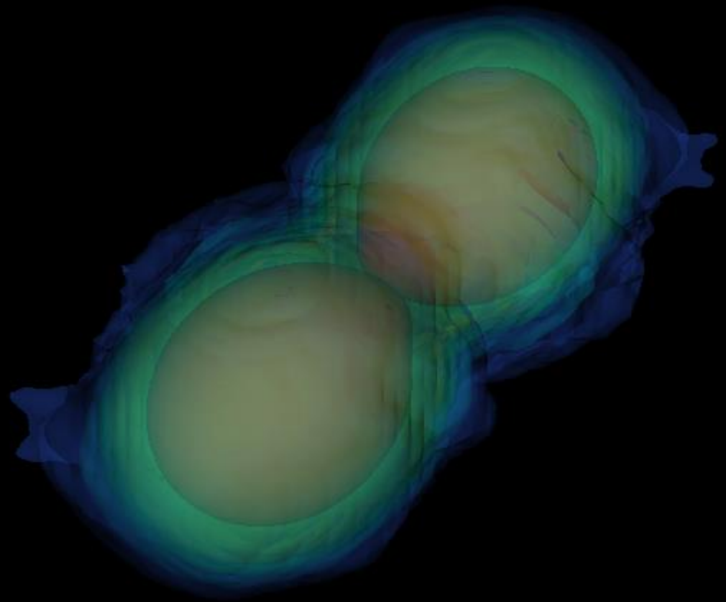
Introduction to GRMHD



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See also my recent review
arxiv:2405.10081

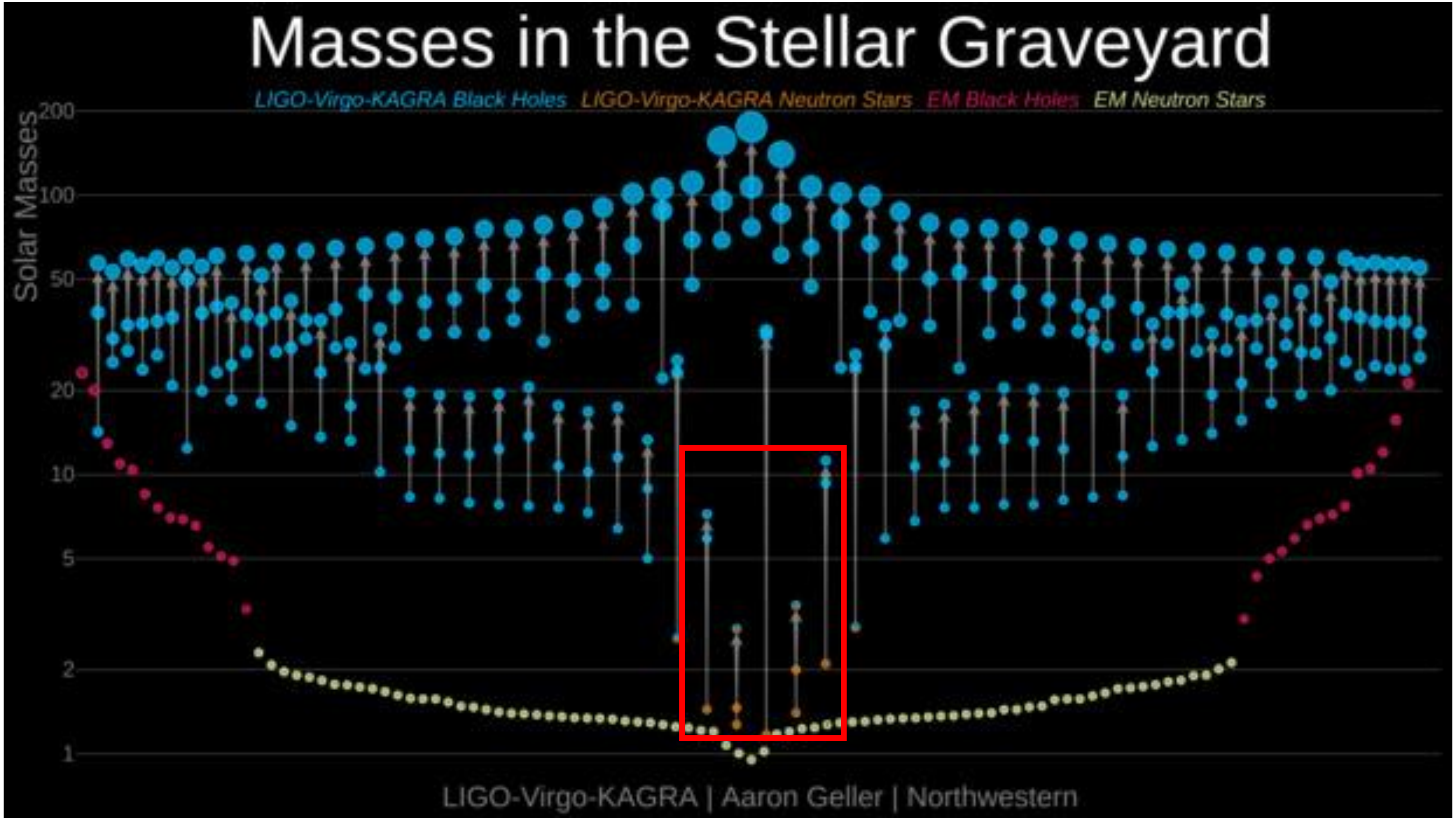
Kenta Kiuchi (CRA)

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

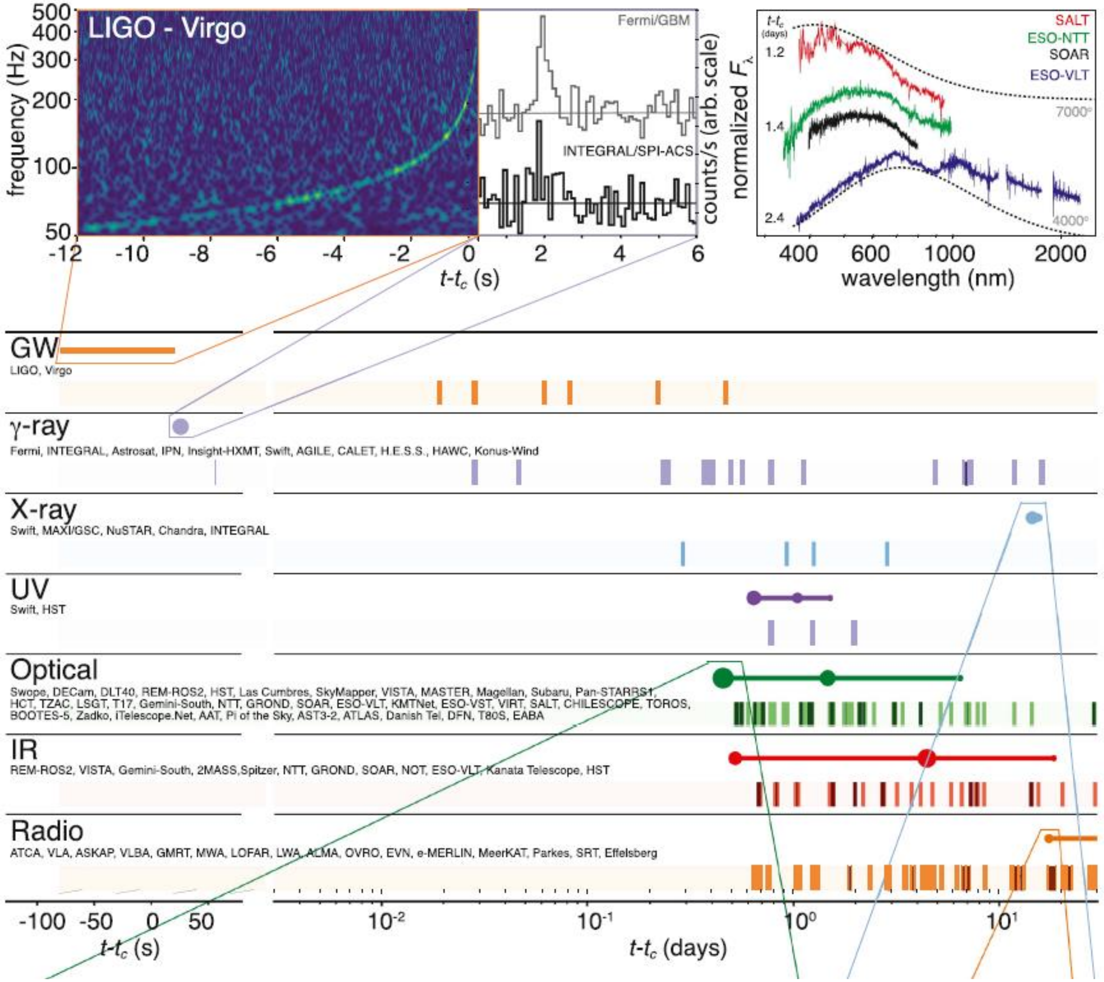
CGPQI
Center for Gravitational Physics and Quantum Information
Yukawa Institute for Theoretical Physics, Kyoto University

Introduction
Dawn of the gravitational wave astrophysics

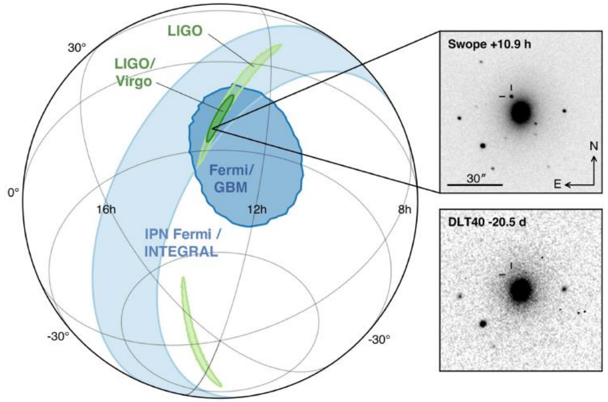
Source mass ($M_\odot$)

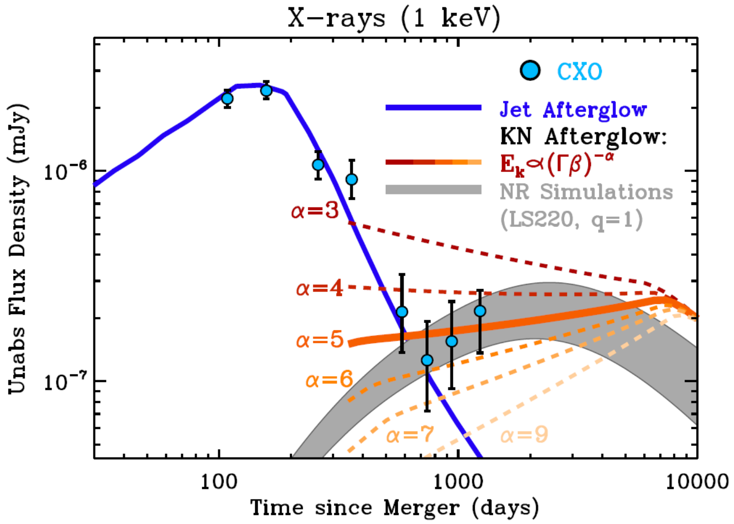


Introduction
Importance of electromagnetic counterpart



LSC-Virgo collaboration 17





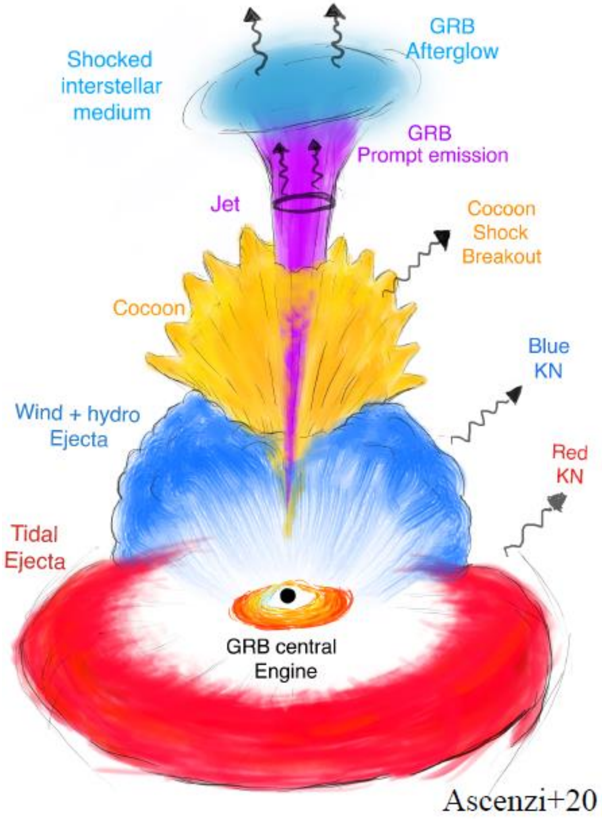
Hajela et al. 21

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 in GW170817



▶ Neutron rich matter are likely to be ejected
(kilonova/macronova associated with the r-process nucleosynthesis)

▶ Riddle on the detailed mass ejection process
Origin of blue and red components?

▶ Riddle on relativistic jet launching mechanism
Driven by BH or massive neutron star?

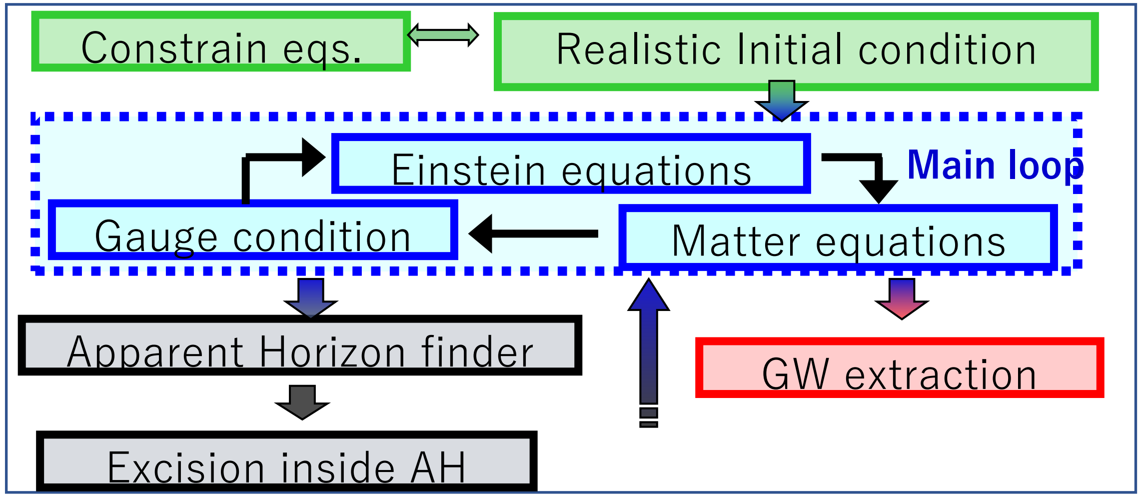
Self-consistent NR modeling for BNS merger from inspiral to post-merger

Introduction

Toward physical modeling of GW sources

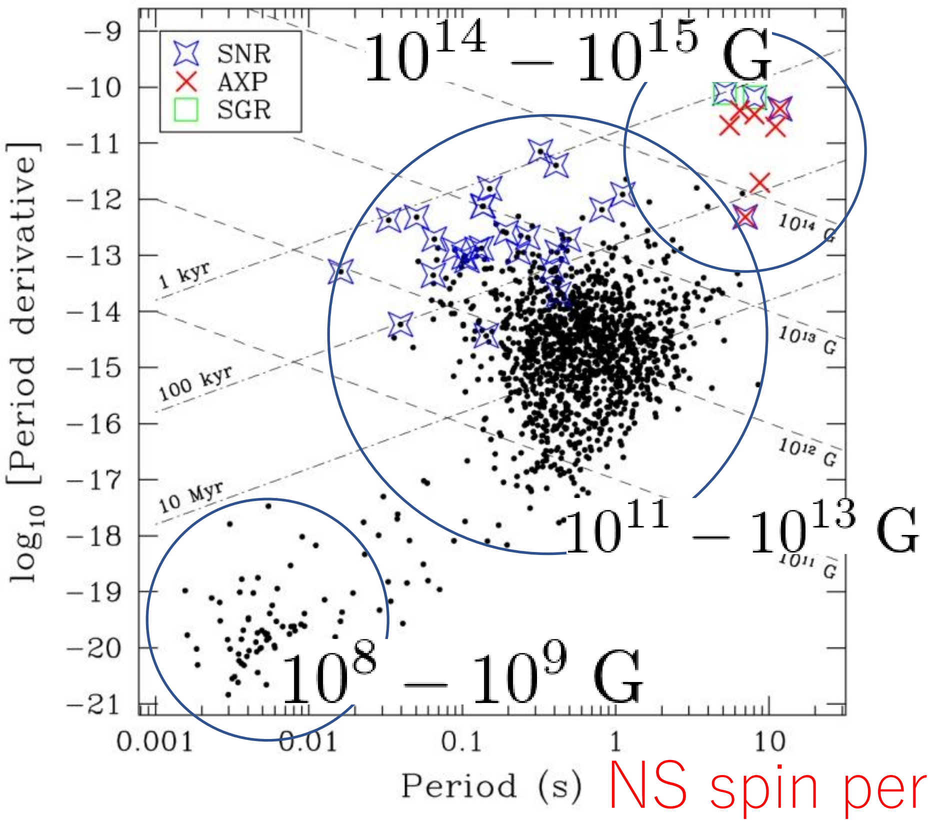
- Gravity (General Relativity)
- Strong interaction (Nuclear matter)
- Weak interaction (Neutrino)
- Electromagnetic interaction (Magnetic field)
- Highly dynamical system (GW!)
- Primarily no spatial symmetry (fully 3D+1 problem)

Slide courtesy of Y. Sekiguchi



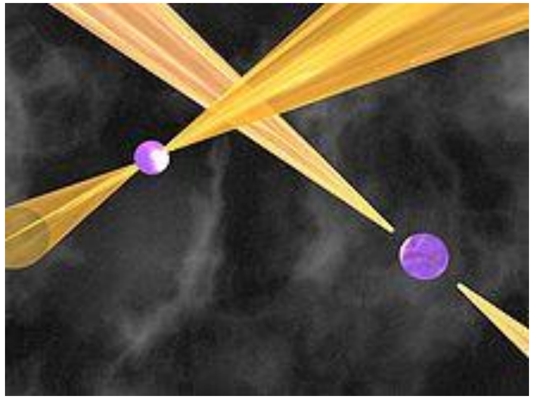
To B or not to B in binary neutron star merger (by Victoria M. Kaspi)

$P - \dot{P}$ Diagram



NS spin period

Image of the binary pulsar



▶ Assumption : Rotational energy is dissipated by the magnetic dipole radiation $\Rightarrow$ $B \propto (P\dot{P})^{1/2}$

To B or not to B in binary neutron star merger (by Victoria M. Kaspi)

▶ B-field in observed binary NSs : $10^{9.7} – 10^{12.2}$ G

Kinetic energy before the merger ~ 10^{53} g cm^2 s^{-2} $(M/2.7M_{sun})(v/0.3c)^2$

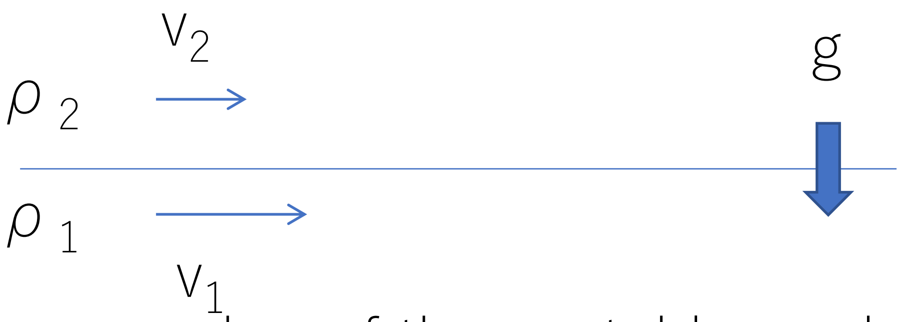
B-field energy ~10^{41} g cm^2 s^{-2} $(B/10^{12}G)^2(R/10^6cm)^3$

B-field is irrelevant in BNS mergers ?

No ! ⇒ Several amplification mechanisms (Magneto Hydro Dynamical instabilities) could amplify the B-filed up to the dynamically important level

A couple of key ingredients I. Kelvin-Helmholtz Instability

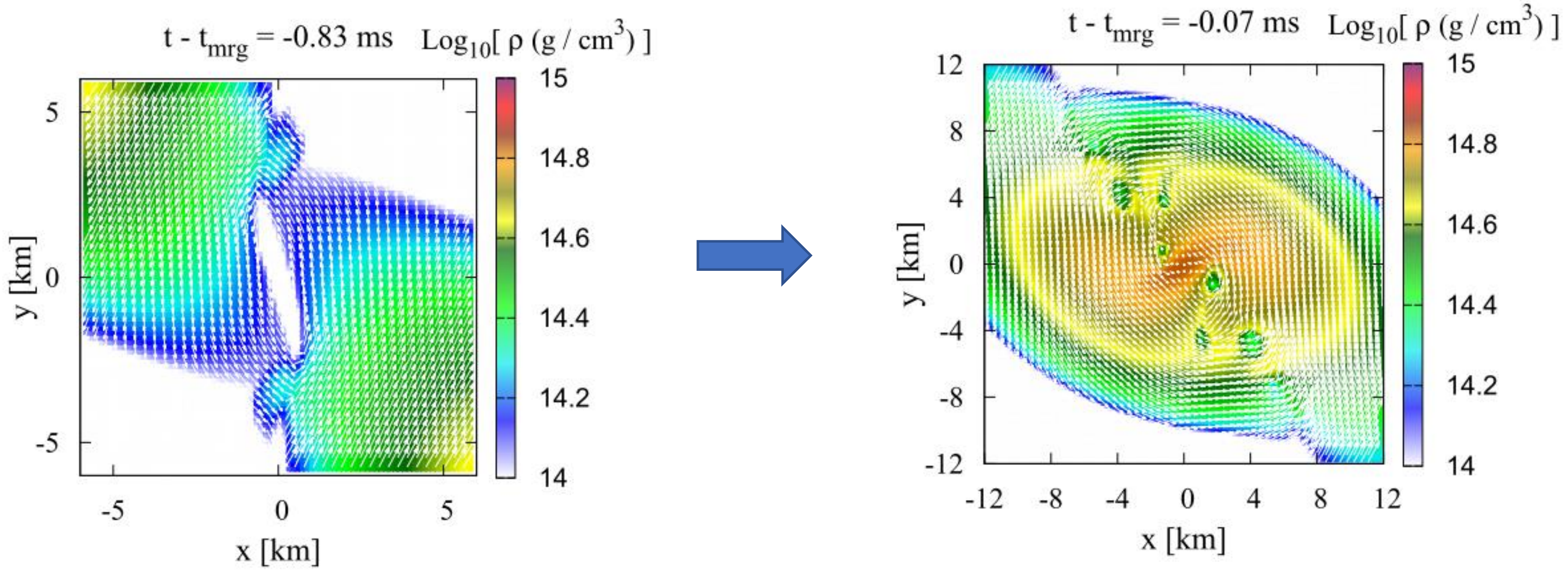
Kelvin Helmholtz instability (Rasio and Shapiro 99, Price & Rosswog 05)



Minimum wave number of the unstable mode ;

$k_{min} \propto g(\rho_1 - \rho_2)/(v_1 - v_2)^2$

⇒ If g = 0, all the mode are unstable. $\sigma \propto k$ ⇒ Spatial grid resolution is key



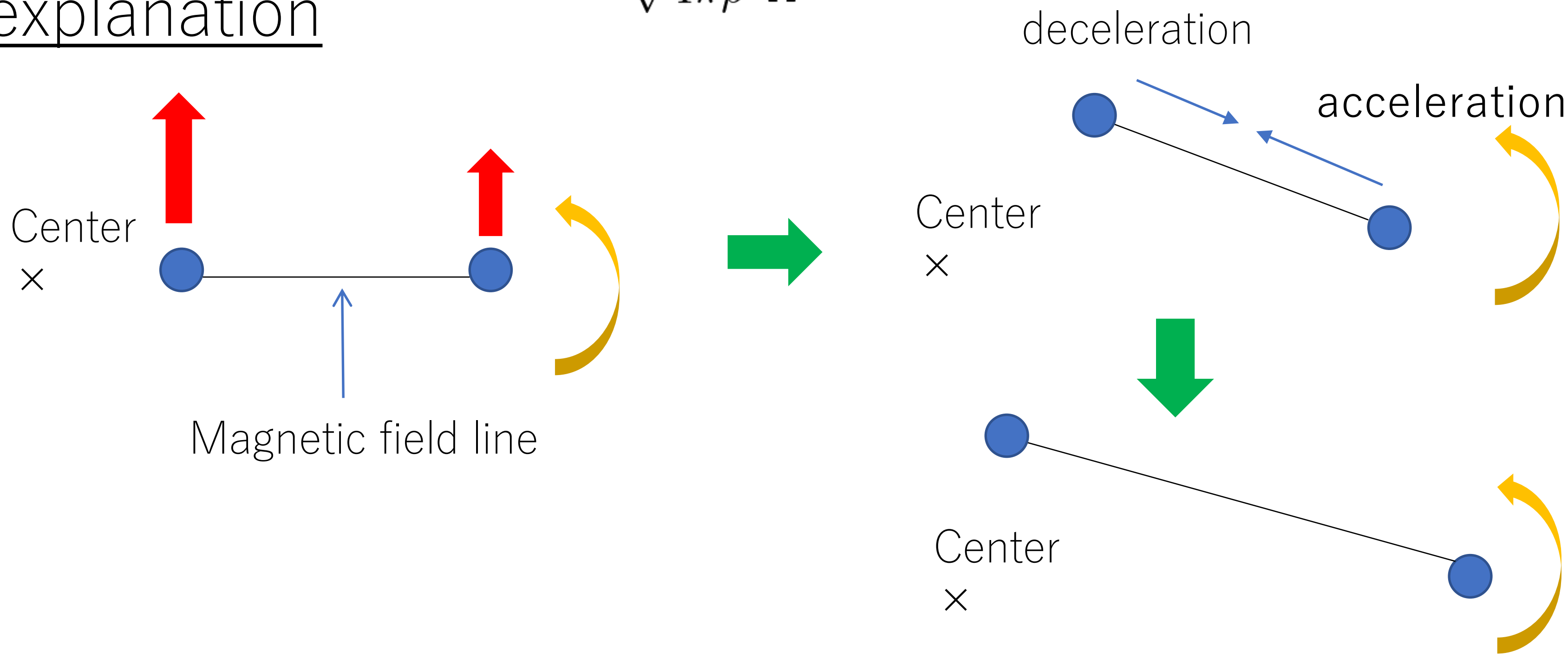
A couple of key ingredients II. Magneto Rotational Instability

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

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

$$\lambda_{\rm MRI} = \frac{B}{\sqrt{4\pi\rho}}\frac{2\pi}{\Omega} \approx 80\ {\rm m}(B_P/10^{15}{\rm G})(\rho/10^{15}{\rm g/cm^3})^{-1/2}(\Omega/8000{\rm rad/s})^{-1}$$

Intuitive explanation



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

A couple of key ingredients III. A large-scale dynamo mechanism

Mean field dynamo theory

$$\mathbf{Q} = \bar{\mathbf{Q}} + \mathbf{q},\ \bar{\mathbf{Q}} = \text{Axisym. Ave.}$$

$$\partial_t \bar{\mathbf{B}} = \nabla \times (\bar{\mathbf{U}} \times \bar{\mathbf{B}} + \bar{\mathcal{E}}),$$

$$\bar{\mathcal{E}} = \overline{\mathbf{u} \times \mathbf{b}}$$

u & b : turbulence of the velocity and b-field.

α Ω dynamo

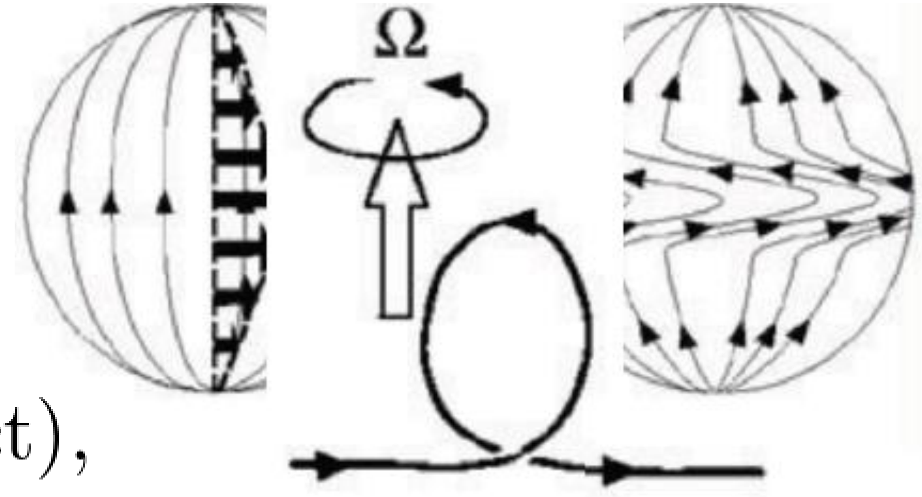
$$\mathcal{E}_i = \alpha_{ij} \bar{B}_j + \beta_{ij} (\nabla \times B)_j$$

In the current context, α_{ij} is dominant

$$\partial_t \bar{B}_\phi = R \bar{\mathbf{B}}_P \cdot \nabla_P \Omega \ (\Omega \text{ effect}),$$

$$\partial_t \bar{B}_R = -\partial_z \mathcal{E}_\phi \approx -\partial_z (\alpha_{\phi\phi} \bar{B}_\phi) \ (\alpha \text{ effect}),$$

$$\partial_t \bar{B}_z = \partial_R \mathcal{E}_\phi \approx \partial_R (\alpha_{\phi\phi} \bar{B}_\phi)$$



Relevance of the resolution study

Magnetic winding timescale from the per-merger large-scale field

$$t_A \sim R/v_A \sim 100\text{s}\ (B/10^{12}\text{G})^{-1}\ (\rho/10^{15}\text{g/cm}^3)^{1/2}\ (R/10^6\text{cm})$$

Therefore, the magnetic winding originating from the per-merger field should be irrelevant in reality.

But, many GRMMHD simulations conducted so far assumed $\sim 10^{15}$-10^{17}G as the pre-merger large-scale field

Why? A: To compensate the high computational cost to resolve the KHI/MRI
⇒ Trade off is to shorten the winding timescale originating from the pre-merger large scale field

Relevance of the resolution study

With a single resolution, it is impossible to disentangle the large-scale field generated by the non-trivial process from the pre-merger large-scale field effect

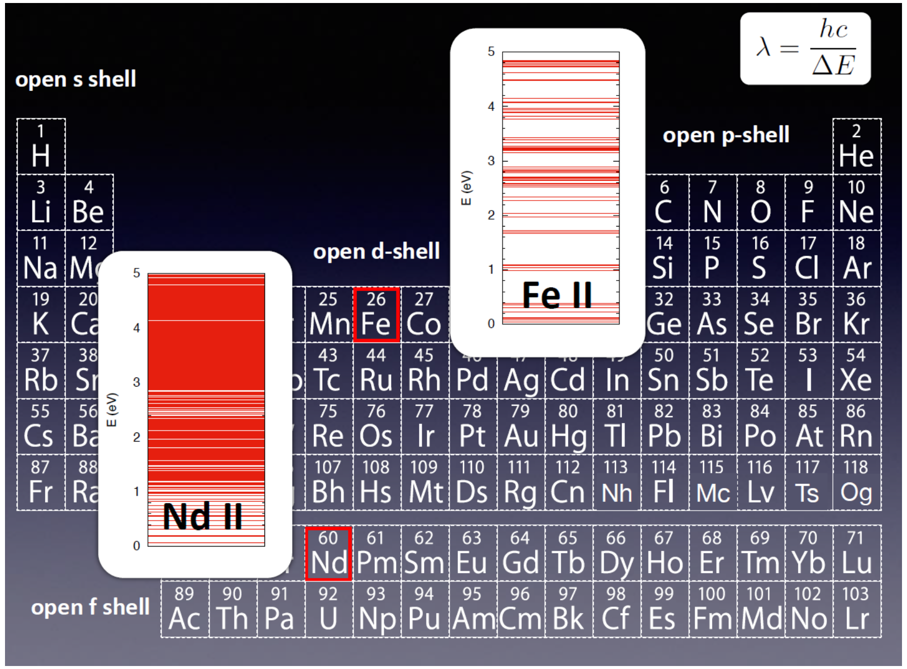
Summary for key ingredients:

(i) Kelvin-Helmholtz instability at the merger
(ii) Magneto Rotational Instability inside the merger remnant
(iii) A large-scale dynamo mechanism inside the merger remnant

Numerically resolving them is necessary condition. To do so, the direct high resolution or effective high resolution with a sub-grid model is essential.

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)

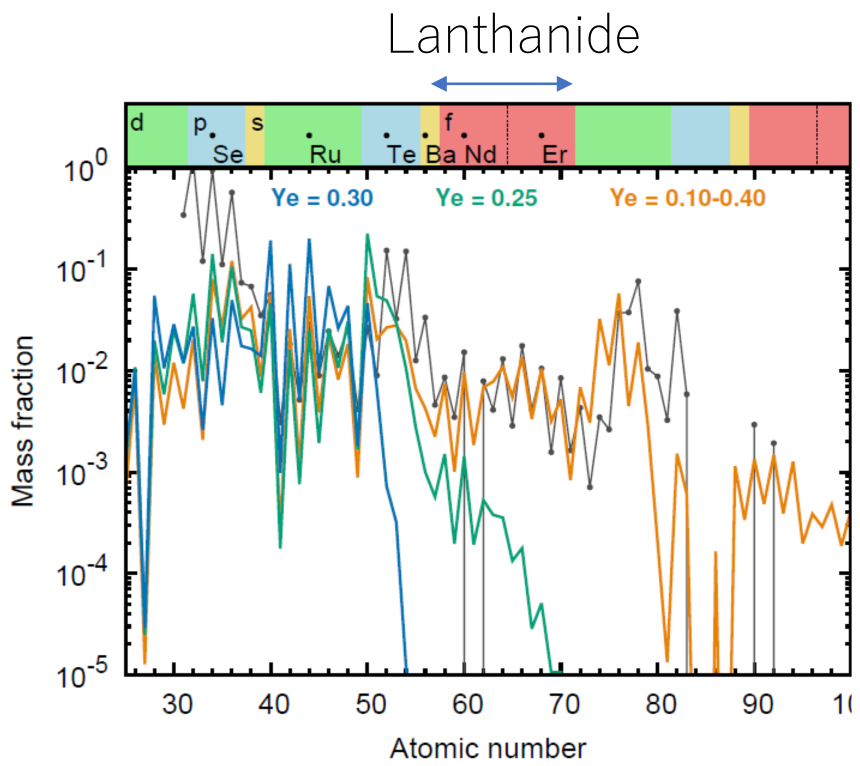
▶ Peak time (diffusion time = dynamical time)

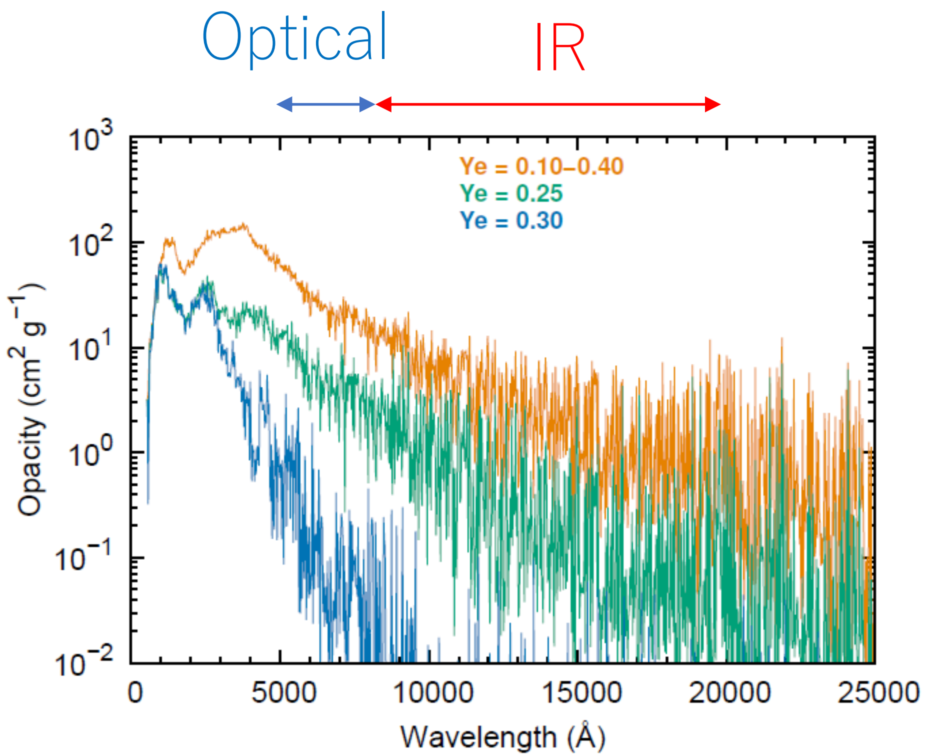
$$t_{\mathrm{peak}} \approx 5.7\,\mathrm{day} \left(\frac{\kappa}{10\,\mathrm{cm^{-2}\,g^{-1}}}\right)^{1/2} \left(\frac{M_{\mathrm{eje}}}{0.03 M_\odot}\right)^{1/2} \left(\frac{v_{\mathrm{ej}}}{0.2c}\right)^{-1/2}$$

▶ Peak Luminosity

$$L \approx \dot{\epsilon} M_{\mathrm{ej}} \approx 6\times 10^{41}\,\mathrm{erg\,s^{-1}} \left(\frac{M_{\mathrm{eje}}}{0.03 M_\odot}\right) \left(\frac{t}{\mathrm{day}}\right)^{-1.3}$$

R-process nucleosynthesis and its opacity



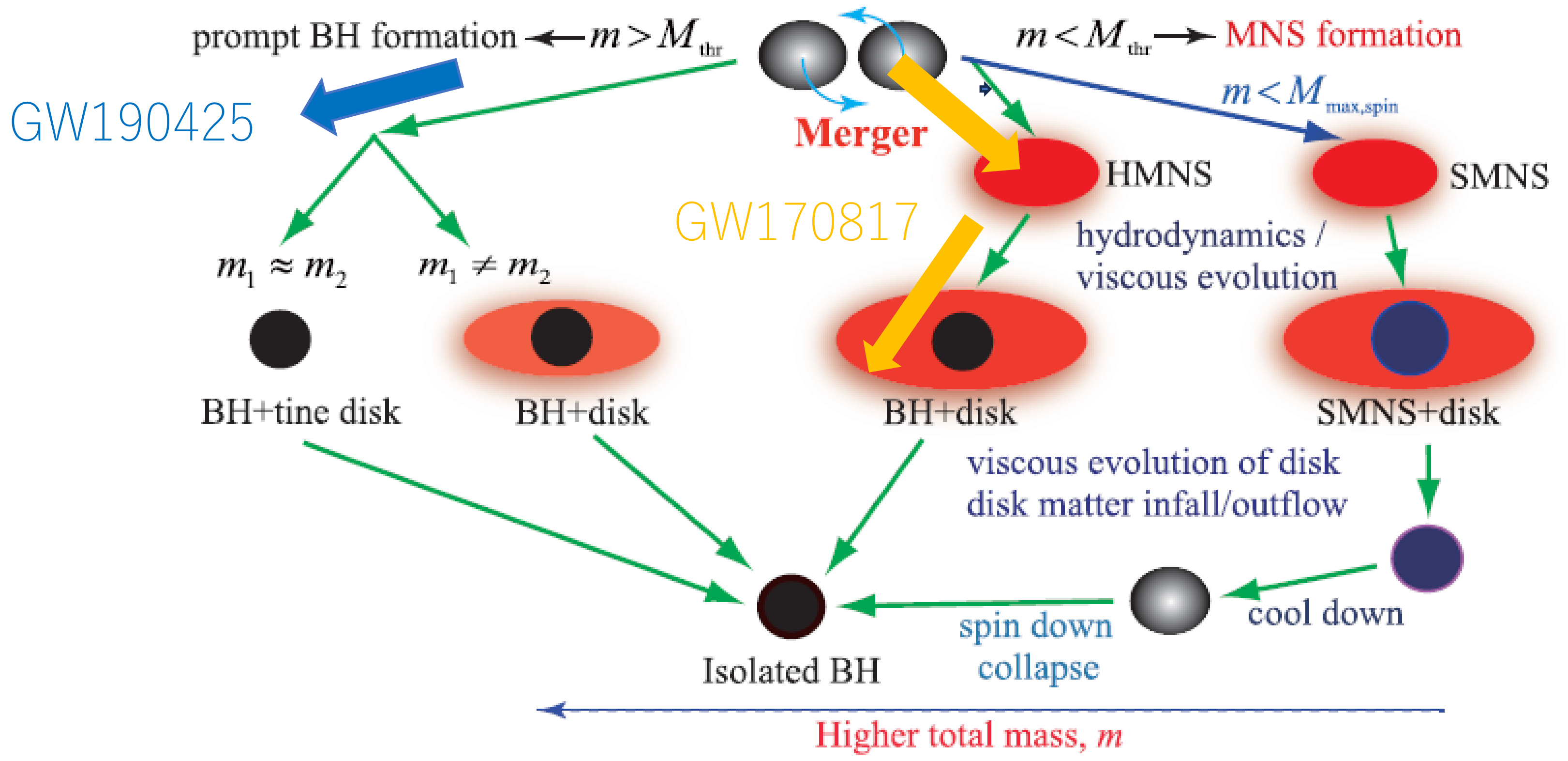


Tanaka et al. 17

- ▶ 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

Numerical modeling of BNS: Short-lived case

Shibata & Hotokezaka 19



▶ Short-lived case is inferred in GW170817, due to non-direction of strong radio flare (Shibata et al. 17, Margalit & Metzger 17, +)

Numerical modeling of BNS: Short-lived case

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, Fujibayashi et al. 20, 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).

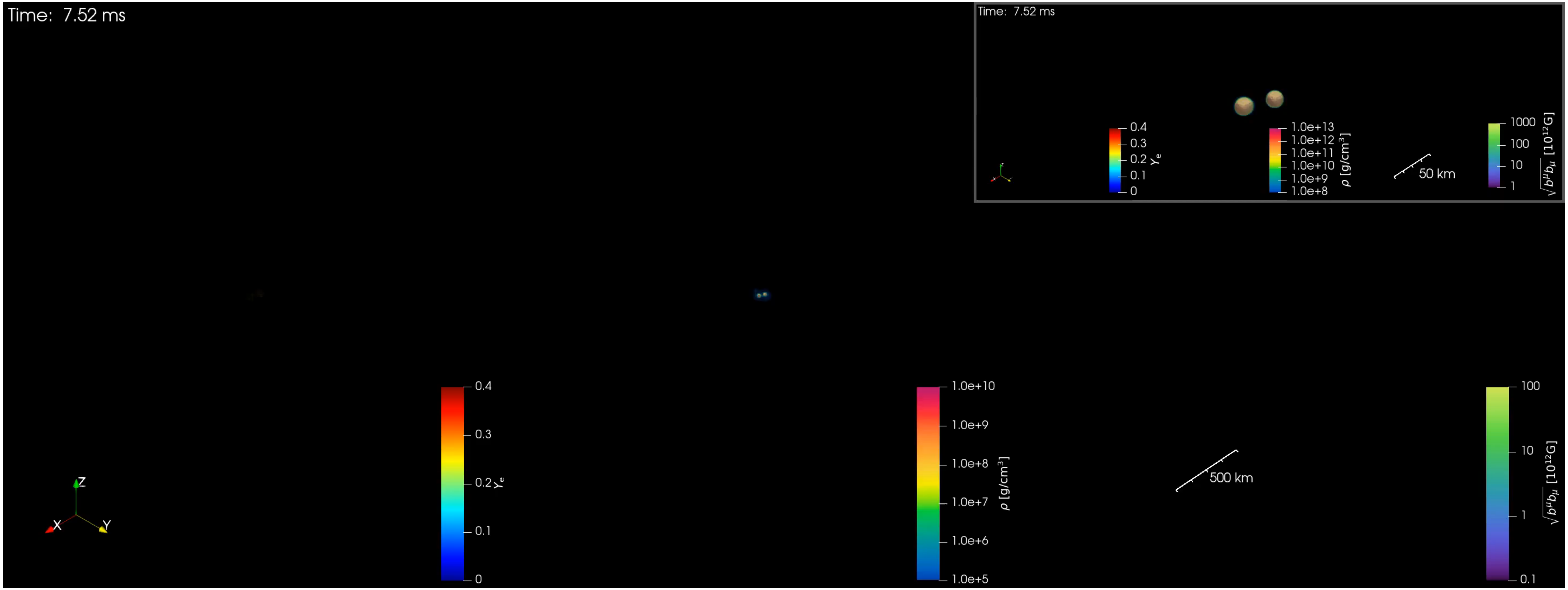
Methodology
Ab initio Numerical Relativity simulation

▶ 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)

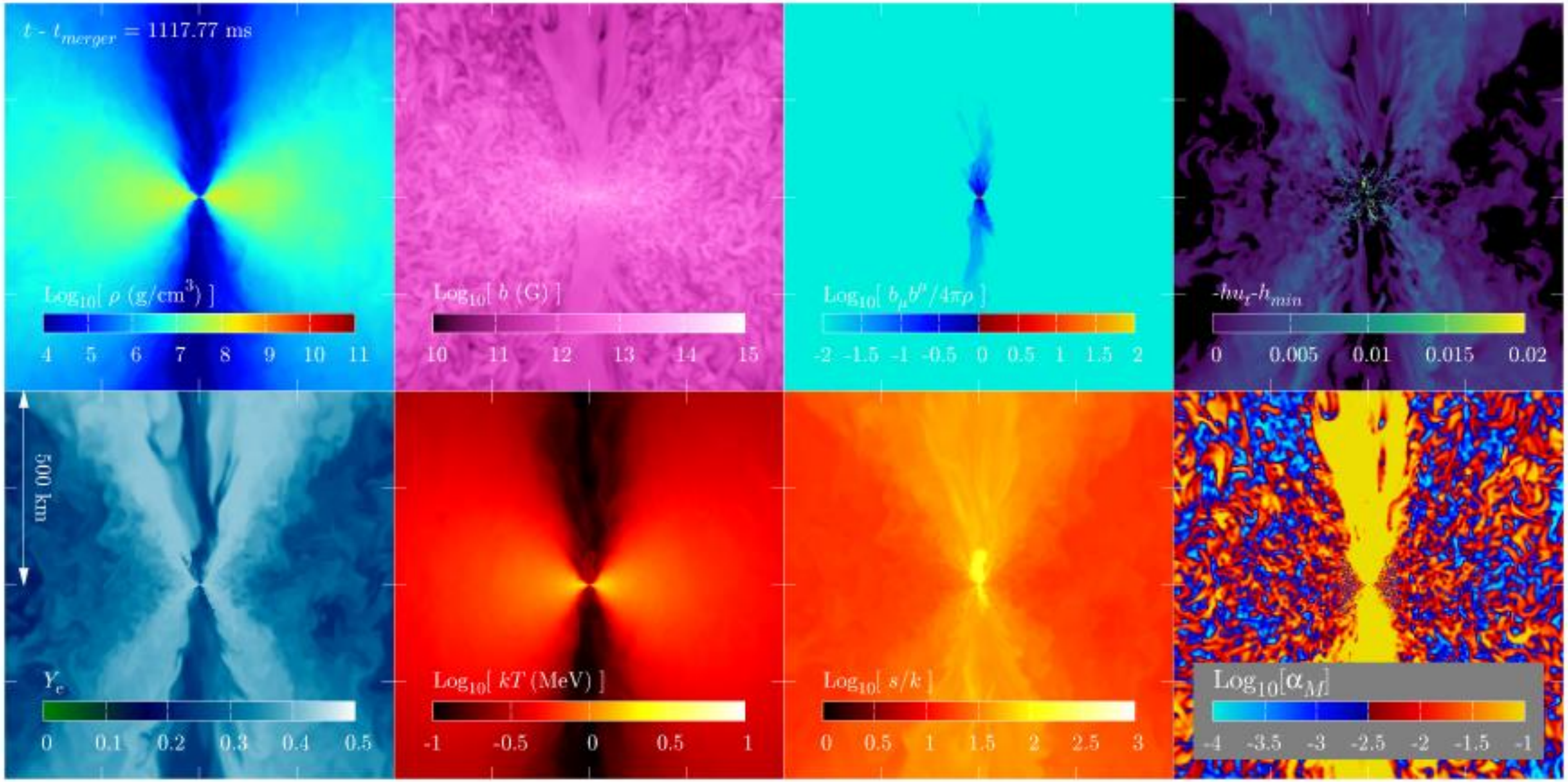
+ for more technical issues e.g., conservative mesh-refinement, see KK et al. 22

We performed a BNS simulation for 1.2s on Fugaku (KK et al. PRL 23).

Numerical modeling of BNS: Short-lived case

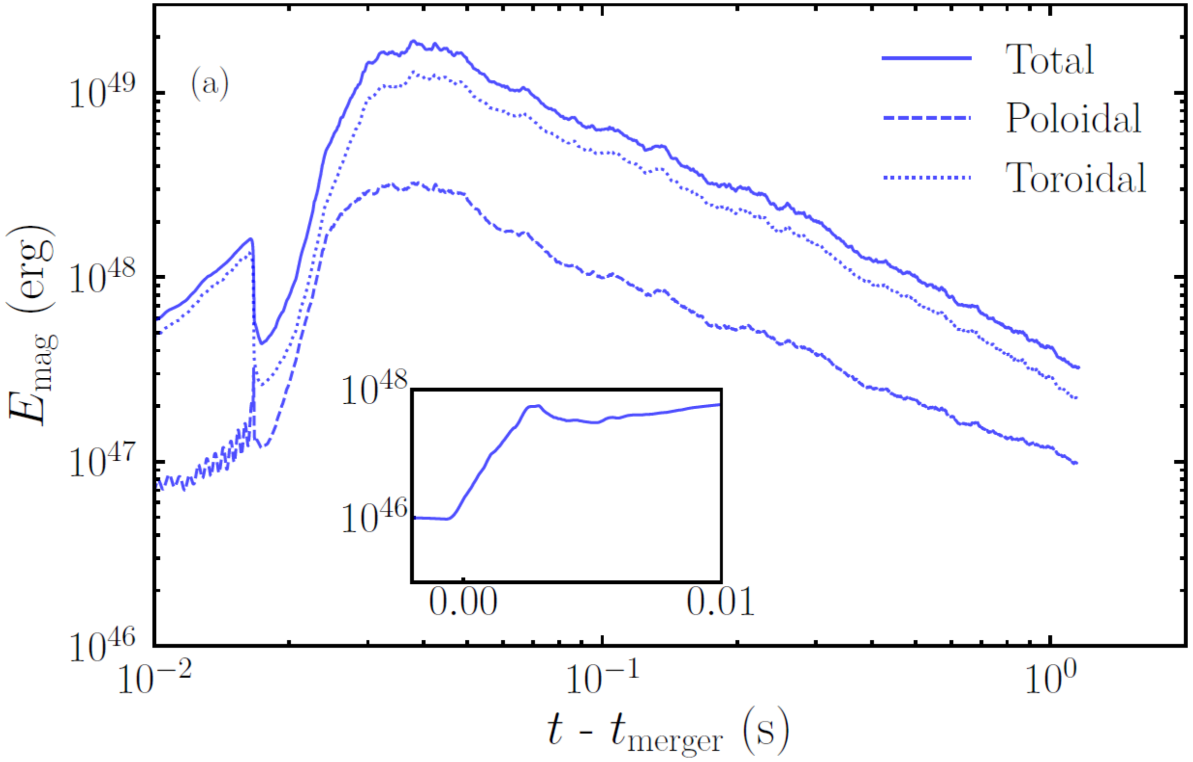


Final snapshot with a meridional cut



B-field amplification and MRI sets in

B-field energy

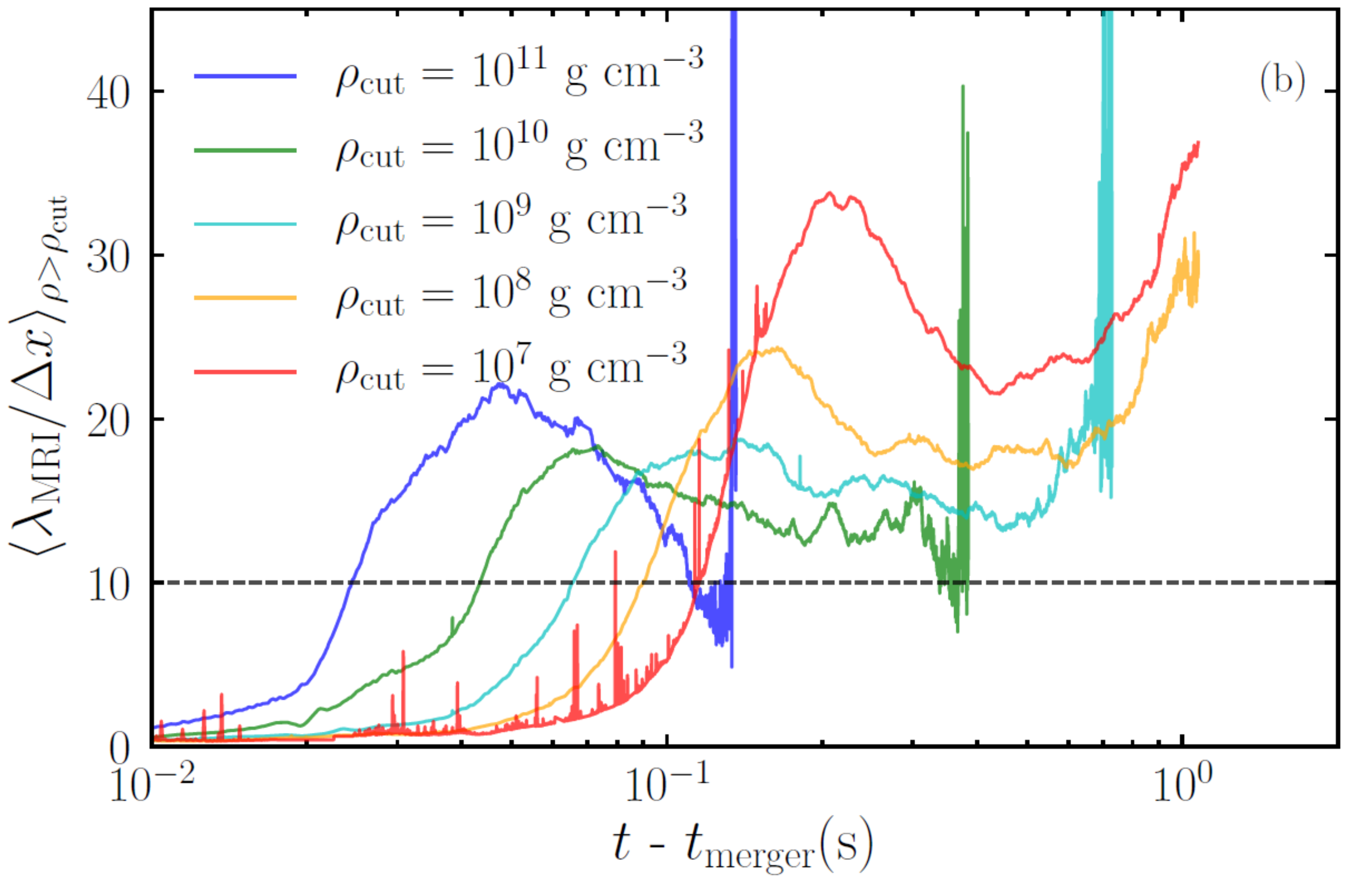


▶ B-field is amplified by the Kelvin-Helmholts instability, winding, non-axisymmetric MRI in a hypermassive neutron star phase (KK et al. 14,15,18)

▶ Winding and axisymmetric MRI after the BH formation

B-field amplification and MRI sets in

MRI quality factor with the cut-off density



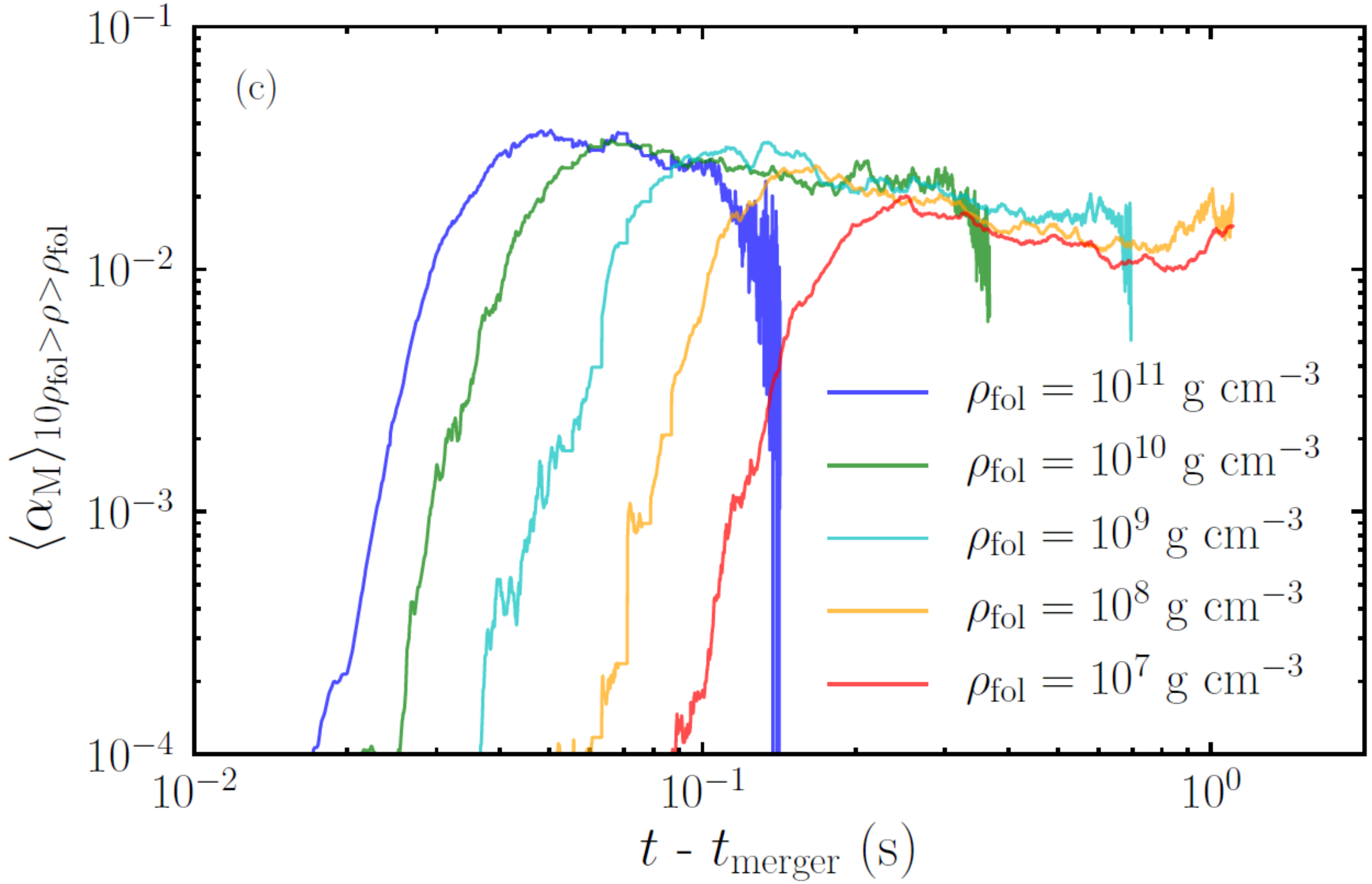
$$\left\langle \frac{\lambda_{\rm MRI}}{\Delta x} \right\rangle_{\rho_{\rm cut}} \equiv \frac{\int_{\rho \geq \rho_{\rm cut}} \lambda_{\rm MRI} d^3x}{\Delta x \int_{\rho \geq \rho_{\rm cut}} d^3x}$$

$$\lambda_{\rm MRI} = \frac{B^z}{\sqrt{4\pi\rho h + b^2}}$$

- ▶ 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



Maxwell stress tensor

$$M^r{}_\phi = \alpha_M \langle P \rangle$$

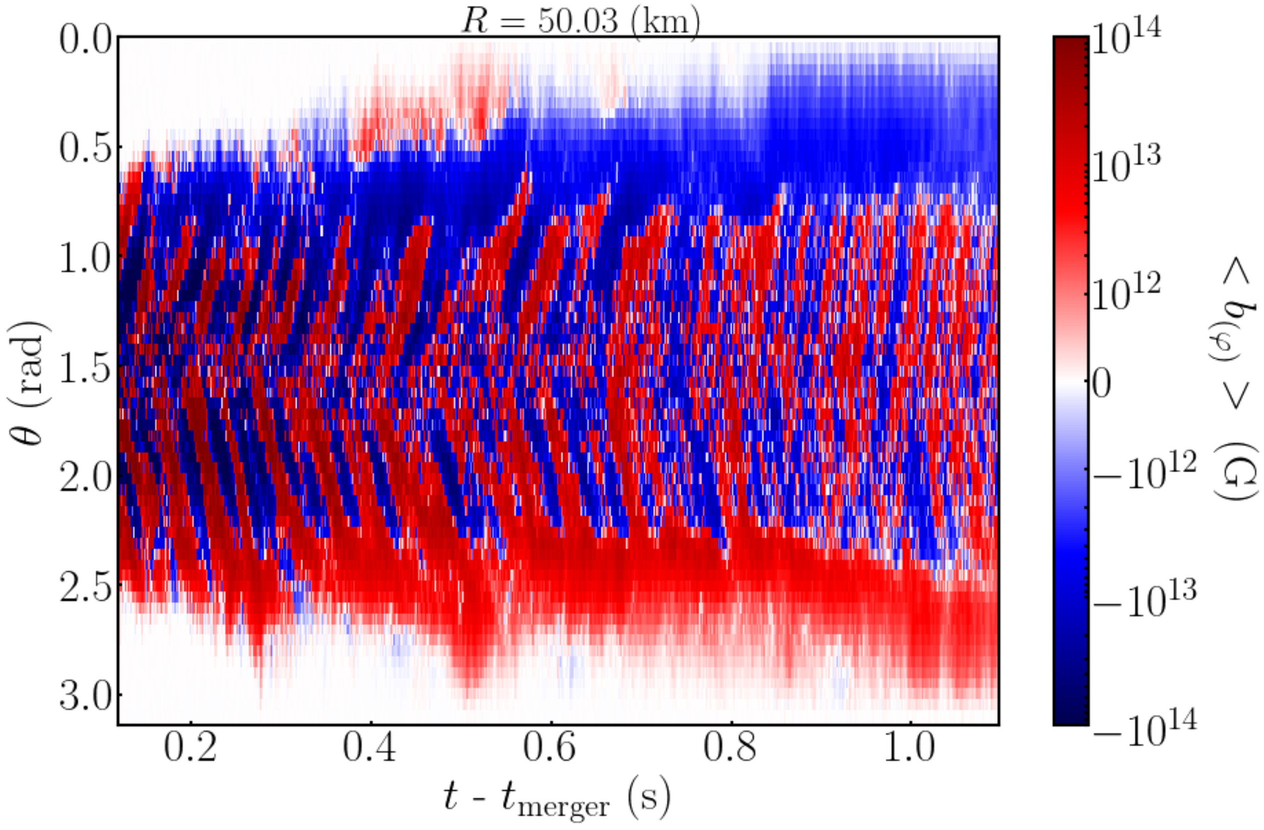
$$\langle\alpha_M\rangle_{10\rho_{fol}\geq\rho\geq\rho_{fol}} \equiv \frac{\int_{10\rho_{fol}\geq\rho\geq\rho_{fol}} \alpha_M d^3x}{\int_{10\rho_{fol}\geq\rho\geq\rho_{fol}} d^3x}.$$

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

⇒ $t_{vis} \sim O(0.1s)$

MRI dynamo to sustain the MRI-driven turbulence

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

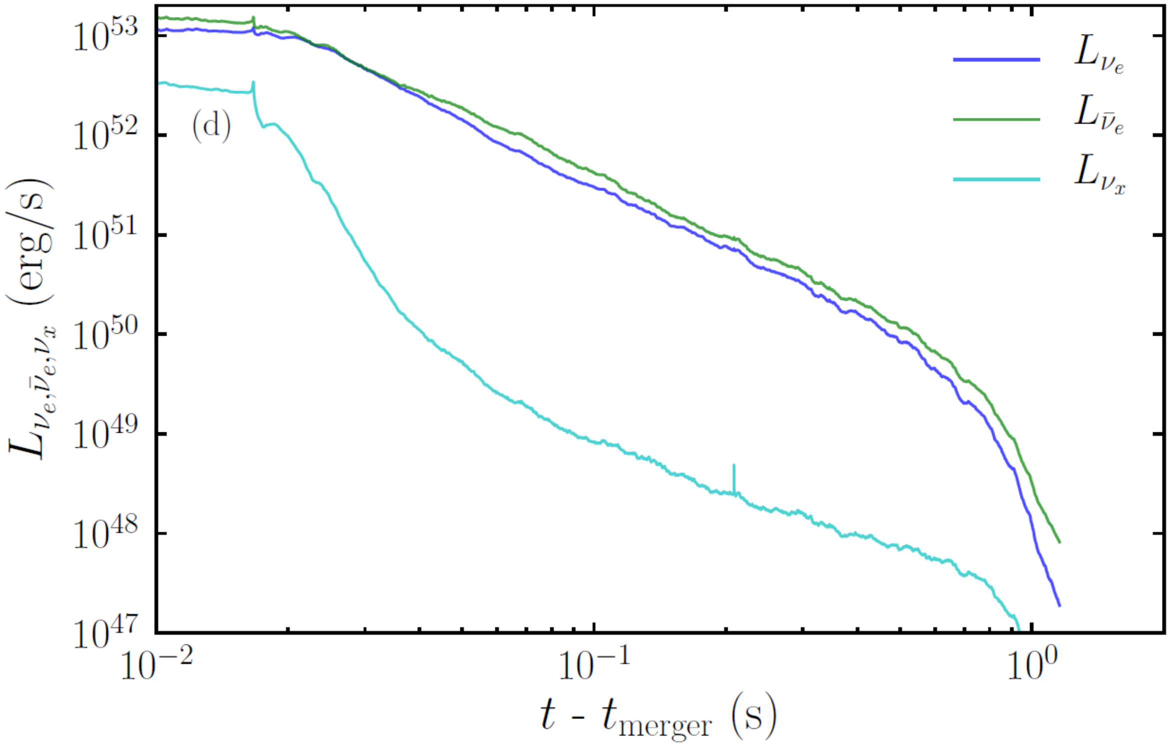


▶It clearly suggests the sign flip pattern which lasts until end of the simulation⇒ MRI dynamo sustains the turbulent state.

Neutrino luminosity evolution

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

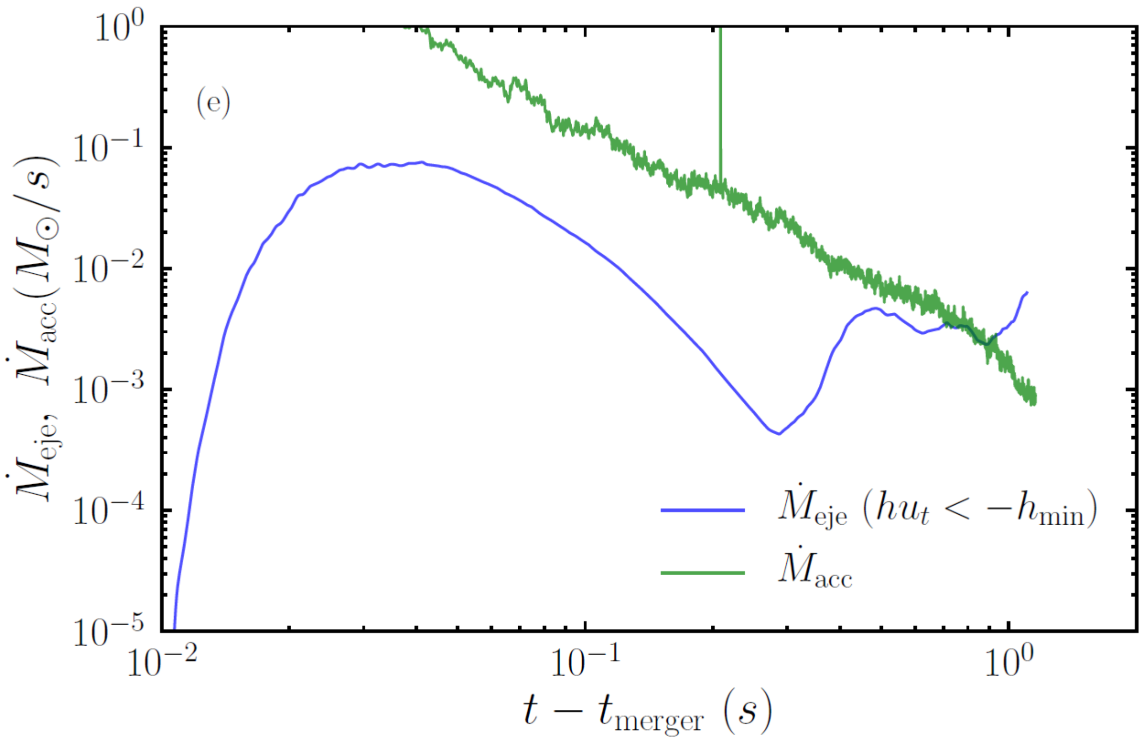
Neutrino luminosity



▶ 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



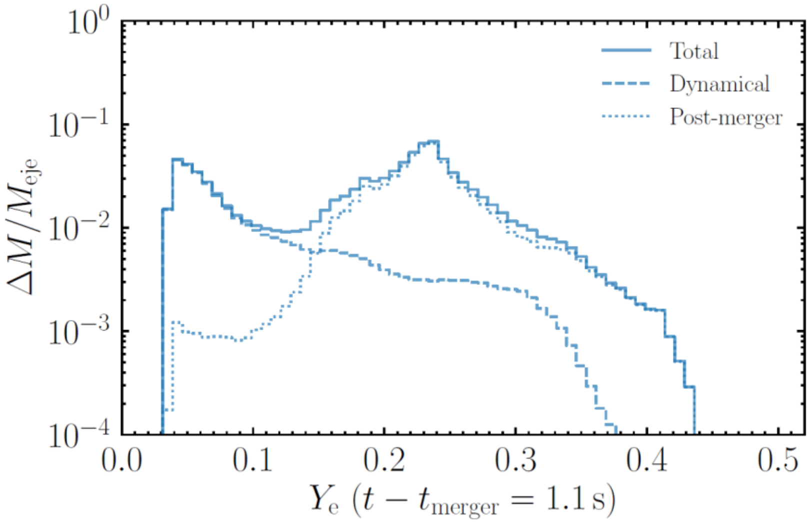
▶ Dynamical ejecta starts to appear at ≈0.01s and peaks around ≈ 0.03-0.04s (Fast tail and mildly relativistic ejecta).

▶ Post-merger ejecta due to the MRI-driven turbulence emerges at ≈ 0.3s.

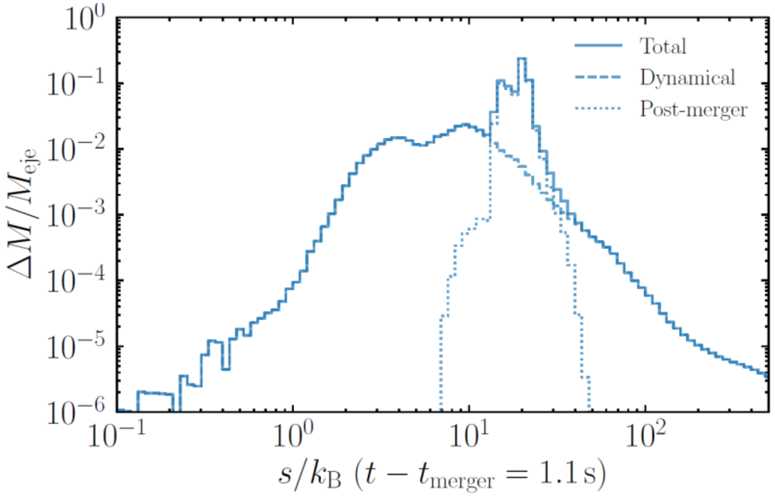
▶ The ejection rate exceeds the accretion rate at ≈ 1.1s.

Ejecta properties

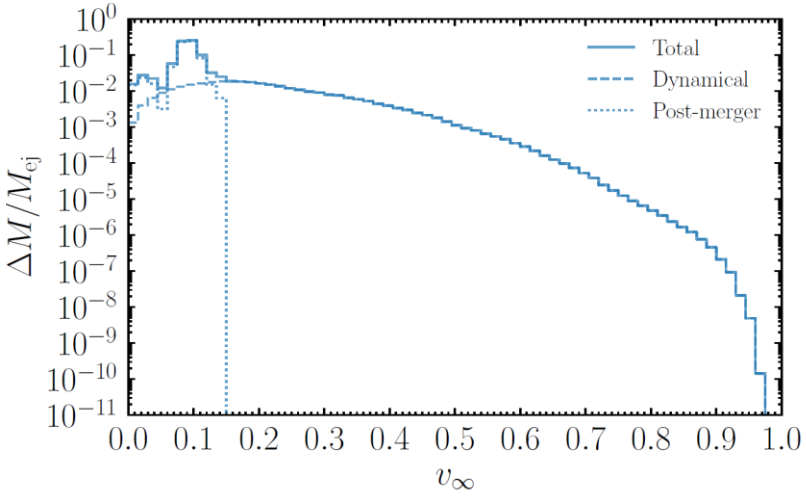
Electron fraction



Entropy per baryon



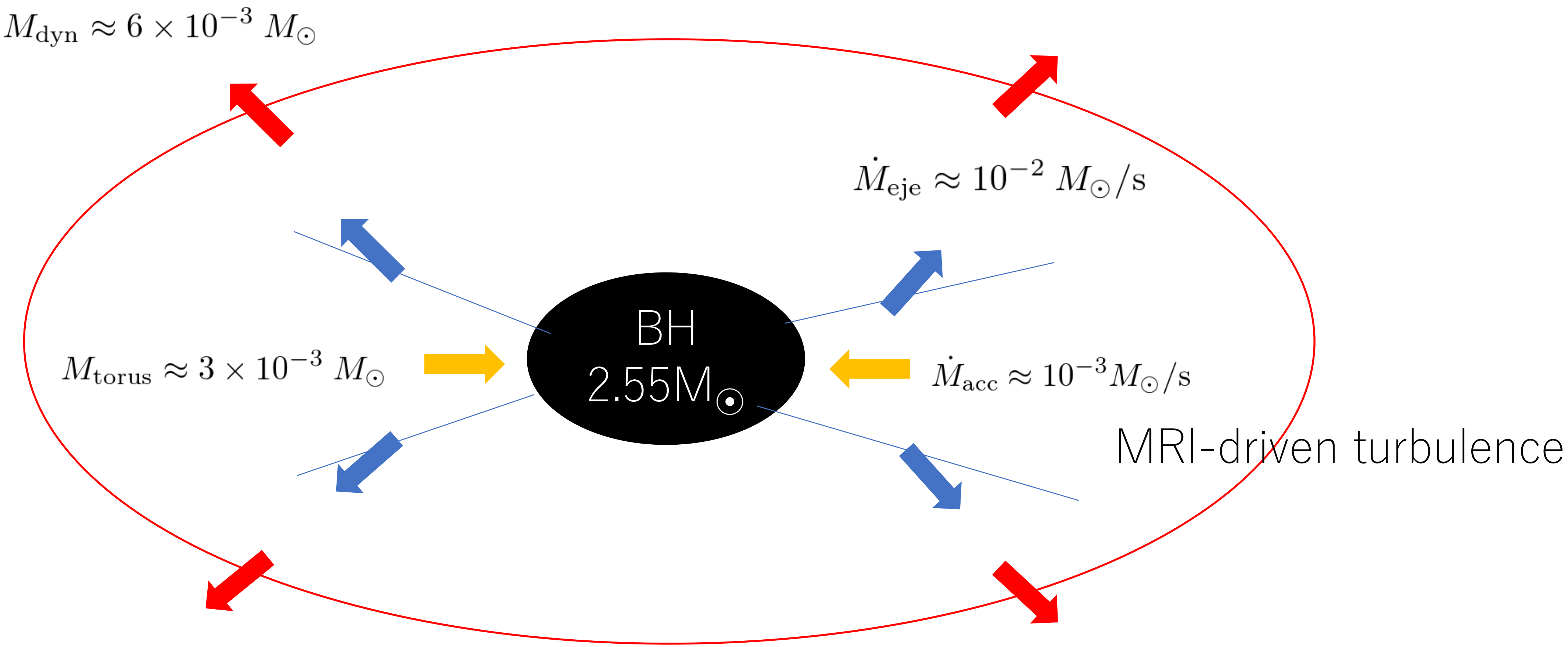
Terminal velocity



▶ 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



▶ $M_{\rm post,eje} \approx 8 \times 10^{-3} M_\odot$, $M_{\rm dyn,eje} \approx 6 \times 10^{-3} M_\odot$

A simple kilonova modeling requires $0.05 M_\odot$ (Hotokezaka & Nakar 20, +)

Jet launching in short-lived case

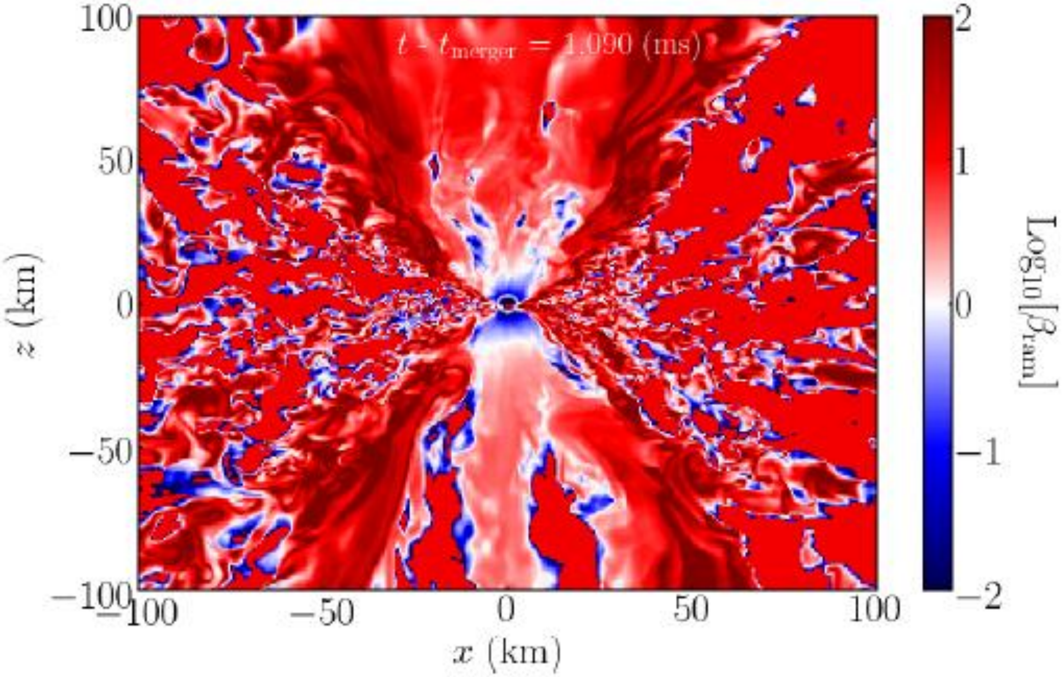
Absence for the launching jet in our simulation

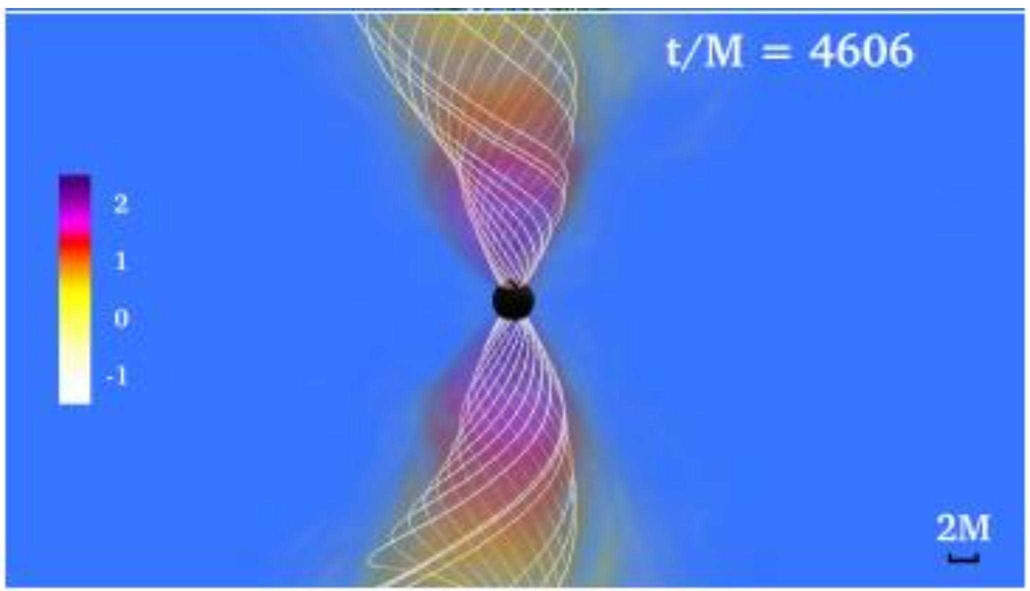
▶ Mild BH spin? $\chi \approx 0.6\text{-}0.65$

▶ Shortness of simulation? Still strong ram pressure due to the fall-back matter. ⇒ Maybe matter of the time?

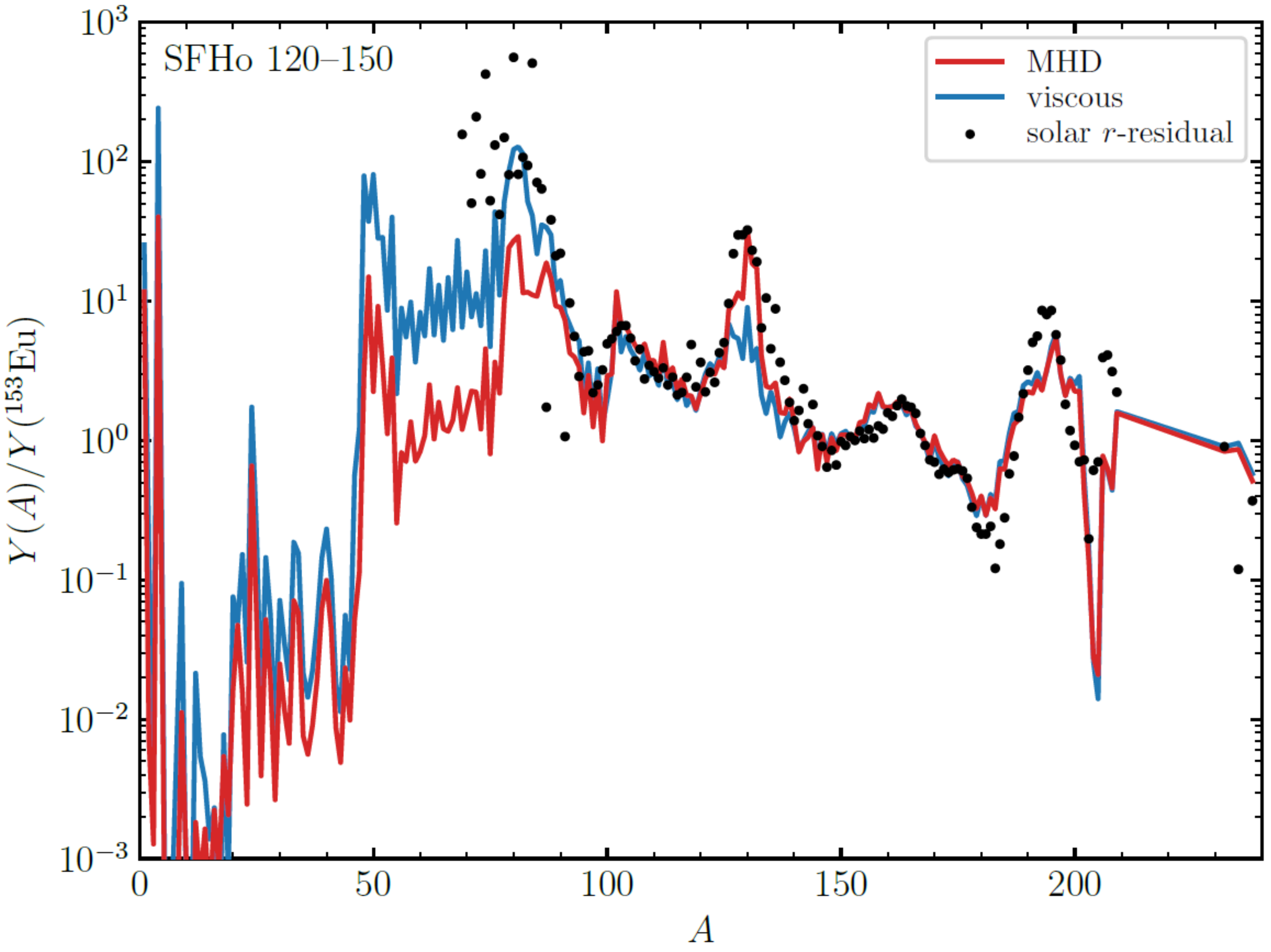
$\beta_{\mathrm{ram}} = P_{\mathrm{ram}}/P_{\mathrm{mag}}$

Ruiz et al. 18, 21, Sun et al. 22, and many



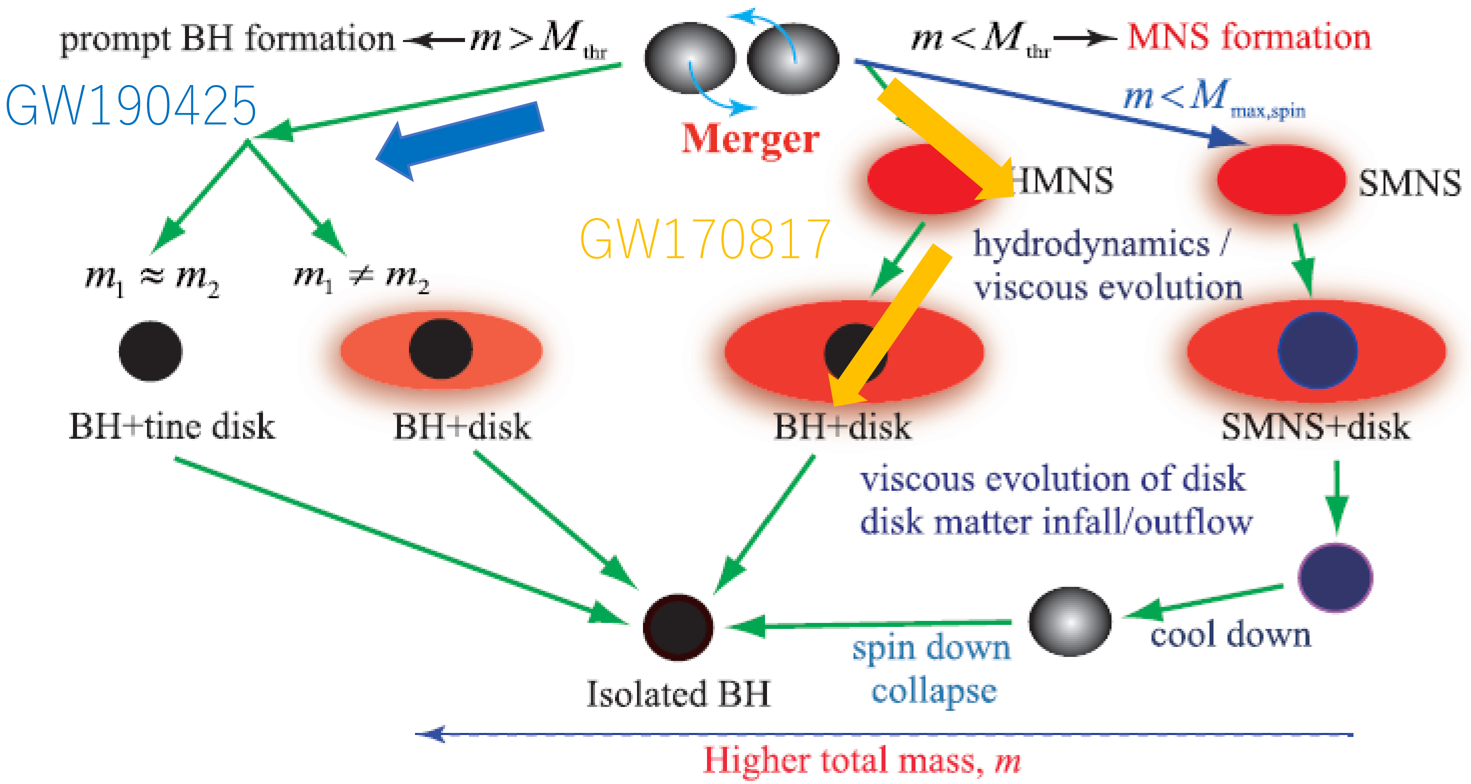


R-process nucleosynthesis
MHD vs viscous hydrodynamics



Numerical modeling of BNS: Long-lived case

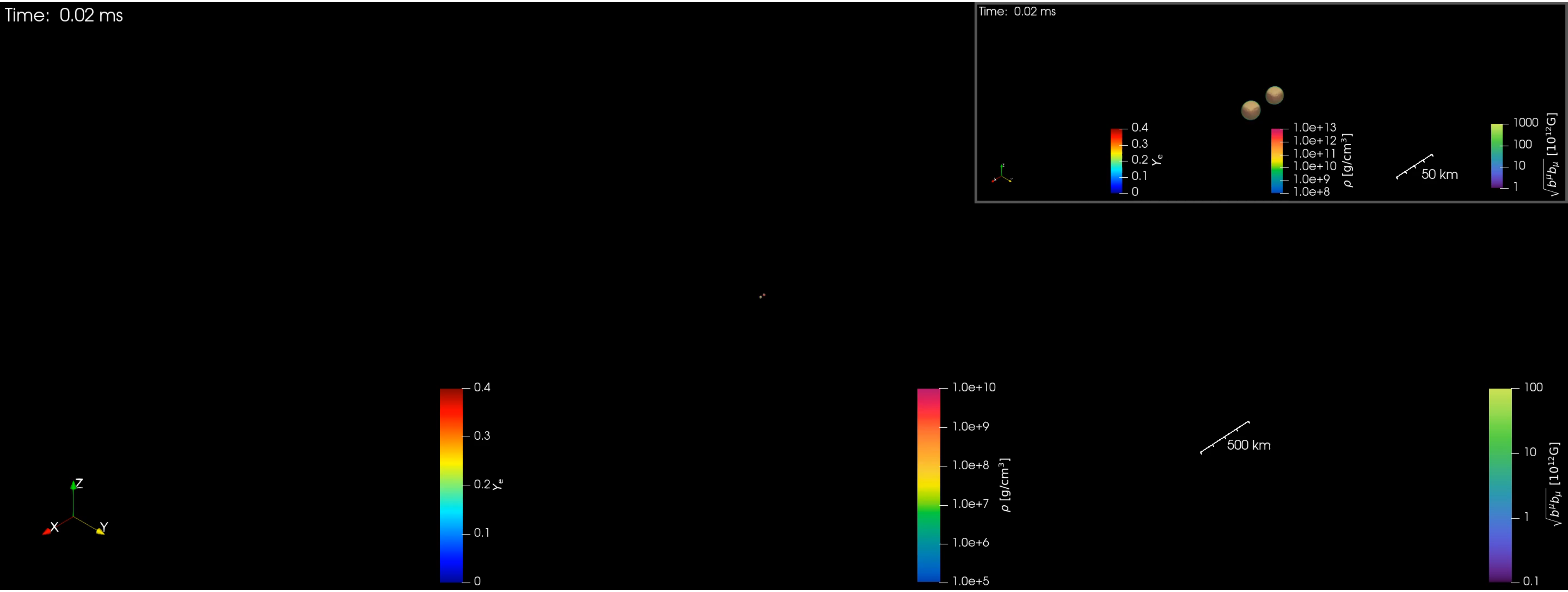
Shibata & Hotokezaka 19



▶ Can a long-lived remnant drive a relativistic outflow to be observed as a short-gamma ray burst? (Metzger et al. 11, Zhang & Meszaros 01)

▶ Different jet launching mechanism from BH case, i.e., the BZ mechanism. Computationally challenging (Mösta et al. 2020 etc.)

Numerical modeling of BNS: Long-lived case



Electron fraction of ejecta　　Density + B-field lines　　B-field strength

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 (DD2) (Banik et al. 14)

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

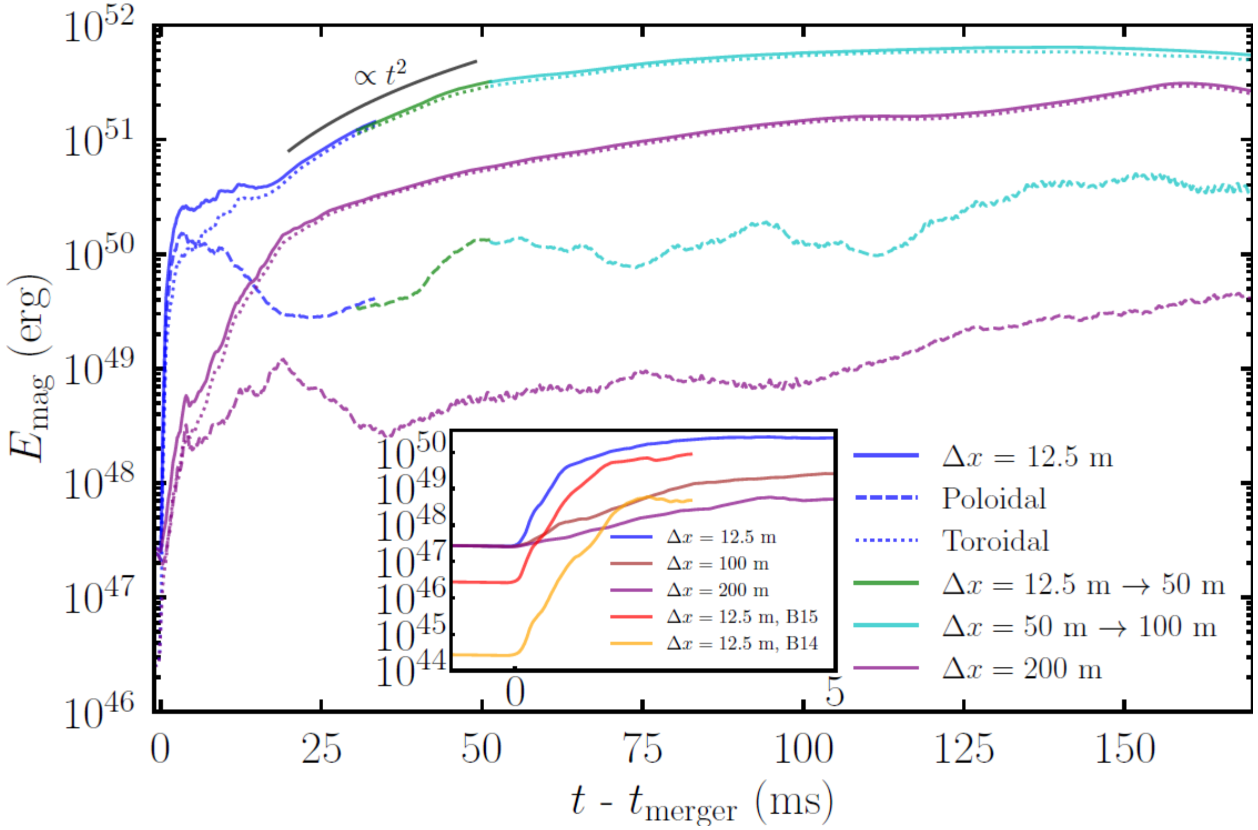
▶ Neutrino-radiation transfer solver (Sekiguchi et al. 12)

+ for more technical issues (see KK et al. 22)

We performed a BNS simulation with Δx_{finest}=12.5m and $B_{0,max}=10^{15.5}$G for 0.2s (KK et al. Nature Astronomy 24)

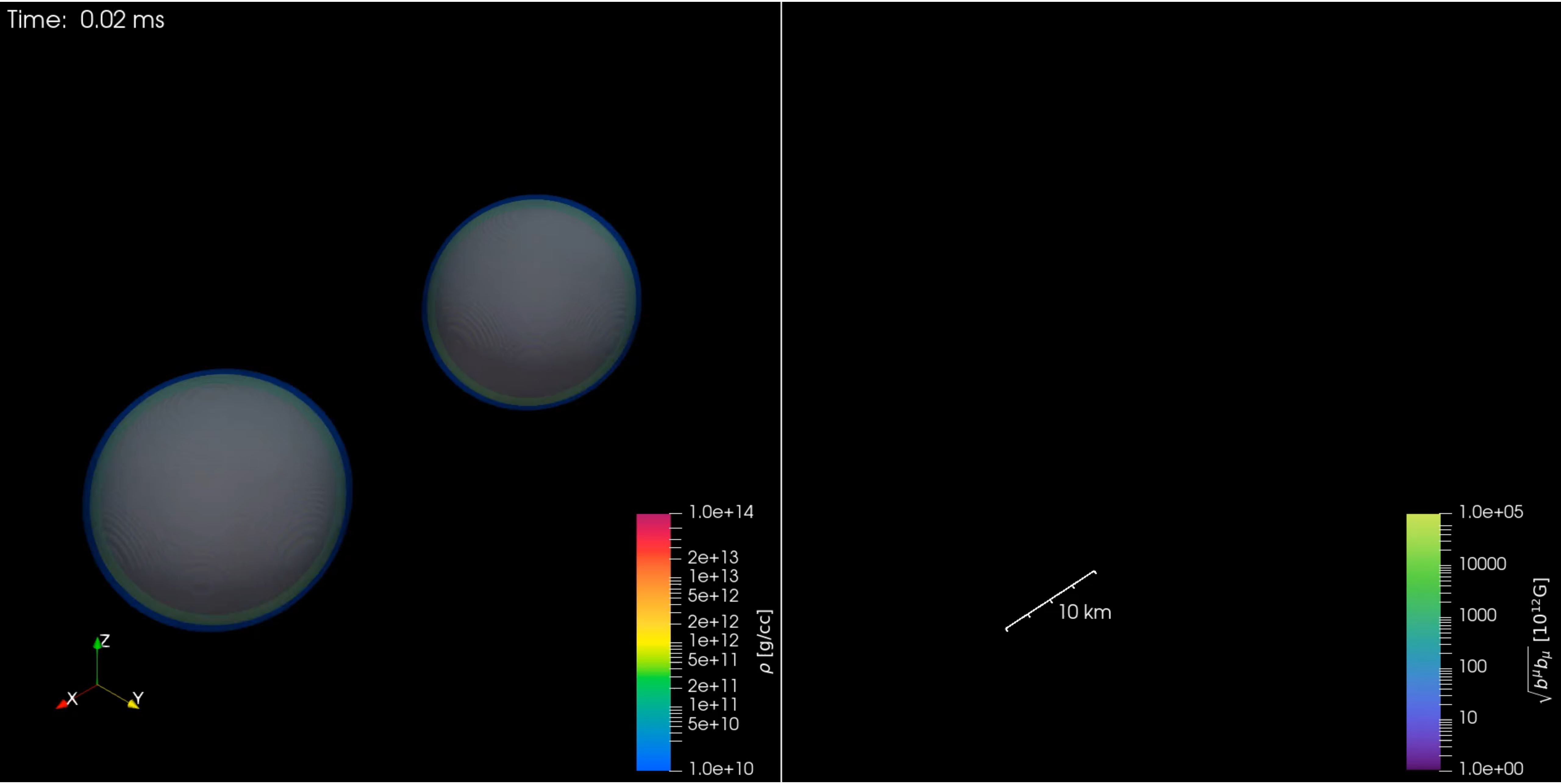
B-field amplification inside the merger remnant

B-field energy



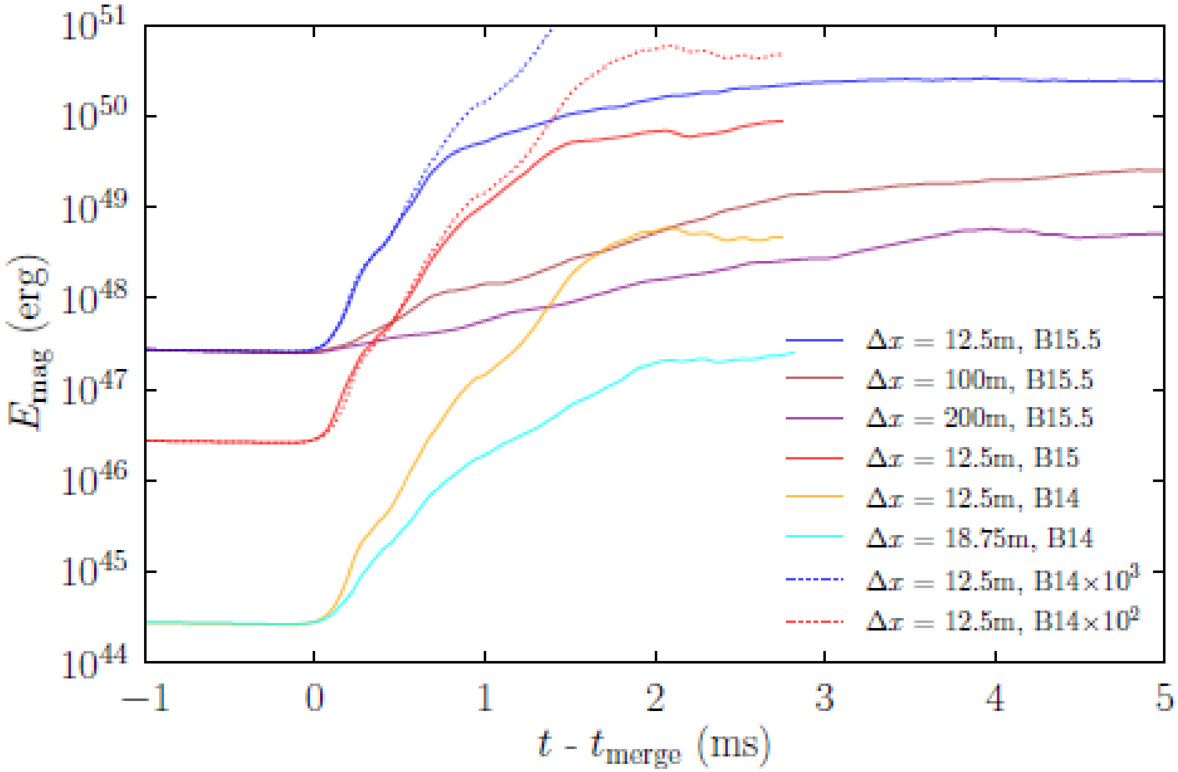
▶ B-field is amplified by the Kelvin-Helmholts instability at the merger (Rasio & Shapiro 95, Price & Rosswog 06, KK et al. 14,15,18)

⇒ Efficient magnetic winding with the coherent poloidal field for $t - t_{\rm merger} \gtrsim 20$ ms

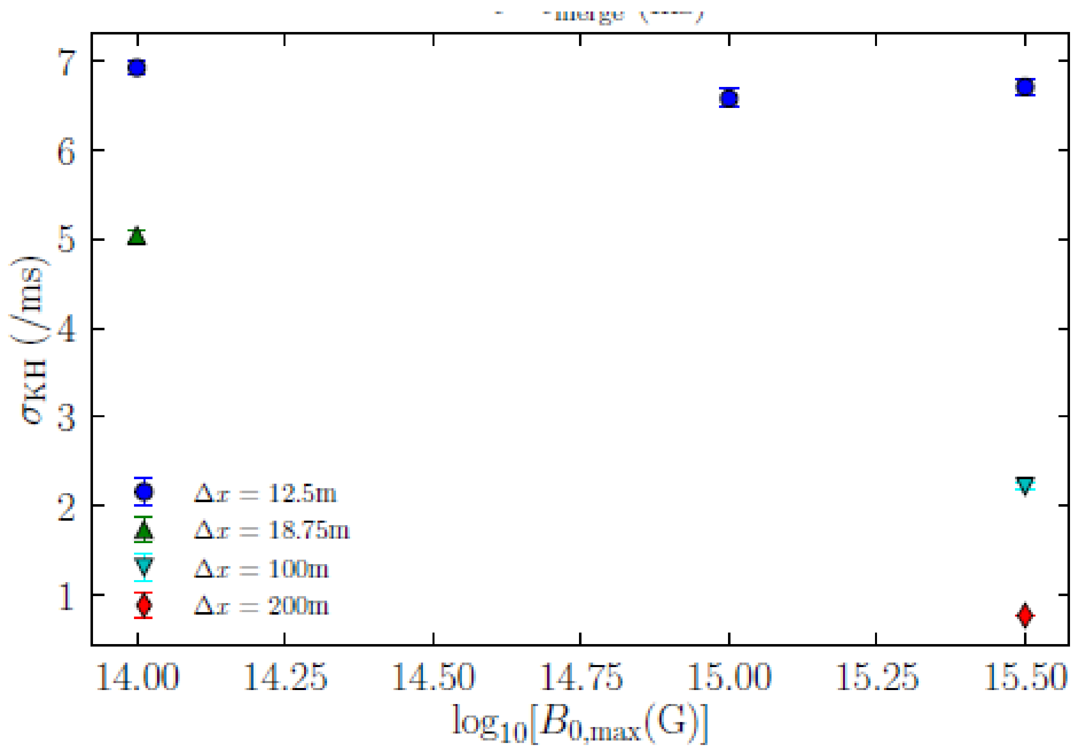

Time: 0.02 ms
1.0e+14
2e+13
1e+13
5e+12
2e+12
1e+12
5e+11
2e+11
1e+11
5e+10
1.0e+10
ρ [g/cc]
Z
X
Y
10 km
1.0e+05
10000
1000
100
10
1.0e+00
$\sqrt{b^\mu b_\mu}$ [10^{12}G]

Kelvin-Helmholtz dynamo at the merger

KH amplification at the merger

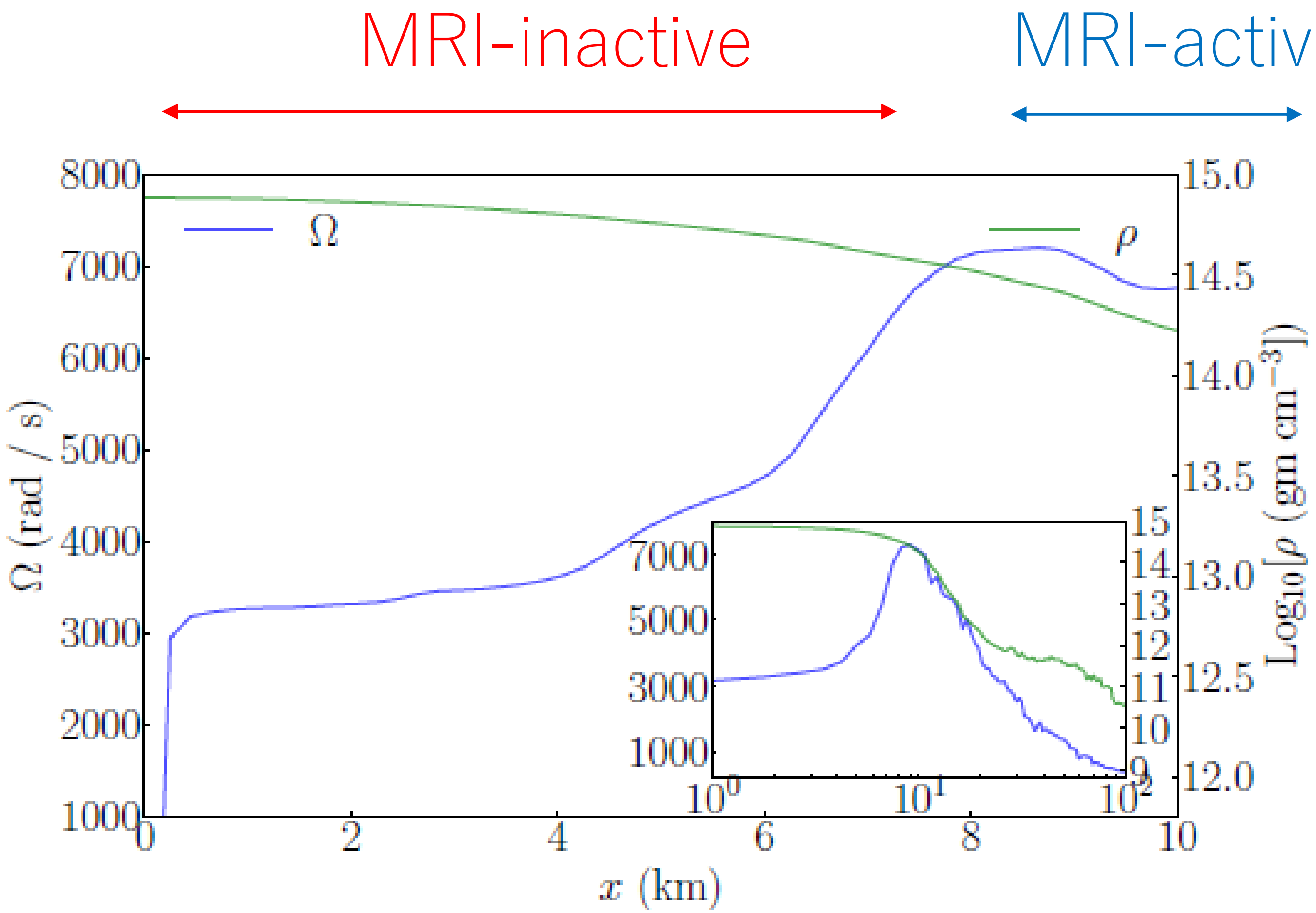


Growth rate vs initial B-field



▶ In reality, the KH dynamo would produce a strong, but small-scale magneto turbulence (see also Palenzuera et al. 22, Aguilera-Miret et al. 22, 23).
A mechanism to generate a globally coherent B-field is necessary.

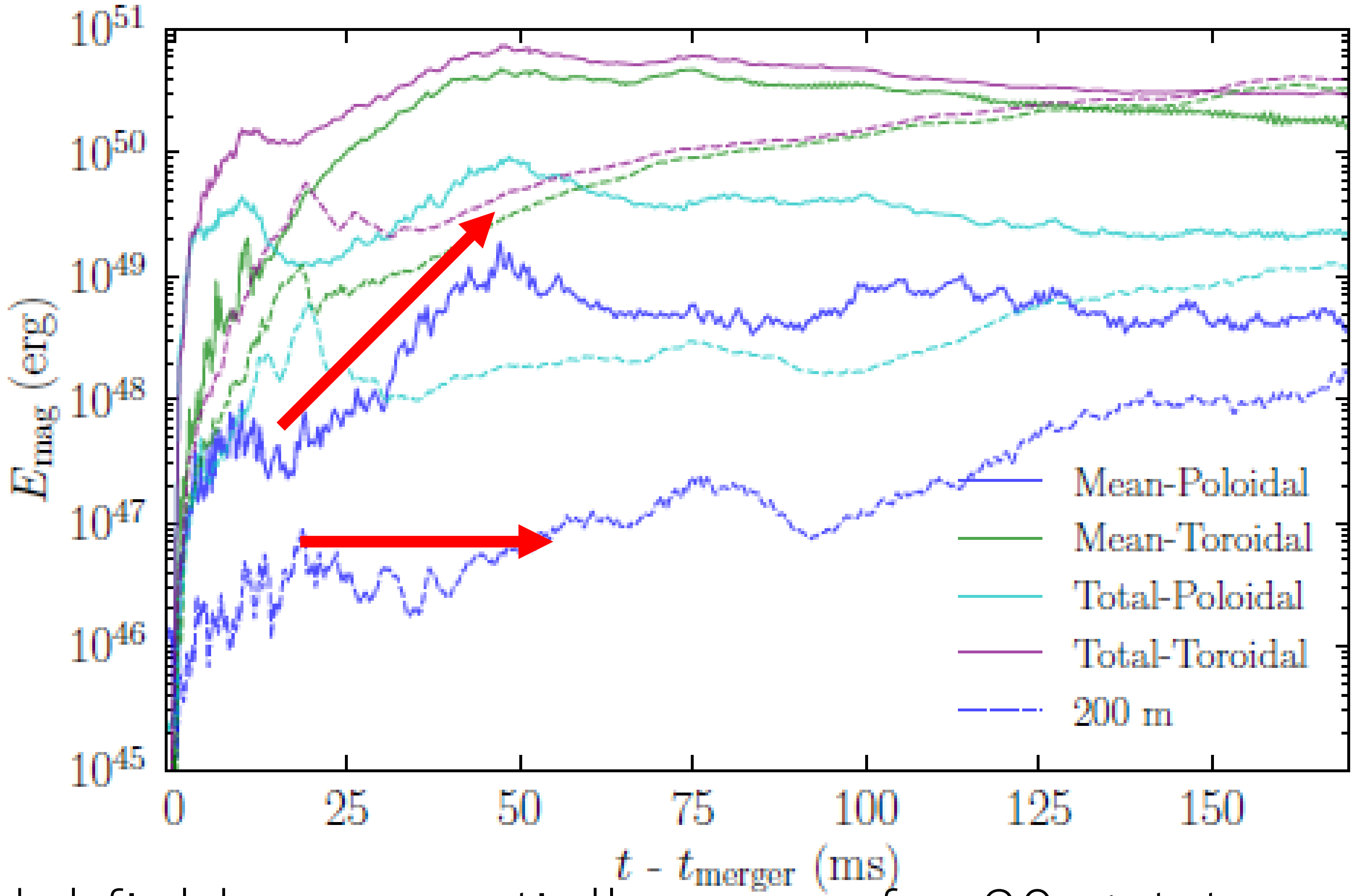
Mean B-field in MRI-active region



- ▶ Deep inside (Outside) core is MRI-inactive (active) region
- ▶ Bulk EM energy is contained in the MRI-inactive region.

Mean B-field in MRI-active region

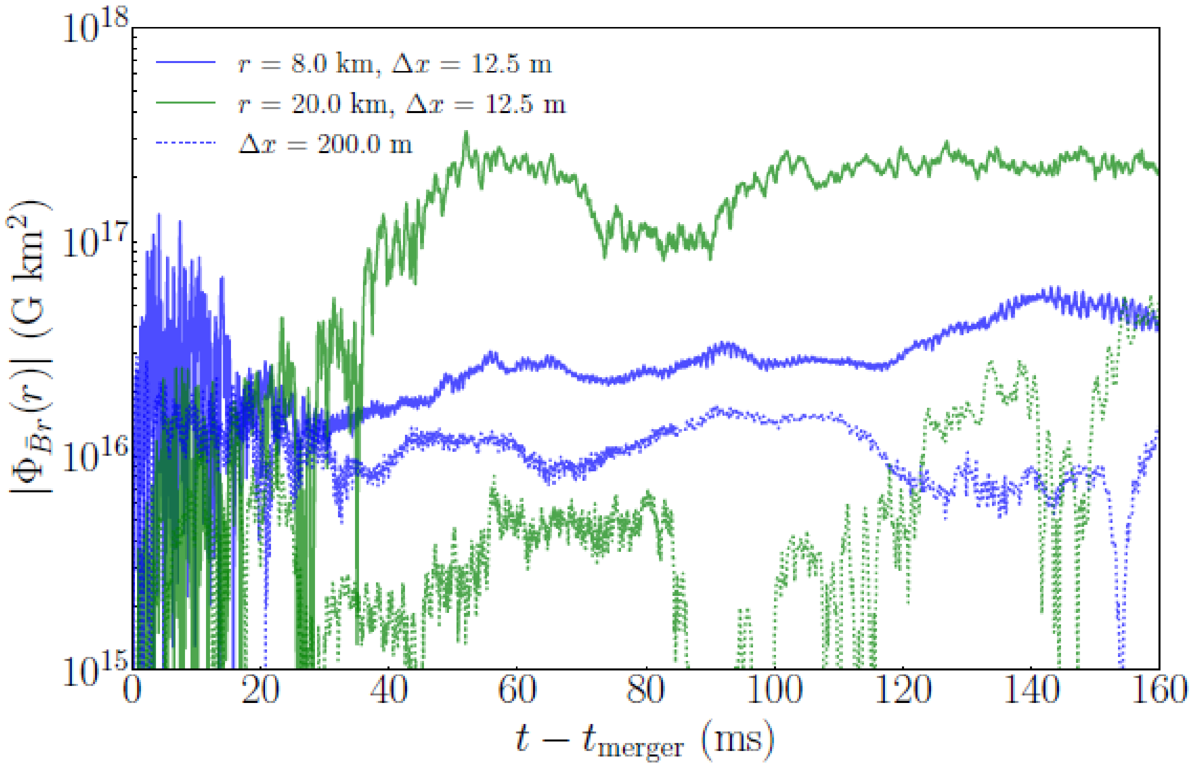
Electromagnetic energy in MRI-active region



- ▶ Mean-Poloidal field exponentially grows for $20 \lesssim$ t-t_{merger} $\lesssim 50$ms
- ▶ High resolution is key

Mean B-field in MRI-active region

Mean-Poloidal magnetic flux on a sphere



- ▶ Mean-Poloidal flux stays an approximately constant in MRI-inactive region
- ▶ Mean-Poloidal flux increases in MRI-active region
- ▶ High resolution is key

A large scale α Ω_dynamo driven by MRI

Mean field dynamo theory

$$\mathbf{Q} = \bar{\mathbf{Q}} + \mathbf{q},\ \bar{\mathbf{Q}} = \text{Axisym. Ave.}$$

$$\partial_t \bar{\mathbf{B}} = \nabla \times (\bar{\mathbf{U}} \times \bar{\mathbf{B}} + \bar{\mathcal{E}}),$$

$$\bar{\mathcal{E}} = \overline{\mathbf{u} \times \mathbf{b}}$$

u & b : turbulence of the velocity and b-field.

α Ω dynamo

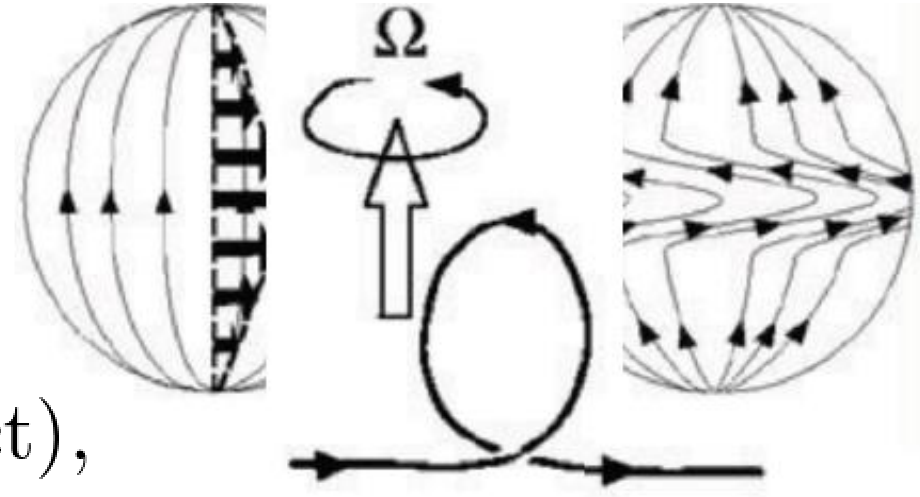
$$\mathcal{E}_i = \alpha_{ij} \bar{B}_j + \beta_{ij} (\nabla \times B)_j$$

In the current context, α_{ij} is dominant

$$\partial_t \bar{B}_\phi = R \bar{\mathbf{B}}_P \cdot \nabla_P \Omega \ (\Omega \text{ effect}),$$

$$\partial_t \bar{B}_R = -\partial_z \mathcal{E}_\phi \approx -\partial_z (\alpha_{\phi\phi} \bar{B}_\phi) \ (\alpha \text{ effect}),$$

$$\partial_t \bar{B}_z = \partial_R \mathcal{E}_\phi \approx \partial_R (\alpha_{\phi\phi} \bar{B}_\phi)$$



Generation of a large-scale field via $\alpha\,\Omega$ dynamo

MRI-driven $\alpha\,\Omega$ dynamo theory prediction

1. B_ϕ should be anticorrelated with B_p
2. E_ϕ should be correlated or anti-correlated with B_ϕ
3. Dynamo cycle period $P_{theory} = 2\pi(\alpha_{\phi\phi} d\Omega/d\ln R\ k_z/2)^{-1/2}$
4. Dynamo wave propagation direction according to the Yoshimura-Parker rule $\alpha_{\phi\phi} \nabla \Omega \times e_\phi$

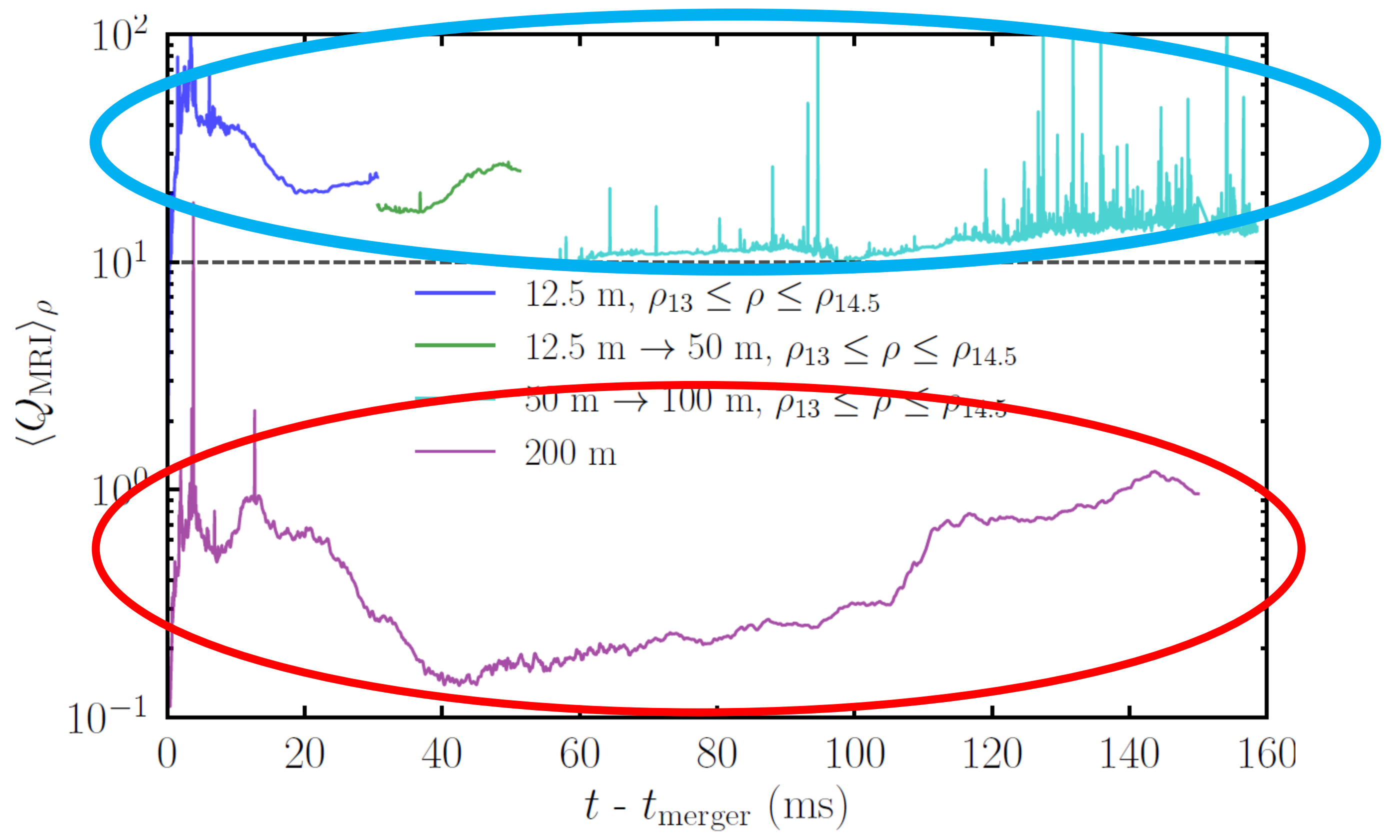
Prerequisite:
Magneto Rotational Instability (MRI) should be resolved to generate EMF

$$\bar{\mathcal{E}} = \overline{\mathbf{u} \times \mathbf{b}}$$

Generation of a large-scale field via $\alpha\ \Omega$ dynamo

Prerequisite

MRI quality factor

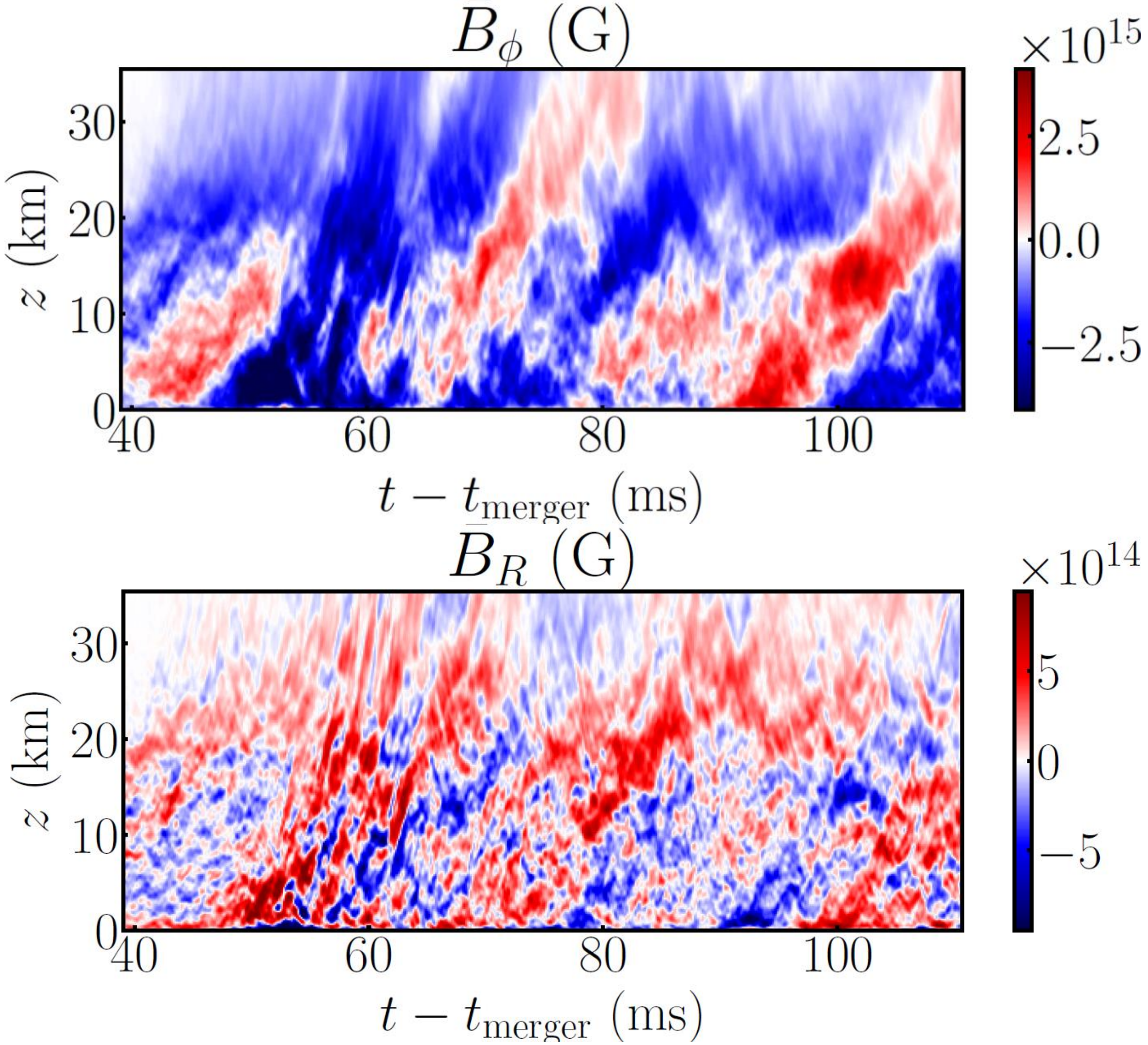


MRI is well resolved in Δx=12.5m run ⇒ Turbulence is developed

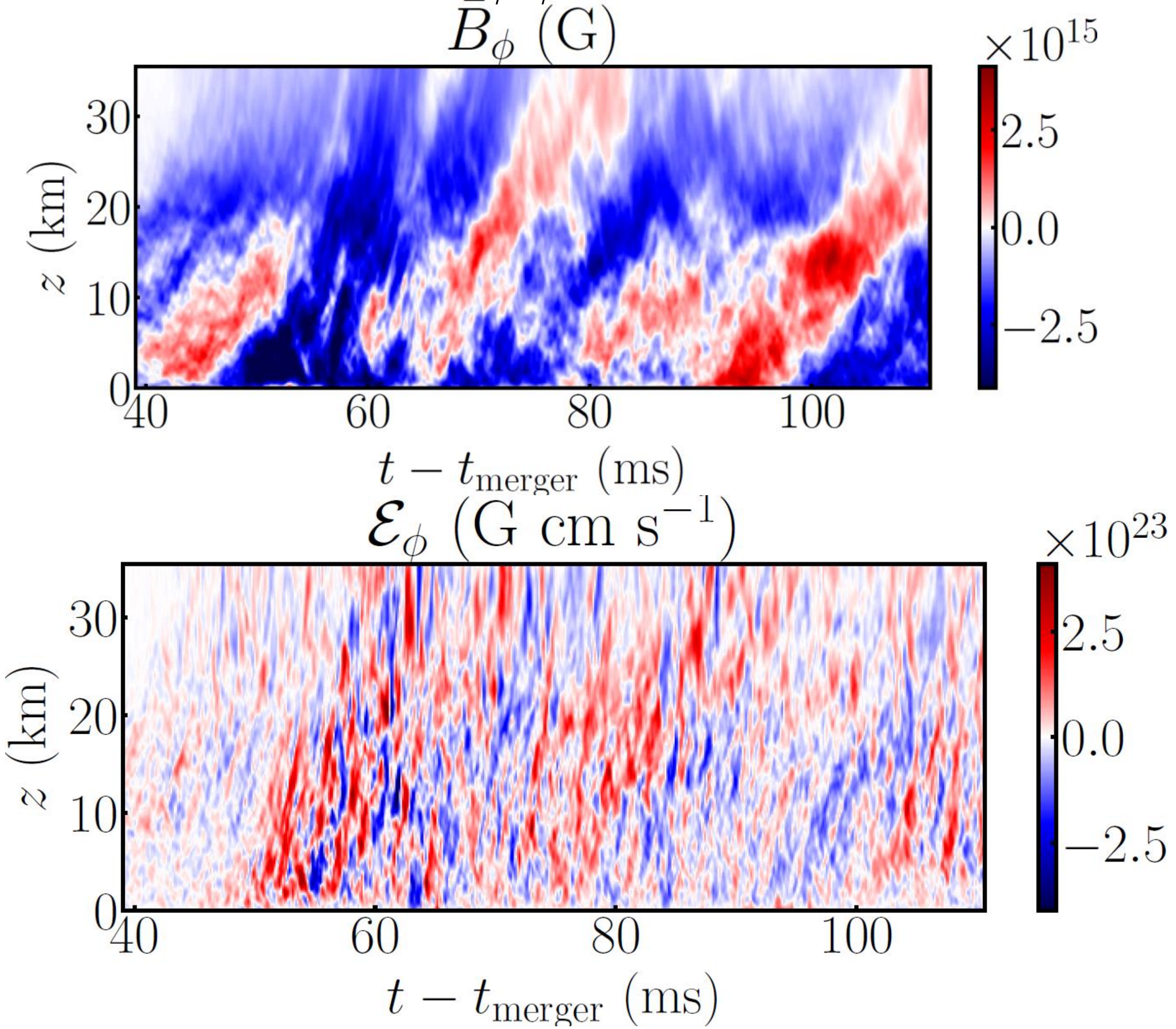
MRI is not resolved in Δx=200m run ⇒ No turbulence

Generation of a large-scale field via $\alpha\ \Omega$ dynamo

Ω effect



$\alpha_{\phi\phi}$ effect



Generation of a large-scale field via $\alpha\ \Omega$ dynamo

Pearson correlation between E_ϕ and B_ϕ

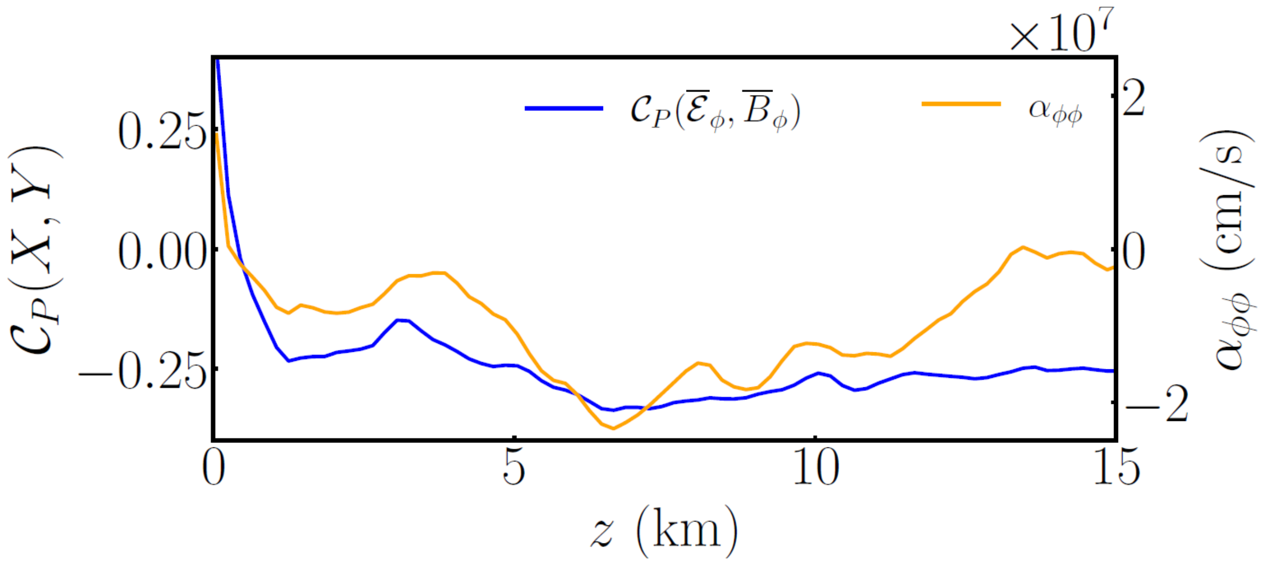
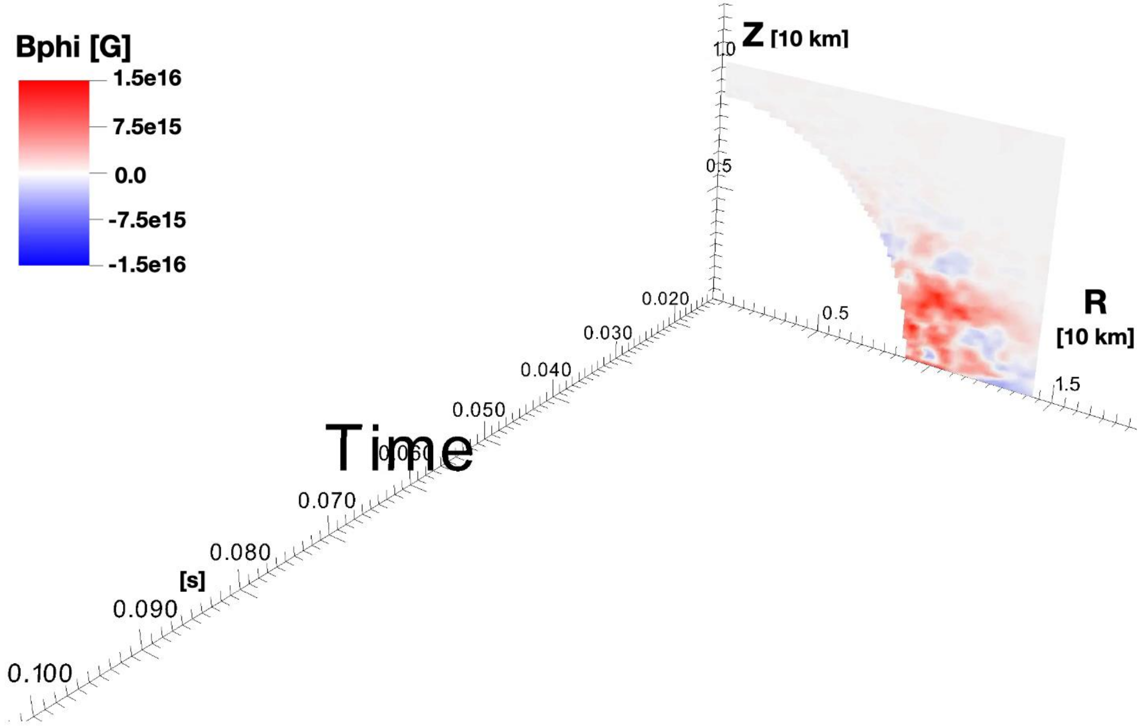


Table 1 The $\alpha\Omega$ dynamo period prediction and simulation data at several radii

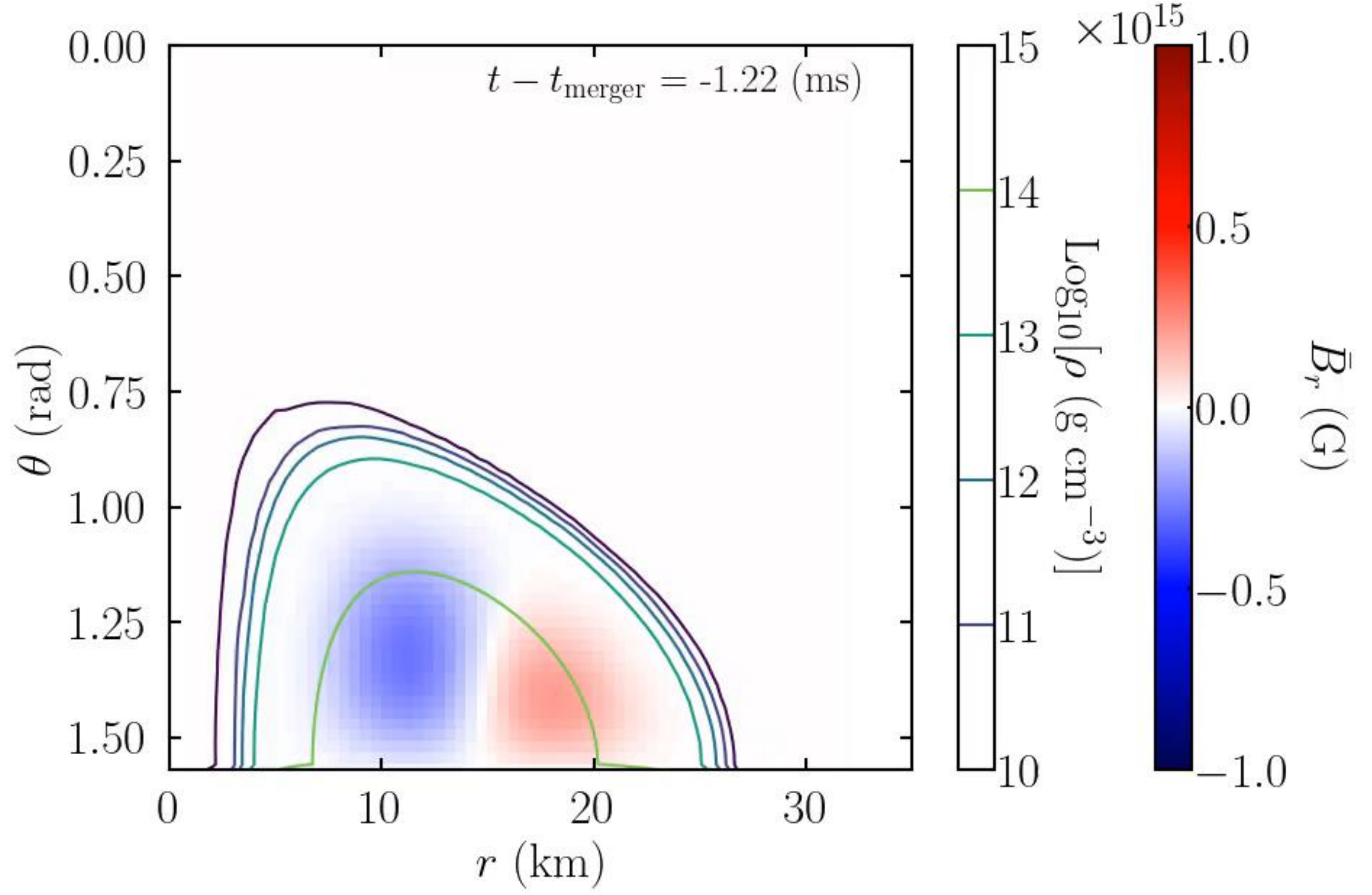
R (km)	$\alpha_{\phi\phi}$ (cm/s)	Ω (rad/s)	Shear rate	k_z (/cm)	$P_{\rm theory}$ (s)	$P_{\rm sim}$ (s)
20	-8.1×10^6	4025	$q = -1.0$	6.3×10^{-6}	0.020	0.018
30	-1.0×10^7	2515	$q = -1.34$	4.2×10^{-6}	0.021	0.018–0.024
40	-1.0×10^7	1688	$q = -1.44$	3.3×10^{-6}	0.037	0.018–0.030
50	-4.4×10^6	1200	$q = -1.50$	2.6×10^{-6}	0.062	0.030–0.040

Generation of a large-scale field via $\alpha\ \Omega$ dynamo



Dynamo wave propagates to the z direction according to the Yoshimura-Parker rule $\alpha_{\phi\phi} \nabla \Omega \, x \, e_{\phi}$

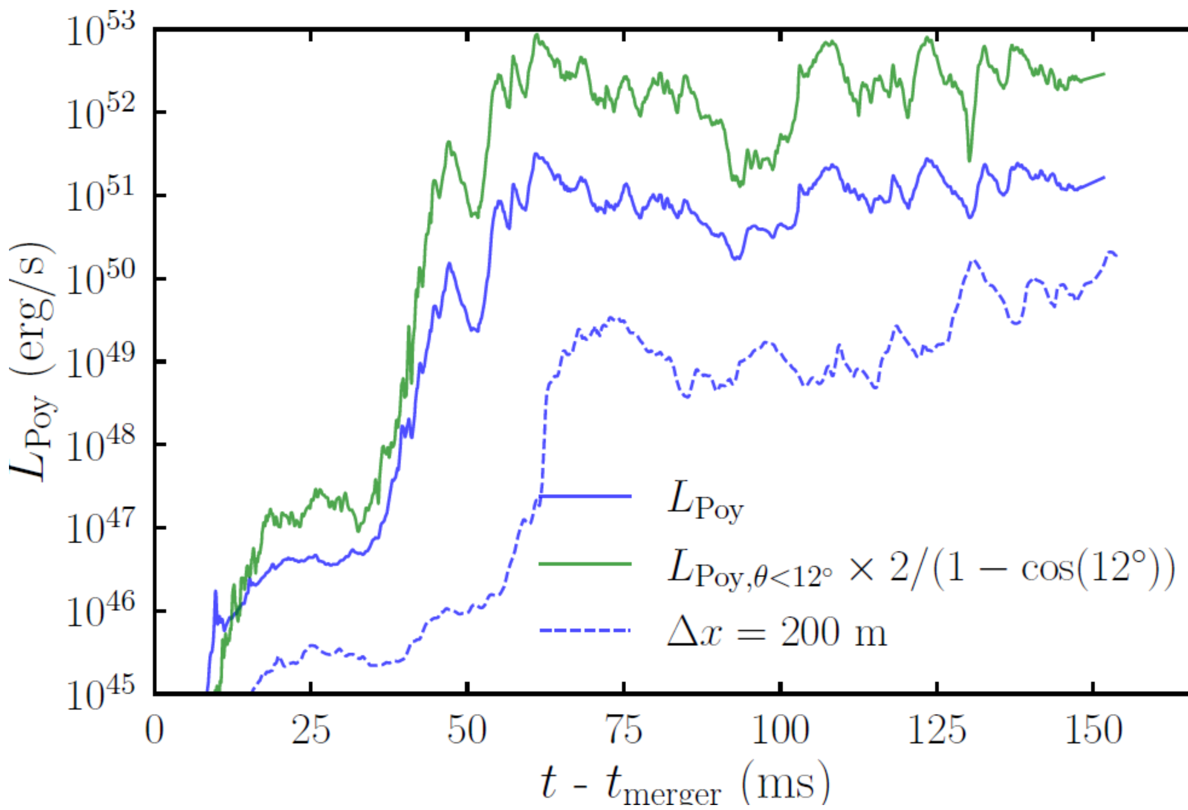
Generation of a large-scale field via $\alpha\ \Omega$ dynamo

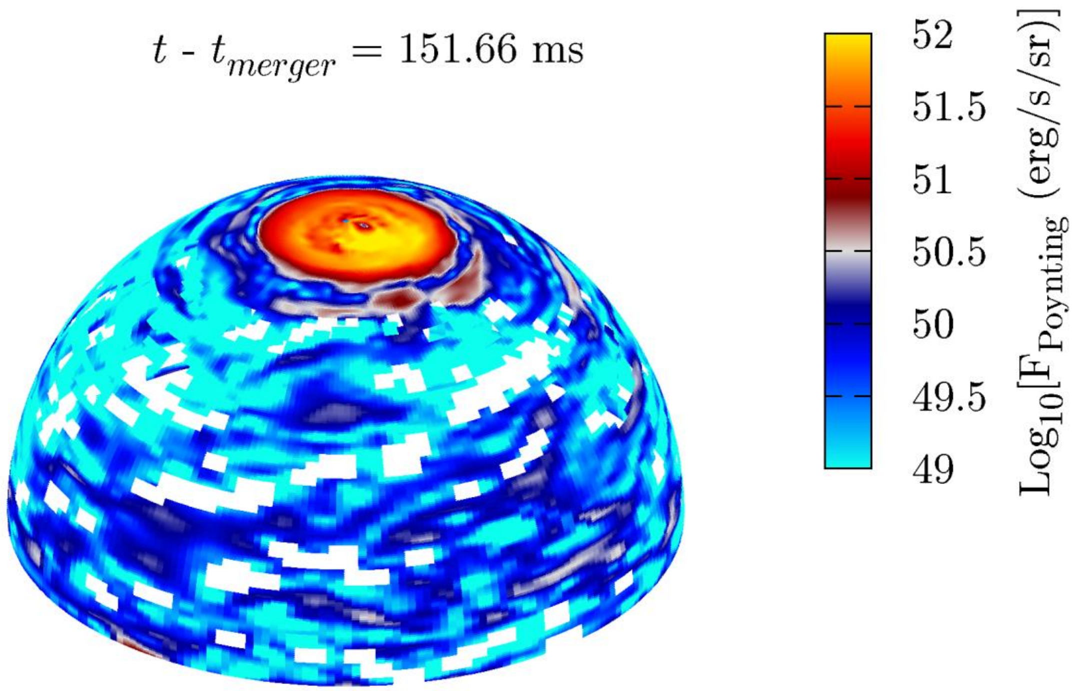


▶ Waves generated in the MRI-active region propagates towards the polar

▶The B-field deep inside the core in the polar region stays buried throughout the simulation

Launching a relativistic outflow

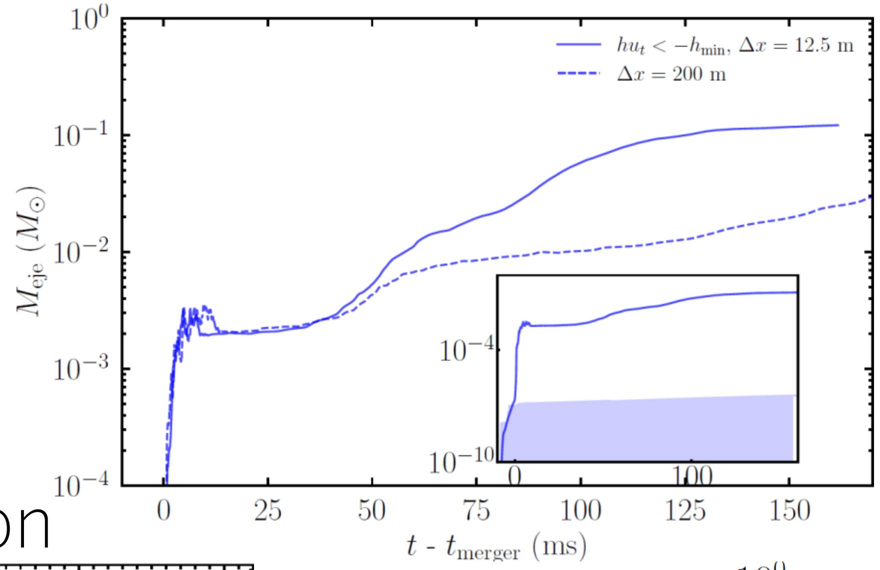




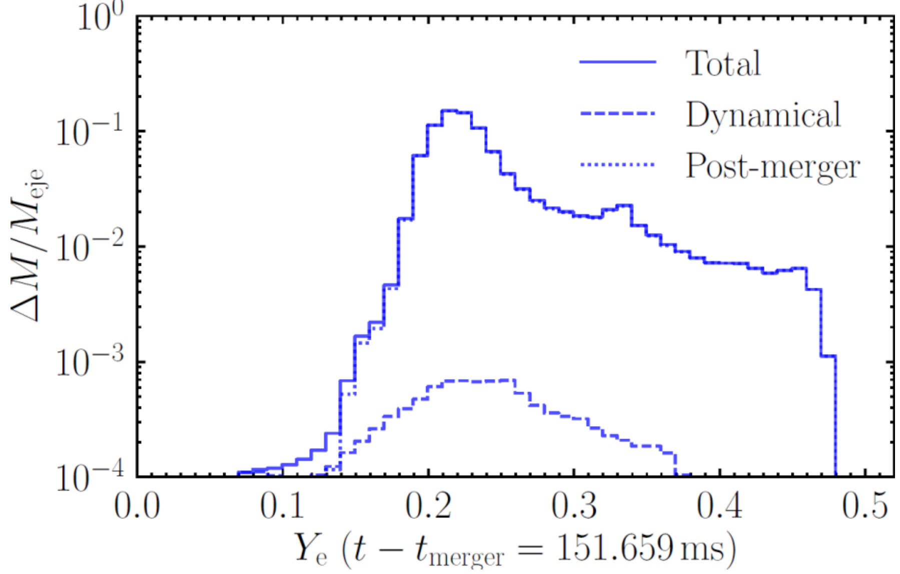
▶Poynting flux dominated outflow launched by the magnetic tower outflow is L_{poy}～10^{51} erg/s

▶ Relativistic outflow is confined in a region with Θ～12° 、 Γ_∞≈10-20

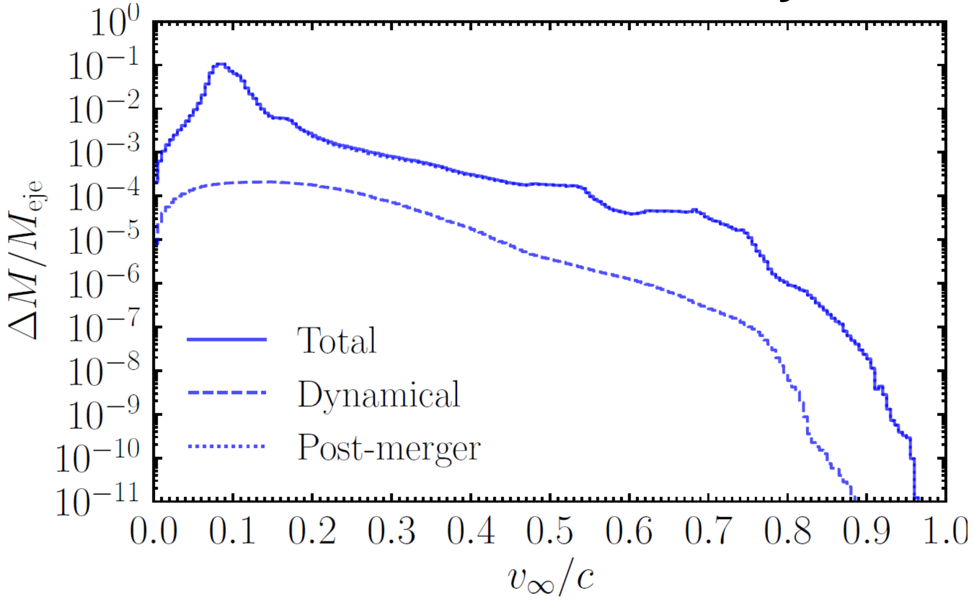
Lorentz force-driven mass ejection



Electron fraction



Terminal velocity



- Post-merger ejecta is ≈0.1 $M_\odot$, $Y_{\rm e,peak}$≈0.2, $v_{\rm peak}$ ≈0.1c

Summary

▶ Direct numerical relativity modeling of GW sources is essential to interpret/predict GW event ⇒ Multimessenger (GW+EM+neutrino?)

▶ For example, O4 runs now. If the information of the GW source is available,

Source parameter of binary neutron star:
Mass of each NSs + unknown equation of state

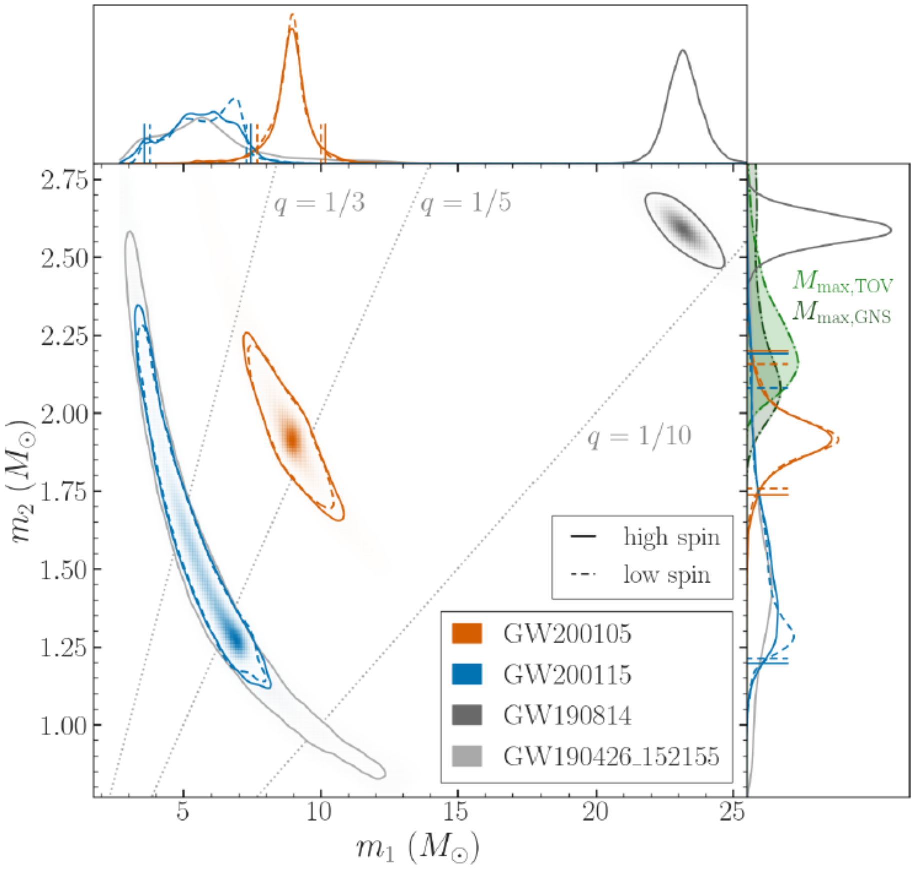
↓ Ab initio simulation on super computers

Multimessenger signals
GW + EM + ?

Back up slide

Application II : Numerical modeling of BH-NS merger

Black hole – Neutron Star merger



LIGO-VIRGO-KAGRA collaboration 21

▶ GW200105, GW200115 *no EM counterpart

Application II : Numerical modeling of BH-NS merger

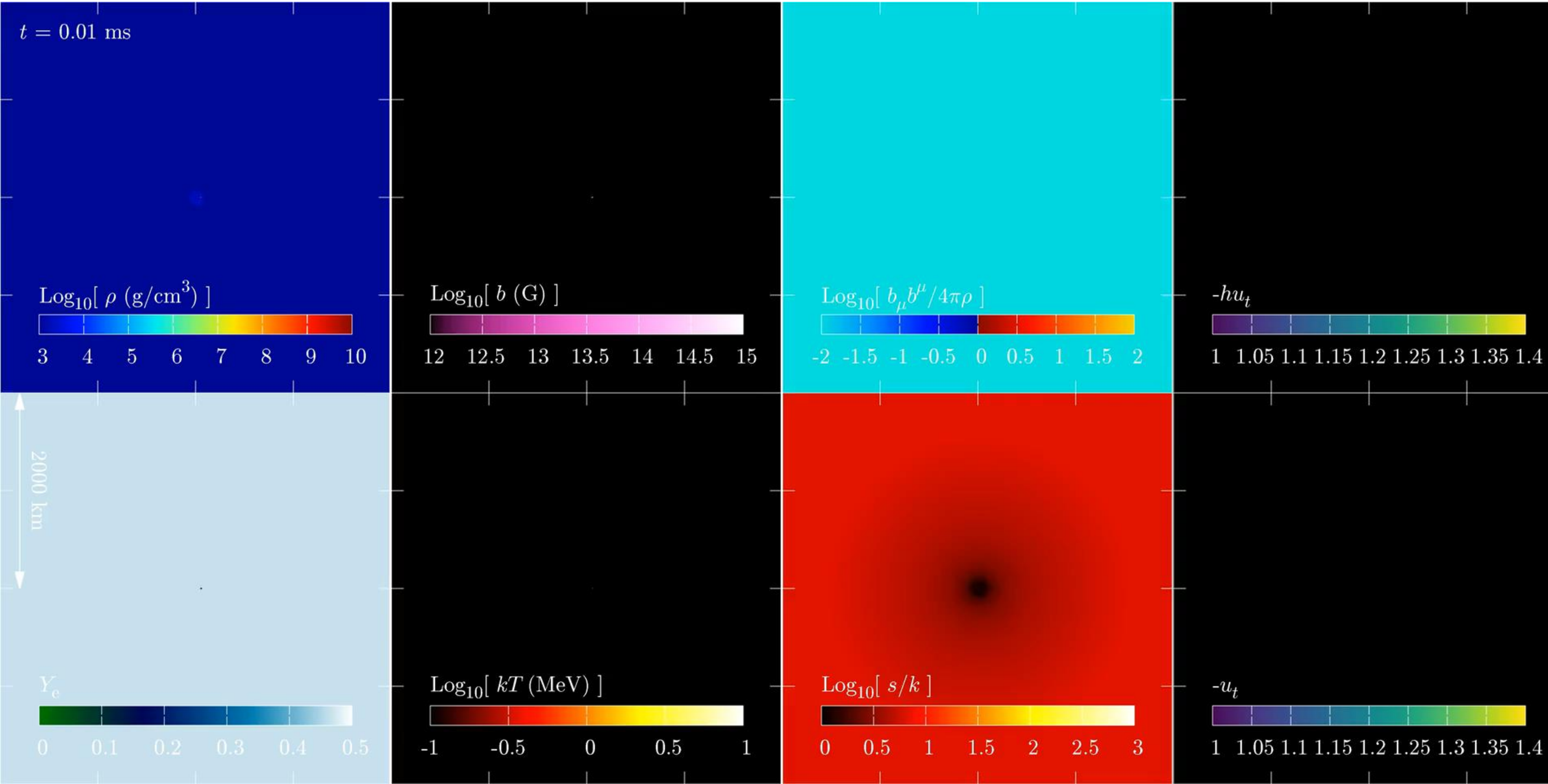
Numerical Relativity-Neutrino-Radiation-Magnetohydrodynamics simulation of BH-NS merger (Hayshi,, KK, et al. 21)

▶ 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

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

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

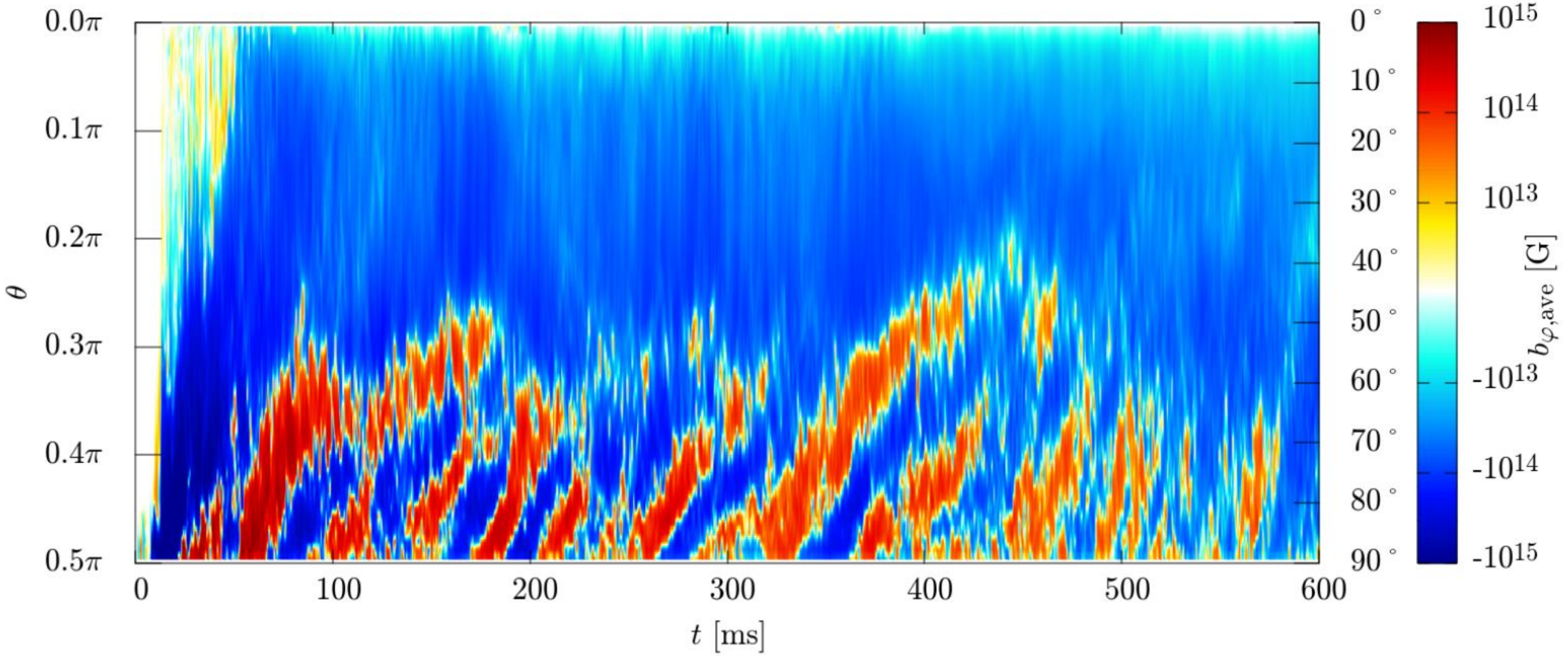


t = 0.01 ms
Log10[ρ (g/cm3)]
3 4 5 6 7 8 9 10
Log10[b (G)]
12 12.5 13 13.5 14 14.5 15
Log10[bμbμ/4πρ]
-2 -1.5 -1 -0.5 0 0.5 1 1.5 2
-hut
1 1.05 1.1 1.15 1.2 1.25 1.3 1.35 1.4
2000 km
Ye
0 0.1 0.2 0.3 0.4 0.5
Log10[kT (MeV)]
-1 -0.5 0 0.5 1
Log10[s/k]
0 0.5 1 1.5 2 2.5 3
-ut
1 1.05 1.1 1.15 1.2 1.25 1.3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

Numerical modeling of BH-NS merger

MRI works?

Butterfly diagram

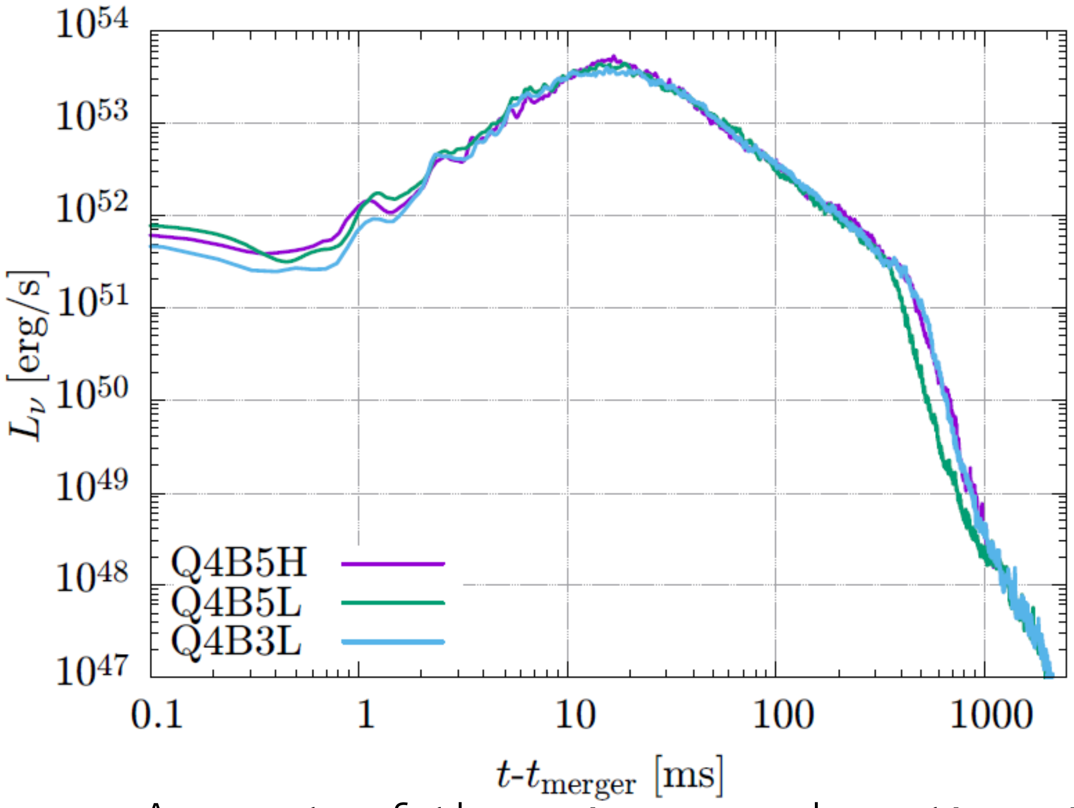


▶ MRI-dynamo works ⇒ Effective turbulent viscosity ($\alpha \approx 0.01$)

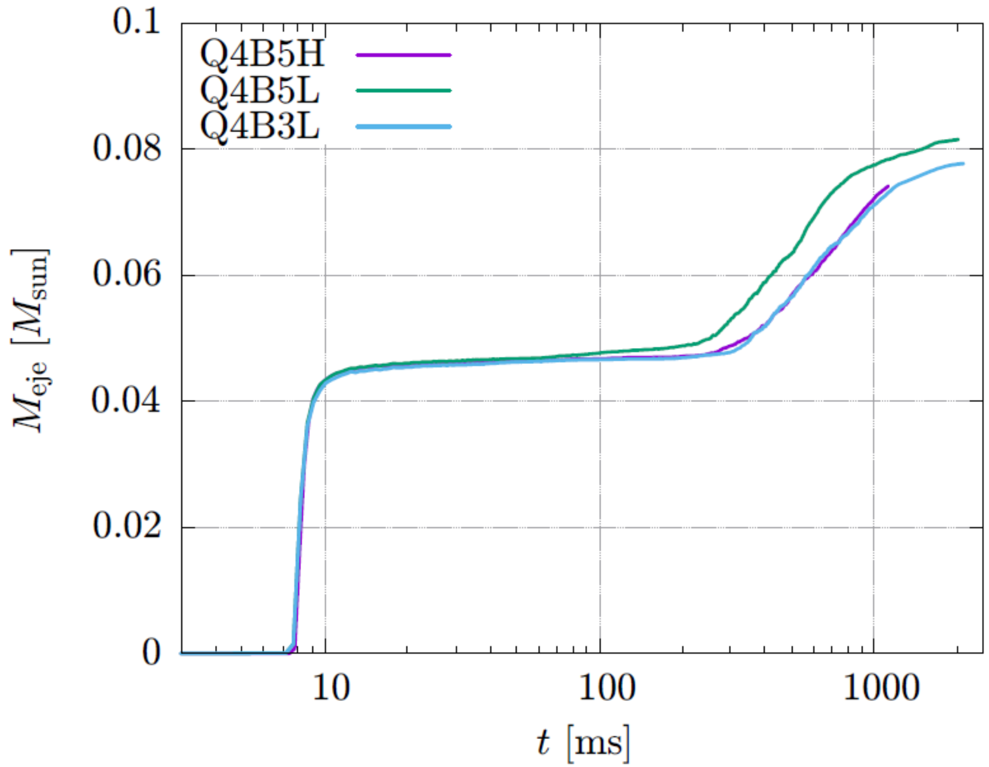
⇒Torus expands due to the angular momentum transport

Numerical modeling of BH-NS merger

Neutrino luminosity



Gravitational unbounded baryonic mass



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

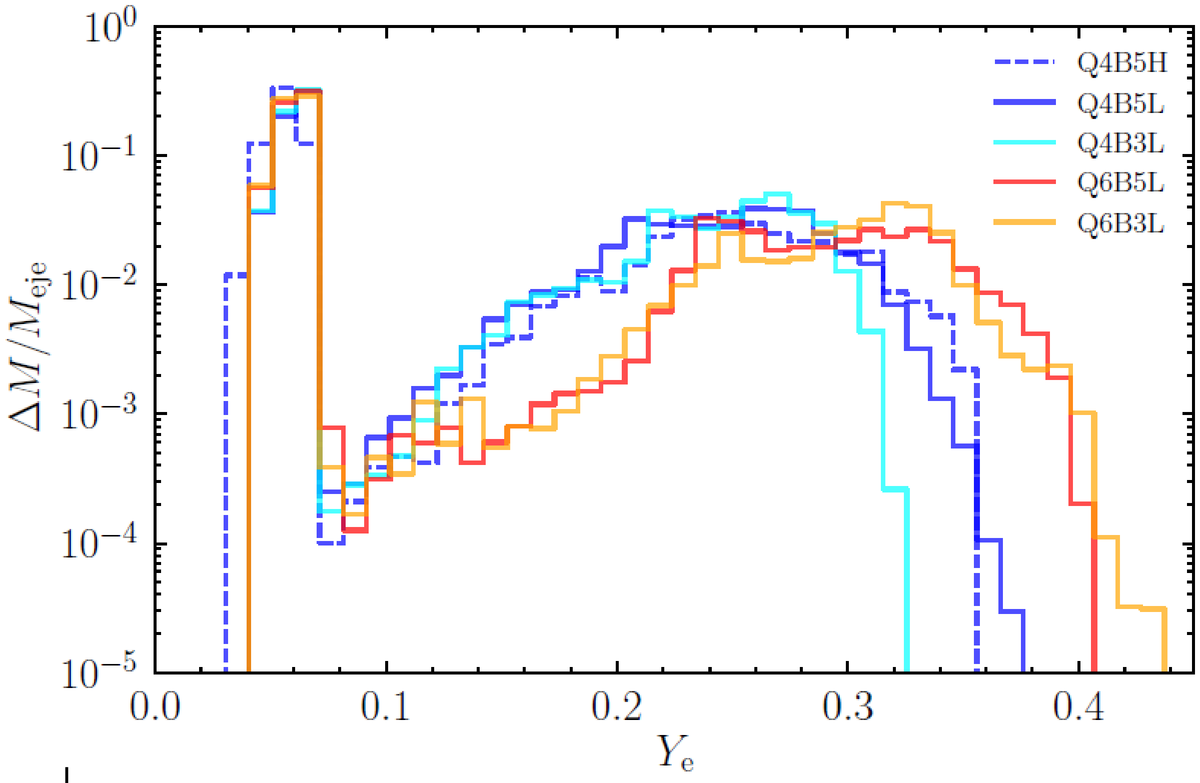
⇒ Temperature decreases due to the torus expansion

⇒ At some point, the neutrino emission becomes inefficient.

⇒ All the viscous heating is used for the torus expansion

Numerical modeling of BH-NS merger

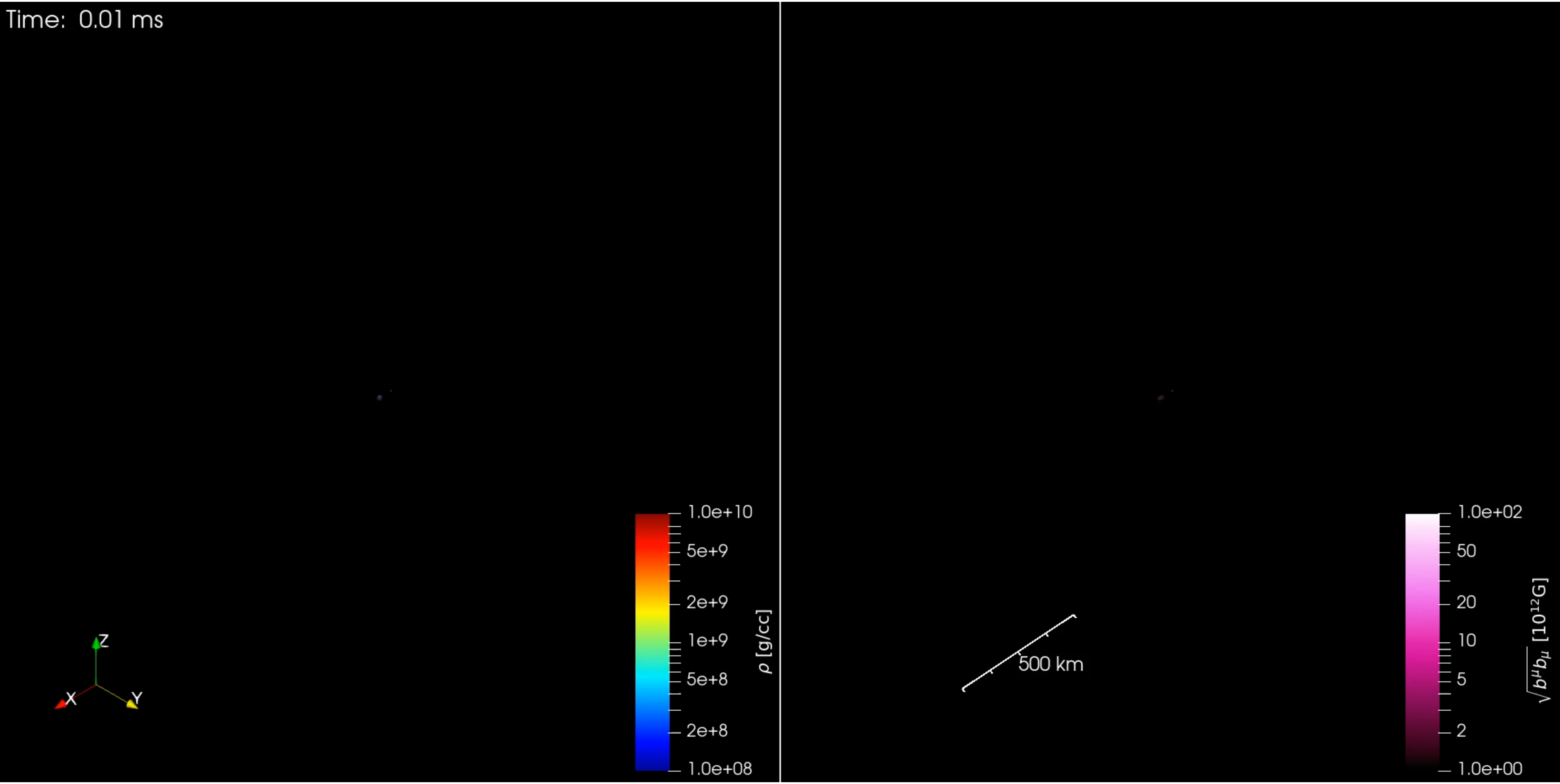
Electron fraction distribution of gravitationally unbounded material



▶ Two distinct peaks

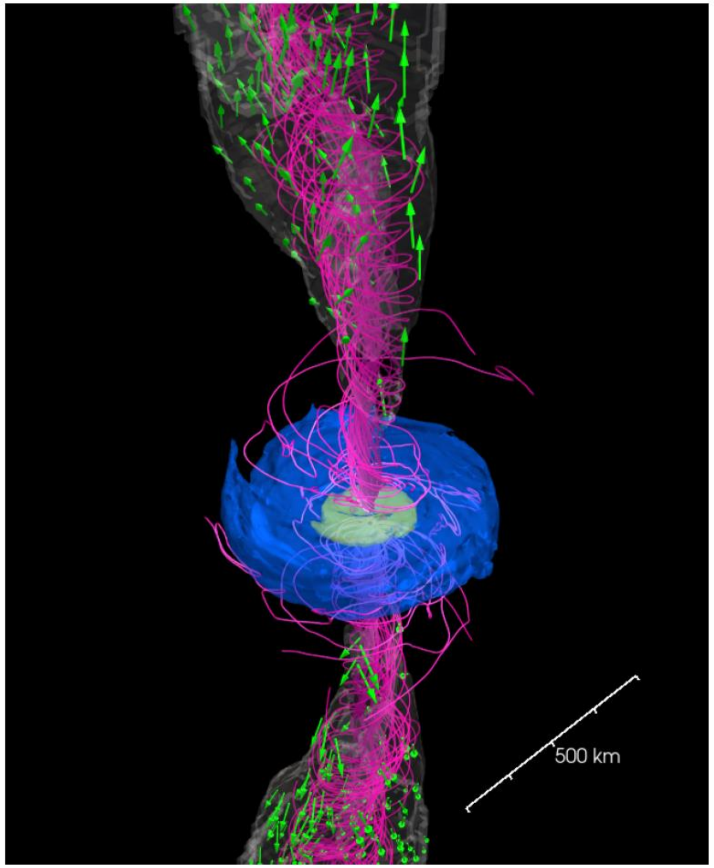
Low Y_e component ⇒ Dynamical ejecta ⇒ NIR band emission

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

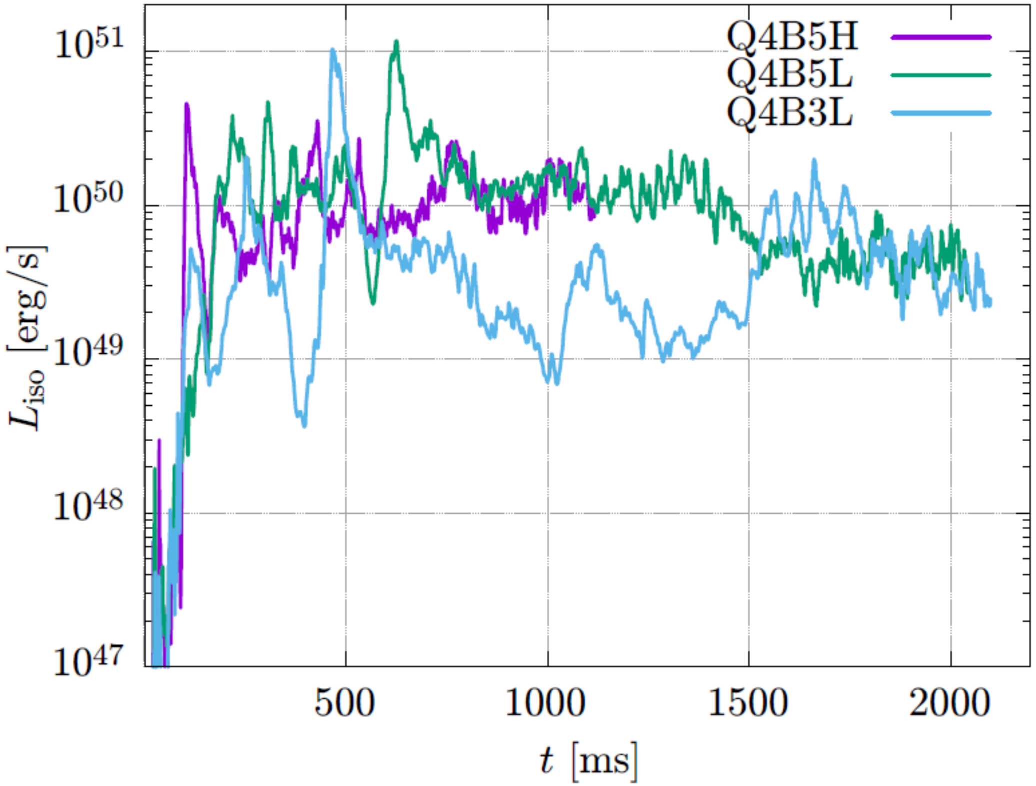

Time: 0.01 ms
1.0e+10
5e+9
2e+9
1e+9
5e+8
2e+8
1.0e+08
ρ [g/cc]
Z
X
Y
500 km
1.0e+02
50
20
10
5
2
1.0e+00
$\sqrt{b^\mu b_\mu}$ [10^{12}G]

Numerical modeling of BH-NS merger

Magnetically tower "jet"



Isotropic Poynting Luminosity

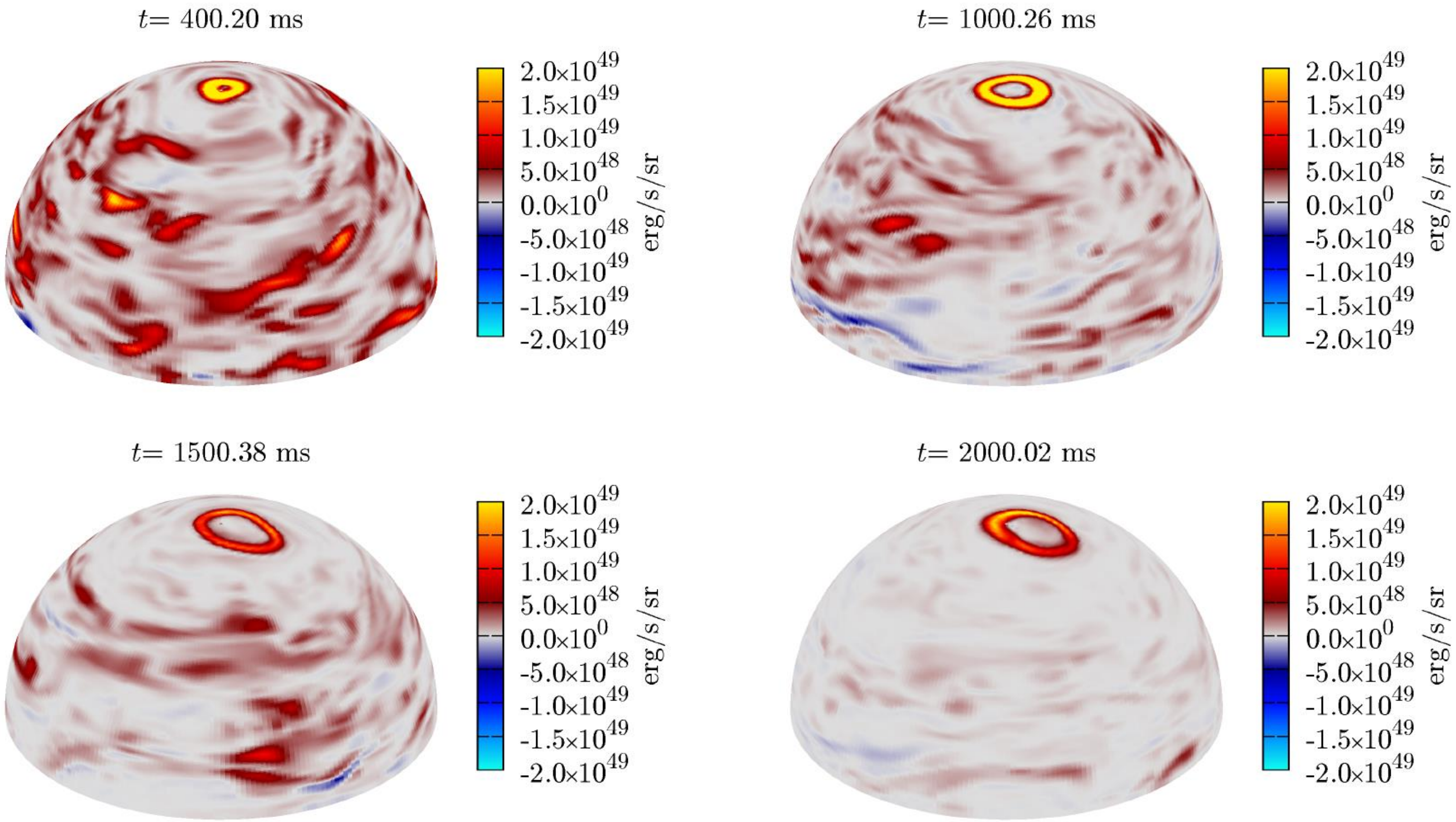


▶ Magnetically tower "jet" builds up magnetosphere

⇒ 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.