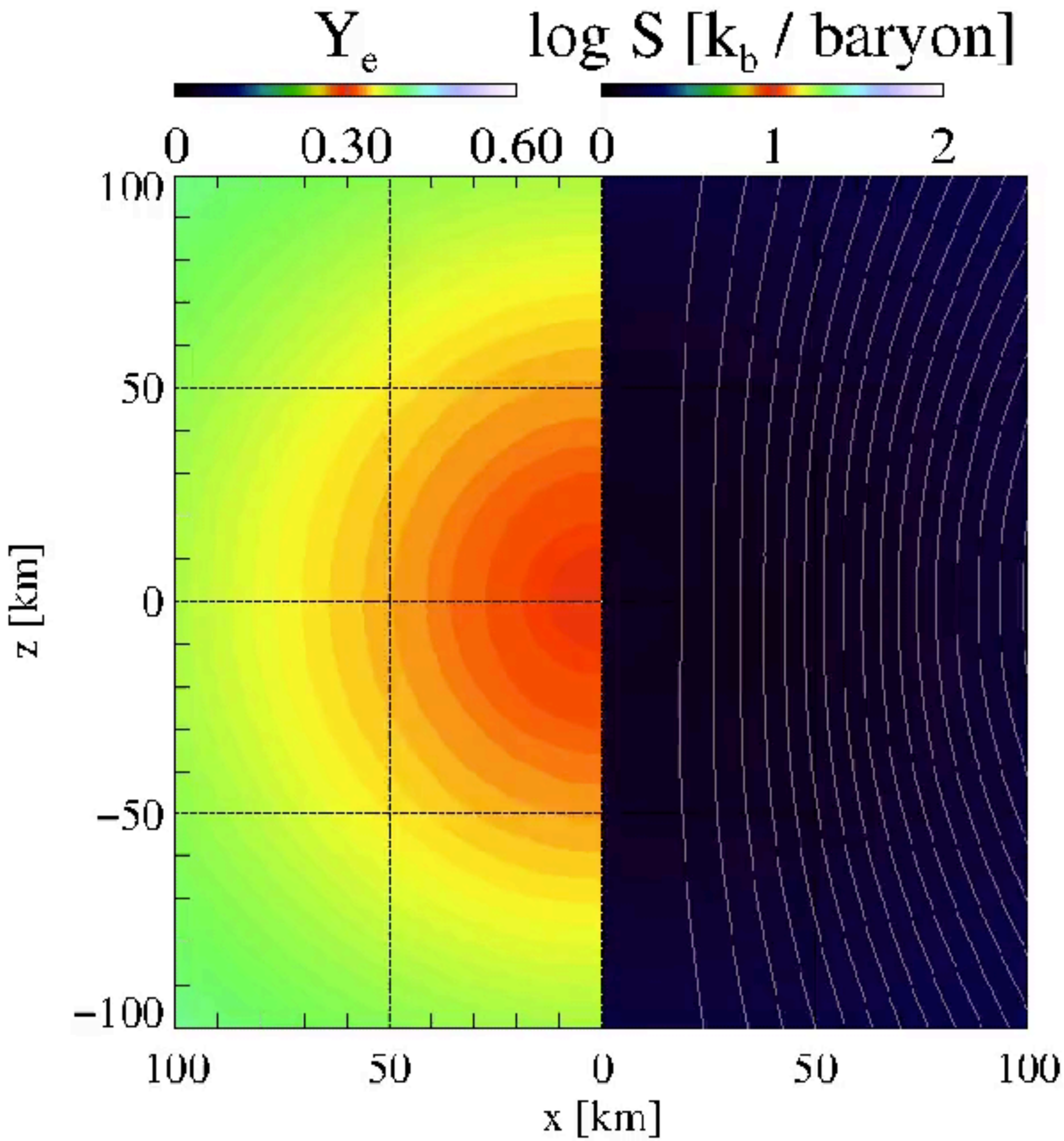
Nishimura et al. 2015, 2017, Winteler et al. 2012, Mösta et al. 2018

Magneto-rotational supernovae: r-process

Neutrinos and late evolution are important
Martin Obergaulinger: 2D, M1, ~1-2s
Progenitor: 35 M_{sun}

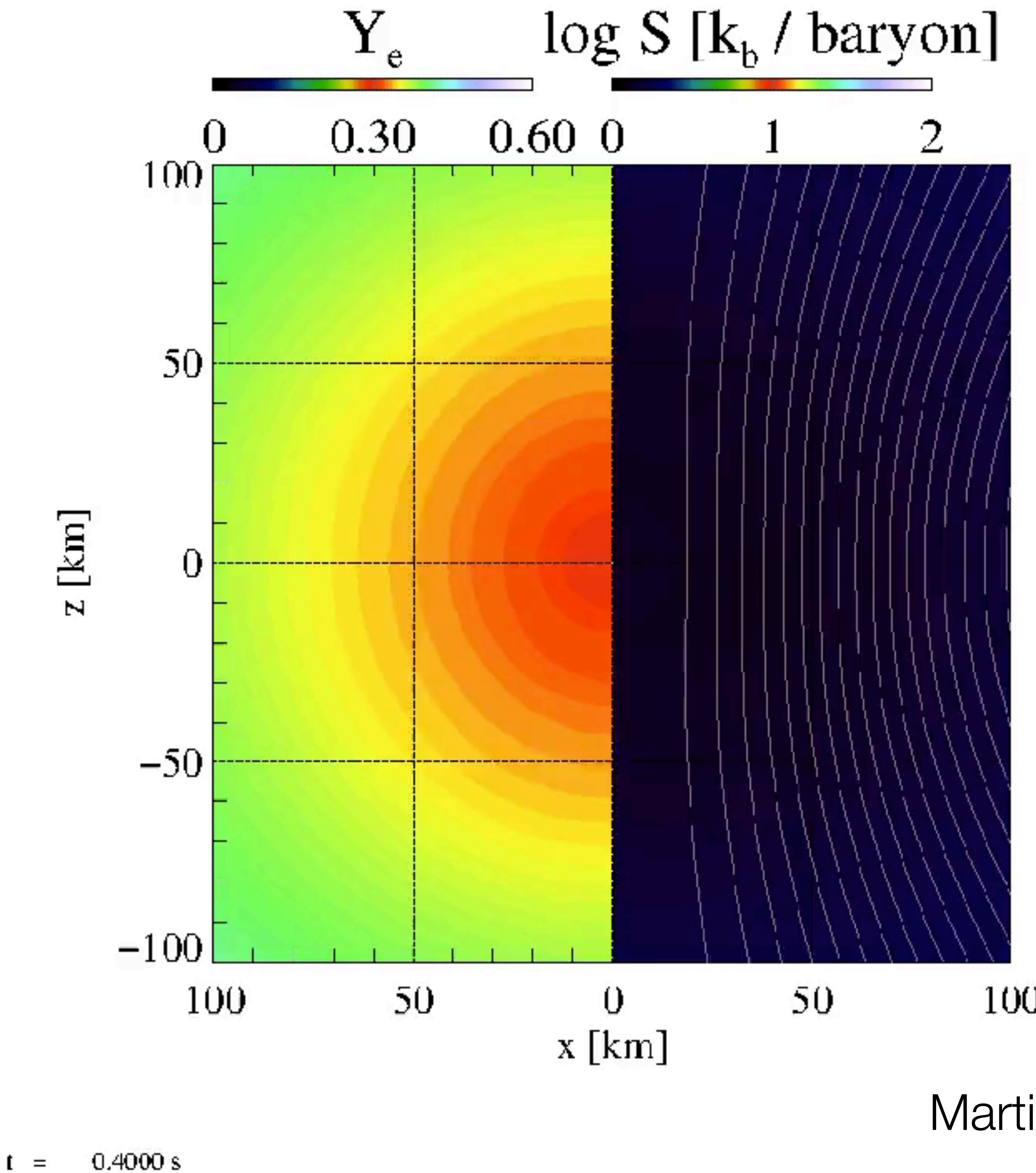


Obergaulinger & Aloy (2017)



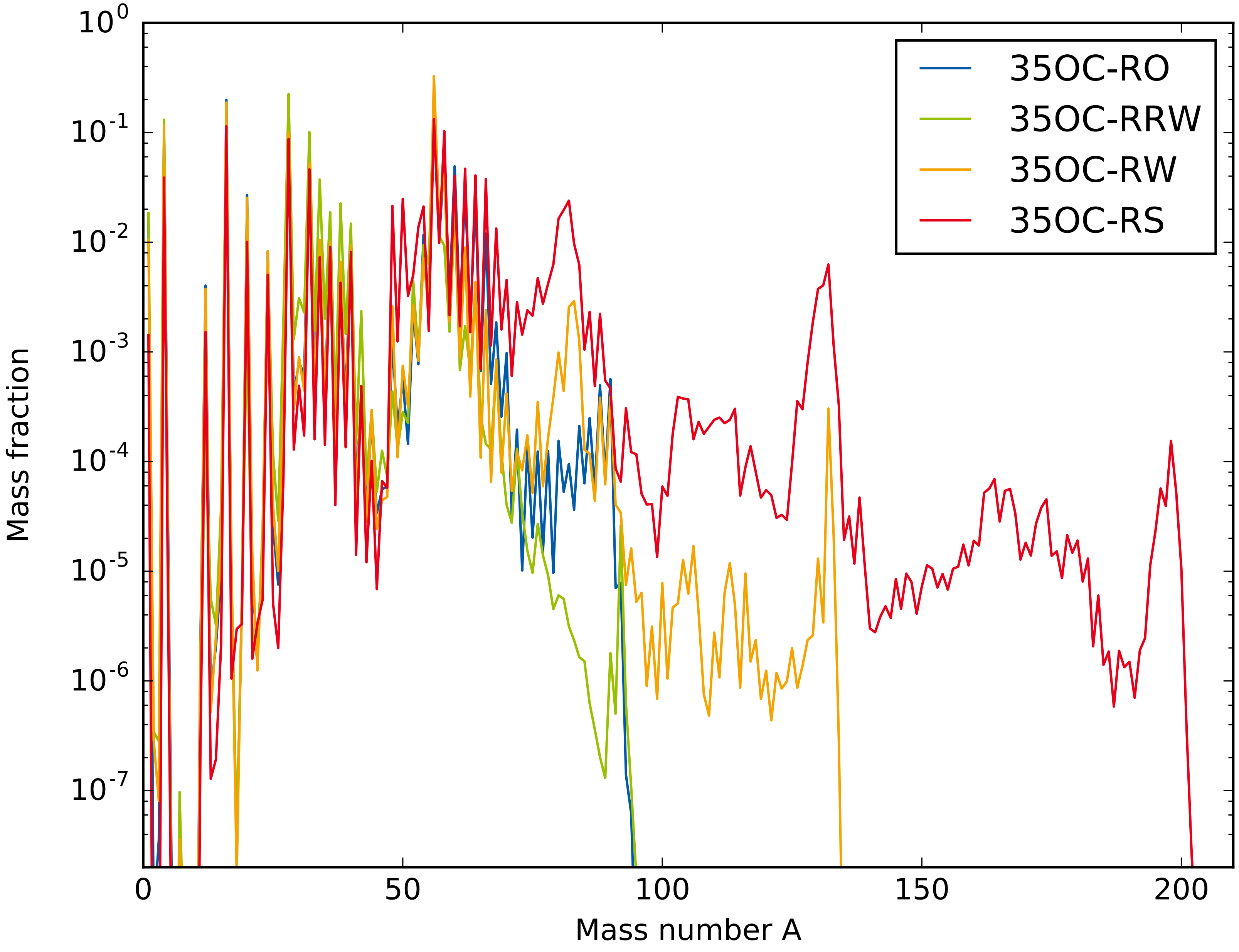
Martin Obergaulinger

t = 0.4000 s

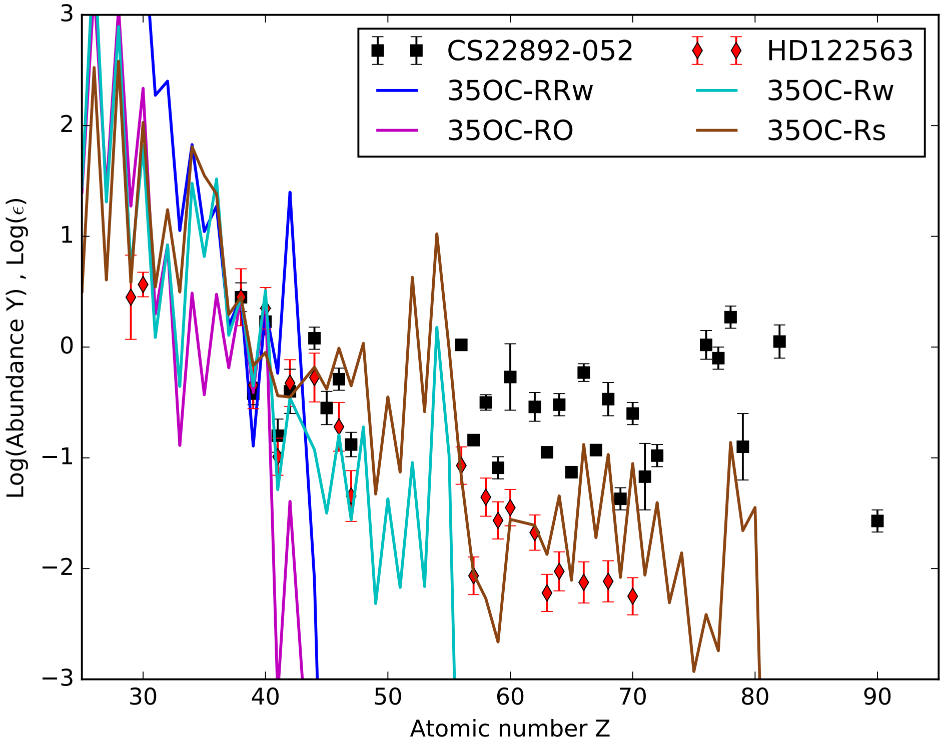


Martin Obergaulinger

Impact of rotation and magnetic field

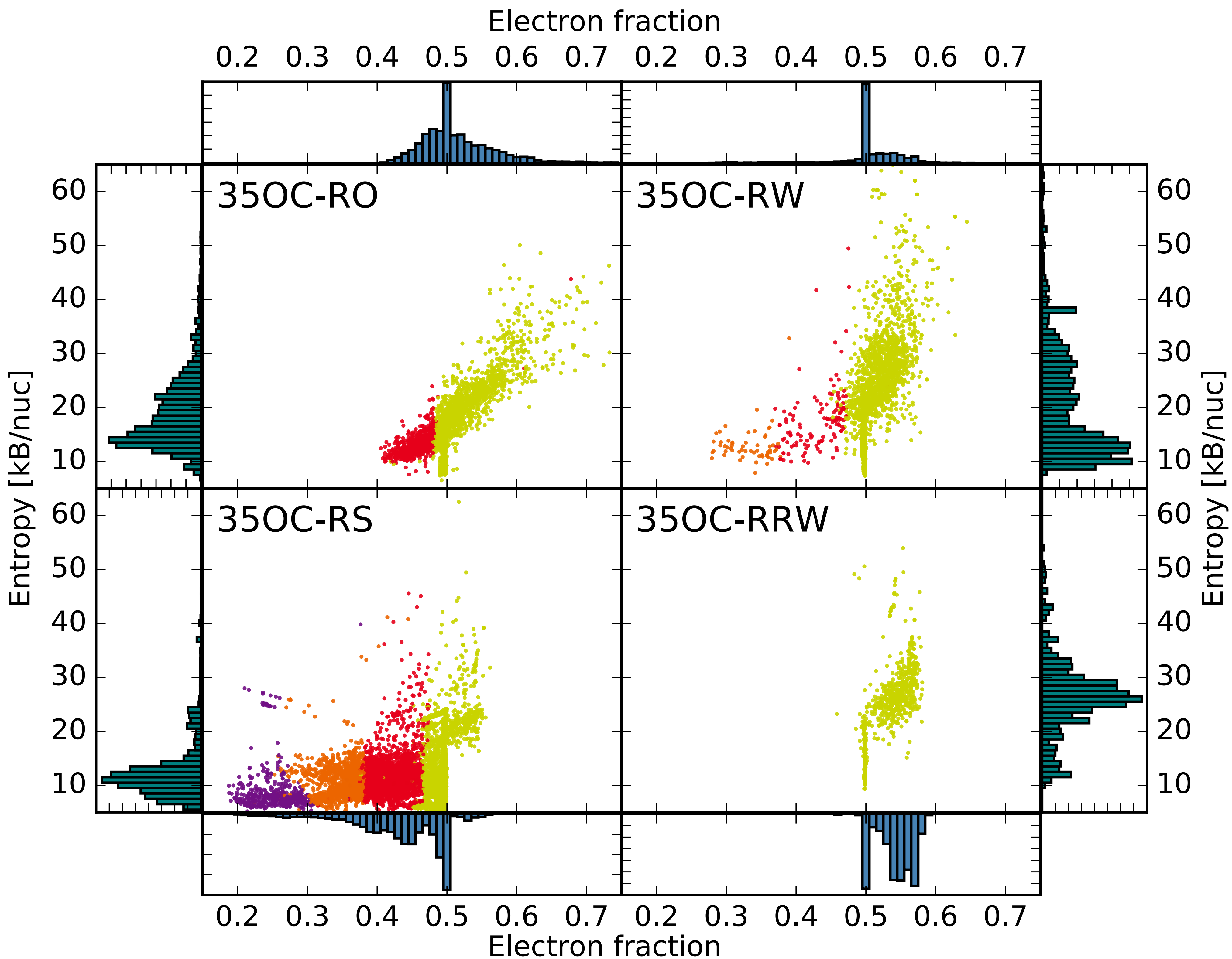


RO: progenitor
RRW: weak mag. field
strong rot.
RW: weak mag. field
RS: strong mag. Field



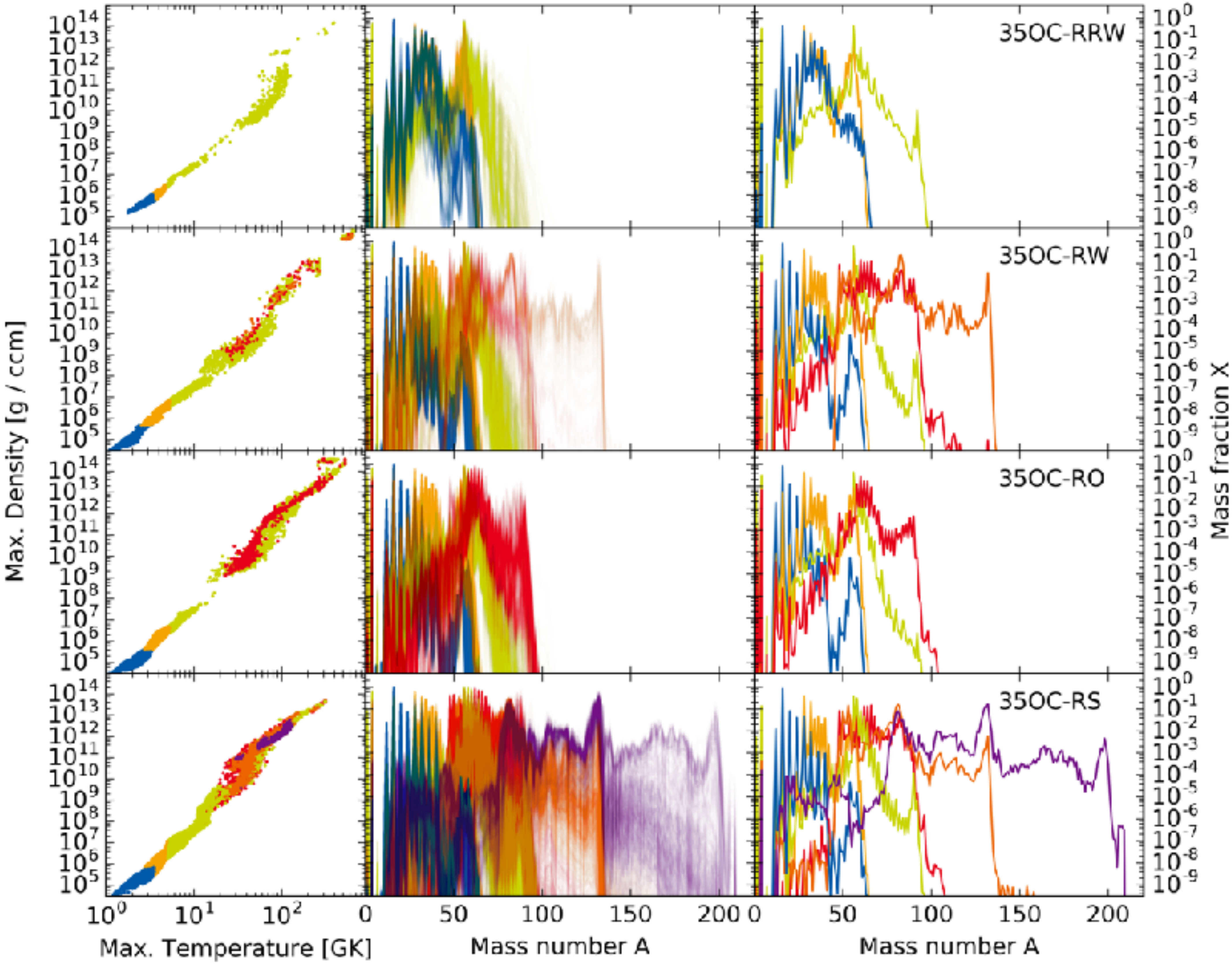
Reichert, Obergaulinger, Aloy, Arcones (in prep)

Individual tracers

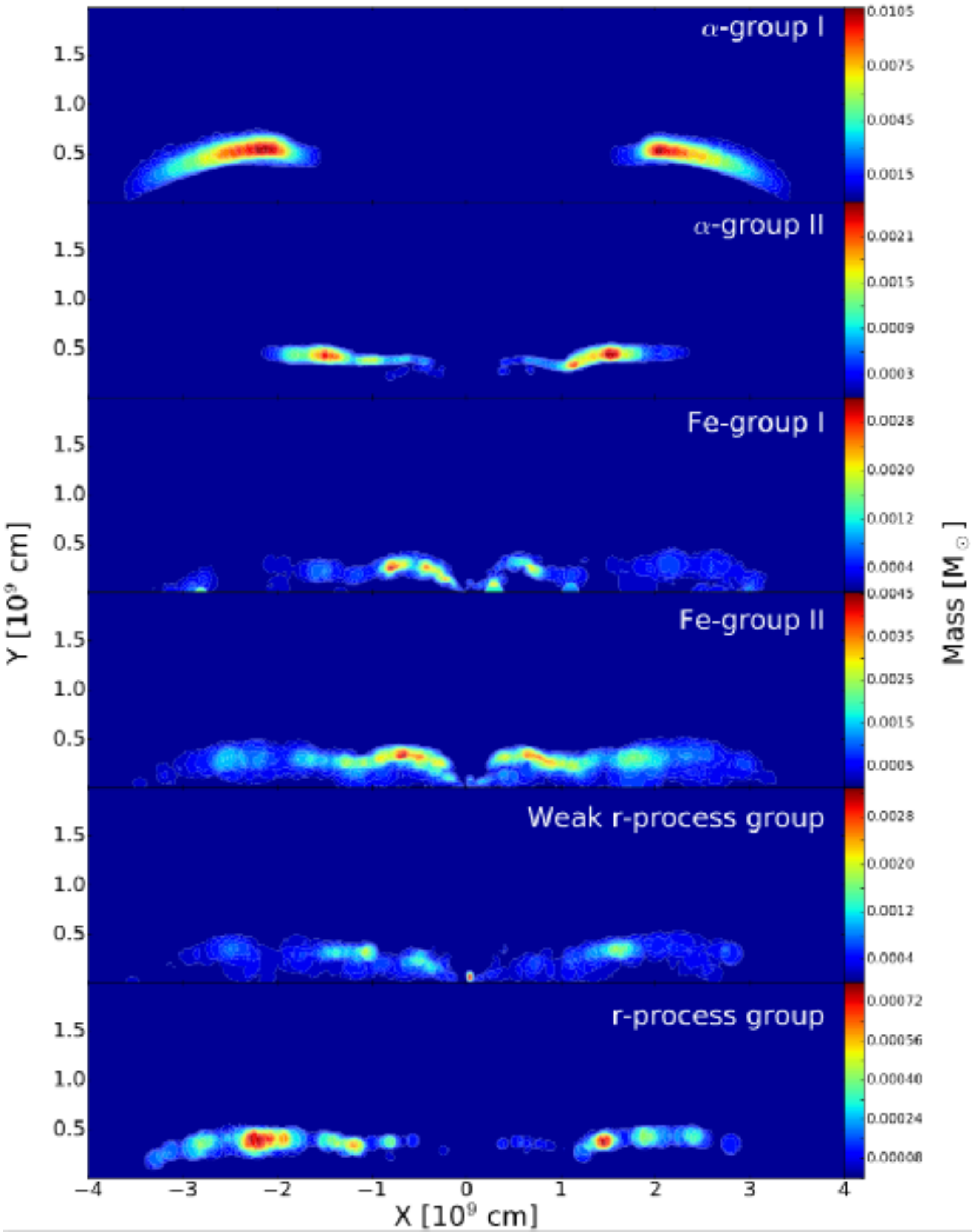


Reichert, Obergaulinger, Aloy, Arcones (in prep)

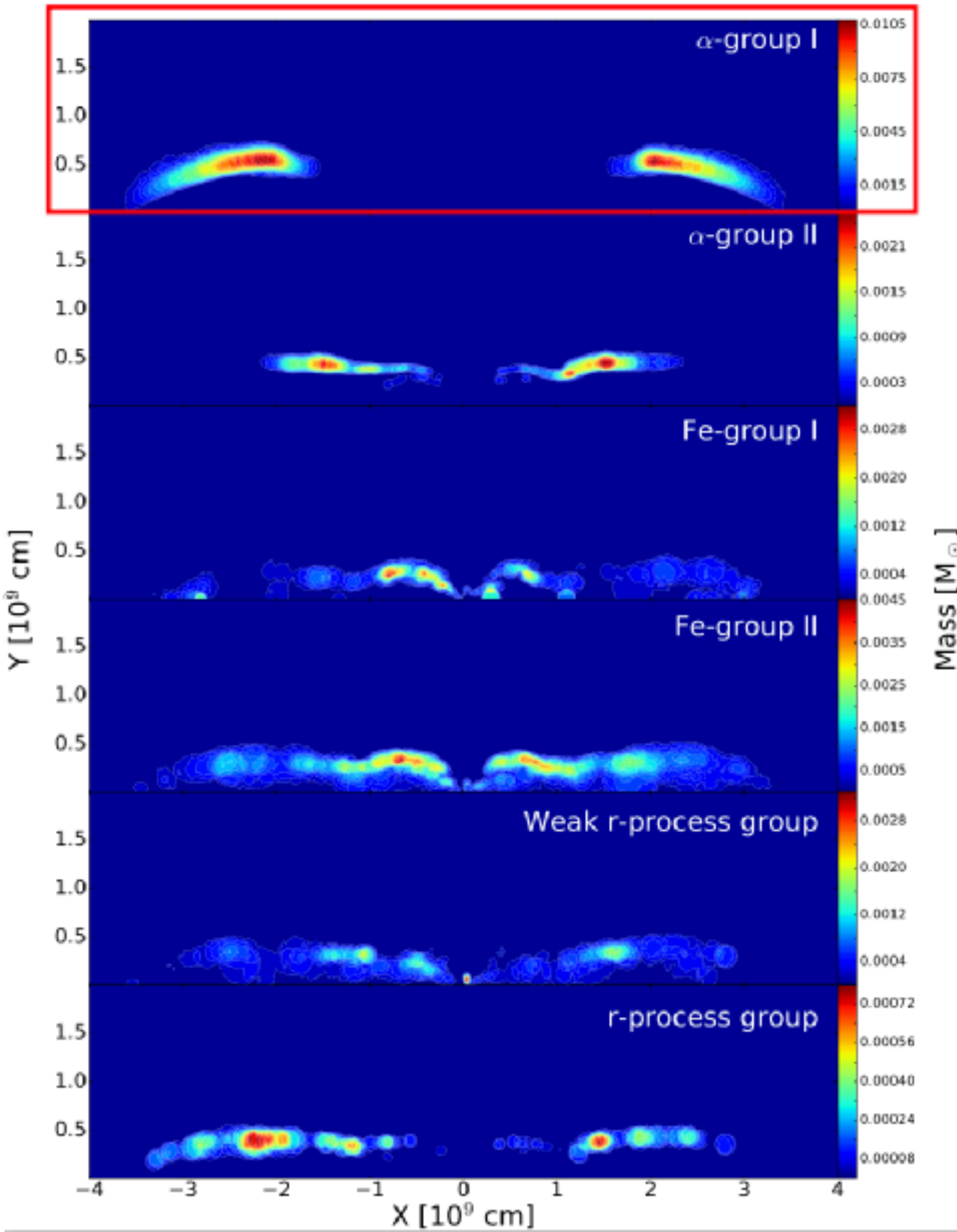
Nucleosynthesis patterns

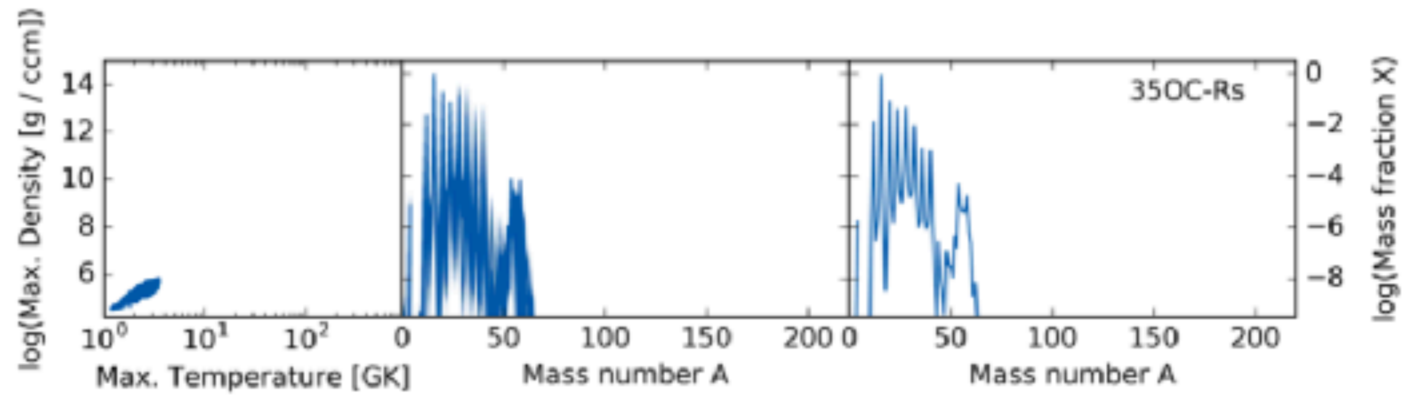


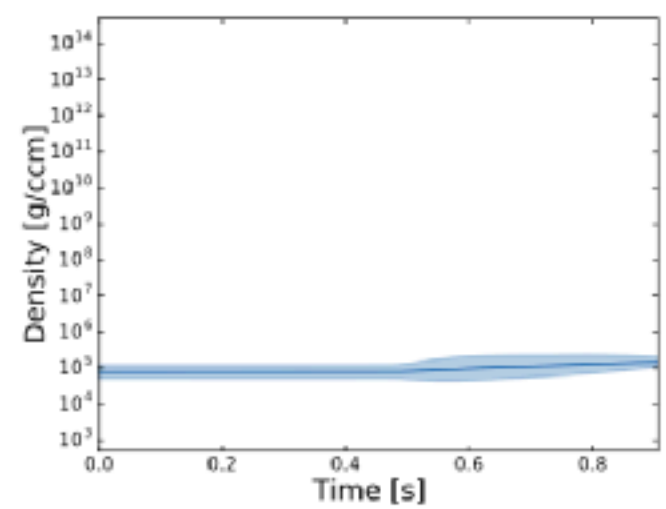
Nucleosynthesis patterns



Nucleosynthesis patterns

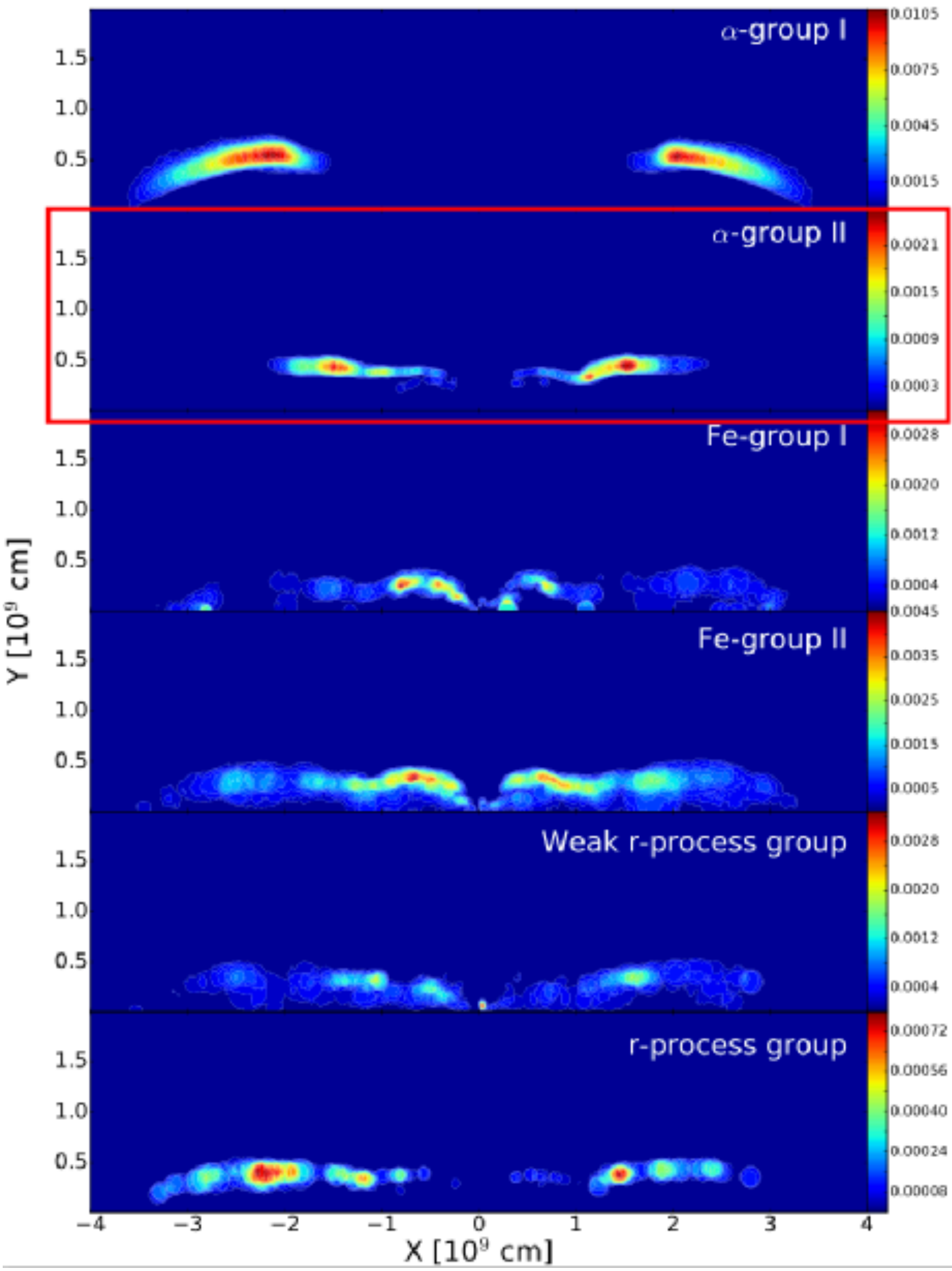


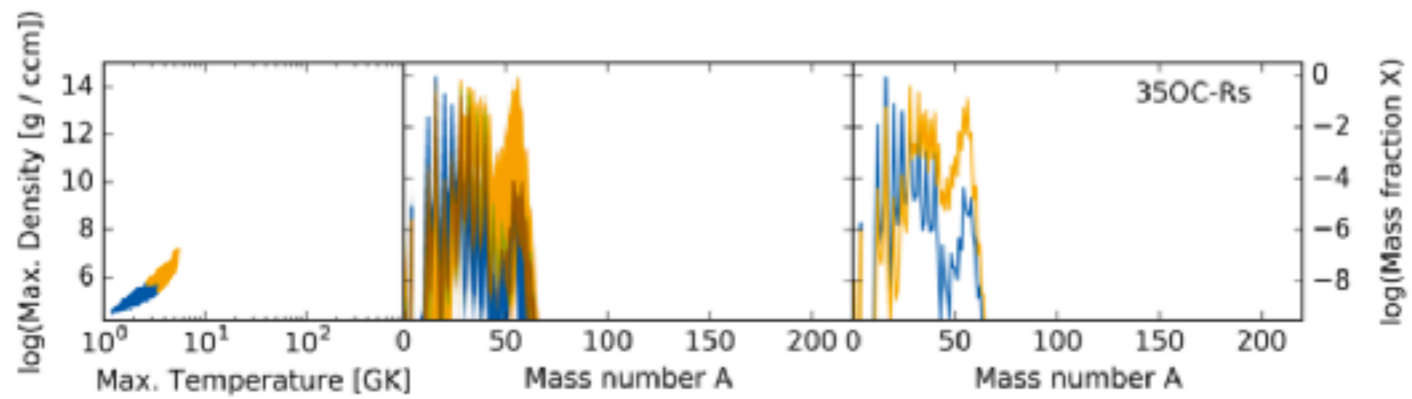


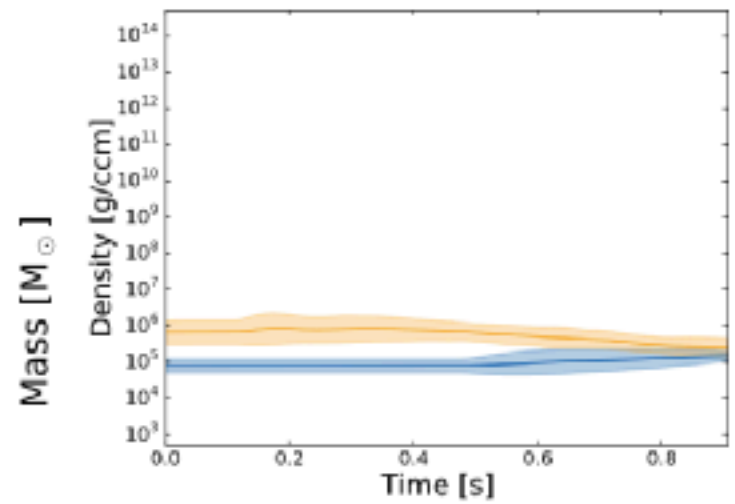


- Progenitor composition
- $T_{\mathrm{max}} \lesssim 3\,\mathrm{GK}$
- $\rho_{\mathrm{max}} \lesssim 10^6\,\mathrm{g}\,/\mathrm{ccm}$

Nucleosynthesis patterns

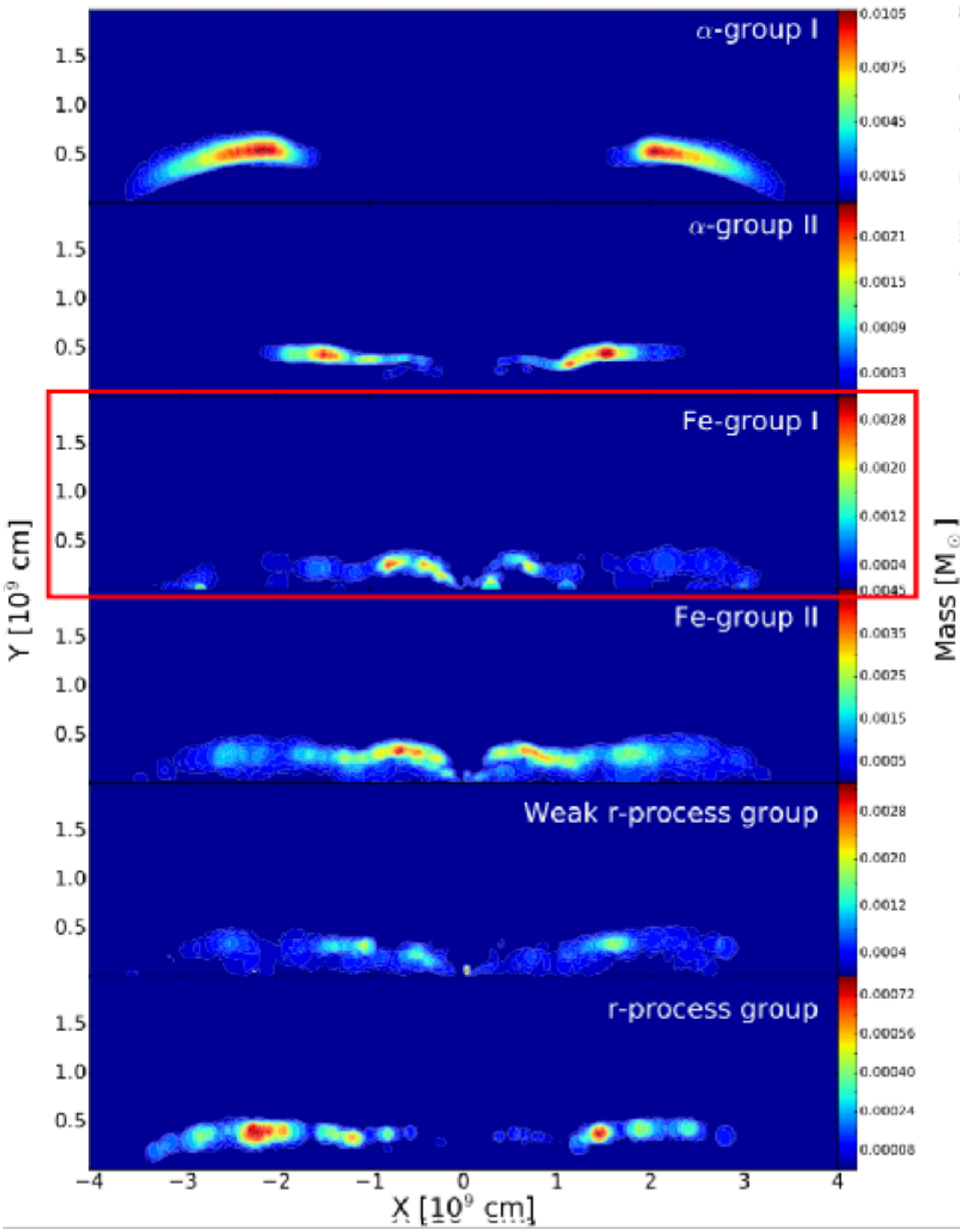


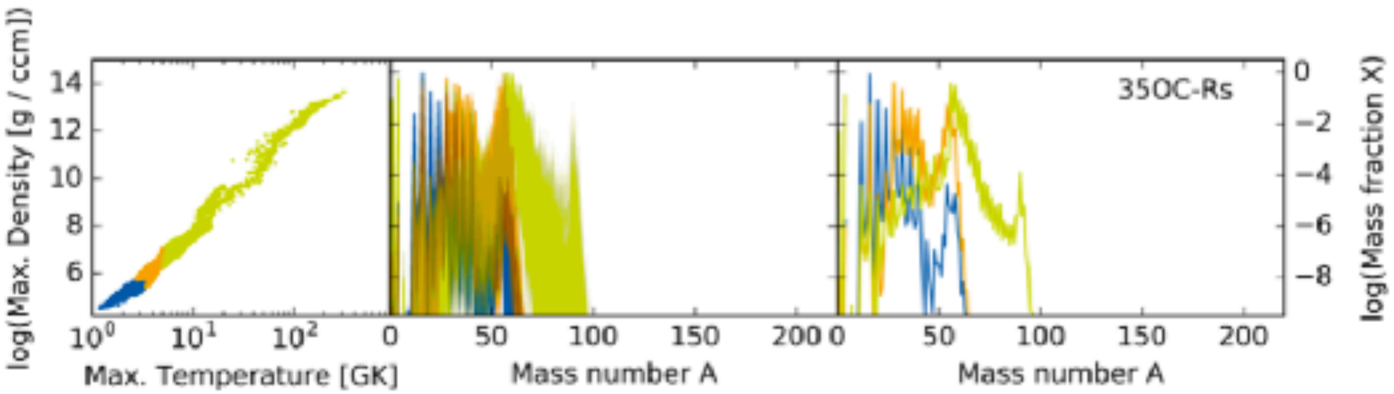


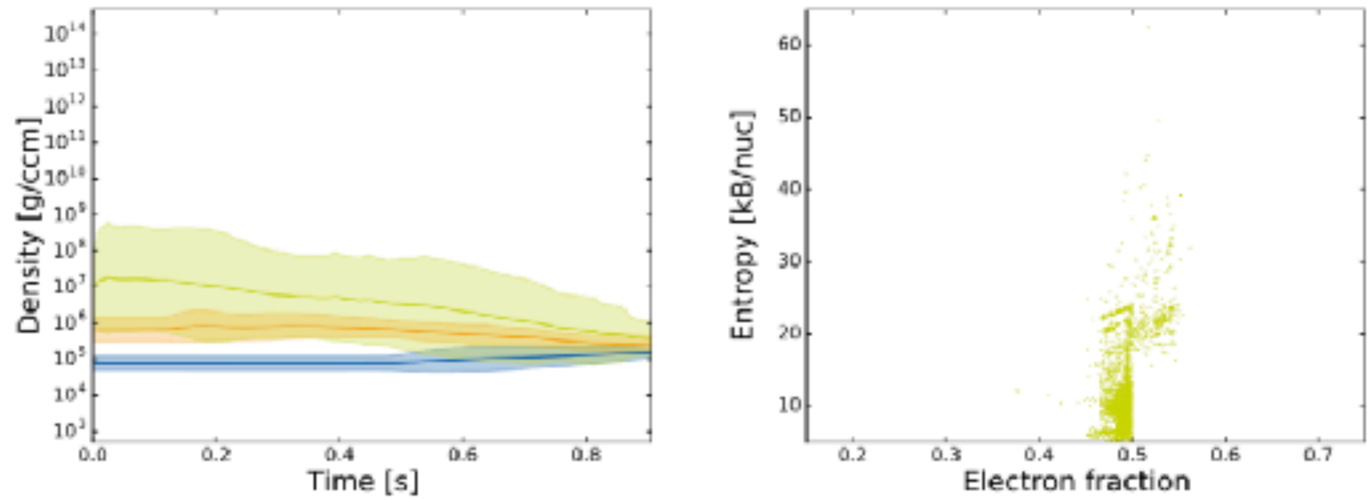


- α+Fe elements
- $T_{\max} \lesssim 5\,\mathrm{G\,K}$
- $\rho_{\max} \lesssim 10^7\,\mathrm{g\,/ccm}$

Nucleosynthesis patterns

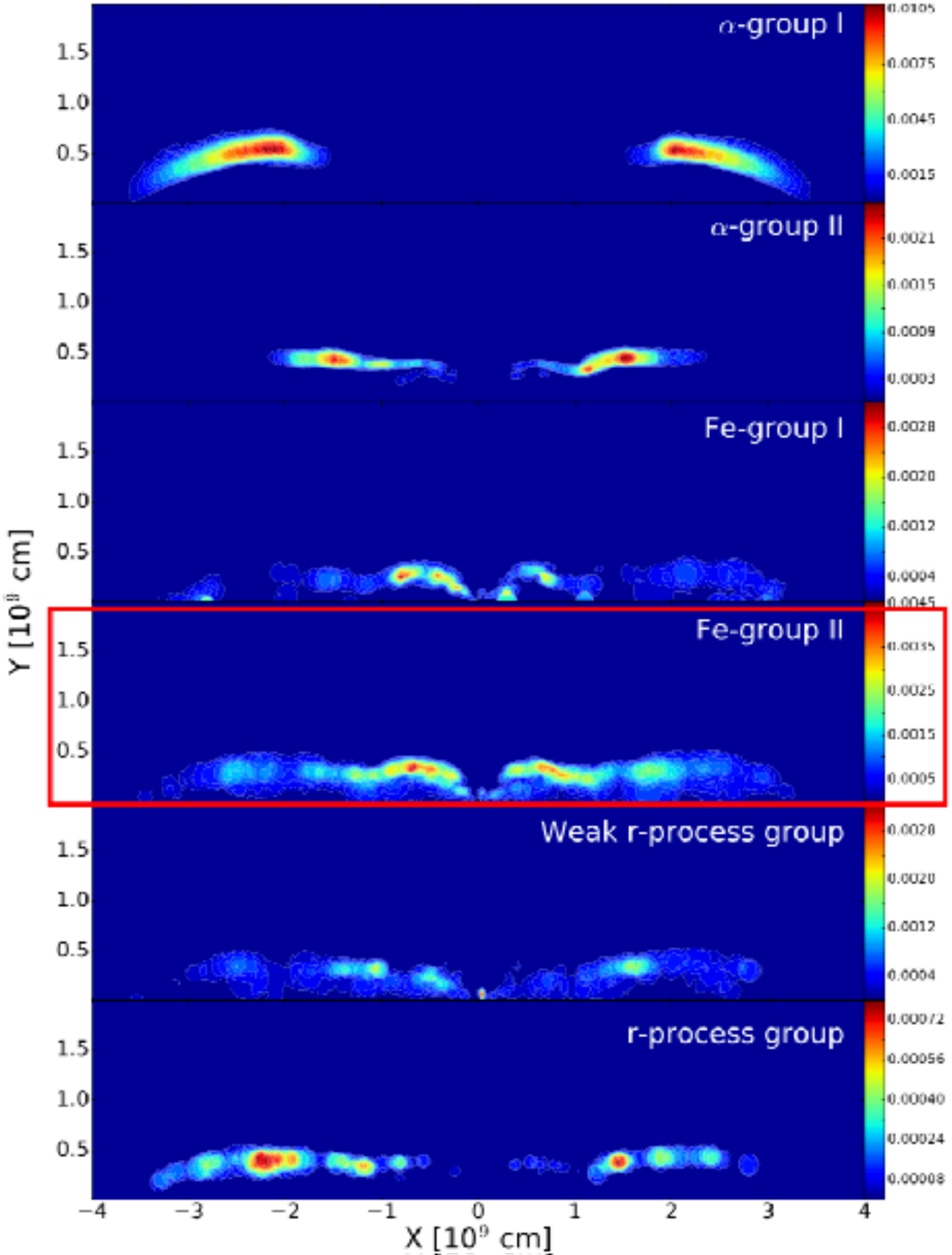


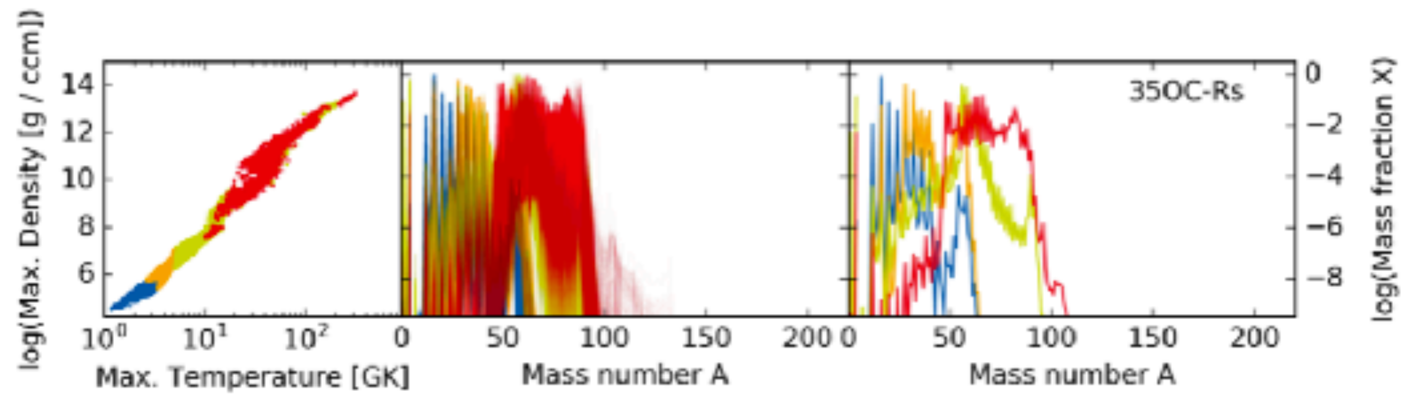


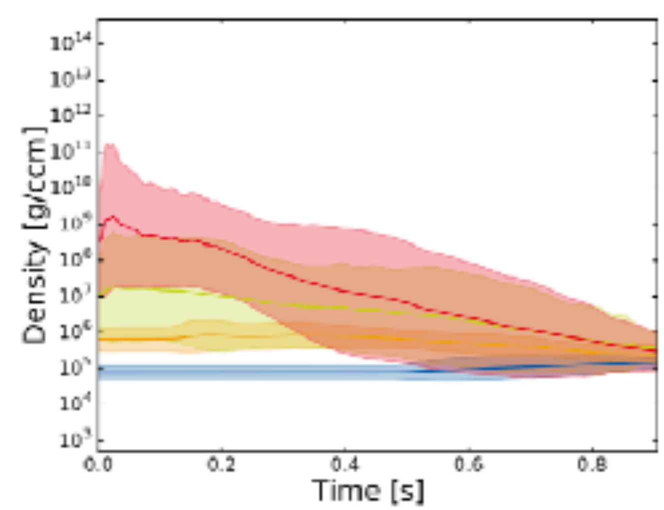


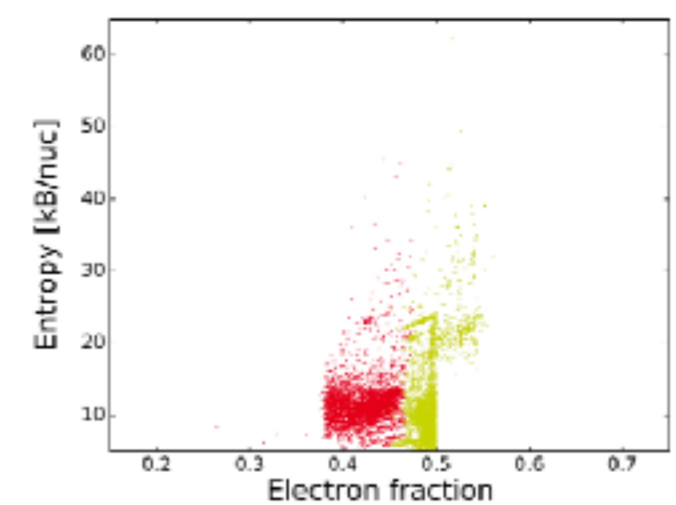
- Fe elements
- $T_{\max} \gtrsim 5\,\mathrm{GK}$
- $\rho_{\max} \gtrsim 10^7\,\mathrm{g\,/ccm}$
- $Y_e \gtrsim 0.47$

Nucleosynthesis patterns



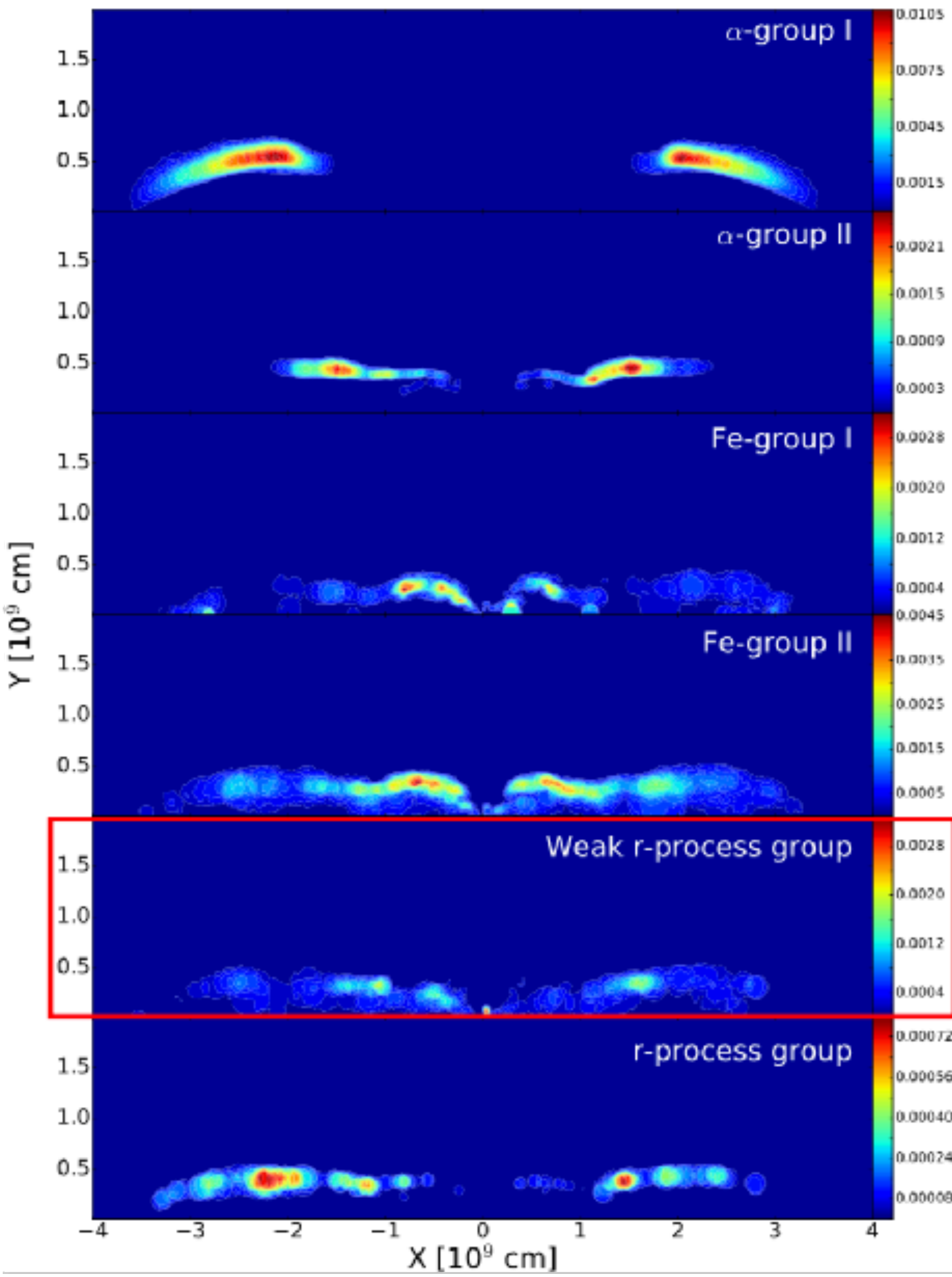


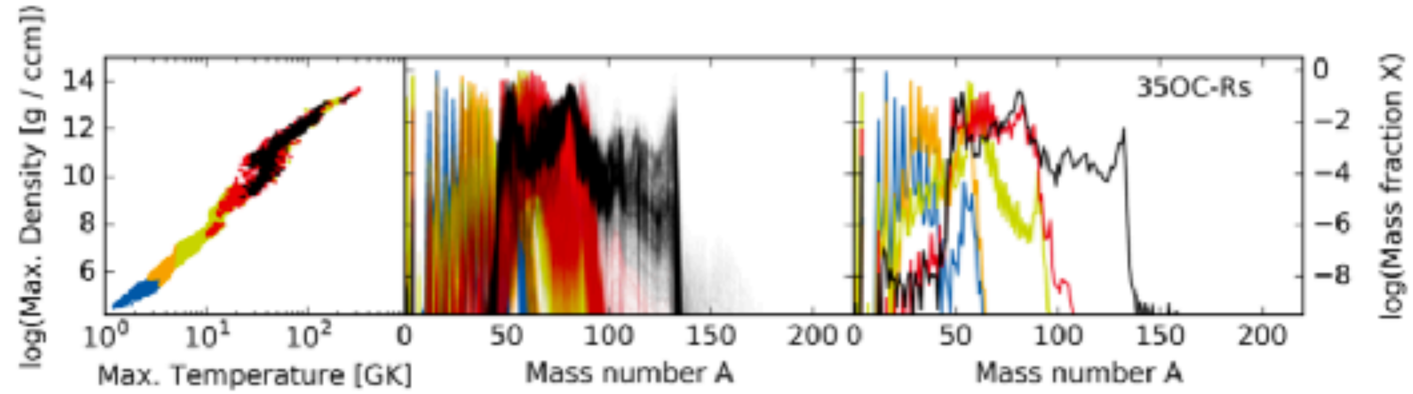


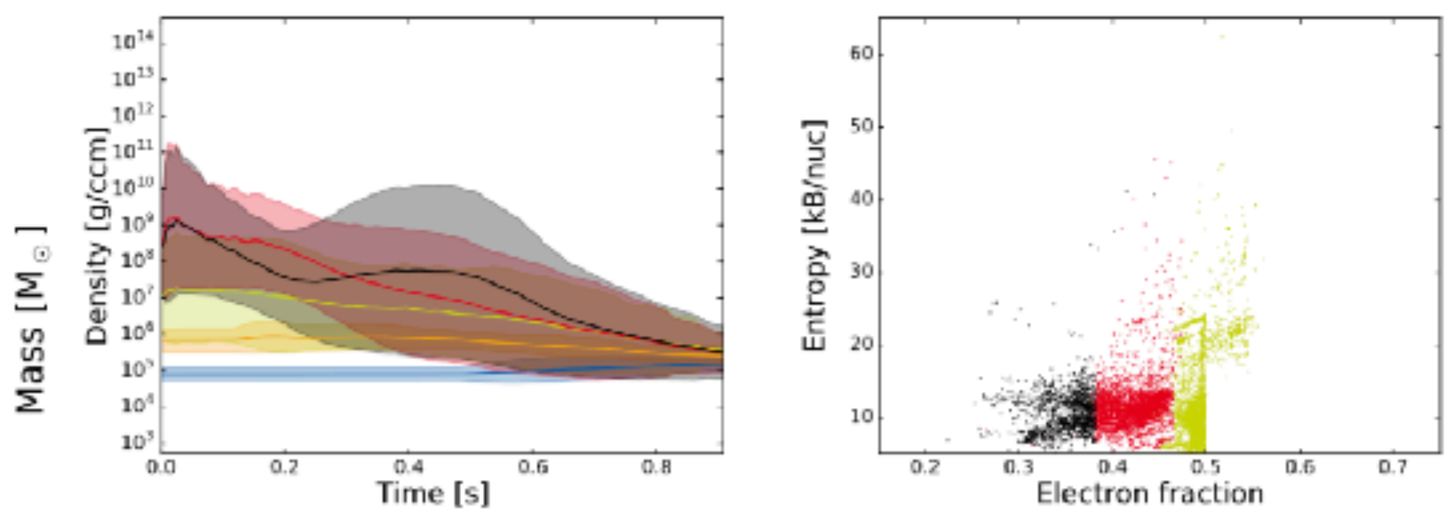


- 1st r-process peak
- $T_{\max} \gtrsim 10\,\mathrm{G\,K}$
- $\rho_{\max} \gtrsim 10^7\,\mathrm{g\,/ccm}$
- $0.38 \lesssim Y_e \lesssim 0.47$

Nucleosynthesis patterns

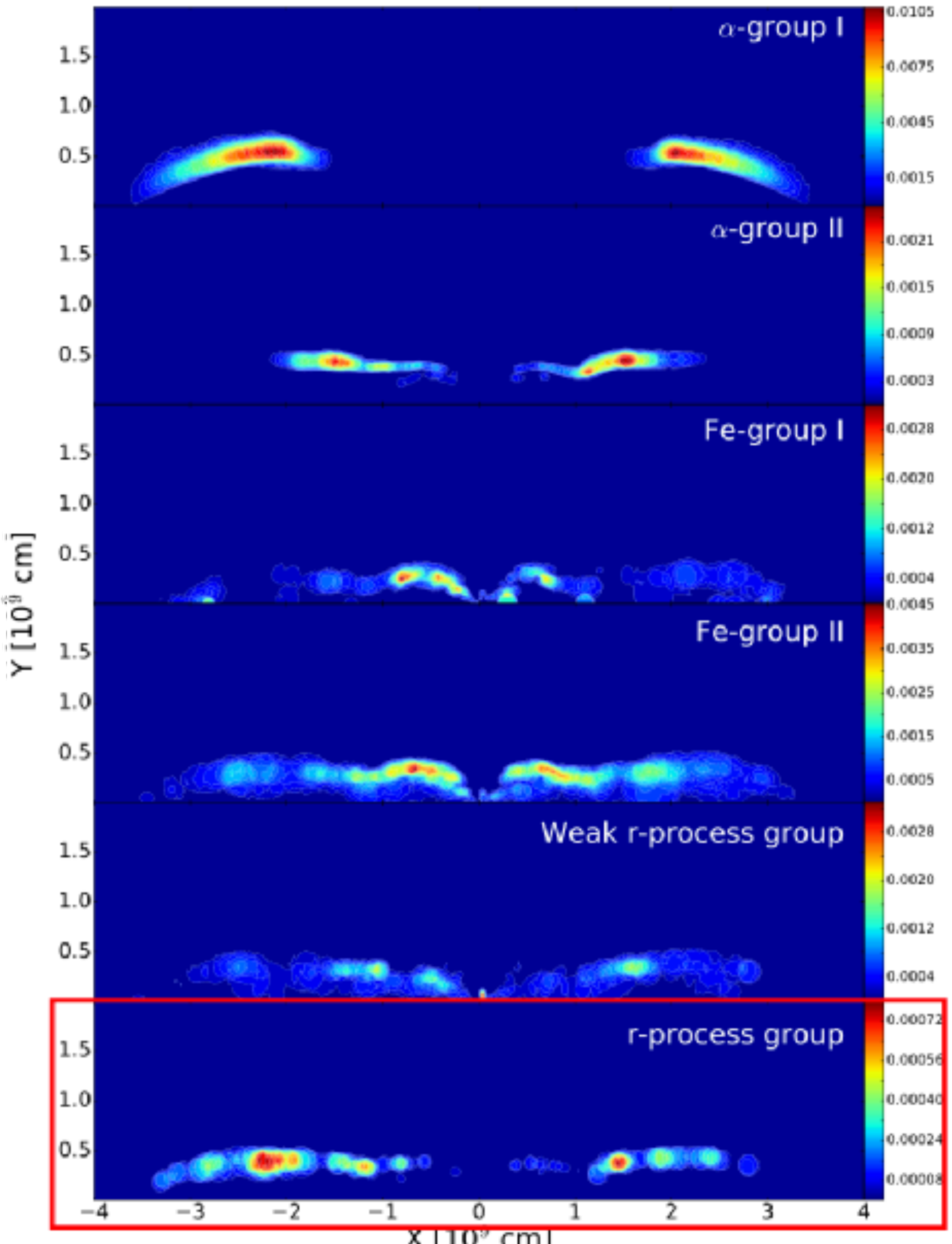


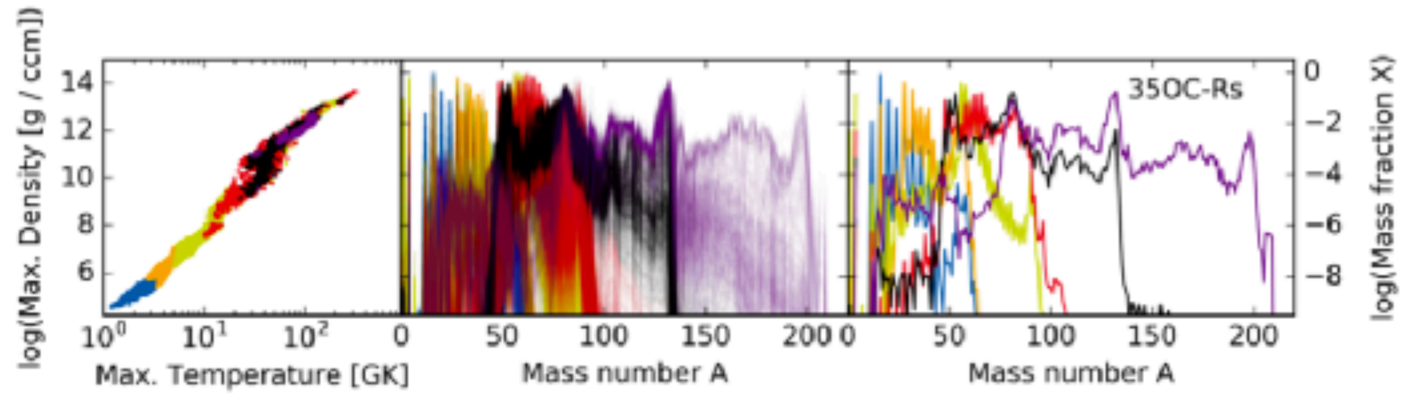


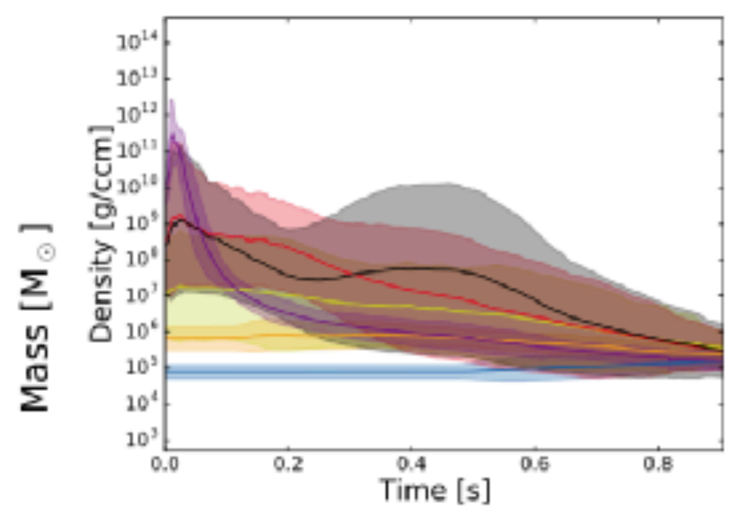


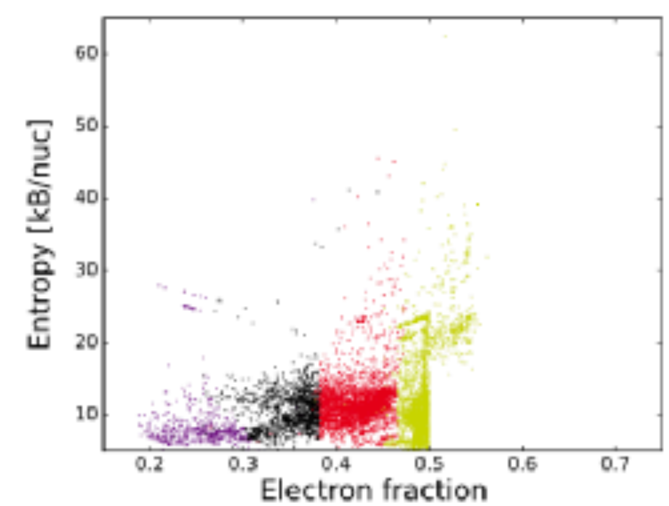
- 2nd r-process peak
- $T_{\max} \gtrsim 20\,\mathrm{G\,K}$
- $\rho_{\max} \gtrsim 10^9\,\mathrm{g\,/ccm}$
- $0.25 \lesssim Y_e \lesssim 0.38$

Nucleosynthesis patterns

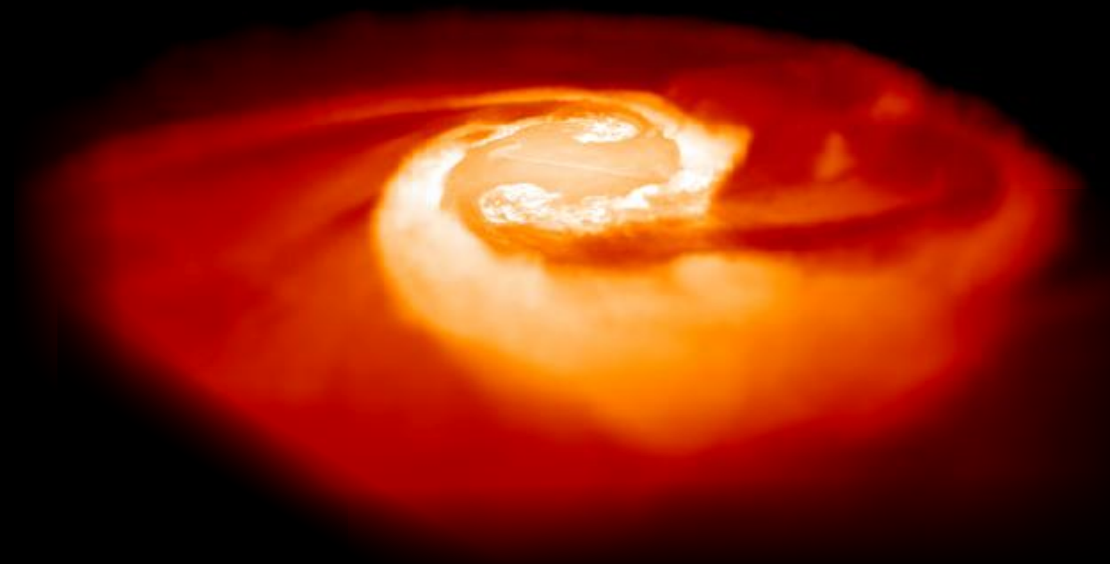








- 3rd r-process peak
- $T_{\max} \gtrsim 30\,\mathrm{G\,K}$
- $\rho_{\max} \gtrsim 10^{11}\,\mathrm{g\,/ccm}$
- $Y_e \lesssim 0.25$
- Steep gradients



R-process nucleosynthesis:
nuclear physics and astrophysics challenges

Astrophysics challenges

Microphysics in simulations: EoS, neutrino reactions

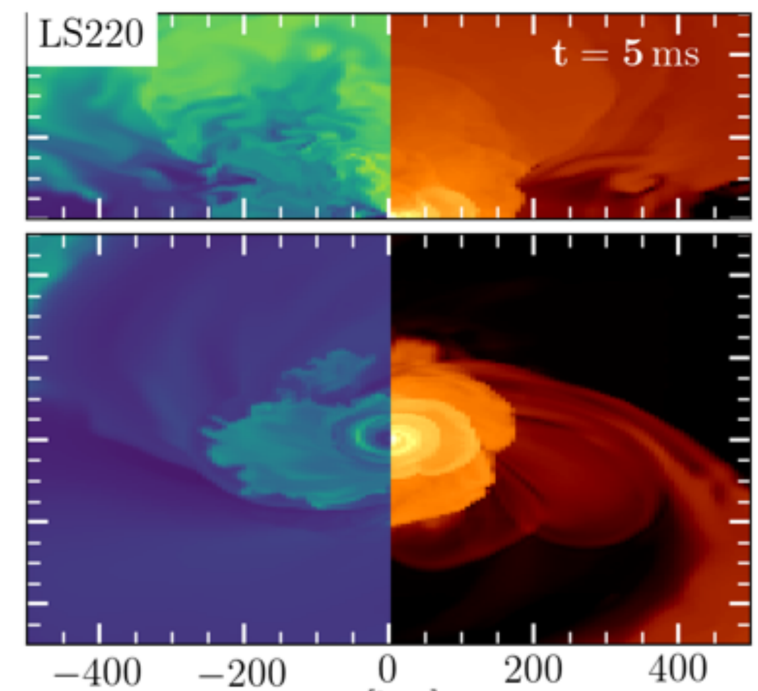
Neutrino transport

Magnetic fields

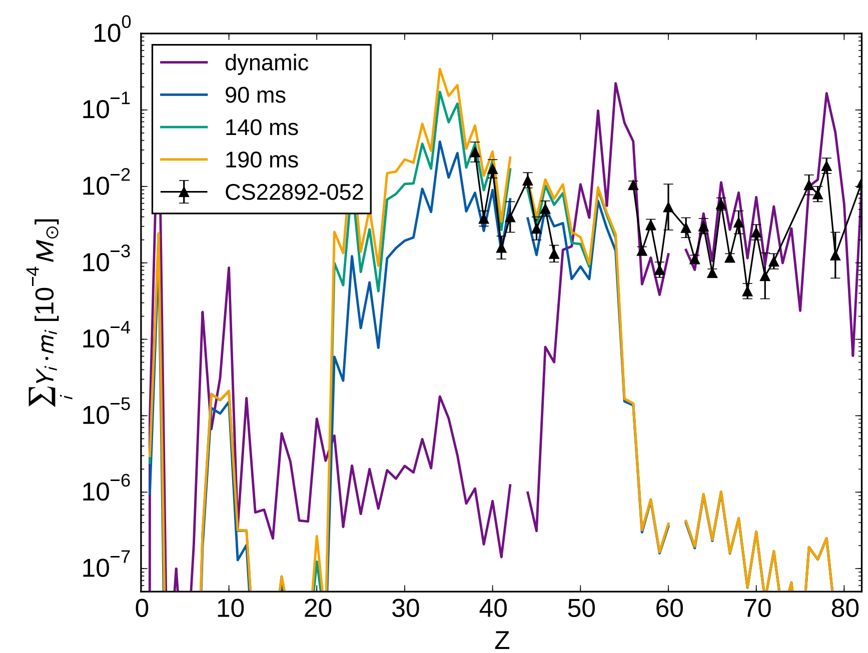
Long time simulations

Kilonova: transport, opacities

….



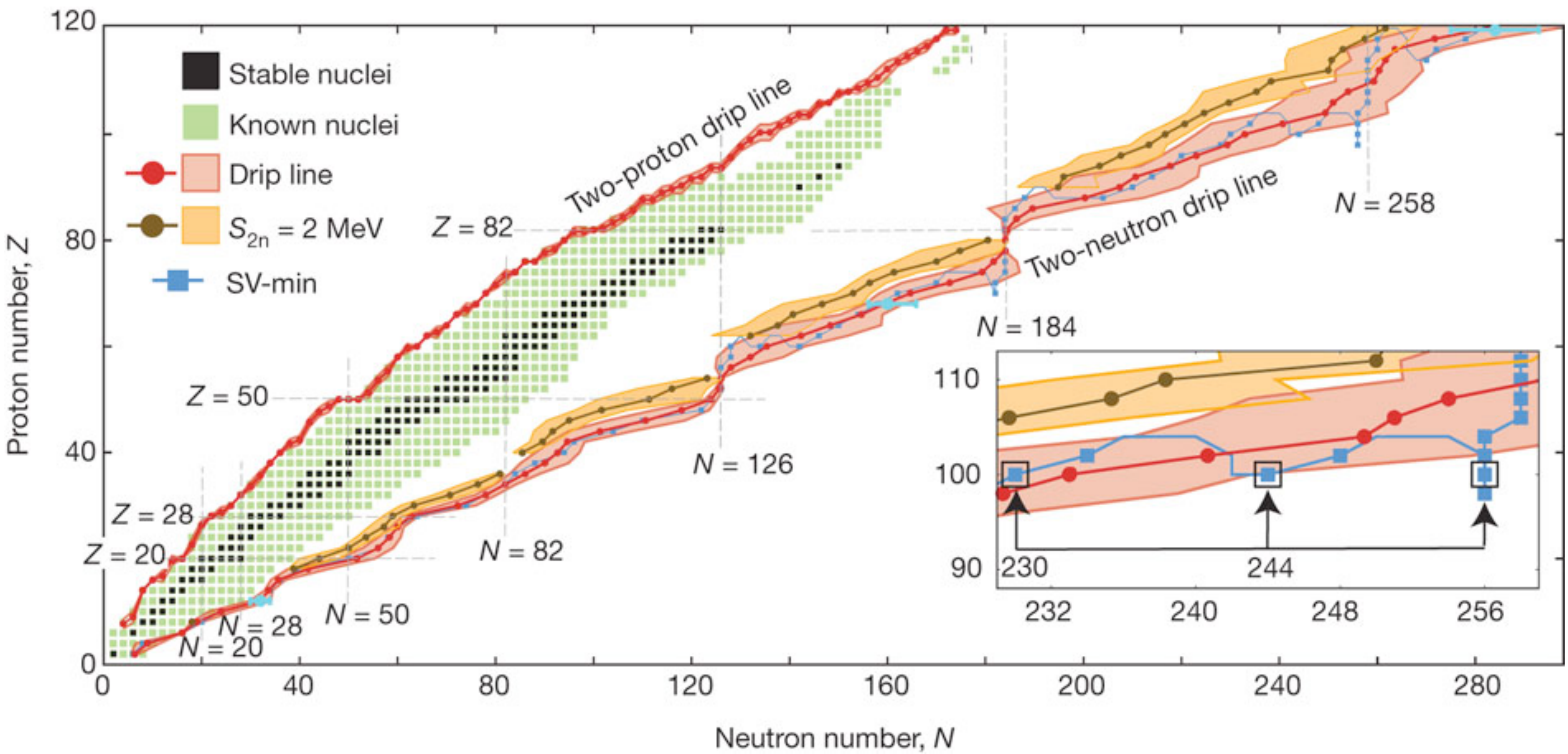
Observations: how many r-processes?



Chemical evolution: how many r-process sites?

Nuclear physics input

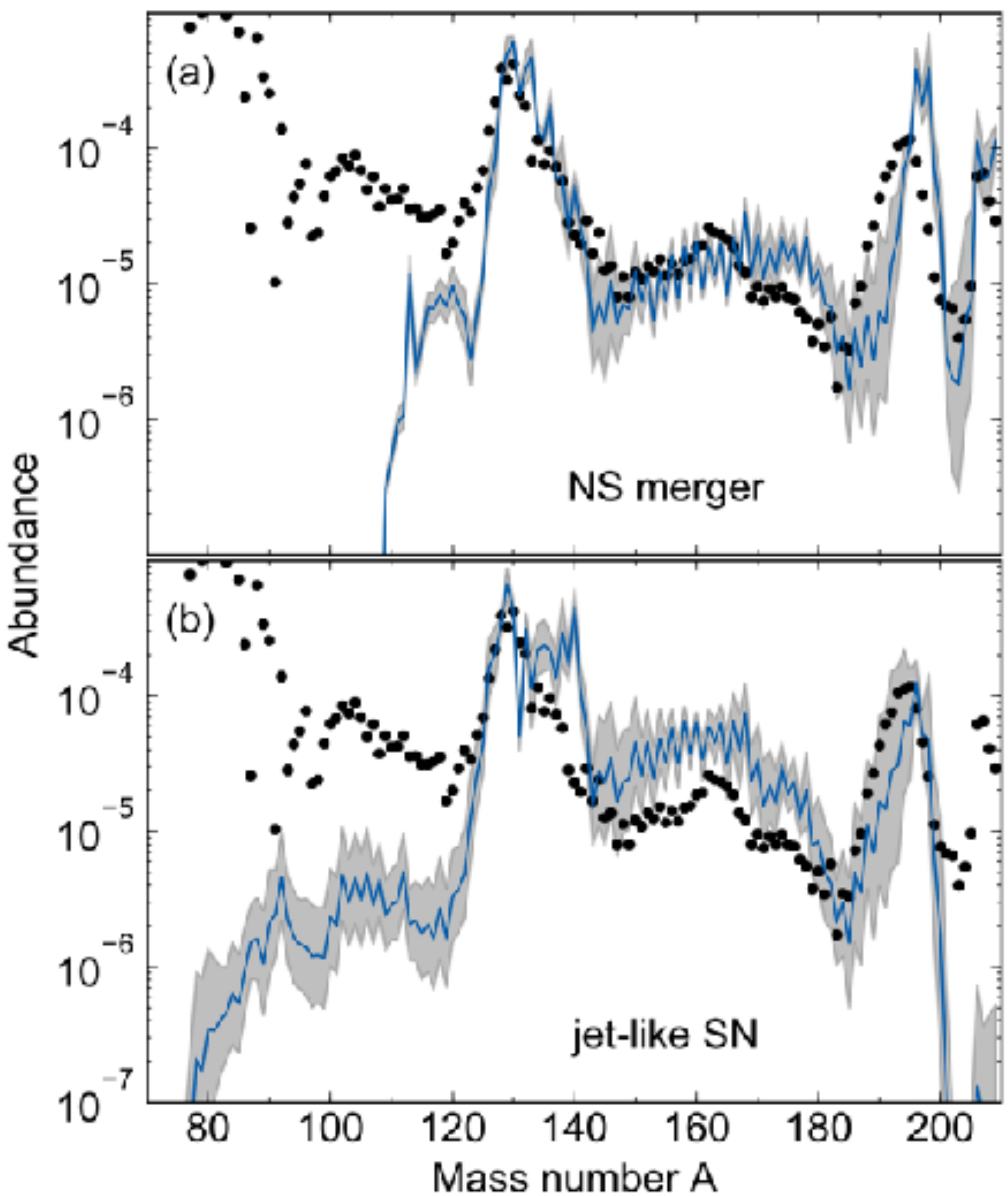
nuclear masses, beta decay, reaction rates (neutron capture), fission



Erler et al. (2012)

Nuclear masses

Abundances based on density functional theory
- six sets of different parametrisation (Erler et al. 2012)
- two realistic astrophysical scenarios: jet-like sn and neutron star mergers



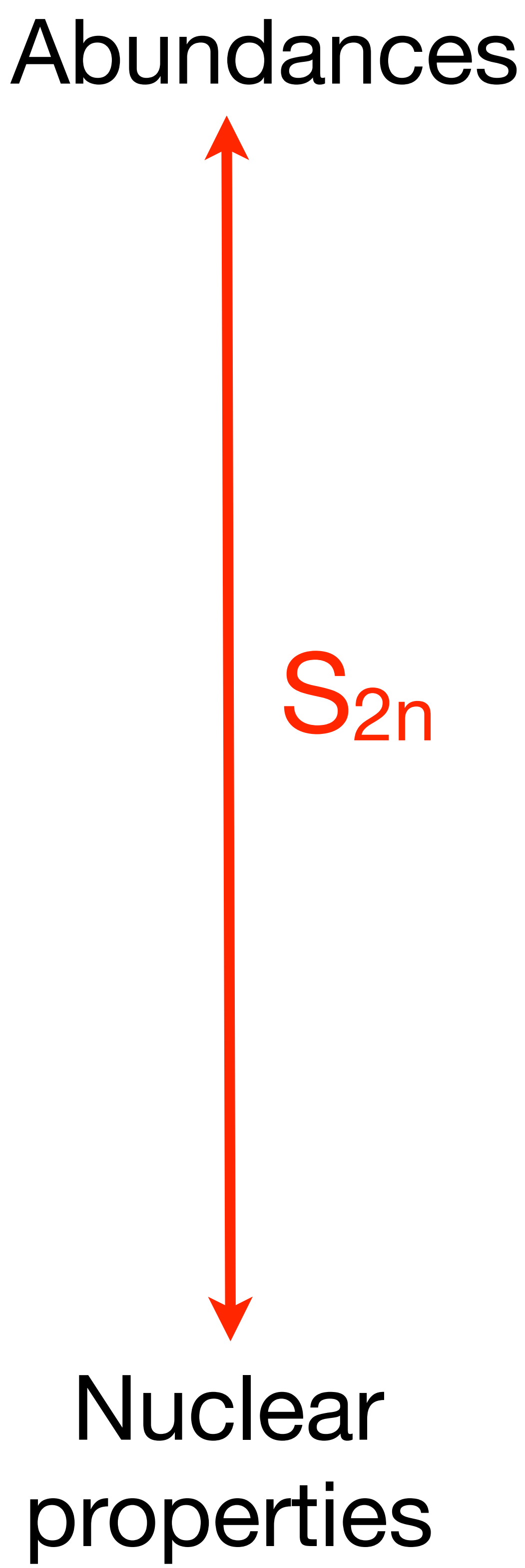
Martin, Arcones, Nazarewicz, Olsen (2016)

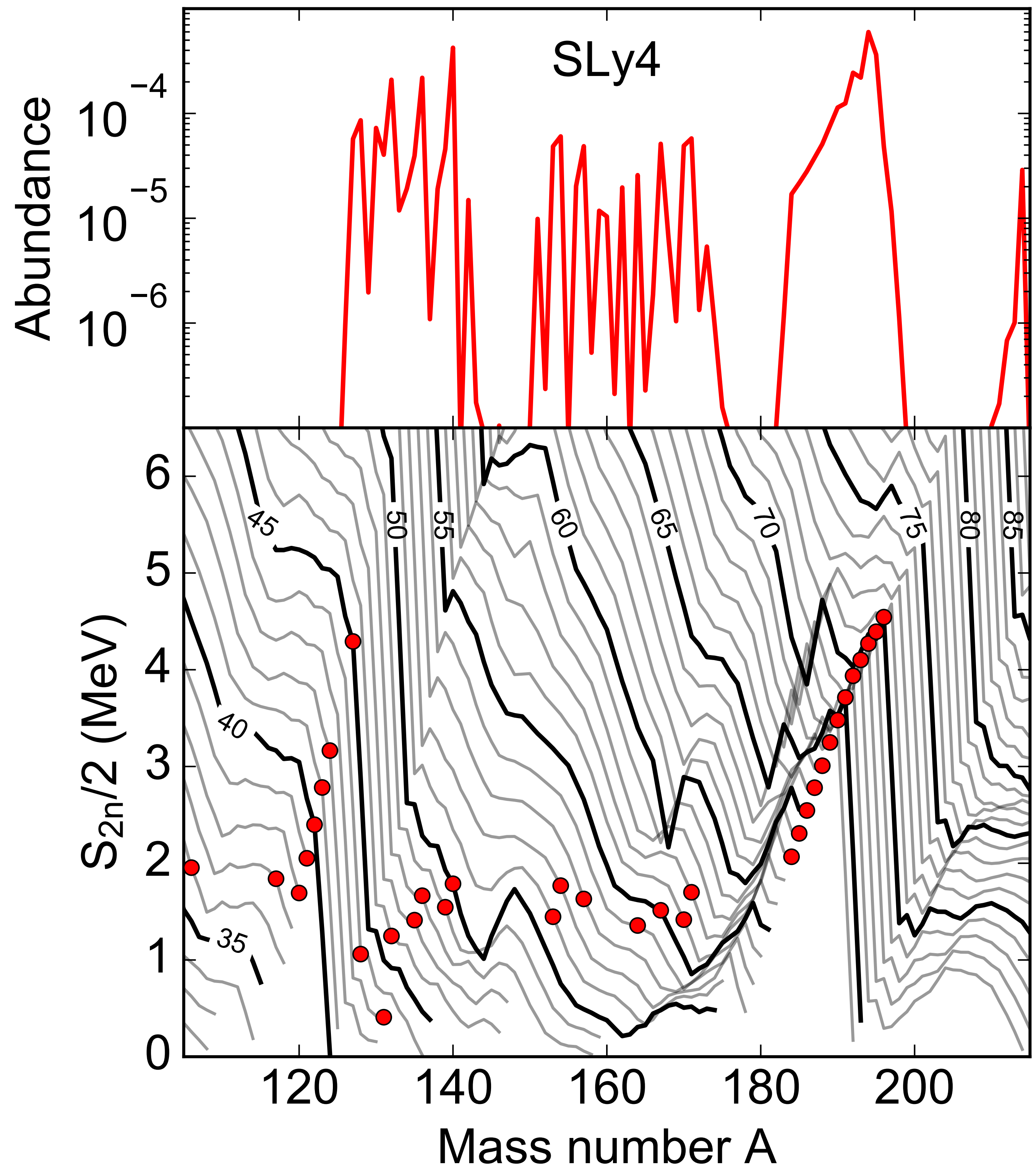
First systematic uncertainty band for r-process abundances

Uncertainty band depends on A, in contrast to homogeneous band for all A
e.g., Mumpower et al. 2015

Can we link masses to r-process abundances?

Two neutron separation energy: abundances



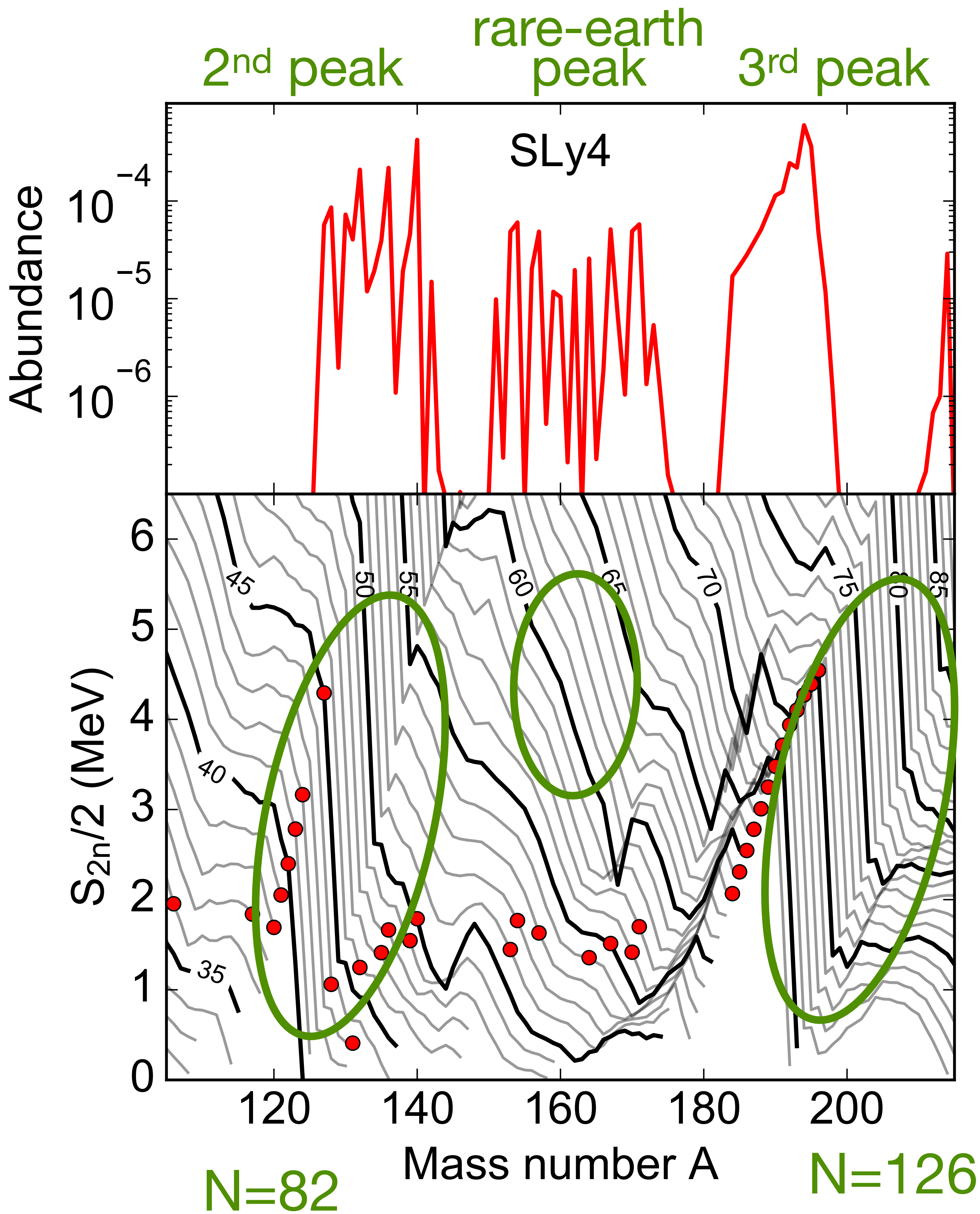


Two neutron separation energy: abundances

Abundances

S_{2n}

Nuclear properties

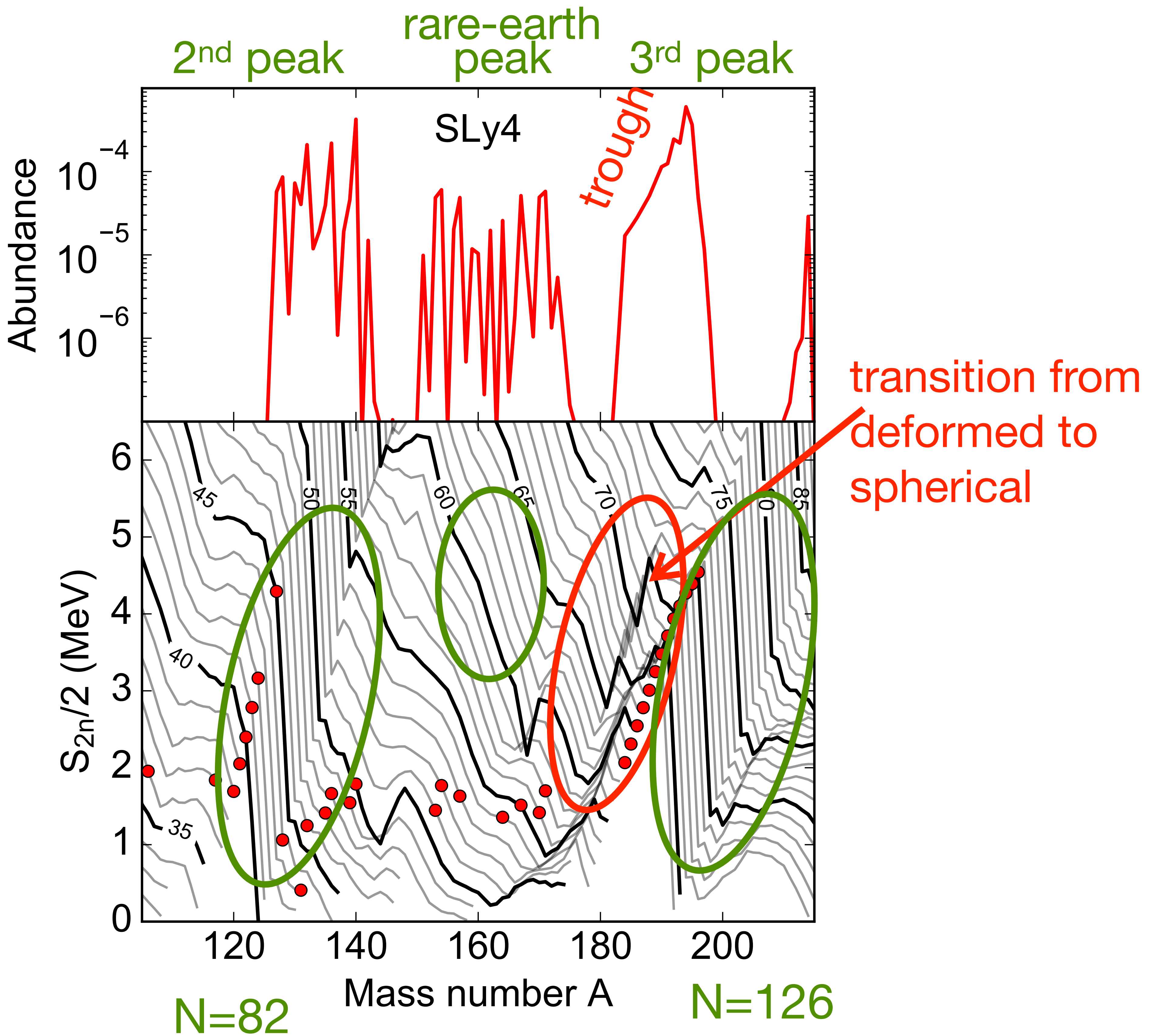


Two neutron separation energy: abundances

Abundances

S_{2n}

Nuclear properties

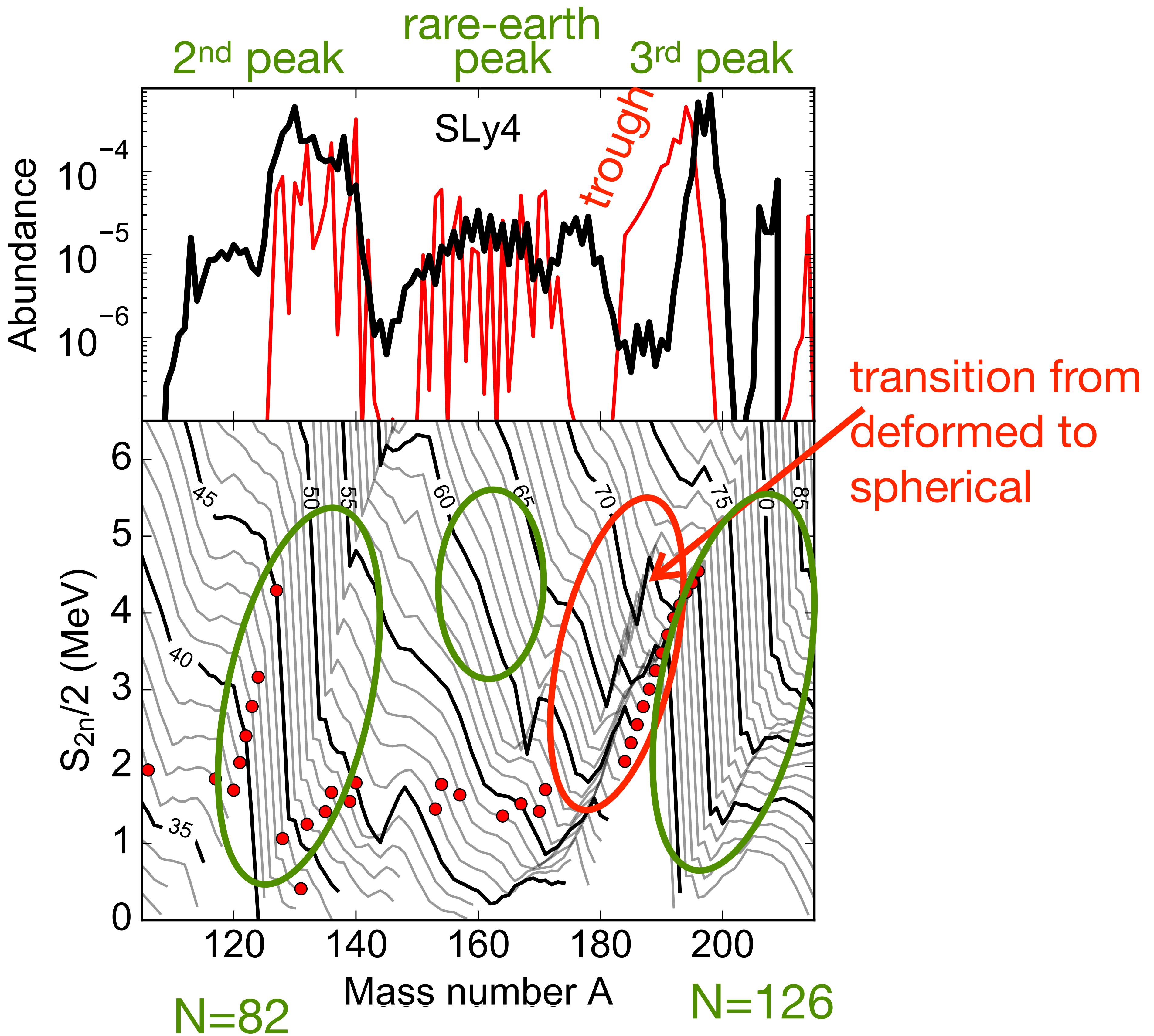


Two neutron separation energy: abundances

Abundances

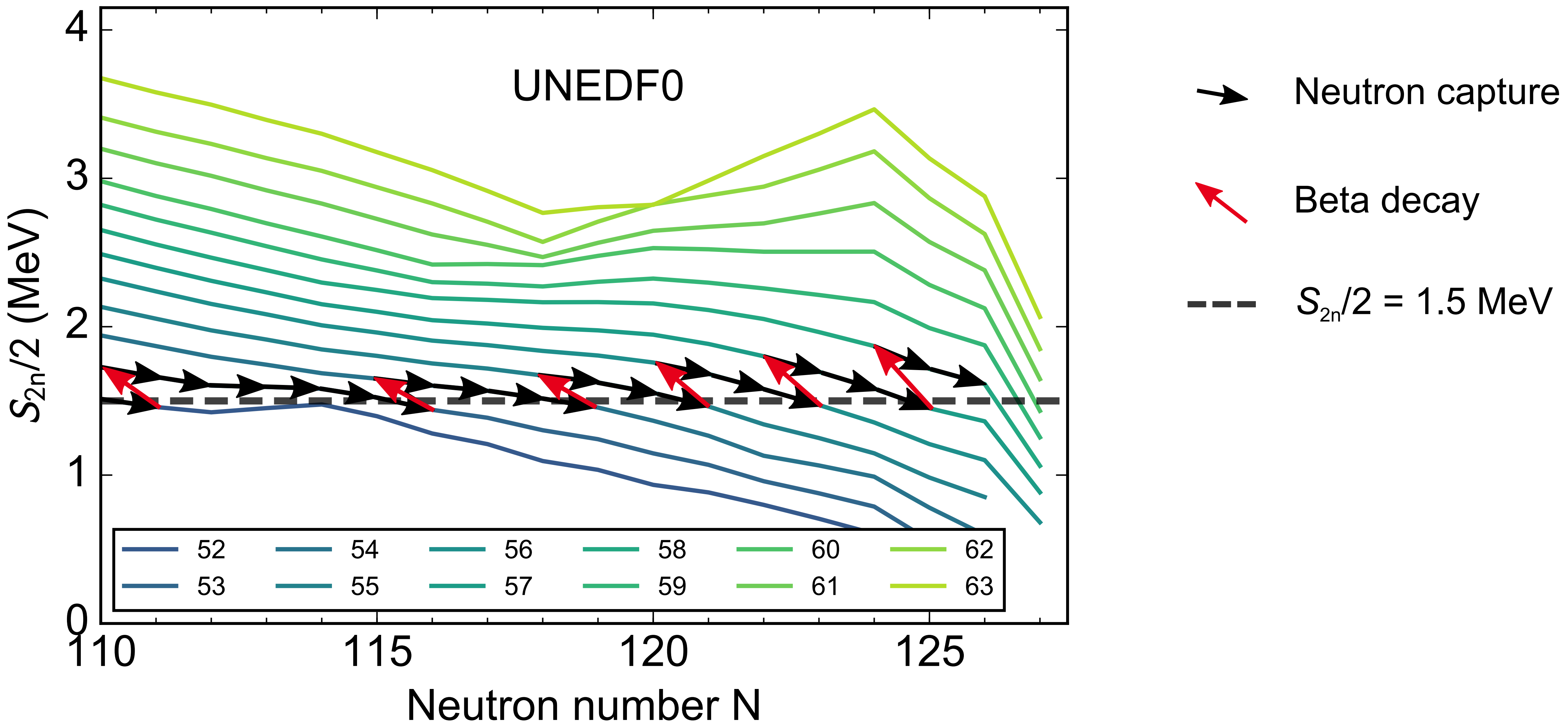
S_{2n}

Nuclear properties



Two neutron separation energy

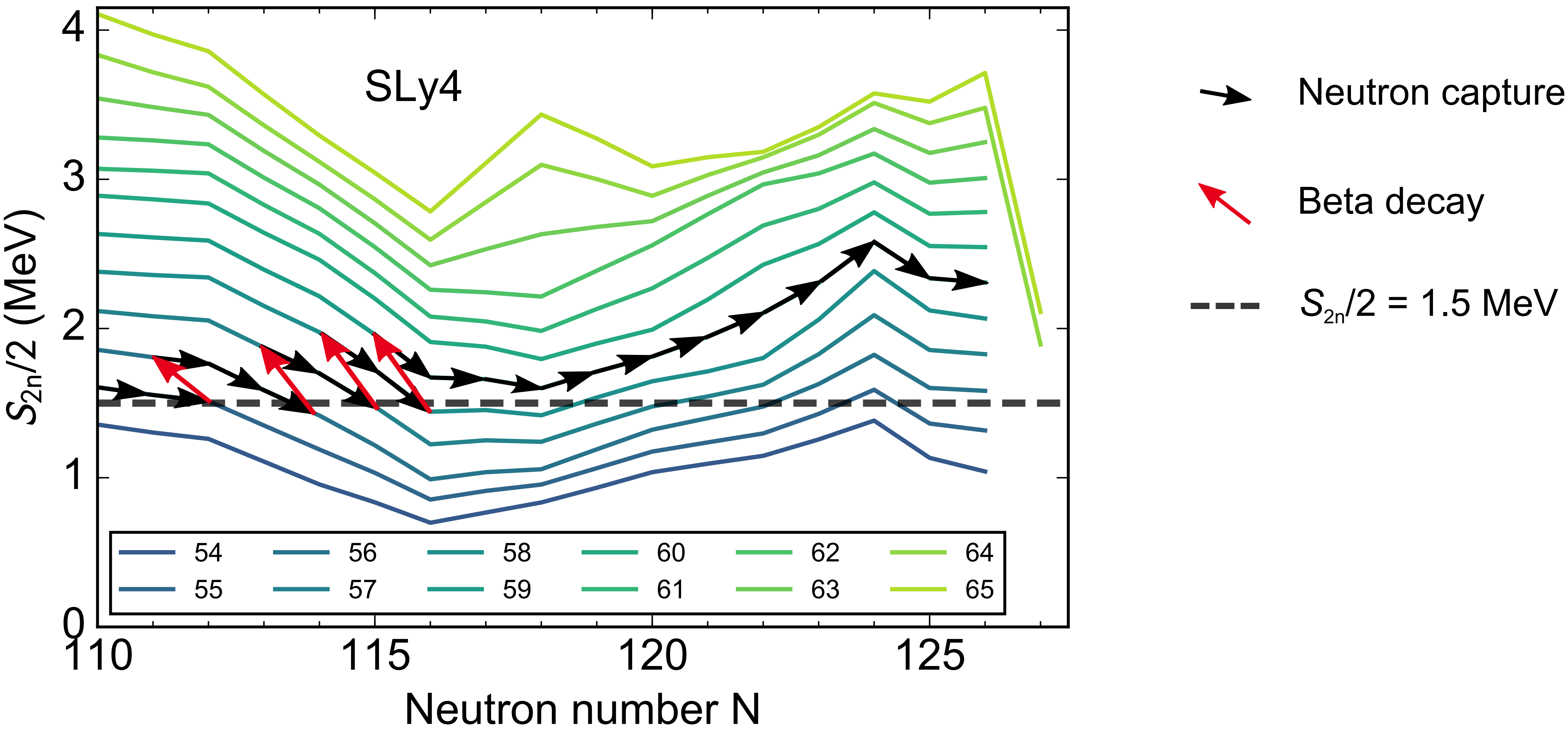
Nucleosynthesis path at constant S_n: (n,γ)-(γ,n) equilibrium



Martin, Arcones, Nazarewicz, Olsen (2016)

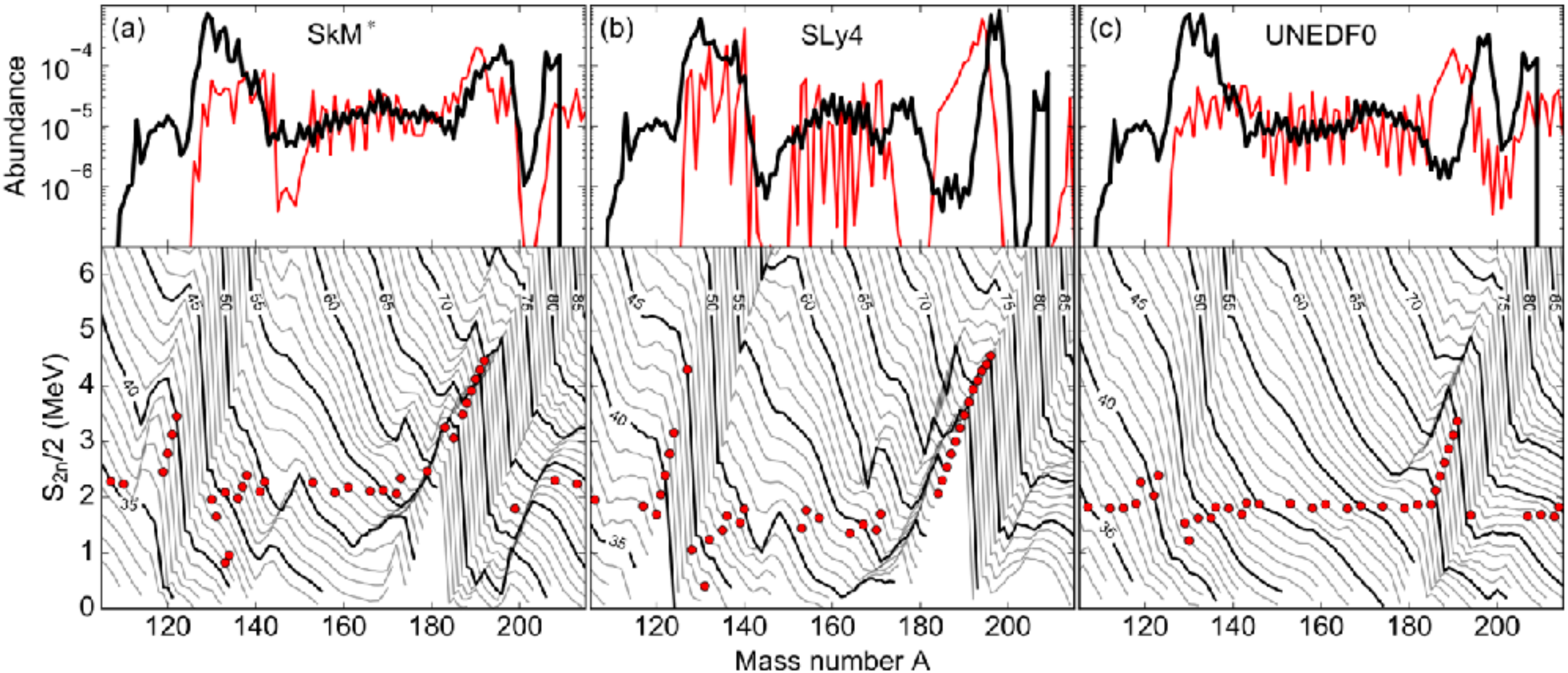
Two neutron separation energy

Nucleosynthesis path at constant S_n: (n,γ)-(γ,n) equilibrium



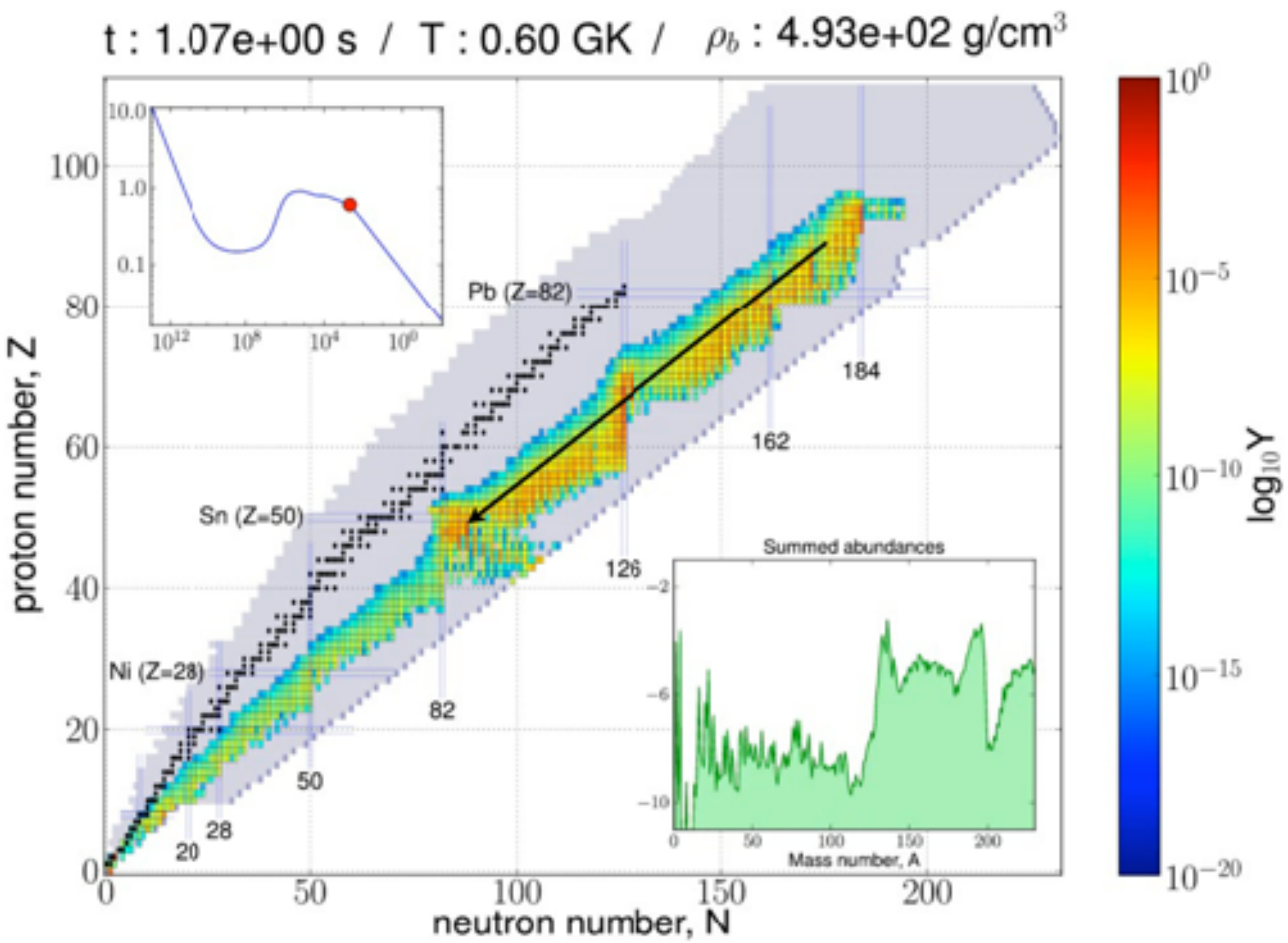
Martin, Arcones, Nazarewicz, Olsen (2016)

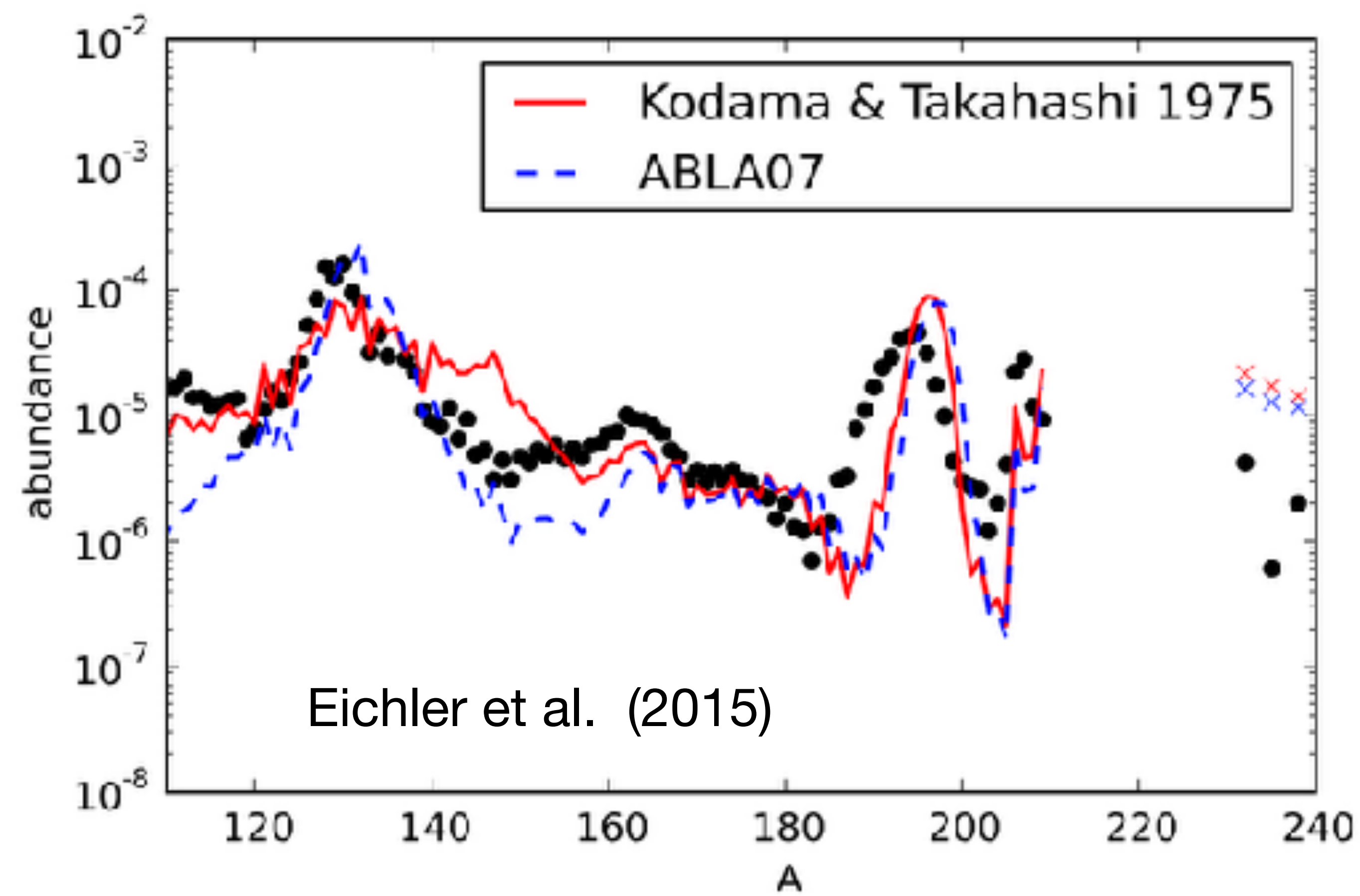
Two neutron separation energy: abundances



Martin, Arcones, Nazarewicz, Olsen (2016)

Fission: barriers and yield distributions

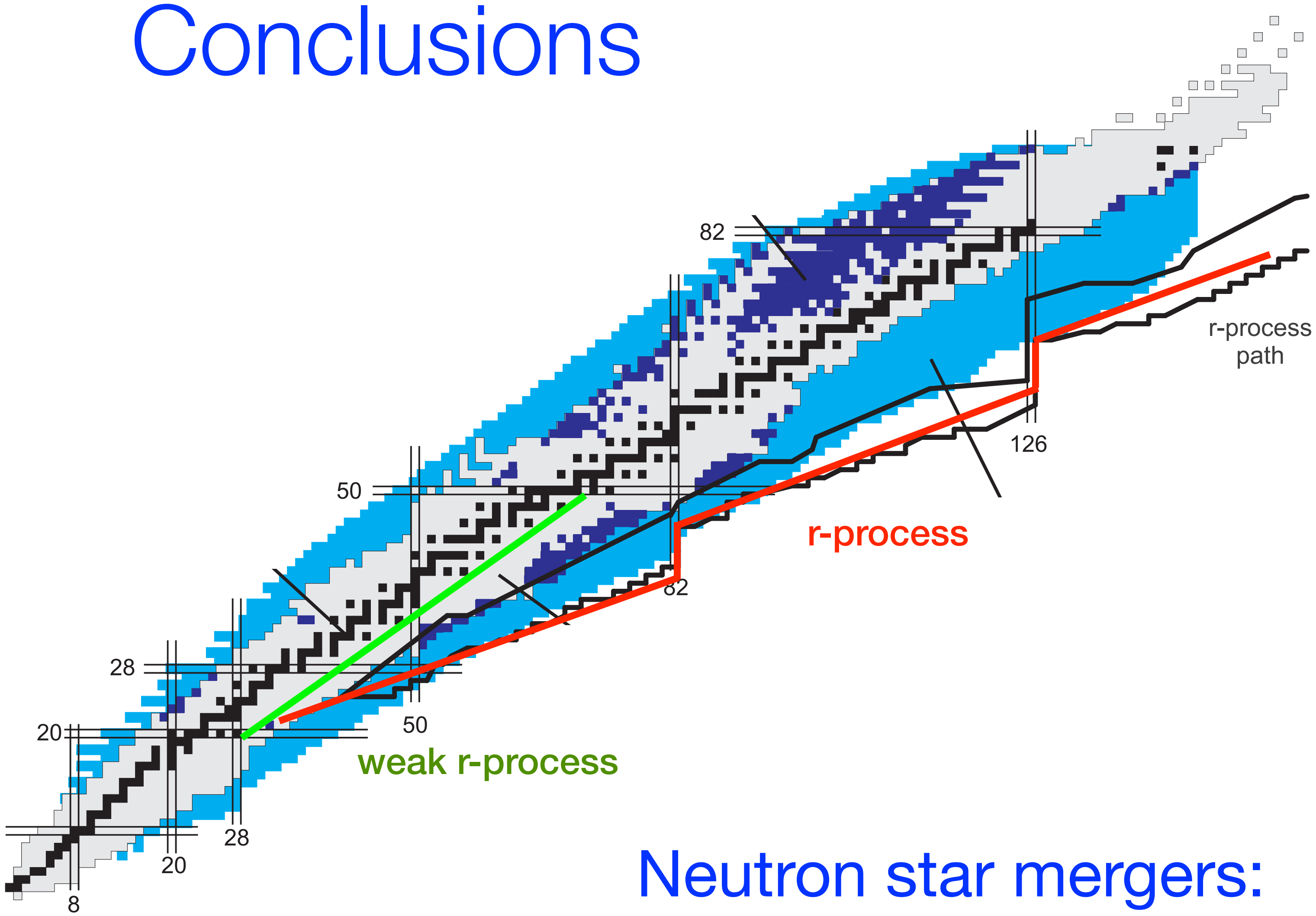




Neutron star mergers: r-process with two fission descriptions

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

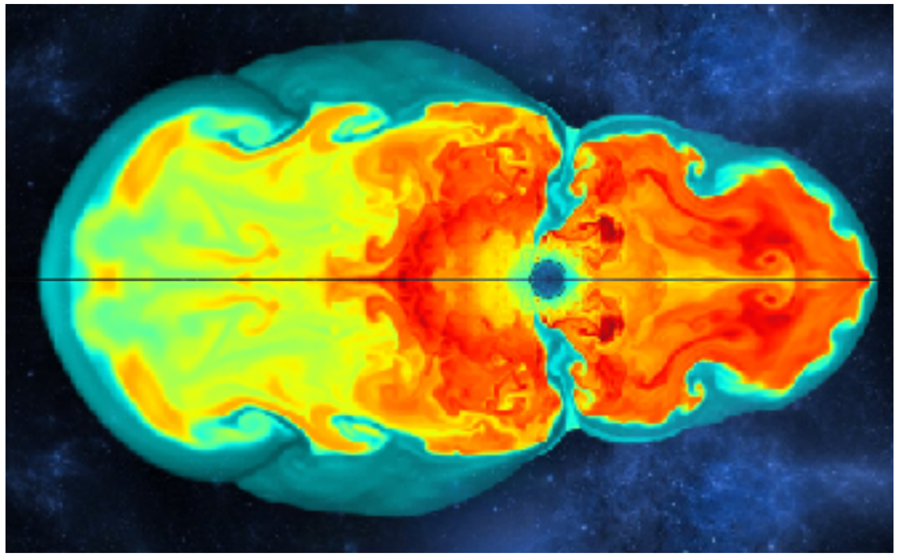
Conclusions



Core-collapse supernovae:

wind: up to ~Ag

Magneto-rot.: r-process

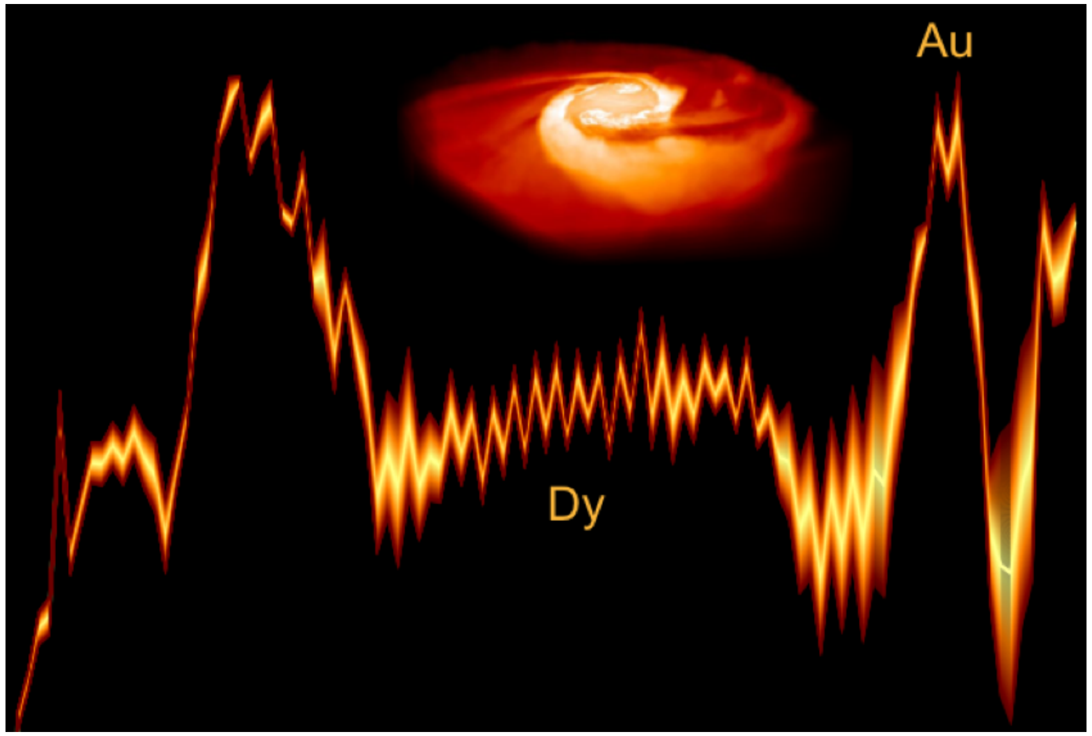


Neutron star mergers:

r-process

weak r-process

Kilonova



Impact of nuclear physics and astrophysics

Observations to constrain astrophysics