多成分の質量放出からなる kilonova/macronova の予測

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Introduction

Gravitational waves

- Gravitational waves (GW): the ripples of curvature that propagate with the speed of light

- GW sources for ground-based GW detectors
  - **Compact binary mergers**
  - Core collapse Super Novae
  - Rotating Neutron stars
  - Primordial GW (Inflation)
  - Cosmic Strings

advanced LIGO

https://www.ligo.caltech.edu/

advanced Virgo

http://www.virgo-gw.eu/

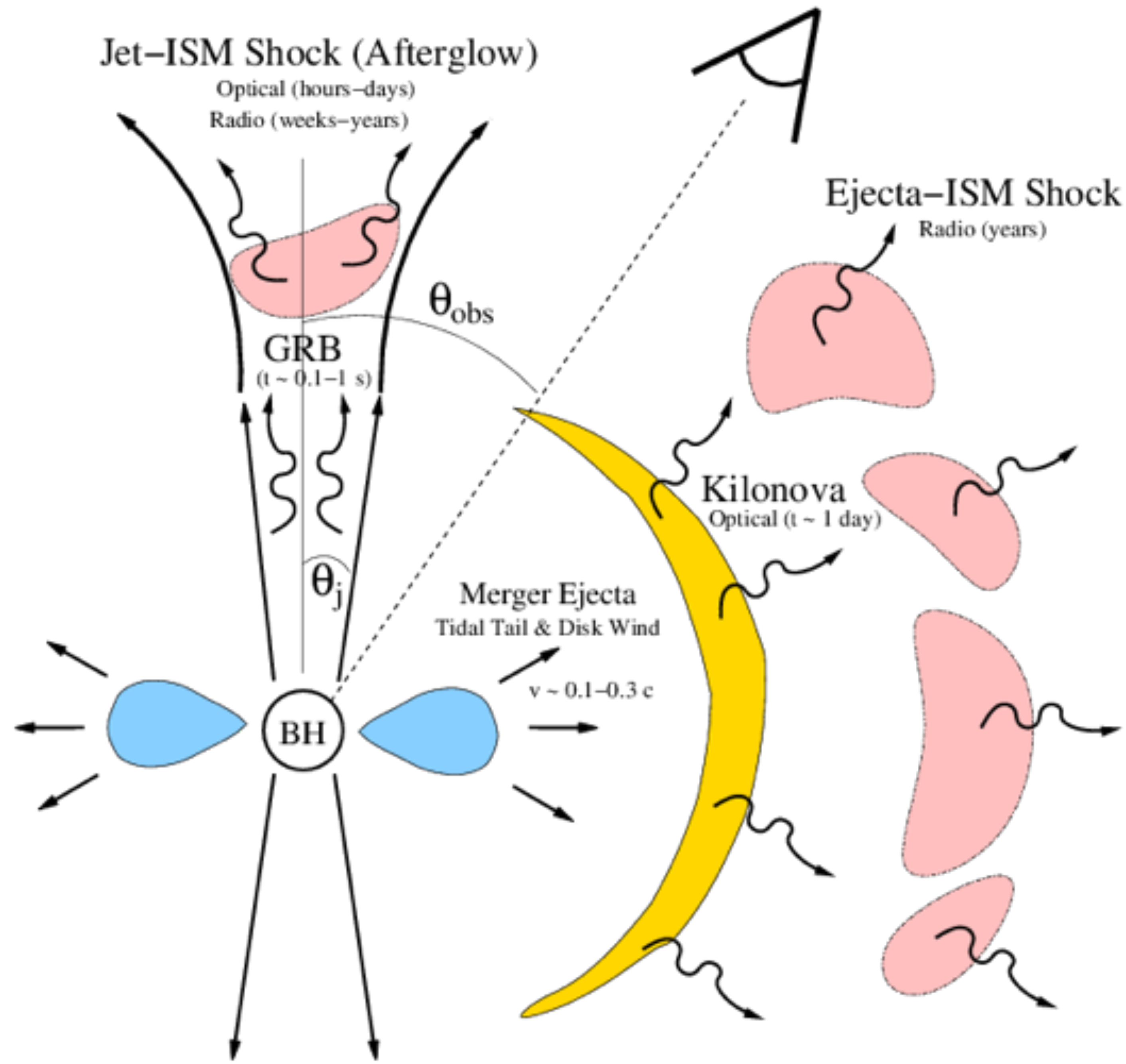
http://gwcenter.icrr.u-tokyo.ac.jp/

- **Compact Binary**—Binary composed of black-holes (BHs) and/or neutron stars (NSs)— efficiently emit gravitational waves shrinking their orbital separation, and the objects gradually merge

- Observation of gravitational waves provides us to the physical information of the binary (masses, spins, inclination…)

Electromagnetic Counterparts to NS binary mergers

- Various transient EM counterparts are proposed for NS binary mergers
- for example,
    - short-hard gamma-ray-burst
    - Afterglow
    - cocoon emission
    - kilonovae/macronovae
    - radio flare, etc.
- Host galaxy identification, remnant properties, environment
- Possible synthesis site of r-process nuclei



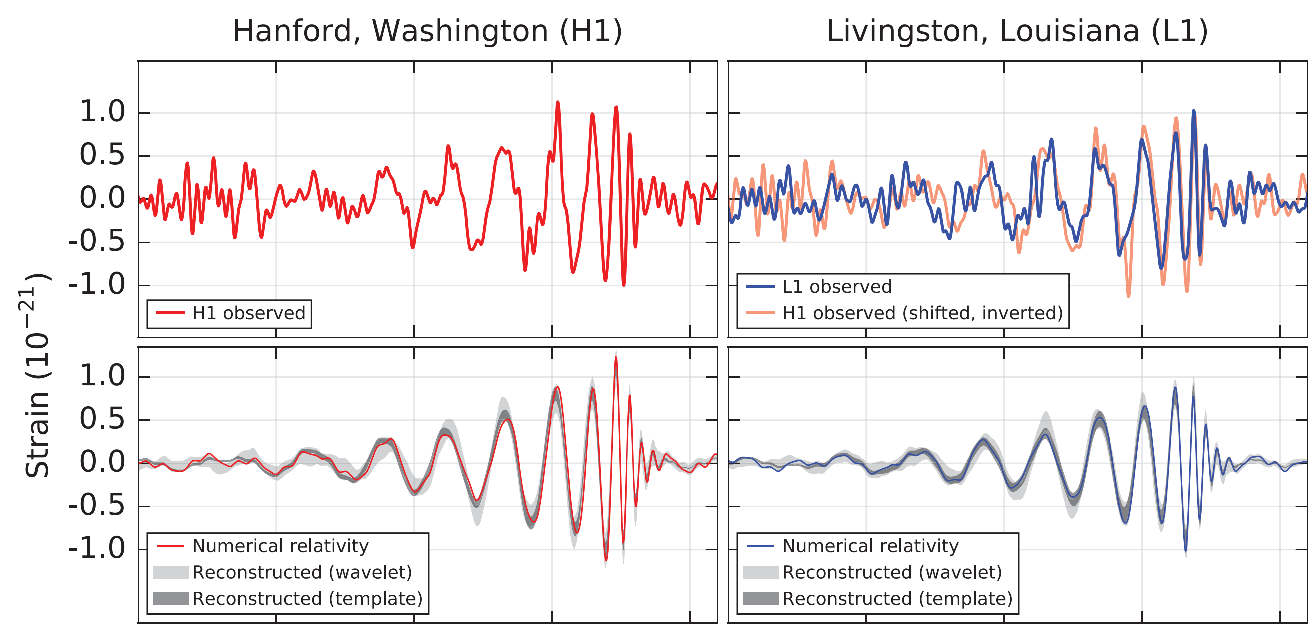
Ref: B. Metzger and E. Berger 2012

Gravitational-wave Astronomy

- Since 14th of September 2015, many GW events have been detected
- Binary BH (BBH; BH-BH)
  - GW150914, GW151226, GW170104, GW170608, GW170814
- Binary NS (BNS; NS-NS) GW170817

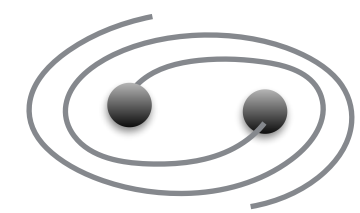
→Simultaneous detection of electromagnetic (EM) counterparts

- GW150914 (The first GW event)



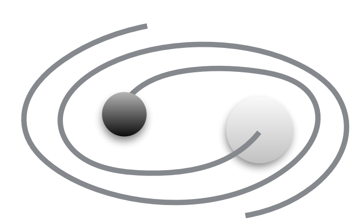
Ref: B.P.Abbot et al. 2016

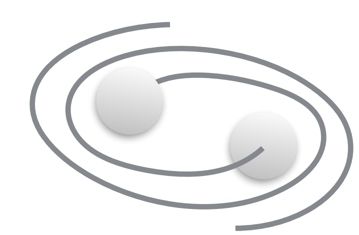
BH-BH



NS Binary

BH-NS



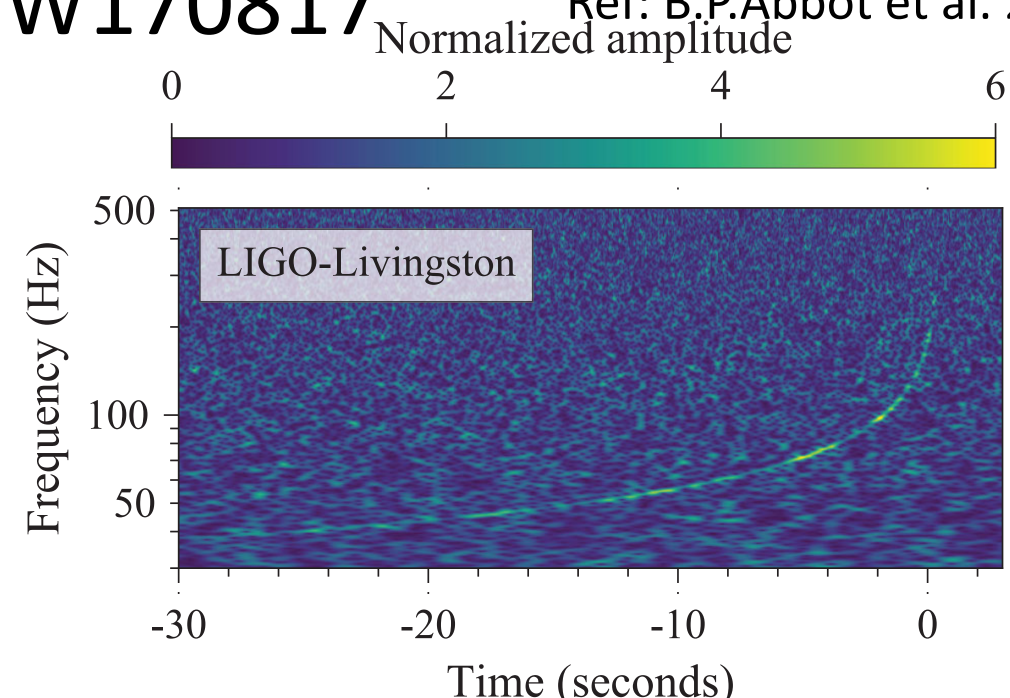


BNS (NS-NS)

GW170817:
Binary Neutron star Merger

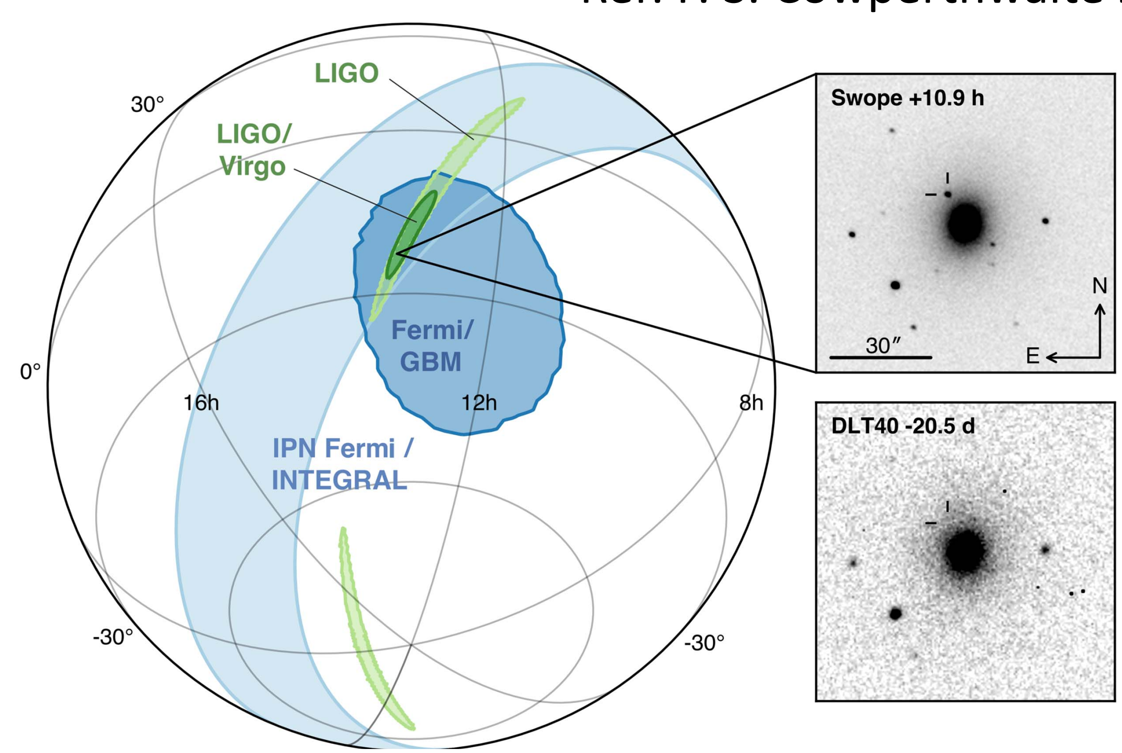
- GW170817

Ref: B.P.Abbot et al. 2017



- On 17th of August 2017, advanced LIGO and advanced Virgo reported the first detection of gravitational waves from a binary BNS merger

Ref: P. S. Cowperthwaite 2017



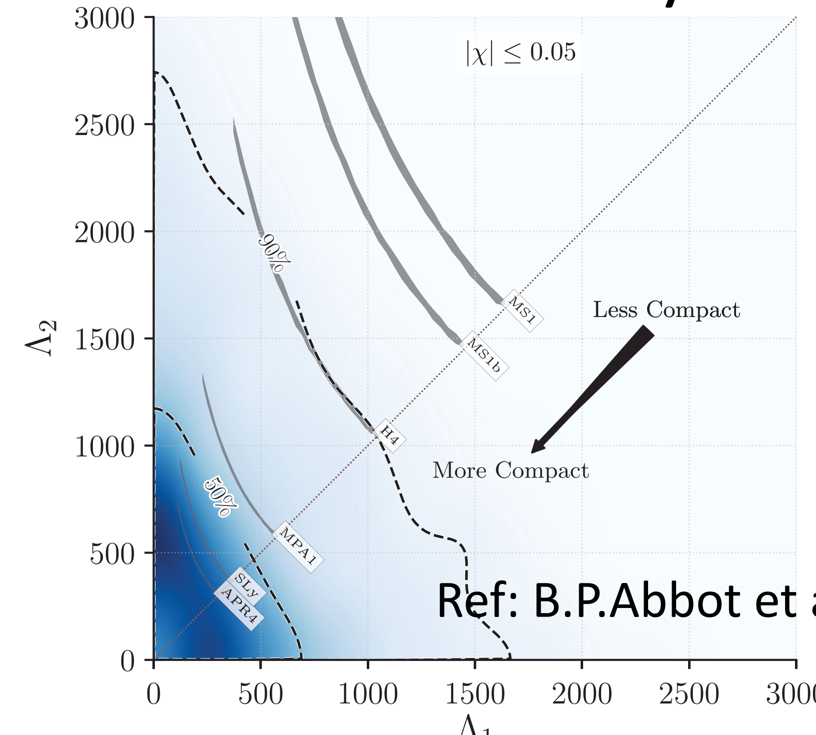
- Electromagnetic (EM) counterparts to GW170817 were observed over the entire wavelength range (from radio to gamma wavelengths)

Multi-messenger Astronomy

- Single event, but many physics
  - Constraints on NS masses, spins
    , and NS equation of state (NS tidal deformability)
  - association of kilonova/macronova (?): mass ejection
    , r-process synthesis
  - Afterglow, radio flare: constraints on relativistic jet
    , environment of the event
  - Host galaxy: Hubble parameter, GW propagation speed
  - etc…

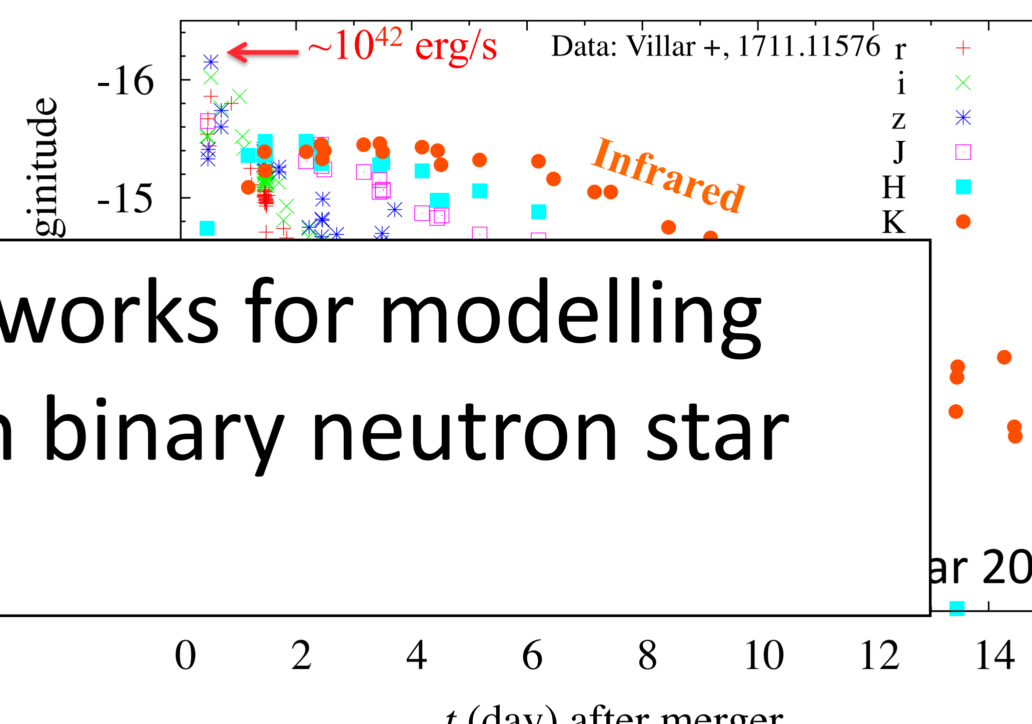
- …and many tasks and problems

NS Tidal deformability



Ref: B.P.Abbot et al. 2017

Optical-IR EM counterparts of GW170817



Today, I will talk about our recent works for modelling electromagnetic counterparts from binary neutron star mergers

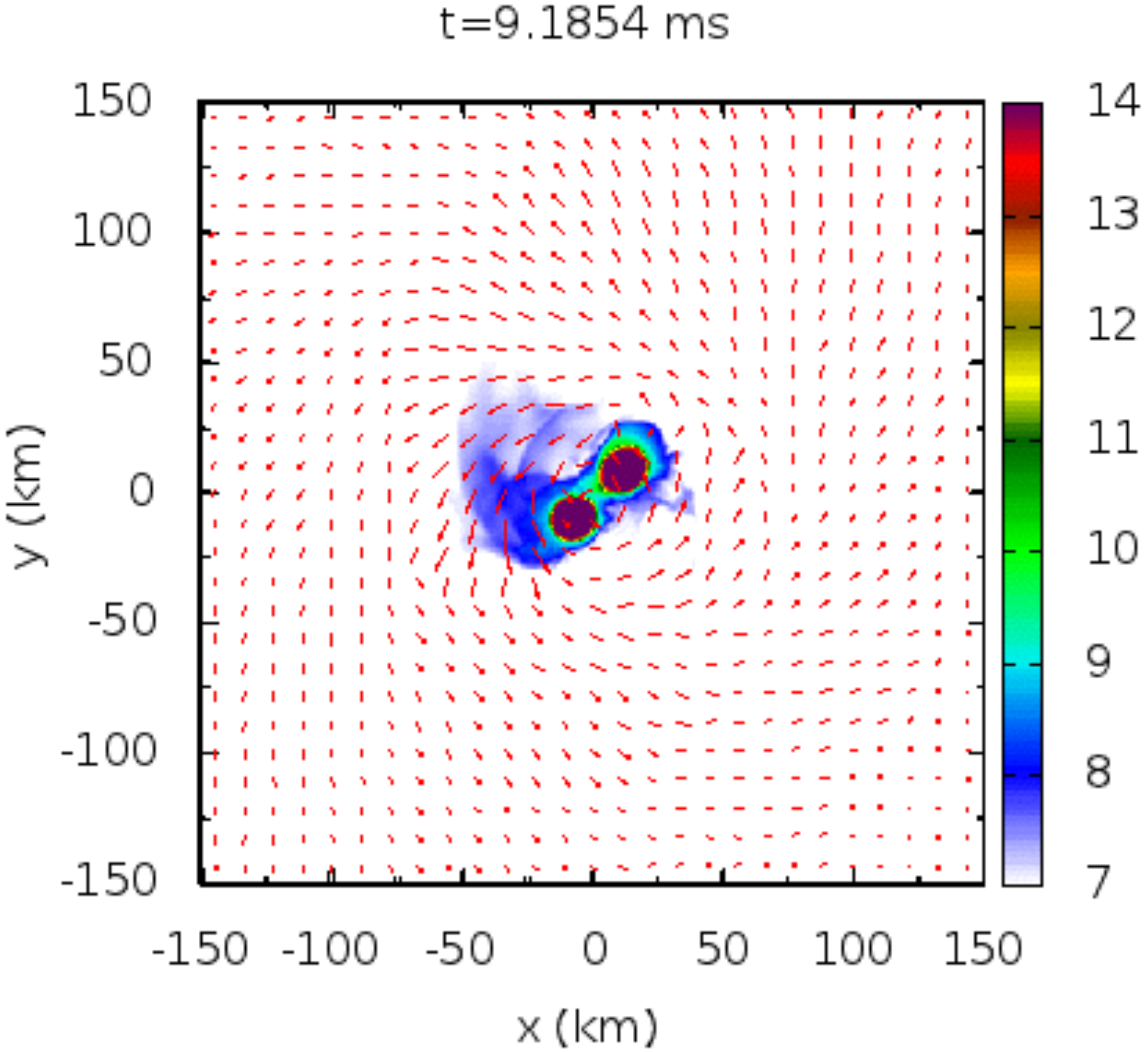
Electromagnetic counterparts to binary neutron stars: Kilonovae/Macronovae

Mass Ejection

- A fraction of NS material would be ejected from the system during the merger

- Ejected material is neutron-rich
→heavy radioactive nuclei would be synthesised in the ejecta by the so-called r-process nucleosynthesis

→EM emission in optical and NIR wavelengths could occur by radioactive decays of heavy elements
: kilonova/macronova (r-process nova)



Li & Paczyński 1998, Kulkarni 2005
, Metzger et al. 2010 …

Ref: K. Hotokezaka et al. 2013

Properties of kilonovae / macronovae

Kilonova/macronova is expected to be nearly **isotropic** emission.
(cf. $\theta_{\rm jet} \sim 10^\circ$ for sGRB)

The peak time of the emission will come in
~1—10 days.
(cf. ~1 year for radio flare)

The most of the emission occurs in around **optical and infrared**.

The mass, velocity, morphology, and <u>the composition(electron fraction)</u> of the ejecta characterize the lightcurve of the kilonova/macronova.

Rough Estimation

$$t_{\rm peak} \approx 3.3\,{\rm days} \times \left(\frac{M}{0.03M_\odot}\right)^{1/2} \left(\frac{v}{0.2c}\right)^{-1/2} \left(\frac{\kappa}{1\,{\rm cm^2/g}}\right)^{1/2}$$

$$L_{\rm peak} \approx 2.0\times10^{41}\,{\rm ergs/s} \times \left(\frac{f}{10^{-6}}\right) \left(\frac{M}{0.03M_\odot}\right)^{1/2} \left(\frac{v}{0.2c}\right)^{1/2} \left(\frac{\kappa}{1\,{\rm cm^2/g}}\right)^{-1/2}$$

$$T_{\rm peak} \approx 3.1\times10^{3}\,{\rm K} \times \left(\frac{f}{10^{-6}}\right)^{1/4} \left(\frac{M}{0.03M_\odot}\right)^{-1/8} \left(\frac{v}{0.2c}\right)^{-1/8} \left(\frac{\kappa}{1\,{\rm cm^2/g}}\right)^{-3/8}$$

$M_{\rm eje}$:ejecta mass

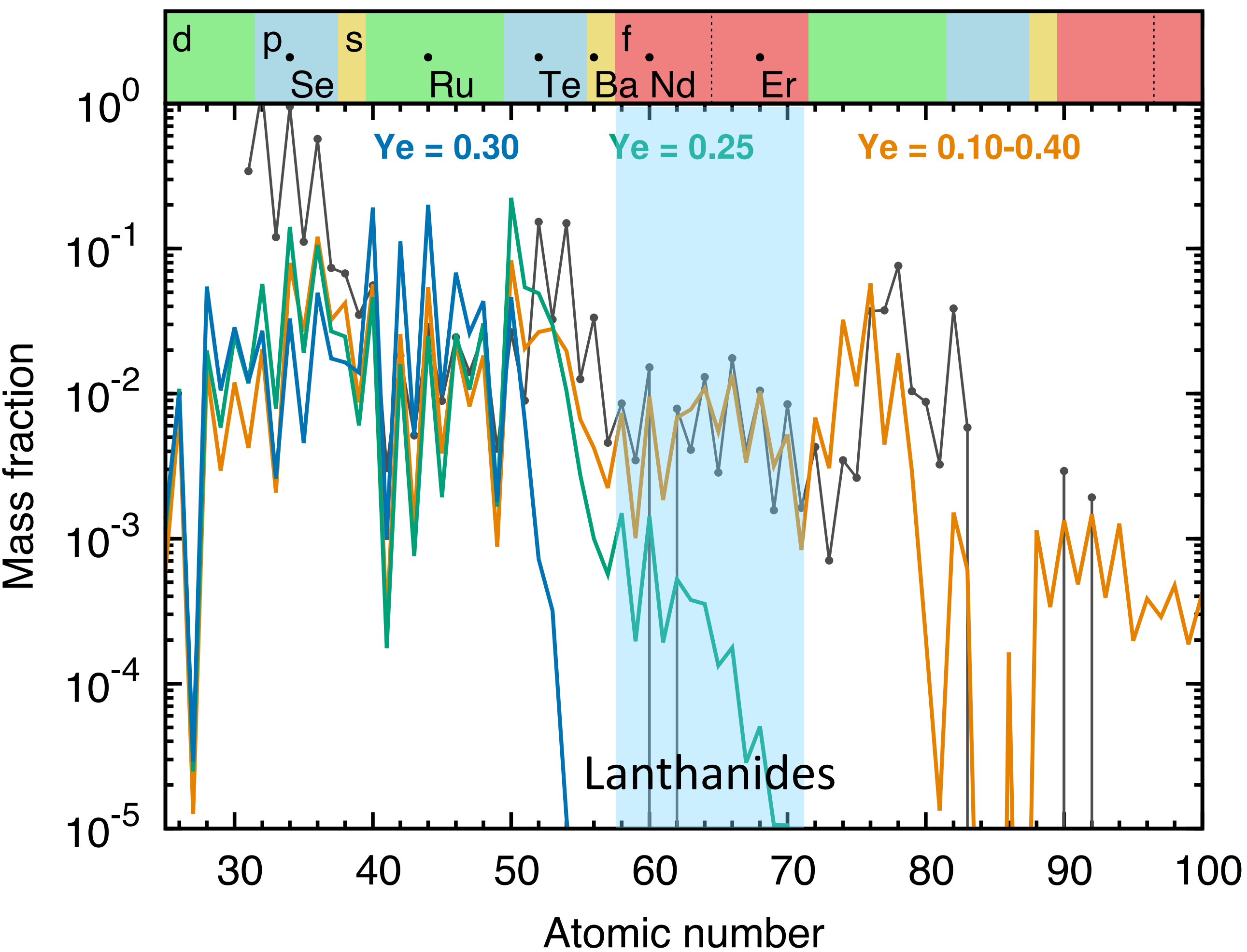
κ :opacity

$v_{\rm eje}$:expanding velocity

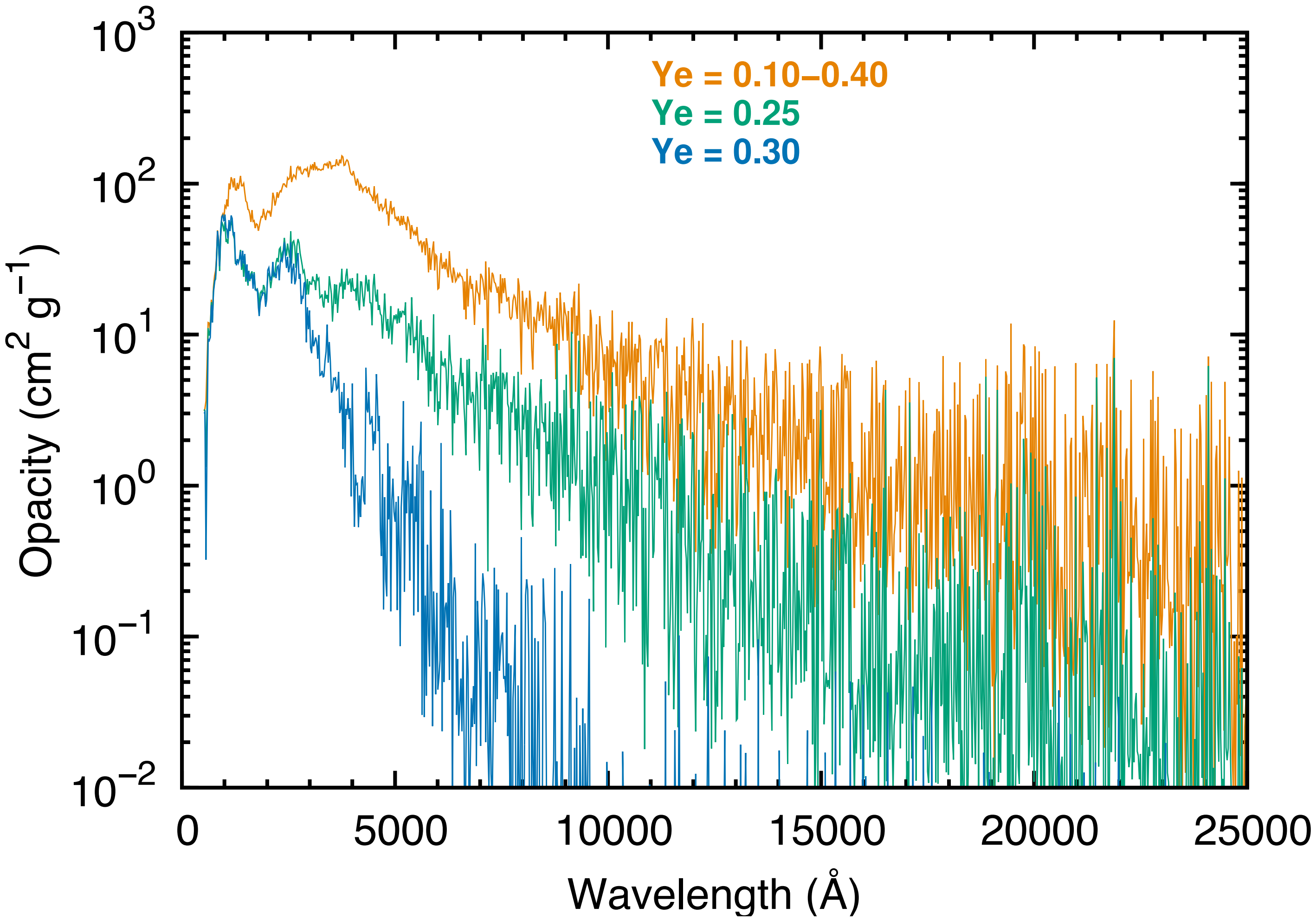
f : energy conversion rate

Ejecta opacity

$$Y_e = \frac{[p]}{[p]+[n]}$$



ref) Tanaka et al. 2018



The value of κ can vary significantly depending on the electron fraction Ye of ejecta κ = 0.1—10 cm^2/g.
(Kasen et al. 2013, Barnes et al. 2013, Tanaka et al. 2013)

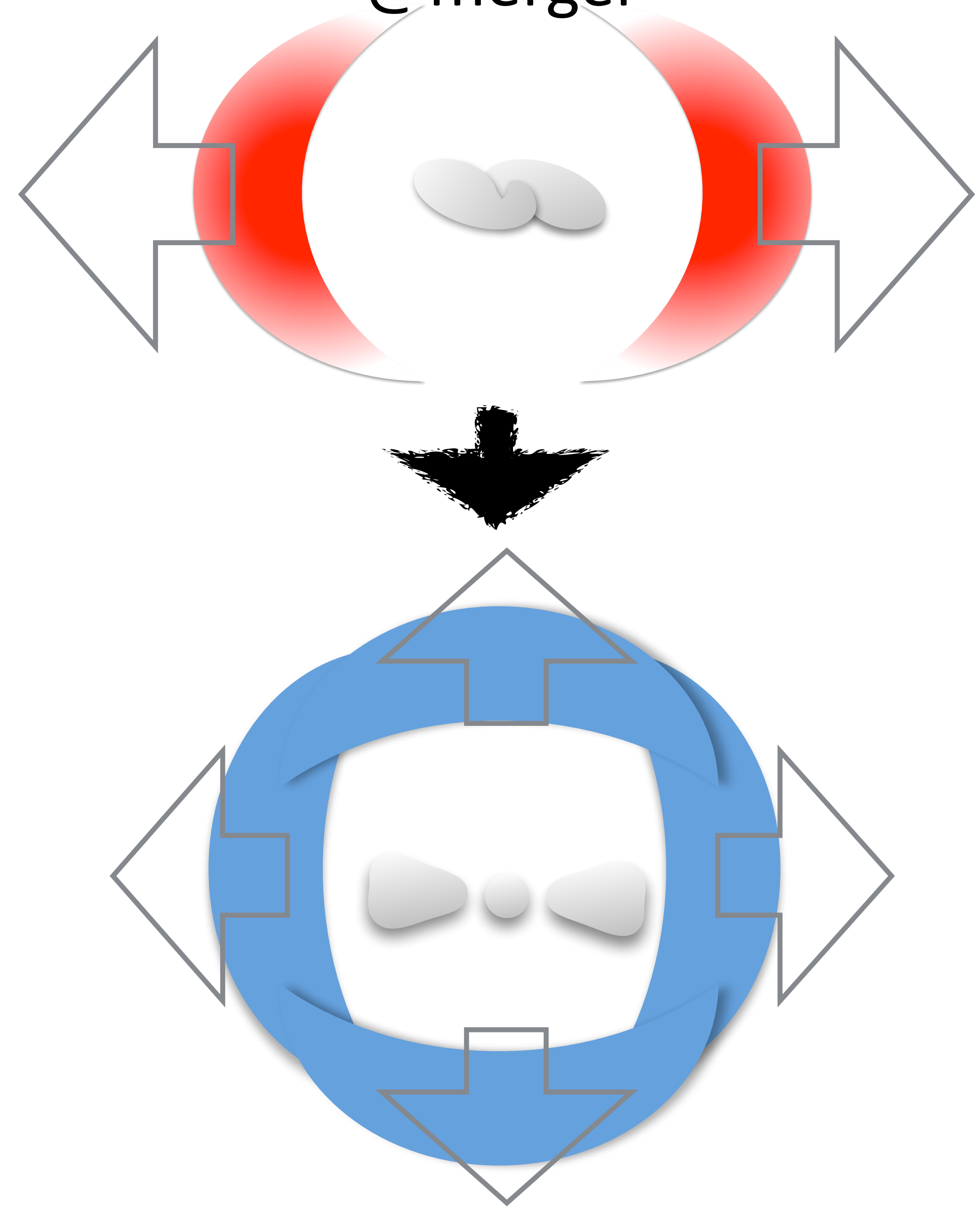
Mass Ejection Mechanisms

- Merger process and evolution of the merger remnant have been studied by
  NR simulations in the last decades revealing the mass ejection process

- **Dynamical mass ejection**
  mass ejection driven by tidal interaction
  or
  shock heating during the collision
  (e.g., Hotokezaka et al. 2013; Bauswein et al. 2013; Sekiguchi et al. 2016; Radice et al. 2016; Dietrich et al. 2017; Bovard et al. 2017)

- **Post-merger mass ejection**
  mass ejection from the merger remnant driven by viscous and neutrino heating
  (e.g., Dessart et al. 2009; Metzger & Fern´andez 2014; Perego et al. 2014; Just et al. 2015; Shibata et al. 2017; Lippuner et al. 2017; Fujibayashi et al. 2018, Siegel et al. 2018, Fernandez et al.2018)

Dynamical mass ejection
@merger

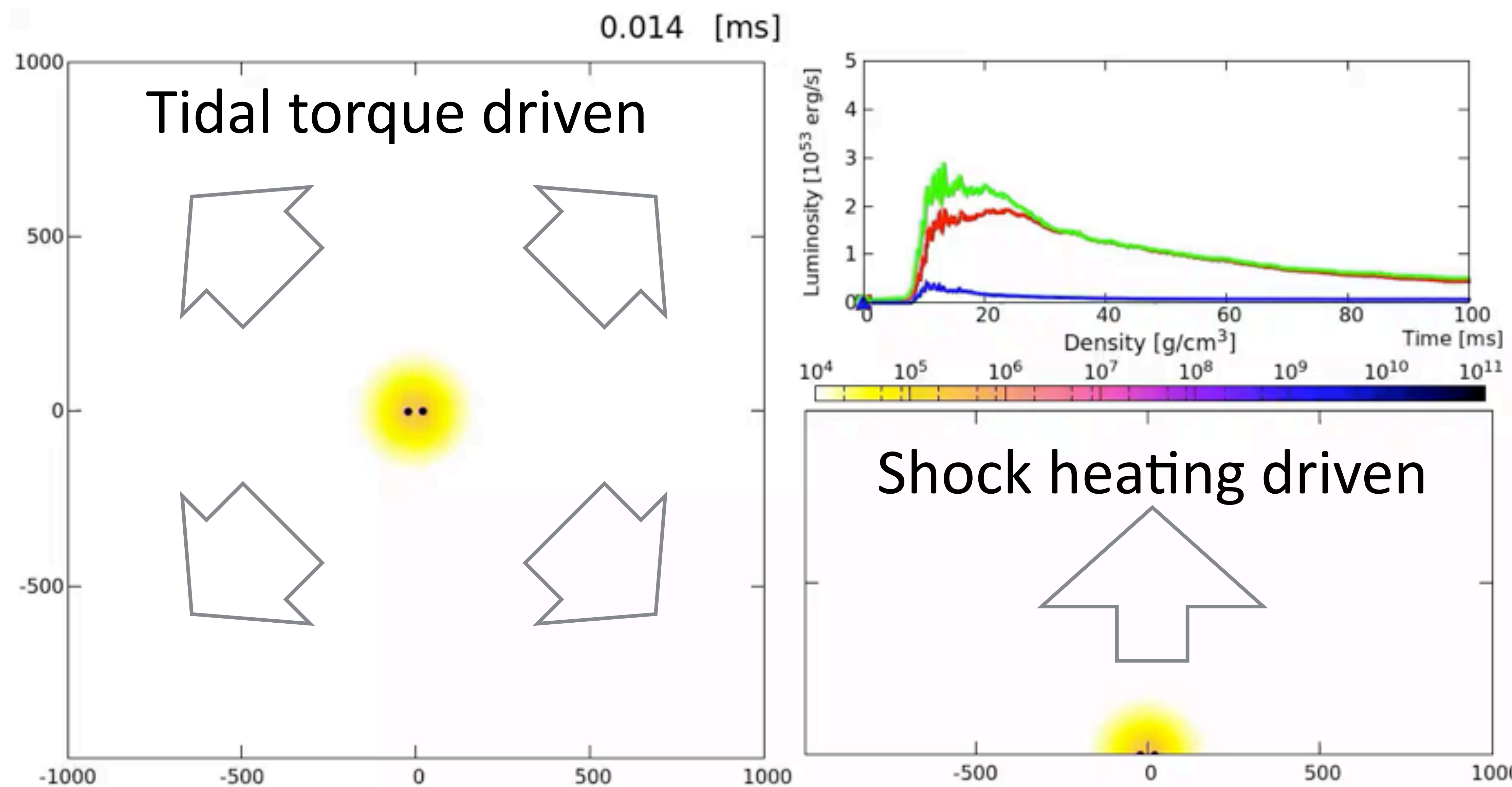


Post-merger mass ejection
@after merger

Dynamical mass ejection

Stiff EOS (DD2, R~13.2 km): 1.30-1.40 M_sun

Ref: Y. Sekiguchi et al. 2016

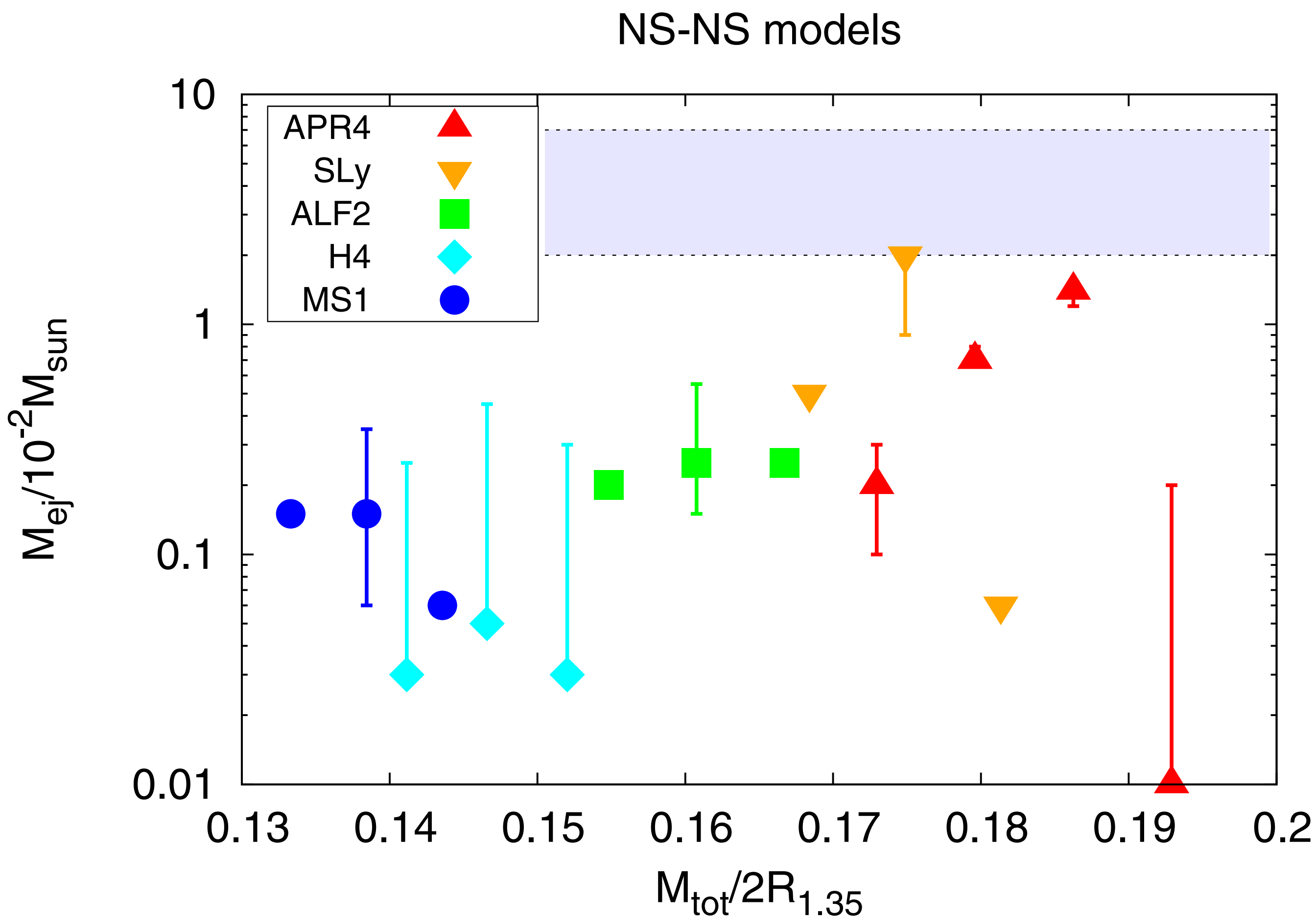


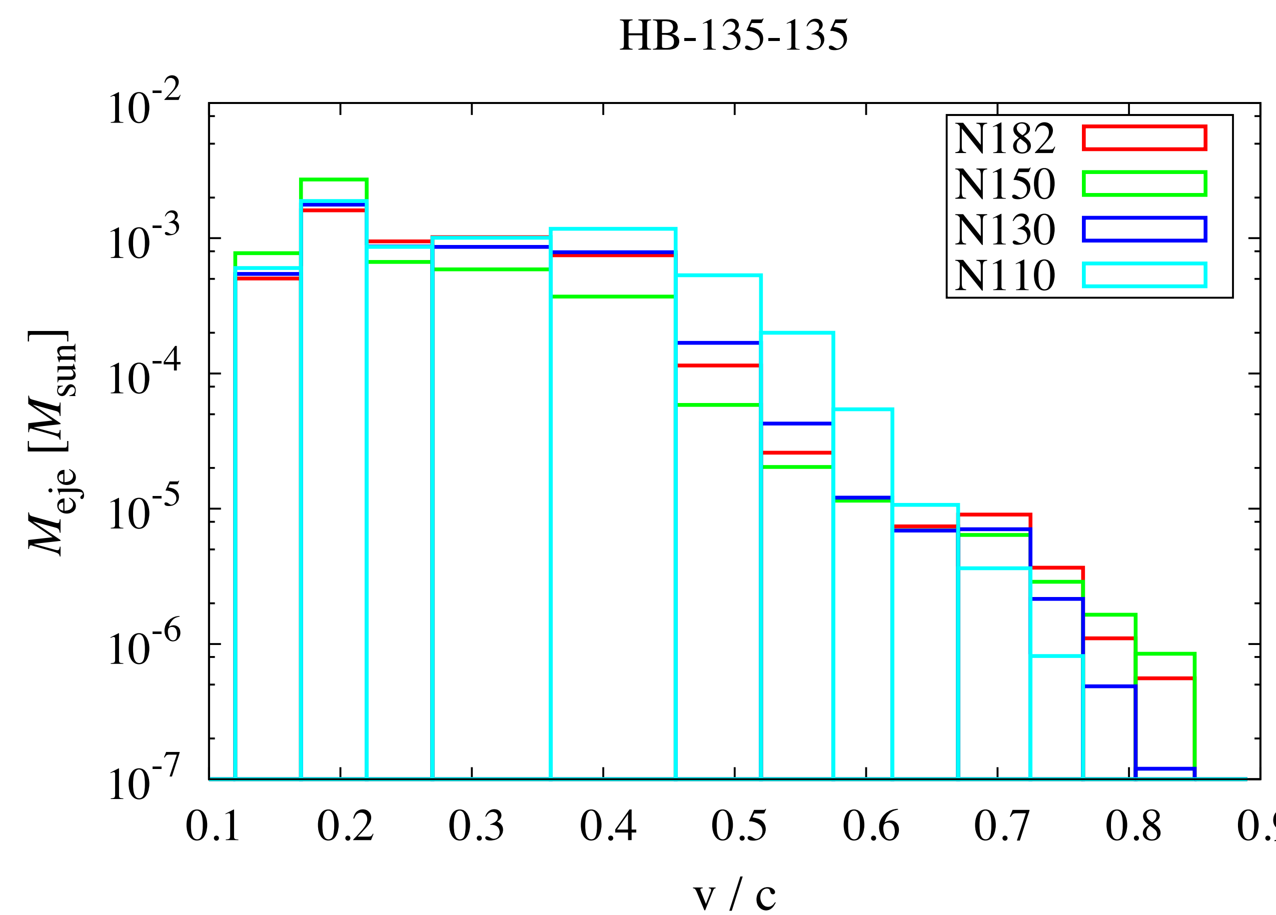
NR simulation considering neutrino transport and its effect on the Ye

$$p+\bar{\nu}_e \rightarrow n+e^+$$

$$n+\nu_e \rightarrow p+e^-$$

Dynamical mass ejection



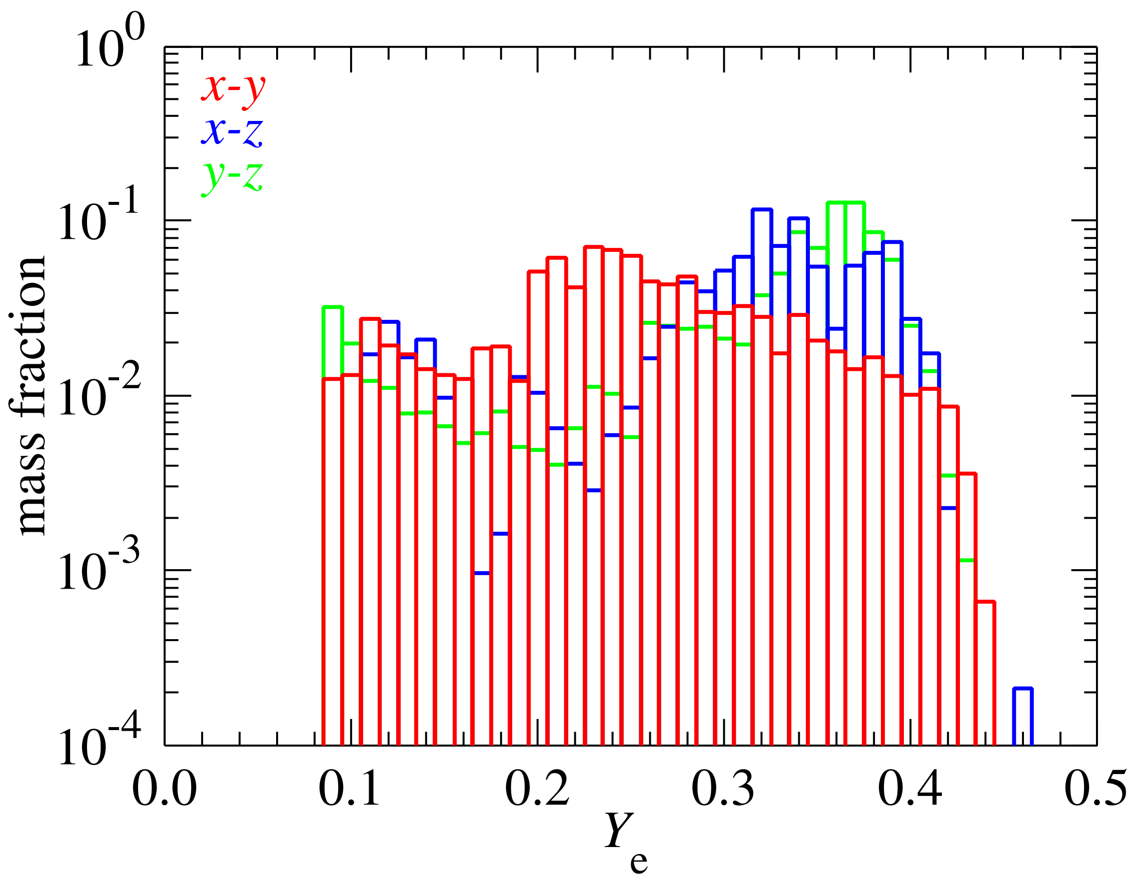


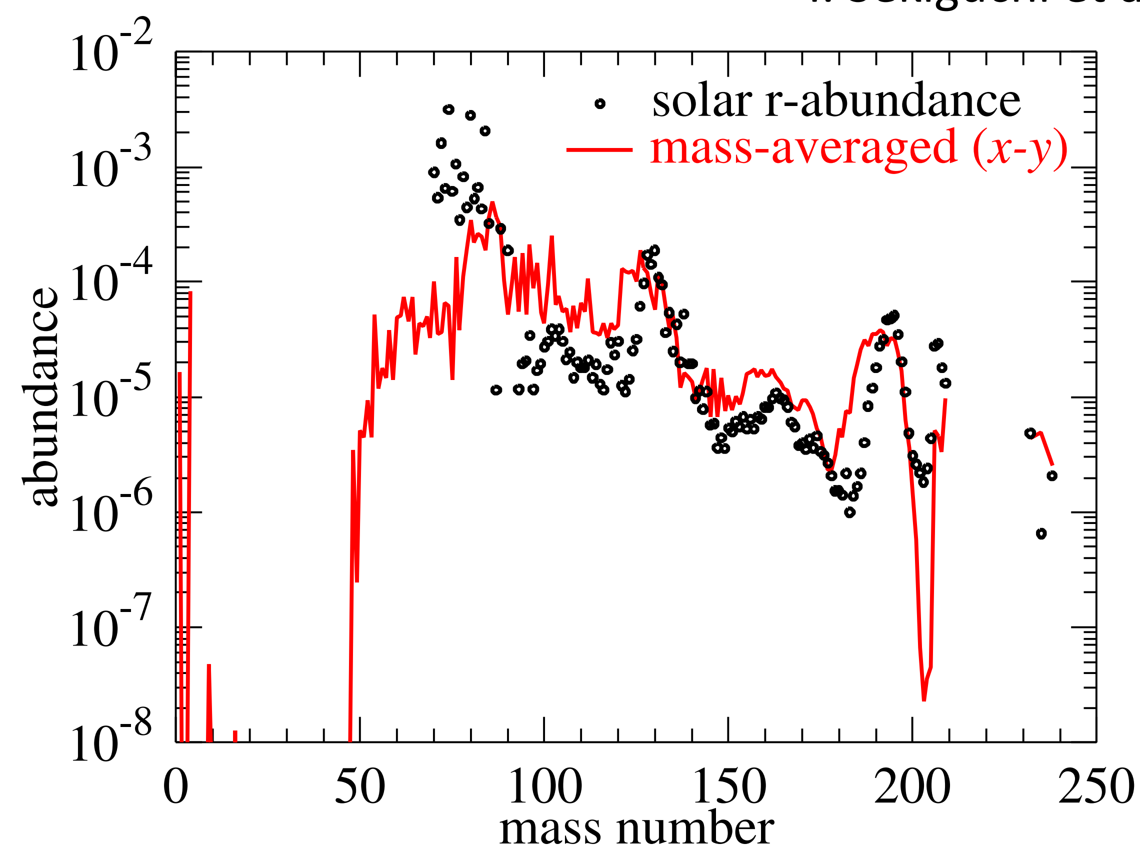
Ref: K. Hotokezaka et al. 2013,
Kiuchi et al. 2017

typical dynamical ejecta mass is 0.0001—0.01 M_sun
depends on the NS mass and EOS
typical velocity ~0.1-0.3 c (some fraction has higher velocity)

Ye distribution

Ref: S. Wanajo et al. 2014
Y. Sekiguchi et al. 2015





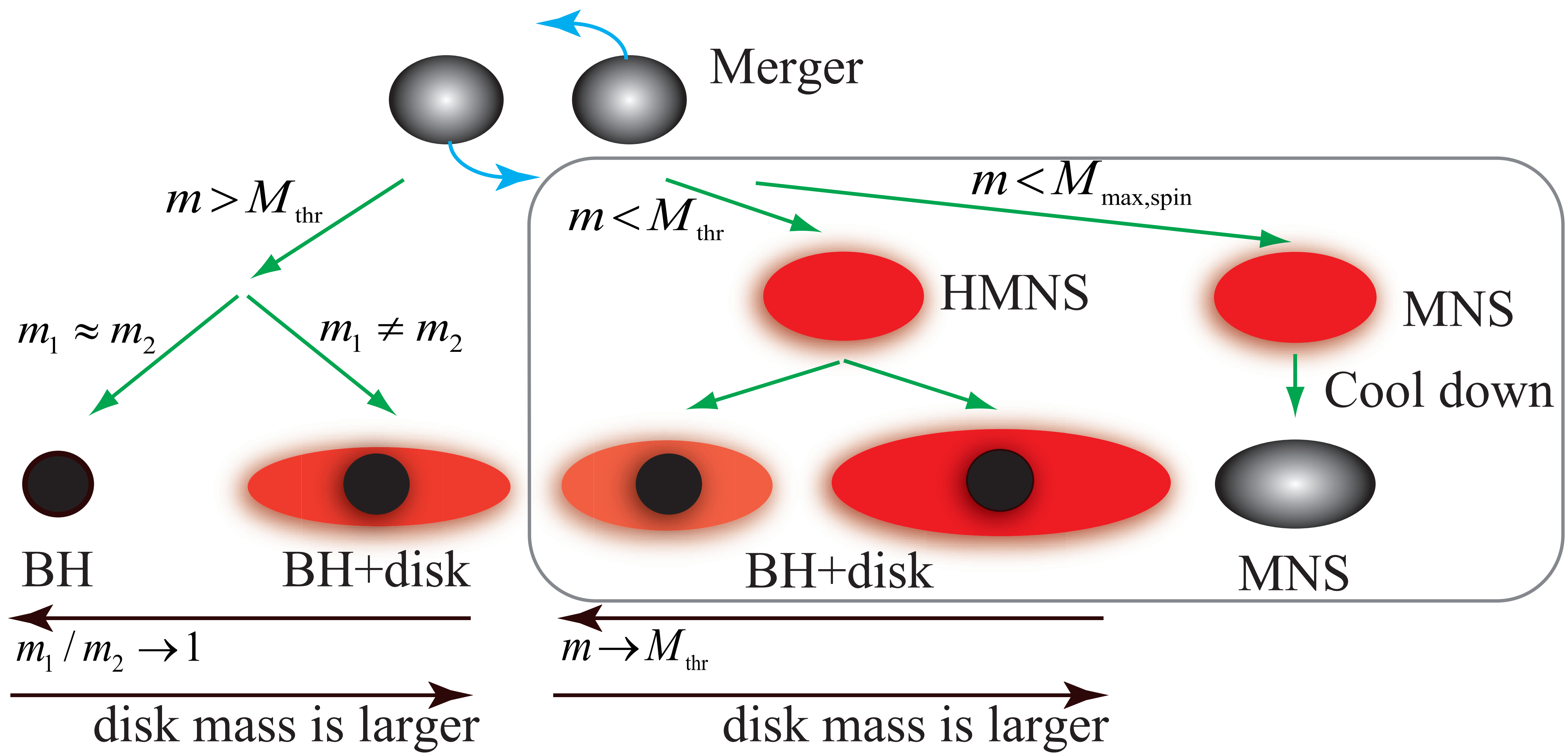
Ye partially becomes large due to shock heating and neutrino irradiation (cf. NS Ye~<0.1) Yet, lanthanide is synthesised→ κ~10cm^2/g

$$t_{\mathrm{peak}} \approx 5.9\,\mathrm{days}\left(\frac{M}{0.01M_\odot}\right)^{1/2}\left(\frac{v}{0.2c}\right)^{-1/2}\left(\frac{\kappa}{10\,\mathrm{cm}^2/\mathrm{g}}\right)^{1/2}$$

$$L_{\mathrm{peak}} \approx 3.4\times 10^{40}\,\mathrm{ergs/s}\left(\frac{f}{10^{-6}}\right)\left(\frac{M}{0.01M_\odot}\right)^{1/2}\left(\frac{v}{0.2c}\right)^{1/2}\left(\frac{\kappa}{10\,\mathrm{cm}^2/\mathrm{g}}\right)^{-1/2}$$

$$T_{\mathrm{peak}} \approx 1.5\times 10^{3}\,\mathrm{K}\left(\frac{f}{10^{-6}}\right)^{1/4}\left(\frac{M}{0.01M_\odot}\right)^{-1/8}\left(\frac{v}{0.2c}\right)^{-1/8}\left(\frac{\kappa}{10\,\mathrm{cm}^2/\mathrm{g}}\right)^{-3/8}$$

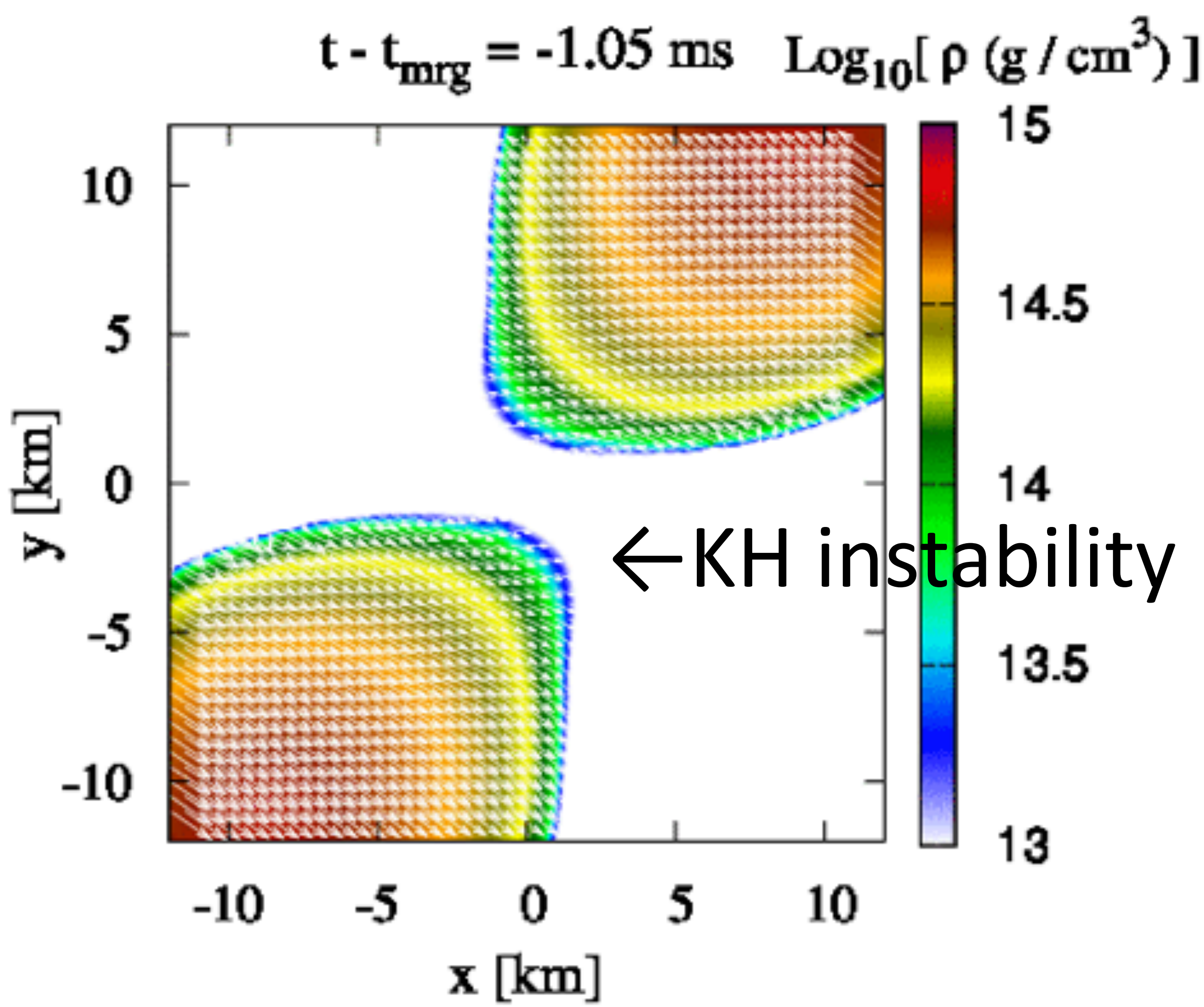
Evolution after the merger

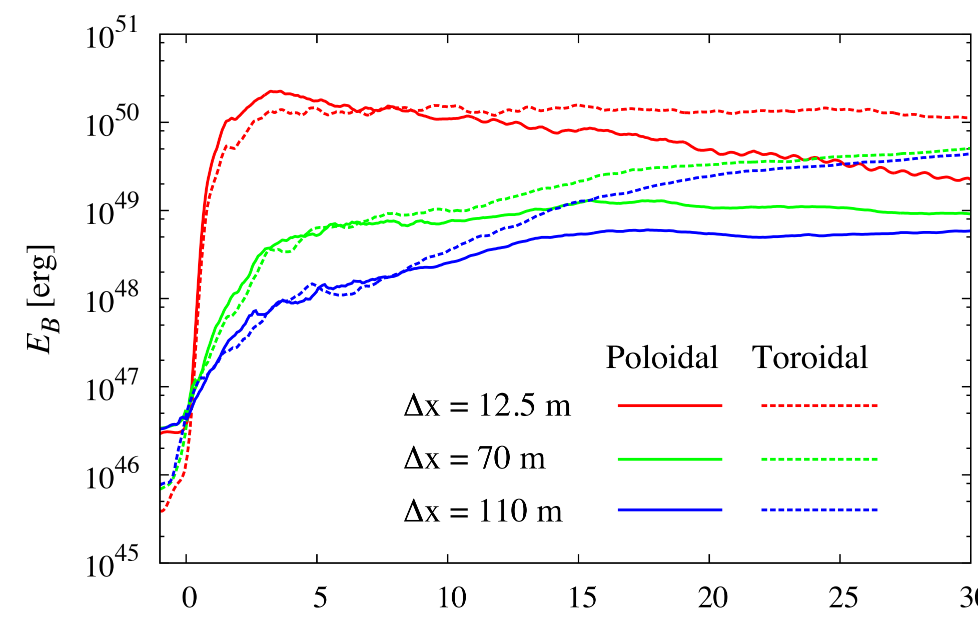


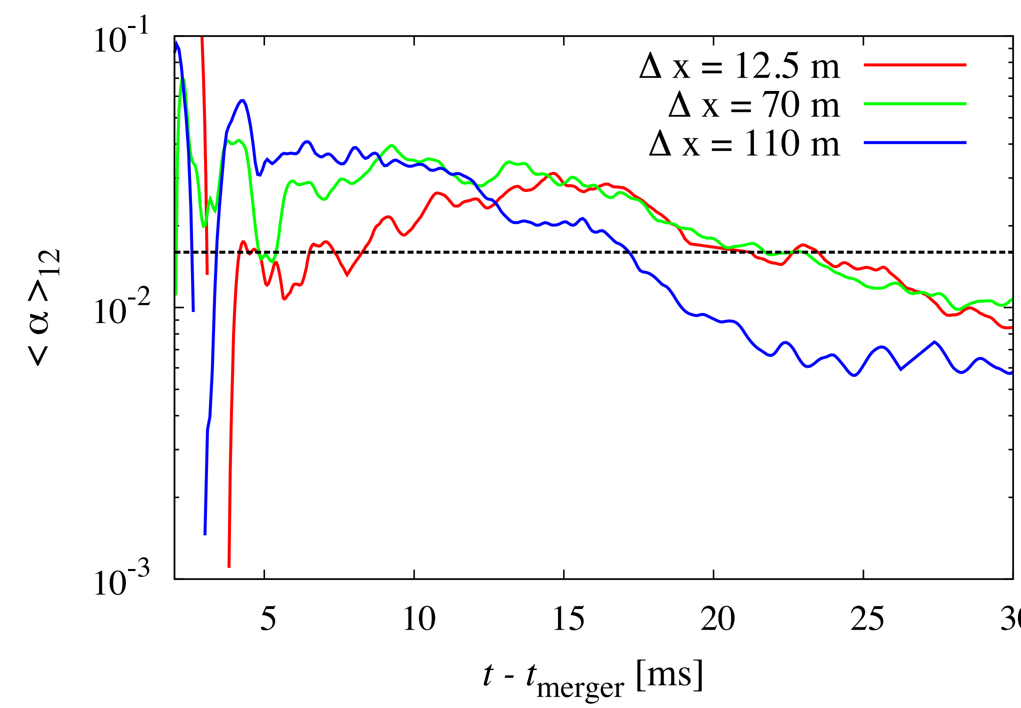
- For Mtot<2.8 M_sun, NS + disk likely to remain after the merger. →neutrino irradiation from the remnant NS would be important

Evolution of Remnant NS & torus: Effective viscosity

Turbulence in the contact surface→amplification of magnetic field →effective viscosity would play a role



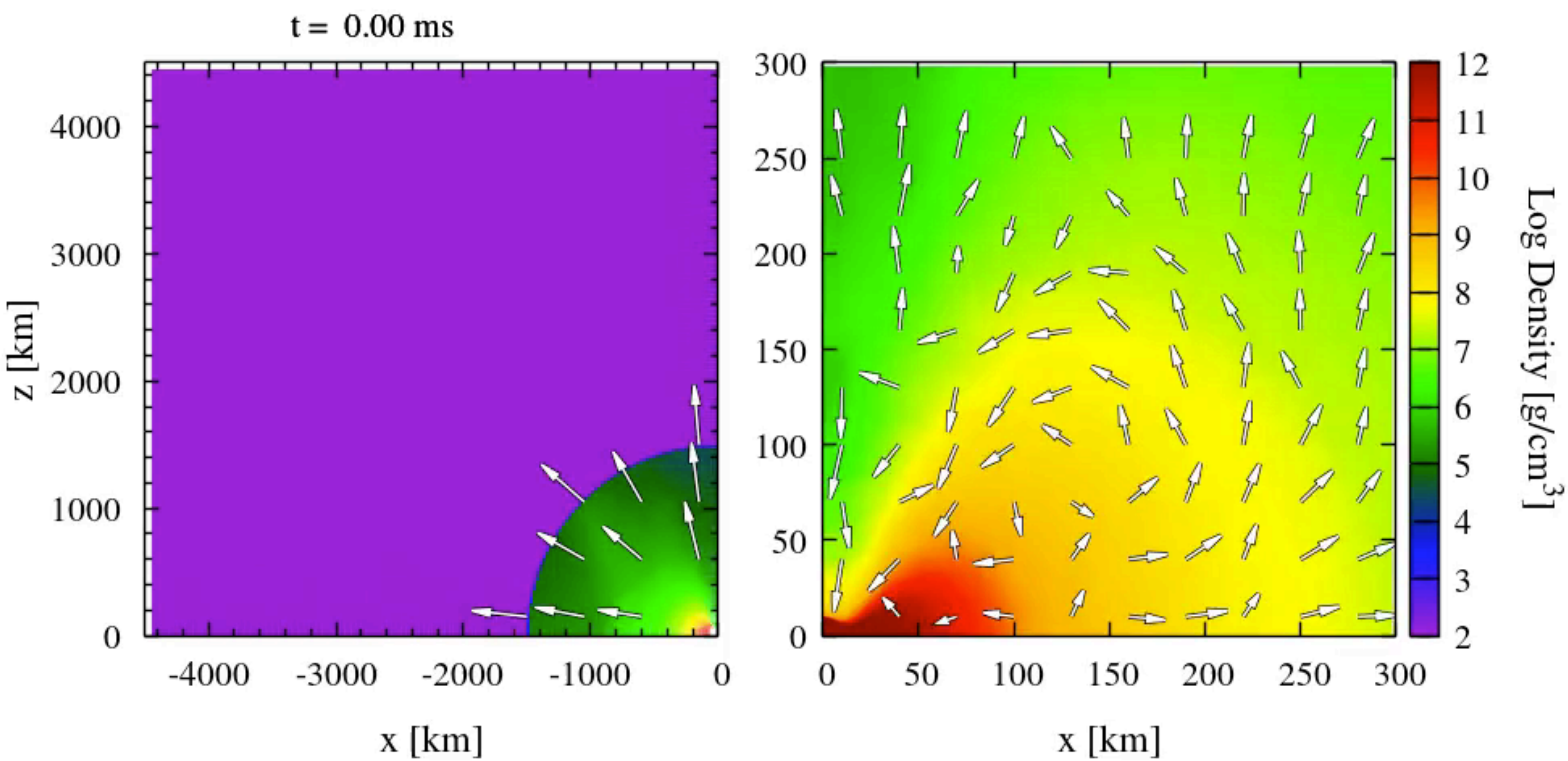




Ref: K. Kiuchi et al. 2015, 2017

Viscous-radiative simulation

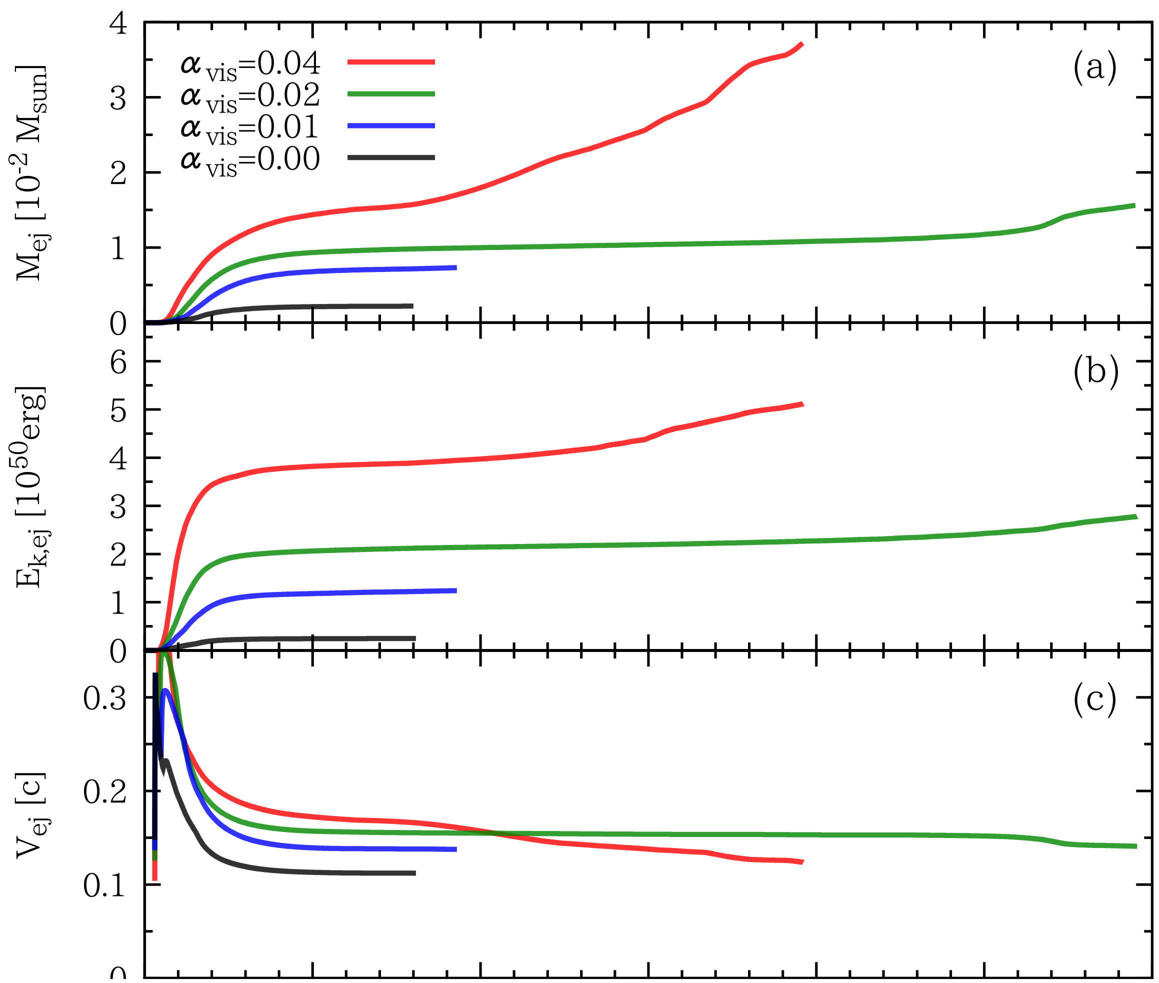
Numerical-relativity simulation considering
the effects of physical viscosity and neutrino radiation

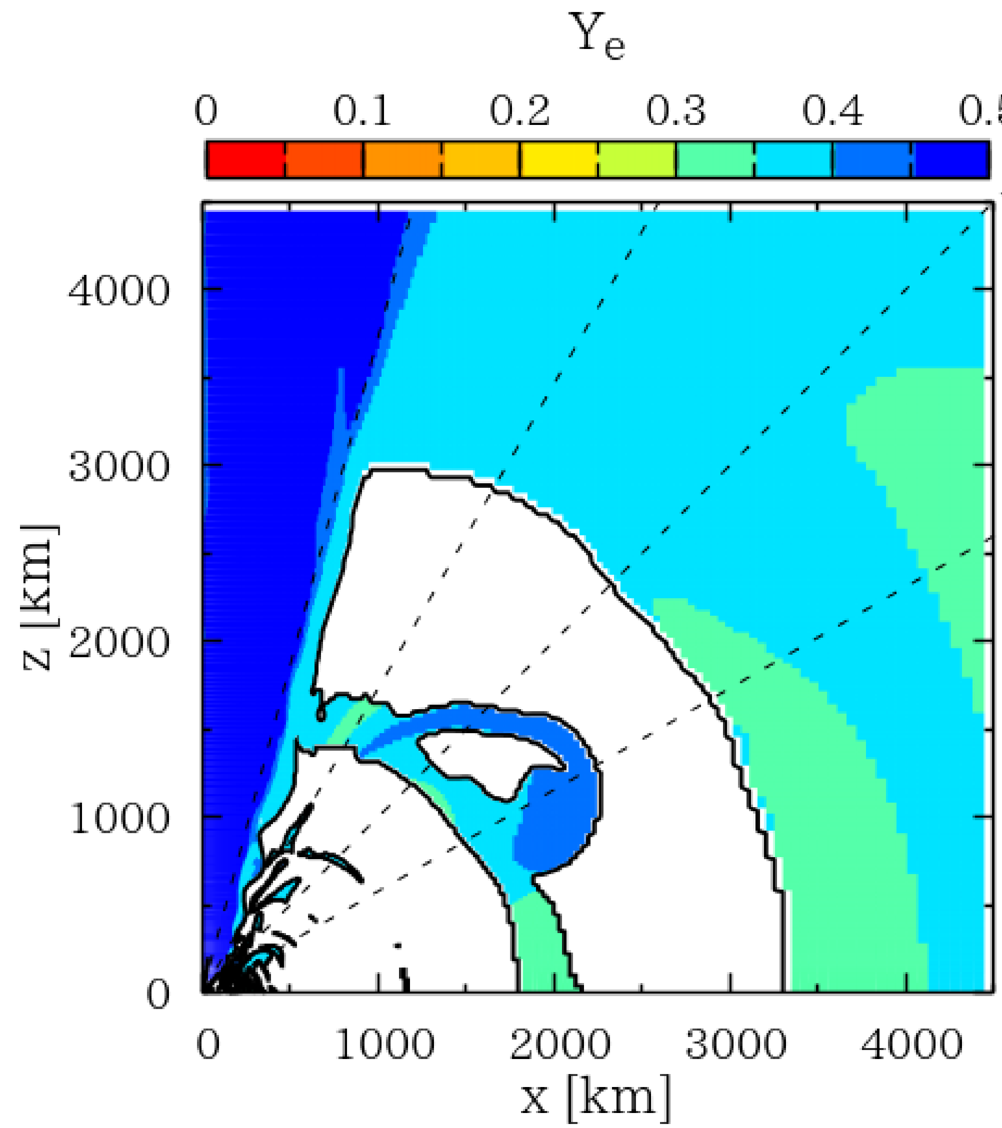


Ref: S. Fujibayashi et al. 2018

Post-merger mass ejection

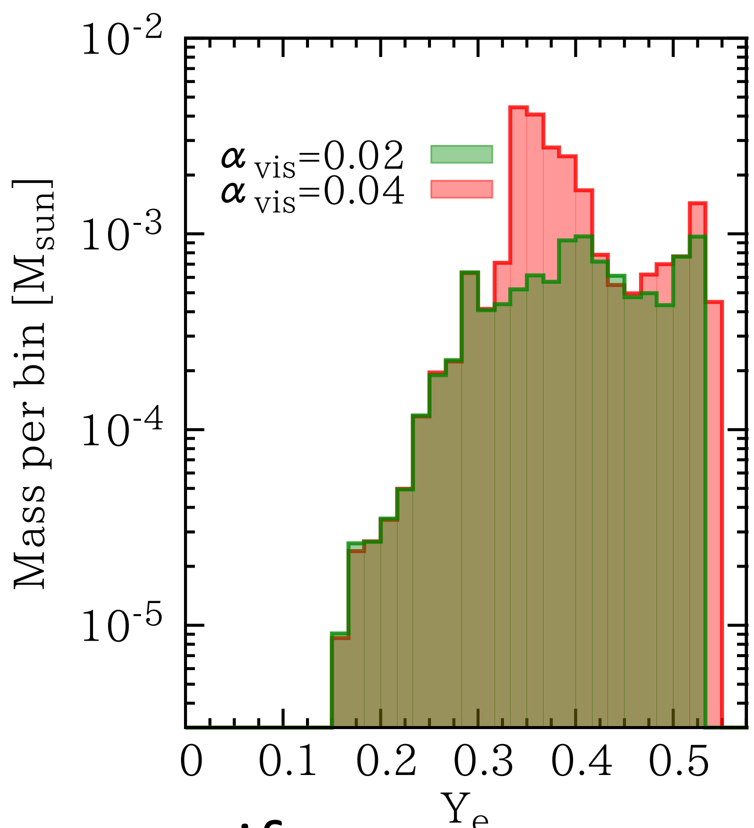
Ref: S. Fujibayashi et al. 2018



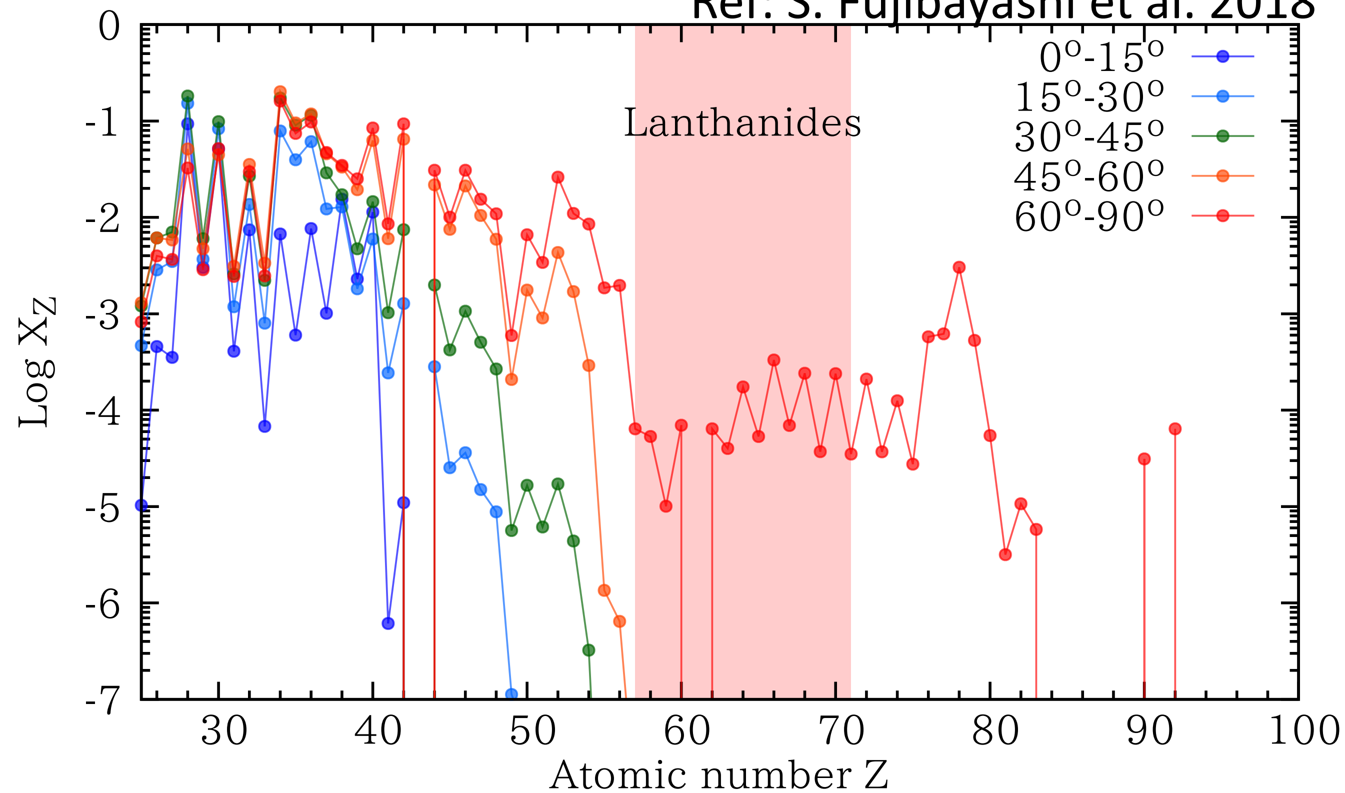


Ejecta mass ~0.01—0.1 M_sun, typical velocity 0.03 — 0.15 c depending on the viscous parameter and the lifetime of the remnant NS

Ye distribution



Ref: S. Fujibayashi et al. 2018



if remnant neutron star is sufficiently long-lived,

post-merger ejecta would typically have Ye>0.25 due to neutrino irradiation

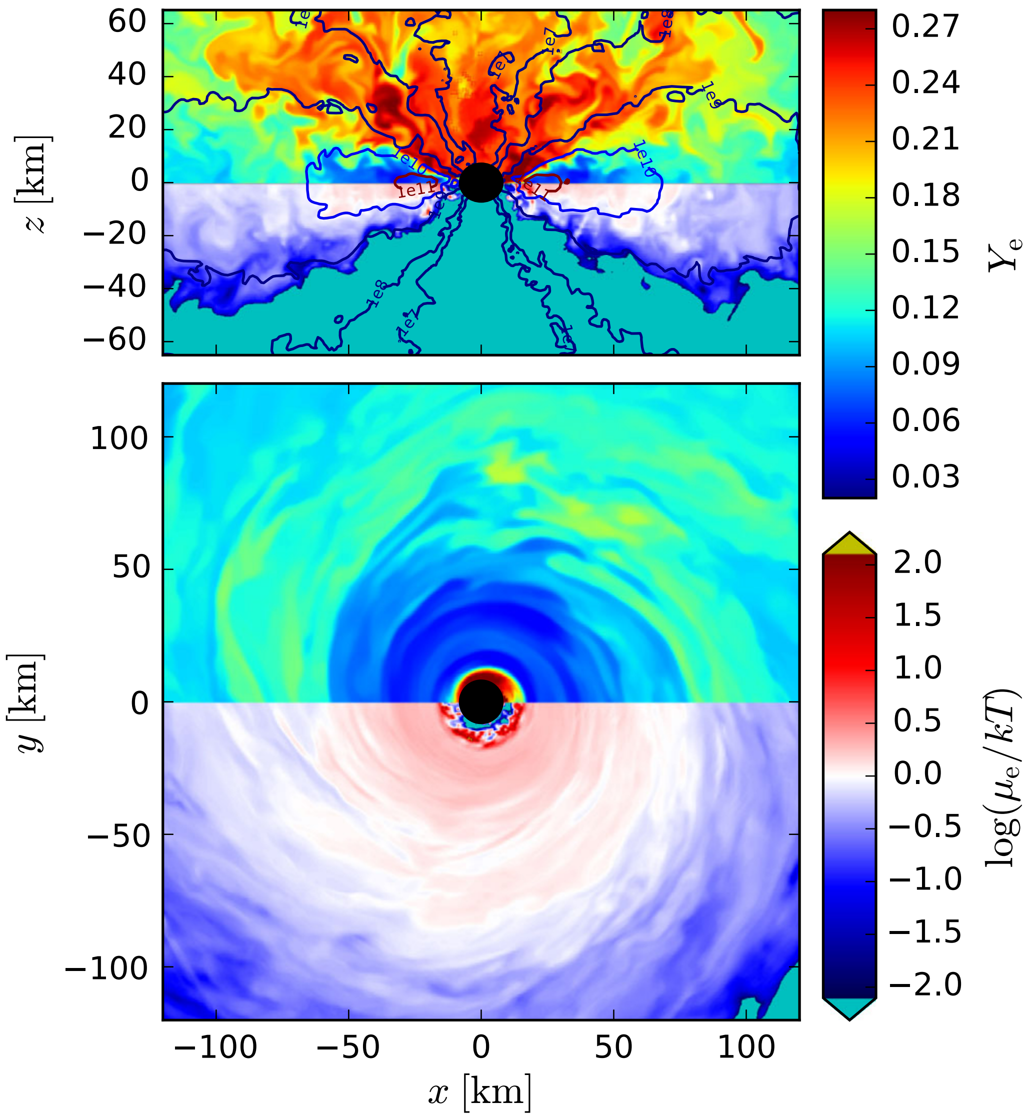
→ lanthanide-free → κ~0.1-1 cm^2/g

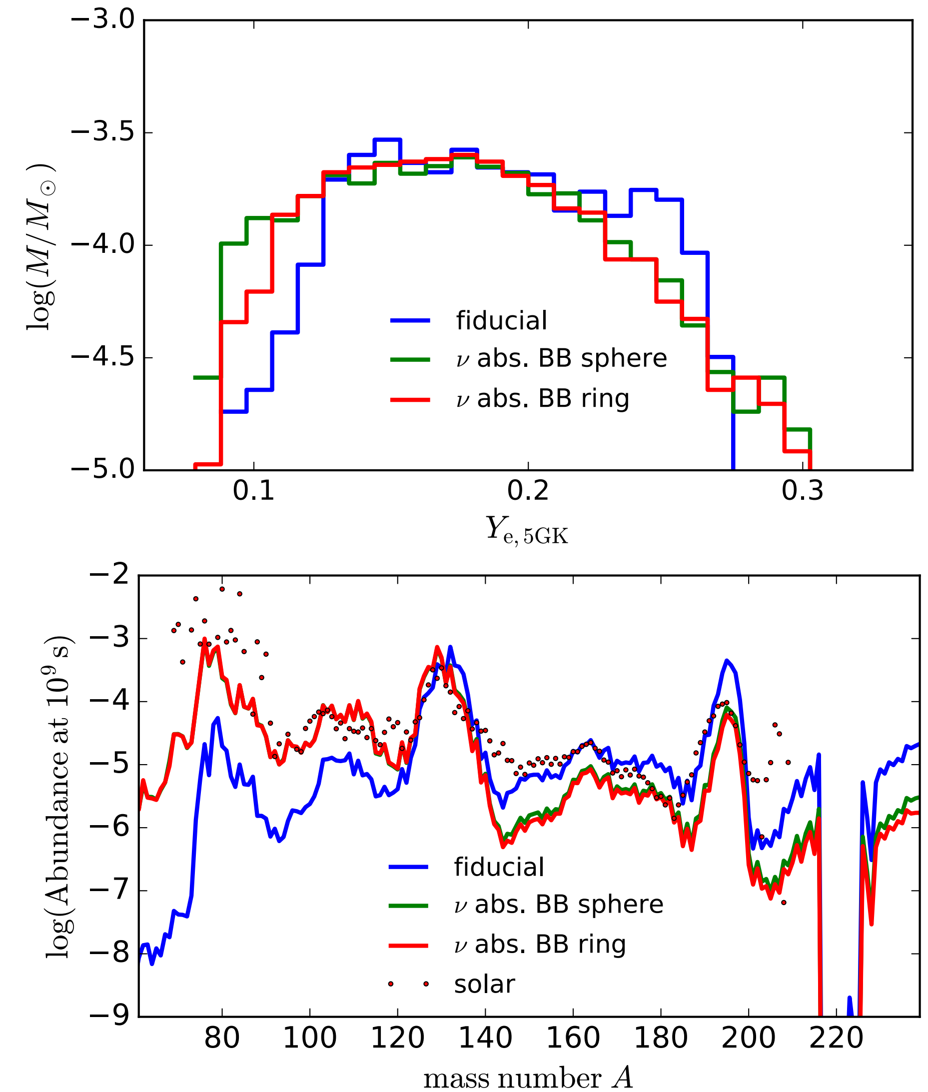
$$t_{\rm peak} \approx 1.5\,{\rm days}\left(\frac{M}{0.03M_\odot}\right)^{1/2}\left(\frac{v}{0.1c}\right)^{-1/2}\boxed{\left(\frac{\kappa}{0.1\,{\rm cm^2/g}}\right)}^{1/2}$$

$$L_{\rm peak} \approx 4.3\times10^{41}\,{\rm ergs/s}\left(\frac{f}{10^{-6}}\right)\left(\frac{M}{0.03M_\odot}\right)^{1/2}\left(\frac{v}{0.1c}\right)^{1/2}\boxed{\left(\frac{\kappa}{0.1\,{\rm cm^2/g}}\right)}^{-1/2}$$

$$T_{\rm peak} \approx 8.0\times10^{3}\,{\rm K}\left(\frac{f}{10^{-6}}\right)^{1/4}\left(\frac{M}{0.03M_\odot}\right)^{-1/8}\left(\frac{v}{0.1c}\right)^{-1/8}\boxed{\left(\frac{\kappa}{0.1\,{\rm cm^2/g}}\right)}^{-3/8}$$

Note:prompt collapse case





Ref: Siegel et al. 2018

if the merger remnant collapse to a black hole
promptly (or in a short time scale t<<1s),
post-merger ejecta would be lanthanide-rich
(see e.g., Wu et al. 2016, Siegel et al. 2018, Fernandez et al. 2018)

kilonova/macronova from different components

- **Dynamical mass ejection**
  M~0.0001—0.01 M_sun, v~0.1-0.2 c
  Ye~0.1-0.5
  →t_peak~10 days,
  long-lasting, dim, low temperature
  (red) kilonova

- **Post-merger mass ejection**
  M~0.01—0.1 M_sun, v~0.03-0.15 c
  Ye~0.3-0.4
  (if remnant NS is sufficiently long-lived)
  →t_peak~1 days,
  short-lasting, bright, high temperature
  (blue) kilonova

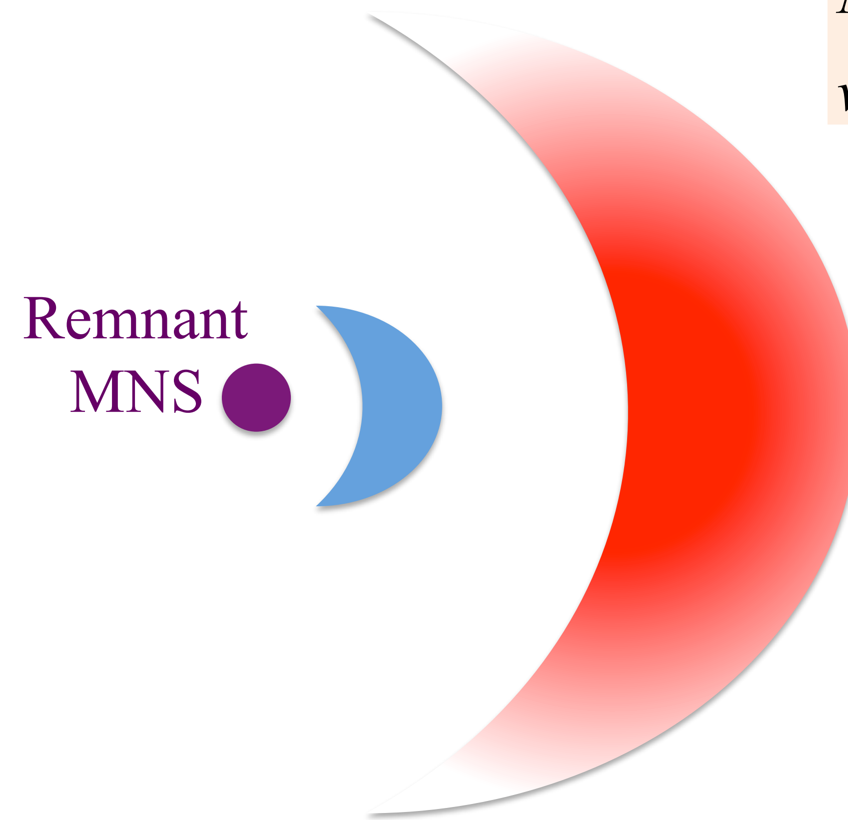
Dynamical ejecta

$Y_e \sim 0.05 - 0.5$

$\rightarrow \kappa \sim 10 \text{ cm}^2/\text{g}$

$M \sim 10^{-2} M_\odot$

$v/c = 0.1 - 0.9$



Post-merger ejecta

$Y_e \sim 0.3 - 0.4$

$\rightarrow \kappa \sim 0.1 \text{ cm}^2/\text{g}$

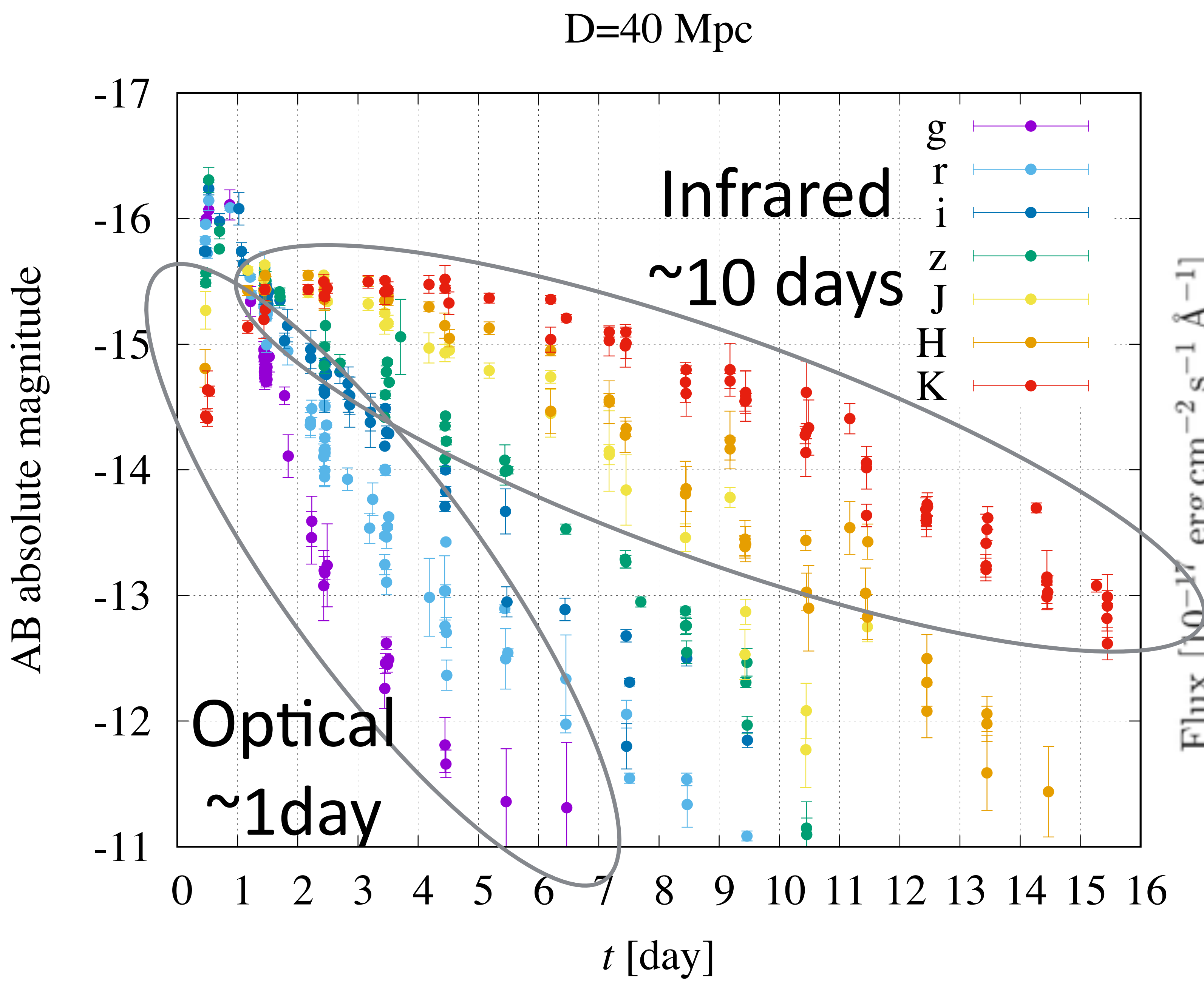
$M \sim 3 \times 10^{-2} M_\odot$

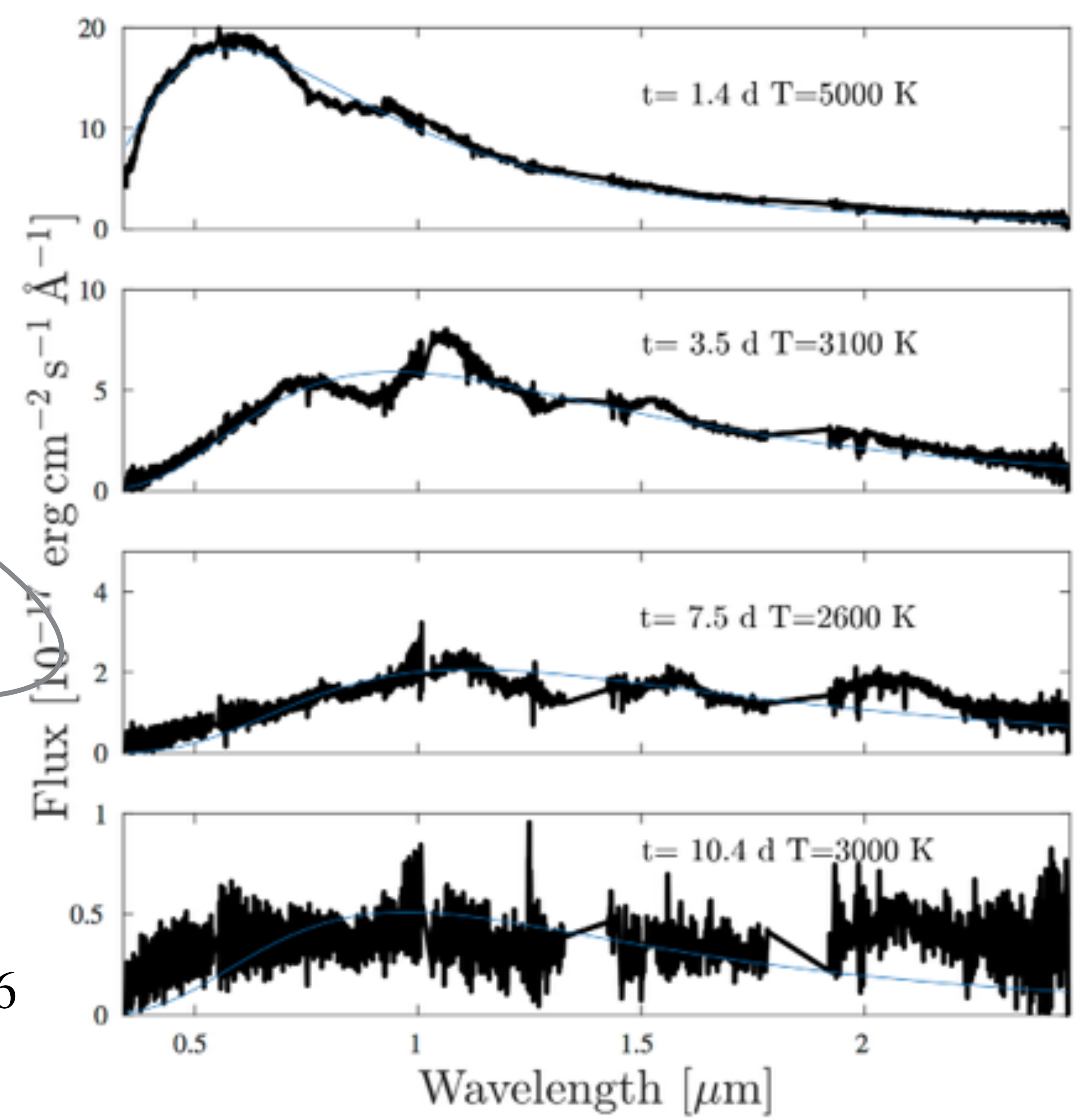
$v/c = 0.03 - 0.1$

SSS17a (GW170817)

Data: Villar et al. 2017

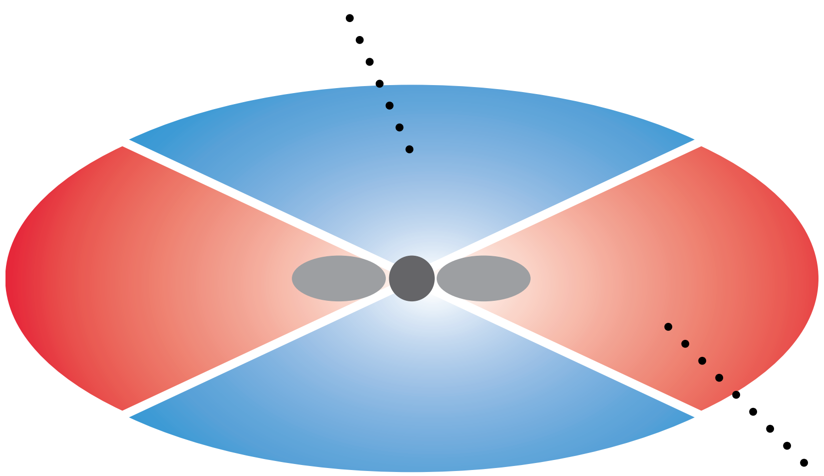
Ref: Waxman et al. 2017





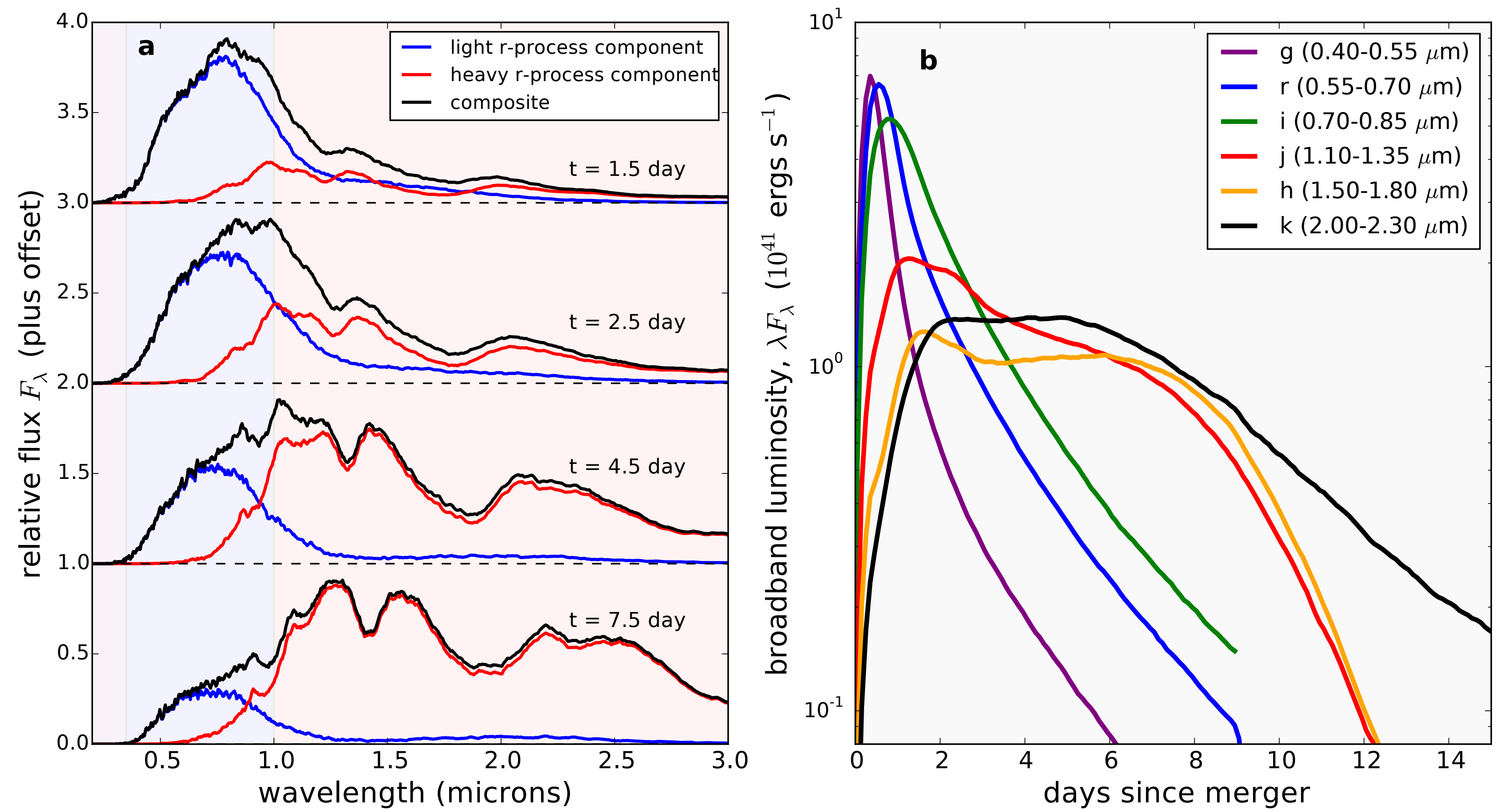
Multiple component Kilonovae/macronovae

Blue (lanthanide-free)



Red (lanthanide-rich)

ref) Tanaka-san's slide



Ref: D. Kasen et al. 2017

- Kilonova/macronova model with multiple components well interprets the observation (see e.g., Kasliwal et al. 2017, Cowperthwaite et al. 2017, Kasen et al. 2017, Villar et al. 2017)
- early-blue component (~1day) from lanthanide-free ejecta

  + long-lasting red component (~10days) from lanthanide-rich ejecta

Problems

- Multiple component ejecta kilonova/macronova seem to work, but…

Figure 5 | A unified kilonova model explaining the optical/infrared counterpart of GW170817. The model is the superposition of the emission from two spatially distinct ejecta components: a 'blue' kilonova (light r-process ejecta with $M = 0.025M_{\odot}$, $\underline{v_k = 0.3c}$ and $X_{lan} = 10^{-4}$) plus a 'red' kilonova (heavy r-process ejecta with $\underline{M = 0.04M_{\odot}}$, $v_k = 0.15c$, and $X_{lan} = 10^{-1.5}$). **a**, Optical–infrared spectral time series, where the black line is the sum of the light r-process (blue line) and heavy r-process (red line) contributions.

Ref: D. Kasen et al. 2017

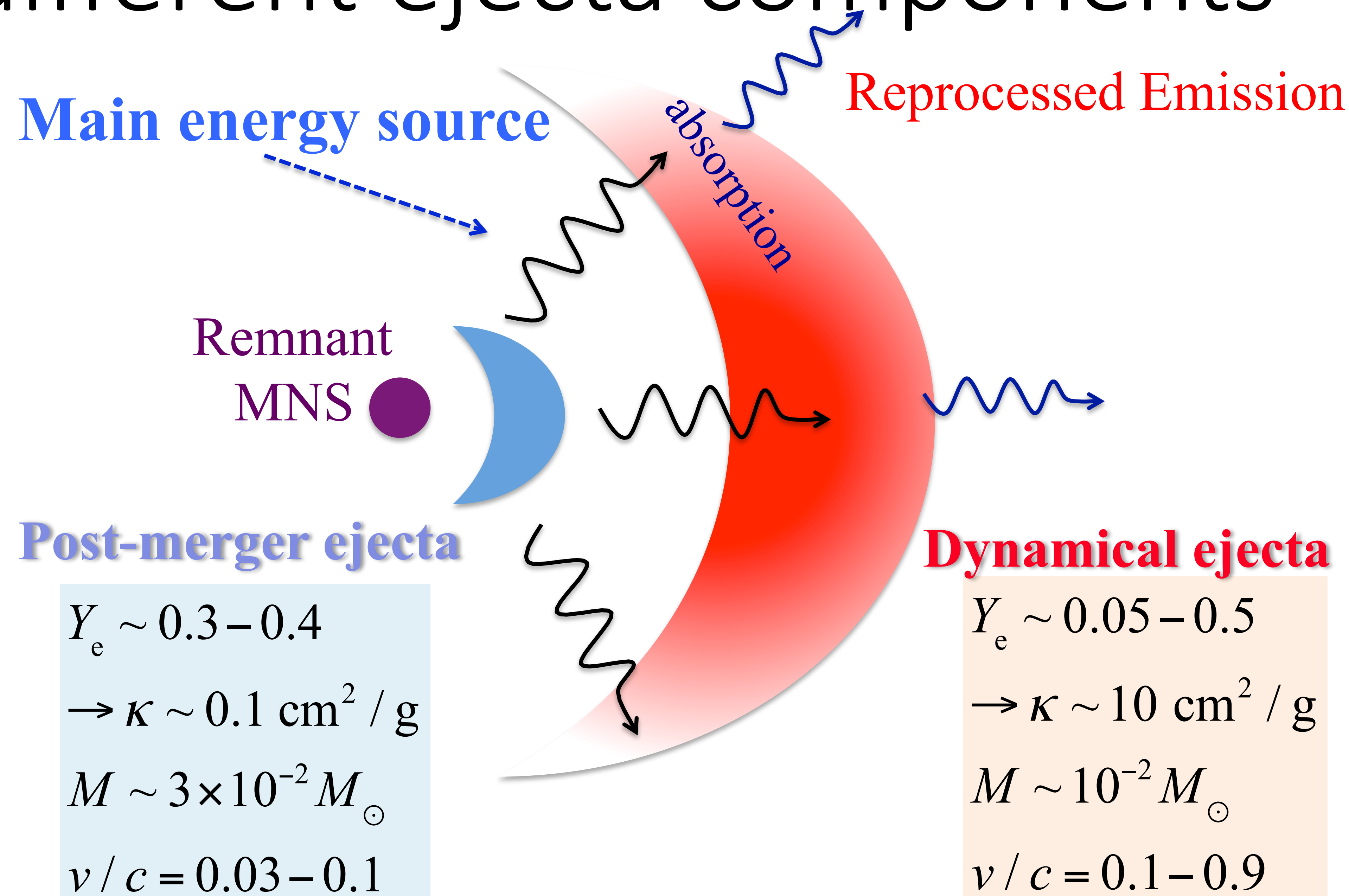
  - lanthanide-rich ejecta with >0.01 M_sun seems too large for the dynamical ejecta (typically less than 0.01 M_sun)

  - velocity of lanthanide-free ejecta ~0.3 c is too high for the post-merger ejecta (typically ~0.05-0.1 c)

- Tension between observed properties and predictions of numerical relativity? (e.g., Waxman et al. 2017, Metzger et al. 2018, Matsumoto et al. 2018)

- **Photon interplay between the dynamical & post-merger ejecta is not taken into account (only simple composition of each lightcurve)**

Radiative transfer between different ejecta components



We perform an axisymmetric radiative transfer simulation for kilonovae/macronovae taking the interplay of multiple ejecta components of non-spherical morphology into account. (see Perego et al. 2017, Wollaeger et al. 2017 for studies with similar setups and also Matsumoto et al. for reprocessing models in different context)

Radiative transfer simulation

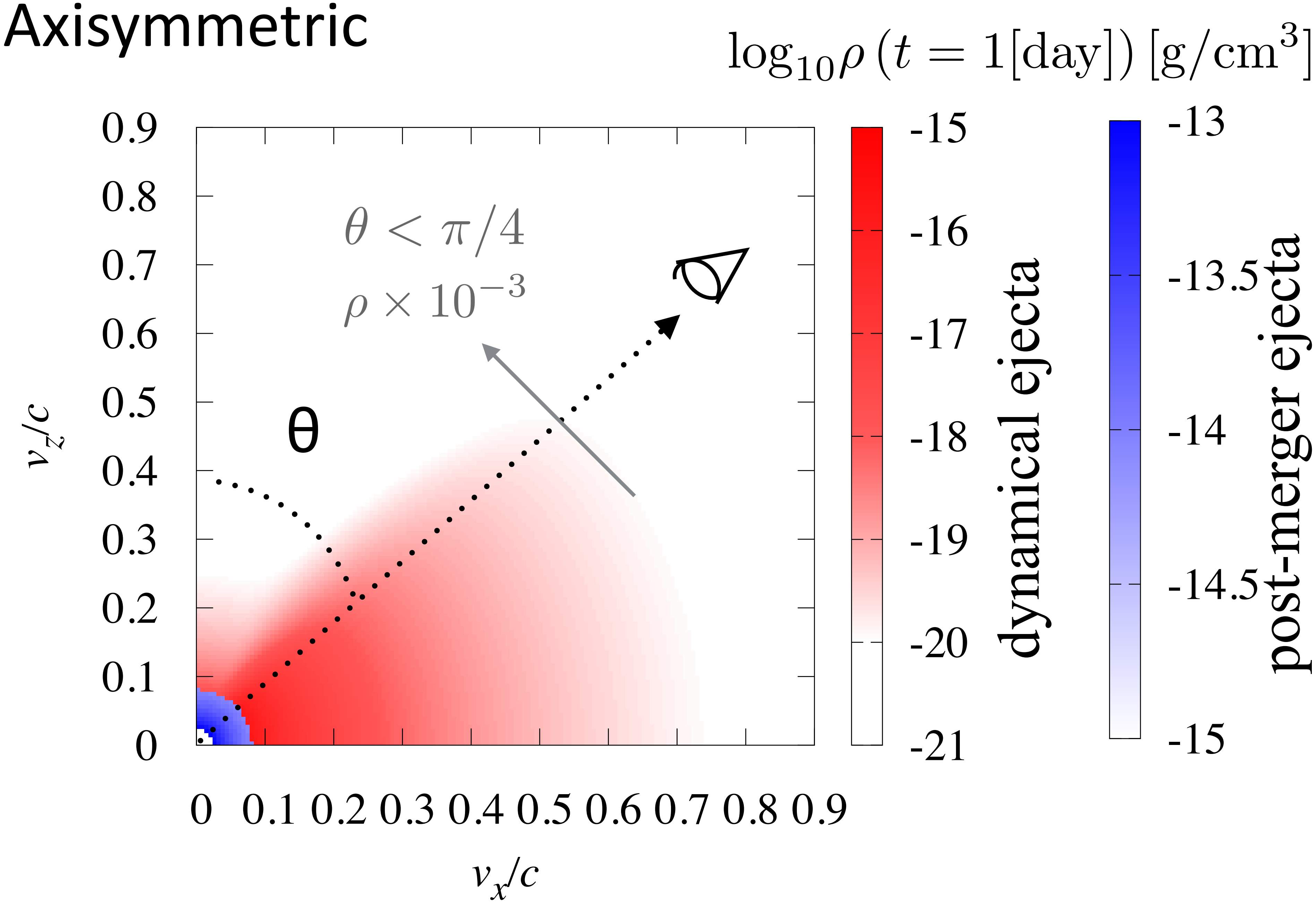
- We employ a wavelength-dependent Monte-Carlo radiative transfer simulation code (M. Tanaka et al. 2013, 2014, 2017)
- The density, velocity, and Ye profiles of ejecta are employed within the range of predictions by numerical-relativity simulations. (e.g., Dietrich et al. 2016, Hotokezaka et al. 2018, Metzger&Fernandez et al. 2014 , Fujibayashi et al. 2018)
- The abundance pattern and nuclear heating rate are given based on r-process nucleosynthesis calculations by (Wanajo et al. 2014)
- Realistic opacity table constructed by the atomic structure calculations (Se, Ru, Te, Nd, and Er)

improved points

- The grid resolution of the simulation is also improved by an oder of magnitude from our previous works by imposing axisymmetry.
- special-relativistic effects on photon transfer are fully taken into account

Density distribution

Axisymmetric



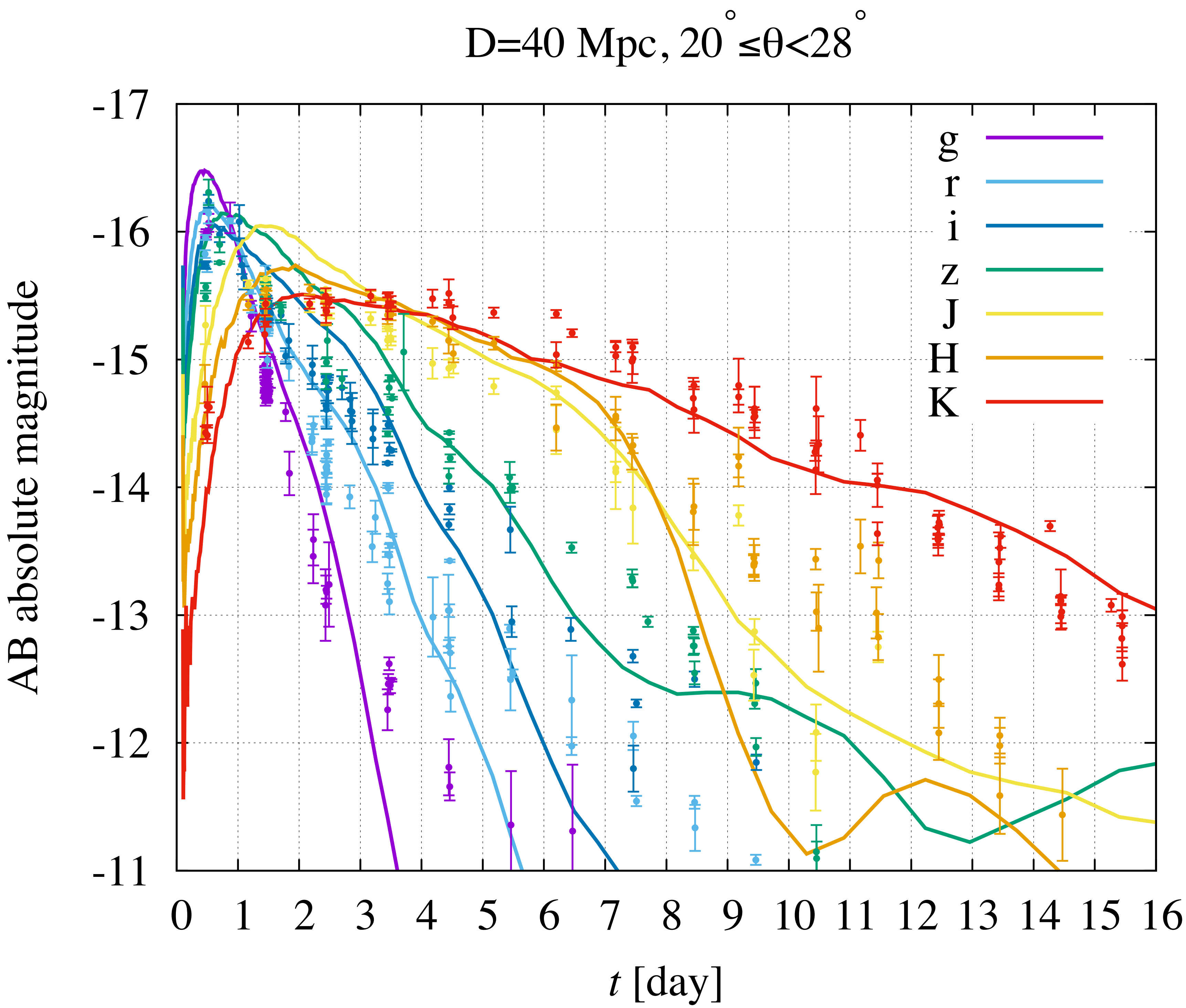
$\rho \propto r^{-p}$

Dynamical ejecta: **0.009 M_sun**, 0.08—0.9 c, Ye=0.1-0.4, p=-6

Post-merger ejecta: 0.02 M_sun, **0.025—0.08 c**, Ye=0.3-0.4, p=-3

* This setups mimics the case with higher density and Ye of the dynamical ejecta in the polar region

Results:Light curves

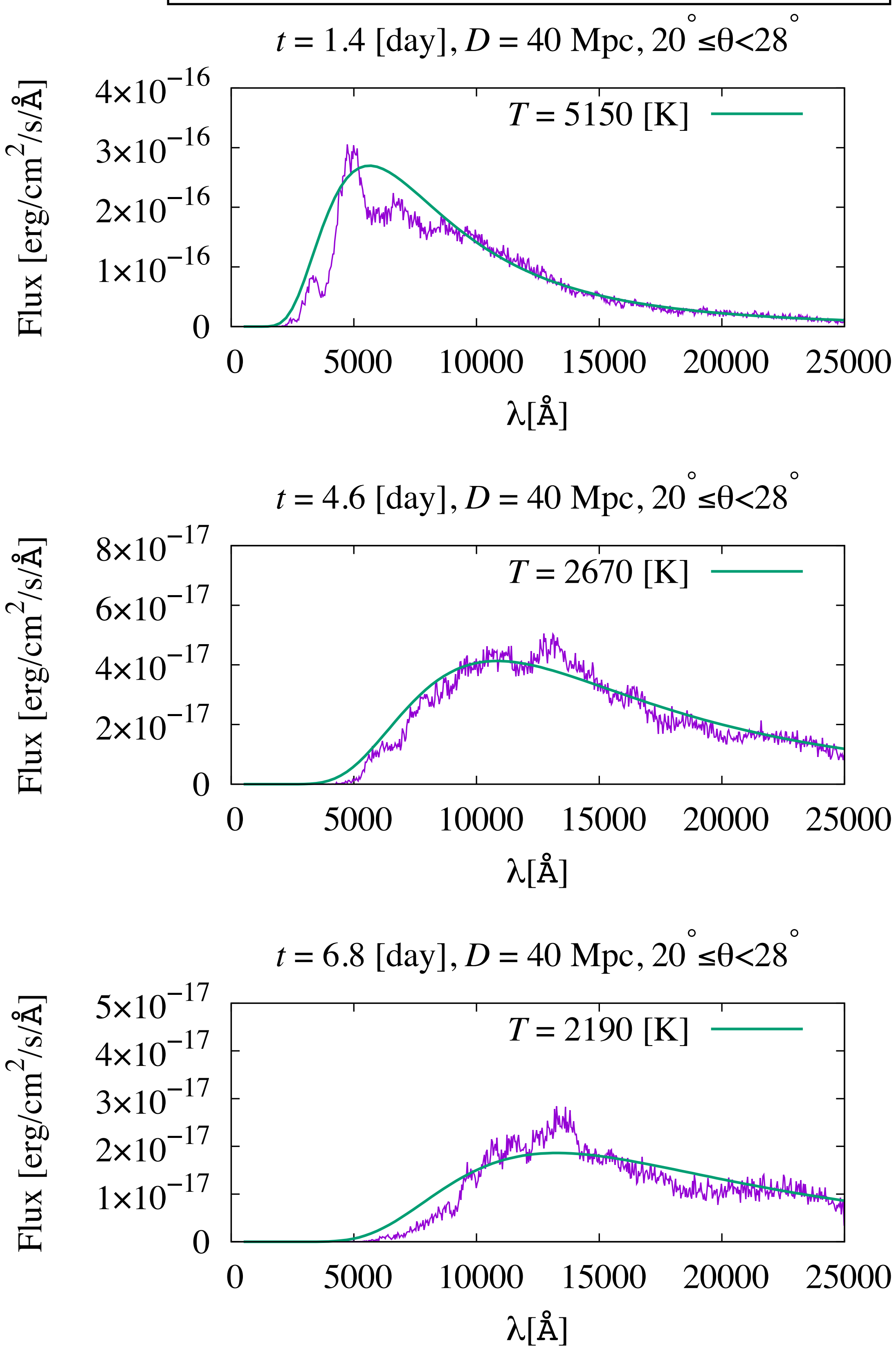


Host galaxy NGC4993: ~40 Mpc

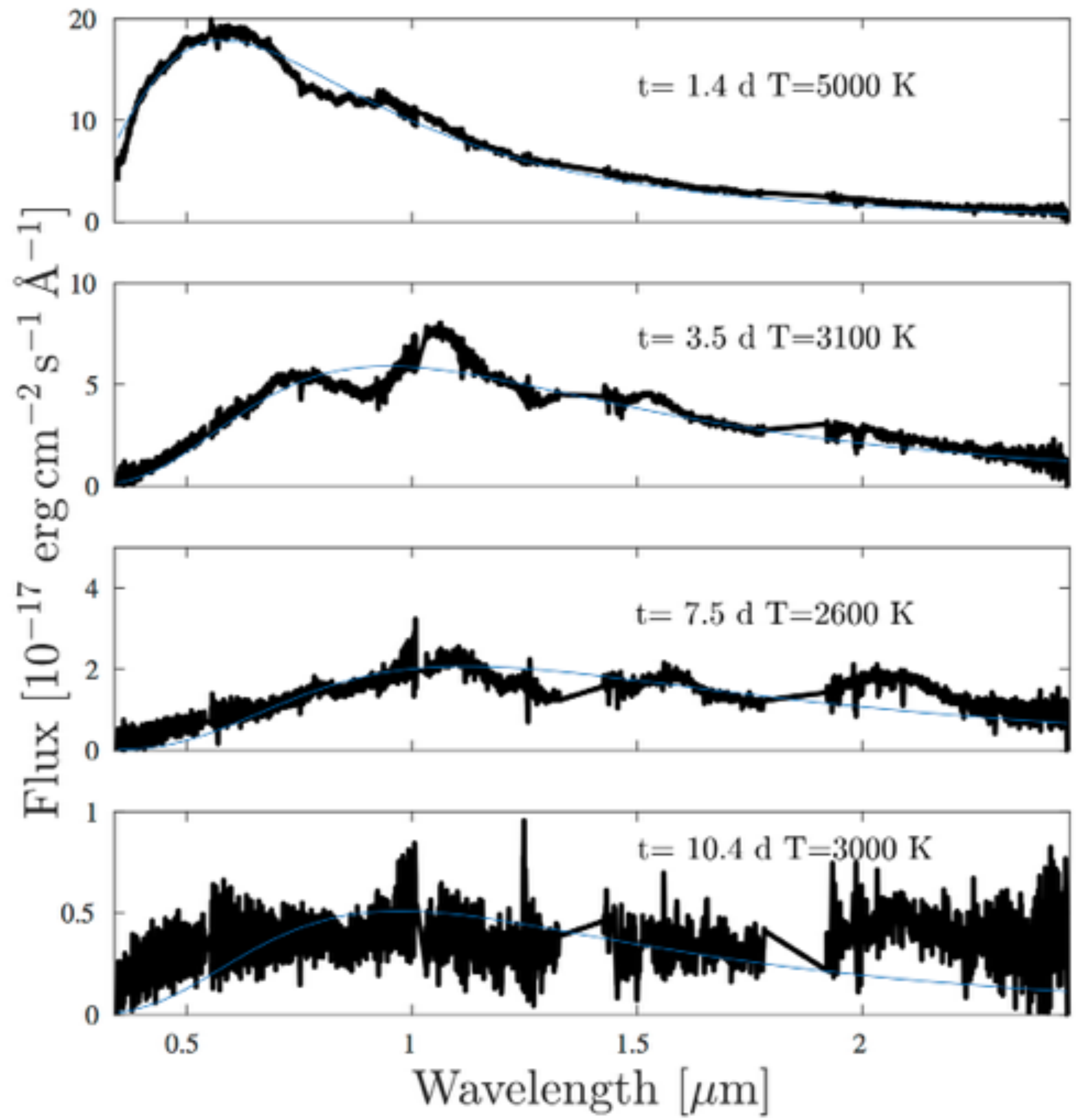
GW data analysis gave a constraint on θ <~30°

Spectra

Our model



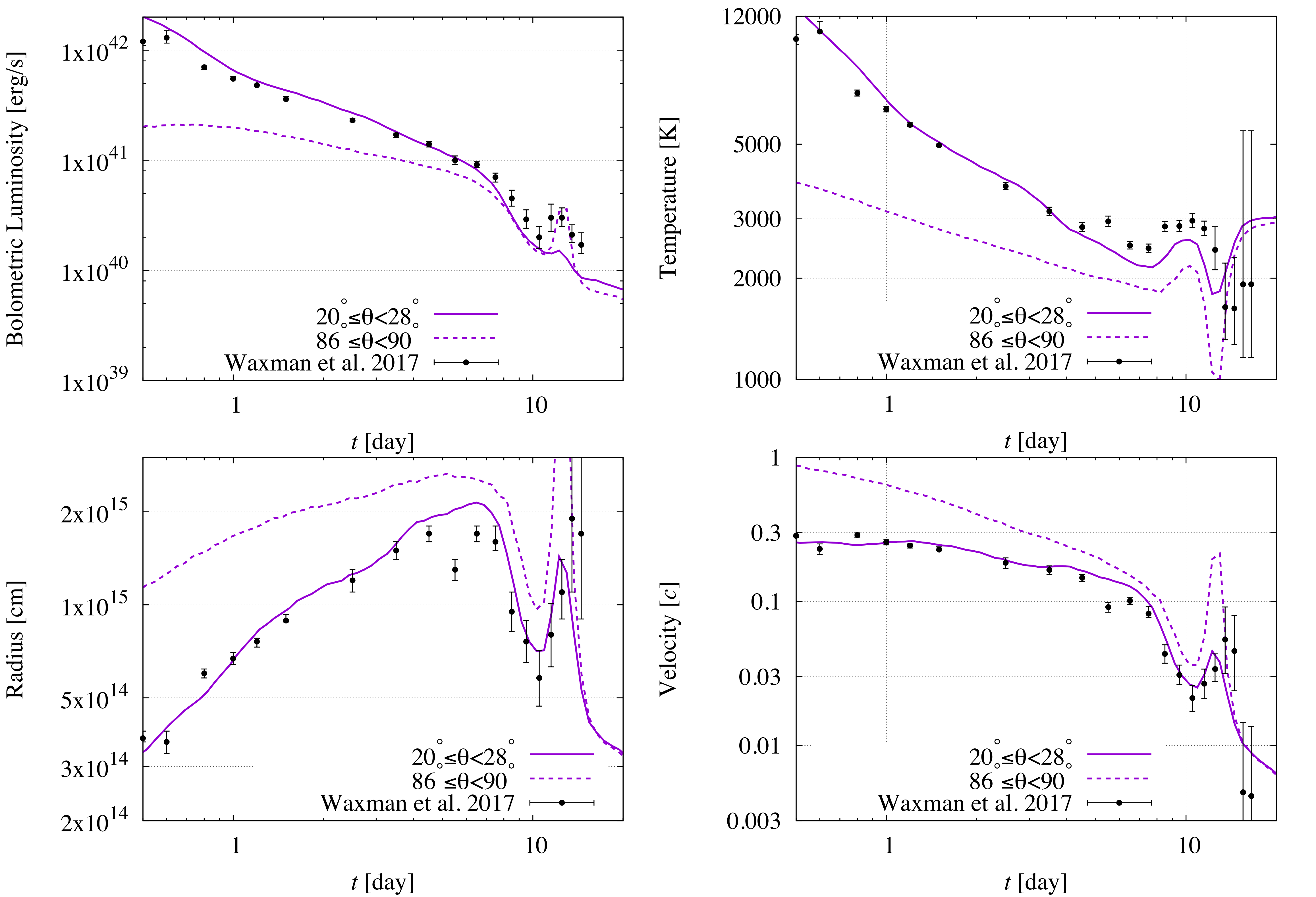
Observation



Ref: Waxman et al. 2017

Photospheric quantities

$$L_{\rm bol} = 4\pi\sigma R_{\rm ph}^2 T_{\rm ph}^4 \qquad v_{\rm ph} = R_{\rm ph}/t$$



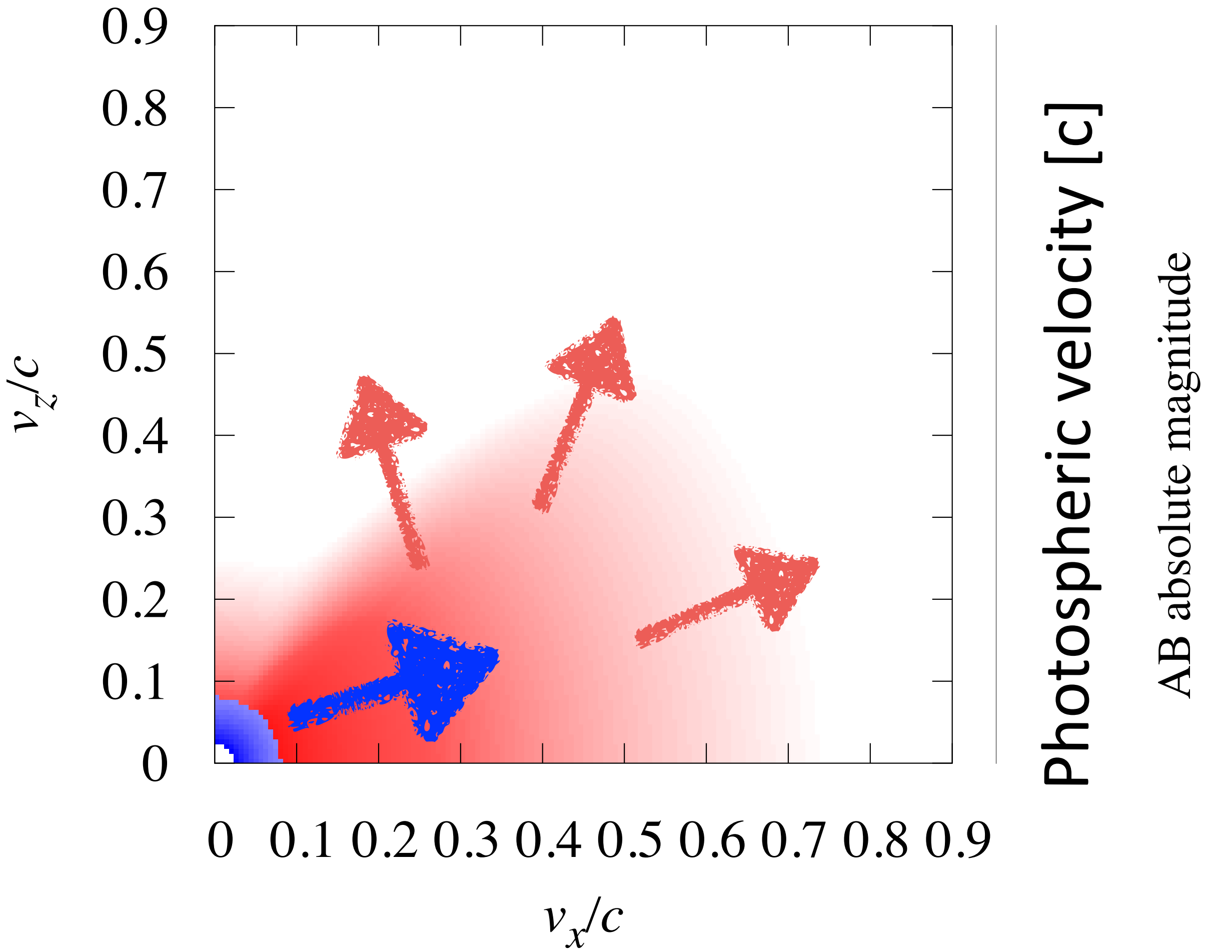
Important points

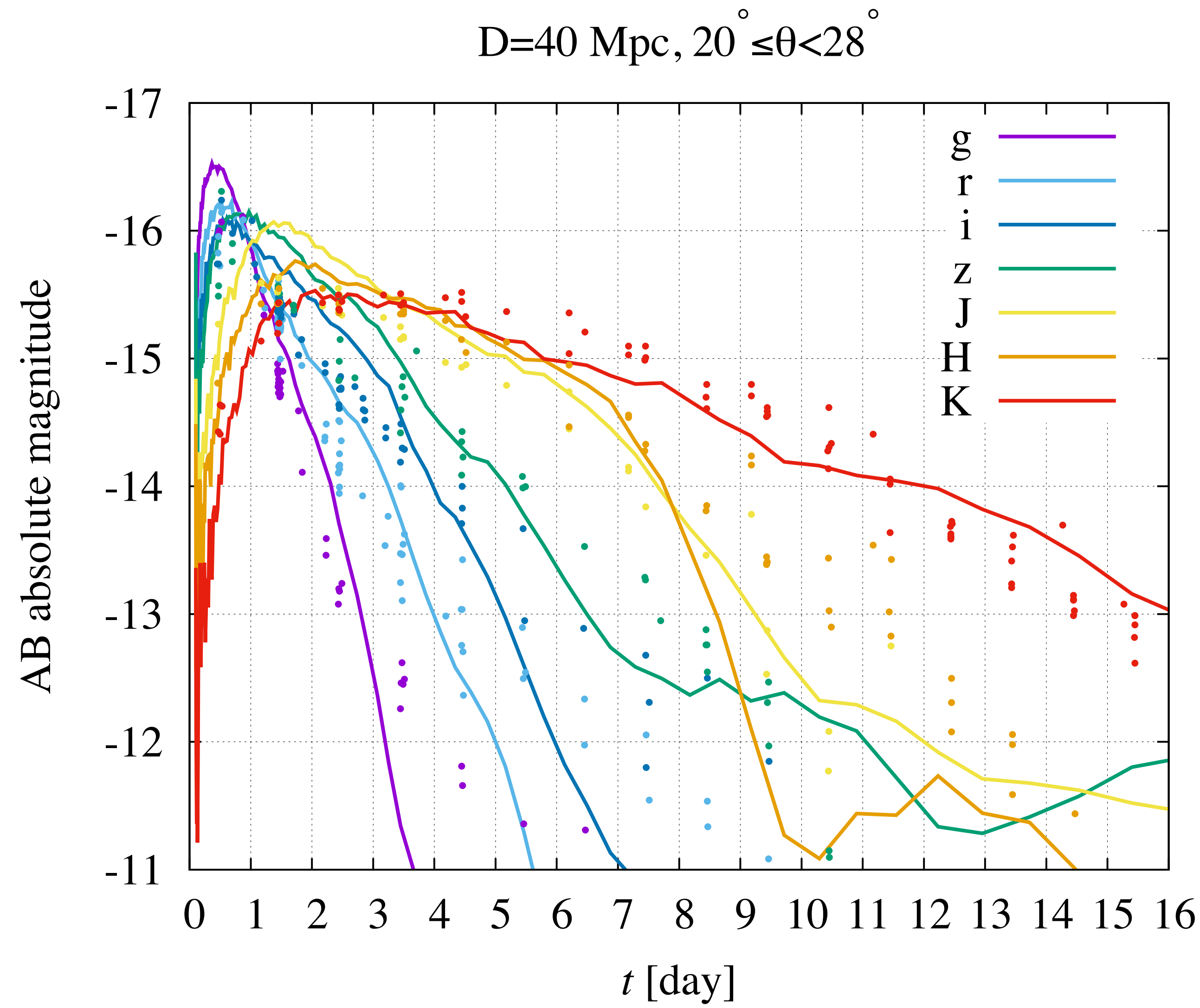
- **A smaller value of mass the dynamical ejecta (<~0.01 M_sun)** than previous studies is needed for reproducing the observed lightcurves, which agrees with the prediction of NR simulations

- **Velocity of the post-merger ejecta (~<0.05 c)** also agrees within the prediction of NR simulations

- **The total mass of ejecta is smaller** than the prediction of previous studies (~0.04-0.08 M_sun -> **~0.03 M_sun**)

Heating up of dynamical ejecta by post-merger ejecta

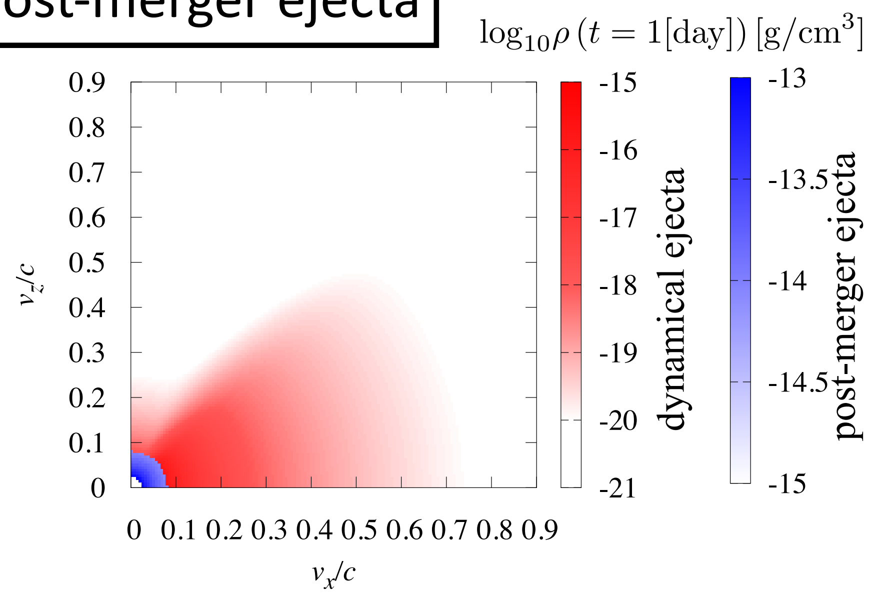




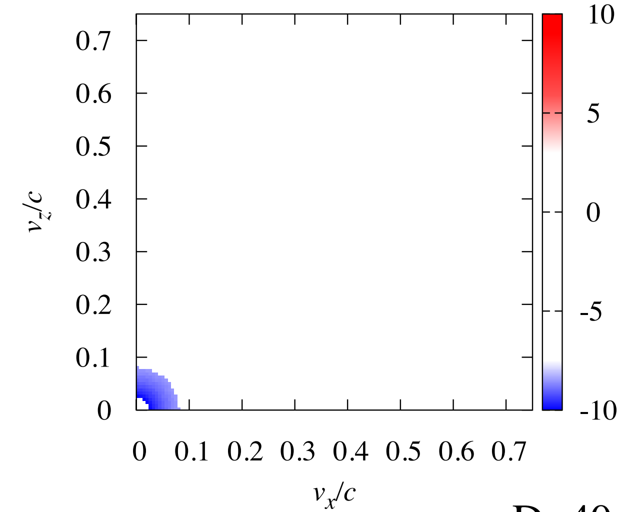
- post-merger ejecta irradiate and heat up the dynamical ejecta, and help the long-lasting NIR lightcurves to be reproduced by less massive dynamical ejecta (see also Perego et al. 2017)

Comparison with composited lightcurves

dynamical + post-merger ejecta

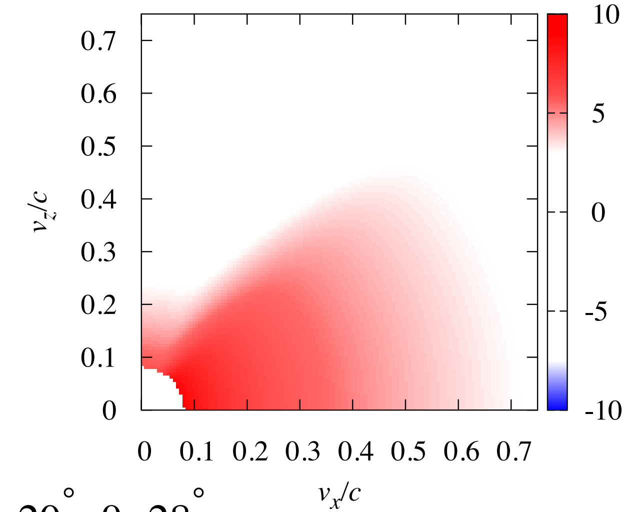


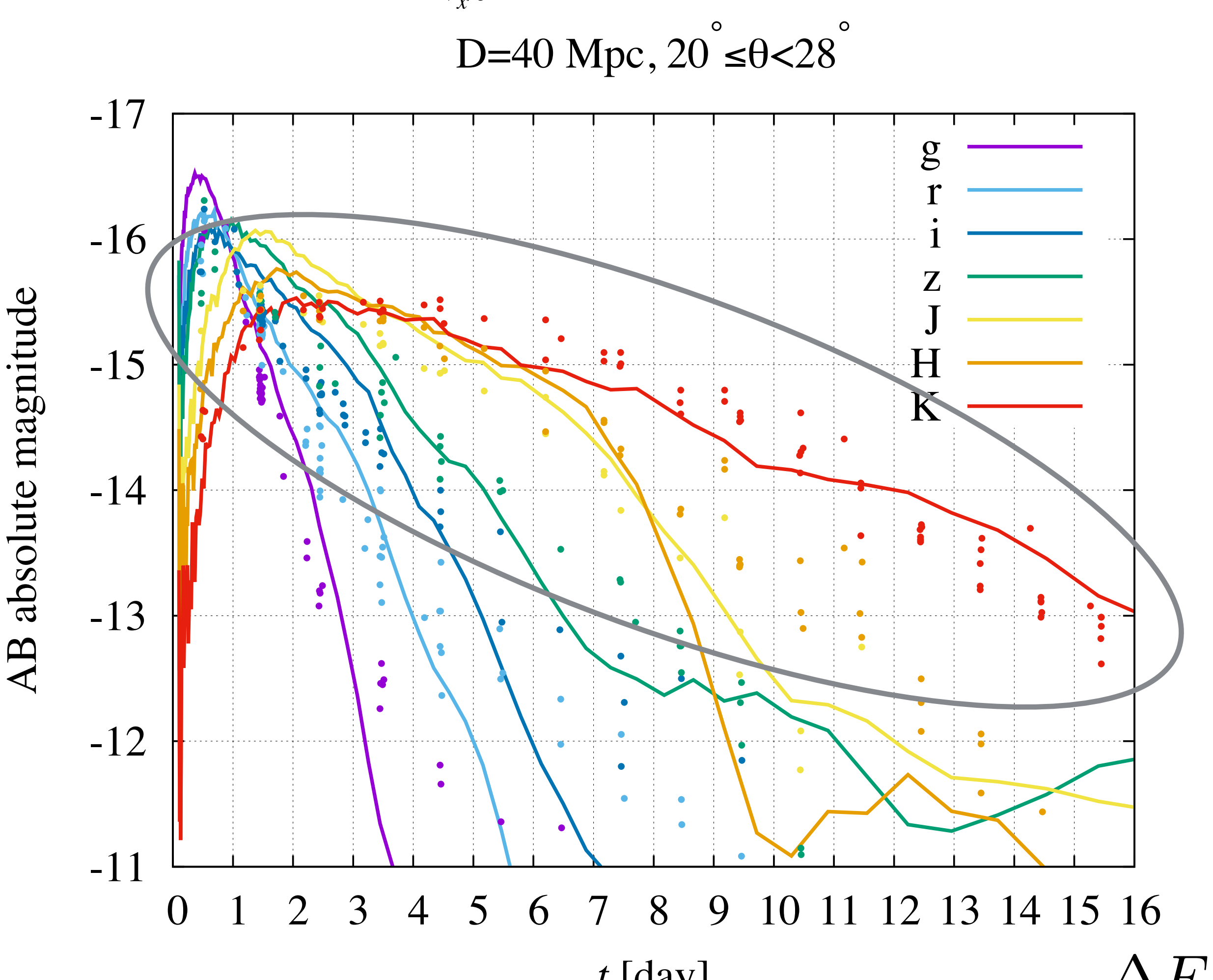
Only post-merger ejecta

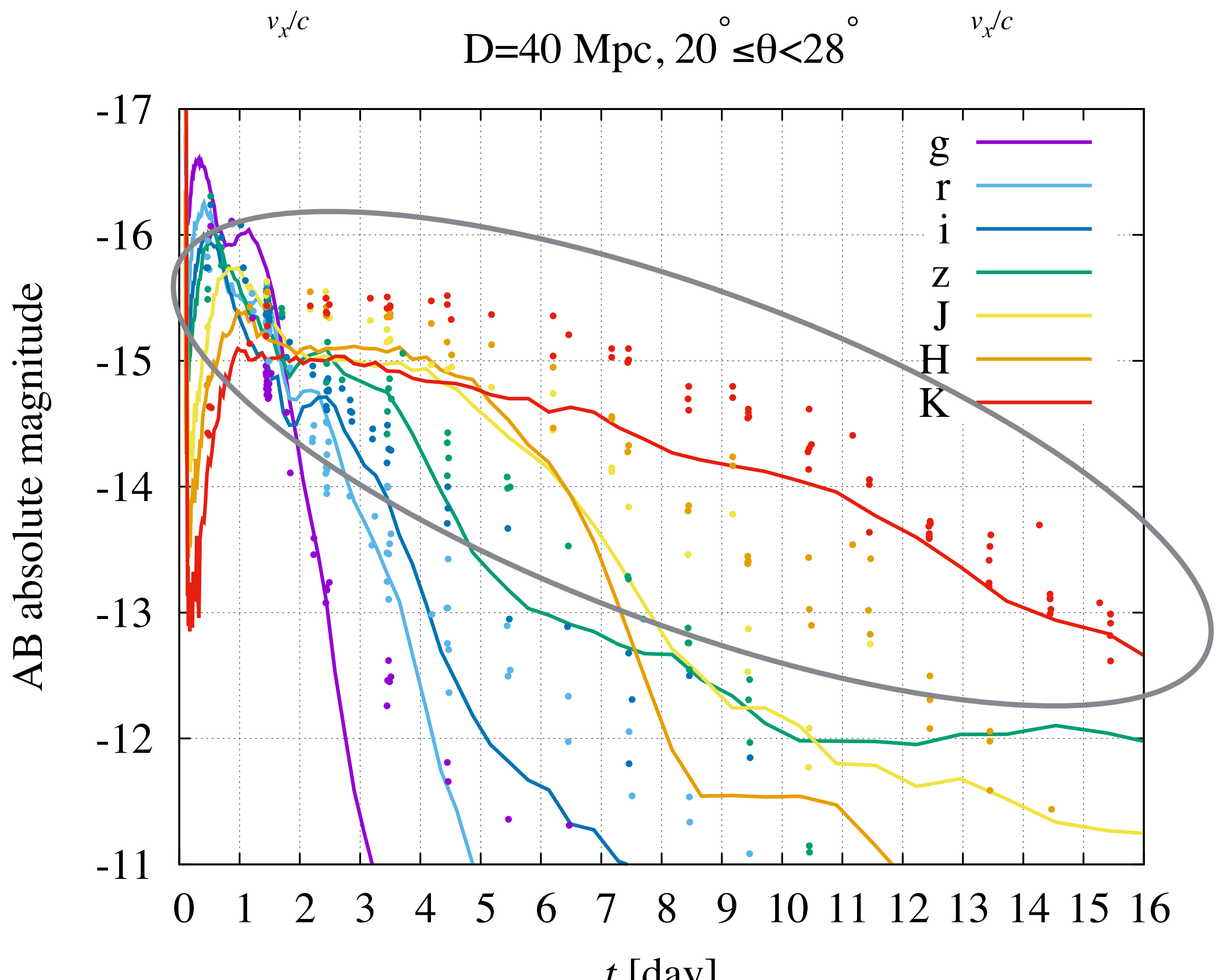


+

Only dynamical ejecta

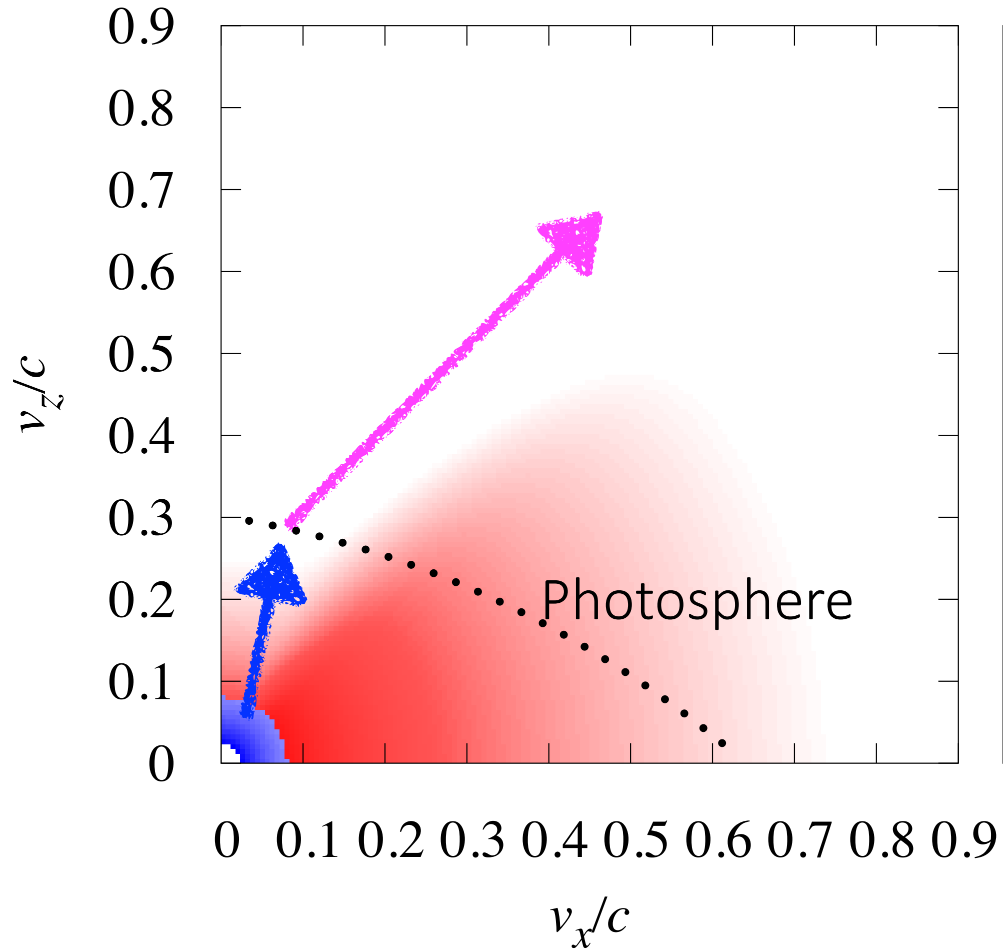


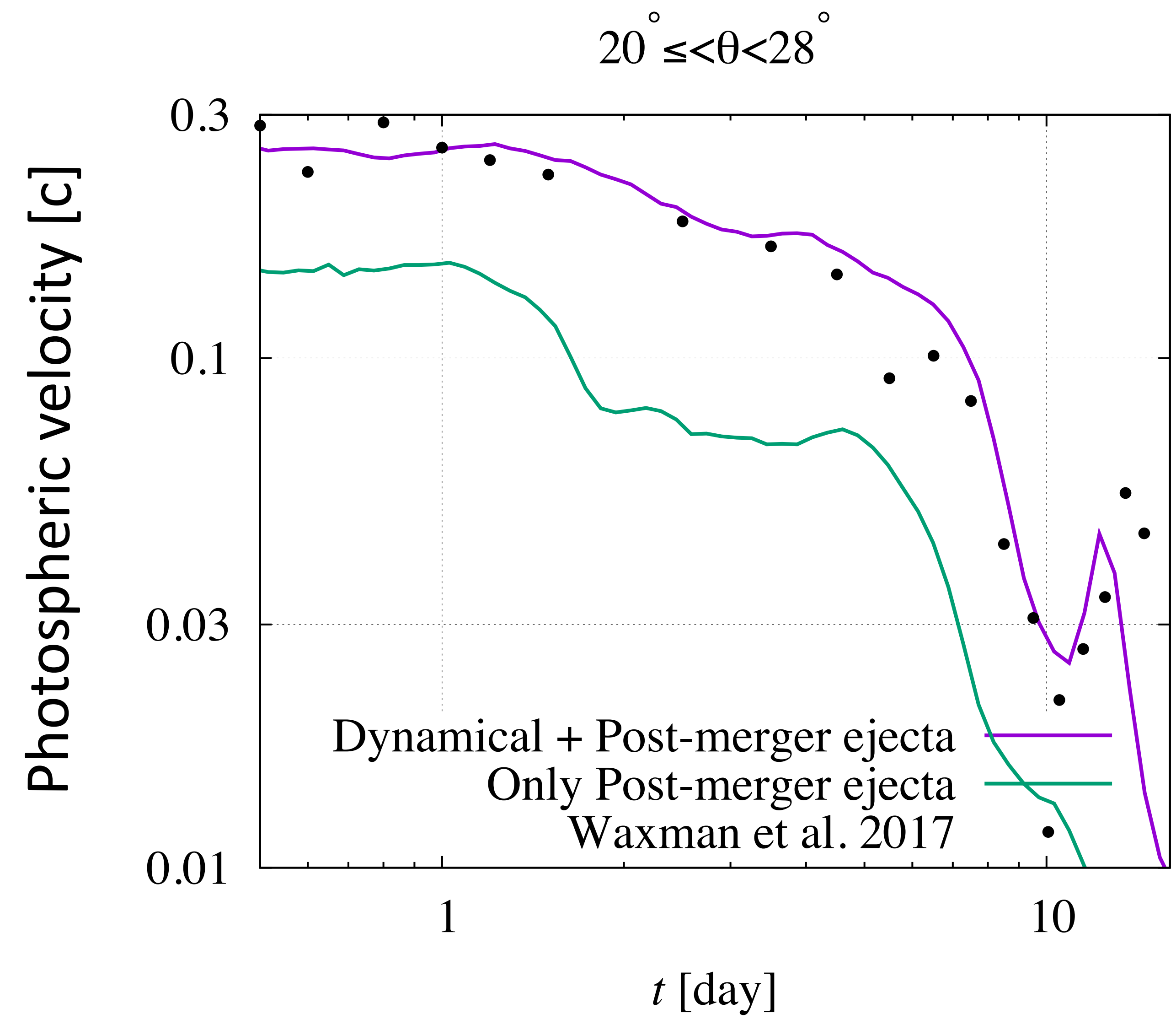




$$\Delta M = 1 \rightarrow \frac{\Delta F}{F} \approx 2.5\,(F:\text{energy flux})$$

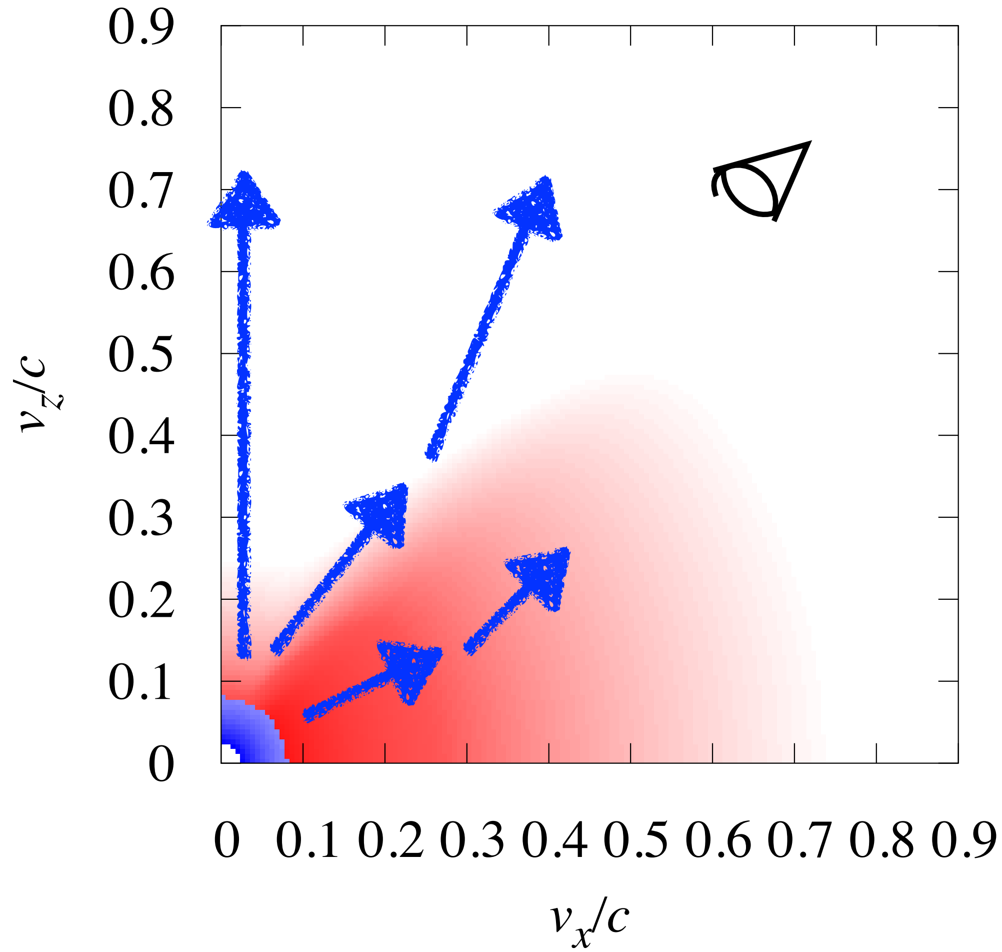
Enhancement of photospheric velocity

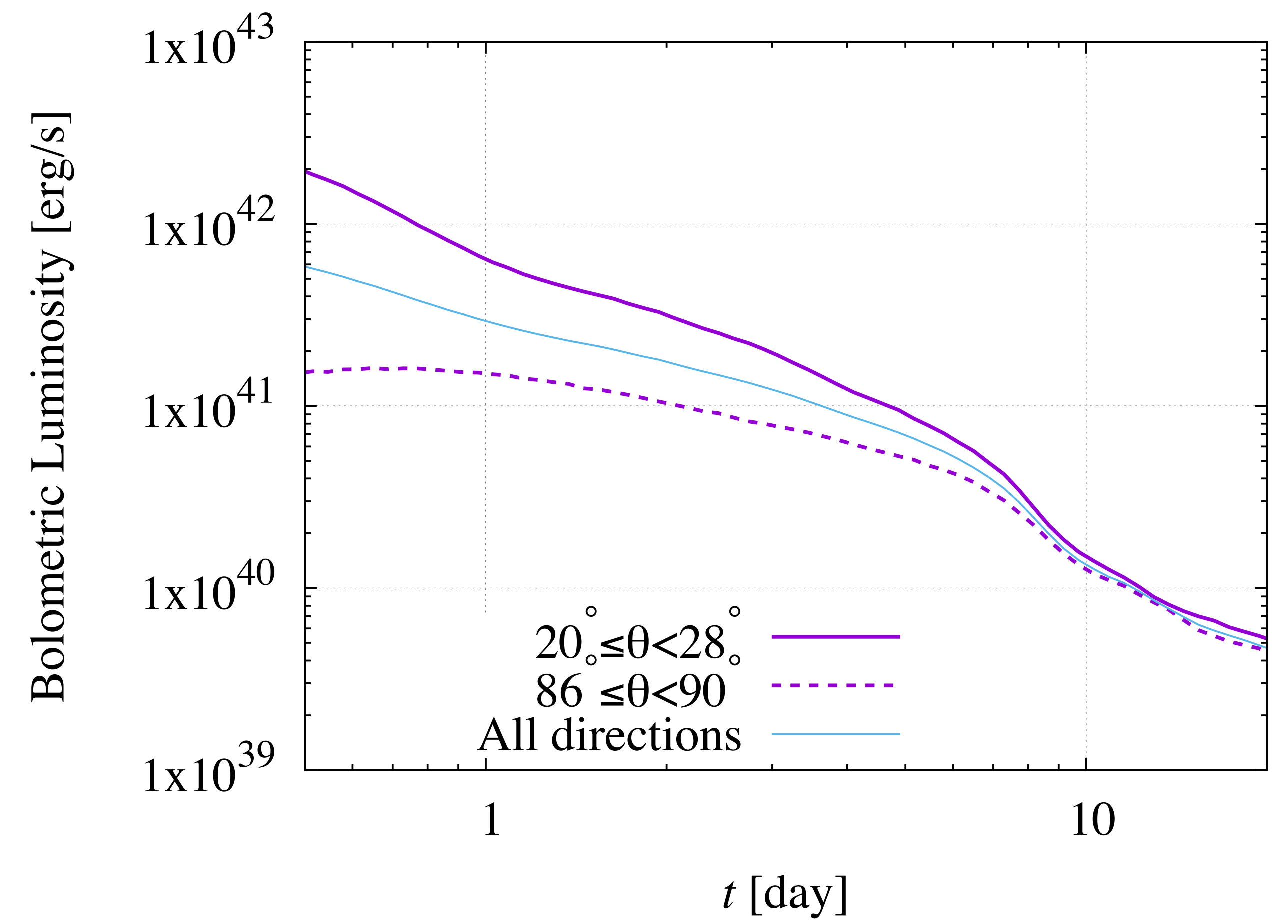




- The reprocess of photons in the dynamical ejecta helps the photospheric velocity to be enhanced

Angular dependence of photon diffusion





- Photons diffuse preferentially to the polar direction in the presence of the optically thick dynamical ejecta in the equatorial plane,
  and then, luminosity is effectively enhanced in the polar direction
  →less ejecta mass is required to reproduced observed (isotropic) luminosity

Summary

- We found that the optical and NIR lightcurves as well as photospheric velocity of SSS17a are reproduced by the ejecta model which is within the prediction of NR simulations, and thus, there is no tension between the prediction of numerical-relativity simulations and the observation of SSS17a

- The interplay of the multiple non-spherical ejecta components via photons plays a key role for the kilonova/macronova lightcurves.

- Our model can be examined by the kilonova/macronova observed from different inclination (for BNS with similar total mass)

Future work

- Variations of Kilonova/macronova lightcurves should be studied:
  ex) smaller total mass system, a black hole-neutron star merger,
  central engine models

- Systematic & Quantitative study varying ejecta parameters, such as the masses and velocity of dynamical and post merger ejecta, are needed to understand the variety of kilonova/macronova lightcurves

- Combined analysis of gravitational waves and kilonova/macronova lightcurves (+other EMs)

  Gravitational waves → total mass, inclination, tidal deformability
  Electromagnetic waves → ejecta mass, Ye (weak process) information

Toward rapid KN prediction: Gaussian Process Regression

RT Data sets (3×3×3=27 models)

$$M_{\rm post} = 0.01, 0.03, 0.05\, M_\odot$$
$$M_{\rm dyn,eq} = 0.001, 0.005, 0.01 (\times 0.72)\, M_\odot$$
$$M_{\rm dyn,polar} = 10^{-5}, 5\times 10^{-5}, 10^{-4} (\times 0.28)\, M_\odot$$

Check model

$$M_{\rm post} = 0.02\, M_\odot$$
$$M_{\rm dyn,eq} = 0.125\, (\times 0.72)\, M_\odot$$
$$M_{\rm dyn,polar} = 2.5\times 10^{-5}\, (\times 0.28)\, M_\odot$$

- Gaussian process regression model may be useful to interpolate the data point of RT simulations
- RT simulation ~1 Day /model → ~1 Minutes/model