

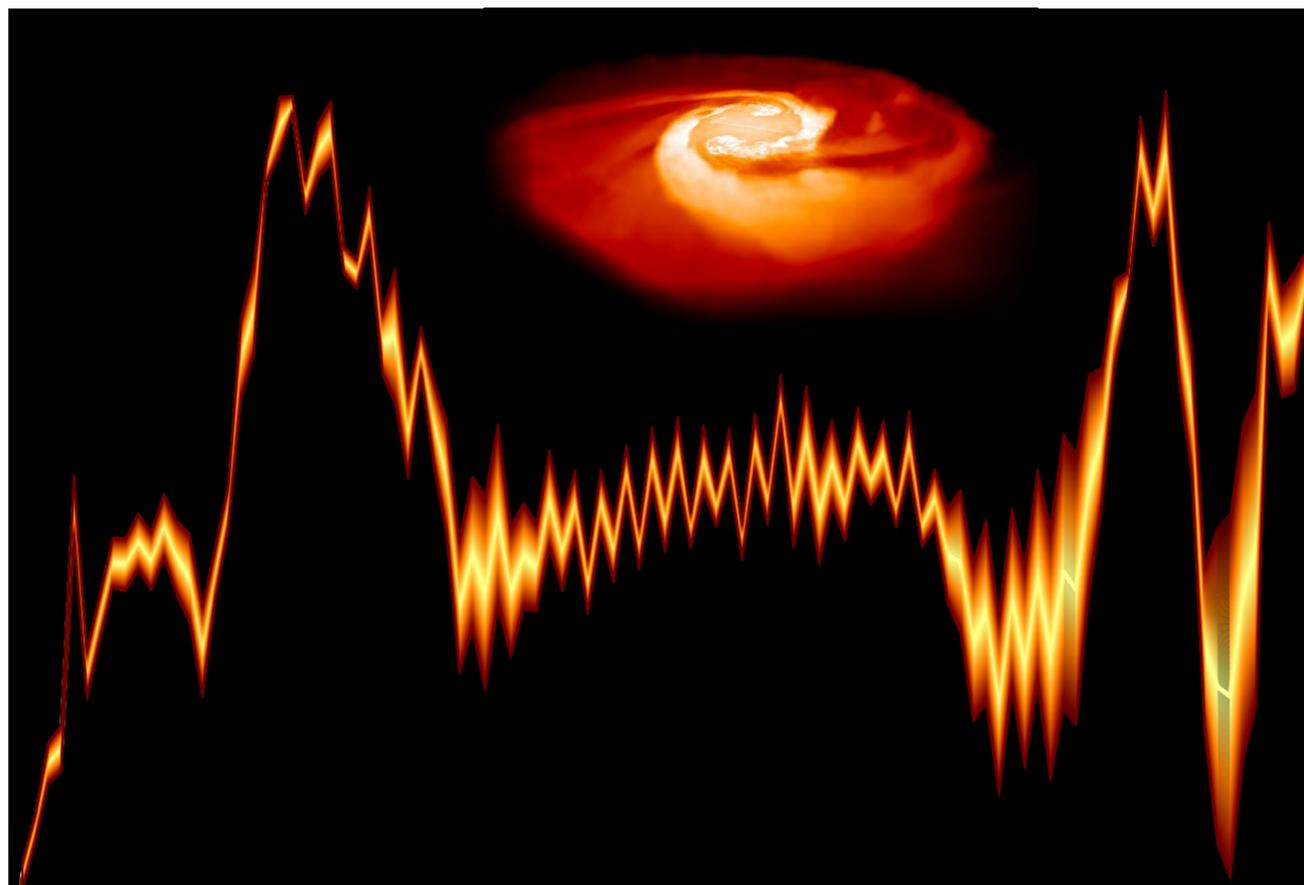


Theory Alliance
FACILITY FOR RARE ISOTOPE BEAMS

Topical Program:
FRIB and the
GW170817
kilonova

16-27 July 2018
NSCL/FRIB at MSU
US/Deutscher Sommer

The r-process in supernovae and neutron star mergers



Almudena Arcones



European Research Council
Funded by the European Commission

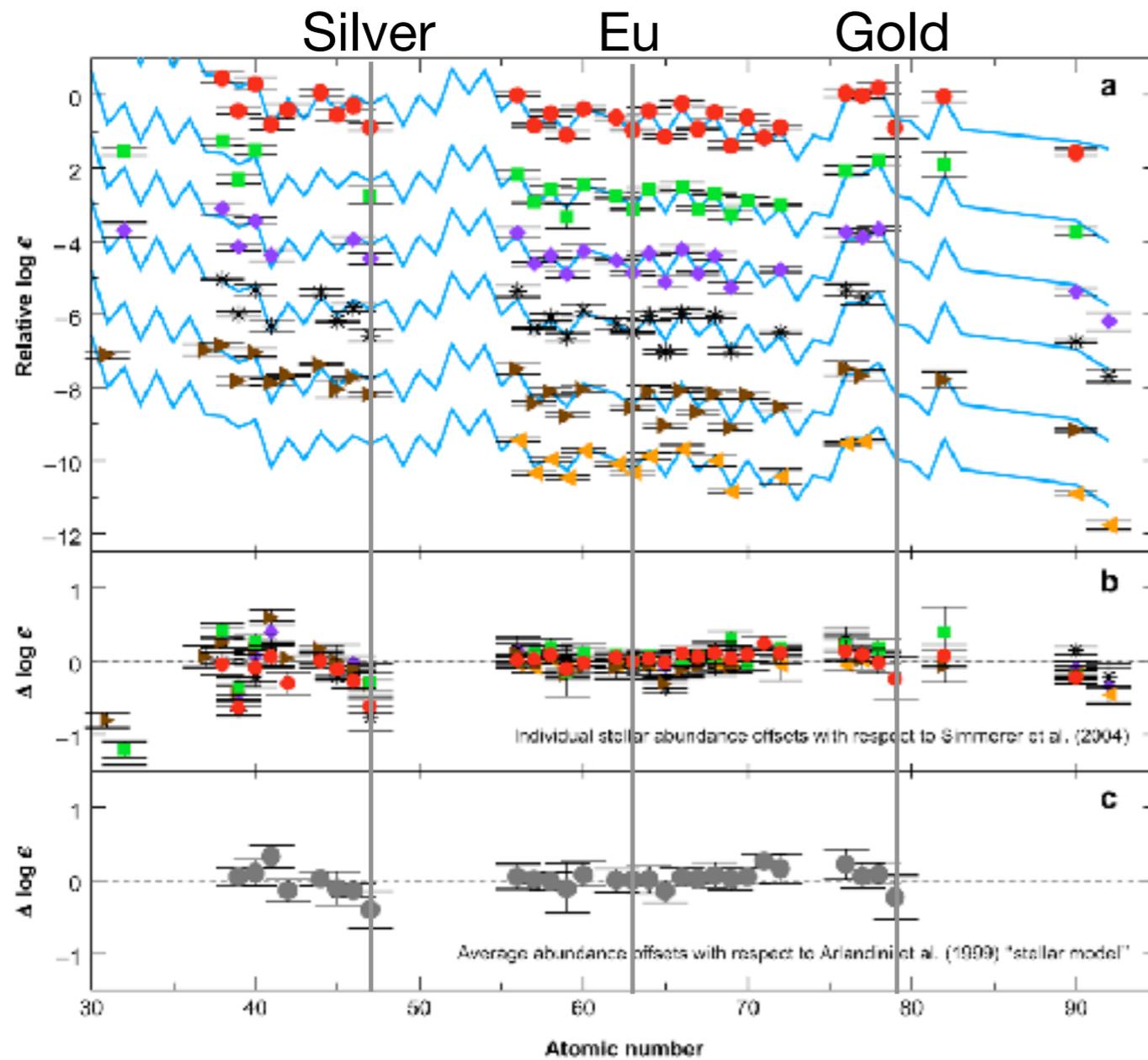


TECHNISCHE
UNIVERSITÄT
DARMSTADT



Bundesministerium
für Bildung
und Forschung

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)

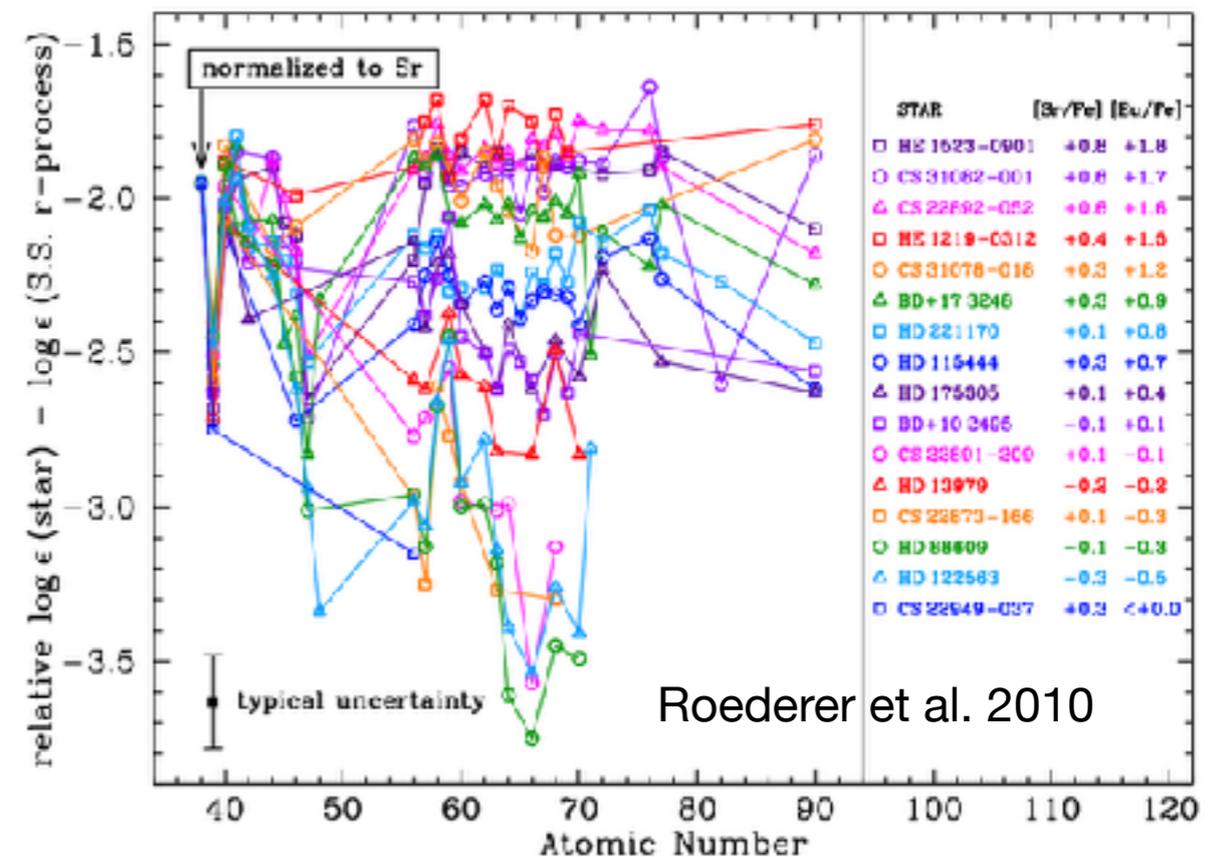
$$\log(\epsilon(E)) = \log(N_E/N_H) + 12$$

Sneden, Cowan, Gallino 2008

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

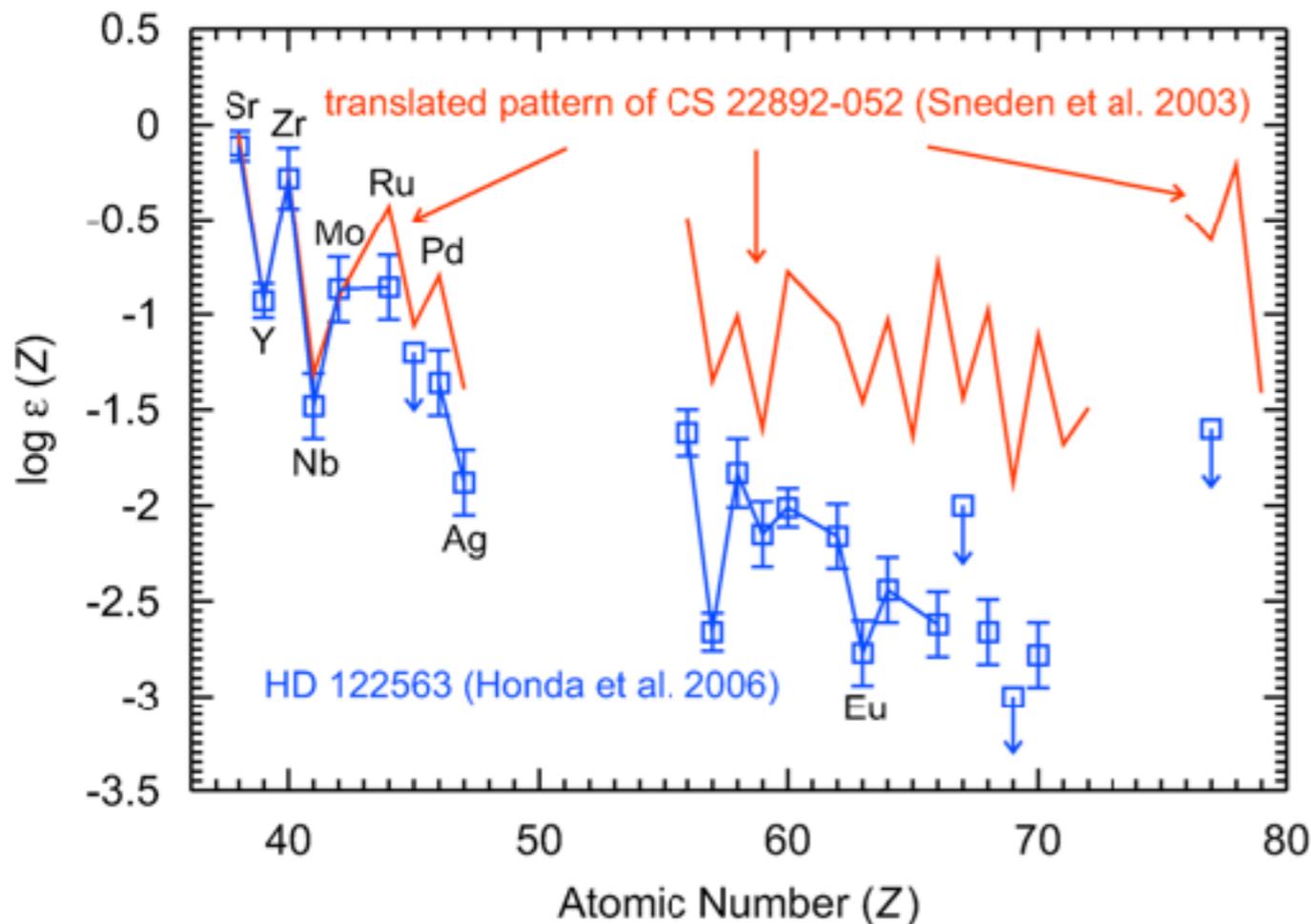
Robust r-process for $56 < Z < 83$

Scatter for lighter heavy elements, $Z \sim 40$

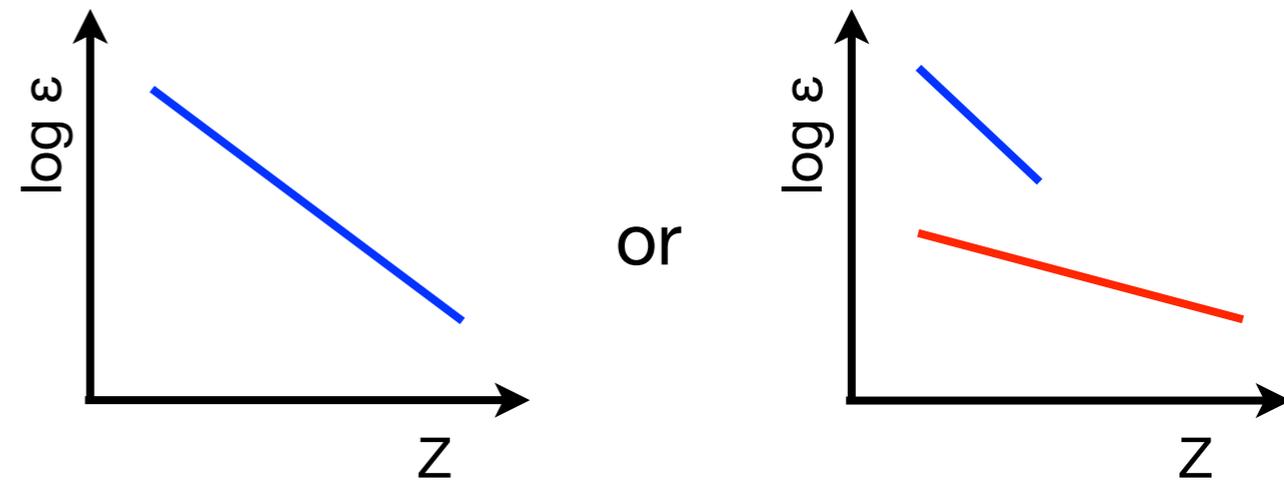


Lighter heavy elements: Sr - Ag

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?

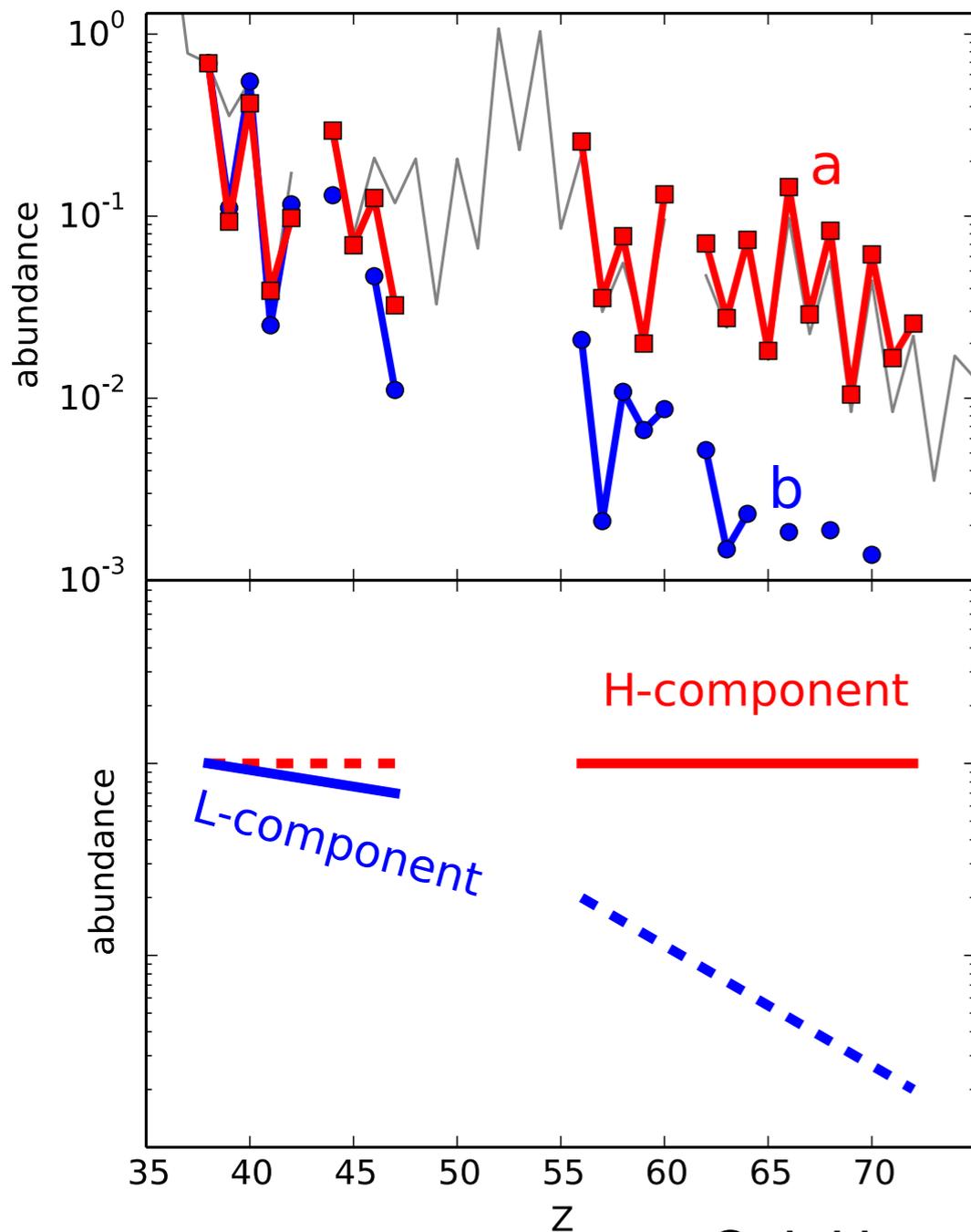


Honda-like = limited r-process

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

Nucleosynthesis components

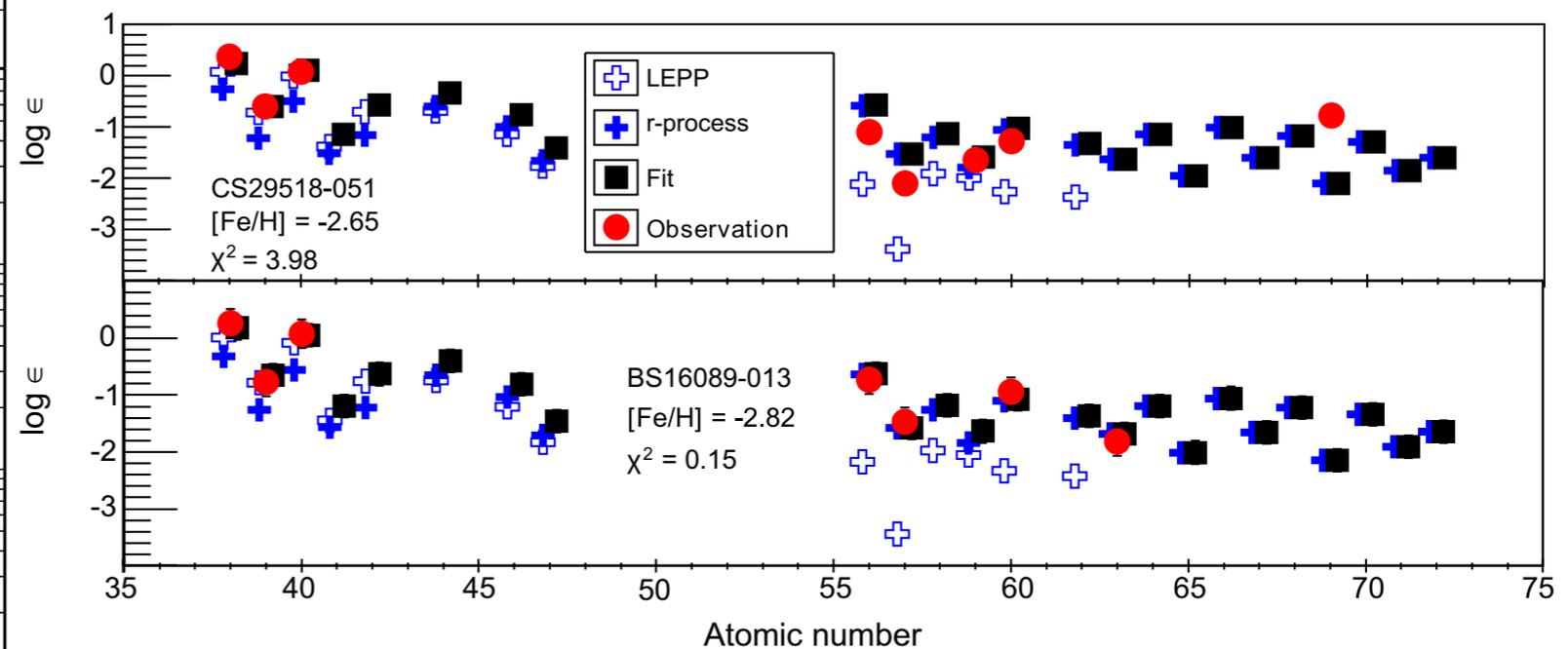
Abundance of many UMP stars can be explained by two components:



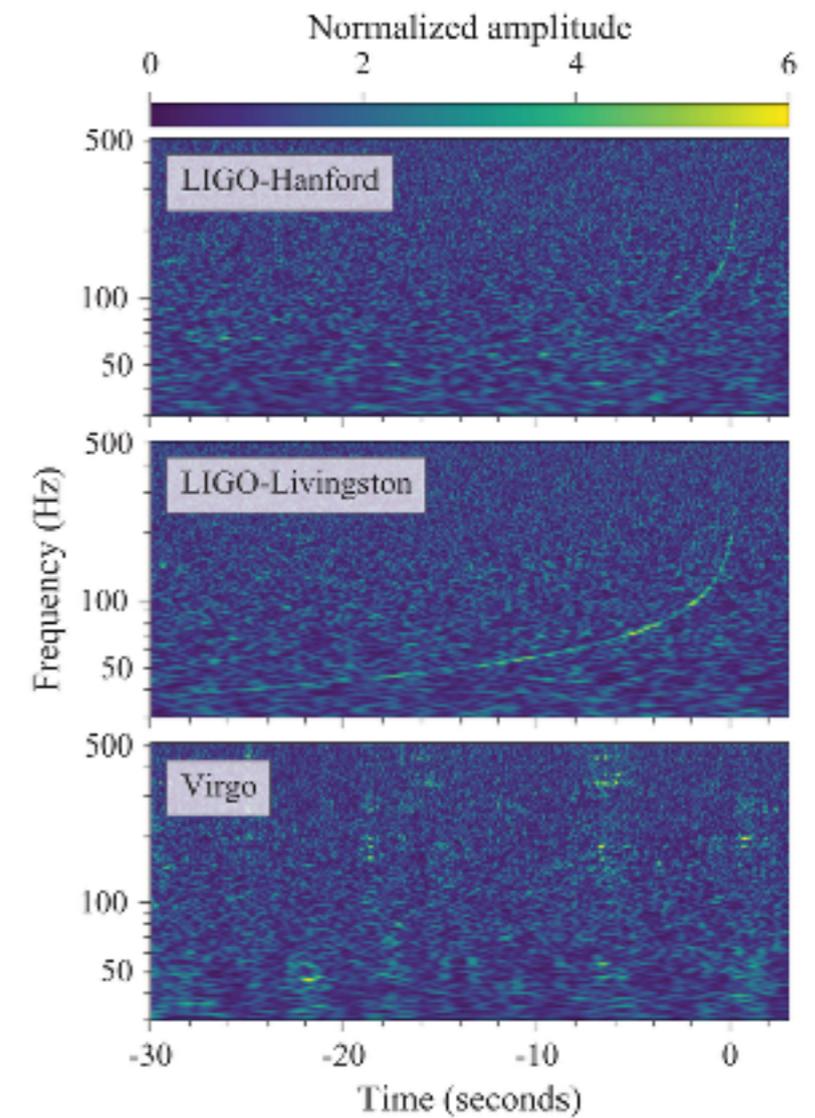
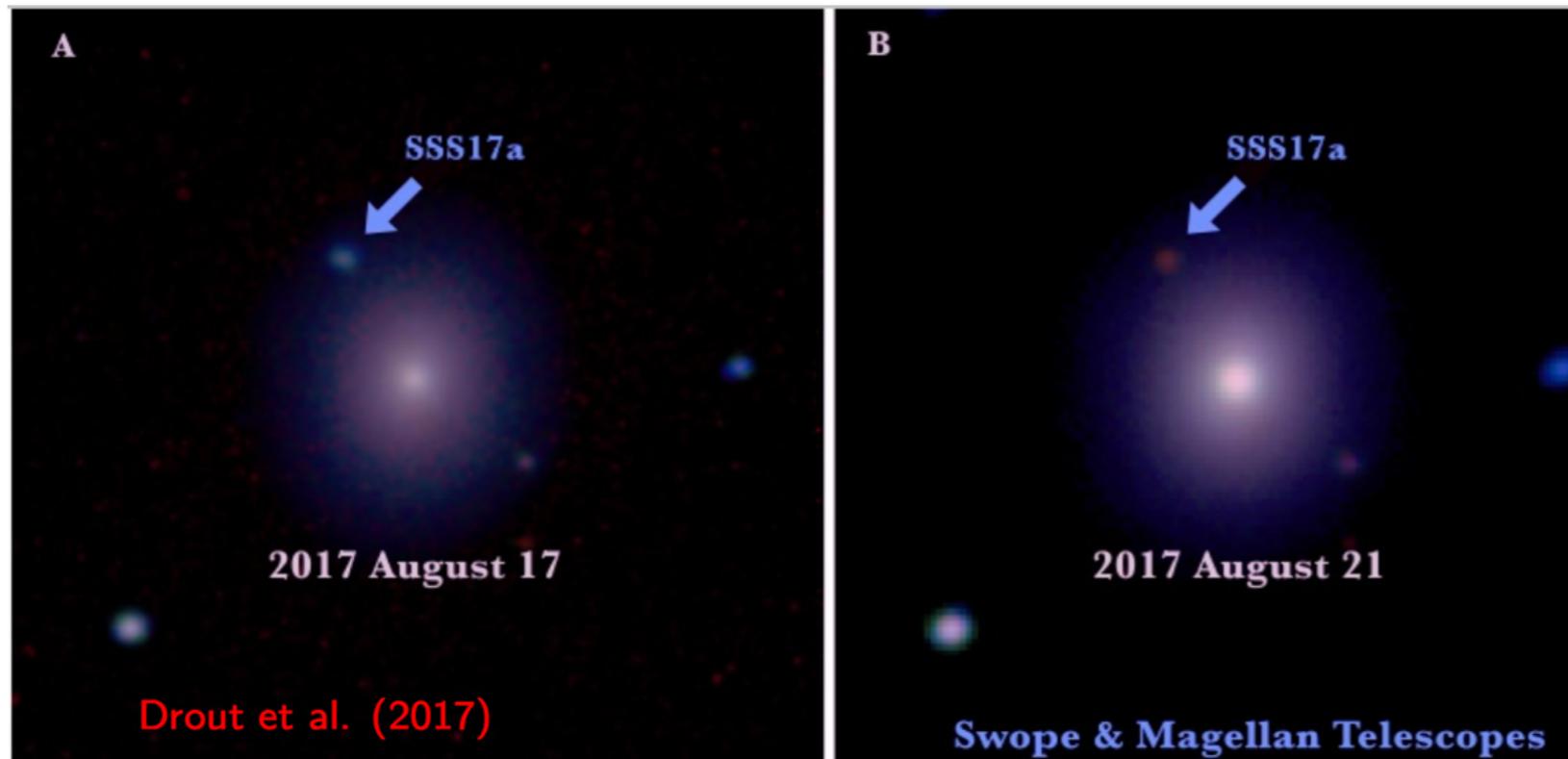
Component abundance pattern: Y_H and Y_L

Fit abundance as combination of components:

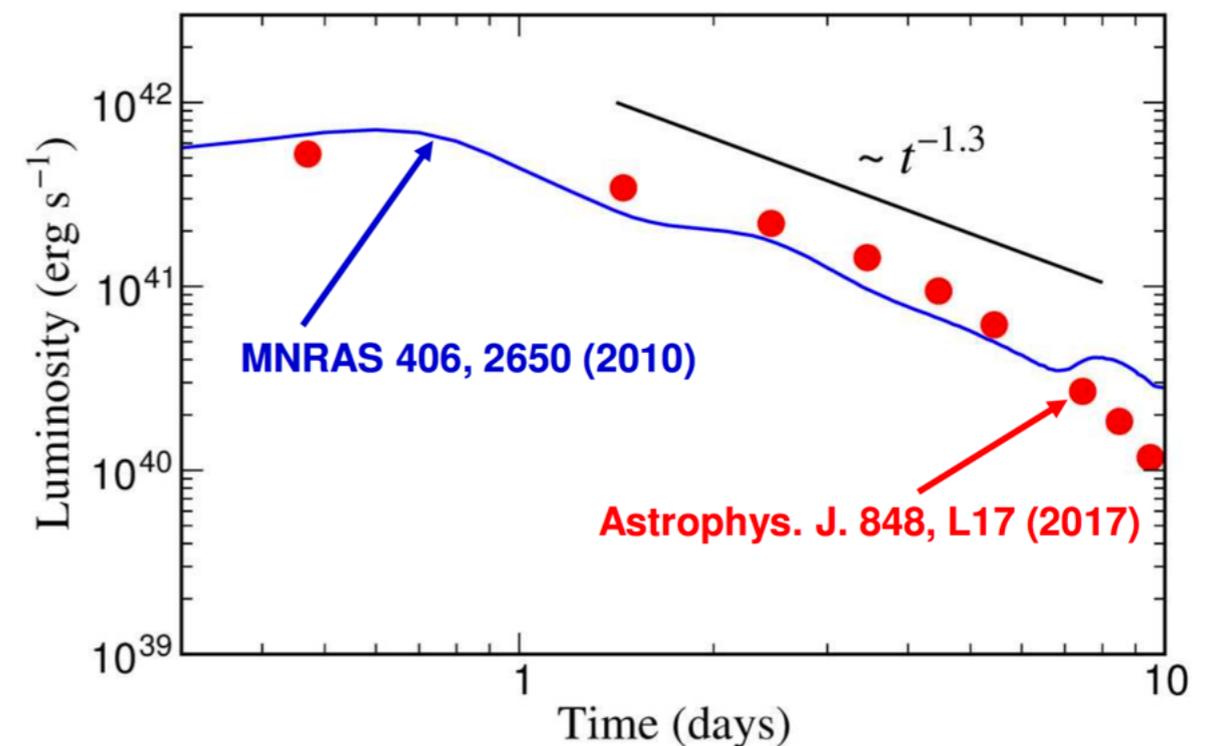
$$Y_{\text{calc}}(Z) = (C_H Y_H(Z) + C_L Y_L(Z)) \cdot 10^{[\text{Fe}/\text{H}]}$$



Neutron star mergers

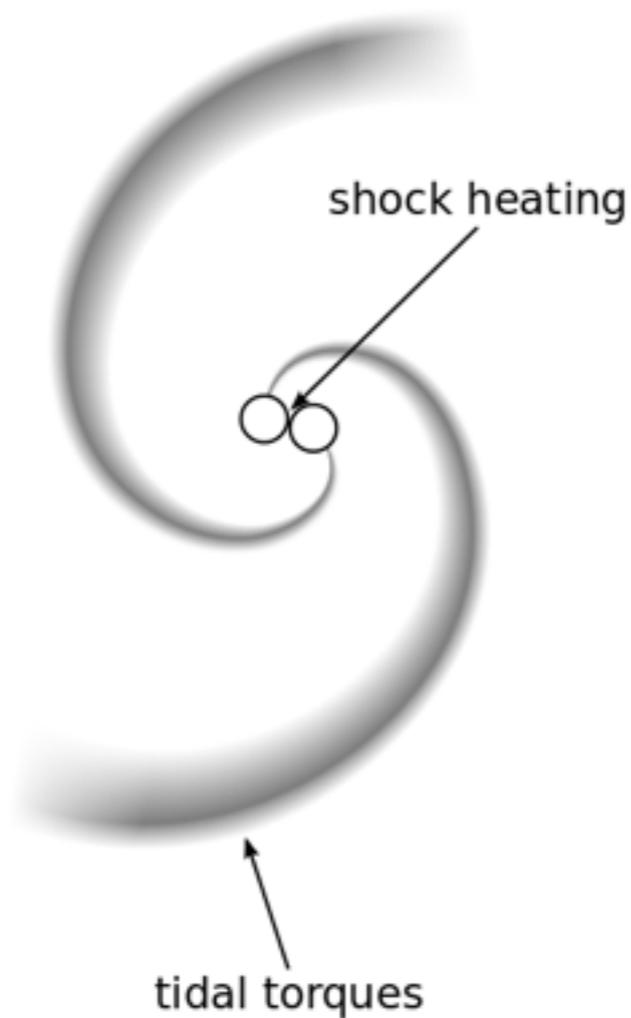


R-process in neutron star mergers confirmed by kilonova (radioactive decay of n-rich nuclei) after gravitational wave detection from GW170817

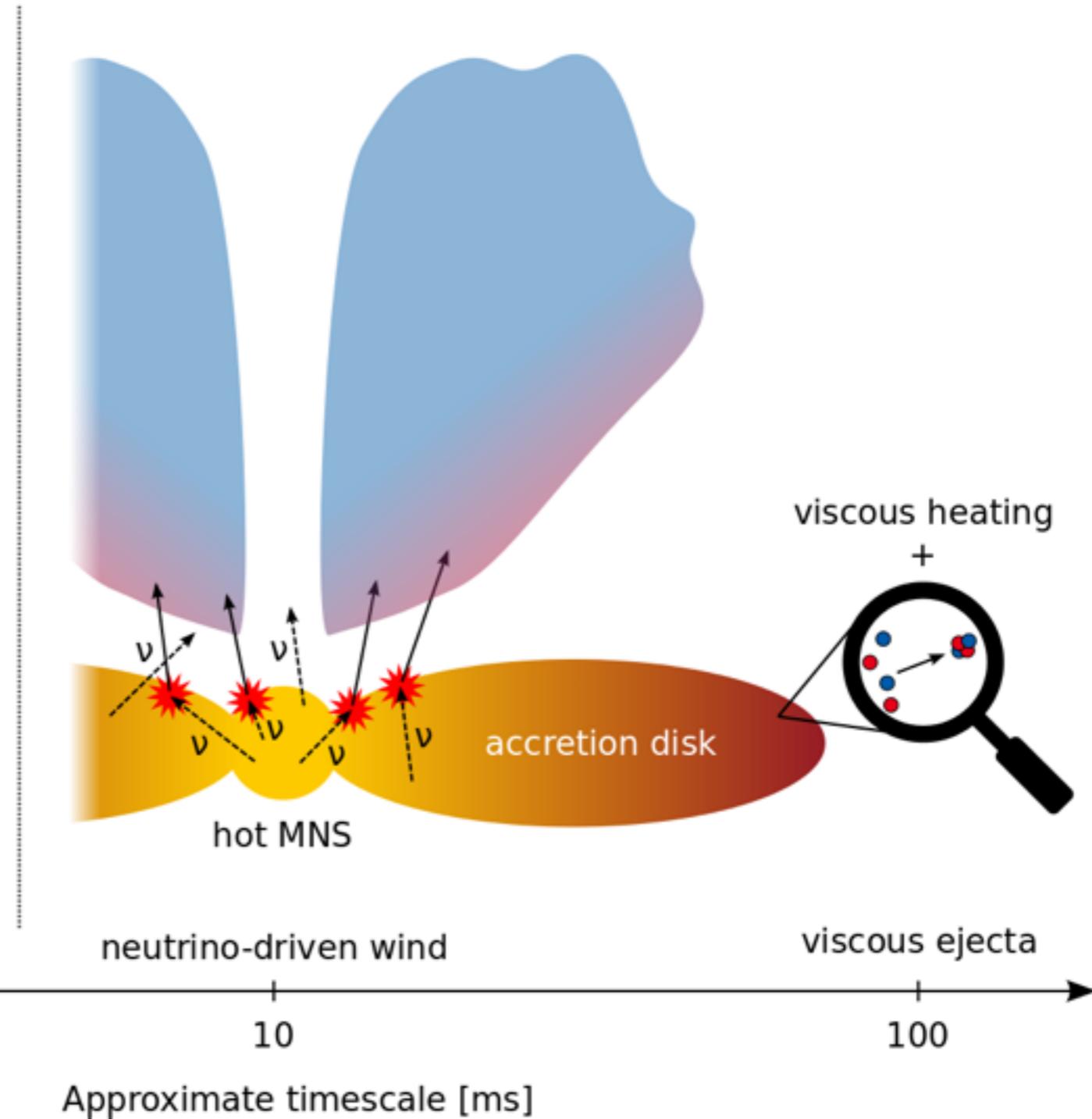


Ejecta and nucleosynthesis

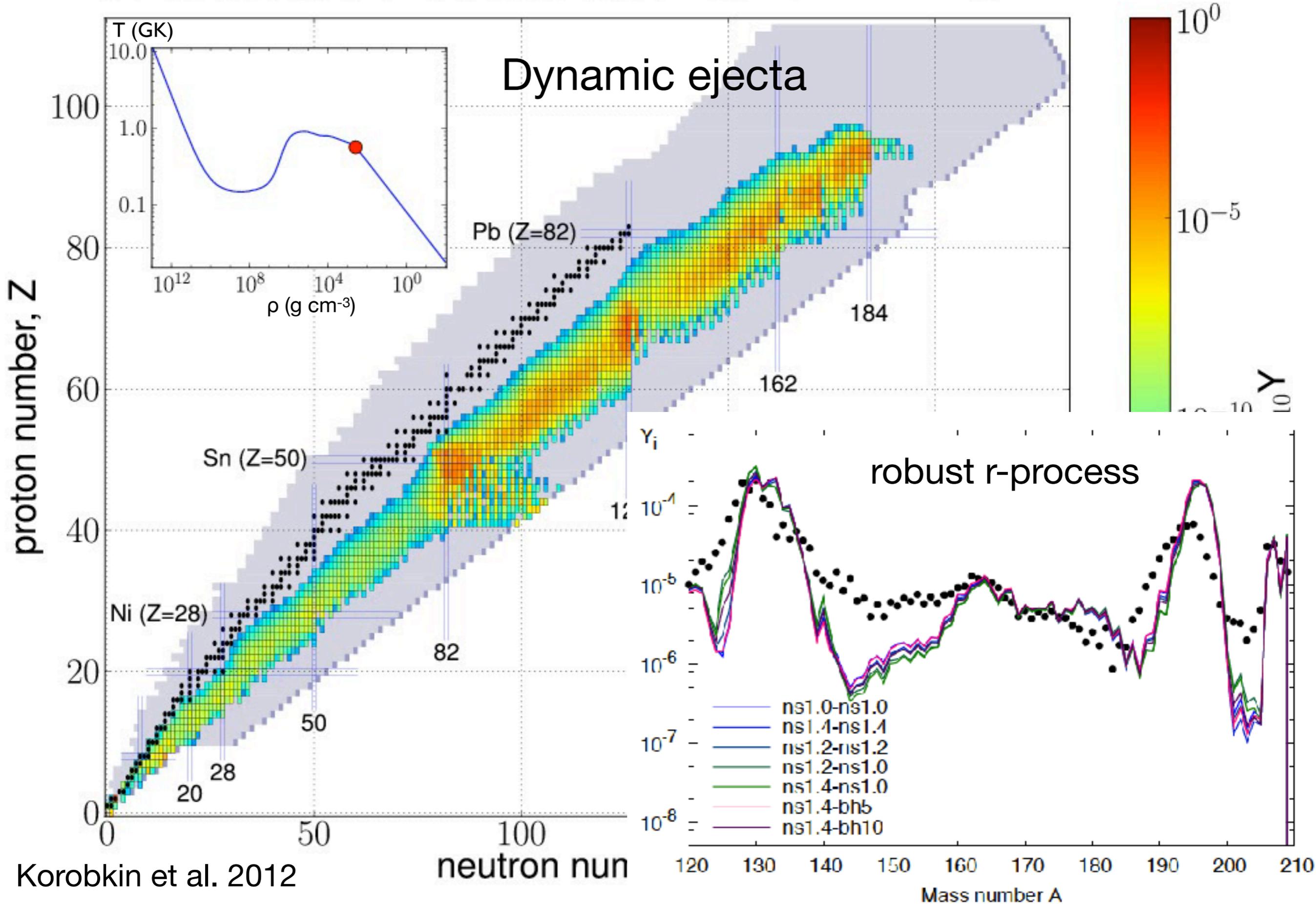
Top view:



Side view:

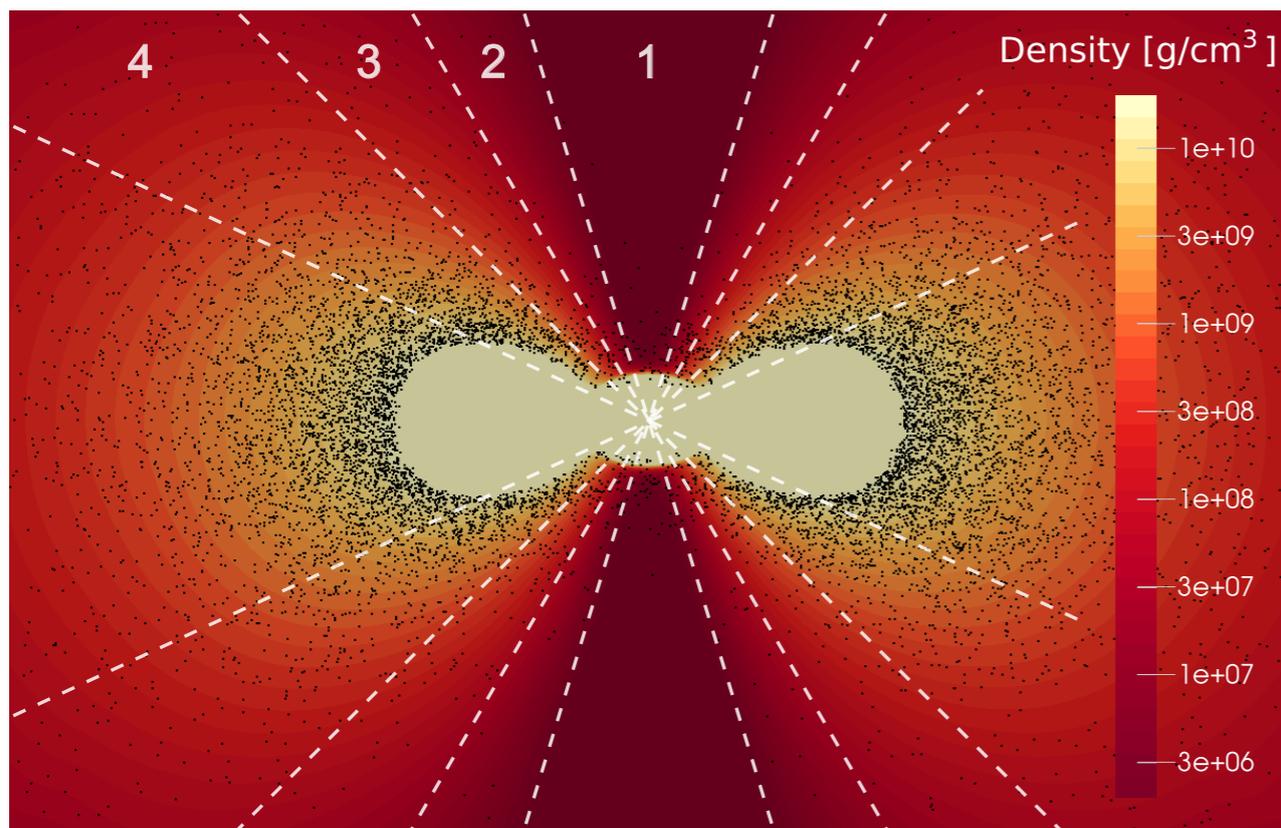


$t : 1.15e+00 \text{ s} / T : 0.56 \text{ GK} / \rho_b : 3.98e+02 \text{ g/cm}^3$

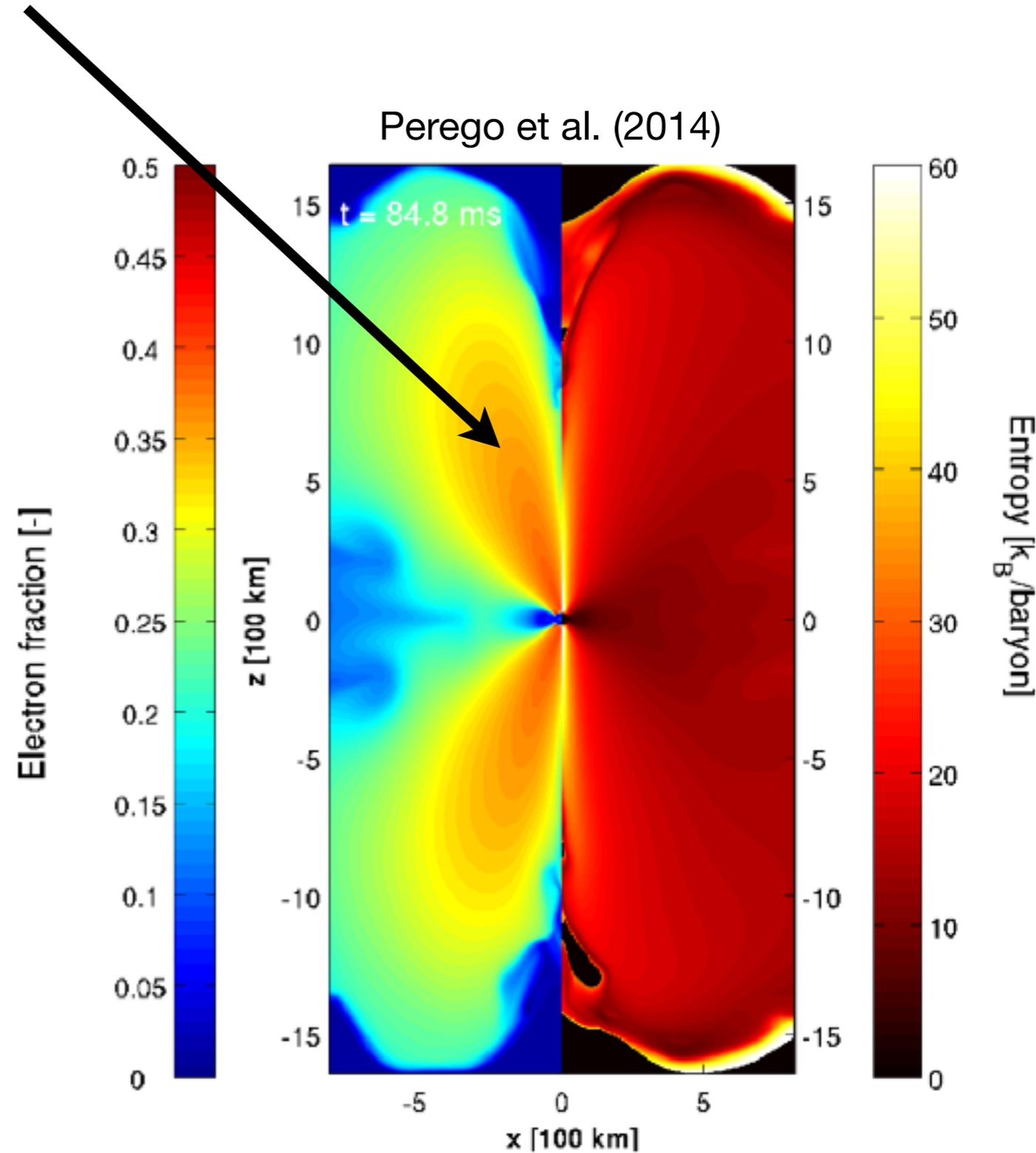


Neutron star mergers: neutrino-driven wind

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



Martin et al. (2015)



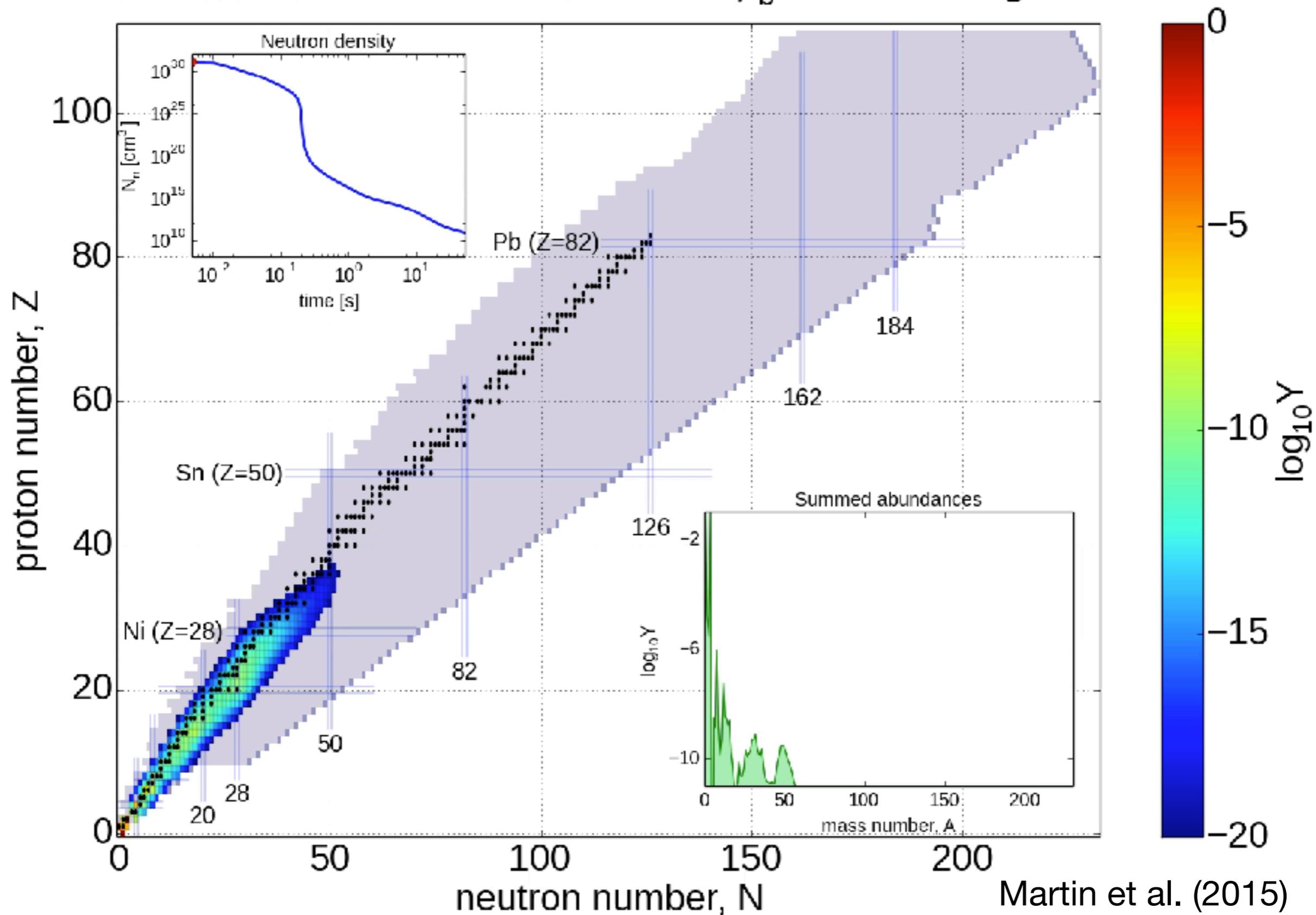
Perego et al. (2014)

see also

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

Neutron star mergers: neutrino-driven wind

$t : 4.89\text{e-}03 \text{ s} / T : 9.00 \text{ GK} / \rho_b : 4.63\text{e+}07 \text{ g/cm}^3$

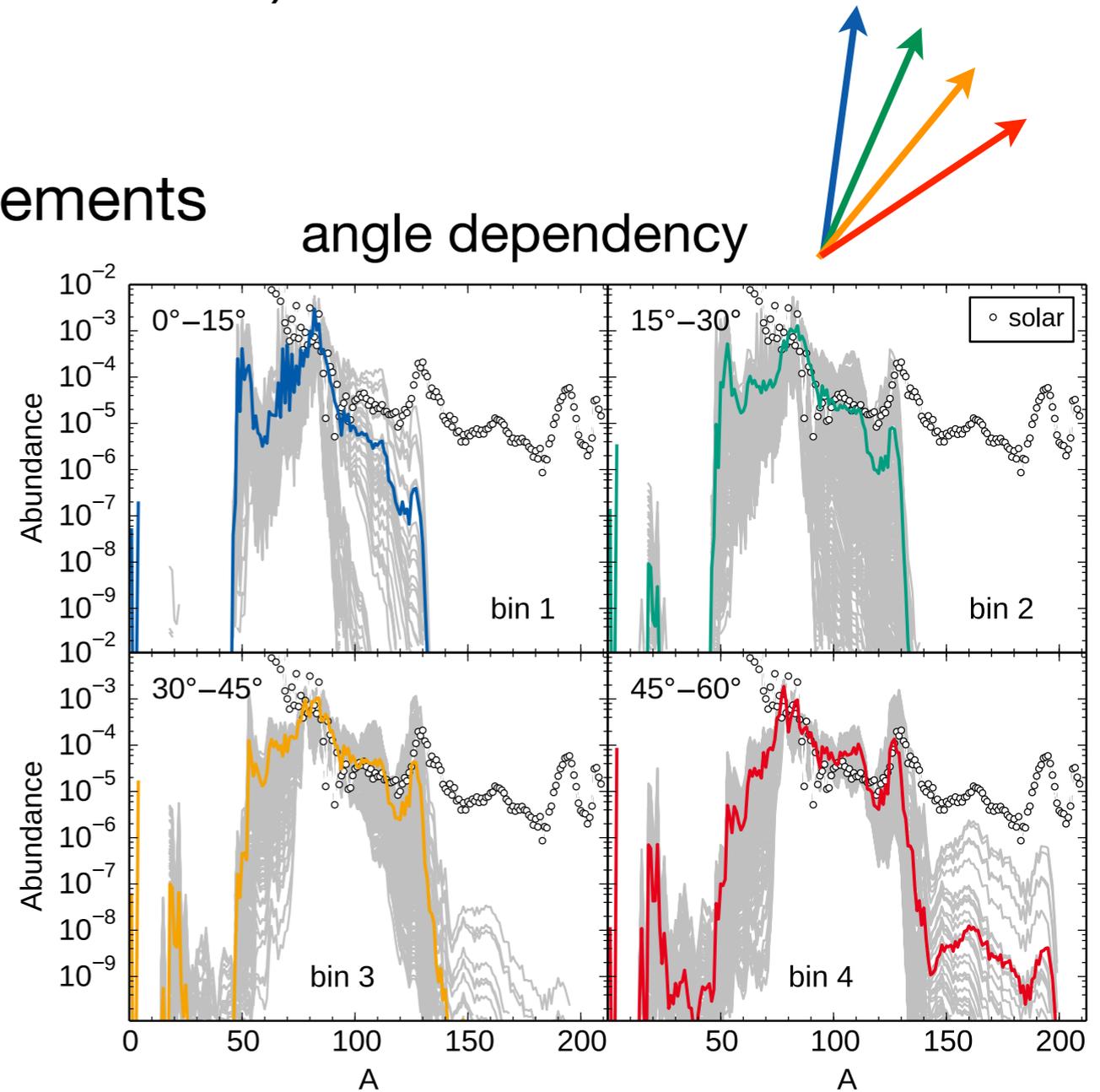
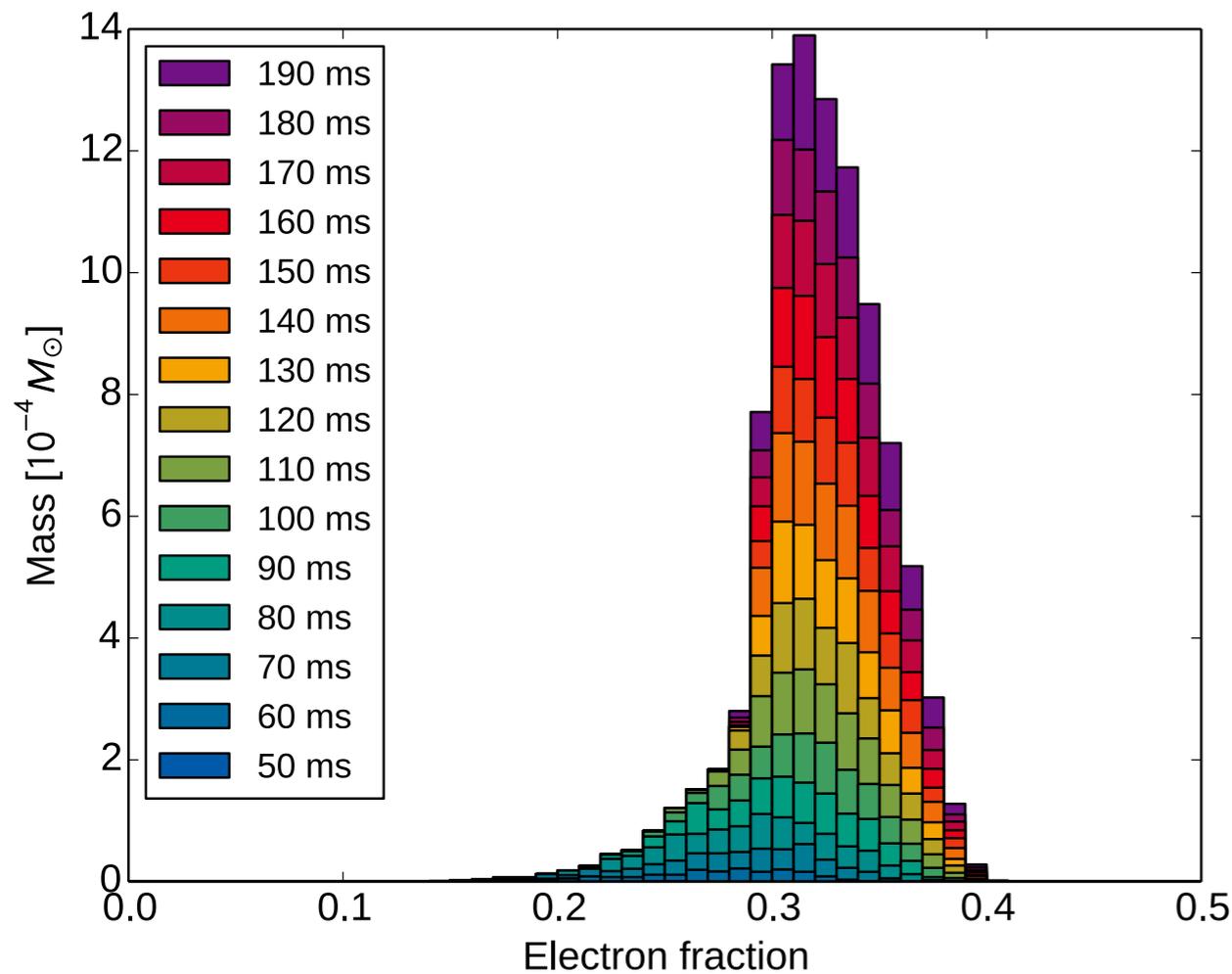


Time and angle dependency

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

Early times: low Y_e : heavy elements

Late times: $Y_e \sim 0.35$: lighter heavy elements

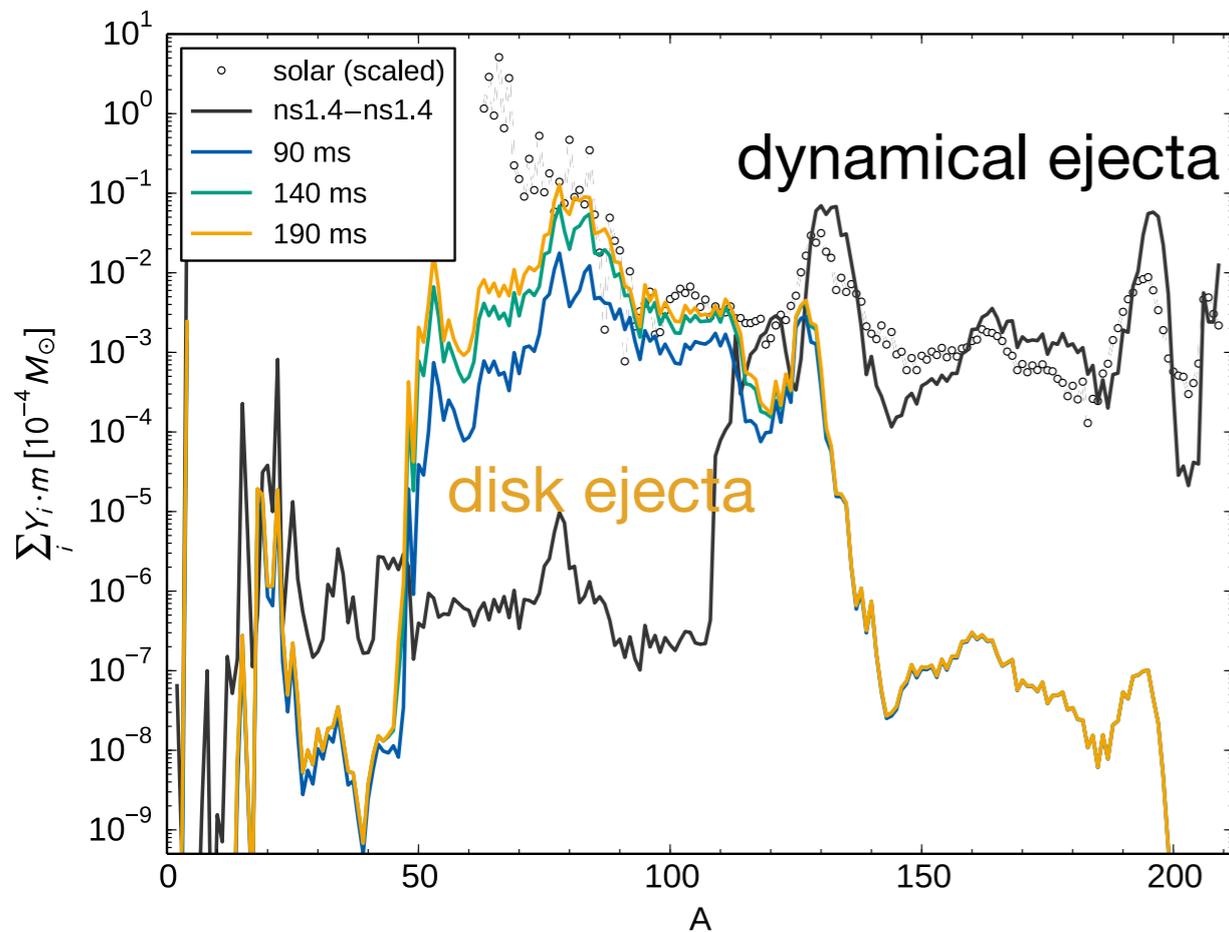


Martin et al. (2015)

Wind and dynamic ejecta

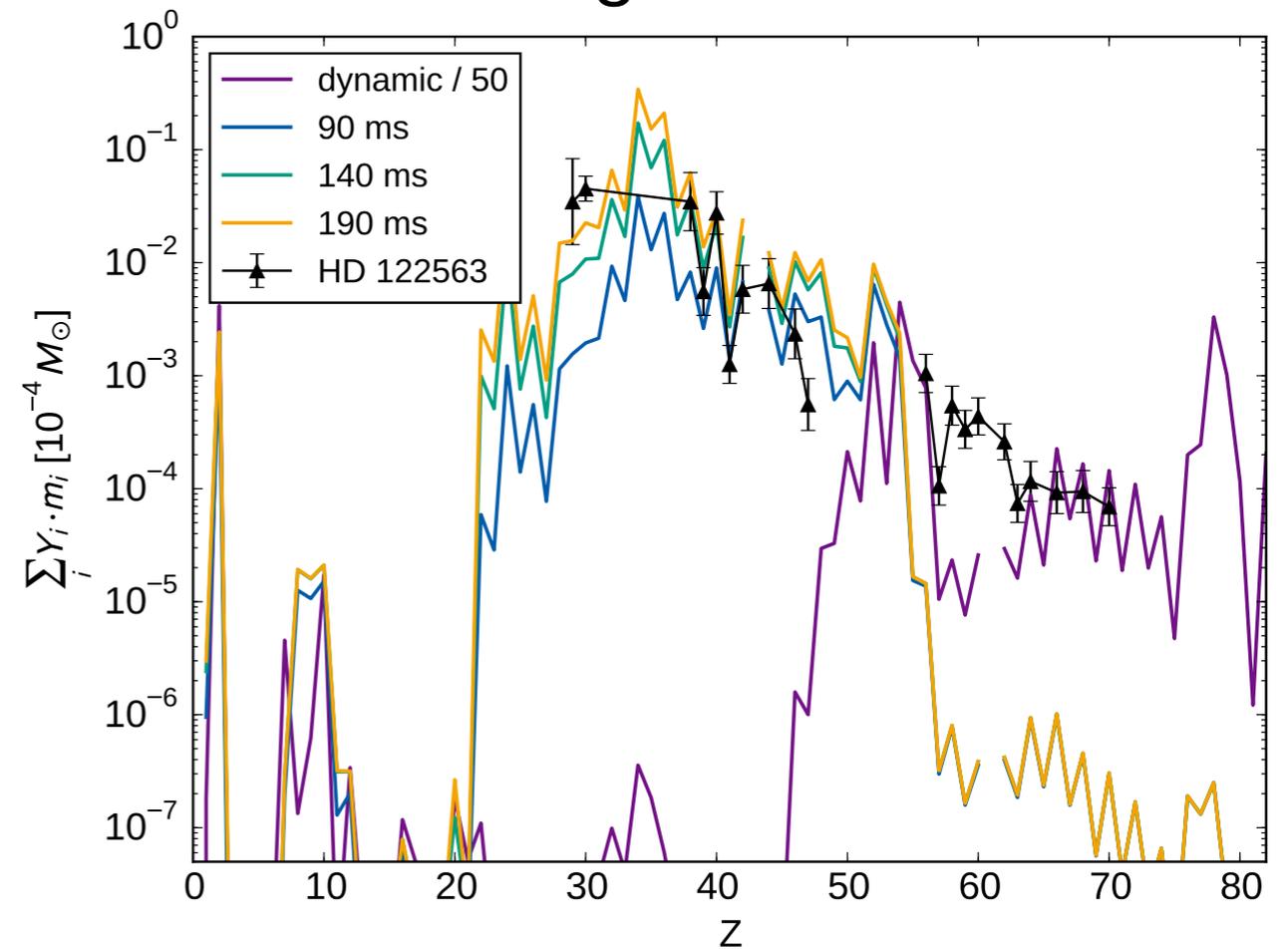
Wind ejecta complement dynamic ejecta

Complete mixing: solar system abundances and UMP stars



Martin et al. (2015)

Partial mixing: Honda-like star?

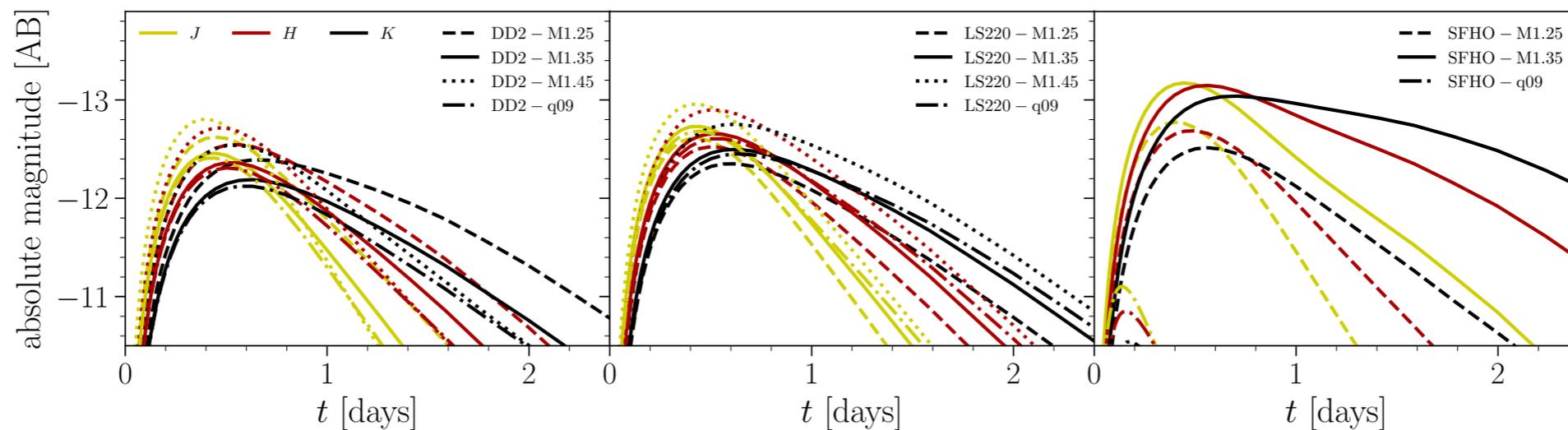
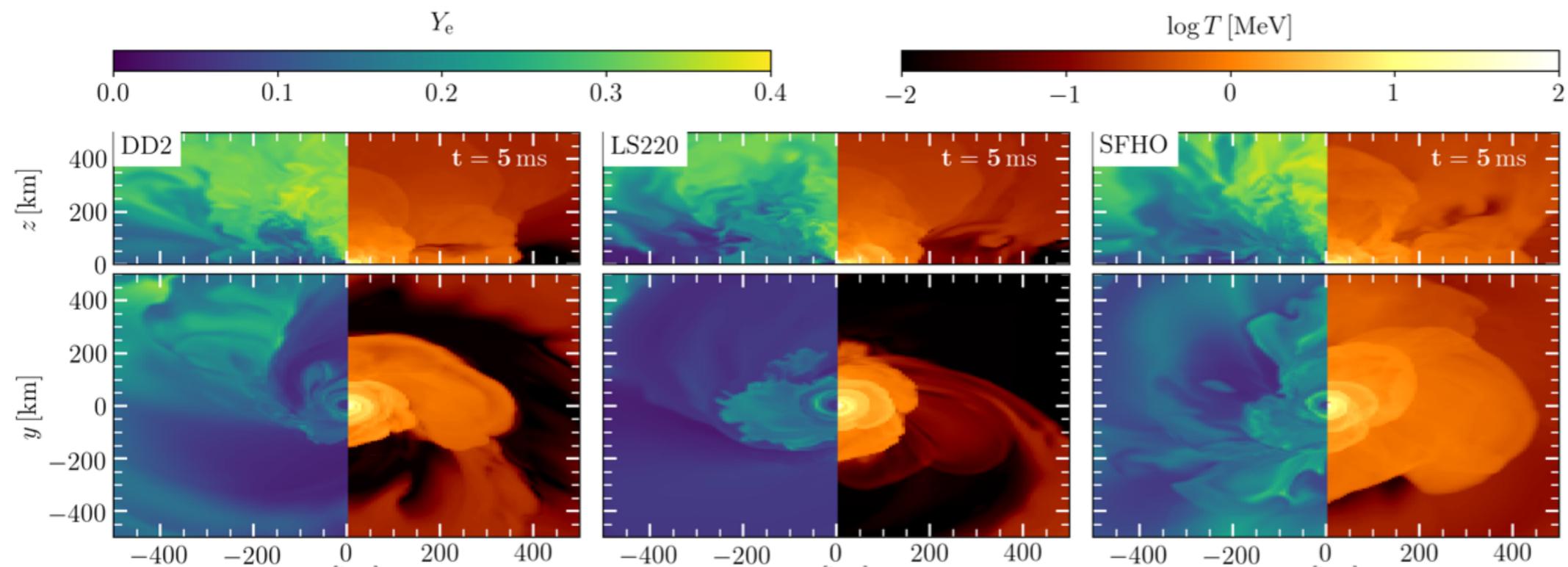


Two components: Hansen et al. 2014

Equation of state and neutrinos

GR simulations: different EoS (Bovard et al. 2017)

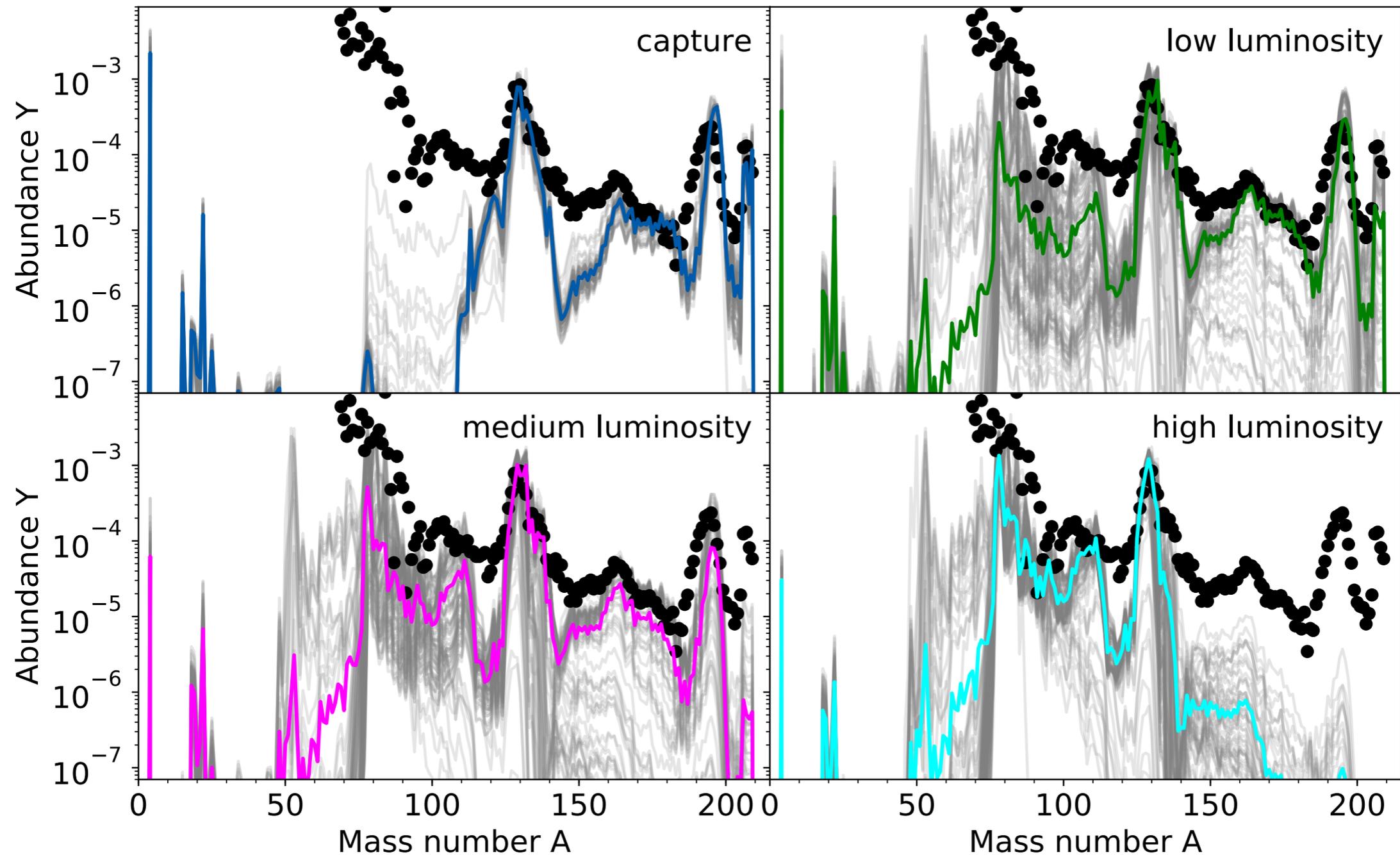
impact of neutrinos (Martin et al. 2018)



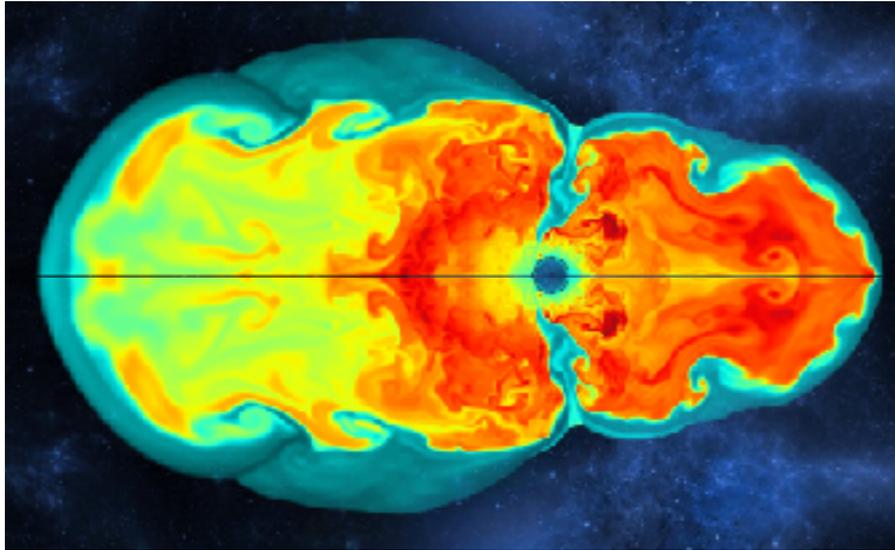
Equation of state and neutrinos

GR simulations: different EoS (Bovard et al. 2017)

impact of neutrinos (Martin et al. 2018)



Core-collapse supernovae

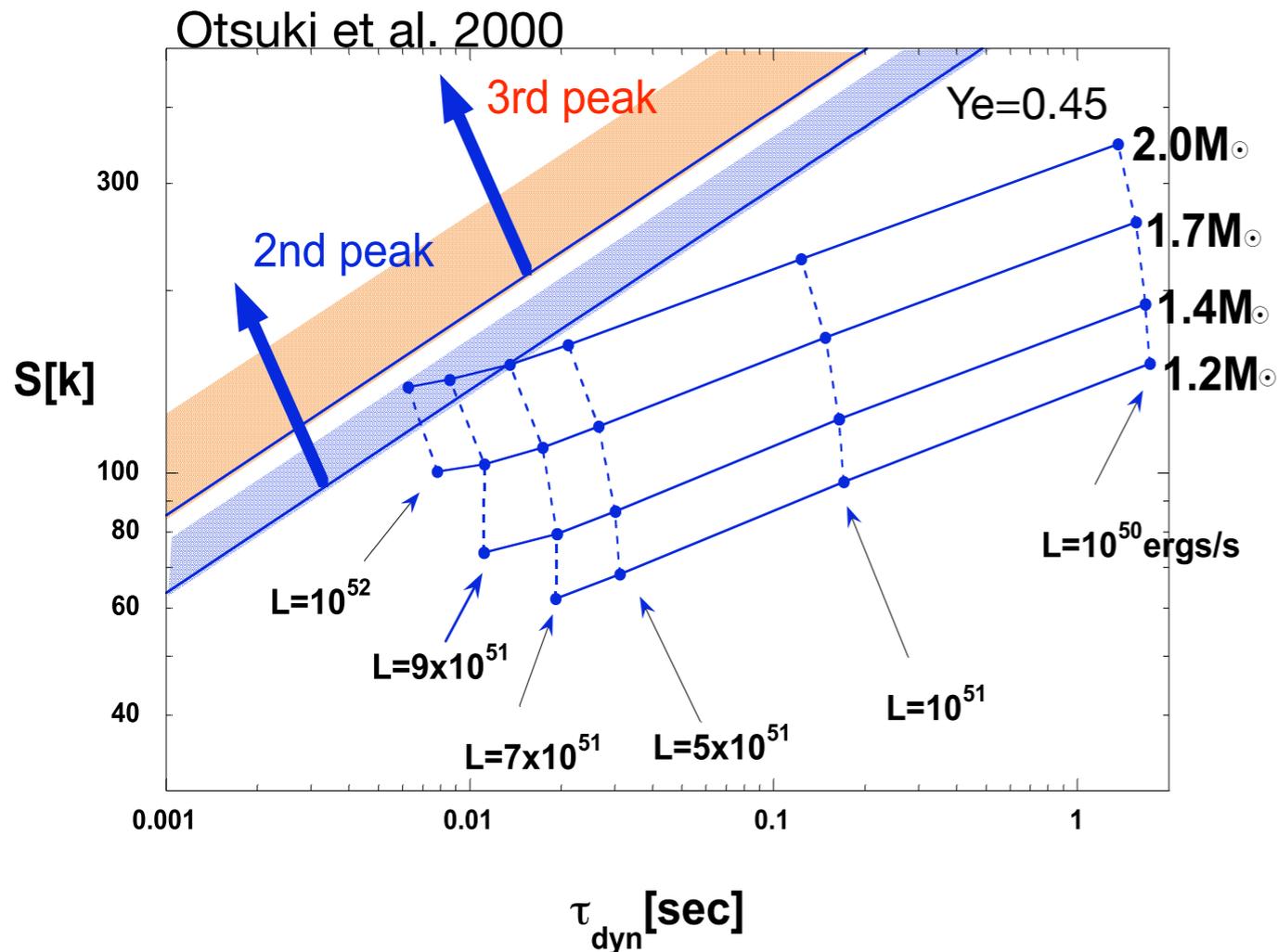


Standard **neutrino-driven supernova**:

Weak r-process and vp-process

Elements up to \sim Ag

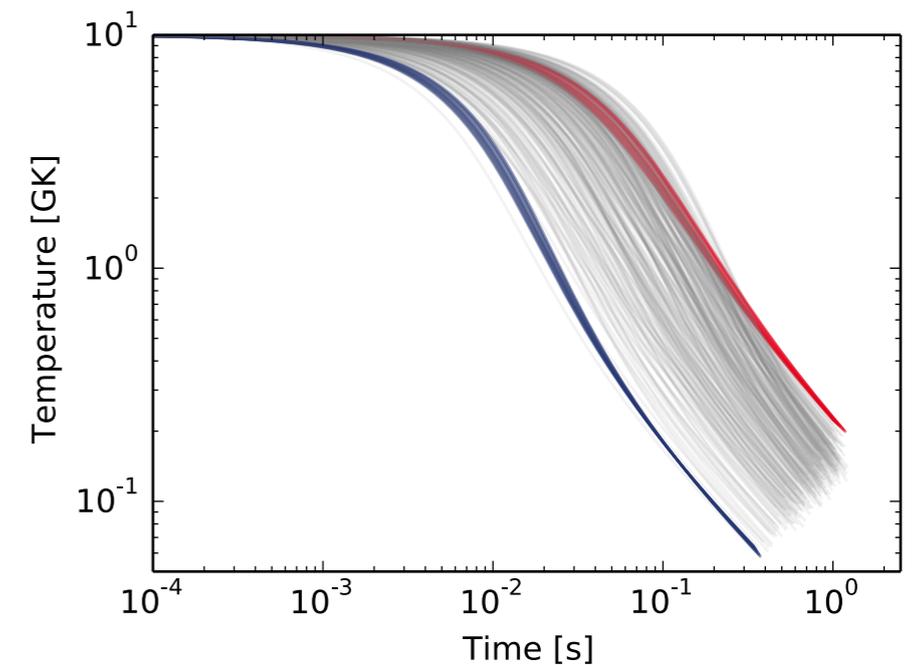
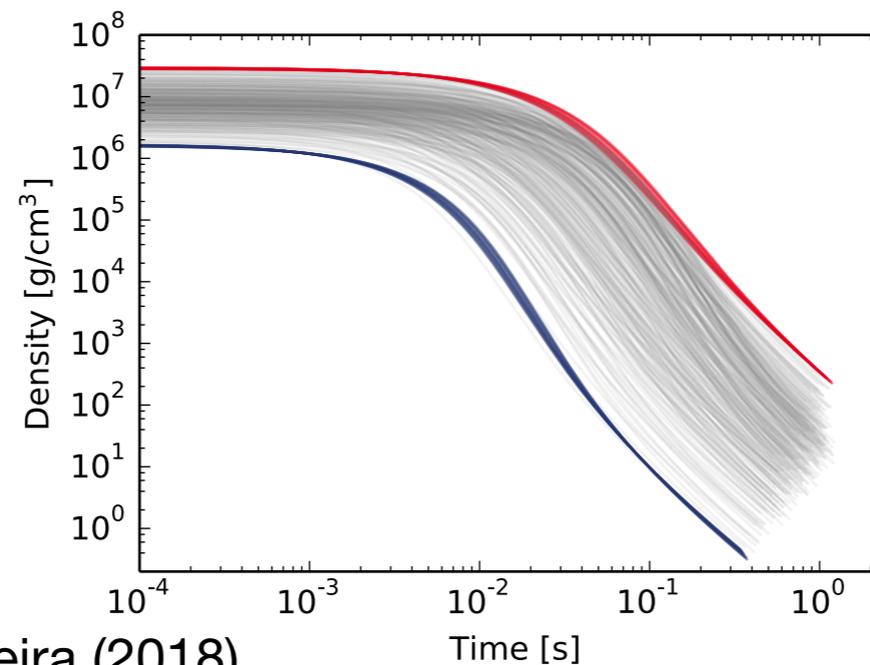
Impact of astrophysical uncertainties



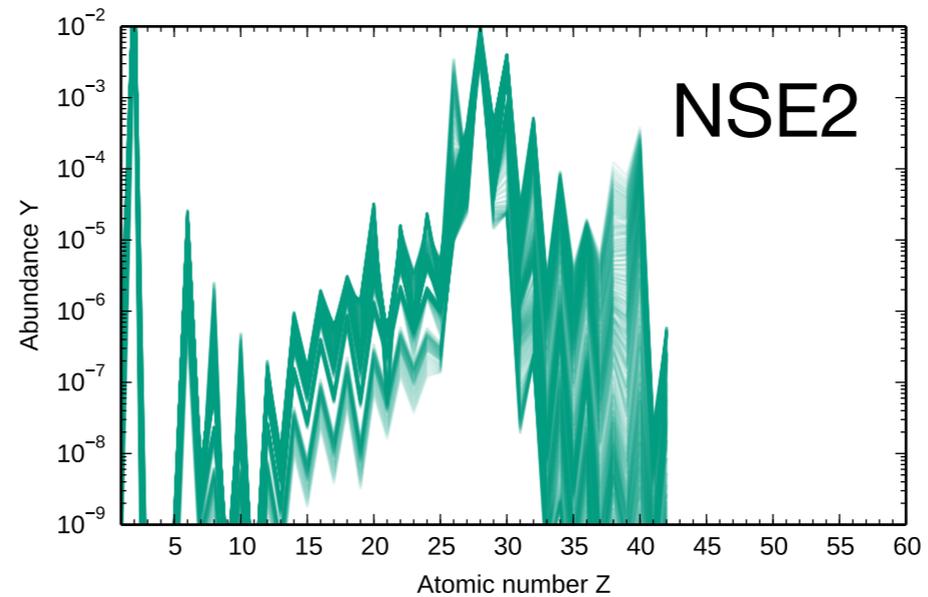
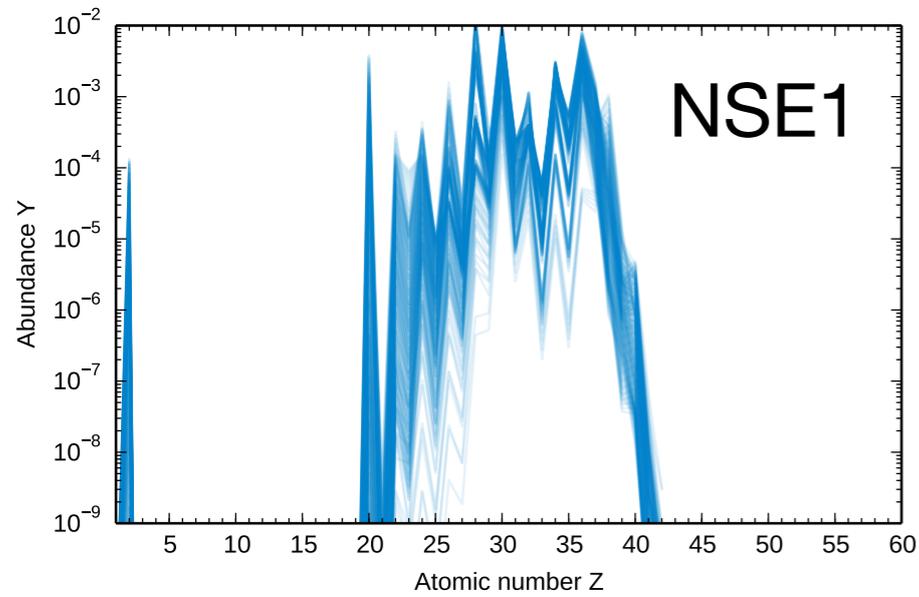
Steady-state model to explore possible nucleosynthesis patterns in neutrino-driven ejecta

Nucleosynthesis ~3000 trajectories

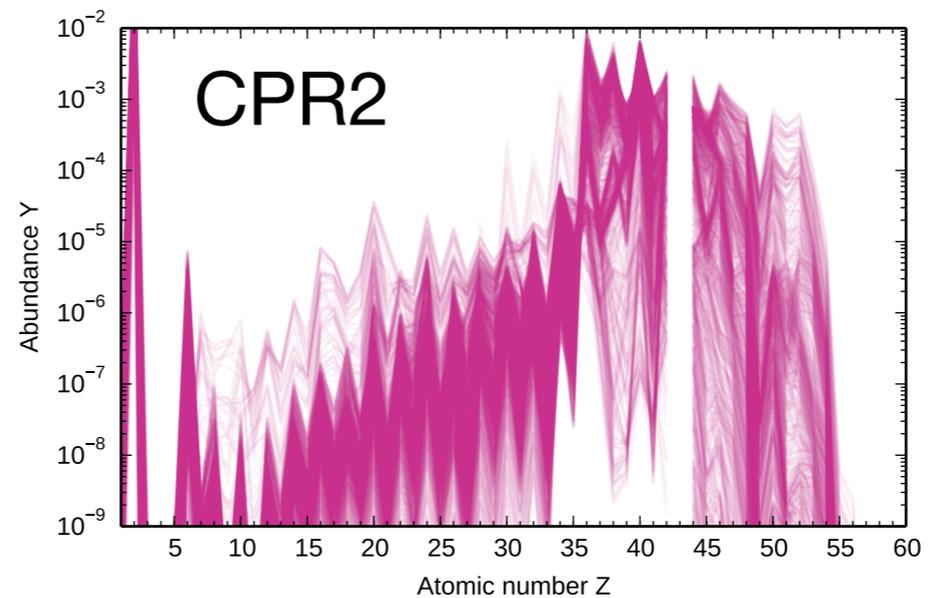
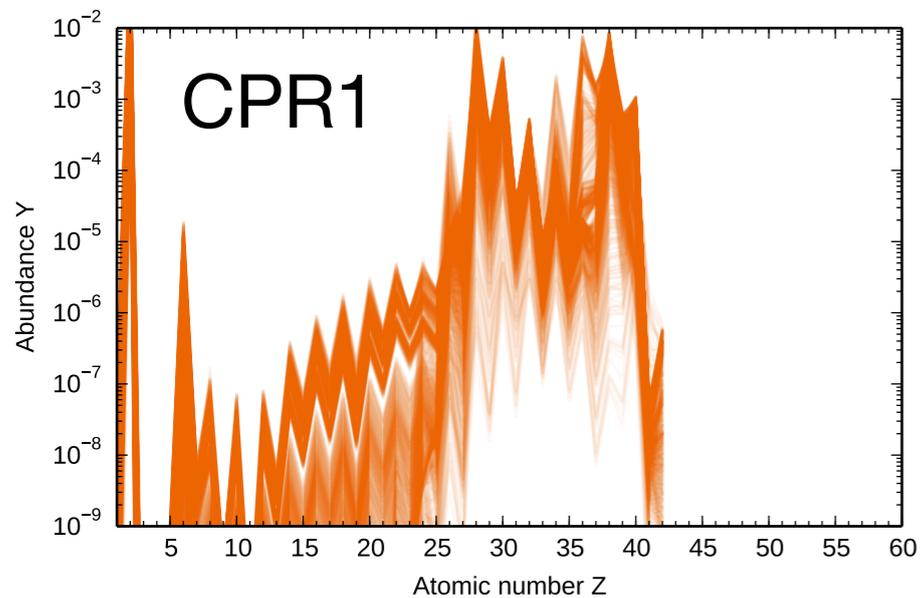
Input parameters:
 M_{ns} , R_{ns} , Y_e



Characteristic nucleosynthesis patterns



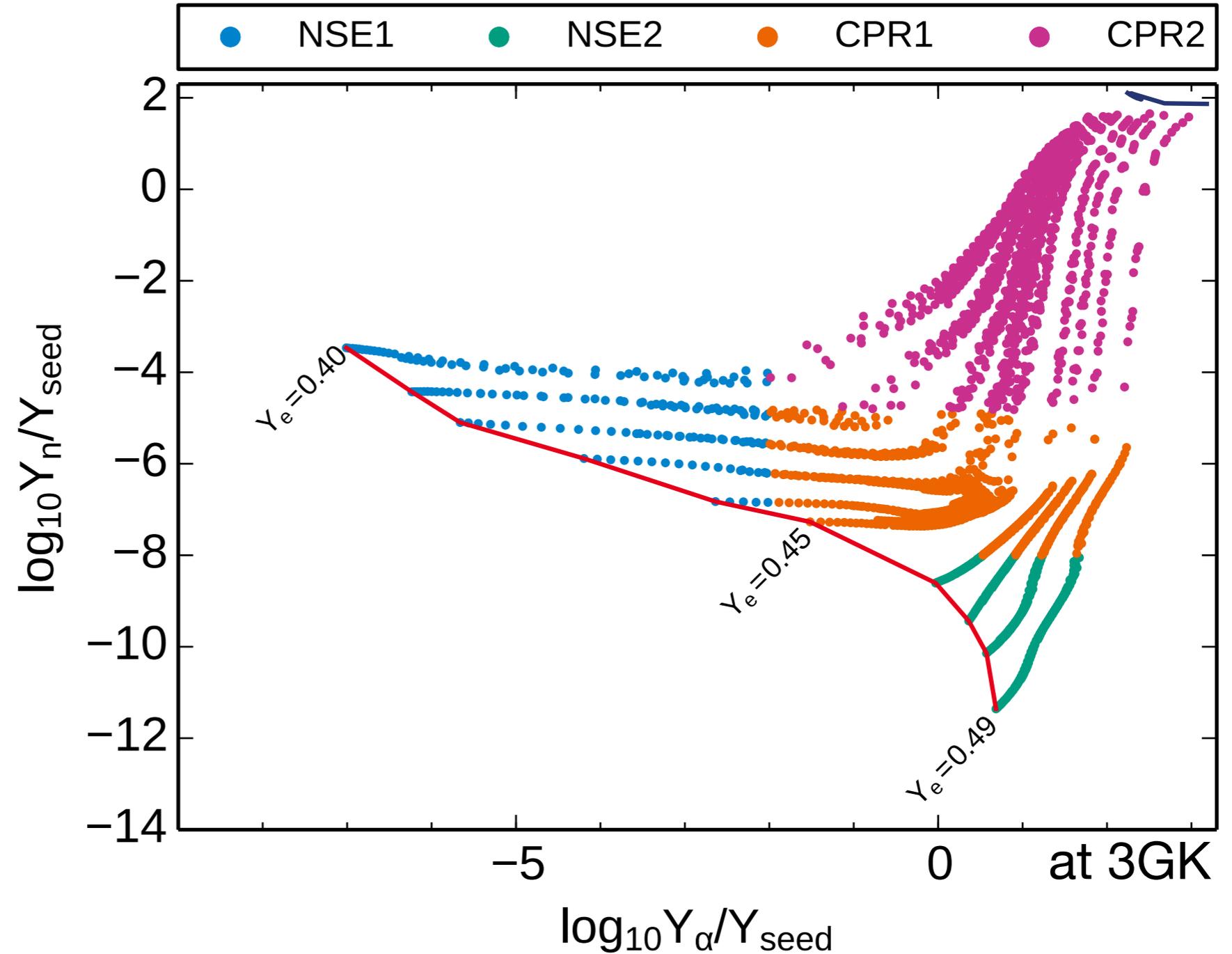
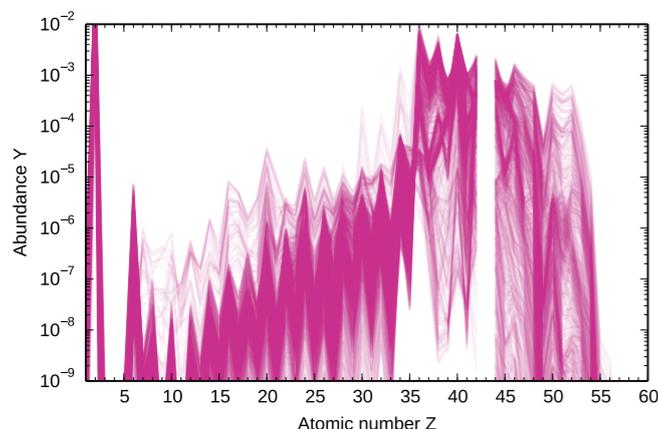
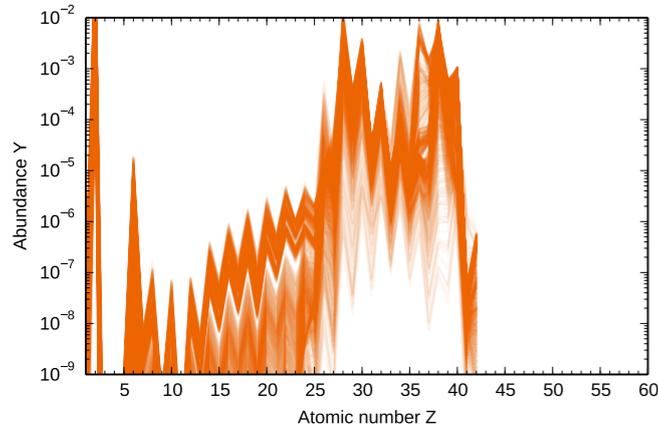
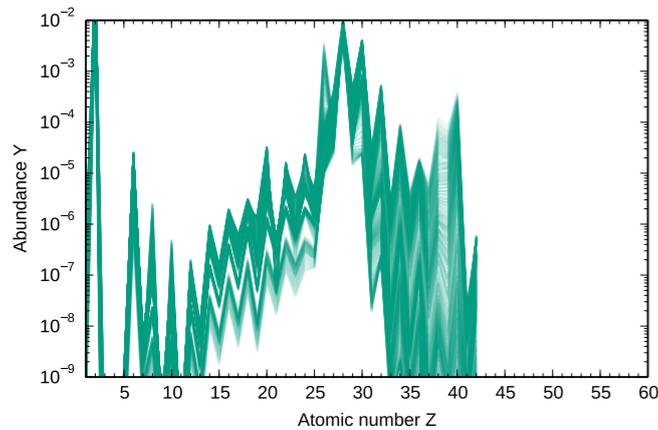
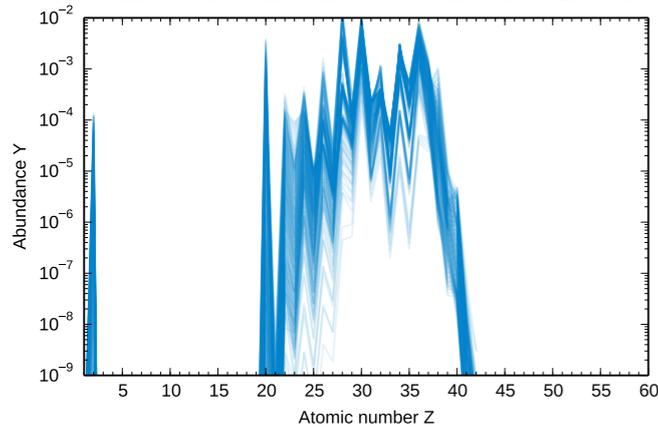
binding energies
partition functions



Q-values of (α ,n) reactions

Individual reactions

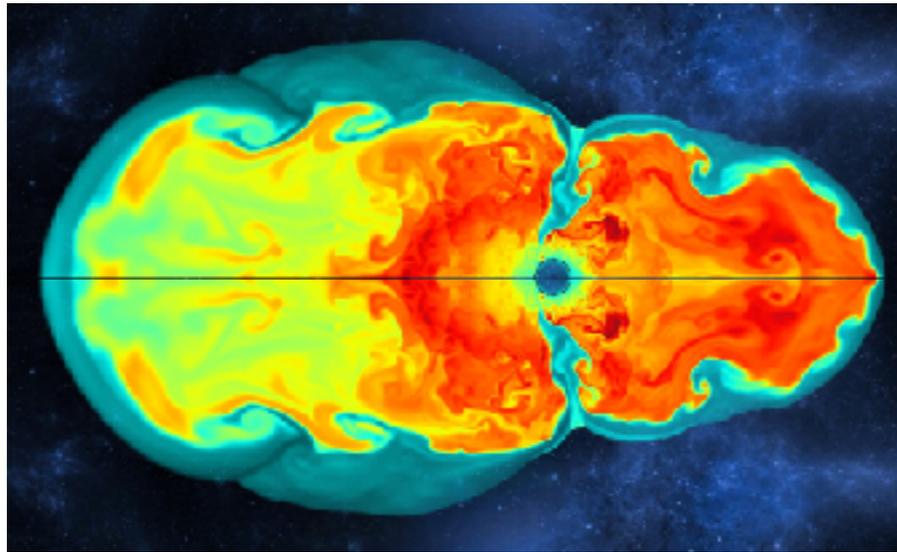
Classification of nucleosynthesis patterns



- Estimate nucleosynthesis based on Y_n , Y_{α} , Y_{seed}
- Provide representative trajectories to explore impact of nuclear physics input (nuc-astro.eu)

Bliss, Witt, Arcones, Montes, Pereira (2018)

Core-collapse supernovae



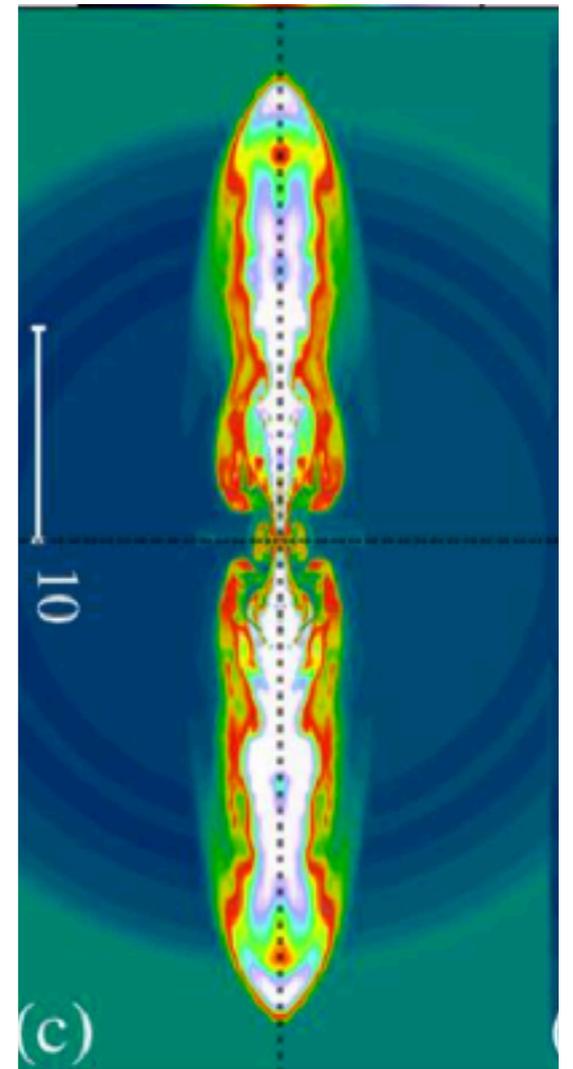
Standard **neutrino-driven supernova**:
Weak r-process and vp-process
Elements up to \sim Ag

Magneto-rotational supernovae

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

2D and 3D + parametric neutrino treatment :

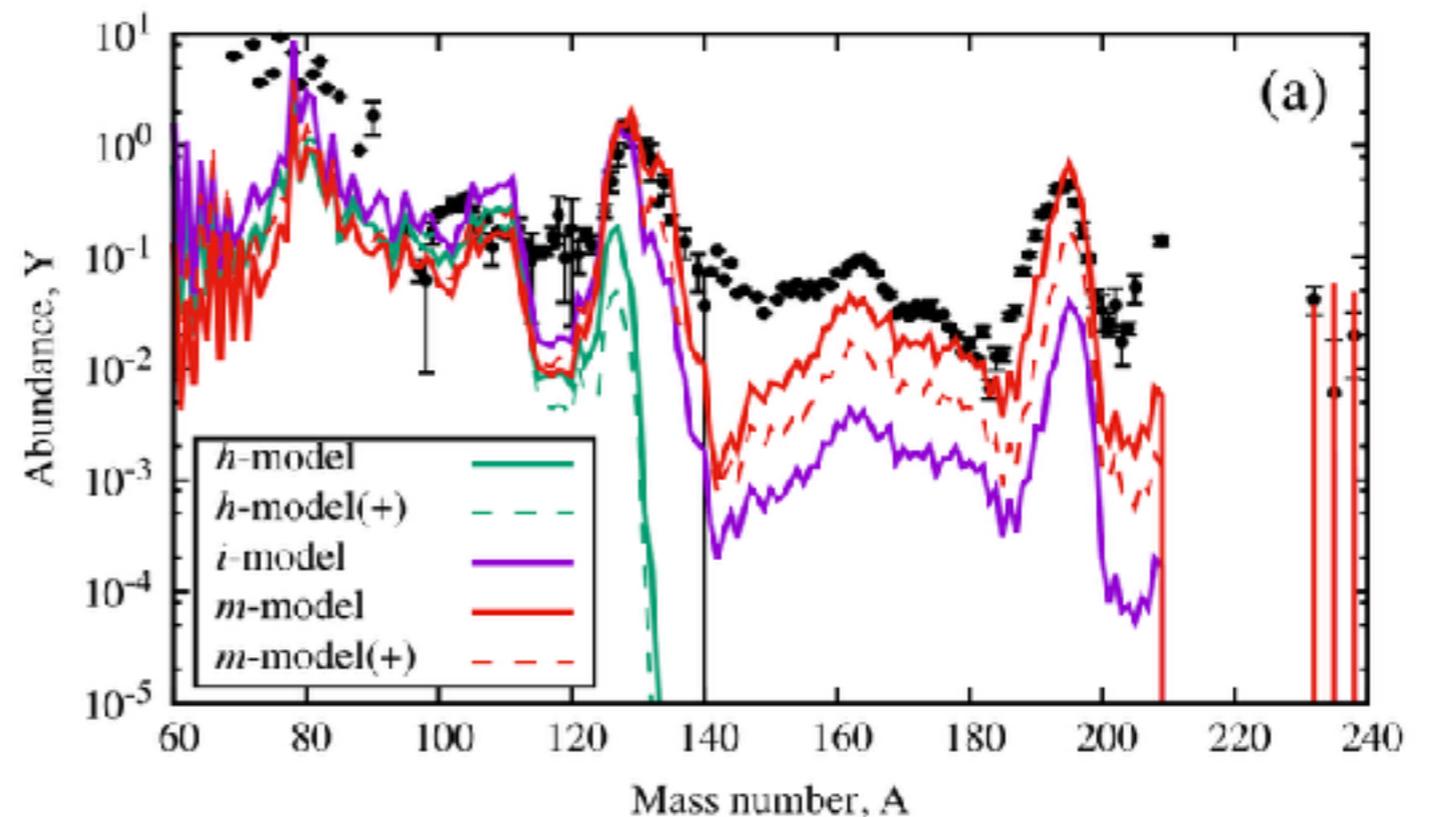
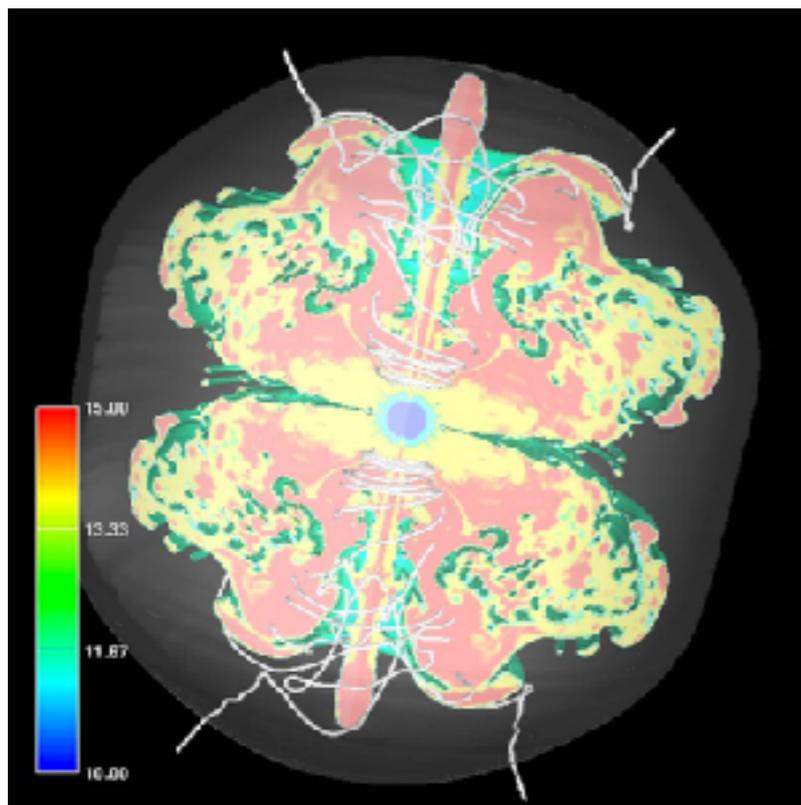
- jet-like explosion: **heavy r-process**
- magnetic field vs. neutrinos: weak r-process



Magneto-rotational supernovae: r-process

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

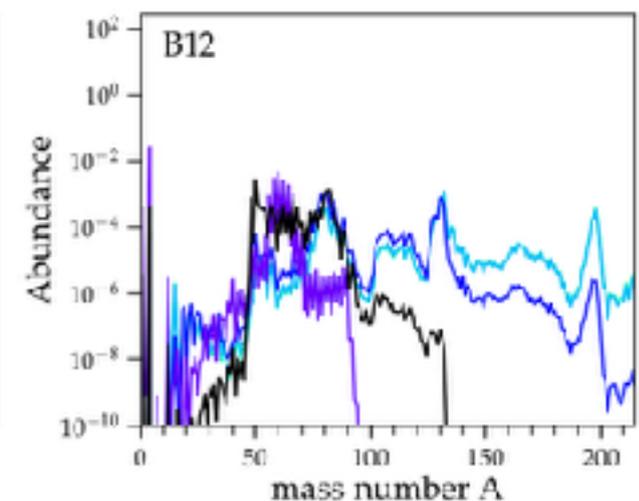
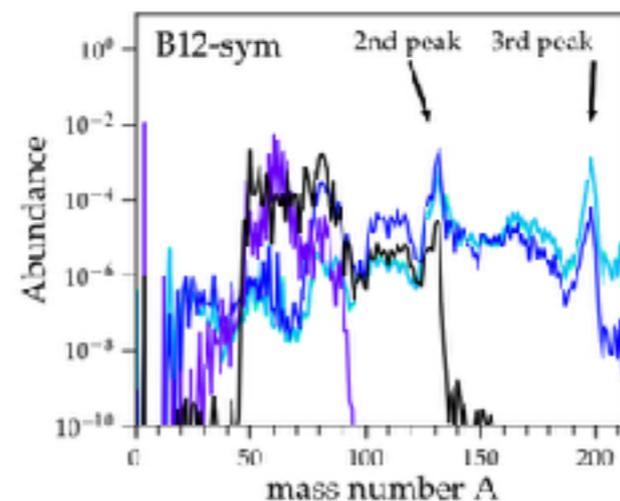
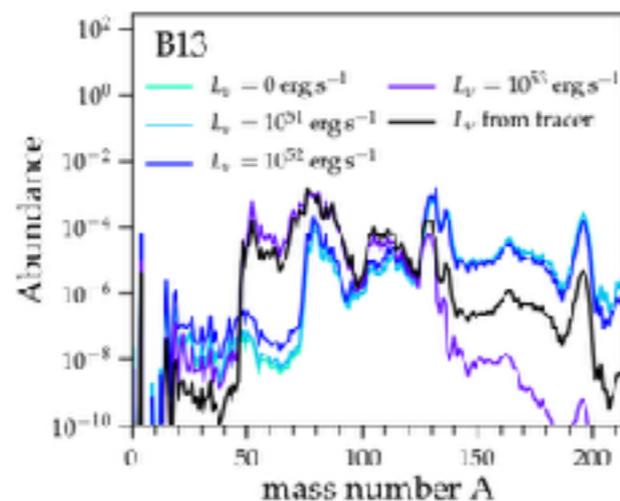
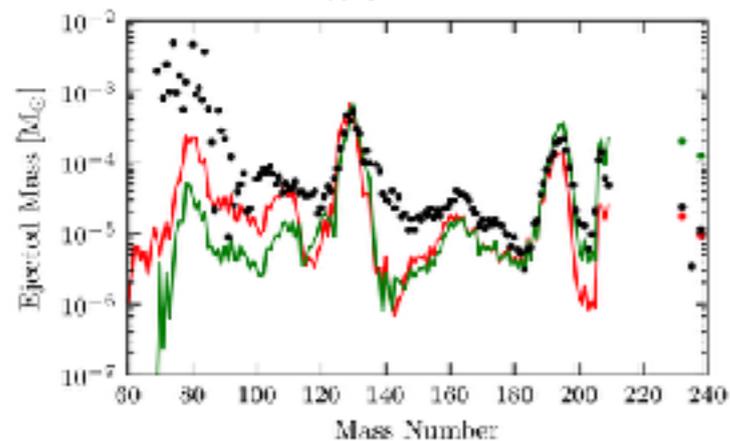
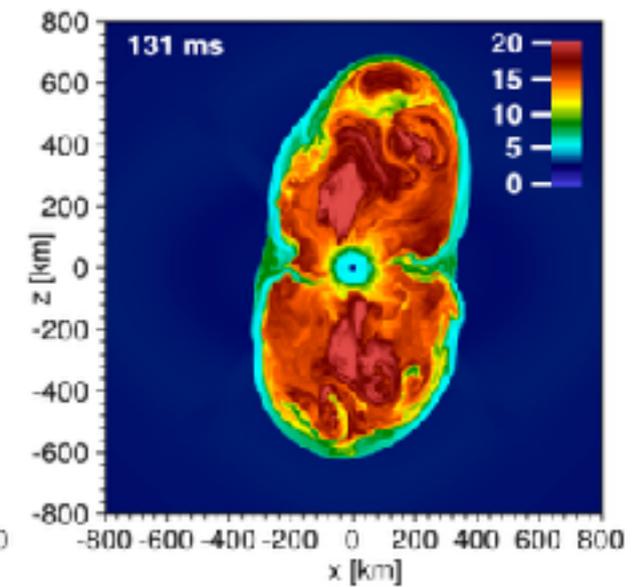
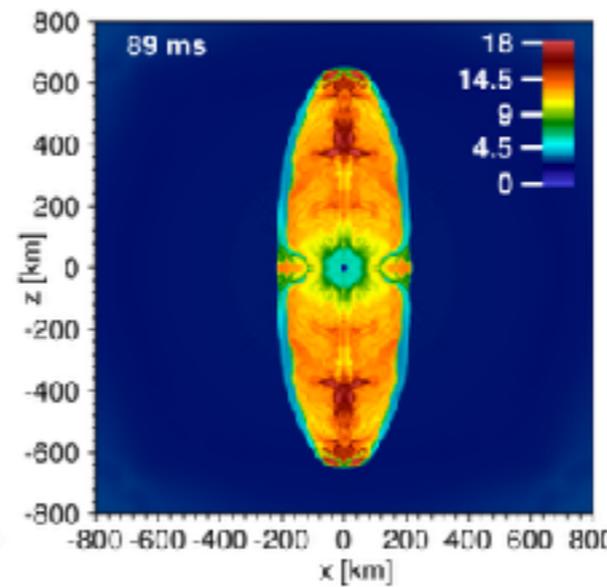
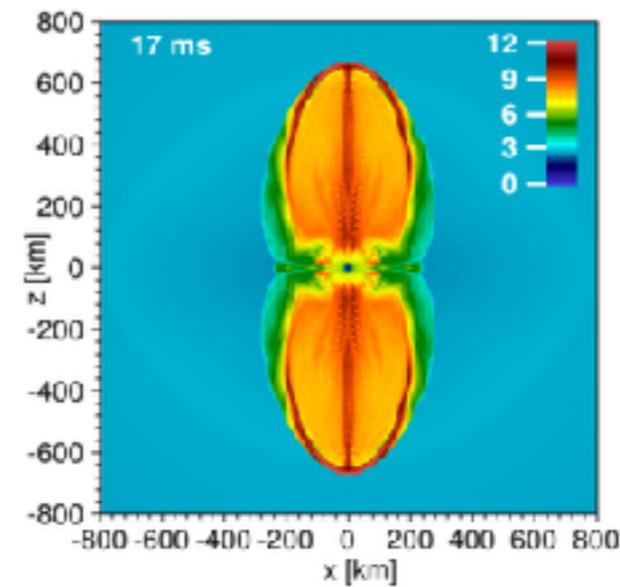
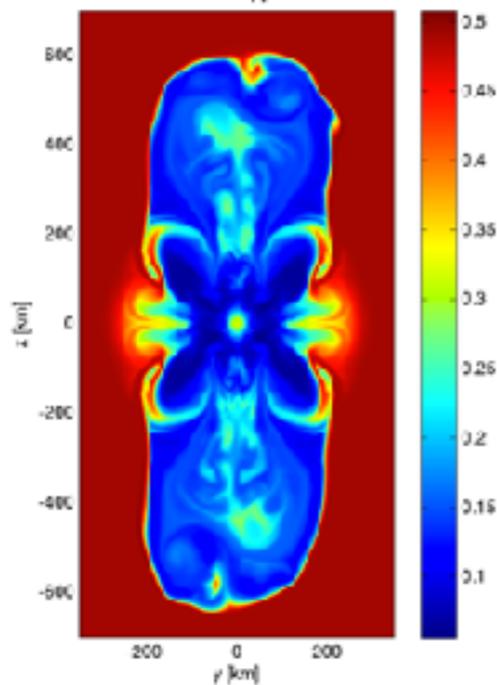
2D, parametric neutrino treatment (Nishimura et al. 2015, 2017)
magnetic field vs. neutrinos



Magneto-rotational supernovae: r-process

3D, leakage (Winteler et al. 2012, Mösta et al. 2017)

- jet-like explosion, heavy r-process: strong magnetic field (10^{13}G) or symmetry ($\sim 2\text{D}$), 10^{12}G
- Weak r-process: 3D, 10^{12}G



Winteler et al. 2012

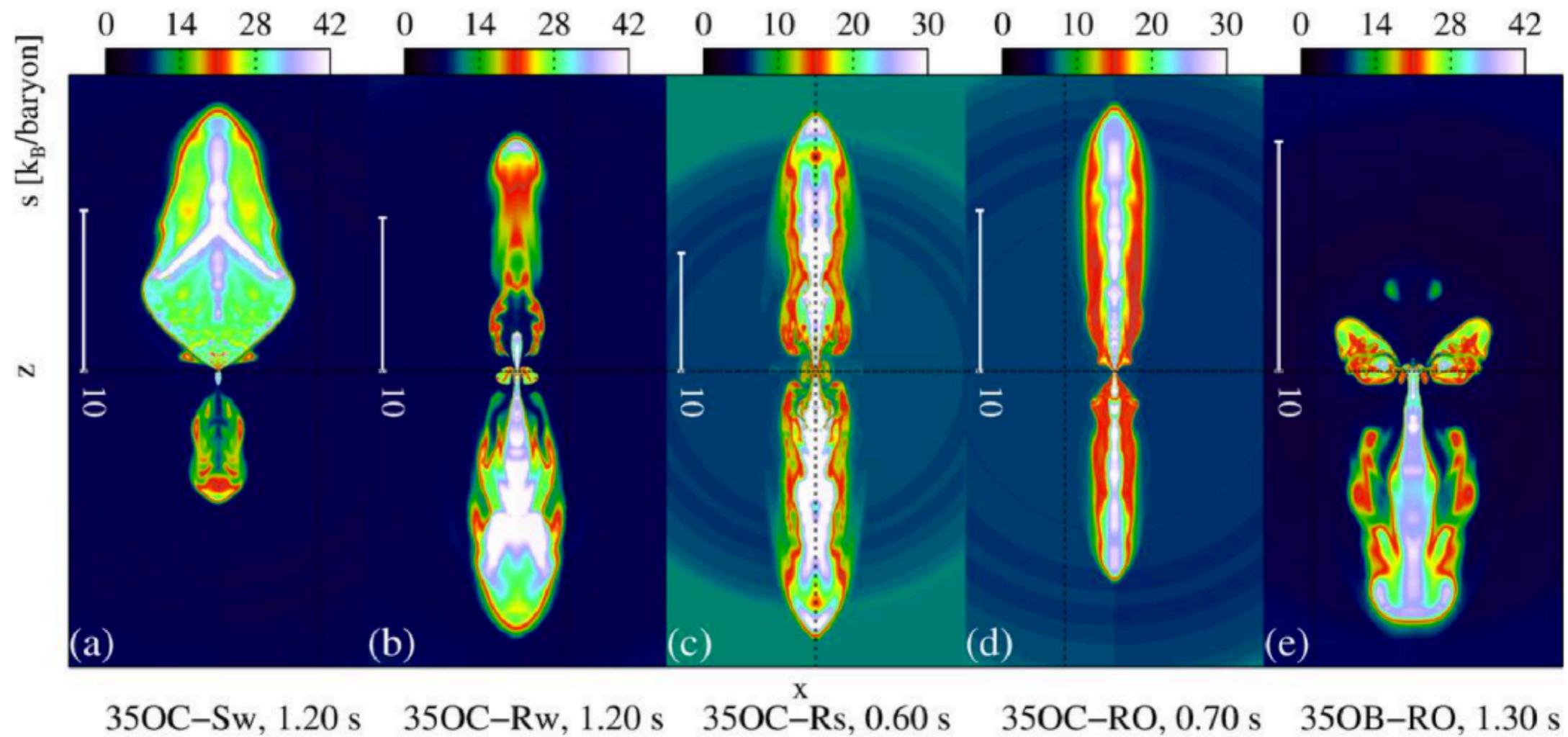
Mösta et al. 2017

Magneto-rotational supernovae: r-process

Neutrinos and late evolution are important

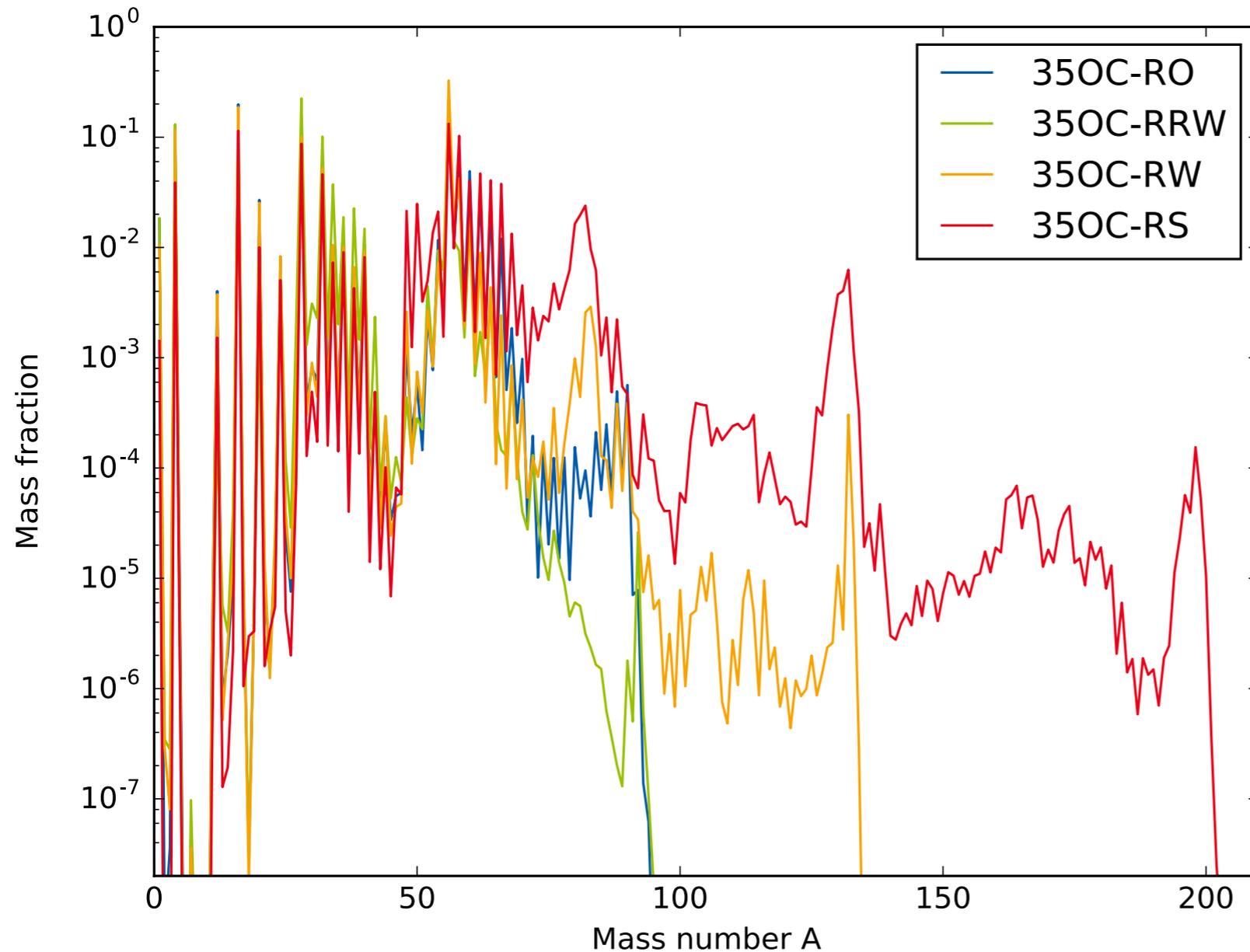
Martin Obergaulinger: 2D, M1, $\sim 1-2$ s

Progenitor: $35 M_{\text{sun}}$

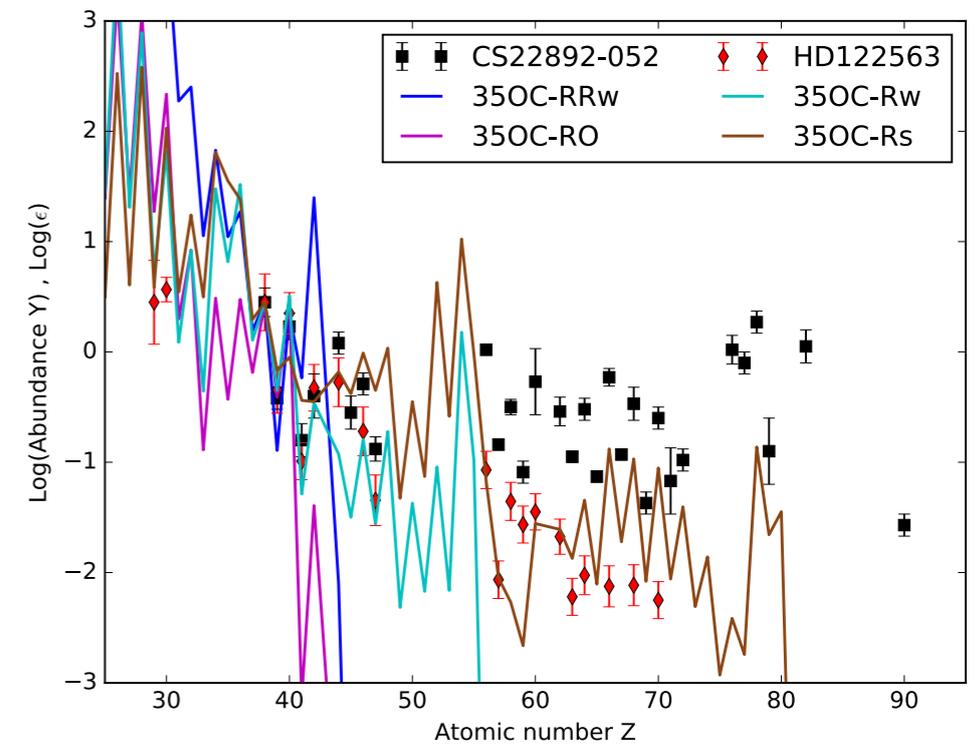


Obergaulinger & Aloy (2017)

Impact of rotation and magnetic field

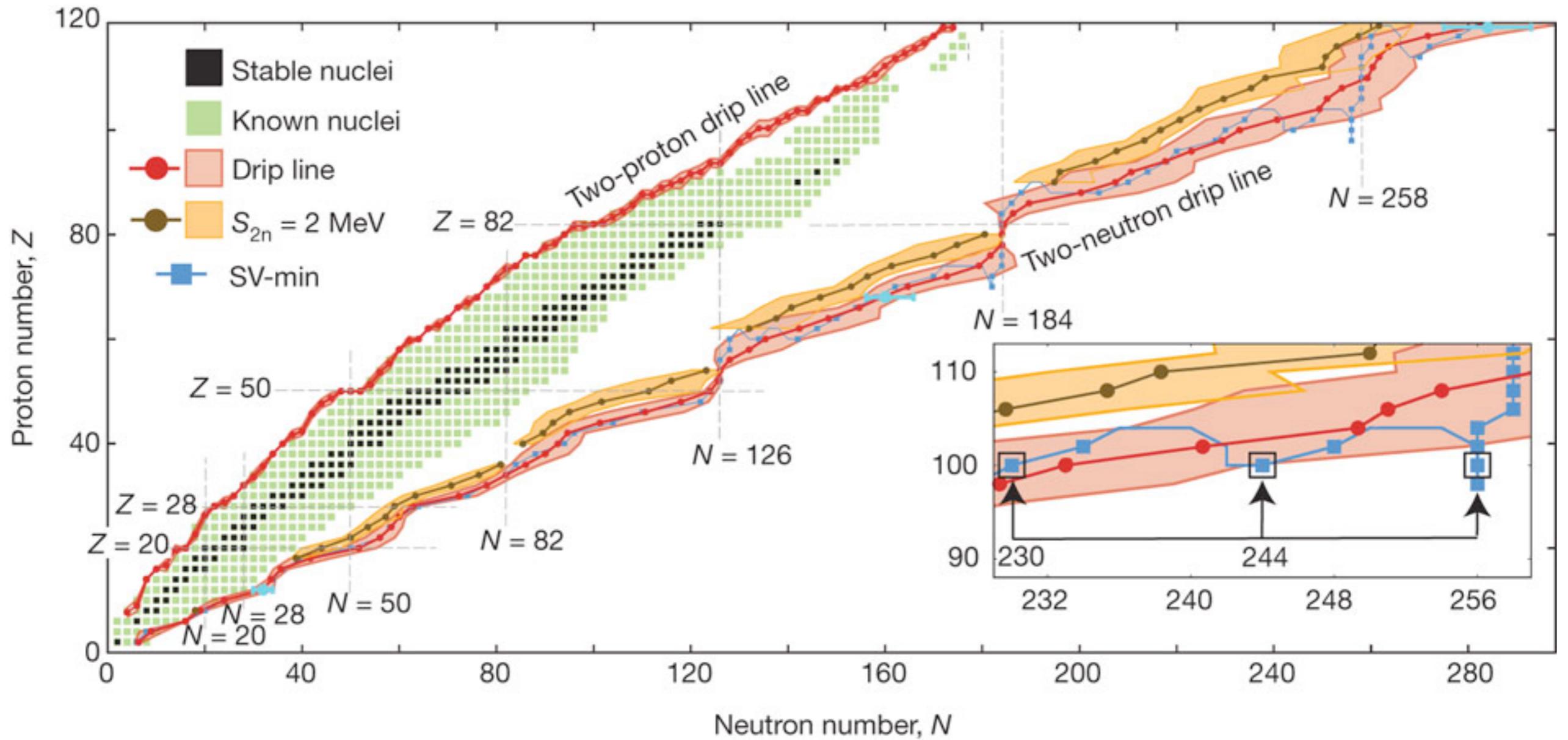


RO: progenitor
RRW: weak mag. field
strong rot.
RW: weak mag. field
RS: strong mag. field



Nuclear physics input

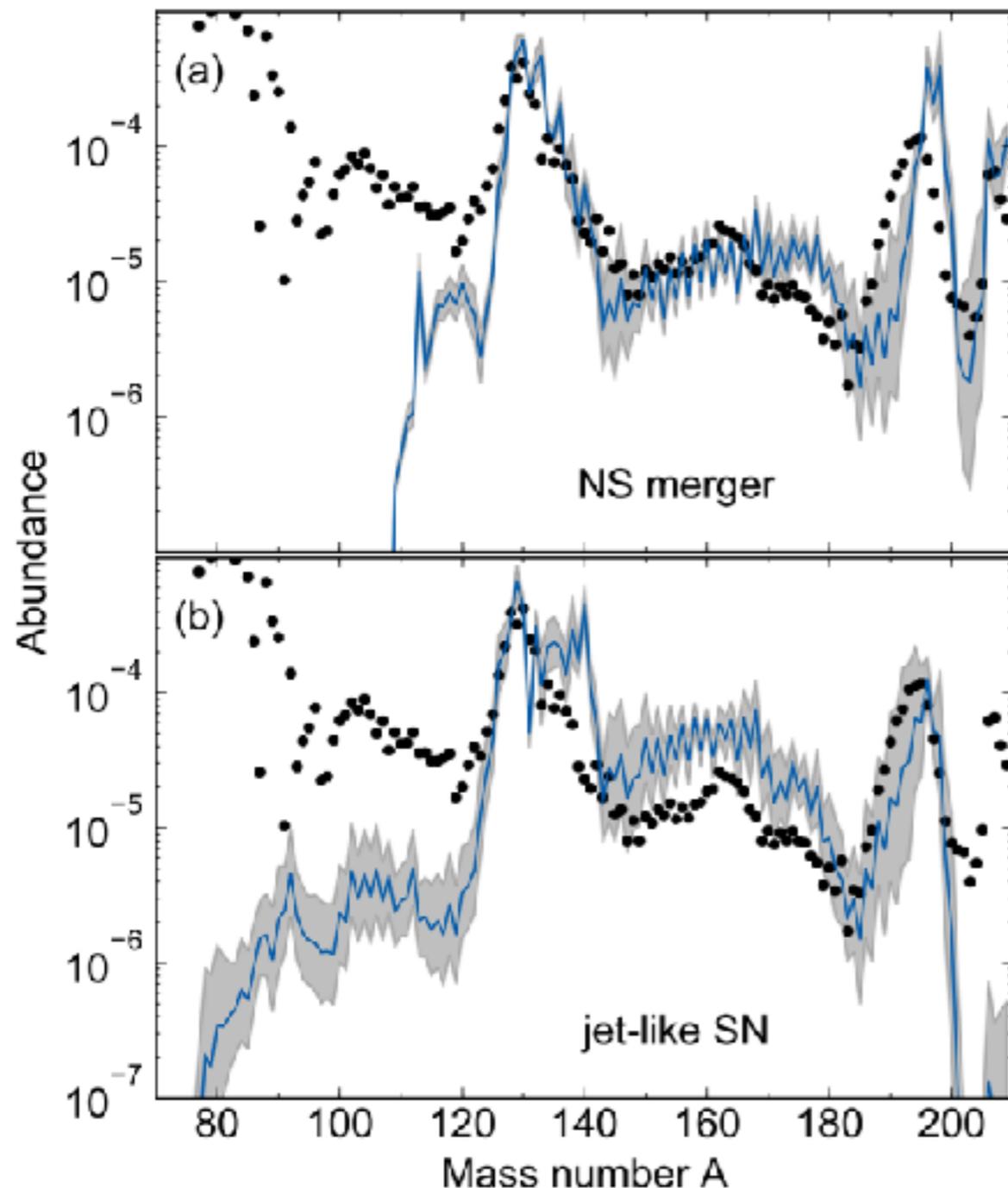
nuclear masses, beta decay, reaction rates (neutron capture), fission



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?

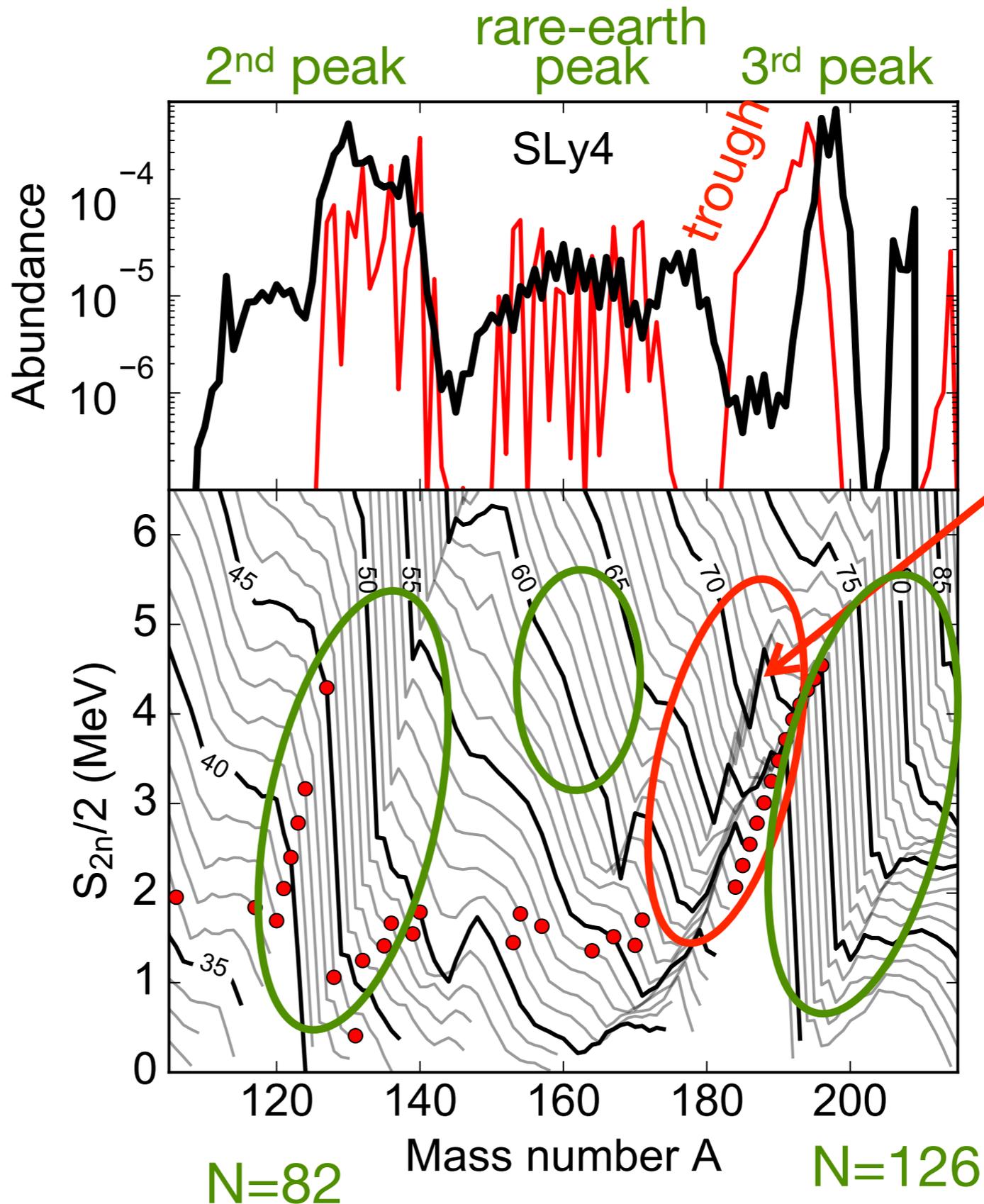
Two neutron separation energy: abundances

Abundances



S_{2n}

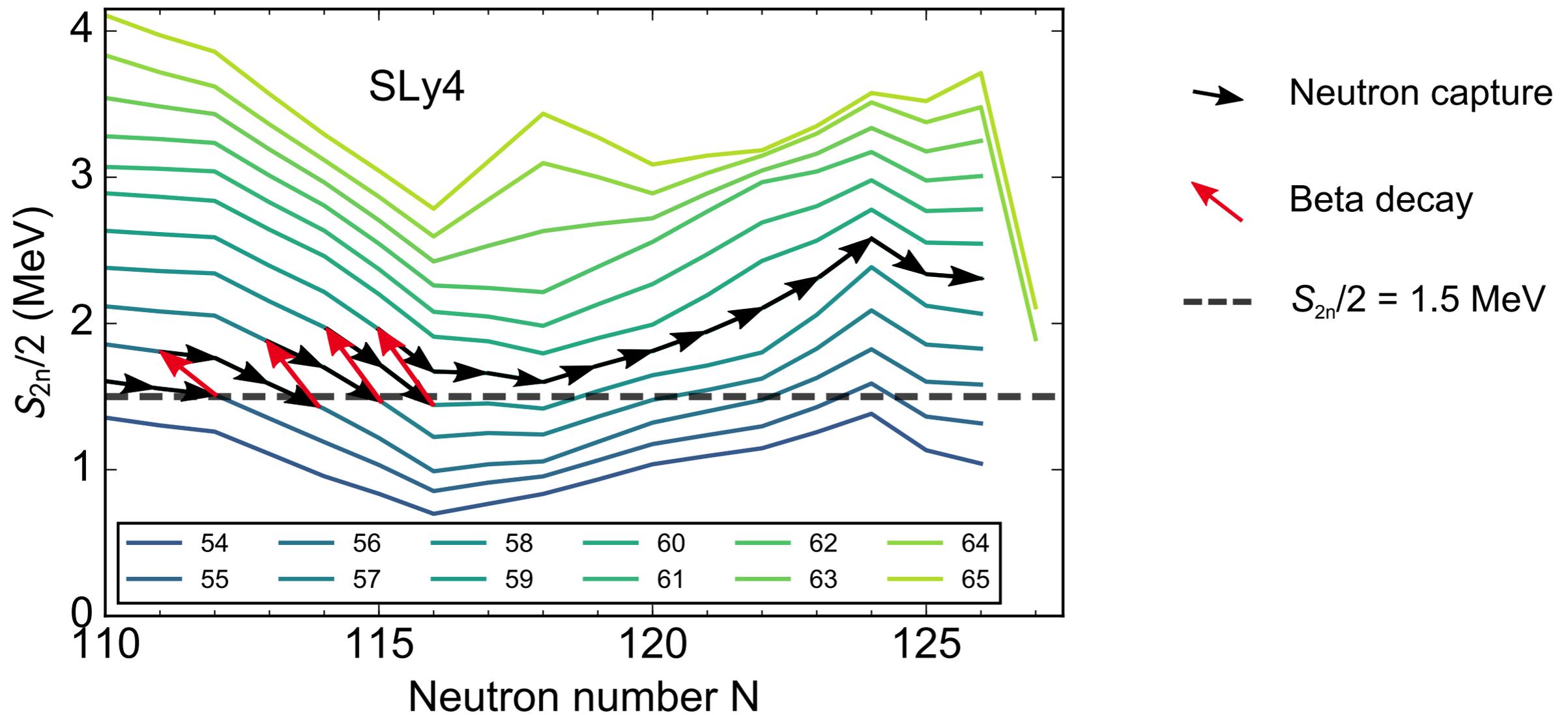
Nuclear properties



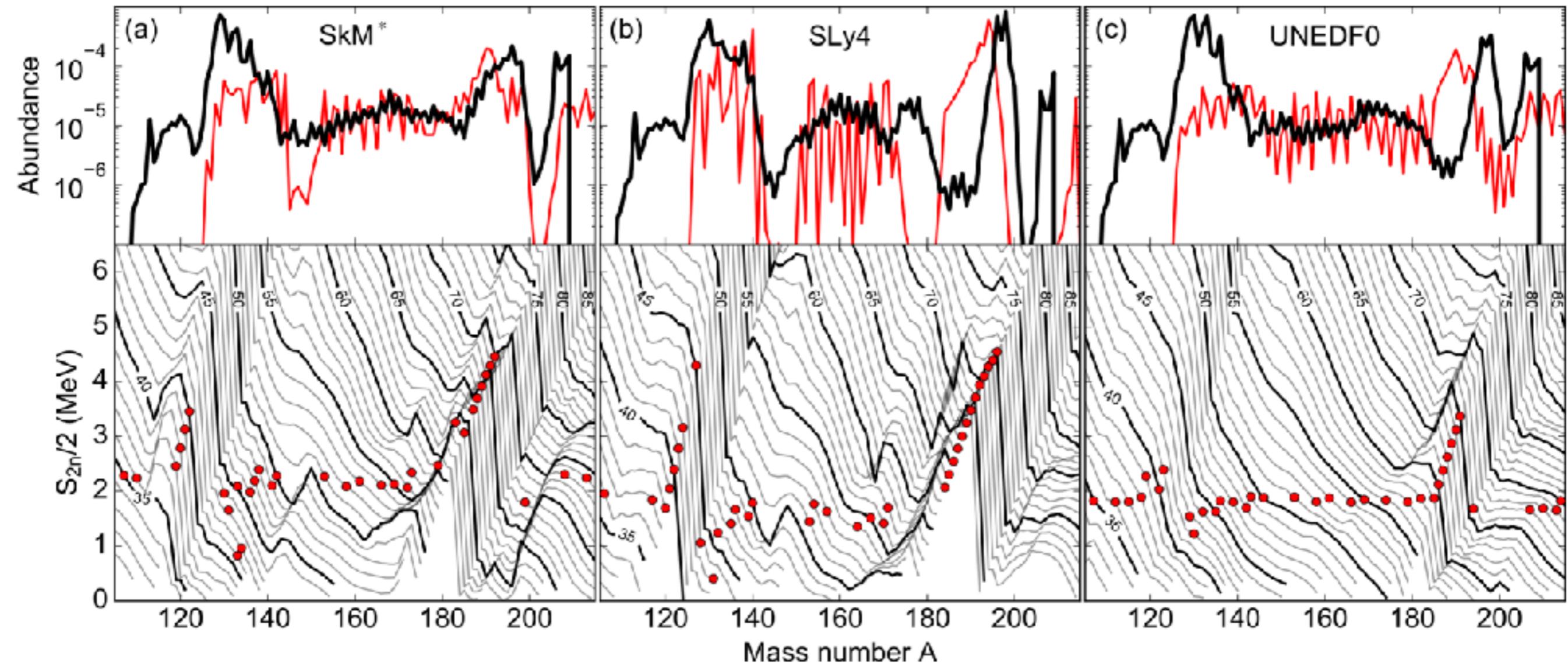
transition from deformed to spherical

Two neutron separation energy

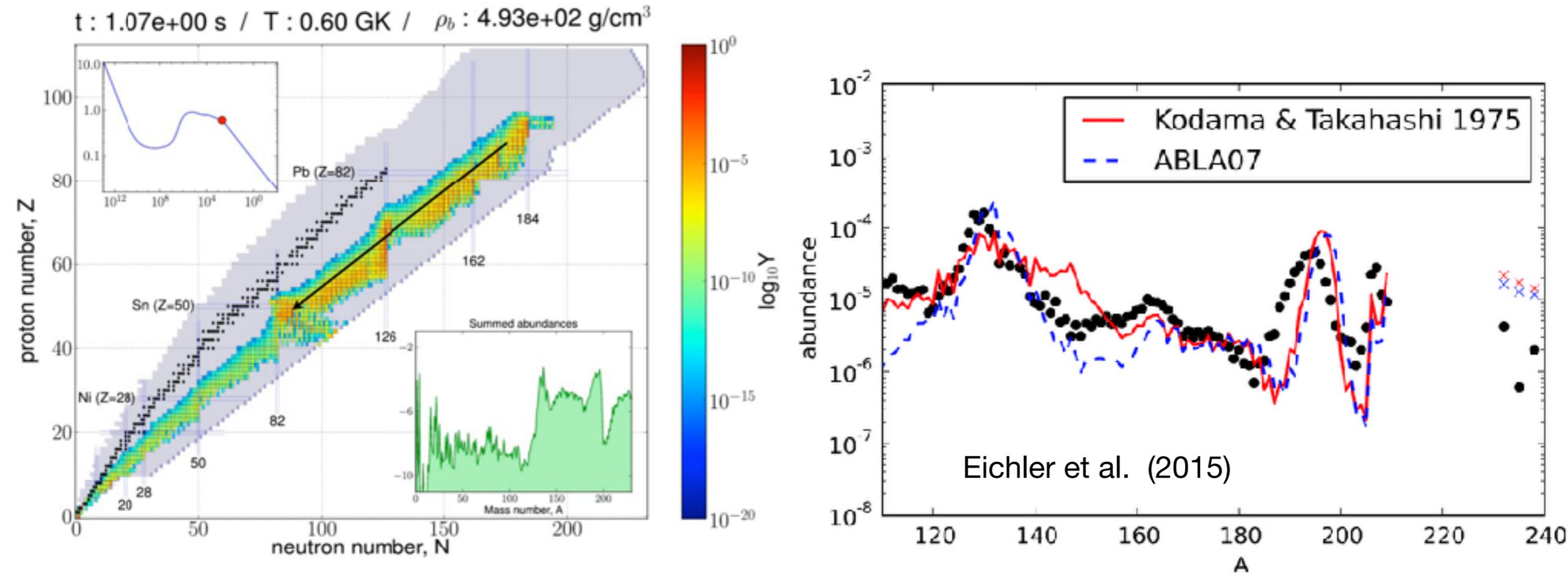
Nucleosynthesis path at constant S_n : (n,γ) - (γ,n) equilibrium



Two neutron separation energy: abundances



Fission: barriers and yield distributions

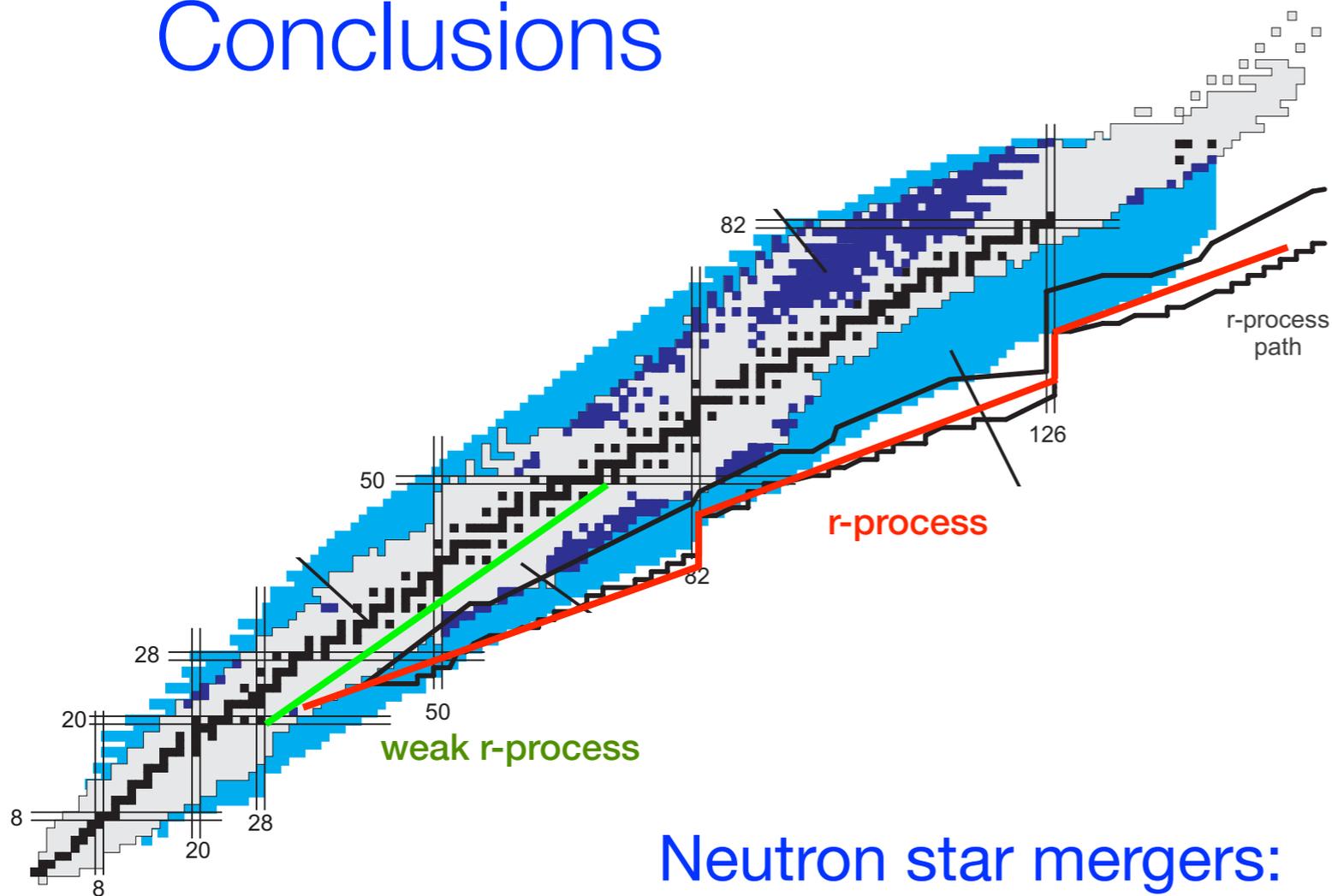


Neutron star mergers: r-process with two fission descriptions

2nd peak ($A \sim 130$): fission yield distribution

3rd peak ($A \sim 195$): mass model, neutron captures

Conclusions



Neutron star mergers:
r-process
weak r-process
Kilonova

Impact of nuclear physics and astrophysics

Observations to constrain astrophysics

Core-collapse supernovae:
wind: up to $\sim Ag$
Magneto-rot.: r-process

