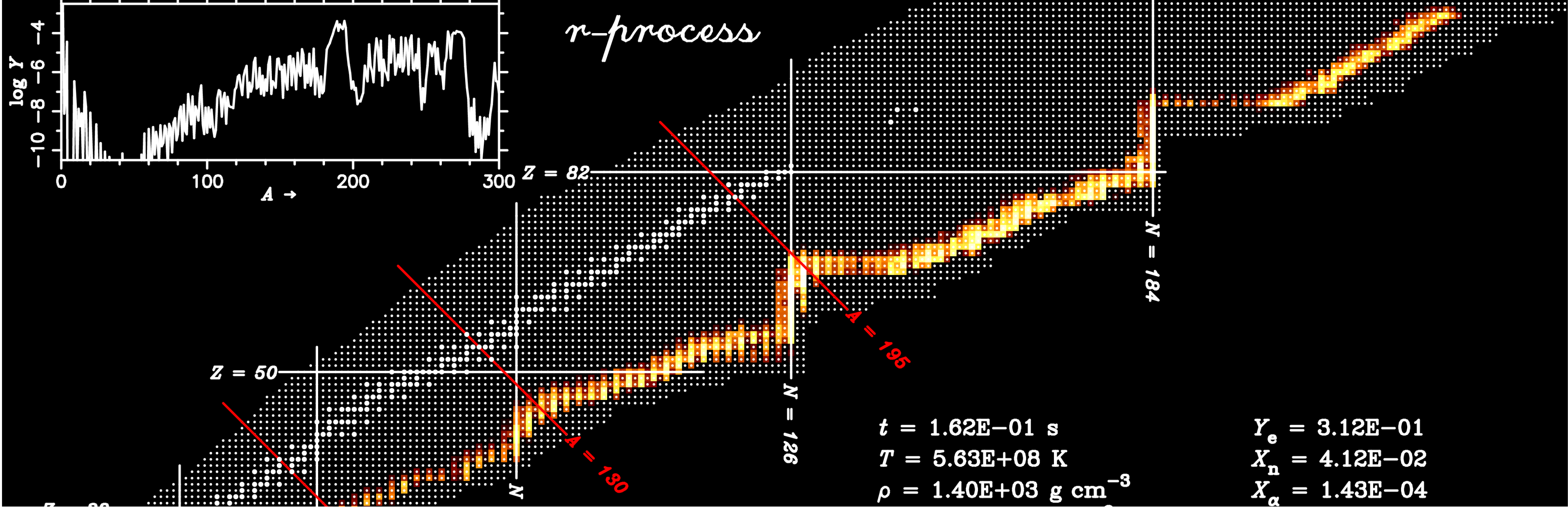

r-process and kilonovae

Shinya Wanajo (Albert Einstein Institute)

Multi-Messenger Astrophysics in the Gravitational Wave Era
September 24 - October 25, 2019, YITP, Kyoto

1. **light curve of the kilonova/GW170817**
2. **r-process and radioactive energies (Wanajo 2018)**
3. **source of the power break at 7 days**

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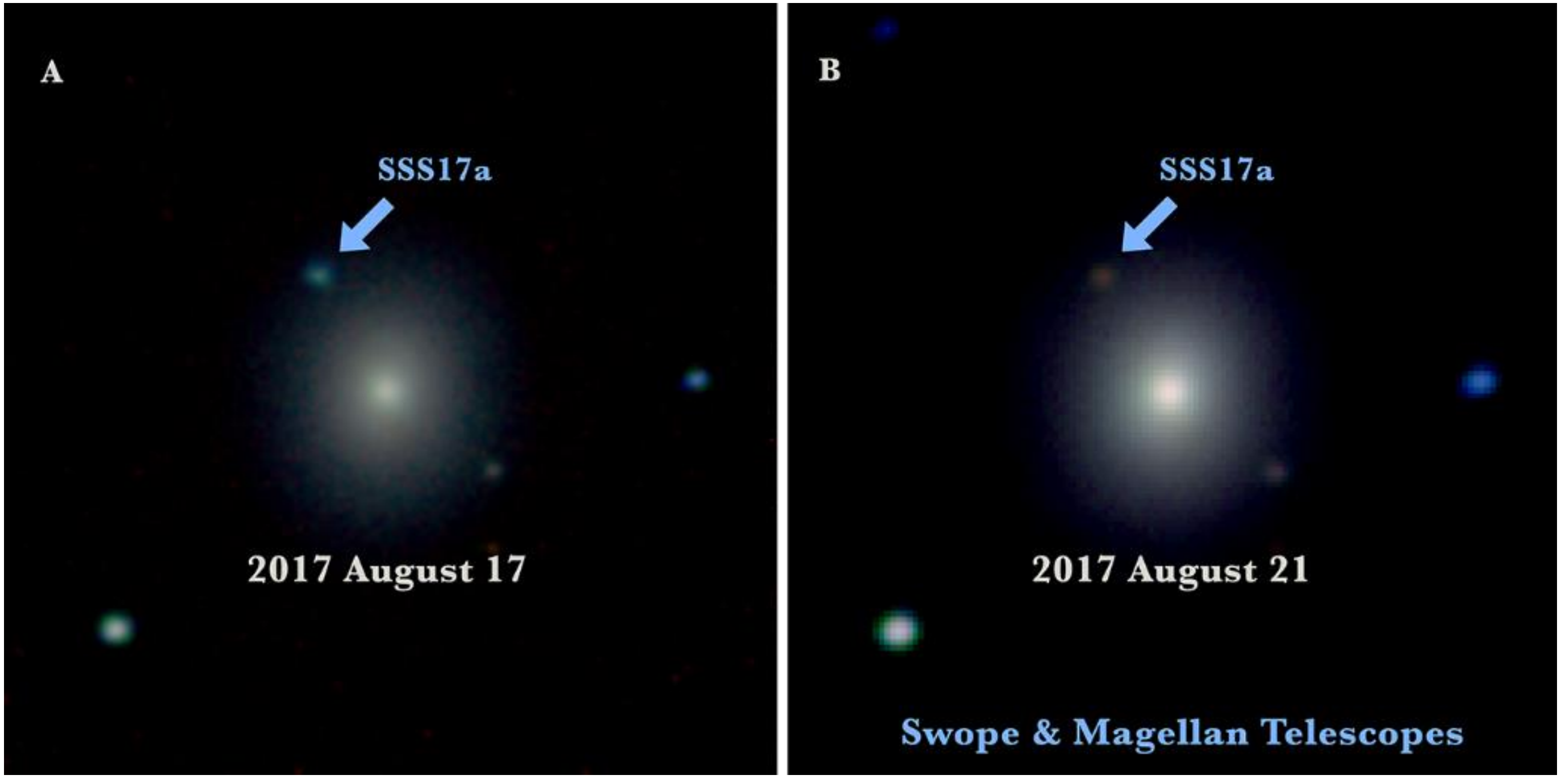
discovery of neutron star mergers

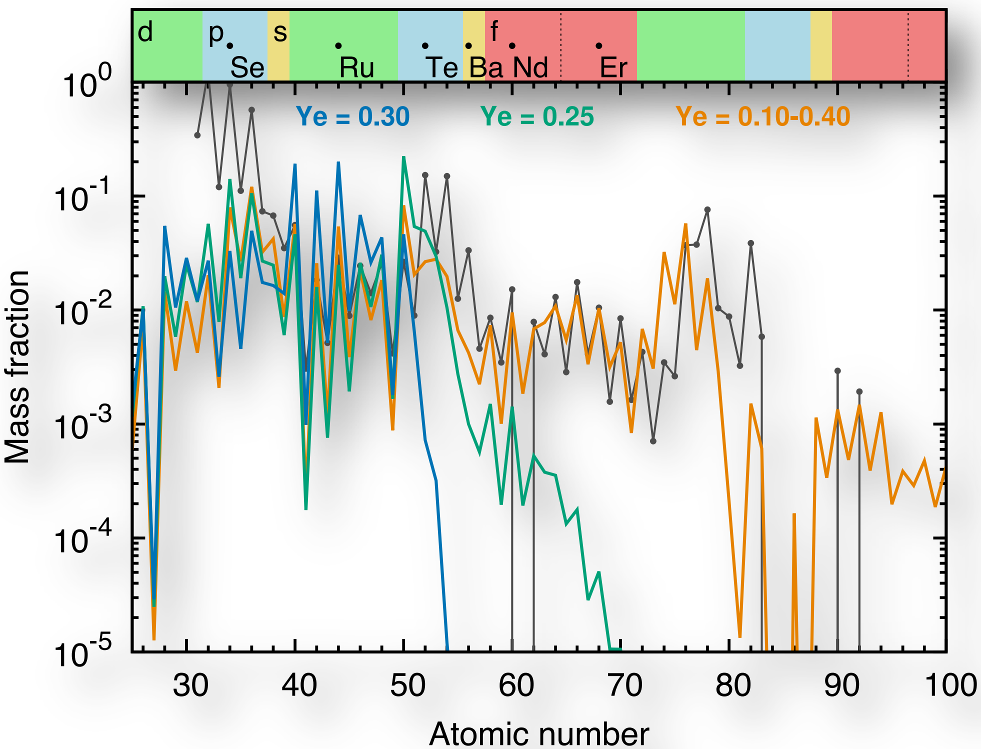


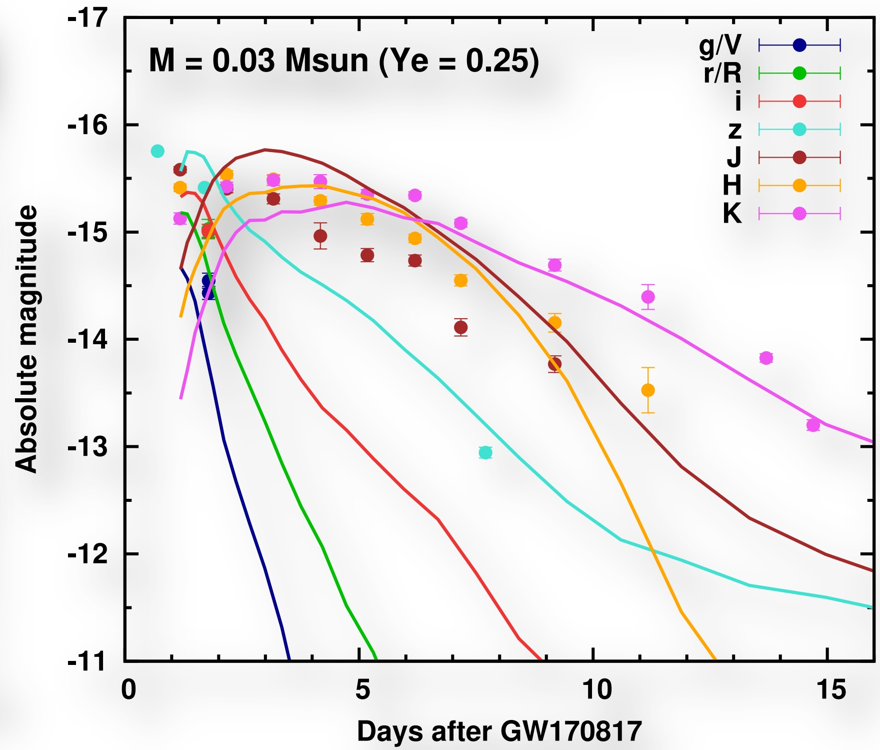
Drout+2017

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

what we learned from the kilonova are …

comparison with GW170817; Tanaka+2017

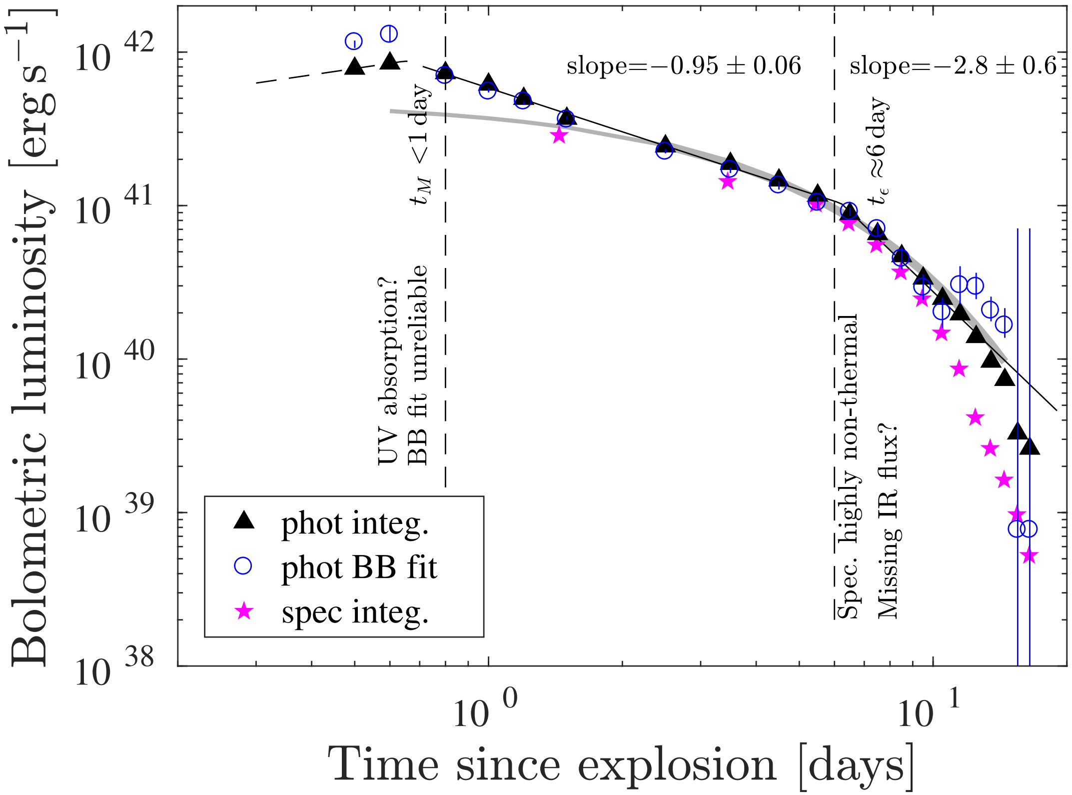




- ❖ total ejecta mass of M_{ej} ≈ 0.03-0.06 $M_{\odot}$ and the lanthanide mass fraction of X_{lan} ≈ 0.001-0.01 (see also Cowperthwaite+2017, etc.)
- ❖ no evidence of heavy r-nuclei production (gold, platinum, …)

what is the source of the break at 7 days?

Waxman+2018

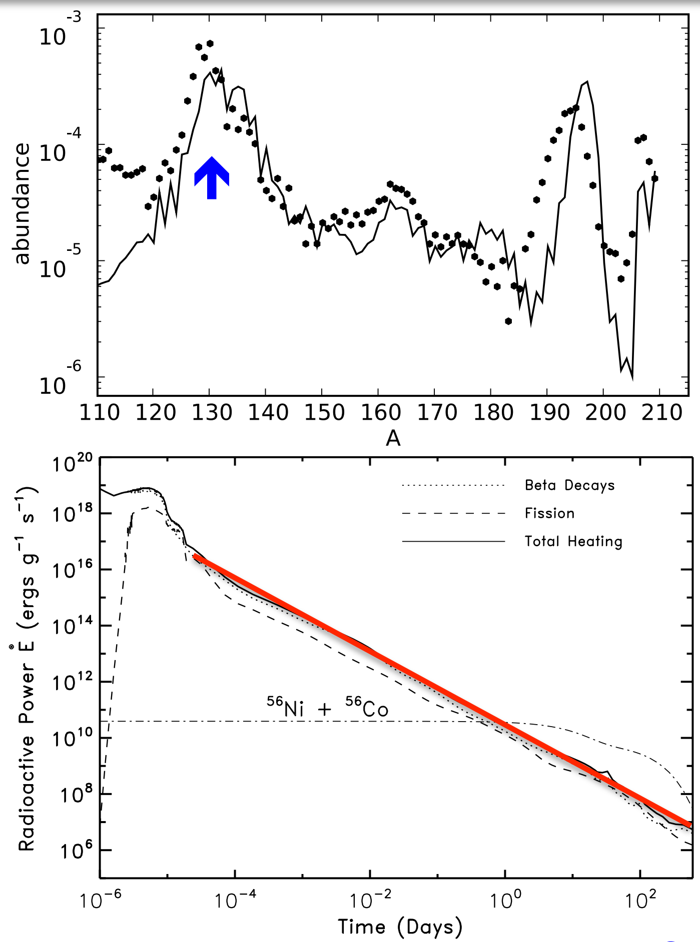


bolometric luminosity: steepening from the power index -1 to -3 at ≈ 7 days because of

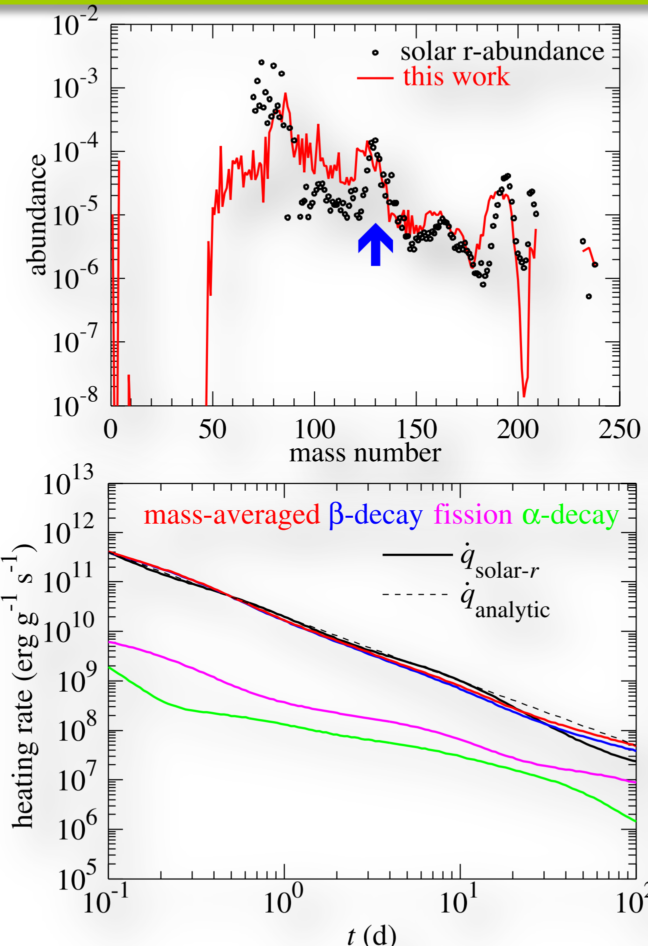
- radioactive decay effect (Wanajo 2018; Wu+2019)
- thermalization effect (Waxman+2018, 2019)
- photon diffusion effect (Kawaguchi+2018; Hotokezaka+2019)

radioactive energy of $t^{-1.3}$ really correct ?

Metzger+2010



Wanajo+2014



❖ heating is dominated by the β-decays of r-nuclei with A ~ 130

❖ heating rate well scaled as ≈ $2 \times 10^{10}\ t^{-1.3}$ erg/g/s with $A > 80$ (e.g., Metzger+2010; Wanajo+2014; Hotokezaka+2016)

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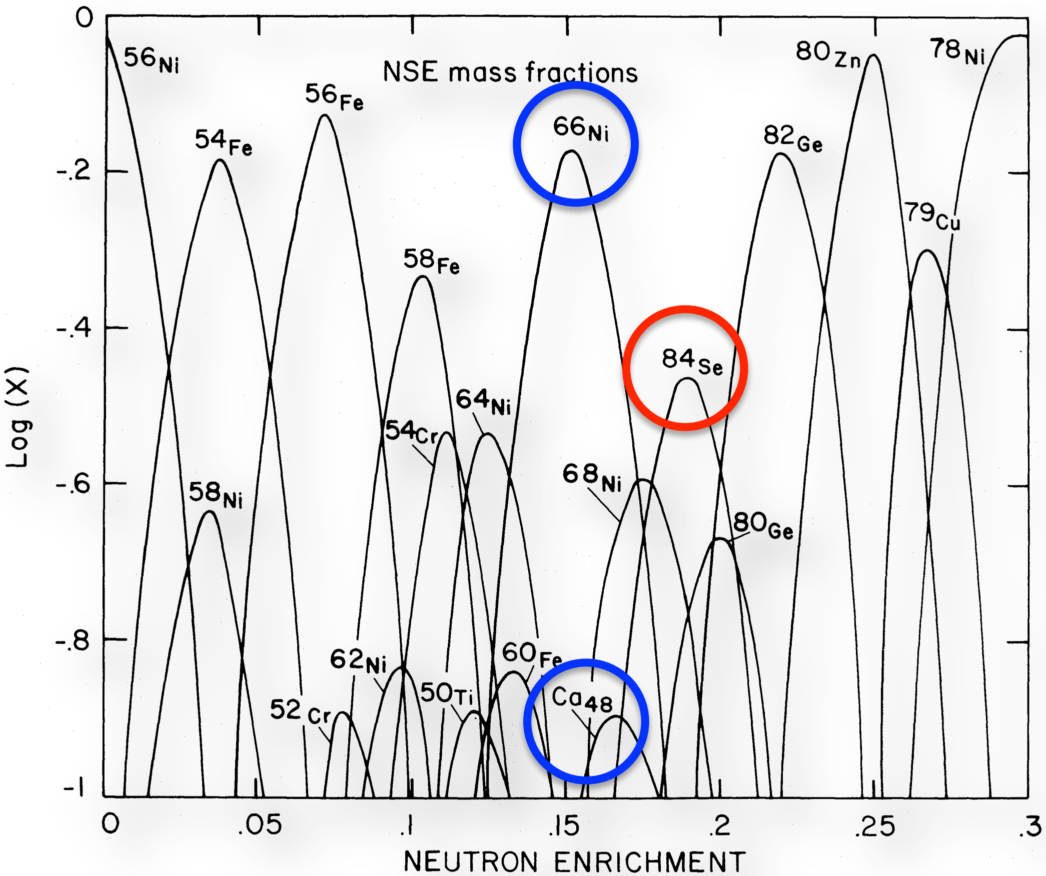
origin of the 1st peak: neutron-rich NSE?

Hartmann+1985;
NSE composition at T = 3.5 GK and $\rho = 10^7$ g cm^{-3}



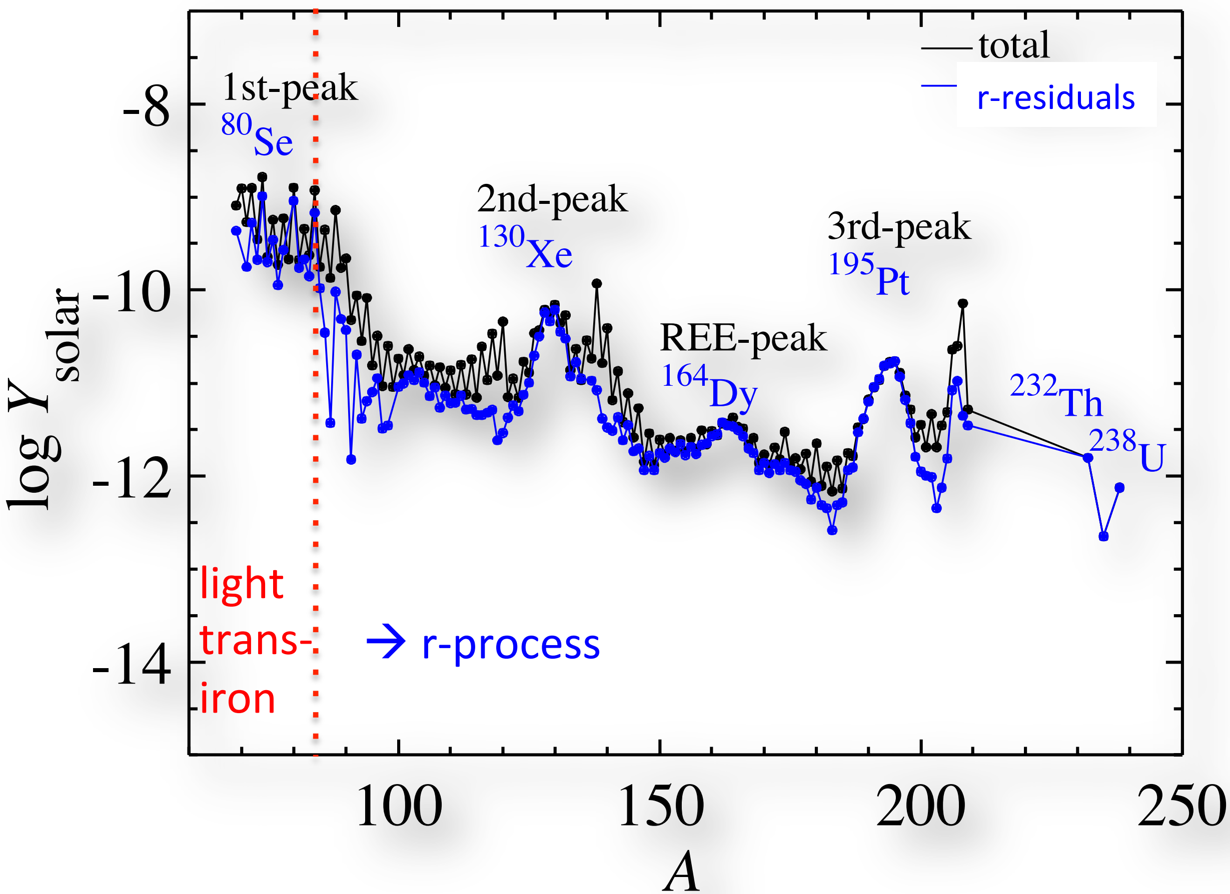
Y_e = 0.5 0.45 0.4 0.35

merger ejecta achieve neutron-rich NSE conditions when Y_e > 0.37 (Wanajo+2018)

- nuclei up to A = 84 are build up in NSE;
  ^{84}Se at $Y_e \approx 34/84 = 0.405$
- lighter nuclei can be co-produced, e.g.,
  ^{48}Ca at $Y_e \approx 20/48 = 0.417$
  ^{66}Ni at $Y_e \approx 28/66 = 0.424$

what are the r-process elements?

r-process residuals to the solar system abundances

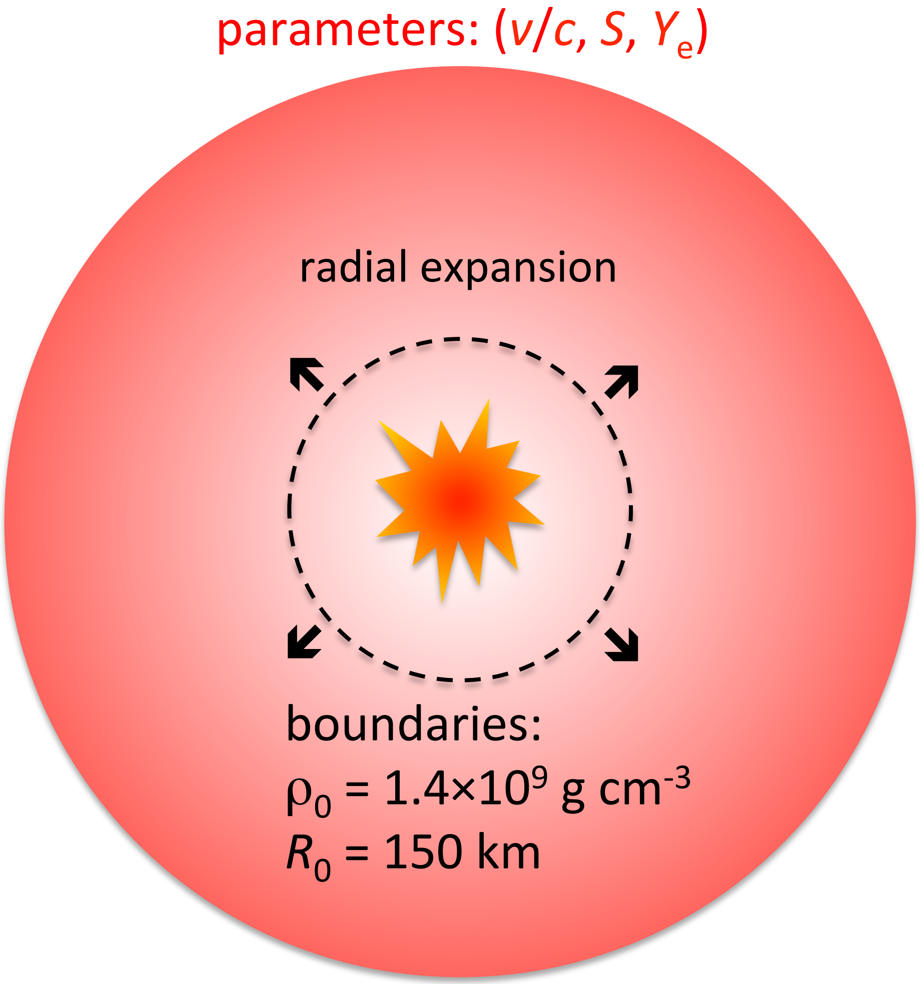


mass number

r-process "residuals"
= solar abundances
– s-process component

- elements of $A > 84$ are made by the r-process (including 2nd and 3rd peaks)
- but, those of $A \leq 84$, "light trans-iron nuclei", can be made in NSE or QSE (including 1st peak)

free expansion (FE) models



Wanajo 2018

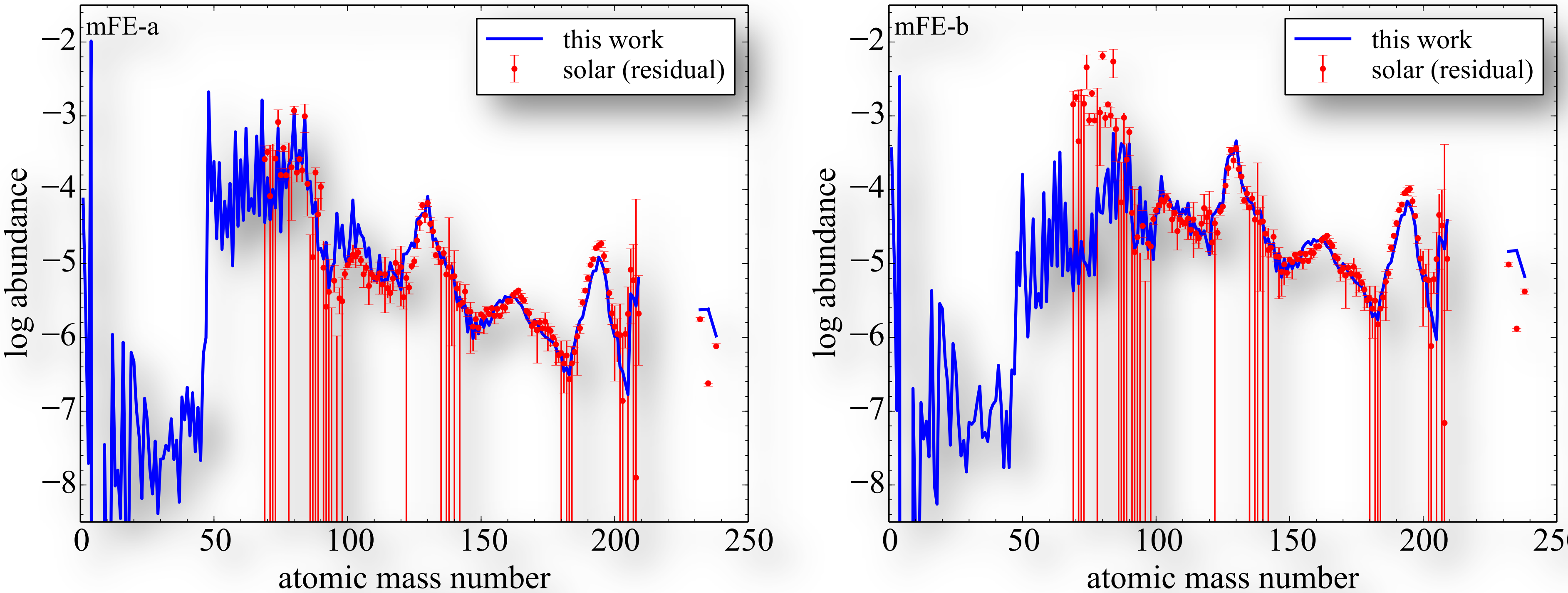
- free expansion (FE) models that mimic the physical conditions of merger outflows (either of dynamical and disk ejecta)

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

- 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)

fitting to the solar r-residuals

Wanajo 2018; r-residuals from Goriely 1999



fit to $A \geq 69$

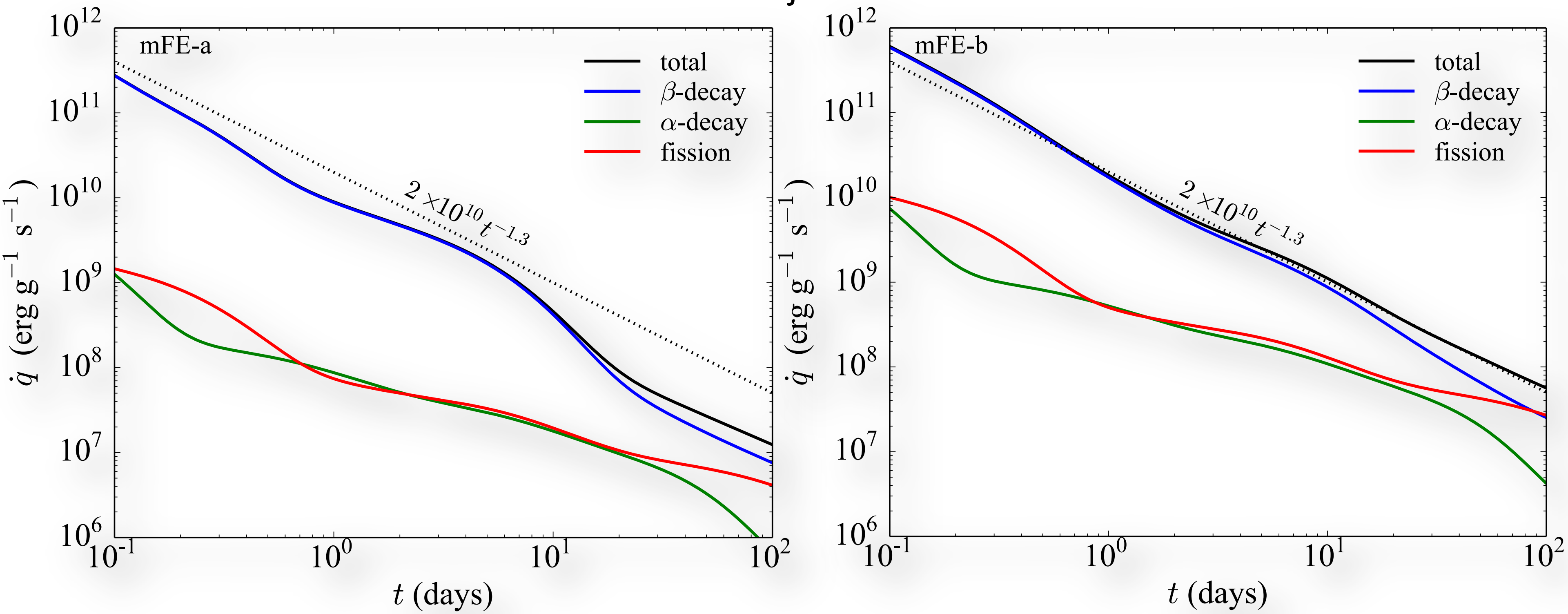
- ❖ X_{lan} = 0.014 (consistent with obs.)
- ❖ lighter nuclei are co-produced (A = 48-68)

fit to $A \geq 88$

- ❖ X_{lan} = 0.086 (inconsistent with obs.)
- ❖ r-process nuclei only

heating rates

Wanajo 2018



fit to $A \geq 69$

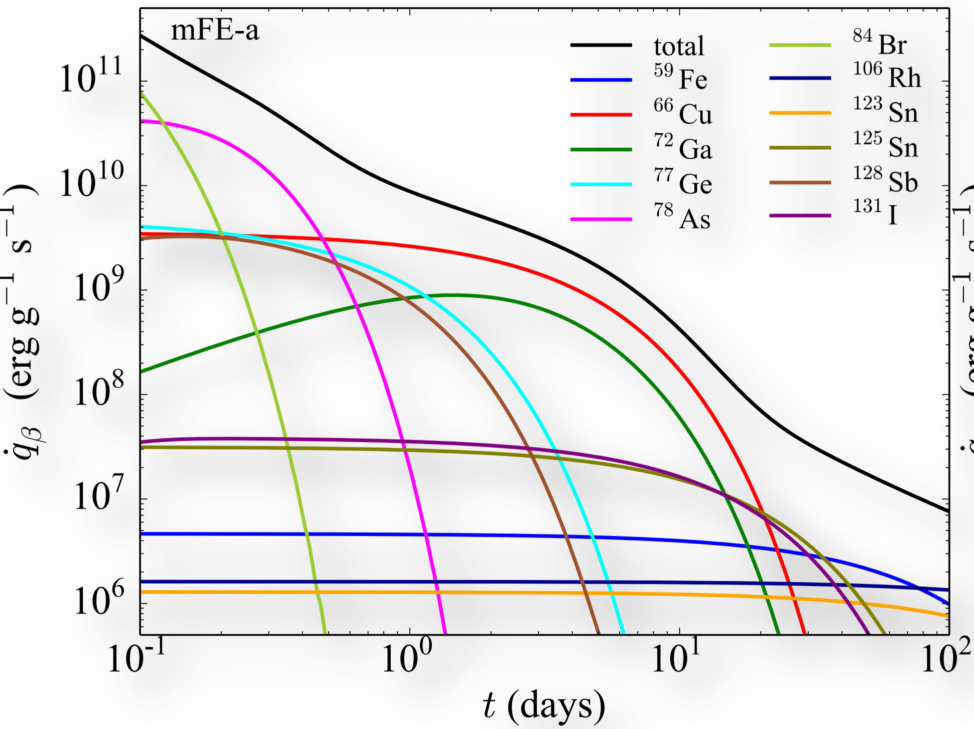
- not scaled by a power law but rather by an exponential during 1-15 days

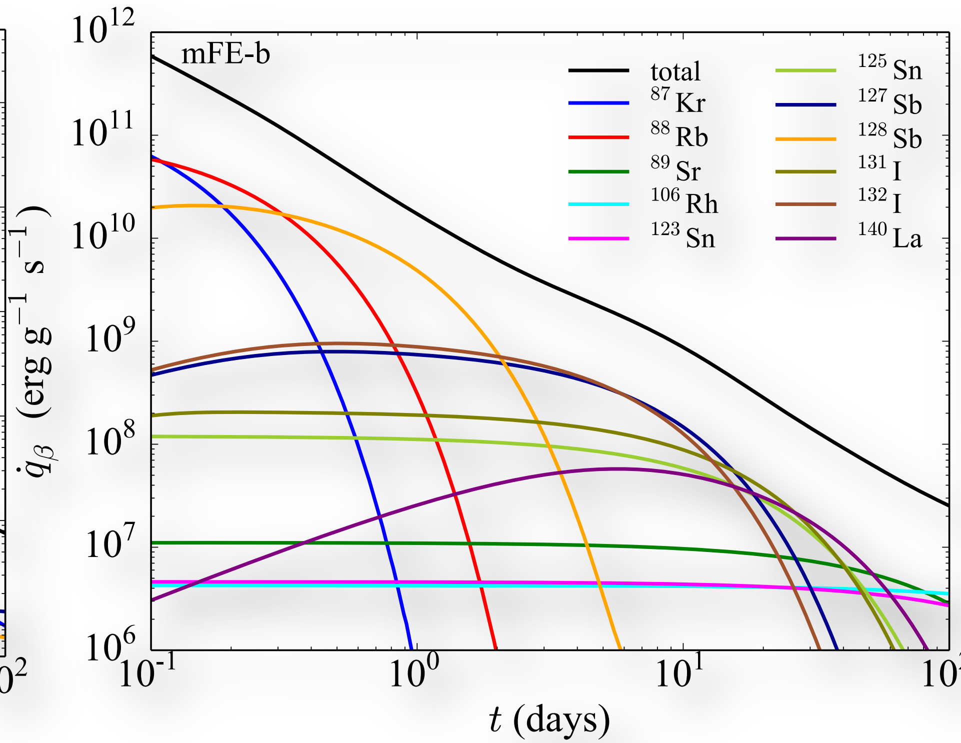
fit to $A \geq 88$

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

heating rates from individual β-decays

Wanajo 2018





fit to $A \geq 69$

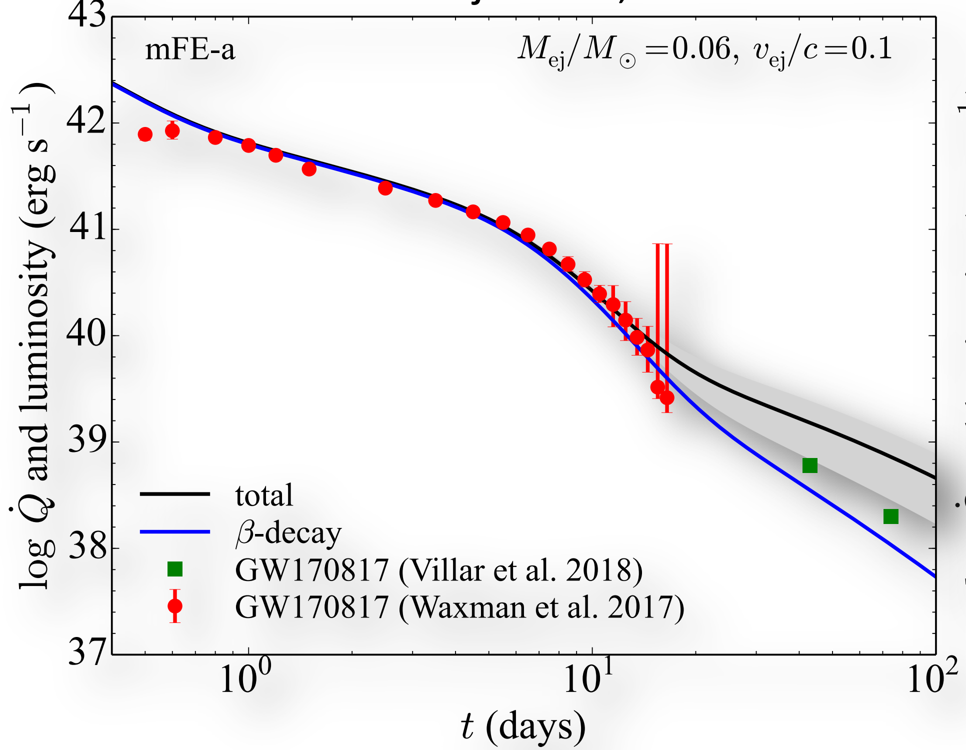
- two decay chains are identified:
  ^{66}Ni (2.3 d) → ^{66}Cu (5.1 m) → ^{66}Zn
  ^{72}Zn (1.9 d) → ^{72}Ga (14 h) → ^{72}Ge

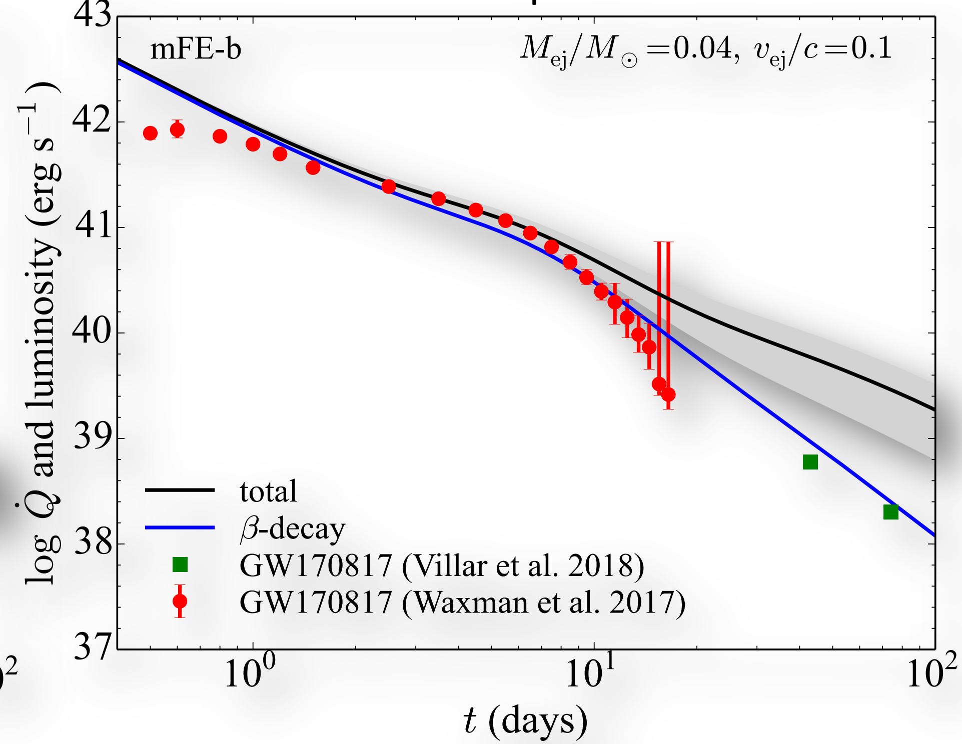
fit to $A \geq 88$

- 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





fit to $A \geq 69$

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

fit to $A \geq 90$

- thermalization effect is insufficient to account for the power break at 7 days

1. light curve of the kilonova/GW170817
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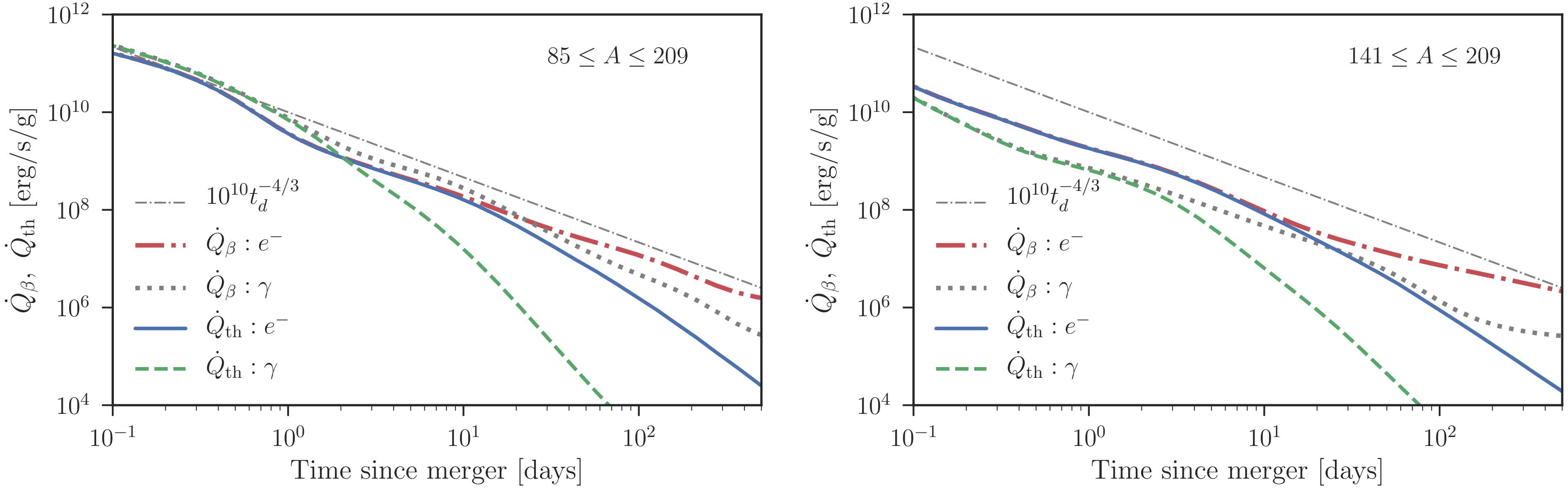
thermalization effect

Hotokezaka+2019; $M_{ej}/M_{\odot}$ = 0.05, $v_{ej}/c \approx 0.1$

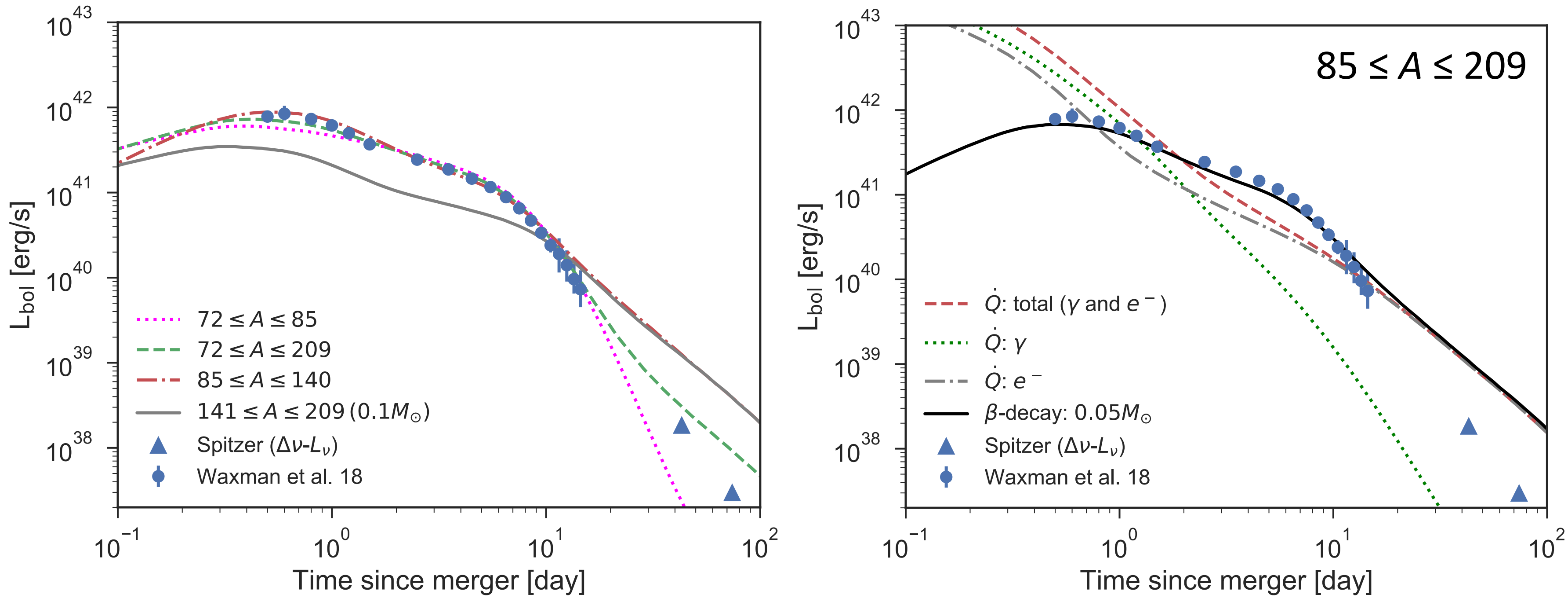


β-decay energies from the solar r-isobars with thermalization effects

- thermalization effects play a role gradually at late times (> 10 days) that cannot be the source of the power break at 7 days

photon diffusion effect

Hotokezaka+2019; $M_{ej}/M_{\odot} = 0.05$, $v_{ej}/c \approx 0.1$

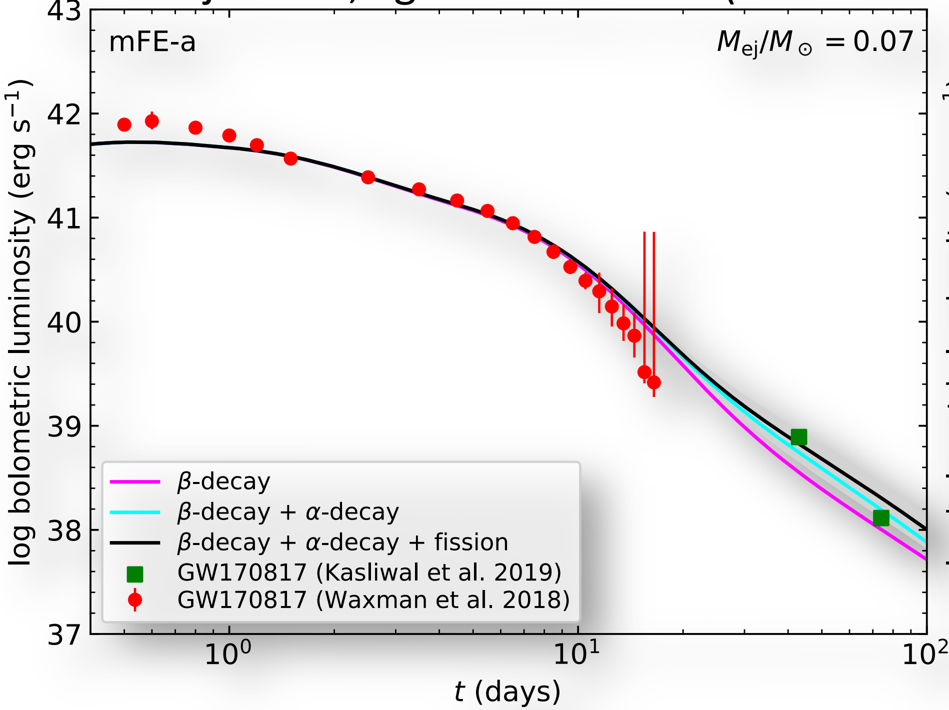


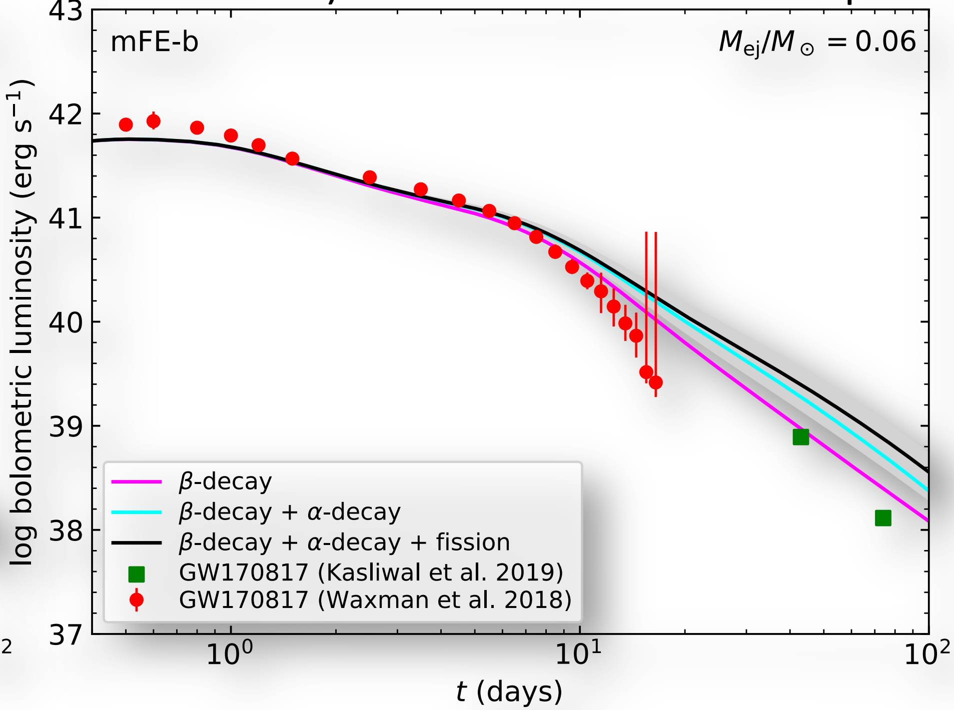
β-decay energies from the solar r-isobars with the improved Arnett-type light curve model (with photon diffusion effects)

- power break at 7 days for both $A \ge 72$ (with trans-Fe) and $A \ge 85$ (r-only) cases (the authors favor the latter) but with α-decay or fission

with α-decay and fission

Wanajo 2018; light curve model (with thermalization effects) in Hotokezaka+2019 adopted





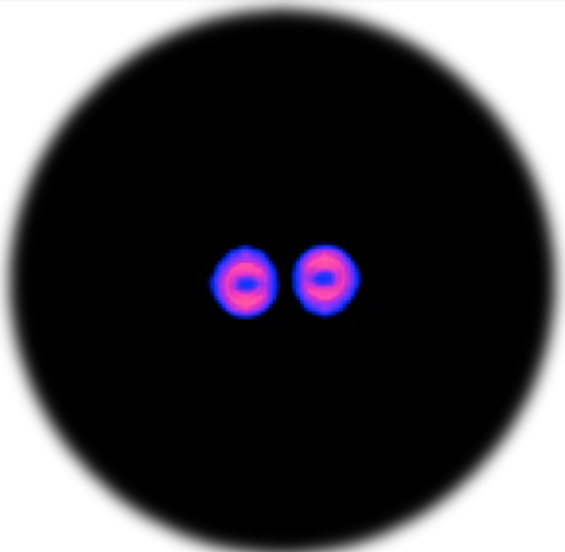
fit to $A \geq 69$

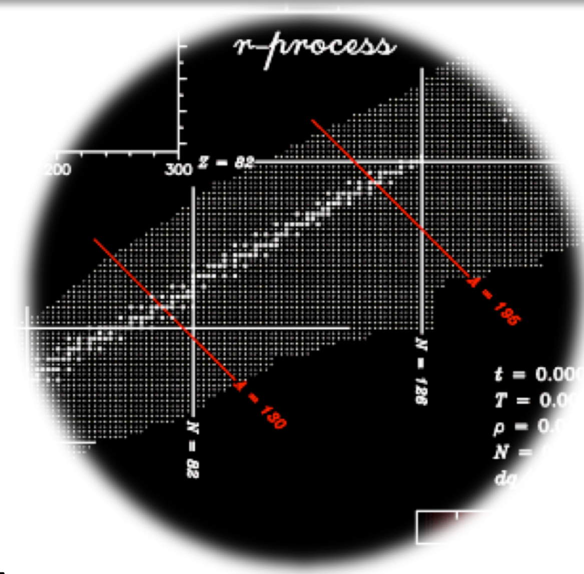
❖ light curve can be well explained with the β-decays of ^{66}Ni and α-decay and fission of trans-Pb

fit to $A \geq 90$

❖ light curve is inconsistent with the heating rate at ~10 days

summary and outlook





- light curve of kilonova/GW170817
  - dominant energy from the β-decay of ^{66}Ni at early times (< 10 days)
  - late-time heating from α-decay and fission of trans-Pb nuclei
  - power break at 7 days because of photon diffusion and radioactive decay (of ^{66}Ni)

- key to the future observation
  - determination of light curves at late times (> 10 days) to be a "smoking gun" of heavy (trans-Pb) r-process nuclei production