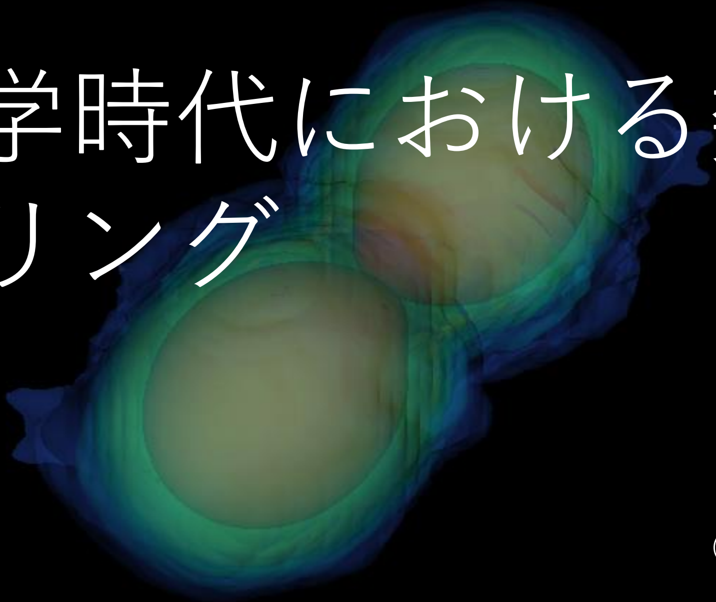
重力波天文学時代における数値相対論による波源のモデリング



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YUKAWA INSTITUTE FOR
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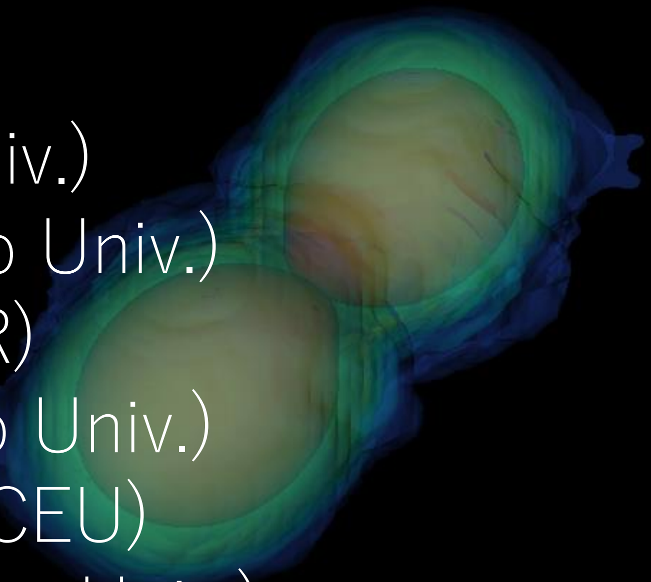

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Talk plan

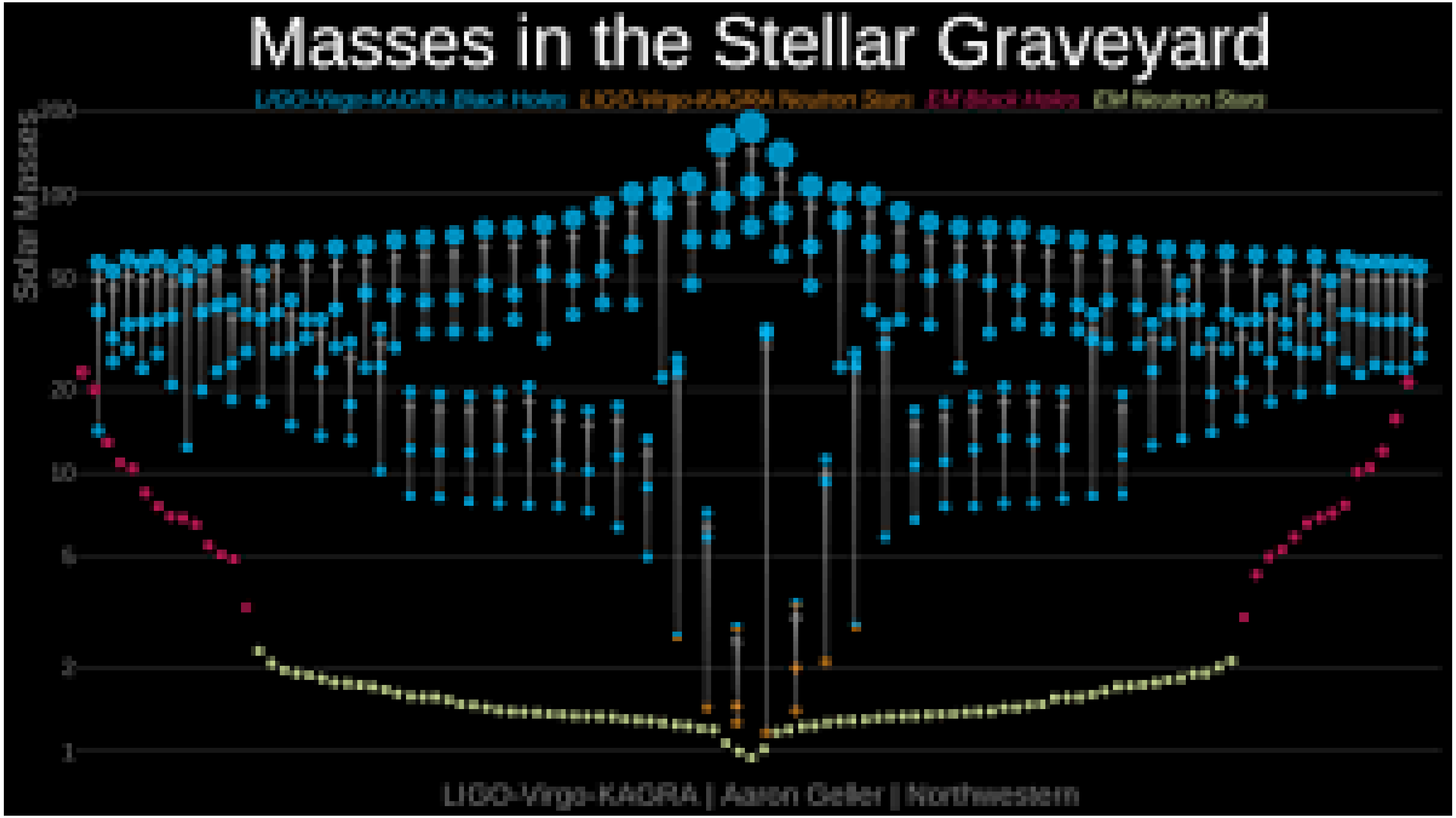
1. Introduction

2. Numerical modeling of a black hole-neutron star merger

3. Summary and prospect

Introduction
Dawn of the gravitational wave astrophysics

Source mass ($M_\odot$)



GWTC-3

Introduction

Dawn of the gravitational wave astrophysics

▶ Binary black hole systems exist. (Abbott et al. 15, many refs.)

⇒ Formation channel, Validity of GR, etc.

▶ Binary neutron stars merged. (Abbott et al., 17, many refs.)

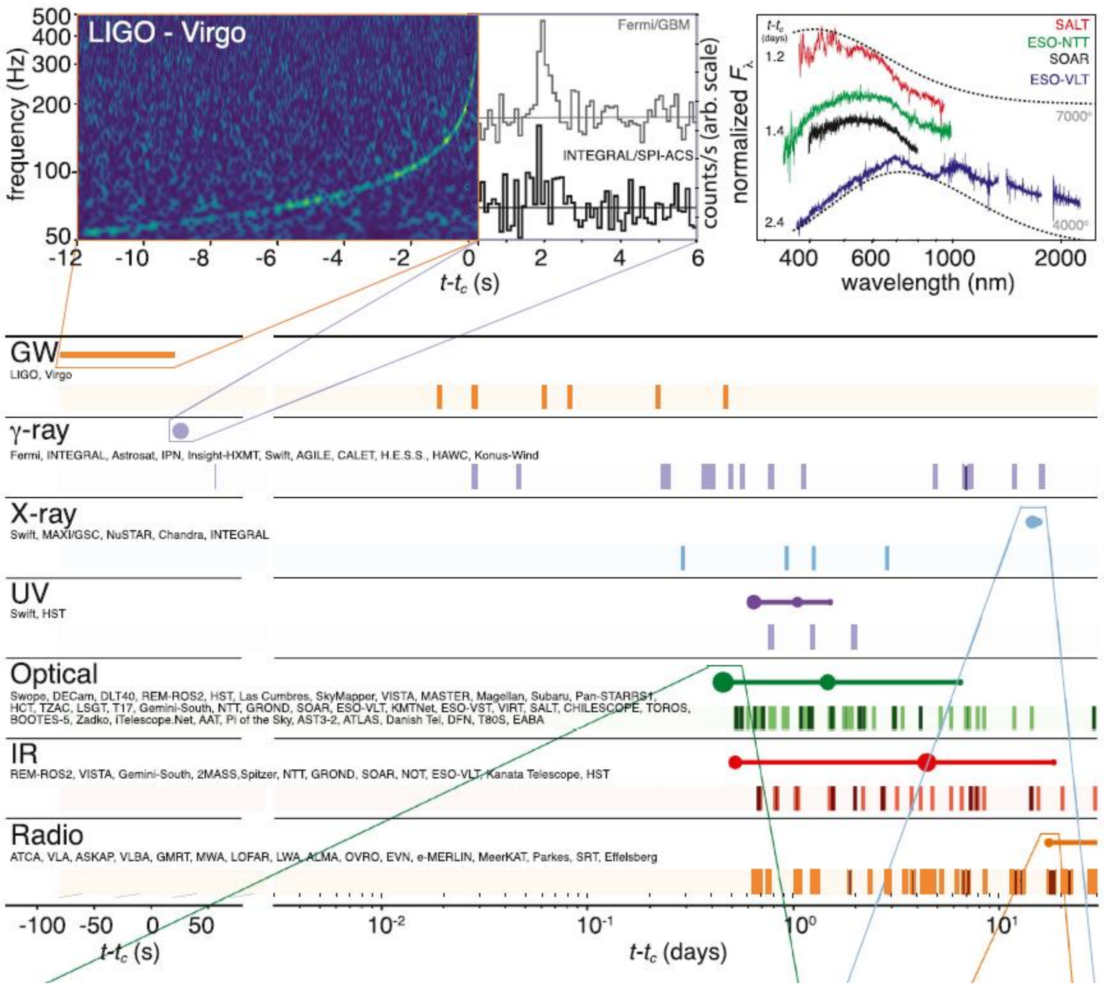
⇒ Equation of state for the nuclear matter, Nucleosynthesis of the heavy elements, Short Gamma-Ray burst central engine, Hubble constant measurement, etc.

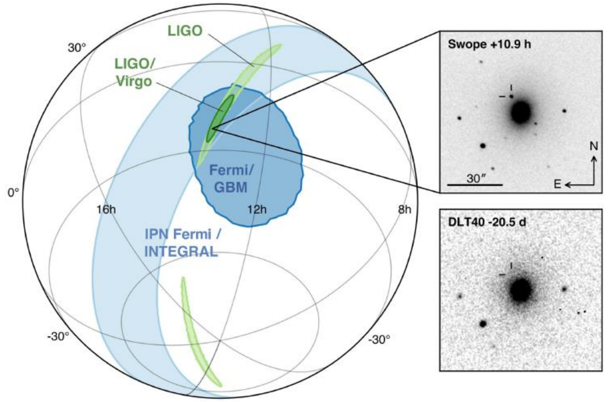
▶ Black hole-neutron star systems exist. (Abbott et al., 21)

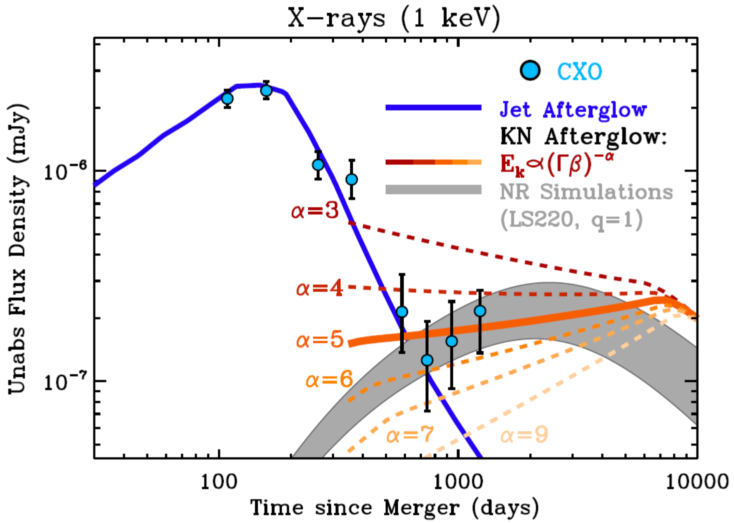
⇒Formation channel, Equation of state of the nuclear matter, etc.

Introduction
Importance of electromagnetic counterpart

LSC-Virgo collaboration 17







Hajela et al. 21

Ishizaki et al., 21

- GW170817 ⇒ γ-ray (1.7s) ⇒ UV, Optical, IR (0.5day) ⇒ X-ray (9day→1234day) ⇒ Radio (16day→700day)

Introduction

A role of numerical relativity : Is it necessary?

Yes!

▶ Without a GW waveform modeling, the equation of state of the nuclear matter cannot be constrained.

▶ What is the physical mechanism of the EM counterpart? How large is the systematics?

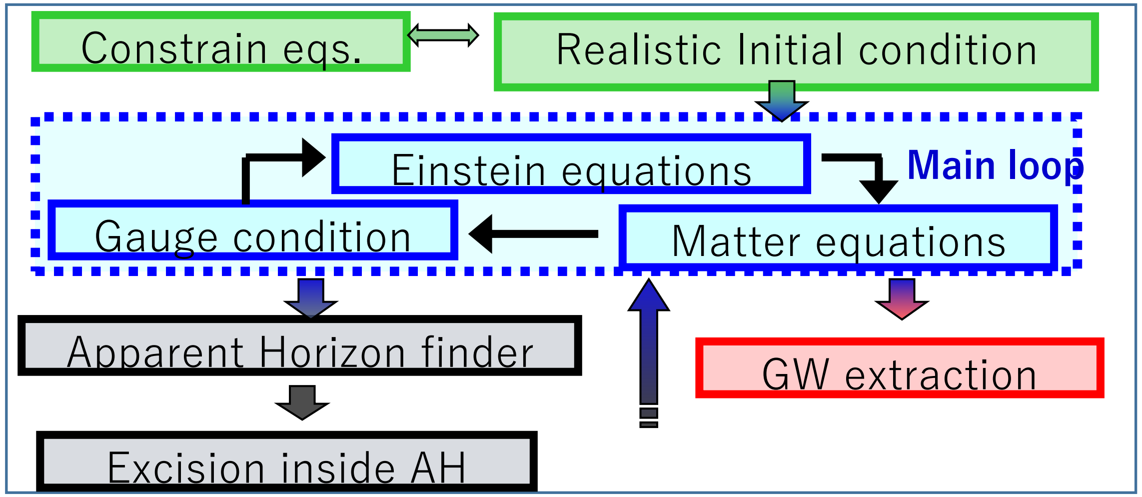
▶ Is GR the unique (final) theory of gravity? (of course, no)

Ultimately, to answer these questions quantitatively (still far).

Introduction

Toward physical modeling of GW sources

- Gravity (General Relativity)
- Strong interaction (Nuclear matter)
- Weak interaction (Neutrino)
- Electromagnetic interaction (Magnetic field)
- Highly dynamical system (GW!)
- Primarily no spatial symmetry (fully 3D+1 problem)



Slide courtesy of Y. Sekiguchi

Introduction

Big computational facility is necessary

FUGAKU@RIKEN, 400PFLOPS RAVEN@MPCDF, 8.8PFLOPS

NR is a powerful tool to predict/interpret gravitational wave events

Source modeling based on NR

GW170817(binary neutron star merger)

Shibata, KK et al. 18, 19 (Kilonova counterpart modeling, EOS constraint)
Fujibayashi, KK et al. 18, 20a,b, 21 (Kilonova modeling)
Hotokezaka, KK et al. 18 (Radio emission modeling)
KK et al. 19 (EOS constraint)
Hamidani, KK et al. 20 (Jet propagation modeling)
Narikawa, KK et al. 20 (Waveform modeling)
+ many from the other NR groups

GW190425 (binary neutron star merger)

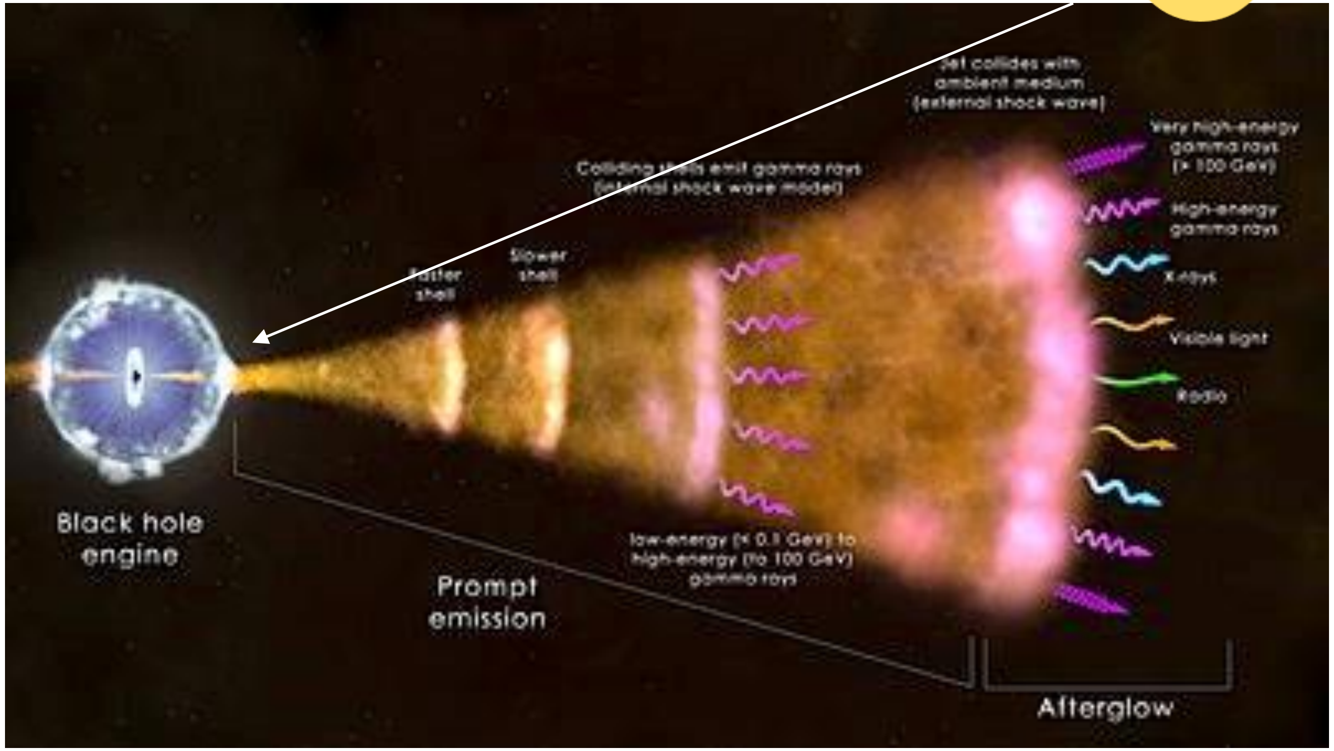
Kyutoku, KK et al. 20 (Kilonova modeling)
Dudi, KK et al. 22 (Kilonova modeling)

GW190521 (Binary black hole merger)

Shibata, KK et al. 21 (BH-torus as an alternative model)

An example : Numerical modeling of BH-NS merger

Short duration Gamma-Ray Burst (SGRB)  GW170817

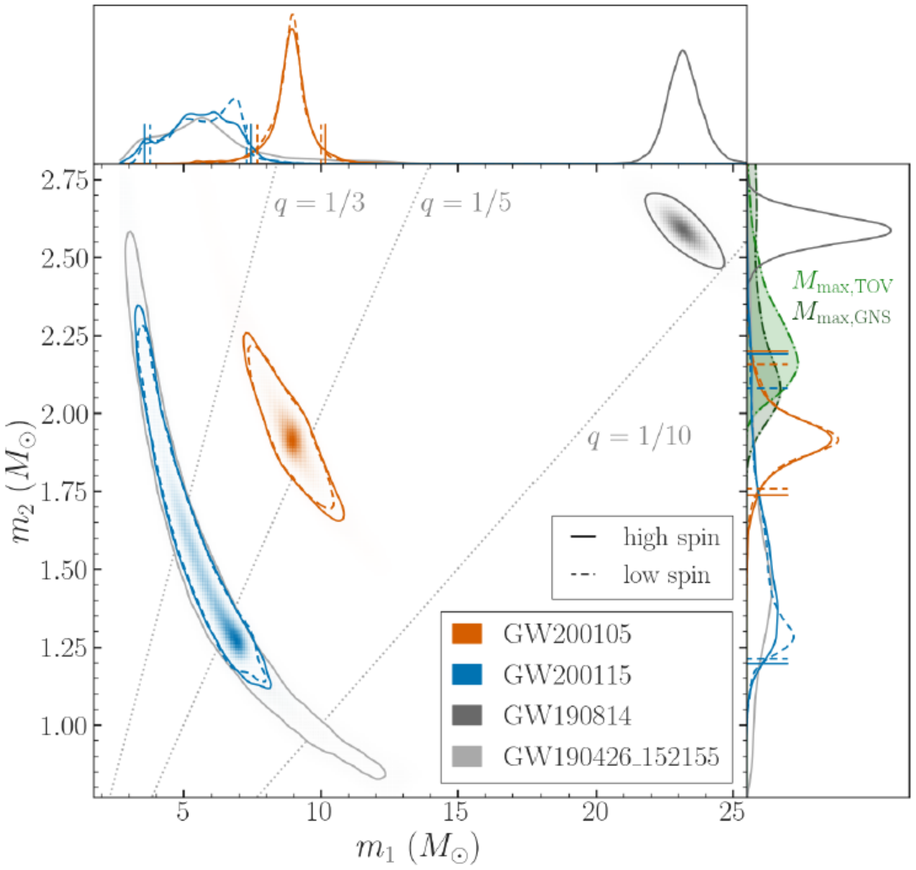


- ▶ It consumes 0.01-0.1% of the rest mass energy of the Sun in a second.
- ▶ GW170817 is the smoking gun of the merger hypothesis.

What about the other possibilities?

An example : Numerical modeling of BH-NS merger

Black Hole – Neutron Star merger



LIGO-VIRGO-KAGRA collaboration 21

- ▶ GW200105, GW200115 *no EM counterpart

An example : Numerical modeling of BH-NS merger

Tidal disruption or not?

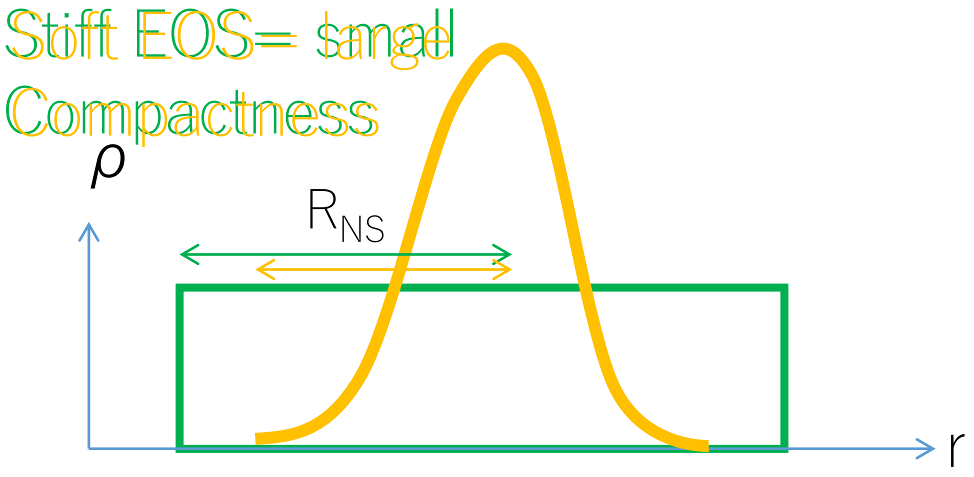
Tidal force > NS self gravity

$\Rightarrow$ $r \lesssim (M_{BH}/M_{NS})^{-2/3} (M_{NS}/R_{NS})^{-1} M_{BH} \equiv r_{tidal}$

If $r_{tidal} > r_{isco}$ $\Rightarrow$ Tidal disruption

$r_{tidal} < r_{isco}$ $\Rightarrow$ No tidal disruption

*ISCO = Inner Stable Circular Orbit

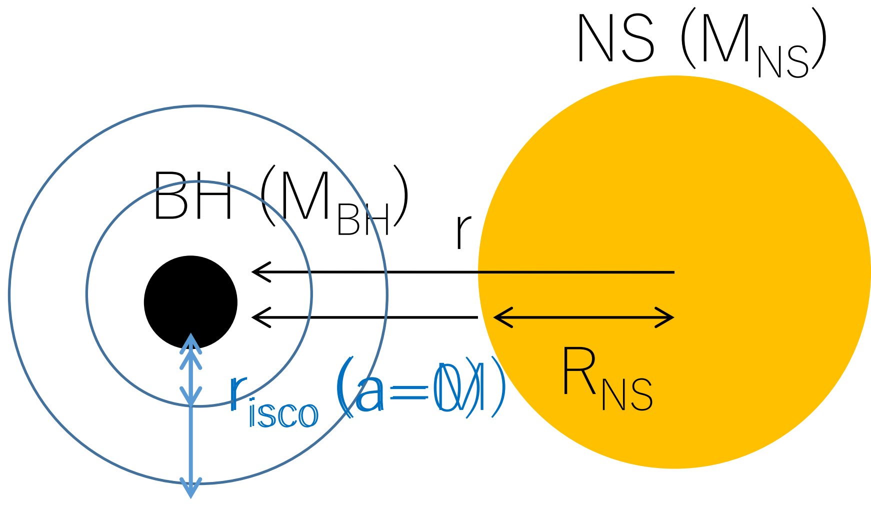


Key ingredients

▶ Spin of BH

▶ Mass ratio (M_{BH}/M_{NS})

▶ Compactness of NS (M_{NS}/R_{NS})

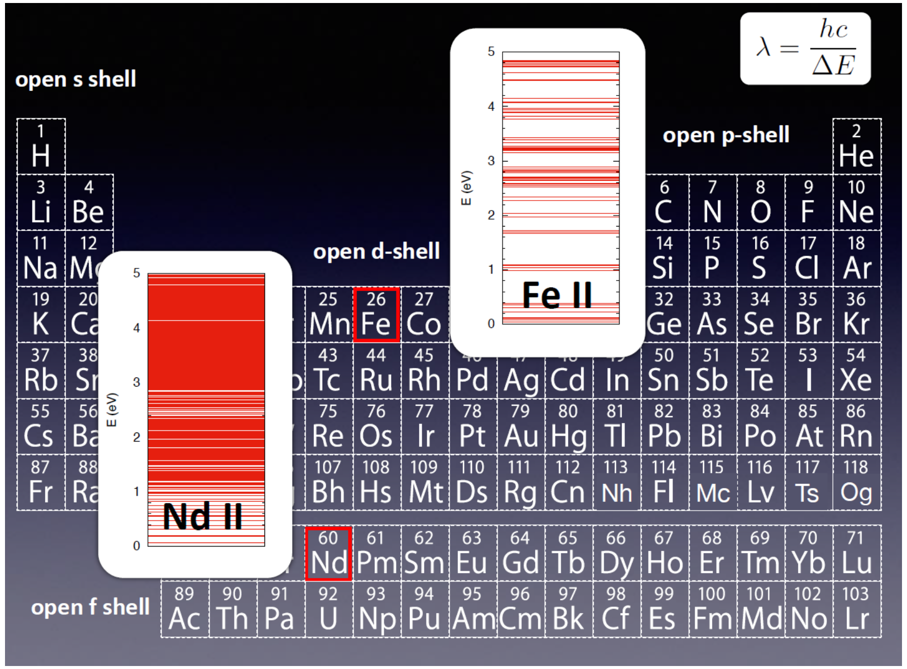


Tidal disruption $\Rightarrow$ Dynamical mass ejection and massive torus formation.

$\Rightarrow$ Important for EM counterpart

Electromagnetic emission in compact binary mergers

R(paid)-process nucleosynthesis and EM
(Lattimer & Schramm 74, Metzger et al. 10, Li & Paczynski 98)



Slide courtesy of M. Tanaka

Role of the r-process elements

▶ Heating source via radio-active decay (Kasen et al. 17)

$$\dot{\epsilon} \approx 10^{10}\,\mathrm{erg\,s^{-1}\,g^{-1}} \left(\frac{t}{\mathrm{day}}\right)^{-1.3}$$

▶ Opacity source (Lanthanide elements)
(Barnes & Kasen 13, Tanaka & Hotokezaka 13)

$$\kappa \approx 10\,\mathrm{cm^2\,g^{-1}}$$

Properties of electromagnetic emission (Optical-IR)

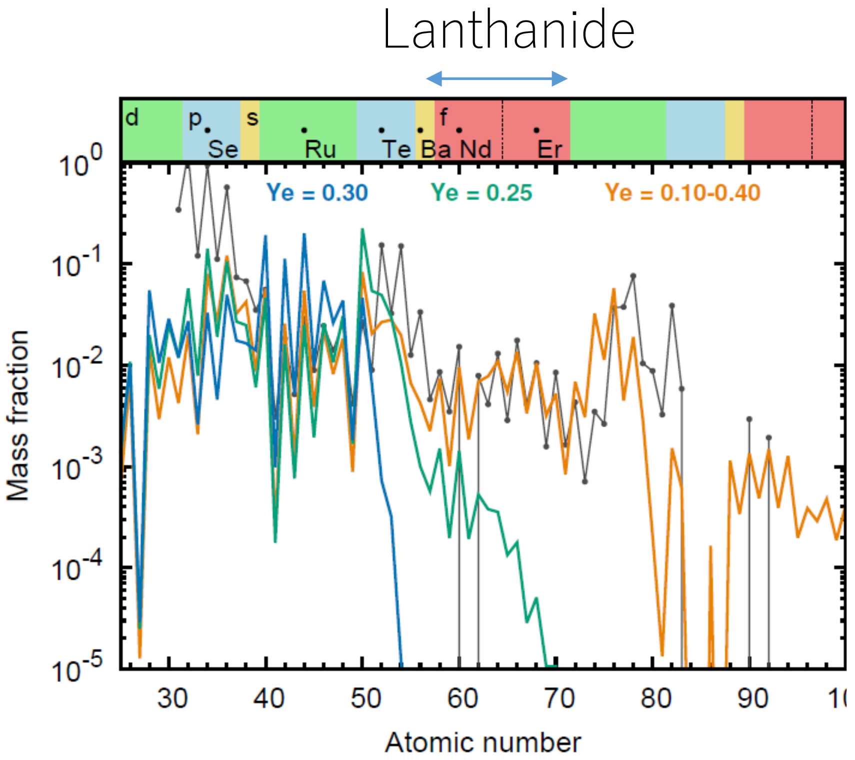
▶ Peak time (diffusion time = dynamical time)

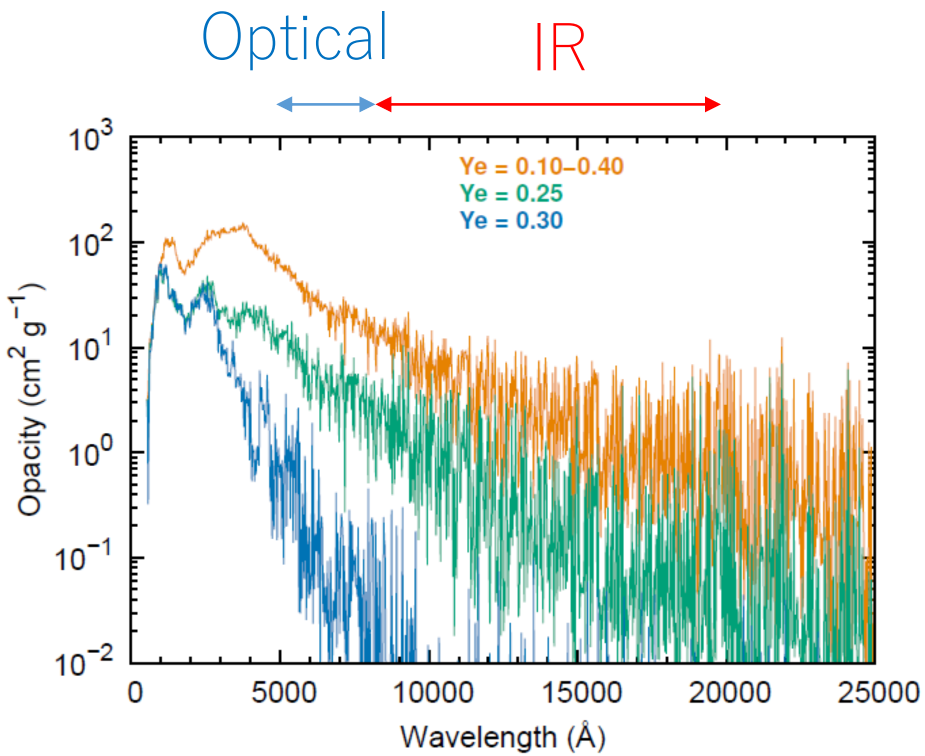
$$t_{\mathrm{peak}} \approx 5.7\,\mathrm{day} \left(\frac{\kappa}{10\,\mathrm{cm^{-2}\,g^{-1}}}\right)^{1/2} \left(\frac{M_{\mathrm{eje}}}{0.03M_{\odot}}\right)^{1/2} \left(\frac{v_{\mathrm{ej}}}{0.2c}\right)^{-1/2}$$

▶ Peak Luminosity

$$L \approx \dot{\epsilon} M_{\mathrm{ej}} \approx 6\times10^{41}\,\mathrm{erg\,s^{-1}} \left(\frac{M_{\mathrm{eje}}}{0.03M_{\odot}}\right) \left(\frac{t}{\mathrm{day}}\right)^{-1.3}$$

R-process nucleosynthesis and its opacity





Tanaka et al. 17

- ▶ Electron fraction Y_e (# of electron/# of baryon) is a key quantity
- ▶ $Y_e \gtrsim$ 0.25 produces negligible / small amount of lanthanide ⇒ low opacity in optical
- ▶ $Y_e \lesssim$ 0.25 produces lanthanide ⇒ high opacity in IR
- ▶ Neutrino reaction determines Y_e of the ejecta

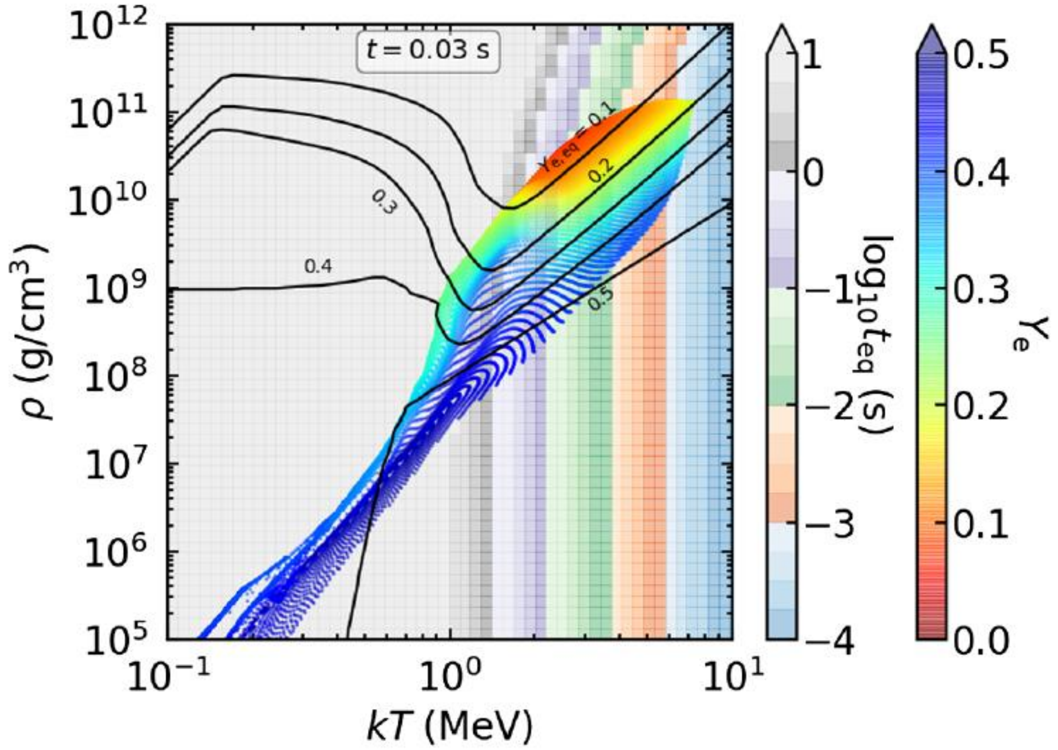
Is the post merger ejecta Lanthanide rich or Lanthanide poor?

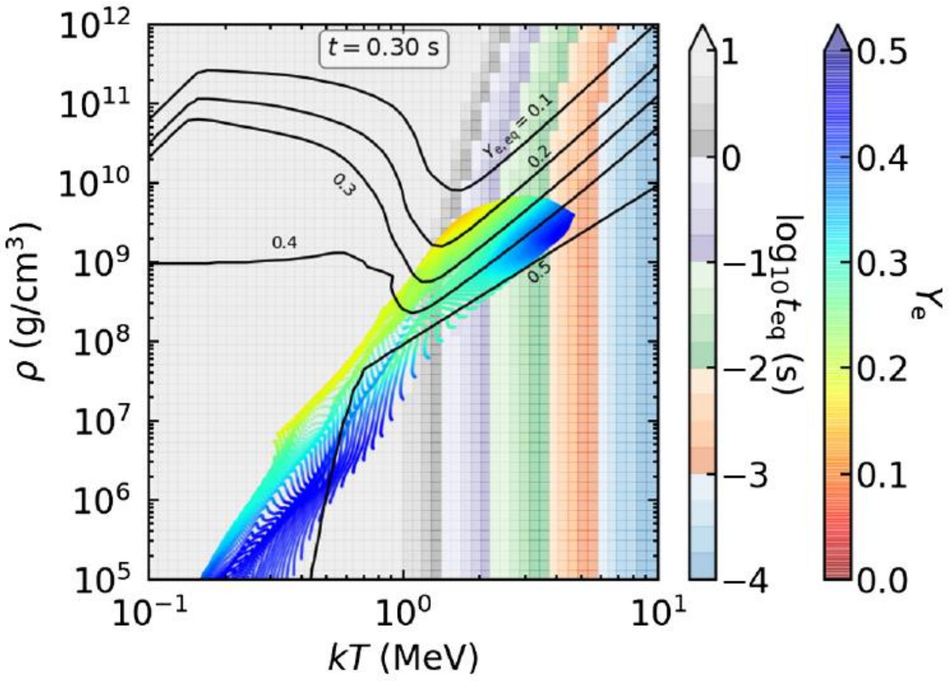
Equilibrium value of the electron fraction (Beloborodov 03)

Electron capture rate = Positron capture rate

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

$Y_{e,eq}$ and t_{eq} , $t_{expansion} > t_{eq}$ (Fujibayashi et al. 20)





At some point $t_{expansion} < t_{eq,}$ ⇒ The weak processes freeze out

An example : Numerical modeling of BH-NS merger

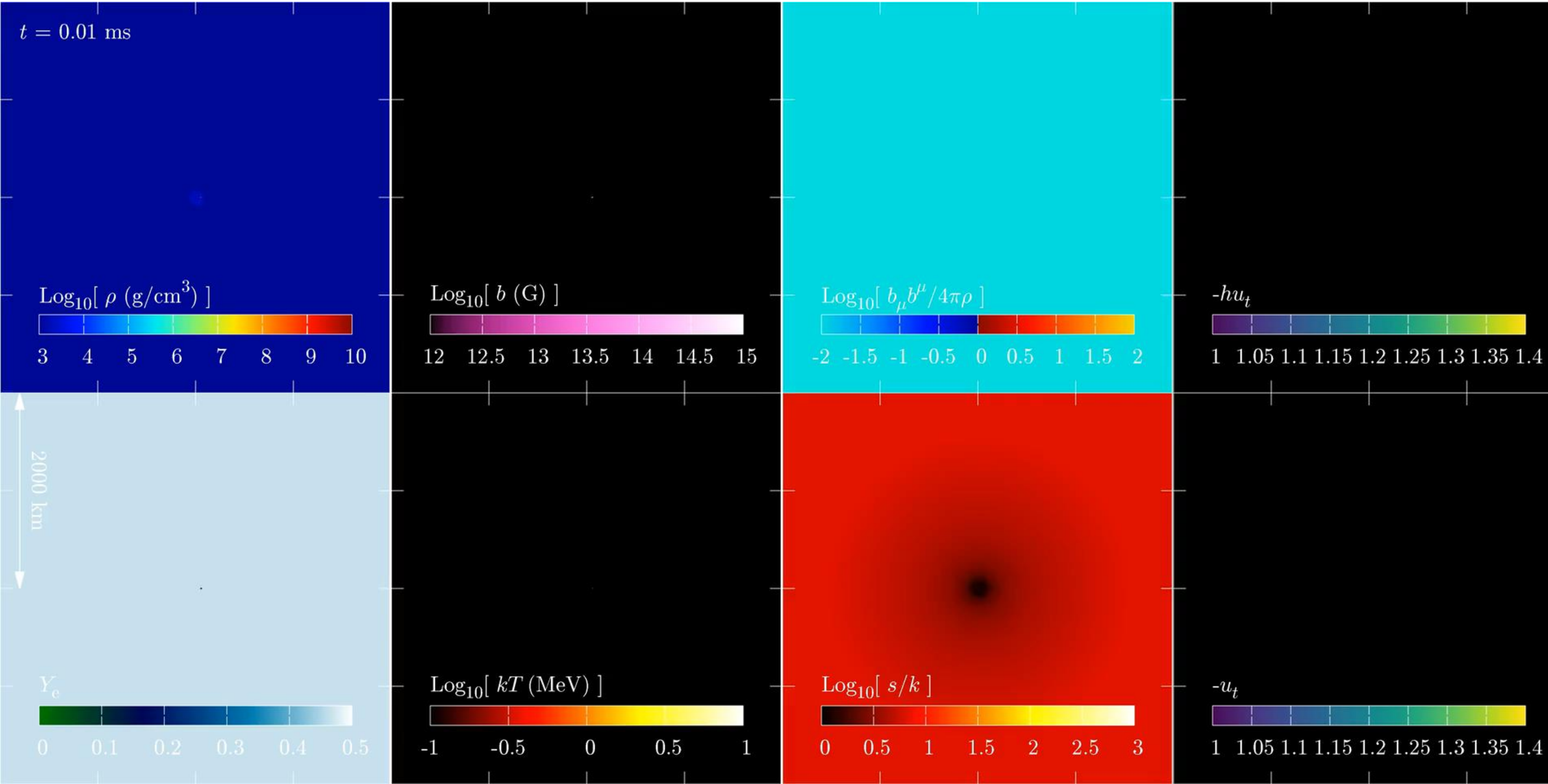
Numerical Relativity-Neutrino-Radiation-Magnetohydrodynamics simulation of BH-NS merger (Hayashi+ KK, et al. 21)

▶ Neutrino radiation transfer is necessary to predict Y_e of the ejecta

▶ Magnetohydrodynamics is necessary to reveal the massive torus evolution, in particular, the angular momentum transport and turbulent viscous heating.

▶ Merger simulation is necessary to build a self-consistent model of the massive torus formation

Extremely long-term simulation ($\approx$ 2 seconds)



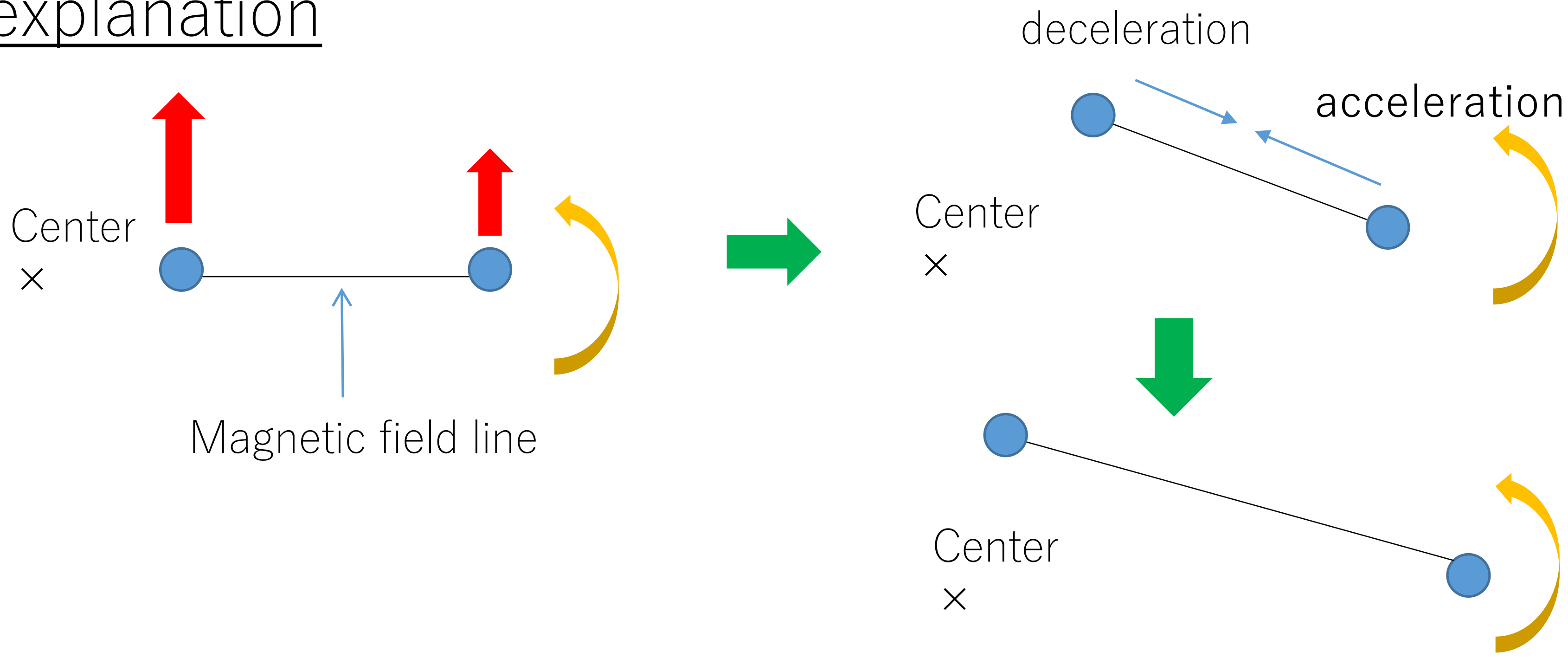
t = 0.01 ms
Log10[ρ (g/cm3)]
3 4 5 6 7 8 9 10
Log10[b (G)]
12 12.5 13 13.5 14 14.5 15
Log10[bμbμ/4πρ]
-2 -1.5 -1 -0.5 0 0.5 1 1.5 2
-hut
1 1.05 1.1 1.15 1.2 1.25 1.3 1.35 1.4
2000 km
Ye
0 0.1 0.2 0.3 0.4 0.5
Log10[kT (MeV)]
-1 -0.5 0 0.5 1
Log10[s/k]
0 0.5 1 1.5 2 2.5 3
-ut
1 1.05 1.1 1.15 1.2 1.25 1.3 1.35 1.4

Numerical modeling of BH-NS merger

Magneto Rotational Instability (MRI) (Balbus & Hawley 91)

▶ Differential rotation $\nabla\Omega < 0 \Rightarrow B(t) \propto \exp(\sigma t),\ \sigma \approx \Omega$

Intuitive explanation

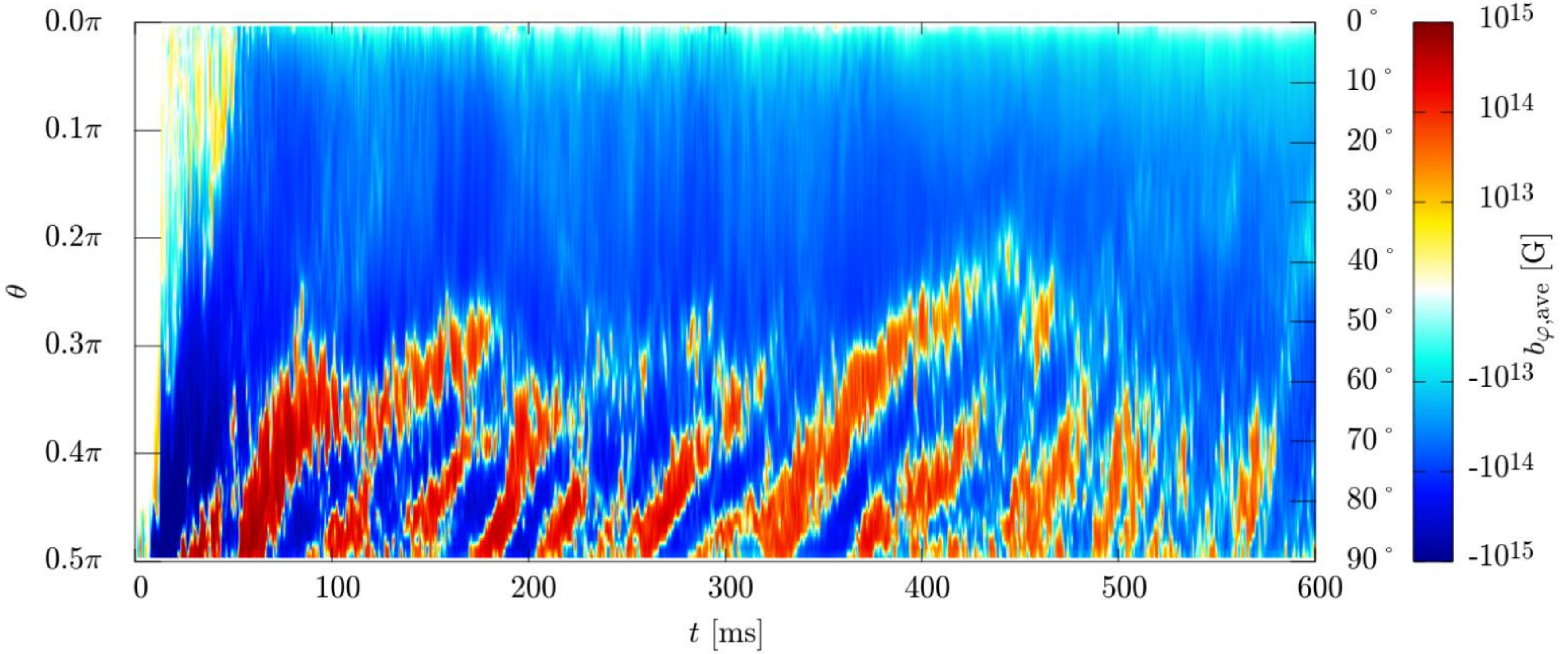


MRI-driven turbulence produces the effective viscosity
⇒ Angular momentum transport and viscous heating

Numerical modeling of BH-NS merger

MRI works?

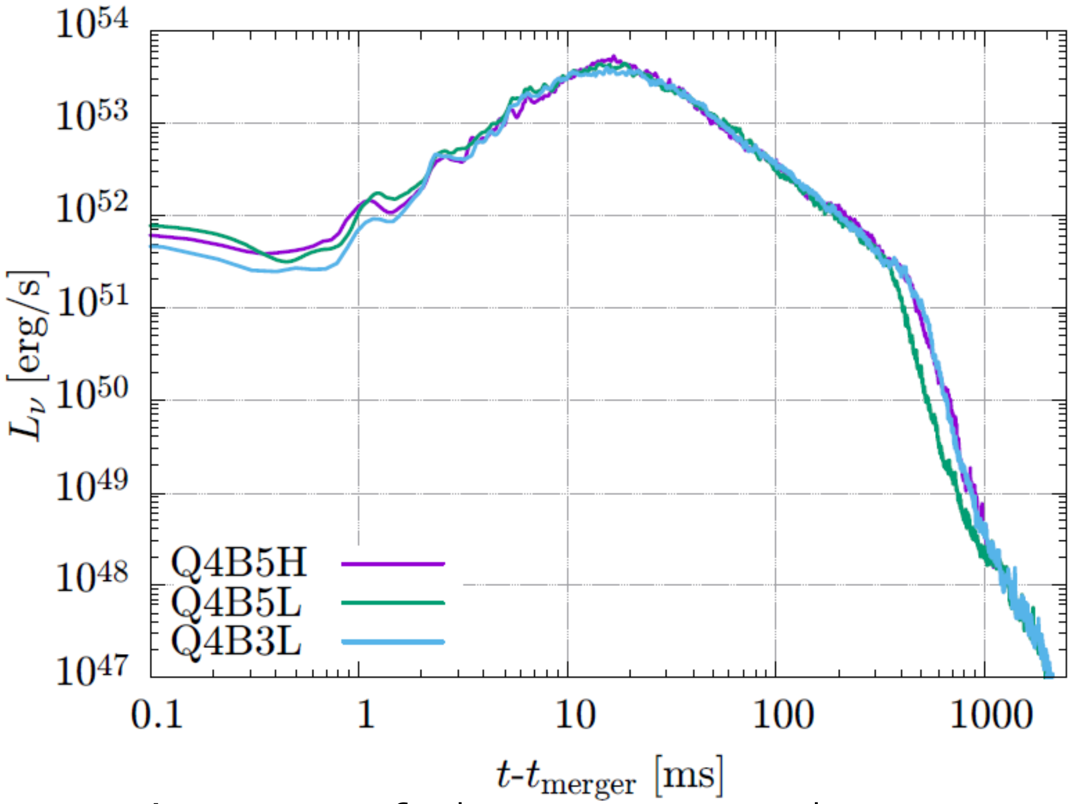
Butterfly diagram



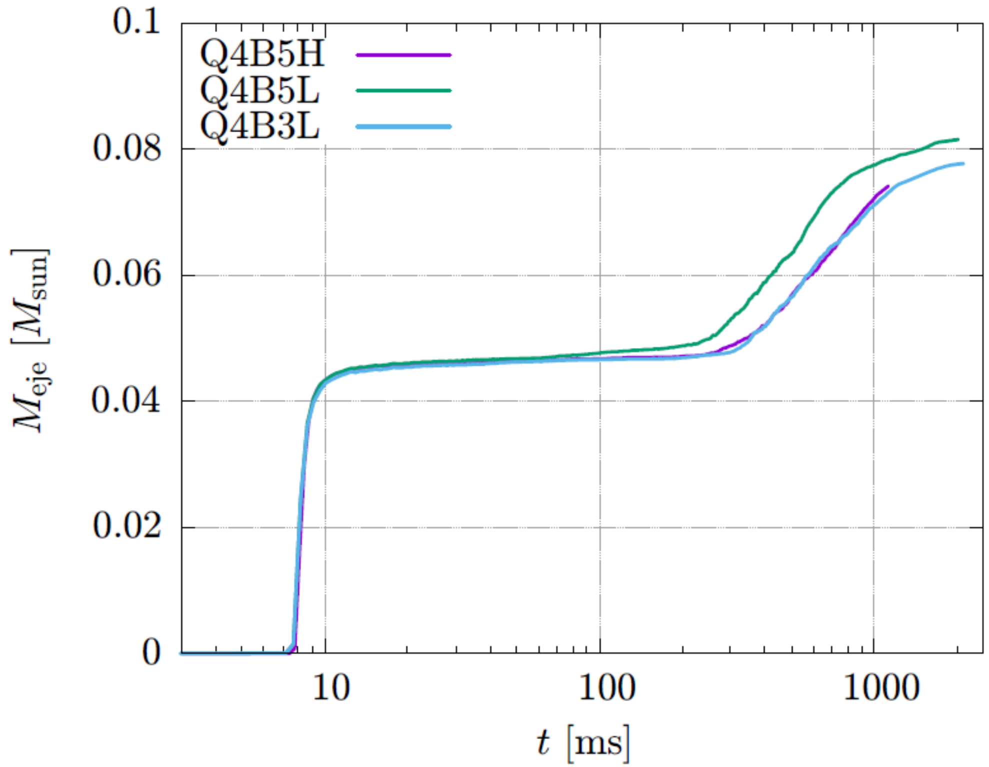
▶ MRI-dynamo works ⇒ Effective turbulent viscosity ($\alpha \approx 0.01$)
⇒Torus expands due to the angular momentum transport

Numerical modeling of BH-NS merger

Neutrino luminosity



Gravitational unbounded baryonic mass



▶ A part of the viscous heating is consumed by the neutrino emission

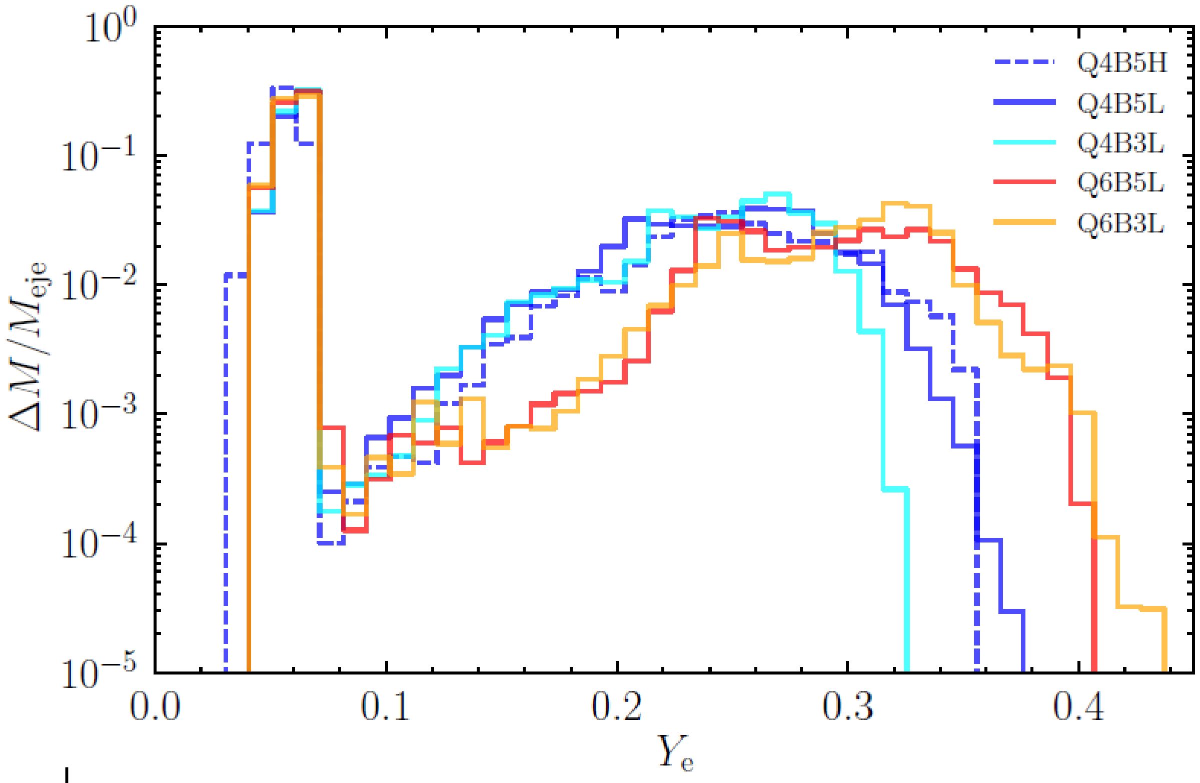
⇒ Temperature decreases due to the torus expansion

⇒At some point, the neutrino emission becomes inefficient.

⇒ All the viscous heating is used for the torus expansion

Numerical modeling of BH-NS merger

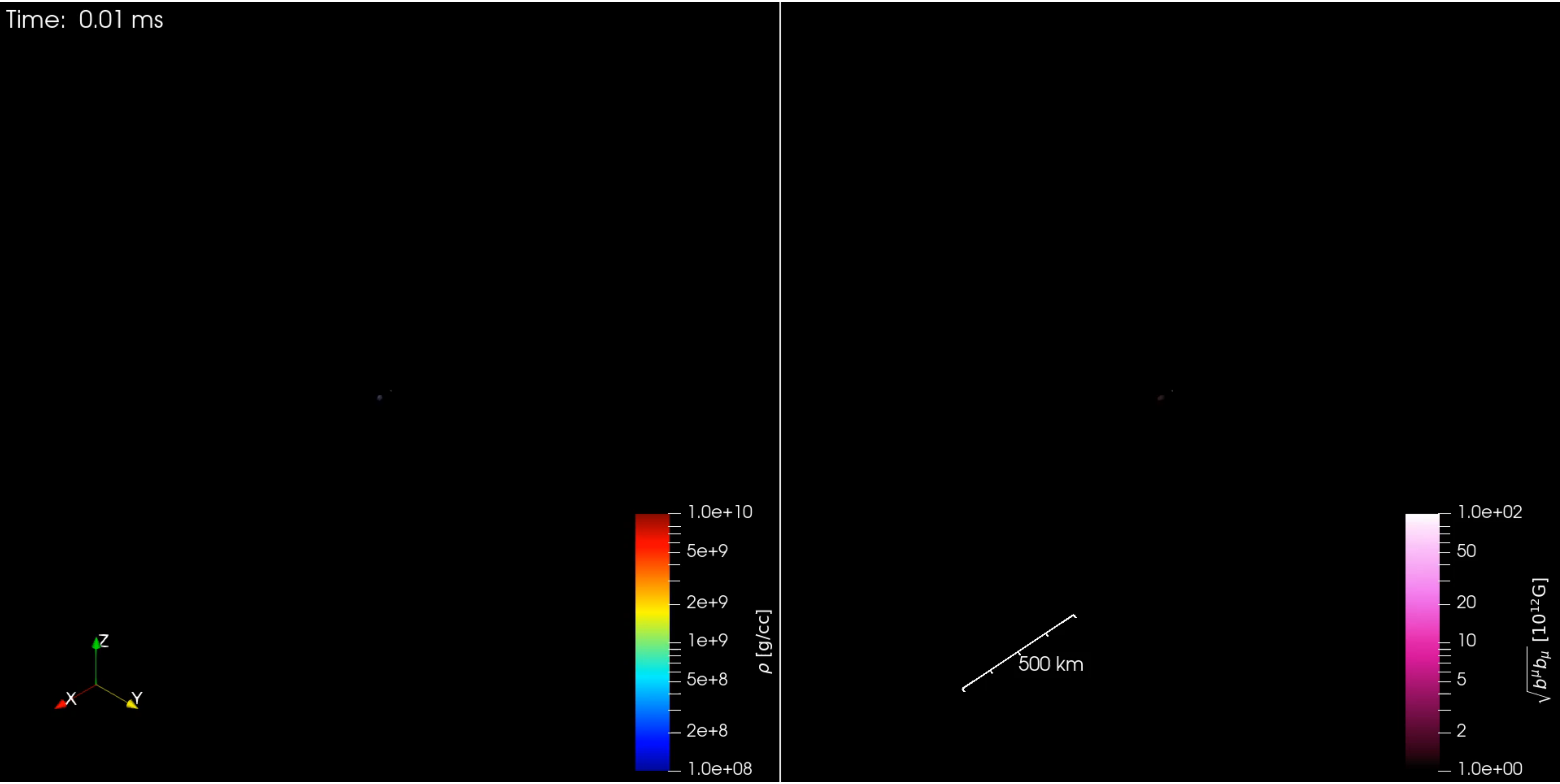
Electron fraction distribution of gravitationally unbounded material



▶ Two distinct peaks

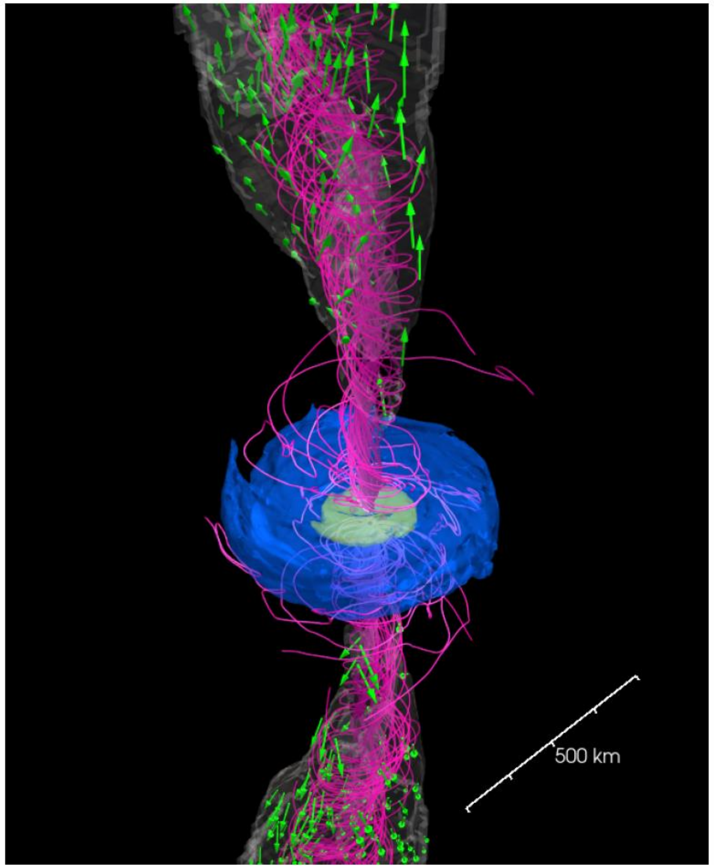
Low Y_e component ⇒ Dynamical ejecta ⇒ NIR band emission

High Y_e component ⇒ Post-merger ejecta ⇒ Optical band emission

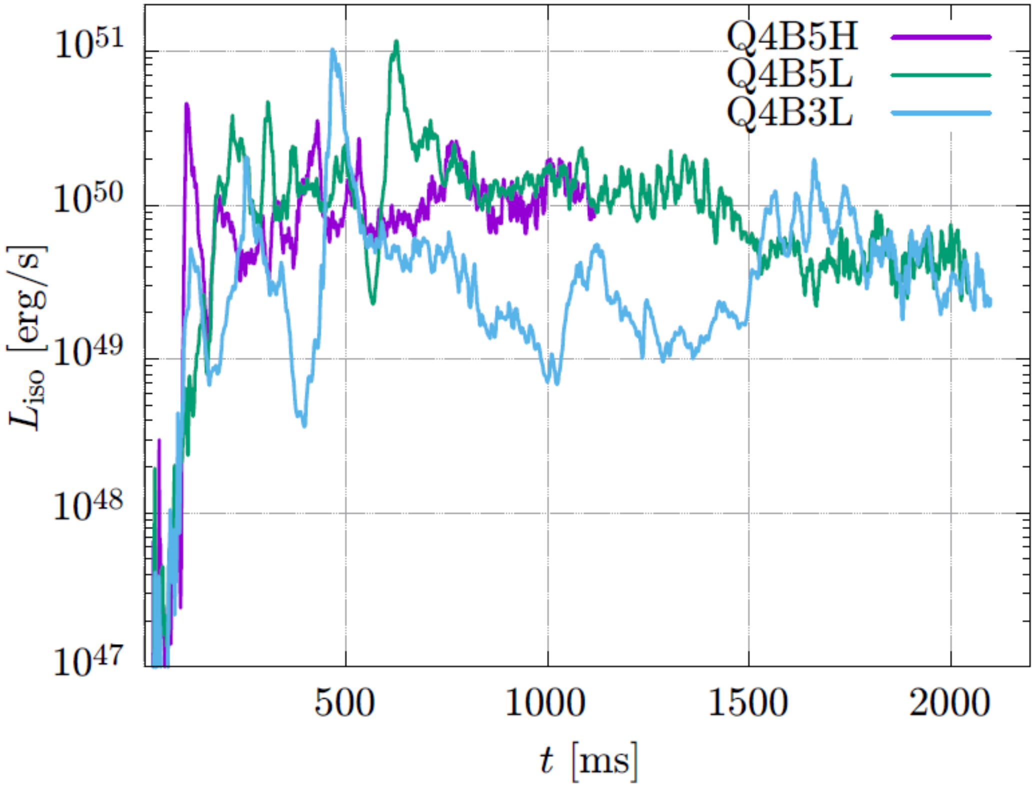

Time: 0.01 ms
Z
X
Y
1.0e+10
5e+9
2e+9
1e+9
5e+8
2e+8
1.0e+08
ρ [g/cc]
500 km
1.0e+02
50
20
10
5
2
1.0e+00
$\sqrt{b^\mu b_\mu}$ [10^{12}G]

Numerical modeling of BH-NS merger

Magnetically tower “jet”



Isotropic Poynting Luminosity

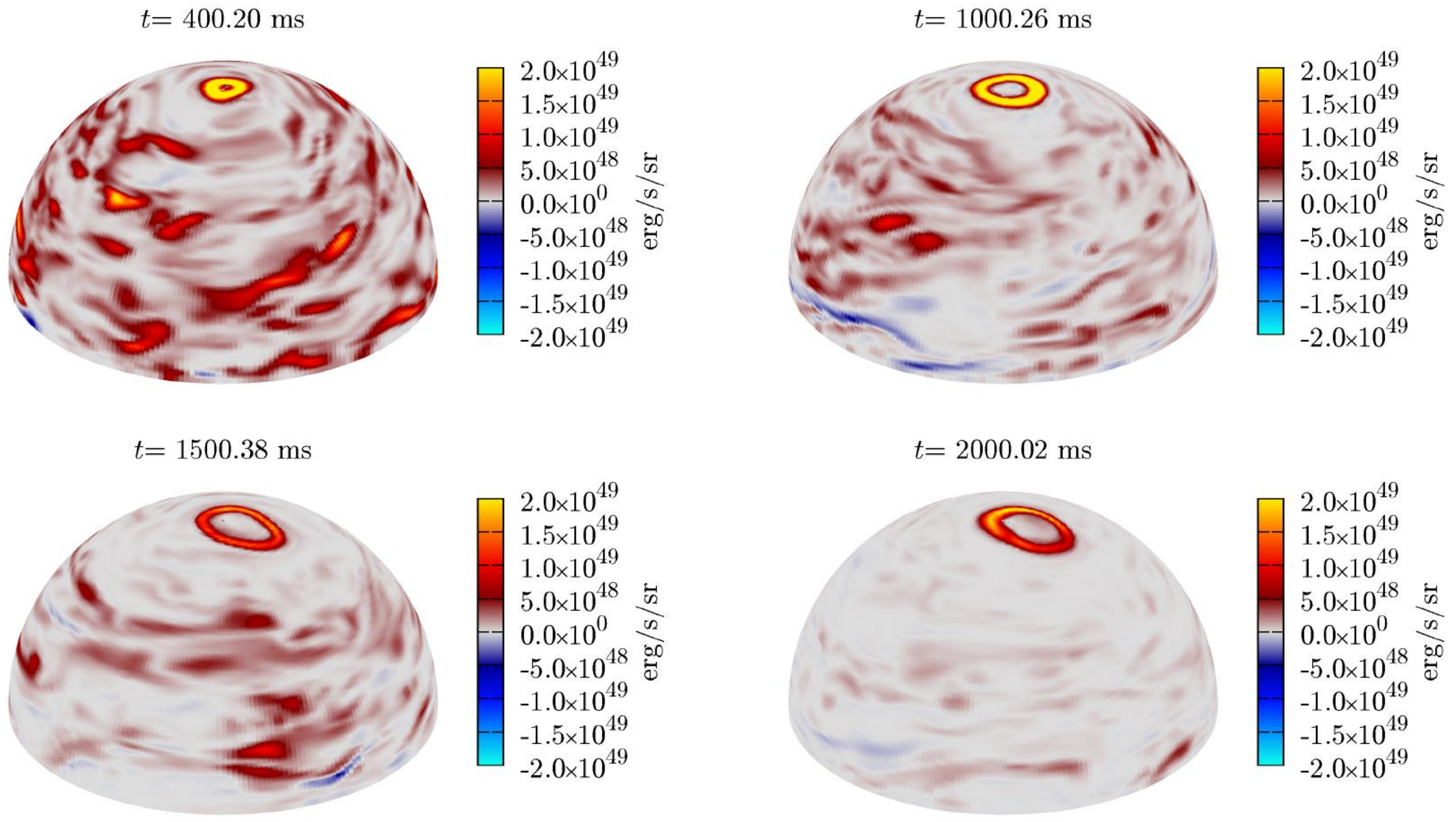


▶ Magnetically tower “jet” builds up magnetosphere

⇒ L_{iso} and θ_{jet} are roughly consistent with the observed values.

Numerical modeling of BH-NS merger

Poynting flux distribution



▶ After 1-2 seconds, the opening angle increases due to the torus expansion

⇒ Agree with the observed duration of the Short Gamma-Ray Bursts.

Conclusion and prospect

▶ In gravitational wave astronomy era, numerical relativity modeling is important to predict/interpret GW events.

▶ A black hole-neutron star merger could drive a Short Gamma-Ray Bursts.

▶ More sophisticated modeling is necessary to mitigate systematic error.