# 重元素の起源

## or, did we see gold and platinum in GW170817?

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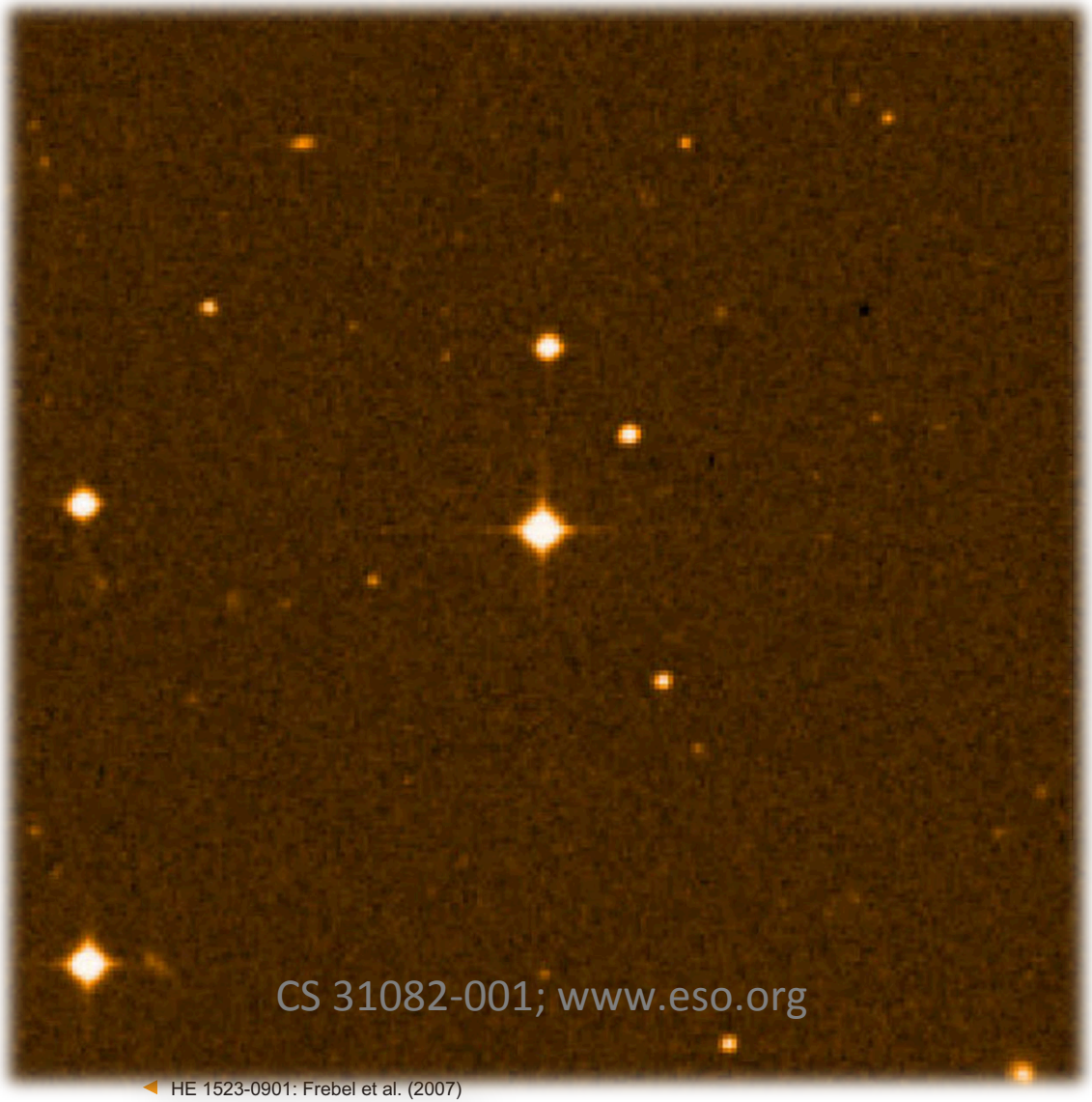
# origin of the “main” r-process elements



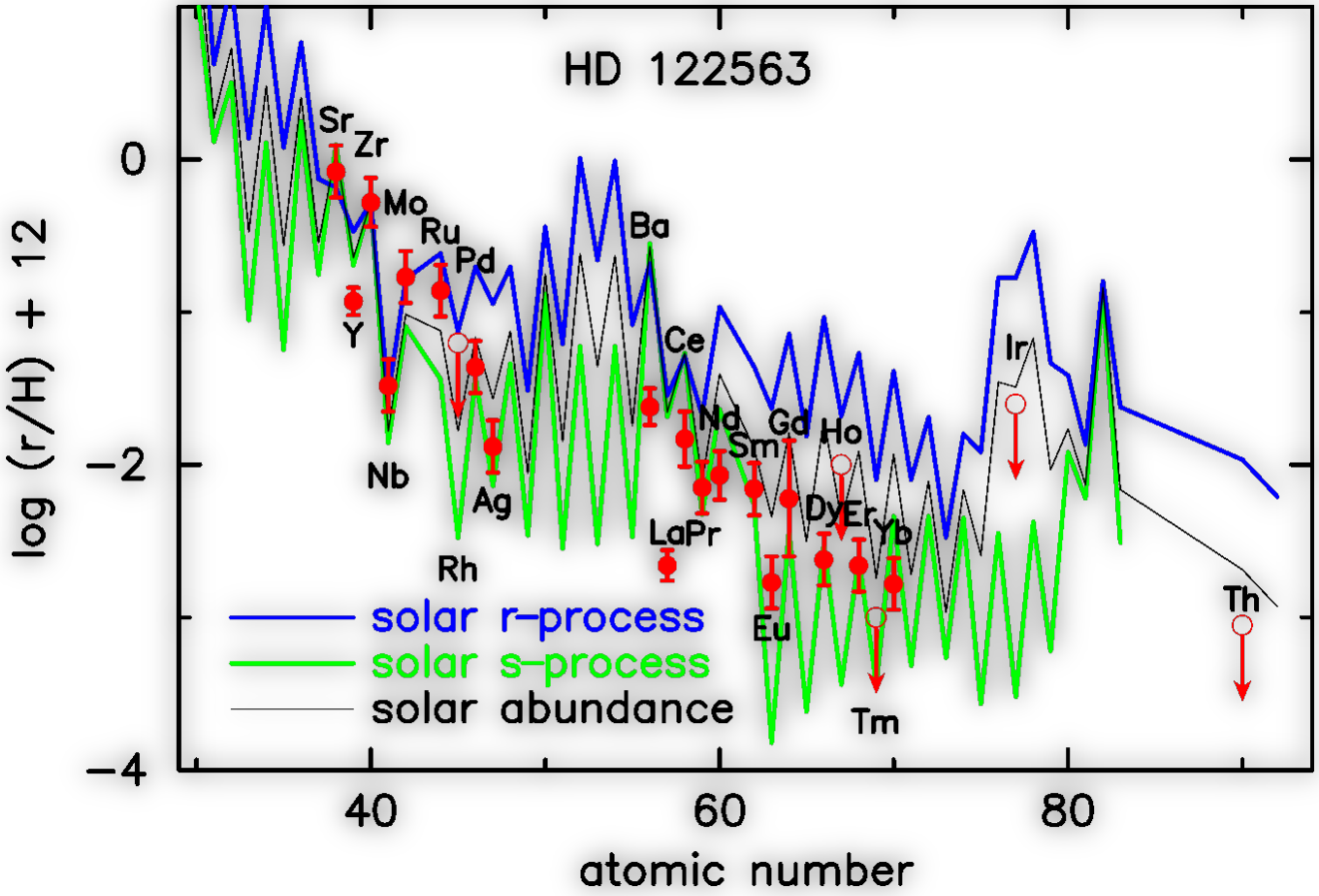

◀ HE 1523-0901: Frebel et al. (2007)

surviving old stars record nucleosynthesis memories in the early universe

- r-process enhanced stars show constant abundance patterns for $50 < A < 80$
- the r-process appears to be robust for $A \geq 56$ and to have variations for $A < 50$ and $A > 80$

# origin of the “weak” r-process elements

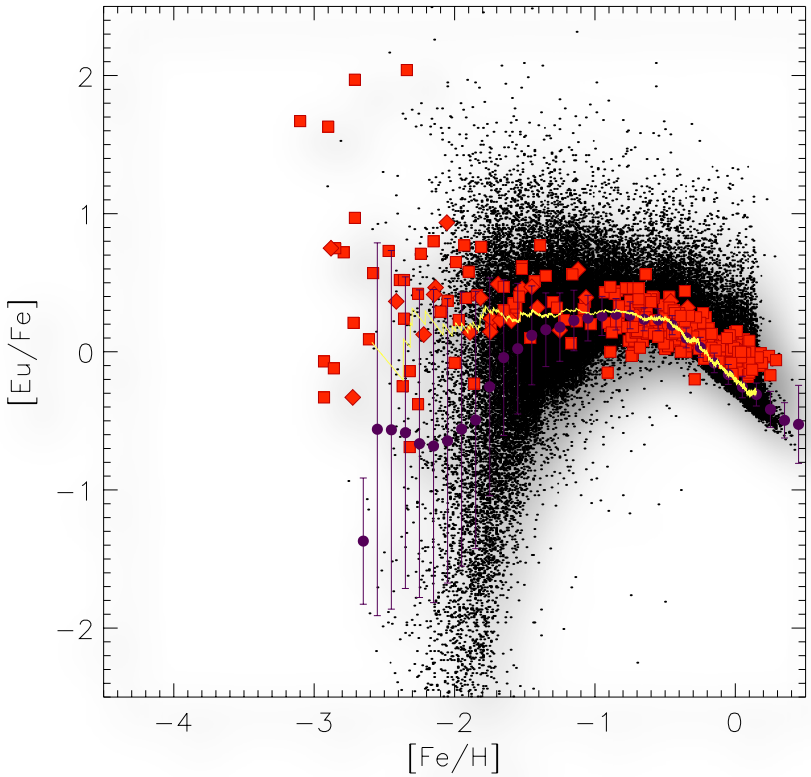
“Honda star”; Honda, Aoki, Ishimaru, Wanajo, Ryan 2006



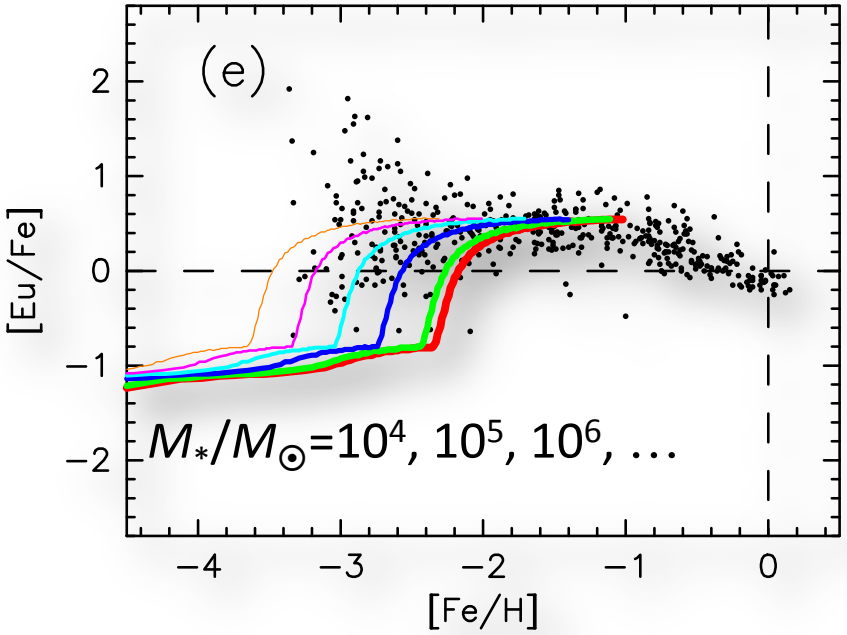

- “normal” (or r-deficient) stars show high Sr/Eu ratio
- “weak” r-process does not make gold (Wanajo & Ishimaru 2016)

# origin of Eu (main r-process) from GCE

Argast+2004



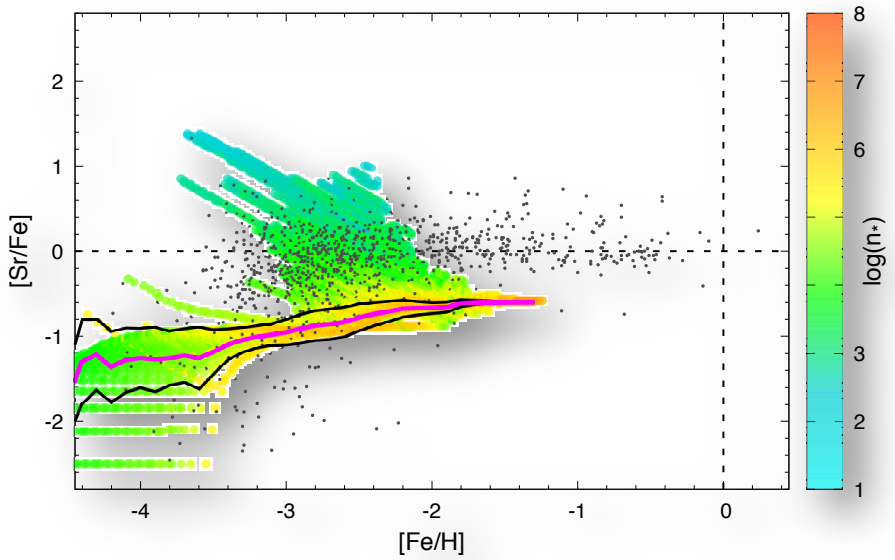

Ishimaru, Wanajo, Prantzos 2015

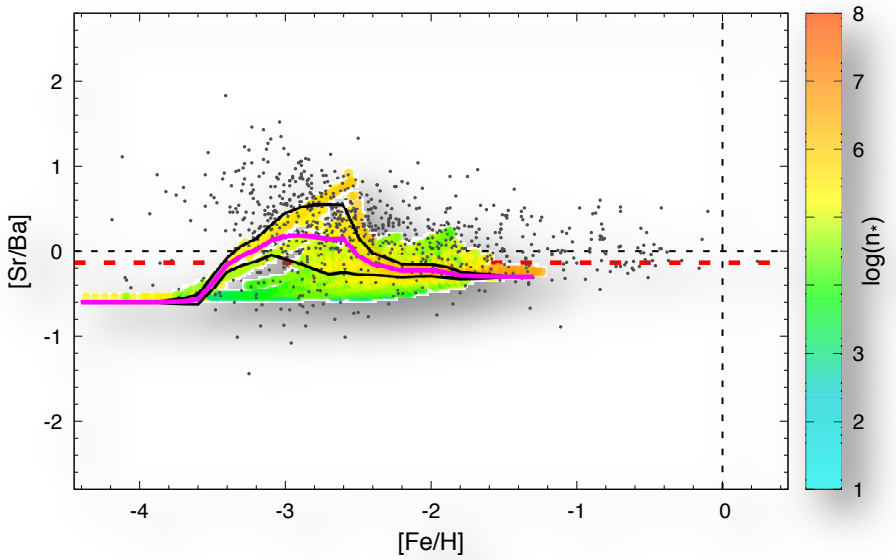



- merger timescales ~ 100 Myr conflict with measured stellar r-process abundances in *single* Galactic halo models?
- NO! r-process abundances at low metallicities can be due to slowly evolving small *sub-halo* components (also Hirai+2015; Komiya et al. 2016)

# origin of Sr (weak r-process) from GCE

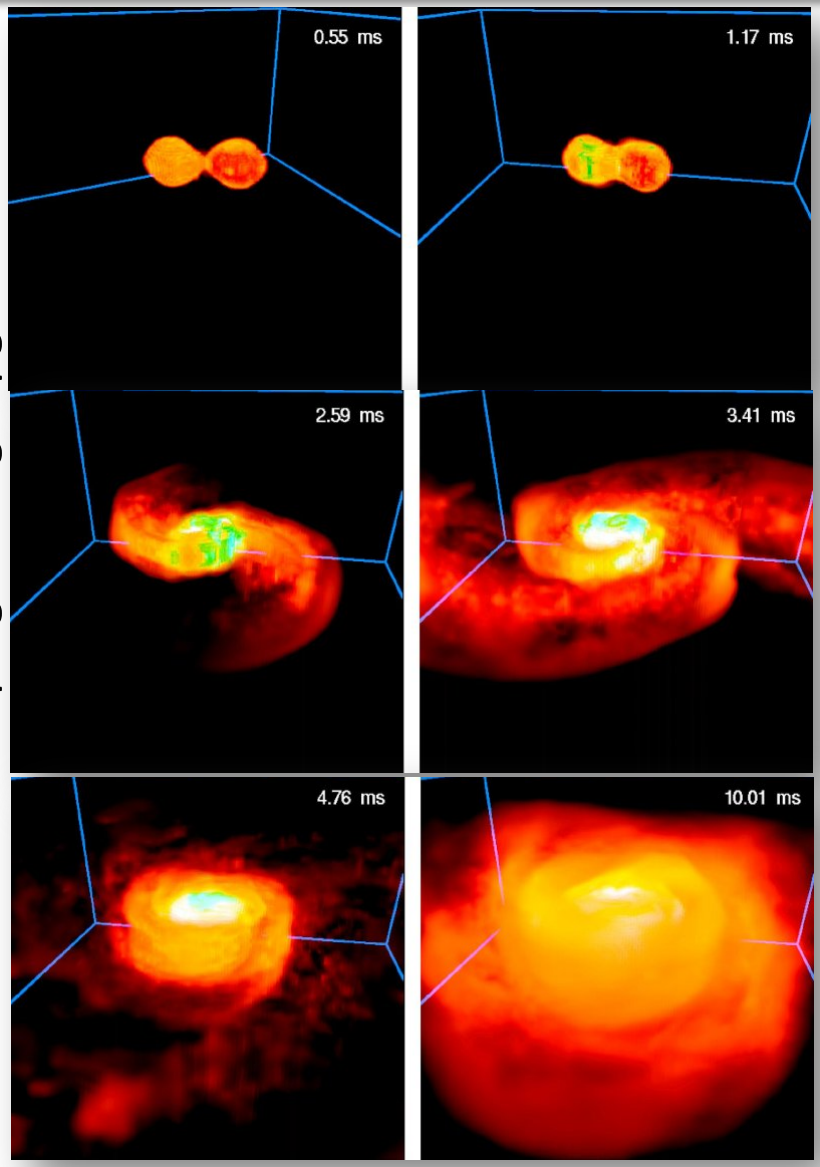
ECSN model; Ojima, Ishimaru, Wanajo, Prantzos, François 2018




- sources may not associate with the main r-process because of large star-to-star scatters in Sr/Ba
- suggested sites include ECSNe (Wanajo+2011), PNS winds (Wanajo 2013; also Aoki+2017), rotating massive stars (Pignatari+2010), but neutron star mergers?

# two mass ejection episodes

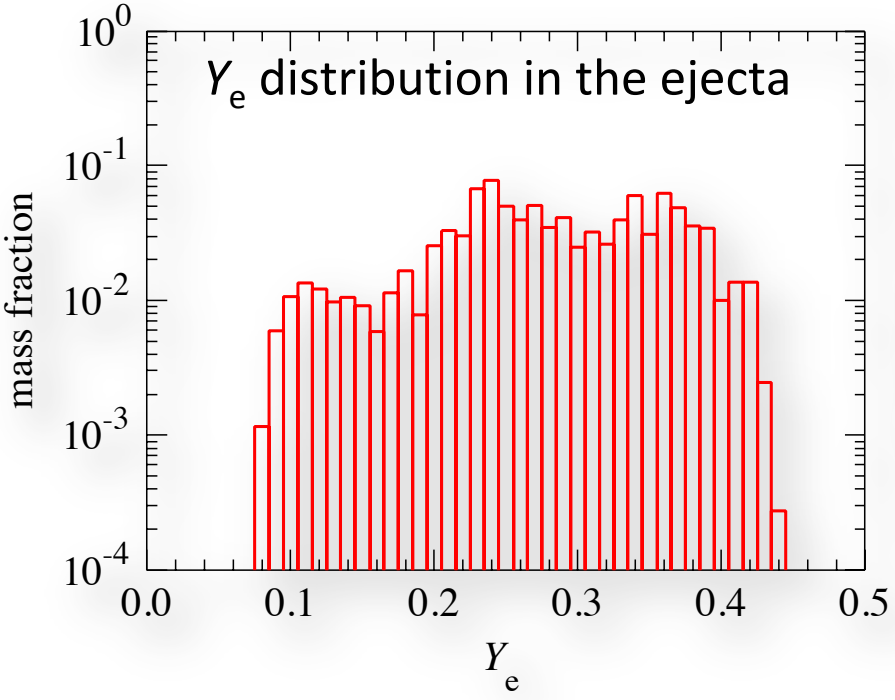



www.mpa-garching.mpg.de

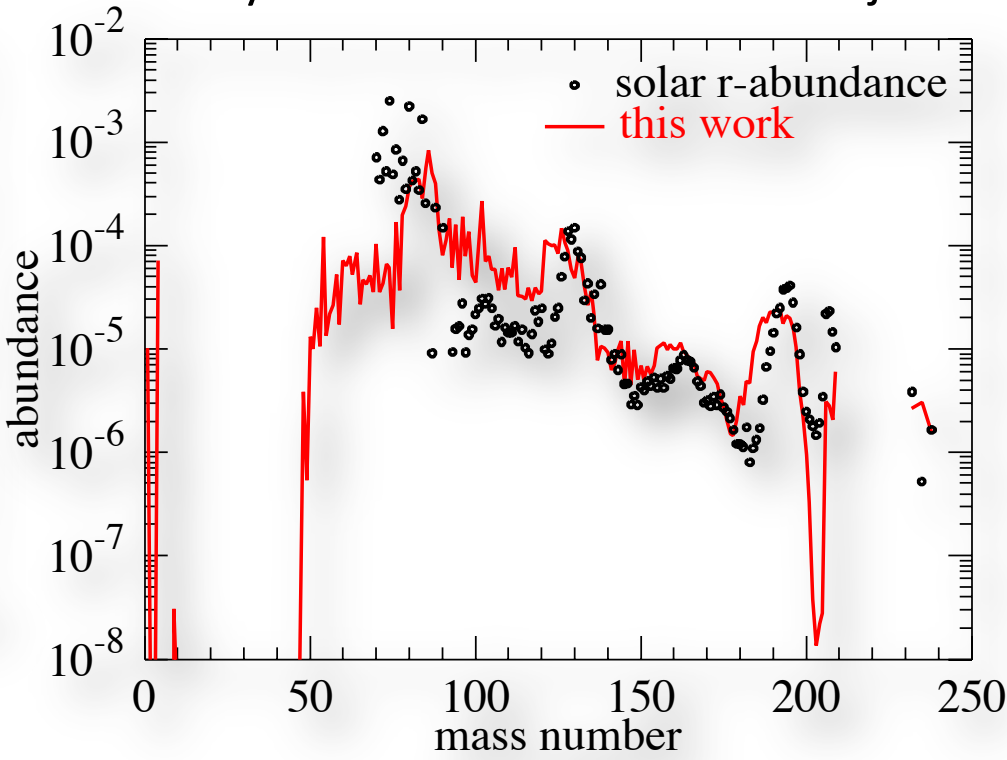
- neutron star collision
- dynamical ejecta (~ 0.01 sec.)
  $M_{ej}$ ~ $10^{-2}$ $M_\odot$
  $Y_e$ ~ 0.1-0.4 (very to slightly n-rich)
- wind ejecta (~ 1 sec.)
  $M_{ej}$ ~ $10^{-2}$ $M_\odot$
  $Y_e$ ~ 0.3? (mildly n-rich?)

# NS mergers: dynamical ejecta

Wanajo+2014




nucleosynthesis abundances in the ejecta

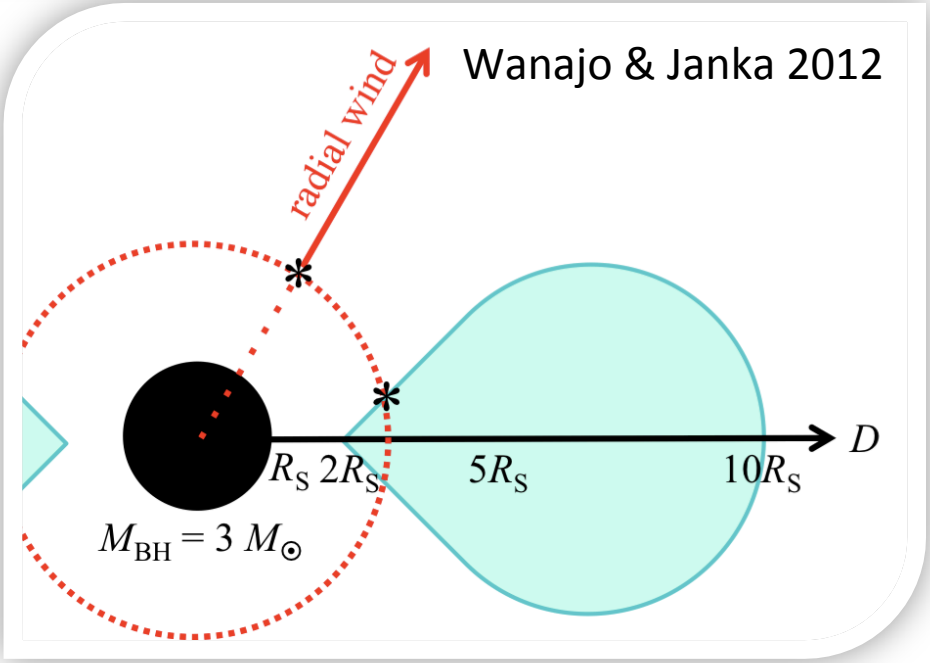


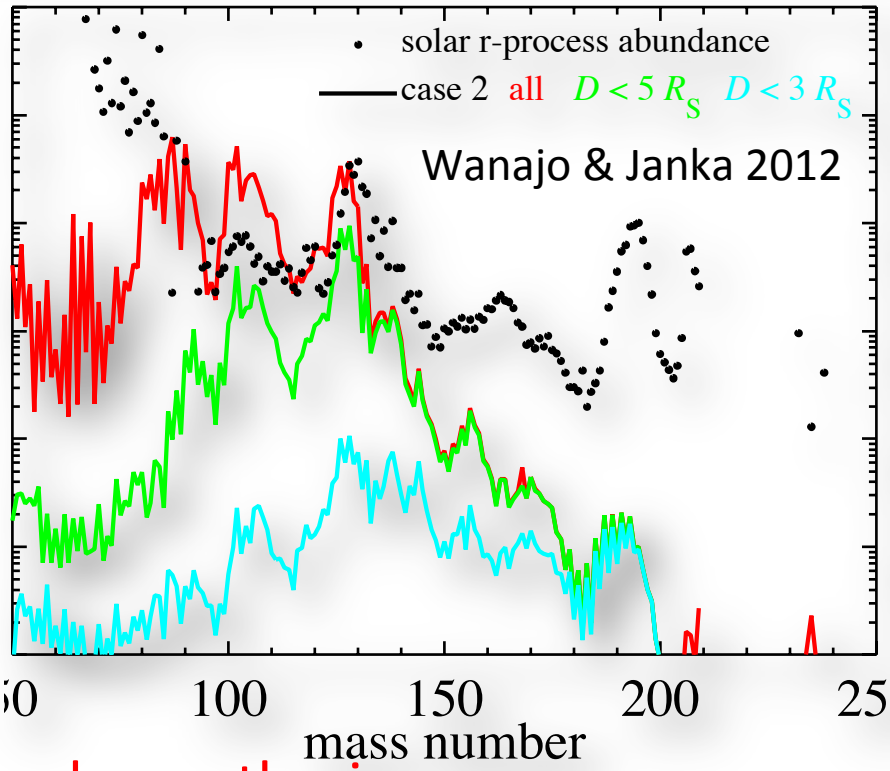

- positron capture and neutrino absorption on free nucleons result in less neutron-rich ejecta with $Y_e$ ~ 0.1-0.45
- good agreement with full solar r-process range for $A$ = 90-240 (similar result by Goriely+2015 but by Radice+2016)

# $1.3+1.3\ M_\odot$ neutron star merger with full-GR and neutrino transport (SFHo)

simulation by Yuichiro Sekiguchi

# NS mergers: wind ejecta




mass ejection from accretion tori

- around a central massive NS or black hole
- due to neutrino heating, viscous heating, nuclear heating, or magnetic field

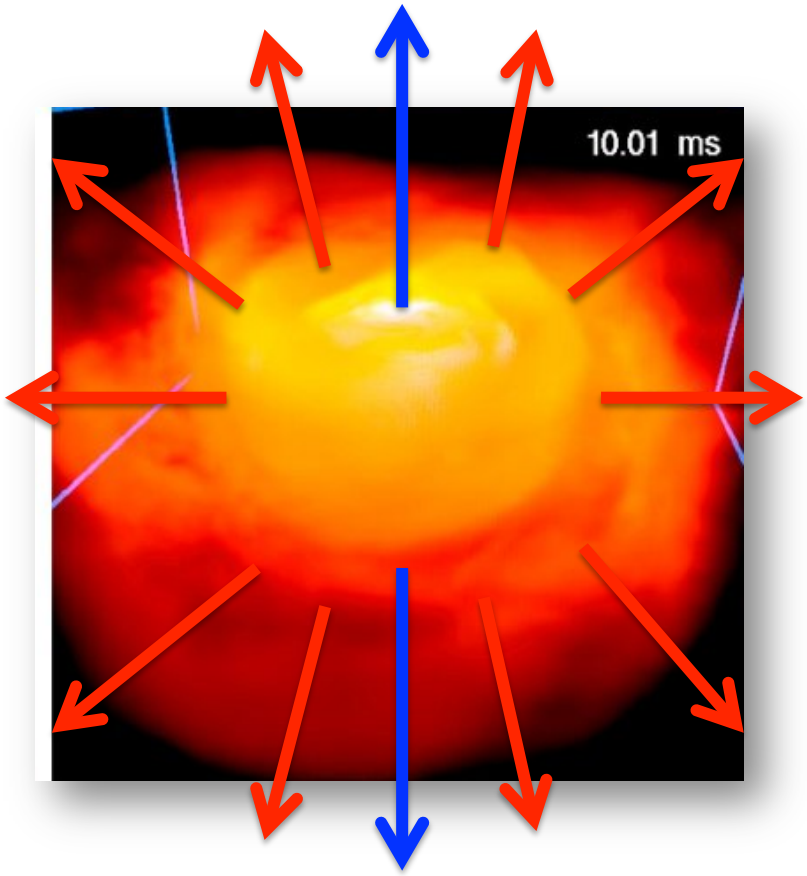
nucleosynthesis

- $Y_e \sim 0.3$
- weak r-process only? (Just+2015; etc. but Wu+2016; Siegel & Metzger 2017)

# First Cosmic Event Observed in Gravitational Waves and Light

August 17, 2017: discovery of the 1st NS merger !!

# electromagnetic emission from mergers

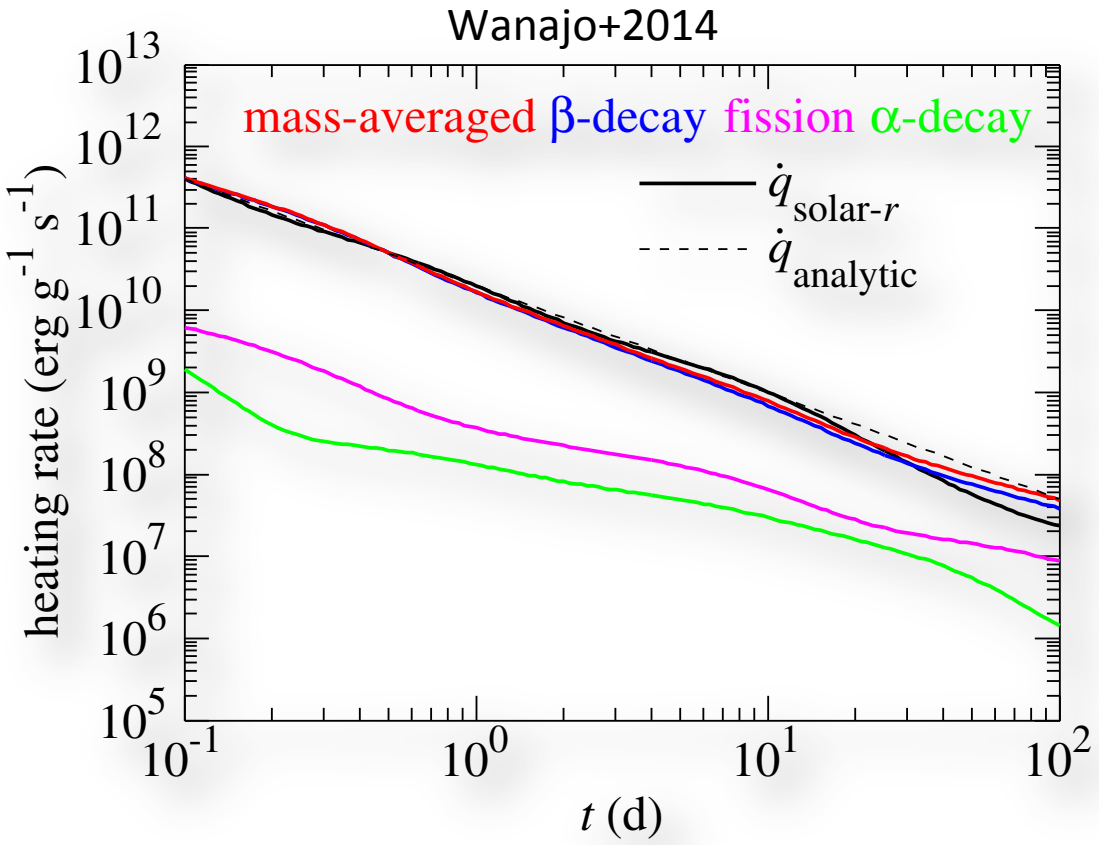



EM (electromagnetic) emission as a counterpart of gravitational wave (GW) signals

- short gamma-ray bursts
  events should be restricted due to narrow beaming

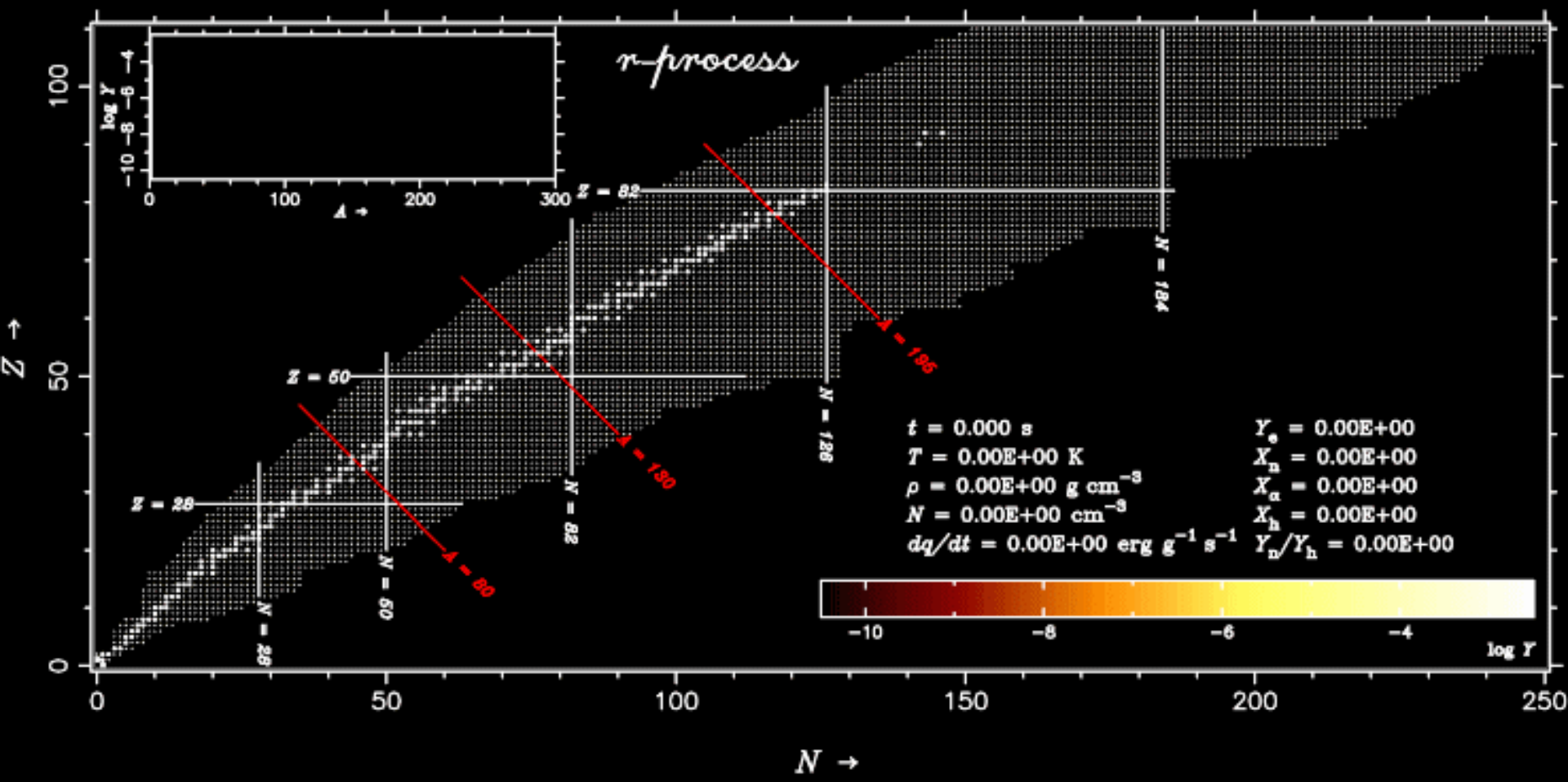
- kilonovae (r-process novae)
  detectable from all directions within the GW horizon

# heating rates that power kilonovae

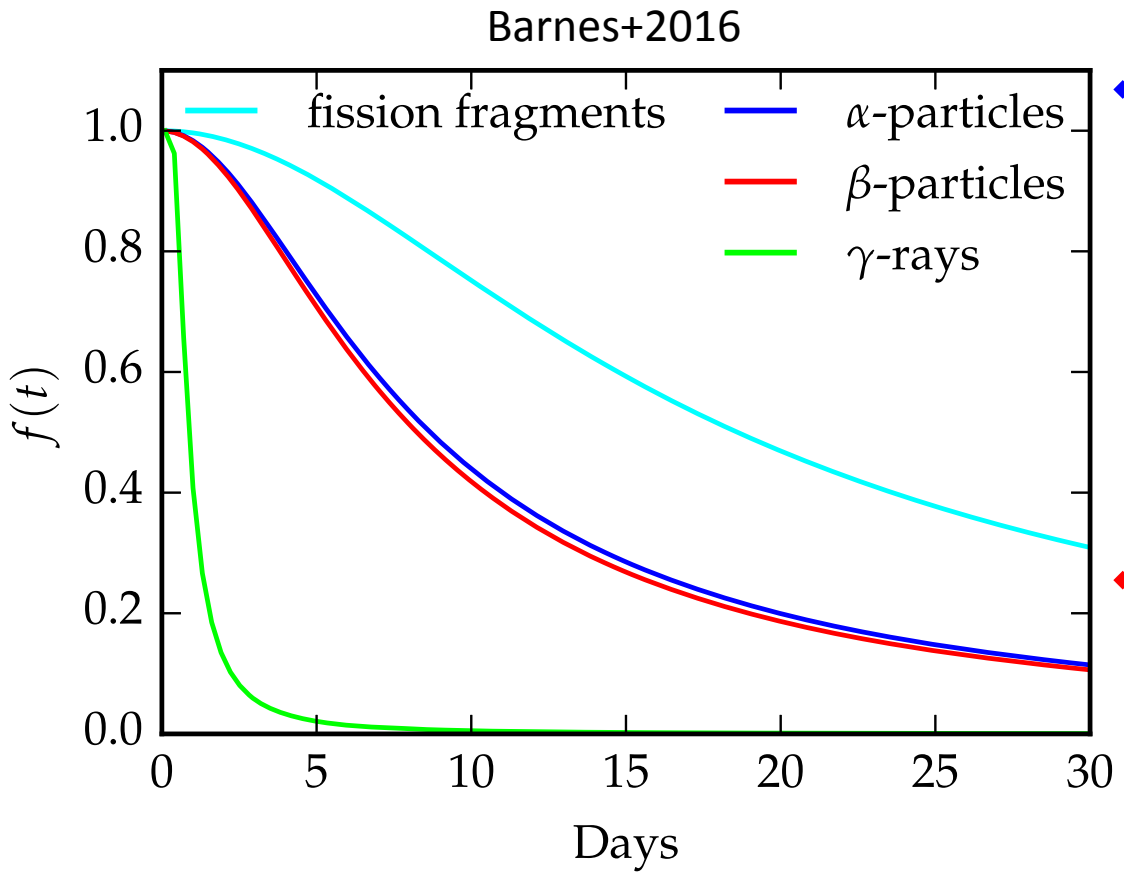



- elements of $Z \leq 83$: heating from $\beta$-decay ($e^-$, $\gamma$, and $\nu$) well scaled as $dq/dt \sim t^{-1.3}$
- elements of $Z > 83$: heating from fission and $\alpha$-decay (kinetic energies) scaled as $dq/dt \sim t^{-1}$

# r-process in merger ejecta ($Y_e$ = 0.09)



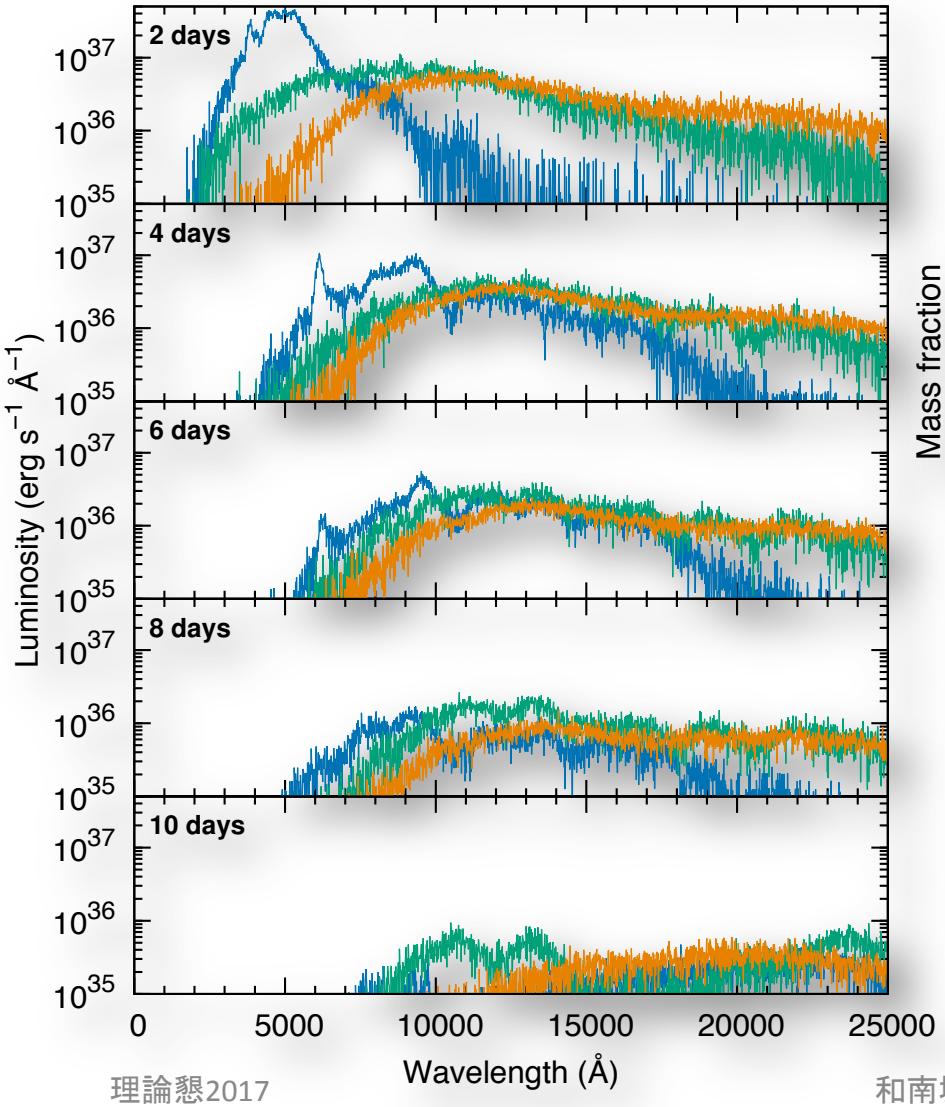
# thermalization factors

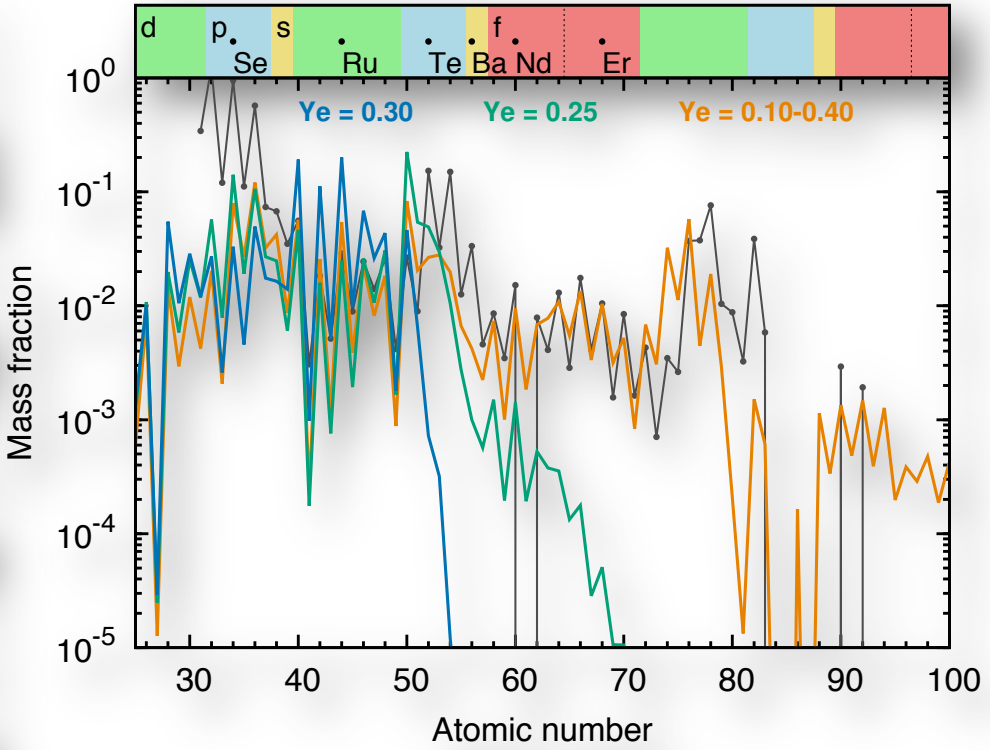



- thermalization efficiency of $\beta$-decay (mostly due to gamma-ray) is very low, 20% at 10 days; less important at late times
- thermalization efficiencies of fission and $\alpha$-decay are high, 40% and 80% at 10 days; important at late times

# prediction of a kilonova emission

Tanaka, Kato, …, Wanajo, Sekiguchi+2017; the draft completed on August 13

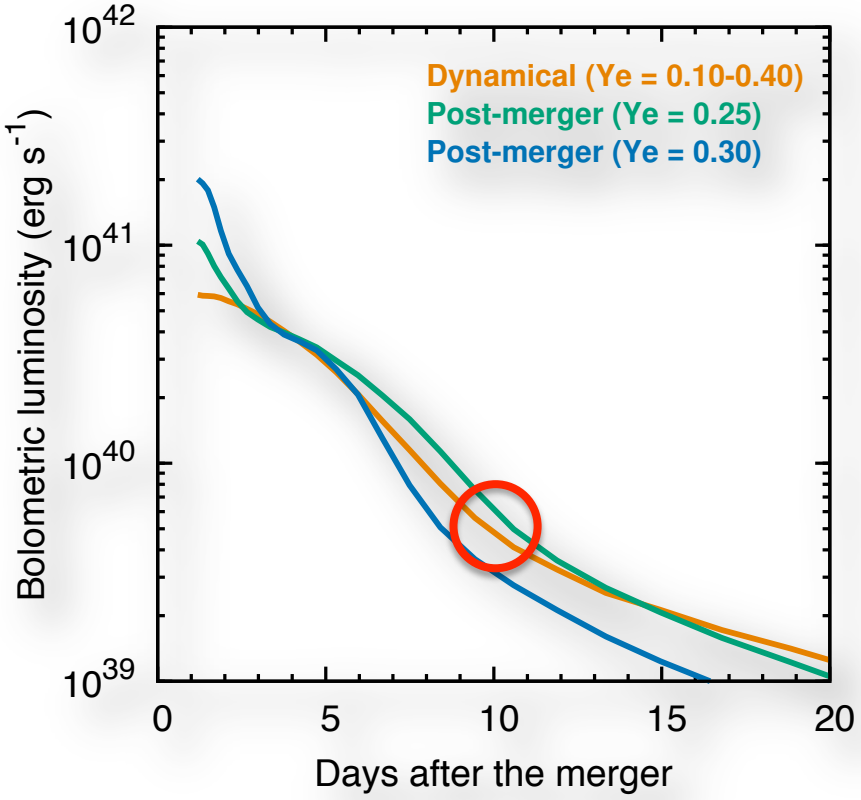


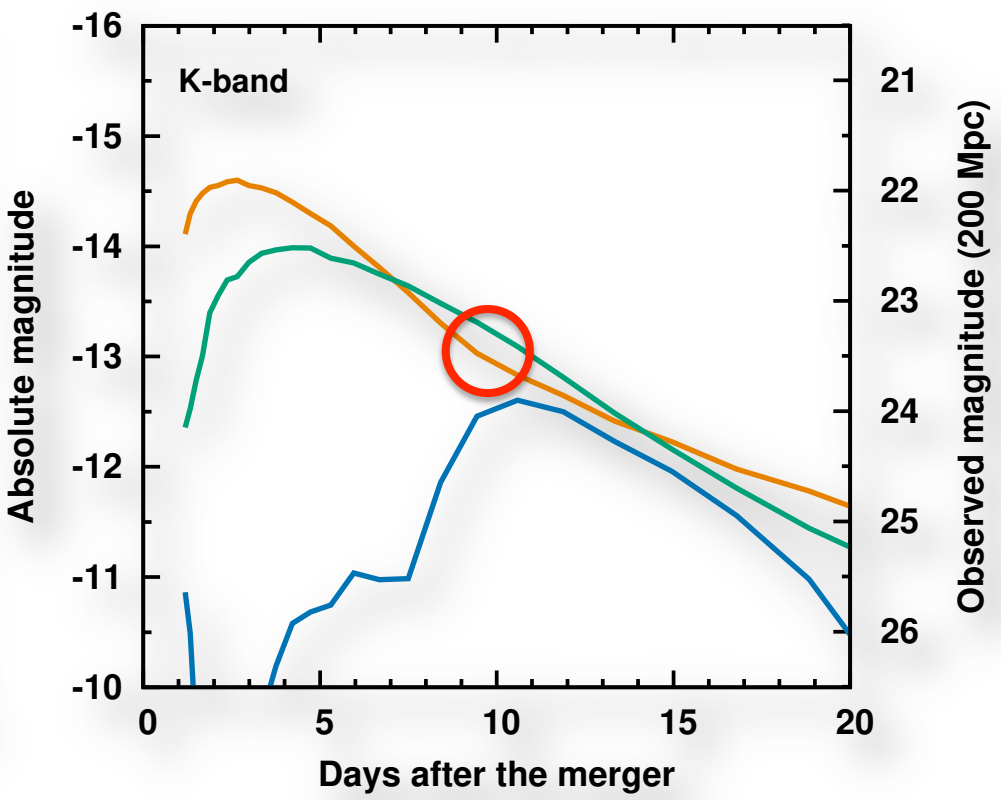




- weak r-process ($Y_e \geq 0.25$): blue and bright
- main r-process ($Y_e$ 0.10-0.25): red and dim

# prediction for production of gold and beyond

Tanaka, Kato, …, Wanajo, Sekiguchi+2017; the draft completed on August 13

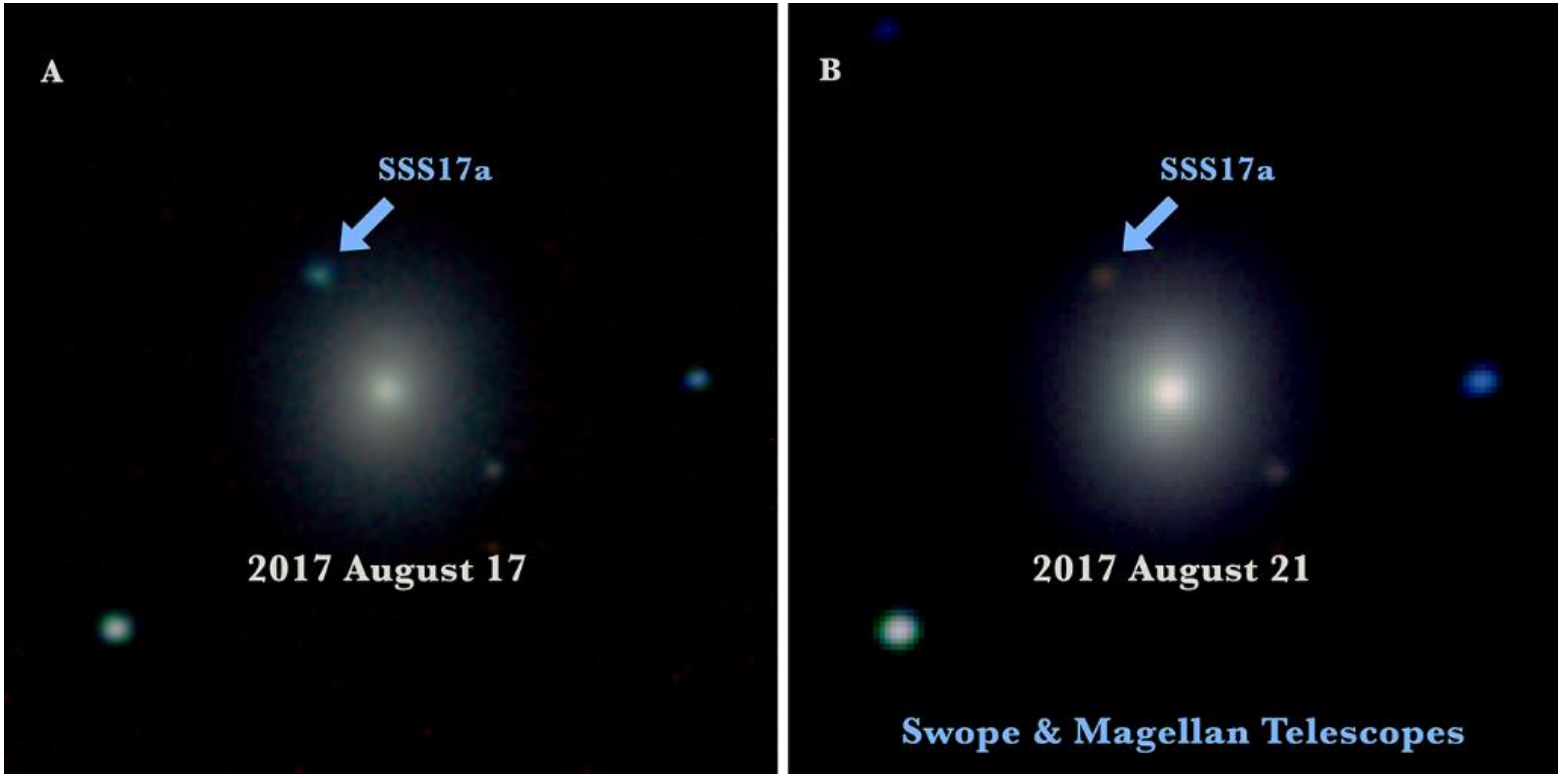



- power-index break (from β-decay to α-decay and fission) was expected at about 10 days
- clearly seen in the K-band (near-infrared, ~ 2.2 μm)

# A bright-blue to dim-red kilonova !

EM transient associated with GW170817; Drout+2017

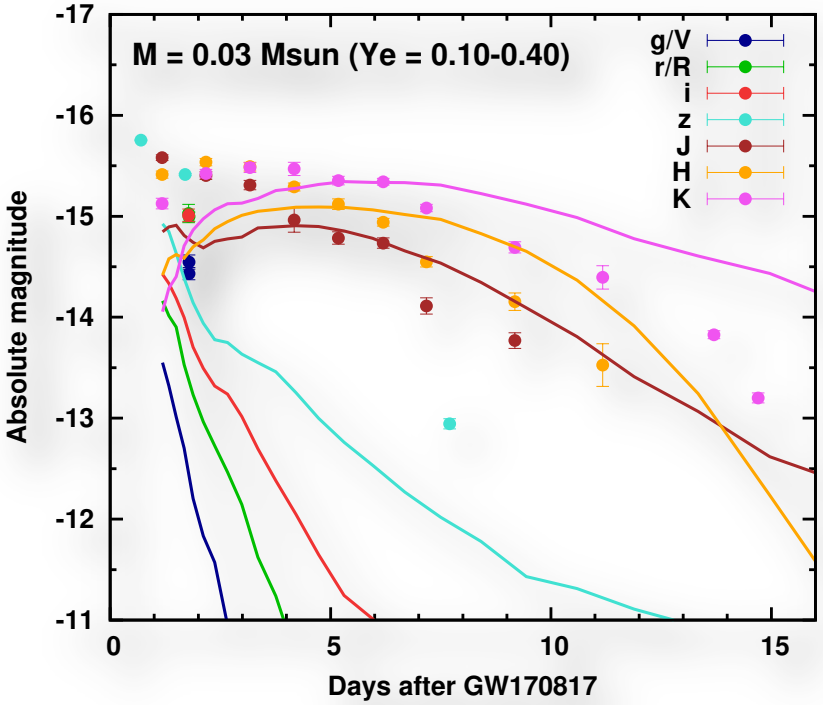


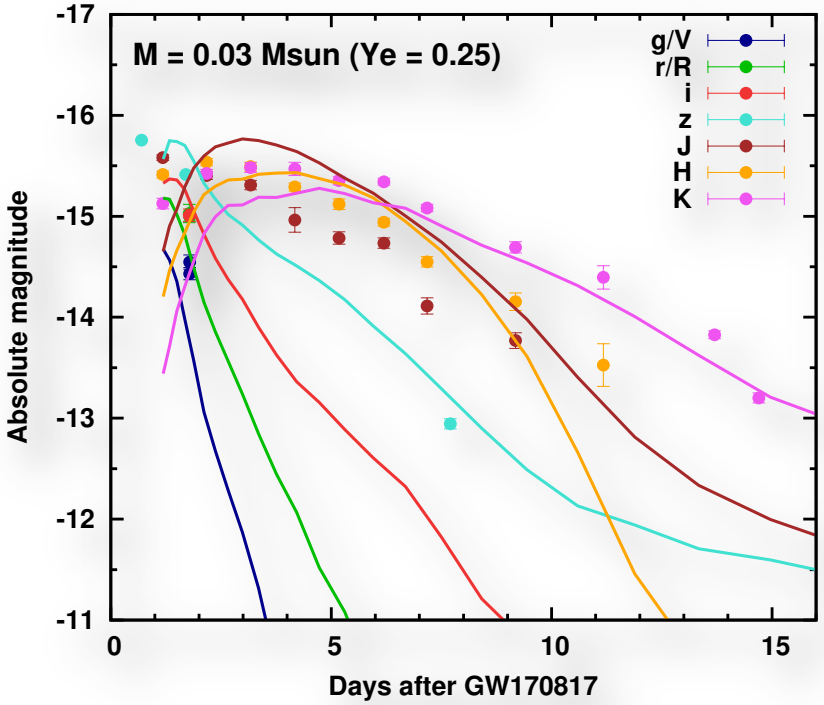

ejecta mass ~ 0.02-0.06 $M_\odot$, ejecta velocity ~ 0.1-0.3 $c$

- light r-process elements of $Z < 50$ ejected in early times and
- heavy r-process elements of $Z > 50$ in late times (if not gold)

# was it an r-process?

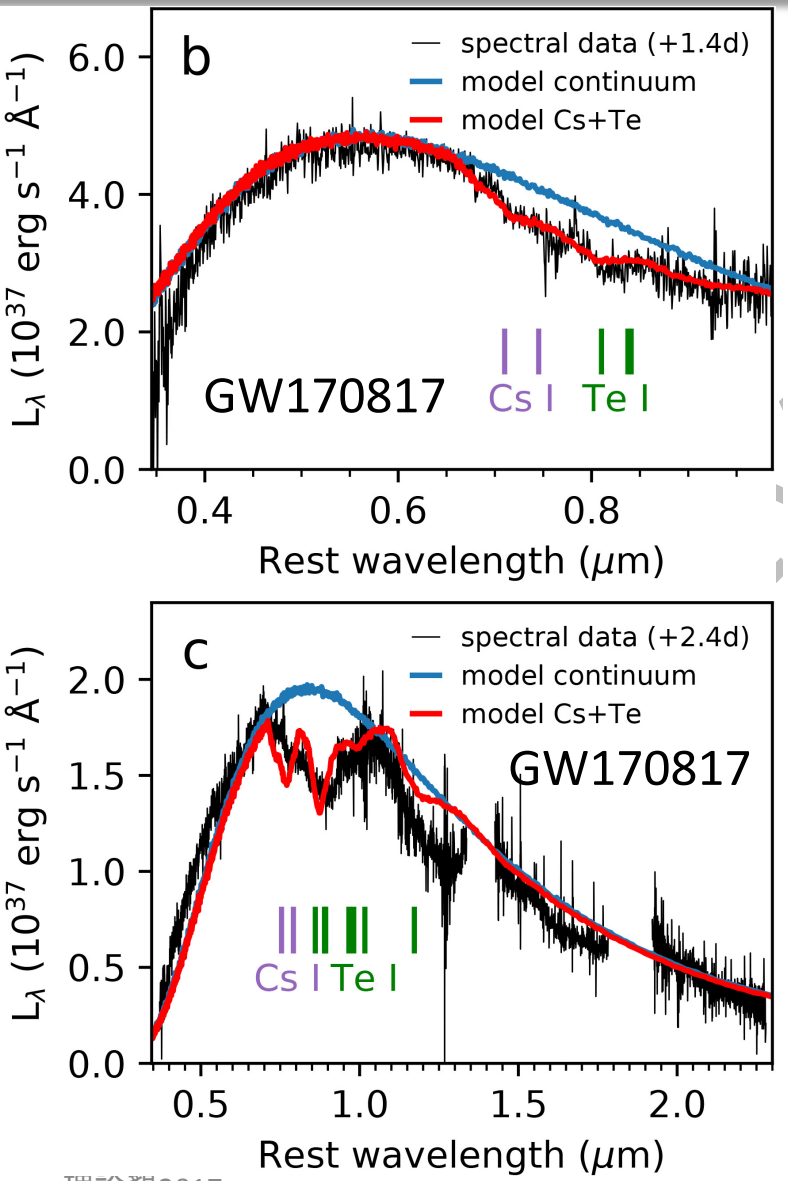
comparison with GW170817; Tanaka+2017




- main r-process model ($Y_e$ (0.10-0.40) does not fit to the light curves
- weak r-process model with a single $Y_e$ (= 0.25) well fit the curves

# Did we find individual elements?

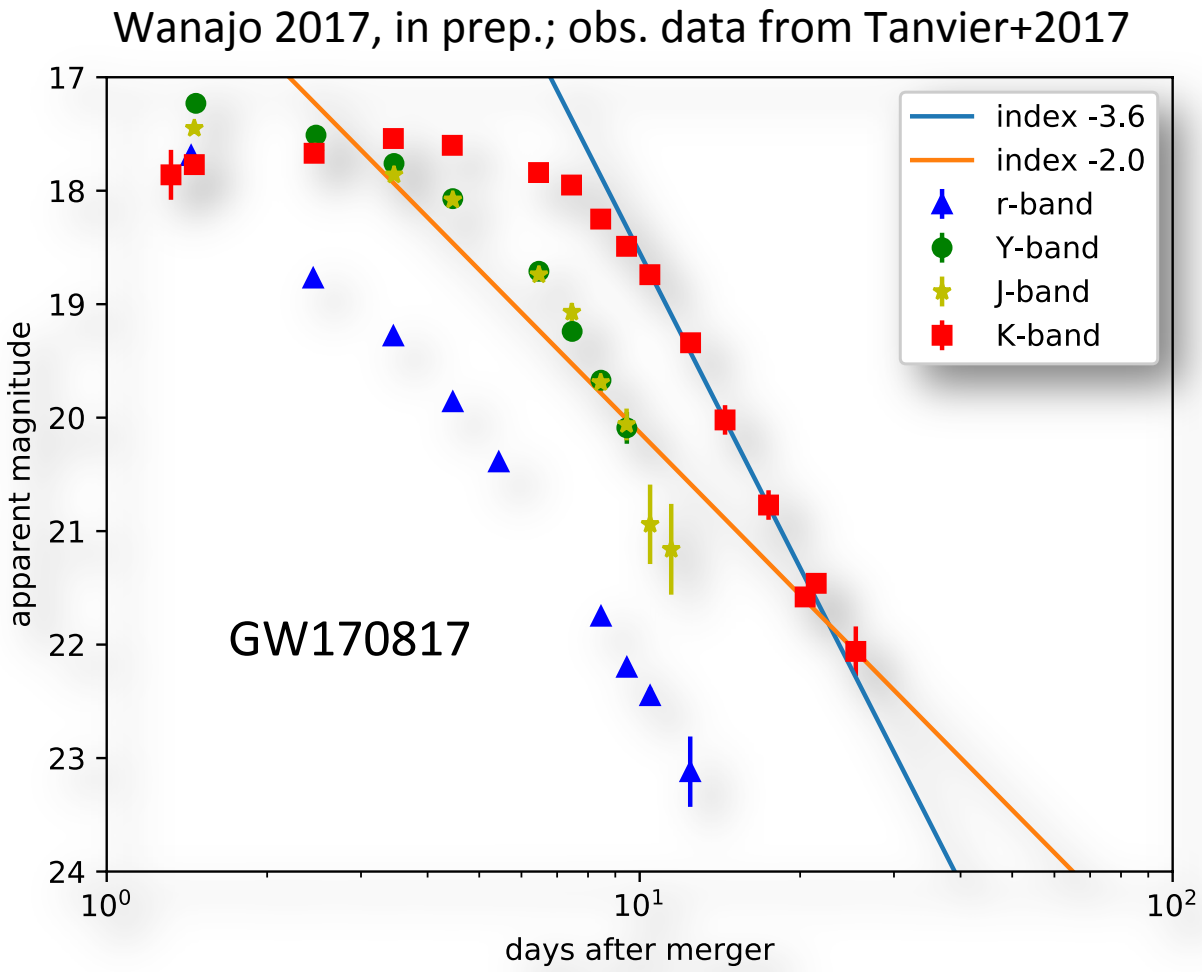



Smartt+2017

It might be likely that

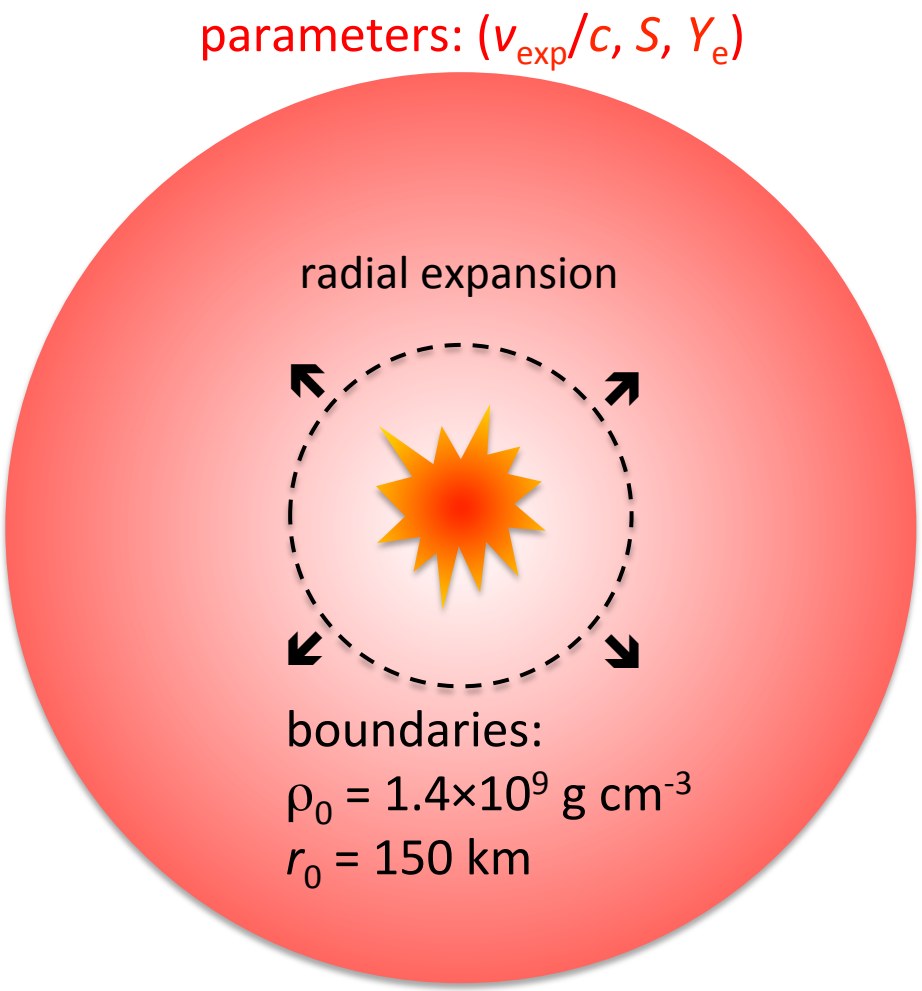
- light r-process elements Te and Cs ($Z$ = 52 and 55) formed in early times??
- but, no visible lines of heavy r-process in late times

# did we see the elements beyond gold?




- marginal power-index break at about 20 days after merger?
- If this is the case, elements of $Z > 83$ were made? (but only a tiny amount; not a main r-process)

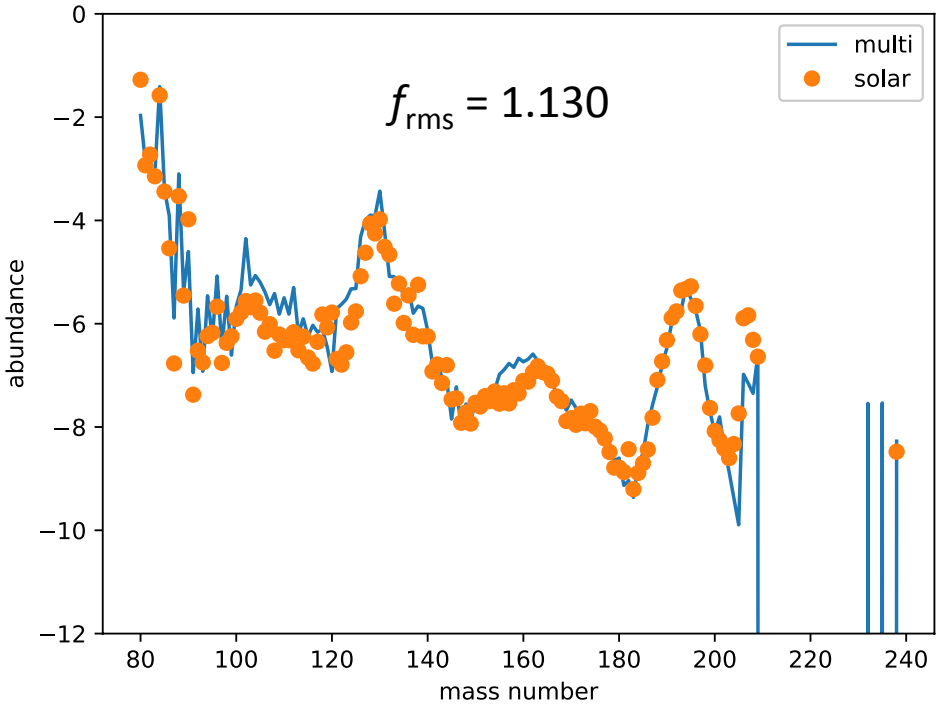
# a site-independent approach




Wanajo 2018, in prep.; preliminary

- free expansion model that mimics the physical conditions of the merger outflows (either of dynamical and wind ejecta)
- three parameters:
  ($v_{exp}/c$, $S$, $Y_e$)
  = (0.05-0.30, 10-60, 0.01-0.50)
  with intervals (0.05, 10, 0.01)
  in total 1800 models
- caution:
  nuclear data assumed to be reliable (it is not the case!)

# fit to the solar r-process abundances




Wanajo 2018, in prep.; preliminary

- the abundance of each species *i* can be reasonably reproduced by an ensemble of *N* models with weight $\phi_j$

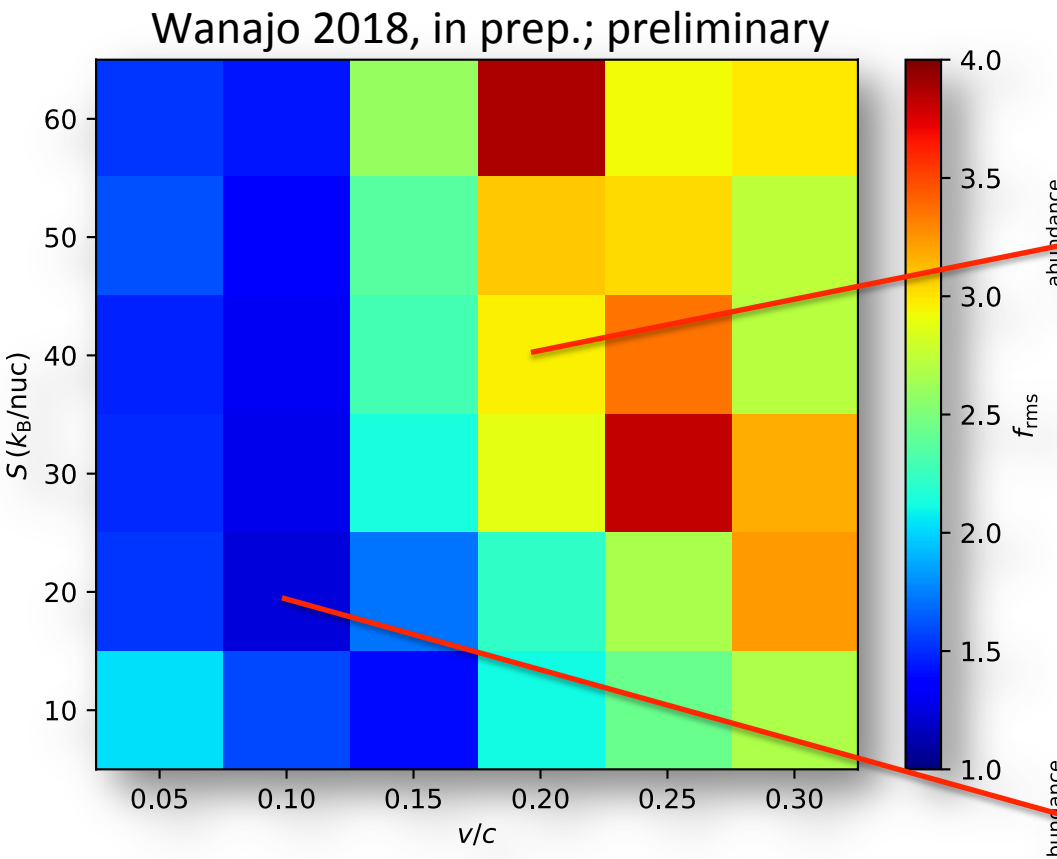
$$Y_{\rm obs,i} \approx \sum_{j=1}^{N} Y_{\rm calc,i,j}\,\phi_j, \qquad \sum_{j=1}^{N} \phi_j = 1$$

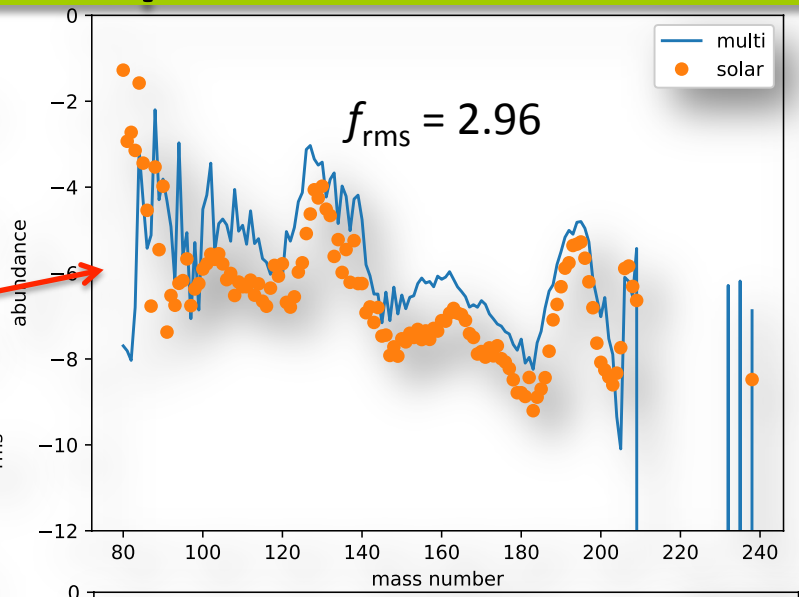
- by minimizing the root-mean-square defined by

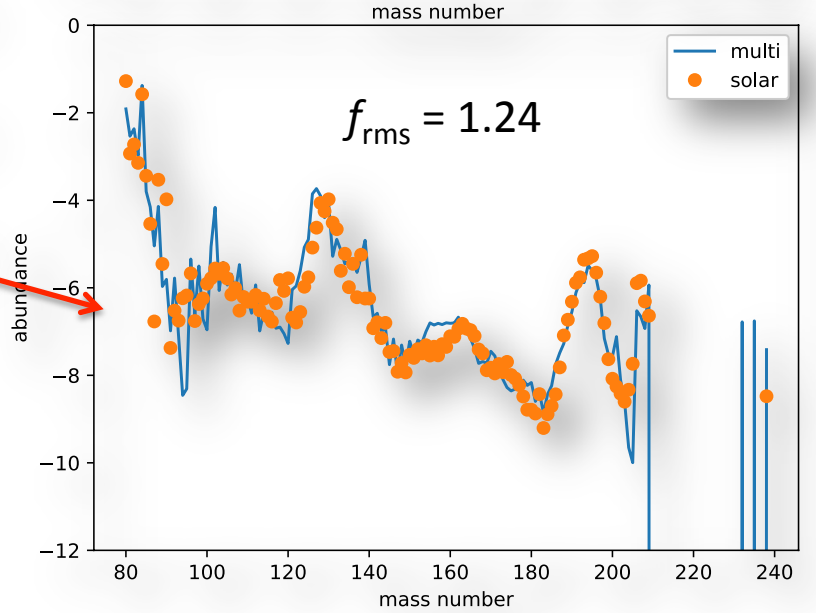
$$f_{\rm rms} = \exp\left(\frac{1}{N}\sum_{j=1}^{N} \ln^2 \frac{Y_{\rm obs,j}}{Y_{\rm calc,j}}\right)^{1/2} \geq 1$$

(Bouquelle+1996)

# restricted models ($v_{exp}$, $S$ = const.)

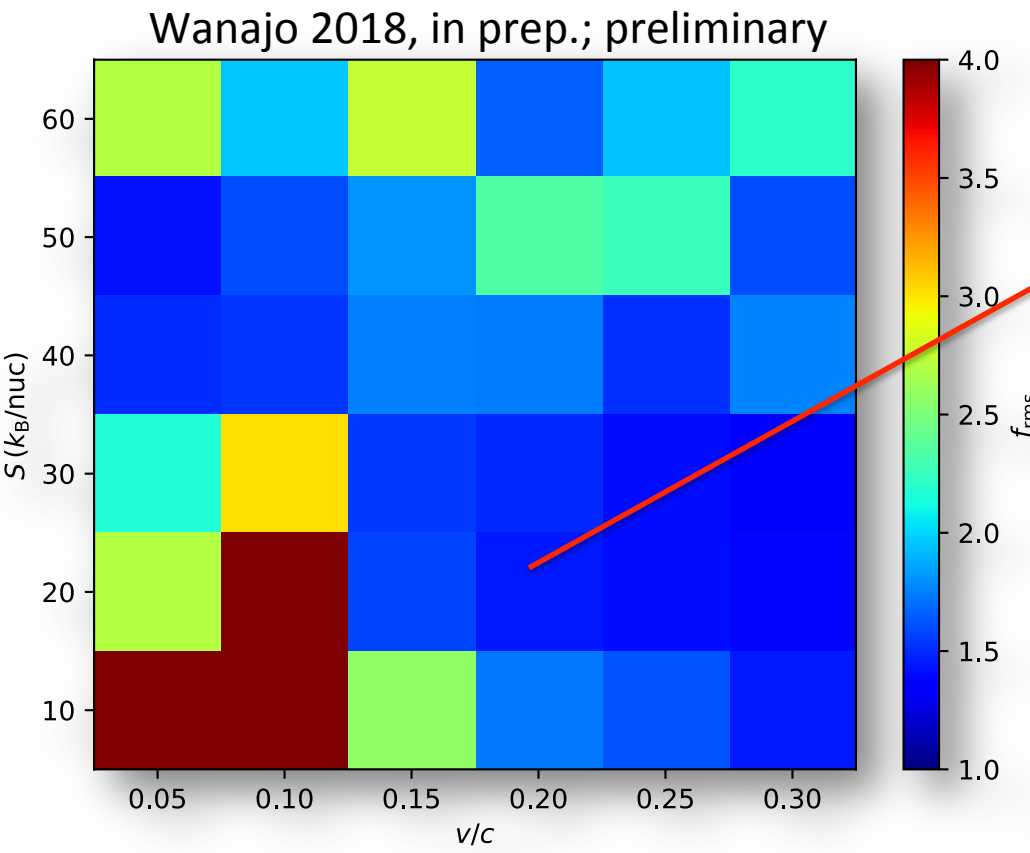


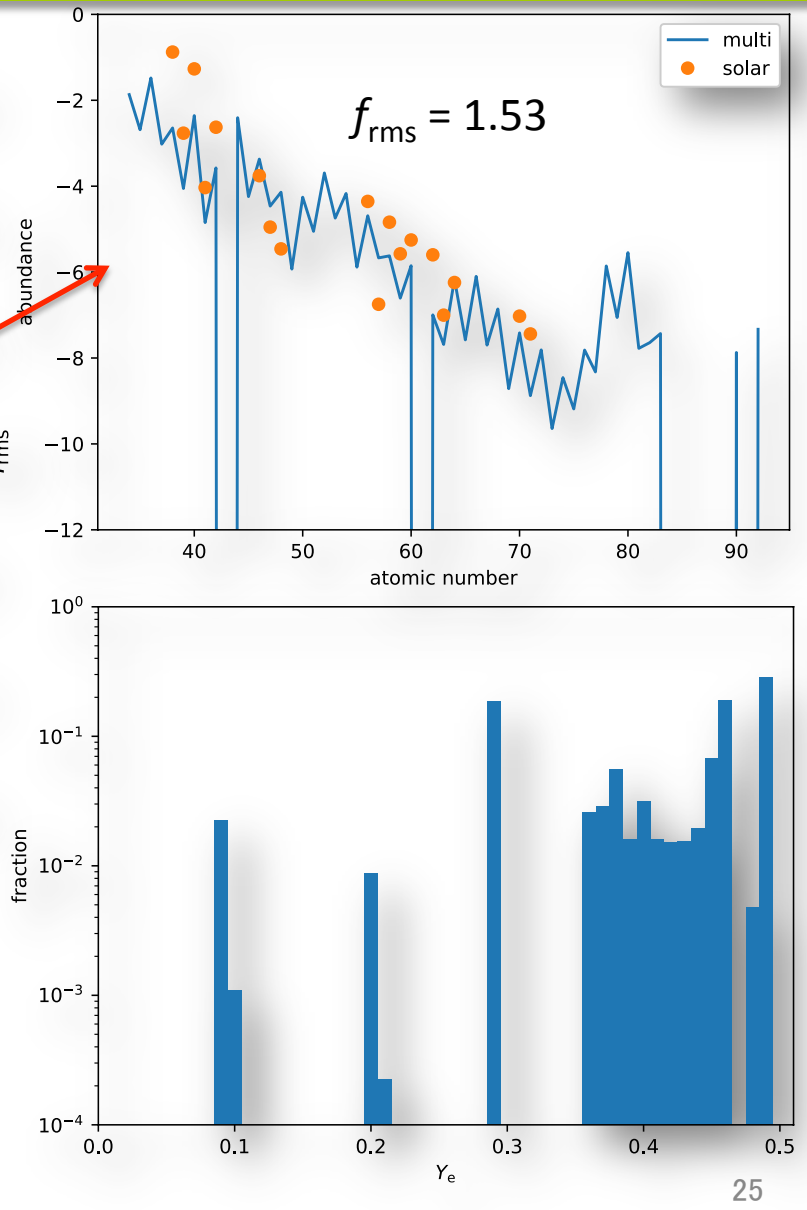




- $v_{exp} < 0.2\ c$ is favored?
  (both dynamical and wind ejecta satisfy the blue region)

# weak r-process model (Honda star)

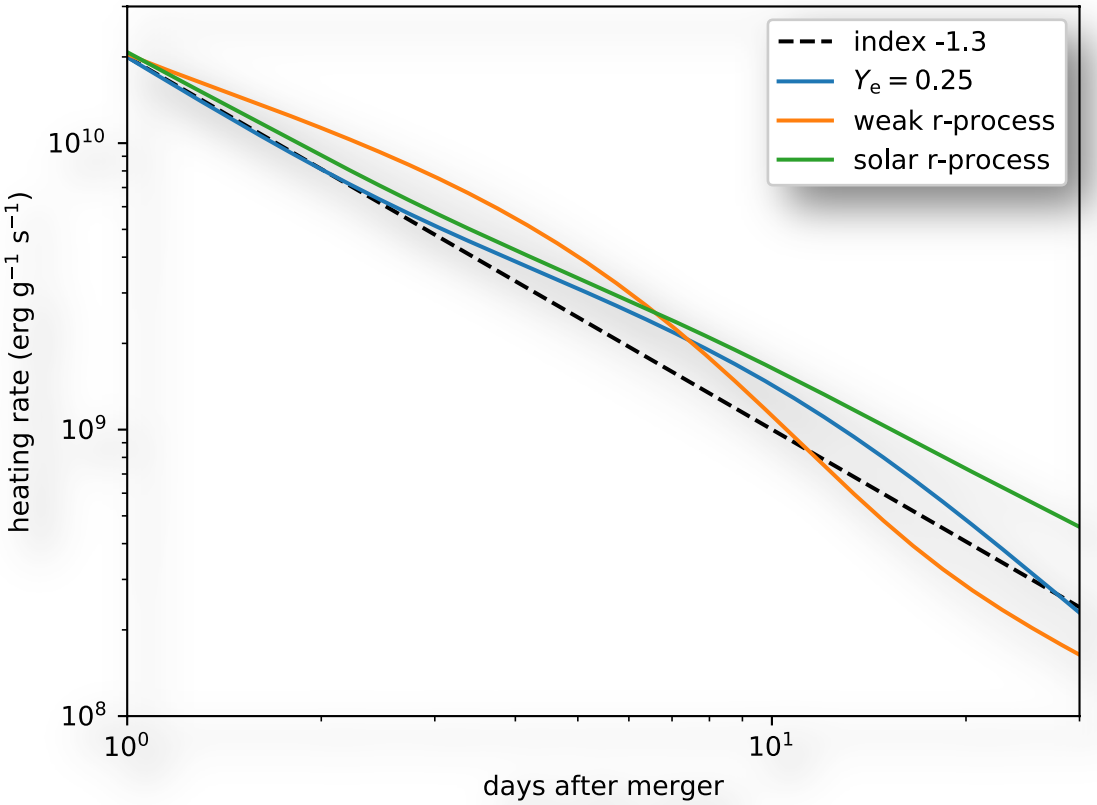



- $v_{exp} > 0.1\,c$ or $S > 30$ is favored? (dynamical ejecta better satisfy the blue region?)

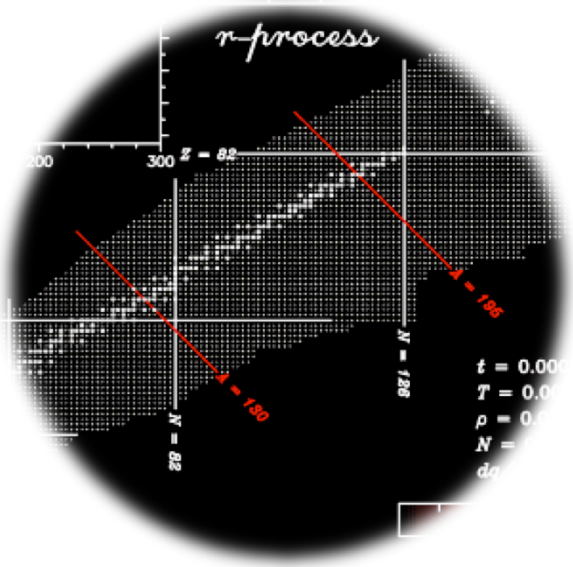
# heating rates for different models

Wanajo 2018, in prep.; preliminary




- clear differences can be seen at > 10 days
- main (solar) r-process model keeps a flat decrease (index of ~ -1 because of fission and $\alpha$-decay)
- weak r-process (and $Y_e$ = 0.25) model quickly decays (because of a consumption of available radioactivities)

# summary and outlook




- EM counterpart (kilonova) of GW170817
  - overall agreement with theoretical predictions
  - ejection of r-elements at least up to $Z \sim 60$, $A \sim 140$
  - it was likely a weak r-process event, making silver but gold
- Better predictions of kilonovae with helps of EMP stars to confirm
  - if NS mergers are *the* origin of heavy r-elements (gold and platinum)
  - early histories of galaxies (see e.g., a talk by Hirai on Friday)