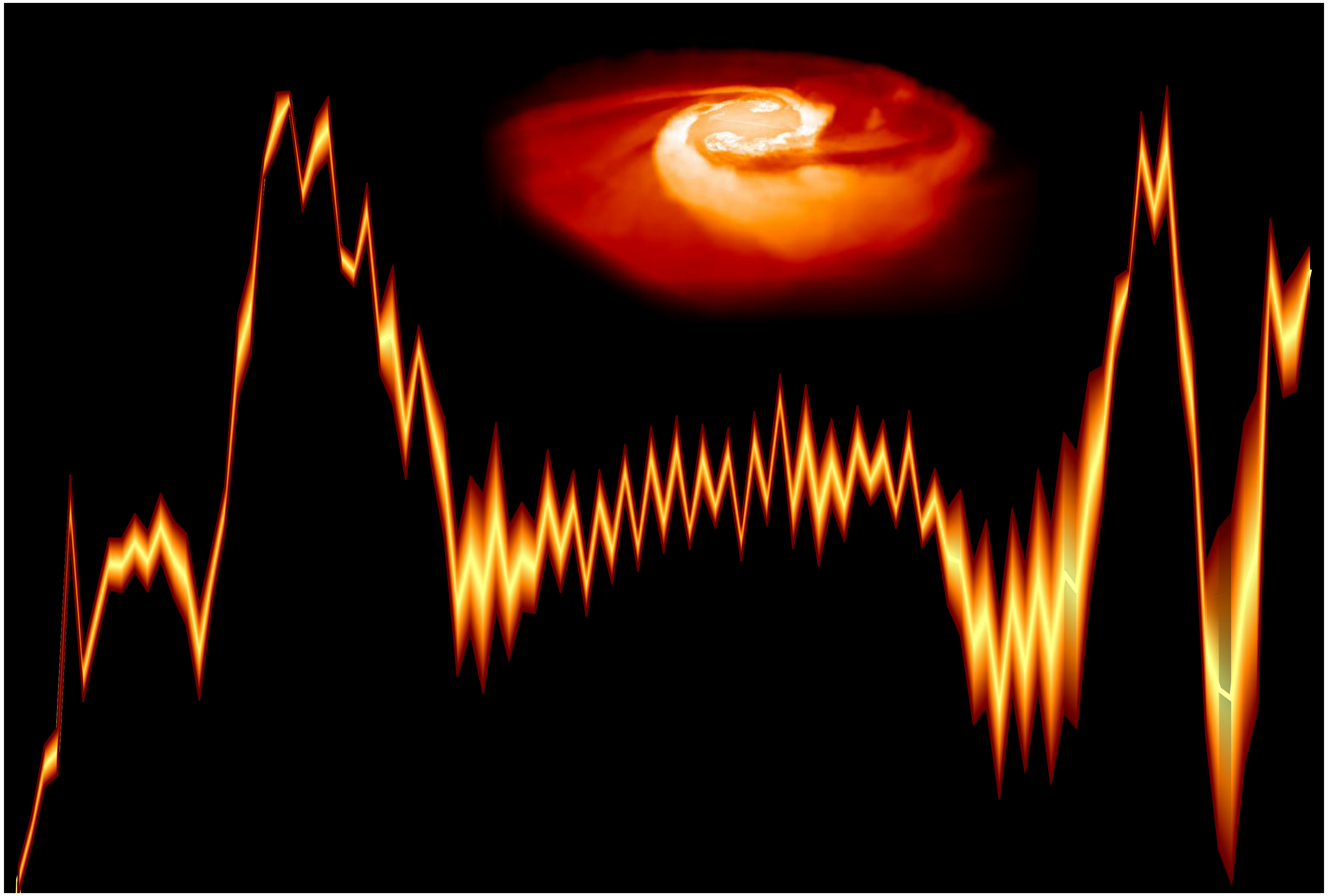
The r-processes and their astrophysical sites



Almudena Arcones

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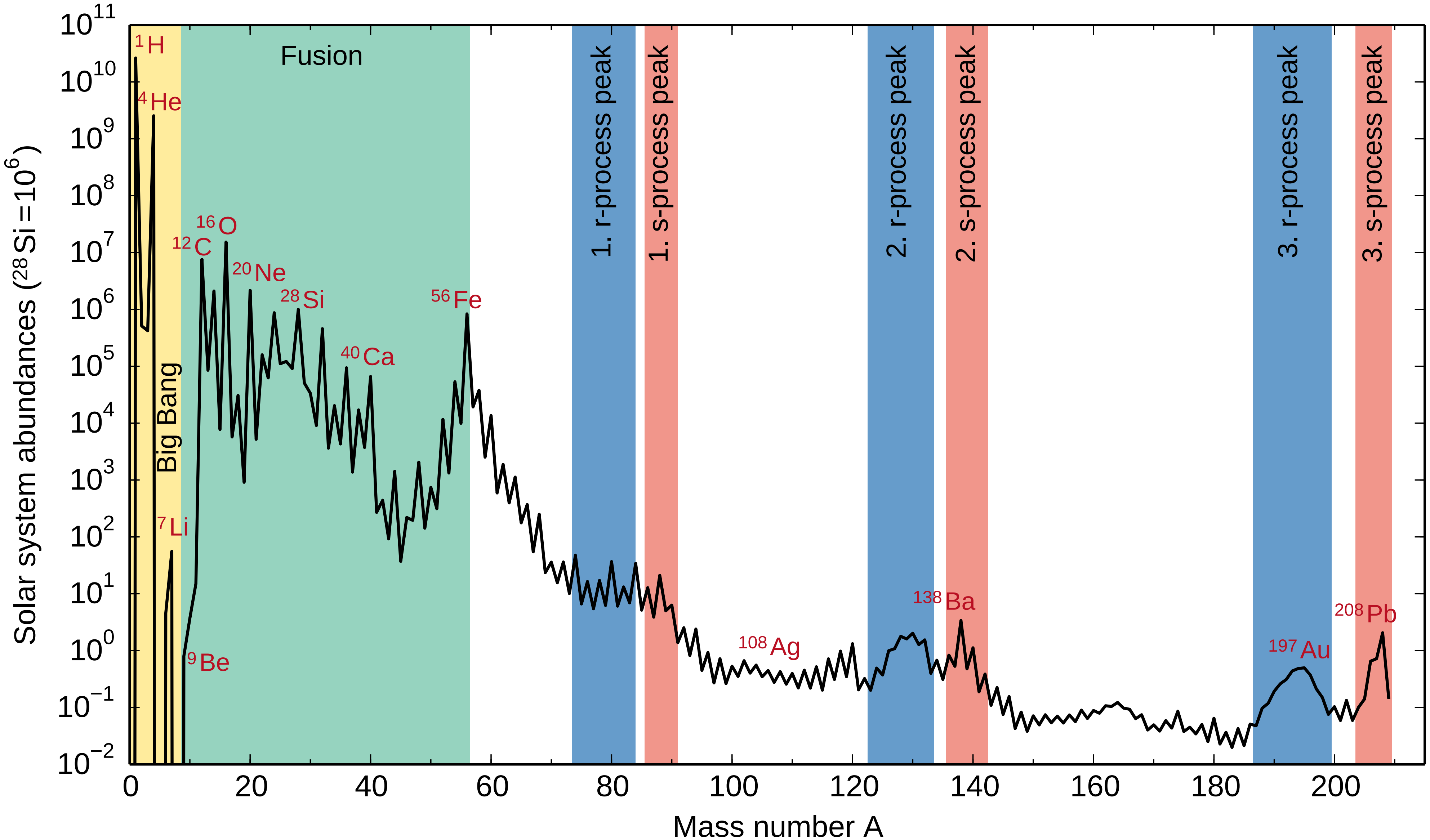
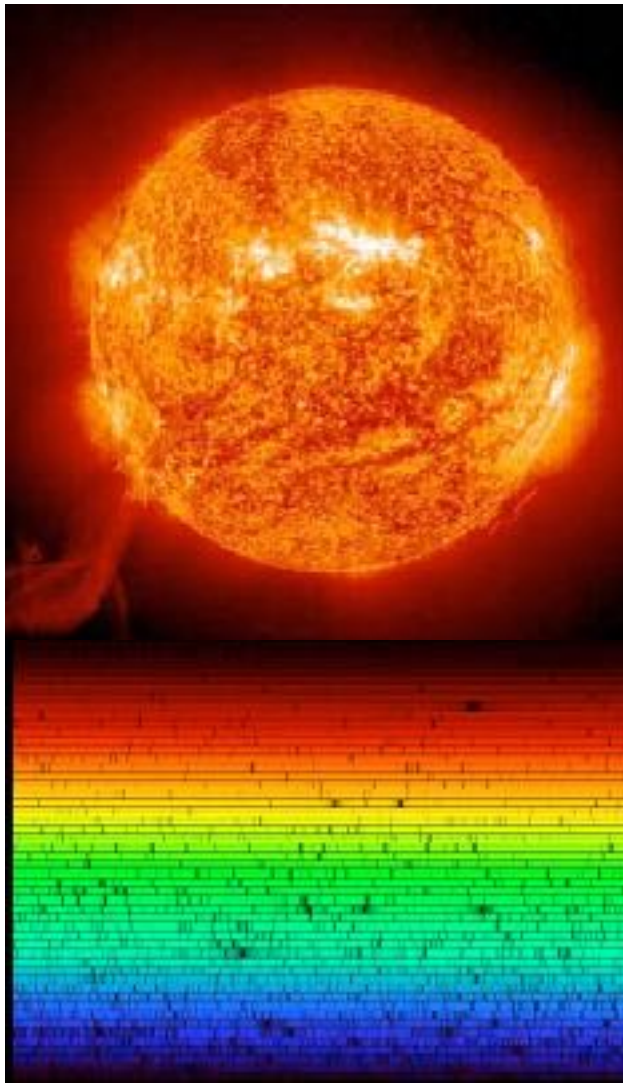
Solar system abundances

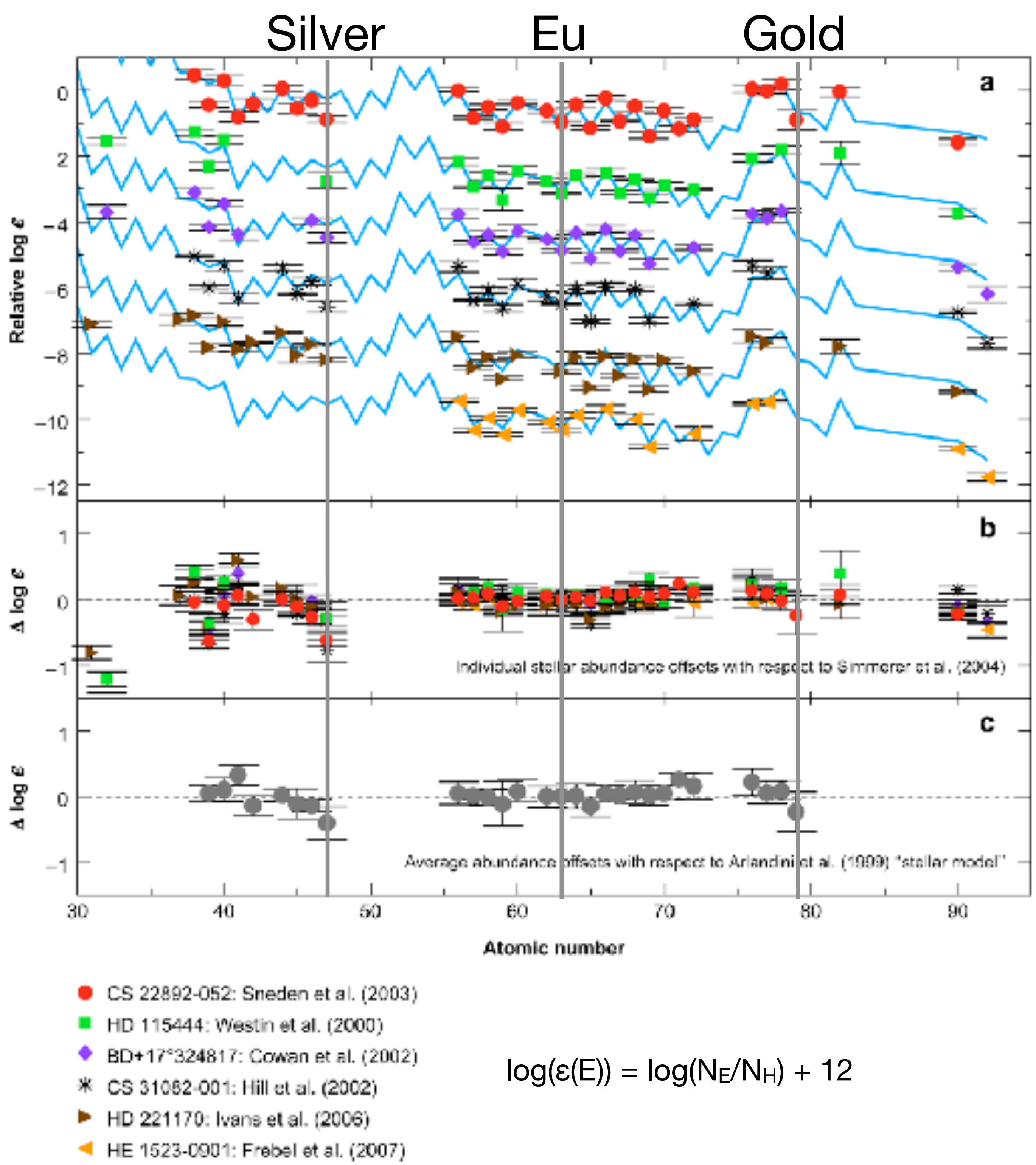
Solar photosphere and meteorites:
chemical signature of gas cloud where the Sun formed

Contribution of all nucleosynthesis processes





r-process in ultra metal-poor stars



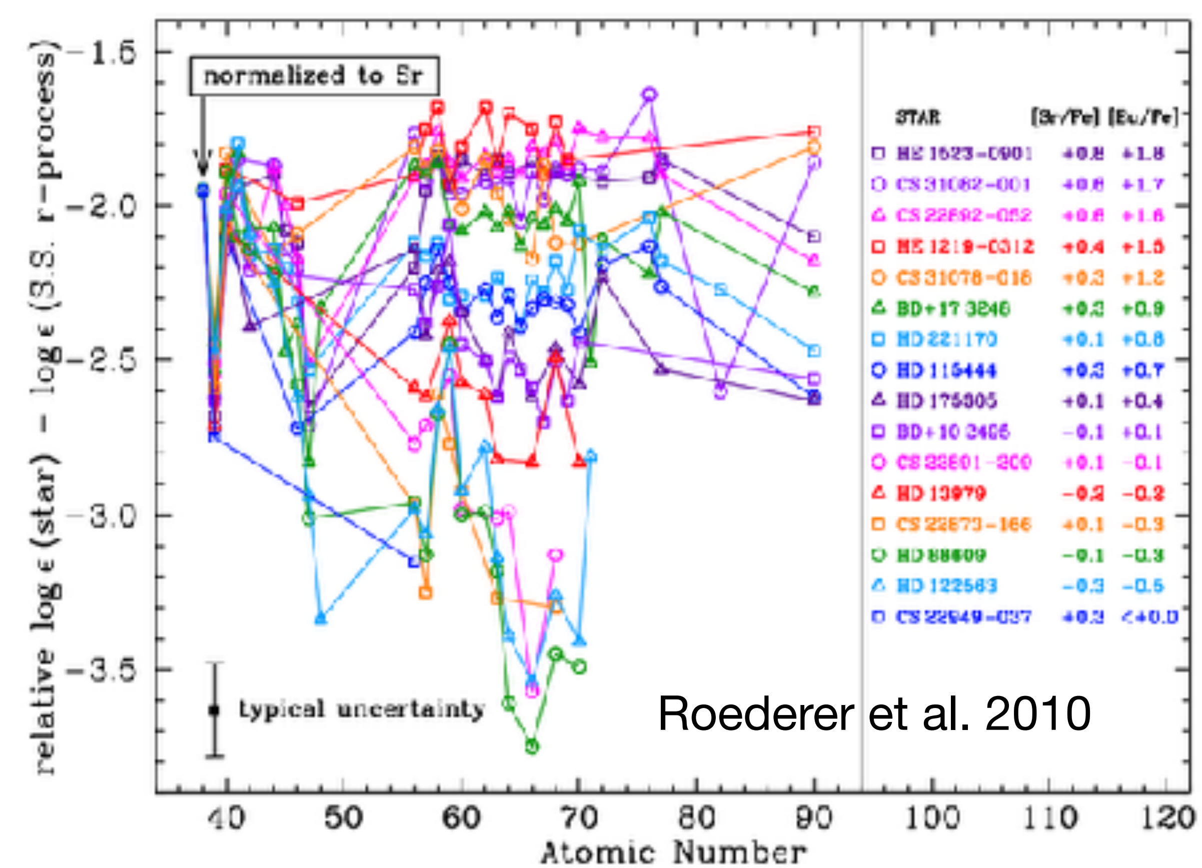
$\log(\varepsilon(E)) = \log(N_E/N_H) + 12$

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

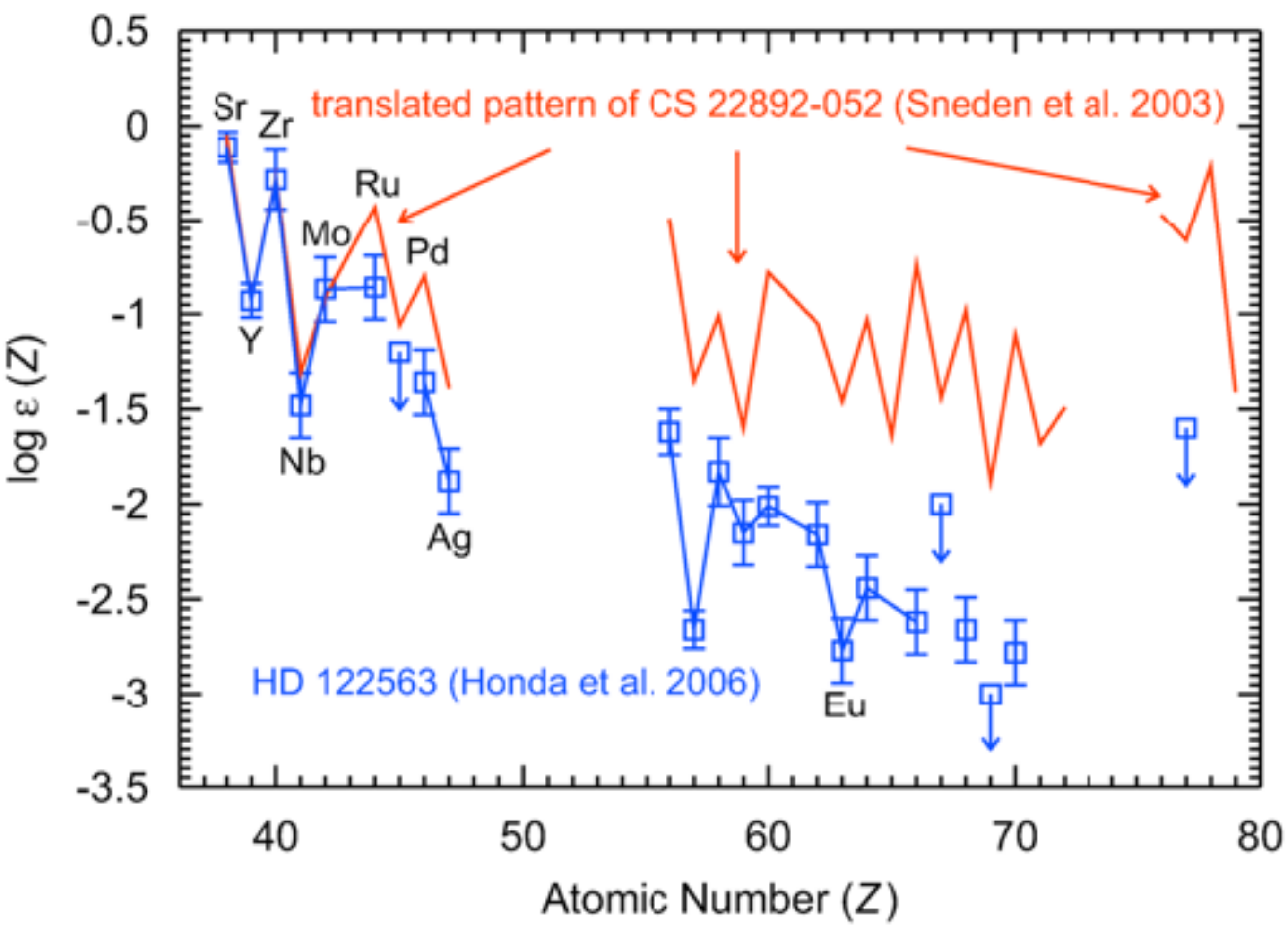
Scatter for lighter heavy elements, Z~40



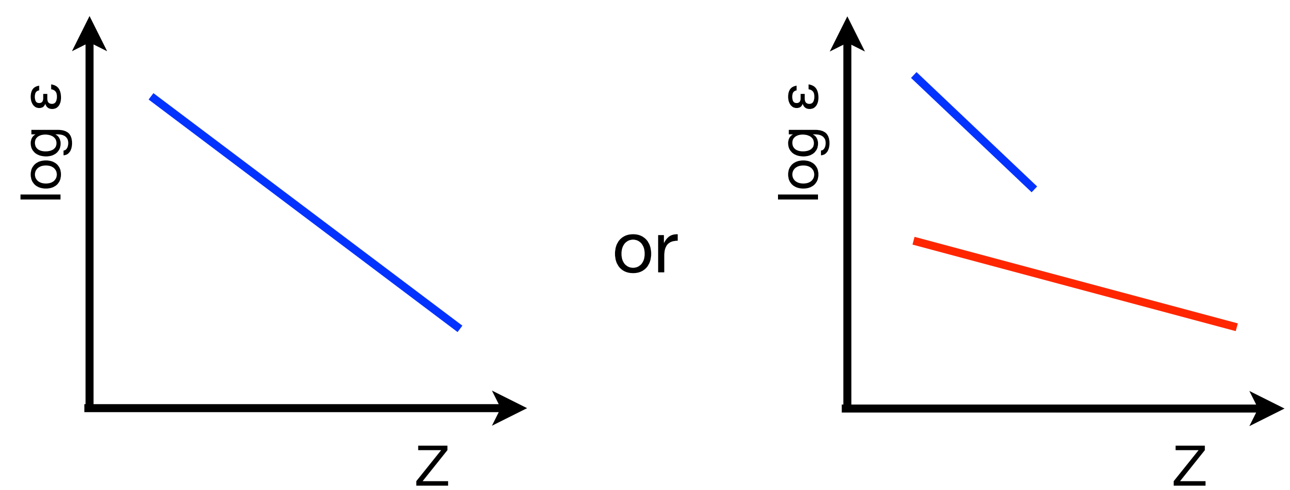
Roederer et al. 2010

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?

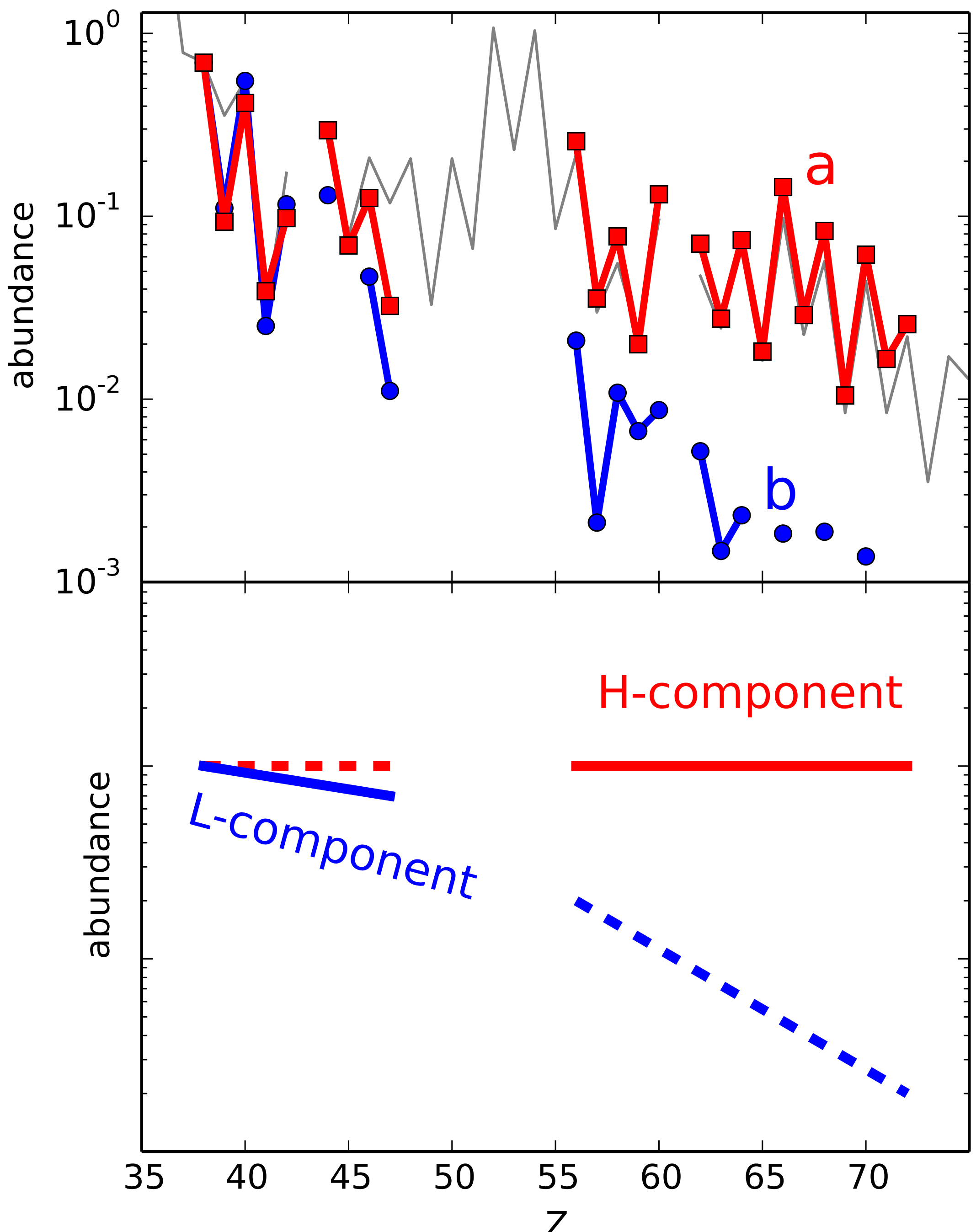


Honda-like = limited r-process

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

Nucleosynthesis components

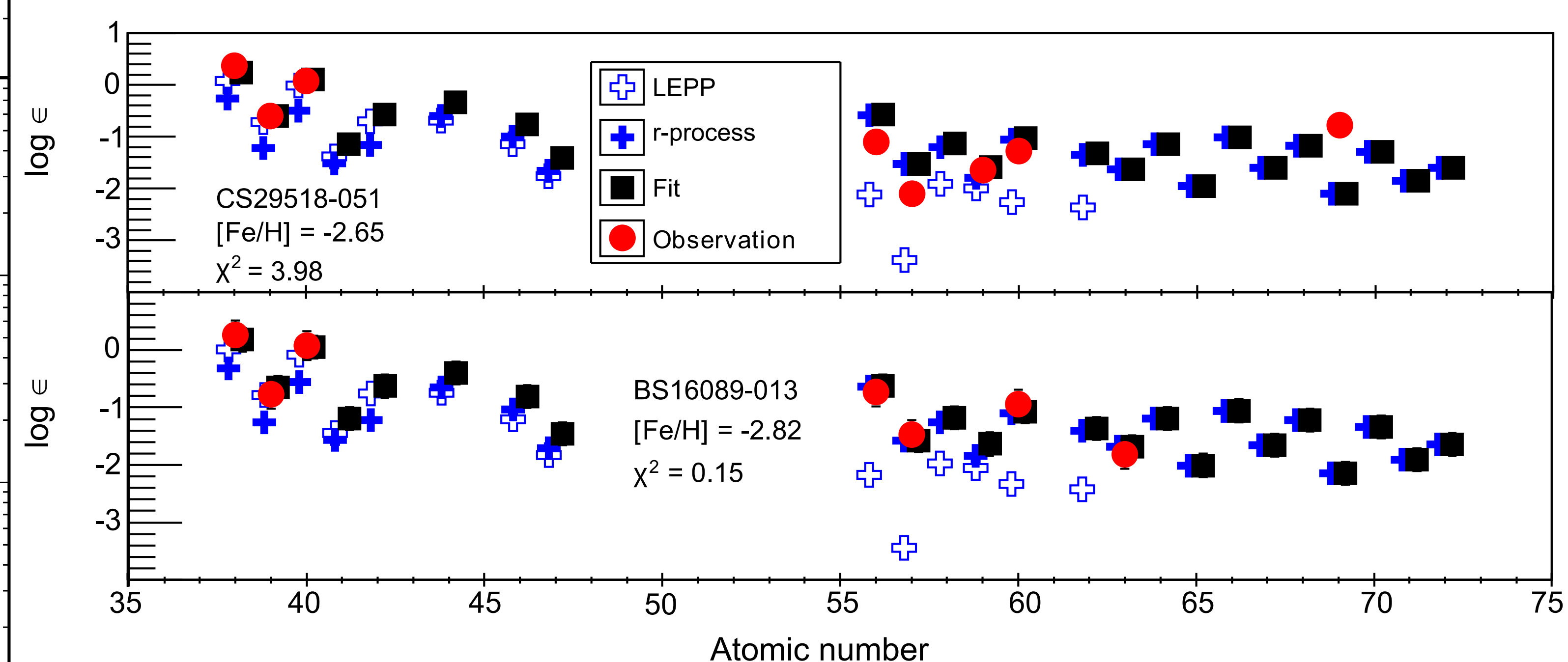
Abundance of many UMP stars can be explained by two components:



Component abundance pattern: Y_H and Y_L

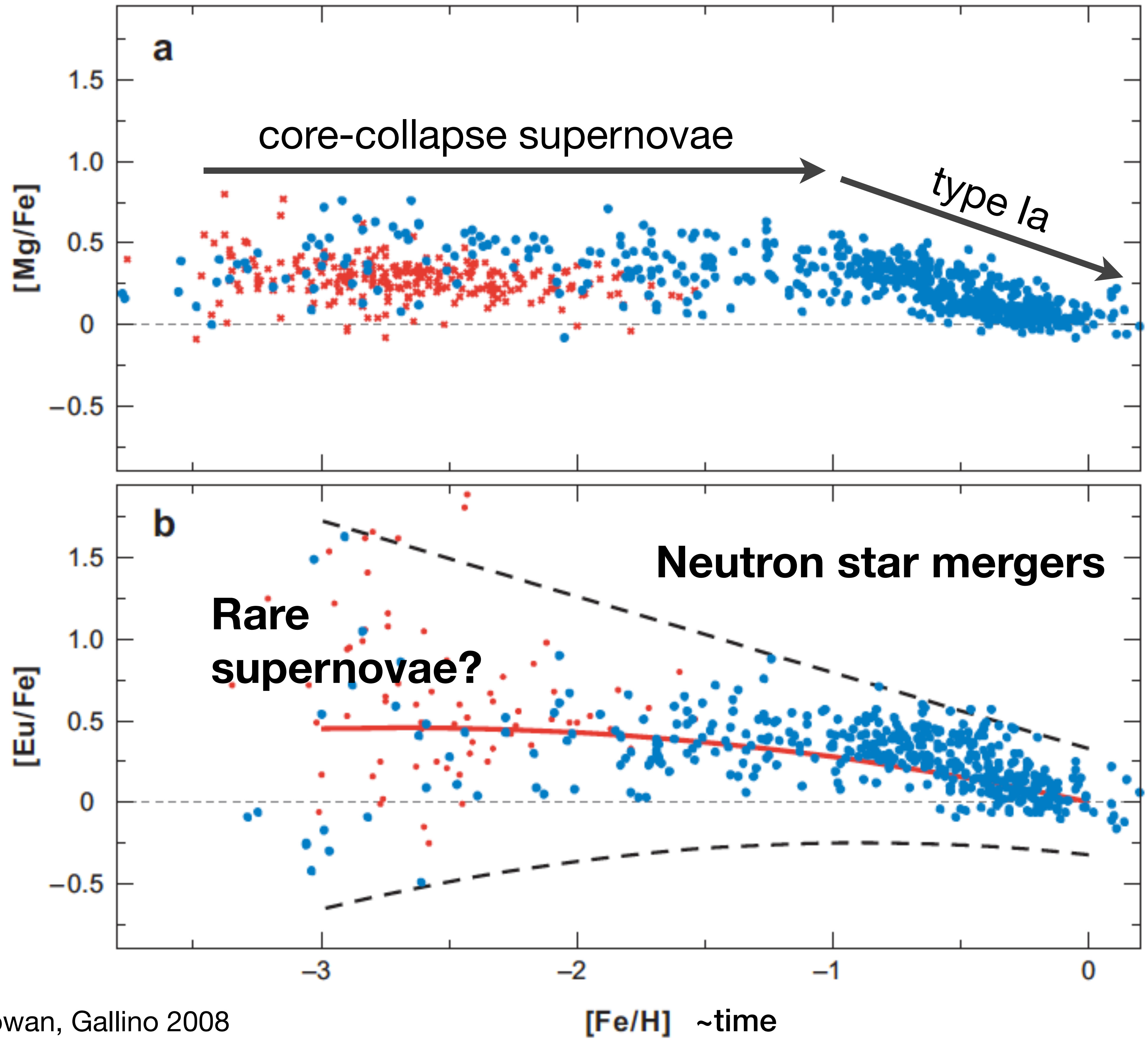
Fit abundance as combination of components:

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



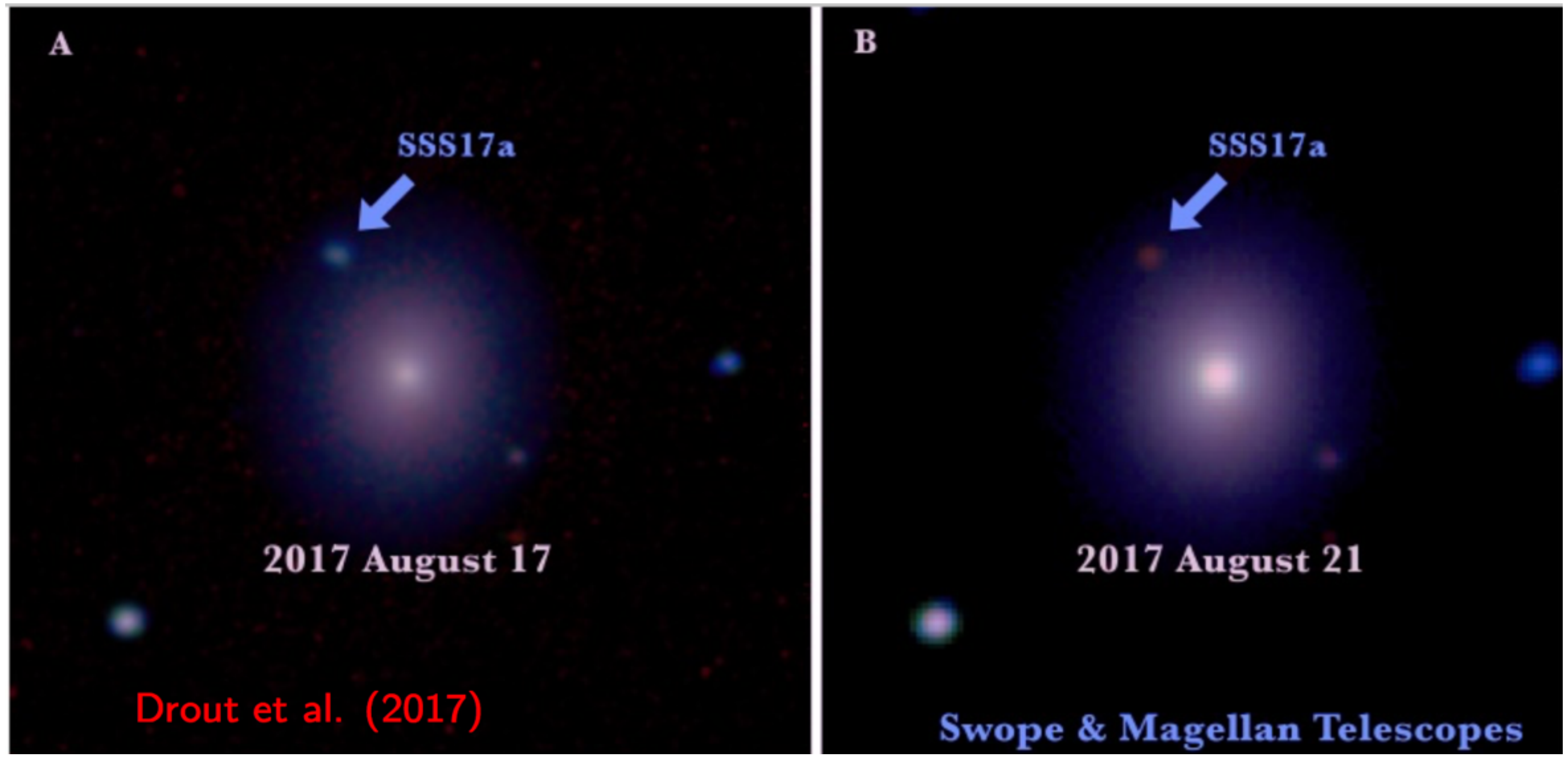
C.J. Hansen, Montes, Arcones (2014)

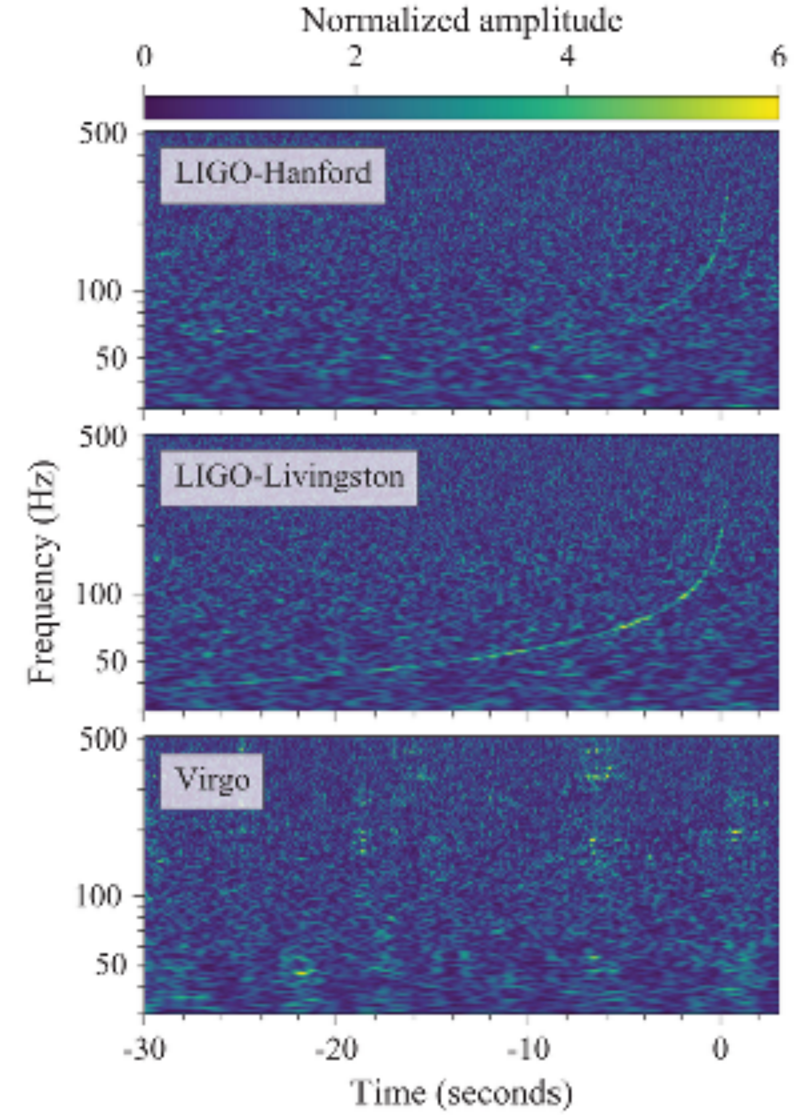
Trends with metallicity



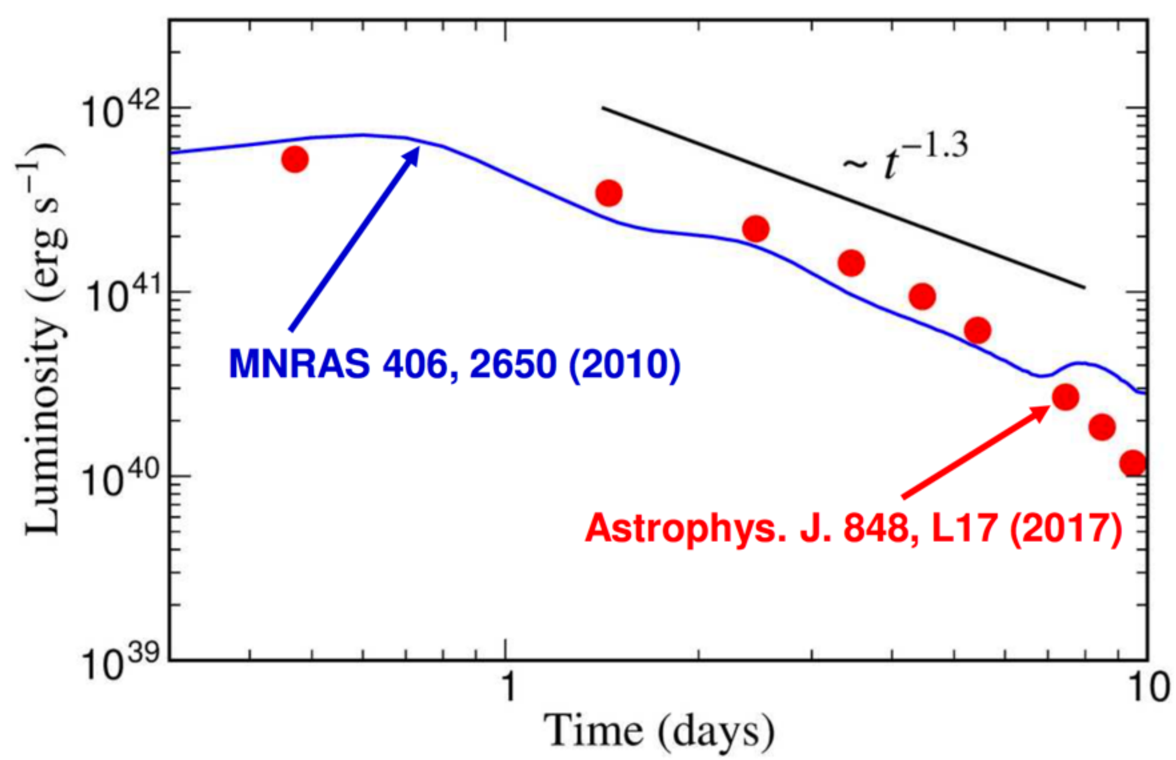
Sneden, Cowan, Gallino 2008

Neutron star mergers

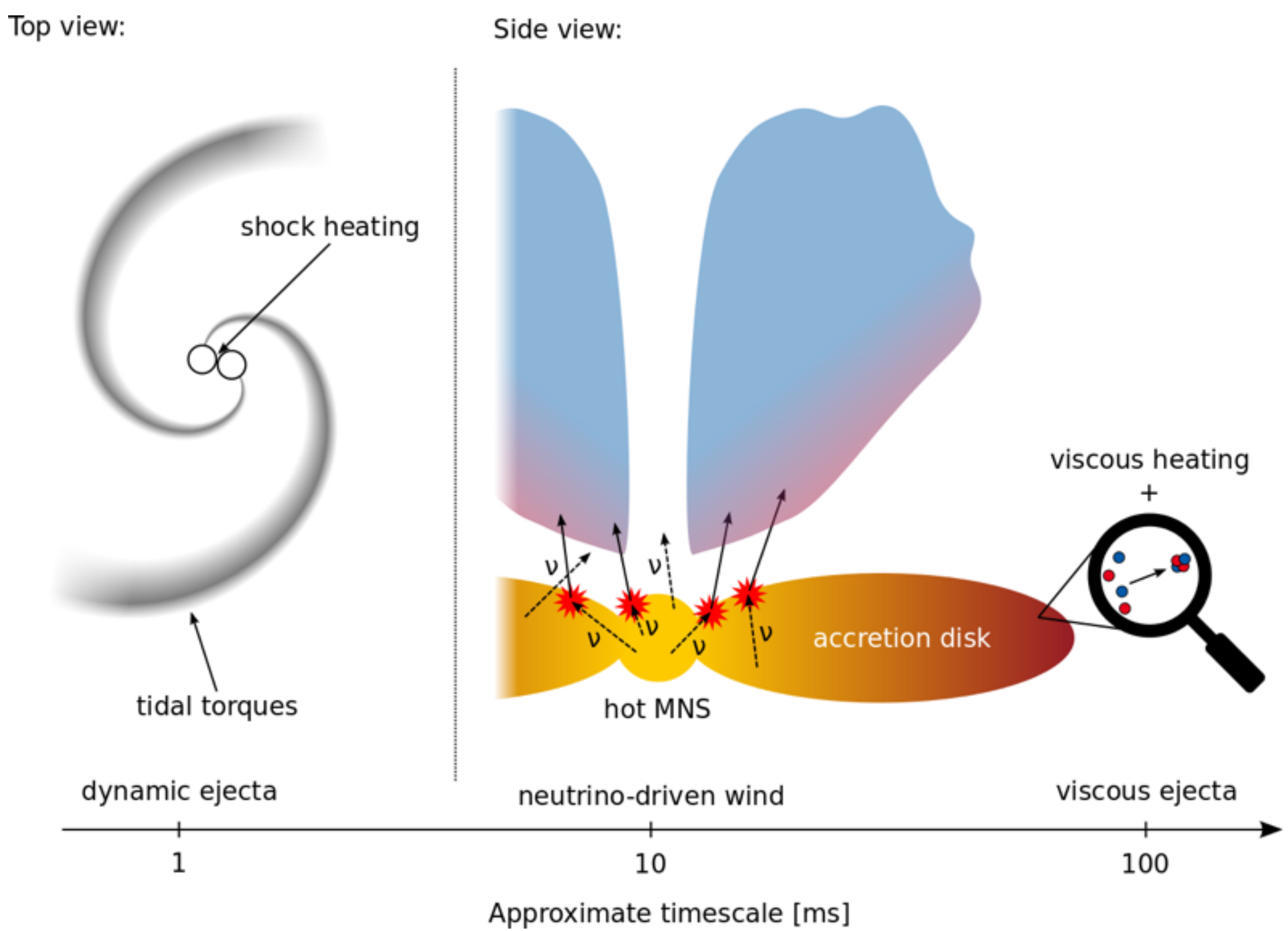


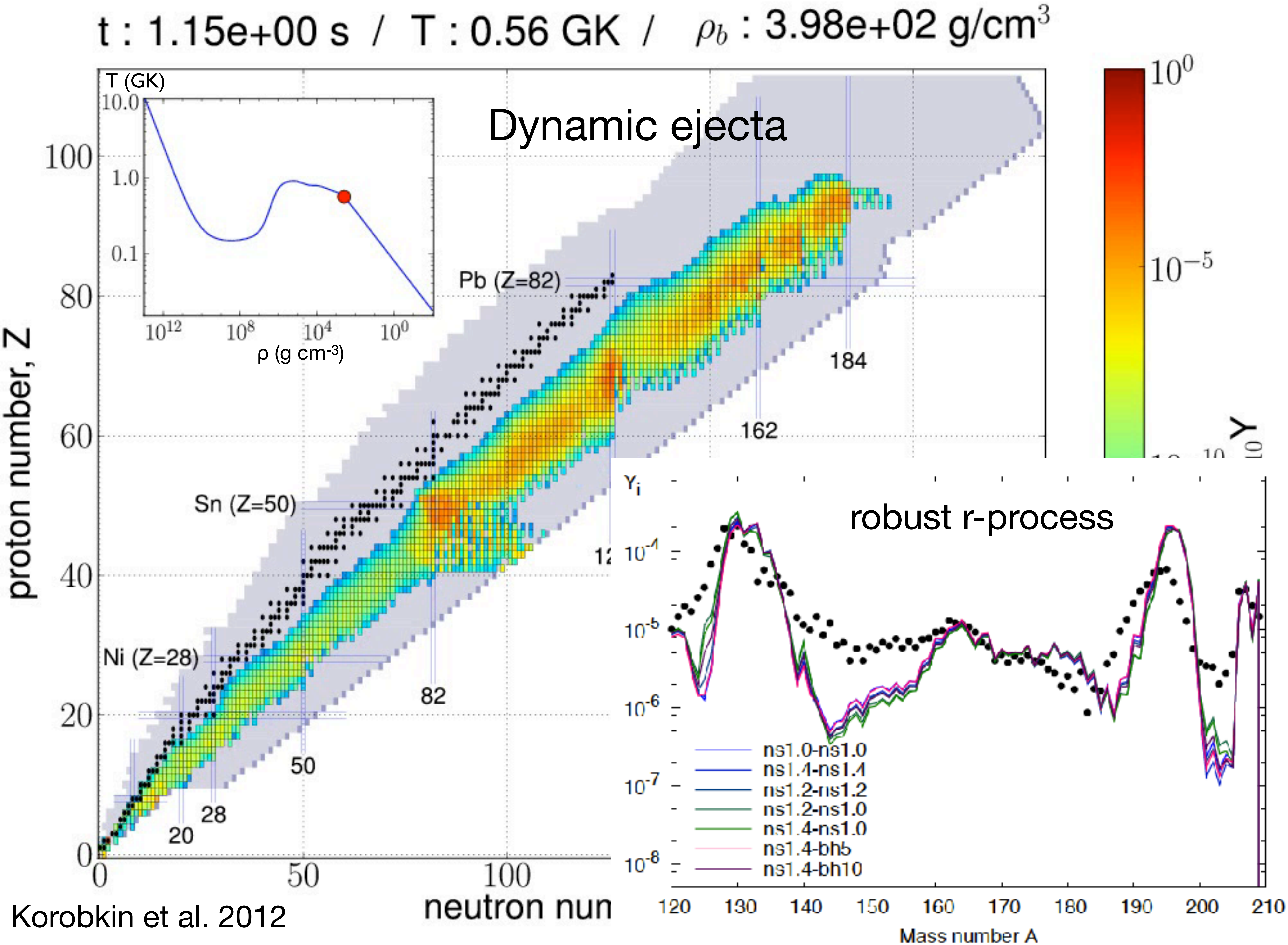


R-process in neutron star mergers confirmed by kilonova (radioactive decay of n-rich nuclei) after gravitational wave detection from GW170817



Ejecta and nucleosynthesis

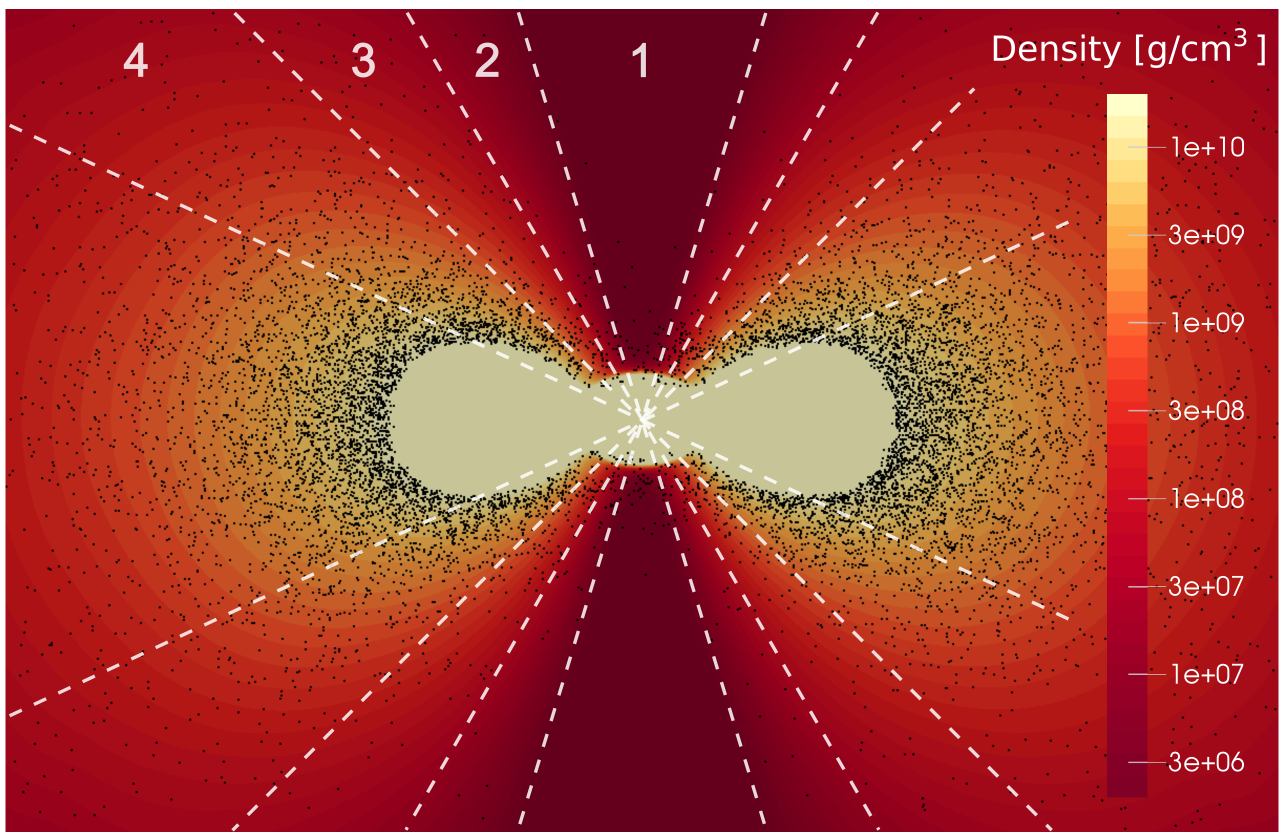




Korobkin et al. 2012

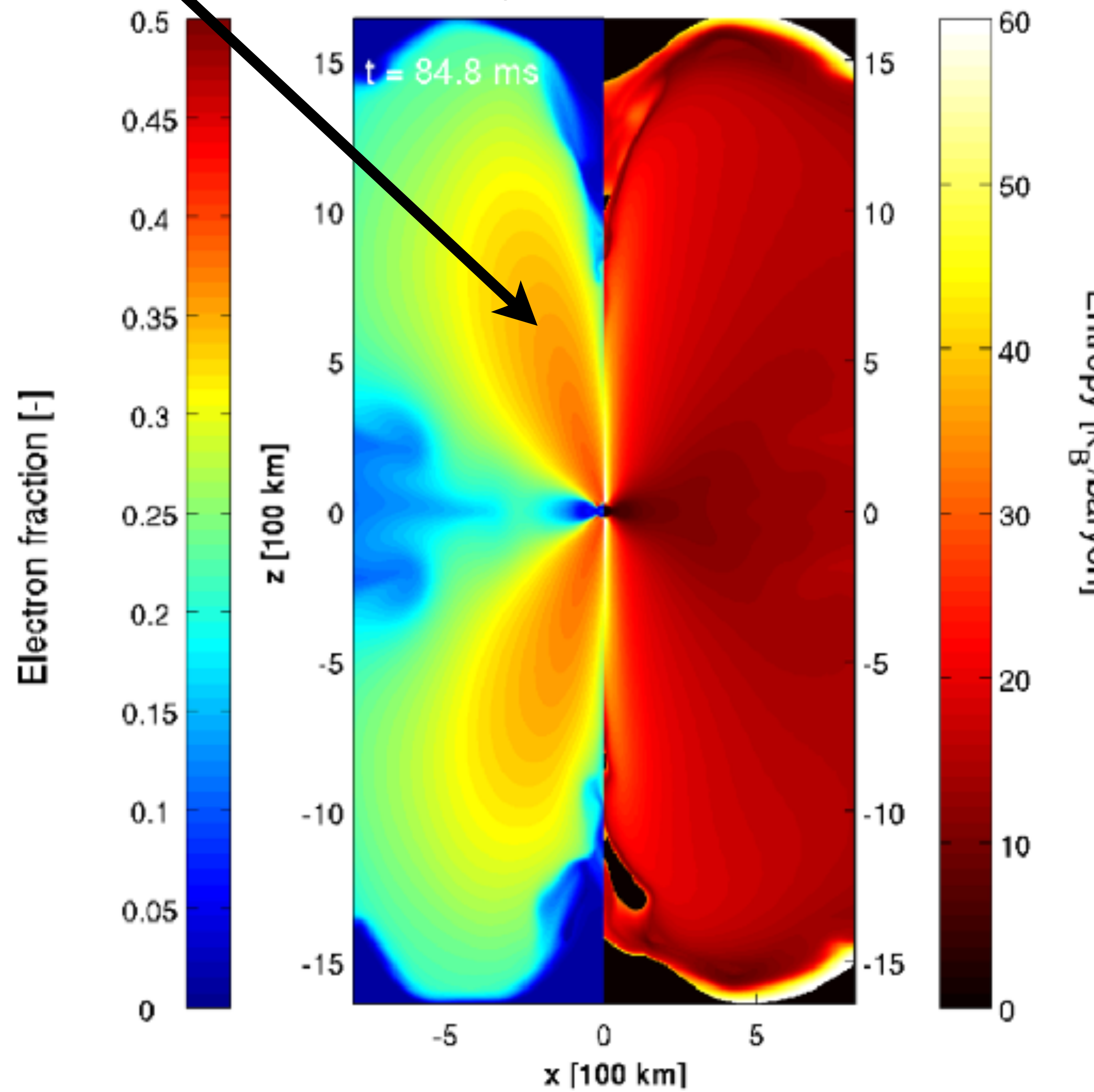
Neutron star mergers: neutrino-driven wind

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



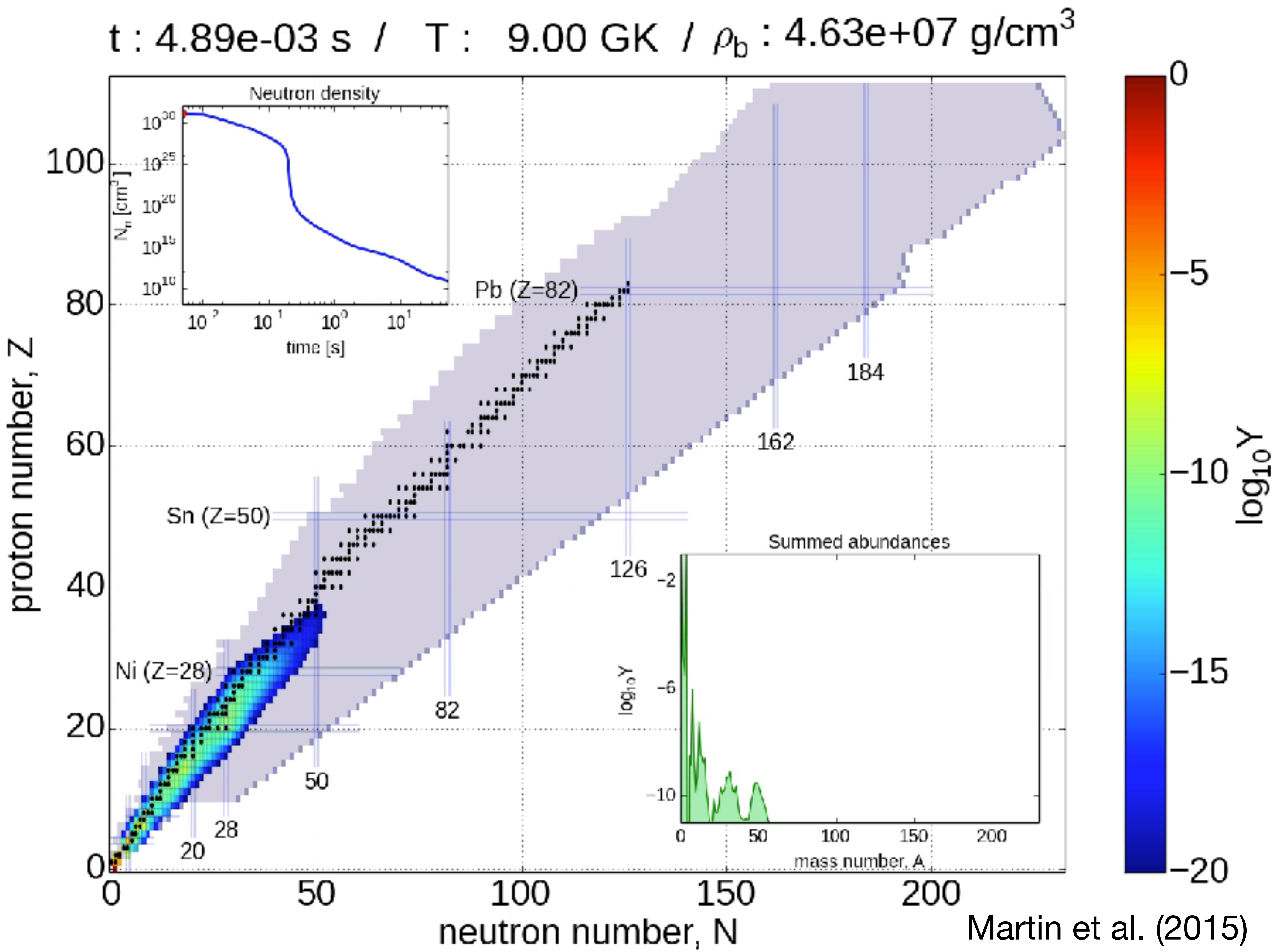
Martin et al. (2015)

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



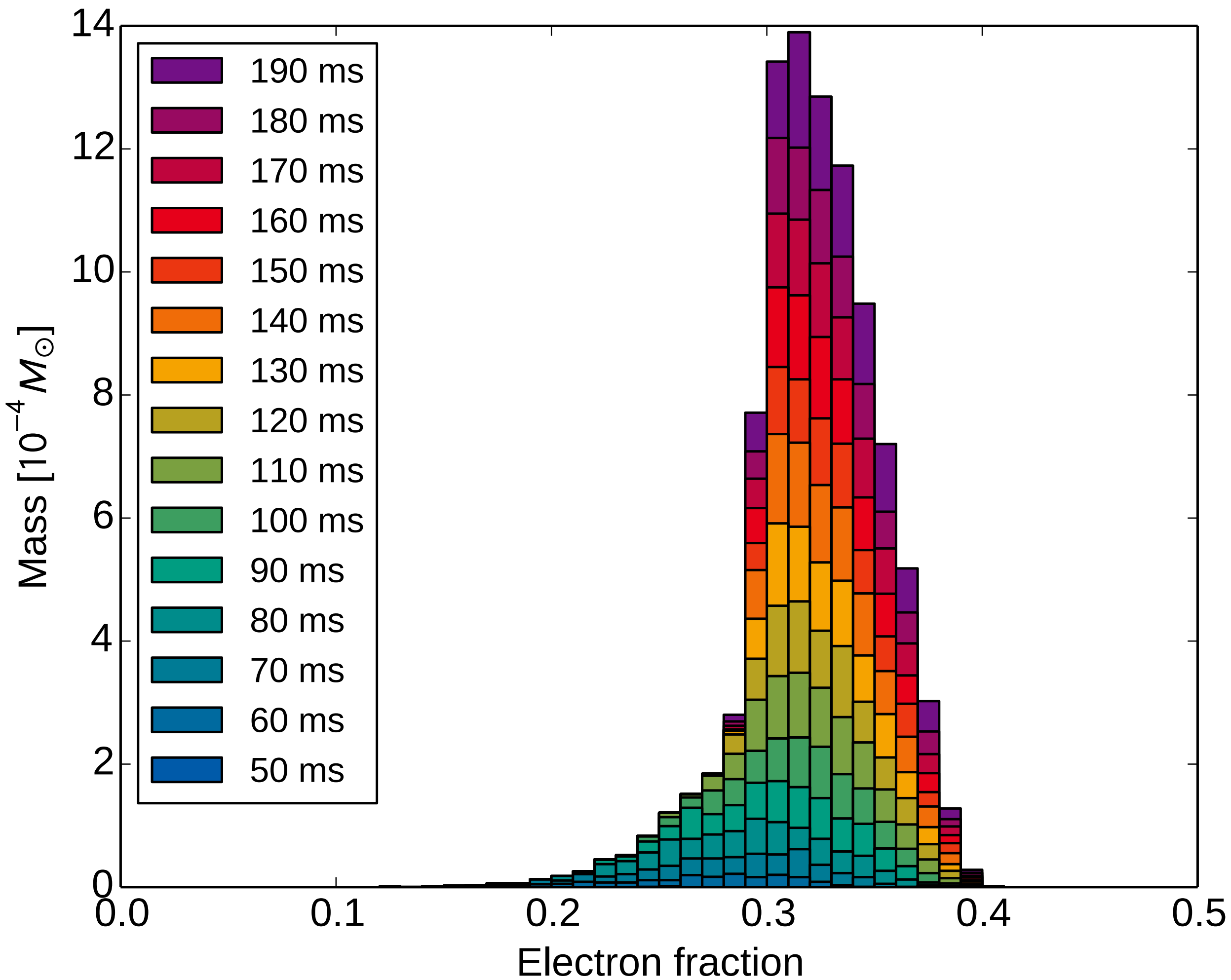
Martin et al. (2015)

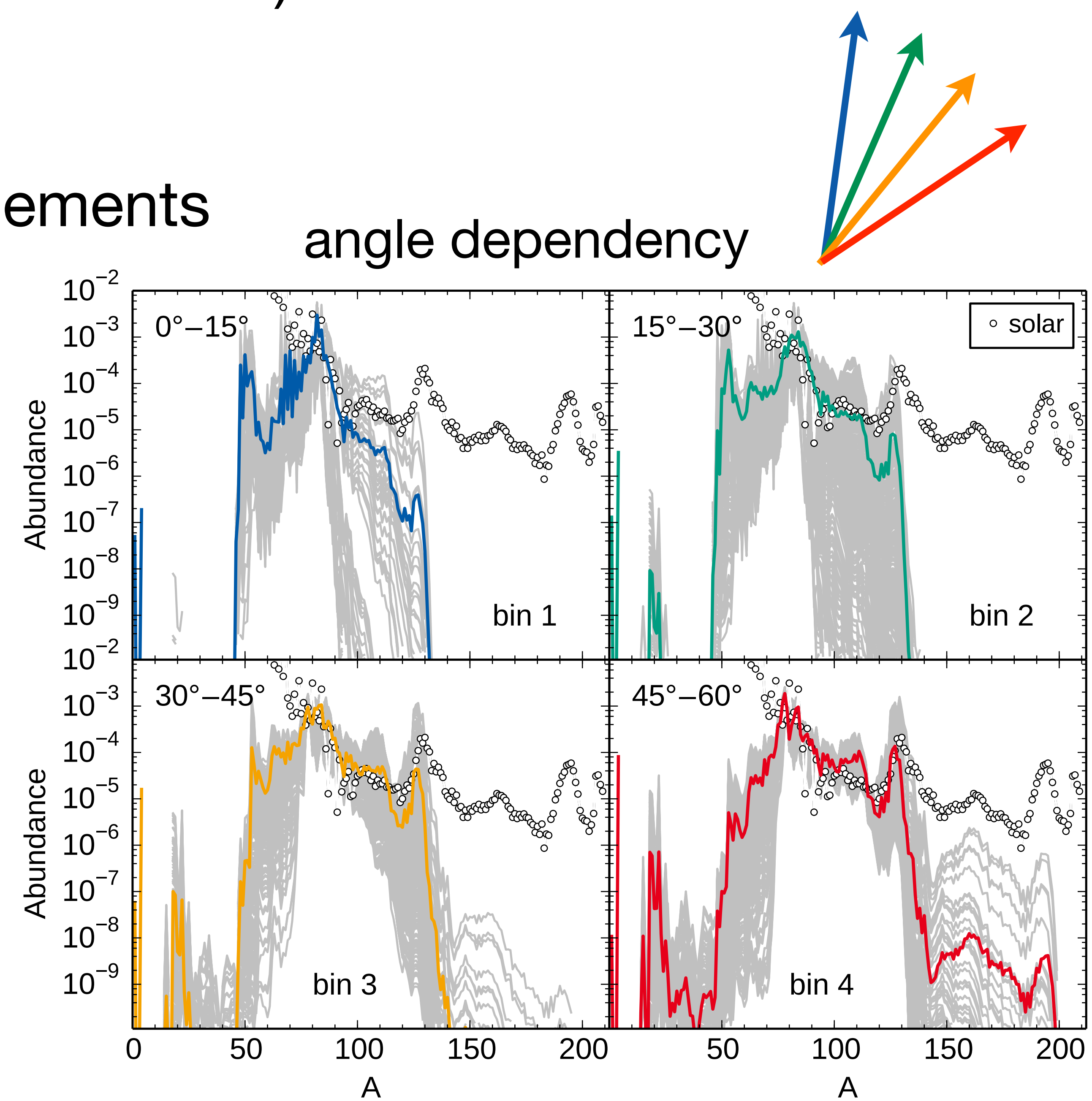
Time and angle dependency

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



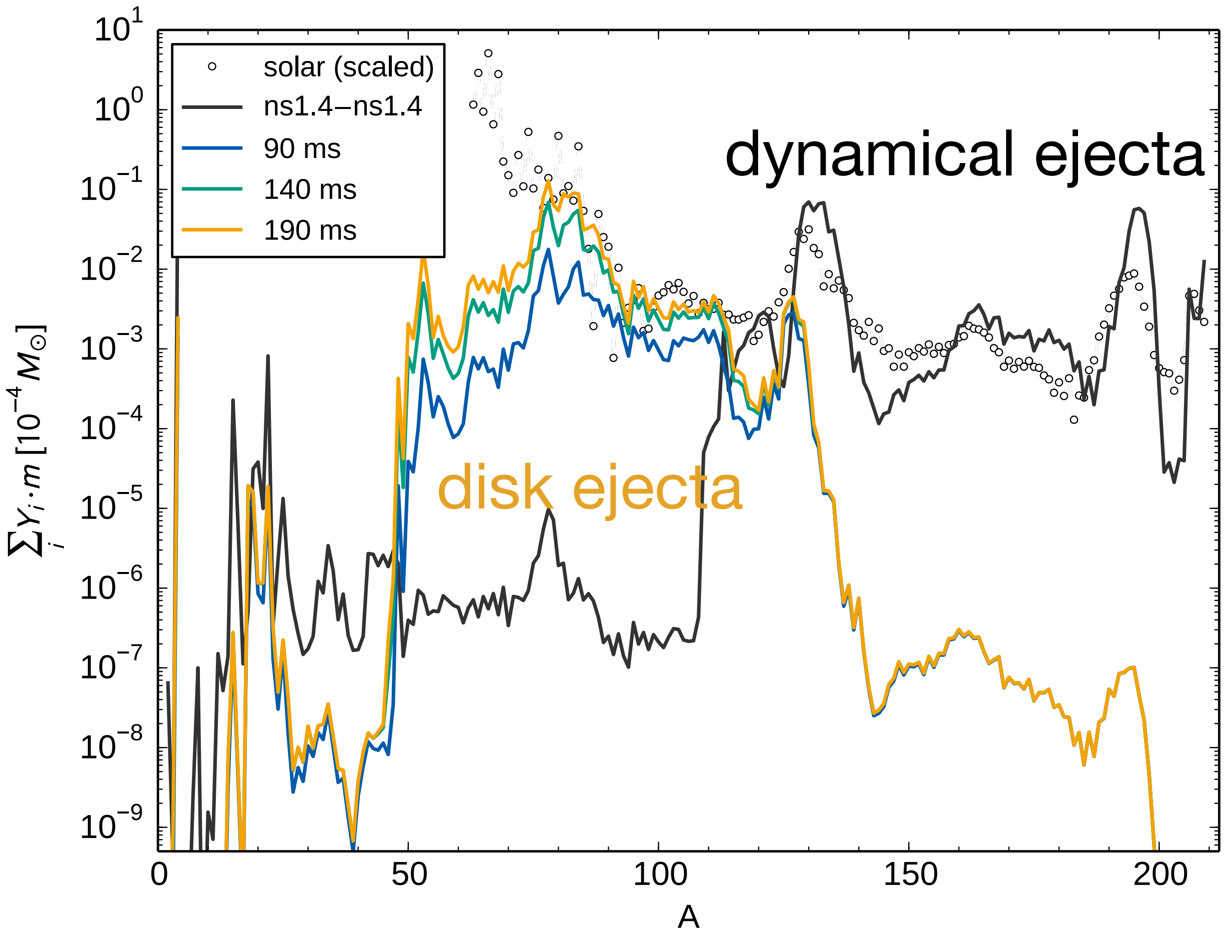


Martin et al. (2015)

Wind and dynamic ejecta

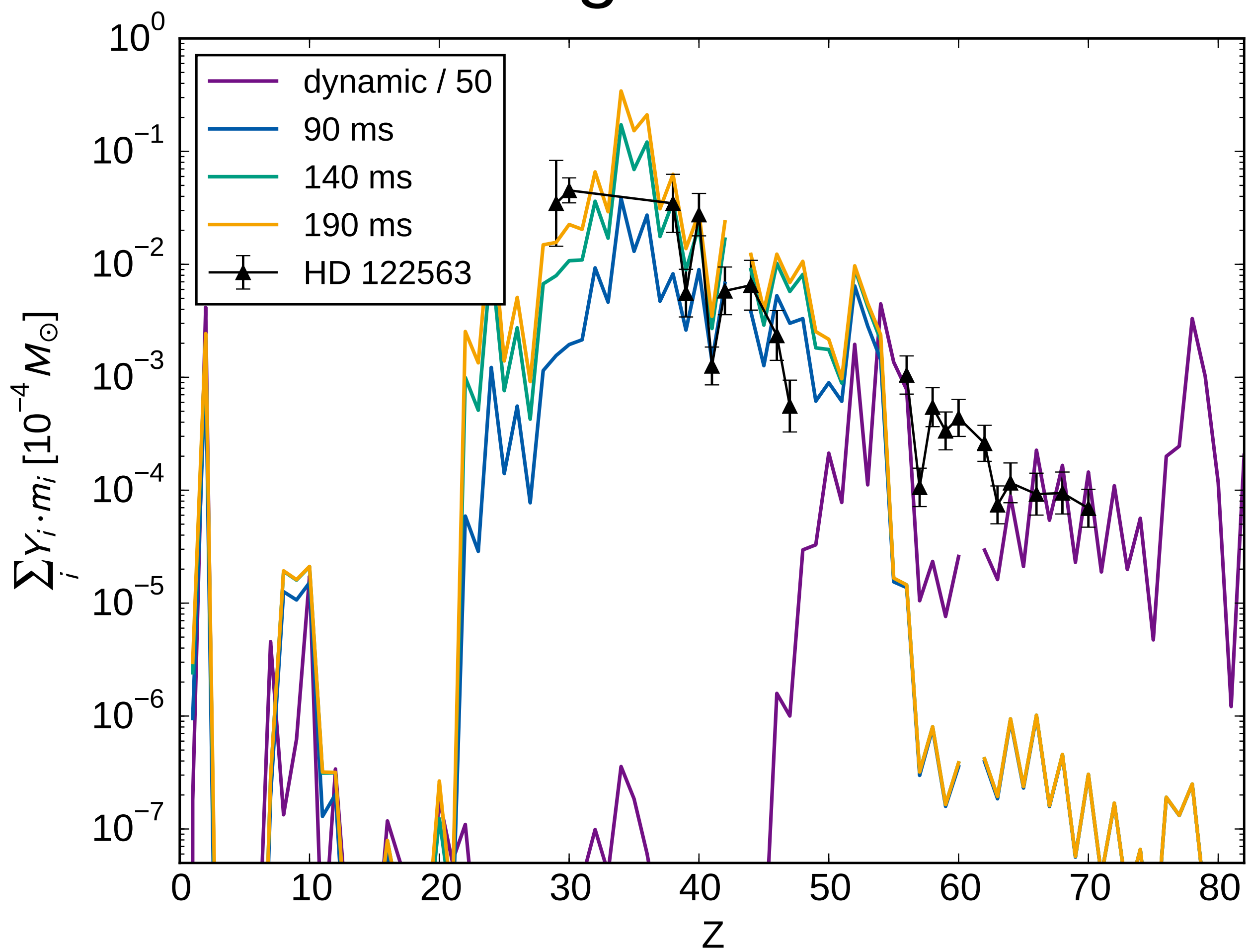
Wind ejecta complement dynamic ejecta

Complete mixing: solar system abundances and UMP stars



Martin et al. (2015)

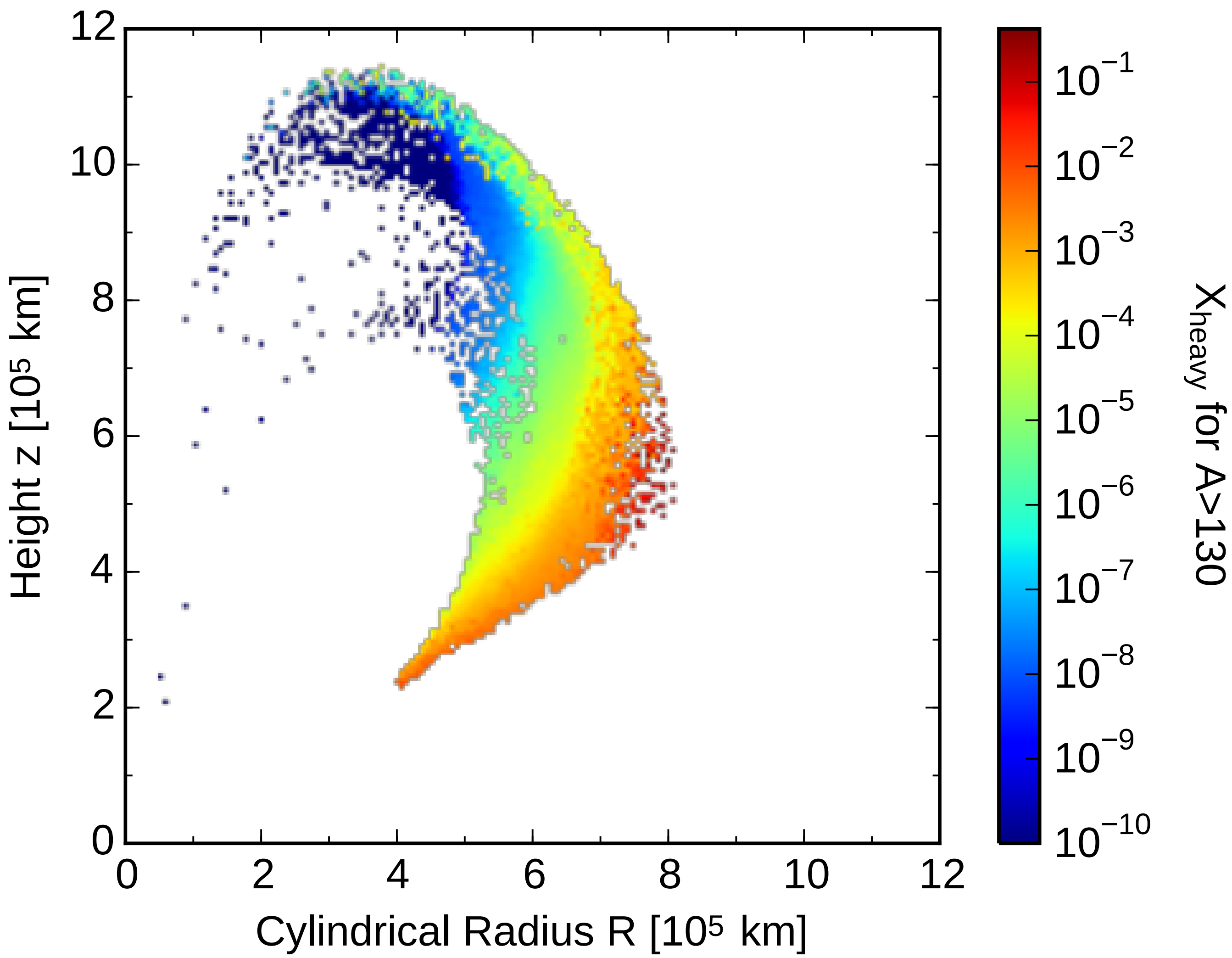
Partial mixing: Honda-like star?



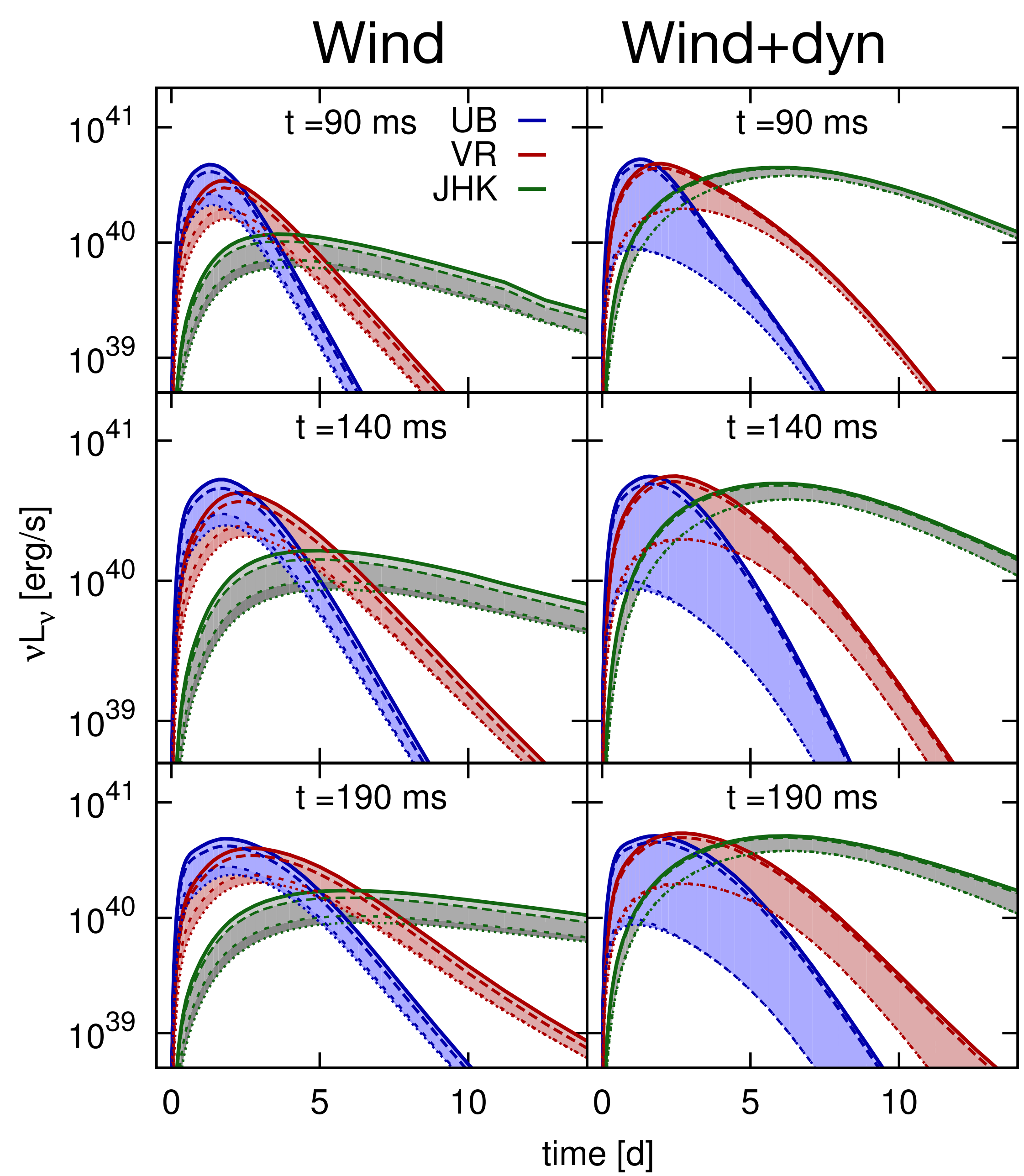
Two components: Hansen et al. 2014

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



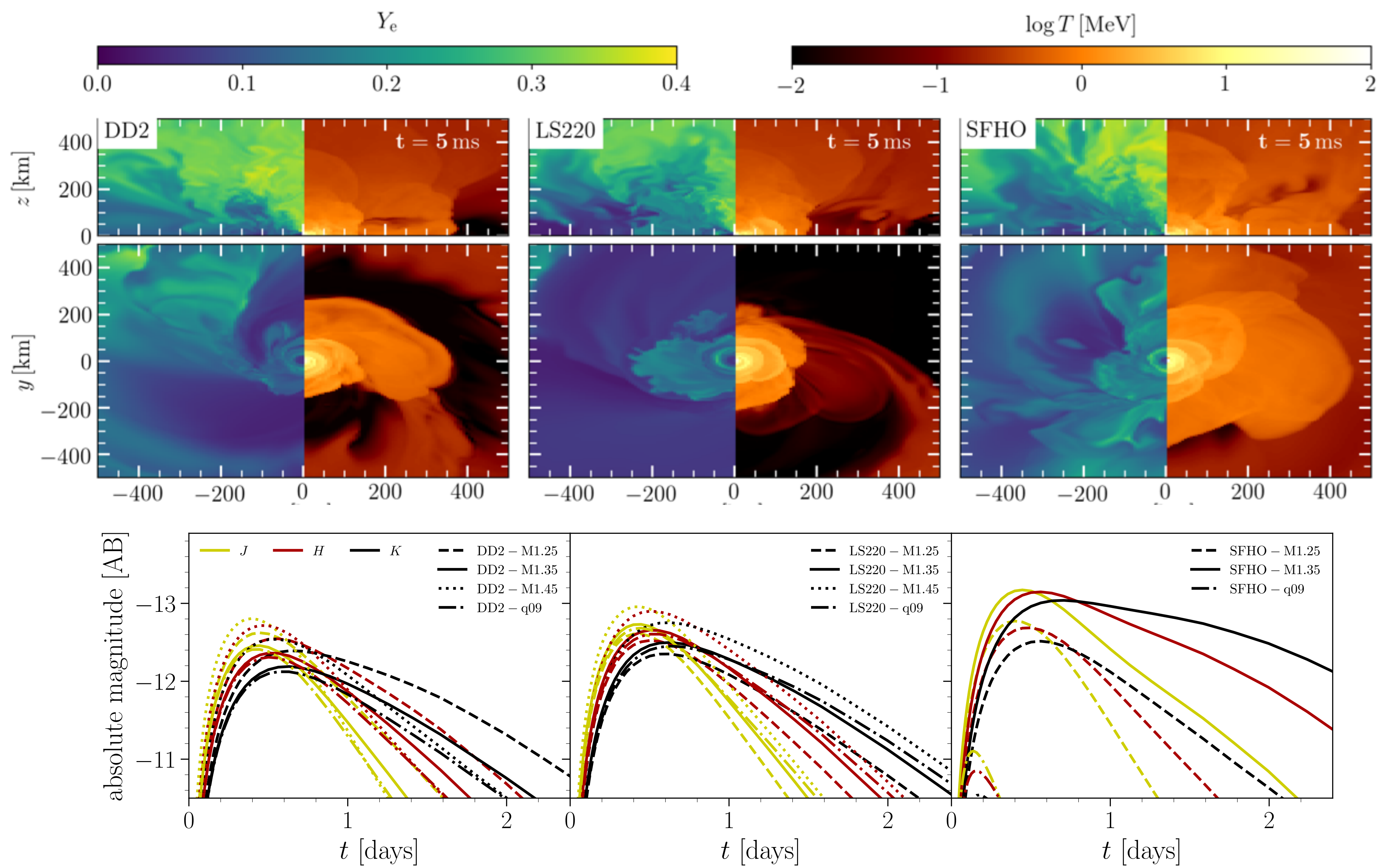
Martin et al. (2015)



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)



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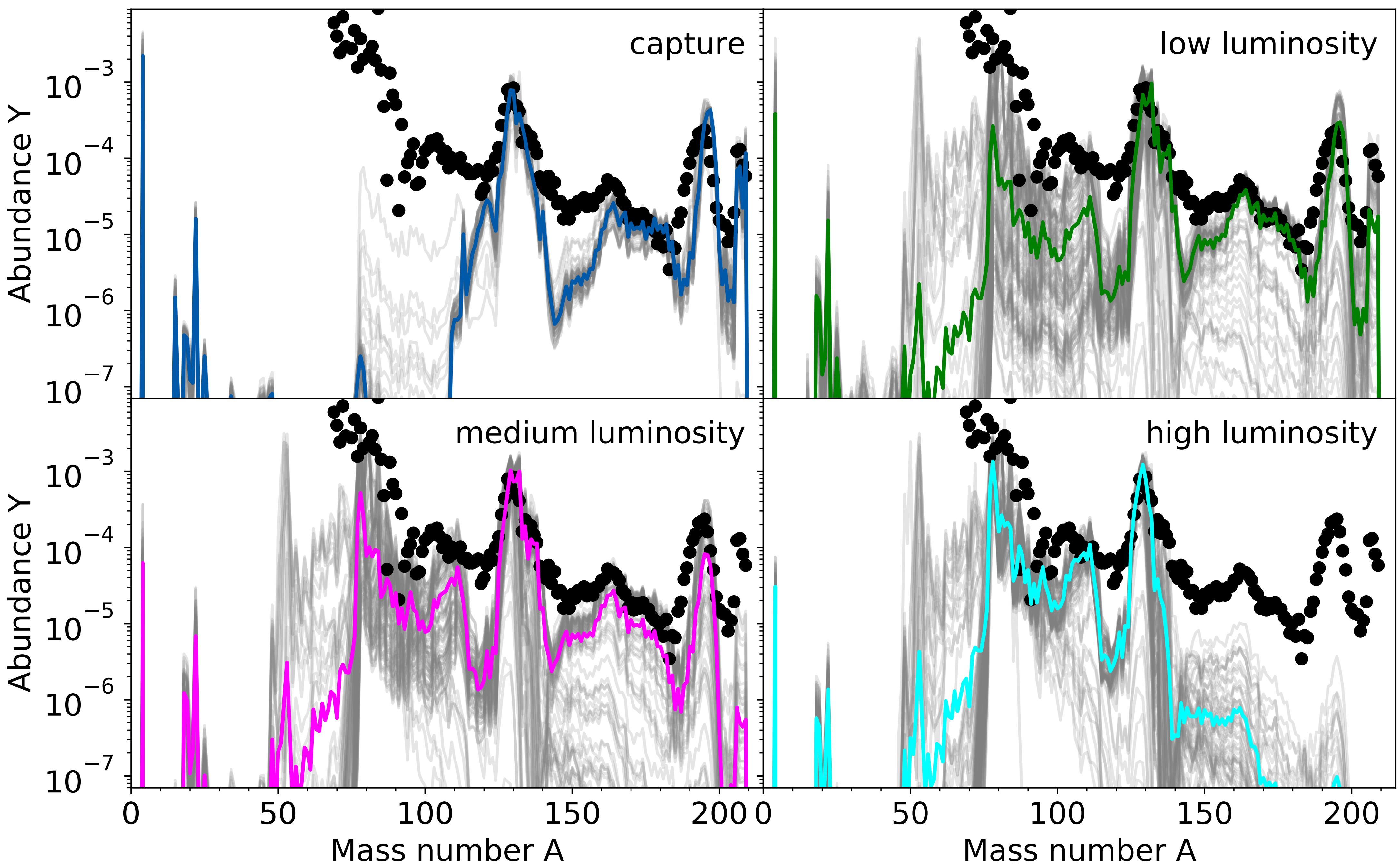
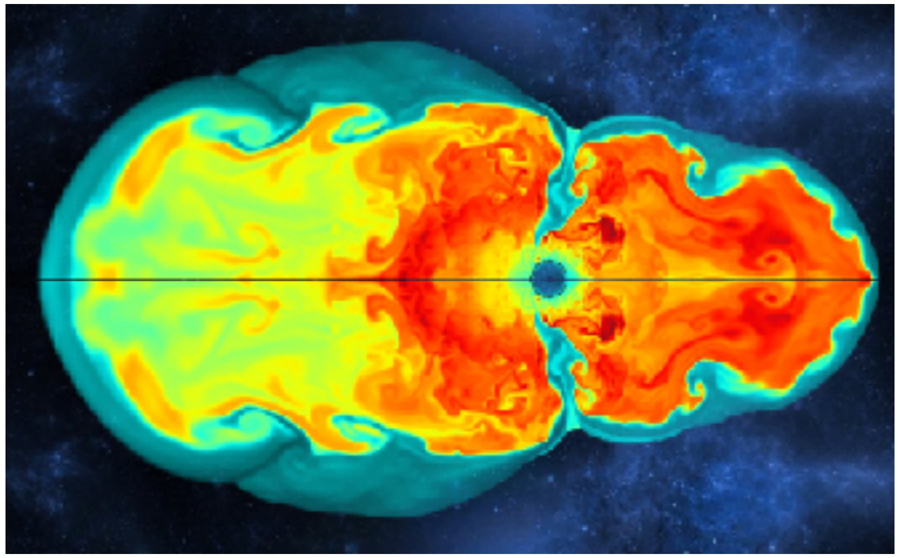


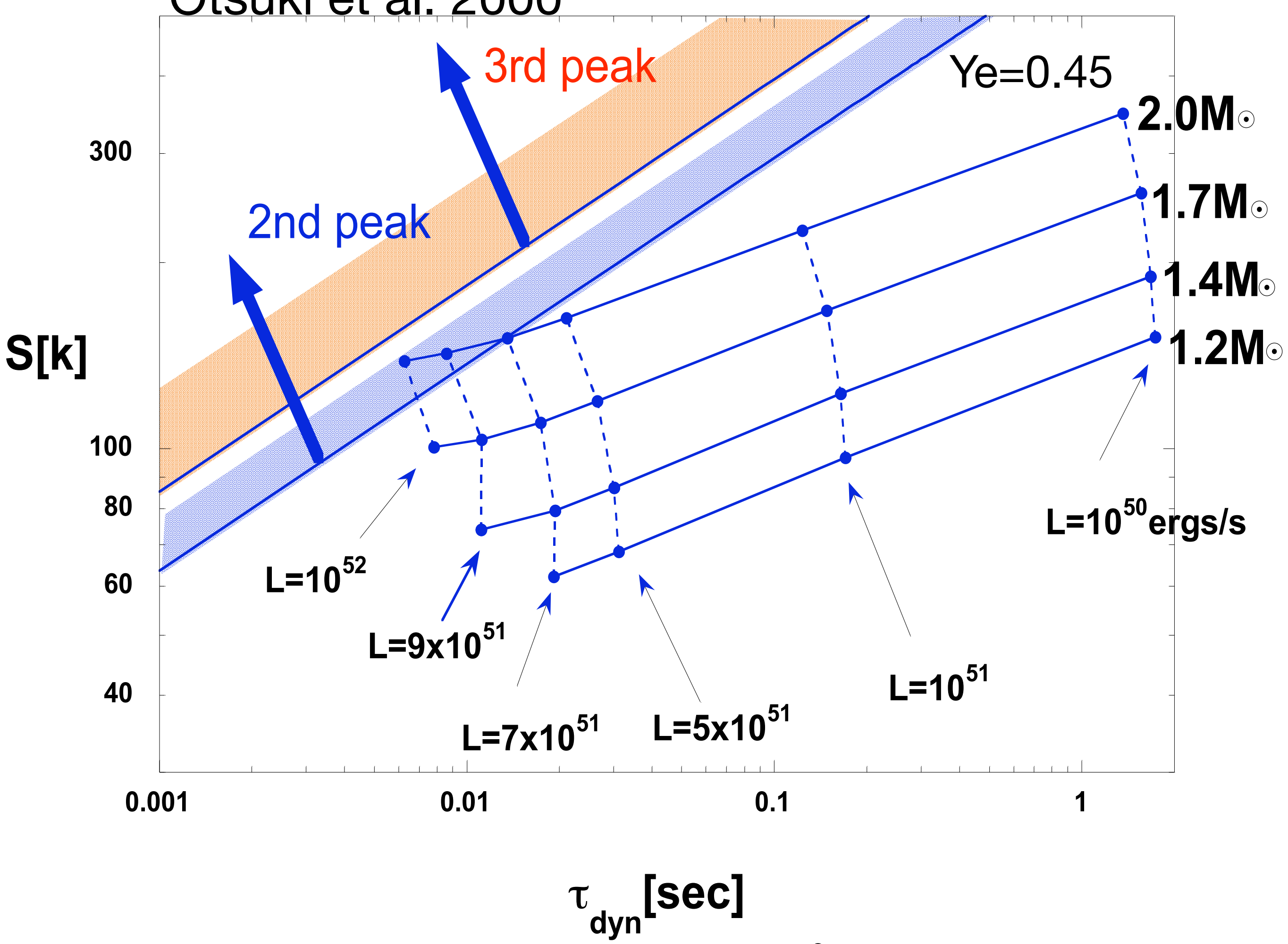
Core-collapse supernovae



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

Impact of astrophysical uncertainties

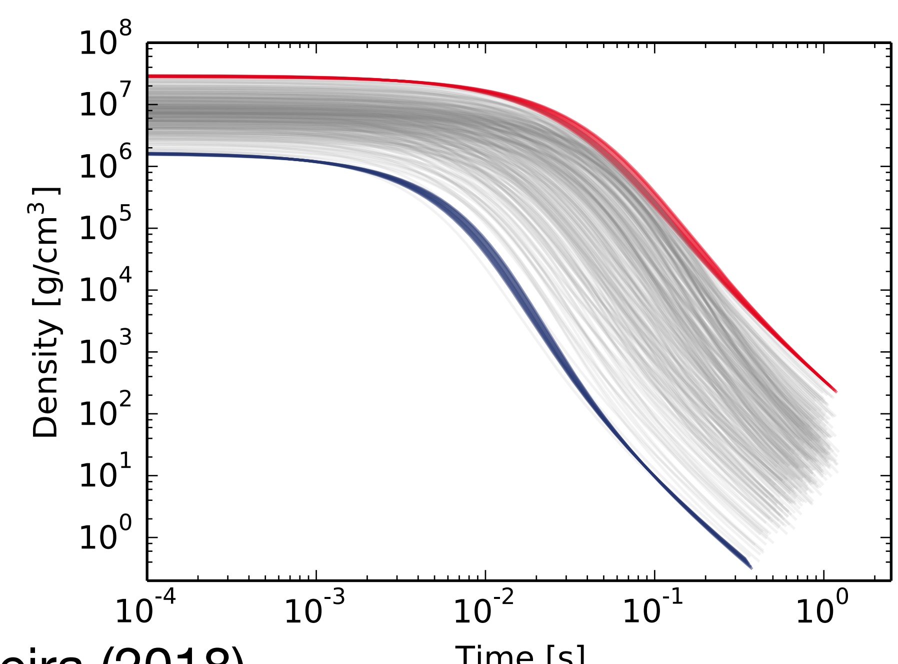
Otsuki et al. 2000

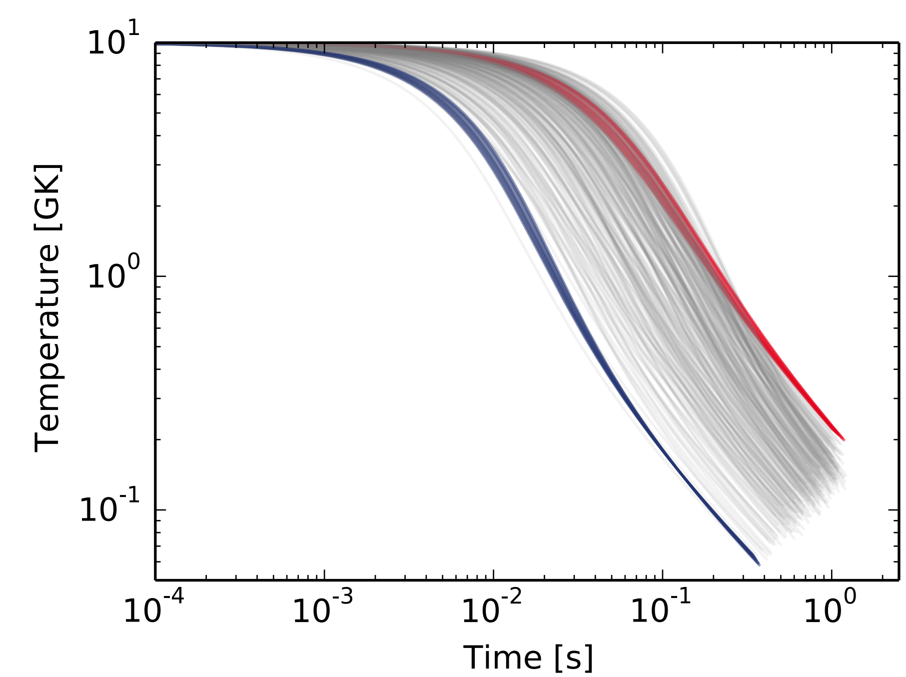


Steady-state model to explore possible nucleosynthesis patterns in neutrino-driven ejecta

Nucleosynthesis ~3000 trajectories

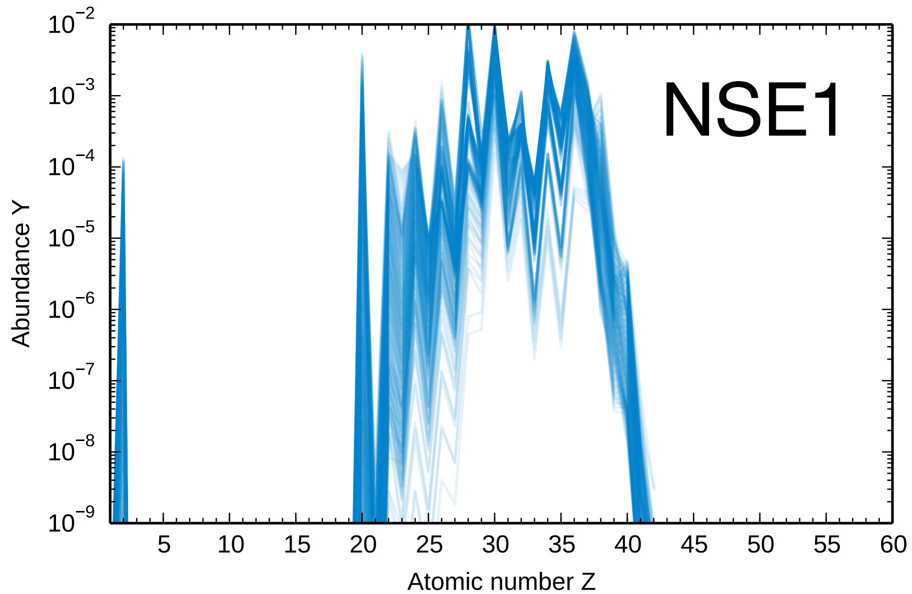
Input parameters:
M_{ns}, R_{ns}, Y_e

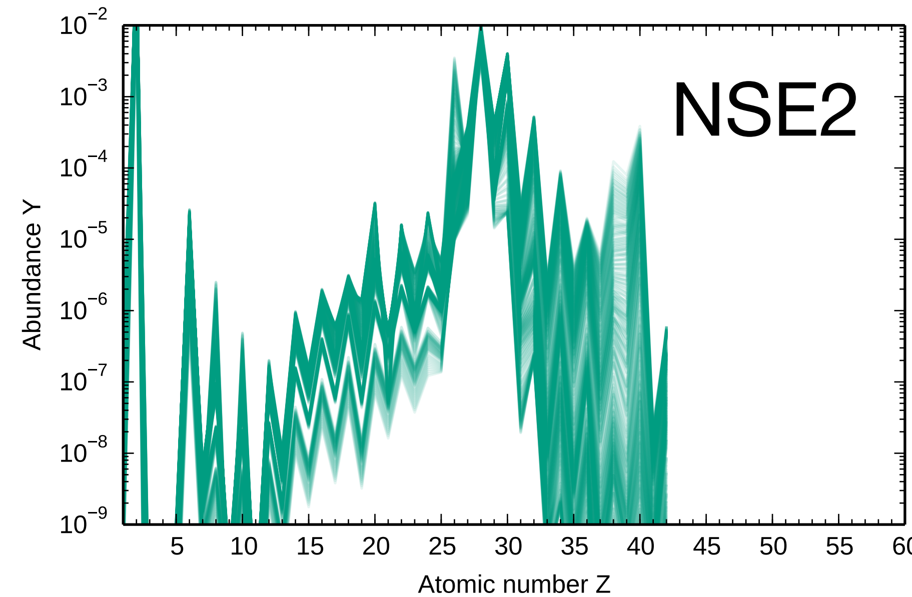




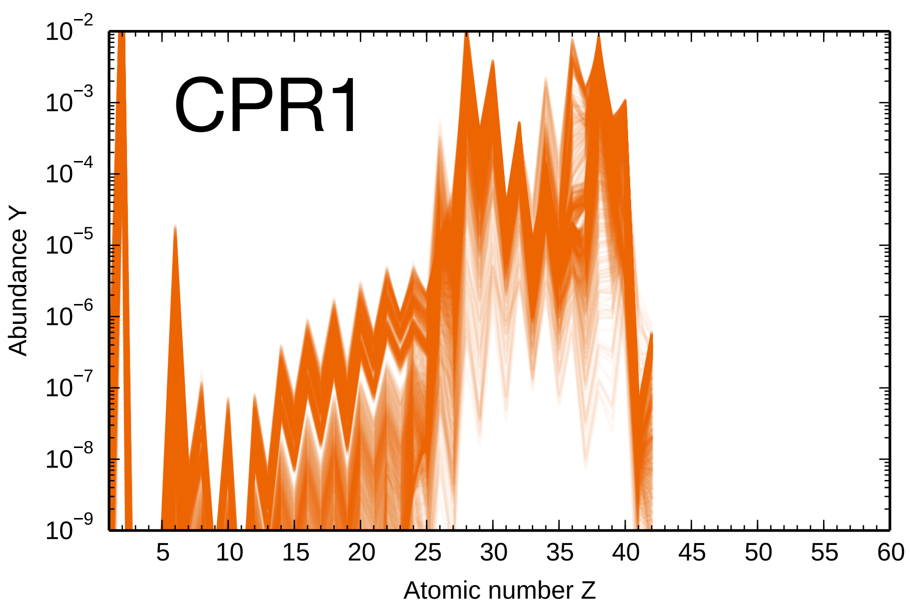
Bliss, Witt, Arcones, Montes, Pereira (2018)

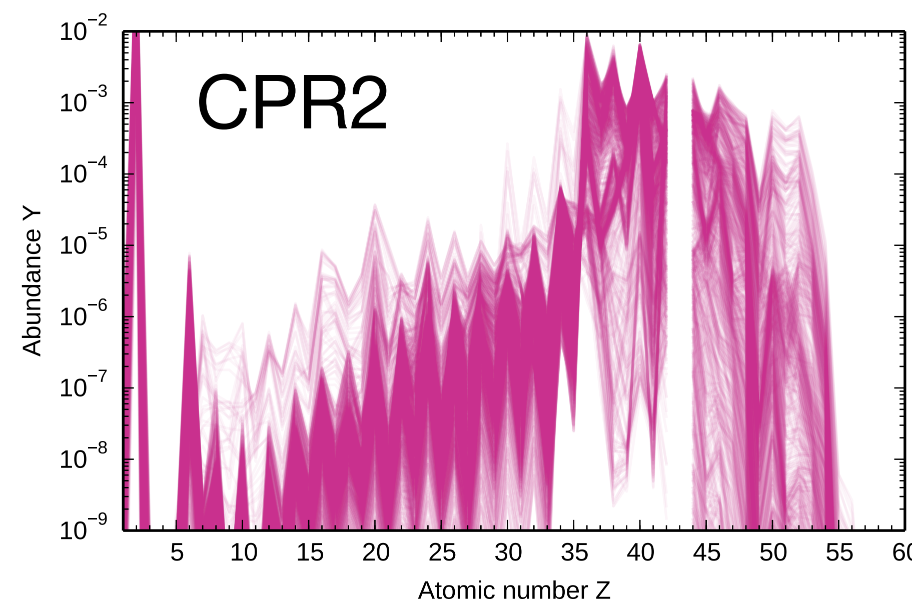
Characteristic nucleosynthesis patterns





binding energies
partition functions



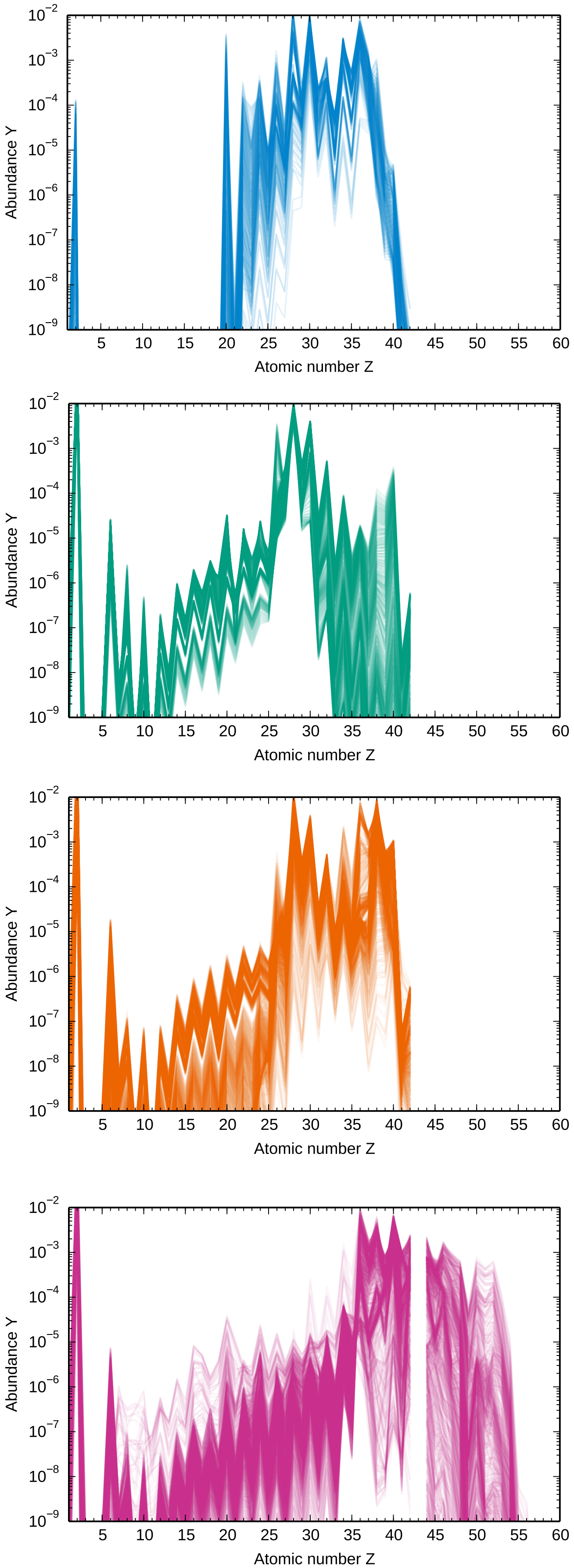


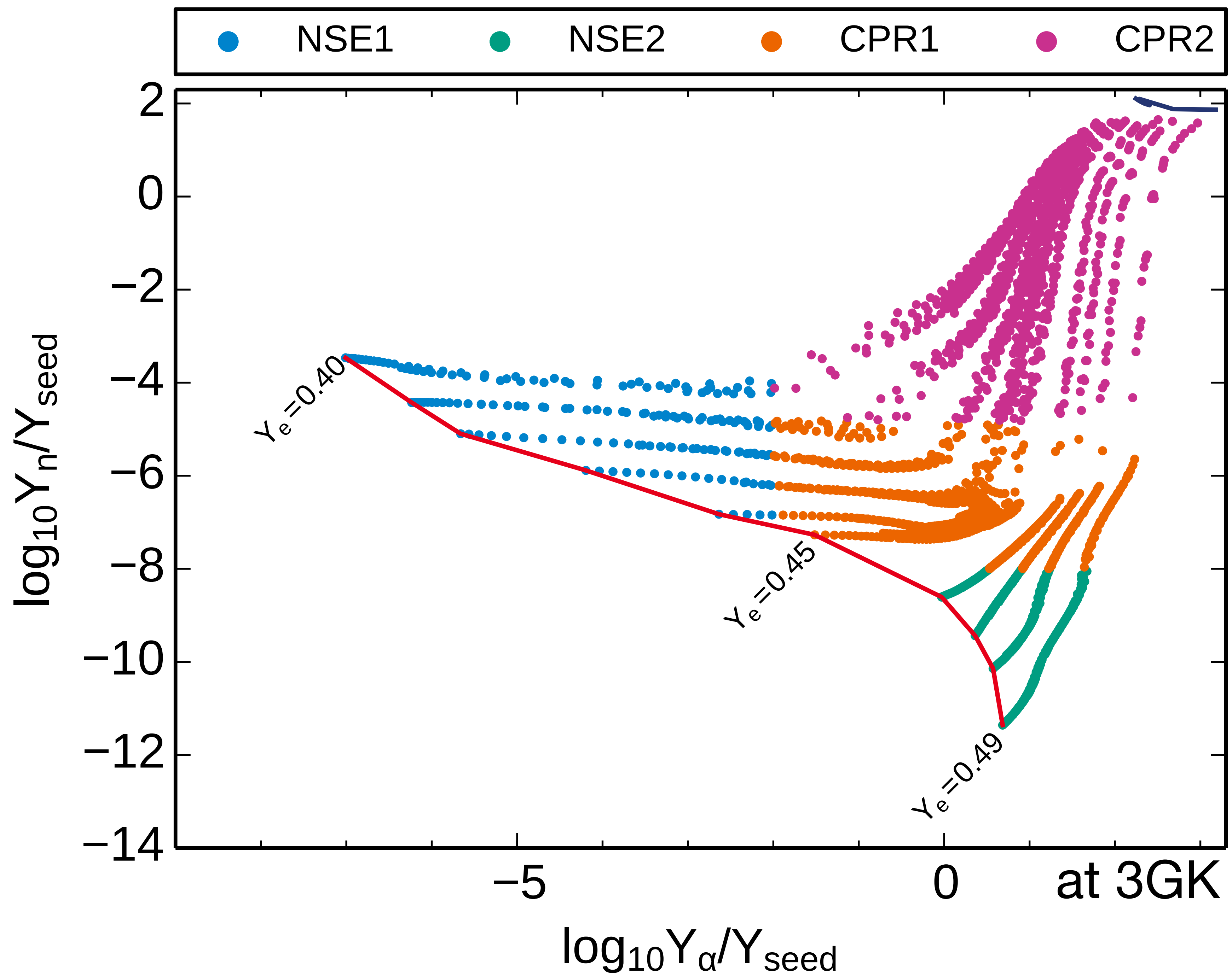
Q-values of (α,n) reactions

Individual reactions

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

Classification of nucleosynthesis patterns



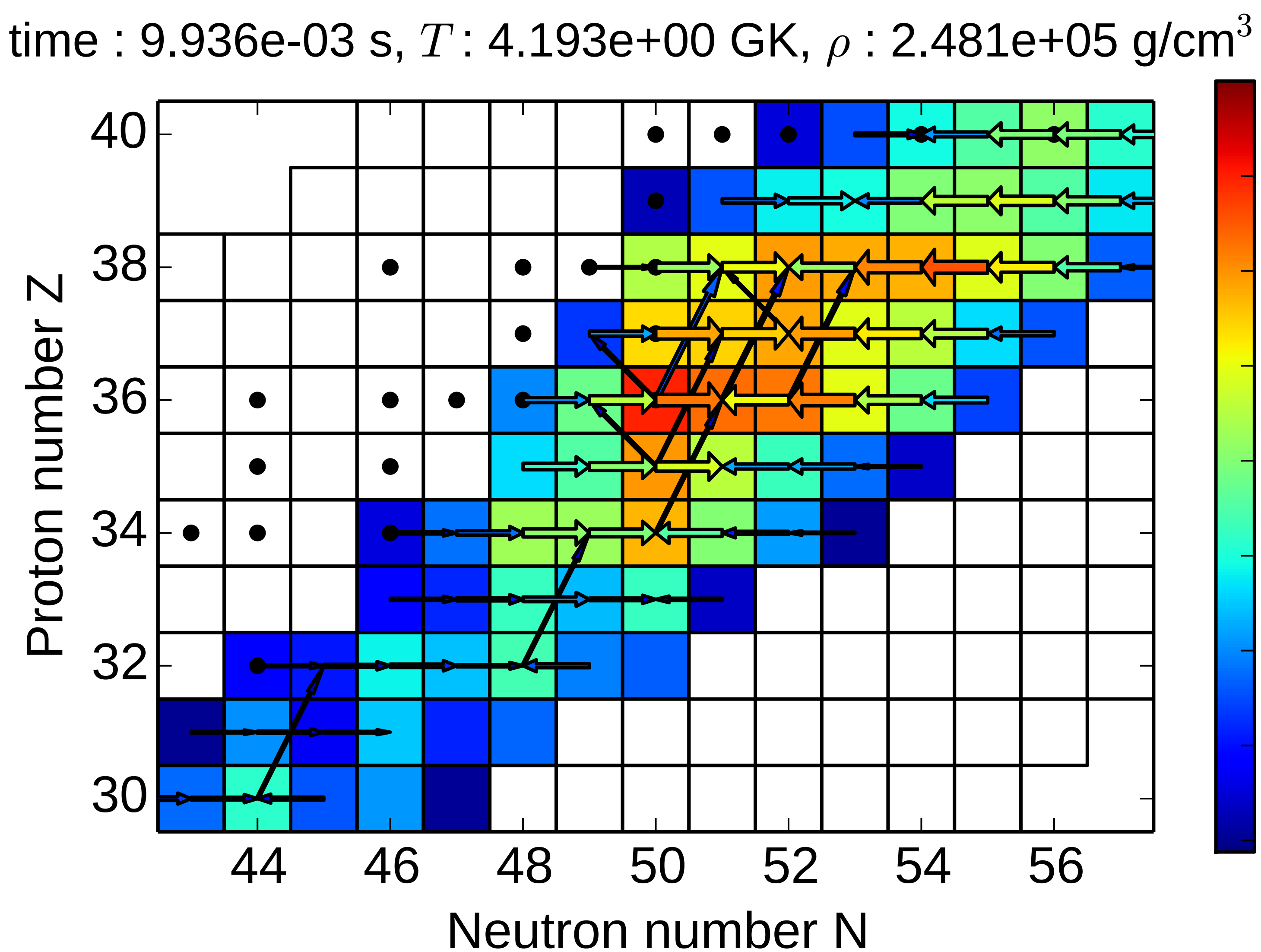


Bliss, Witt, Arcones, Montes, Pereira (2018)

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

Reactions in neutrino-driven supernova ejecta

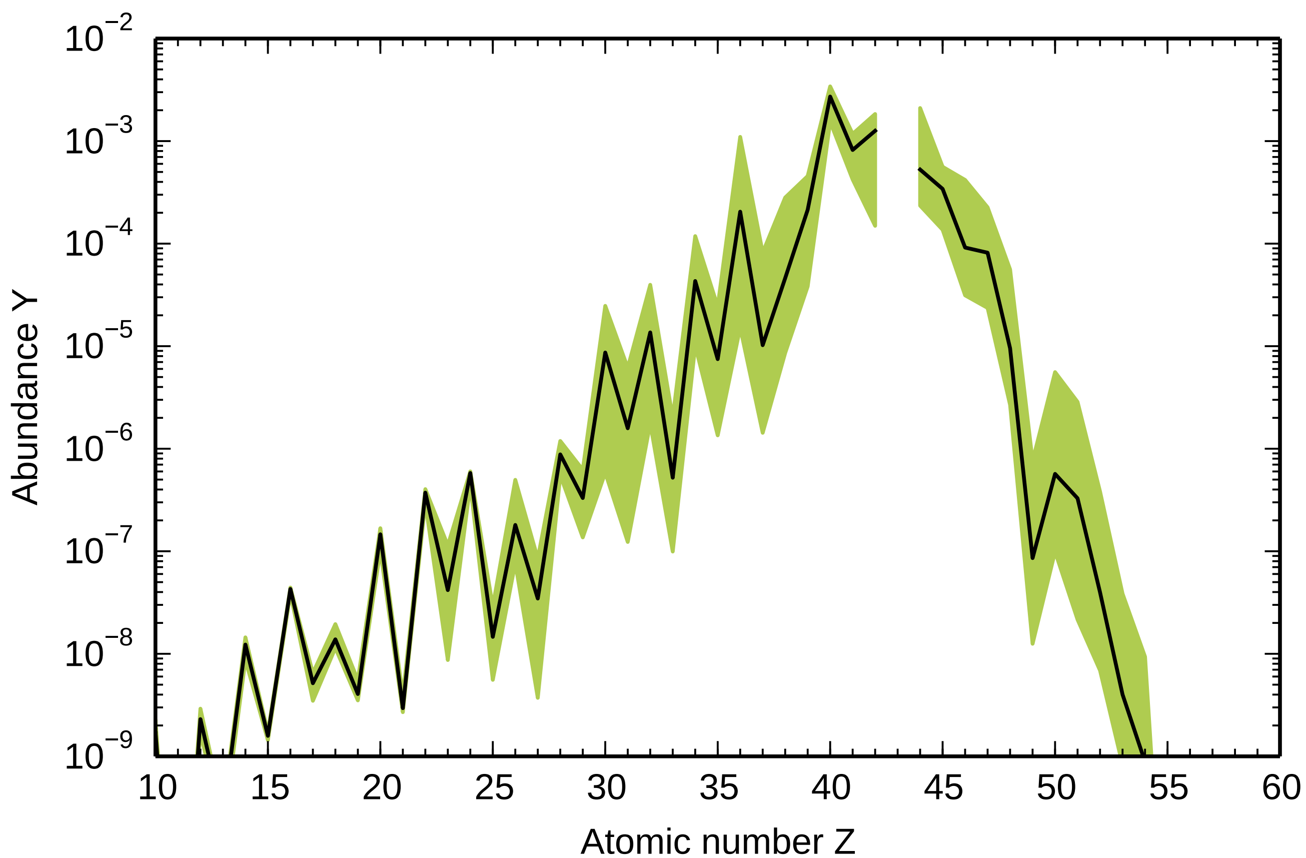
- Important reactions: α-, n-, p-capture reactions, β-decays
- $\tau_{expansion} << \tau_{\beta}$ → (α,n) are key reactions
- α-process (Hoffman & Woosley 1992)
- Absence of relevant experiments
  → theoretical reaction rates based on Hauser-Feshbach model

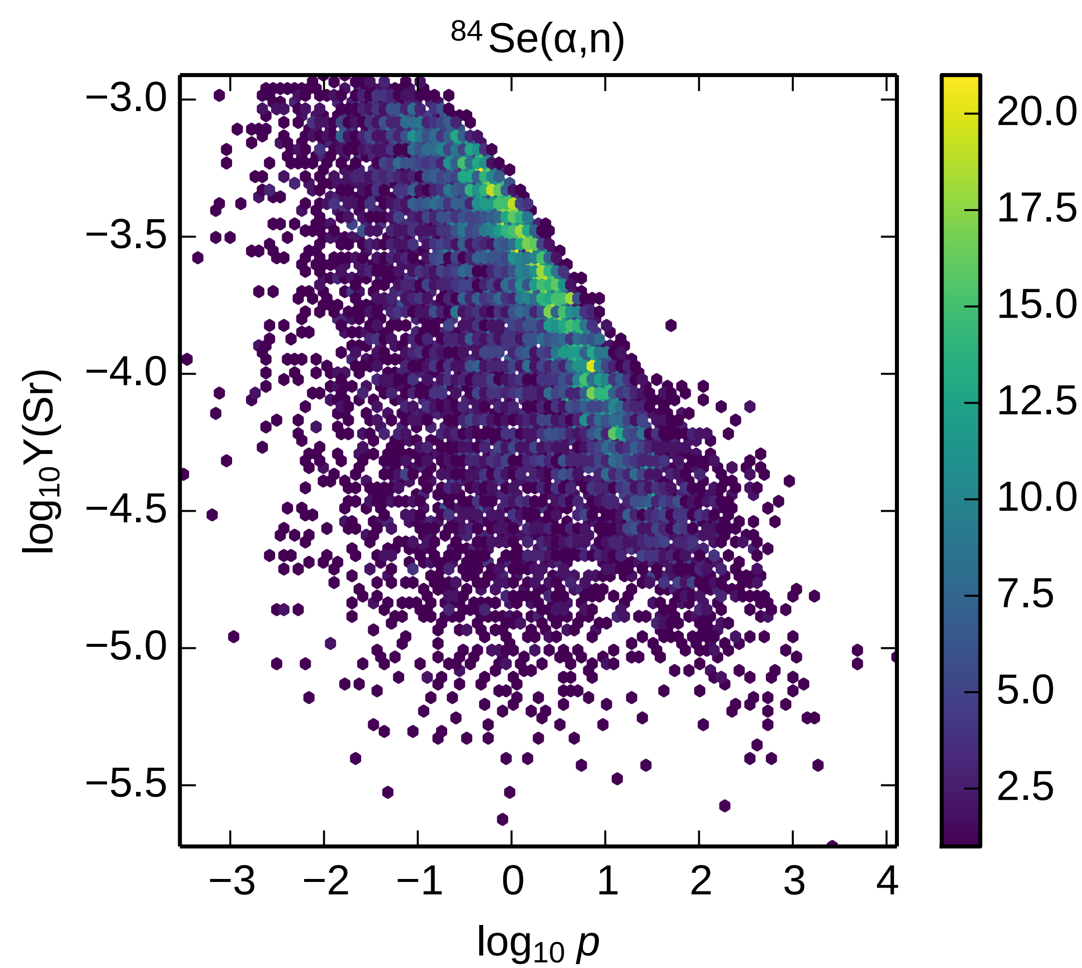


J. Bliss, A. Arcones, F. Montes, and J. Pereira (2017)

(α,n) reactions: sensitivity study

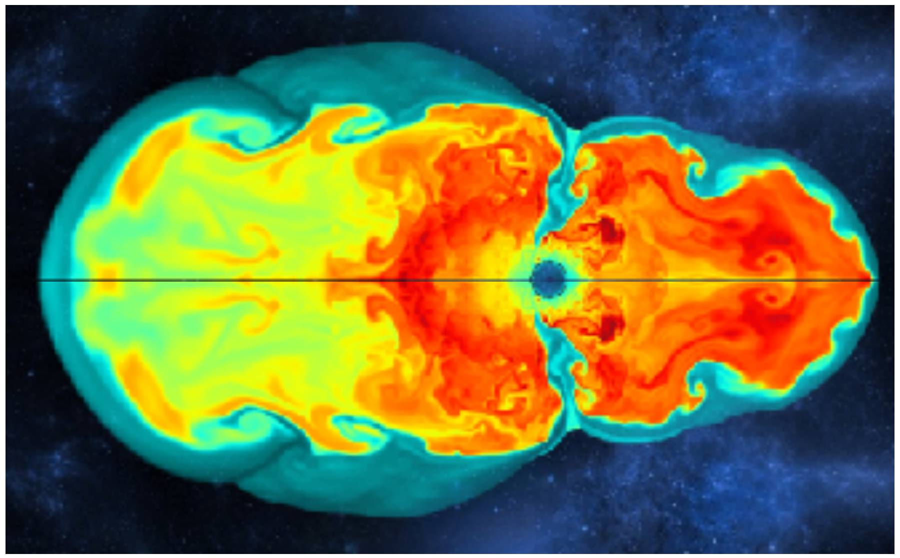
- Independently vary each (α,n) rate between Fe and Rh by a random factor
- Identification of key reactions → large correlation and abundance change
- ^{82}Ge, ^{84,85}Se, ^{85}Br(α,n) strongly affect abundance of Z=36–39
- Measurement of key (α,n) reactions to reduce nuclear physics uncertainties:
  → ^{75}Ga(α,n) and ^{85}Br(α,n) at ReA3 (NSCL/MSU)
  → need more experiments



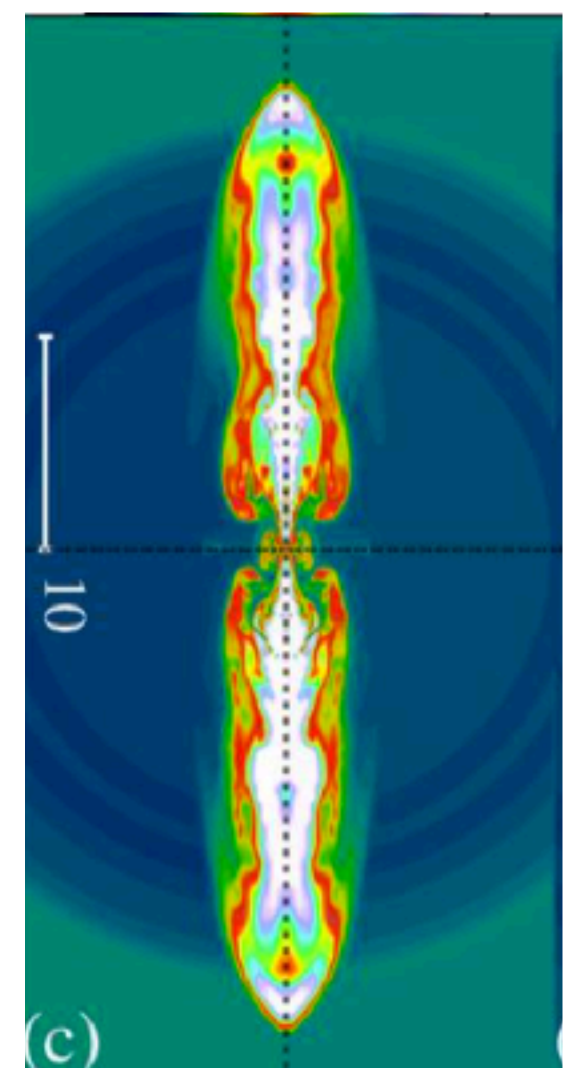


J. Bliss, A. Arcones, F. Montes, and J. Pereira in preparation

Core-collapse supernovae



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

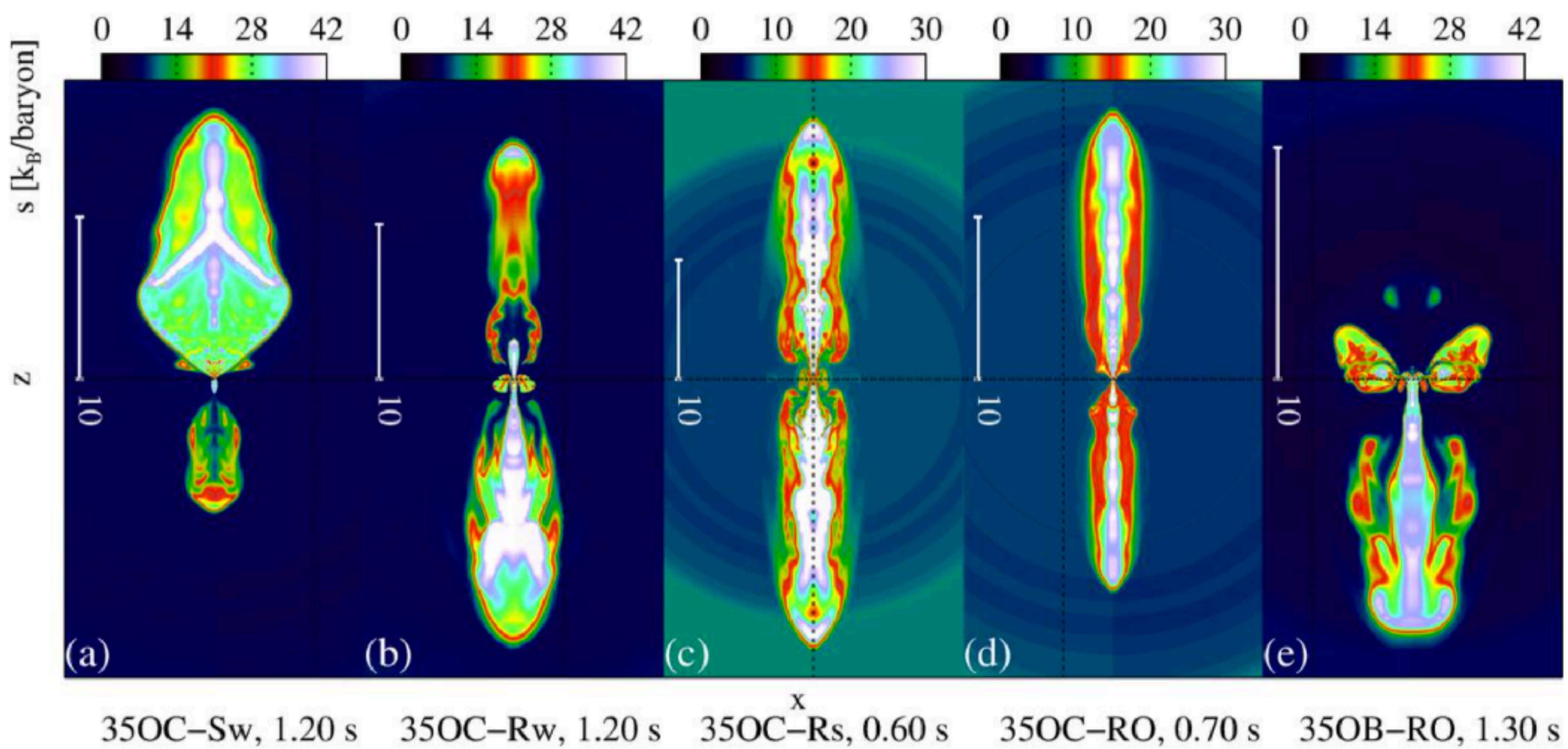
Nishimura et al. 2015, 2017, Winteler et al. 2012, Mösta et al. 2018

Magneto-rotational supernovae: r-process

Neutrinos and late evolution are important

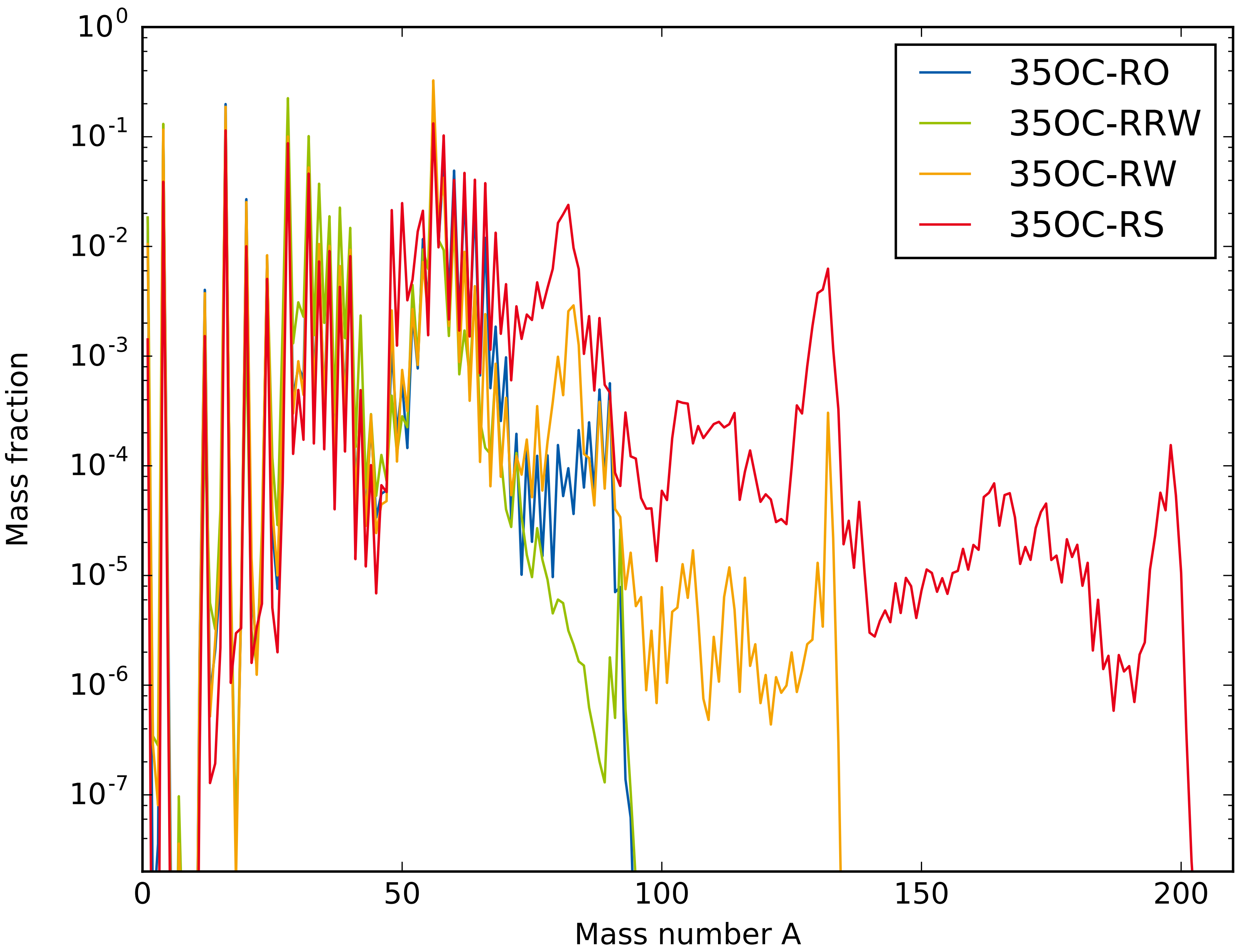
Martin Obergaulinger: 2D, M1, ~1-2s

Progenitor: 35 M_{sun}

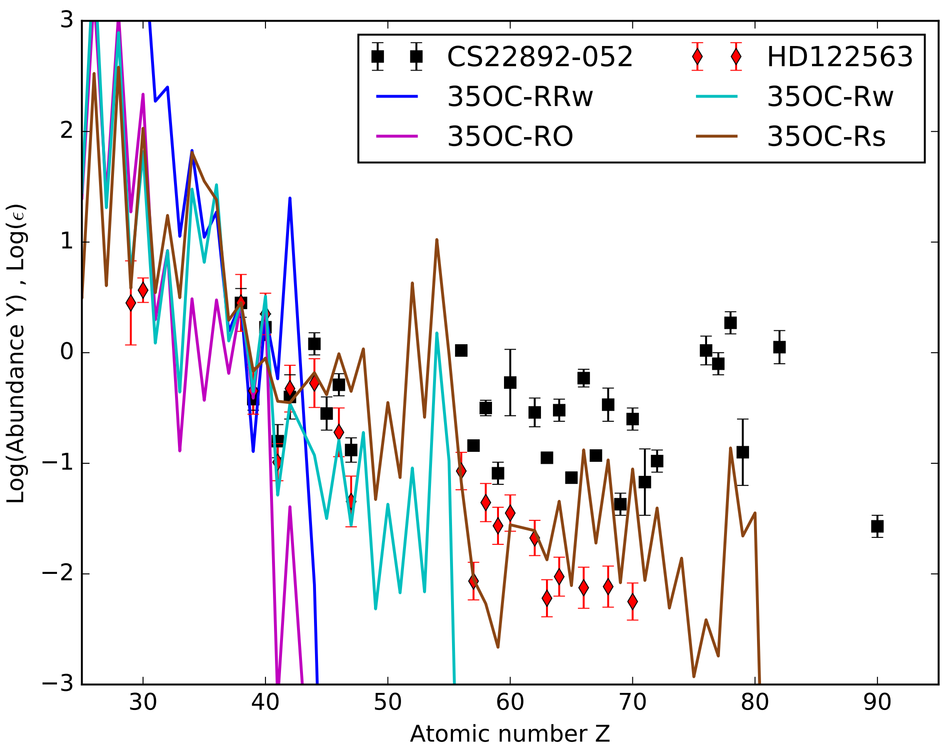


Obergaulinger & Aloy (2017)

Impact of rotation and magnetic field

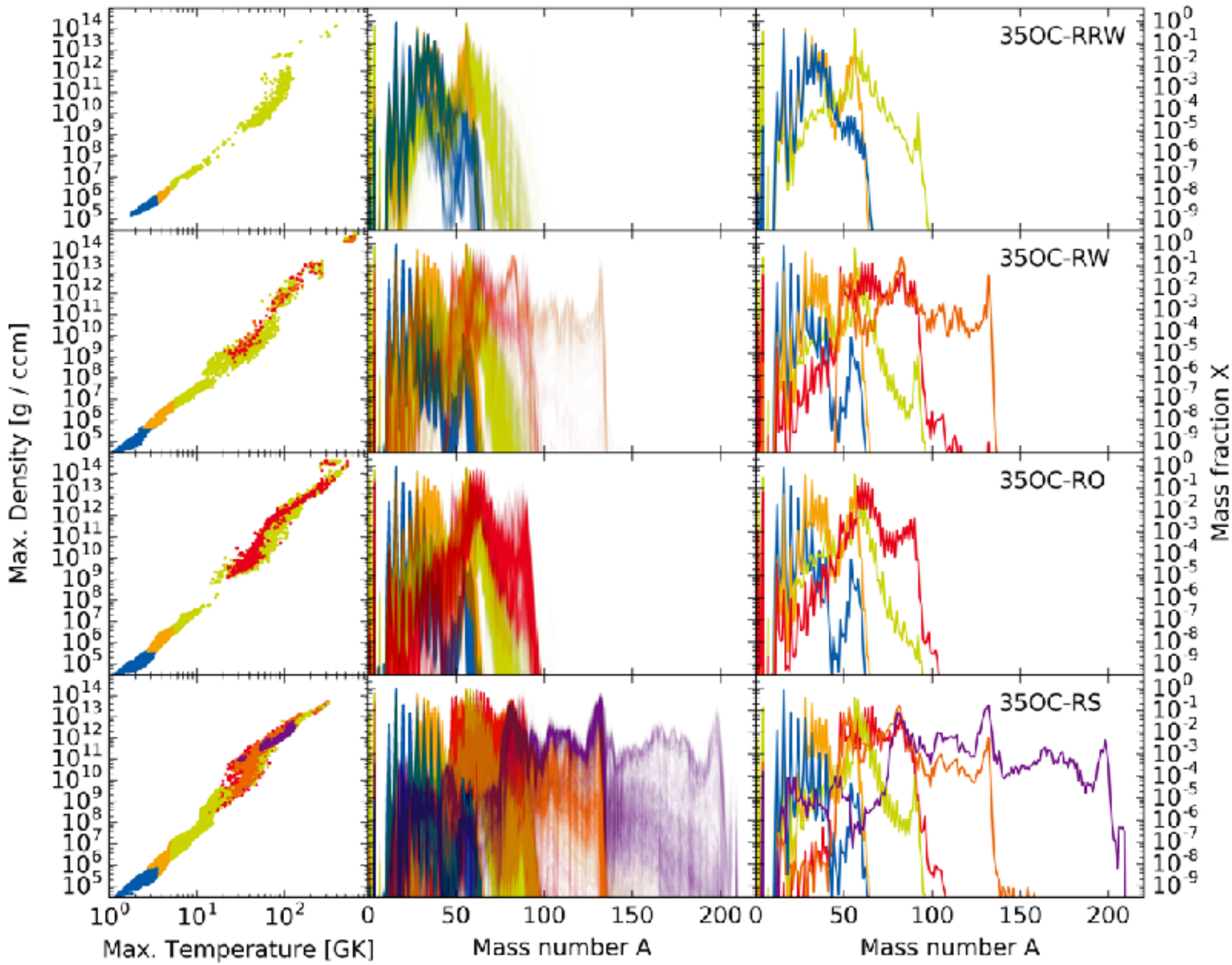


RO: progenitor
RRW: weak mag. field
strong rot.
RW: weak mag. field
RS: strong mag. field

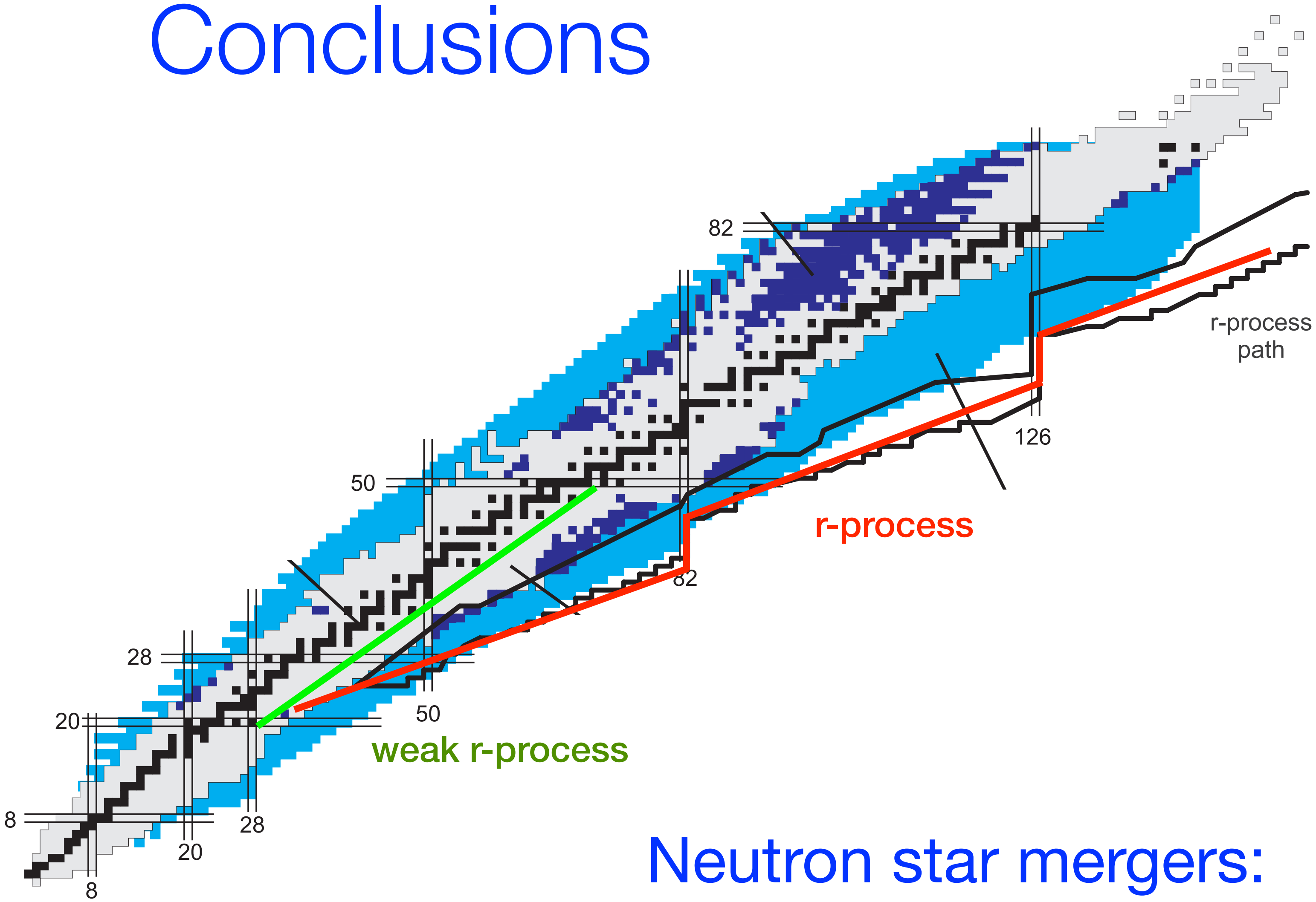


Reichert, Obergaulinger, Aloy, Arcones (in prep)

Nucleosynthesis patterns



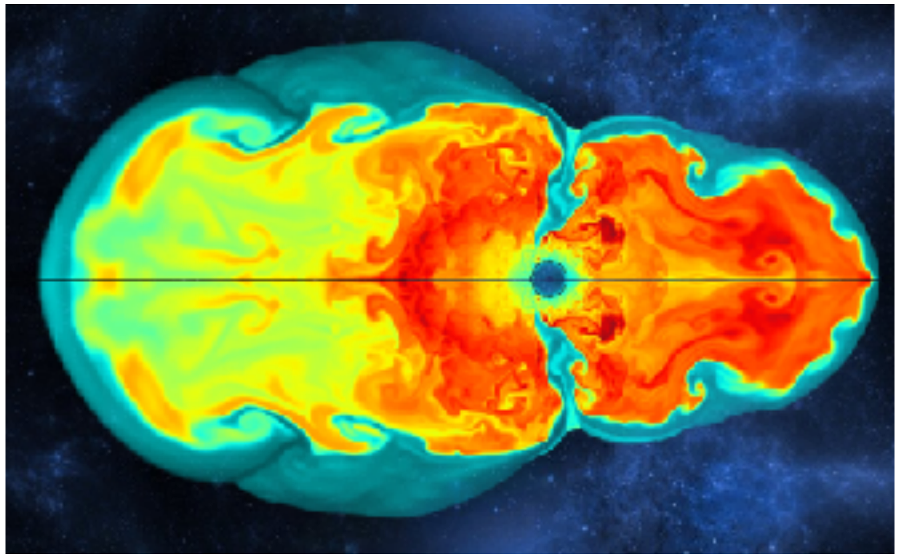
Conclusions



Core-collapse supernovae:

wind: up to ~Ag

Magneto-rot.: r-process

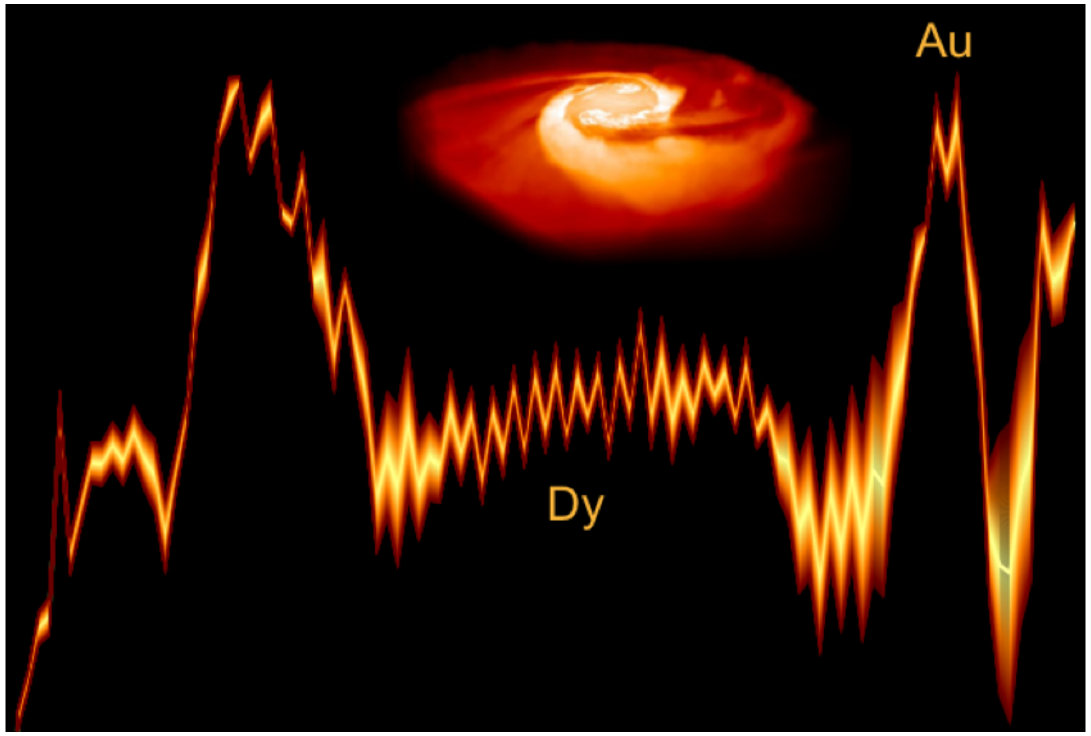


Neutron star mergers:

r-process

weak r-process

Kilonova



Impact of nuclear physics and astrophysics

Observations to constrain astrophysics