Towards realistic modeling of the electromagnetic counterparts of neutron star mergers

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"Ready, set, go! Preparing for the O4 LIGO-Virgo-KAGRA observing run"
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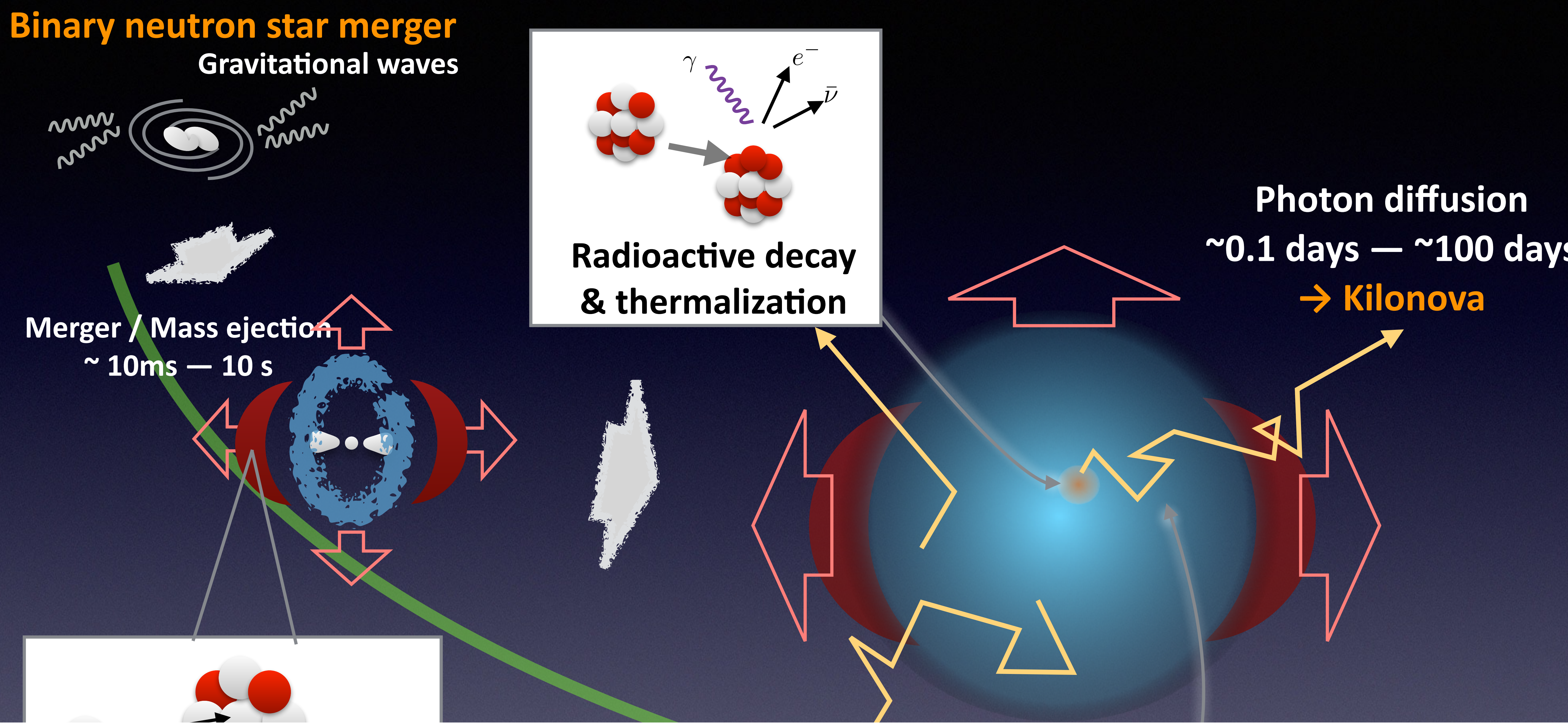
Kilonova: Overview



Li & Paczynski 1998, and e.g., Kulkarni 2005, Metzger et al. 2010, Hotokezaka et al. 2014, Tanaka et al. 2013, 2014, Kasen et al. 2013, 2015, Barnes et al. 2016, Wollaeger et al. 2018, Tanaka et al. 2018, Wu et al. 2019, Kawaguchi et al. 2018, Hotokezaka & Nakar 2019, Kawaguchi et al. 2019, Bulla 2019, Zhu et al. 2020, Darbha & Kasen 2020, Korobkin et al. 2020, Bulla et al. 2021, Zhu et al. 2021, Barnes et al. 2021, Nativi et al. 2020, Kawaguchi et al. 2021, Wu et al. 2021, Just et al. 2021b, Curtis et al. 2021, Wollaeger et al. 2021, Just et al. 2022, Bulla et al. 2020, Hotokezaka et al. 2022, Pognan et al. 2021, 2022, Banerjee et al. 2022, Neuweiler et al. 2022, Collins et al. 2022, Fontes et al. 2022, Just et al. 2023…

Keys for the realistic prediction of Kilonova

- Ejecta mass, velocity, and thermodynamics property → • Numerical relativity simulation in the merger and post merger phase

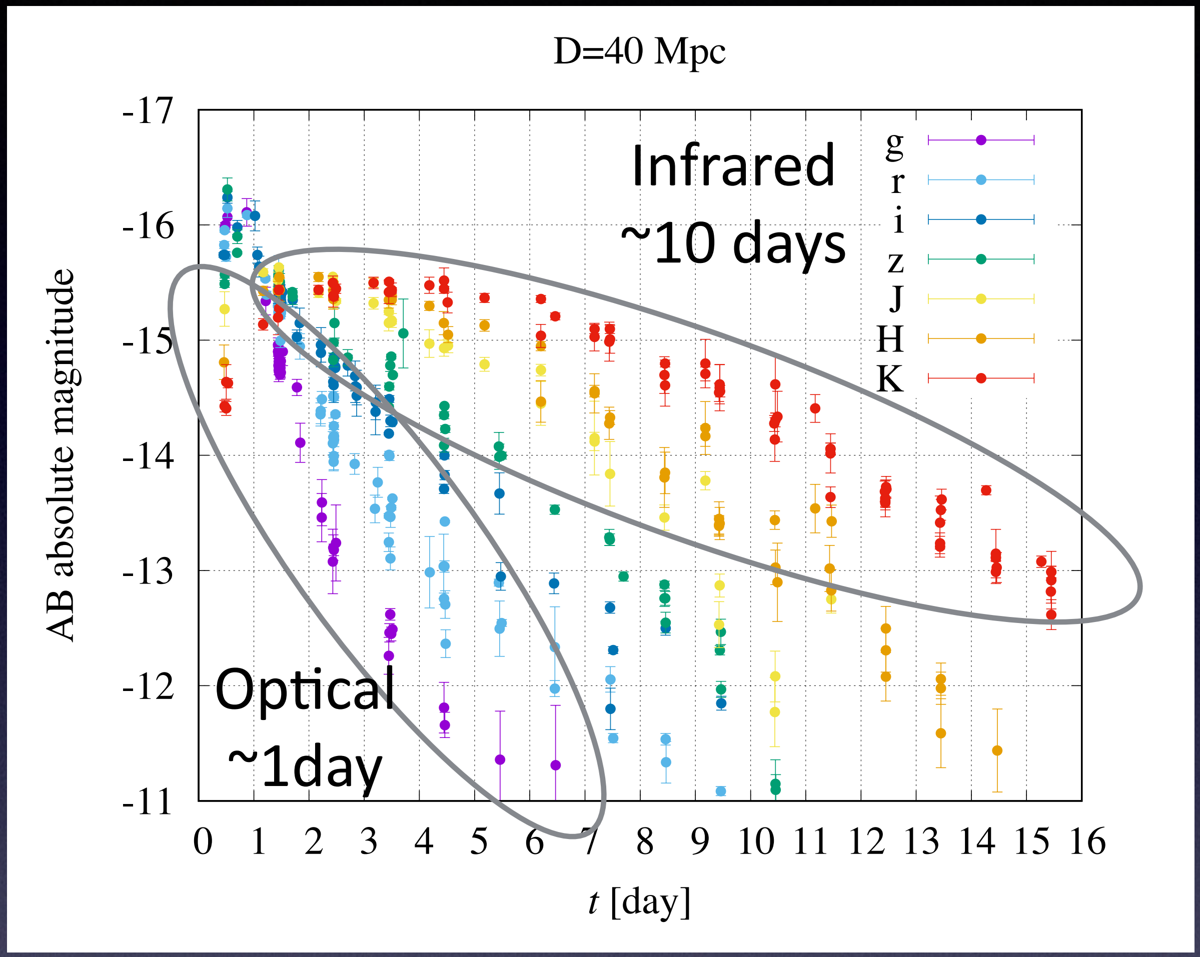
- Element/Isotope abundances and radioactive heating rate → • Nucleosynthesis calculation

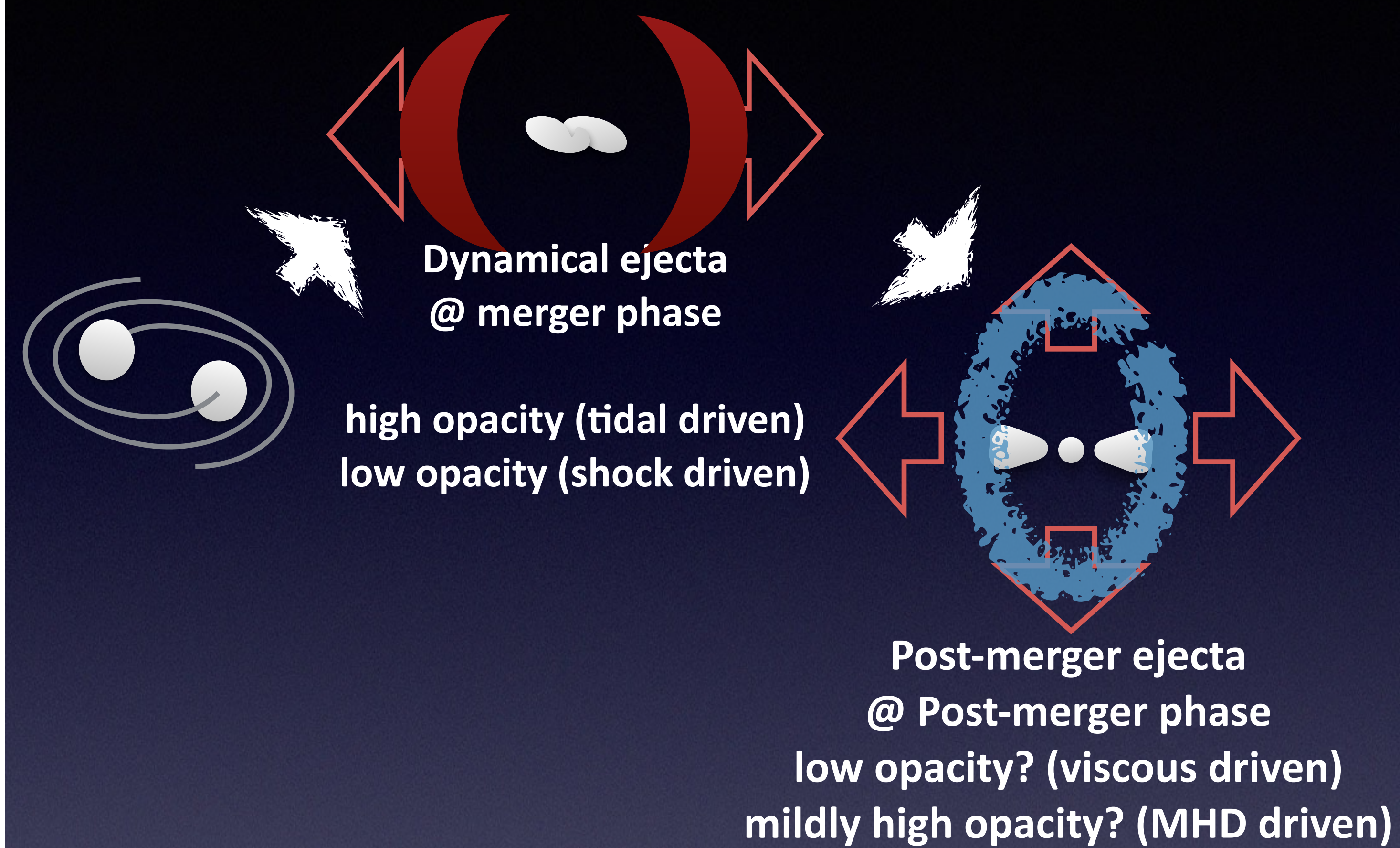
- Opacity table / transition rate → • Atomic structure calculation / experimental data

- Light curve / spectra → • Radiative transfer calculation

Origin of ejecta in GW170817

GW170817: Summarized in Villar et al. 2017





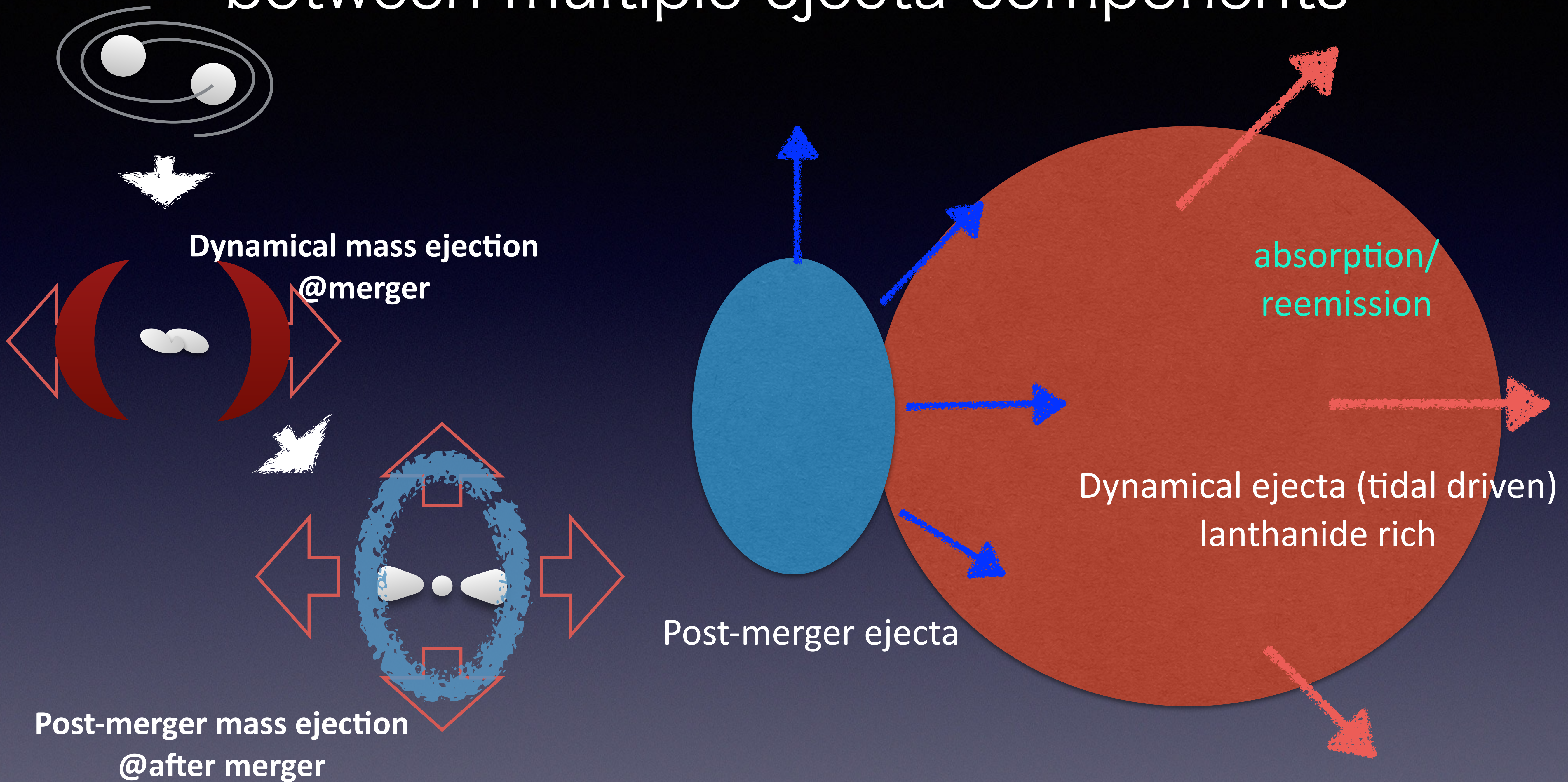
- A Kilonova with multiple ejecta components well interprets the optical-Infrared observation in GW170817 (e.g., Kasliwal et al. 2017, Drout et al. 2017, Cowperthwaite et al. 2017, Kasen et al. 2017, Villar et al. 2017)

- Multi-band light curve fitting by the combination of 1d models implies
  - early optical component (~1day) from **a "blue component"**

    (~0.01 M_sun, opacity ~0.1-1 cm^2/g, v~0.3 c) → too massive/fast to be shock / viscous driven ejecta?
  - long-lasting infrared component (~10days) from **a "red component"**

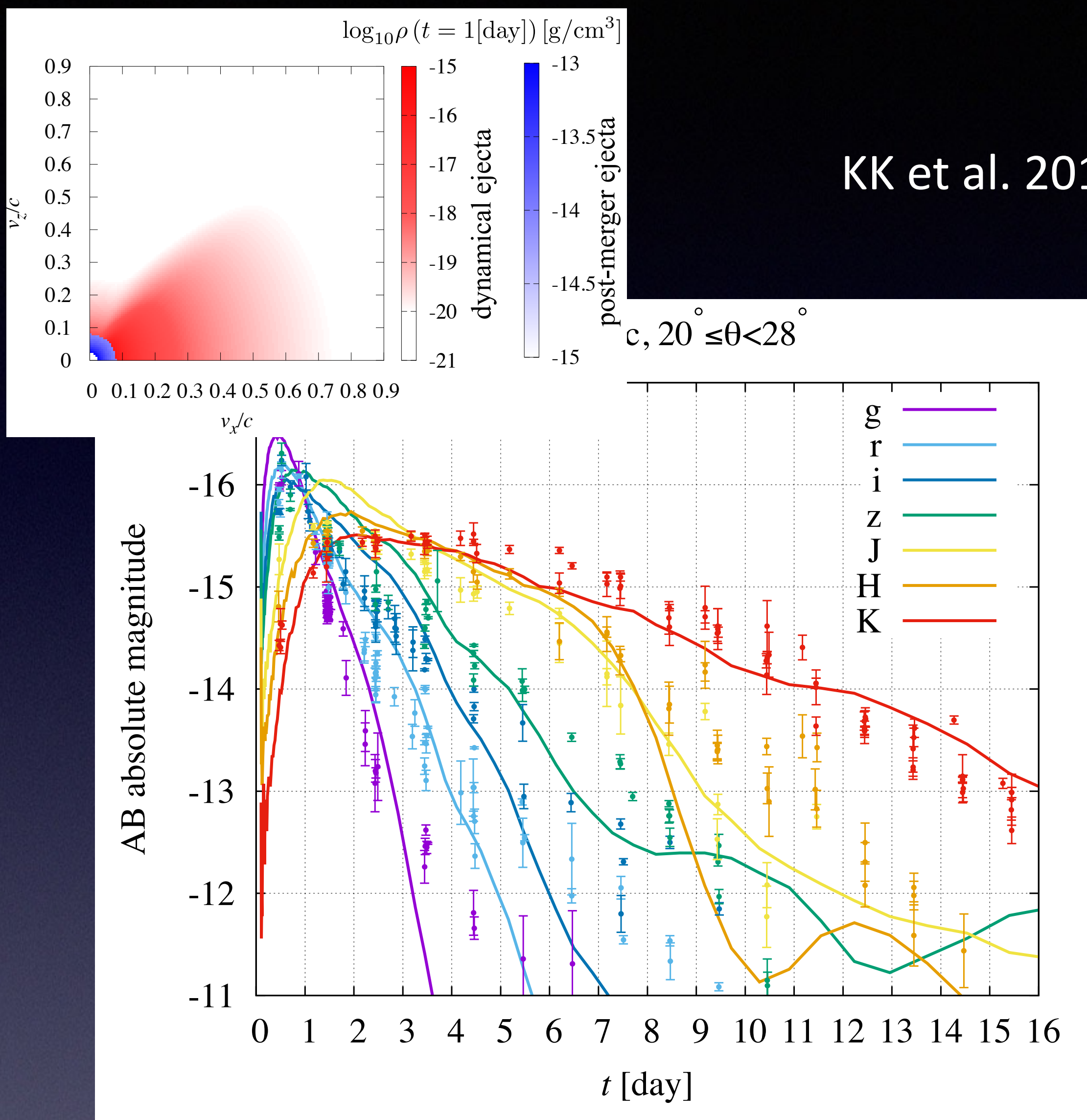
    (~0.05-0.1 M_sun, opacity ~10 cm^2/g, v~0.1 c) → too massive to be tidally driven dynamical ejecta?

Effect of geometry and radiative interaction between multiple ejecta components



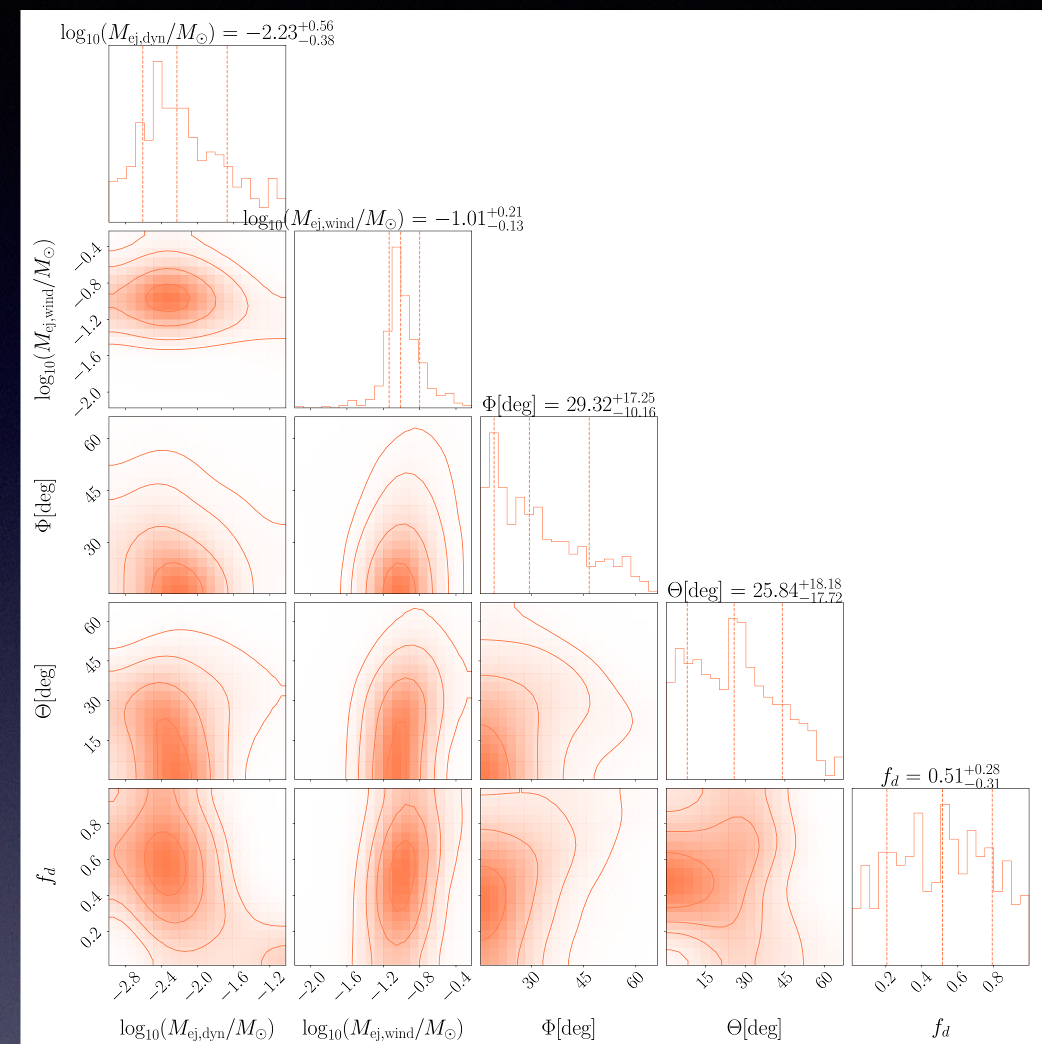
Taking the radiative transfer effect of photons in the multiple ejecta components of non-spherical morphology into account has a large impact on the lightcurve predictions (see also Kasen et al. , Perego et al. 2017, Wollaeger et al. 2017, Bulla et al. 2019)

Effect on ejecta parameter estimation



KK et al. 2018

Almualla et al. 2022



- Light curves consistent with the observation of GW170817 can be reproduced by the ejecta profile consistent with numerical merger simulations, such as

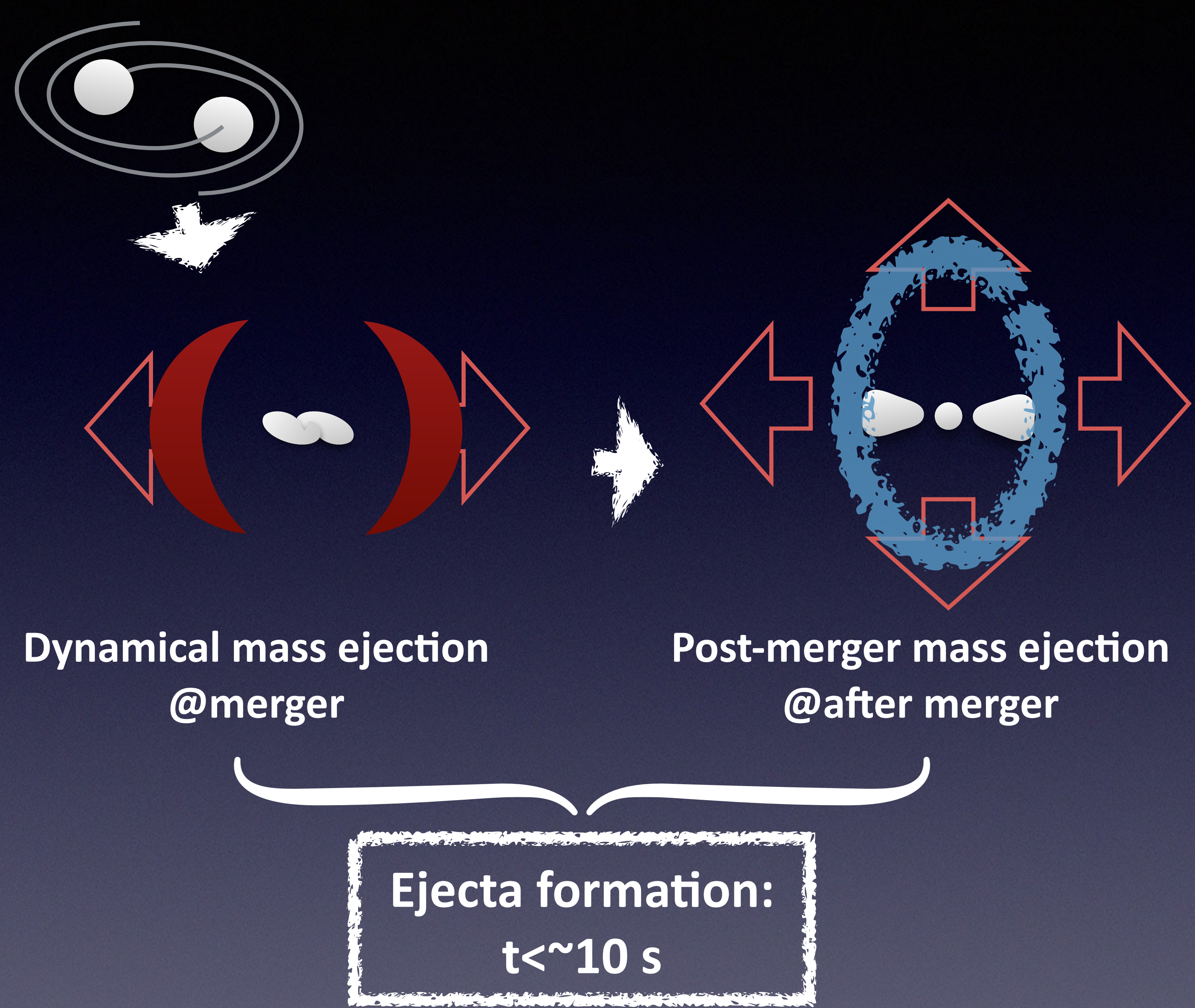
  Dynamical ejecta: Lanthanide-rich ejecta, ~0.001-0.01 Msun
+Post-merger ejecta: Lanthanide-poor ejecta: ~0.01-0.1 Msun

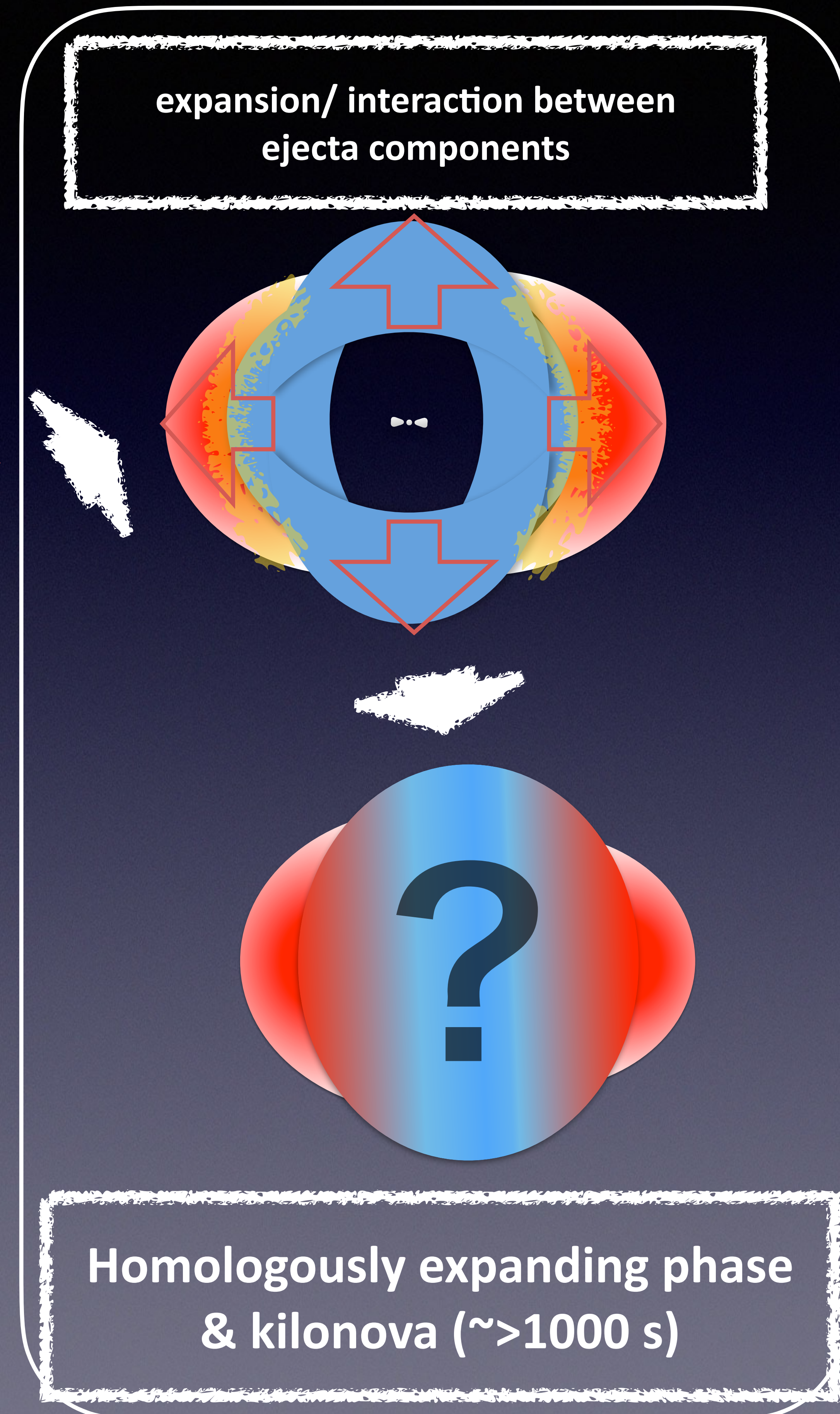
, if the effects of ejecta geometry and radiative interaction between multiple ejecta components are taken into account
(e.g., Perego et al. 2017, Tanvir et al. 2017, KK et al 2018, Bulla et al. 2019, Almualla et al. 2022, Kedia et al. 2022)

Keys for the realistic prediction of Kilonova

• Ejecta mass, velocity, and thermodynamics property	⟶	• Numerical relativity simulation in the merger and post merger phase
• Element/Isotope abundances and radioactive heating rate	⟶	• Nucleosynthesis calculation
• Ejecta / abundance profile in the homologously expanding phase	⟶	• Longterm Hydrodynamics evolution of ejecta
• Opacity table / transition rate	⟶	• Atomic structure calculation / experimental data
• Light curve / spectra	⟶	• Radiative transfer calculation

Long-term hydrodynamics evolution of ejecta





The ejecta profile at the time of kilonova emission is not trivial only from the simulations in the ejecta formation time scale

(see also Rosswog et al. 2014, Grossman et al. 2014, Fernandez et al. 2015, 2017, Foucart et al. 2021, Wu et al. 2021, Collins et al. 2022, Neuweiler et al. 2022, Just et al. 2023)

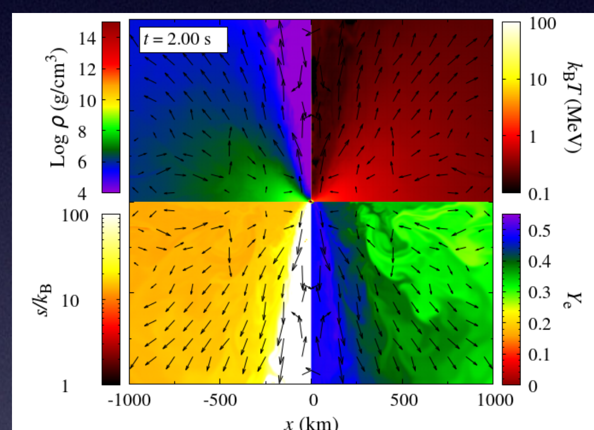
Comprehensive EM prediction from merger simulations

3D GR-R-HD BNS merger simulation

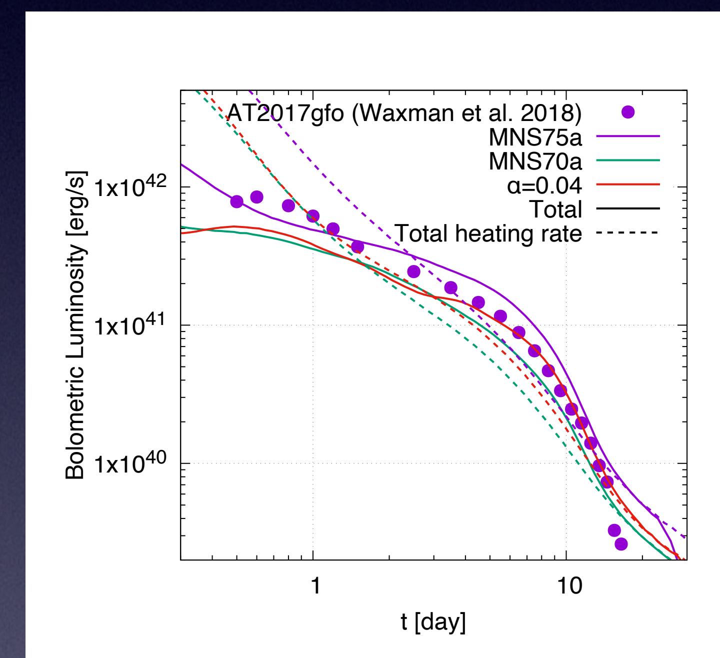
S. Fujibayashi et al. 2020,
M. Shibata et al. 2021

Axisymmetrize

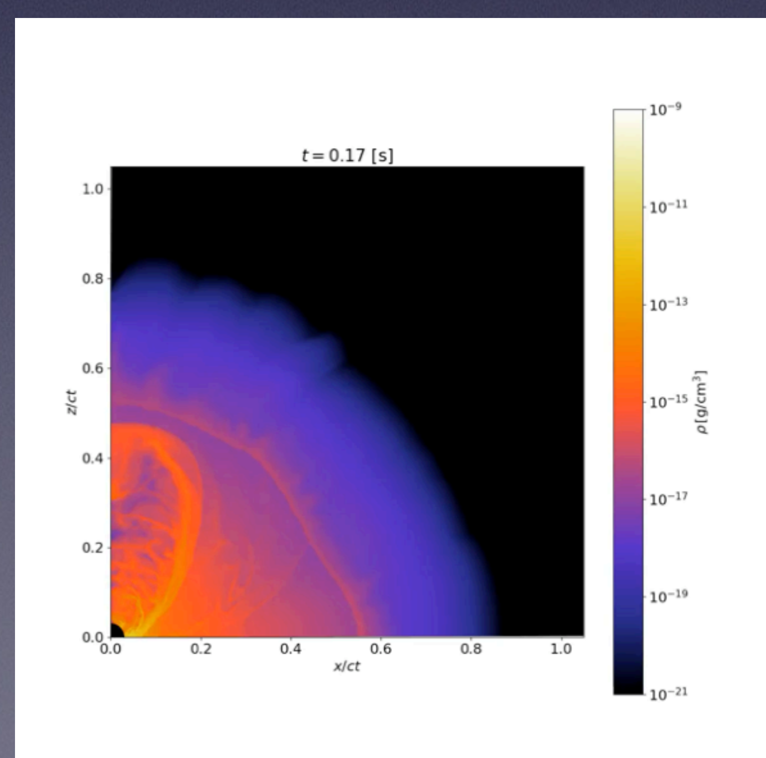
Long-term axisymmetric
GR-R-viscous/MHD simulation (~1 s-10 s)



Radiative transfer simulation/
Synchrotron emission calculation



Extract ejecta component



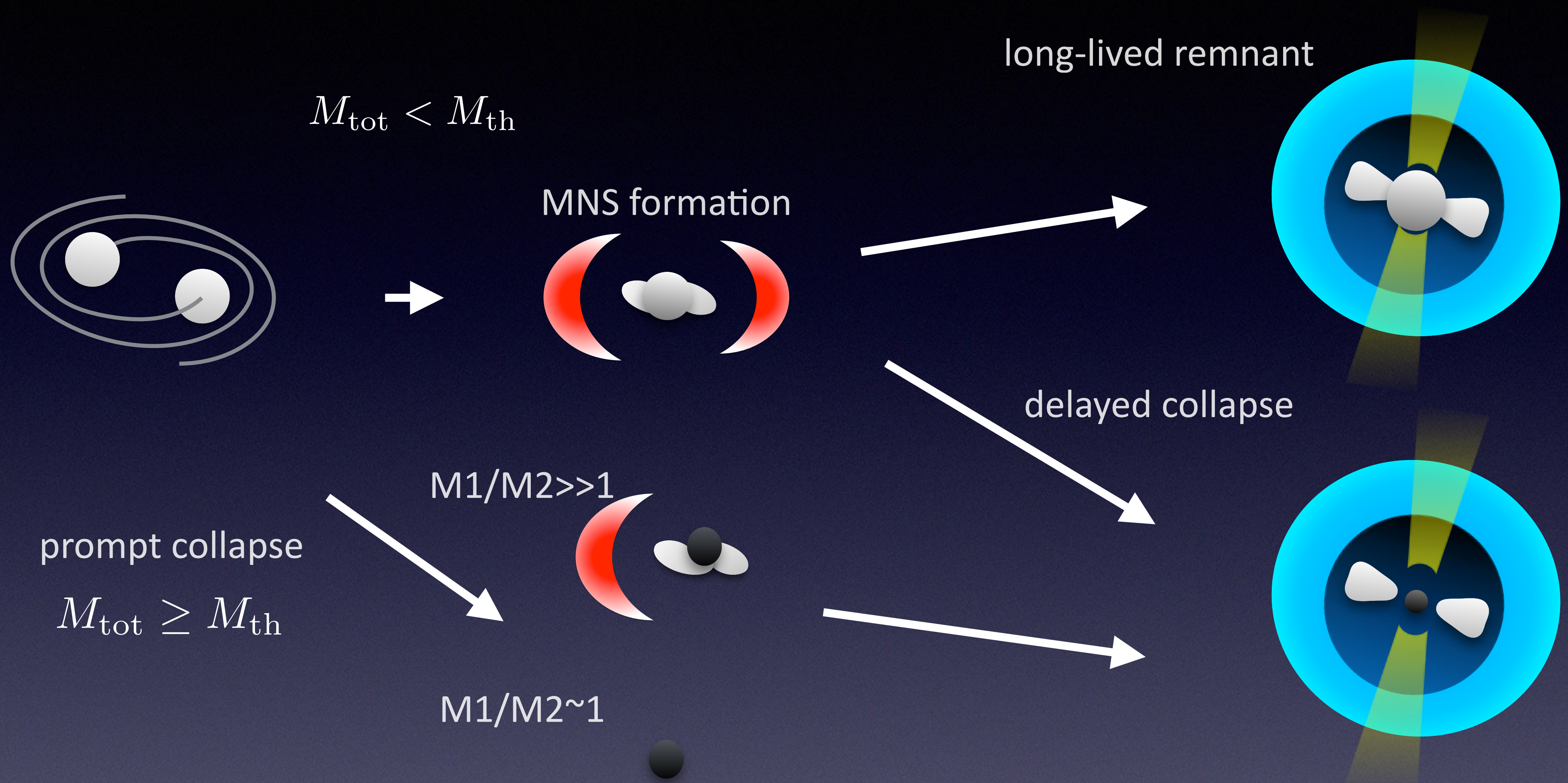
GR-HD simulation for the longterm ejecta evolution (~0.1 d)
KK et al. 2021, 2022

KK et al. 2021, 2022

EM counterpart prediction

Multi-color RT code:
Tanaka et al, 2013,2014, KK. et. al. 2018, 2021
Opacity Table:
Tanaka et al. 2020, Domoto et al. 2021, 2022
Synchrotron calculation:
Hotokezaka et al. 2018

Models: Various BNS cases with different fates

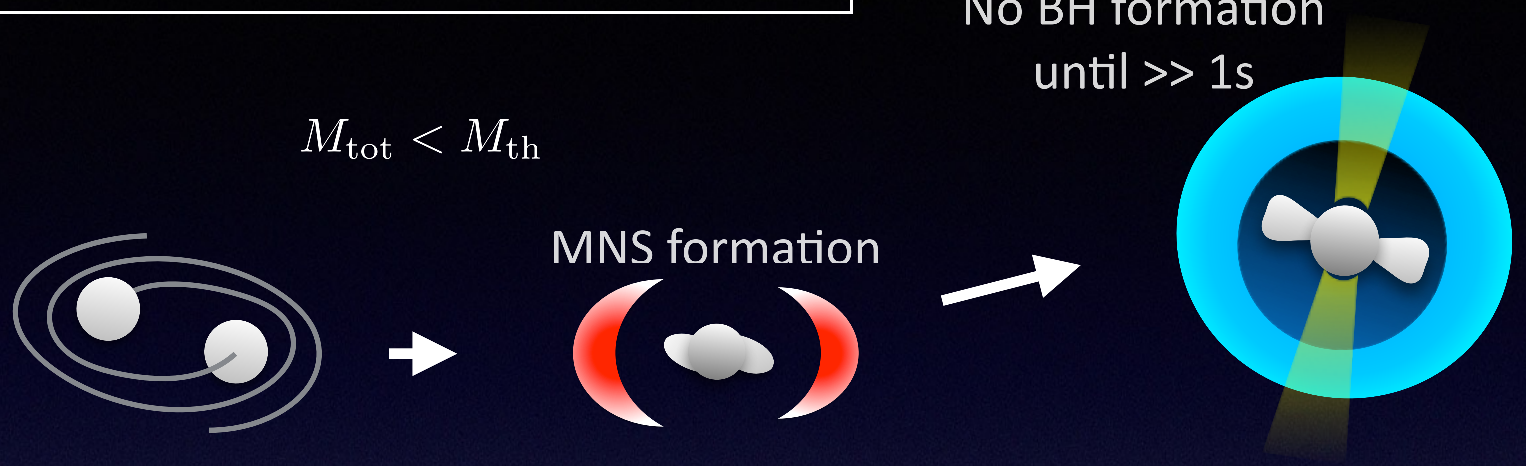


- **Long-lived remnant (>>1s) cases (S. Fujibayashi et al. 2020)**
  1.25 Msun-1.25 Msun, 1.35 Msun-1.35 Msun, DD2 EOS (13.2 km@1.35 Msun)
- **Long-lived remnant with strong magnetic dynamo effects (M. Shibata et al. 2021)**
- **Short-lived remnant (<20 ms) cases (S. Fujibayashi et al. 2022)**
  Mtot = 2.7 Msun, 2.8 Msun, M1/M2=0.8-1.0, SFHo EOS (11.9 km@1.35 Msun)

Long-lived remnant case

DD2 EOS, 1.25 Msun + 1.25 Msun

S. Fujibayashi et al. 2020,
KK et al. 2021, 2022

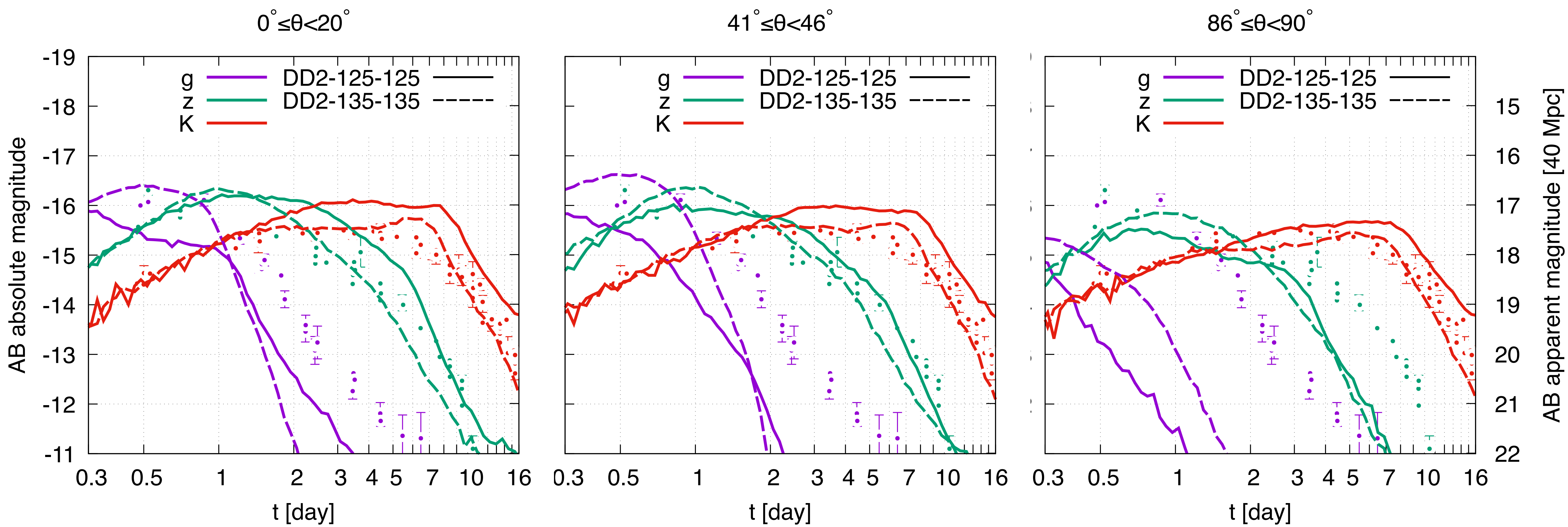


$$Y_e = \frac{[e]}{[p]+[n]}$$

BroadBand magnitudes

KK et al. 2021, 2022

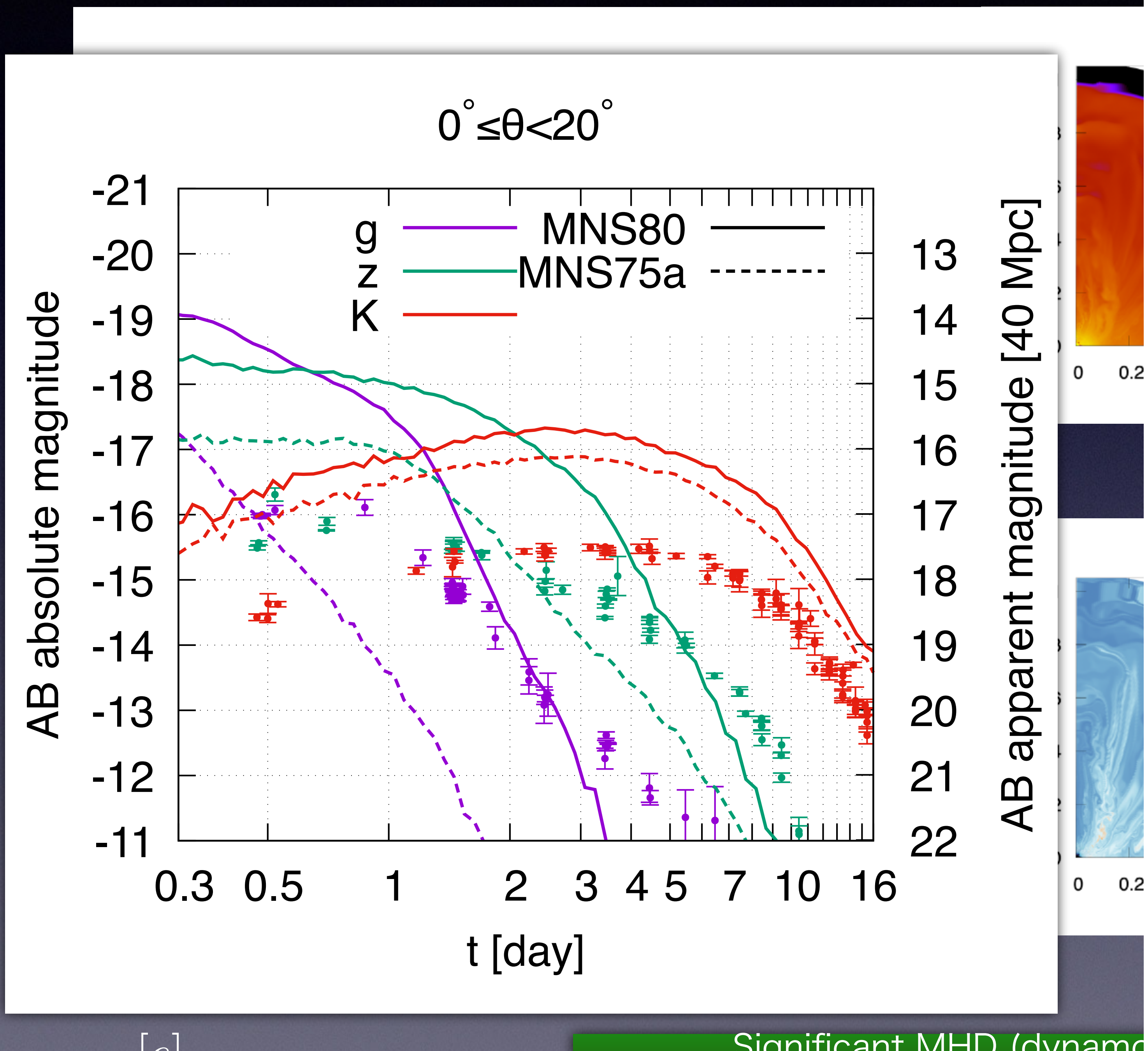
Data points: GW170817/AT2017gfo (Villar et al. 2017)

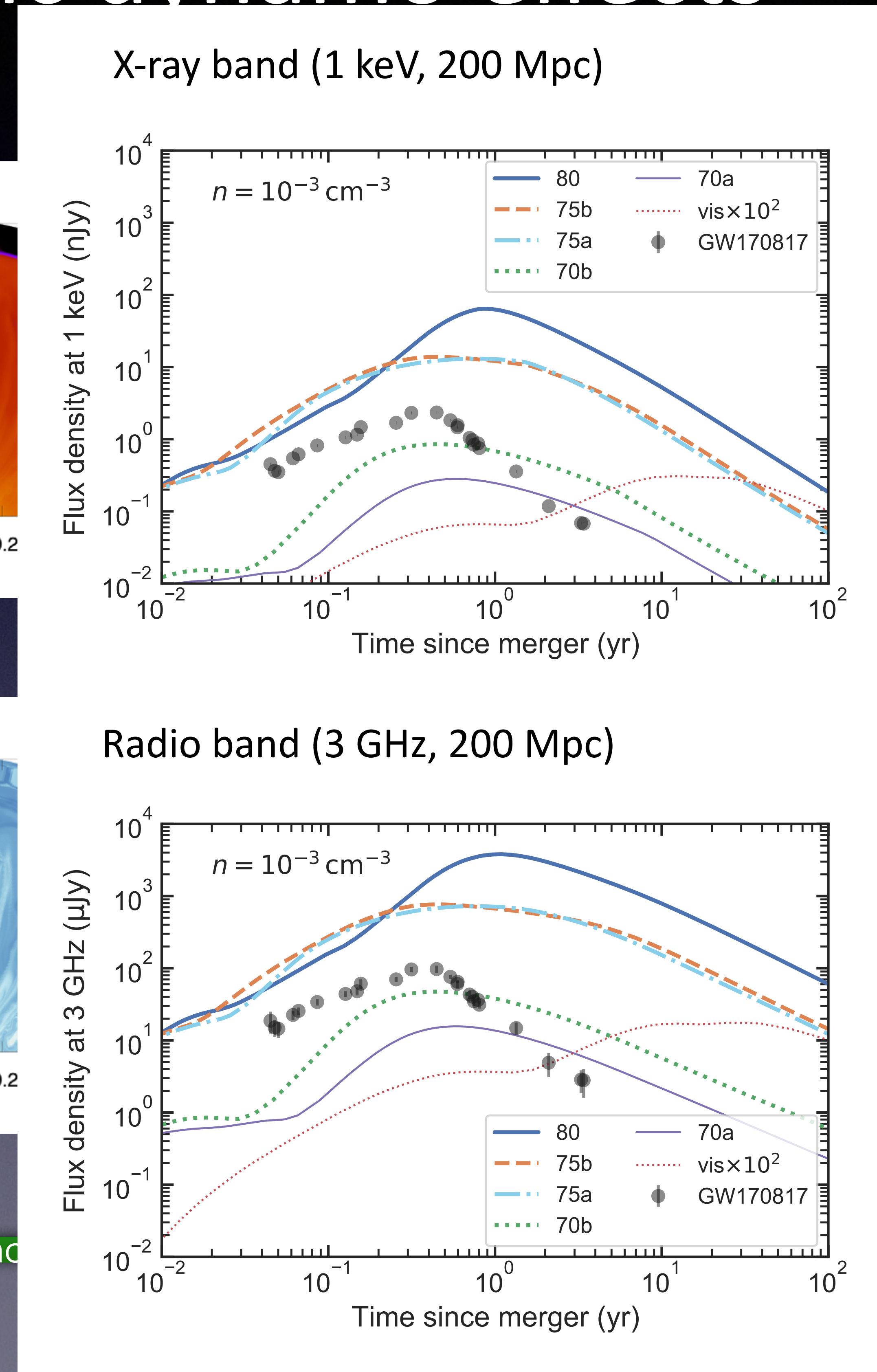


Long-lived remnant cases with significant magnetic dynamo effects

Model : 1.35 M_{sun} + 1.35 M_{sun} (DD2 EOS)

Density profile @ t = 0.1 d



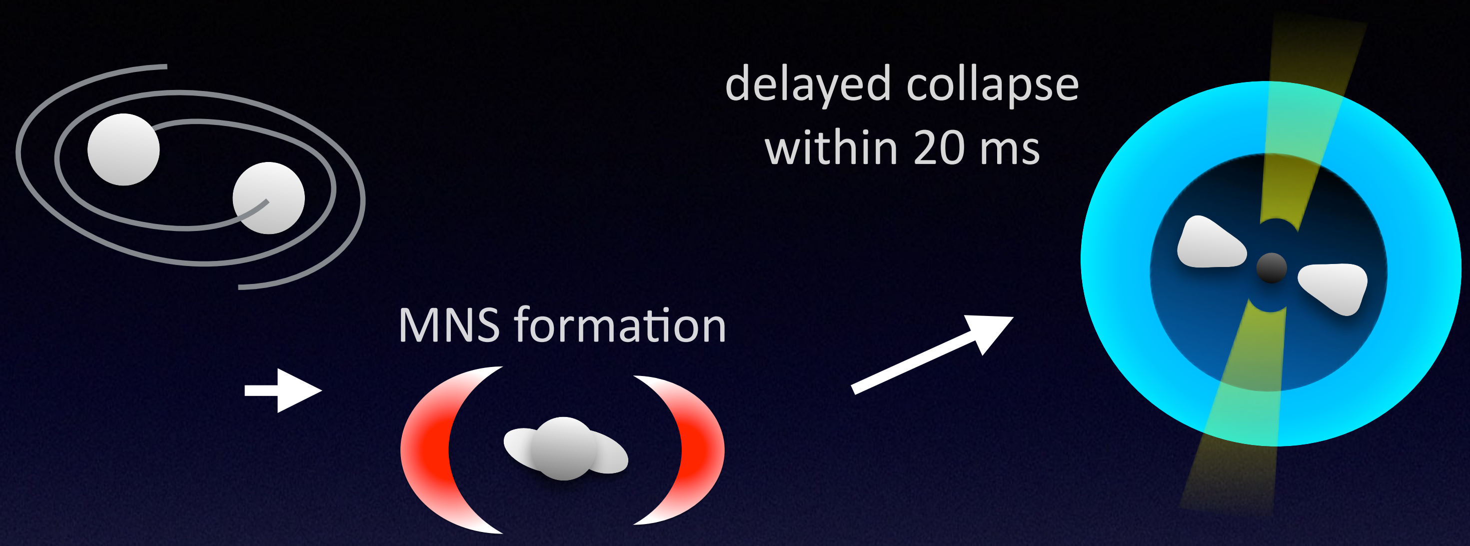


$$Y_e = \frac{[e]}{[p]+[n]}$$

Relativistic jet can also affect the resultant light curves by modifying ejecta profiles (see Nativi, Klion et al. 2020)

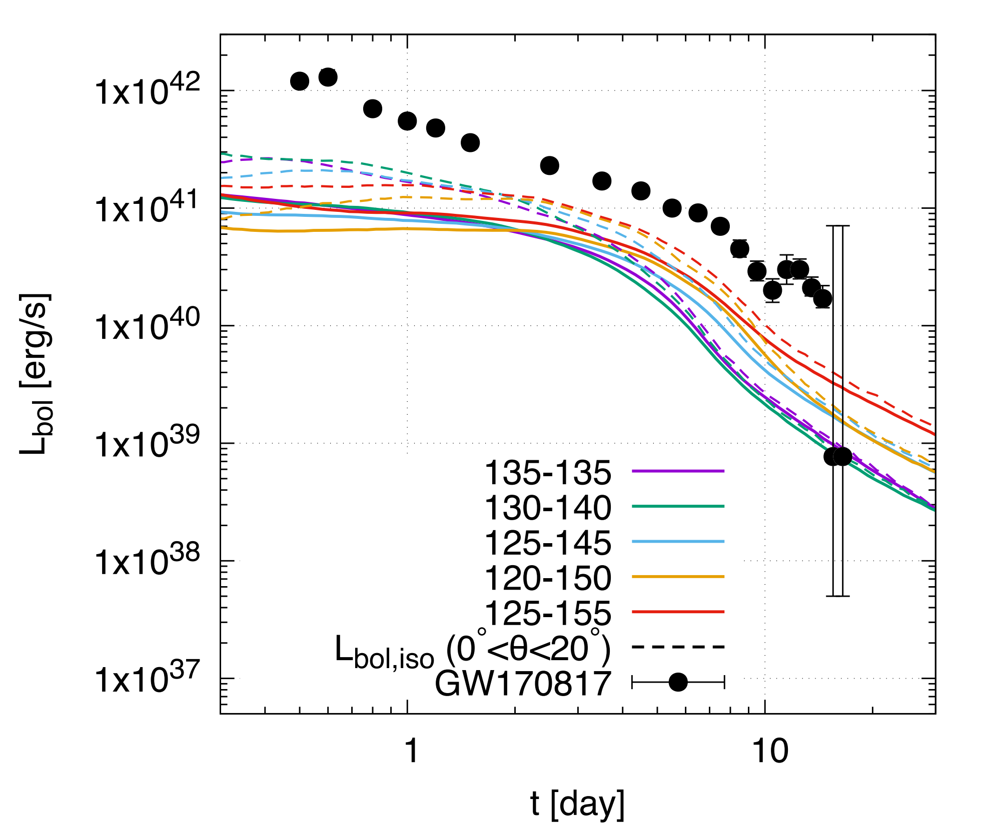
Short-lived remnant cases

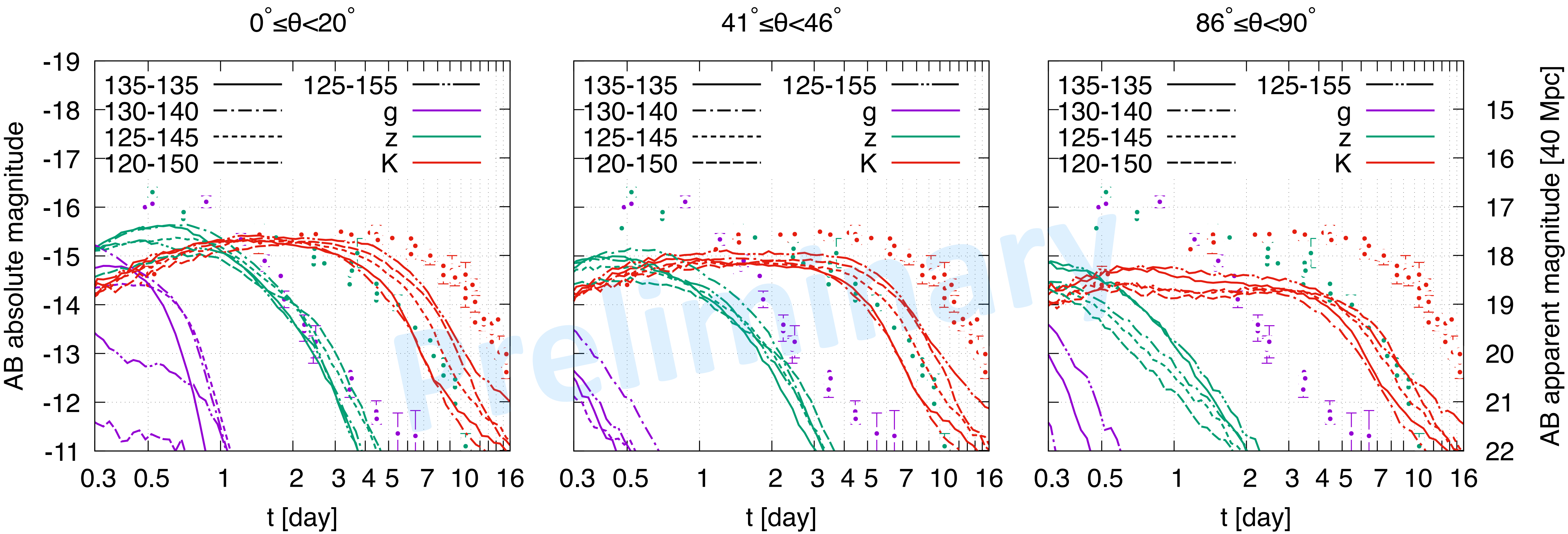
SFHo EOS, Mtot=2.7, 2.8 Msun, M1/M2=0.8-1



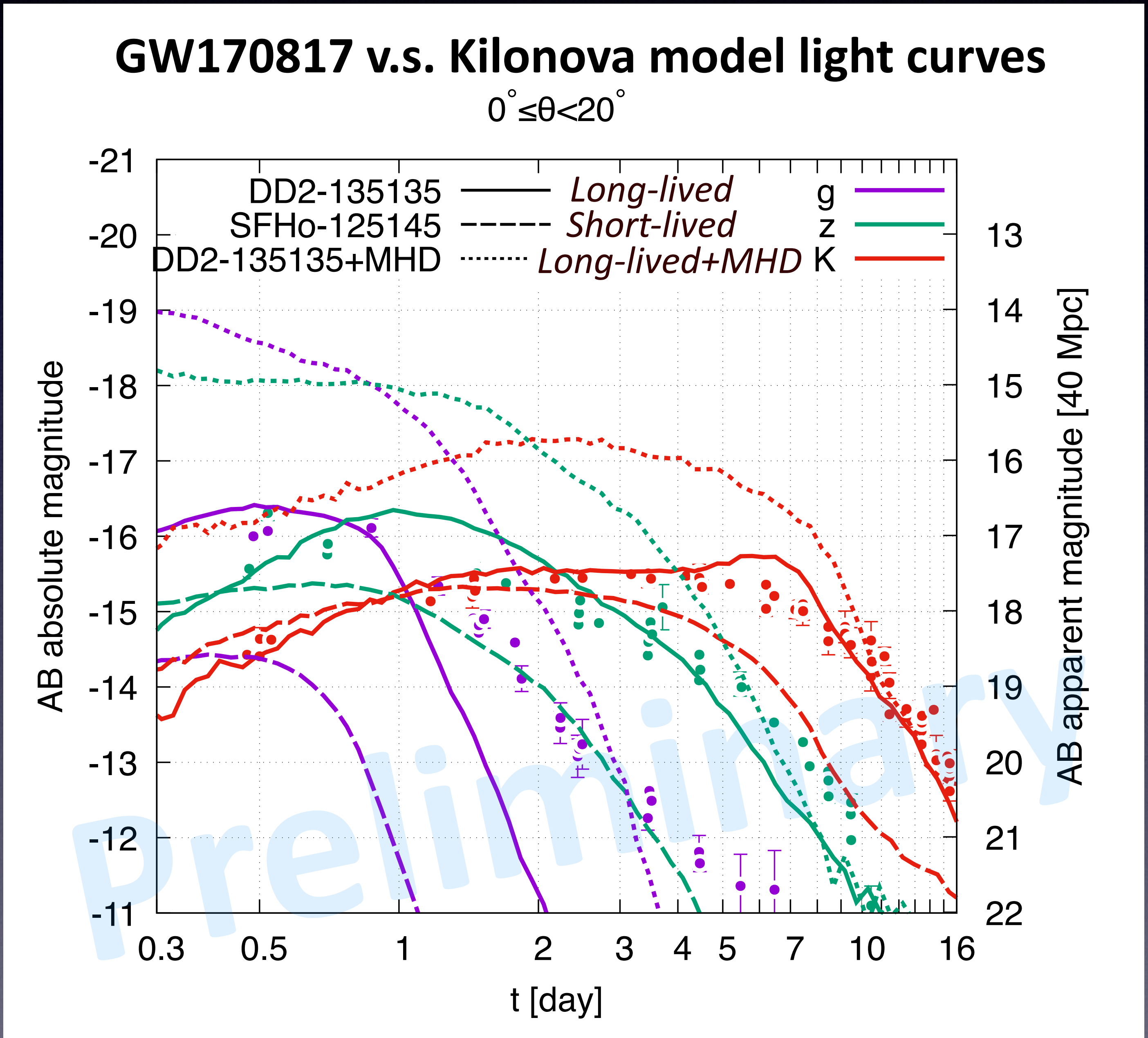
Meje=0.01-0.02

S. Fujibayashi et al. 2022,
KK et al. in prep.





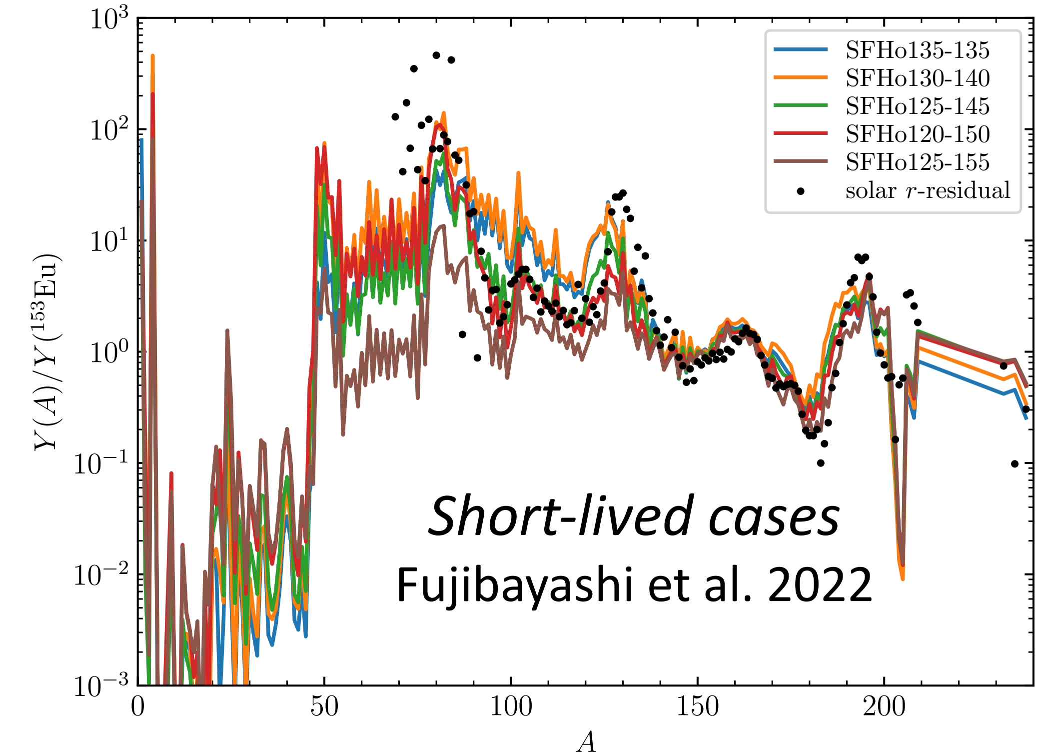
GW170817: short (<~10ms) or long-lived (>>1s)?

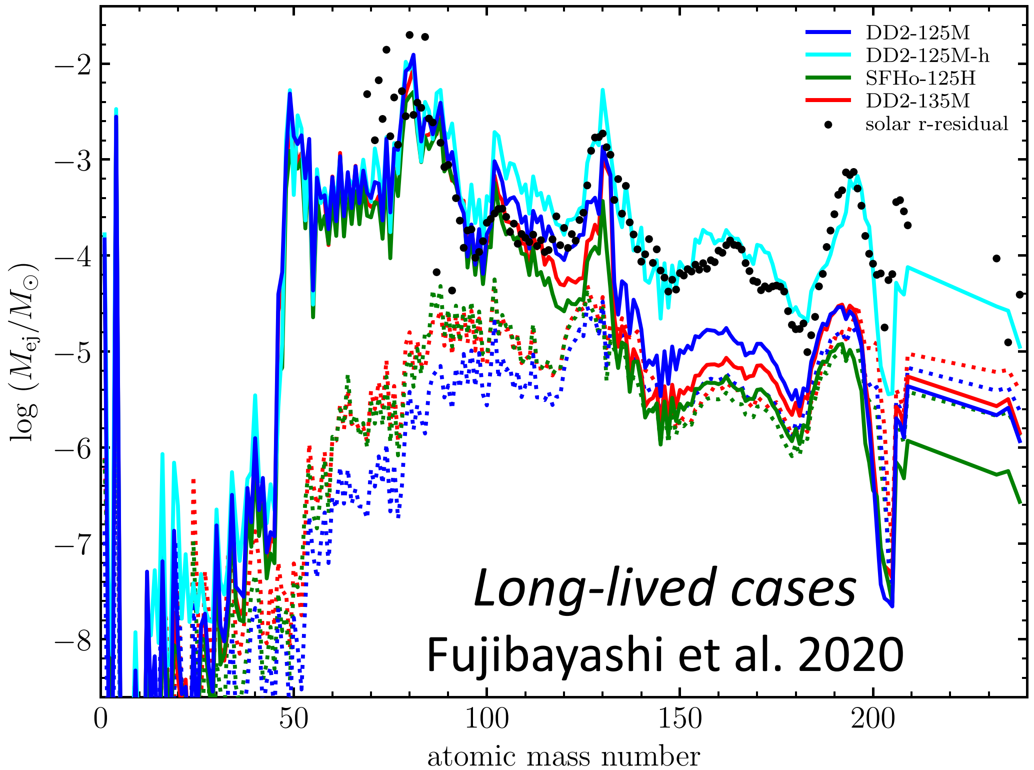


KK et al. 2021, 2022, in prep.

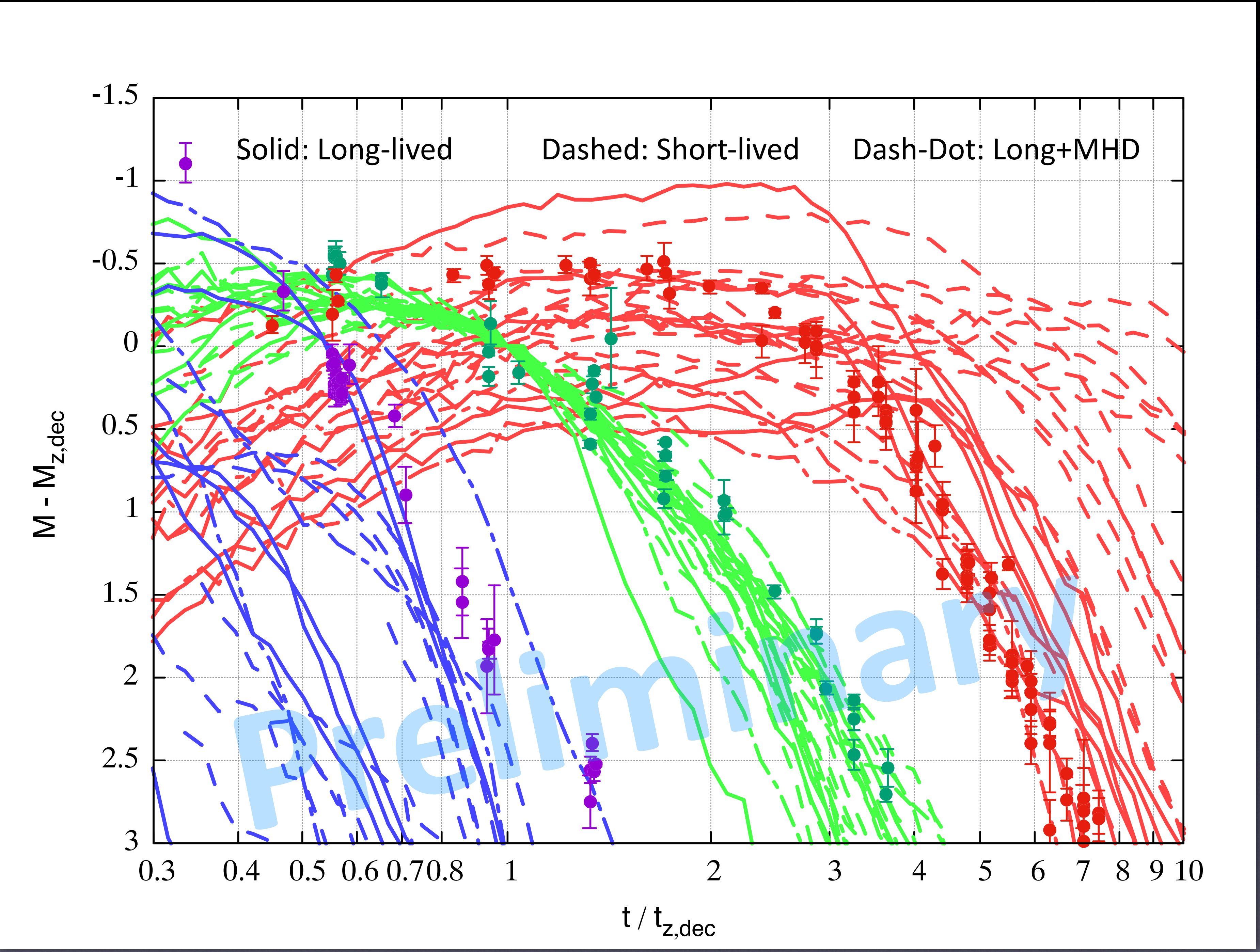
See Just et al. 2023 for similar implications

Nucleosynthesis yields v.s. Solar abundances





Quasi-Scaling law?



KK et al. in prep.

$$\frac{d\ln F_z}{d\ln t} = -1 @ t = t_{z,\mathrm{dec}}$$

Summary

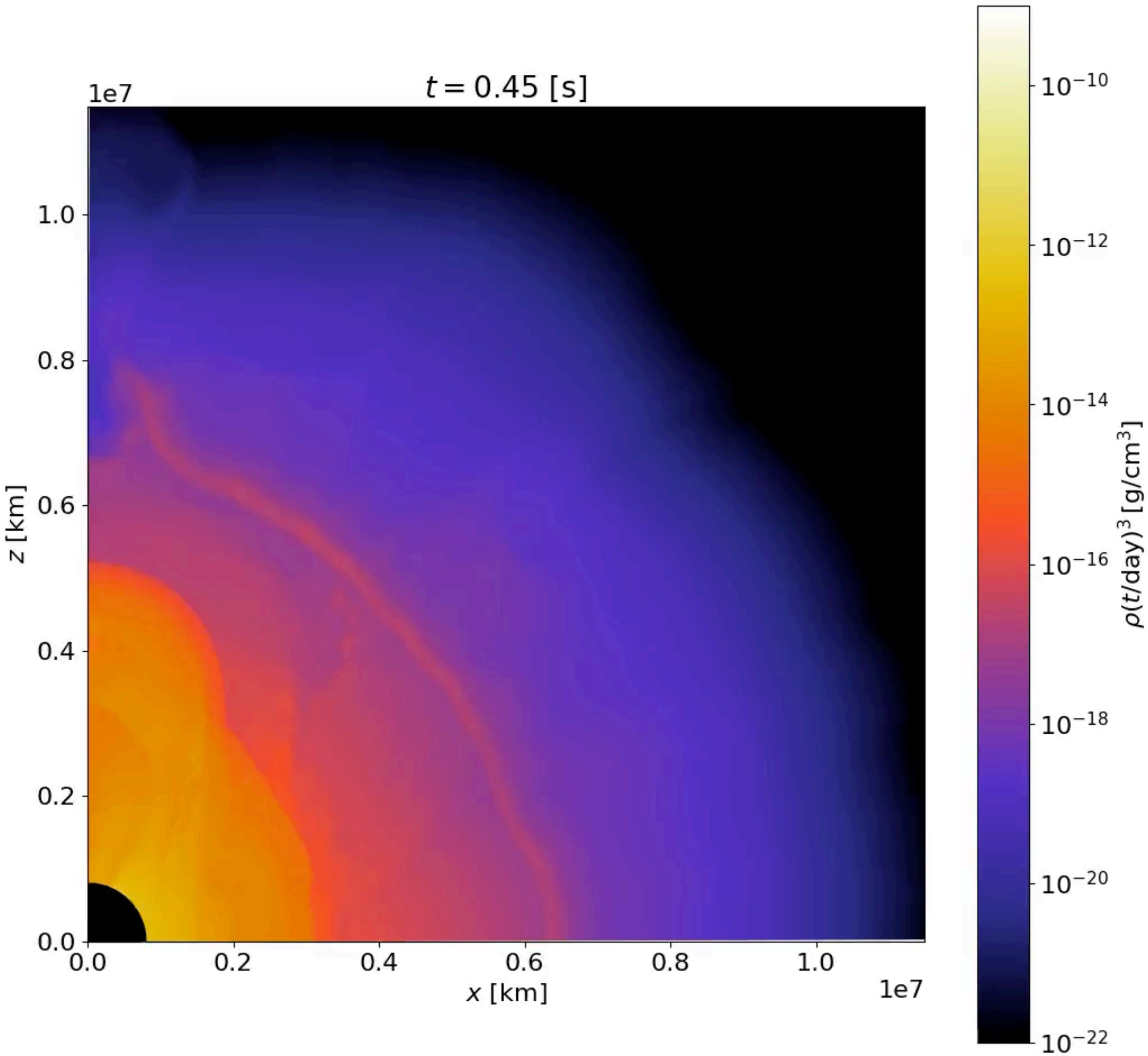
- Constructing realistic EM counterpart models is crucial to interpret the observations not only quantitatively but even qualitatively sense:
  - Radiative interaction between the multiple ejecta components with non-spherical geometry can change the whole picture of the interpretation
  - Employing ejecta profiles in the homologously expanding phase can also has a great impact on predicting the kilonova light curves
    - Direct, comprehensive prediction from merger simulations is now feasible, which also helps us to reduce the number of the model parameters
- Formation of a short-lived (<20ms) or a long-lived (>>1s) remnant with significant magnetic dynamo effects is not likely to be the case in GW170817.
  - Still many questions: blackbody-like spectra and the absorption like features, nucleosynthesis yields…
    May be more other possibly missing ingredients needed to interpret the observation data fully consistently: magnetic field dynamo effects, non-LTE effect, jet-ejecta interaction…and various uncertainties/varieties
  - new events and those multifaceted/integrated investigation are crucial!

Appendix

Longterm ejecta evolution (long-lived case)

Rest-mass density profile
(1.25-1.25 Msun: DD2)

Fujibayashi et al. 2020
KK et al. 2021



Reaches Homologous expansion phase at ~1000s

Caveats: many uncertainties/varieties

- Model systematics/uncertainty
  - ejecta profile ←KN afterglow (fast tail)
  - nuclear model ←nuclear experiment

  ←Chemical abundance

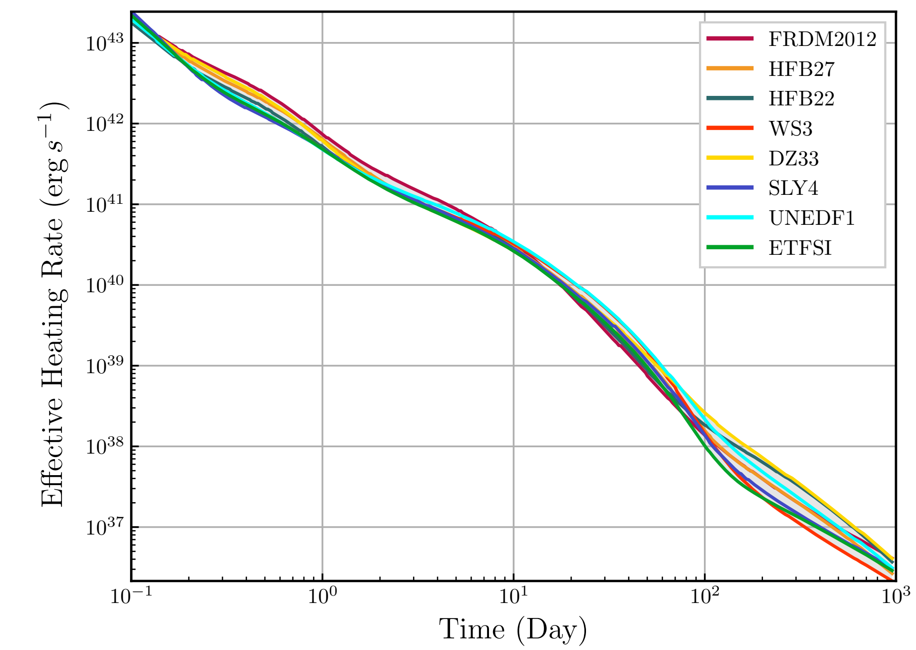
  - opacity ←atomic experiment
  - LC modeling
  - NS equation of state ←NS observation
- Astrophysical variety
  - NS mass, spin, (eccentricity)
  - binary composition (NSNS, BHNS…)
  - viewing angle
  - environment

  ←GW

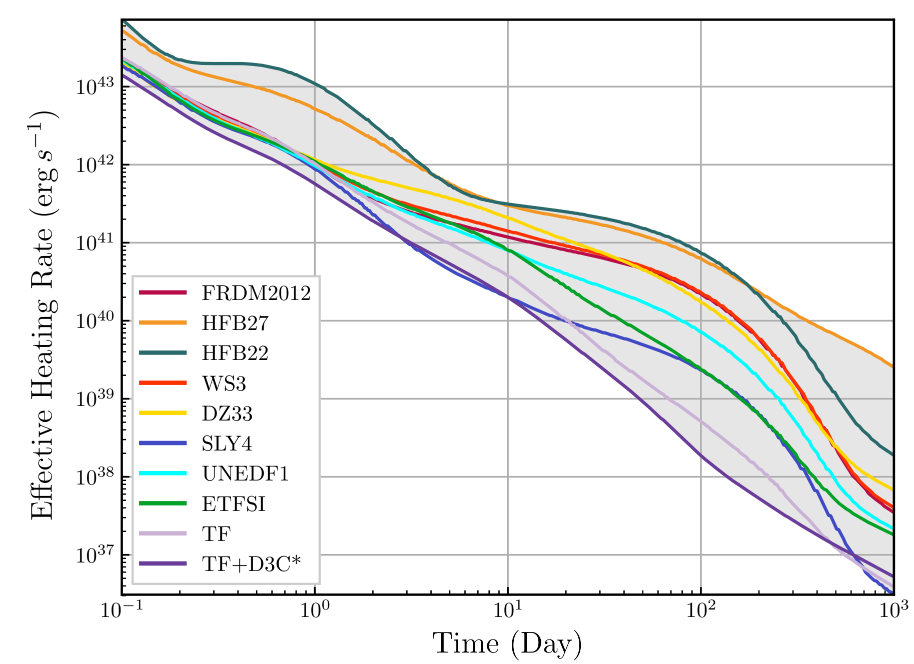
  ←GRB after glow

Effective heating rate for various nuclear models

ref) Zhu et al. 2020, Barnes et al. 2020



(a) Simulations with $Y_e = 0.24$.

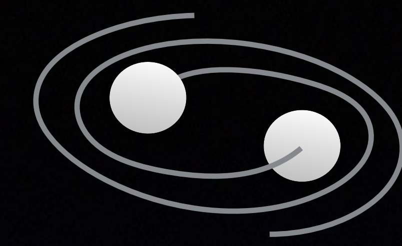


(b) Simulations with $Y_e = 0.16$.

Ingredients

- Ejecta property :
  mass, (internal energy), velocity, composition, geometry
- Heating source
- Opacity

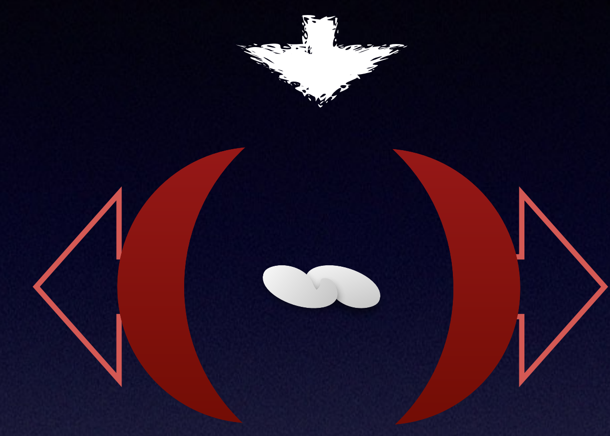
Ejecta property



- **Dynamical mass ejection**
  mass ejection driven by
  tidal interaction/ collisional shock heating

$$M_{\rm eje} \sim 0.001 - 0.01 M_\odot$$

(e.g., Bauswein et al. 2013, Hotokezaka et al. 2013, Sekiguchi et al. 2016, Radice et al. 2016, Dietrich et al. 2017, Bovard et al. 2017, Kiuchi et al. 2018, Foucart et al. 2018, Bernuzzi et al. 2020, Just et al. 2021, Kullmann et al. 2022, Combi et al. 2022, Foucart et al. 2022)

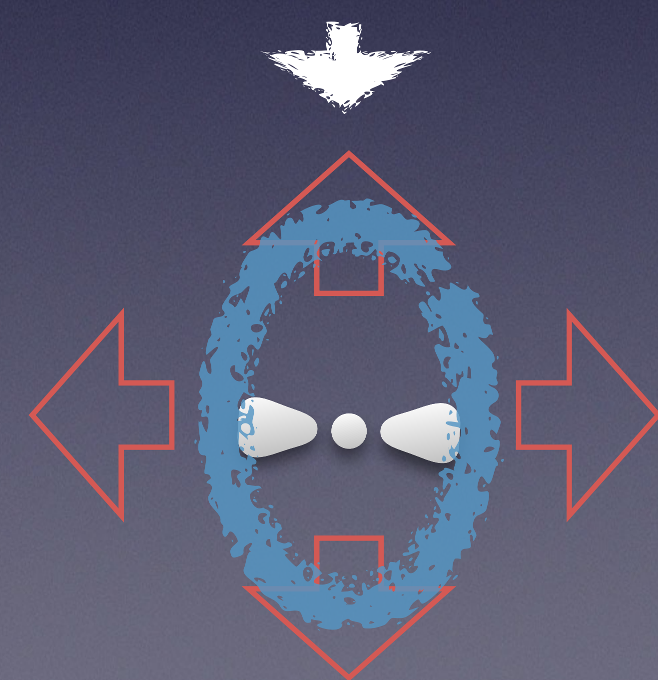


Dynamical mass ejection @merger

- **Post-merger mass ejection**
  mass ejection from the merger remnant driven by
  magnetic fields / effective viscosity / neutrino heating/
  alpha recombination

$$M_{\rm eje} \sim 0.01 - 0.1 M_\odot$$

(e.g., Dessart et al. 2009; Metzger & Fernández 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, Christie et al. 2019, Millar et al. 2019, Fujibayashi et al. 2020, Ciolfi & Kalinani 2020, Foucart et al. 2020, Ferńandez et al. 2020, Mosta et al. 2020, Nedora et al. 2021, Shibata et al. 2021, De & Siegel 2021, Li & Siegel 2021, Just et al. 2021, 2022, Fujibayashi et al. 2022, Kiuchi et al. 2022)



Post-merger mass ejection @after merger

- **Relativistic jets**

(e.g., Rezzolla et al. 2011, Ruiz et al. 2016, 2021, Sun et al. 2022)

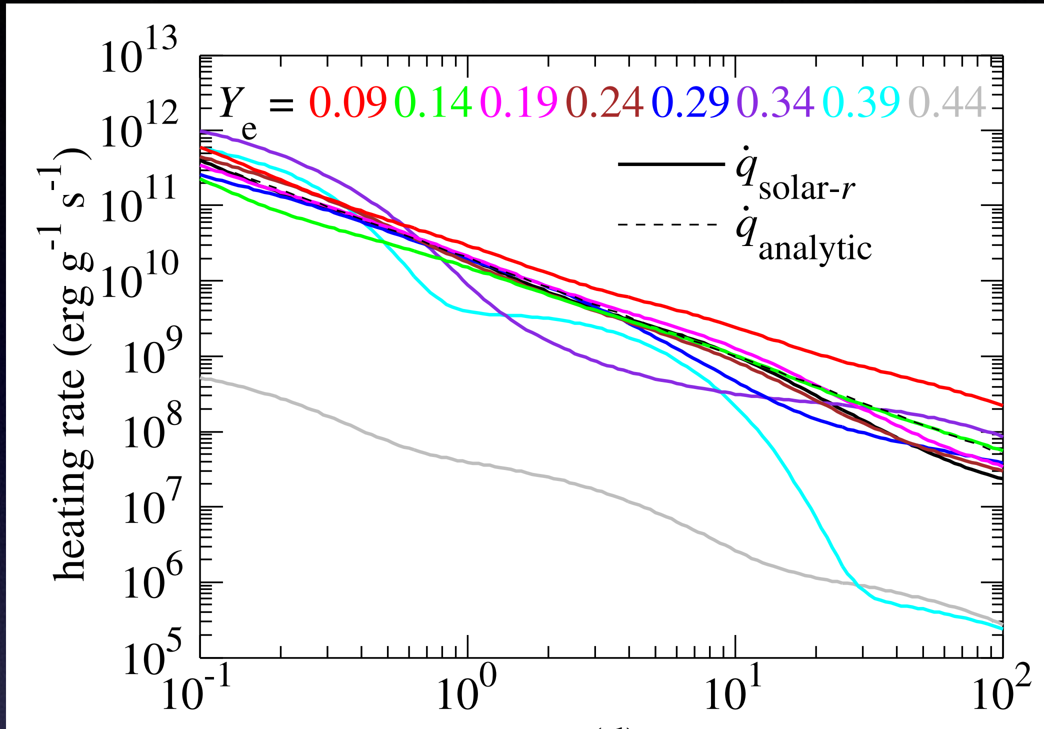
Different ejection mechanism results in ejecta with different velocity and composition (electron fraction), and geometory

Heating Source

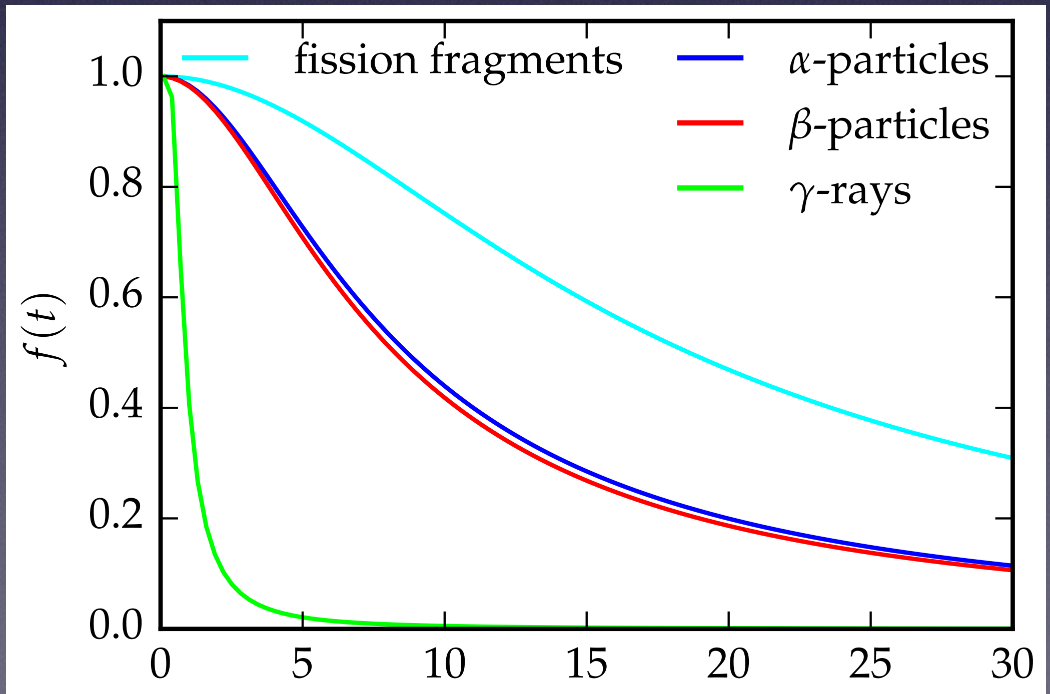
electron fraction
(~neutron poorness)

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

- **Radioactive decay**
  (e.g., Li et al. 1998, Qian et al. 2008, Korobkin et al. 2012, Wanajo et al. 2014, Lippuner et al. 2015)
  - β decay (high energy e, γ, ν)/ α decay/ Spontaneous fission
- **Thermalization**
  (e.g., Metzger et al. 2010, Hotokezaka et al. 2016, Barnes et al. 2016, Kasen et al. 2018, Waxman et al. 2019, Hotokezaka et al. 2020)
  - photo-ionization (γ)
    collisional ionization /excitation
    (β-electron, α particle, nuclei)
- **Another possible energy source:**
  - Free neutron decay (~a few hours)
    (e.g., Metzger et al. 2014, Gottlieb et al. 2020)
  - Release of Internal energy (cocoon)
    (e.g., Nakar et al. 2017, Piro et al. 2017, Kasliwal et al. 2017, Gottlieb et al. 2020)
  - a new-born magnetor / BHfall-back accretion
    (e.g., Yu et al. 2013, Wang et al. 2013, Metzger et al. 2014, Kisaka et al. 2015, Matsumoto et al. 2018, Li et al. 2018)



ref) Wanajo et al. 2014



ref) Barnes et al. 2016

Opacity

electron fraction
(~neutron poorness)

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

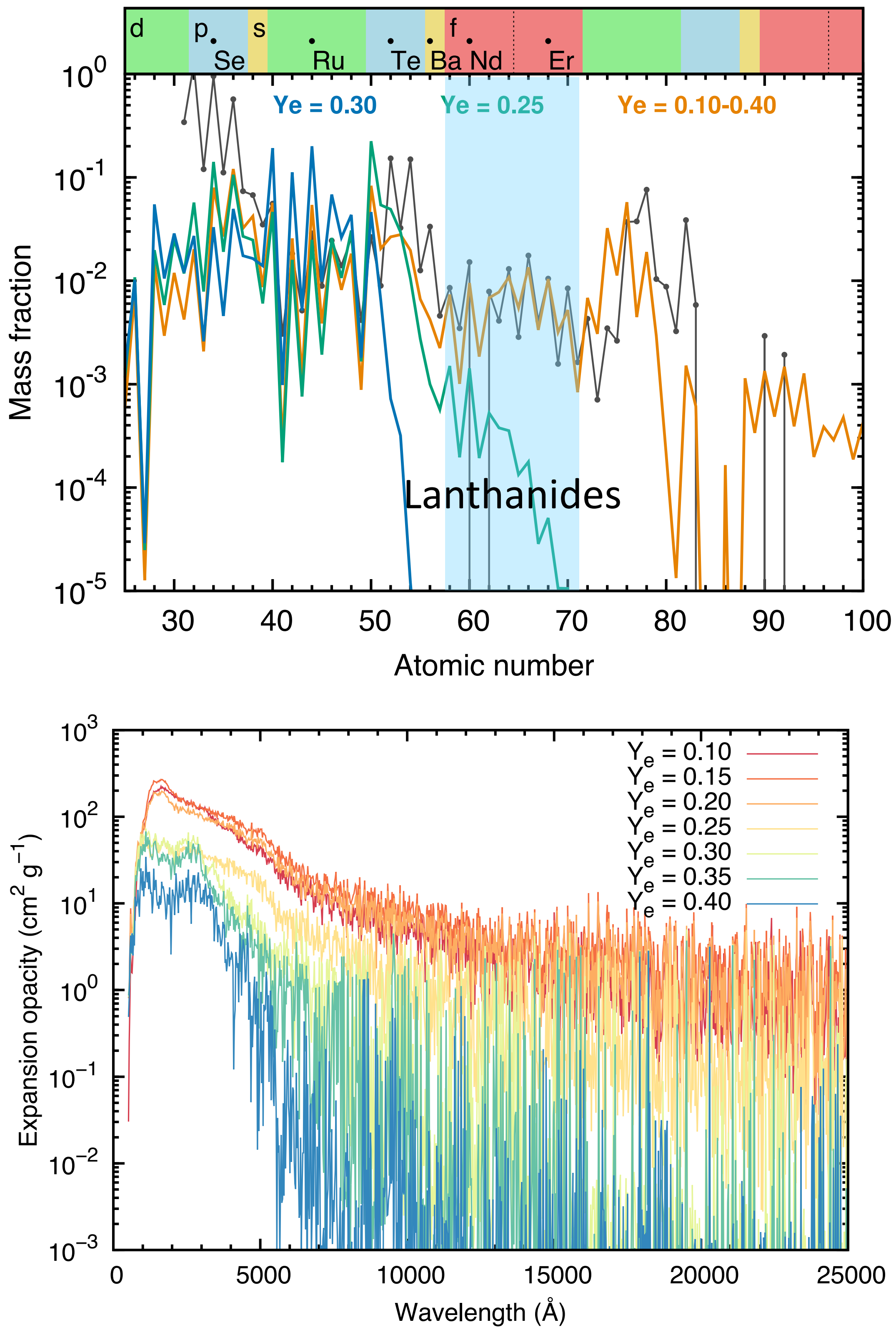
- Bound-bound transision opacity of heavy elements dominates opacity in kilonova ejecta
  (e.g., Barnes et al. 2013, Kasen et al. 2013, 2015, Metzger et al. 2014, Tanaka et al. 2013, 2018, 2020, Fontes et al. 2020, 2022)

- Strong dependence on the element abundances, such as the presence of lanthanide elements

  - **Not only lanthanides:**
    Opacity of the 1st-peak r-process elements, such as, Zr and Y also play important roles
    (see Watson et al. 2019, KK et al. 2020, 2021, Ristiks et al. 2022, Gillanders et al. 2022)

- Also crucial to take the wavelegnth, density, temparature, and temporal denependence into account

Wanajo et al. 2014, Tanaka el al. 2020



Diffusion and Nebular phases

Optical depth:

$$\tau = \kappa \rho R_{\rm eje} \qquad M_{\rm eje} = \frac{4\pi}{3} R_{\rm eje}^3 \rho$$

$$R_{\rm eje} = v_{\rm eje} t$$

κ :opacity $R_{\rm eje}$:ejecta radius

ρ :ejecta mass density $M_{\rm eje}$:ejecta mass

t : elapsed time $v_{\rm eje}$:expanding velocity

Optical thin time: $\tau \approx 1 @ t = t_{\rm thin}$

$\Rightarrow$

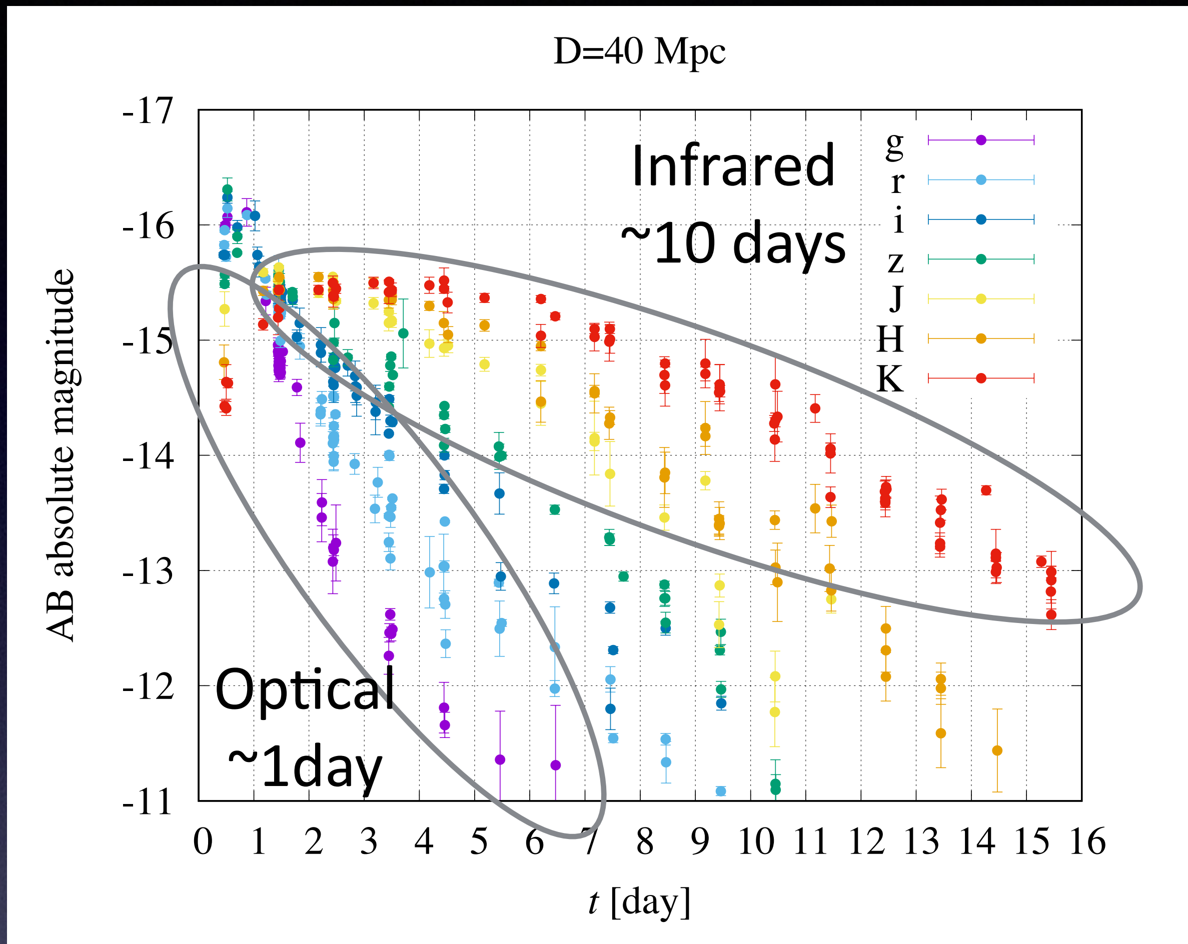
$$t_{\rm thin} = \sqrt{\frac{3\kappa M_{\rm eje}}{4\pi v_{\rm eje}^2}} \approx 13\,{\rm day} \left(\frac{M_{\rm eje}}{0.01\,M_\odot}\right)^{1/2} \left(\frac{\kappa}{10\,{\rm cm^2 g^{-1}}}\right)^{1/2} \left(\frac{v_{\rm eje}}{0.2\,c}\right)^{-1}$$

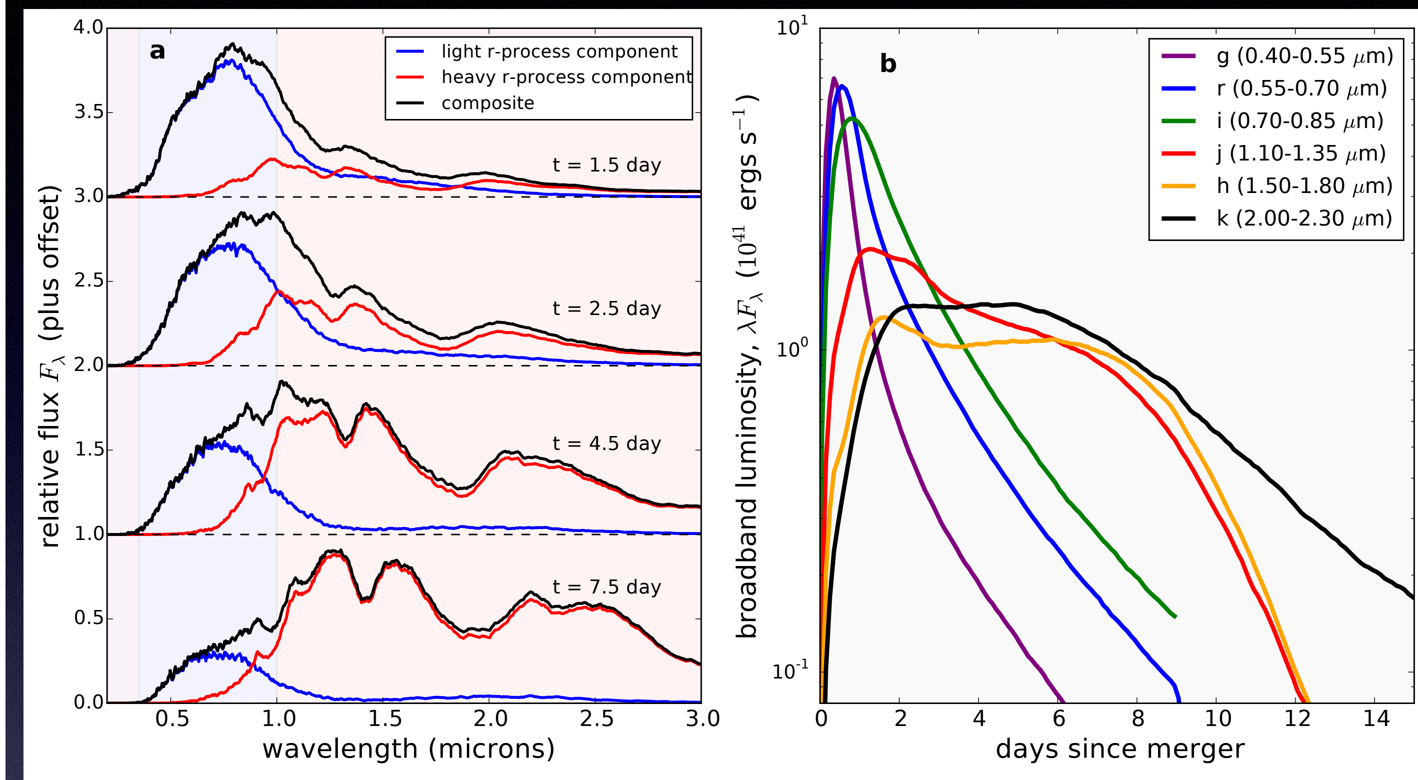
- *Optically thick Diffusion phase: t<<t_thin*
  complex spatial & geometrical dependence / simple microphysics (LTE)

- *Optically thin Nebular phase: t>>t_thin*
  simple spatial & geometrical dependence /complex microphysics (non-LTE)

Diffusion phase Light curve

GW170817: Summarized in Villar et al. 2017





Ref: D. Kasen et al. 2017

Fitting of multi-band lightcurves of continuum emission tells us many about ejecta property

- A Kilonova model consist of multiple ejecta components well interprets the optical-Infrared observation in GW170817 (e.g., Kasliwal et al. 2017, Drout et al. 2017, Cowperthwaite et al. 2017, Kasen et al. 2017, Villar et al. 2017)

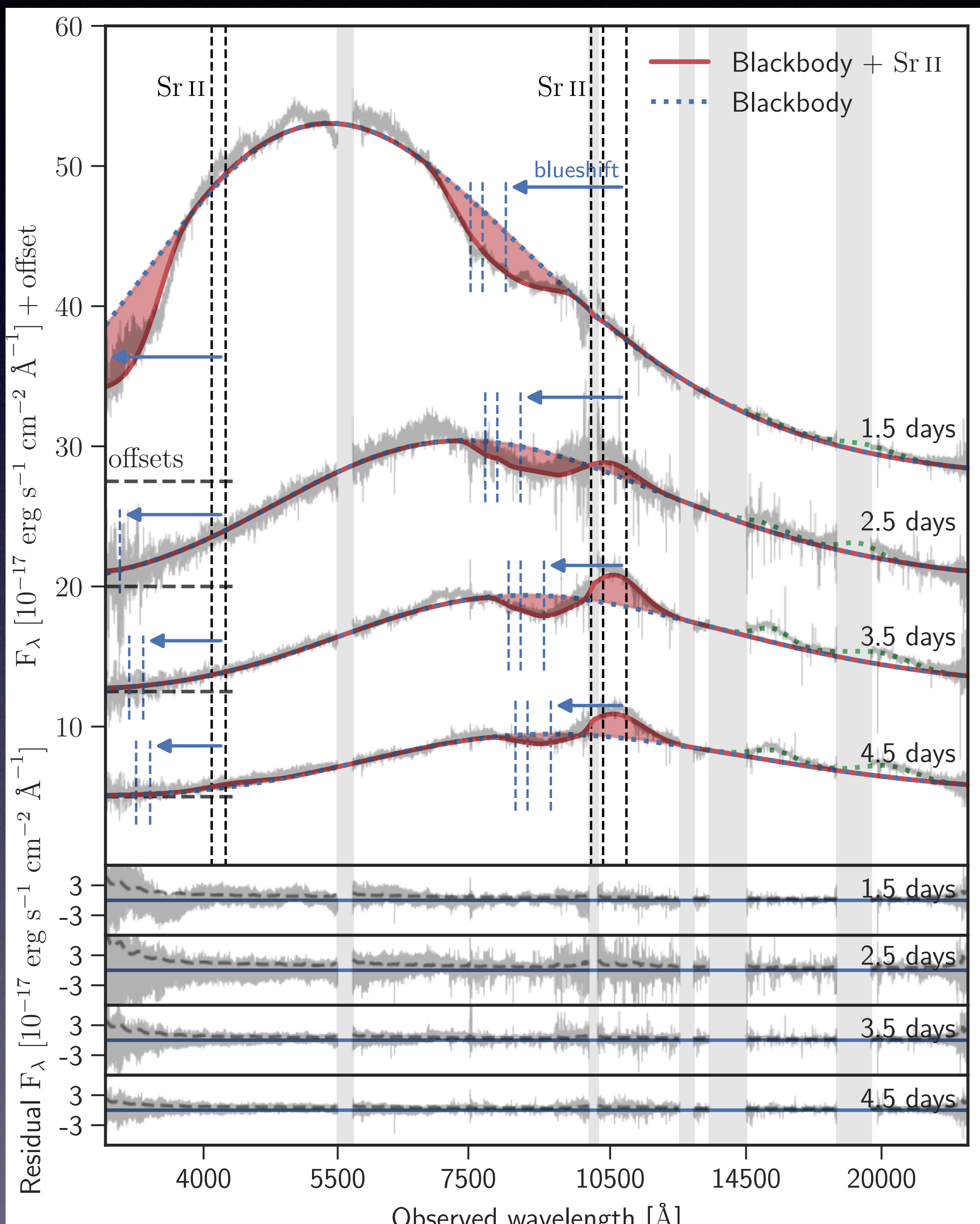
  early optical component (~1day) from **a lanthnide free "blue component"**

  long-lasting infrared component (~10days) from **a lanthanide rich "red component"**

- Alternative interpretation: e.g., the cental engine activity powered emission (e.g., Matsumoto et al. 2018, Li et al. 2018)
- **Early phase light curve will be critical for determining emission mechanism (I. Arcavi et al. 2018, Banerjee et al. 2020, 2022)**

Spectra analysis

Watson et al. 2019



More information about element abundance: atomic data with accurate line wavelengths are required

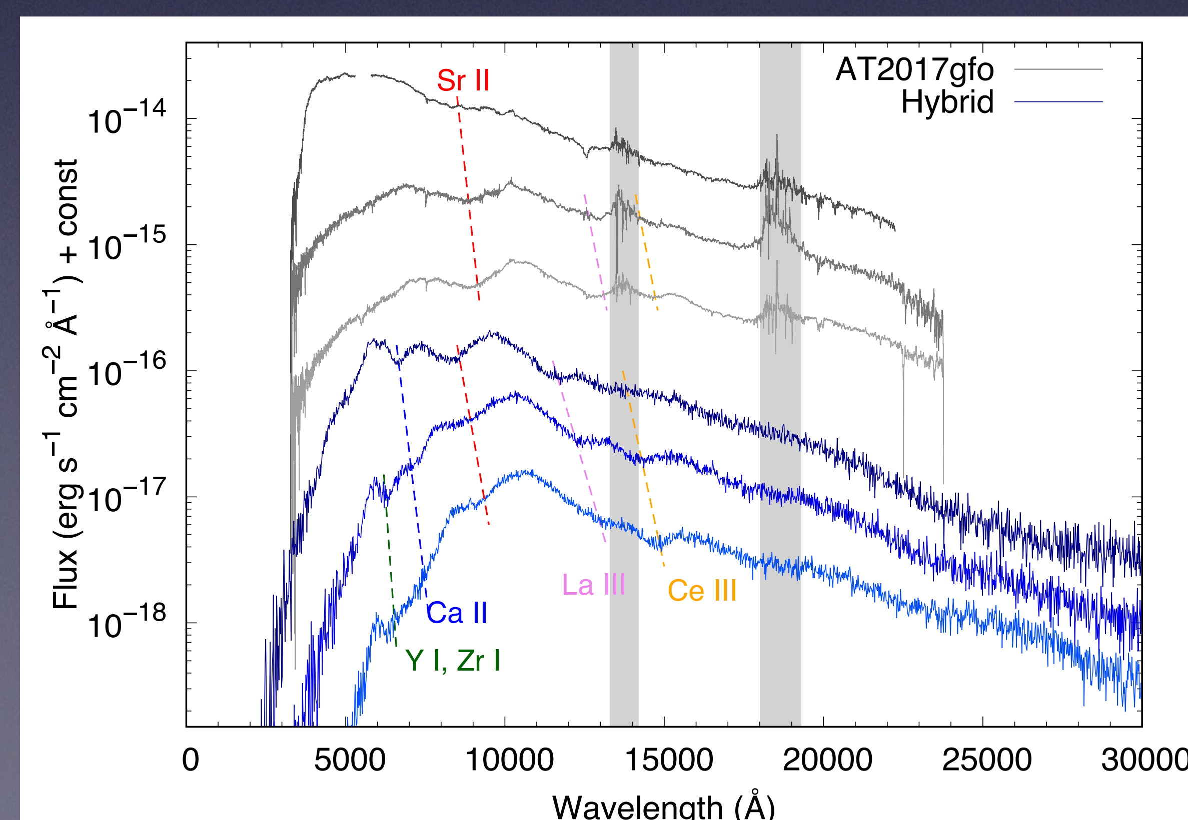
- Probable identification of SrII line:

  (Watson et al. 2019, Domoto et al. 2021 , Gillanders et al. 2022)

  - He I line with NLTE effect? (Perego 2021)

- Probable identification of LaIII and CeIII lines:

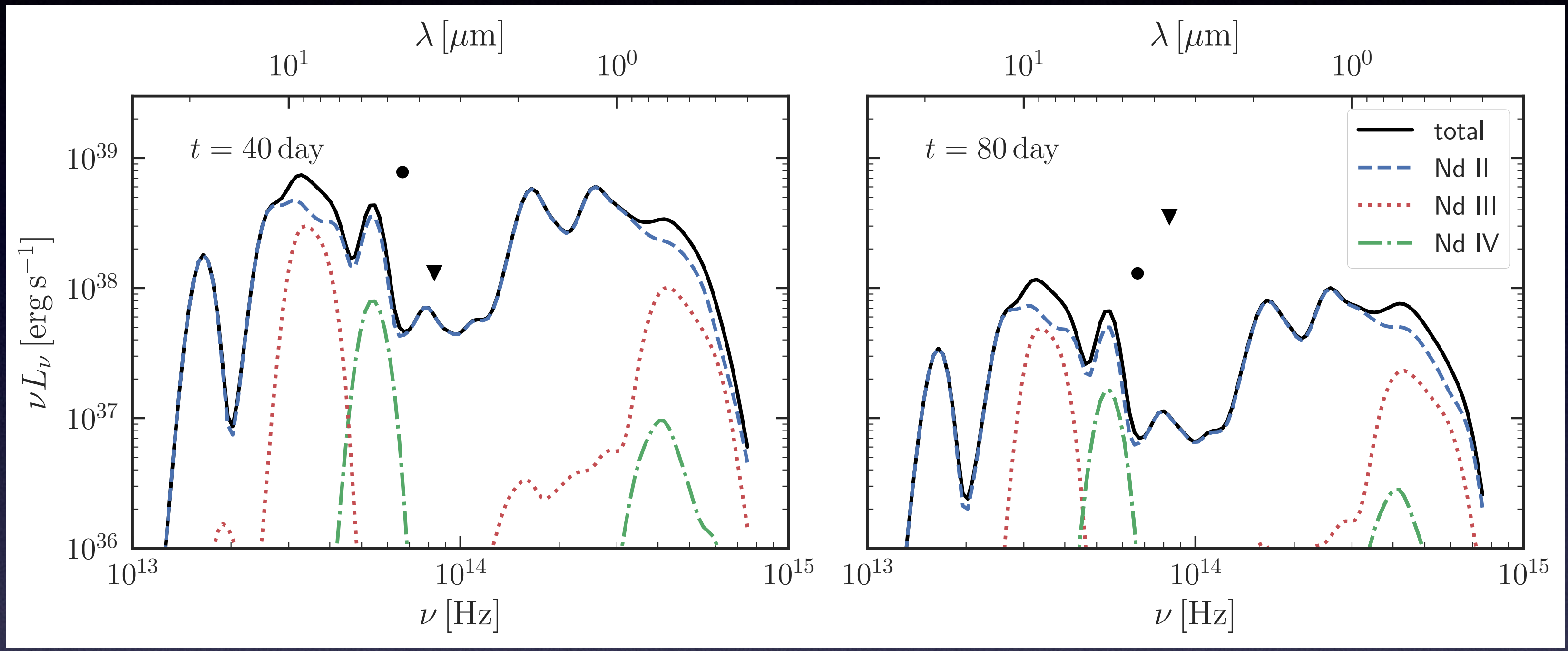
  (Domoto et al. 2022)



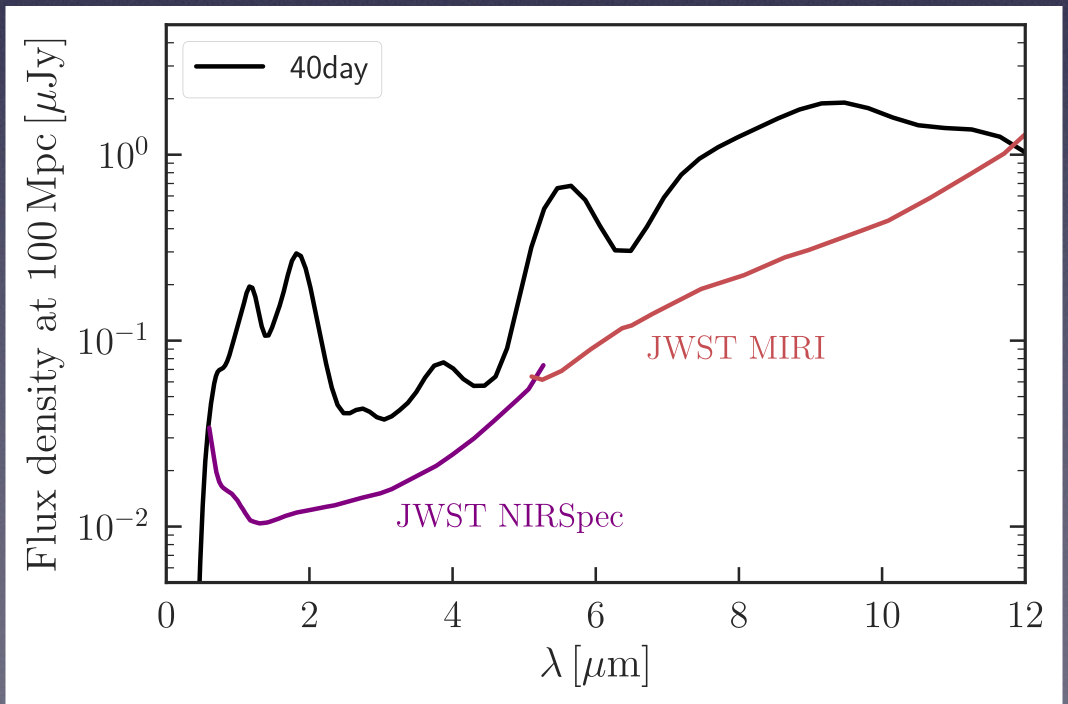
N. Domoto et al. 2022

Nebula phase spectra

K. Hotokezaka et al. 2020



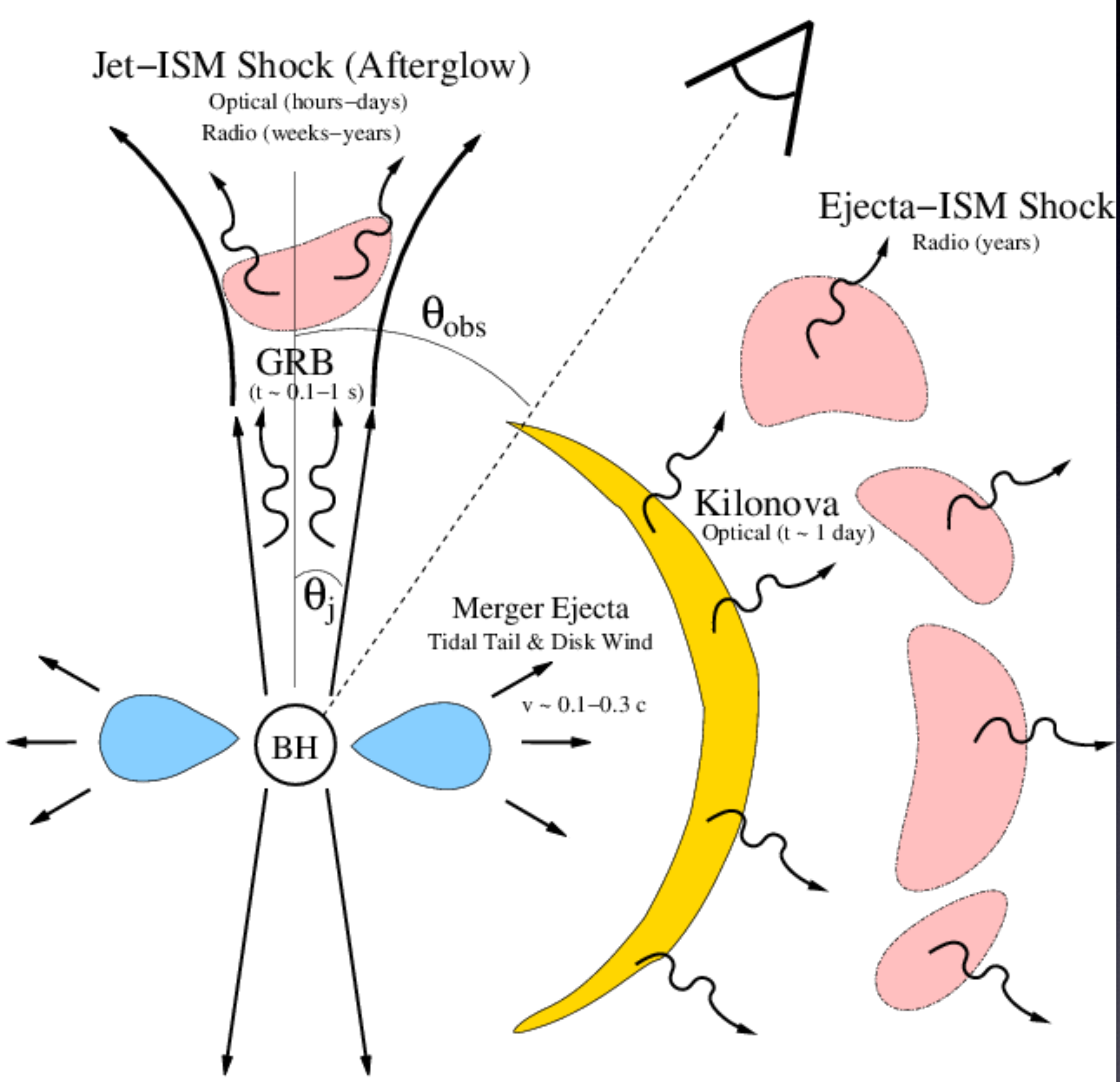
- Accurate atomic data (ionization/excitation rate recombination rate) **+ Non-LTE treatment**
  - Nd (Hotokezaka et al. 2021)
  - Au and Pt (Gillander et al. 2021)
  - Se / W, Os, Rh, Ce (Hotokezaka et al. 2022)
- See also Pognan et al. 2021, 2022 for the study for non-LTE property



Electromagnetic Counterparts of Neutron star binary mergers

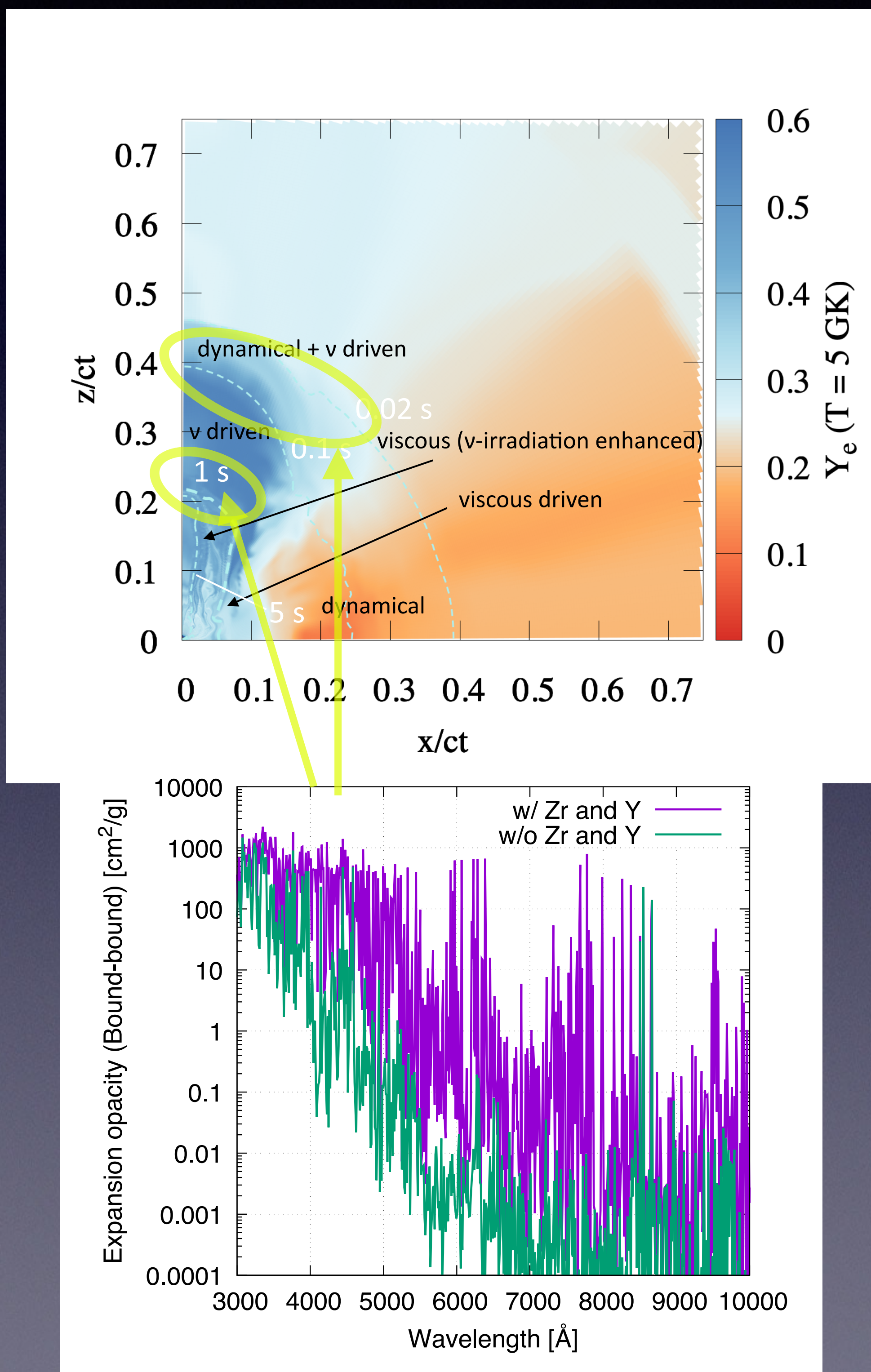
- A neutron star (NS) binary merger: one of the main target for ground-based gravitational wave detectors (LIGO, Virgo, KAGRA)

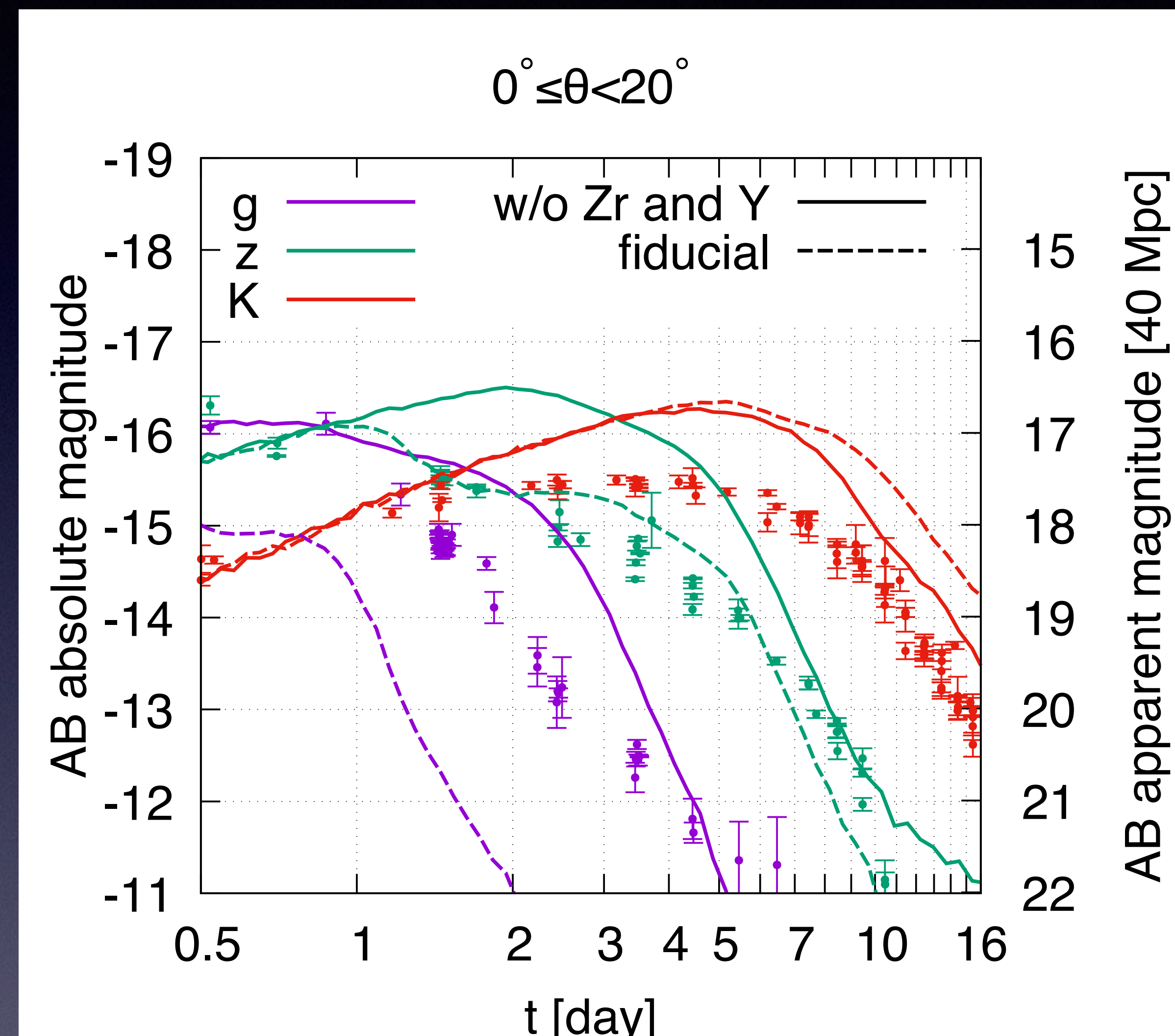
- Various transient EM counterparts that associate with NS binary mergers:
  - Merger Precursor
  - short-hard gamma-ray-burst
  - Afterglow
  - cocoon emission
  - kilonovae/macronovae
  - radio flare, etc.
- Host galaxy identification, remnant properties, environment



Ref: B. Metzger and E. Berger 2012

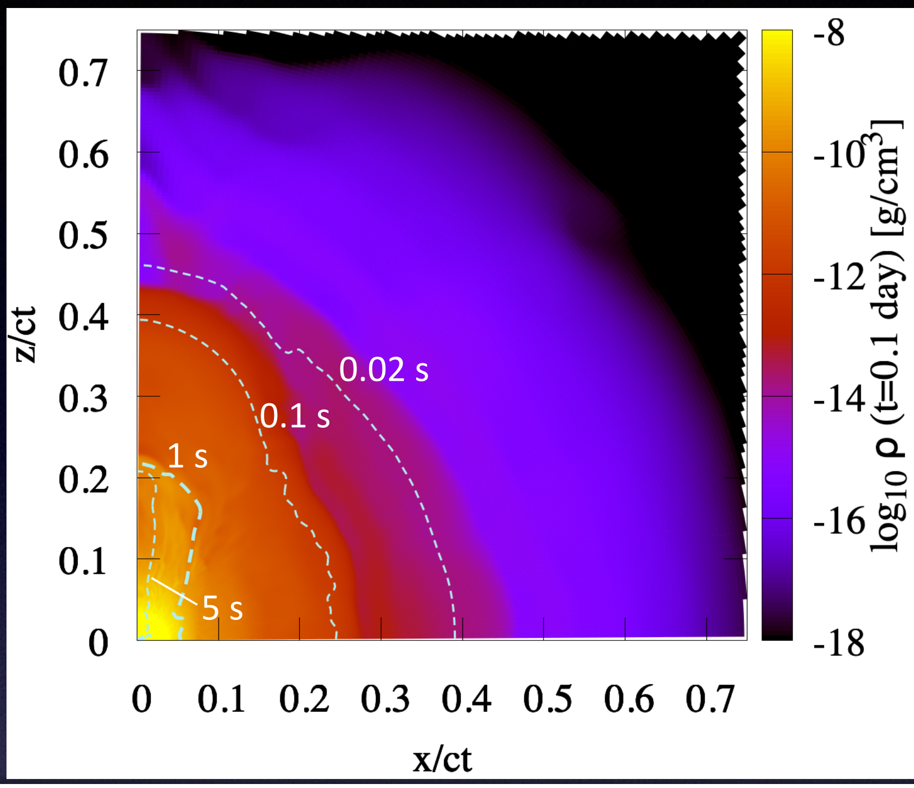
Not only lanthanides: Opacity of the 1st-peak r-process elements

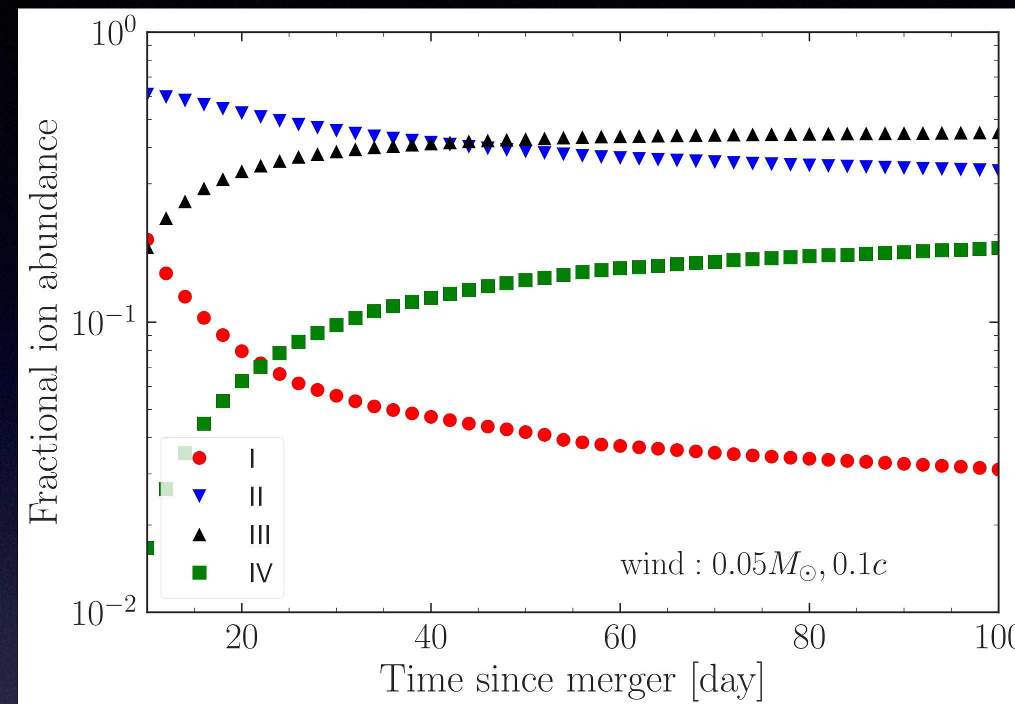




- a large amount of 1st r-process peak elements including **Zr (Z=40) and Y (Z=39)** are present in the polar high velocity region
- Zr and Y (d-shell element) have a great contribution to the opacity in the optical band (**~>4000 Å)** **(see also Watson et al. 2019, Gillanders et al. 2022)**

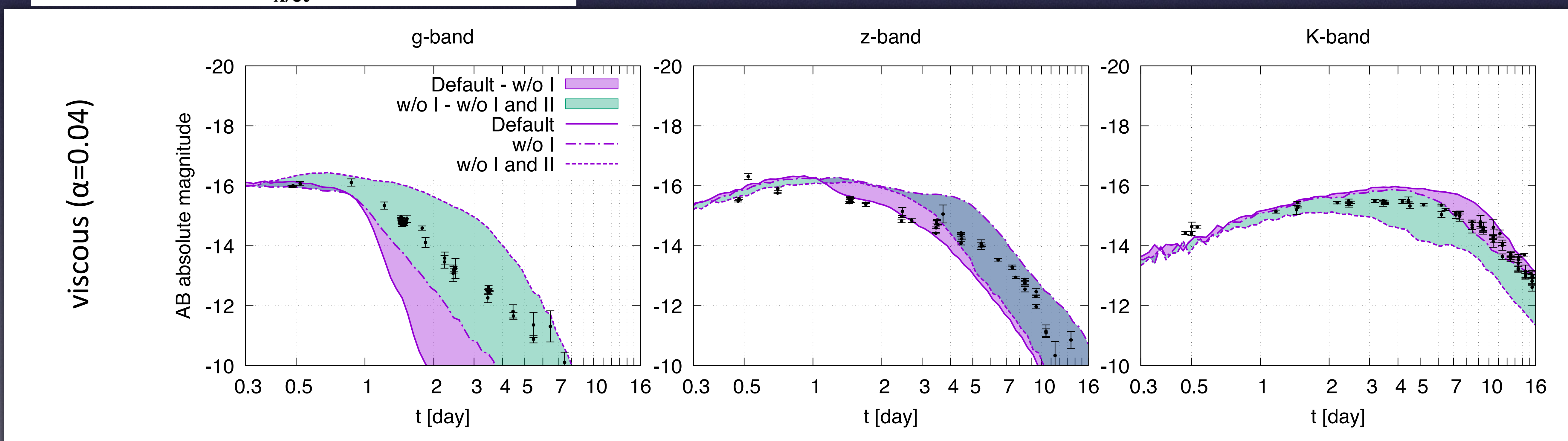
Possible Non-LTE effect in Diffusion phase





Hotokezaka et al. 2020

KK et al. 2021, 2022



see also Q. Pognan et al. 2021,2022 for the study of non-LTE property
and J. Barnes et al. 2021 for the impact of heating rate uncertainty to the ionization structure

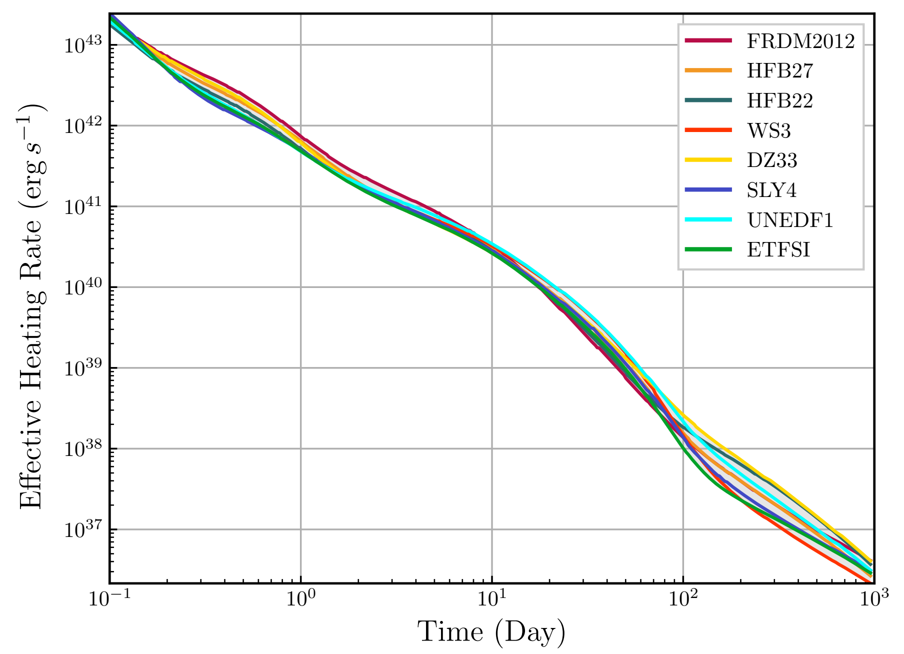
Caveats: many uncertainties/varieties

- Model systematics/uncertainty
  - ejecta profile ←**KN afterglow (fast tail) chemical abundance**
  - nuclear model ←**nuclear experiment**
  - opacity ←**atomic experiment/ stellar observation**
  - LC modeling
  - NS equation of state ←**NS observation**
- Astrophysical variety
  - NS mass, spin, (eccentricity)
  - binary composition (NSNS, BHNS…)
  - viewing angle
  - environment

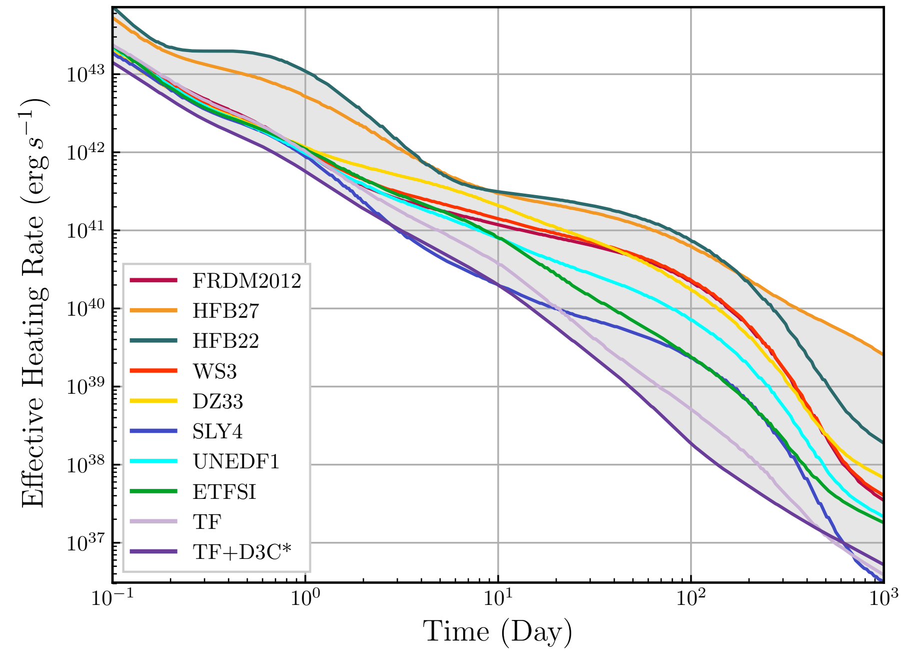
(NS equation of state through viewing angle ←**GW**; viewing angle and environment ←**GRB after glow**)

Effective heating rate for various nuclear models

ref) Zhu et al. 2020

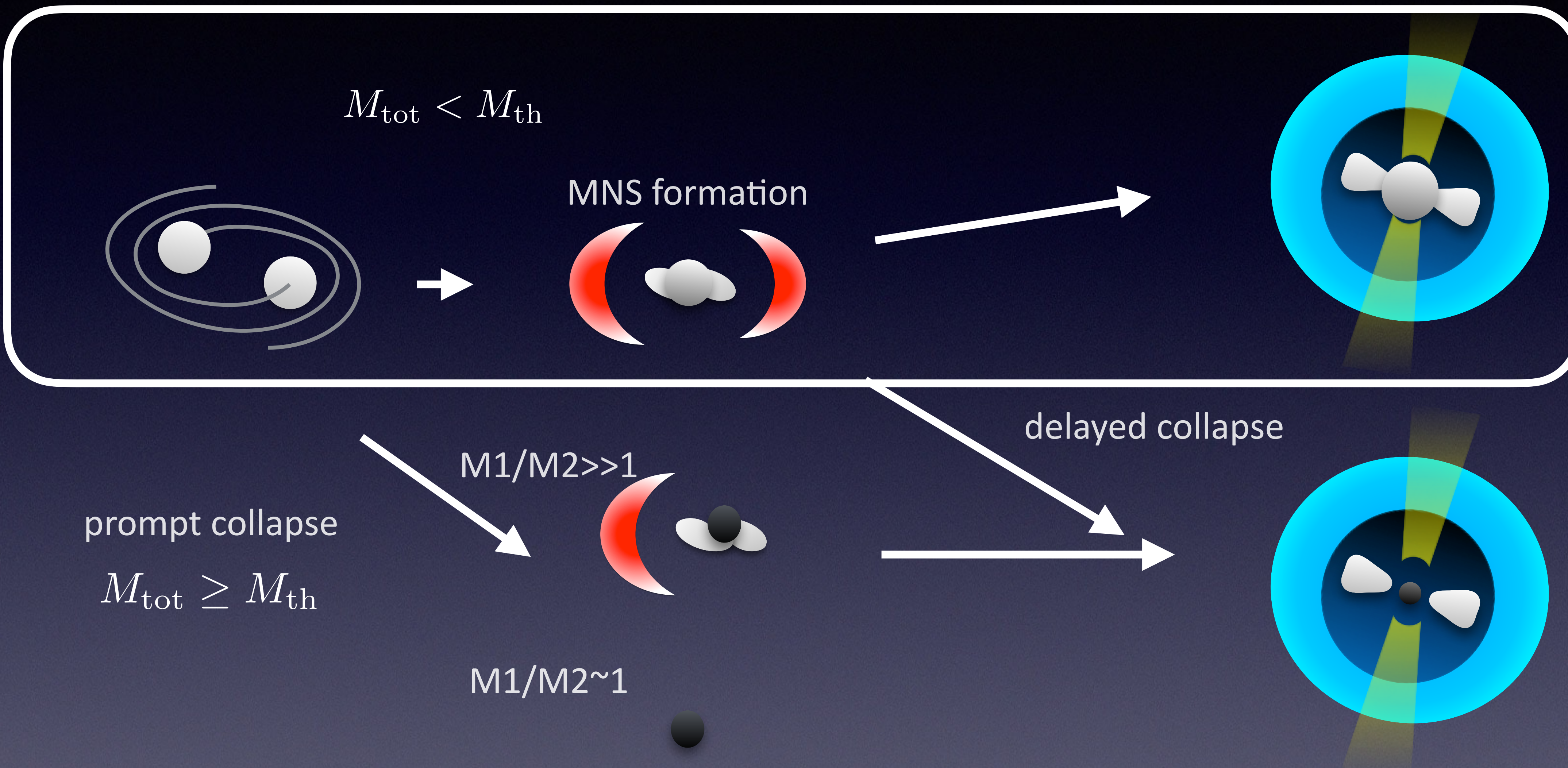


(a) Simulations with $Y_e = 0.24$.



(b) Simulations with $Y_e = 0.16$.

Model: BNS with a Long-lived remnant NS



- **DD2-125M in Fujibayashi et al. 2020:**
  1.25 Msun-1.25 Msun, DD2 EOS (13.1 km@1.25 Msun)
  The remnant massive NS survives for ~>8 s after the merger

Long-term Hydrodynamics simulation of ejecta

- Relativistic Eulerian hydrodynamics code with a fixed background spacetime metric (axis & equatorial symmetry)

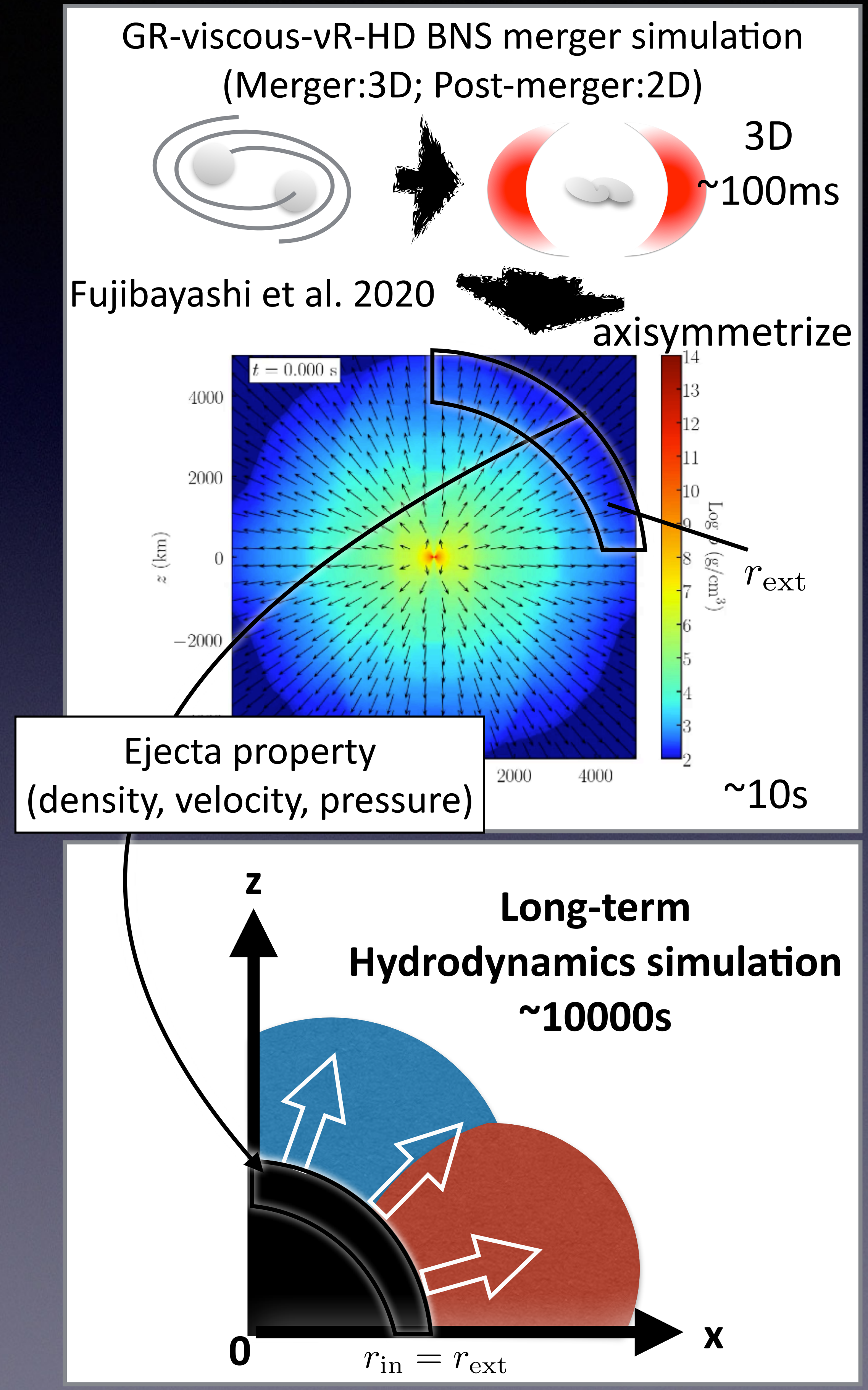
  r: log uniform, θ: uniform mesh (r:1024 , θ:128 grid points)

- Set outflow data obtained by Numerical relativity simulations of BNS mergers as the inner boundary condition (r=8000km) in the ejecta hydrodynamics simulation （dynamical+post merger ejecta)

- The long-term hydrodynamics evolution of the ejecta is followed until it reaches the homologously expanding phase (~0.1 day)

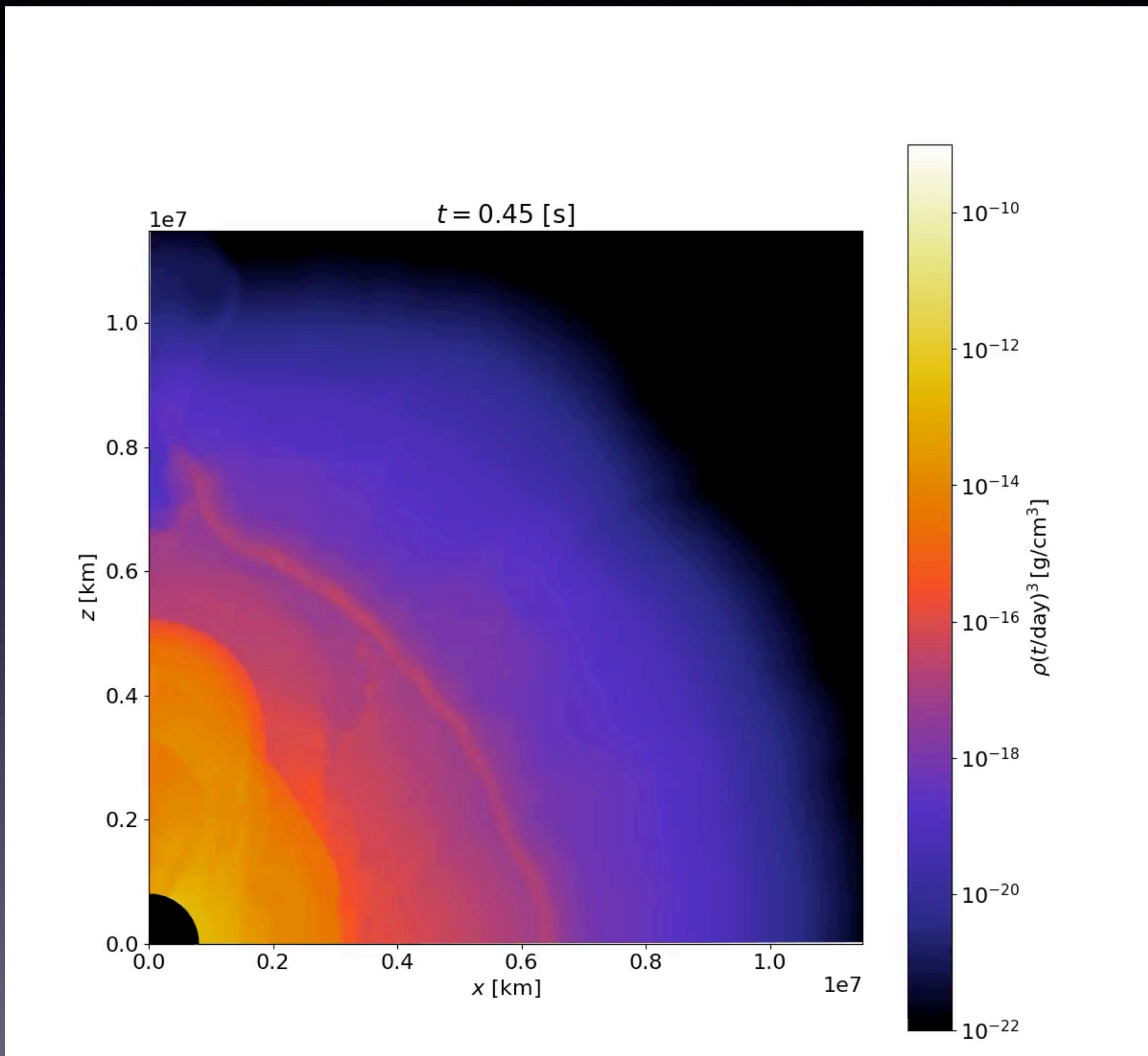
- Radioactive heating is incorporated in each fluid-element referring the heating rate obtained by the pre-computed nucleosynthesis calculation

- Ideal Γ-law equation of state （Γ=4/3; rad. press. dom.）



Result: Hydrodynamical simulation

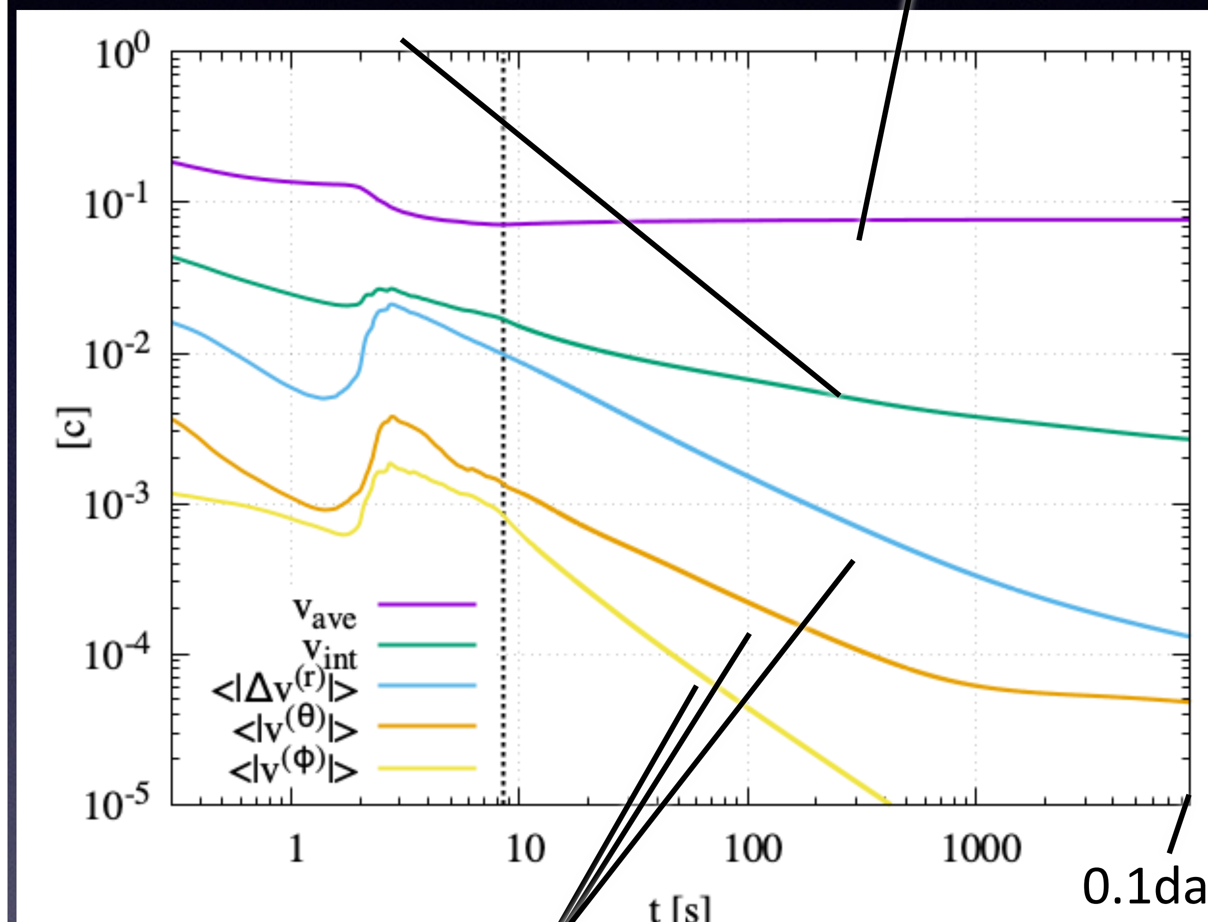
Rest-mass density evolution



KK et al. 2021

r.m.s. average velocity

internal energy contribution
(~sound speed)



0.1day

deviation from homologous expansion

$$M_{\rm eje} = 0.096\, M_\odot$$

$$v_{\rm ave} = 0.08\, c$$

- ~>1000 s :
  homologously expanding phase
  $$v^r \approx r/t$$

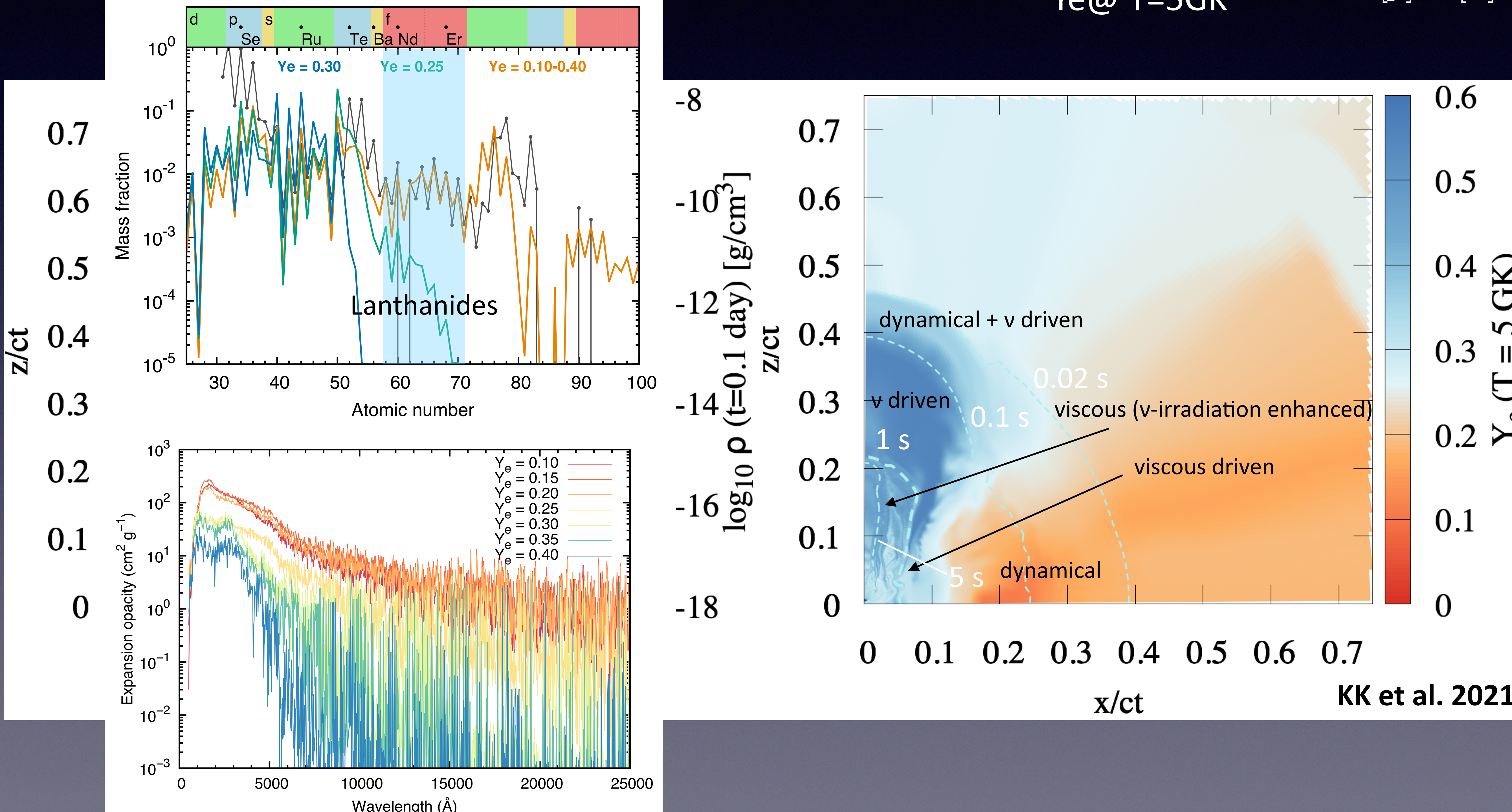
Density & Ye profile@homologous expansion

Snapshot at t=0.1 day

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

Wanajo et al. 2014, Tanaka el al. 2020

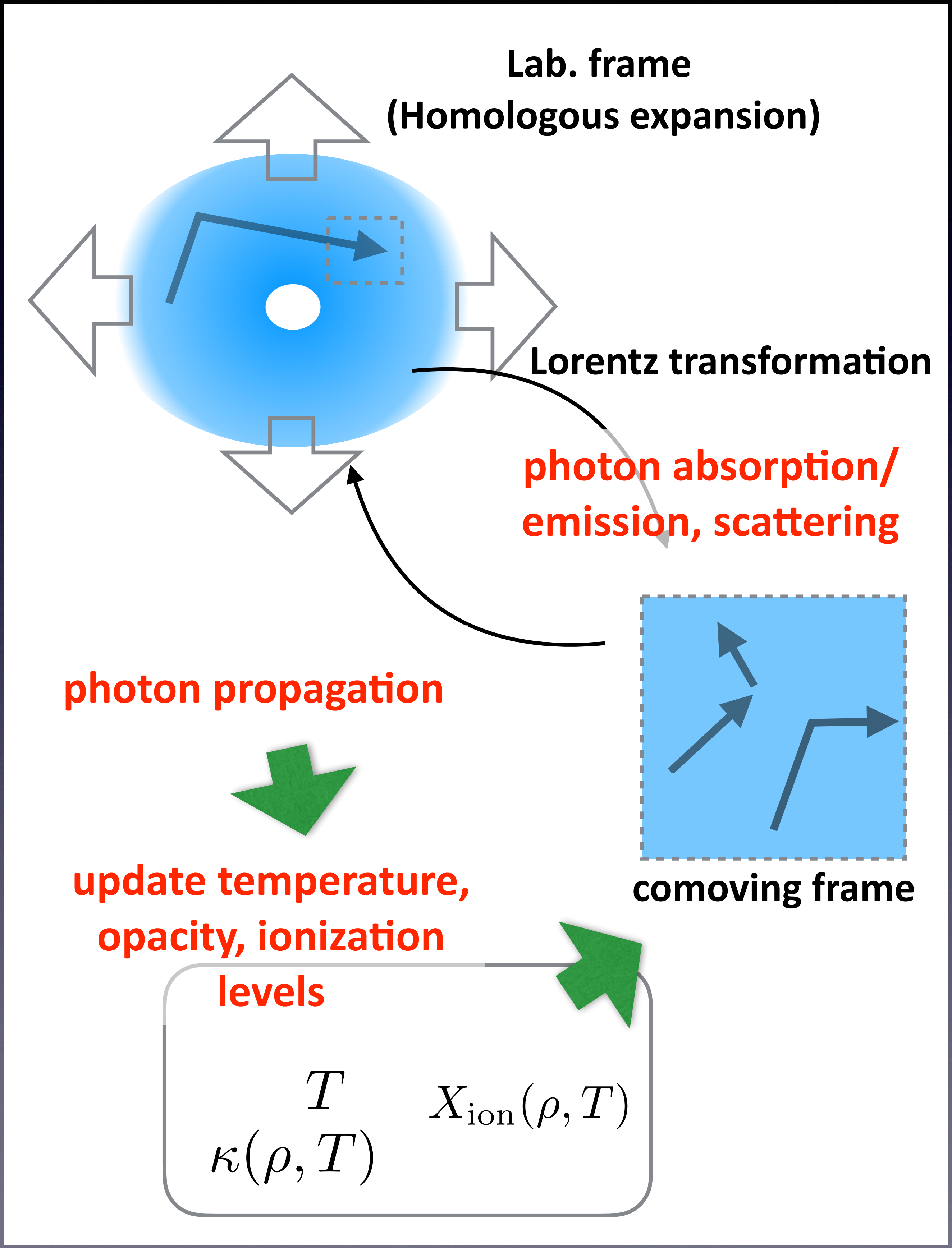
Ye@ T=5GK



KK et al. 2021

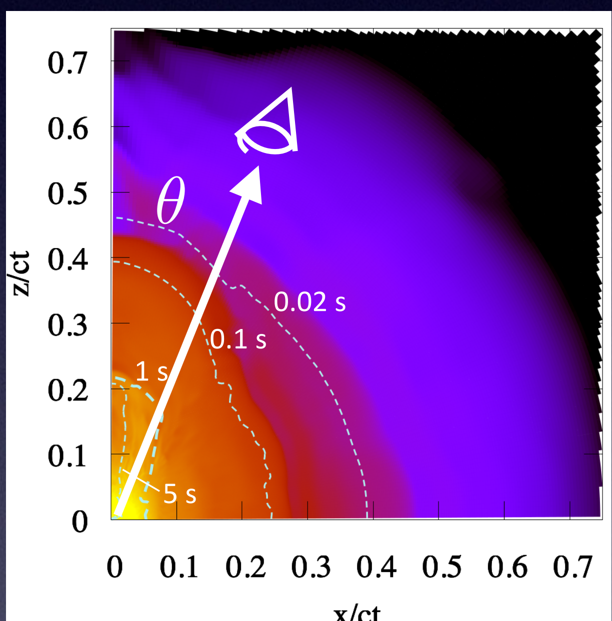
Setup:Radiative transfer simulation

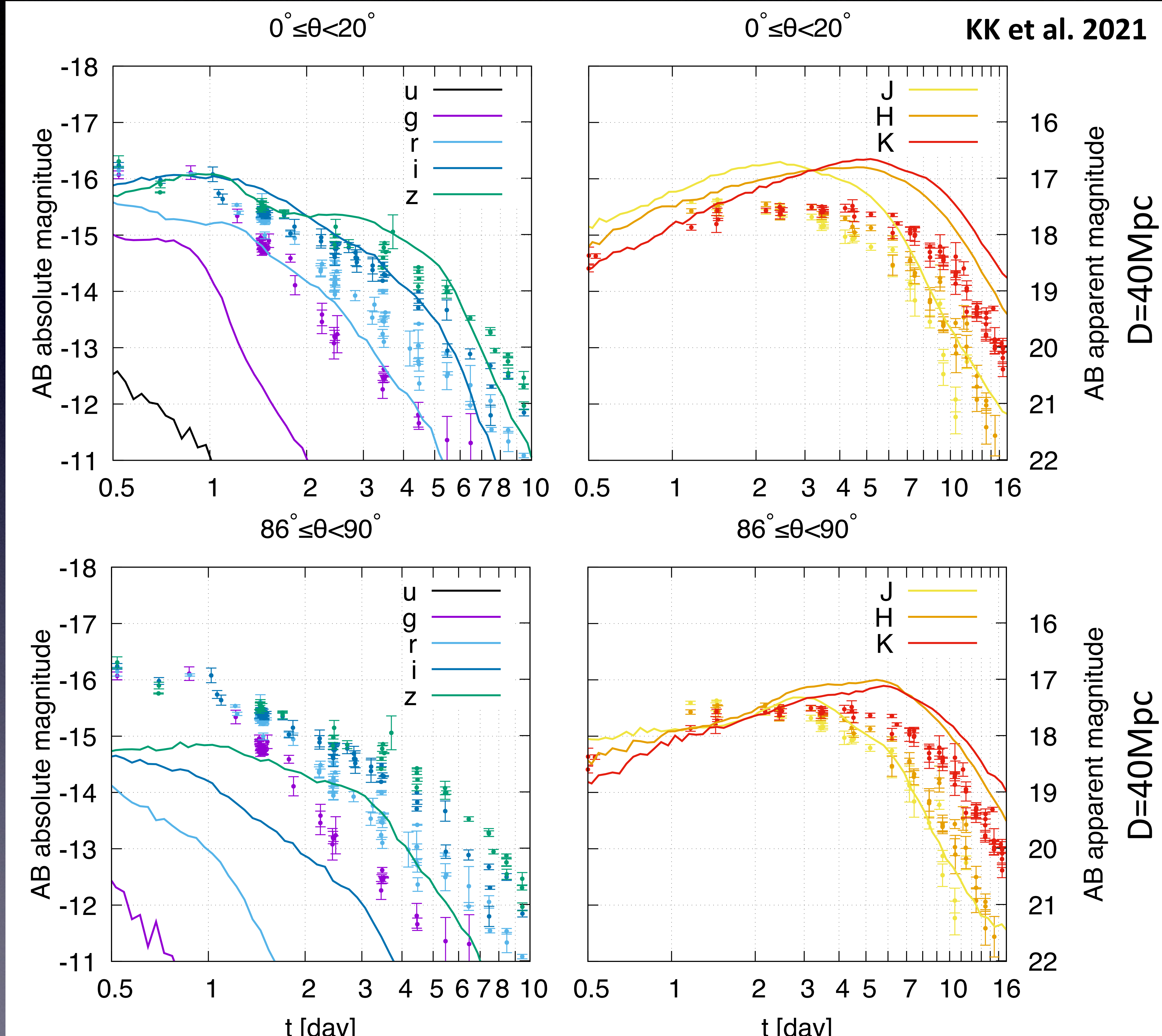
- **Multi-wavelength Monte-Carlo Radiative transfer code**
  (M. Tanaka et al. 2013, 2014, 2017, Kawaguchi 2018, 2020)
  - KN light curves during 0.1 -30day after the merger
- **The snapshot of the rest-mass & internal-energy density profile at t=0.1 day** obtained by the ejecta hydrodynamics simulation
- **homologous expansion can be safely assumed**
- the (thermal) energy deposition rate and element abundance in each fluid element are determined
  from **the result of nucleosynthesis calculation**
  - an analytical thermalization efficiency model of Barnes et al. 2016 is applied to the (thermal) energy deposition rate
- **bound-bound opacity:**
  Z=26~92: line opacity table by systematic atomic calculations (Tanaka et al 2020
  Z<26: experimental data (Kurucz & Bell 1995)
  - (up to the 3rd ionization states)
- Excitation & ionization state populations are determined from Saha's equation assuming
  the local-thermodynamical equilibrium (LTE)



Result:Radiative transfer

BroadBand magnitudes





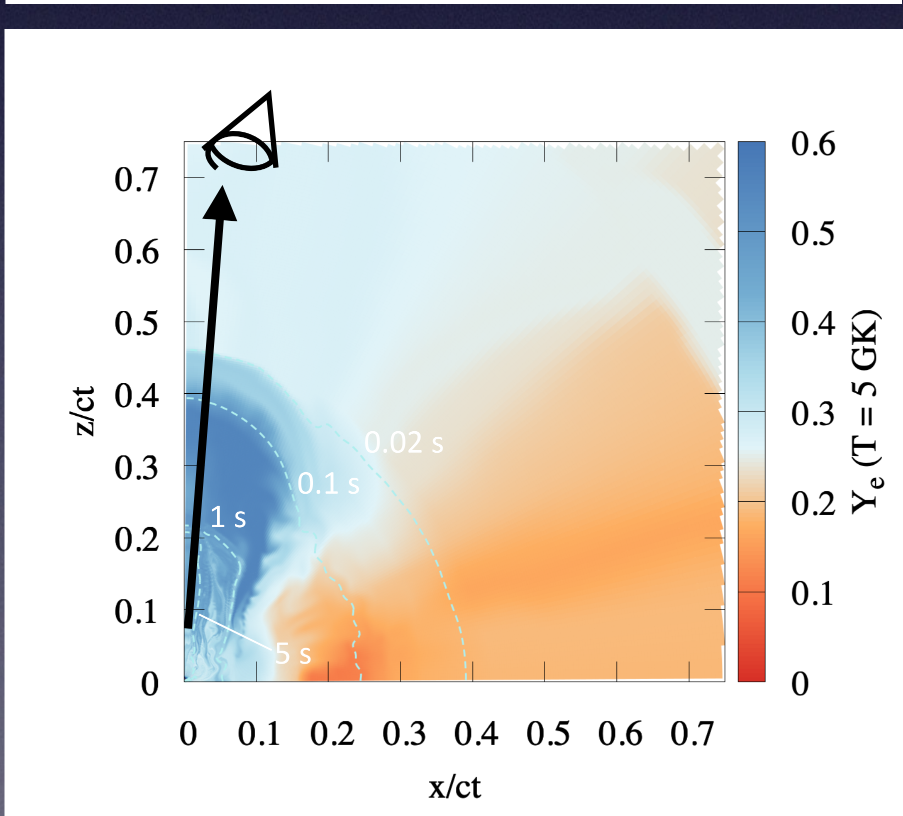
Data points:
GW170817/AT2017gfo
(Villar et al. 2017)

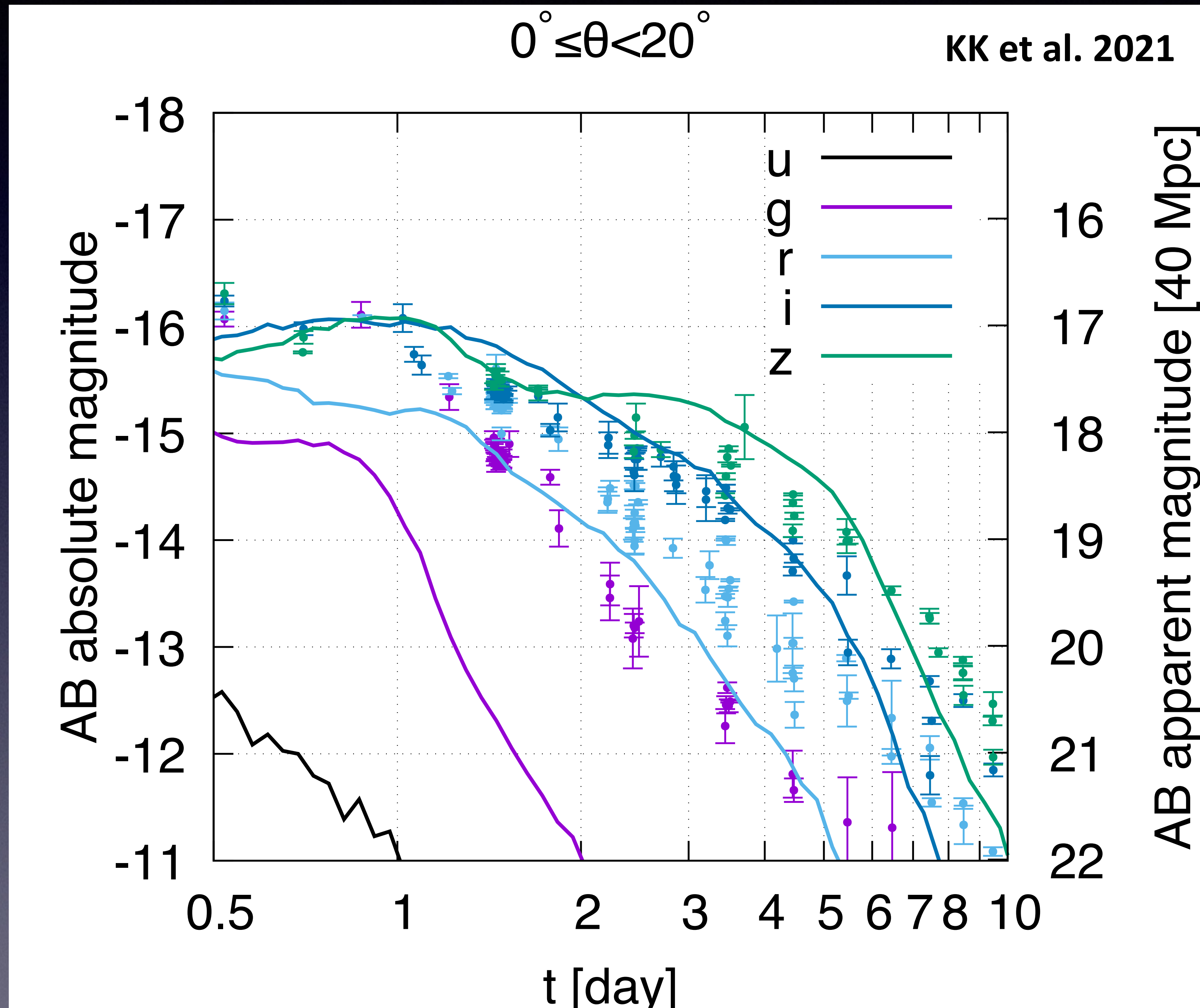
High-Ye/lanthanide free in the polar region, but not blue (not bright in optical wavelength)

$$M_{\rm eje} = 0.096\,M_\odot$$

$$v_{\rm rms} = 0.08\,c$$

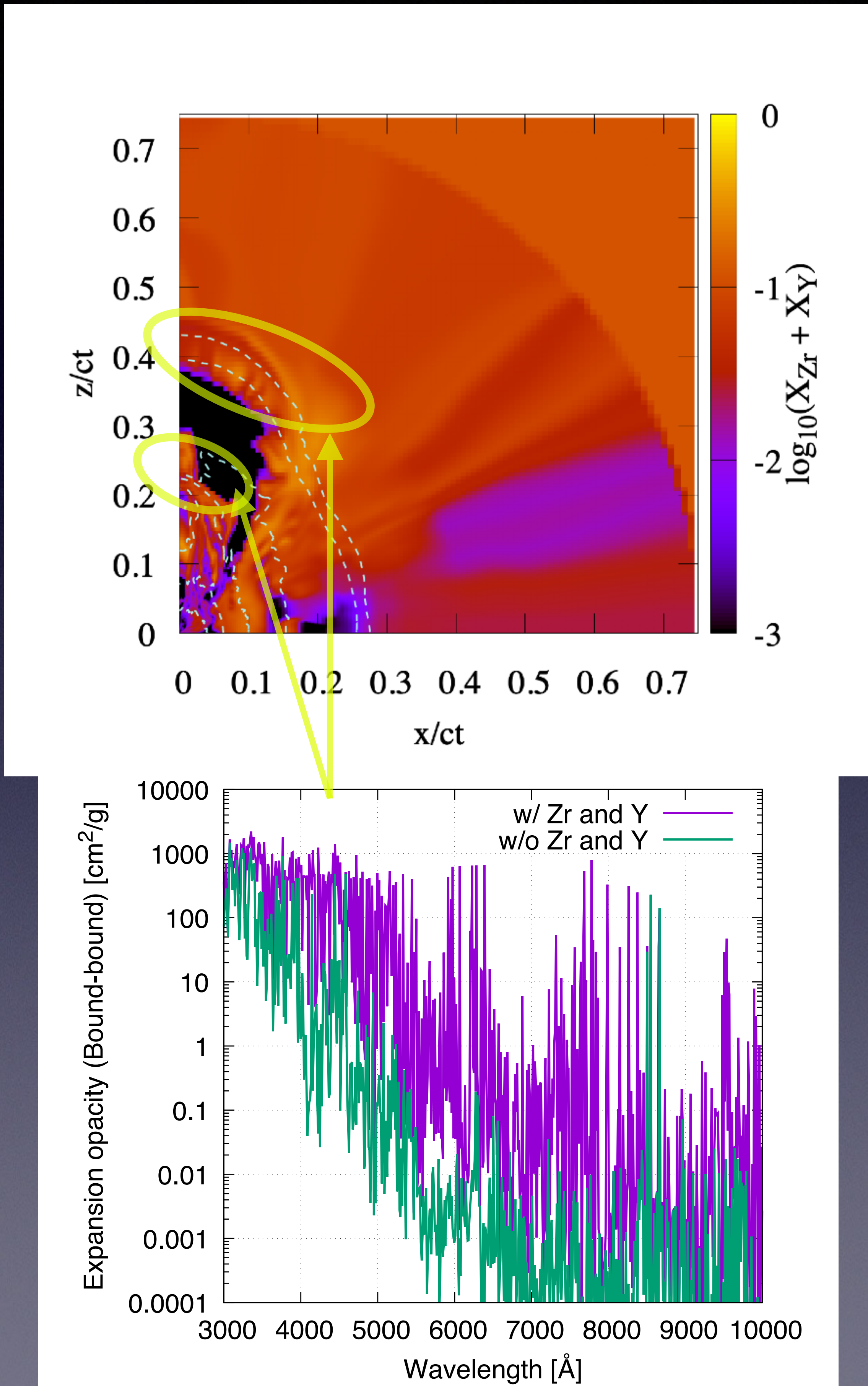
$$X_{\rm lan} = 0.0045$$

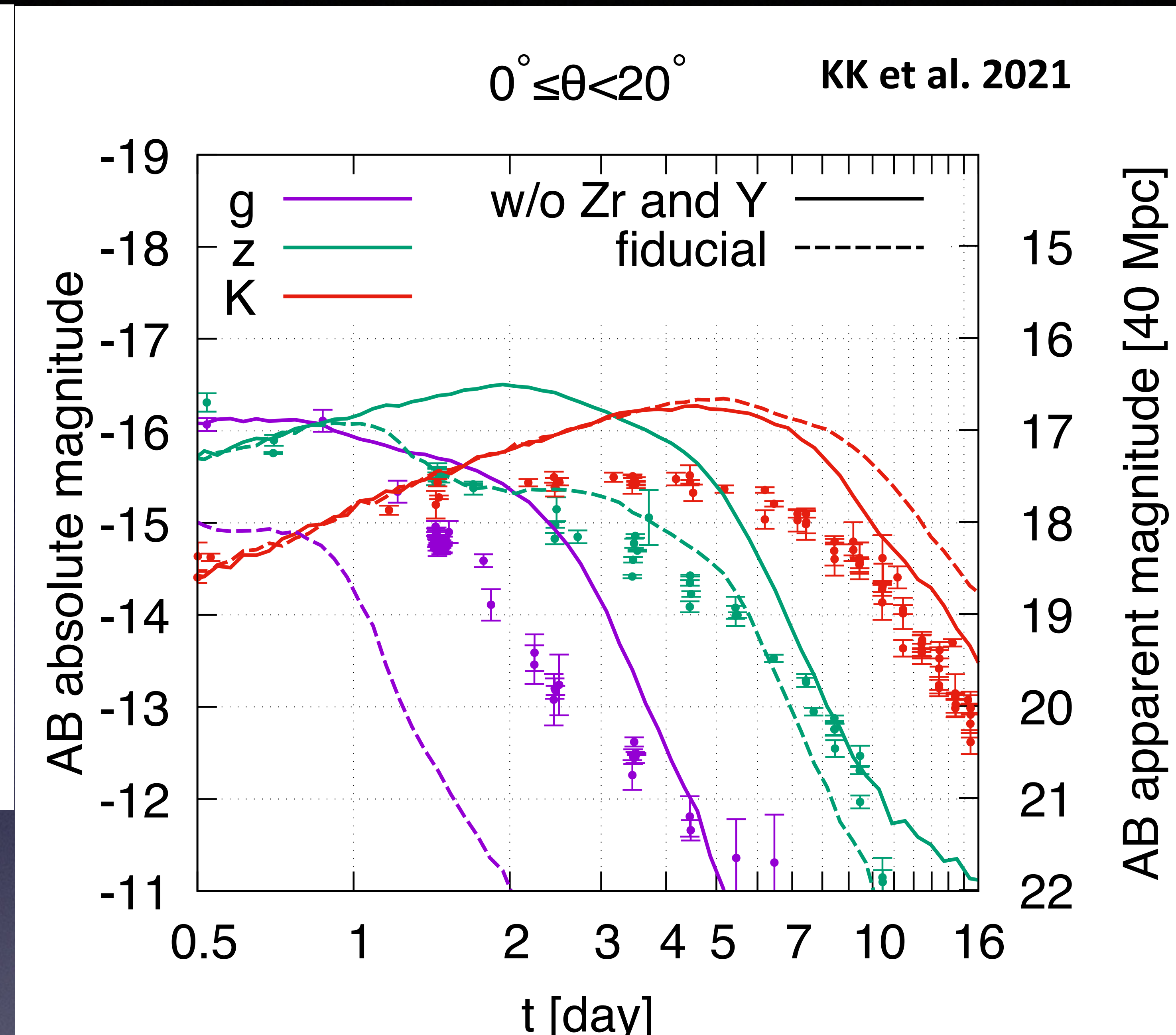




- Contrary to a naive expectation from the large ejecta mass and low lanthanide fraction in the polar region, the optical (g, r-band) emission is not as bright as that in GW170817/AT2017gfo.

Opacity of the 1st-peak r-process elements

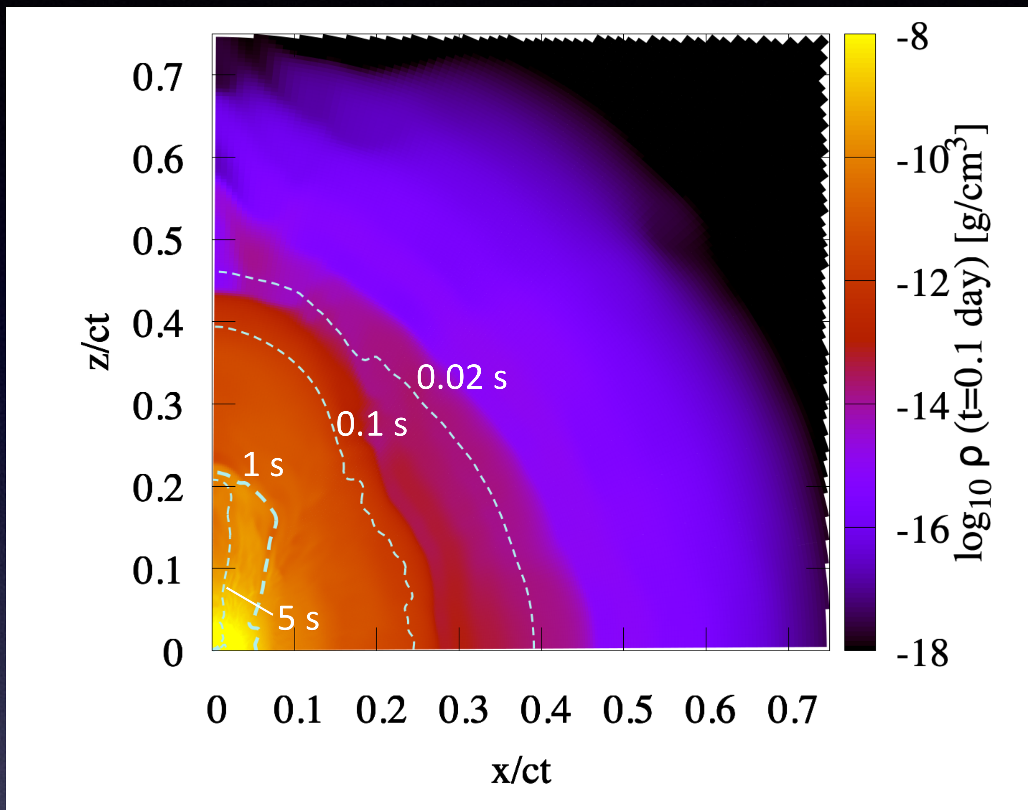


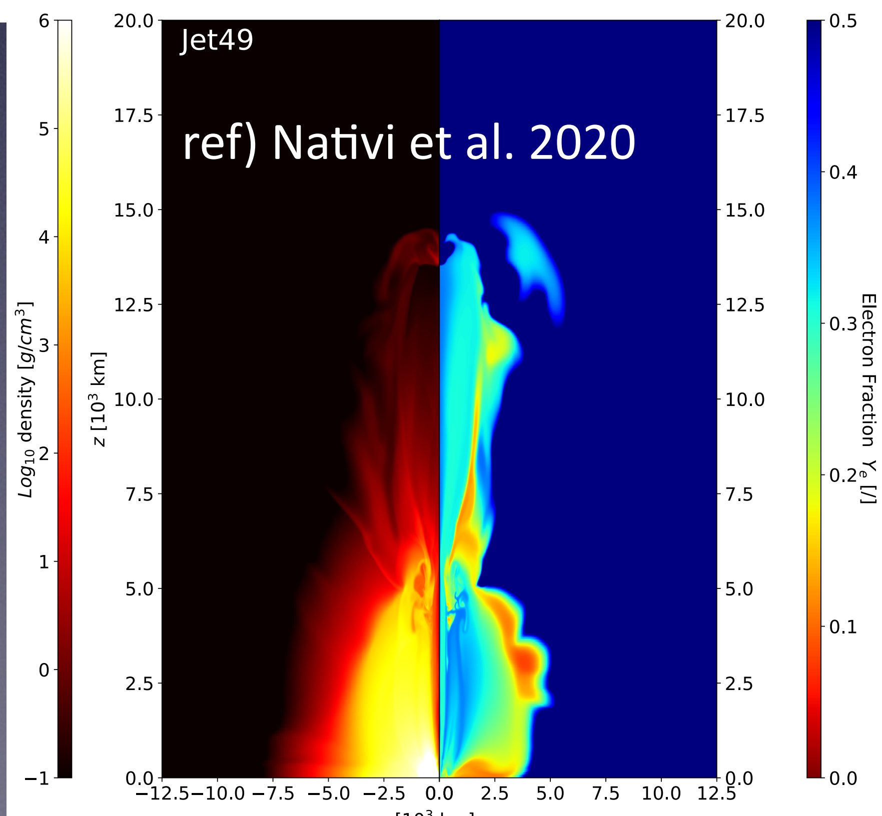


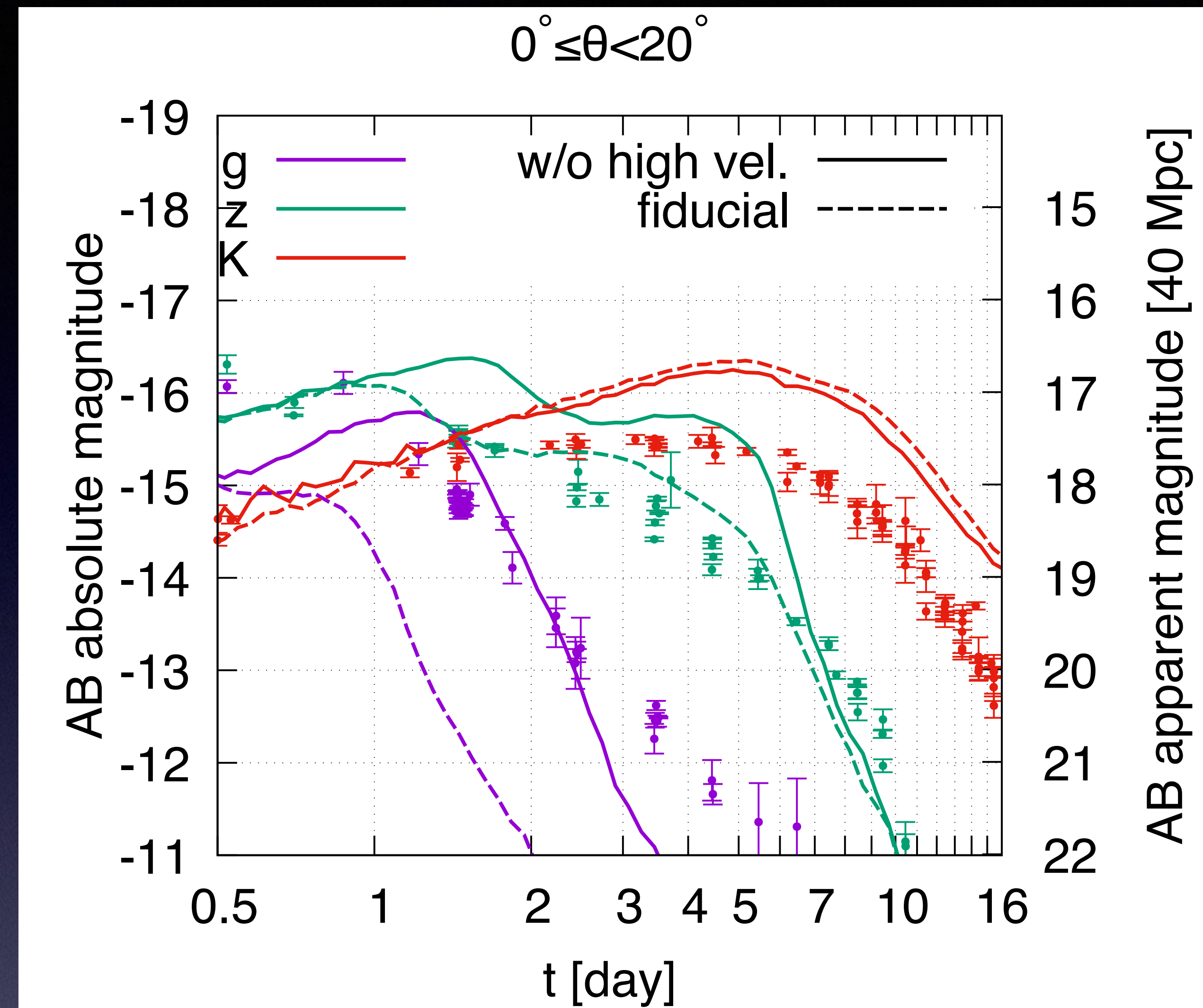
- a large amount of 1st r-process peak elements including **Zr (Z=40) and Y (Z=39)** are present in the polar high velocity region
- Zr and Y (d-shell element) have a great contribution to the opacity in the optical band (**~>4000 Å)** **(see also Watson et al. 2019, Gillanders et al. , Ristilc et al. 2022)**

What is the origin of GW170817?

a model in which the outflow
in θ<30° is suspended after t~200ms



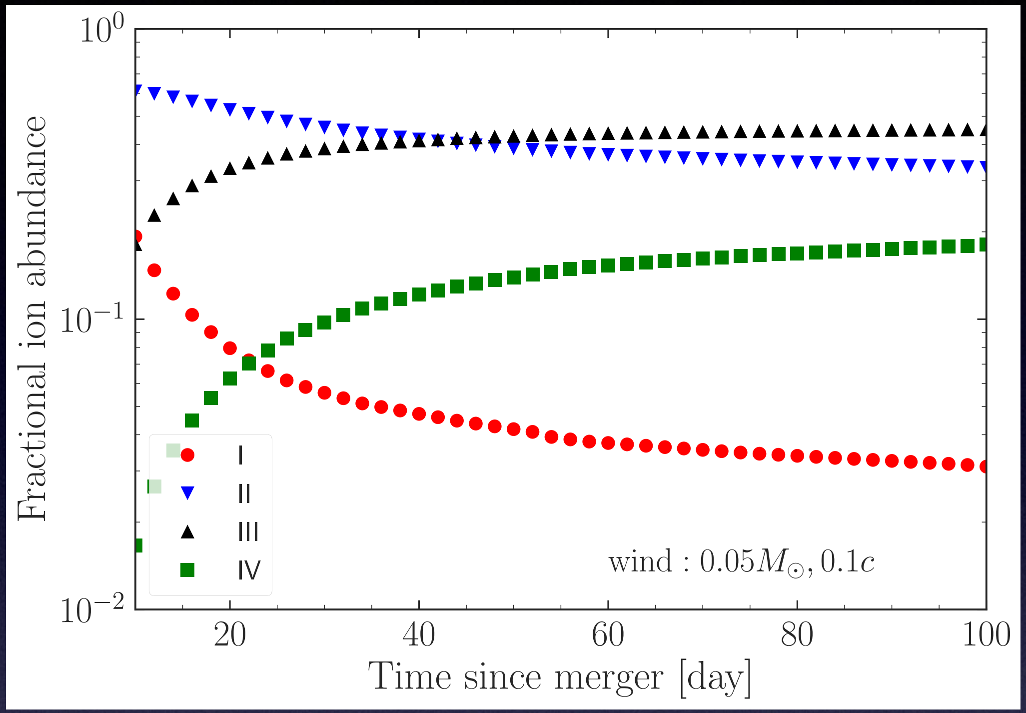




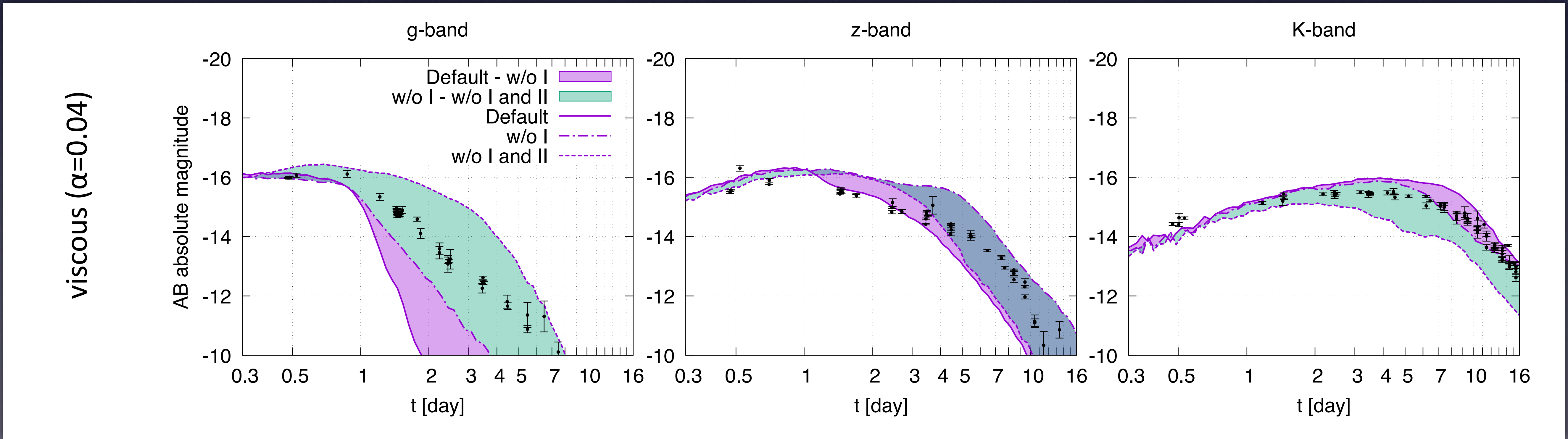
- The blue (optical) emission is enhanced for a model in which the outflow in $\theta < 30°$ is suspended after t~200ms
  - may suggest that the remnant in GW170817 is unlikely to be a long-lived NS, but might have collapsed to a black hole in a short time scale (~100ms)
- Relativistic jets may revive the blue emission of the KN by blowing up the ejecta with Zr and Y (see Nativi, Klion et al. 2020)
- non-LTE effects on ionization states may also be important

possible non-LTE effect

Hotokezaka et al. 2020

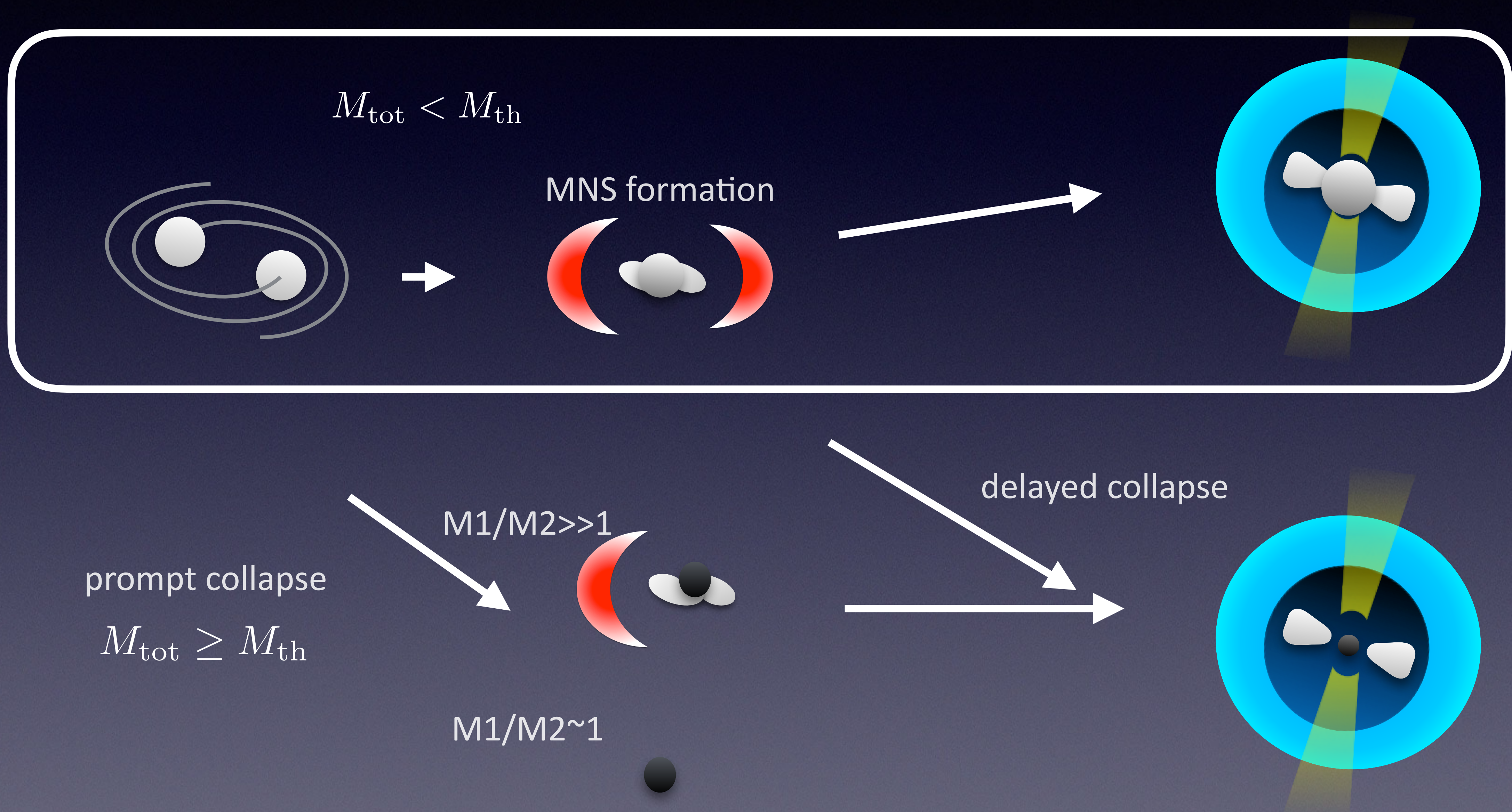


KK et al. 2021, 2022



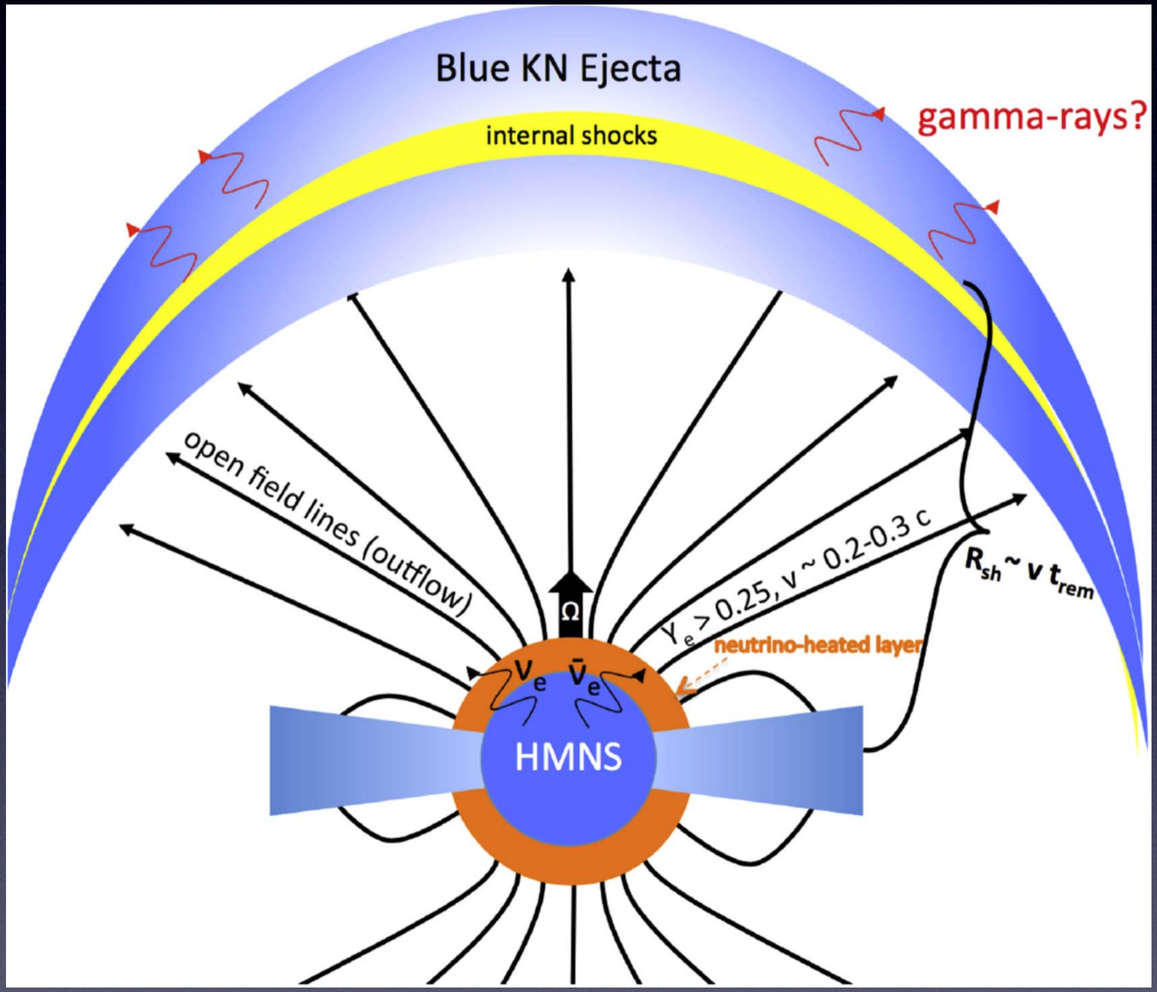
see Pognan et al. 2021,2022 for the non-LTE discussion
and Barnes et al. 2021 for the impact of heating rate uncertainty to the ionization structure

Model: BNS with a Long-lived remnant NS



Long-lived strongly magnetized remnant MNS

Metzger et al. 2018



Rotational kinetic energy of MNS: $E_{\rm rot} \sim 10^{52}\,{\rm erg}$

e.g. Metzger & Bower 2014, Horesh et al. 2016
Shibata et al. 2017, Metzger et al. 2018, Beniamini & Lu 2021

Electromagnetic counterparts of a NS merger with a strongly magnetized long-lived MNS

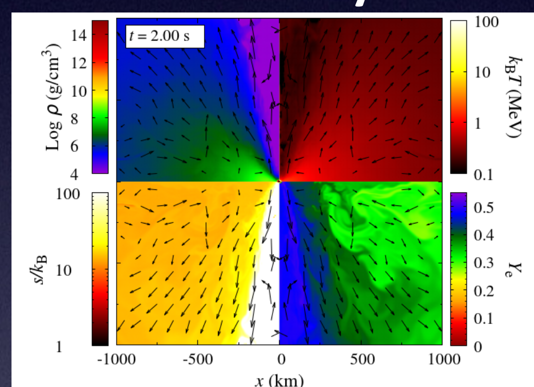
Model : 1.35 M_{sun} + 1.35 M_{sun} (DD2 EOS)

3D GRRHD BNS merger simulation

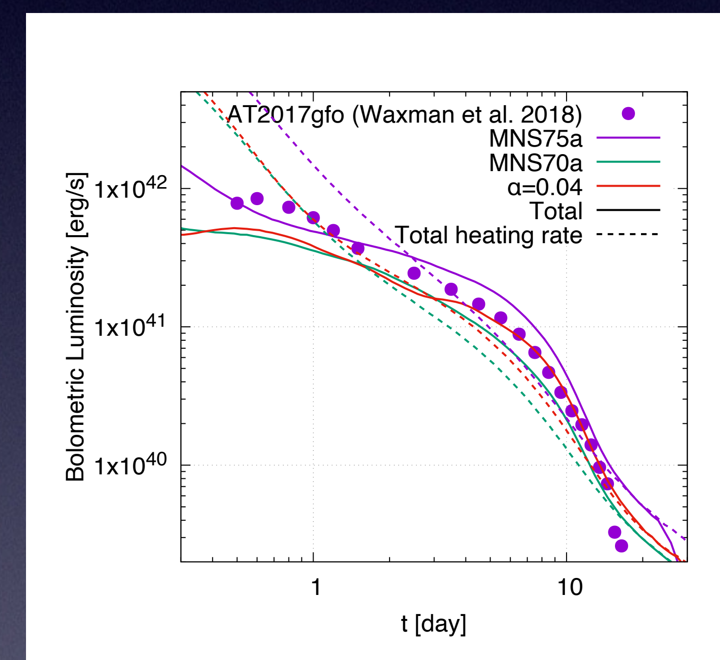
Shibata et al. 2021, KK et al. 2022

Long-term GR-R-MHD simulation (~3 s) with mean-field dynamo terms

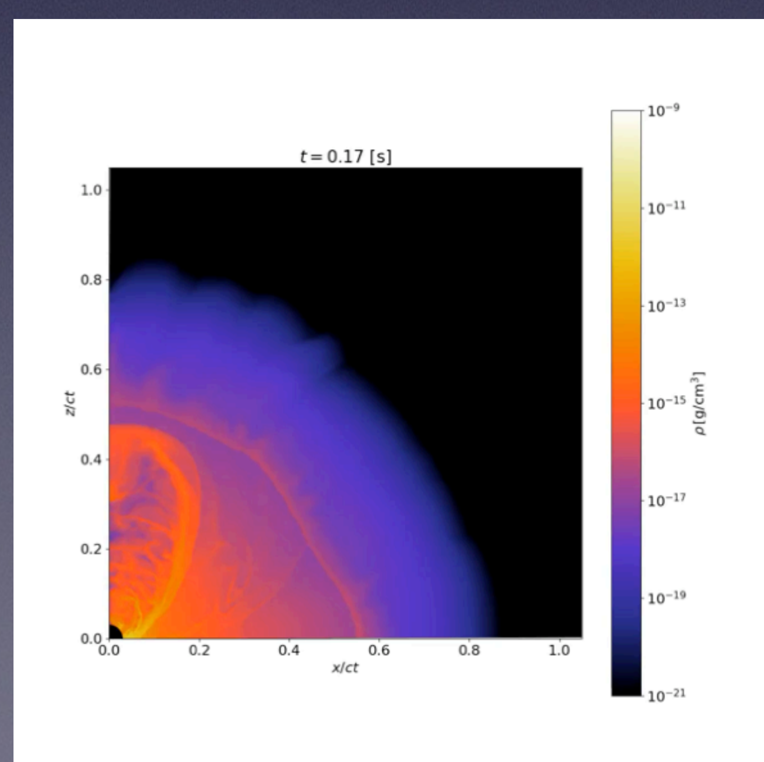
Axisymmetrize



Radiative transfer simulation
synchrotron emission calculation



Extract ejecta component



EM counterpart prediction

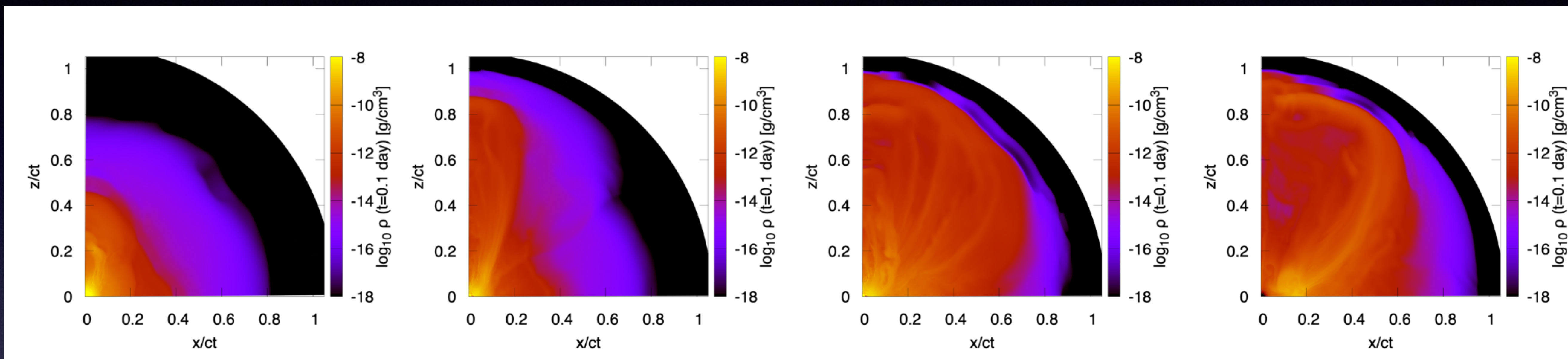
GR-HD simulation for the longterm ejecta evolution (~0.1 d)

Ejecta profile

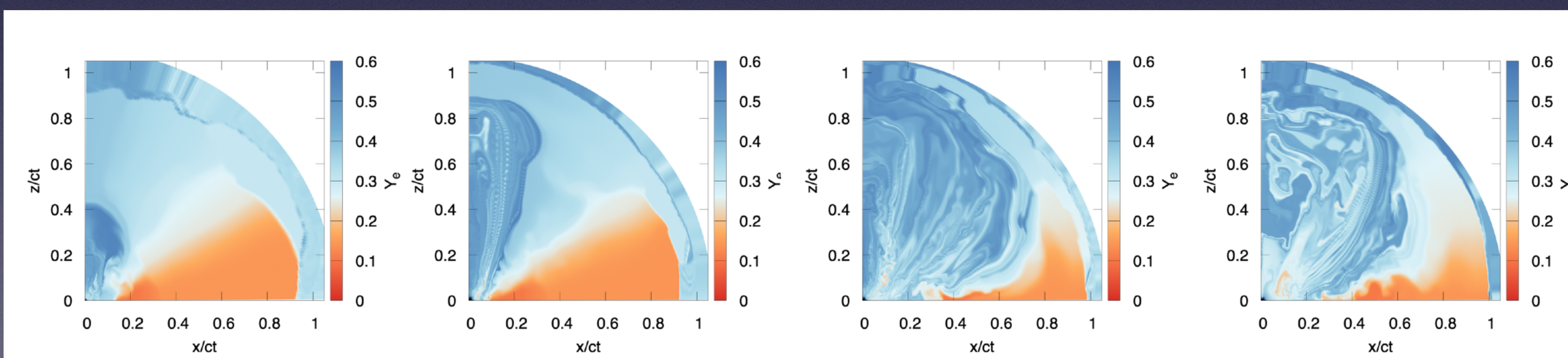
Model : 1.35 M_{sun} + 1.35 M_{sun} (DD2 EOS)

Density profile @ t = 0.1 d

Shibata et al. 2021, KK et al. 2022



Electron fraction profile @ t = 0.1 d



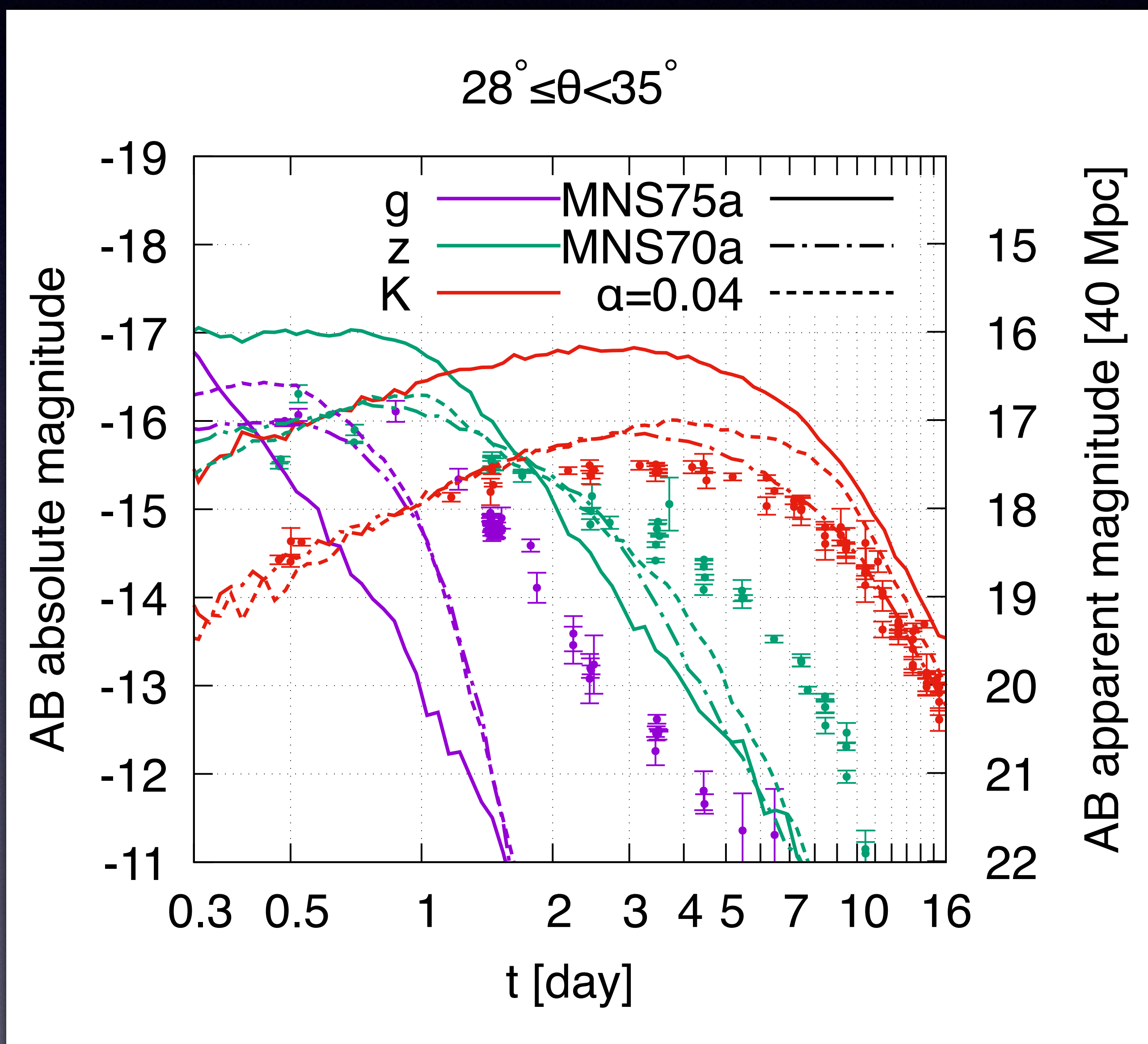
α=0.04 (viscous) | MNS70a | MNS75a | MNS80

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

Significant MHD (dynamo) effect

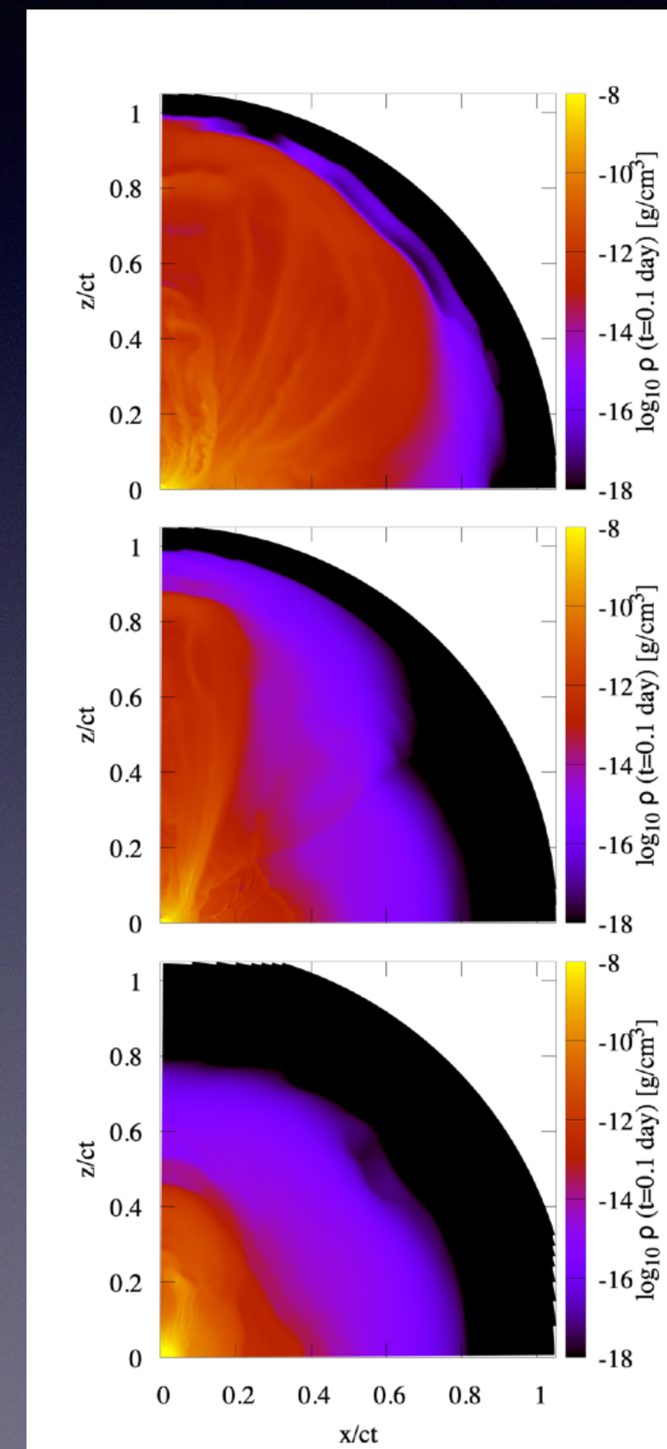
Kilonova emission

Kilonova Lightcurves
(data: GW170817/AT2017gfo)



KK et al. 2022

Density profile @ t = 0.1 d



MNS75a

MNS70a

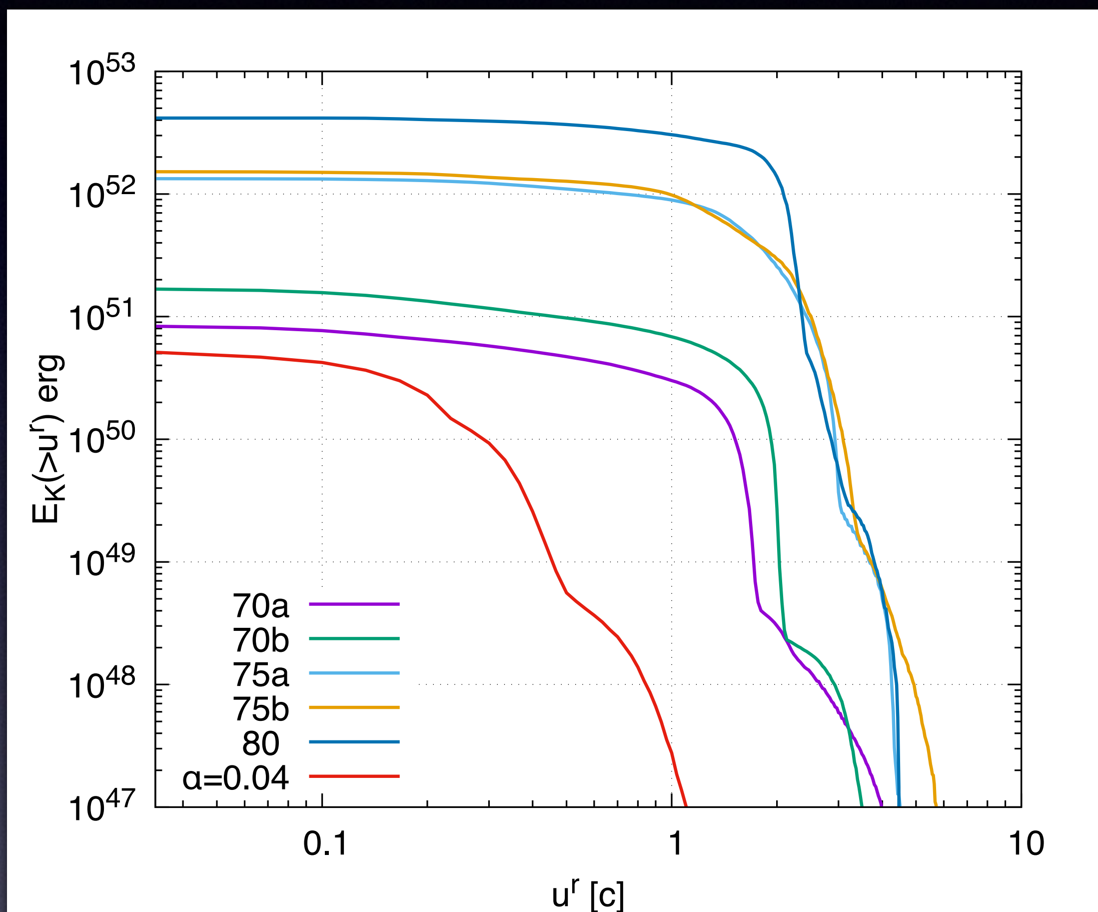
α=0.04
(viscous)

Significant MHD (dynamo) effect

**Radiative transfer simulation code & opacity data:
Tanaka et al. 2013,2017,2018, KK et al. 2018**

Synchrotron emission from the ISM-ejecta interaction

Ejecta kinetic energy (cumulative) distribution



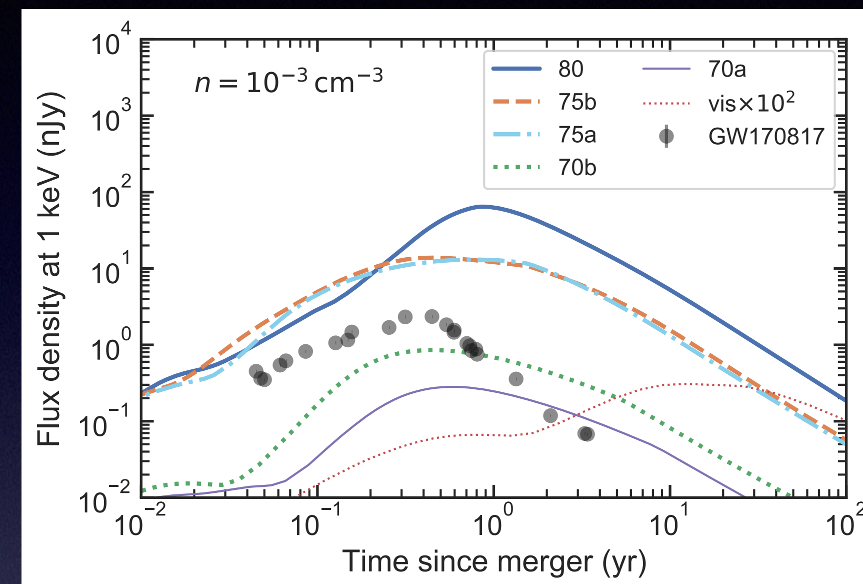
70a,b < 75a,b < 80
Significant ejecta acceleration
from the remnant MNS through MHD effects

$$\epsilon_e = 0.1,\ \epsilon_B = 0.01,\ p = 2.2$$

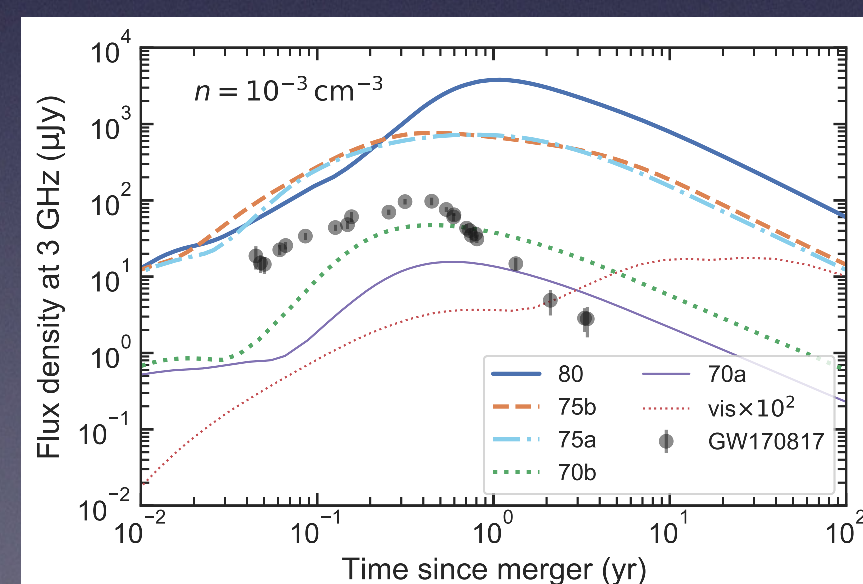
KK et al. 2022

(See also K. Hotokezaka & T. Piran et al. 2015)

X-ray band (1 keV, 200 Mpc)



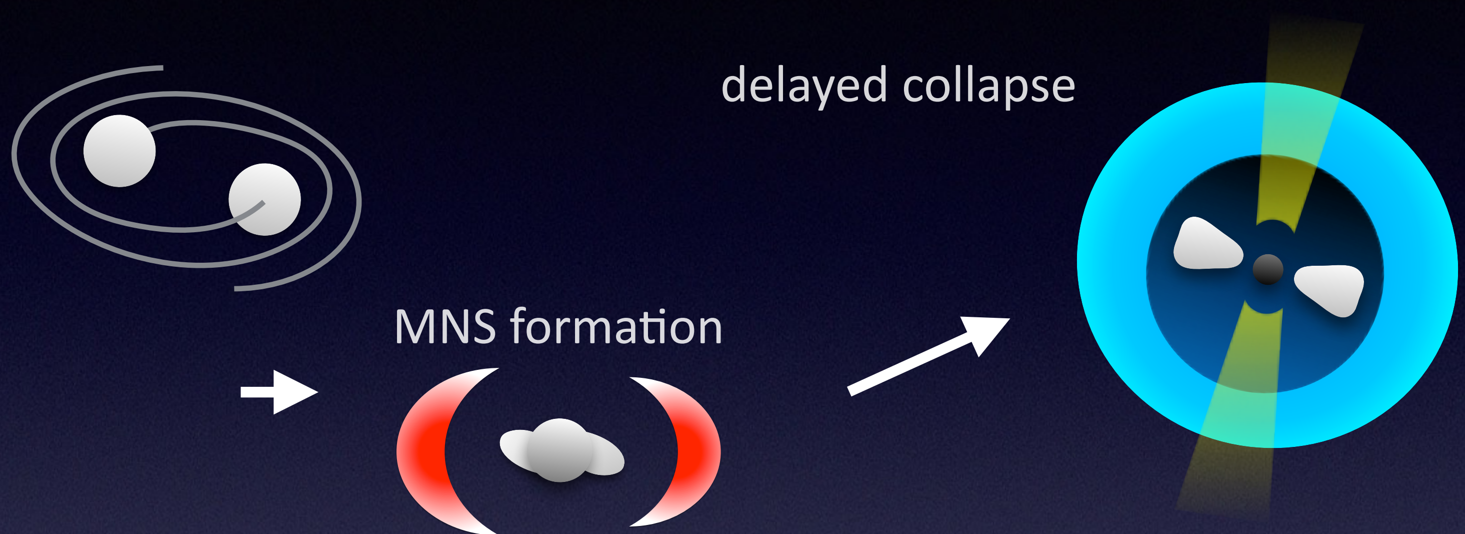
Radio band (3 GHz, 200 Mpc)



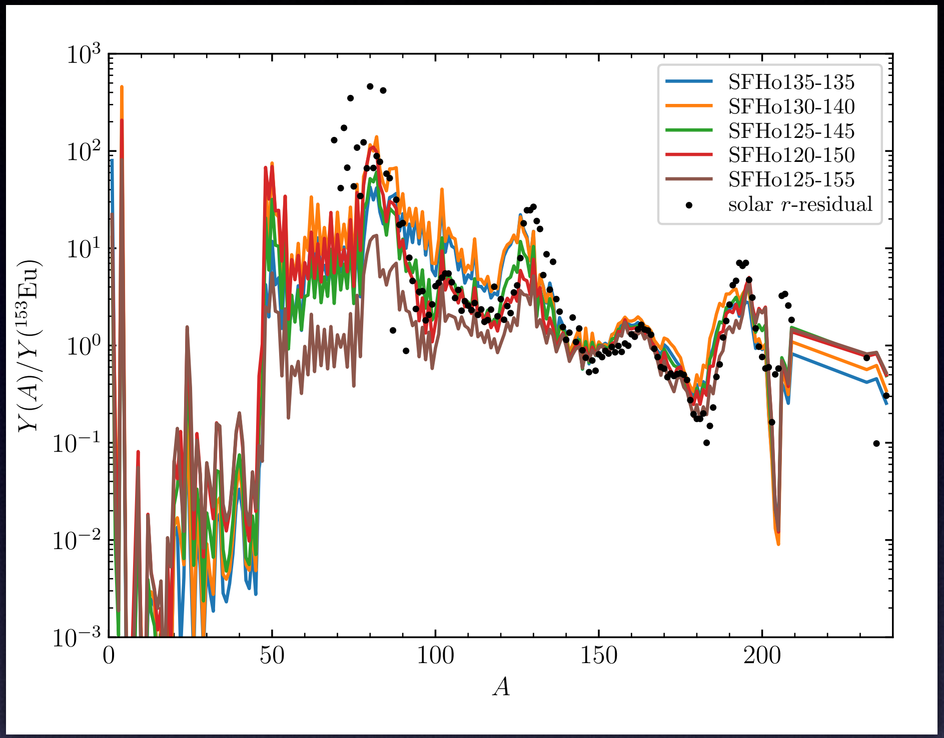
Surface density for radio trangent >170 uJy :
< 0.013 deg^{-2}. (Dobie et al. 2022)
→80 like BNS fraction ~< 30 % (for log n=-3, R_{BNS}~300 Gpc^{-3} yr^{-1})

Ongoing work

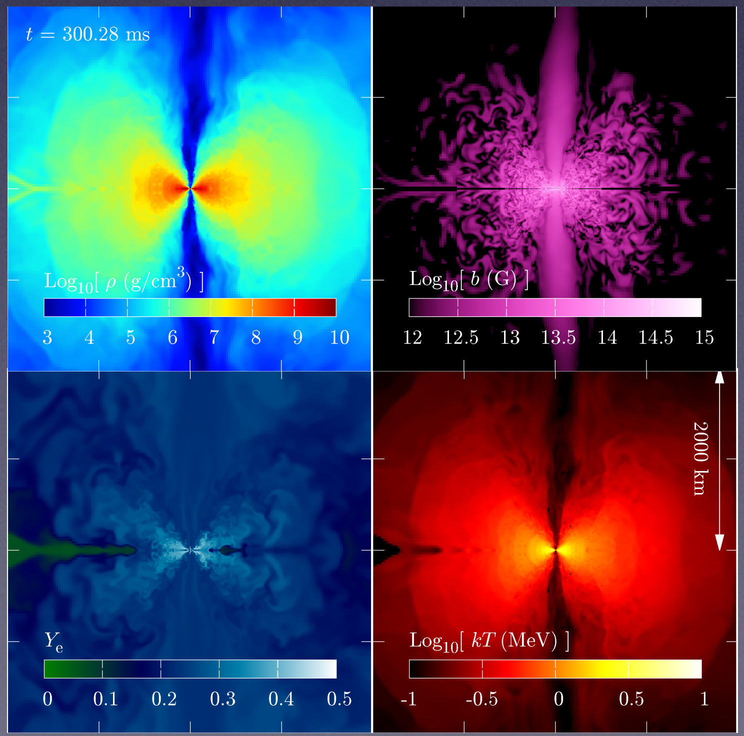
Study for a BNS with a short-lived remnant NS



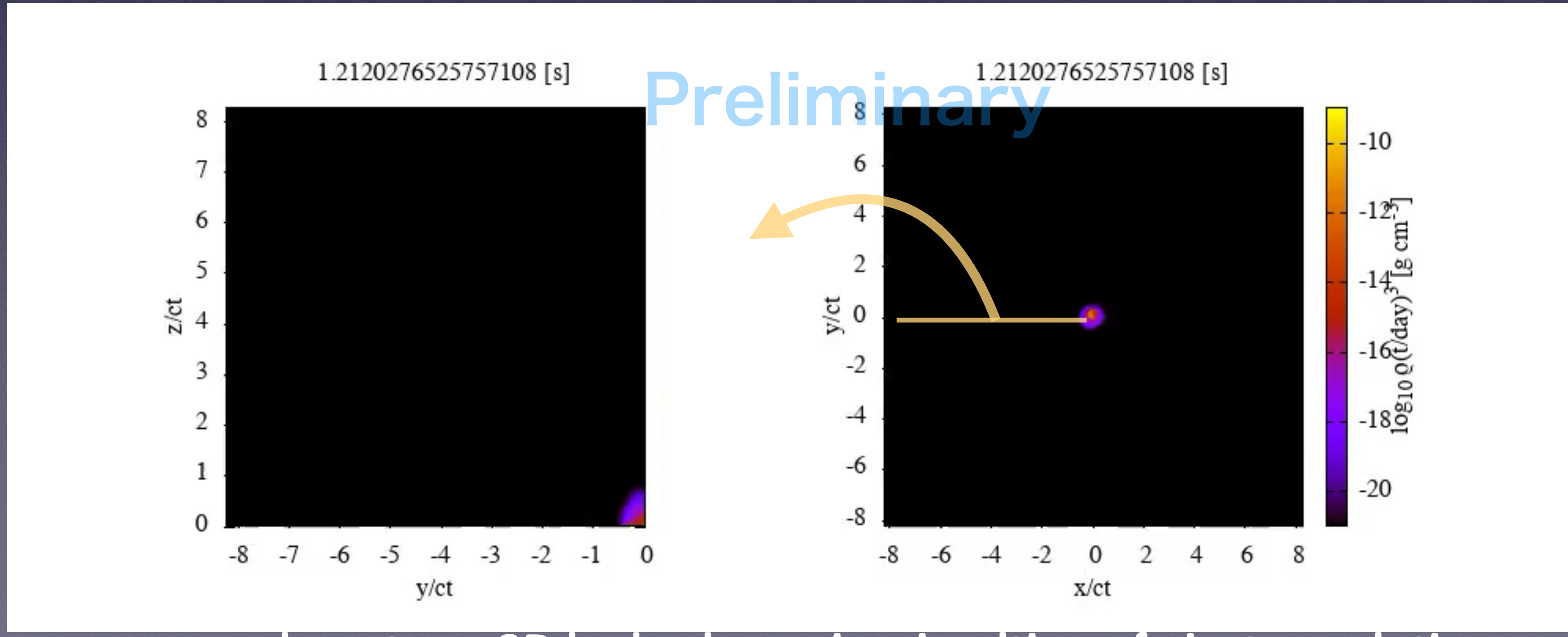
Fujibayashi et al. 2022



Black-hole neutron-star merger



Hayashi et al. 2022

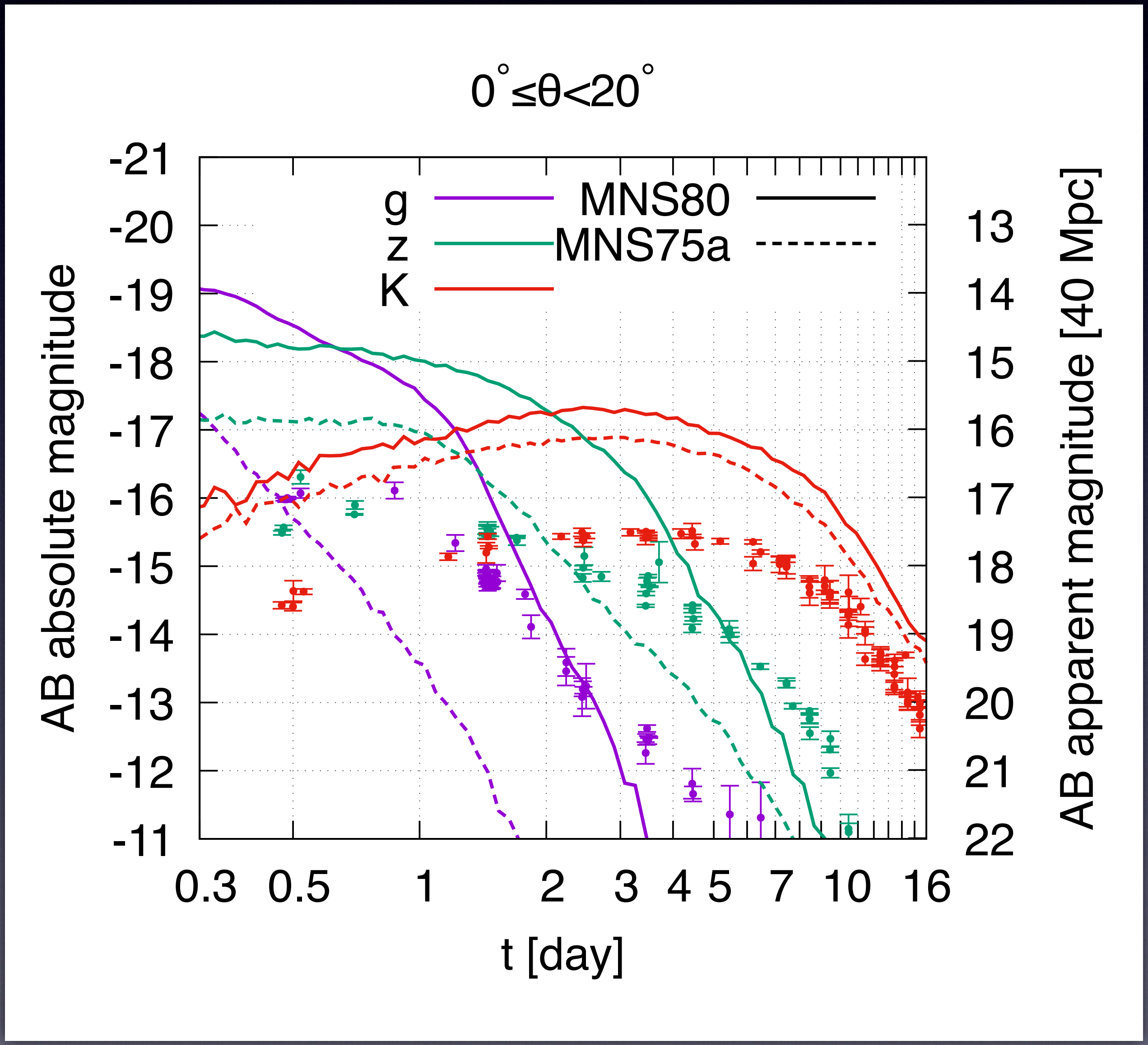


a long-term 3D hydrodynamics simultion of ejecta evolution

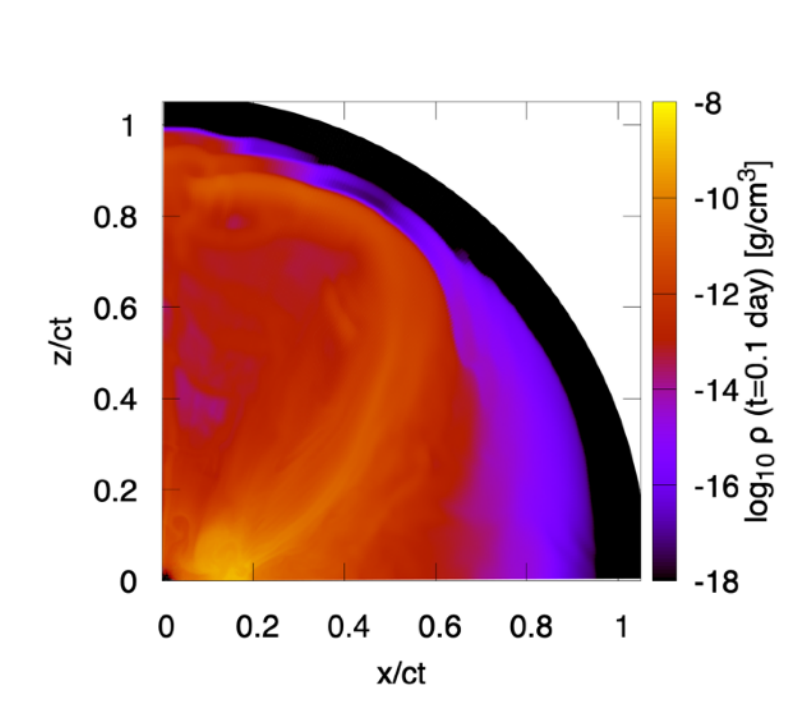
Kilonova emission

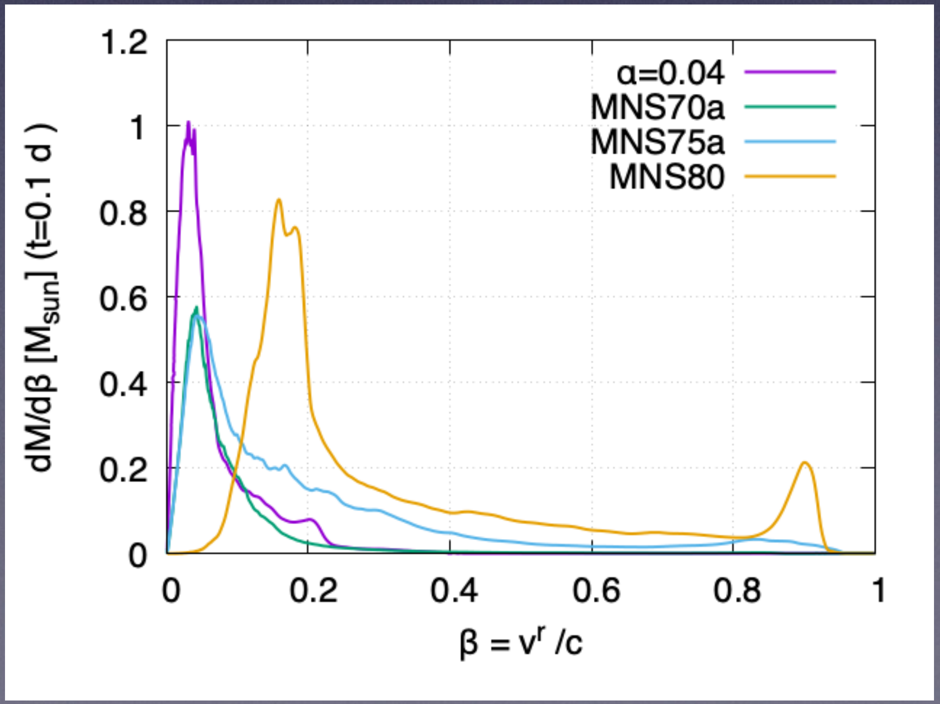
Kilonova Lightcurves
(polar view. data: AT2017gfo)

KK et al. 2022



Density profile @ t = 0.1 d
MNS80



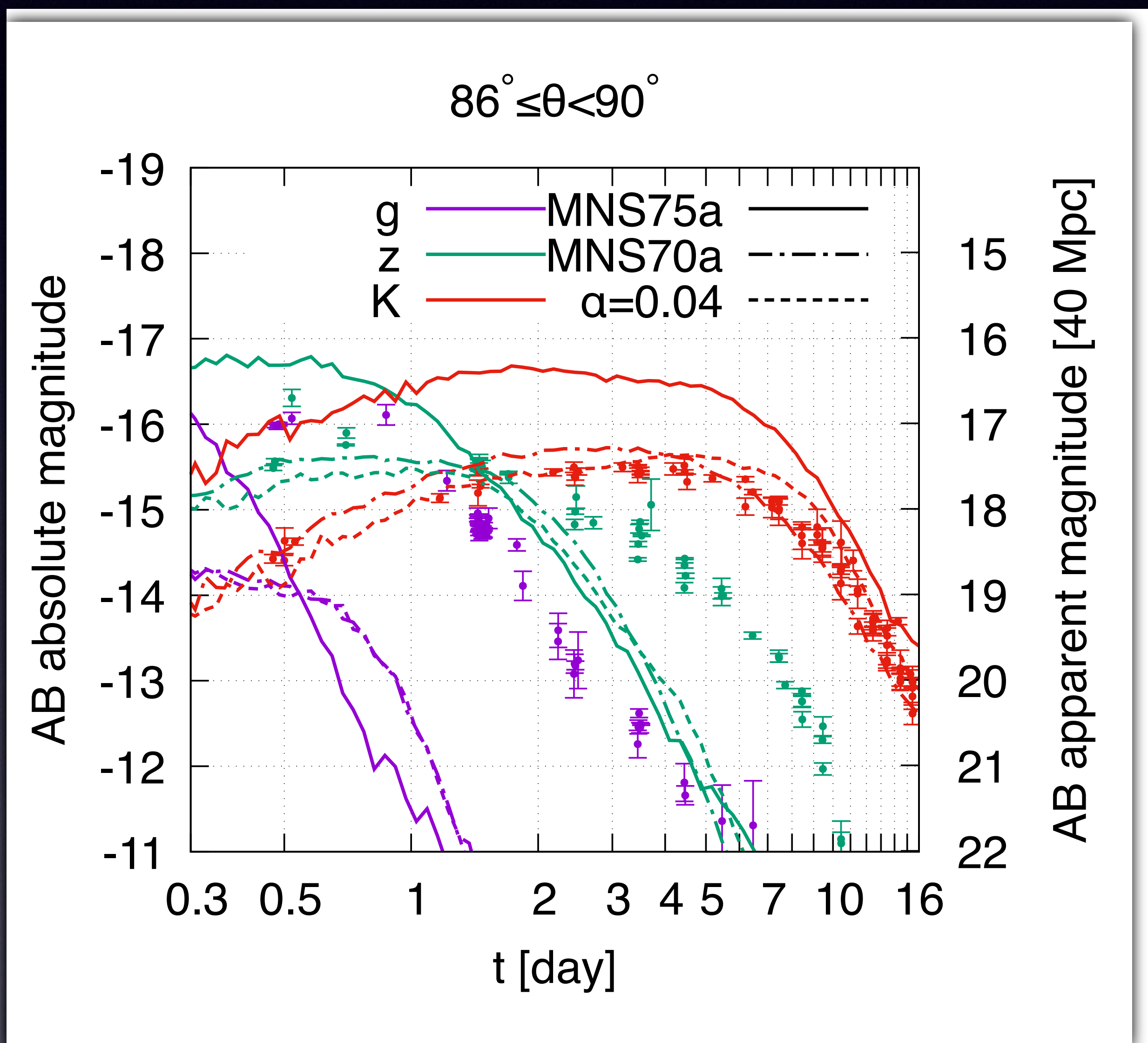


Radiative transfer simulation code & opacity data:
Tanaka et al. 2013,2017,2018, KK et al. 2018

Kilonova emission

Kilonova Lightcurves
(polar view. data: GW170817/AT2017gfo)

KK et al. 2022



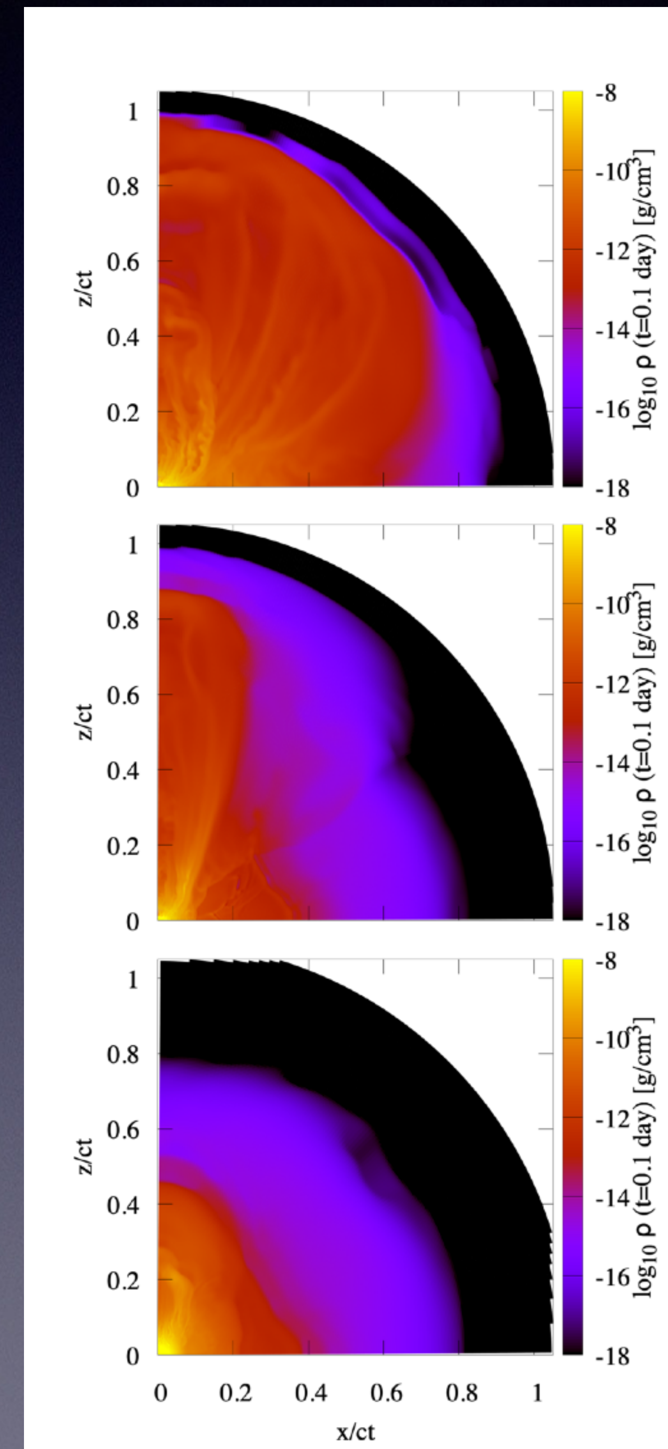
Radiative transfer simulation code
& opacity data:
Tanaka et al. 2013,2017,2018, KK et al. 2018

Density profile @ t = 0.1 d

MNS75a

MNS70a

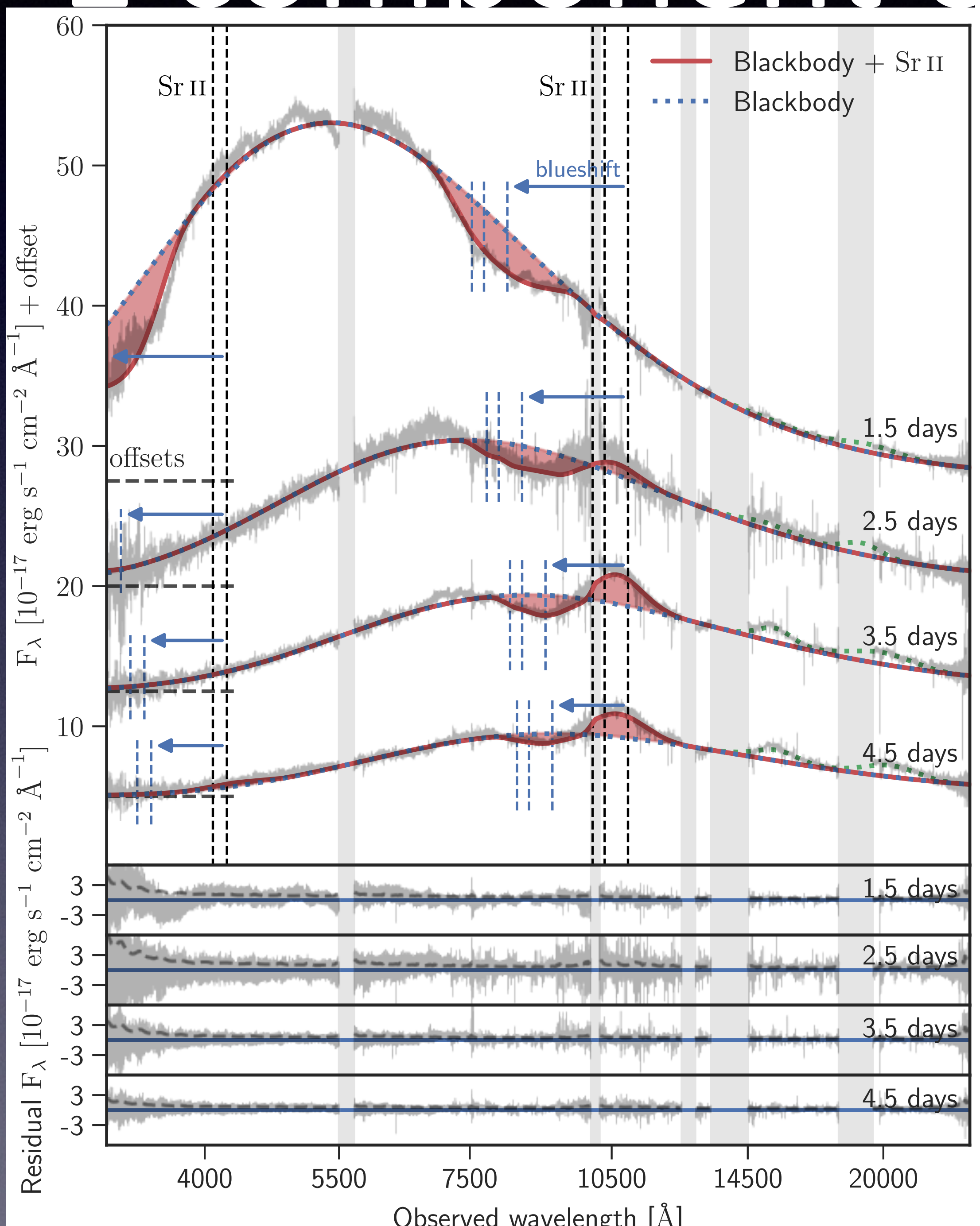
α=0.04
(viscous)



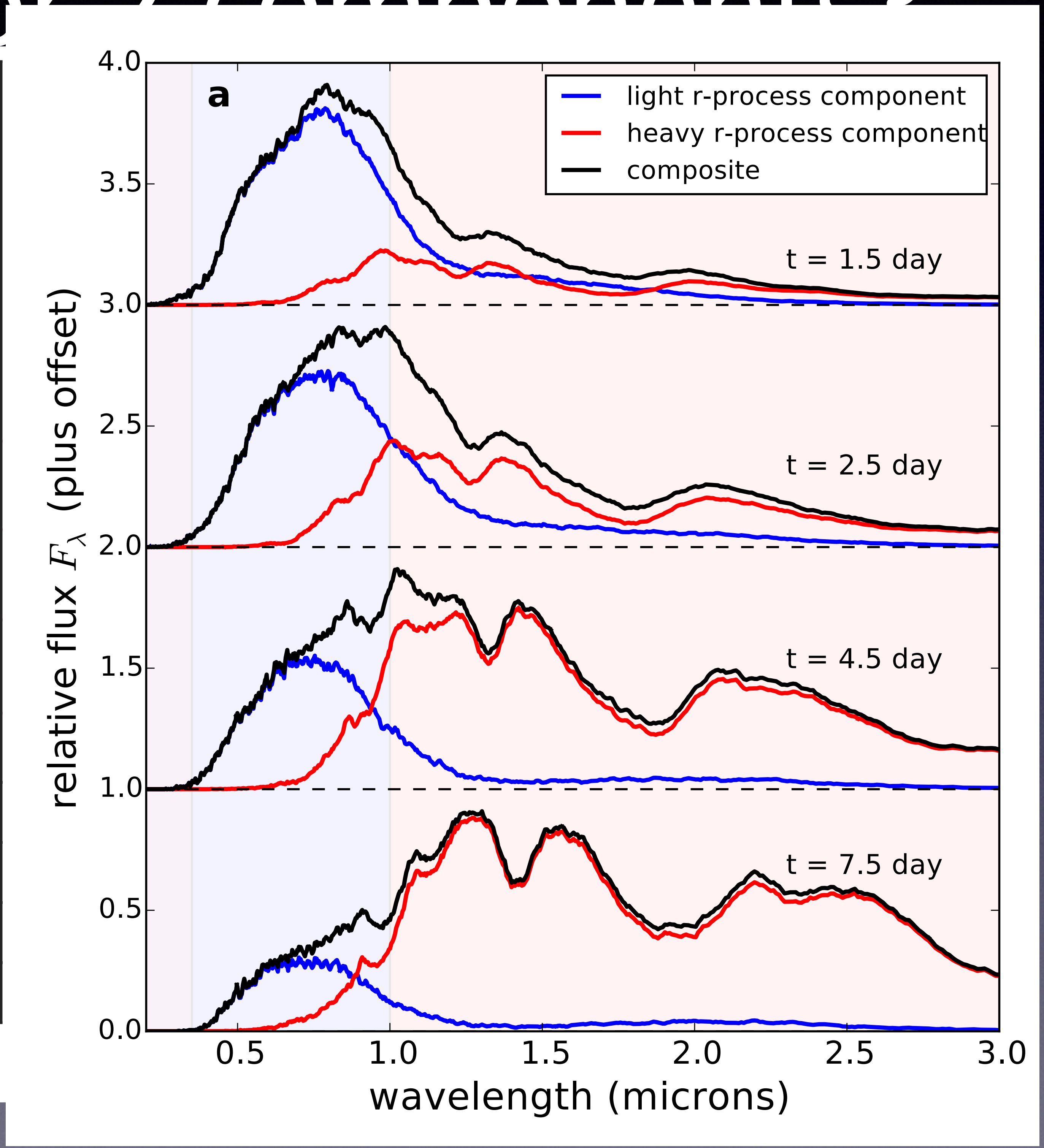
Significant MHD (large dynamo) effect

GW170817:

1 component or 2 components?



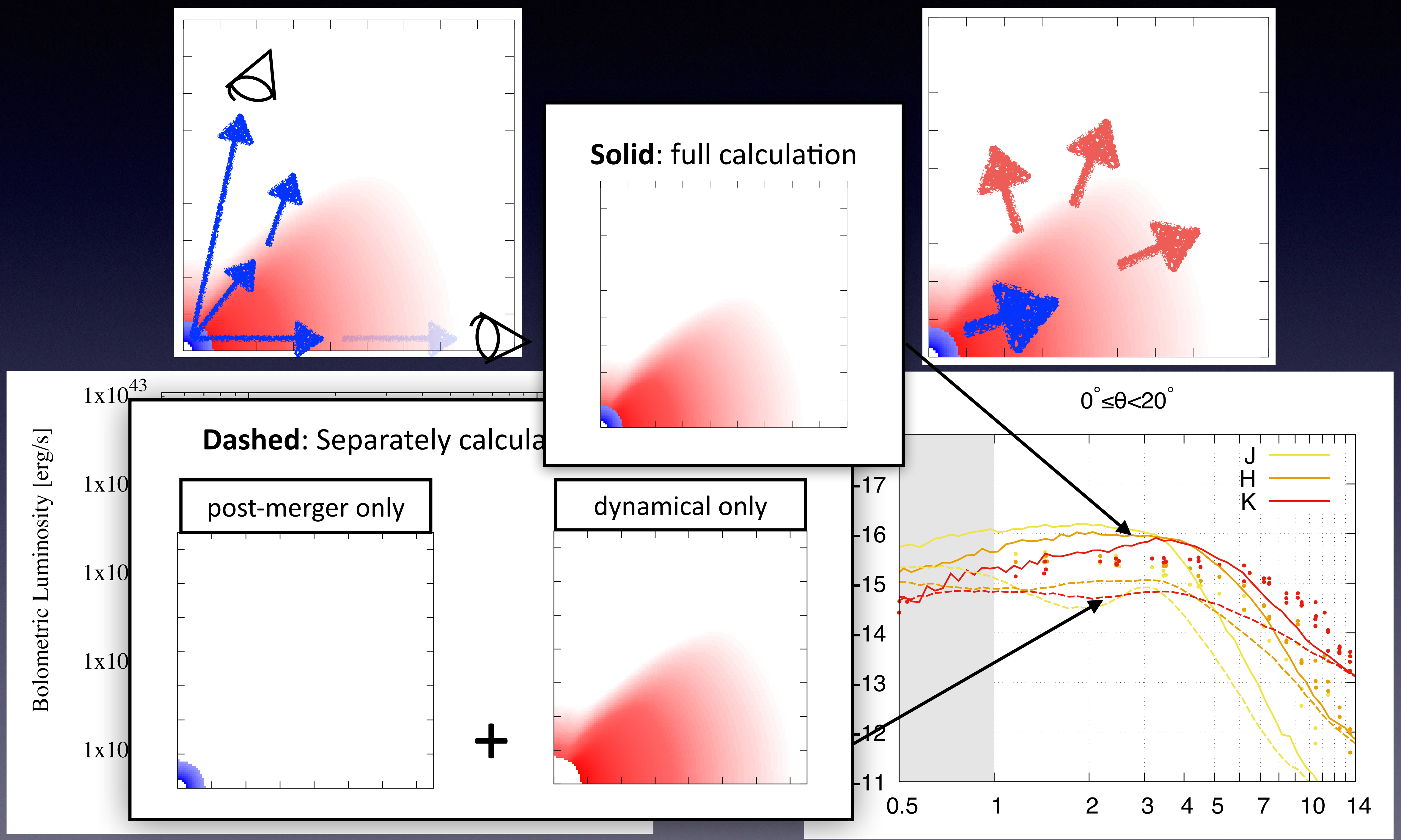
D. Watson et al. 2019



D. Kasen et al. 2017

Effect of geometry and radiative interaction between multiple ejecta components

- **Blocking effect**
- **Reprocessed emission**



Taking the radiative transfer effect of photons in the multiple ejecta components of non-spherical morphology into account is crucial for the lightcurve prediction

BNSs with a short-lived remnant MNS

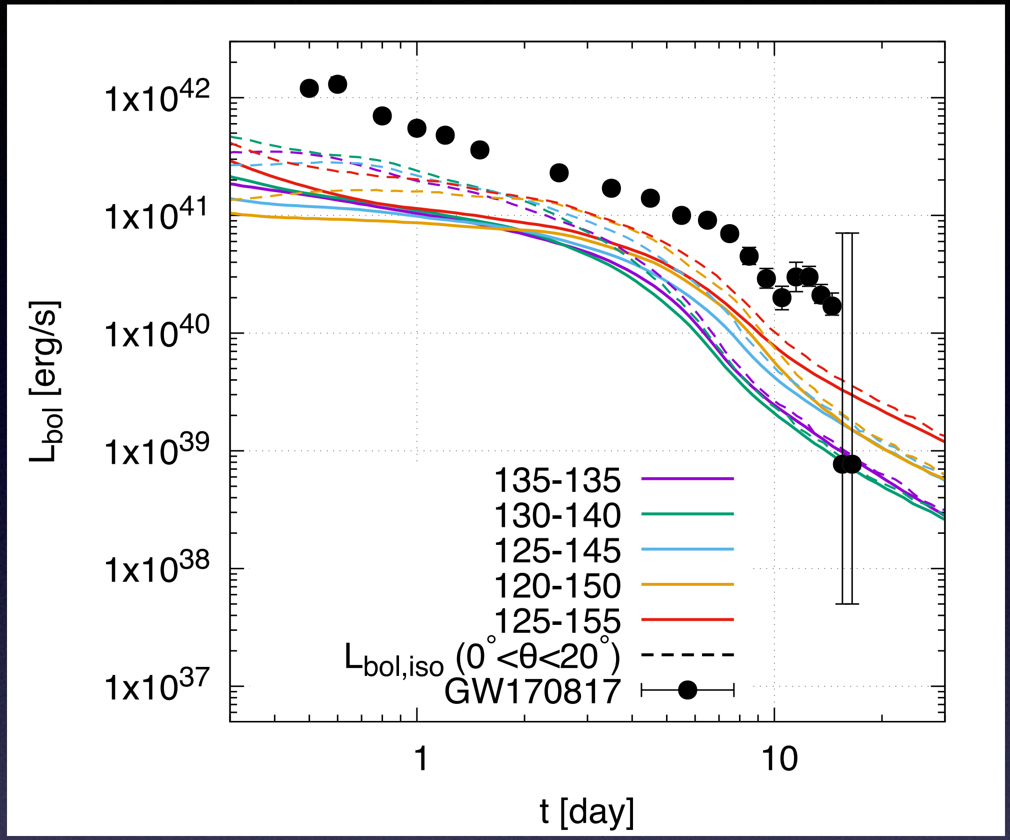
Fujibayashi et al. 2023

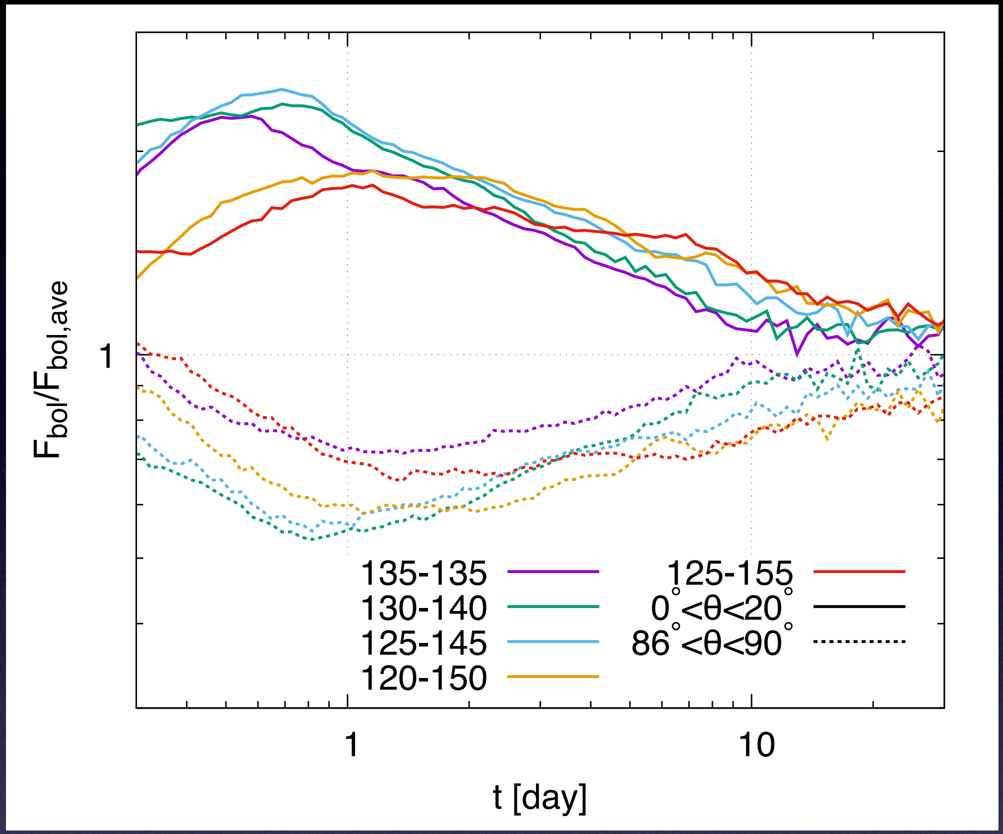
Model	$M_1/M_\odot$	$M_2/M_\odot$	M_2/M_1	$t_{\rm BH}$ (ms)	$M_{\rm BH}/M_\odot$	$\chi_{\rm BH}$	$M_{\rm disk}\,(10^{-2}M_\odot)$	$M_{\rm dyn}\,(10^{-2}M_\odot)$	$\langle Y_{\rm e,dyn}\rangle$
SFHo135-135	1.35	1.35	1.00	13	2.56	0.67	1.2	0.69	0.23
SFHo130-140	1.40	1.30	0.93	16	2.55	0.67	3.0	0.46	0.24
SFHo125-145	1.45	1.25	0.86	17	2.54	0.66	3.6	0.54	0.16
SFHo120-150	1.50	1.20	0.80	18	2.50	0.64	6.5	0.37	0.13
SFHo125-155	1.55	1.25	0.81	3	2.68	0.75	4.3	0.86	0.09

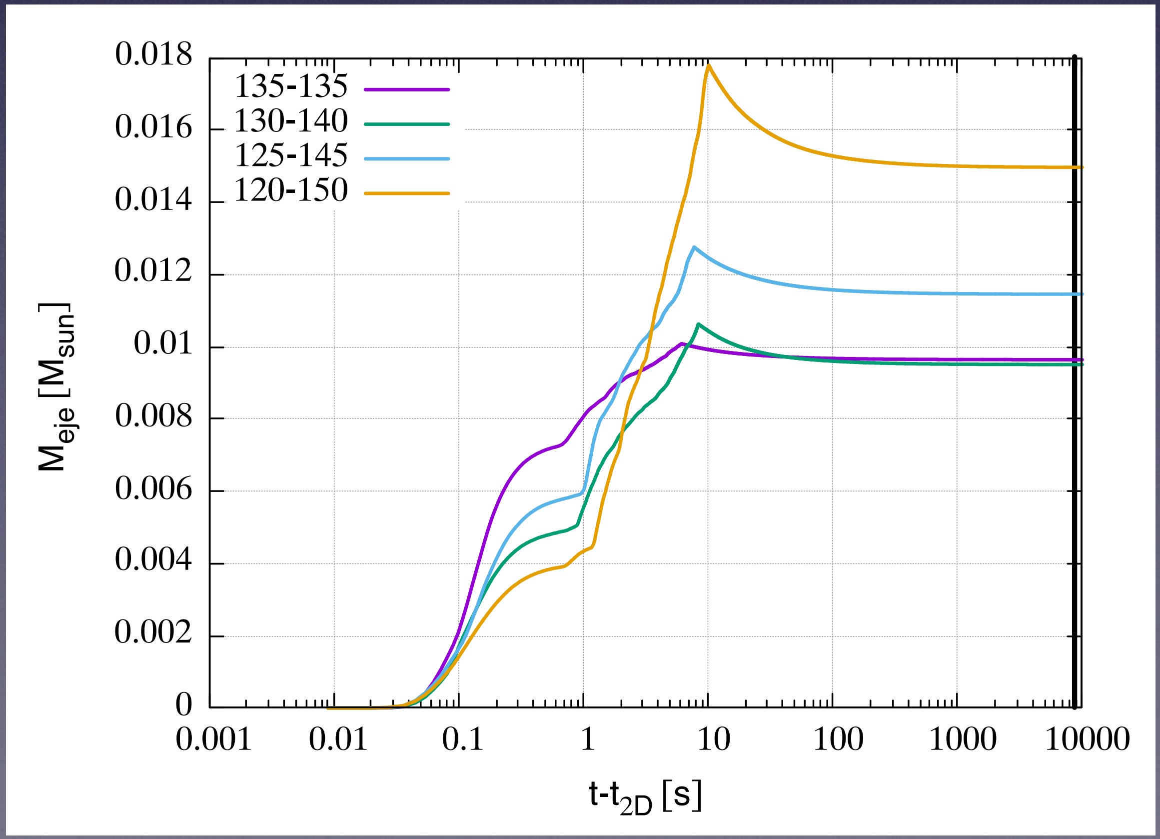
Model	Δx_0 (m)	N	L (km)	$\alpha_{\rm vis}H_{\rm tur}$ (m)	$M_{\rm post}\,(10^{-2}M_\odot)$	$M_{\rm post}/M_{\rm dyn}$
SFHo135-135	$70 \to 200$	$937 \to 689$	$9237 \to 8908$	400	0.22	0.32
SFHo130-140	$70 \to 200$	$937 \to 689$	$9237 \to 8908$	400	0.53	1.19
SFHo125-145	$70 \to 200$	$937 \to 689$	$9237 \to 8908$	400	0.69	1.26
SFHo120-150	$70 \to 200$	$937 \to 689$	$9237 \to 8908$	400	1.33	3.58
SFHo125-155	$70 \to 200$	$937 \to 689$	$9237 \to 8908$	400	0.83	0.99

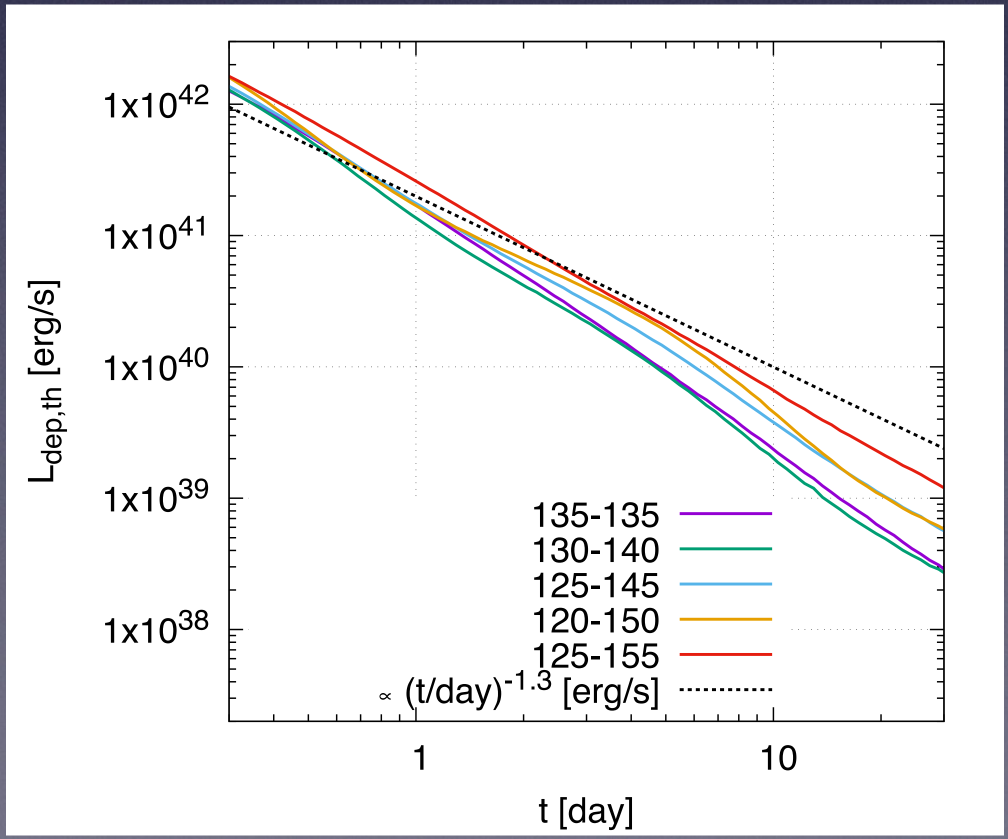
$M_{\rm dyn}$ ~ 0.005-0.01 $M_{\rm sun}$, $M_{\rm post}$~0.005-0.01 $M_{\rm sun}$

Bolometric Lightcurves

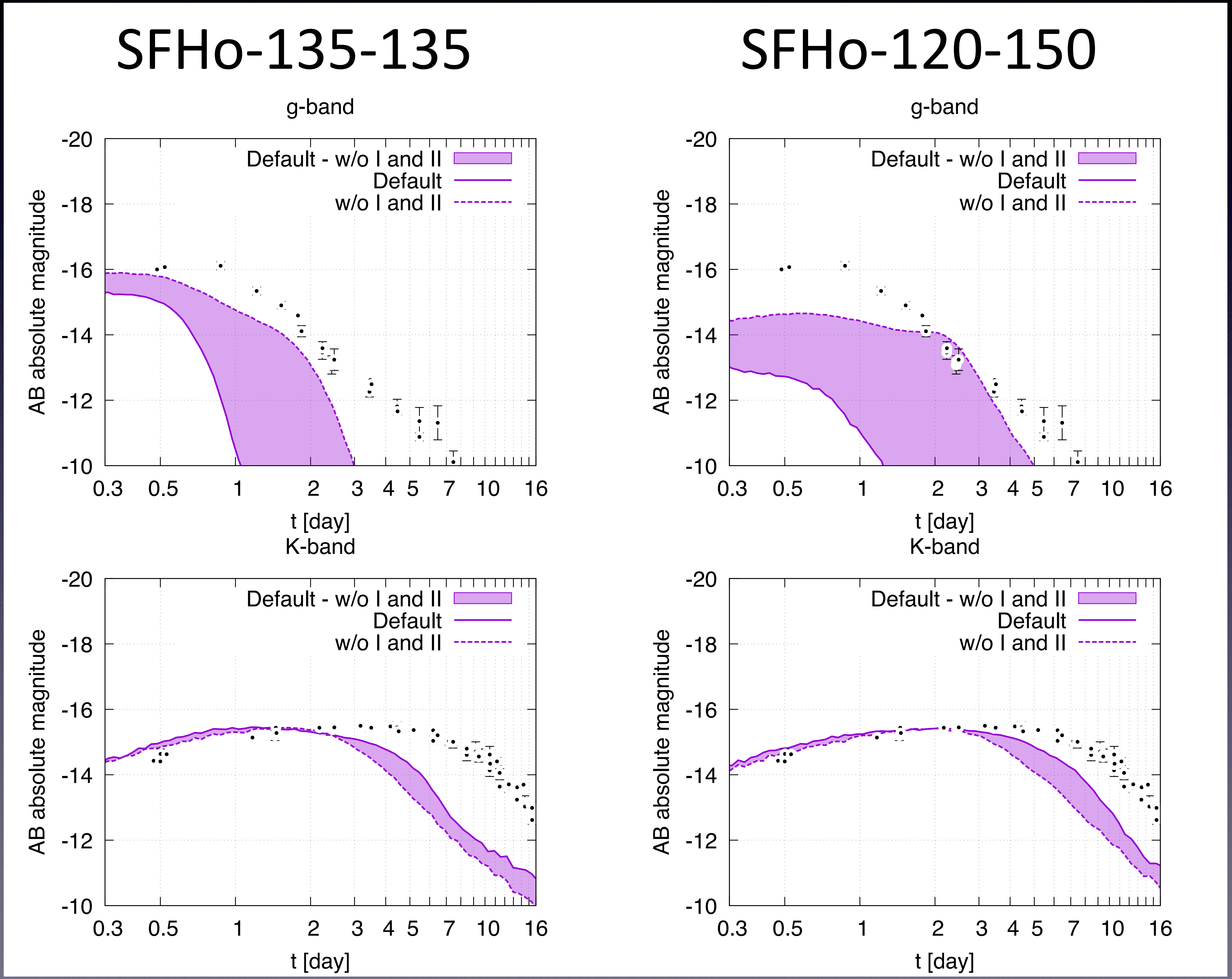




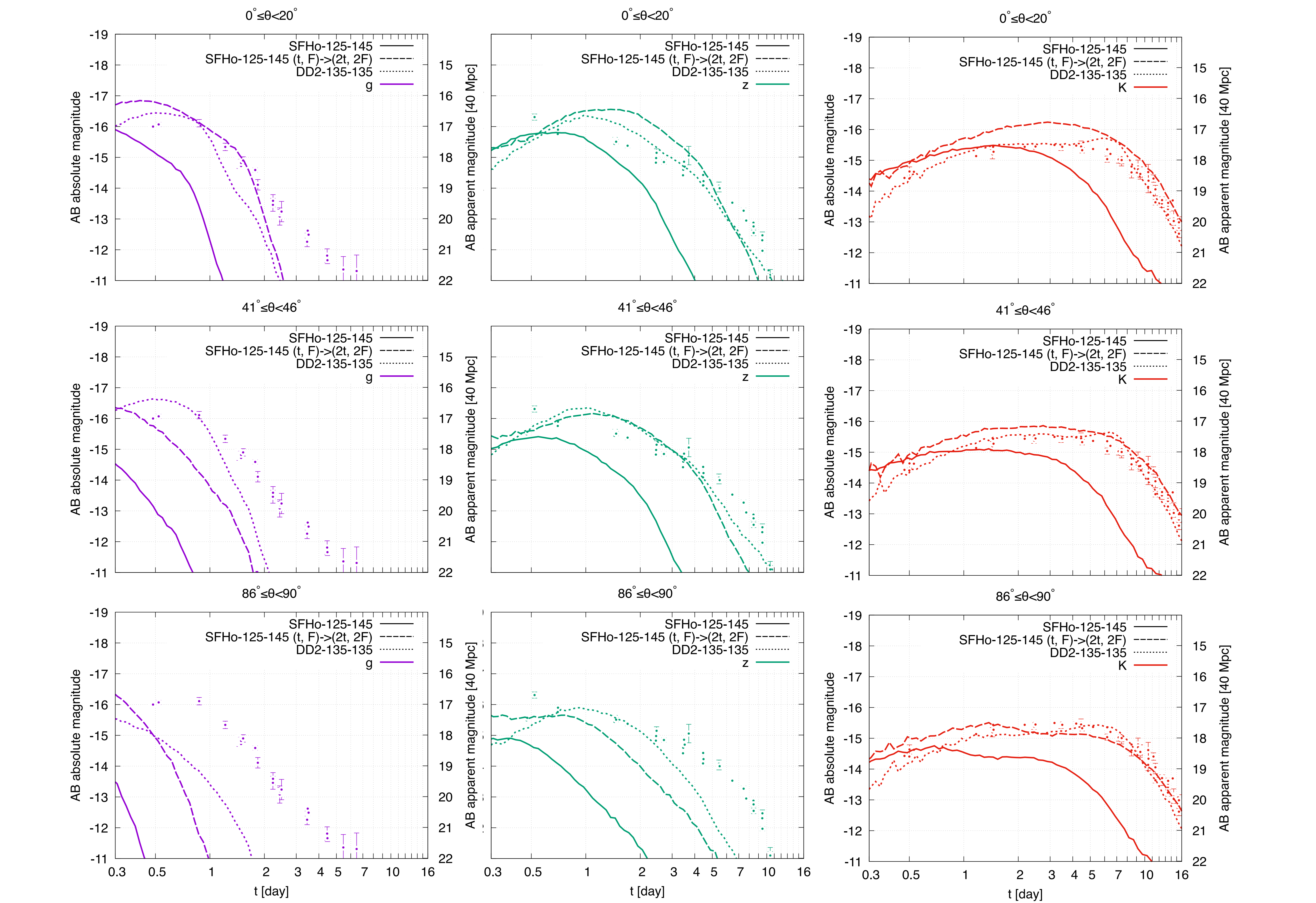




possible uncertainty by non-LTE effects (to ionization population)



Scaling law?



0°≤θ<20°
41°≤θ<46°
86°≤θ<90°
SFHo-125-145
SFHo-125-145 (t, F)->(2t, 2F)
DD2-135-135
g
z
K
AB absolute magnitude
AB apparent magnitude [40 Mpc]
t [day]