r-process and kilonovae

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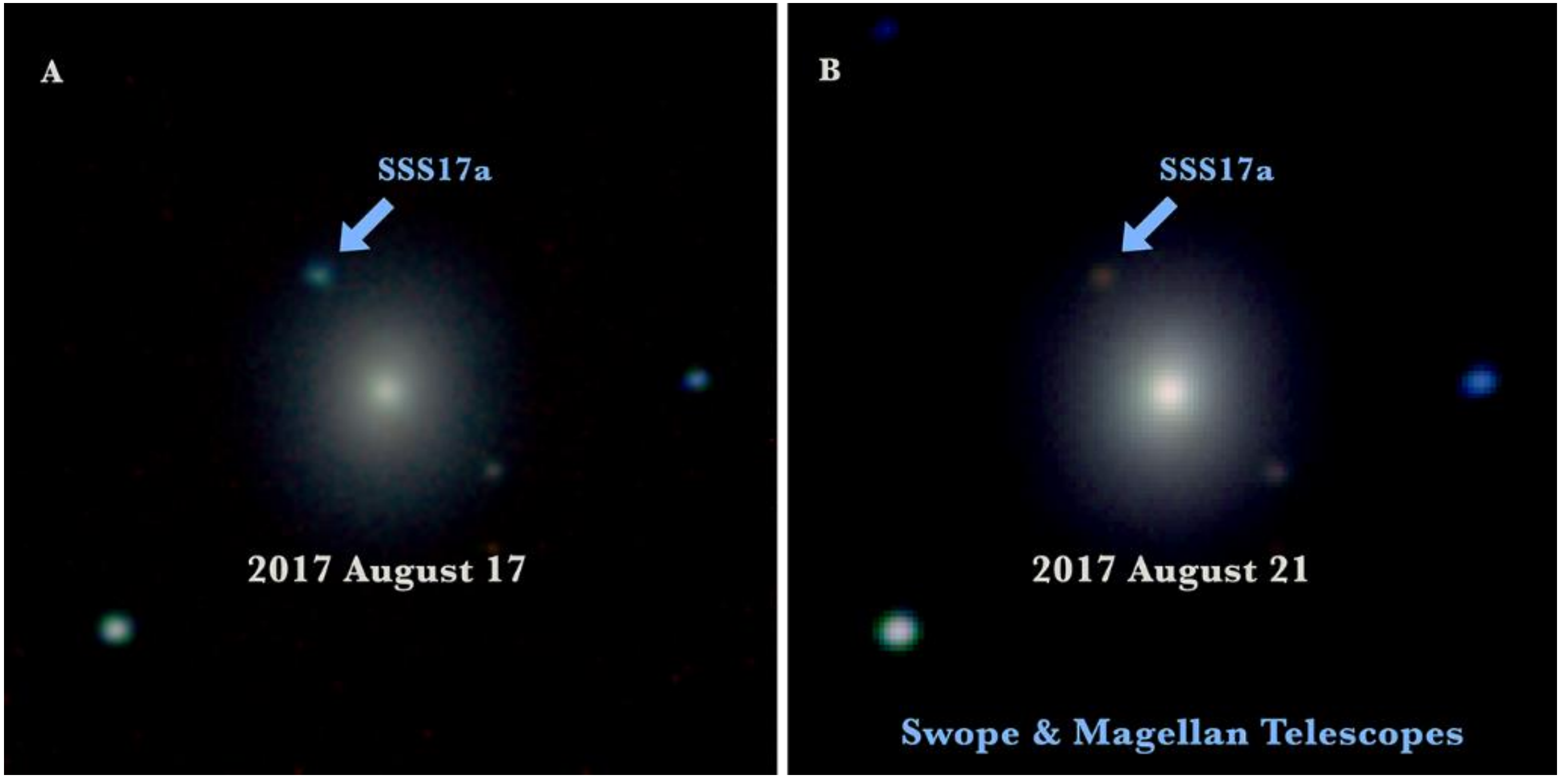
The 15th International Symposium on Origin of Matter and Evolution of Galaxies (OMEG15) , July 2-5, 2019, YITP, Kyoto

1. **neutron star mergers and Galactic chemical evolution**
2. **mass ejection from a neutron star merger**
3. **radioactive sources of the kilonova/GW170817 (Wanajo 2018)**
4. **radioactive heating in disk ejecta (Fujibayashi, Wanajo, et al. 2019, in prep.)**

discovery of neutron star mergers

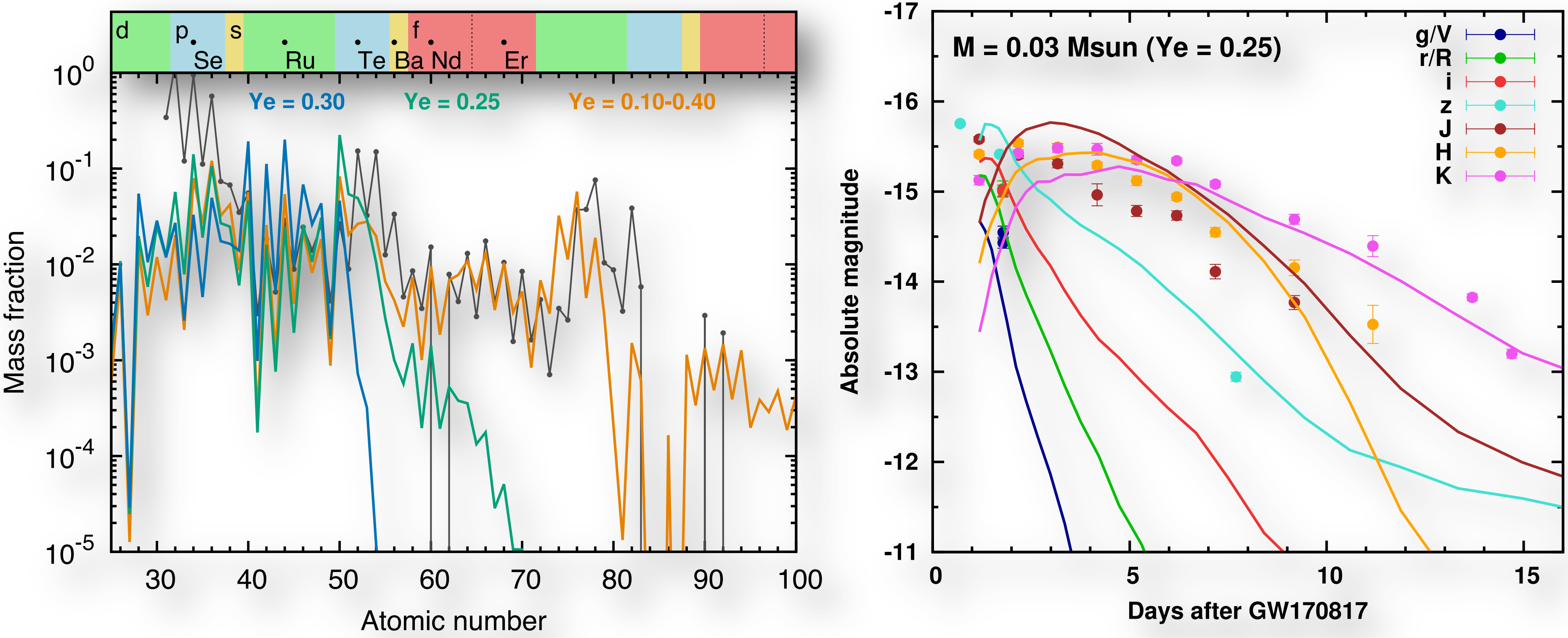


Drout+2017

- 6 (possible) neutron star mergers have been reported by LIGO/Virgo
- 1 neuron star merger, GW170817, with EM emission (kilonova)
- higher frequency than expected (0-5 events per year in O3)

what we learned from the kilonova are …

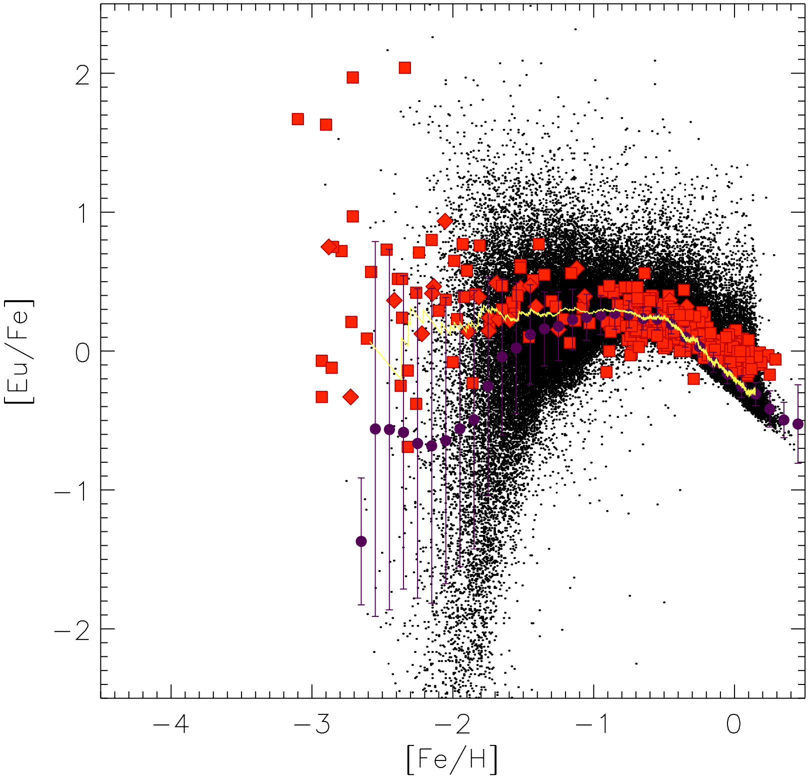
comparison with GW170817; Tanaka+2017



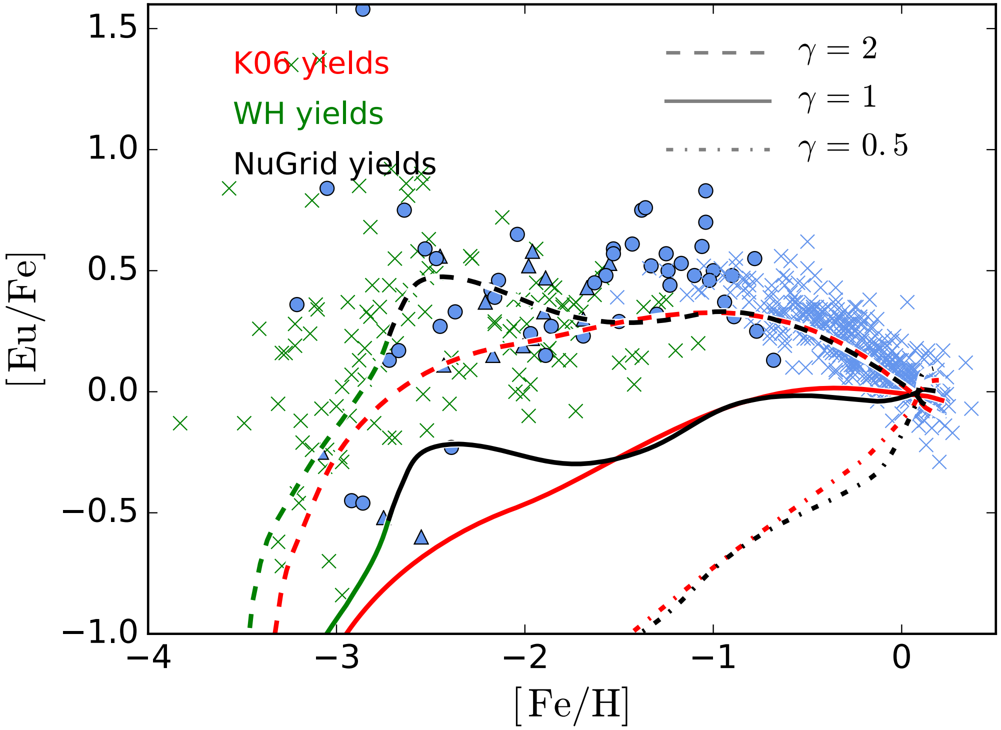
- total ejecta mass of $M_{\rm ej} \approx 0.03\text{-}0.06\ M_{\odot}$ and the lanthanide mass fraction of $X_{\rm lan} \approx 0.001\text{-}0.01$ (see also Cowperthwaite+2017, etc.)
- no evidence of heavy r-nuclei production (gold, platinum, …)

problems in Galactic chemical evolution

single halo, [Fe/H] < −1; Argast+2004



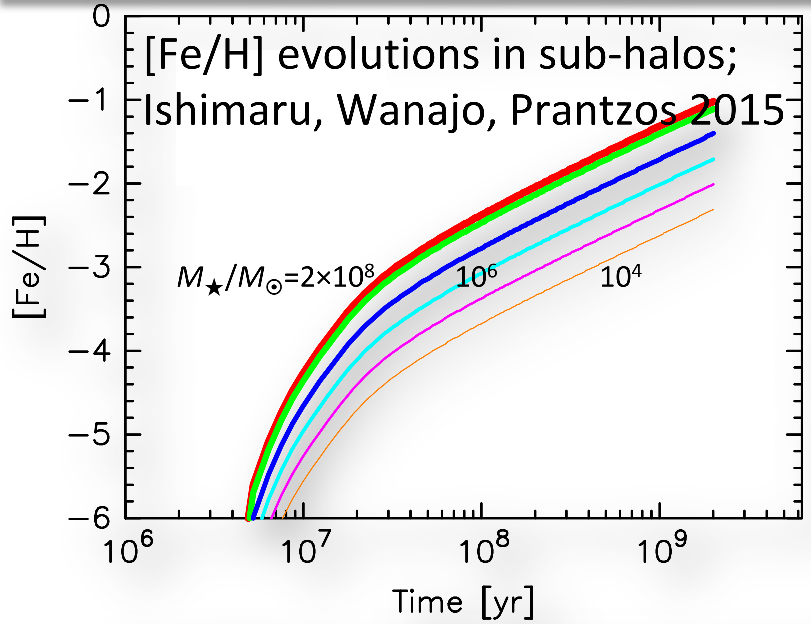
disk, [Fe/H] > −1; Côte+2017



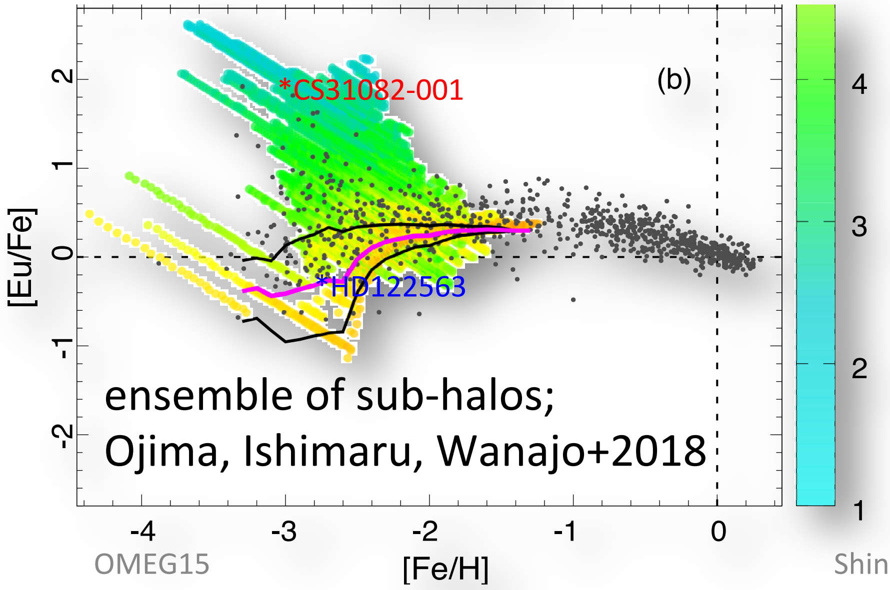
- delay time of neutron star mergers (> a few 10 Myrs) → [Fe/H] > −2 only (see also Wehmeyer+2015)

- delay time distribution of neutron star mergers (~ $t^{-\gamma}$, $\gamma \approx 1$) → flat [Eu/Fe] trend (see also Hotokezaka+2018)

problems solved?



[Fe/H] evolutions in sub-halos;
Ishimaru, Wanajo, Prantzos 2015

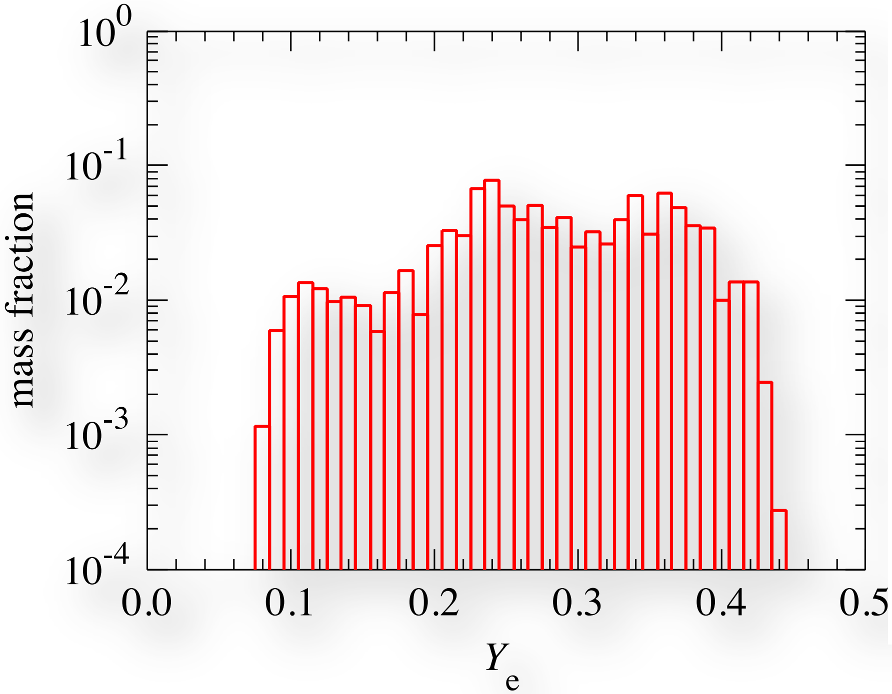


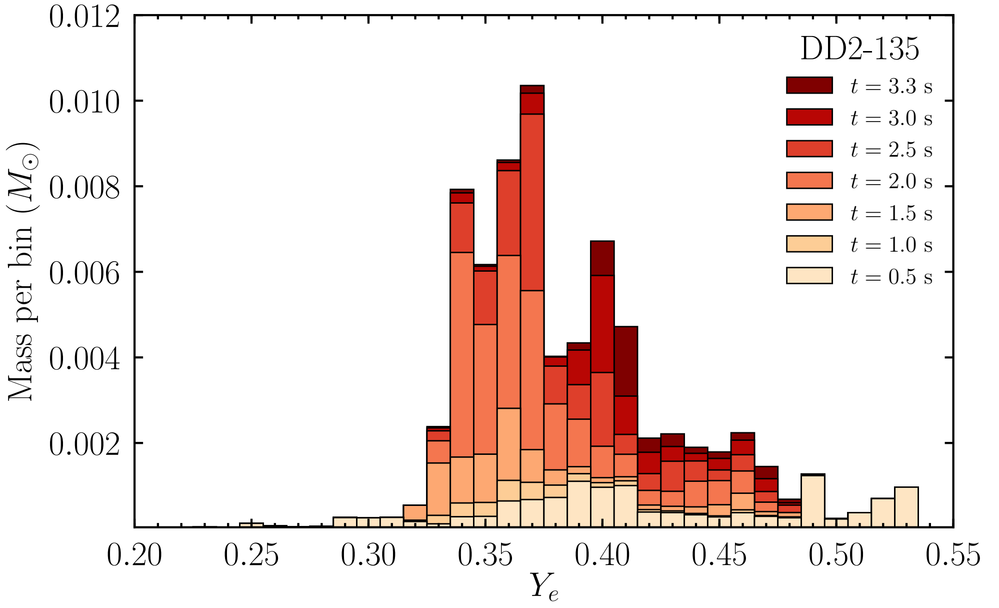
ensemble of sub-halos;
Ojima, Ishimaru, Wanajo+2018

- Galactic halo is an ensemble of sub-halos with different chemical evolutions
  → r-enhanced stars were born in low-mass (UFD-like) sub-halos at low metallicity

- a problem in the Galactic disk may be solved by considering complex star formation (Shönrich+2019) or radial migration (Tsujimoto+2019)?
  → or another site plays a role? (see a talk by N. Nishimura)

n-richness (or Y_e) in dynamical/disk ejecta


dynamical ejecta; Wanajo+2014

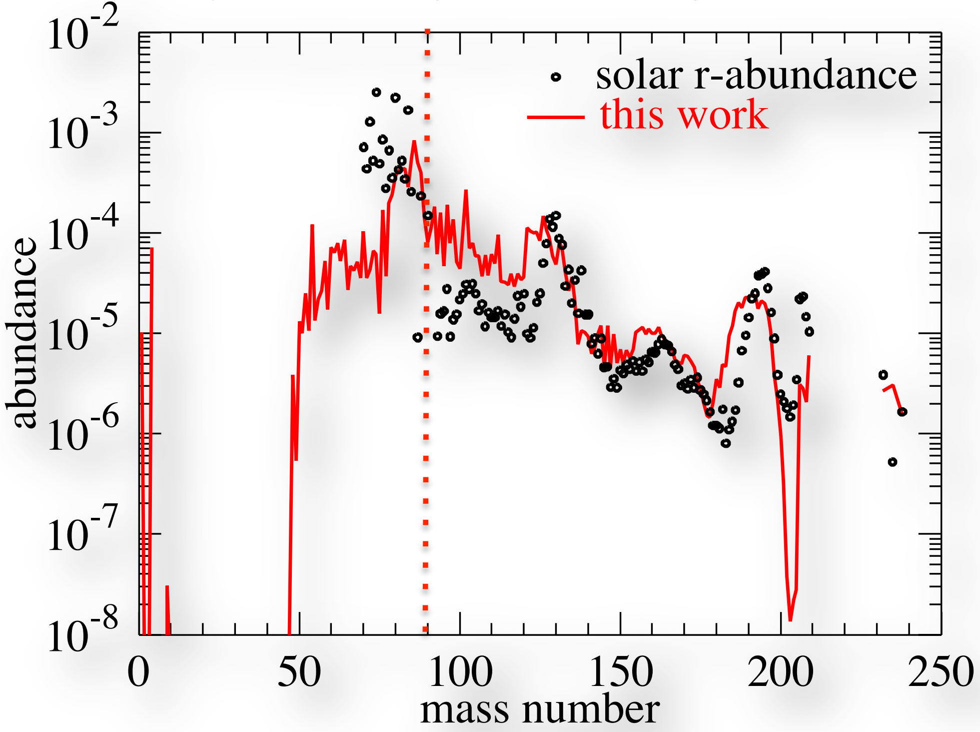

disk wind; Fujibayashi+2019, in prep.

- ❖ tidal ejecta (low Y_e) and shock-heated ejecta (high Y_e) → broad distribution of $Y_e \sim 0.09\text{-}0.45$ (see also Goriely+2015; Radice+2018)

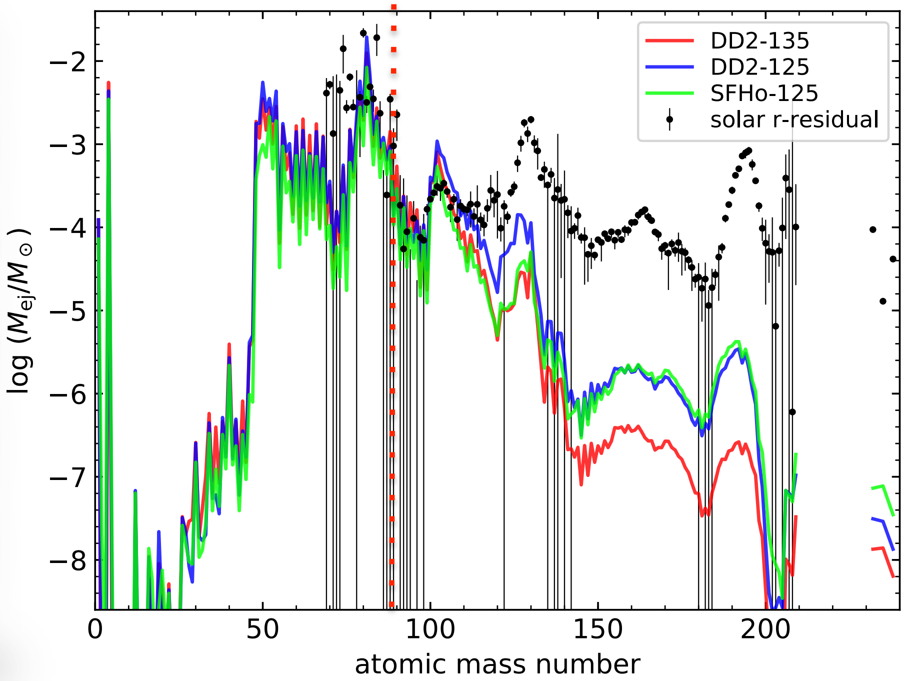
- ❖ neutrino absorption in the viscously heated ejecta → high $Y_e > 0.3$ (see also Just+2015; Lippner+2017)

nucleosynthesis in dynamical/disk ejecta

dynamical ejecta; Wanajo+2014



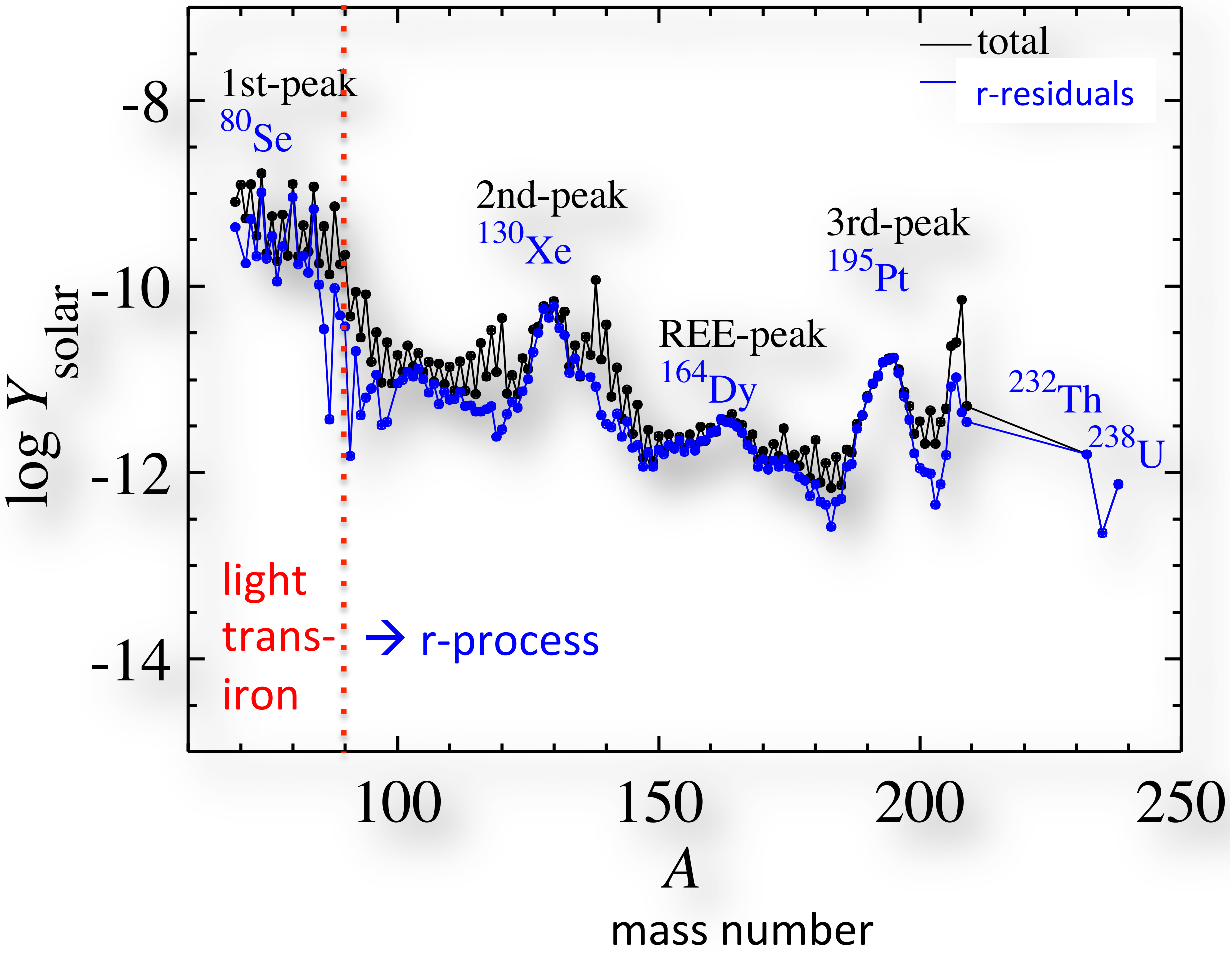
disk ejecta; Fujibayashi+2019, in prep.



- production of r-elements with few light trans-iron elements (see also Goriely+2015; Radice+2018)
- production of light trans-iron elements with few r-elements (see also Just+2015; Lippner+2017)

what are the r-process elements?

r-process residuals to the solar system abundances



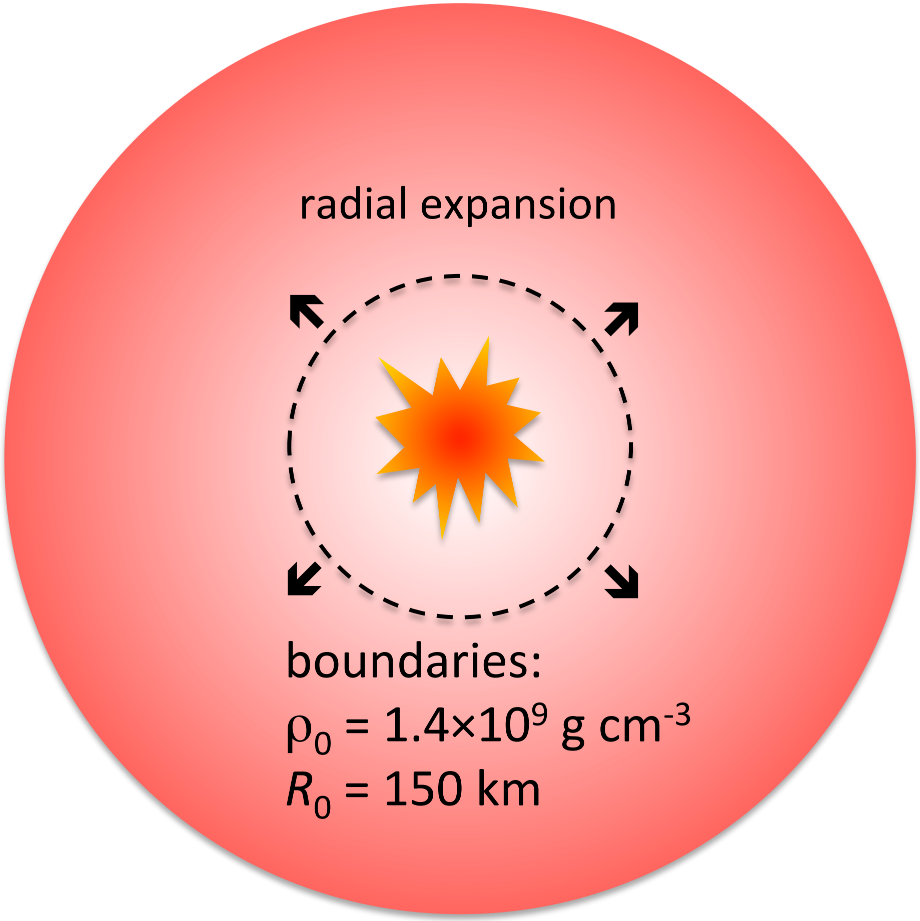
r-process “residuals”
= solar abundances
– s-process component

❖ elements of $A > 90$ are made by the r-process (including 2nd and 3rd peaks)

❖ but, those of $A < 90$, “light trans-iron nuclei”, can be made in NSE or QSE (including 1st peak)

free expansion (FE) models

parameters: (v/c, S, Y_e)



radial expansion

boundaries:
$\rho_0 = 1.4\times10^9$ g cm^{-3}
$R_0 = 150$ km

Wanajo 2018

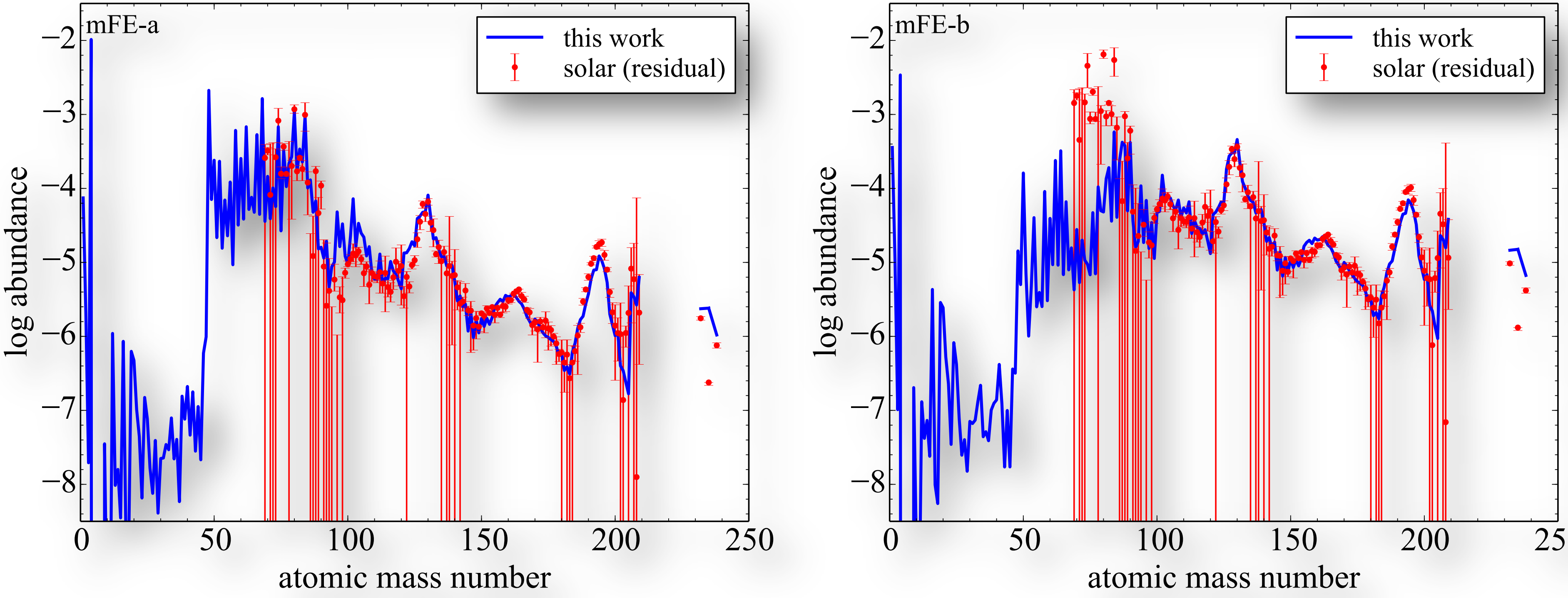
- free expansion (FE) models that mimic the physical conditions of merger outflows (either of dynamical and disk ejecta)

$$\rho(t) = \rho_0 \left(1 + \frac{t}{R_0/v}\right)^{-3}$$

- three parameters:
  (v/c, S, Y_e)
  = (0.05-0.30, 10-35, 0.01-0.50)
  with intervals (0.05, 5, 0.01)
  in total N_{FE} = 1800 models
  (S is in units of k_B/nuc)

let's think of two fittings to r-residuals

Wanajo 2018; r-residuals from Goriely 1999



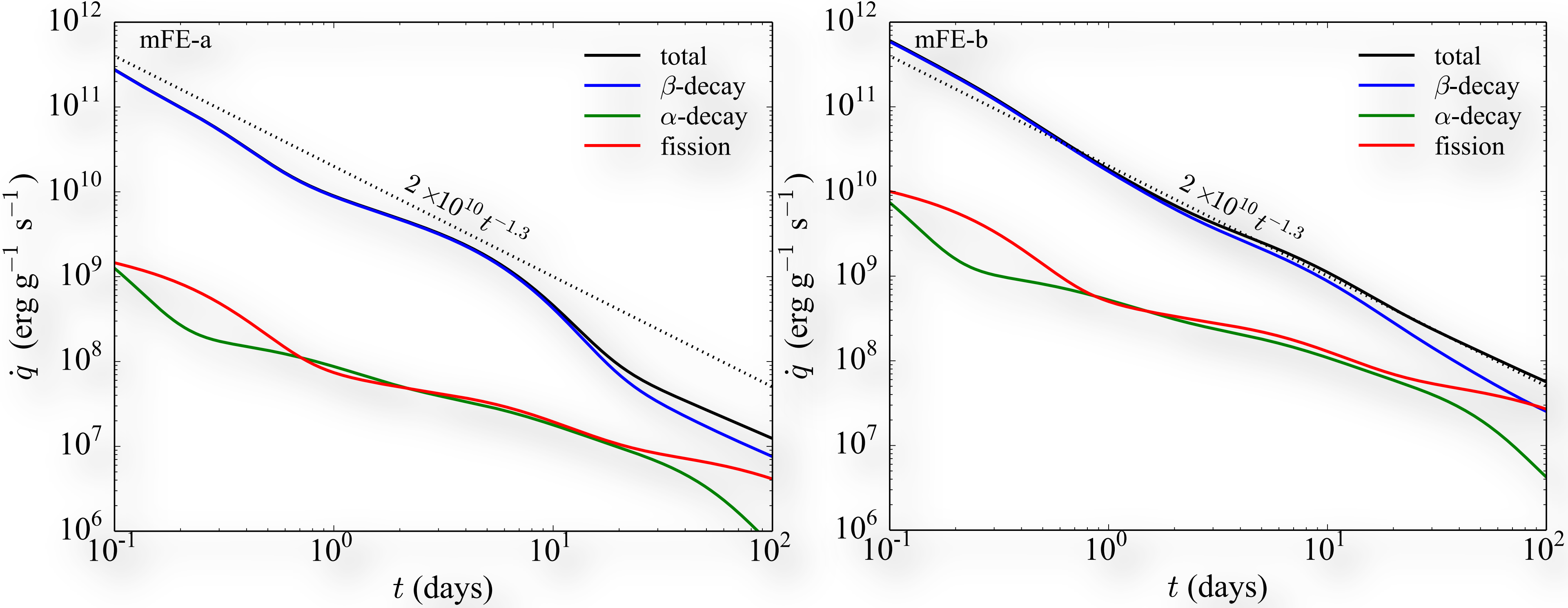
A ≥ 69 (light trans-Fe + r-elements)

- X_{lan} = 0.014 (consistent with obs.)

A ≥ 90 (r-elements only)

- X_{lan} = 0.086 (inconsistent with obs.)

heating rates



Wanajo 2018

A ≥ 69 (light trans-iron dominant)

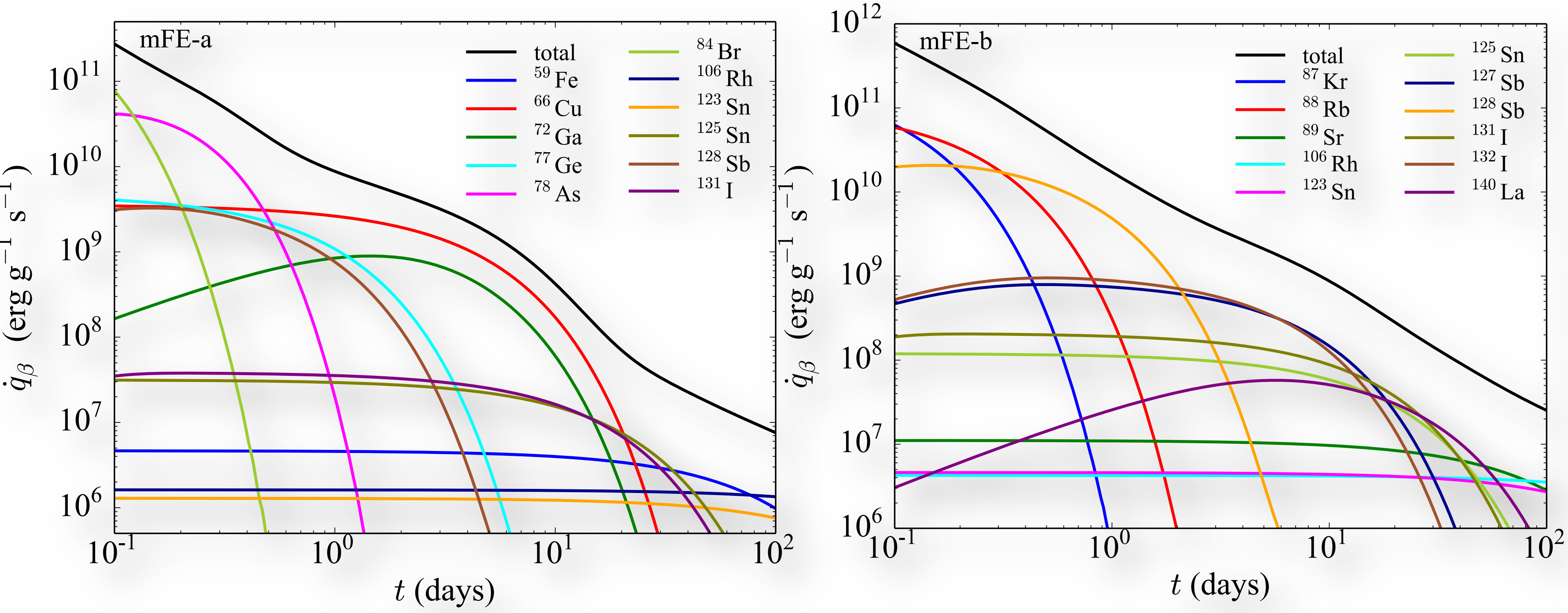
- not scaled by a power law but rather by an exponential during 1-15 days

A ≥ 90 (r-process dominant)

- well scaled by a power law as in previous studies (e.g., Metzger et al. 2010)

heating rates from individual β-decays

Wanajo 2018



$A \geq 69$ (light trans-iron dominant)

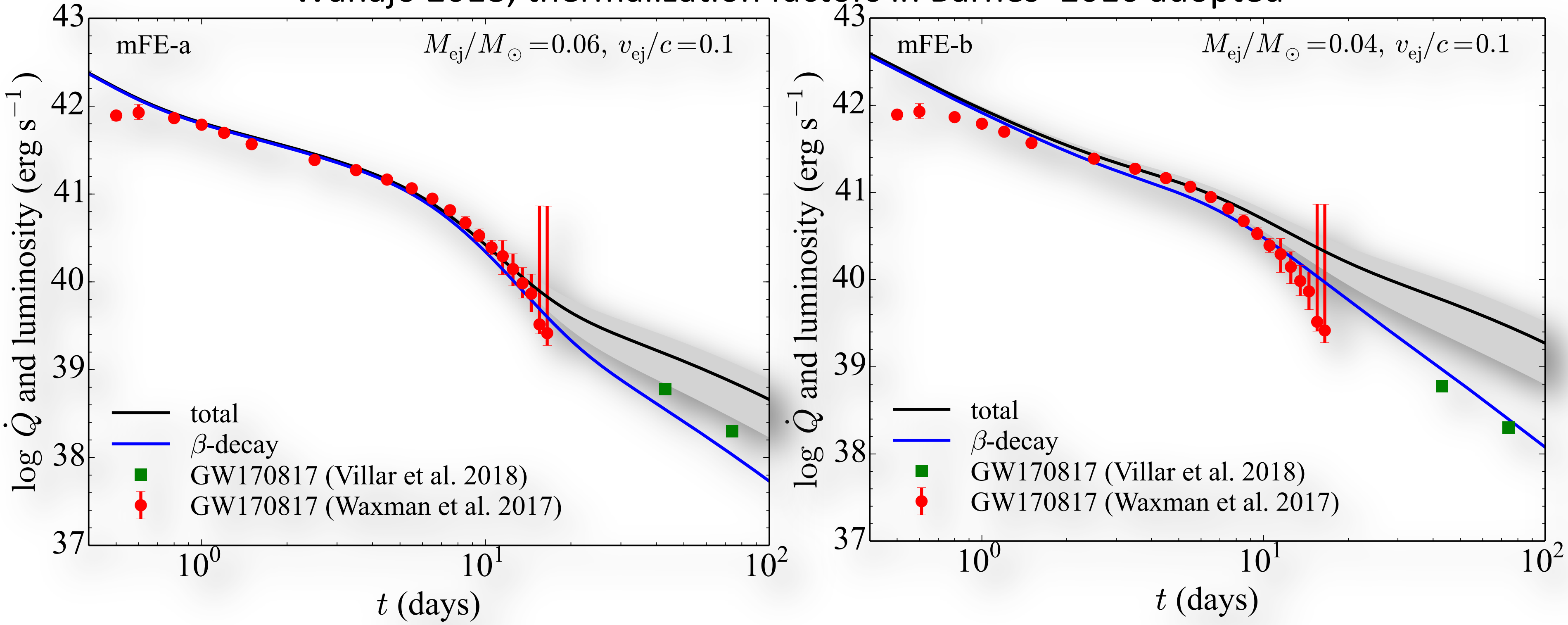
- two decay chains are identified:
  ^{66}Ni (2.3 d) → ^{66}Cu (5.1 m) → ^{66}Zn
  ^{72}Zn (1.9 d) → ^{72}Ga (14 h) → ^{72}Ge

$A \geq 90$ (r-process dominant)

- a number of A ~ 130 nuclei contribute as in previous studies (e.g., Metzger+2010)

comparison with kilonova of GW170817

Wanajo 2018; thermalization factors in Barnes+2016 adopted



A ≥ 69 (light trans-iron dominant)

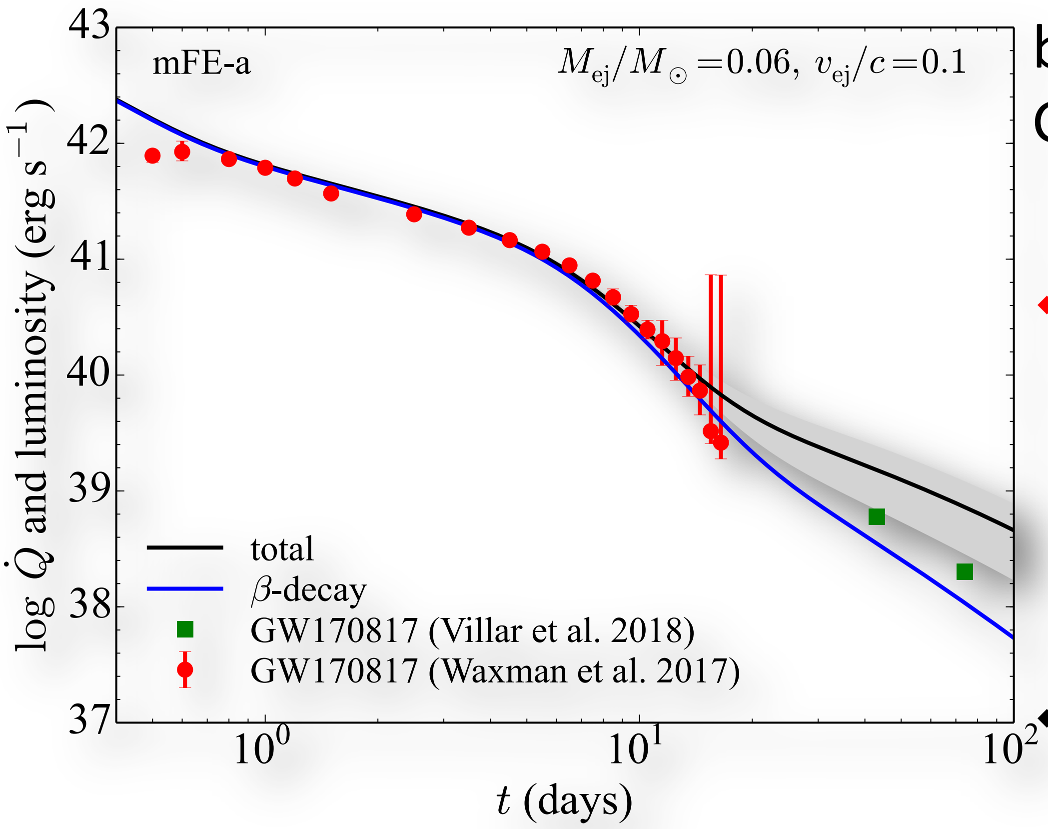
- light curve can be well explained by the decays of ^{66}Ni and ^{72}Zn

A ≥ 90 (r-process dominant)

- light curve is inconsistent with the heating rate

if this is the case for GW170817…

Wanajo 2018



bulk ejecta of the NS merger GW170817

- ❖ 85% (≈ 0.05 $M_\odot$) are light trans-iron nuclei made in NSE/QSE (not r-process)
  → disk ejecta?

- ❖ only 15% (≈ 0.01 $M_\odot$) are r-process nuclei
  → dynamical ejecta?

nucleosynthesis in disk ejecta

DD2-135; Fujibayashi, Wanajo+2019, in prep.

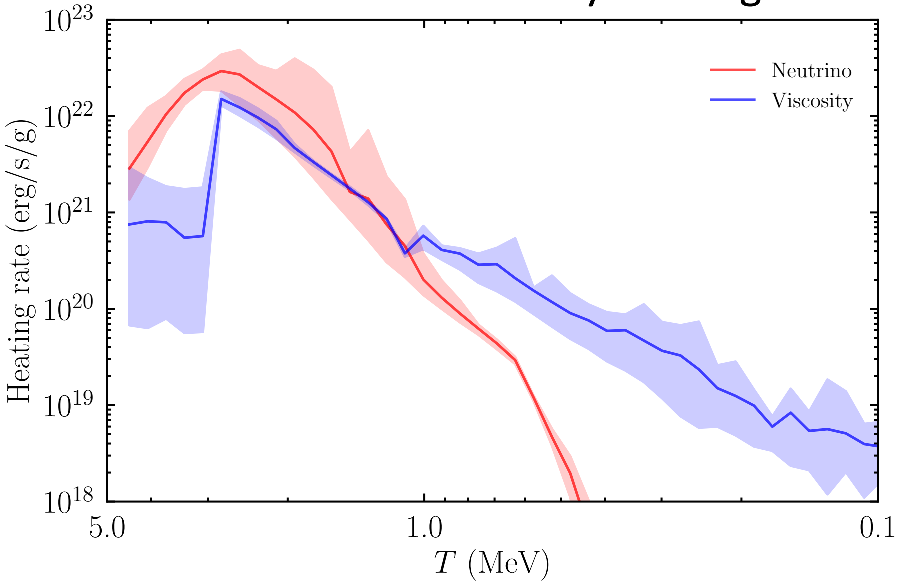
2D simulation with general relativistic and (approx.) neutrino transport

- three combinations of EOSs and (equal) neutron star masses:
  DD2-135 (1.35 $M_\odot$)
  DD2-125 (1.25 $M_\odot$)
  SFHo-125 (1.25 $M_\odot$)
- no BH formation (< 2-4 s)
- (M_{ej}, v_{ej}/c)
  = (0.073, 0.089): DD2-135
  = (0.092, 0.074): DD2-125
  = (0.042, 0.109): SFHo-125

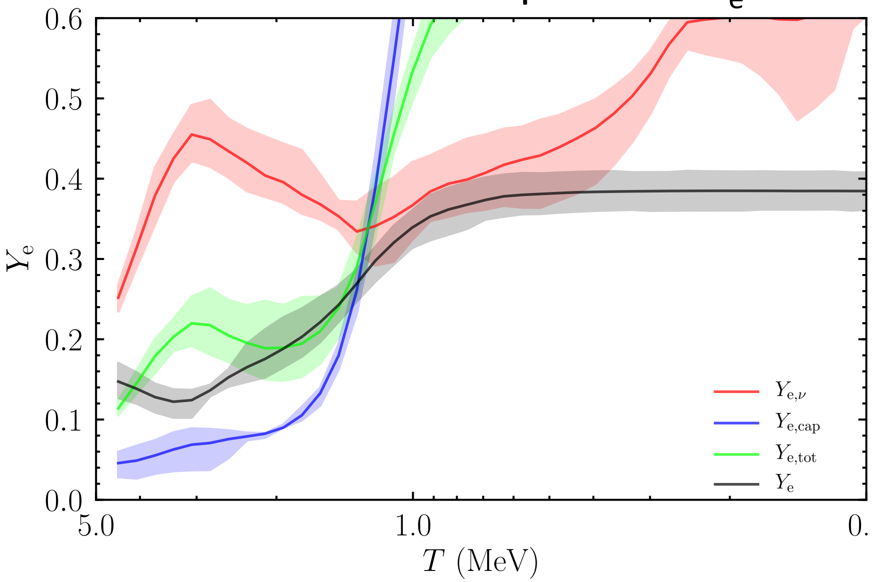
role of neutrinos

Fujibayashi, Wanajo+2019, in prep.

neutrino vs. viscosity heating



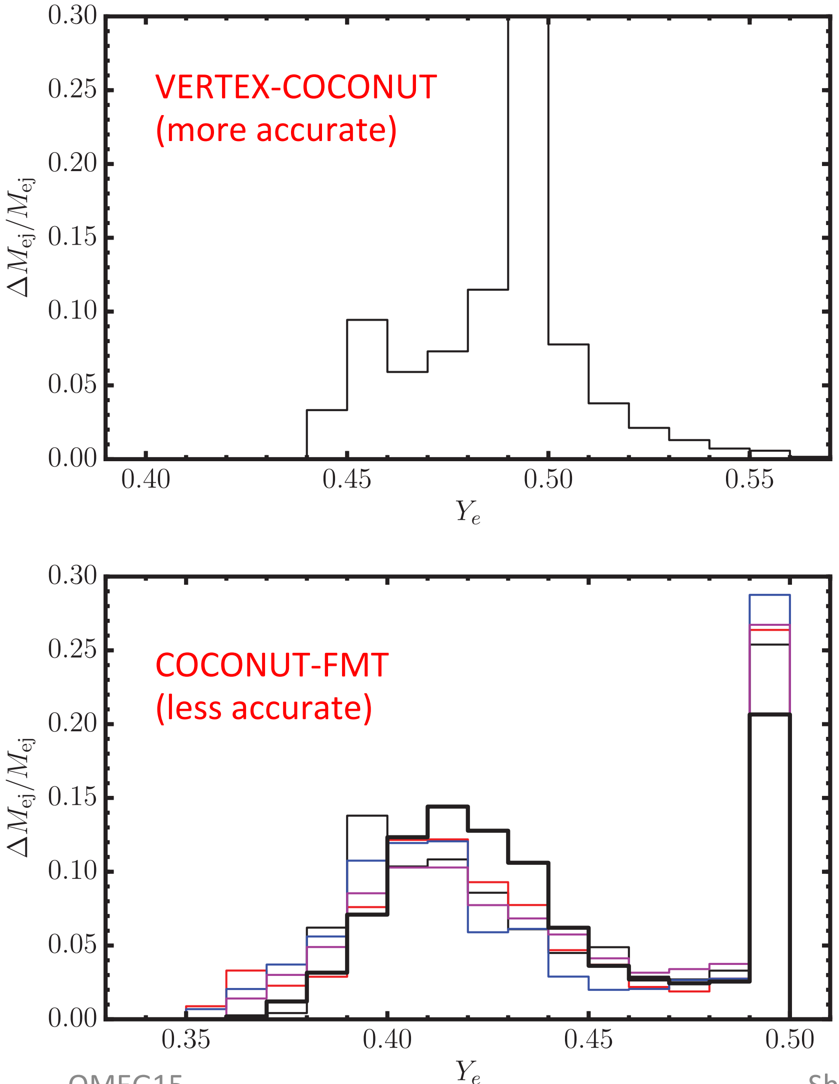
neutrino vs. e-capture for Y_e



- mass ejection is predominantly due to viscosity heating (assuming a_{vis} = 0.04), but
- neutrino flux is high enough to reach equilibrium (Y_e ~ 0.35 at freezeout; ~ 1 MeV) similar to CCSNe

same problems as CCSNe?

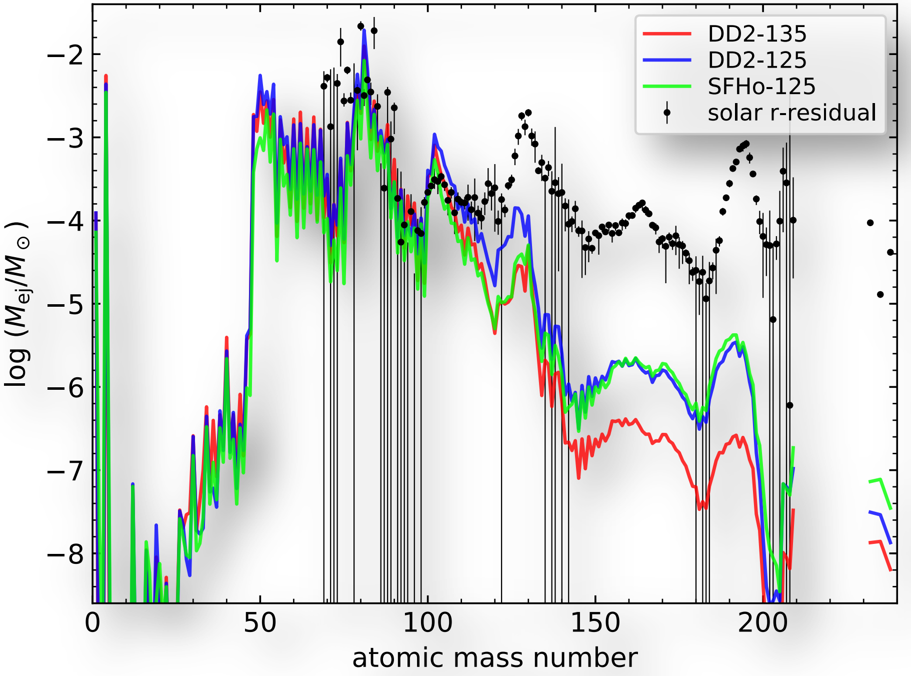
Y_e distribution for a 9.6 $M_\odot$ CCSN; Müller 2016



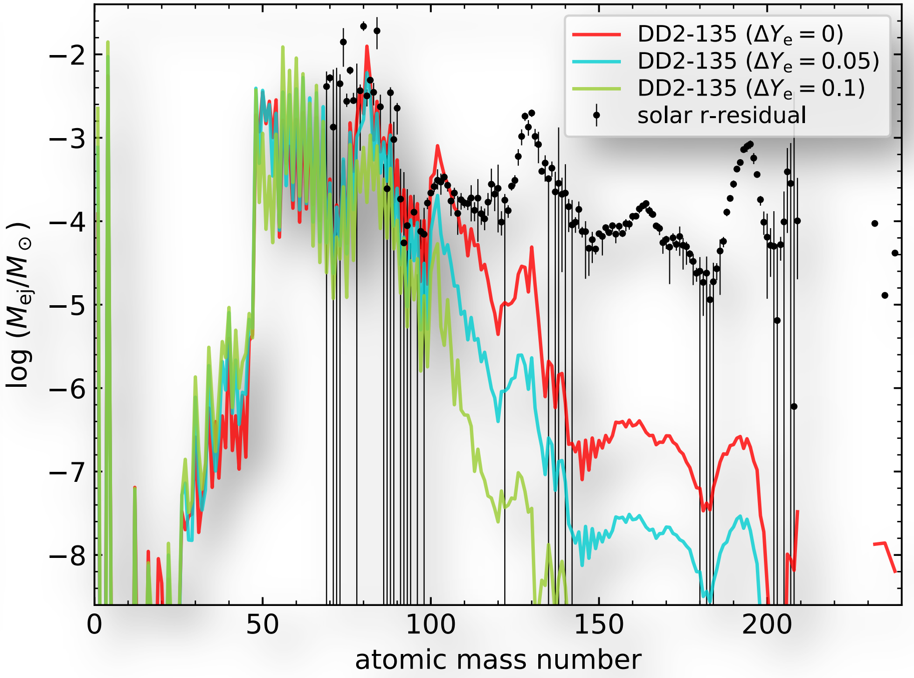
- in CCSN simulations, a simplified neutrino transport schemes (like those used in this study) underpredict Y_e values by $\Delta Y_\mathrm{e} \sim 0.1$
- therefore, we test the cases with Y_e distributions systematically shifted by $\Delta Y_\mathrm{e} \sim +0.05$ and $+0.1$

nucleosynthesis

comparison for different models



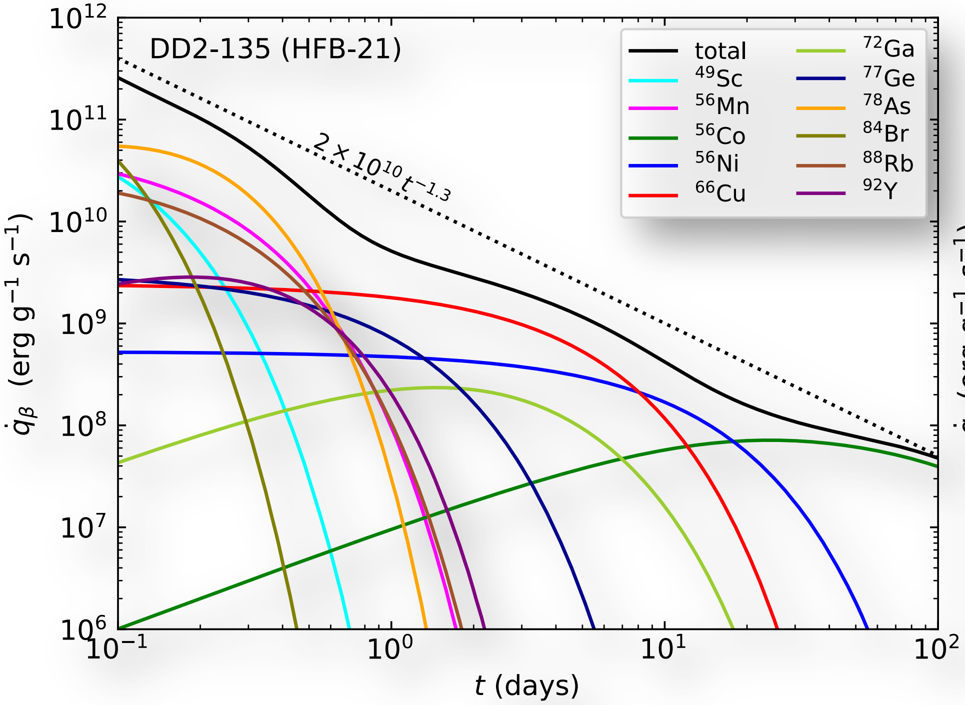
comparison for different Y_e distribution



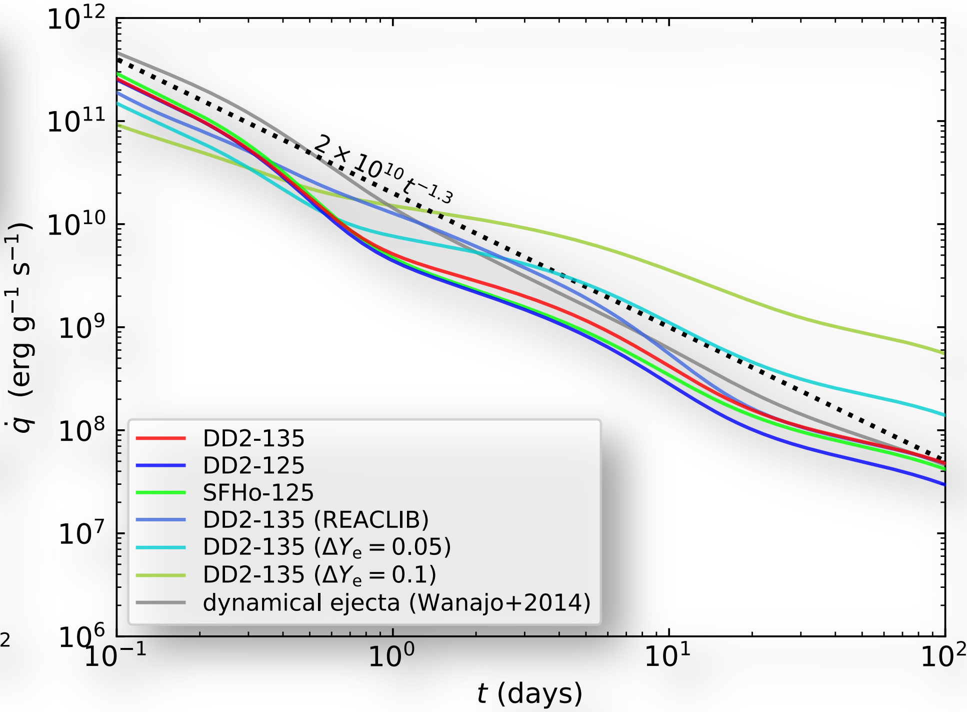
- ❖ similar results among three models with dominant production of A = 50-100 but few heavy r-nuclei
- ❖ higher Y_e cases obtain more nuclei of A = 50-70 including ^{56}Ni and ^{66}Ni

heating rates from β-decays

individual heating rates for DD2-135



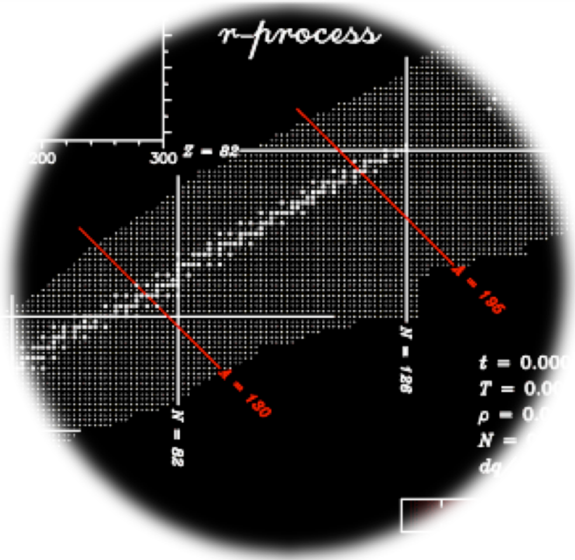
total heating rates for different models



- two dominant decay chains:
  ^{56}Ni (6.1 d) → ^{56}Co (77 d) → ^{56}Fe
  ^{66}Ni (2.3 d) → ^{66}Cu (5.1 m) → ^{66}Zn

- higher Y_e cases exhibit greater heating rates (by factors of 2 and 4) because of more abundant ^{56}Ni and ^{66}Ni

summary and outlook



❖ kilonova associated with GW170817
- dominant radioactive energy likely from ^{66}Ni and ^{56}Ni (not r-nuclei)
- ejecta are dominated by light trans-iron elements from disk ejecta
- no evidence for production of heavy r-nuclei beyond lanthanides

❖ problems to be solved
- ejecta mass cannot be constrained better than a factor of several
- more accurate neutrino transport is needed for better Y_e prediction
- what can be a “smoking gun” of heavy r-nuclei production?