Predicting kilonova light curves with the long-term hydrodynamics evolution of merger ejecta

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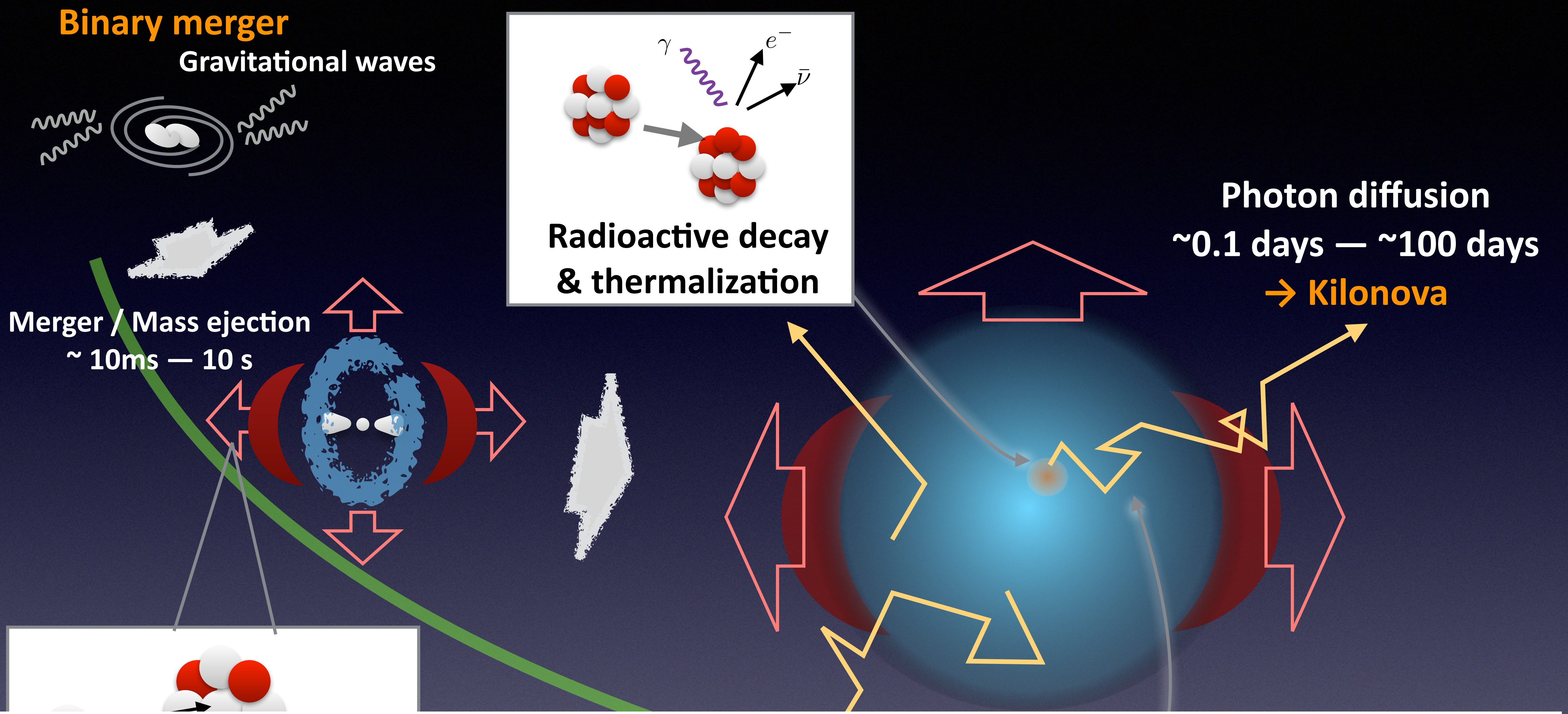
EMMI+IReNA workshop @ Darmstadt 2022/10/20

Kilonova: Overview



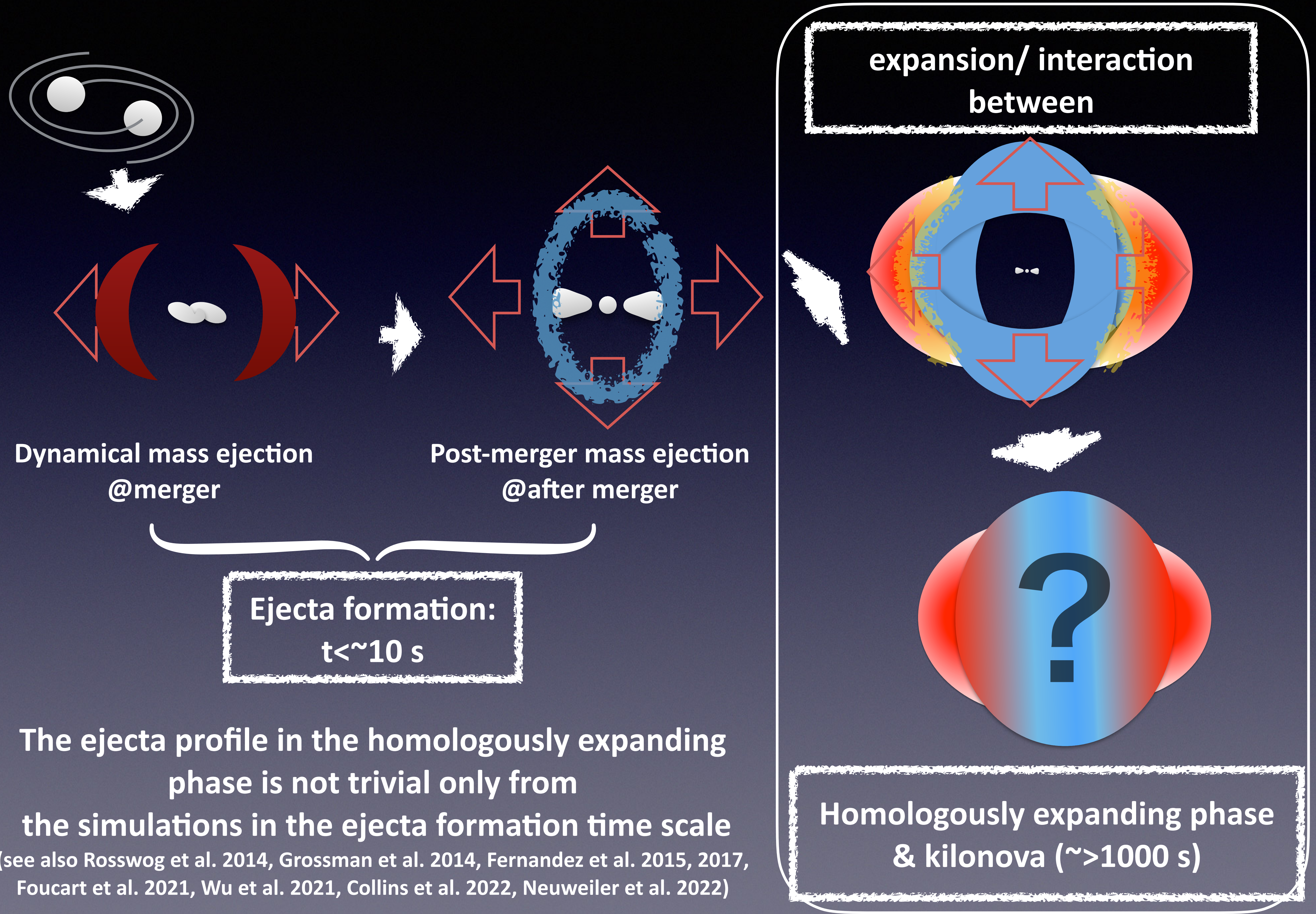
Li & Paczynski 1998, and e.g., Kulkarni 2005, Metzger et al. 2010, Hotokezaka et al. 2014, Tanaka et al. 2013, 2014, Kasen et al. 2013, 2015, Barnes et al. 2016, Wollaeger et al. 2018, Tanaka et al. 2018, Wu et al. 2019, Kawaguchi et al. 2018, Hotokezaka & Nakar 2019, Kawaguchi et al. 2019, Bulla 2019, 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…

(bound-bound)

Keys for the realistic prediction of Kilonova

- Ejecta mass, velocity, and thermodynamics property → Numerical relativity simulation in the merger and post merger phase
- Elemental/Isobaric abundances and radioactive heating rate/ thermalization efficiency → Nucleosynthesis calculation/ thermalization simulation
- **Ejecta / abundance profile in the homologously expanding phase** → **Longterm Hydrodynamics evolution of ejecta**
- Opacity table /recombination/ collision → Atomic structure calculation/ experimental data
- Light curve / spectra → Radiative transfer calculation

the Long-term hydrodynamics evolution of ejecta



Dynamical mass ejection
@merger

Post-merger mass ejection
@after merger

Ejecta formation:
t<~10 s

expansion/ interaction
between

Homologously expanding phase
& kilonova (~>1000 s)

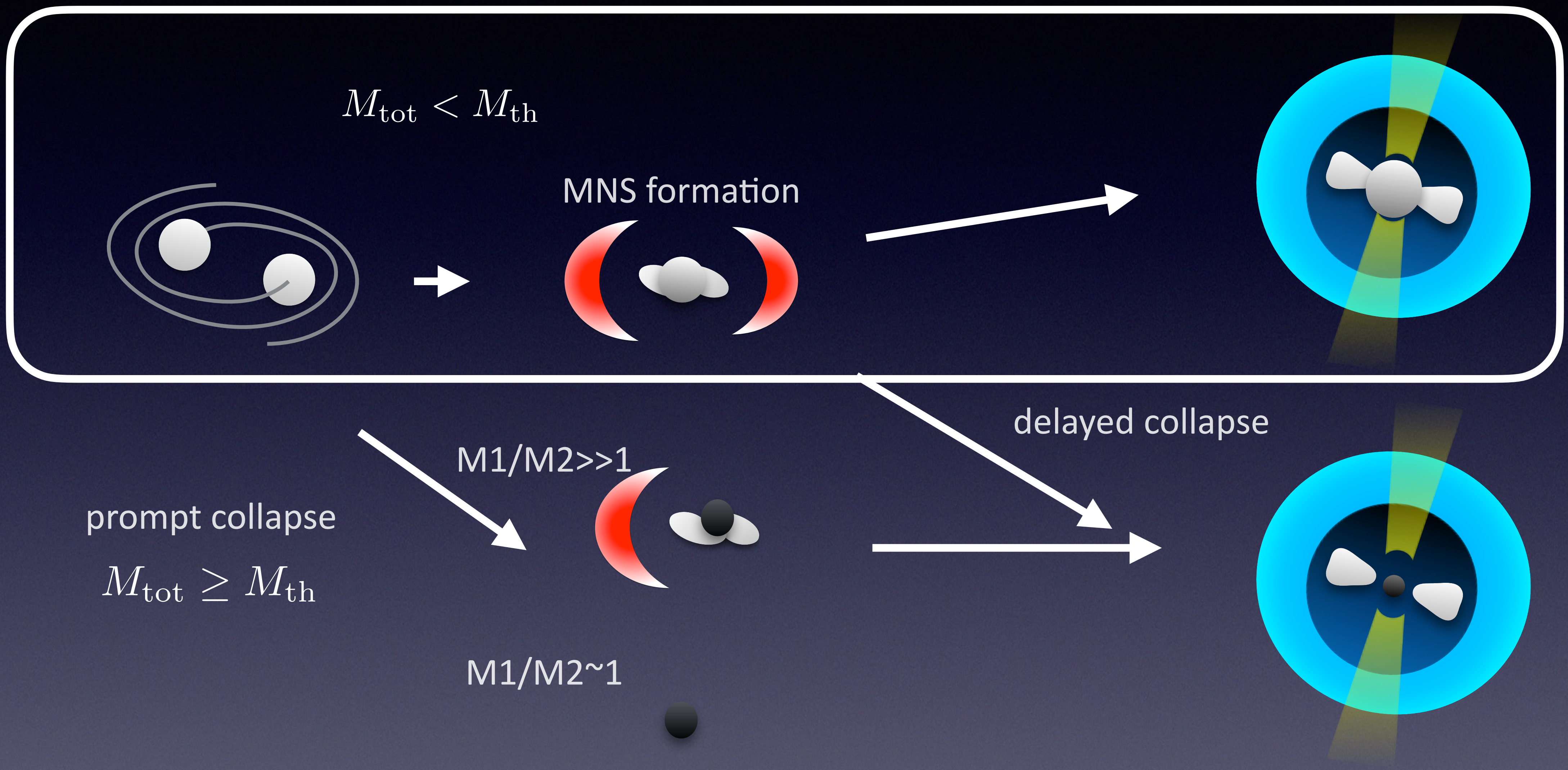
The ejecta profile in the homologously expanding phase is not trivial only from the simulations in the ejecta formation time scale

(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)

the long-term evolution of merger ejecta
&
the kilonova light curve

K. Kawaguchi et al. 2021, ApJ., 913, 100
K. Kawaguchi et al. 2022, ApJ., 933, 22

Model: BNS with a Long-lived remnant NS



$M_{\rm tot} < M_{\rm th}$

MNS formation

delayed collapse

M1/M2>>1

prompt collapse

$M_{\rm tot} \geq M_{\rm th}$

M1/M2~1

- **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)

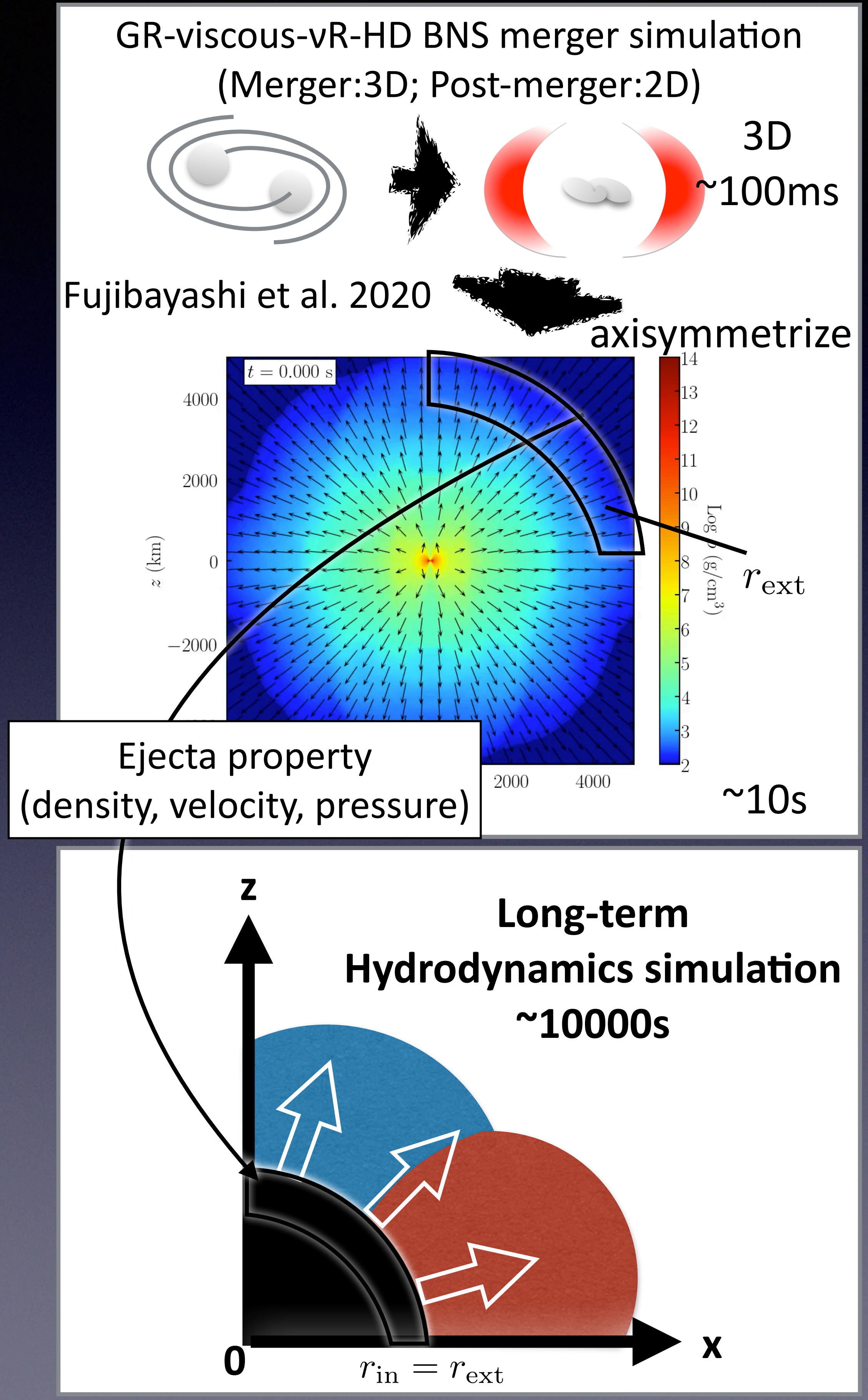
  r: log uniform, θ: uniform mesh (r:1024 , θ:128 grid points)

- 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.)



GR-viscous-νR-HD BNS merger simulation
(Merger:3D; Post-merger:2D)

3D
~100ms

Fujibayashi et al. 2020

axisymmetrize

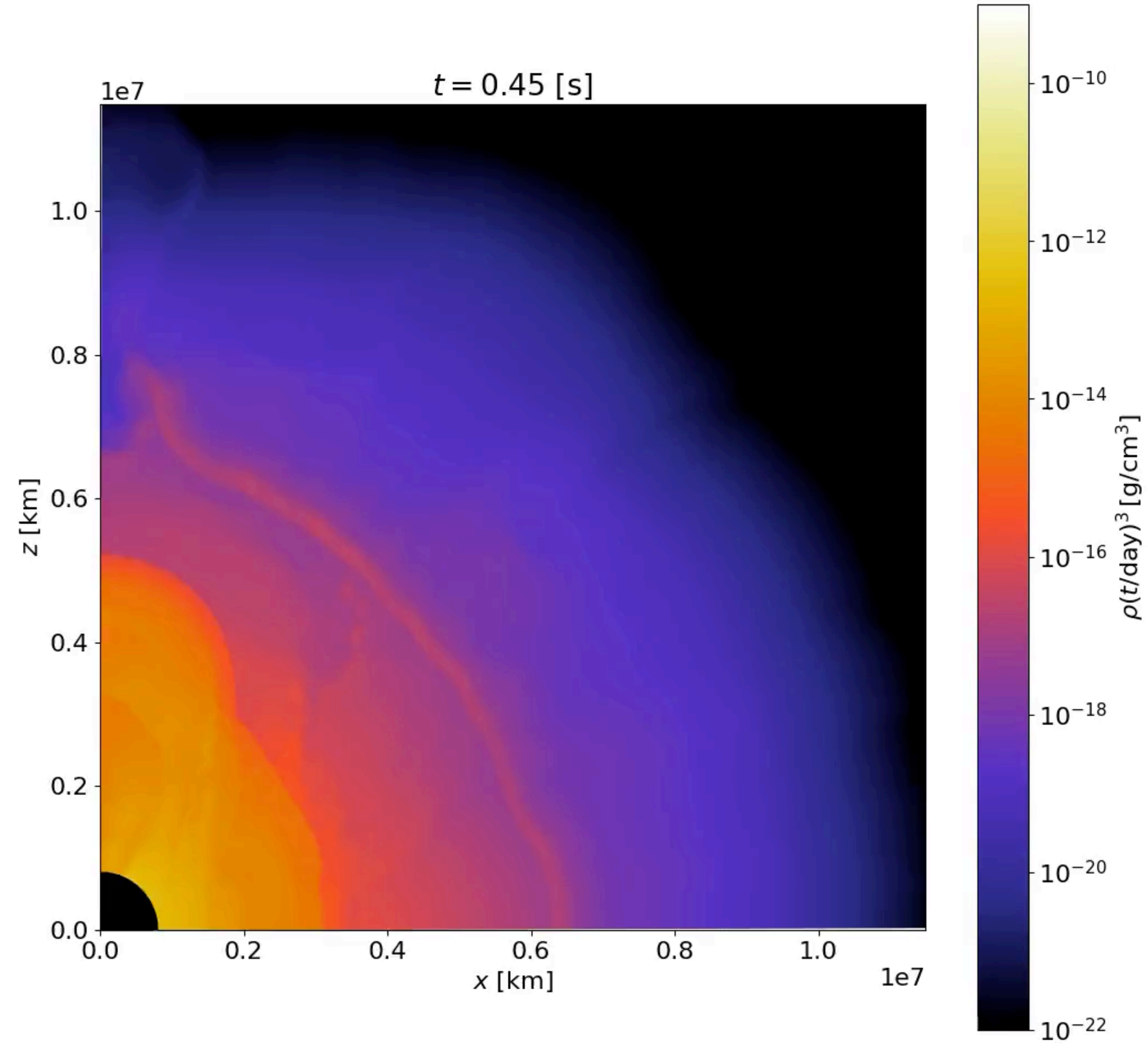
Ejecta property
(density, velocity, pressure)

~10s

Long-term
Hydrodynamics simulation
~10000s

Result: Hydrodynamical simulation

Rest-mass density evolution



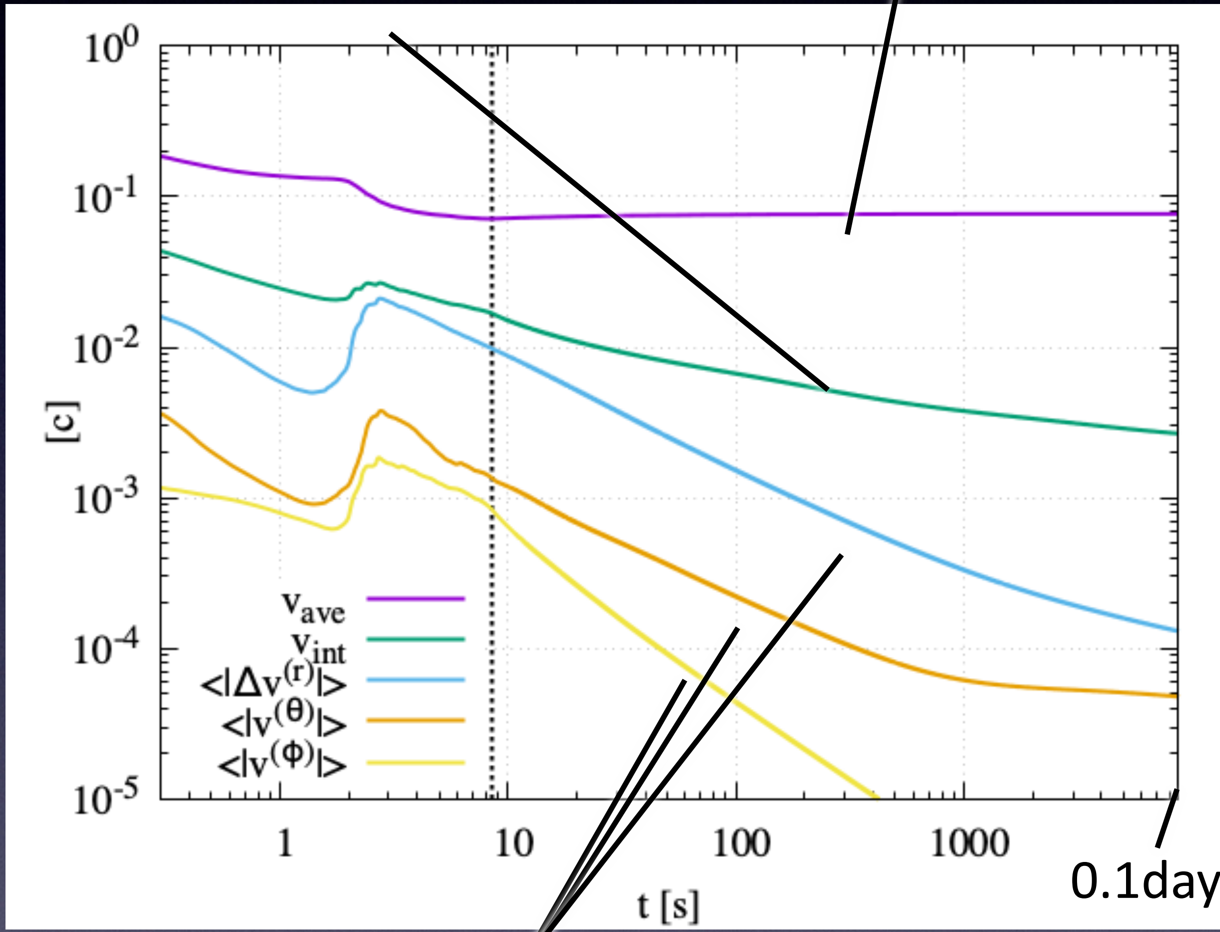
KK et al. 2021

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

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

r.m.s. average velocity

internal energy contribution
(~sound speed)



0.1day

deviation from homologous expansion

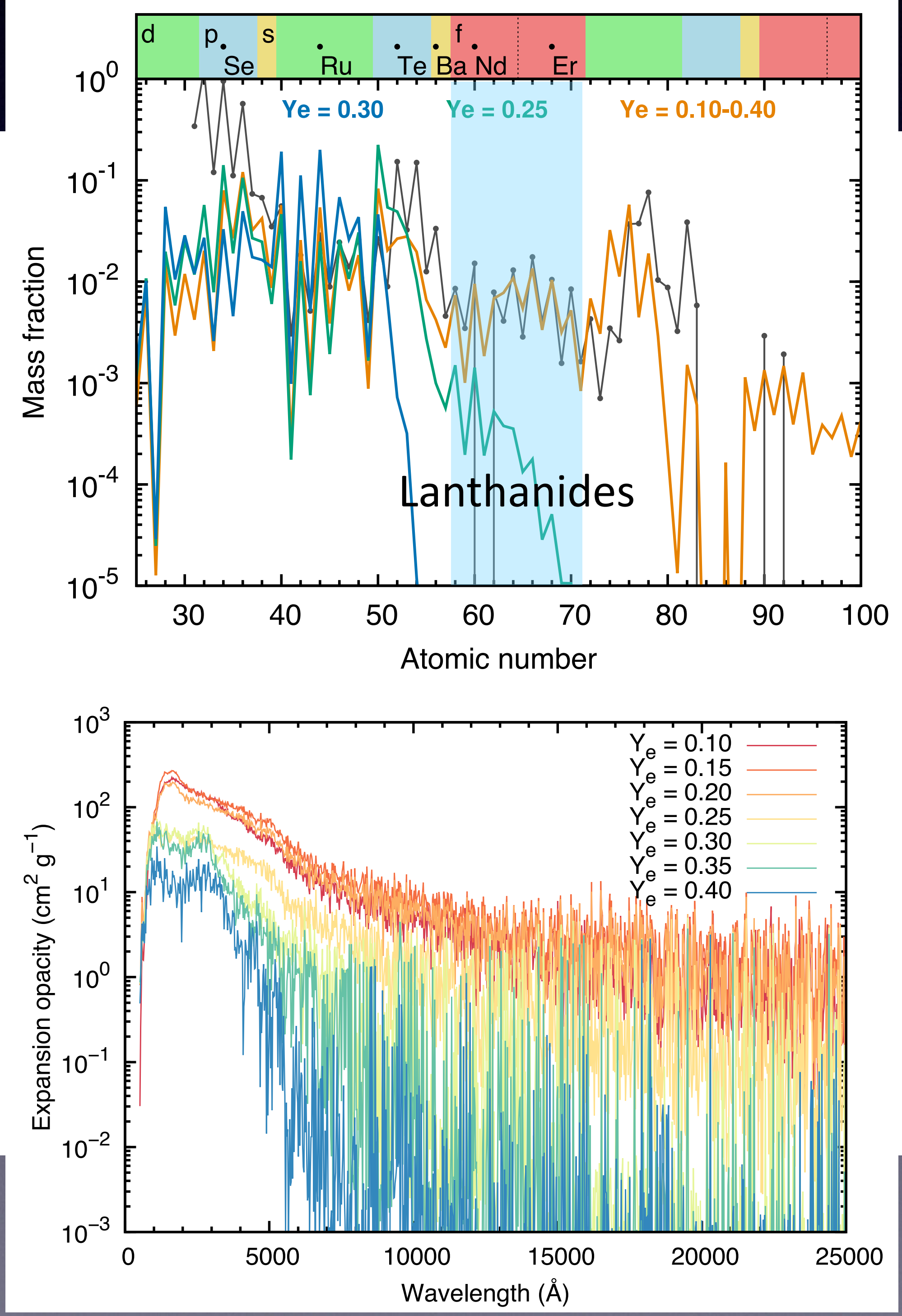
- ~>1000 s :
  homologously expanding phase

$$v^r \approx r/t$$

Density & Ye profile@homologous expansion

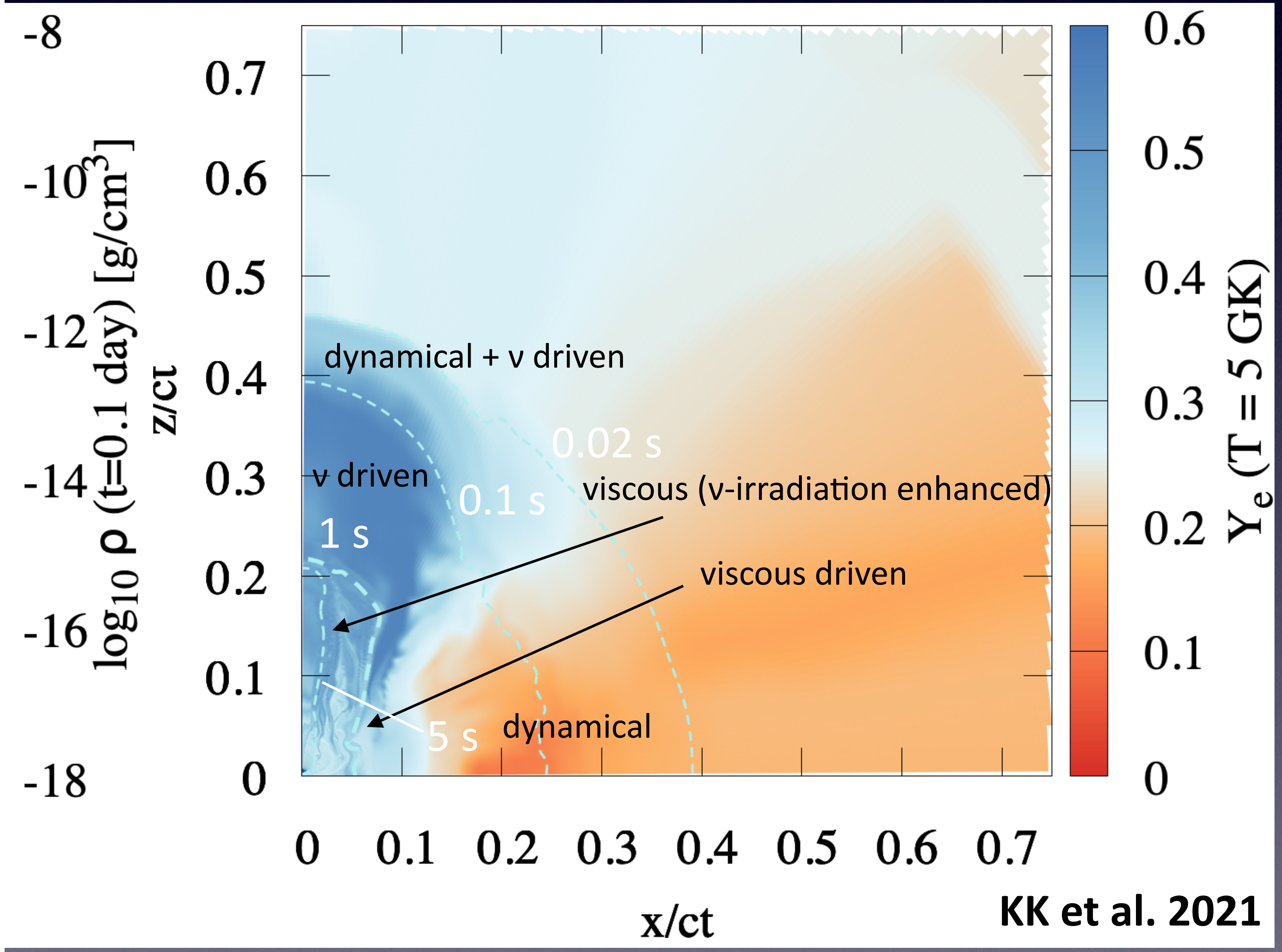
Snapshot at t=0.1 day

Wanajo et al. 2014, Tanaka el al. 2020



Ye@ T=5GK

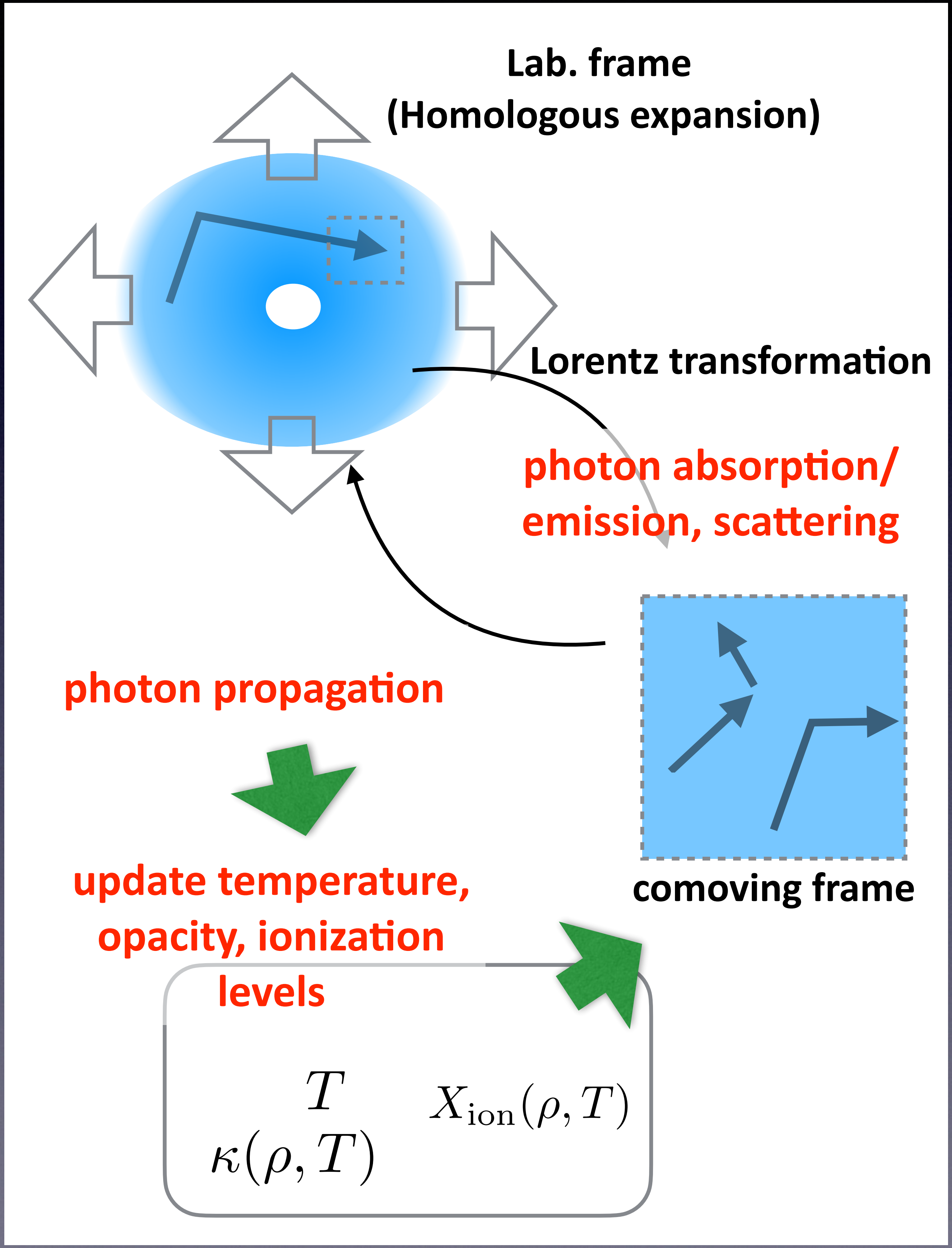
$$Y_e = \frac{[e]}{[p]+[n]}$$



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)**



Lab. frame
(Homologous expansion)

Lorentz transformation

photon absorption/ emission, scattering

comoving frame

photon propagation

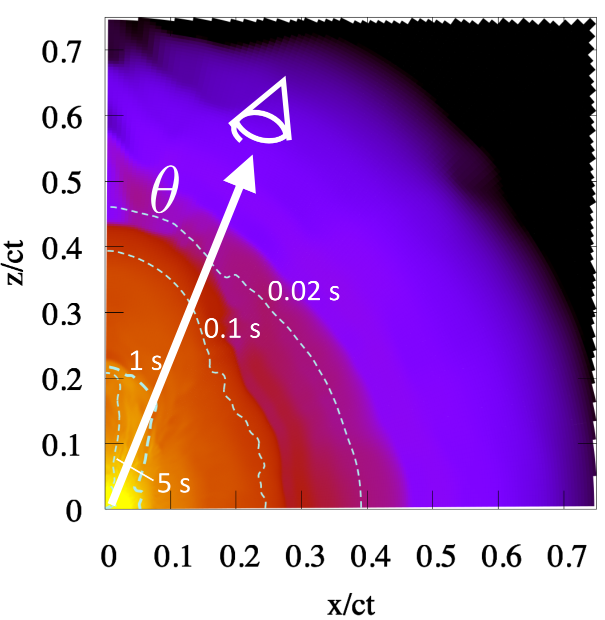
update temperature, opacity, ionization levels

T $X_{\rm ion}(\rho, T)$

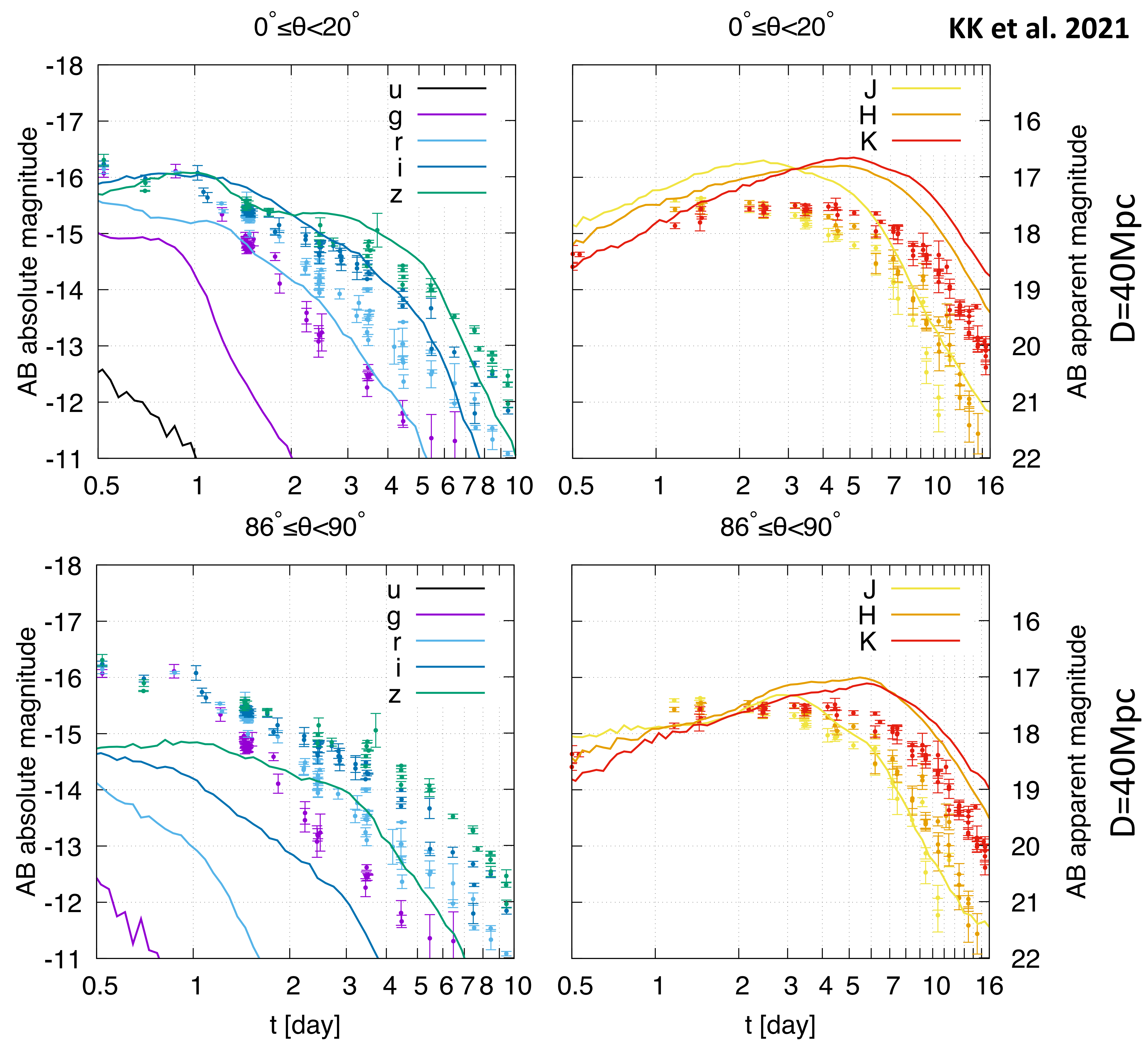
$\kappa(\rho, T)$

Result:Radiative transfer

BroadBand magnitudes



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



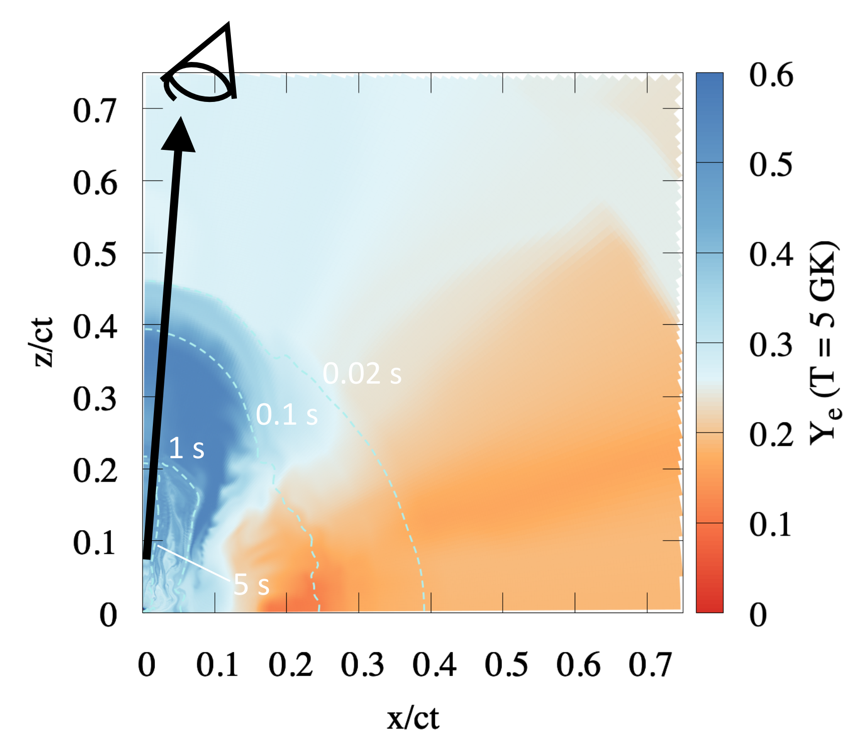
KK et al. 2021

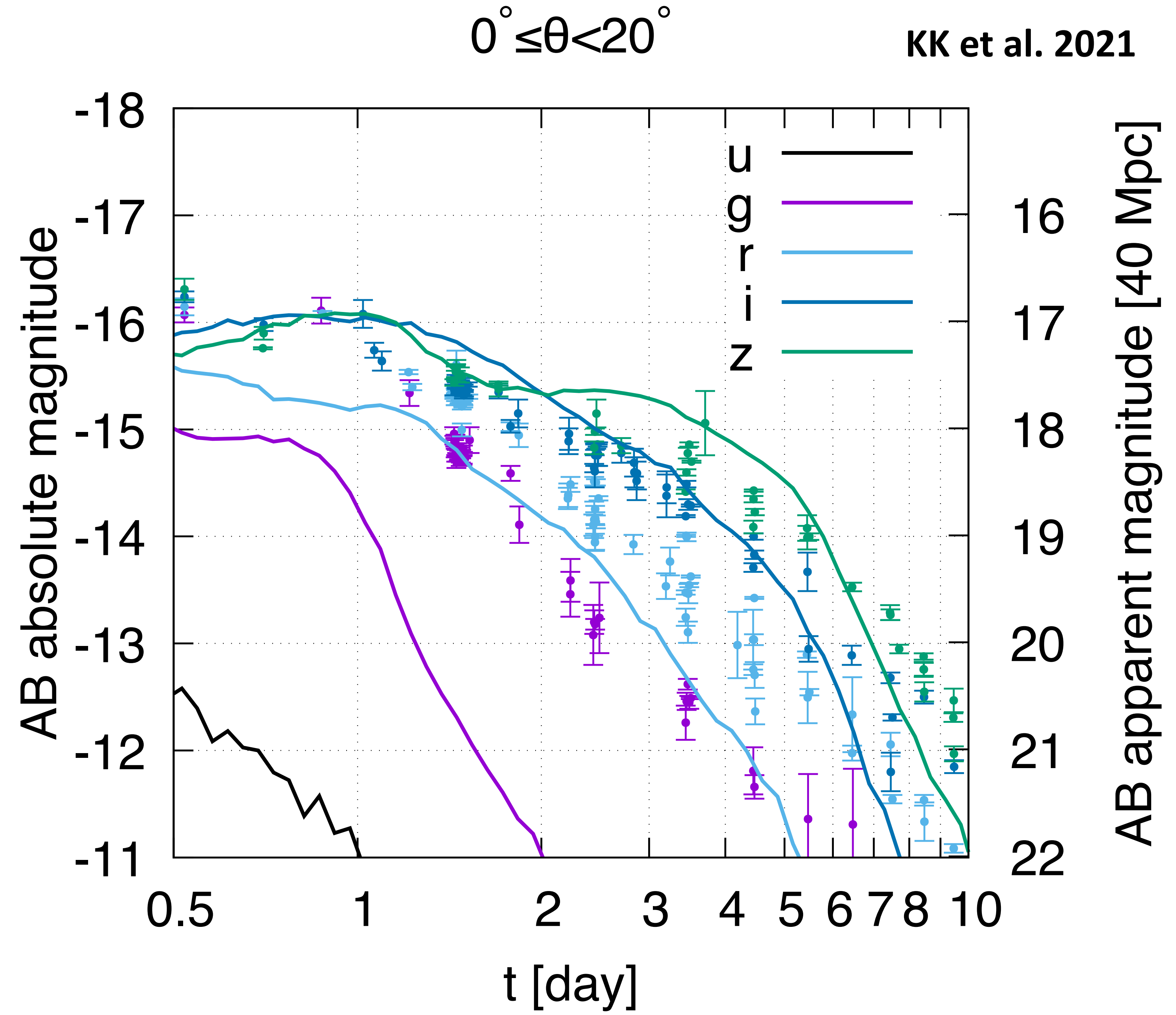
High-Ye/lanthanide free in the polar region, but not blue (not bright in optical wavelength)

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

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

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

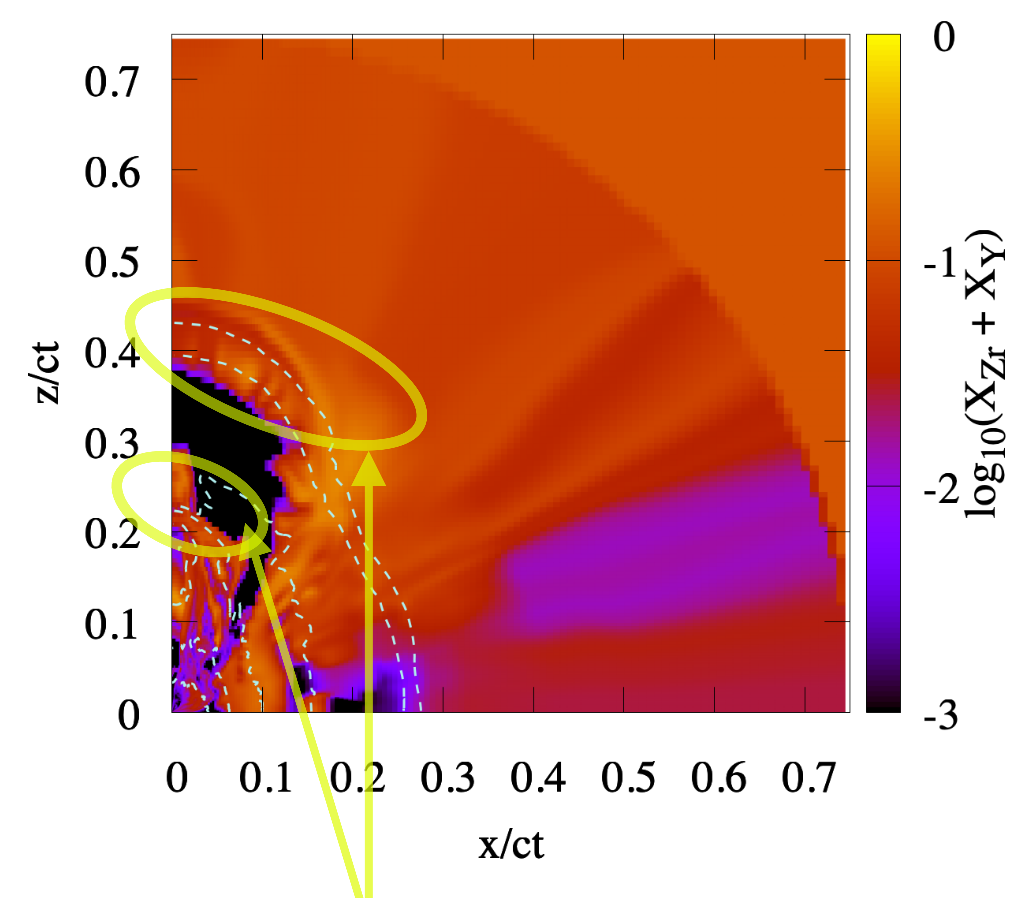


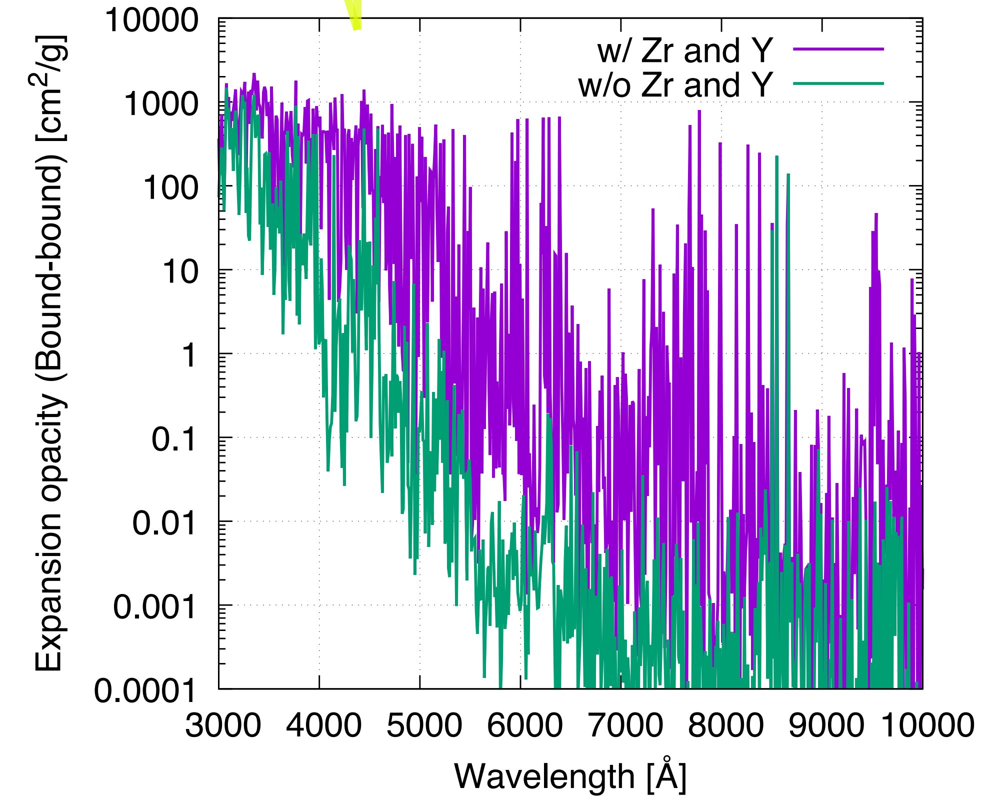


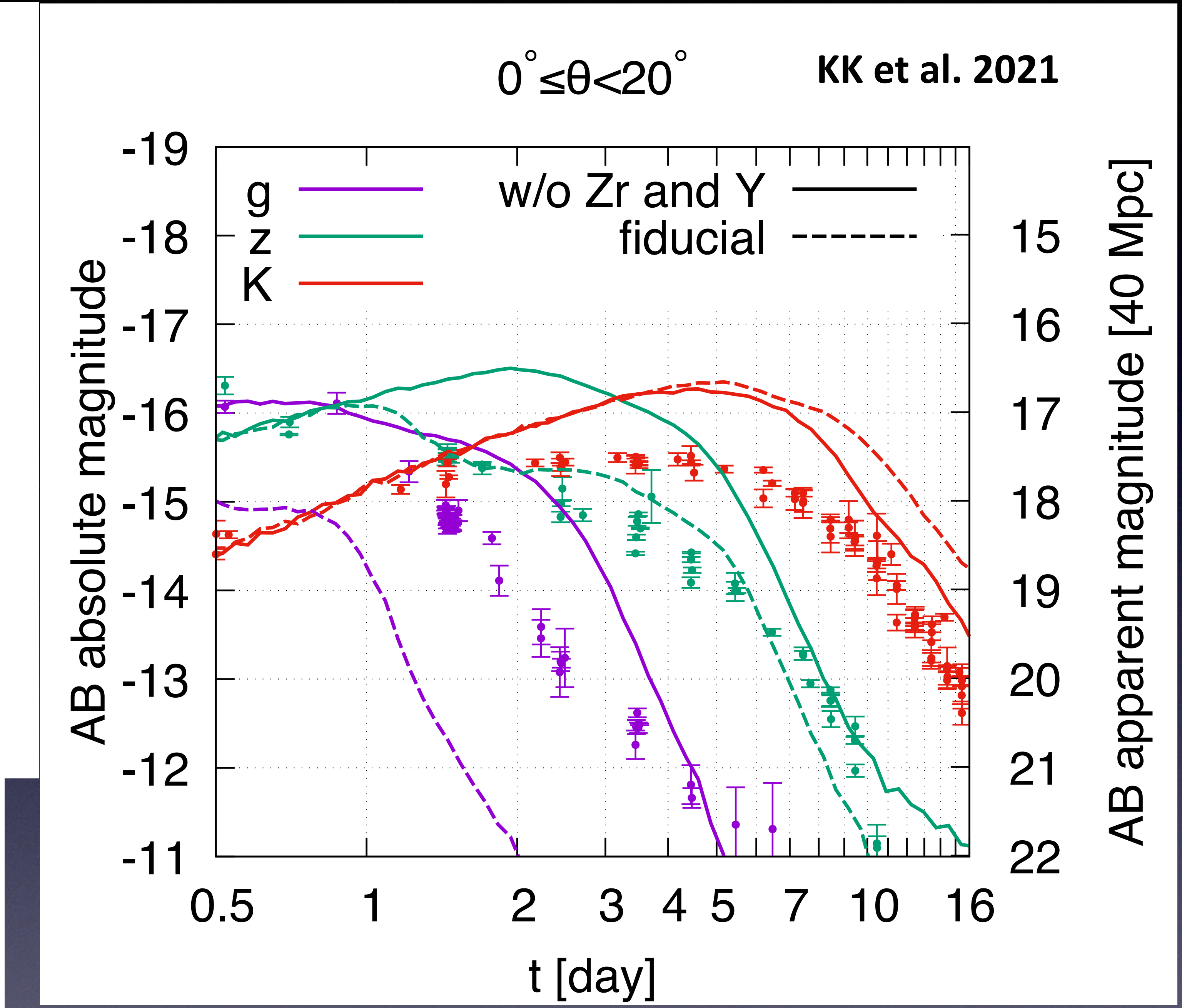
KK et al. 2021

- 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



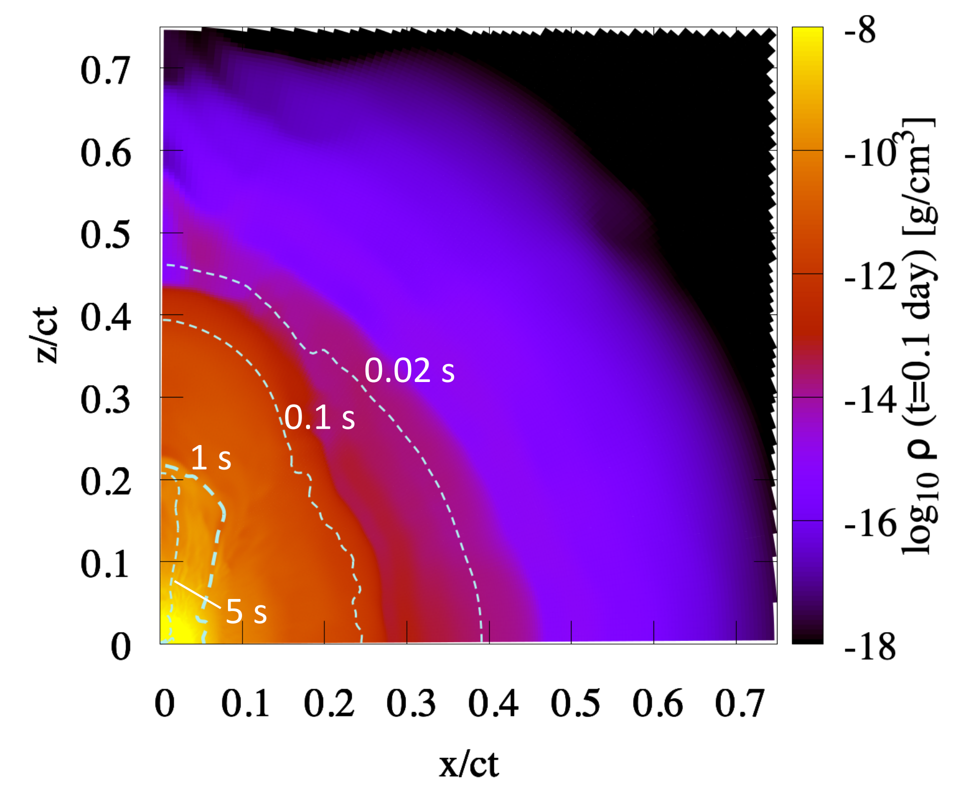


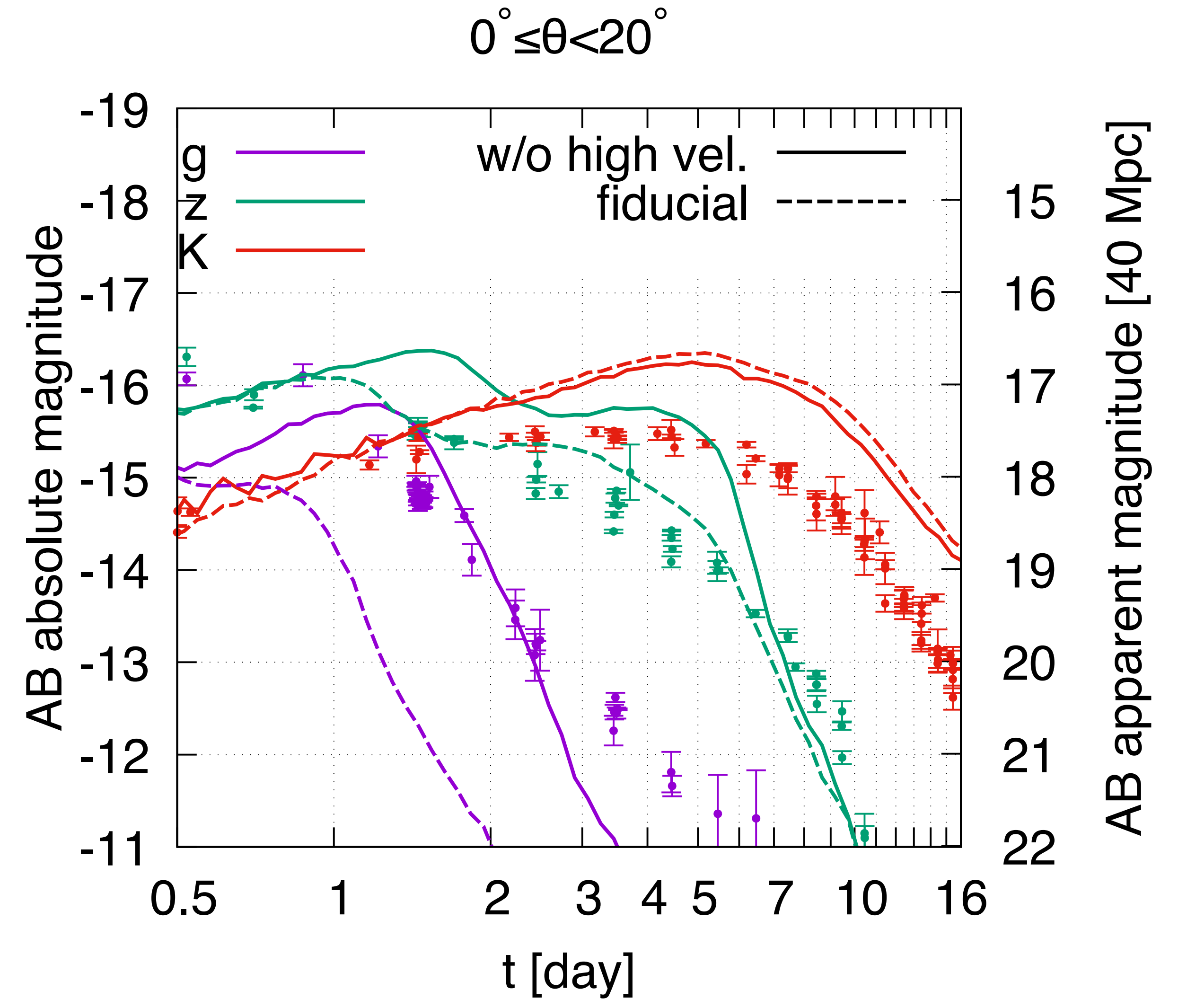


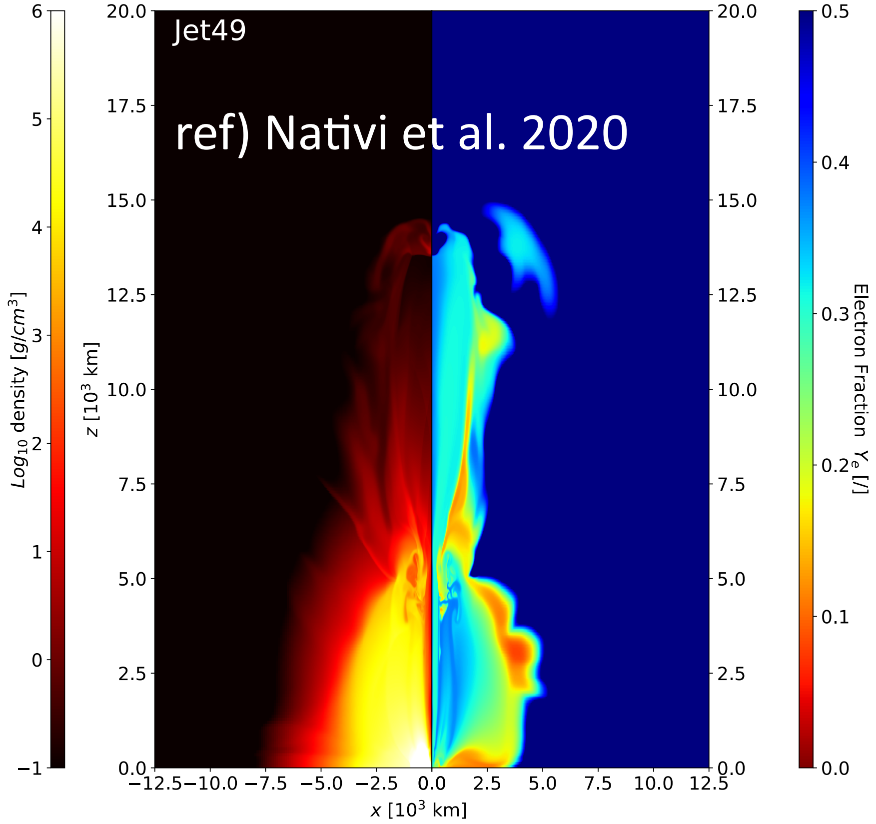
- a large amount of 1st r-process peak elements including **Zr (Z=40) and Y (Z=39)** are present in the polar high velocity region
- Zr and Y (d-shell element) have a great contribution to the opacity in the optical band (**~>4000 Å)** **(see also Watson et al. 2019, Gillanders et al. , Ristilc et al.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

What is the origin of GW170817?

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





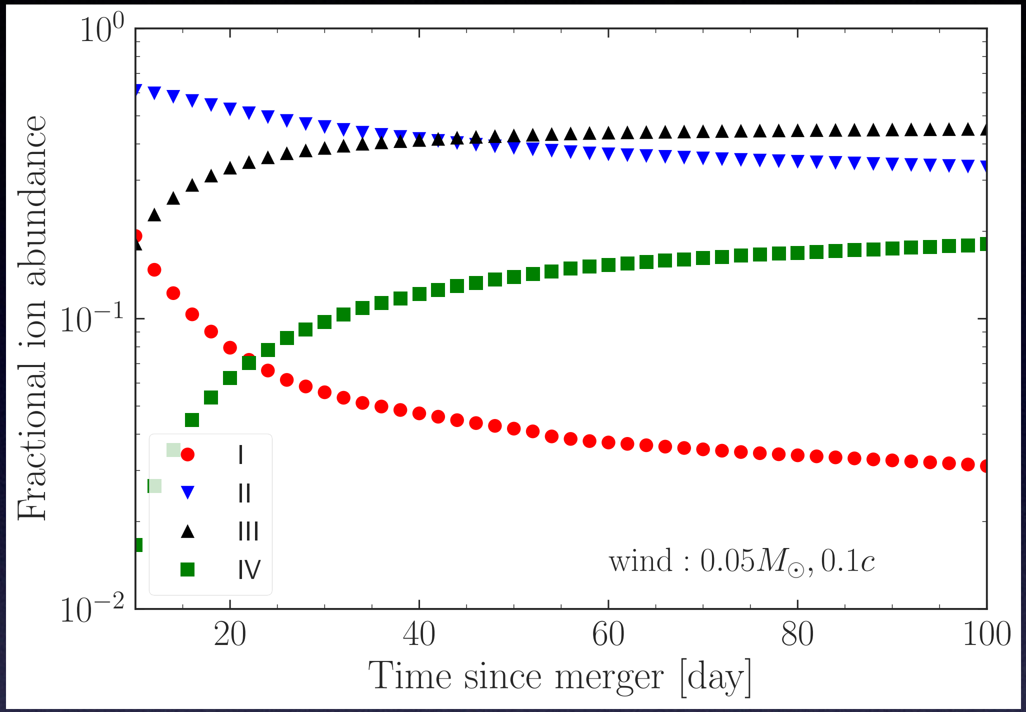


ref) Nativi et al. 2020

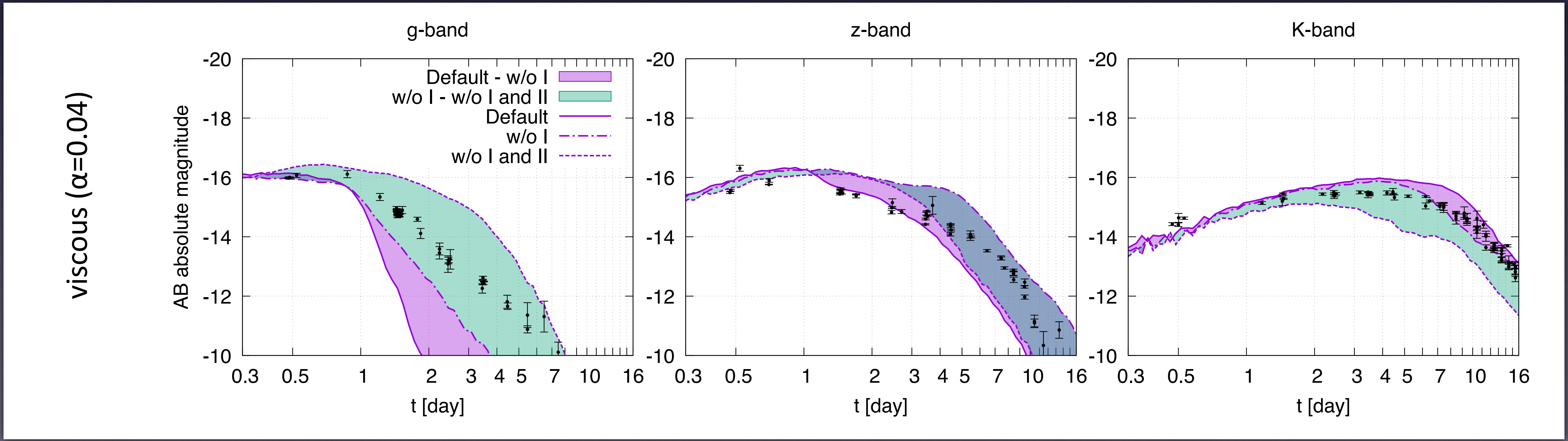
- The blue (optical) emission is enhanced for a model in which the outflow in θ<30° is suspended after t~200ms
  - may suggest that the remnant in GW170817 is unlikely to be a long-lived NS, but might have collapsed to a black hole in a short time scale (~100ms)
- Relativistic jets may revive the blue 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

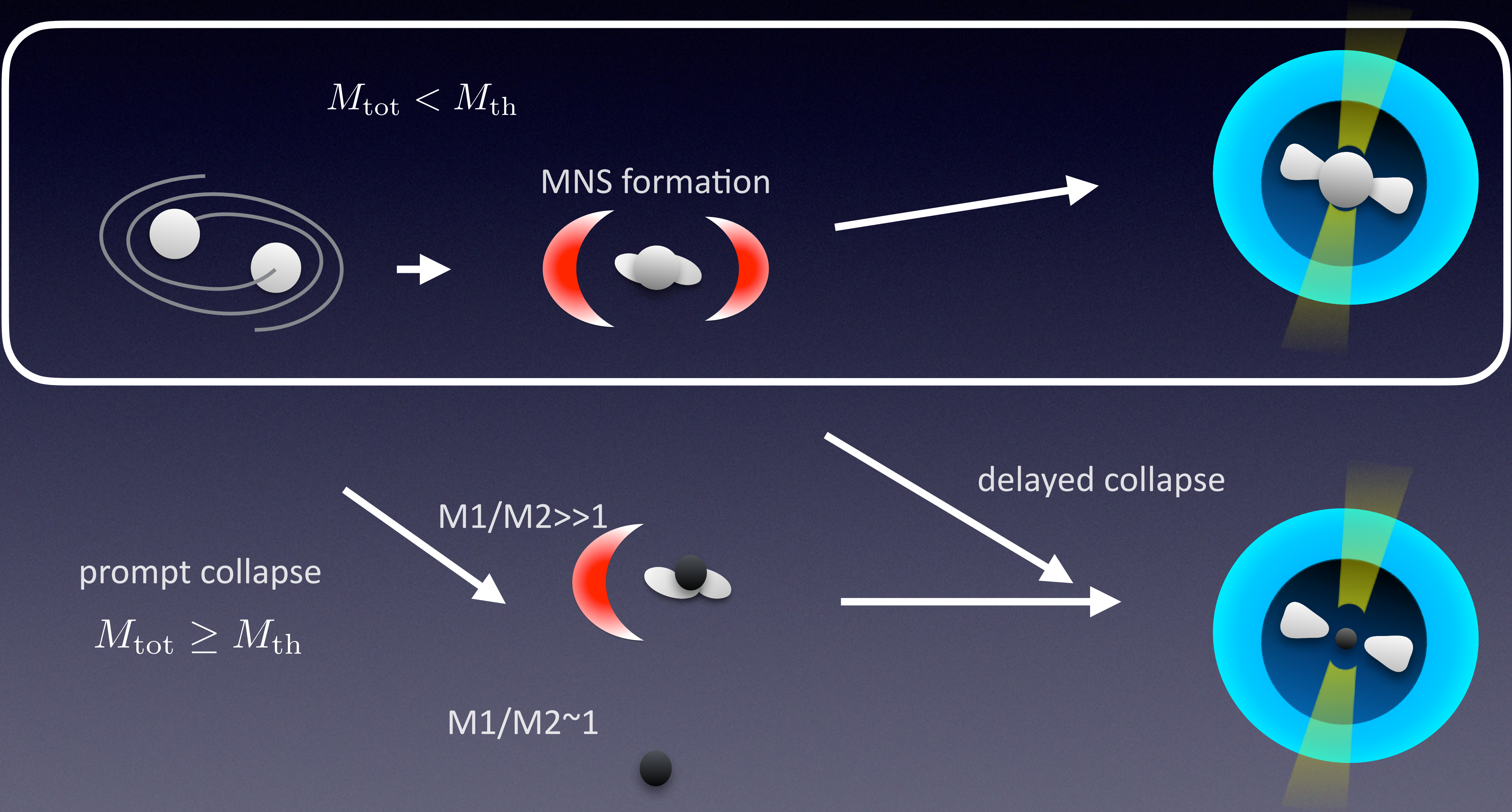


KK et al. 2021, 2022



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



$M_{\mathrm{tot}} < M_{\mathrm{th}}$

MNS formation

delayed collapse

M1/M2>>1

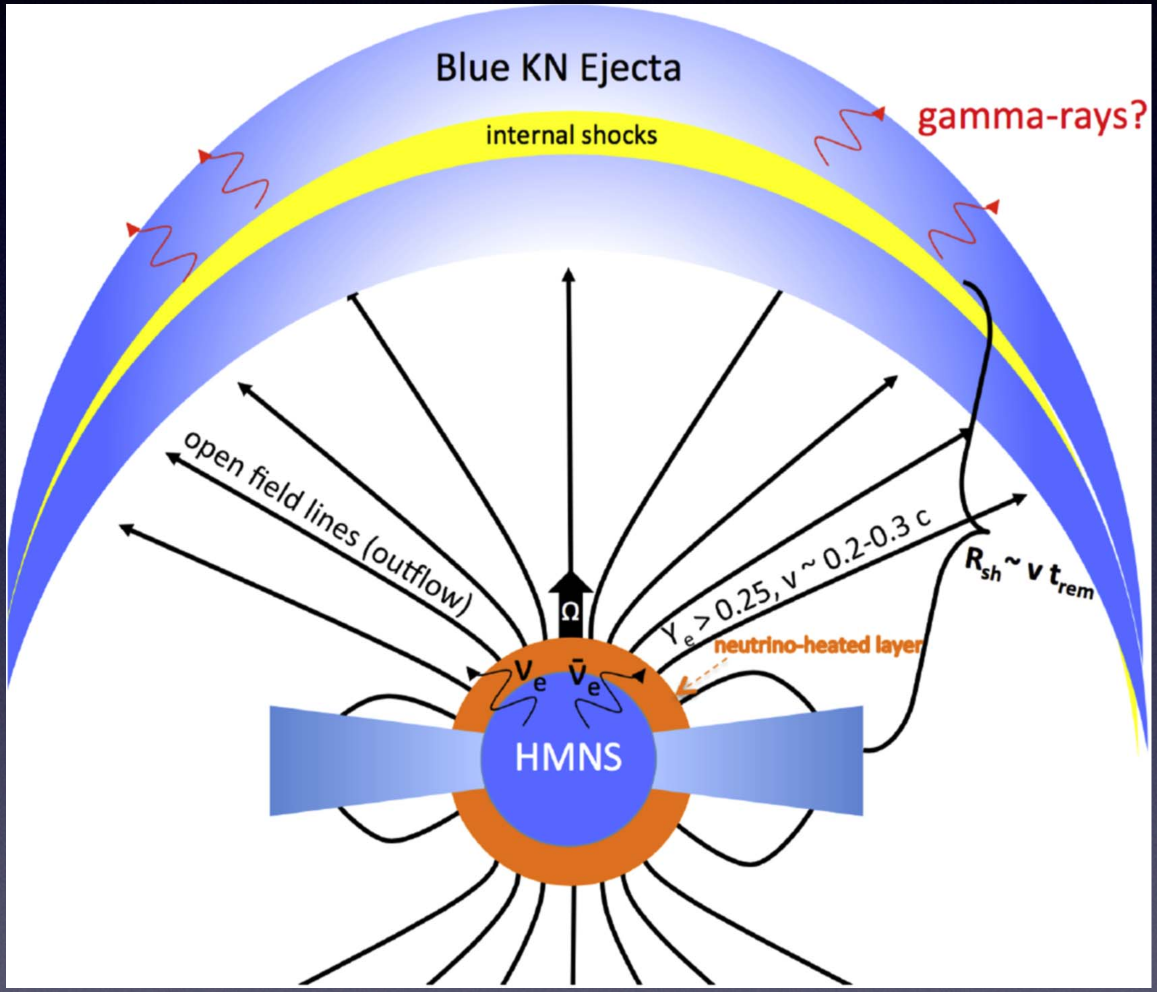
prompt collapse

$M_{\mathrm{tot}} \geq M_{\mathrm{th}}$

M1/M2~1

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

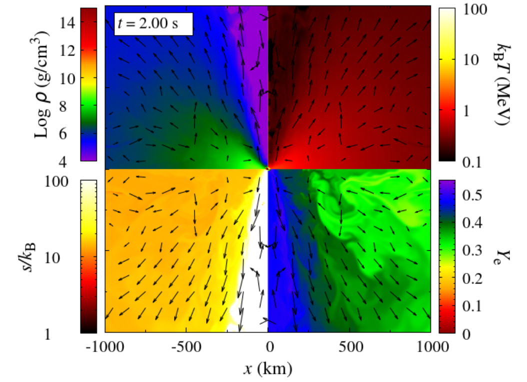
Model : 1.35 M_{sun} + 1.35 M_{sun} (DD2 EOS)

3D GRRHD BNS merger simulation

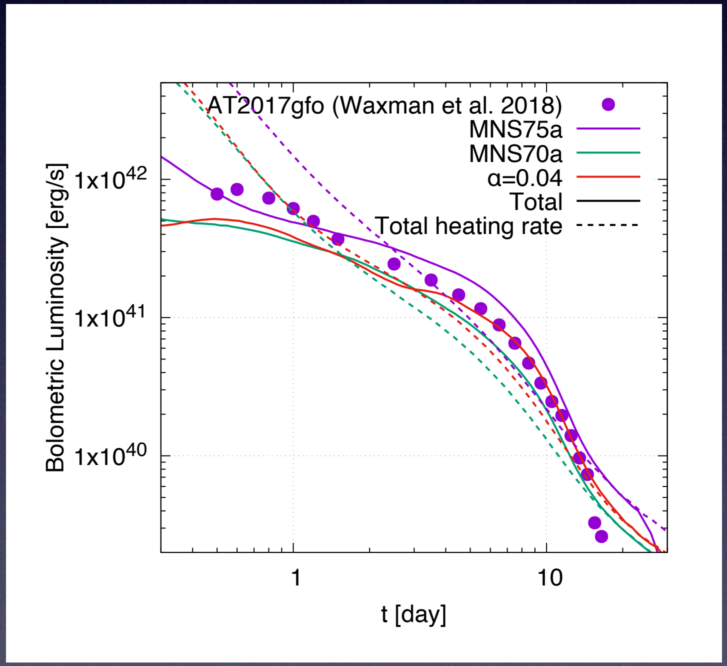
Shibata et al. 2021, KK et al. 2022

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

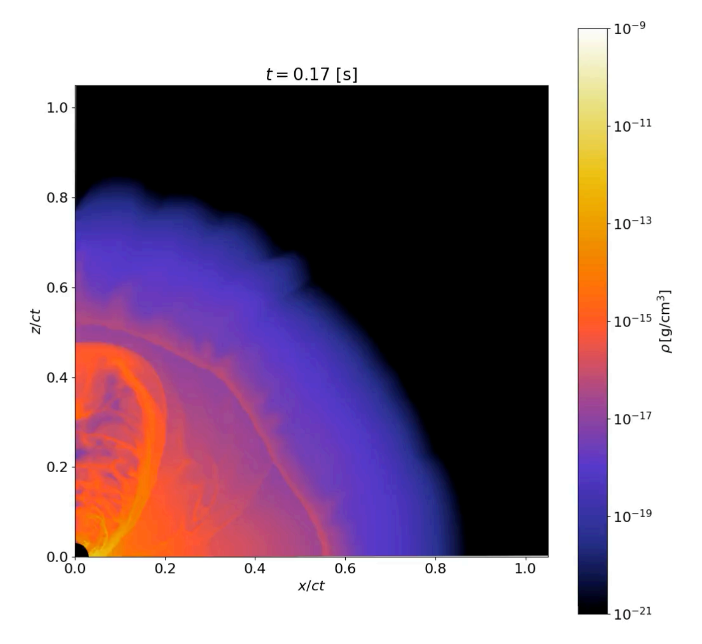
Axisymmetrize



Radiative transfer simulation synchrotron emission calculation



Extract ejecta component



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

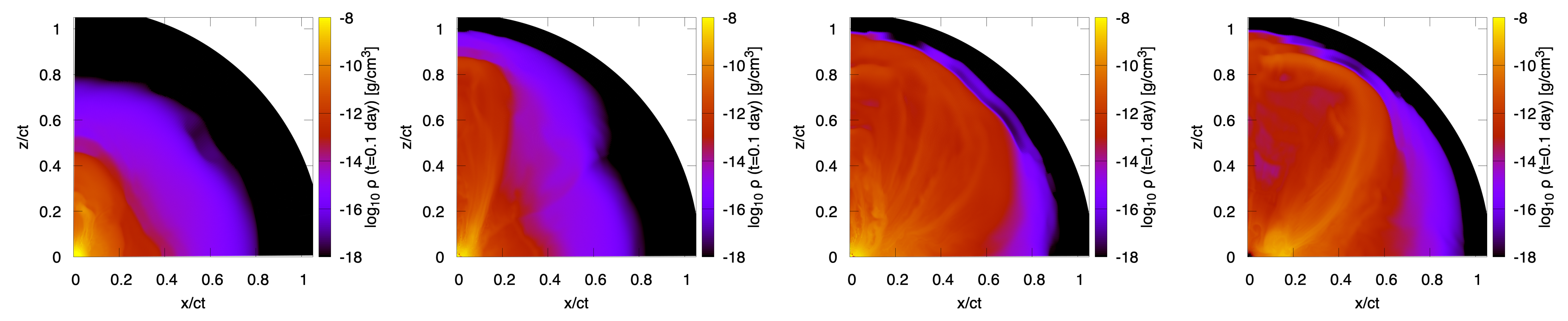
EM counterpart prediction

Ejecta profile

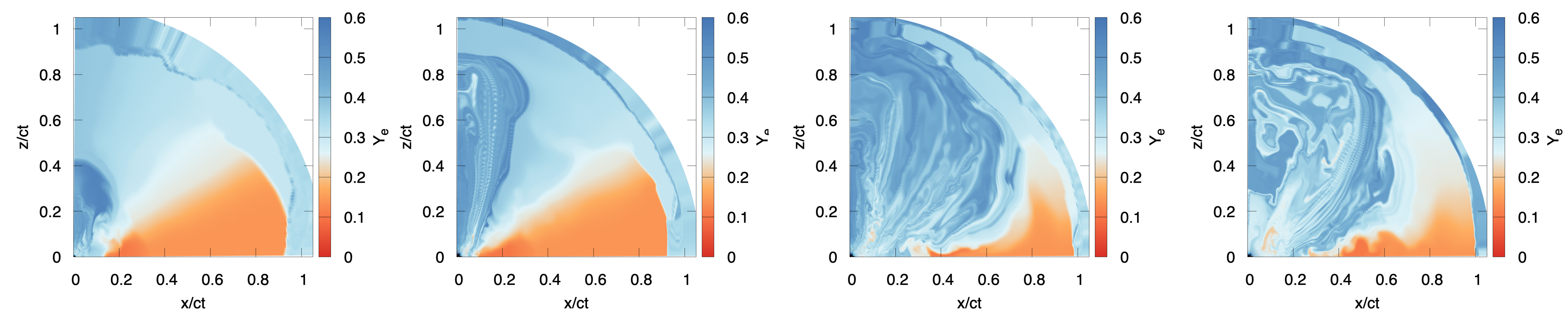
Model : 1.35 M_{sun} + 1.35 M_{sun} (DD2 EOS)

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

Significant MHD (dynamo) effect

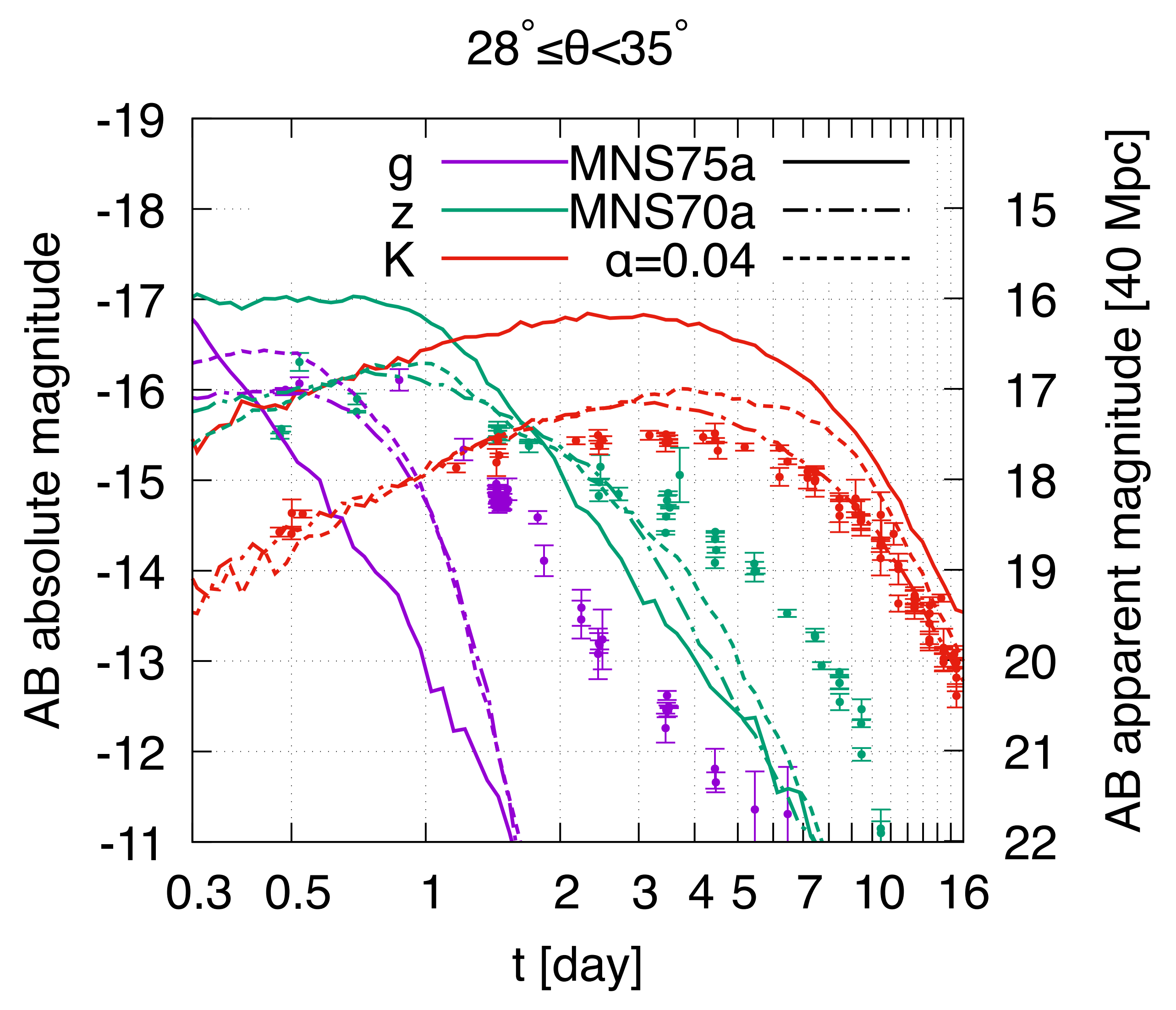
$$Y_e = \frac{[e]}{[p]+[n]}$$

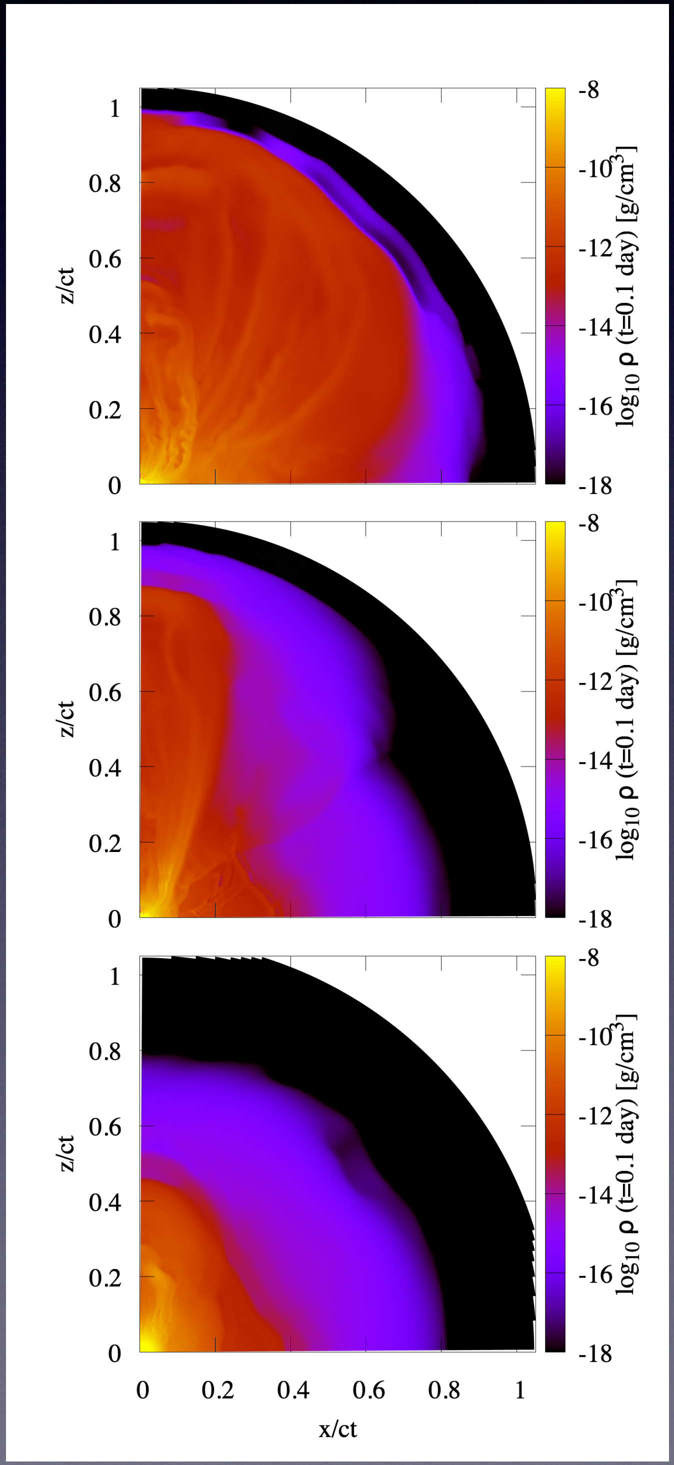
Kilonova emission

Kilonova Lightcurves
(data: GW170817/AT2017gfo)

KK et al. 2022

Density profile @ t = 0.1 d





MNS75a

MNS70a

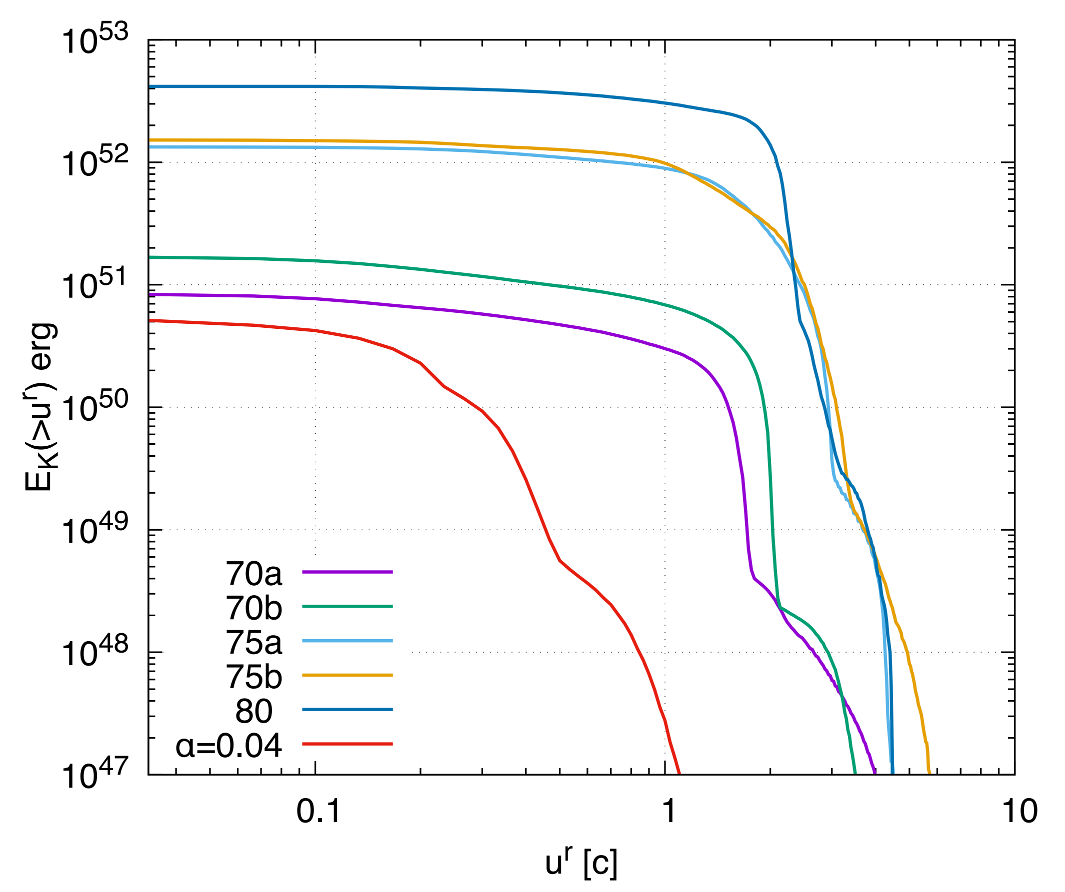
α=0.04
(viscous)

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

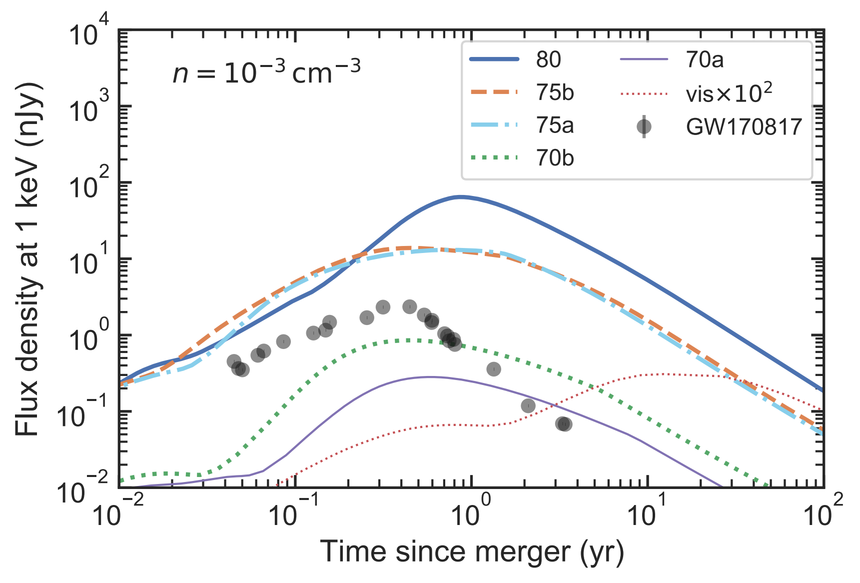


70a,b < 75a,b < 80
Significant MHD (dynamo) effect

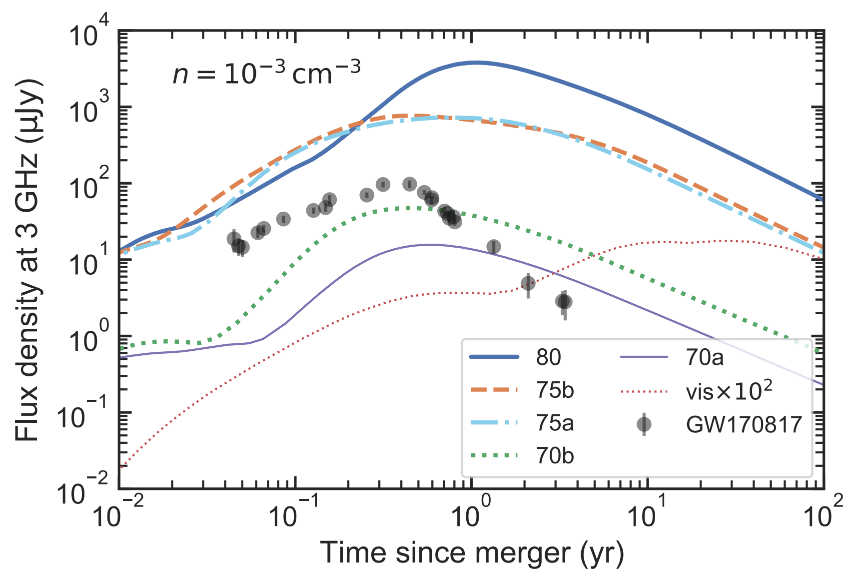
KK et al. 2022
(see also Hotokezaka & Piran et al. 2015)

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

X-ray band (1 keV, 200 Mpc)



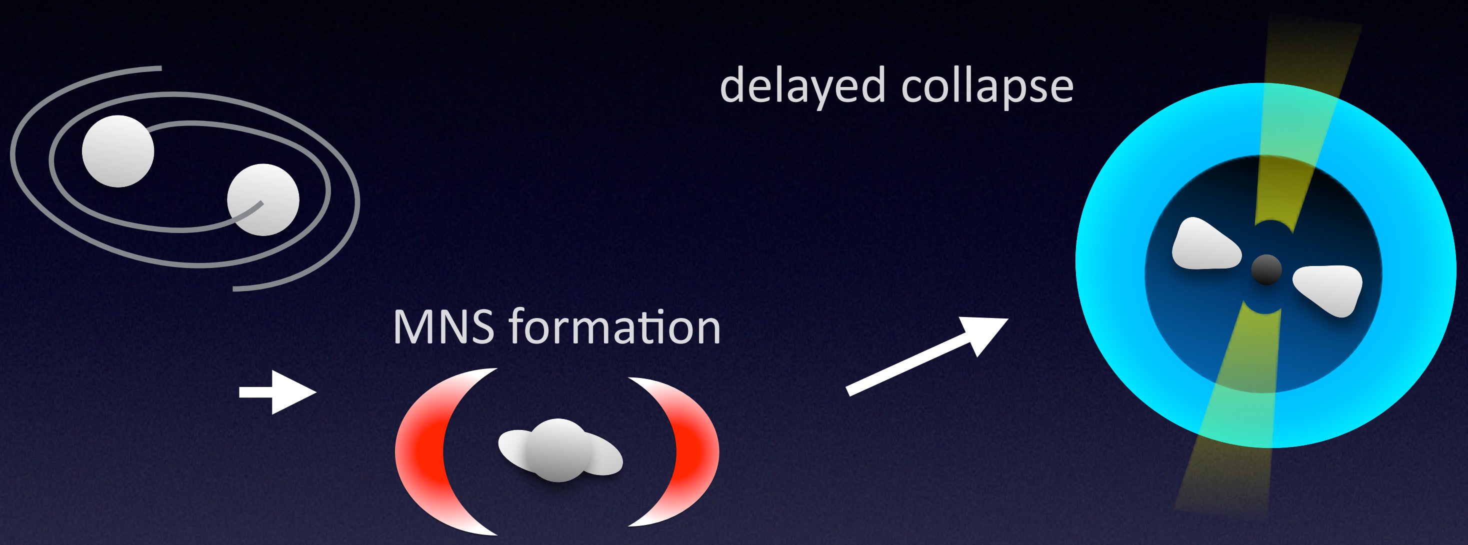
Radio band (3 GHz, 200 Mpc)



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

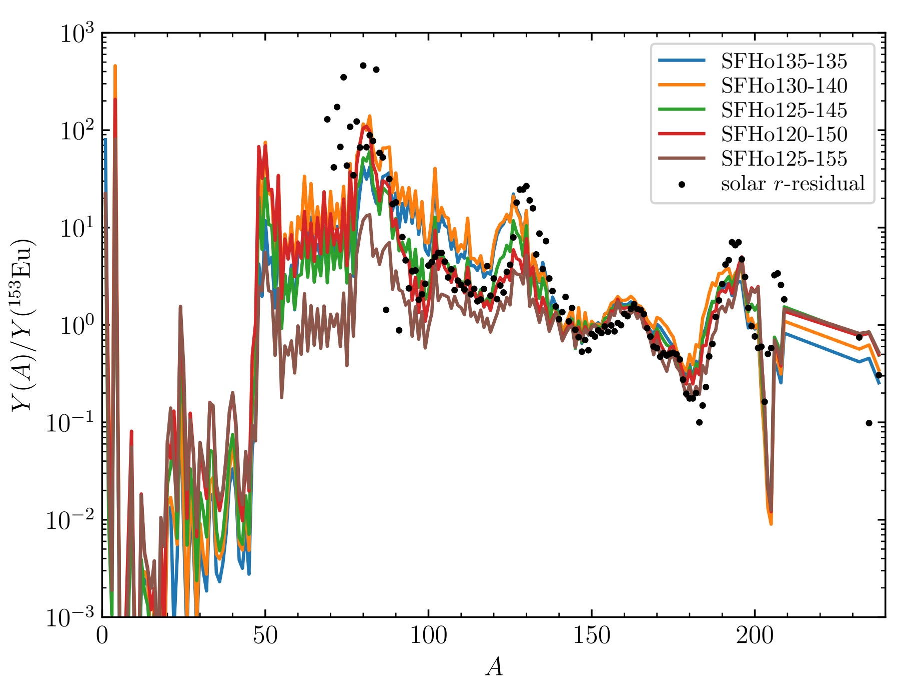
Study for a BNS with a short-lived remnant NS



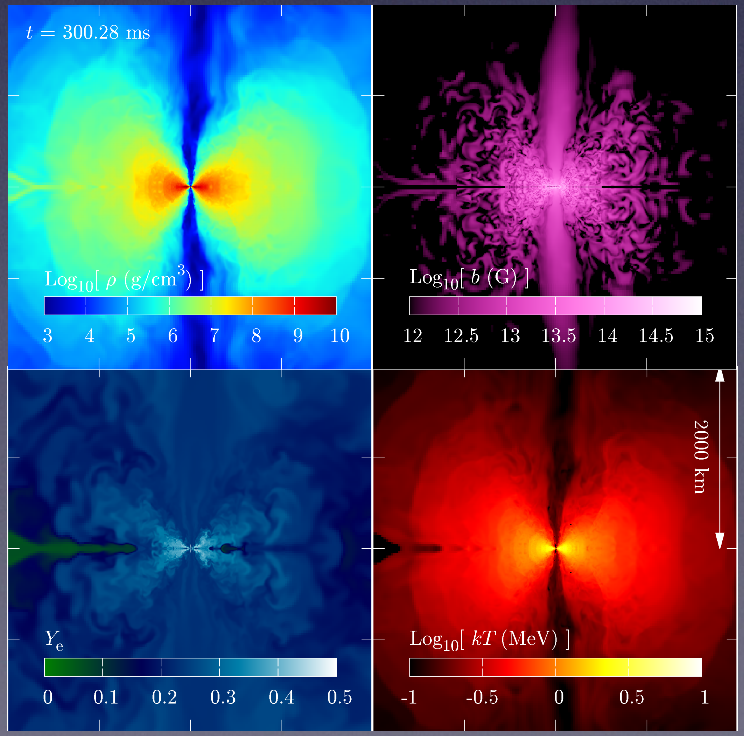
delayed collapse

MNS formation

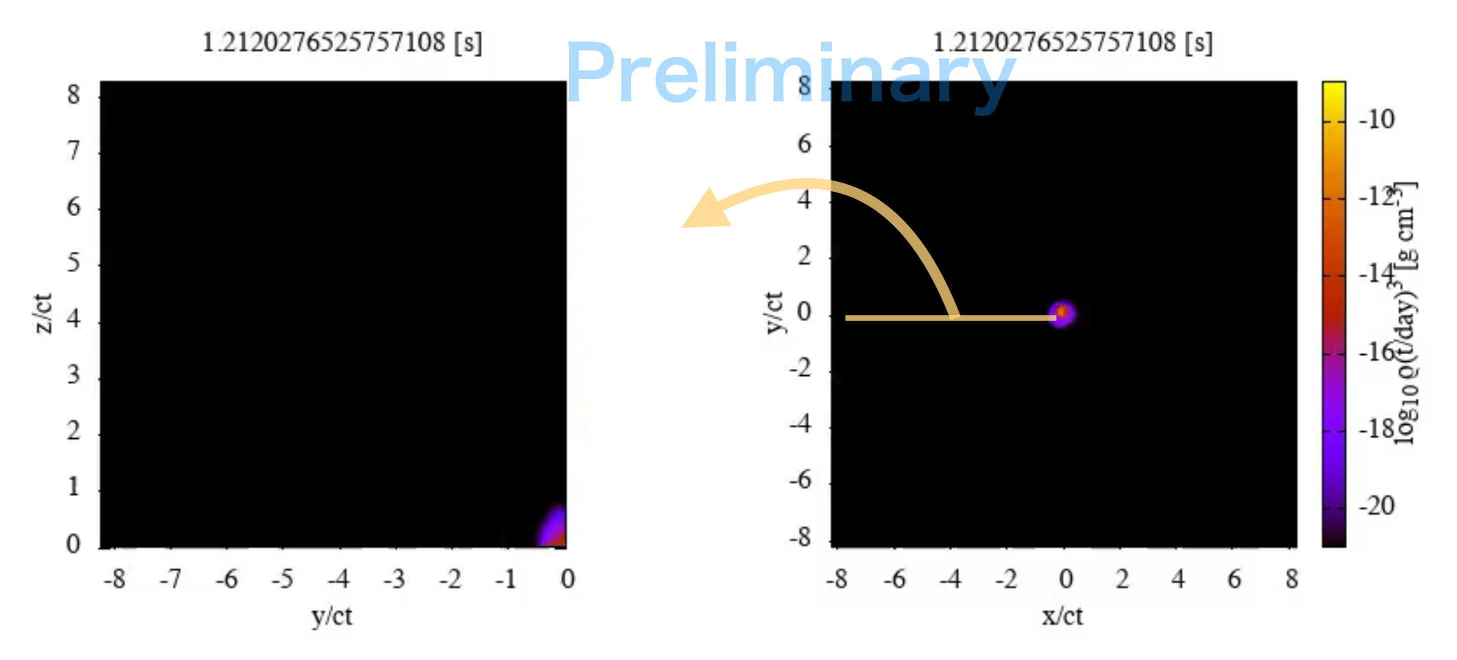
Fujibayashi et al. 2022



Black-hole neutron-star merger



Hayashi et al. 2022



a long-term 3D hydrodynamics simultion of ejecta evolution

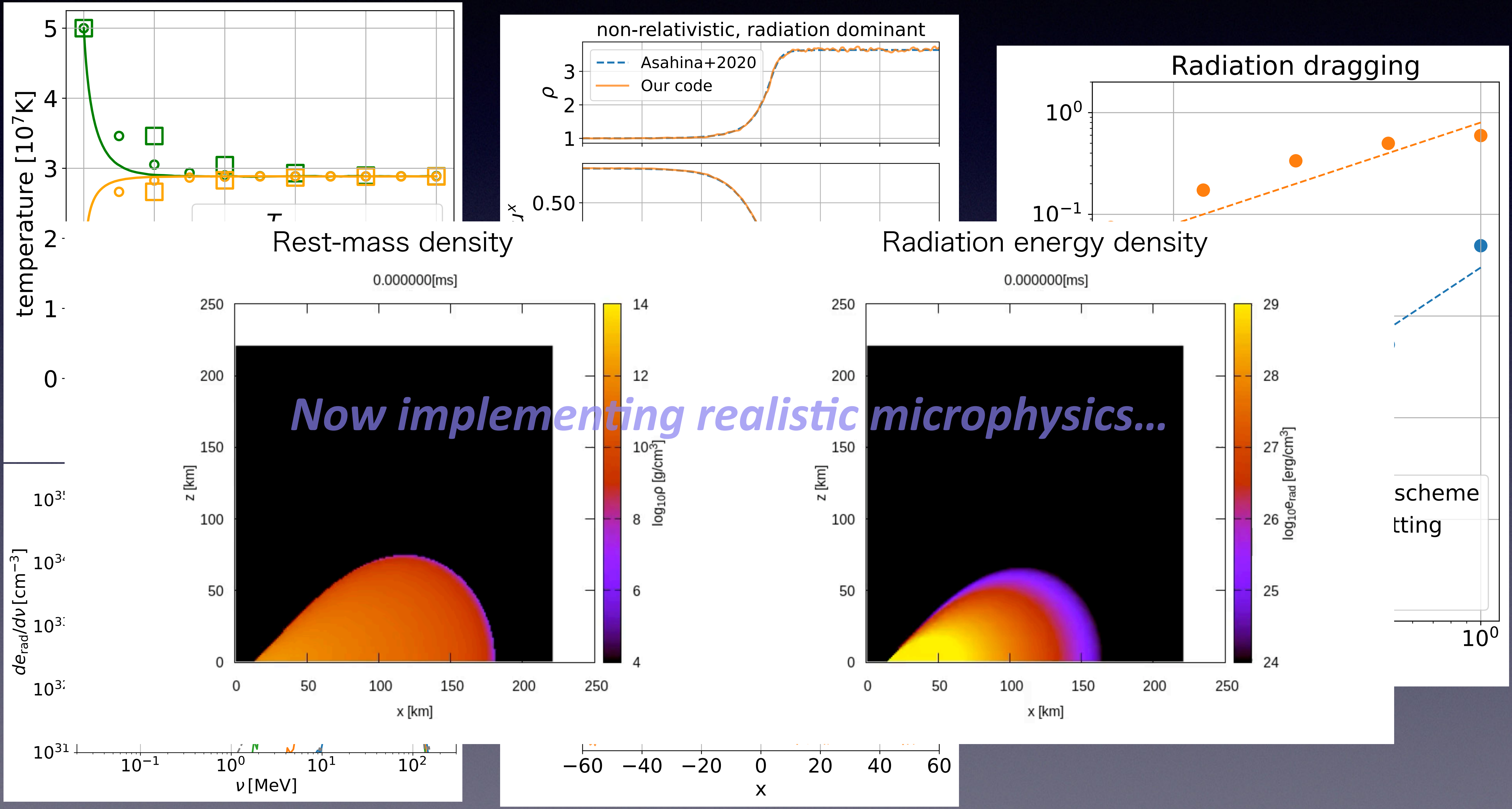
Summary

- Great progress has been made for the realistic prediction of EM counterparts of BNS mergers particularly since the first detection
  - We have developed a framework to predict the light curves of the EM counterparts consistently from the merger simulation, incorporating the longterm hydrodynamics evolution of ejecta
  - Employing the ejecta profile in the homologously expanding phase has a great impact on predicting the kilonova light curves even qualitatively
  - Not only lanthanides but also the 1st-peak r-process elements can play an important role for opacity
- More other possibly missing parts to fully interpret the observation data
  - non-LTE effect, Jet-ejecta interaction …

Development of a Monte-Carlo based Radiative hydrodynamics code with a higher-order integration scheme

KK et al. arXiv:2209.12472

Thermalization test Radiation mediated shock Conversion test



Now implementing realistic microphysics…

- The 2nd order accuracy in time and space is achieved in our code (in the limit of infinite packet numbers)

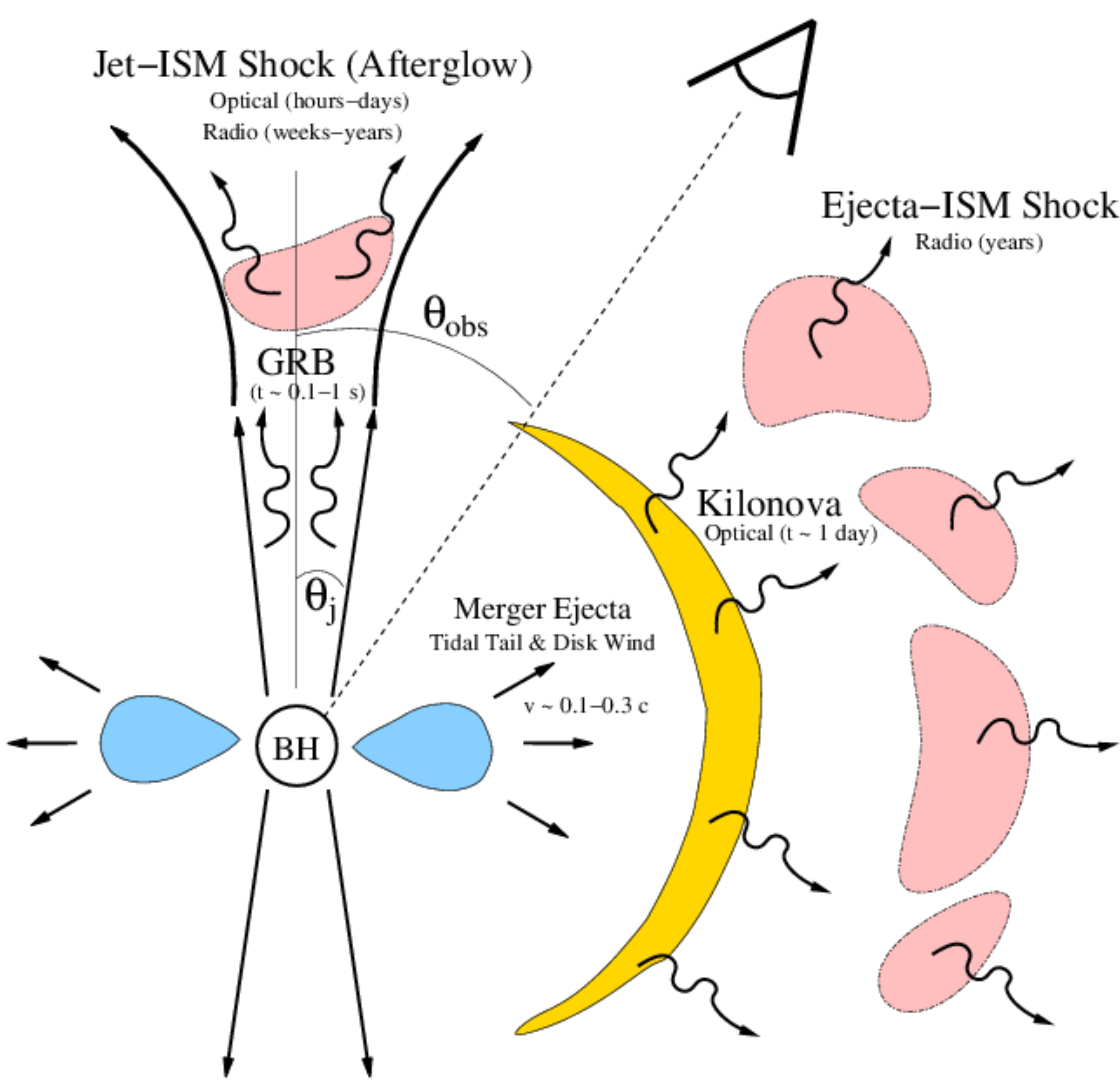
Thank you for listening!

Appendix

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

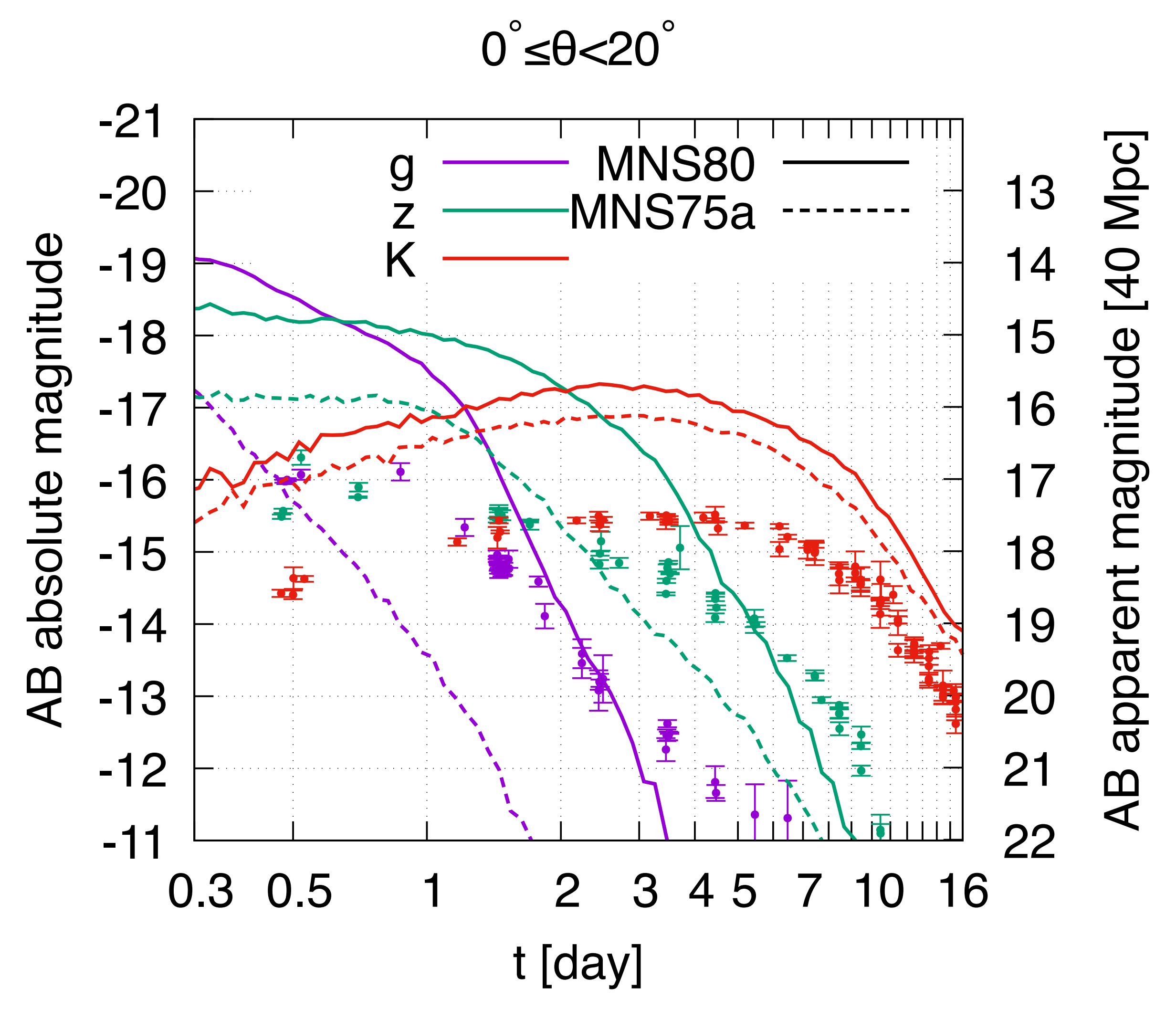


Ref: B. Metzger and E. Berger 2012

Kilonova emission

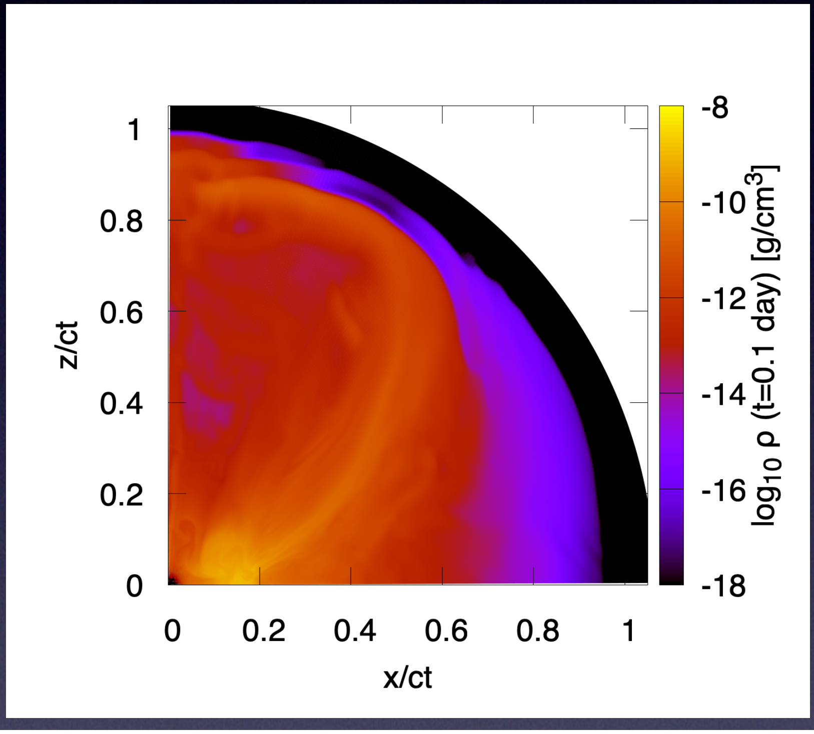
Kilonova Lightcurves
(polar view. data: AT2017gfo)

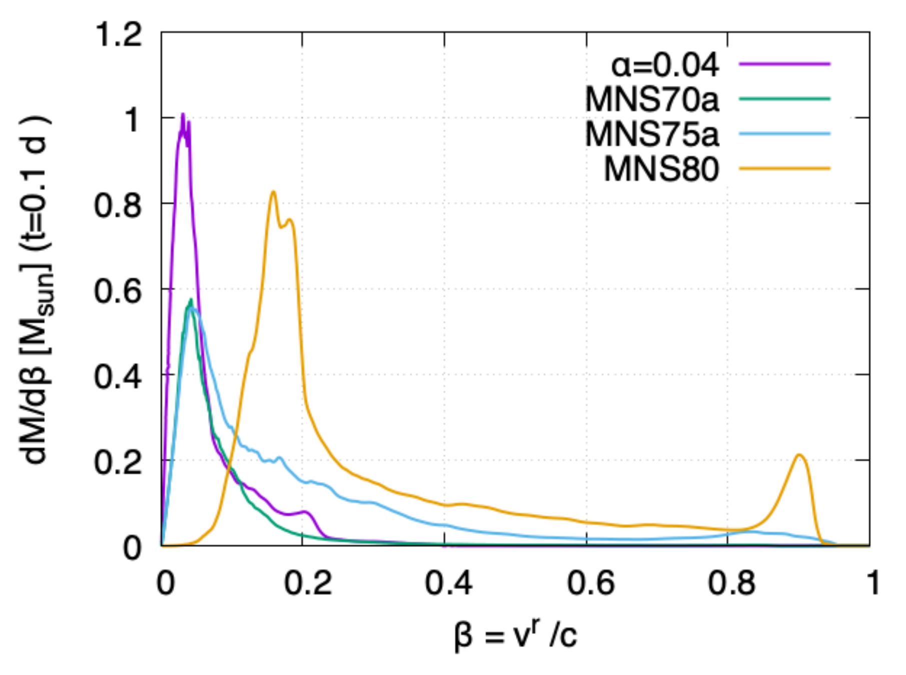
KK et al. 2022



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

Density profile @ t = 0.1 d
MNS80

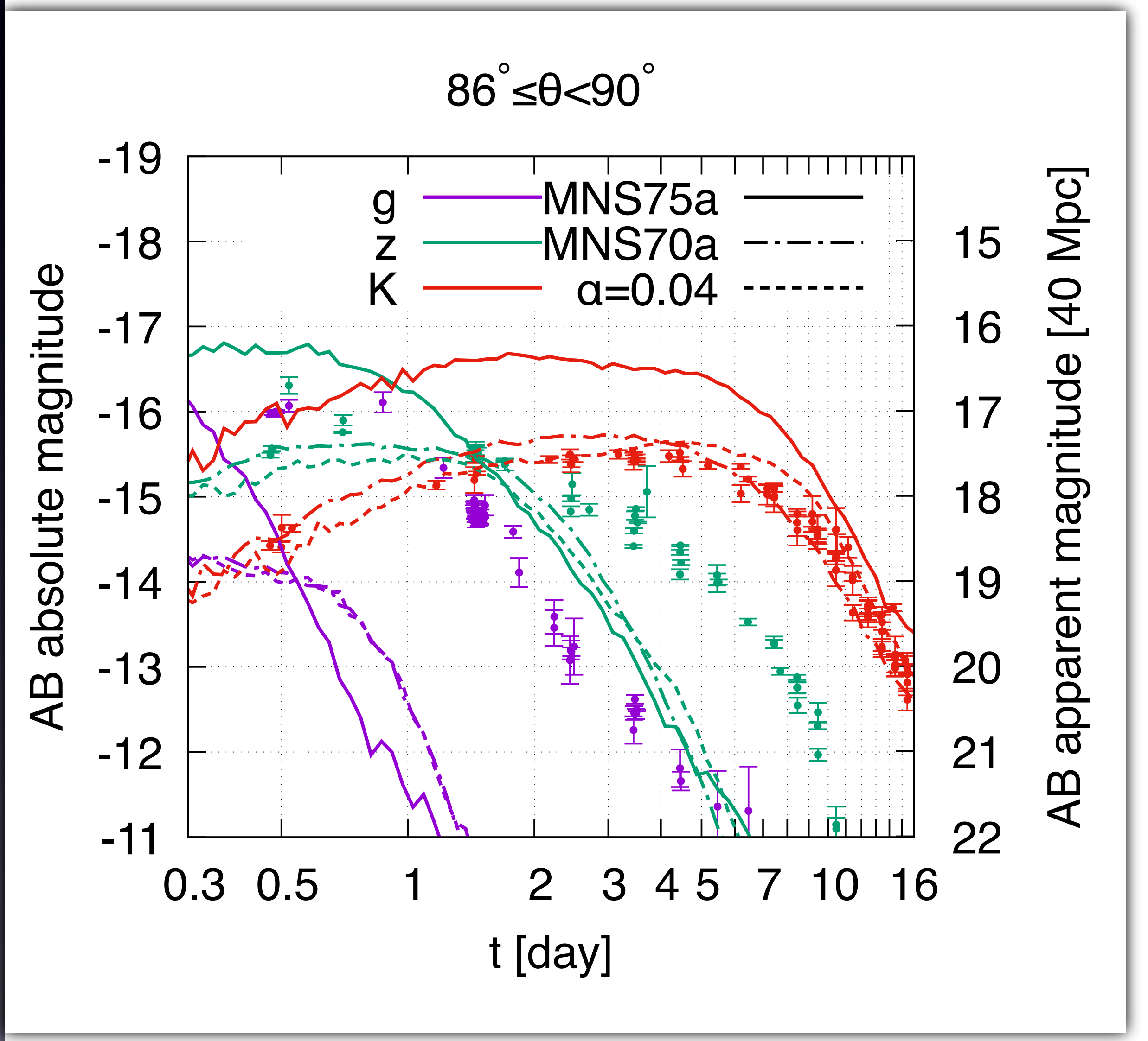




Kilonova emission

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

KK et al. 2022



Radiative transfer simulation code & opacity data:
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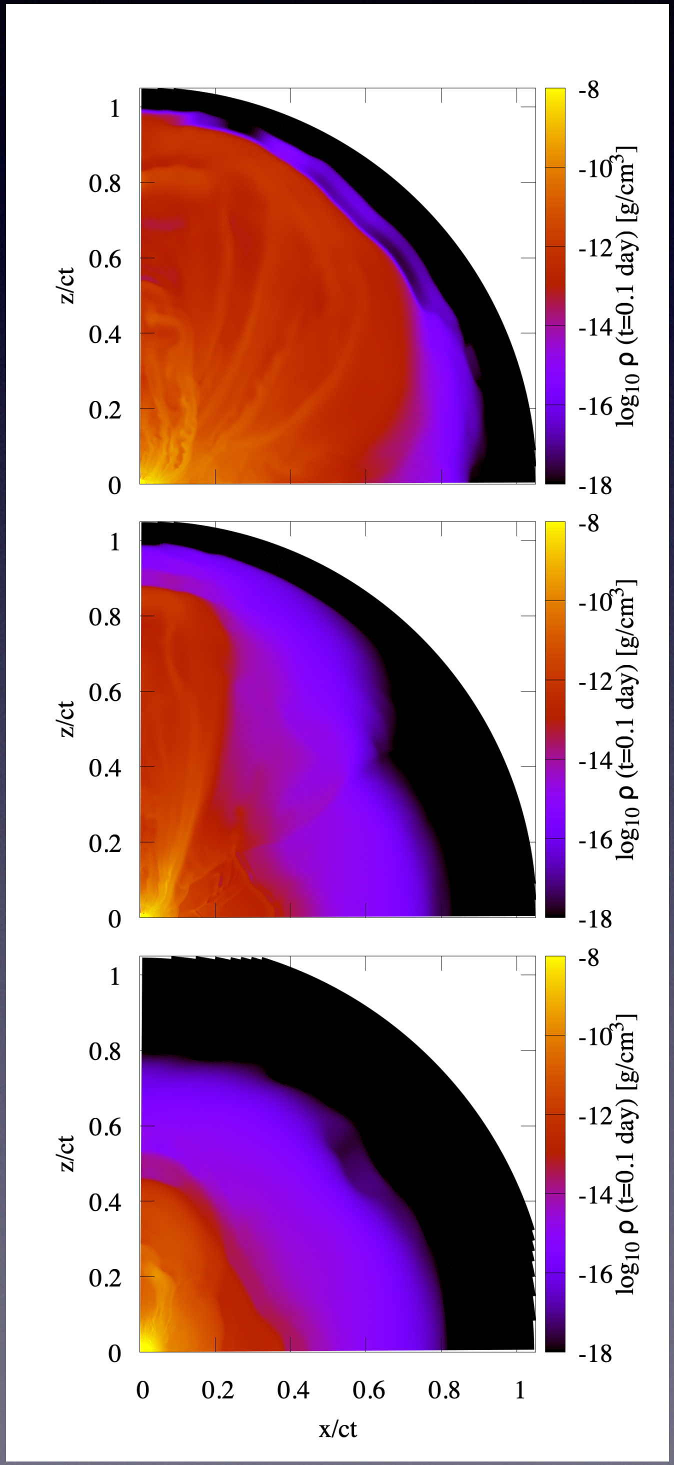
Density profile @ t = 0.1 d

MNS75a

MNS70a

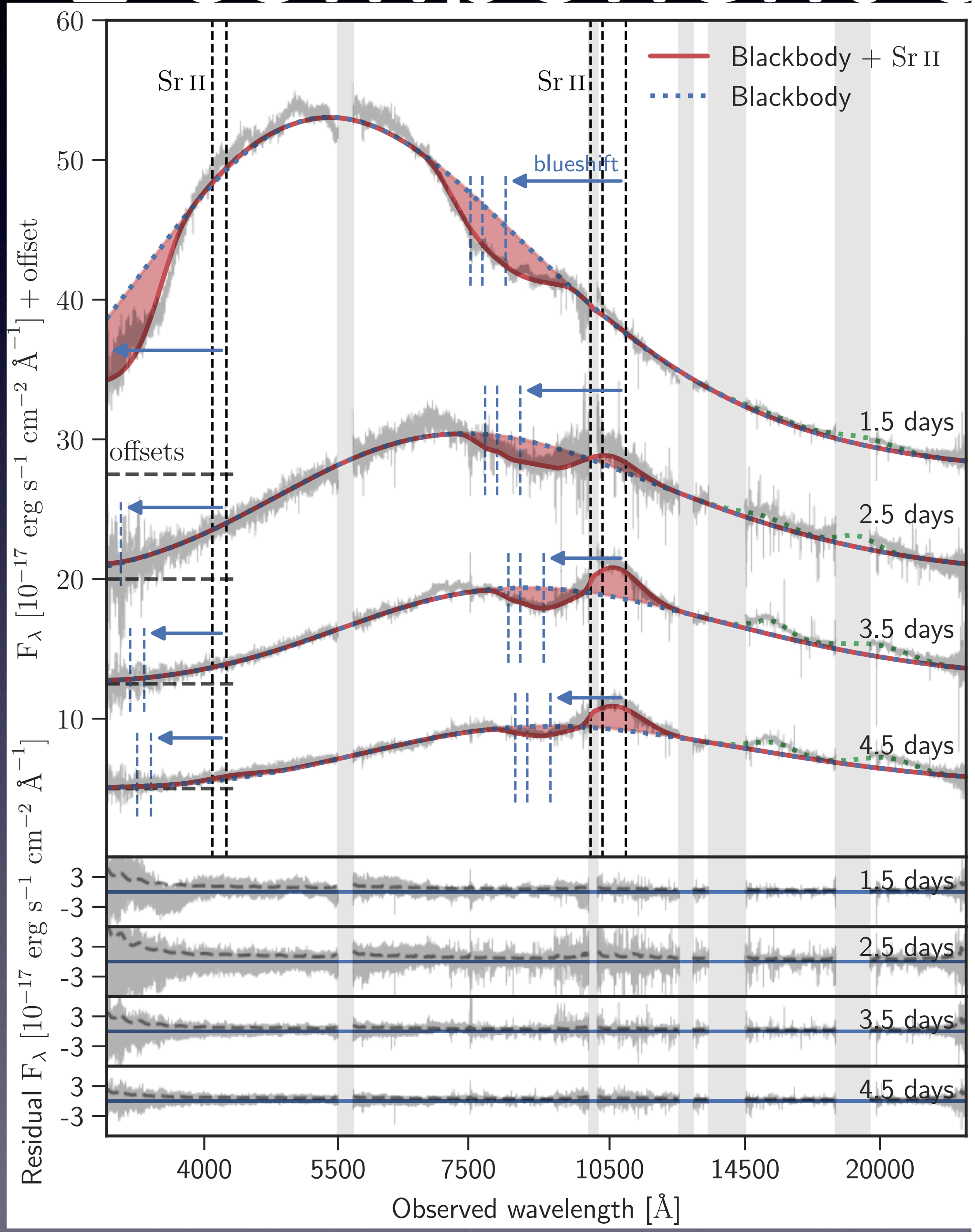
α=0.04
(viscous)



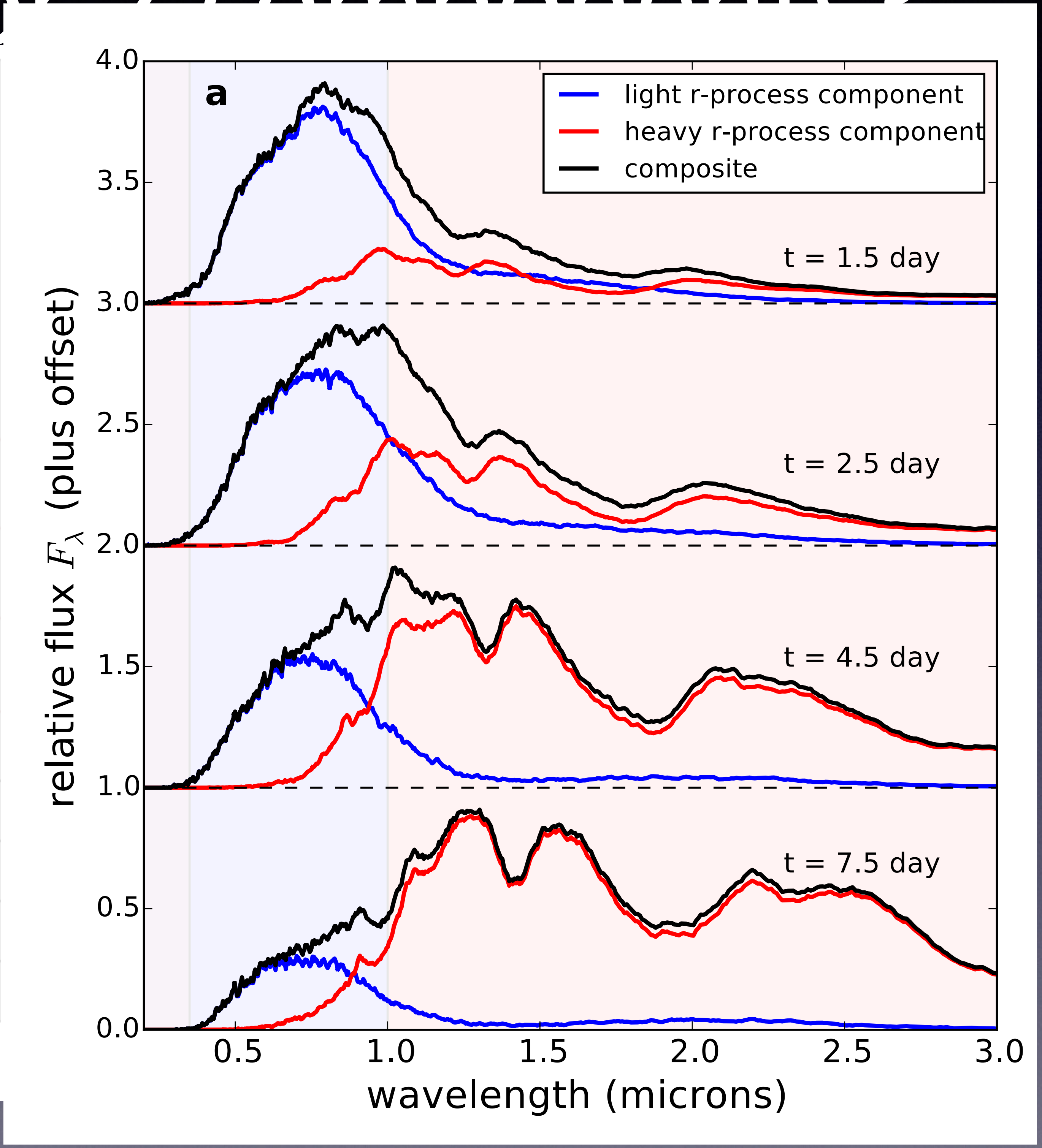
Significant MHD (large dynamo) effect

GW170817:

1 component or 2 components?



D. Watson et al. 2019



D. Kasen et al. 2017

Development of
a Monte-Carlo based
Radiative hydrodynamics code

arXiv:2209.12472

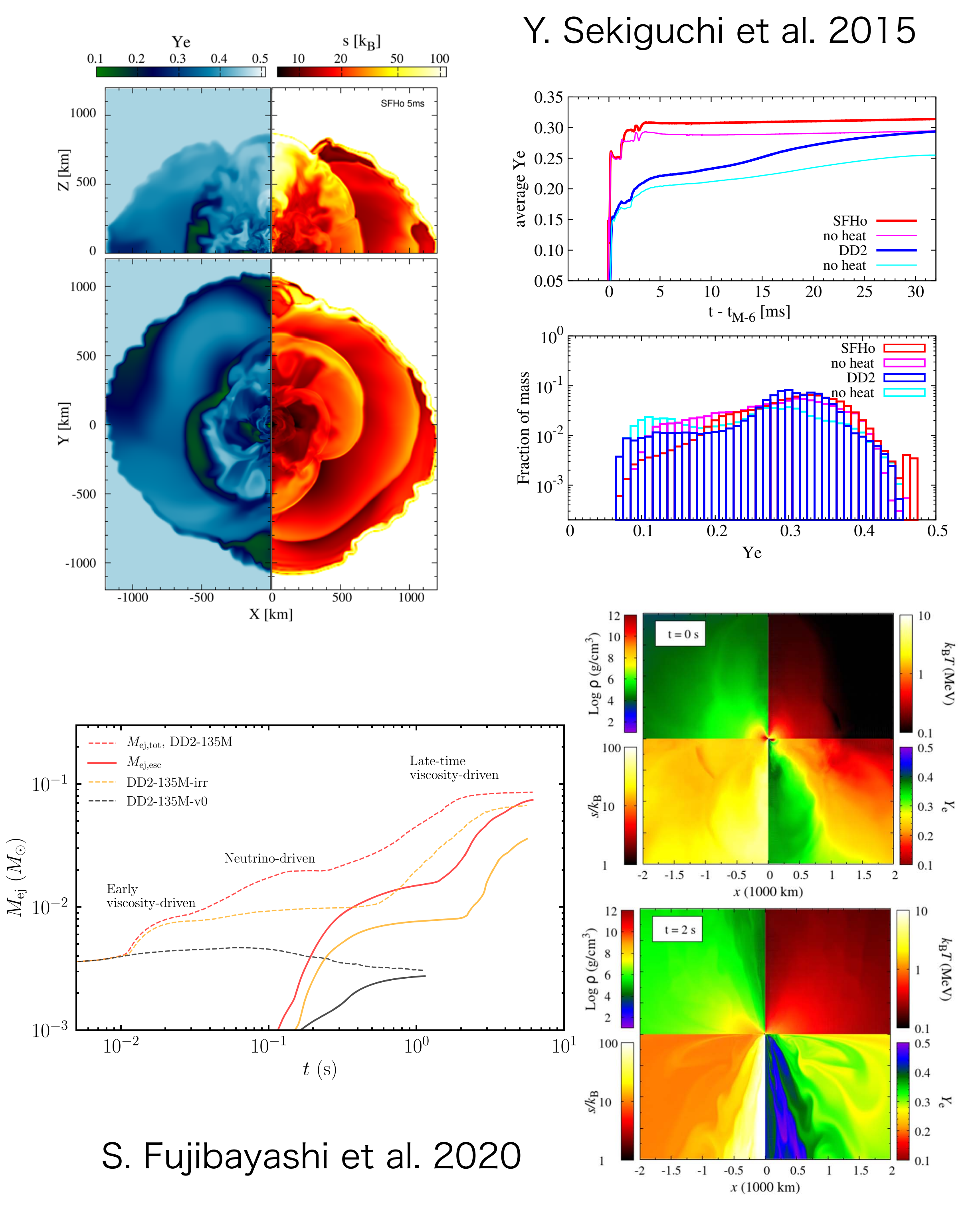
Neutrino-matter interaction

Neutrino-matter interaction plays an important role in the merger/post-merger phase of a BNS merger:

- Determines the thermodynamical property of the remnant NS and disk
- Determines nucleosynthesis in the outflow
- Possible mechanism for launching a relativistic outflow / jet (pair-annihilation)

The moment formalism M1(M0) method is often used for the latest merger simulations to take the effect of neutrino transport into account

(K. Thorne 1981, M. Shibata et al. 2011, Y. Sekiguchi et al. 2015, 2016 , F. Foucart et al. 2015, D. Radice et al. 2016, see also McKinney et al. 2014, Sadowski et al. 2014, Takahashi et al. 2016 for GR-RMHD)

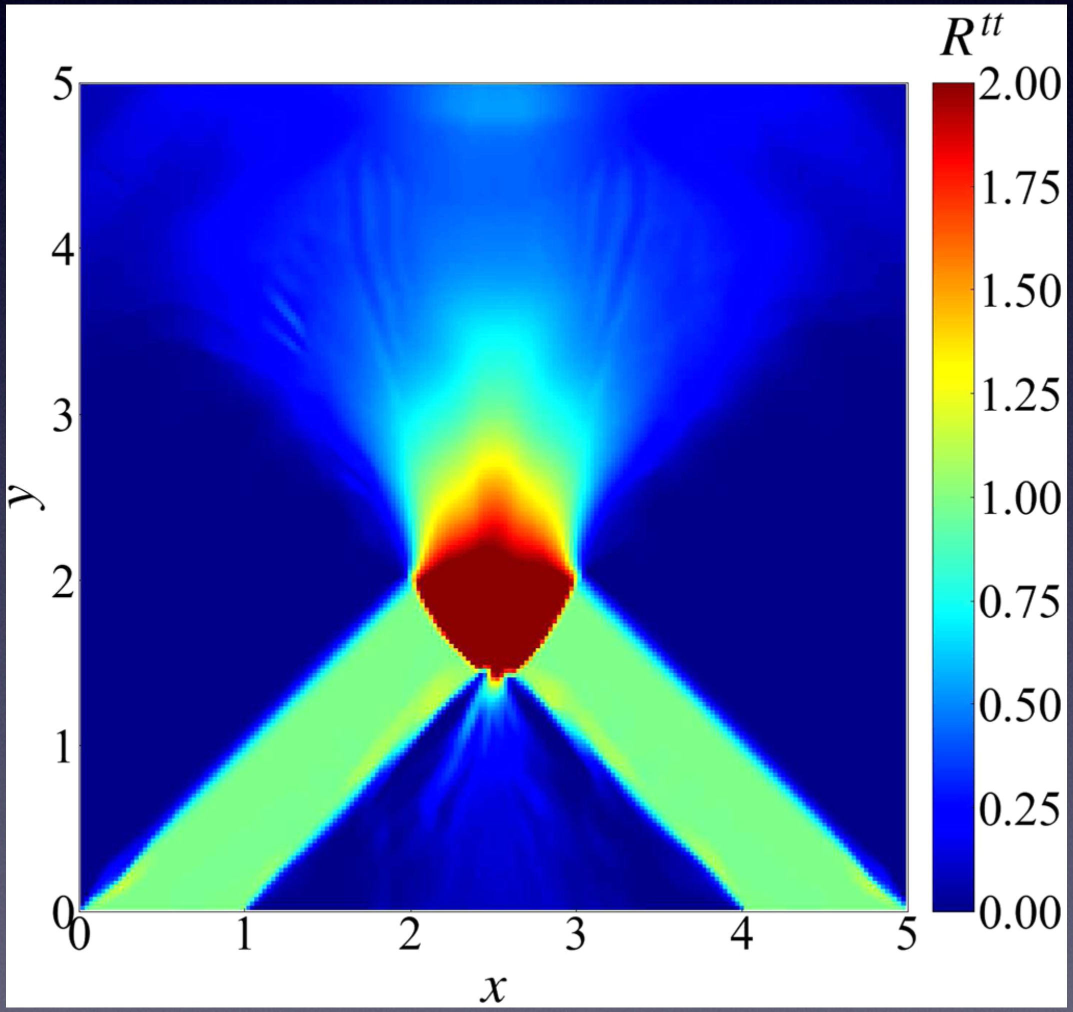


Y. Sekiguchi et al. 2015

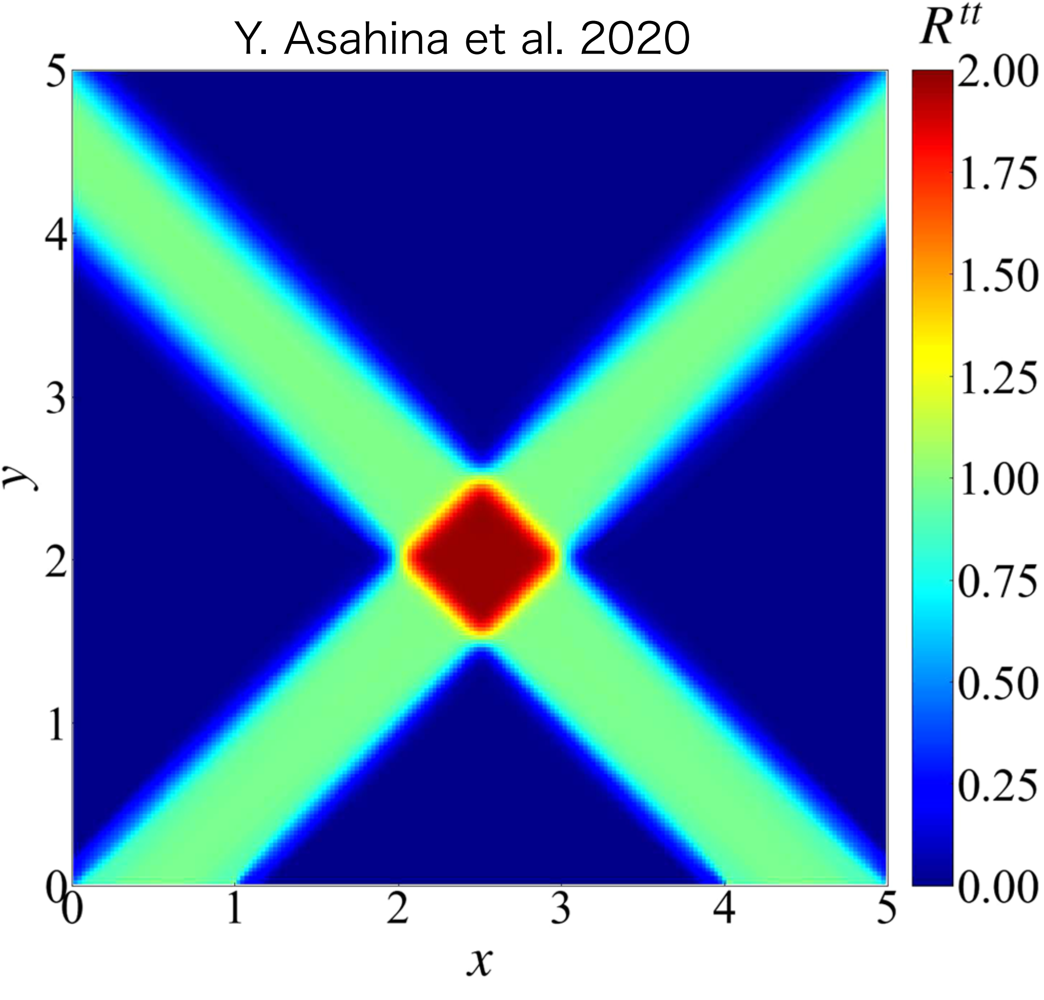
S. Fujibayashi et al. 2020

Limitation of M1 method (truncated-moment formalism)

M1-method



Full Boltzmann (grid-based)



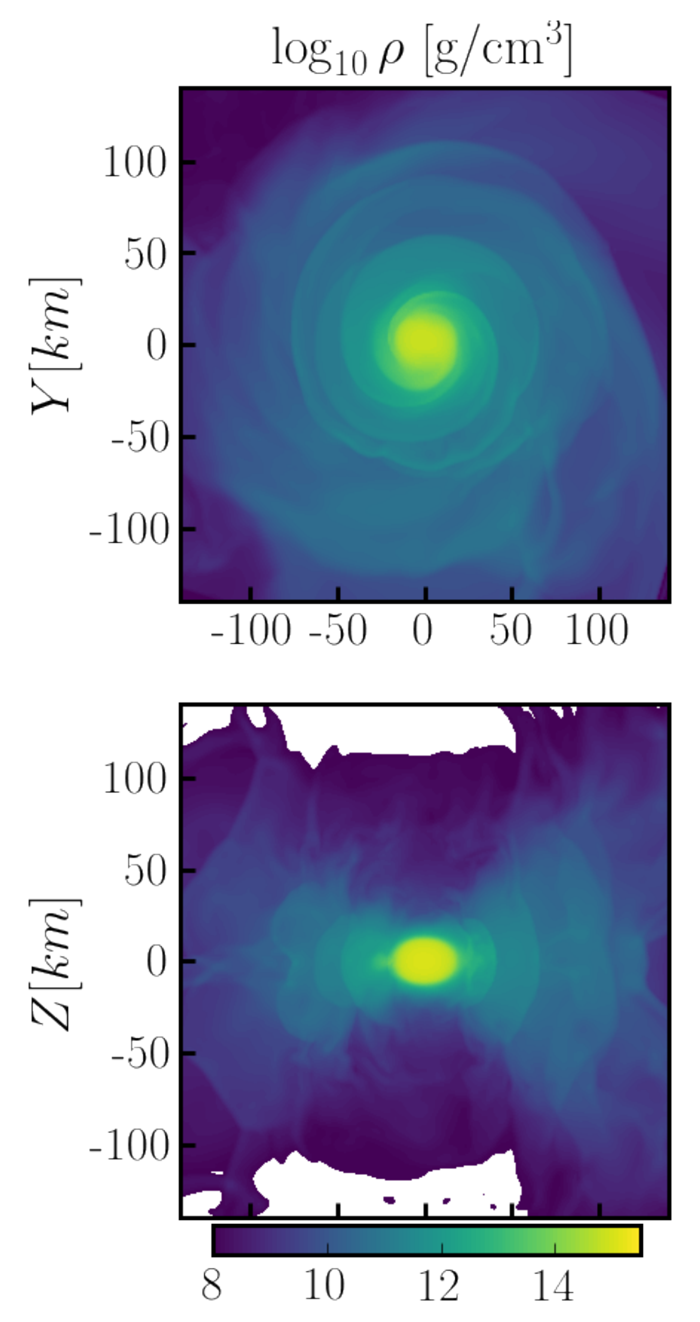
M1 method do not always guarantee to provide physically correct results.

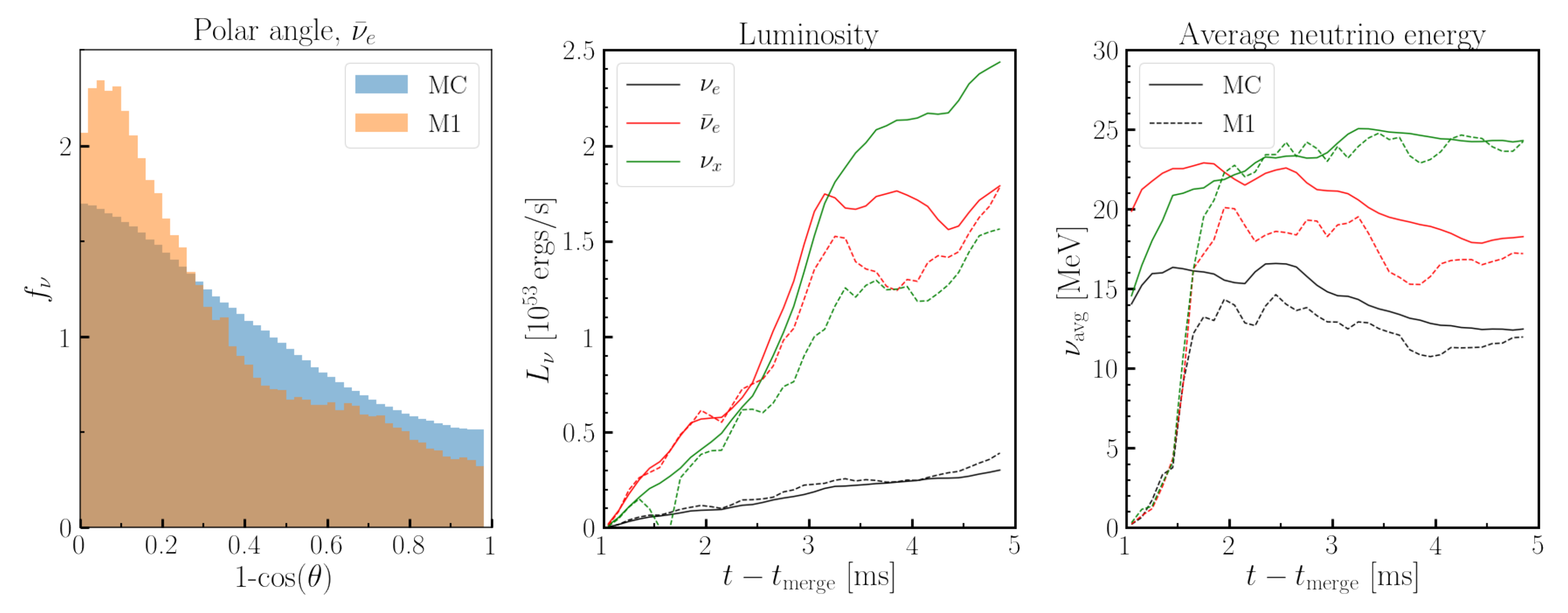
(see, e.g., H. Nagakura et al. 2017, Jiang et al. 2014, 2022, Y. Asahina et al. 2020 for grid-based full-Boltzmann method in GR)

Monte Carlo radiation transport

Neutron star merger simulation
(GRHD+MCRadiation)

F. Foucart et al. 2020

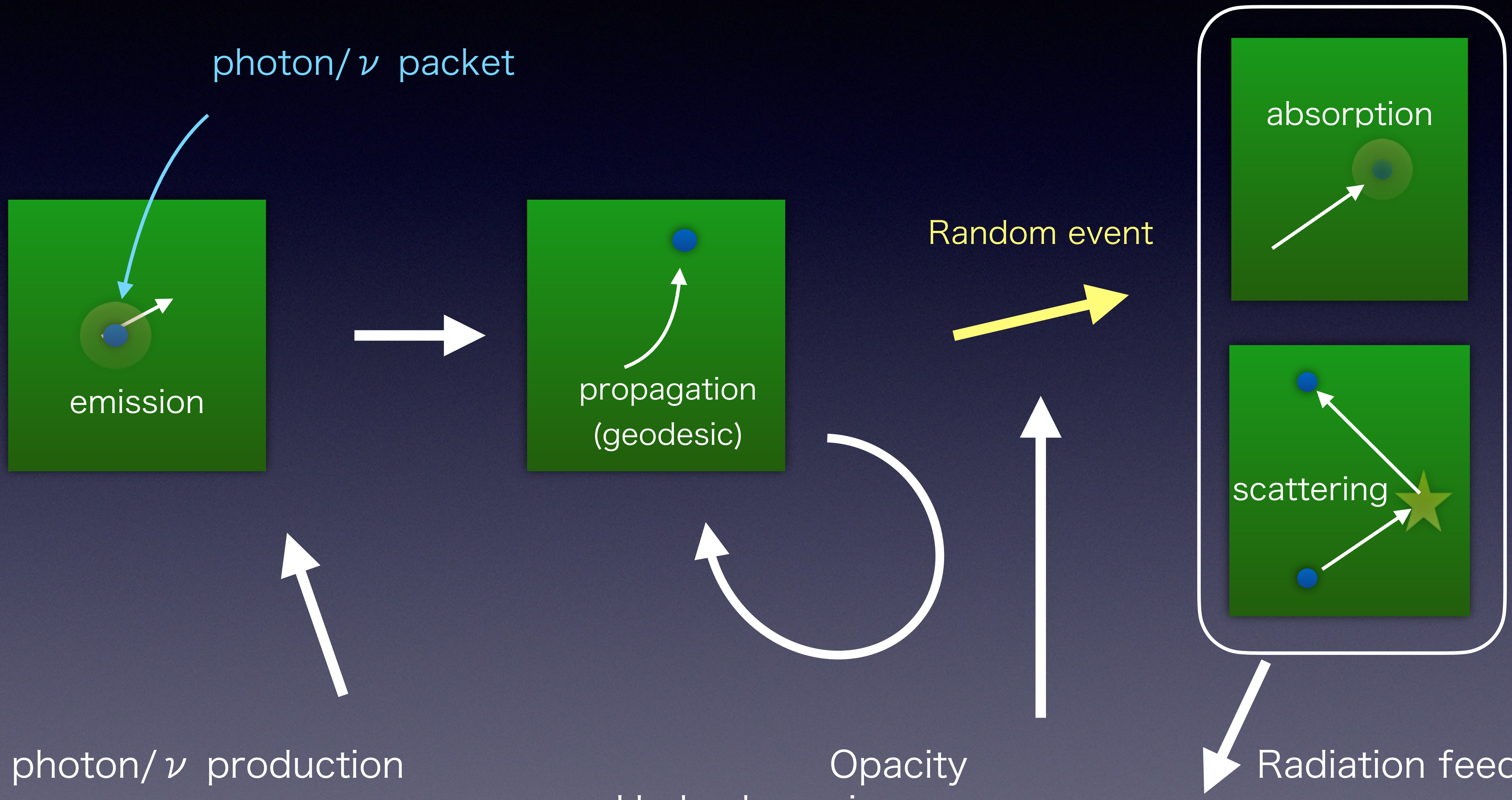




GR Monte-Carlo RHD:

N. Roth & D. Kasen 2015
Ryan et al. 2015, 2022
Miller et al. 2019, 2020
F. Foucart et al. 2017, 2018, 2020

Monte-Carlo method: Procedure



photon/ν packet

emission

propagation (geodesic)

Random event

absorption

scattering

photon/ν production

Opacity

Radiation feedback

Hydrodynamics

$$(\rho, u_x, u_y, u_z, e_{\rm int}, Y_e)$$

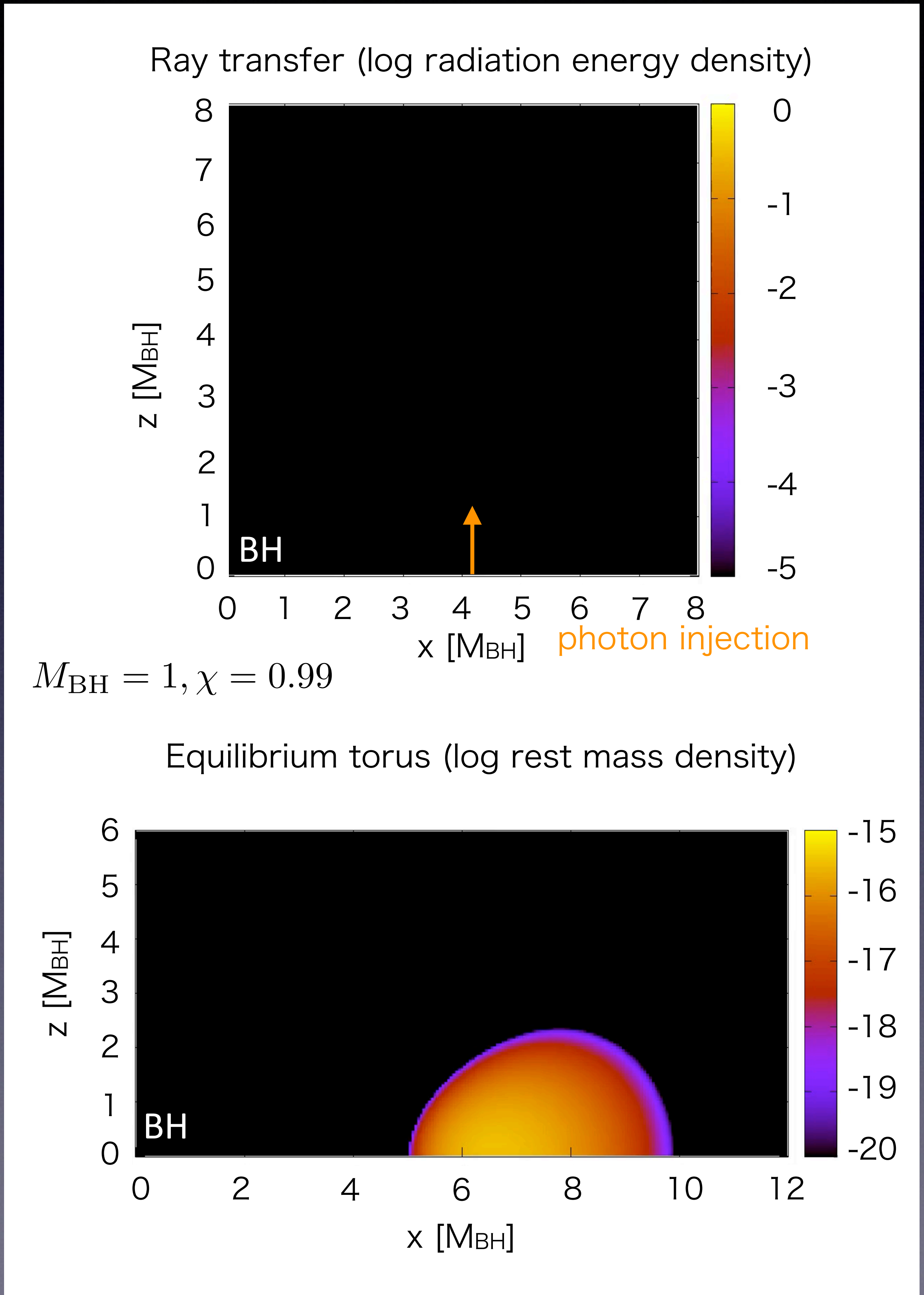
Advantage and disadvantage

- Advantage:
  - Straightforward incorporation of the complicated frequency and angular dependence
  - Parallelization of packet evolutions is trivial
- Disadvantage:
  - The Monte-Carlo shot noise: the slow convergence property of the statistical error due to the finite Monte-Carlo packets ($\propto N^{-1/2}$)
  - The operator splitting method for the matter-radiation interaction: only 1st order accuracy in time

We develop a new Monte-Carlo based radiation hydrodynamics code with various improvements

Axisymmetric GR-MCRHD code

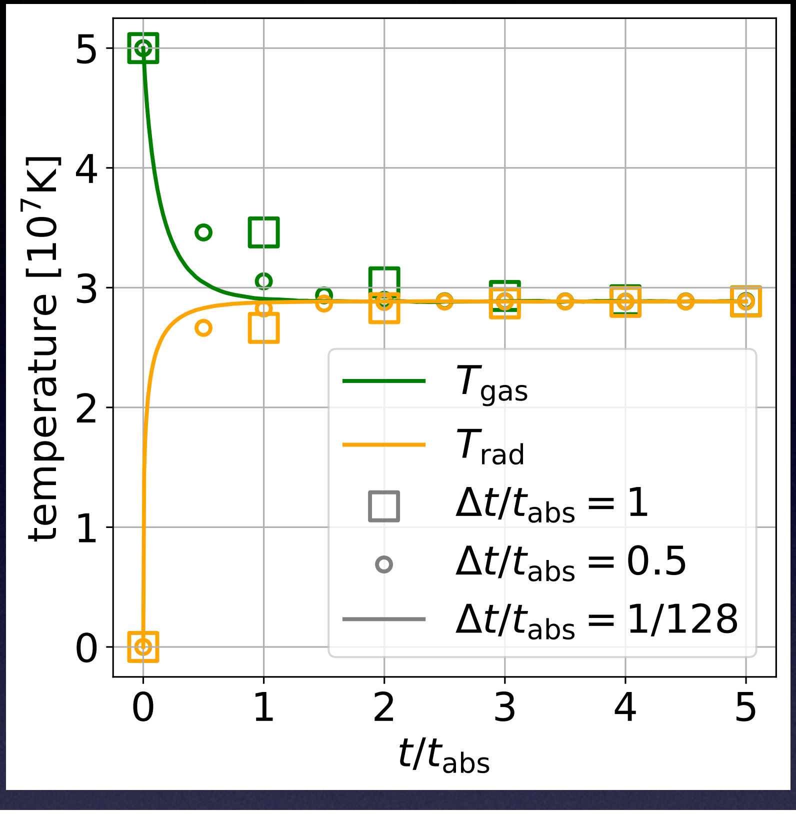
- Geodesic:
  4th order spatial interpolation
- Hydrodynamics:
  GR hydro (fixed metric)
  3rd Order MUSCL
  + Kurganov-Tadmor (central)
  scheme
- Time integration:
  SSP-RK3 (the 3rd order)
  for hydro & geodesic solver
- isotropic scattering
  (as a first step)

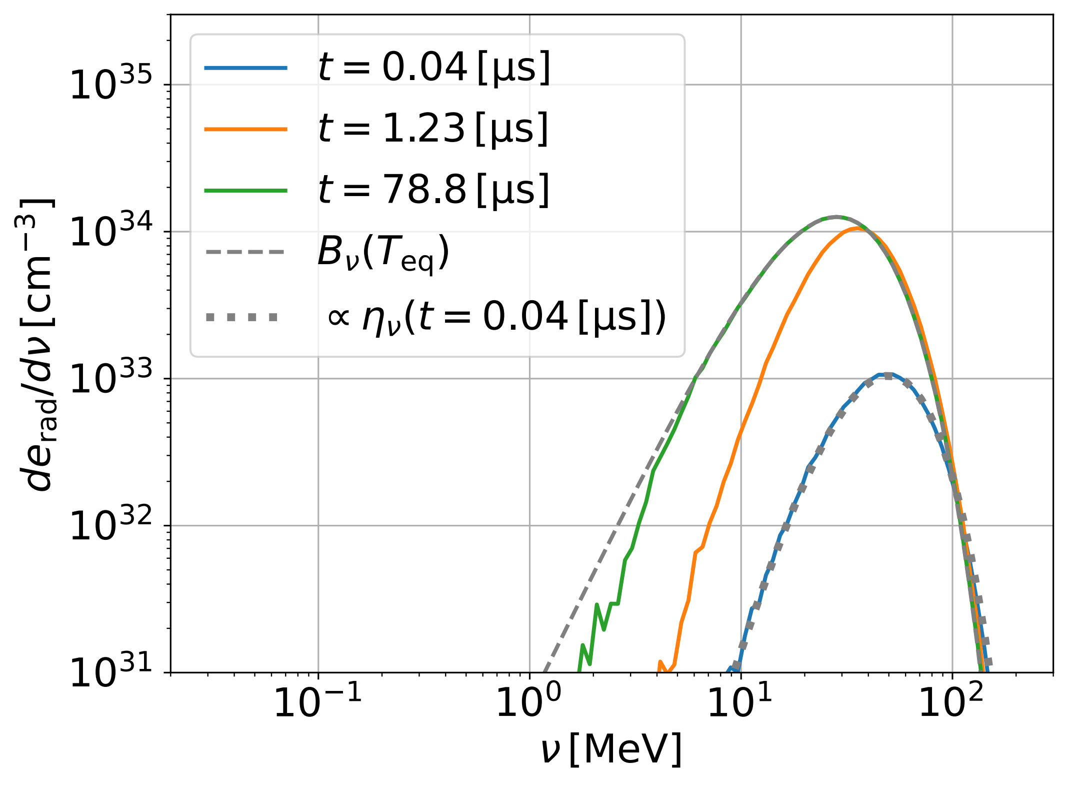


$M_{\rm BH} = 1, \chi = 0.99$

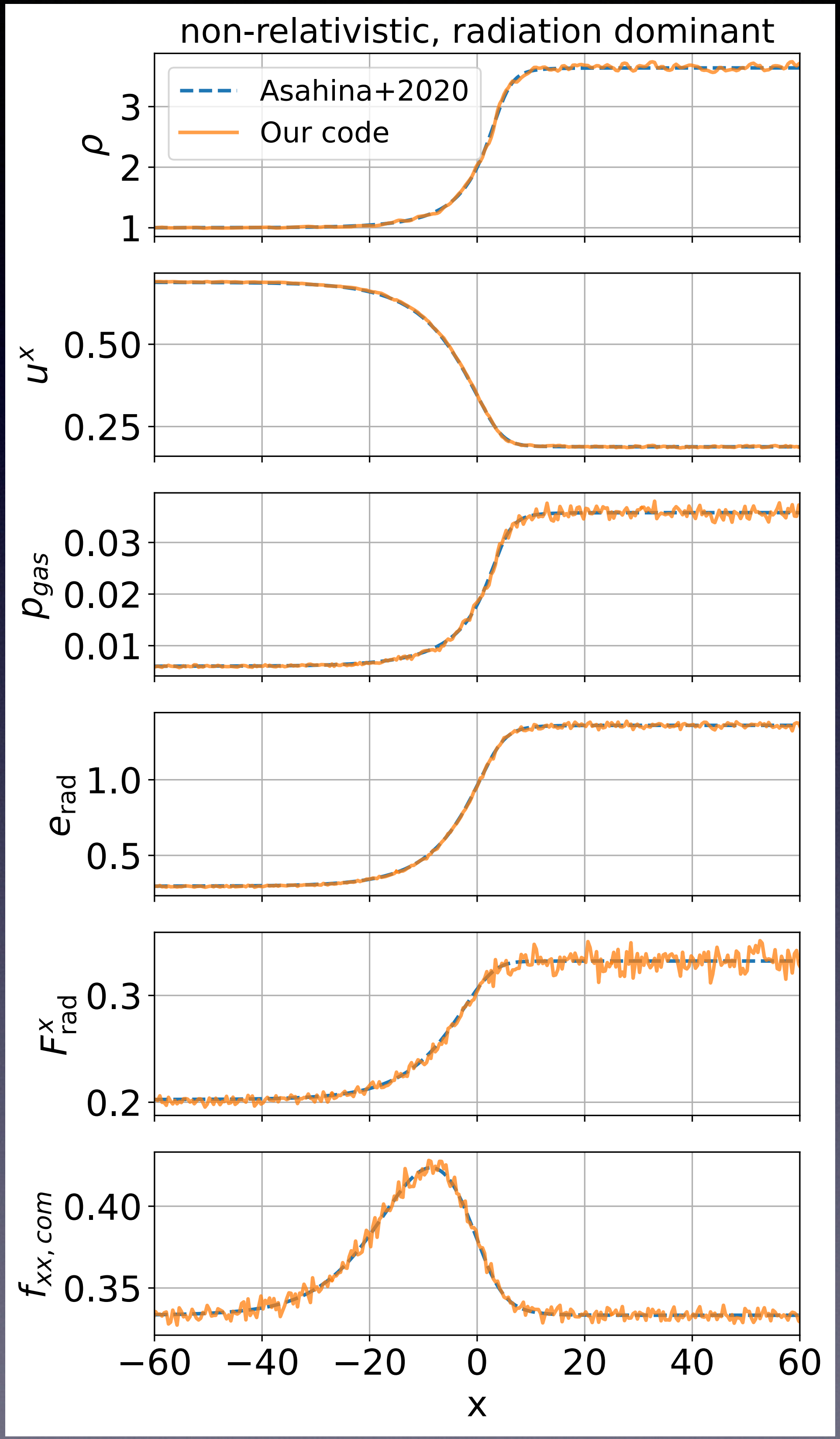
Code validation with Several Test Problems

Thermalization test





Radiation mediated shock



- We confirmed that our code reproduces physically appropriate results with reasonable accuracy

Prescription for optically thick region

Dynamical timescale
(resolution in the simulation)

$$\Delta t_{\rm LC} = \frac{\Delta x}{c}$$

Thermal timescale

$$\Delta t_{\rm ems} = \frac{u_{\rm gas}}{\Delta u_{\rm ems}} = \frac{u_{\rm gas}}{\Delta u_{\rm ems}} = \frac{1}{\kappa\rho c}\frac{u_{\rm gas}}{u_{\rm rad}}$$

$$\frac{\Delta t_{\rm ems}}{\Delta t_{\rm LC}} = \frac{1}{\kappa_{\rm abs}\rho\Delta x}\frac{u_{\rm gas}}{u_{\rm rad}} = \frac{1}{\Delta\tau}\frac{u_{\rm gas}}{u_{\rm rad}} \ll 1 \; (\text{for } \Delta\tau \gg 1)$$

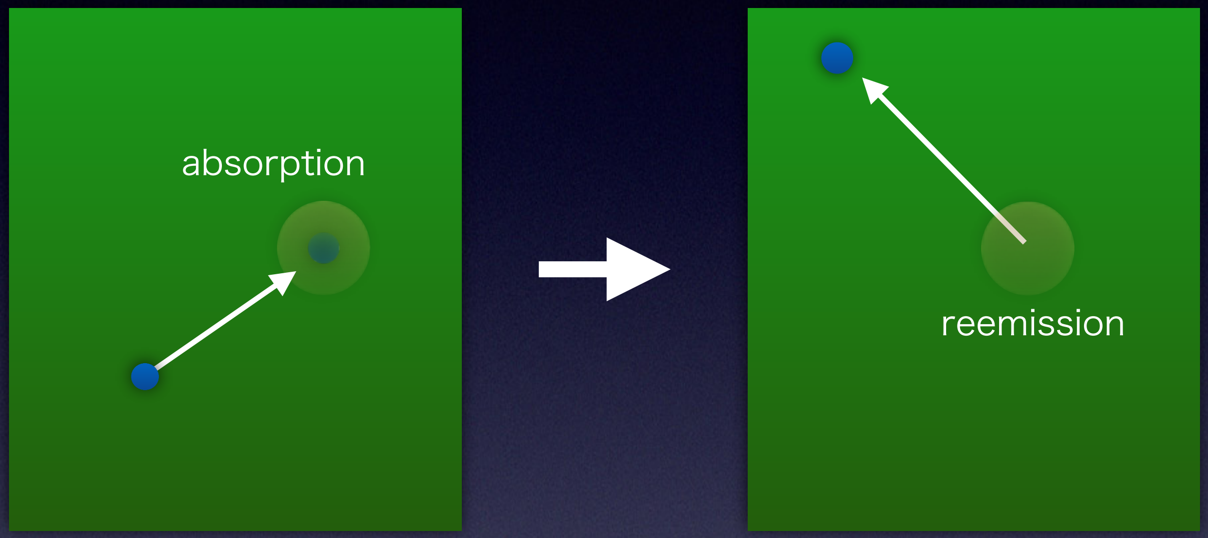
Prescription:
(Foucart et al. 2020, Fleck & Cummings 1971)

$$\kappa_{\rm abs} \to \kappa'_{\rm abs} = (1-\lambda)\kappa_{\rm abs}$$

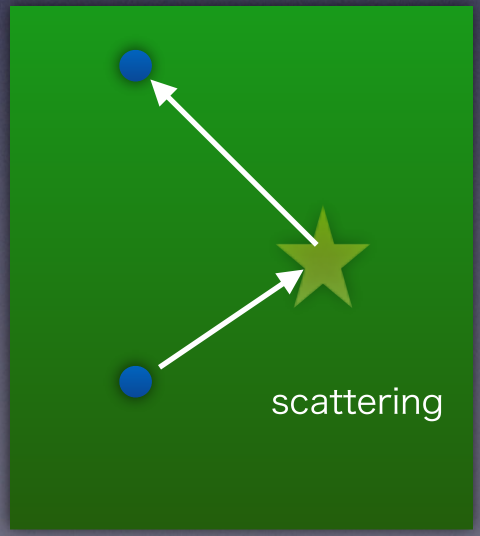
$$\kappa_{\rm sct} \to \kappa'_{\rm sct} = \kappa_{\rm sct} + \lambda\kappa_{\rm abs}$$

Justified if the state in the cell is
close to thermal equilibrium

$\Delta t_{\rm ems} \ll \Delta t$

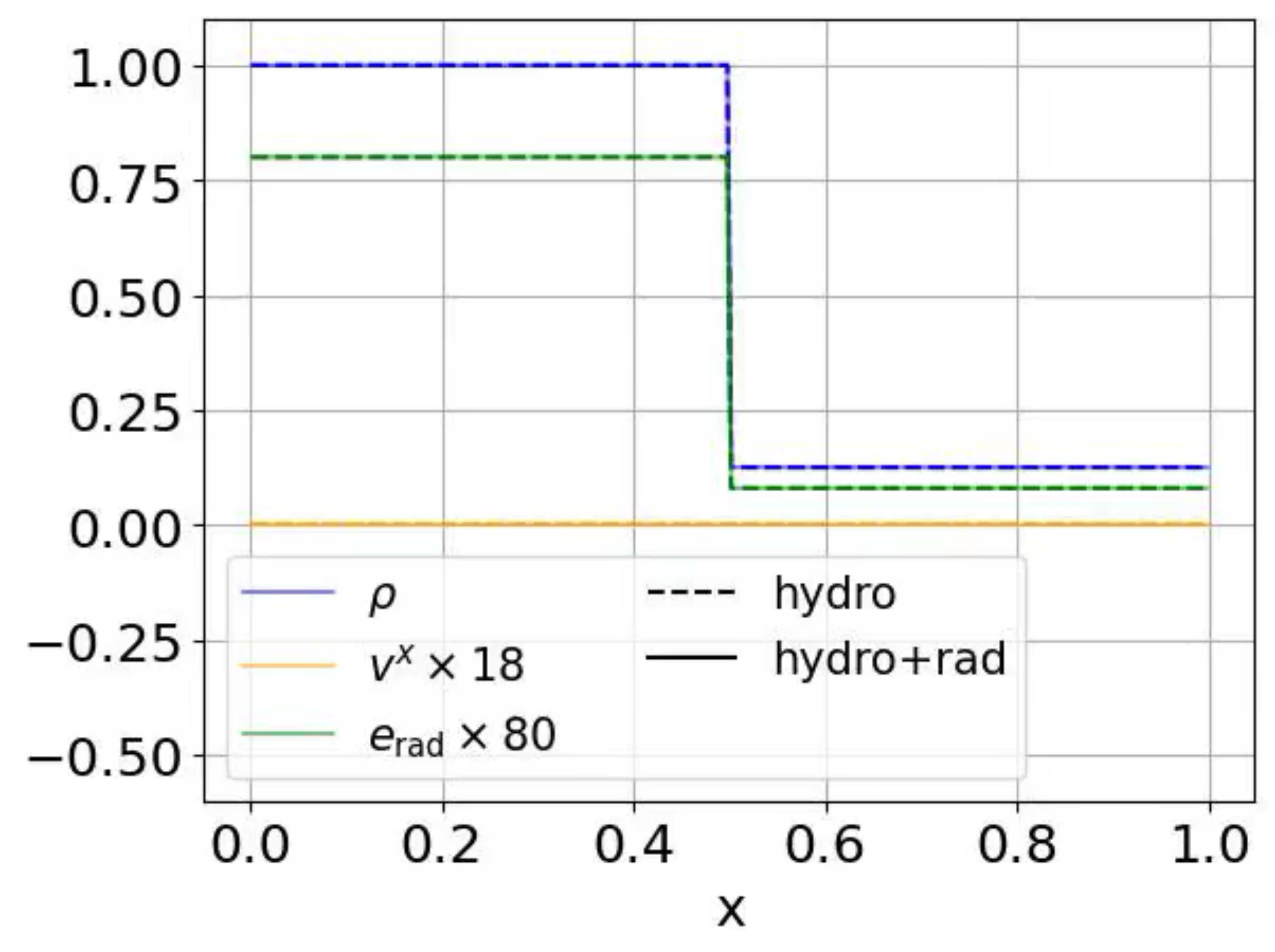


$\approx$



Optically thick shock tube

$p_{\rm gas}/p_{\rm rad} = 0.1$: radiation pressure dominant system

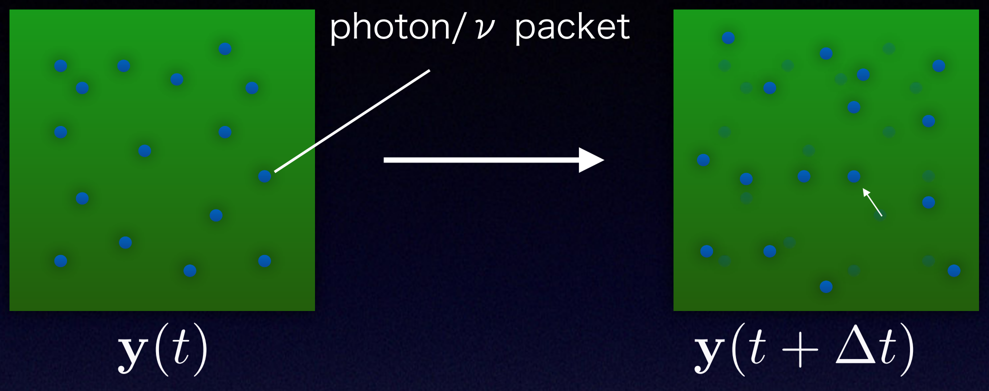


$\Delta\tau = \kappa\rho\Delta x = 50 - 400$

Time integration

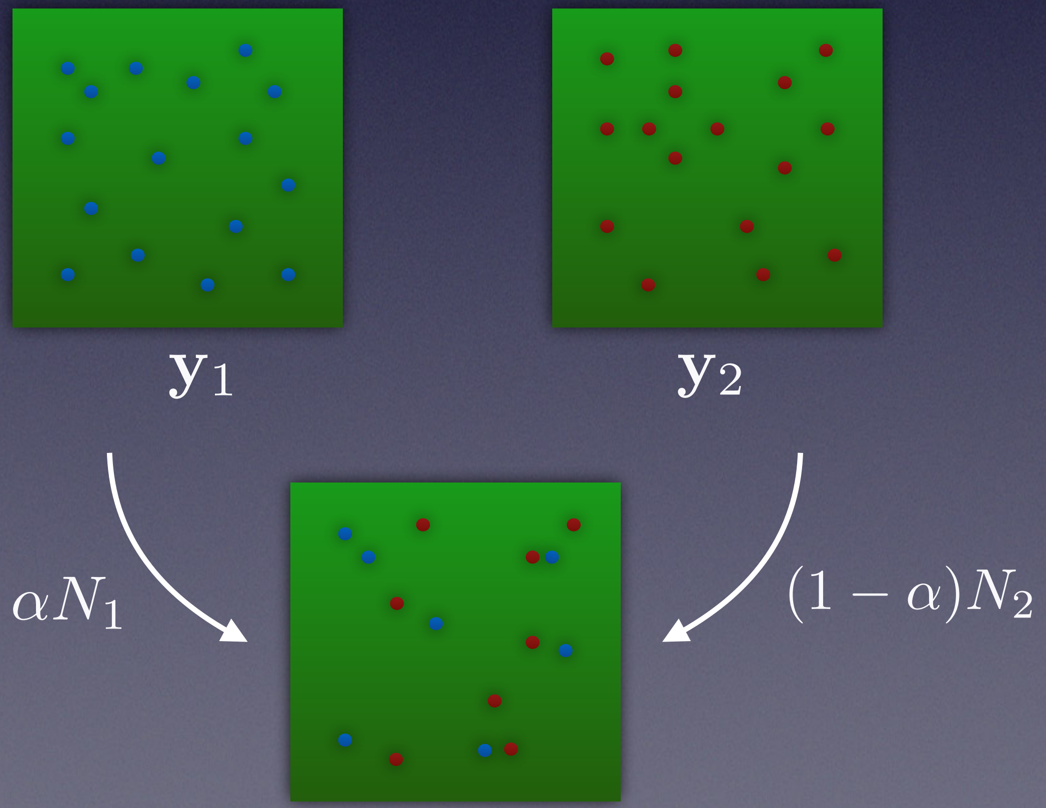
- Operator splitting method is often employed for the coupling between radiation field and fluid part:
  → time integration is 1st order for entire simulation
  N. Roth & D. Kasen 2015, Ryan et al. 2015, Miller et al. 2019, 2020,
  F. Foucart et al. 2017, 2018, 2020
- How can we implement higher-order time integration scheme?
  - Usual iterative higher-order time integration schemes are not directly applicable for radiation field described by MC packets
  - Algebraic addition of radiation field can be defined by appropriate thinning and joint of MC packets

Radiation field



$$\Delta \mathbf{y} = \mathbf{y}(t+\Delta t) - \mathbf{y}(t)? \quad \text{X}$$

"Addition" of radiation field



$$\mathbf{y}_* = \alpha \mathbf{y}_1 + (1-\alpha)\mathbf{y}_2 \quad (\alpha \in [0,1])$$

Higher-order scheme

$\mathbf{u}_n, \mathbf{y}_n$: matter and radiation field at n-th time step

$$\begin{aligned}\mathbf{u}_1 &= \mathbf{u}_n + \Delta\mathcal{F}\left(\mathbf{u}_n, \mathbf{y}_n\right)\\ \mathbf{y}_1 &= \mathcal{G}\left(\mathbf{y}_n, \mathbf{u}_p\right)\end{aligned}$$

$$\begin{aligned}\mathbf{u}_2 &= \mathbf{u}_n + \Delta\mathcal{F}\left(\mathbf{u}_1, \mathbf{y}_n\right)\\ \mathbf{y}_2 &= \mathcal{G}\left(\mathbf{y}_n, \mathbf{u}_p\right)\end{aligned}$$

$$\begin{aligned}\mathbf{u}_3 &= \mathbf{u}_n + \Delta\mathcal{F}\left(\mathbf{u}_p, \mathbf{y}_n\right)\\ \mathbf{y}_3 &= \mathcal{G}\left(\mathbf{y}_n, \mathbf{u}_p\right)\\ \mathbf{u}_p &= \frac{1}{2}\mathbf{u}_n + \frac{1}{4}\left(\mathbf{u}_1 + \mathbf{u}_2\right)\end{aligned}$$

$$\mathbf{y}(t+\Delta t)|_{\mathbf{u}} = \mathcal{G}\left[\mathbf{y}(t), \mathbf{u}\right]$$

$$\frac{d\mathbf{u}}{dt}\Delta t = \Delta\mathcal{F}\left[\mathbf{u}, \mathbf{y}(t)\right]$$

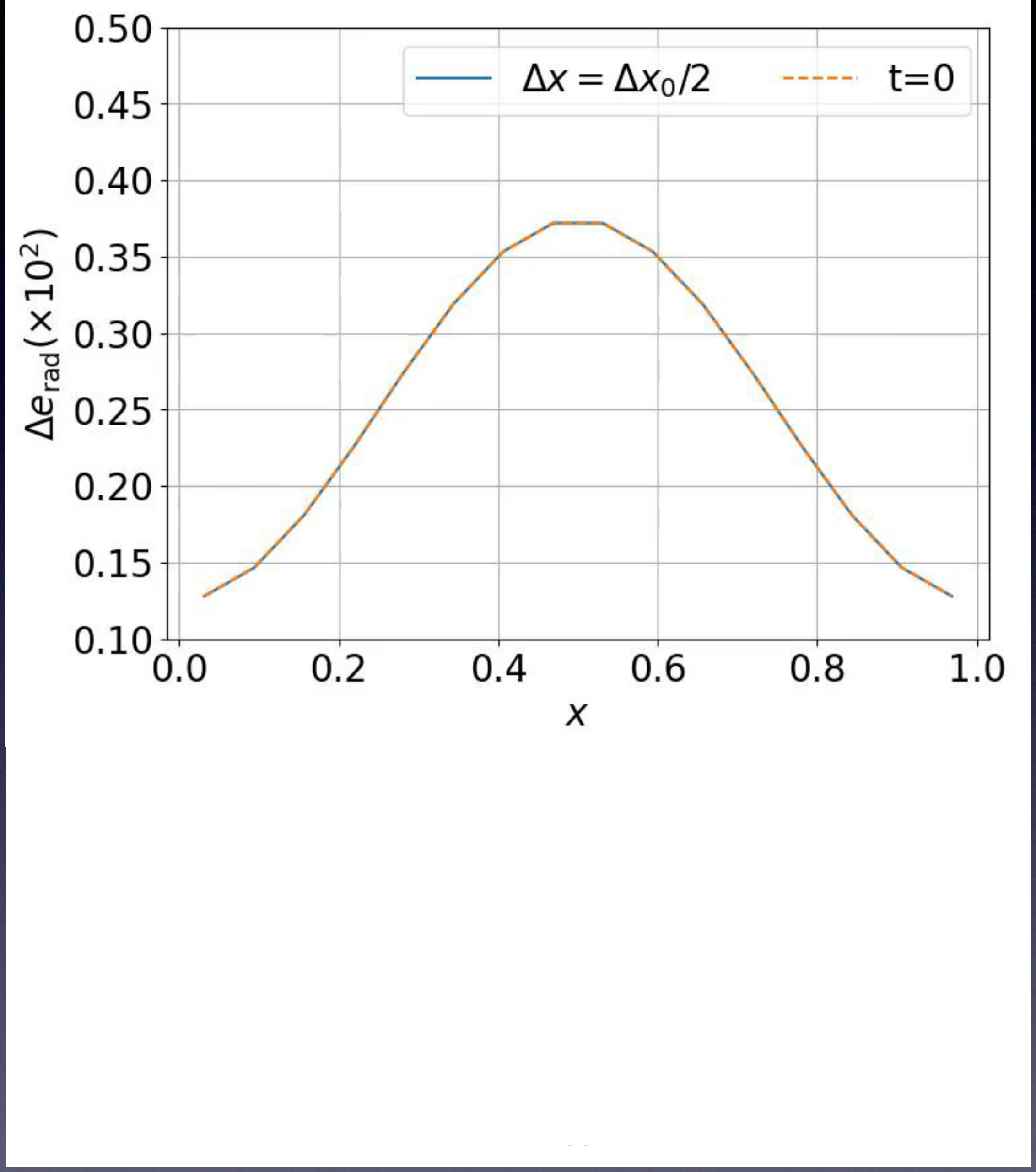
*including feed back from
radiation field during t~t+Δt

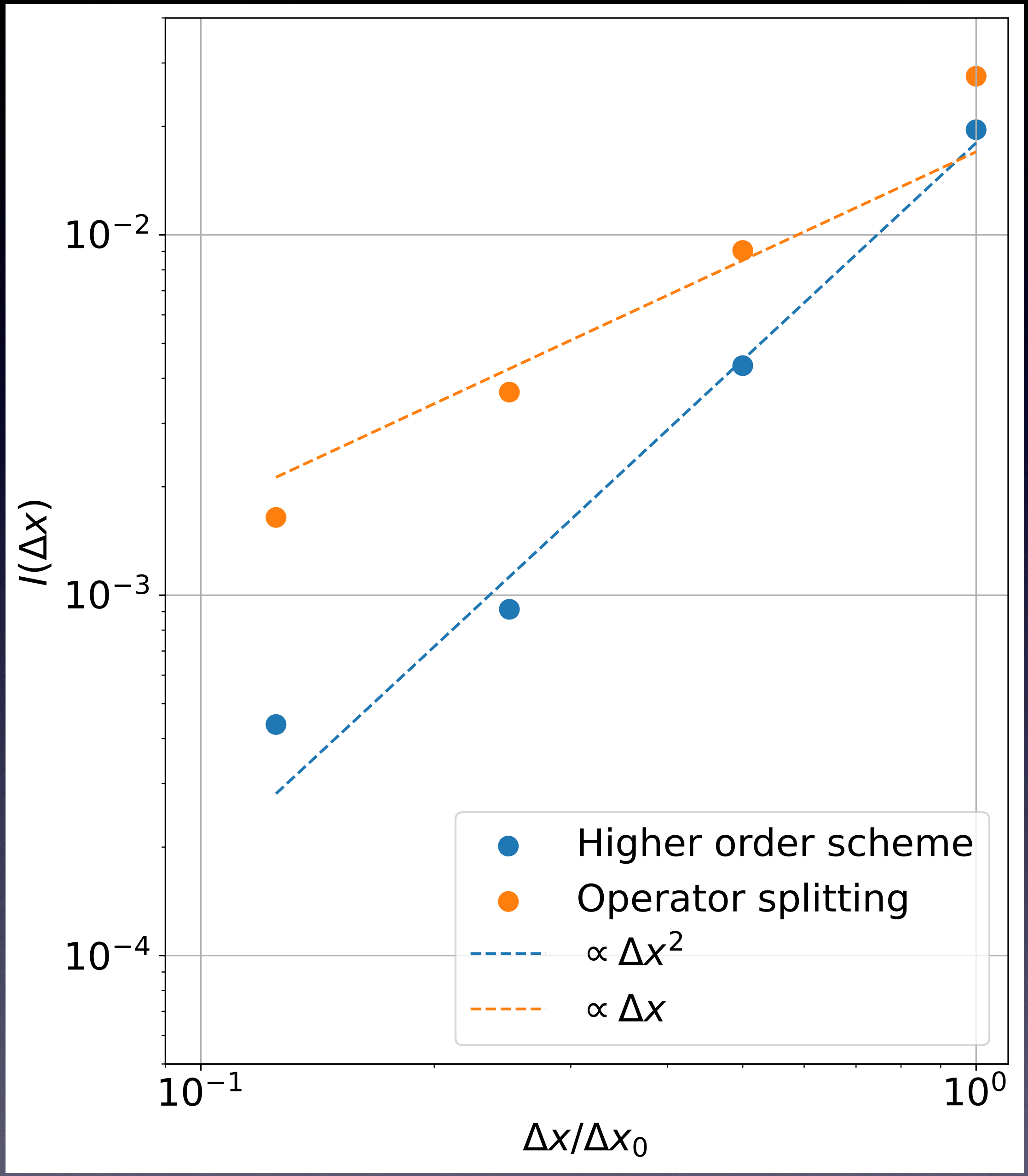
$$\boxed{\begin{aligned}\mathbf{u}_{n+1} &= \frac{1}{6}\mathbf{u}_1 + \frac{1}{6}\mathbf{u}_2 + \frac{2}{3}\mathbf{u}_3\\ \mathbf{y}_{n+1} &= \frac{1}{6}\mathbf{y}_1 + \frac{1}{6}\mathbf{y}_2 + \frac{2}{3}\mathbf{y}_3\end{aligned}}$$

Guarantees 2nd order accuracy for time integration in the limit of a large MC packet number
*hydro scheme reduces to the 3rd order Runge Kutta scheme (SSP-RK3)
for the case that radiation field is negligible

Convergence test

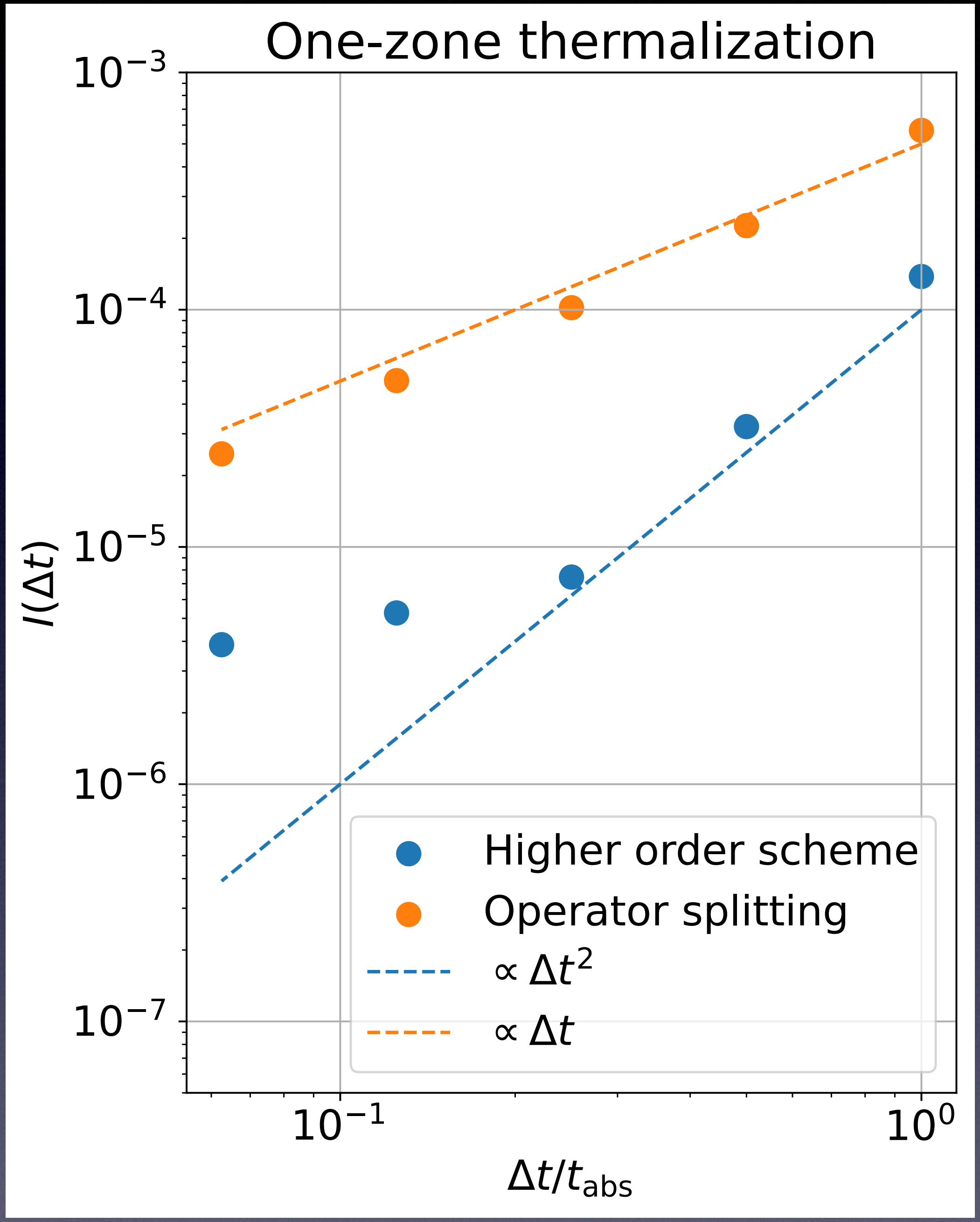
1d Clump evolution

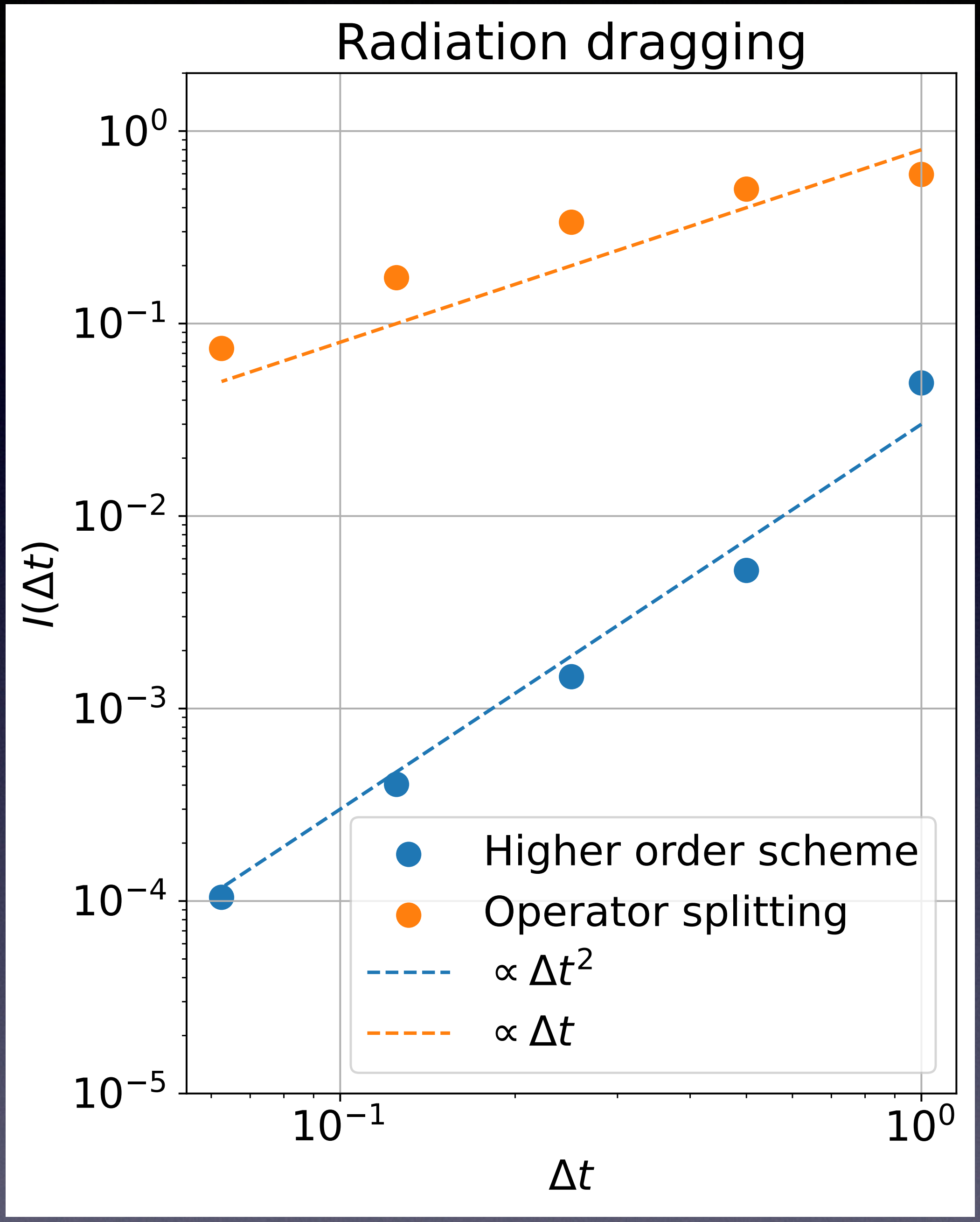


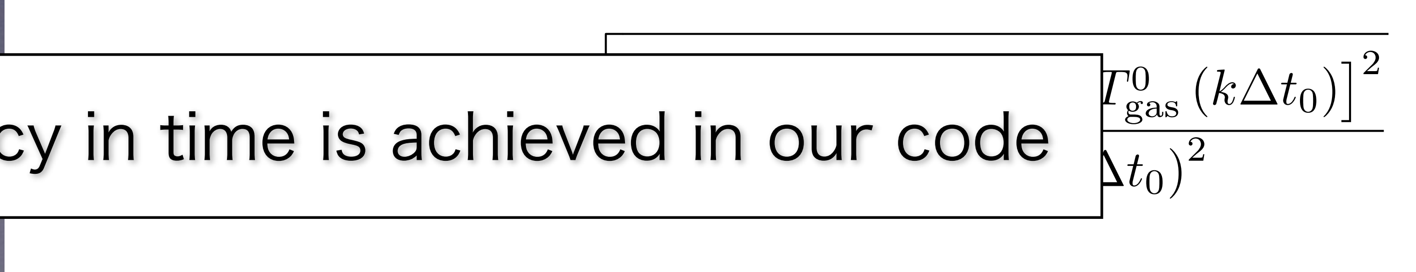


the 2nd order accuracy in time and space is achieved in our code

Convergence test







the 2nd order accuracy in time is achieved in our code

Tasks

- The implementation of realistic microphysics, such as the equation of state, emissivity, and opacity
- Evolution in the dynamical spacetime
- The implementation of the approximation method for highly optically thick regions
- Efficient parallelization with MPI computing