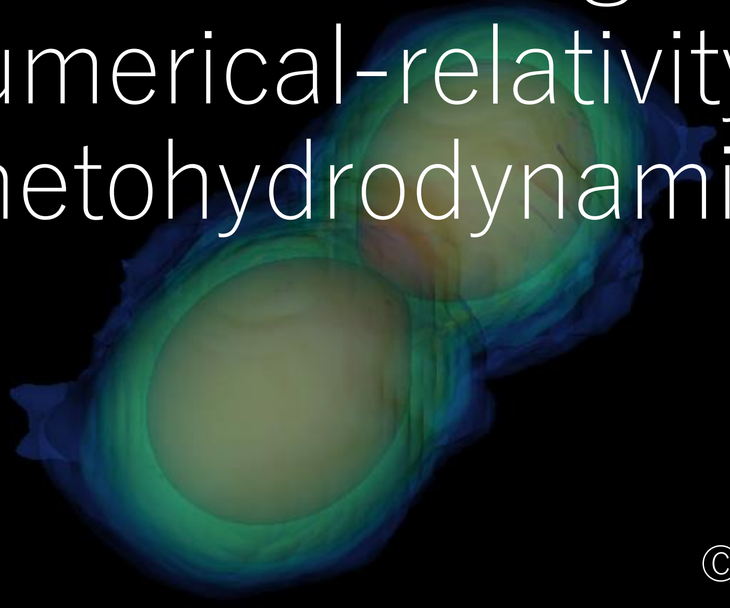
Self-consistent picture of the mass ejection from one-second lasting binary neutron star merger in numerical-relativity neutrino-radiation magnetohydrodynamic simulation



© Sho Fujibayashi

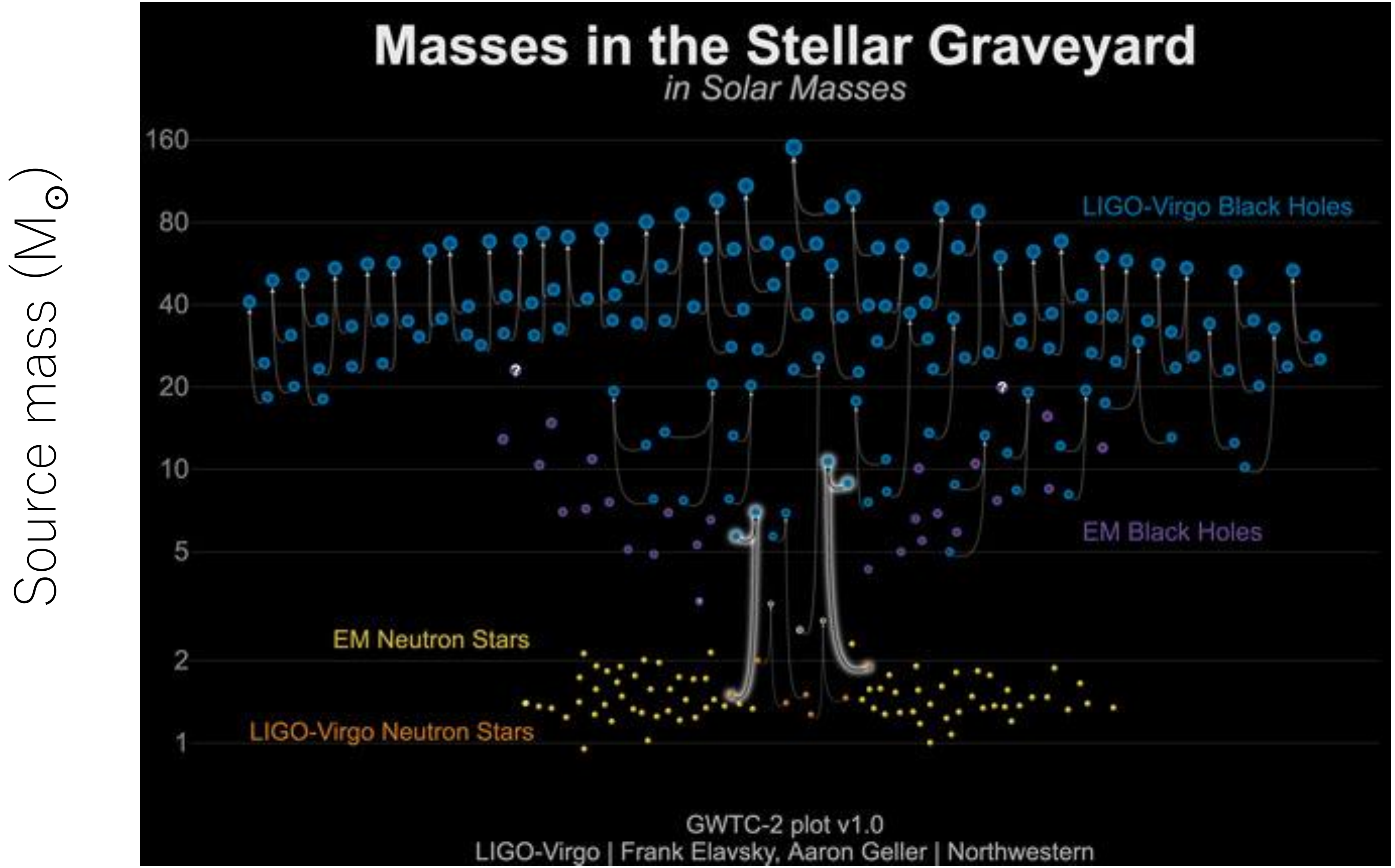
Kenta Kiuchi (CRA/YITP)

Max-Planck-Institut
für Gravitationsphysik
(Albert-Einstein-Institut)

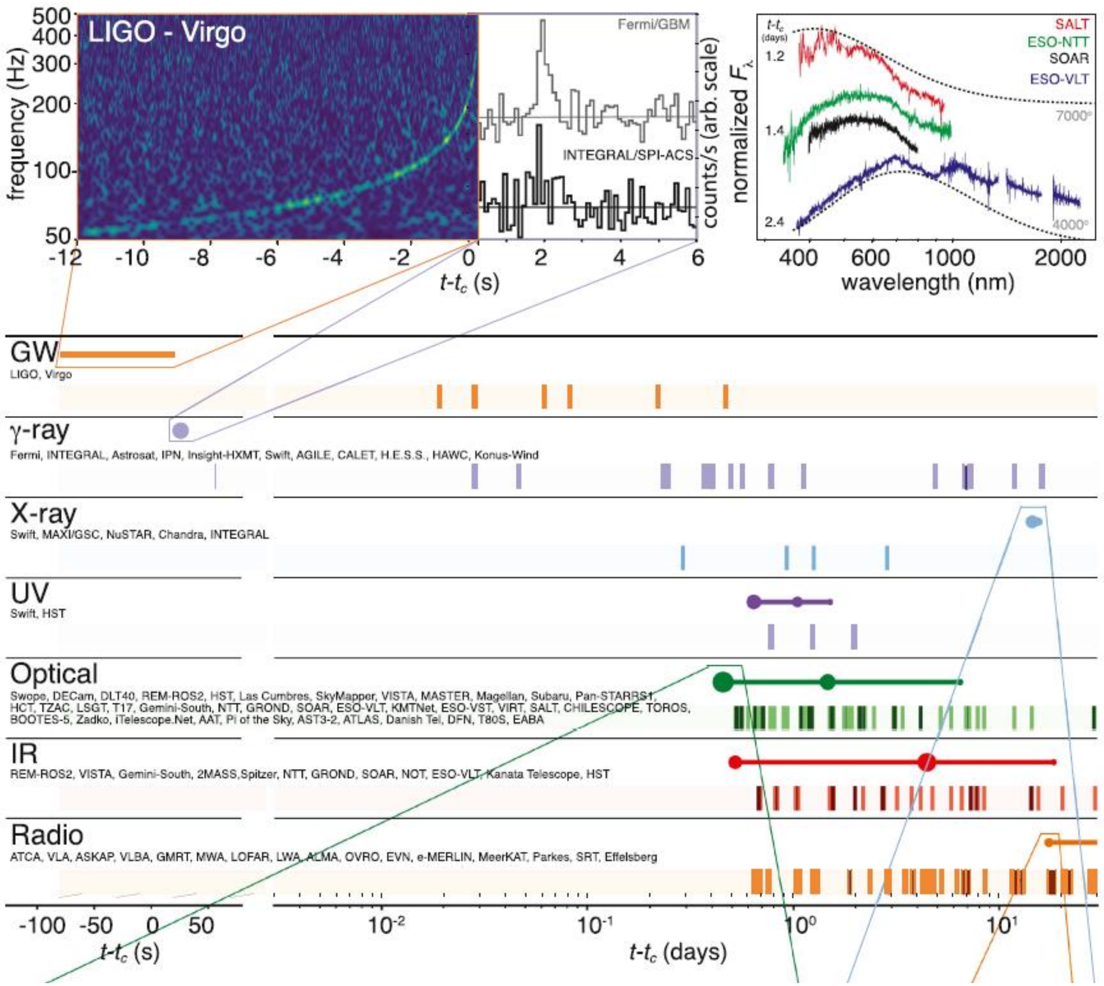
Kiuchi et al. 2211.07637

YITP
YUKAWA INSTITUTE FOR
THEORETICAL PHYSICS

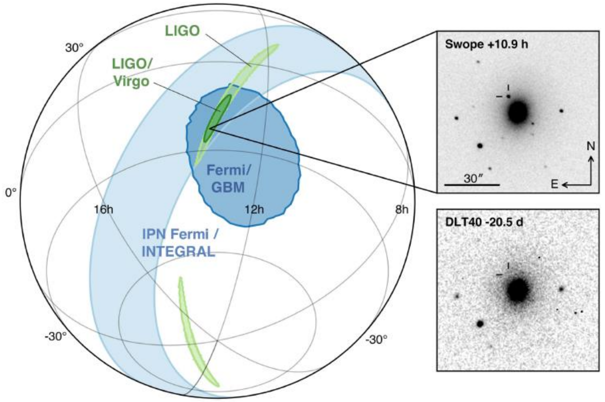
Introduction
Dawn of the gravitational wave astrophysics

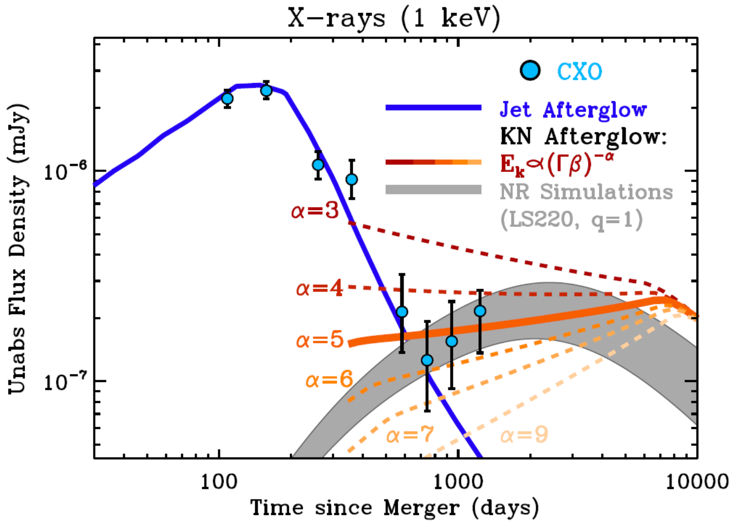


Introduction
Importance of electromagnetic counterpart



LSC-Virgo collaboration 17





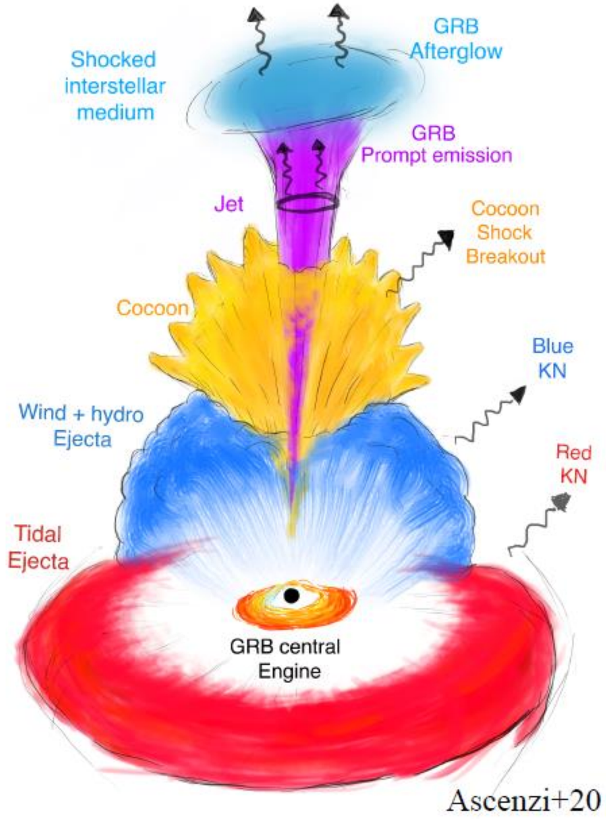
Hajela et al. 21

Ishizaki et al., 21

- GW170817 ⇒ γ-ray (1.7s) ⇒ UV, Optical, IR (0.5day) ⇒ X-ray (9day→1600day) ⇒ Radio (16day→700day)

Introduction

Solved and unsolved problems



Ascenzi+20

▶ Neutron rich matter are likely to be ejected (kilonova/macronova associated with the r-process nucleosynthesis) (Metzger et al. 10, Li & Paczynski 98, Kulkarni 05)

▶ No consensus for the detailed mass ejection process, e.g., two or three components, the mechanism for the mass ejection (Shibata et al. 17, Kasen et al. 17, Waxman et al. 18, and many)

▶ Relativistic jet launching is a subtle issue, no consensus in NR community (Ruiz et al. 18, Fernandez et al. 19, Moesta et al. 20)

Requirement: Self-consistent NR modeling for BNS merger from inspiral to post-merger with O(1) s

Introduction

Downside of the previous works

▶ Short-term simulation of O(0.1)s at most (Radice et al. 18, Zappa et al. 18, Foucart et al. 22, and many)

▶ Non-self-consistent model of the merger remnants, e.g., BH+torus (Fernandez et al. 19, Siegel & Metzger 18, and many)

▶ Phenomenological prescription to model the MRI-driven turbulent viscosity (Fujibayashi et al. 20a,b, 22, Radice et al. 18)

We are tackling the problem using Japanese supercomputer Fugaku (400PFLOPS, Top 2).

Methodology

Ab initio Numerical Relativity simulation

▶ Einstein's solver (Shibata & Nakamura 95, Baumgarte & Shapiro 98, Barker et al, 06, Campanelli et al. 06, Hilditch et al. 13)

▶ Nuclear theory-based equation of state for the NS matter (SFHo) (Steiner et al. 13)

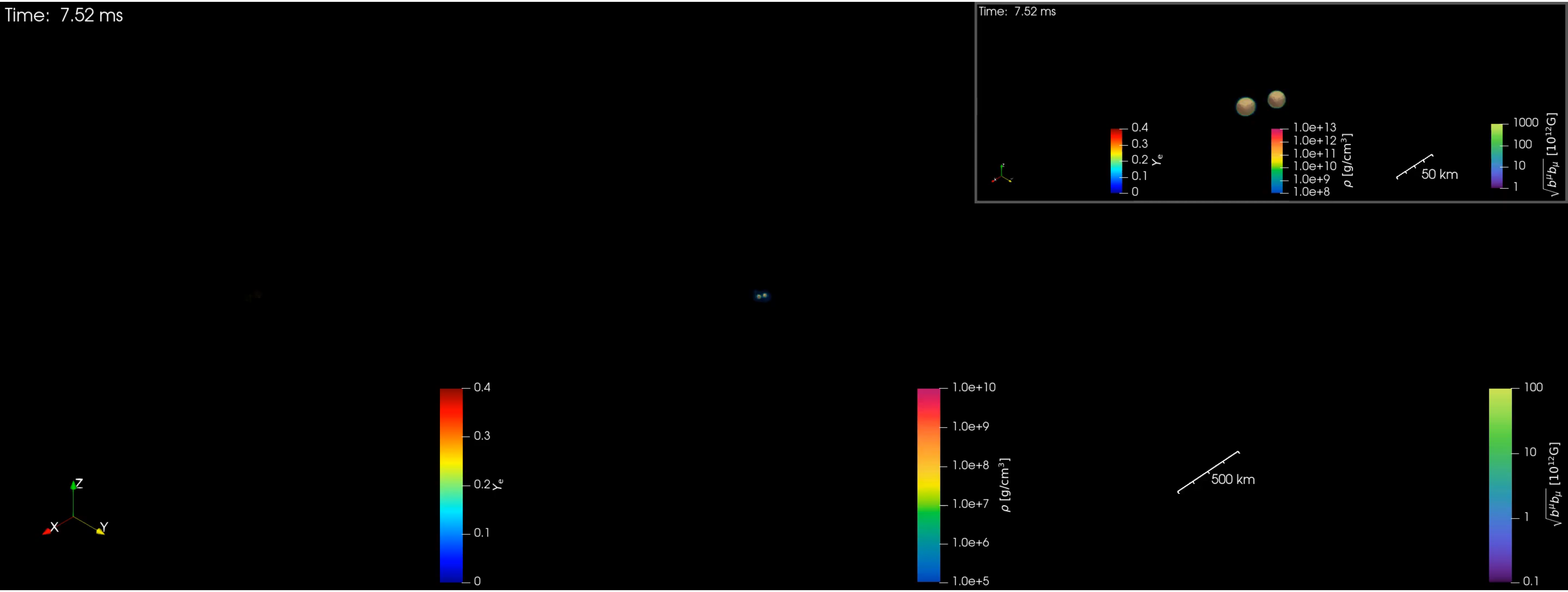
▶ Relativistic magnetohydrodynamics solver (KK et al. 22, Migone et al. 09, Gardiner & Stone 08)

▶ Neutrino-radiation transfer solver (Sekiguchi et al. 12)

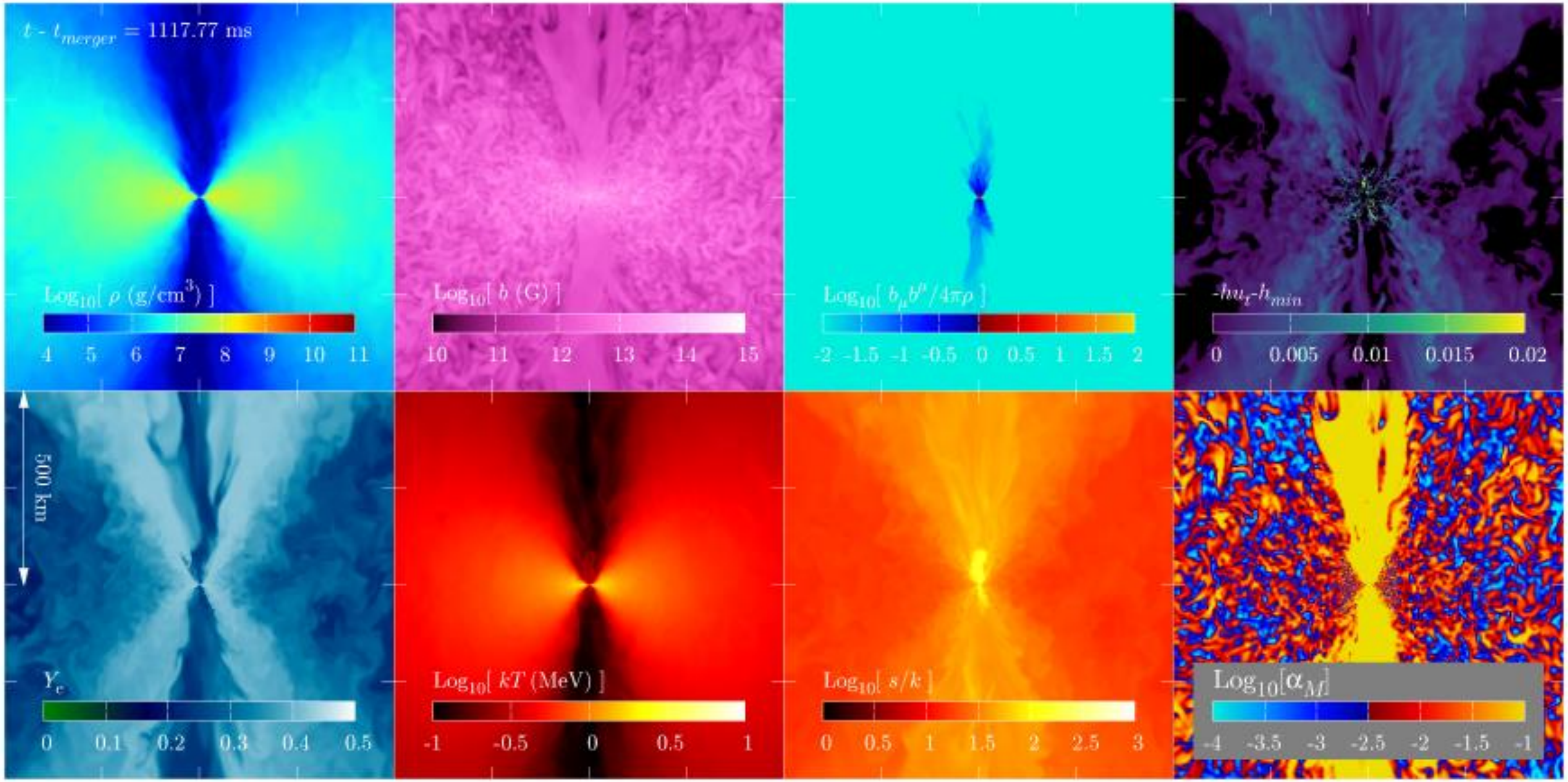
+ for more technical issues e.g., conservative mesh-refinement, see KK et al. 22

We performed a BNS simulation for 1.1s on Fugaku.

SFHo-1.2$M_\odot$-1.5$M_\odot$

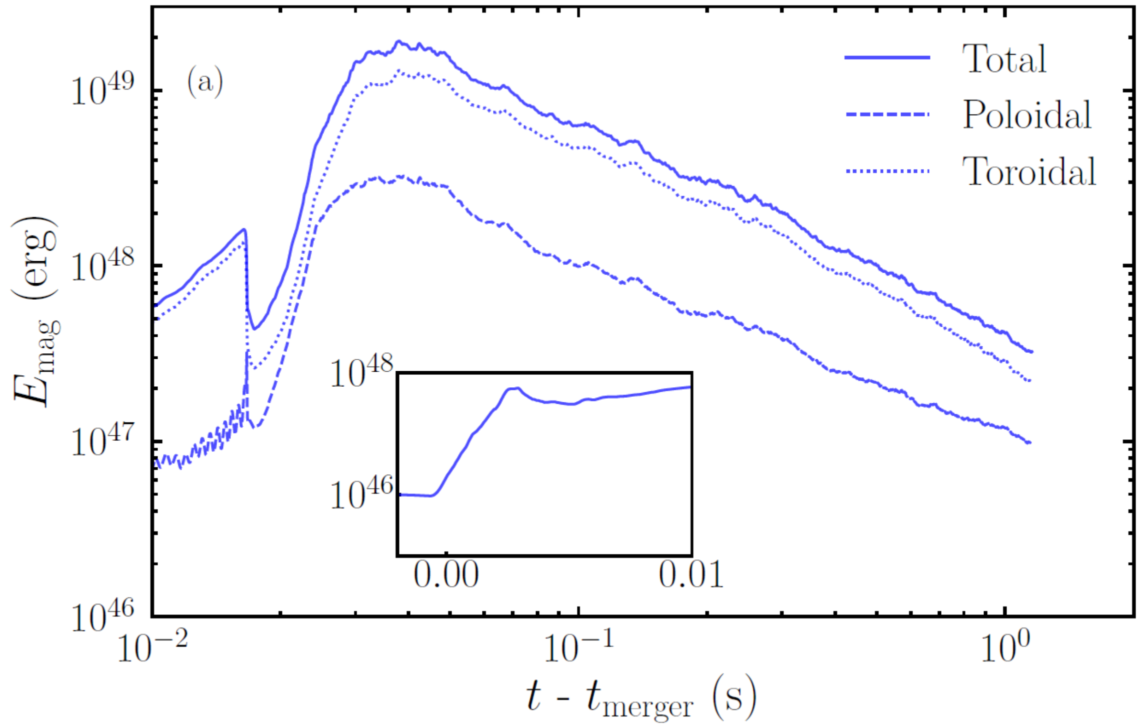


Final snapshot with a meridional cut



B-field amplification and MRI sets in

B-field energy

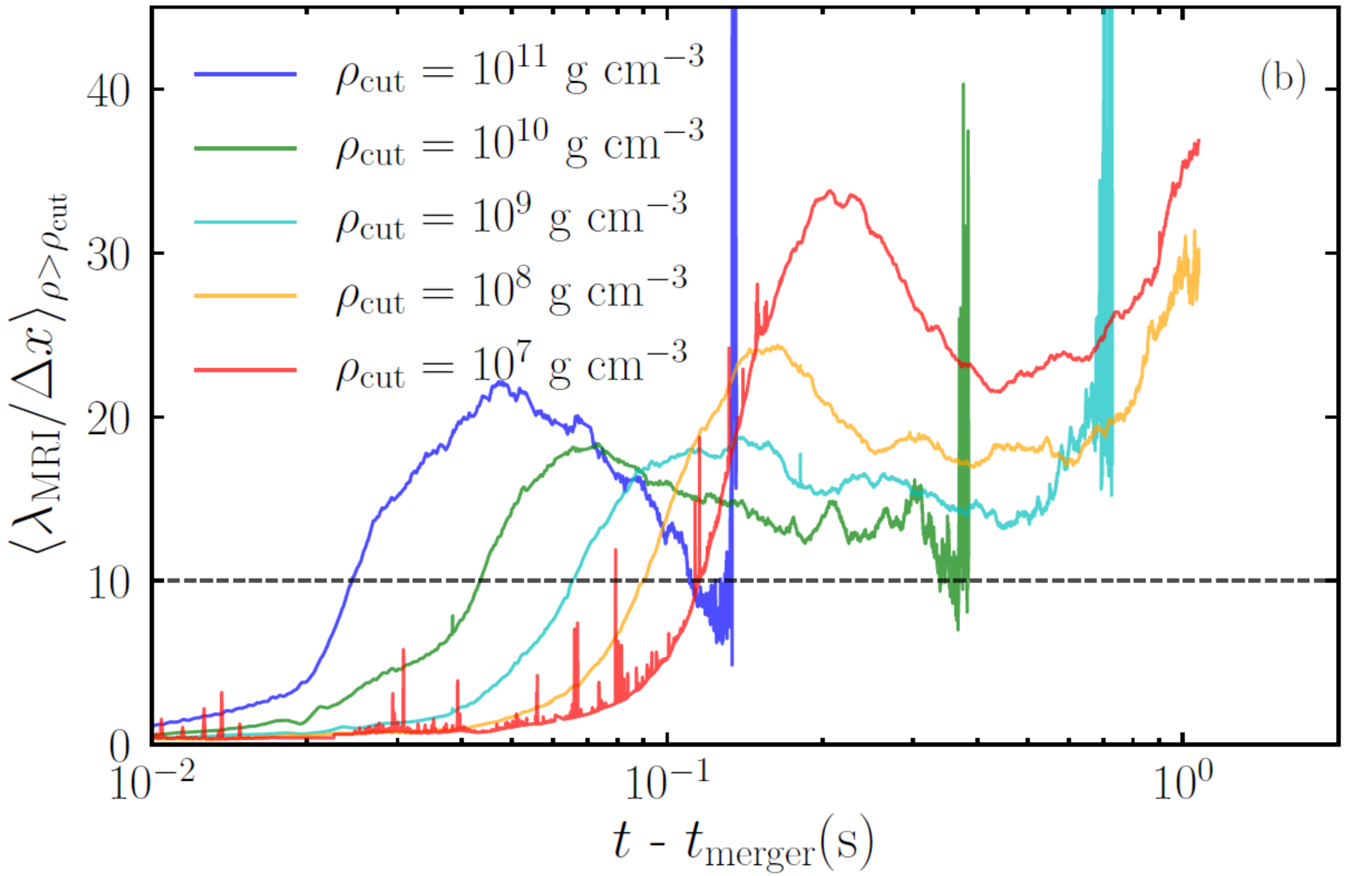


▶ B-field is amplified by the Kelvin-Helmholts instability, winding, non-axisymmetric MRI in a hypermassive neutron star phase (KK et al. 14,15, 18)

▶ Winding and axisymmetric MRI after the BH formation

B-field amplification and MRI sets in

MRI quality factor with the cut-off density

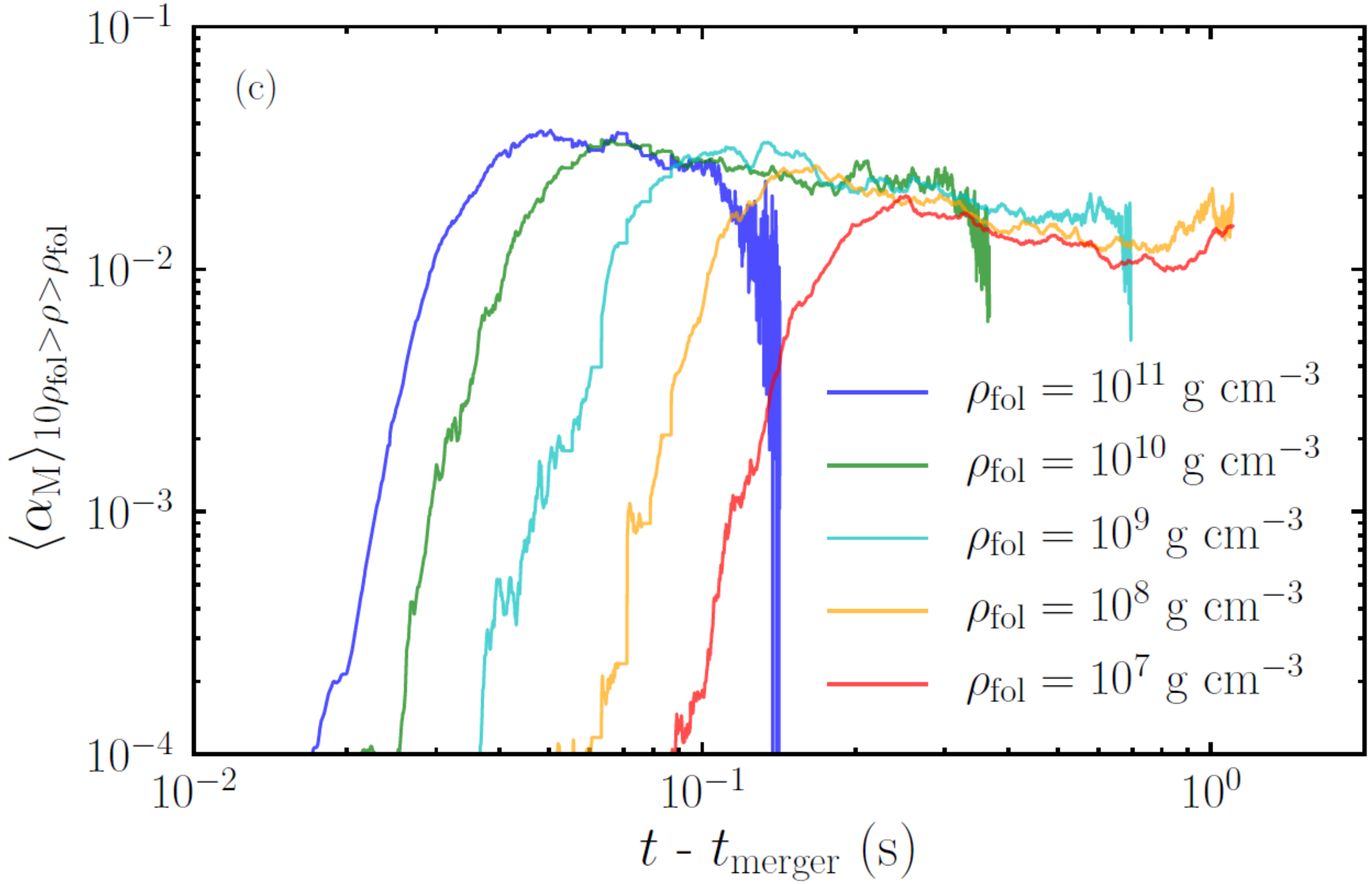


$$\left\langle \frac{\lambda_{\rm MRI}}{\Delta x} \right\rangle_{\rho_{\rm cut}} \equiv \frac{\int_{\rho \geq \rho_{\rm cut}} \lambda_{\rm MRI} d^3x}{\Delta x \int_{\rho \geq \rho_{\rm cut}} d^3x}$$

- ▶ MRI is completely resolved in a bulk region of the torus after 0.1s.
- ▶ MRI-driven turbulent state is established.

MRI-driven turbulent viscosity

Shakura-Sunyaev parameter

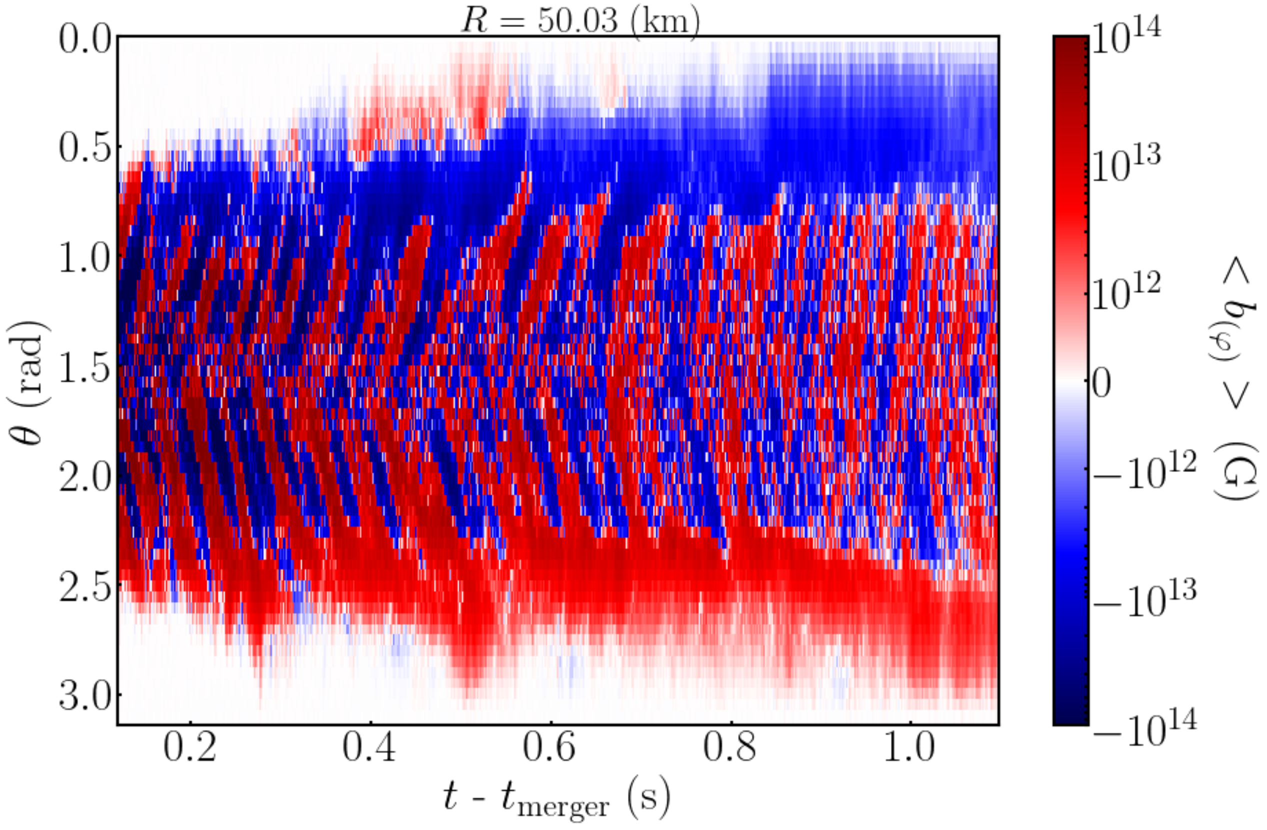


$$\langle \alpha_{\rm M} \rangle_{10\rho_{\rm fol} \geq \rho \geq \rho_{\rm fol}} \equiv \frac{\int_{10\rho_{\rm fol} \geq \rho \geq \rho_{\rm fol}} \alpha_{\rm M} d^3x}{\int_{10\rho_{\rm fol} \geq \rho \geq \rho_{\rm fol}} d^3x}.$$

▶ MRI-turbulent viscosity is produced and it is 0.01-0.03.

MRI dynamo to sustain the MRI-driven turbulence

Butterfly Diagram for the toroidal B-field (R=50km)

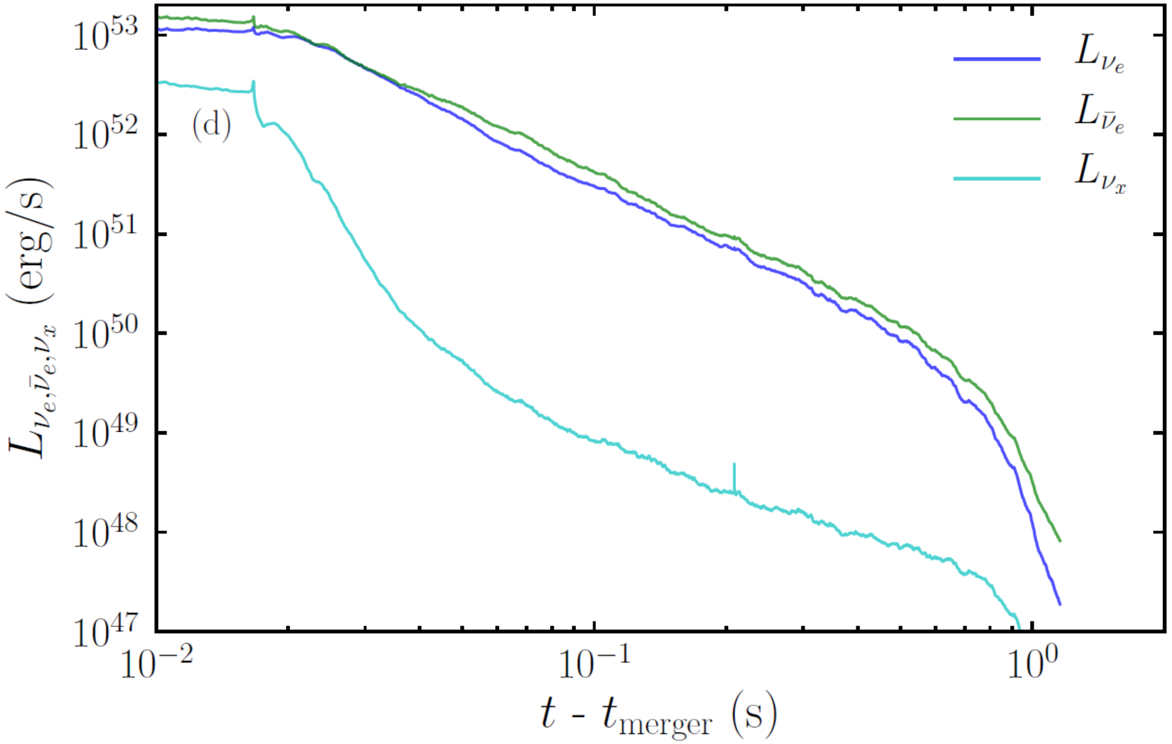


▶ It clearly suggests the sign flip pattern which lasts until end of the simulation ⇒ MRI dynamo sustains the turbulent state.

Neutrino luminosity evolution

▶ MRI-driven turbulent viscosity facilitates the angular momentum transport ⇒ The torus expands and the temperature drops.

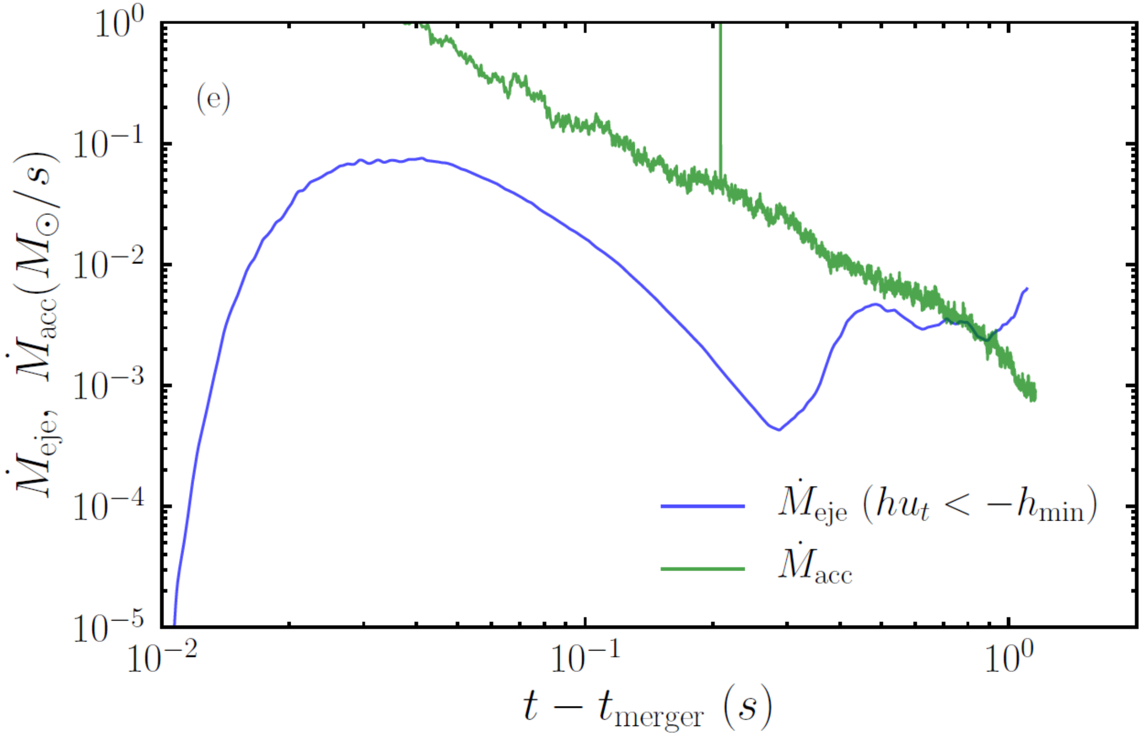
Neutrino luminosity



▶ Neutrino luminosity decreases, and it becomes steep around ≈ 0.7s.
⇒ All the turbulent viscous heating is consumed by the torus expansion.

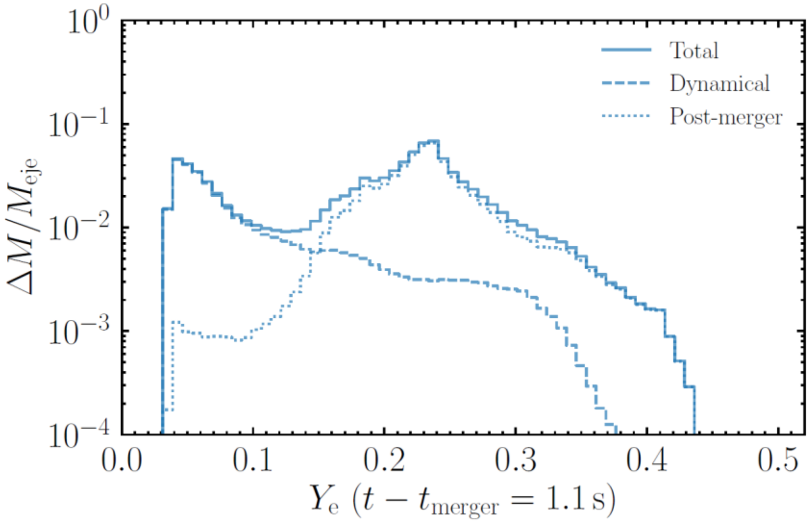
Mass ejection (Dynamical and Post-merger)

Mass ejection rate measured on R=3,000km

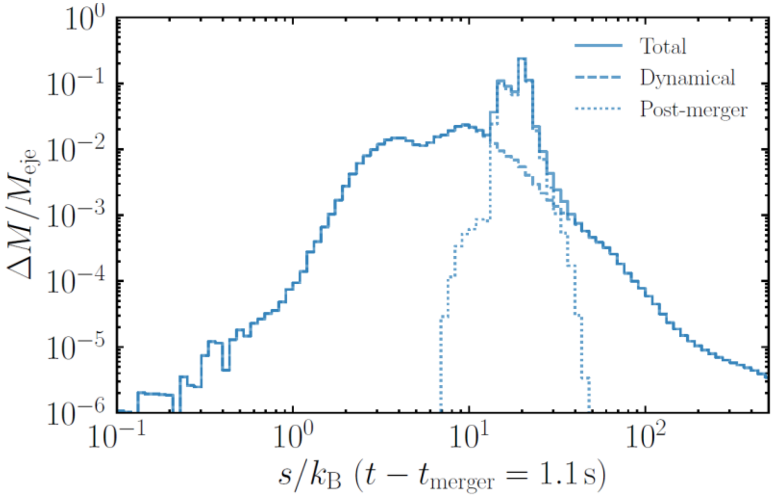


- ▶ Dynamical ejecta starts to appear at ≈0.01s and peaks around ≈ 0.03-0.04s (Fast tail and mildly relativistic ejecta).
- ▶ Post-merger ejecta due to the MRI-driven turbulence emerges at ≈ 0.3s.
- ▶ The ejection rate exceeds the accretion rate at ≈ 1.1s.

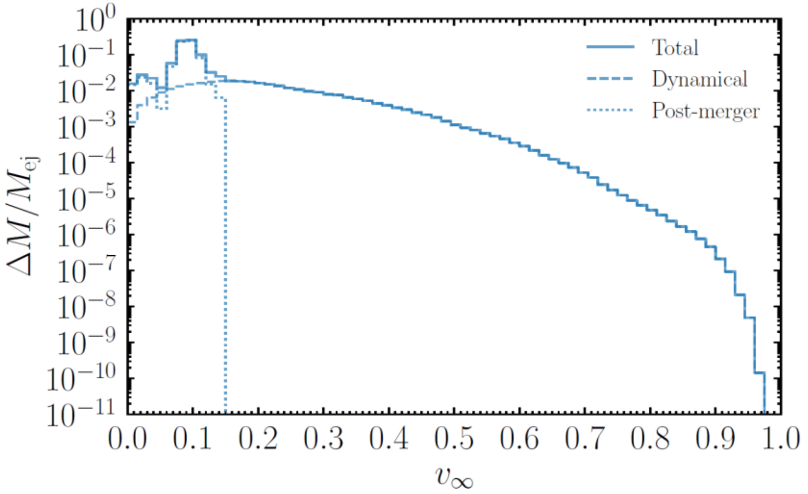
Ejecta properties



Electron fraction



Entropy per baryon

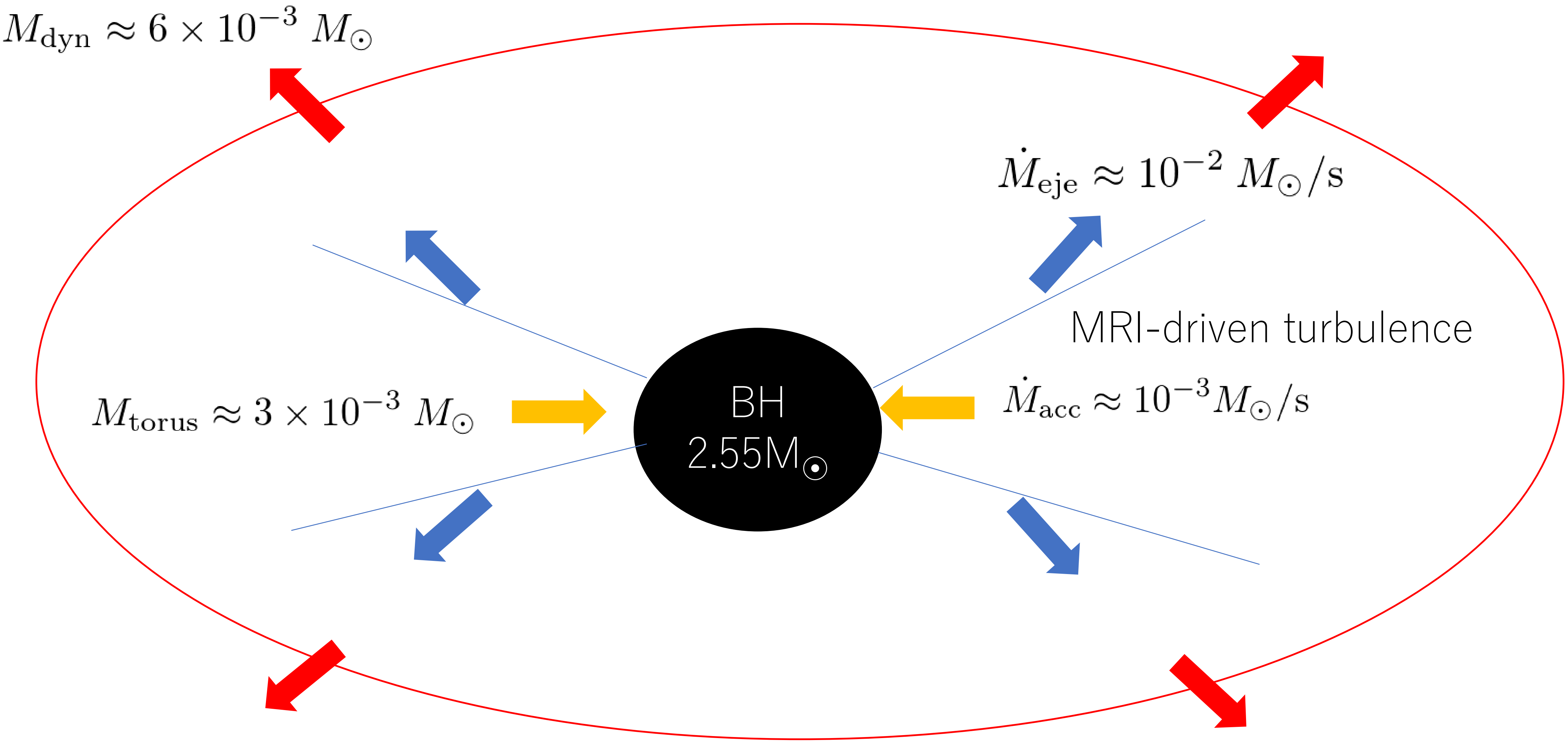


Terminal velocity

▶ Electron fraction distribution has two distinct peaks at ≈ 0.03 (dynamical) and ≈ 0.24 (post-merger). The latter is determined when the weak interaction freezes out.

▶ The low-Ye component corresponds to the $s/k_B \approx 3$ (tidal) and 10 (shocked) components. The high-Ye corresponds to the $s/k_B \approx 20$ with $v_\infty/c \approx 0.1$ (post-merger).

Self-consistent picture of the mass ejection from a BNS merger



$M_{\rm dyn} \approx 6 \times 10^{-3}\ M_\odot$

$\dot{M}_{\rm eje} \approx 10^{-2}\ M_\odot/{\rm s}$

MRI-driven turbulence

$M_{\rm torus} \approx 3 \times 10^{-3}\ M_\odot$

BH
2.55M$_\odot$

$\dot{M}_{\rm acc} \approx 10^{-3} M_\odot/{\rm s}$

Conclusion

▶ NR-RMHD simulation of a BNS merger for 1.1s. ⇒ Dynamical ejecta composed of the fast tail and mildly relativistic components and post-merger ejecta due to the MRI-driven turbulence naturally emerge in a single simulation.

Caveat

The launch of the Poynting-flux dominated outflow is not observed until the end of the simulation. Ram pressure due to the fall back material? Shortness of the simulation? (Spurious) BH spin down?

⇒ More accurate and long-term simulations are necessary.

The long-lived remnant case is more challenging to accurately simulate the KHI and MRI because of the requirement of the super-high resolution.

Long-lived remnant case (KK et al. in prep)