GW170817: Modeling based on numerical relativity and its implication

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Outline

I. Brief introduction of GW170817

II. Scenarios of NS-NS merger

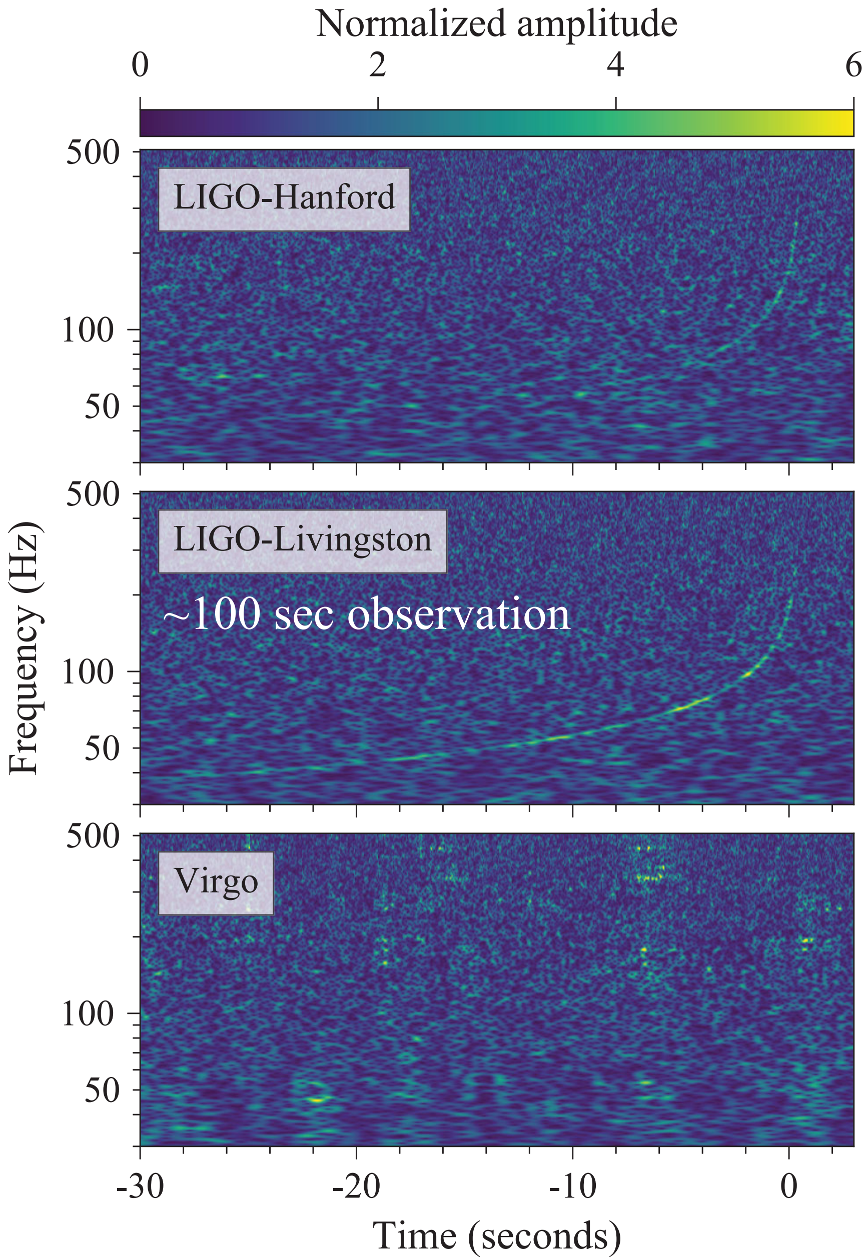
III. Mass ejection of GW170817

- Dynamical mass ejection
- Viscous ejection from merger remnants

IV. Interpreting EM counterparts of GW170817

V. Summary

I Brief introduction of GW170817



Chirp $M = m_1^{3/5} m_2^{3/5} (m_1 + m_2)^{-1/5}$

Key parameters in this talk:

- Chirp mass = $1.188^{+0.004}_{-0.002}\ M_{sun}$
  → **Total mass = 2.73—2.78 M_{sun}**
  (90%CL, reasonable spin assump.)

  → **Binary neutron stars**

- Assuming reasonable spin of NSs,
  Mass ratio = 0.7—1.0 (90% CL)
  → **Not very asymmetric**
- **Viewing angle < ~30°**
- **Tidal deformability < 800**
  → NS radius < 13.5 km

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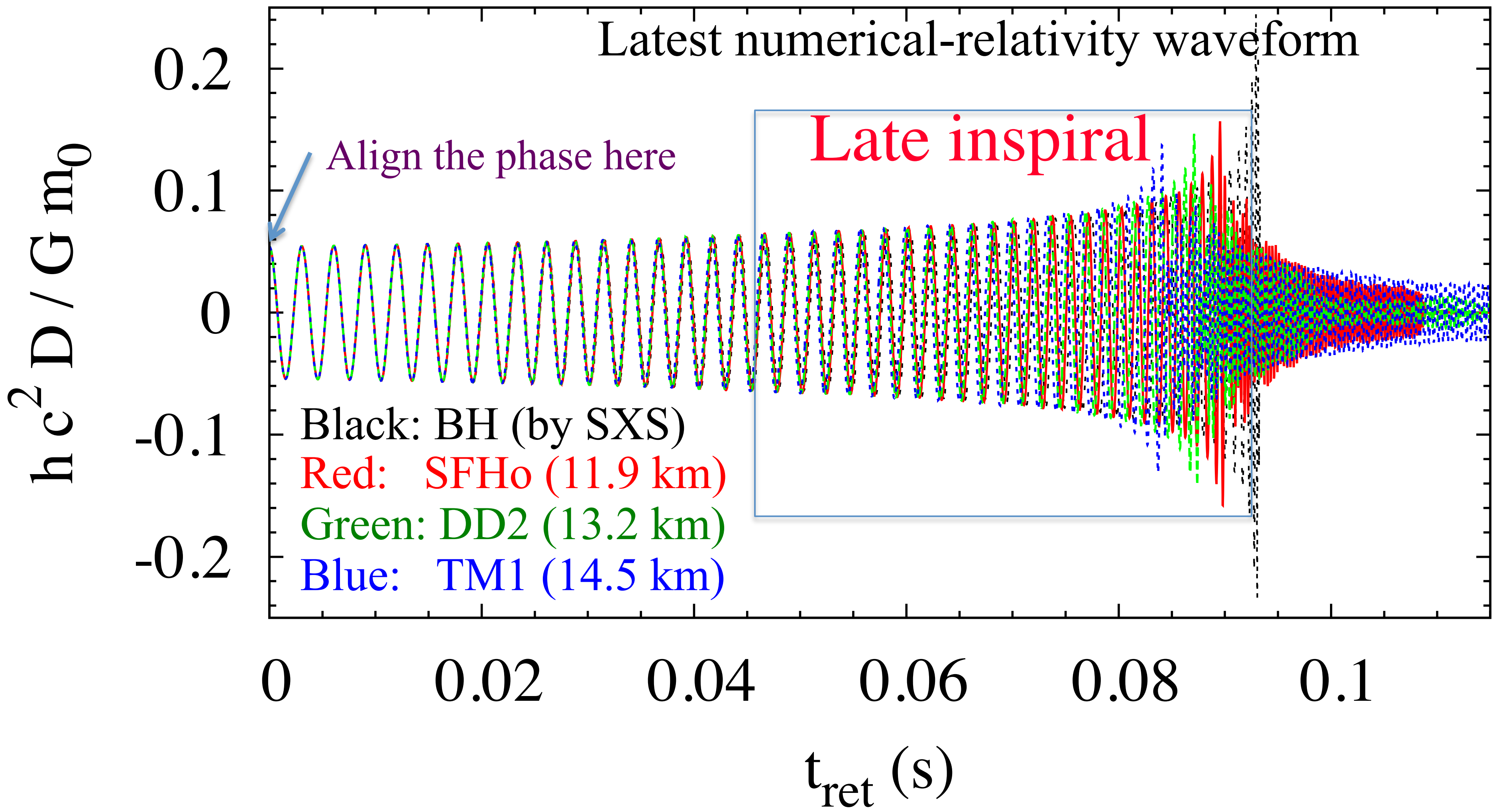
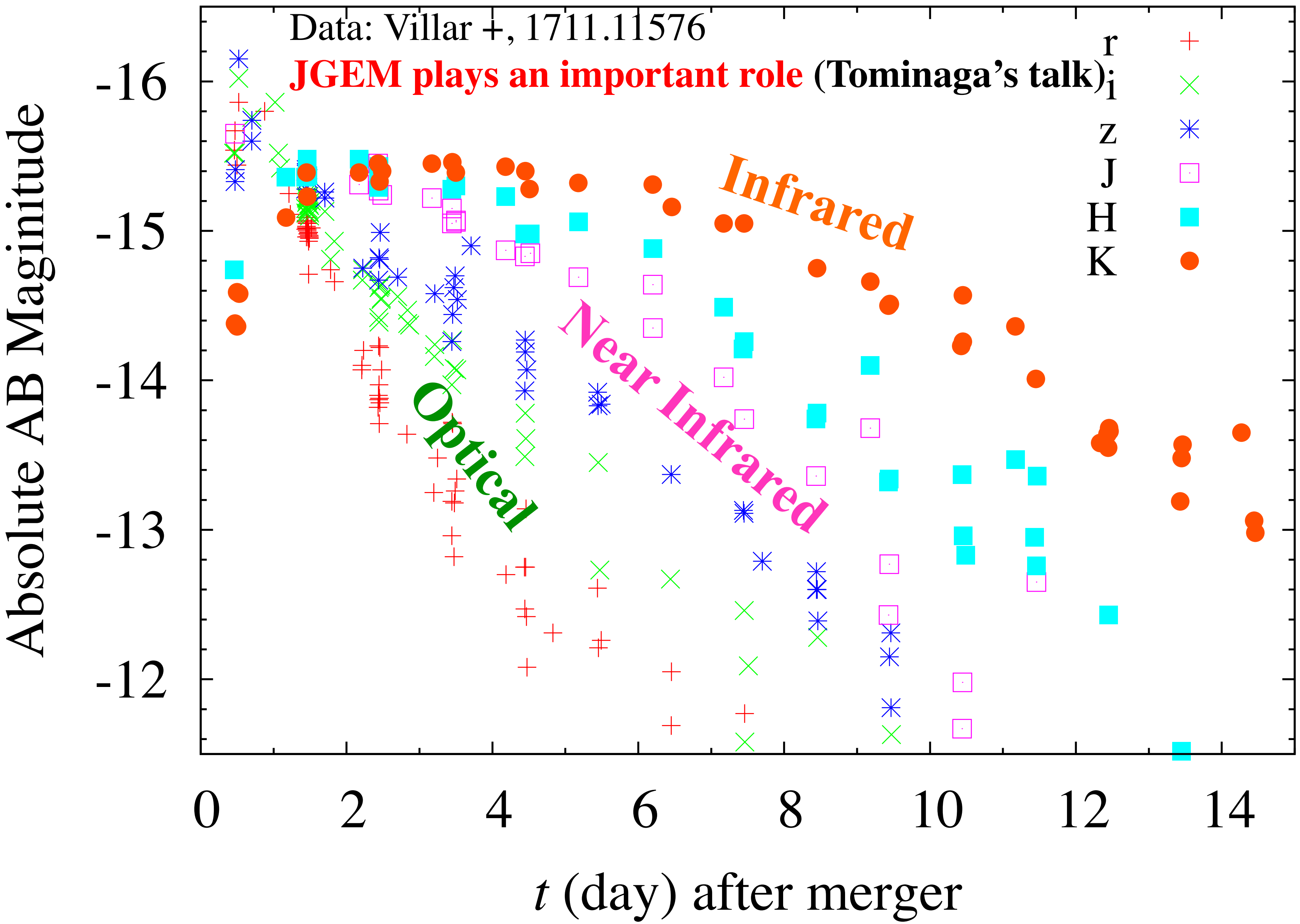
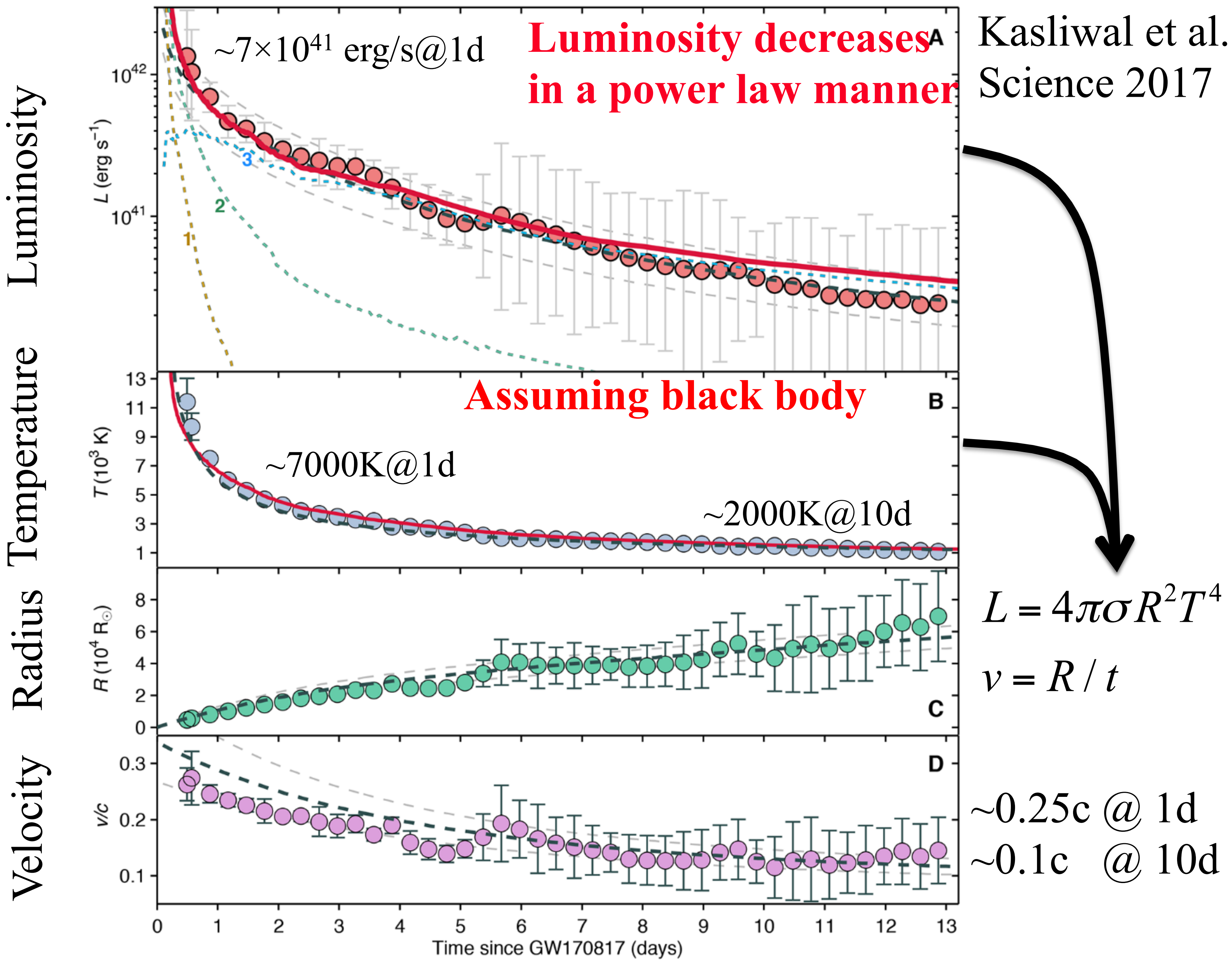
Gravitational waveform from NS-NS:
(1.35-1.35 solar mass)



Hotokezaka et al. 2016 (Bernuzzi et al., Kiuchi et al. 2017,…)

Optical-IR EM counterparts of GW170817

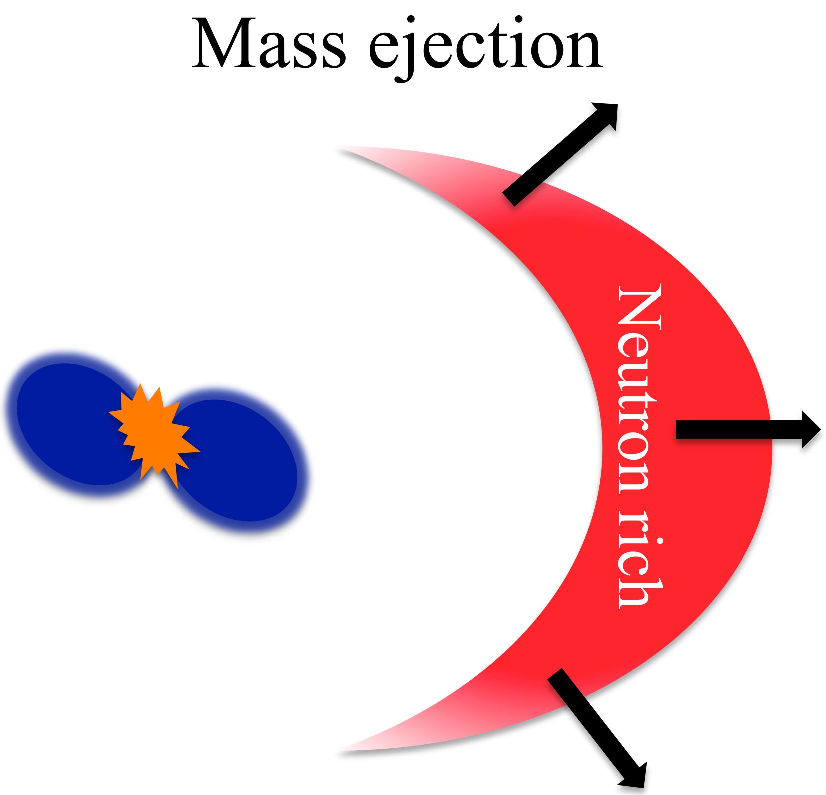




Luminosity
Temperature
Radius
Velocity
~7×10^41 erg/s@1d
Luminosity decreases
in a power law manner
Assuming black body
~7000K@1d
~2000K@10d
A
B
C
D
L (erg s^-1)
T (10^3 K)
R (10^4 R_☉)
v/c
Time since GW170817 (days)
Kasliwal et al.
Science 2017
$L = 4\pi\sigma R^2 T^4$
$v = R / t$
~0.25c @ 1d
~0.1c @ 10d

Consistent with Kilonova/Macronova model

(Li-Paczyski 1998, Metzger et al. 2010)



Neutron rich ejecta

$$\tau_{n-\mathrm{capture}} < \tau_{\beta-\mathrm{decay}}$$

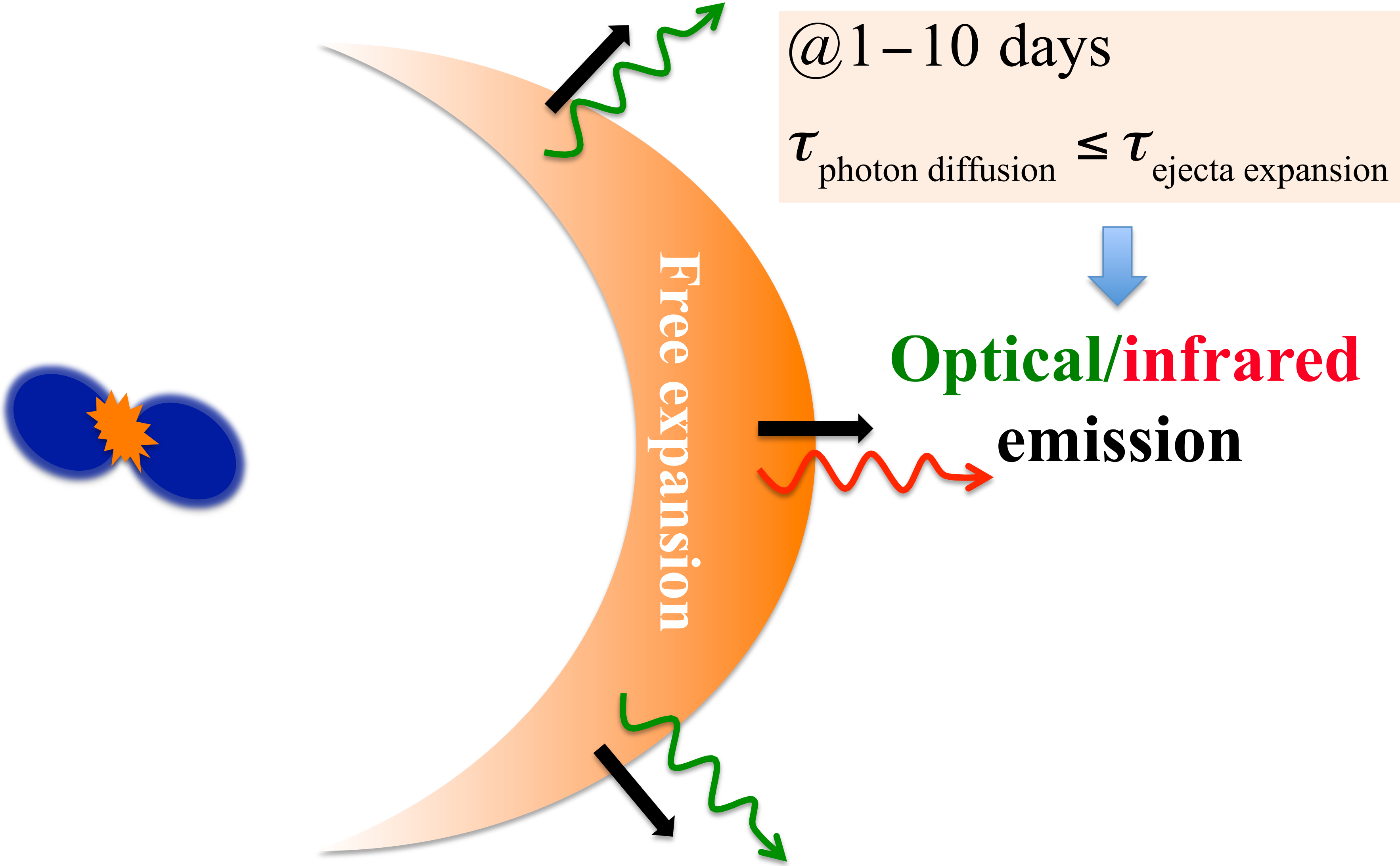
→ **r-process nucleosynthesis**

Decay of unstable nuclei
→ Heating

But, in the early phase,
optically thick
→ Consumption via
adiabatic expansion

Consistent with Kilonova/Macronova model

(Li-Paczynski 1998, Metzger et al. 2010)



Peak luminosity & time of macronova/kilonova

(Li-Paczyski 1998, Metzger et al. 2010)

10^{-6} at ~ 1 day:
Depends on time

$$\tau_{\text{photon diffusion}} \sim \tau_{\text{ejecta expansion}}$$

$$L_{\text{peak}} \sim 2\times 10^{41}\ \text{ergs/s}\left(\frac{M}{0.01 M_\odot}\right)^{1/2}\left(\frac{v}{0.2c}\right)^{1/2}\left(\frac{\kappa}{1\ \text{cm}^2/\text{g}}\right)^{-1/2}\left(\frac{f_{\text{r-proc}}}{1\times 10^{-6}}\right)$$

$$\text{at}\quad t \sim 1\ \text{days}\left(\frac{M}{0.01 M_\odot}\right)^{1/2}\left(\frac{v}{0.2c}\right)^{-1/2}\left(\frac{\kappa}{1\ \text{cm}^2/\text{g}}\right)^{1/2}$$

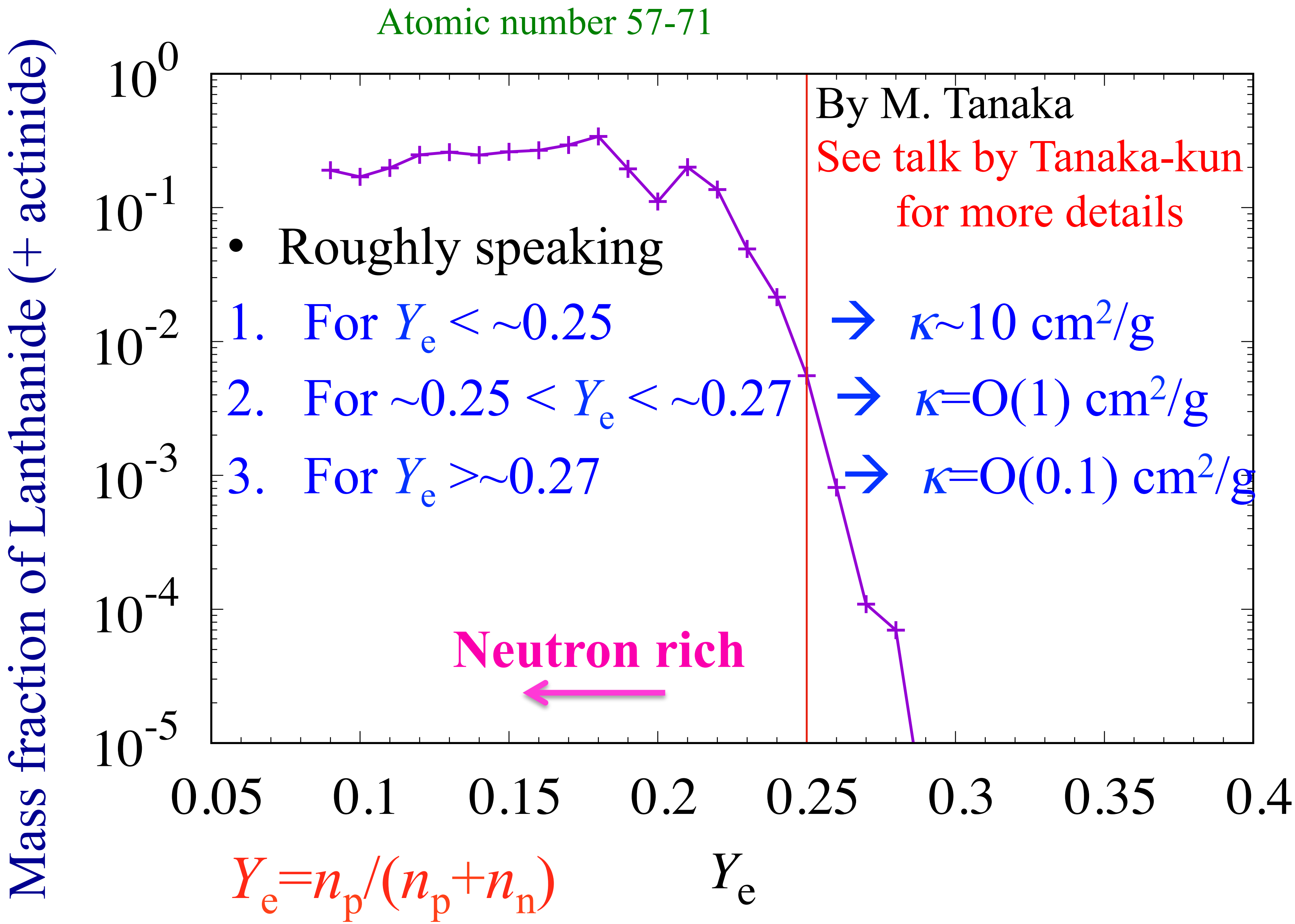
Qualitatively agree with GW170817 but not quantitatively

Depend on ejecta mass, velocity, opacity

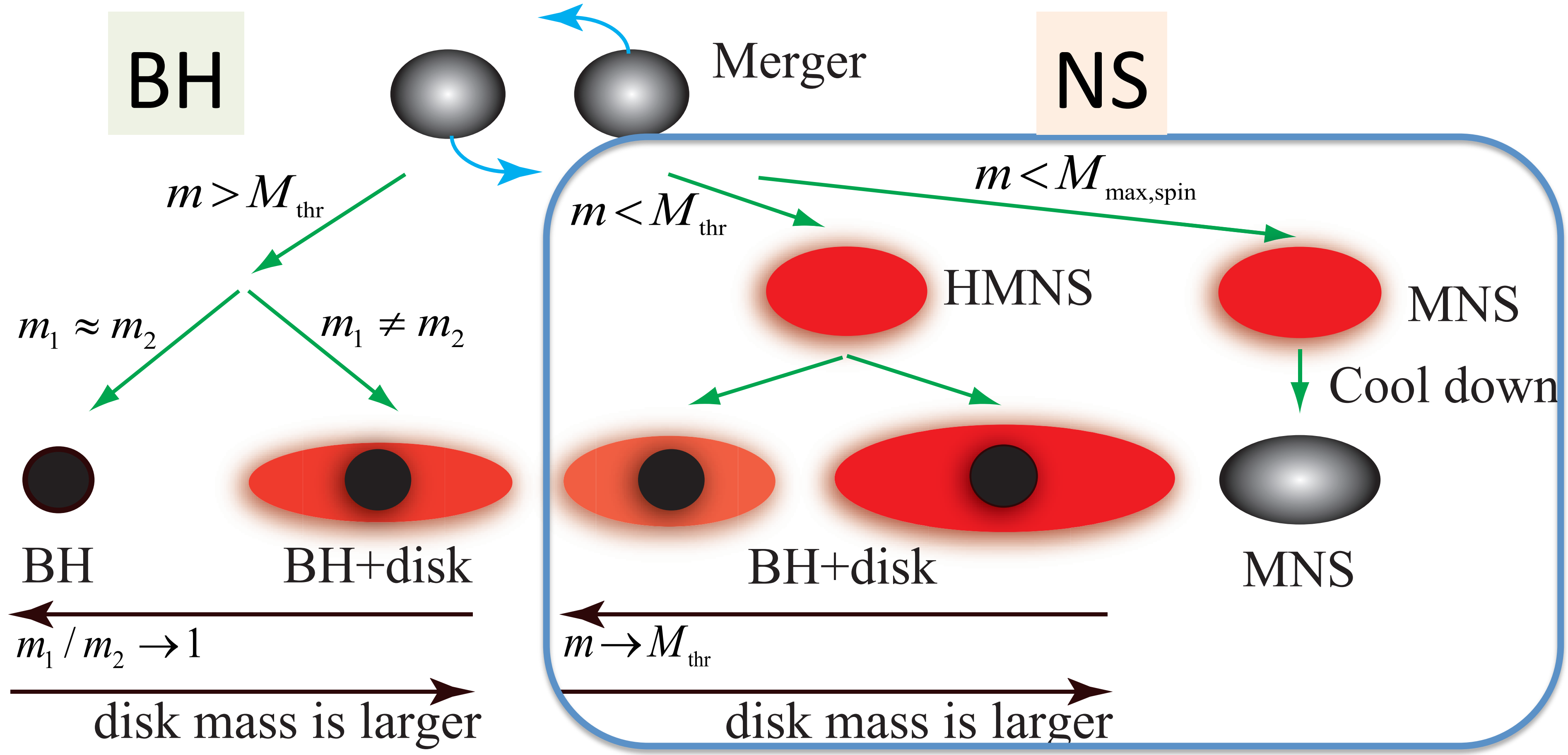
Uncertainty of opacity: ~ 2 orders of magnitude which is determined by *lanthanide fraction*

(See talk by M. Tanaka for more details)

Fraction of lanthanides vs electron fraction



II Scenarios of NS-NS mergers in NR



NR simulations with EOS of M_{max}>2M_{sun}
→ Likely for M_{tot}< ~2.8M_{sun}

Total mass of GW170817 is 2.73—2.78 M_{sun} (90%CL)

Mass ejection history for MNS formation

Time after merger

0 10 100 1000 ms

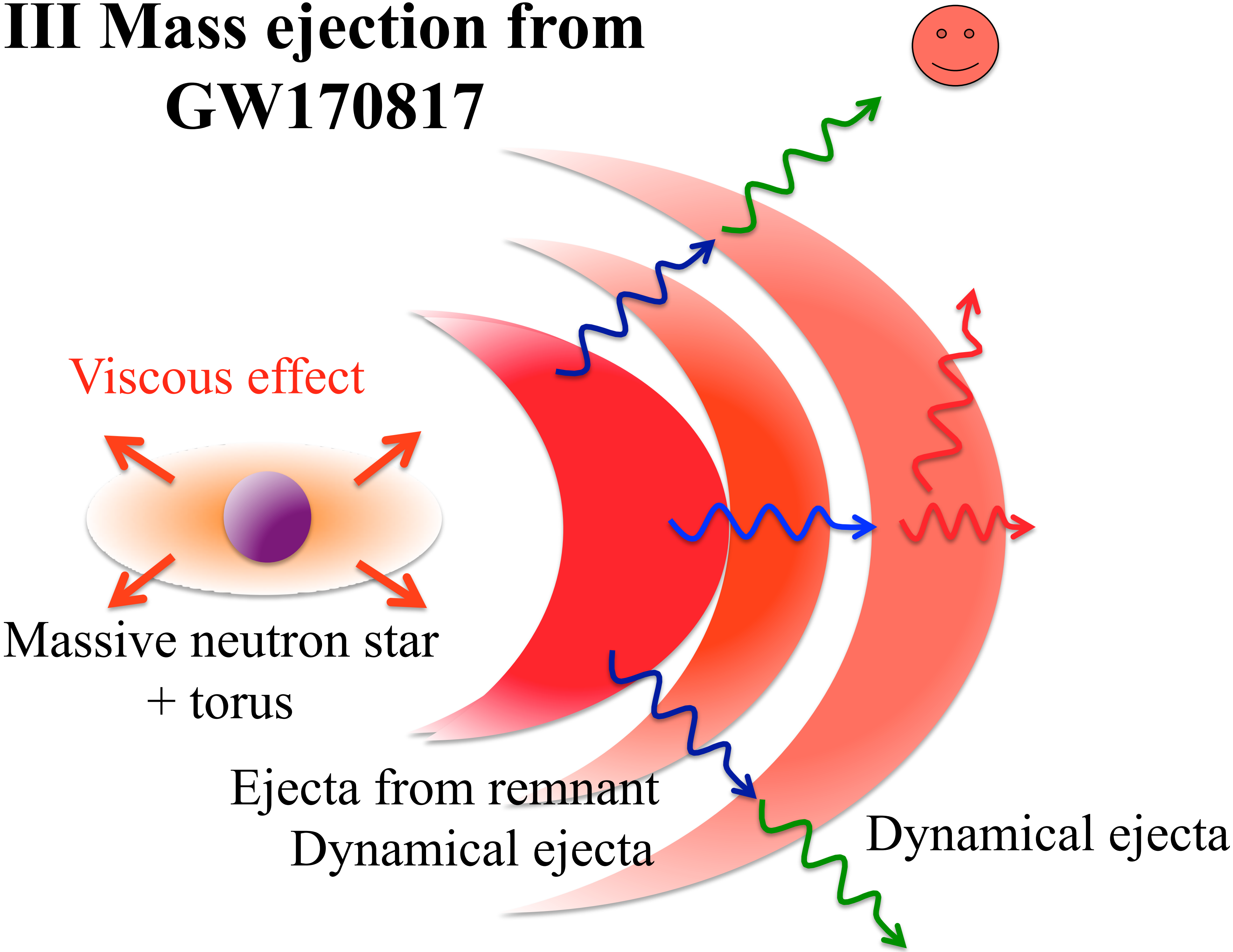
Dynamical ejection
(determined by dynamical timescale of NS)

MHD/viscous ejection
(by viscous timescale of remnant)

MNS BH

Neutrino irradiation (for neutrino emission timescale)
Minor effects on mass ejection
but play a crucial role for **determining Y_e**

III Mass ejection from GW170817

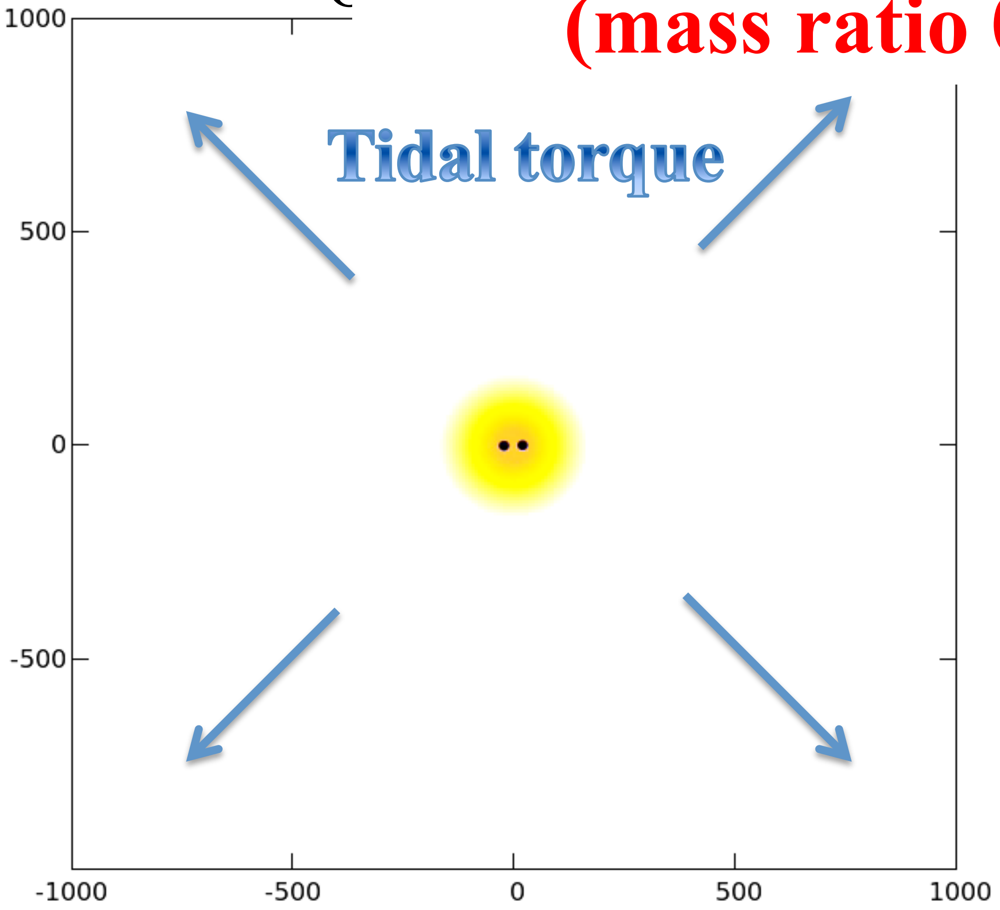


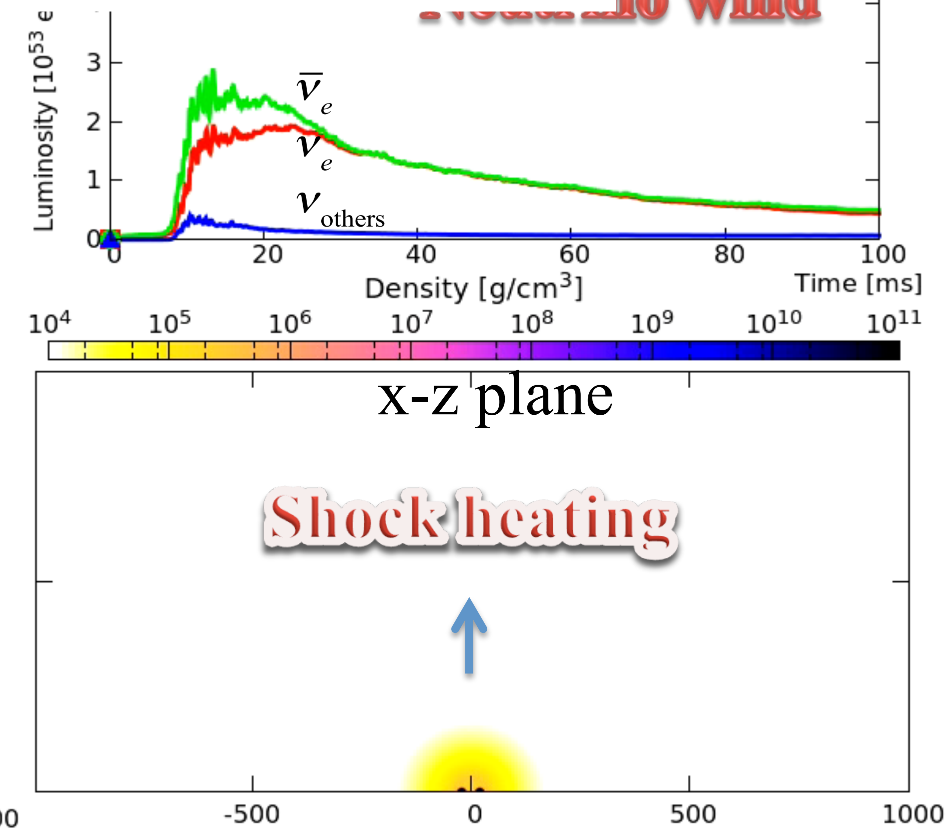
1 Neutrino-radiation hydro for dynamical ejecta

Sti n

Total mass ~ 0.001—0.01 M_{sun} depending on EOS & each mass (mass ratio 0.8—1.0)

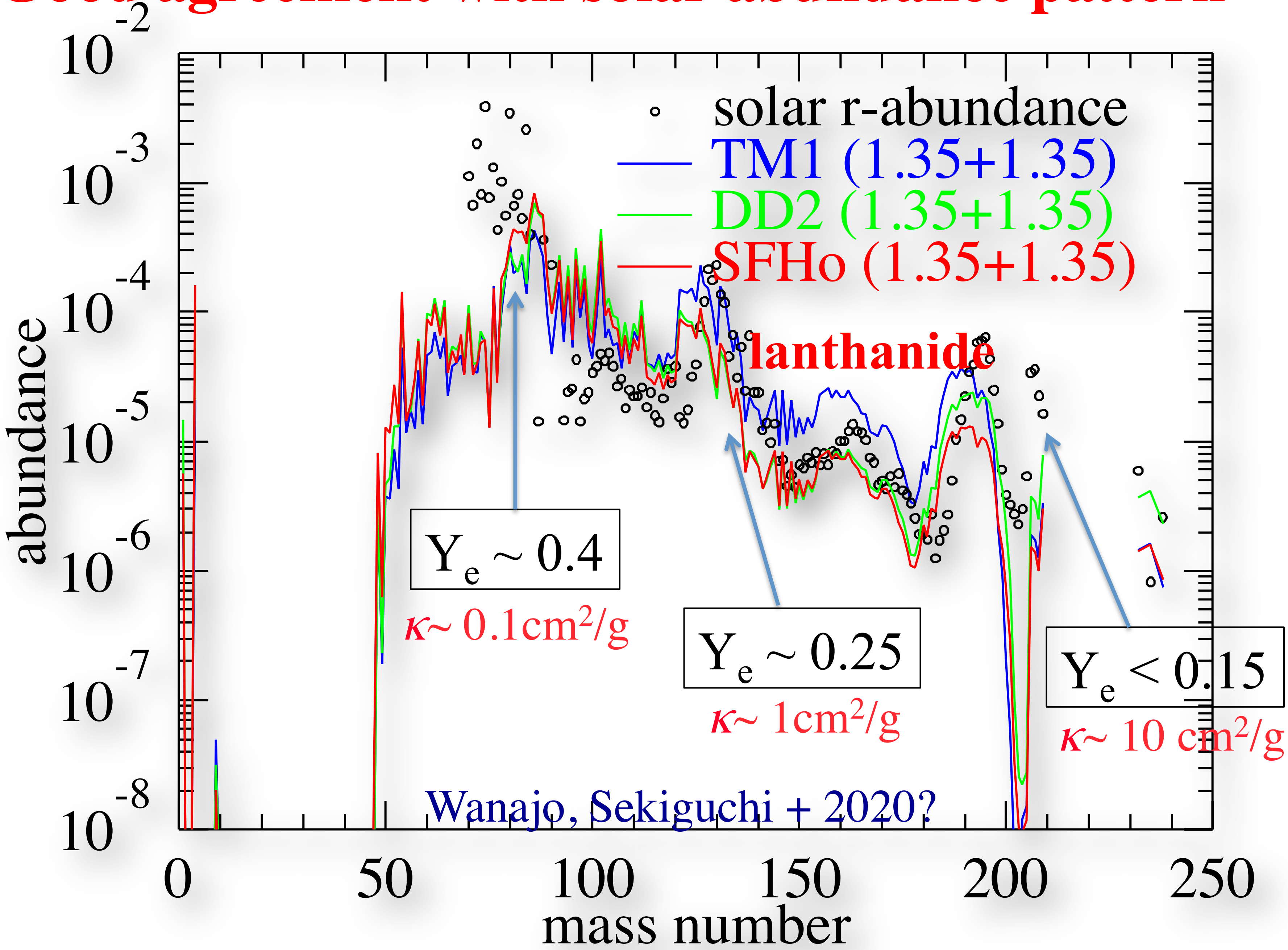
C luminosity





Sekiguchi et al. 2016

Good agreement with solar abundance pattern



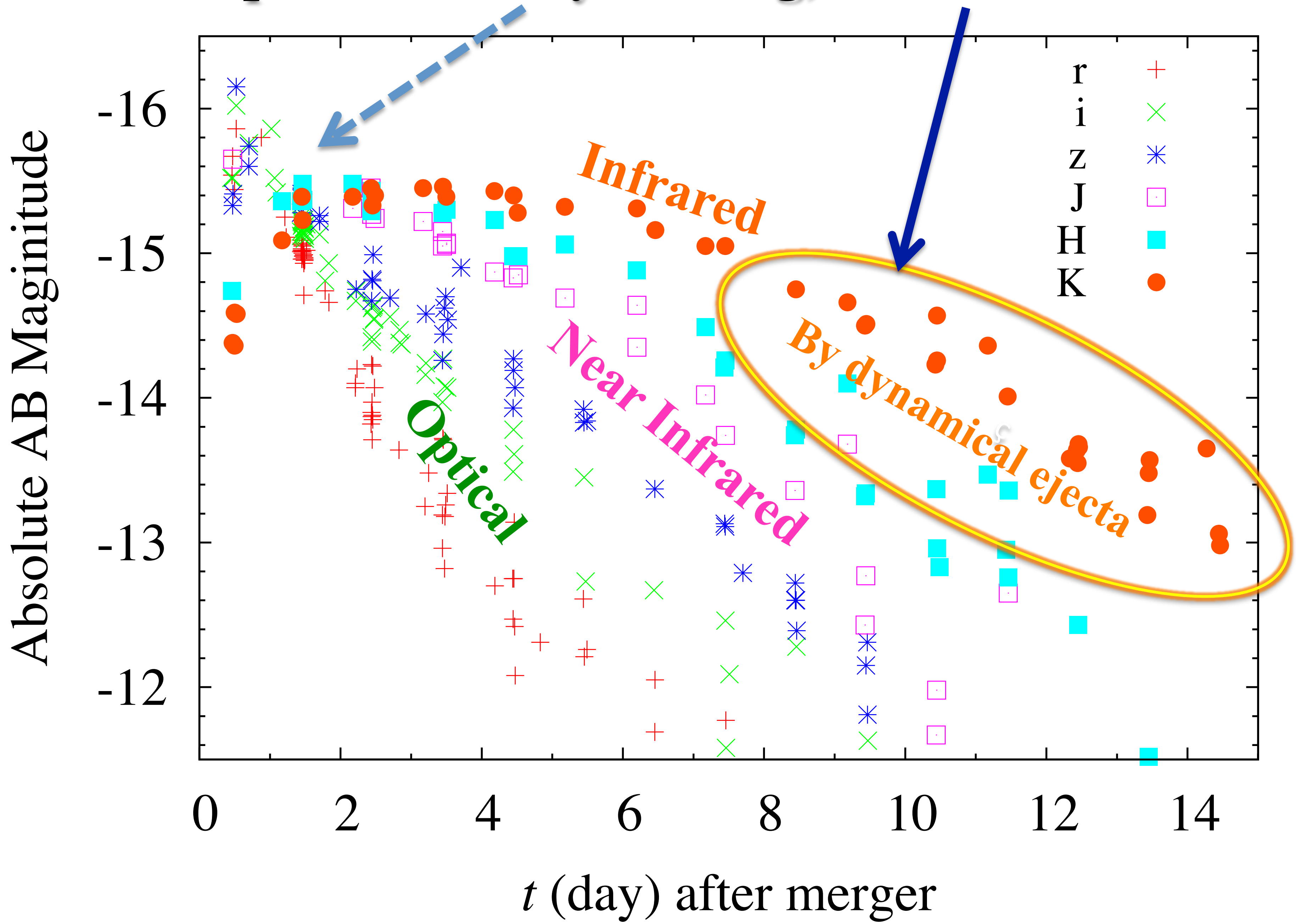
Properties of dynamical ejecta for NS-NS

- Very good for r-process nucleosynthesis but
  → $\boxed{\kappa \sim 10\ \mathrm{cm}^2/\mathrm{g}}$: large value
- **Mass**: ~ 0.001—$0.01\ M_{sun}$
- **"Average" velocity**: 0.15—0.25c

$$L_{\max} \sim \underbrace{1\times 10^{41}\ \mathrm{ergs/s}}_{\textbf{dim}} \left(\frac{M}{0.01 M_\odot}\right)^{1/2} \left(\frac{v}{0.2c}\right)^{1/2} \left(\frac{\kappa}{10\ \mathrm{cm}^2/\mathrm{g}}\right)^{-1/2} \left(\frac{f_{\text{r-proc}}}{10^{-6}}\right)$$

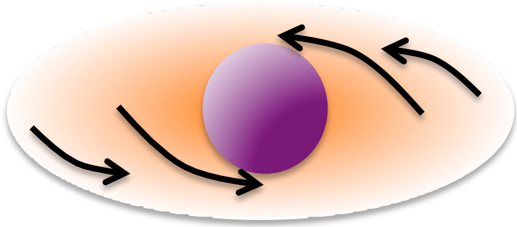
$$\text{at } t \sim \underbrace{3.5\ \mathrm{days}}_{\textbf{late}} \left(\frac{M}{0.01 M_\odot}\right)^{1/2} \left(\frac{v}{0.2c}\right)^{-1/2} \left(\frac{\kappa}{10\ \mathrm{cm}^2/\mathrm{g}}\right)^{1/2}$$

Cannot reproduce early shining, but late infrared



2 Mass ejection from merger remnant

- Realistic remnants = **Magnetized massive NS + torus in differential rotation**



→ **MHD turbulence**

→ Viscous hydrodynamics effect plays an important role

→ **Viscous radiation hydrodynamics simulation**
(Fujibayashi et al. ApJ ‘18)

Viscous-rad hydrodynamics for post-merger MNS

(S. Fujibayashi et al. ApJ 2018)

Rest-mass density α_{ν}=0.04

$M \sim 0.05$ solar mass, $v \sim 0.05\, c$

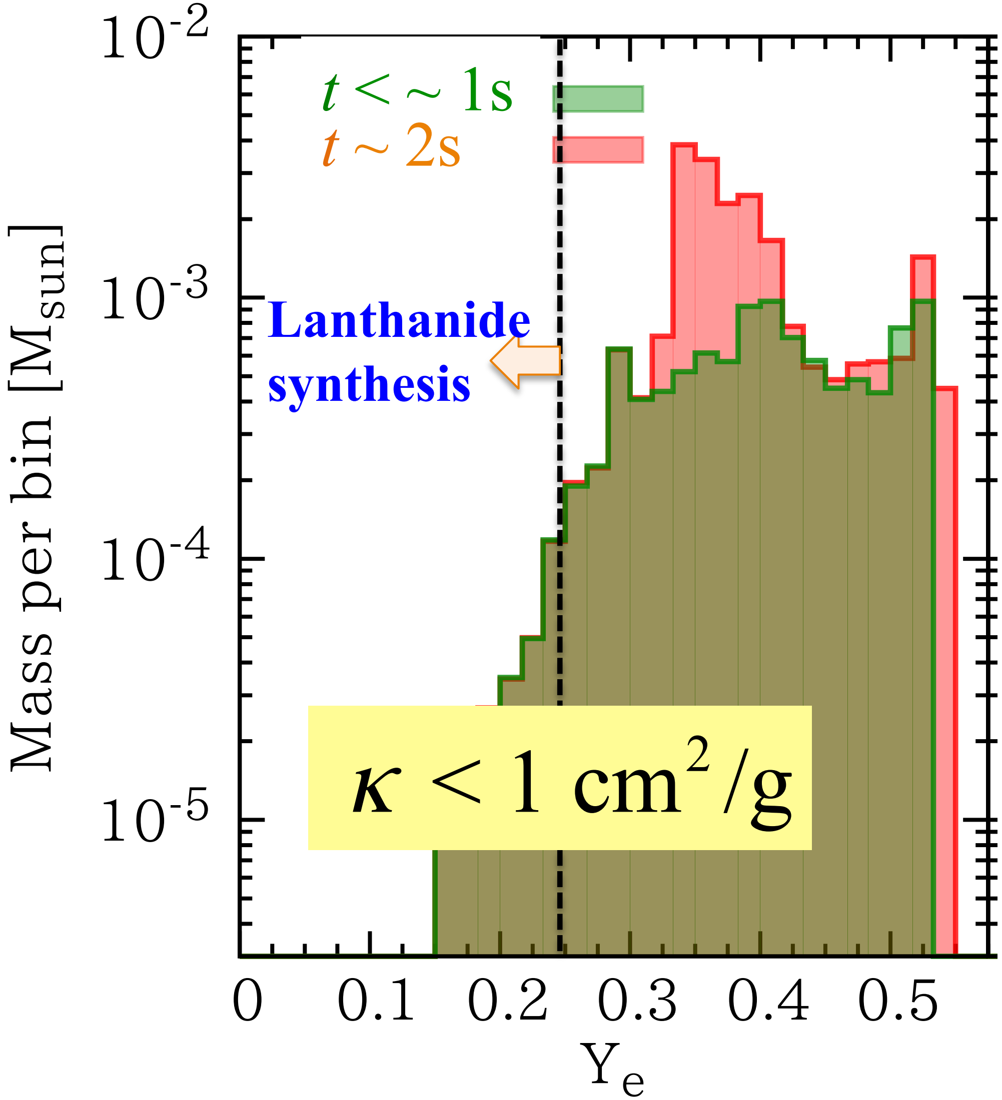
Substantial fraction of disk mass is ejected

Wide 4500×4500 km

FOCUS ON THIS

300×300 km

Electron fraction distribution by viscosity (total)



Neutrino irradiation from MNS

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

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

$$\Downarrow$$

Longterm irradiation

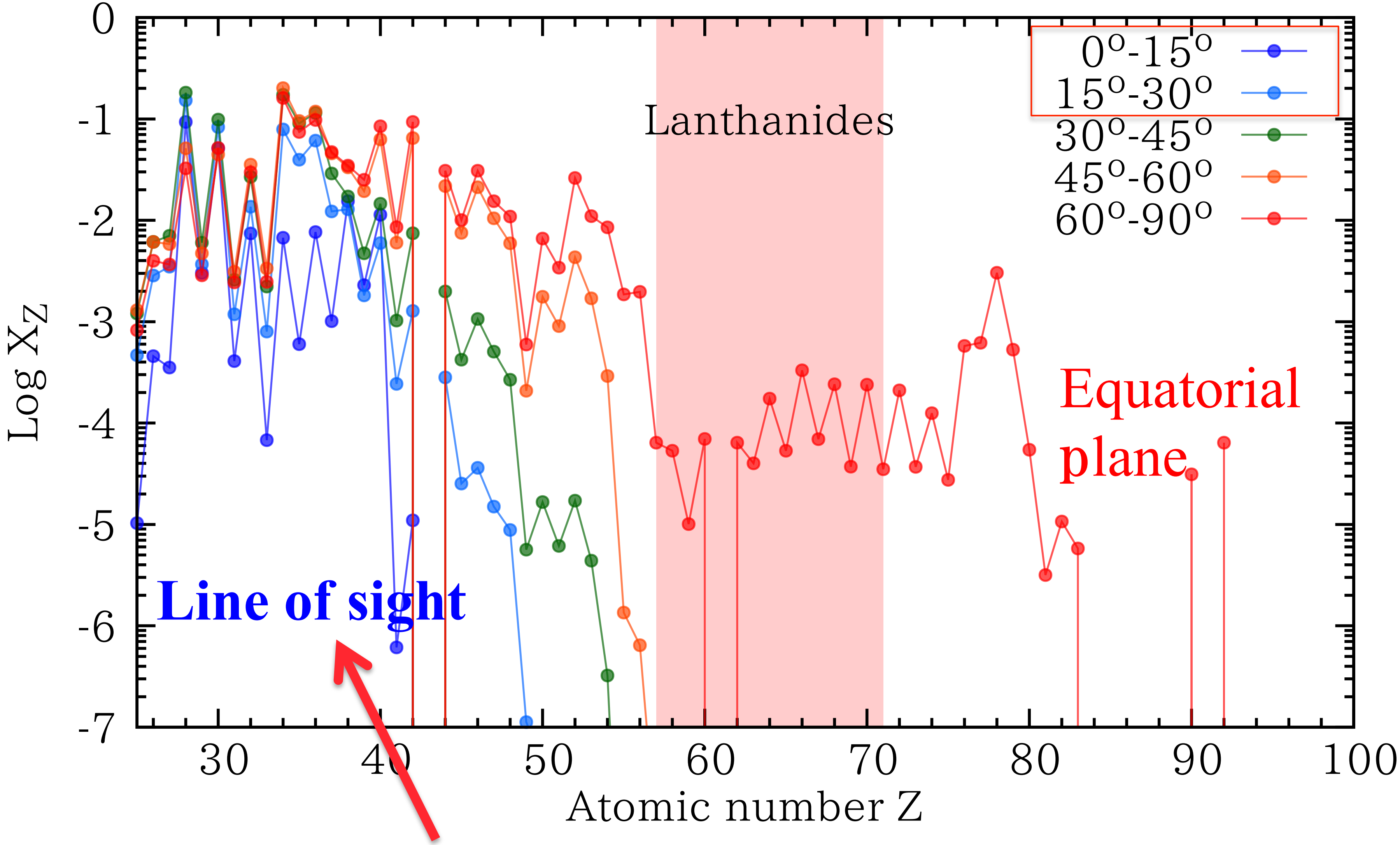
$$\Downarrow$$

$$Y_{e,equil} \sim \left[1 + \frac{L_{\bar{\nu}_e}}{L_{\nu_e}} \frac{\langle E_{\bar{\nu}_e} \rangle - 2(m_n - m_p)}{\langle E_{\nu_e} \rangle + 2(m_n - m_p)} \right]$$

(Qian & Woosley, 1996)

Only ***small lanthanide synthesis*** due to **strong neutrino irradiation from remnant NS**: very good

No lanthanide along the line of sight from merger remnant ejecta



Neutrino irradiation from remnant neutron star

Peak luminosity and peak time for the merger remnant ejecta

$$L_{\max} \sim \underline{\underline{1\times10^{42}\ \text{ergs/s}}}\left(\frac{M}{0.04M_\odot}\right)^{1/2}\left(\frac{v}{0.05c}\right)^{1/2}\left(\frac{\kappa}{0.1\ \text{cm}^2/\text{g}}\right)^{-1/2}\left(\frac{f_{\text{r-proc}}}{10^{-6}}\right)$$

bright

$$\text{at}\quad t \sim \underline{\underline{1\ \text{days}}}\left(\frac{M}{0.04M_\odot}\right)^{1/2}\left(\frac{v}{0.05c}\right)^{-1/2}\left(\frac{\kappa}{0.1\ \text{cm}^2/\text{g}}\right)^{1/2}$$

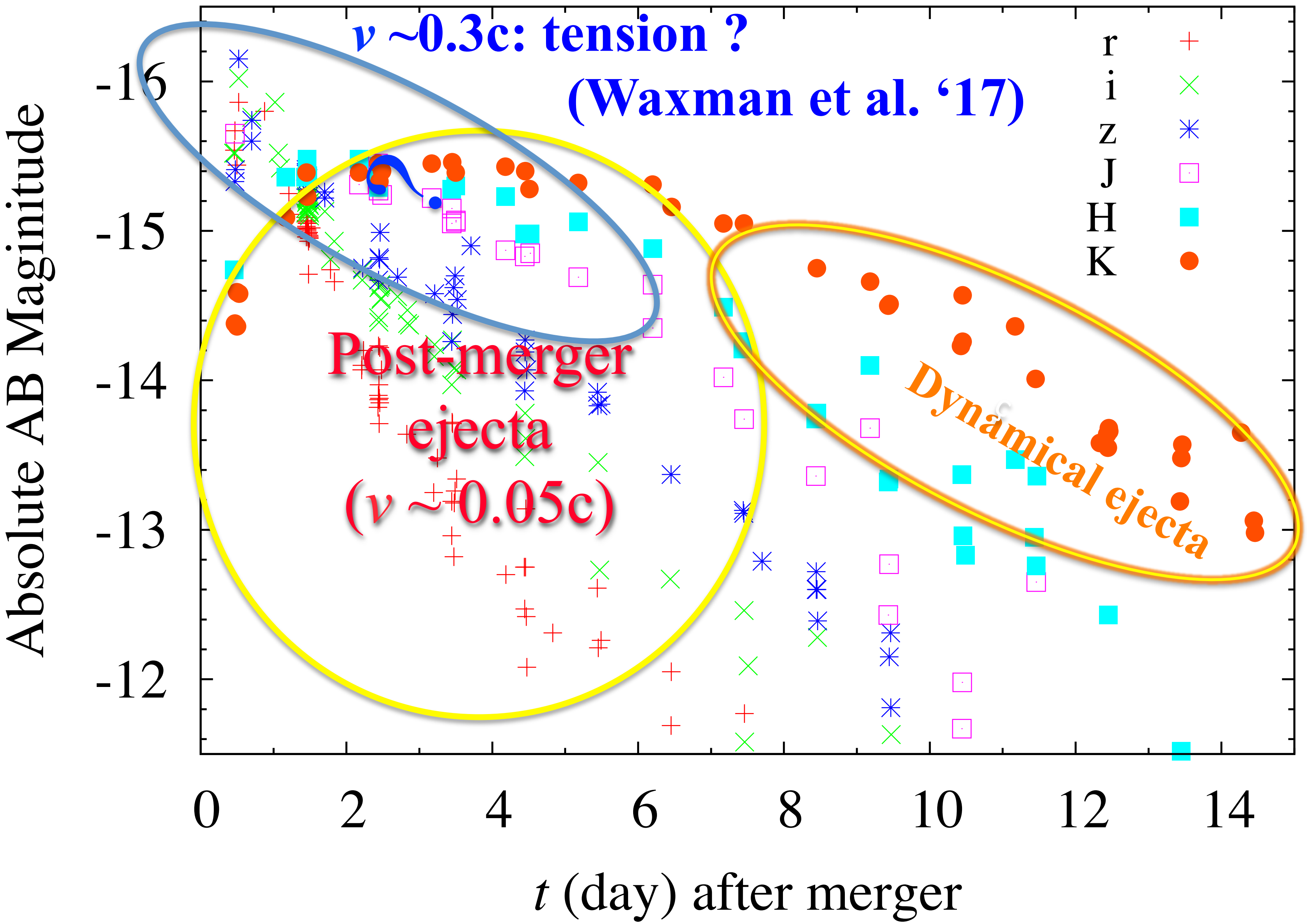
fast

$$\Downarrow$$

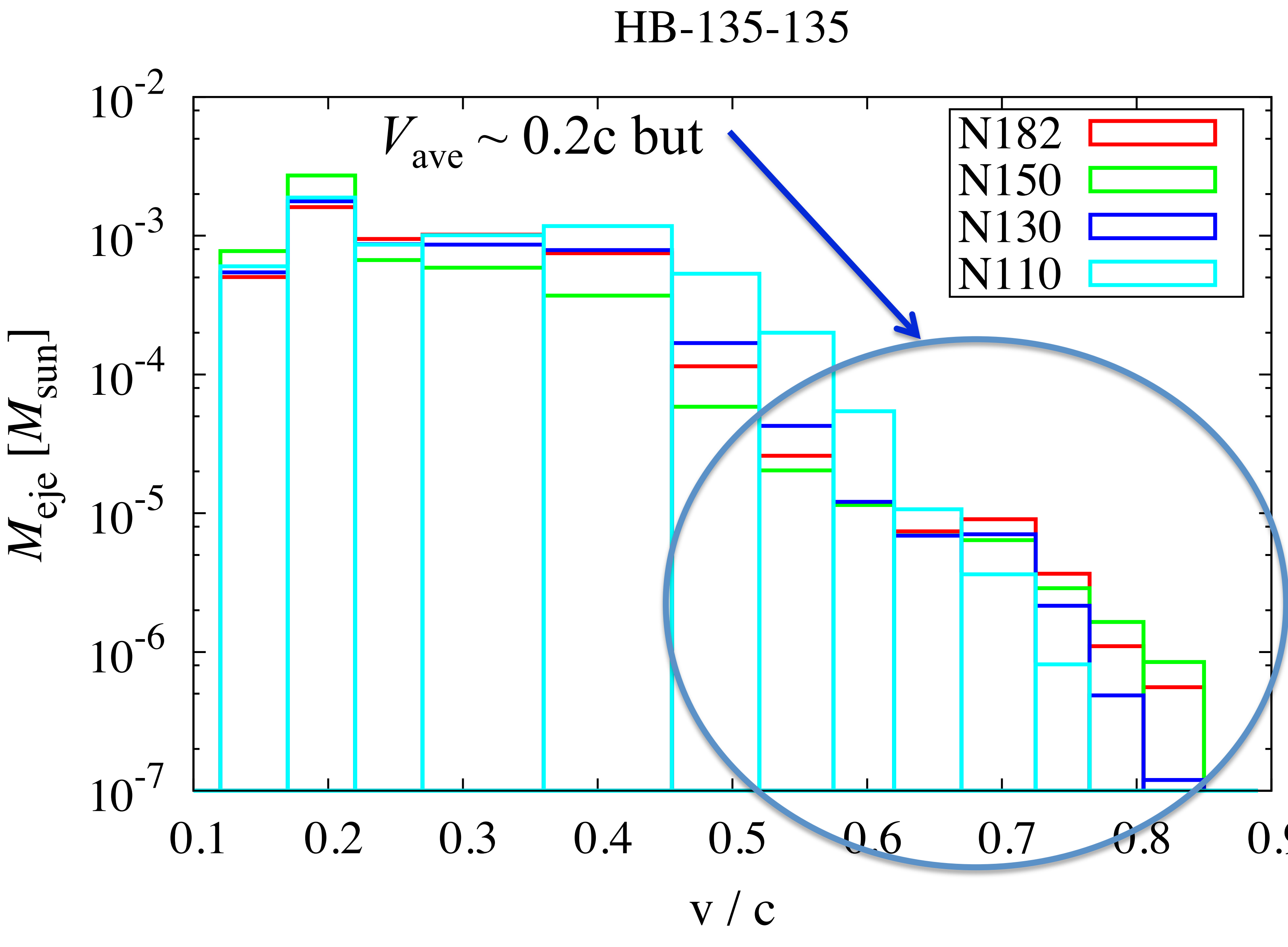
$$L_{\max} \sim 10^{42}\ \text{ergs/s} \quad \& \quad t \sim 1\ \text{days}\ \ \text{for}\ \ M \sim 4\times10^{-2} M_\odot$$

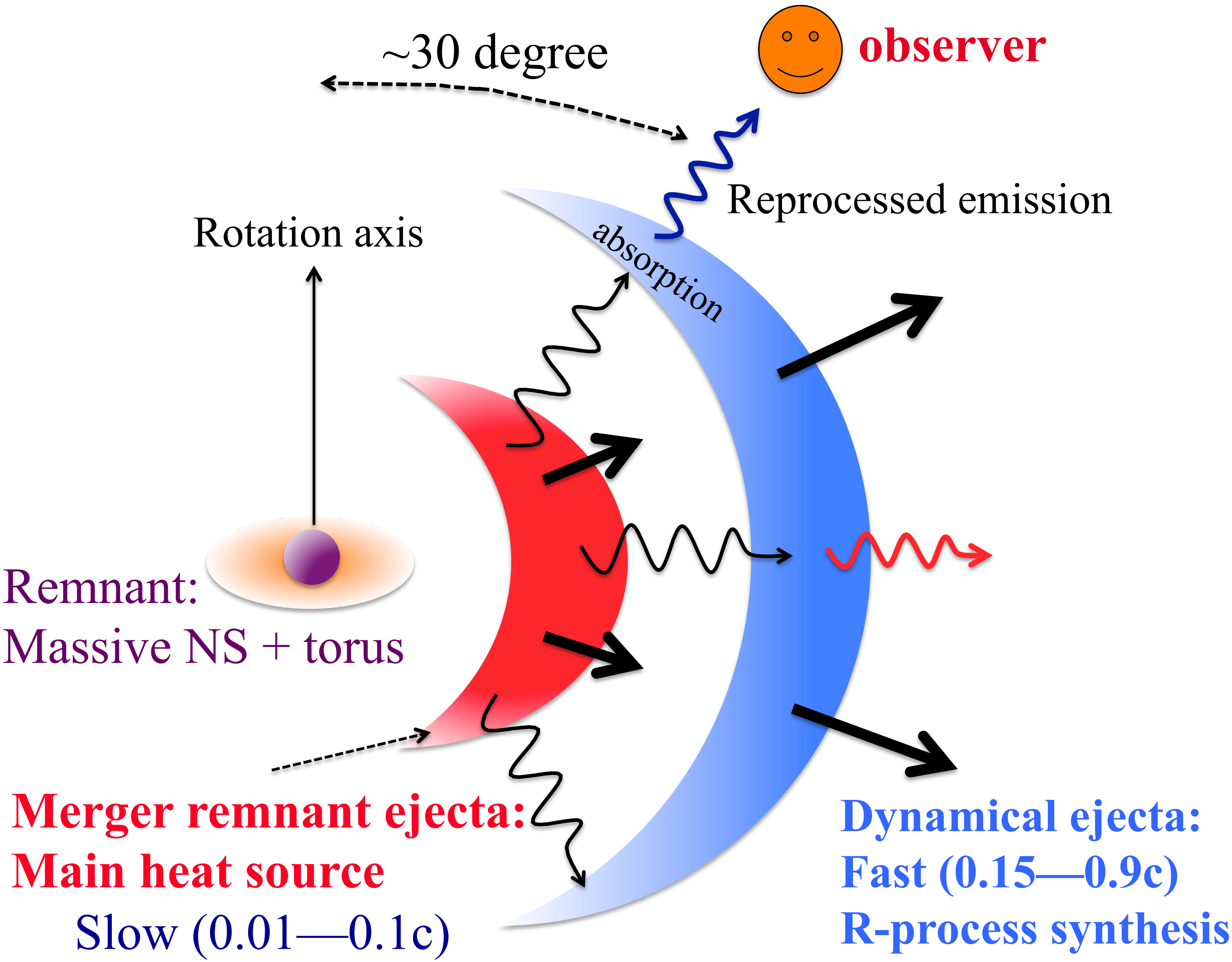
Shine at one day

IV Model of EM counter part of GW170817



Dynamical ejecta has very fast component

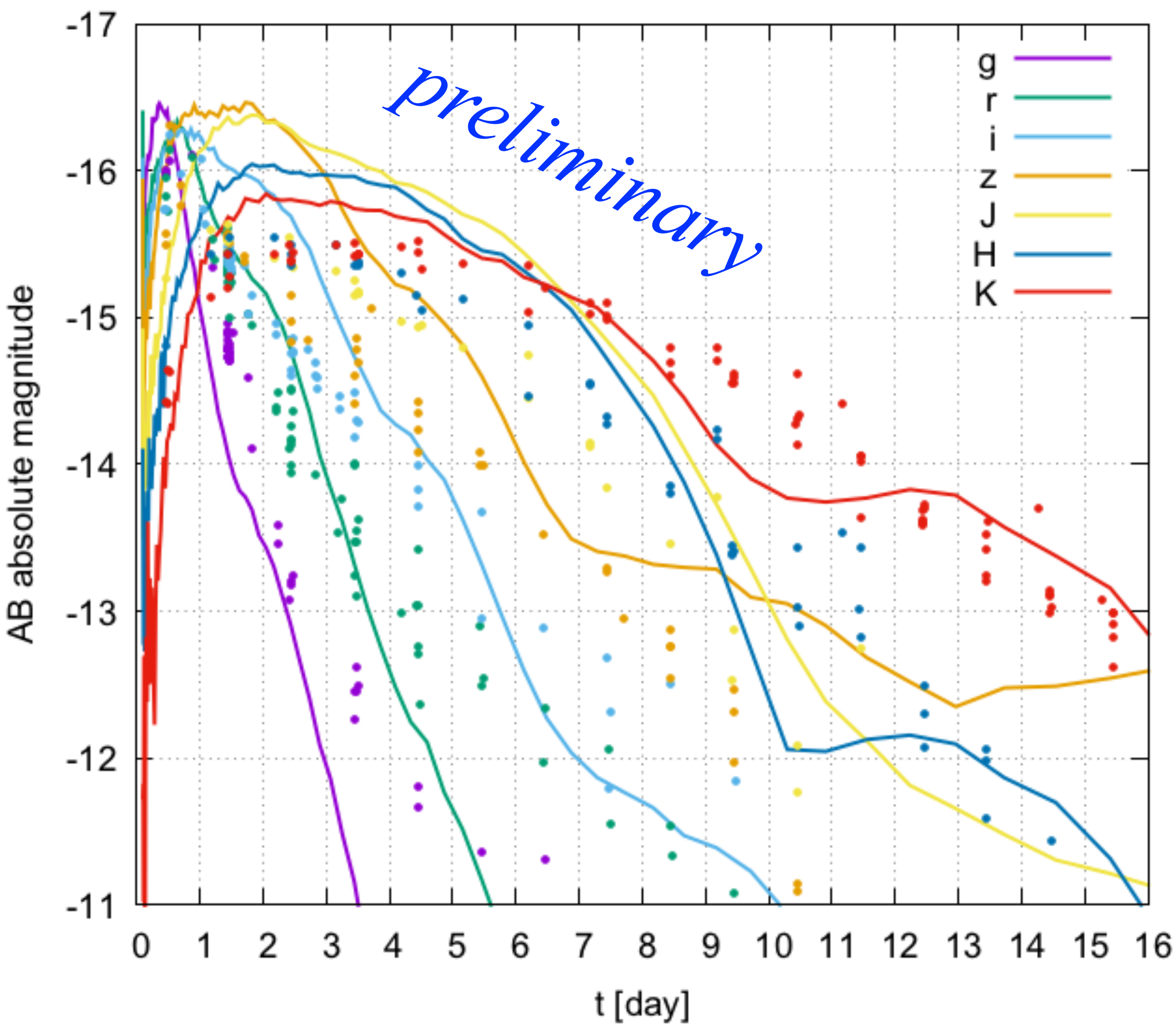




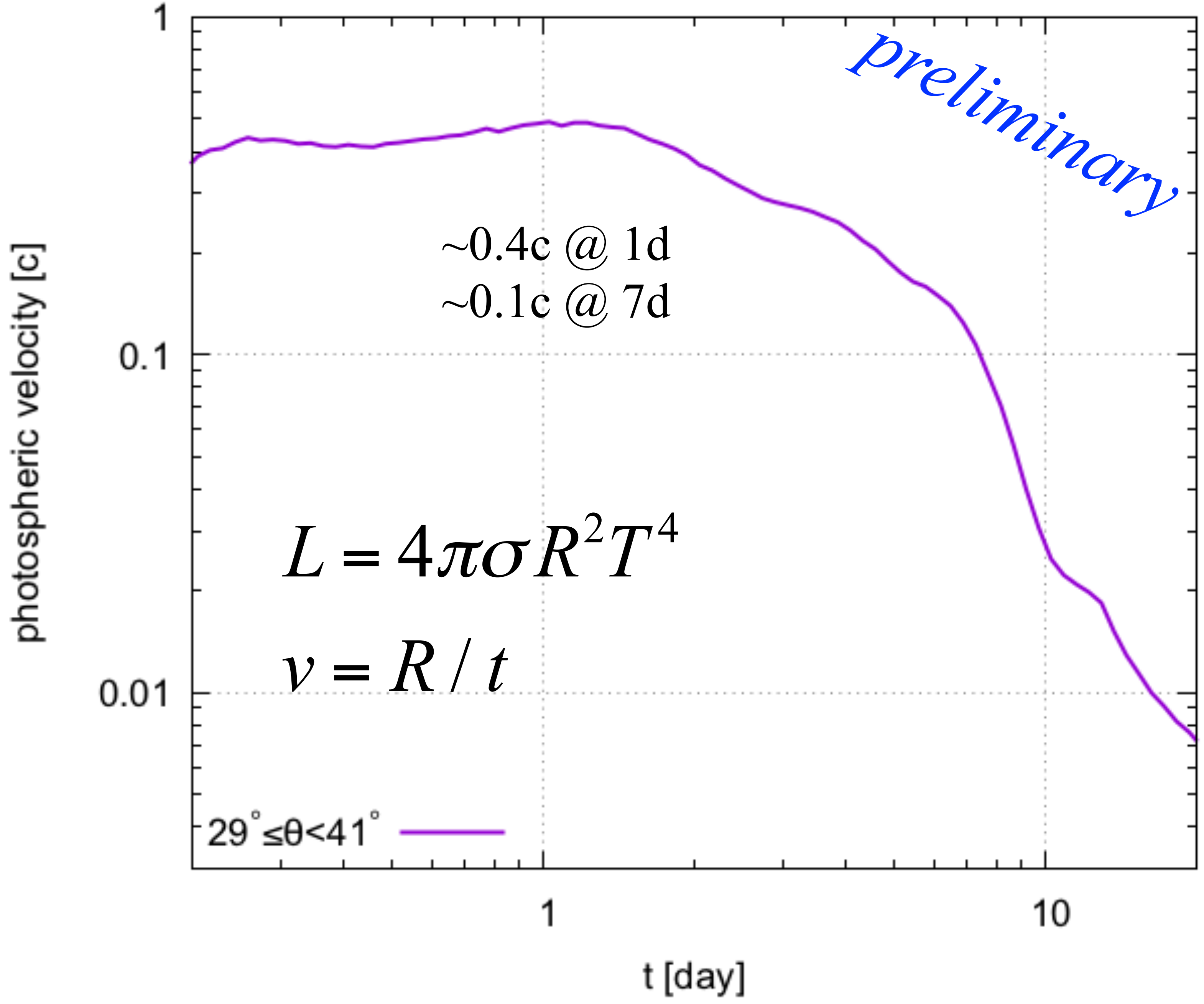
~30 degree
observer
Reprocessed emission
Rotation axis
absorption
Remnant:
Massive NS + torus
Merger remnant ejecta:
Main heat source
Slow (0.01—0.1c)
Dynamical ejecta:
Fast (0.15—0.9c)
R-process synthesis

Radiation transfer simulation: good agreement

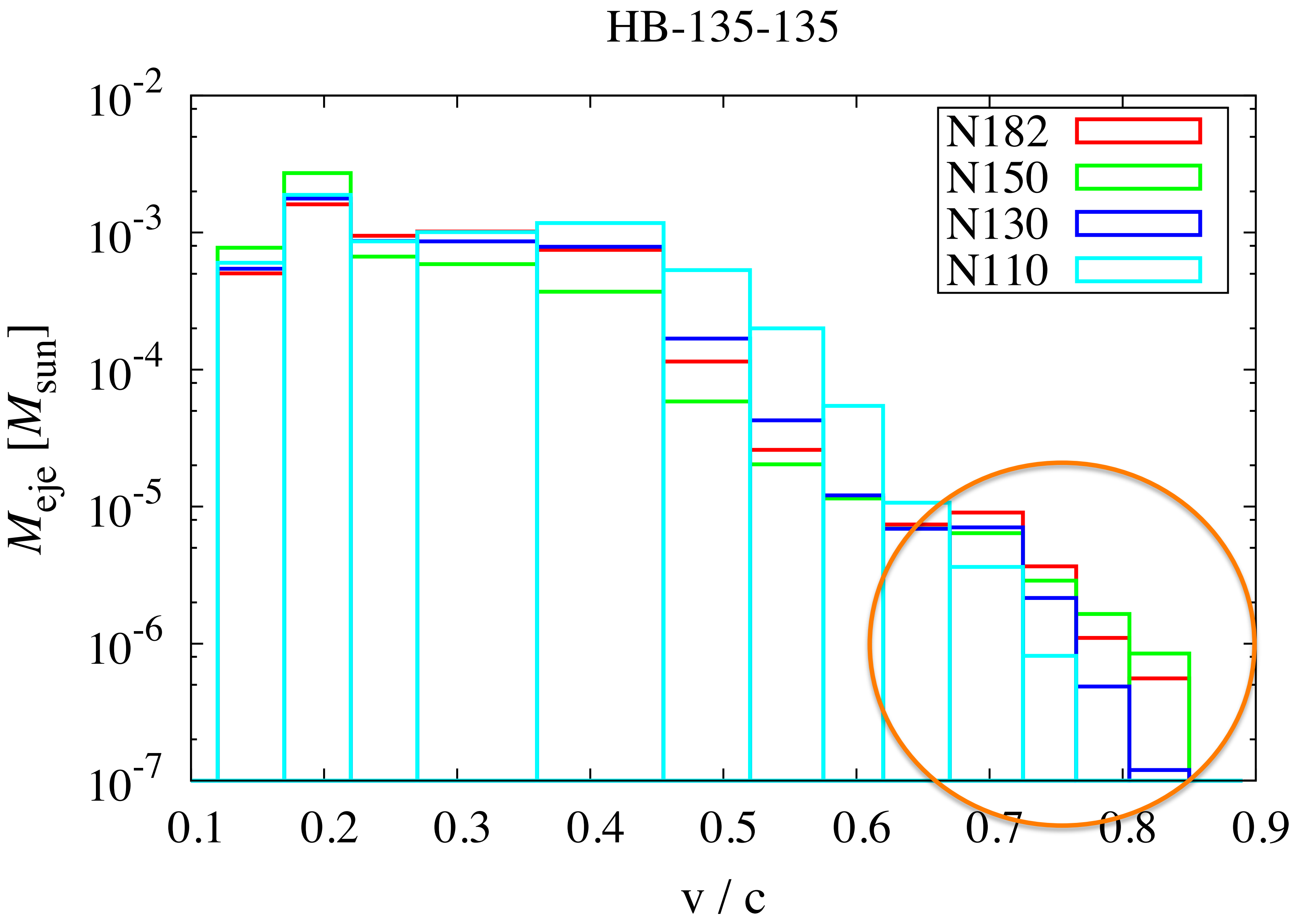
(K. Kawaguchi, M. Tanaka, MS; **See talk by Tanaka for details**)



Looks fast (apparently)



Consistent with radio, optical, X (synchrotron rad)

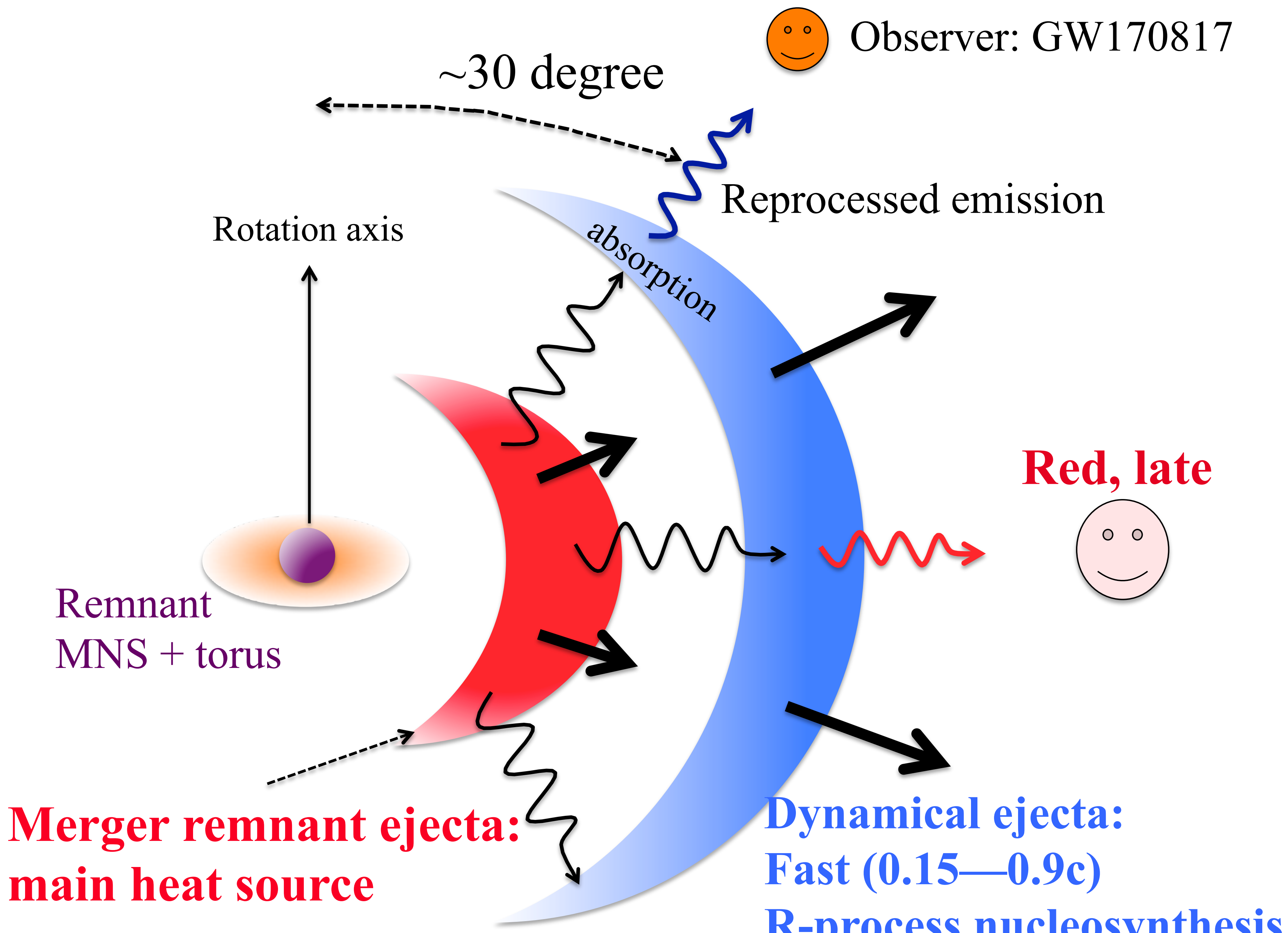


V Summary

- **EM counterparts of GW170817 can be well interpreted by numerical-relativity results self-consistently except for (tiny-energy) gamma-ray emission**
- Fully physical argument, not phenomenological (artificial)
- Too good, plausible ?? The reason for the agreement is

✧ **We know the initial condition of the merger well, so that we can get correct results by accurate simulation**

- Next observation hopefully would confirm this fact
- **Note however that the next observational results could be significantly different from the GW170817**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