General Relativistic neutrino-Radiation MagnetoHydroDynamics (GRRMHD) simulations of binary neutron star mergers

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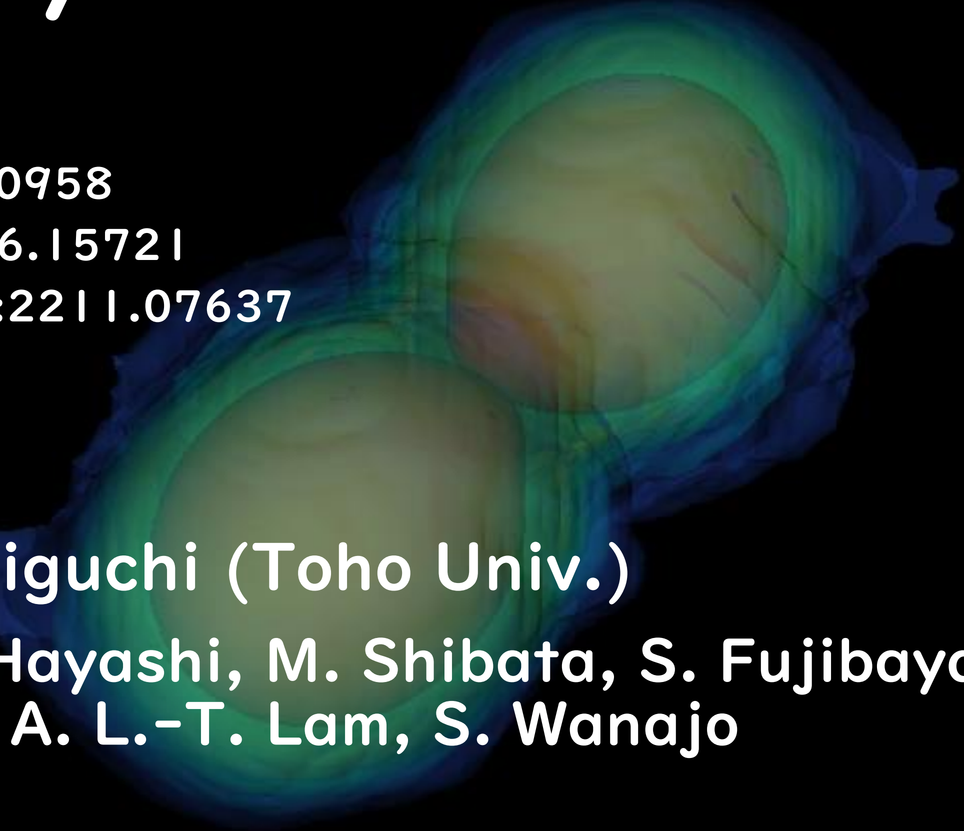
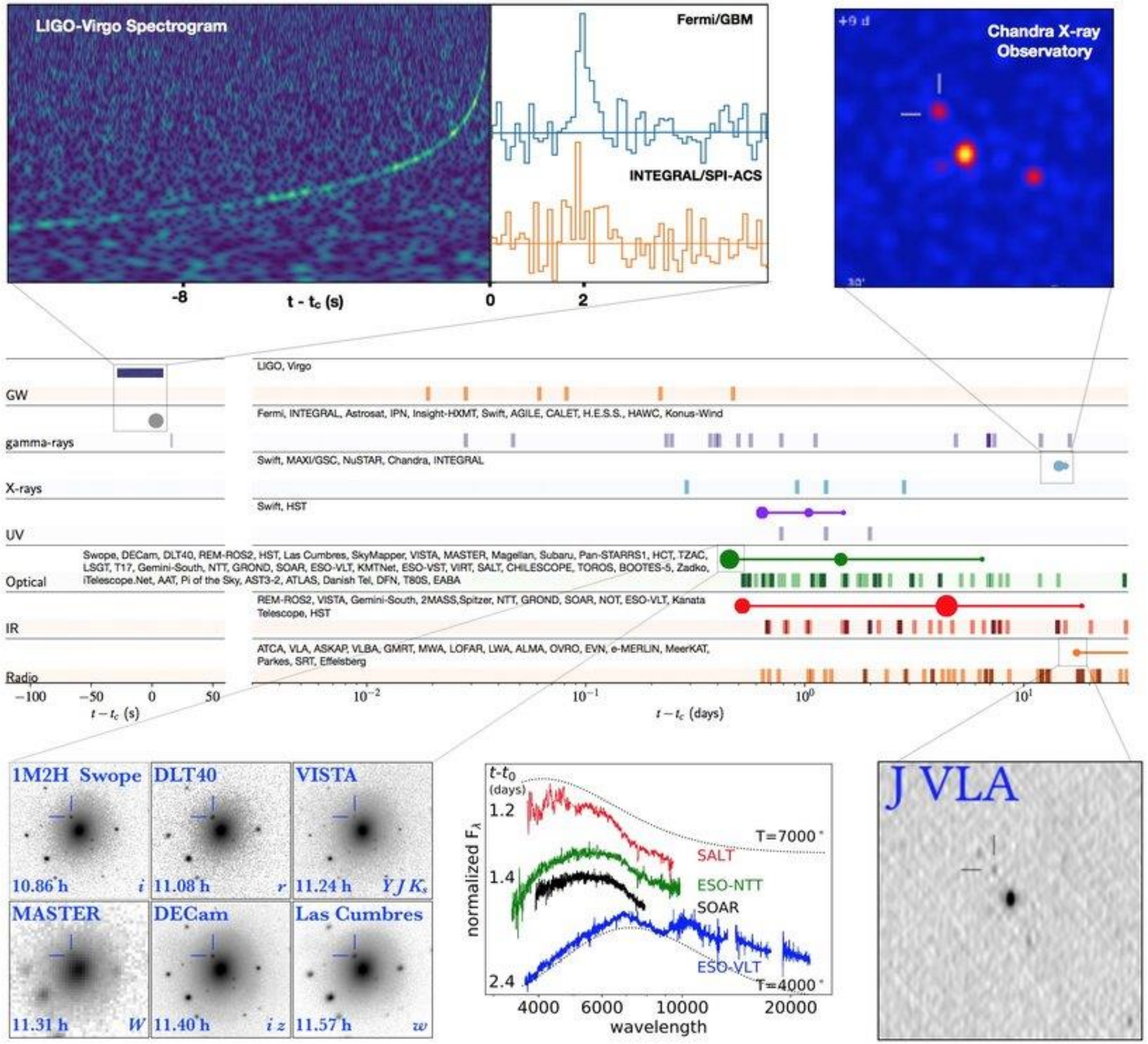


Yuichiro Sekiguchi (Toho Univ.)

Collaborators: K. Kiuchi, K. Hayashi, M. Shibata, S. Fujibayashi, A. Reboul-Salze, A. L.-T. Lam, S. Wanajo

GW170817: dawn of Multi-messenger astrophysics with GW

- **Detection of GW170817**
  - constraint on neutron star (NS) equation of state by tidal deformability of NS in the late inspiral stage
  - measurement of Hubble constant
- **Observation of AT2017gfo**
  - the origin of r-process elements like rare earth elements (Lanthanides), Au, Pt, and U is likely to be binary NS
- **Association of GRB170817**
  - the central engine of (at least a part of) short hard GRB is binary neutron star merger



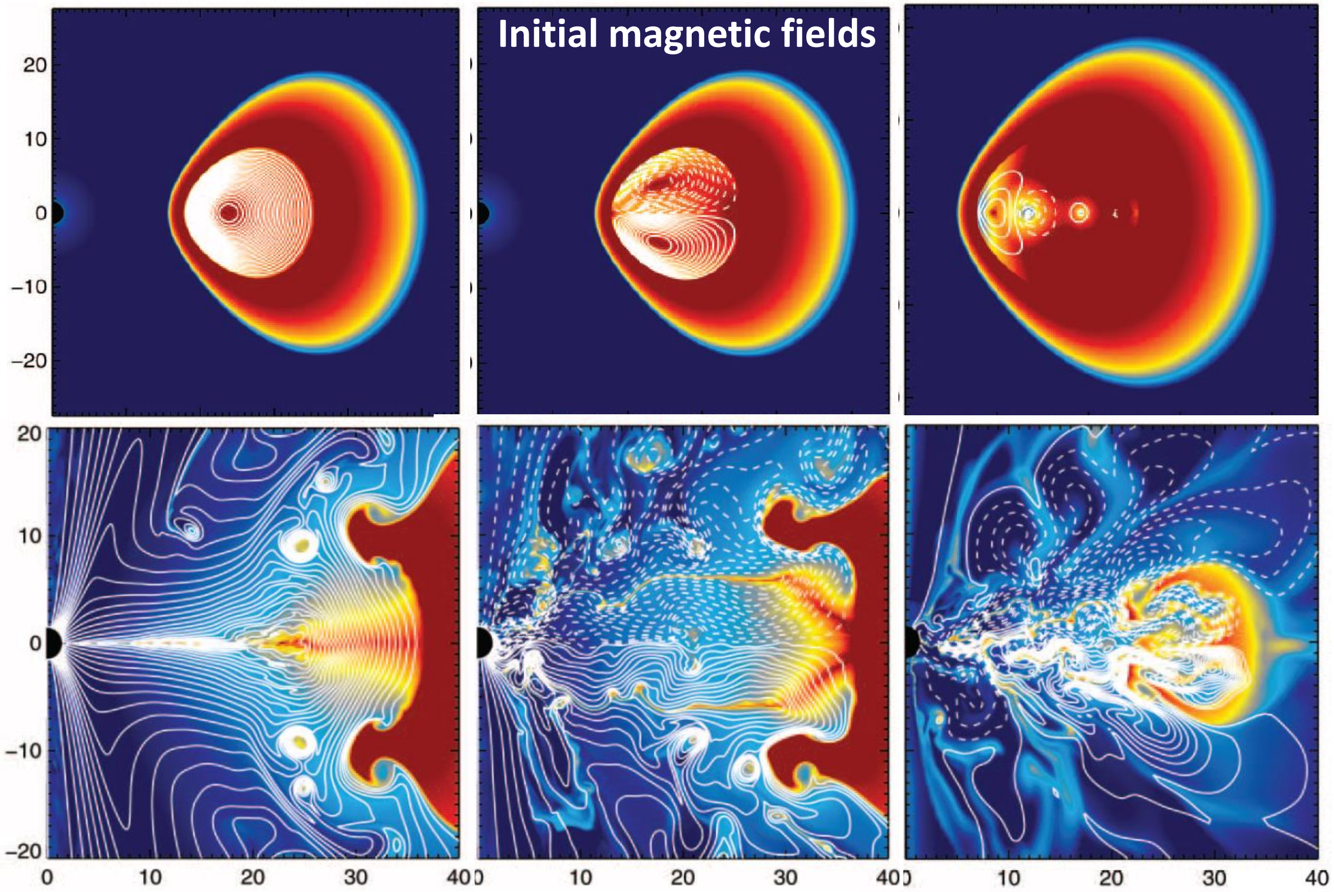
Abbott et al. 2017

How to drive a short GRB jet ?

- **Blandford-Znajek mechanism** is a promising mechanism to launch the short GRB jet
- **Strong** ($\gtrsim 10^{15}$ G) **and coherent magnetic fields** which thread the BH horizon are necessary to launch an energetic jet
- Poloidal magnetic fields of binary pulsars estimated by the spin-down period : $B_p \sim 10^{8-12}$ G $\ll 10^{15}$ G

Tauris et al. 2017

Beckwith et al. 2008



Key question

How to make such a strong coherent magnetic field from NS magnetic field

Generation of coherent magnetic fields

e.g., Moffatt (1978) "Magnetic field generation in electrically conducting fluids"

The averaged induction equation

$$\partial_t \overline{\boldsymbol{B}} = \nabla \times (\overline{\boldsymbol{U}} \times \overline{\boldsymbol{B}} + \overline{\boldsymbol{\mathcal{E}}})$$

Electromotive force

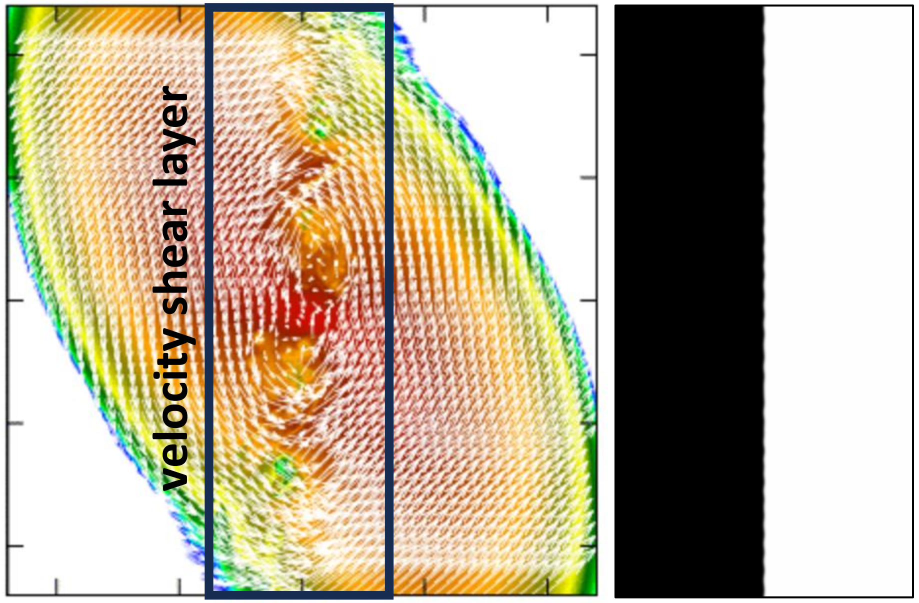
$$\overline{\boldsymbol{\mathcal{E}}} = \overline{\boldsymbol{u} \times \boldsymbol{b}}$$

mean field random field

$$\boldsymbol{Q} = \overline{\boldsymbol{Q}} + \boldsymbol{q}$$

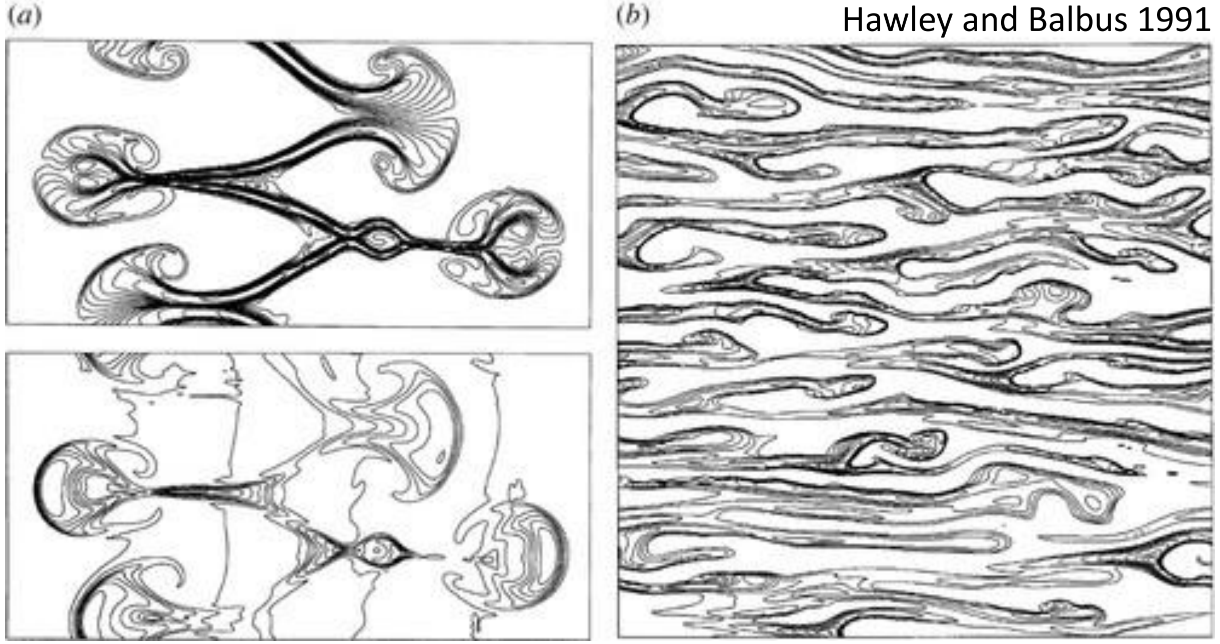
⇒ small scale turbulent velocity and magnetic fields can generate coherent fields

Kiuchi et al. 2015, 2018



Kelvin-Helmholtz (KH) instability at the contact shear

Hawley and Balbus 1991



Magneto-rotational instability (MRI) in the torus

Generation of coherent magnetic fields

e.g., Moffatt (1978) “Magnetic field generation in electrically conducting fluids”

The averaged induction equation

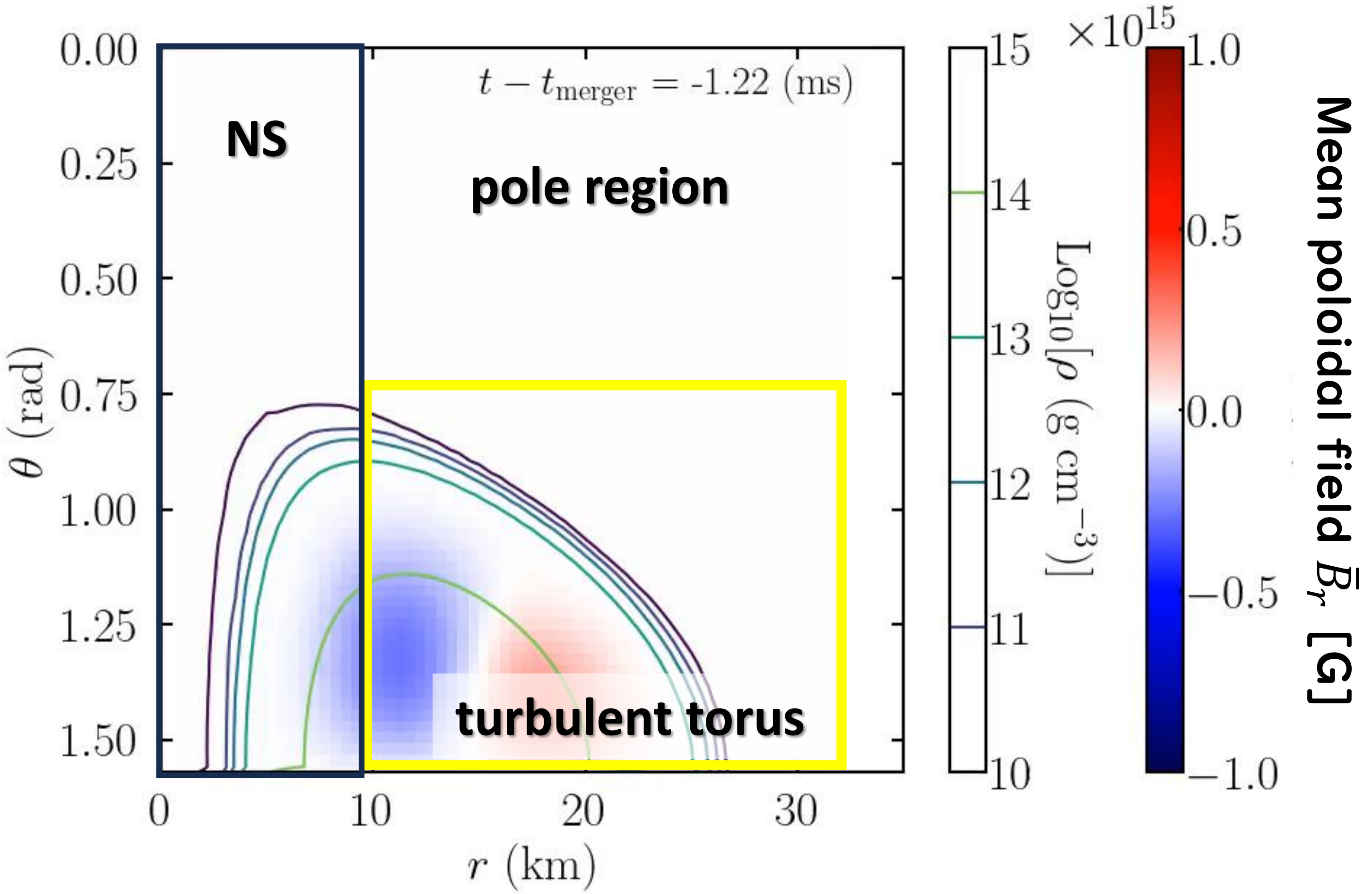
$$\partial_t \overline{\boldsymbol{B}} = \nabla \times (\overline{\boldsymbol{U}} \times \overline{\boldsymbol{B}} + \overline{\boldsymbol{\mathcal{E}}})$$

Electromotive force

$$\overline{\boldsymbol{\mathcal{E}}} = \overline{\boldsymbol{u} \times \boldsymbol{b}}$$

mean field, random field

$$\boldsymbol{Q} = \overline{\boldsymbol{Q}} + \boldsymbol{q}$$



Kiuchi et al. 2024

Generation of coherent magnetic fields

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The averaged induction equation

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

Electromotive force

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

mean field \ random field

$$\boldsymbol{Q} = \bar{\boldsymbol{Q}} + \boldsymbol{q}$$

Phenomenological Prescription

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

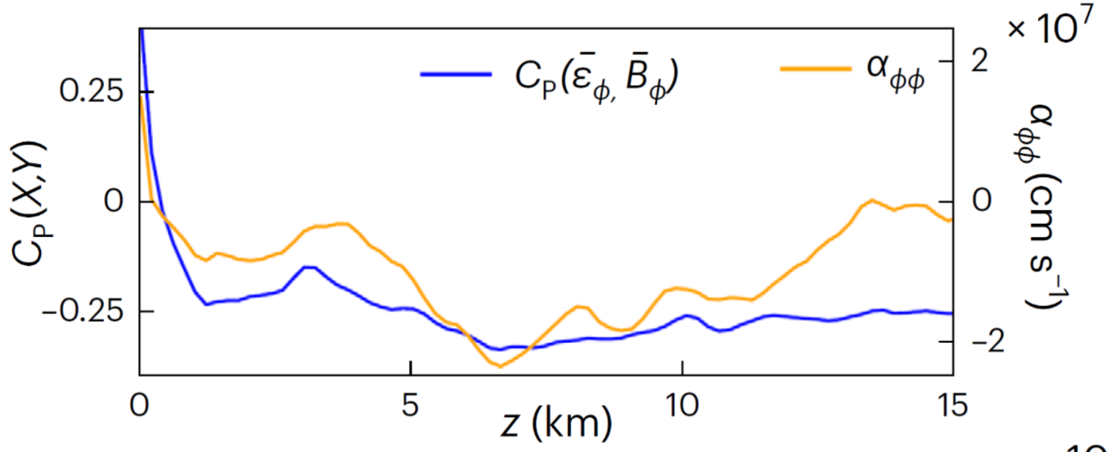
$$\partial_t \bar{B}_R = -\partial_z(\alpha_{\varphi\varphi}\bar{B}_\varphi) \qquad R = \sqrt{x^2 + y^2}$$

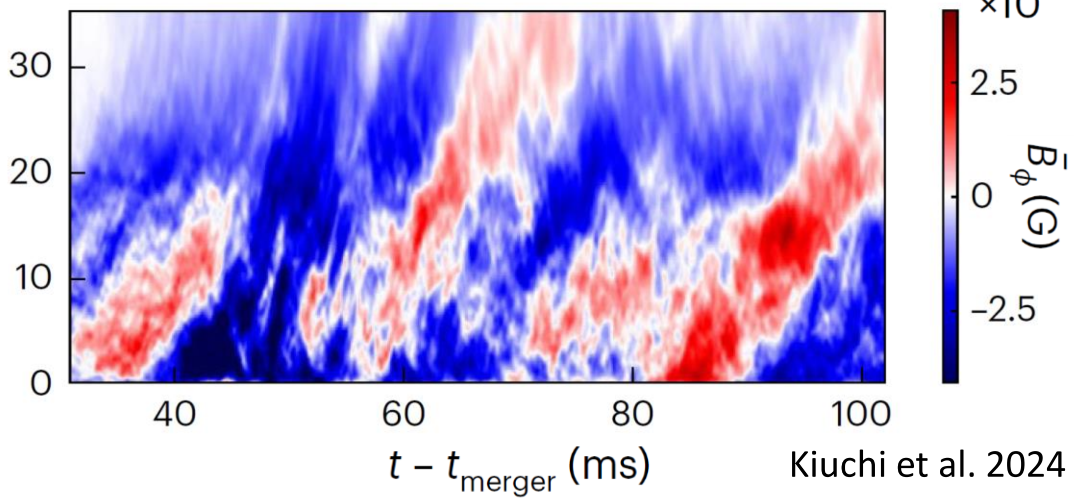
$$\partial_t \bar{B}_\varphi = r \sin\theta \, (\bar{\boldsymbol{B}}_{\mathrm{pol}} \cdot \boldsymbol{\nabla}\Omega)$$

$\alpha\Omega$ dynamo

- ✓ (anti-correlation between $\bar{B}_\varphi$ and $\bar{\mathcal{E}}_\varphi$
- ✓ dynamo-wave propagate to $\alpha_{\varphi\varphi}\nabla\Omega \times \boldsymbol{e}_\varphi \propto -\boldsymbol{e}_\theta$
- ✓ dynamo-cycle period :

$$\tau_{\mathrm{dynamo}} \sim \sqrt{2}\pi \left(\alpha_{\varphi\varphi} k_z \frac{d\Omega}{d\ln R}\right)^{-1/2} \sim \text{a few 10 ms}$$

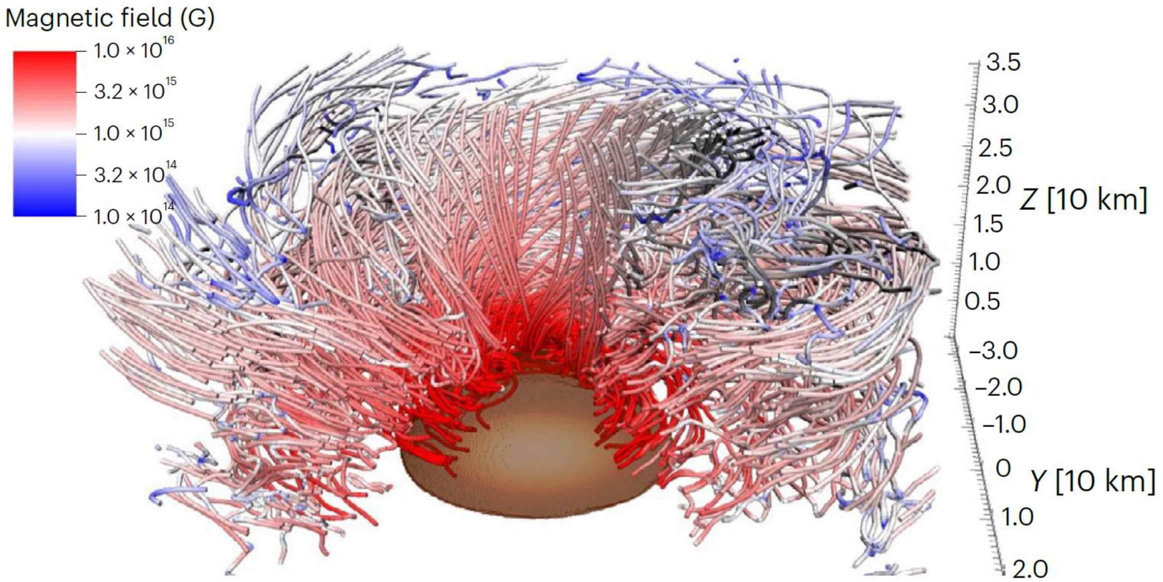


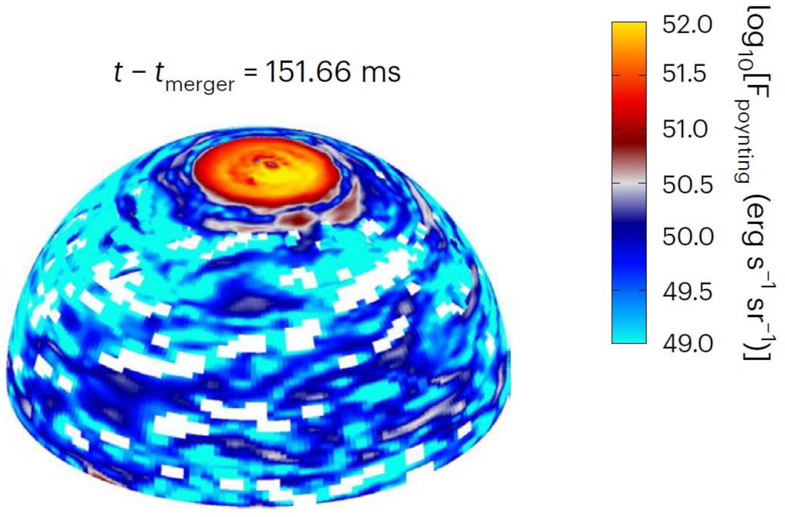


Kiuchi et al. 2024

prompt collapse $O(0.01\ \mathrm{sec})$ $O(0.1\ \mathrm{sec})$ $< O(1\ \mathrm{sec})$

Remnant NS lifetime





- ✓ Magnetic field amplification by Kelvin-Helmholtz instability and magneto-rotational instability
- ✓ Subsequent mean field generation by $\alpha\Omega$ dynamo
- ✓ Collimated ($\theta_{\mathrm{jet}} \approx 12°$), Poynting flux dominated jet launched with $L_{\mathrm{Poy}} \sim 10^{51}\ \mathrm{erg/s}$ (this is NOT the isotropic-equivalent luminosity)
- ✓ Mildly neutron-rich ($X_{n,\mathrm{ave}} \sim 0.7$) ejecta with $M_{\mathrm{ej}} \geq 0.1 M_{\odot}$

領域研究会 2023； Kiuchi et al. 2024

GW190425 and Prompt collapse to a BH

Brief summary of GW190425

Abbott et al. 2020

- ✓ Total mass of BNS : $M_{\mathrm{total}} = 3.3{\sim}3.4 M_{\odot}$
  ⇒ expected to collapse promptly to a BH
- ✓ Poor sky localization due to a single detector event
- ✓ no electromagnetic counterpart is detected

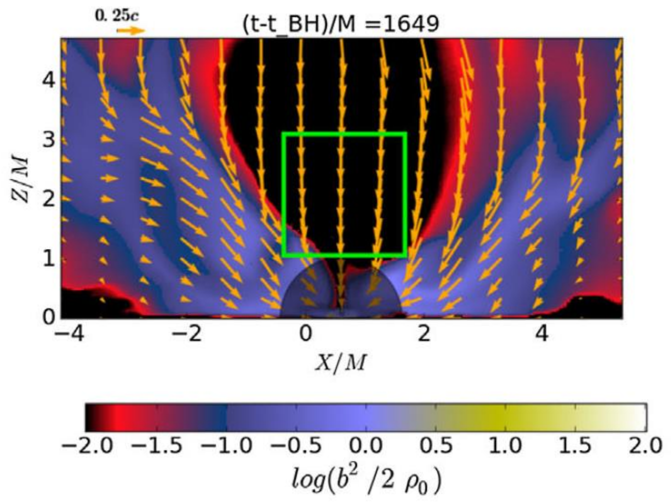
Source Properties for GW190425

	Low-spin Prior ($\chi < 0.05$)	High-spin Prior ($\chi < 0.89$)
Primary mass m_1	1.60–1.87 $M_{\odot}$	1.61–2.52 $M_{\odot}$
Secondary mass m_2	1.46–1.69 $M_{\odot}$	1.12–1.68 $M_{\odot}$
Chirp mass $\mathcal{M}$	$1.44^{+0.02}_{-0.02}$ $M_{\odot}$	$1.44^{+0.02}_{-0.02}$ $M_{\odot}$
Detector-frame chirp mass	$1.4868^{+0.0003}_{-0.0003}$ $M_{\odot}$	$1.4873^{+0.0008}_{-0.0006}$ $M_{\odot}$
Mass ratio m_2/m_1	0.8 – 1.0	0.4 – 1.0
Total mass m_{tot}	$3.3^{+0.1}_{-0.1}$ $M_{\odot}$	$3.4^{+0.3}_{-0.1}$ $M_{\odot}$
Effective inspiral spin parameter χ_{eff}	$0.012^{+0.01}_{-0.01}$	$0.058^{+0.11}_{-0.05}$
Luminosity distance D_{L}	159^{+69}_{-72} Mpc	159^{+69}_{-71} Mpc
Combined dimensionless tidal deformability $\tilde{\Lambda}$	$\leqslant 600$	$\leqslant 1100$

Previous GRMHD simulation for prompt collapse

Ruiz and Shapiro 2017

- ✓ Poynting flux dominated jet are NOT launched
- ✓ No evidence for coherent magnetic field formation
- ✓ (Nearly) equal mass binary ⇒ small disk mass $\lesssim 10^{-3} M_{\mathrm{tot}}$
- ✓ Short-term simulations up to 26 ms after the merger



Set-up of simulation

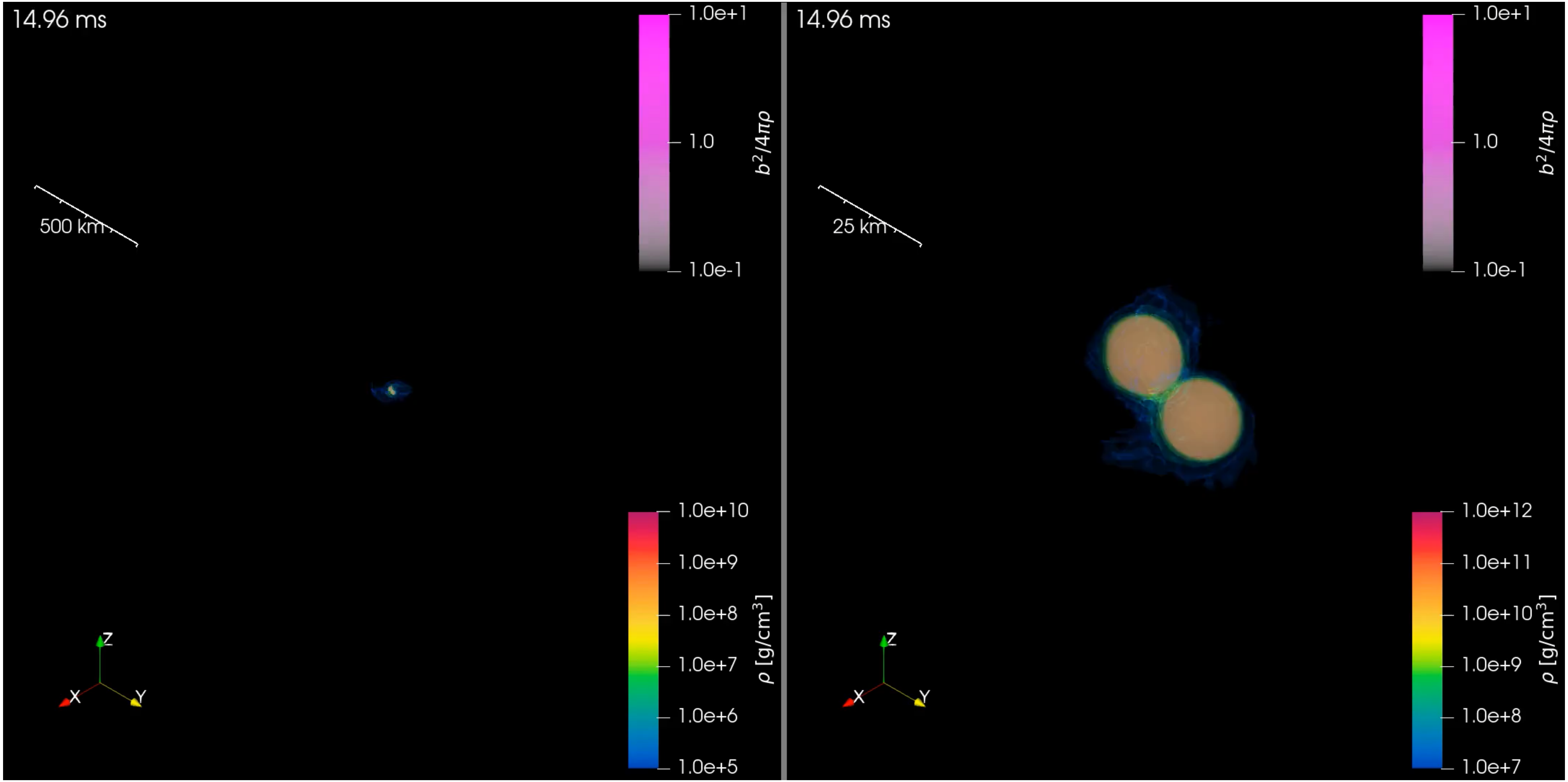
- **Einstein's equations :**
  - ✓ BSSN formalism (Shibata and Nakamura 1995; Baumgarte and Shapiro 1998)
  - ✓ Moving puncture method (Campanelli et al. 2006; Baker et al. 2006)
  - ✓ Z4c constraint propagation (Hilditch et al. 2013)
- **Magnetohydrodynamics :** (Kiuchi et al. 2022)
  - ✓ HLLD Rieman solver (Mignone et al. 2009)
  - ✓ Divergence-B constraint transport (Gardiner and Stone 2008)
  - ✓ Magnetic-flux preserving mesh refinement (Balsara 2009)
- **Neutrino transfer :** (Sekiguchi et al. 2012)
  - ✓ M1 closure (Shibata et al. 2011)
  - ✓ Neutrino heating (Fujibayashi et al. 2017)

- **Prescription of BNS :**
  - ✓ SFHo equation of state (Steiner et al. 2013) : $M_{\rm max} \approx 2.1 M_\odot$
  - ✓ $1.25 M_\odot$-$1.65 M_\odot$ unequal mass binary ($M_{\rm tot} = 2.9\, M_\odot$)
  - ✓ prompt collapse to a BH with $M_{\rm BH} \approx 2.8\, M_\odot$, $a_{\rm BH} = 0.76$
  - ✓ accretion disk with $M_{\rm disk} \approx 0.06\, M_\odot$ is formed
- **Magnetic field :**
  - ✓ poloidal magnetic field is superimposed inside the NSs

    $A_j = A[(x - x_{NS})\delta_j^y - (y - y_{NS})\delta_j^x] \cdot max(P/P_{max} - 2 \cdot 10^{-4}, 0)^{1/2}$
  - ✓ maximum field strength is $\approx 10^{15}$ G
- **Grid set-up and timescale :**
  - ✓ 13-level fixed mesh refinement
  - ✓ finest grid resolution : $\Delta x = 150$ m enable to follow the fastest growing mode of magneto-rotational instability

    $$\lambda_{\rm MRI} \sim \frac{v_{\rm Alfven}}{\Omega} \sim \frac{B}{\Omega\sqrt{4\pi\rho}}$$
  - ✓ Long-term (> 1 sec) simulation

animation by K. Hayashi

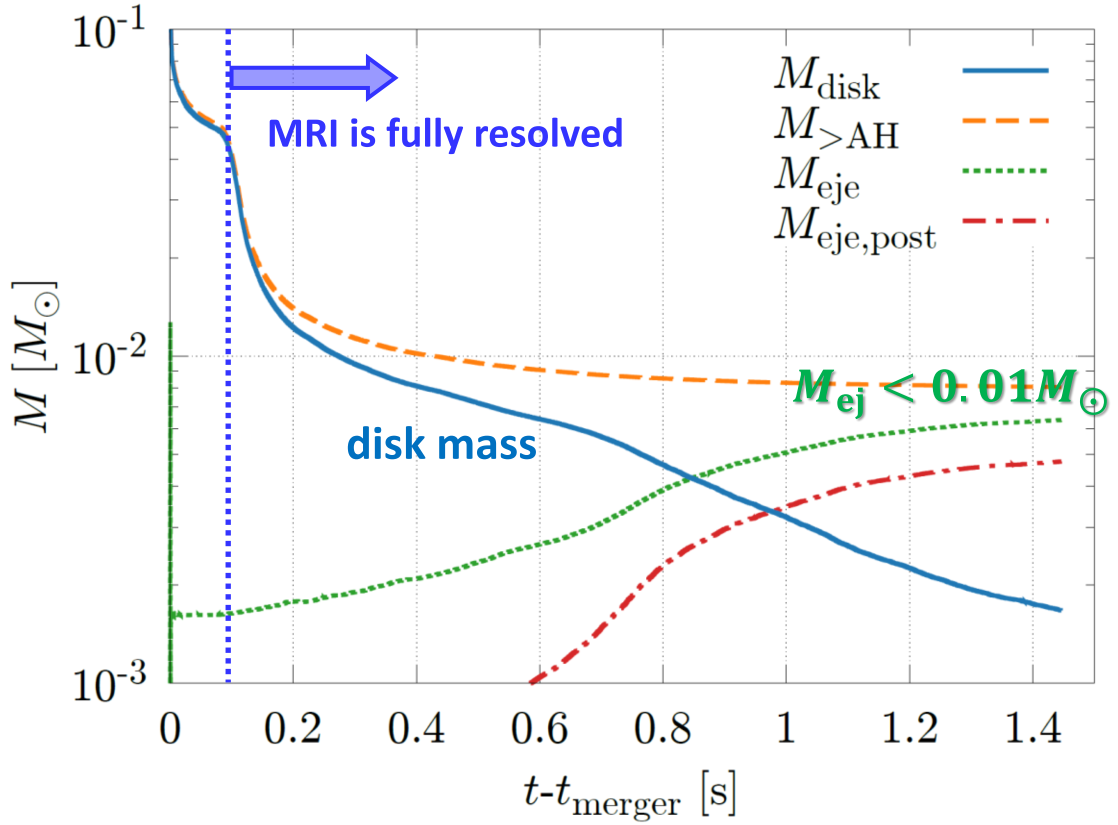


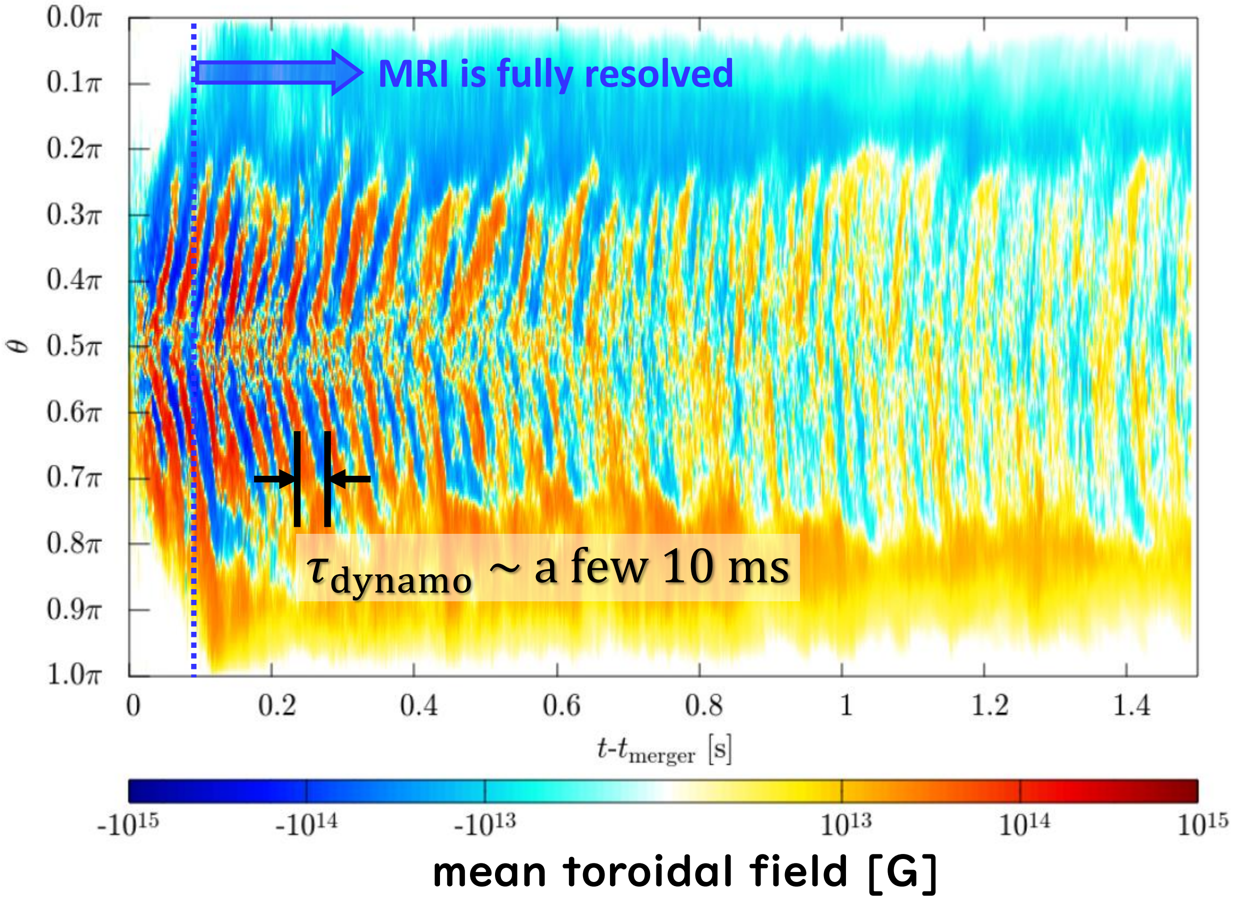
Hayashi et al. submitted to PRL

MRI induced viscosity and dynamo

The fastest growing mode is resolved : partially ($t - t_{merger} \gtrsim 10$ ms), fully ($t - t_{merger} \gtrsim 100$ ms)

- ✓ MRI driven turbulence induces effective viscosity and disk mass decays
- ✓ MRI driven turbulence activates the dynamo cycle and coherent magnetic fields are formed

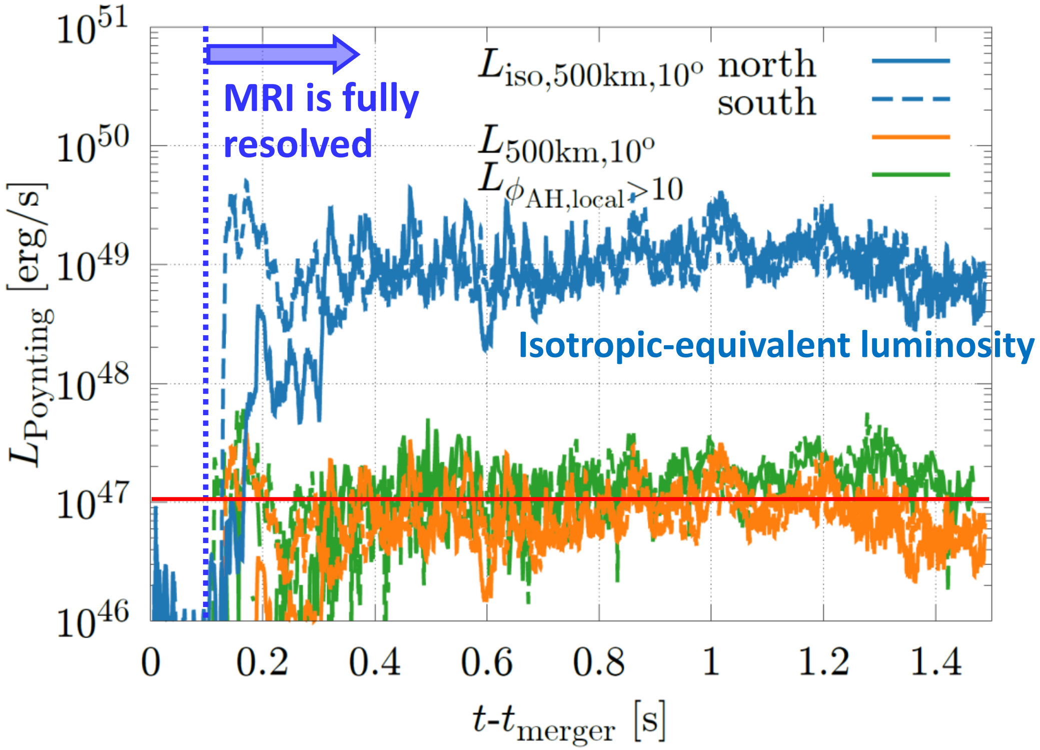


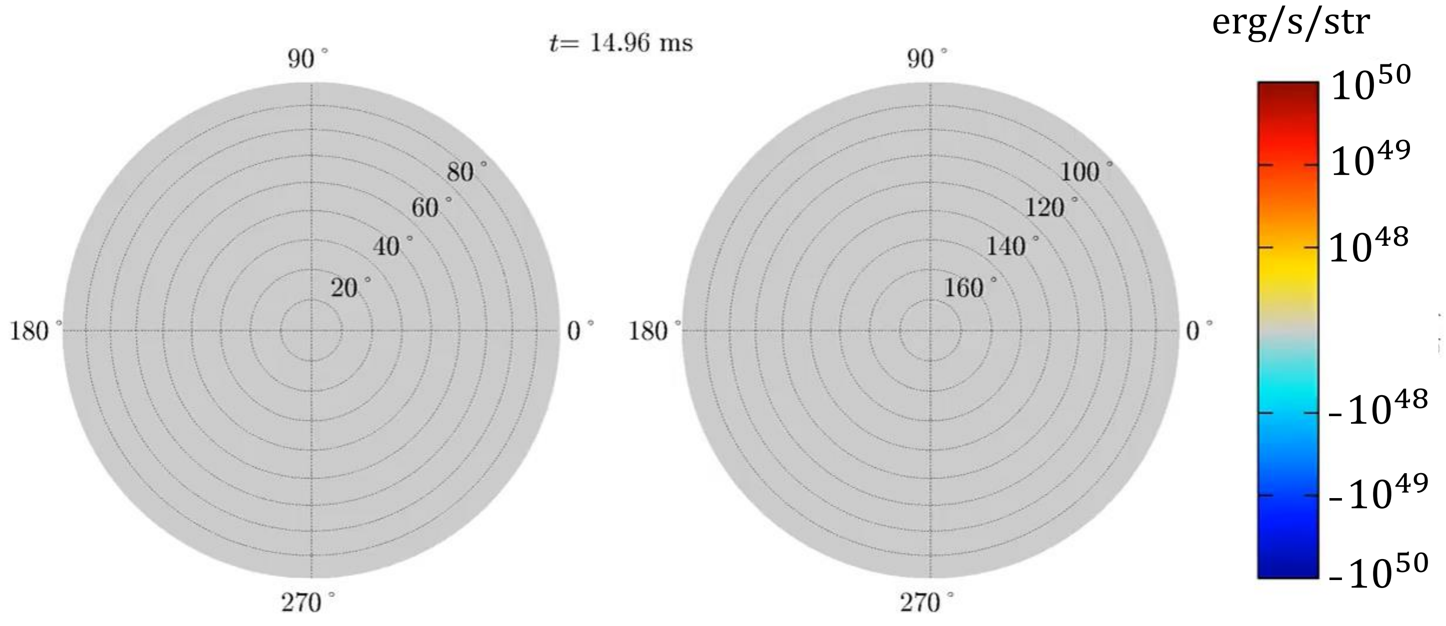


Hayashi et al. submitted to PRL

(Weak) Poynting flux dominated jet is launched

- ✓ Coherent magnetic fields accrete the BH and further amplified by winding
  - ✓ Note also that Prompt collapse to BH ⇒ density and ram pressure in the pole region is smaller
- ✓ Collimated ($\theta_{\rm jet} \sim 10°$), Poynting flux dominated jet launched with $L_{\rm Poy} \sim 10^{47}$ erg/s
  - ✓ Jet angle gradually increases as matter pressure, which confines the jet, decreases





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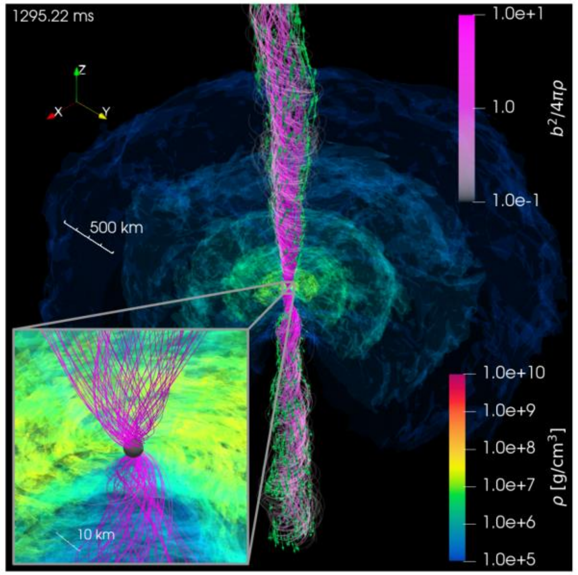
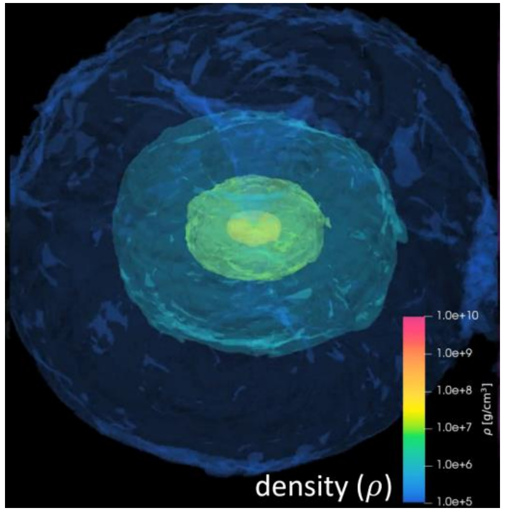
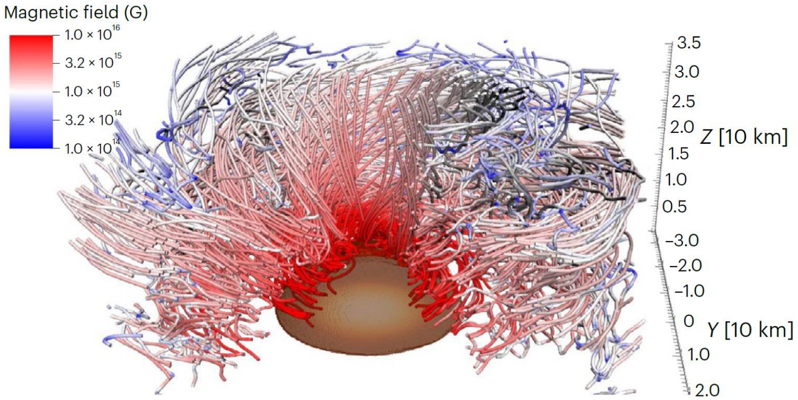






- ✓ Prompt BH formation
- ✓ mean field generation by MRI-induced dynamo
- ✓ ram pressure is smaller
- ✓ $L_{\rm Poy} \sim 10^{47}$ erg/s , $\theta_{\rm jet} \sim 10°$
- ✓ $M_{\rm ej} \lesssim 0.01 M_\odot$

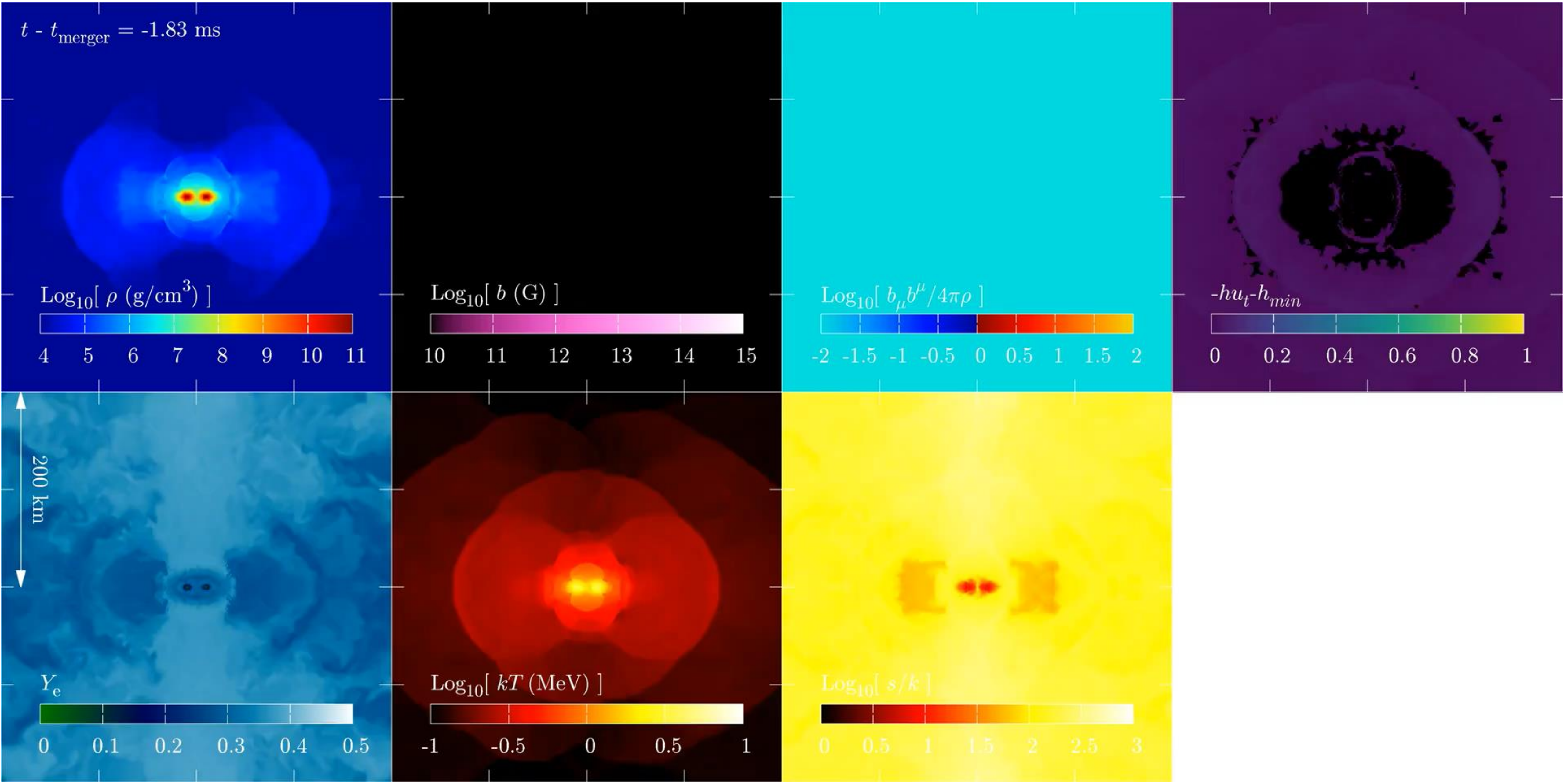
Hayashi et al. PRL submitted

- ✓ delayed BH formation
- ✓ MRI is resolved
- ✓ ram pressure is stronger than magnetic pressure
- ✓ Jet is not launched in 1 sec after the merger

Kiuchi et al. PRL 2023

- ✓ Long-lived NS : amplification by KH instability and MRI
- ✓ mean field generation by $\alpha\Omega$ dynamo
- ✓ $L_{\rm Poy} \sim 10^{51}$ erg/s , $\theta_{\rm jet} \approx 12°$
- ✓ $M_{\rm ej} \geq 0.1 M_\odot$ $(X_{n,\rm ave} \sim 0.7)$

Kiuchi et al. Nature Astronomy 2024

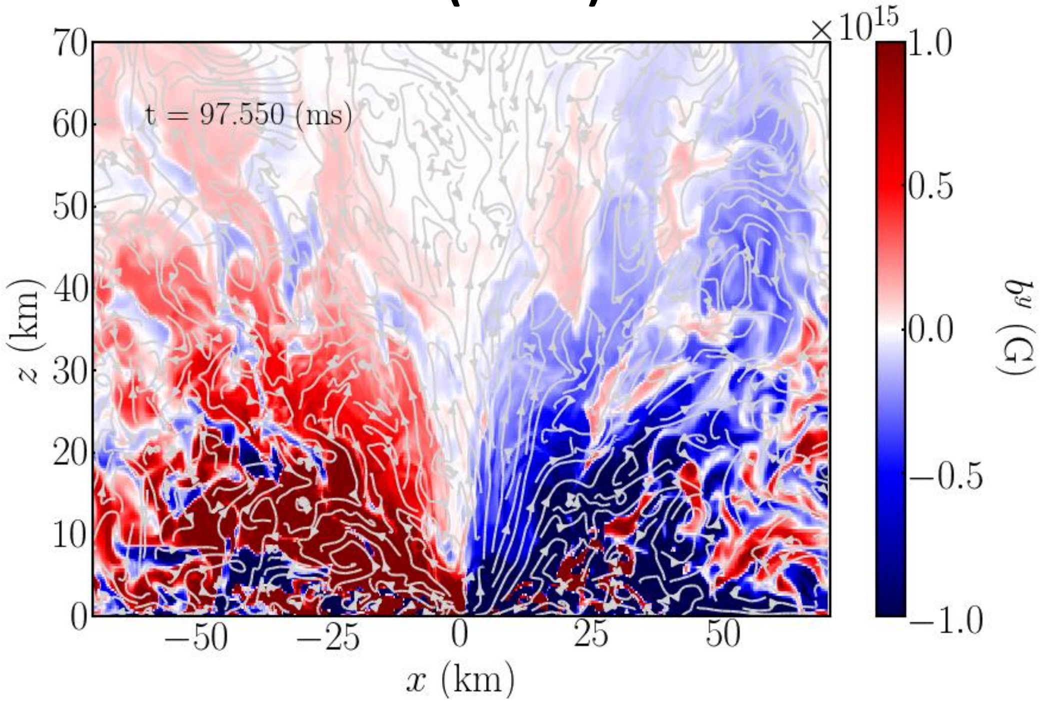


t - $t_{\rm merger}$ = -1.83 ms
Log$_{10}$[ρ (g/cm^3)]
4 5 6 7 8 9 10 11
Log$_{10}$[b (G)]
10 11 12 13 14 15
Log$_{10}$[$b_\mu b^\mu/4\pi\rho$]
-2 -1.5 -1 -0.5 0 0.5 1 1.5 2
-hu_t-h_{min}
0 0.2 0.4 0.6 0.8 1
200 km
$Y_{\rm e}$
0 0.1 0.2 0.3 0.4 0.5
Log$_{10}$[kT (MeV)]
-1 -0.5 0 0.5 1
Log$_{10}$[s/k]
0 0.5 1 1.5 2 2.5 3

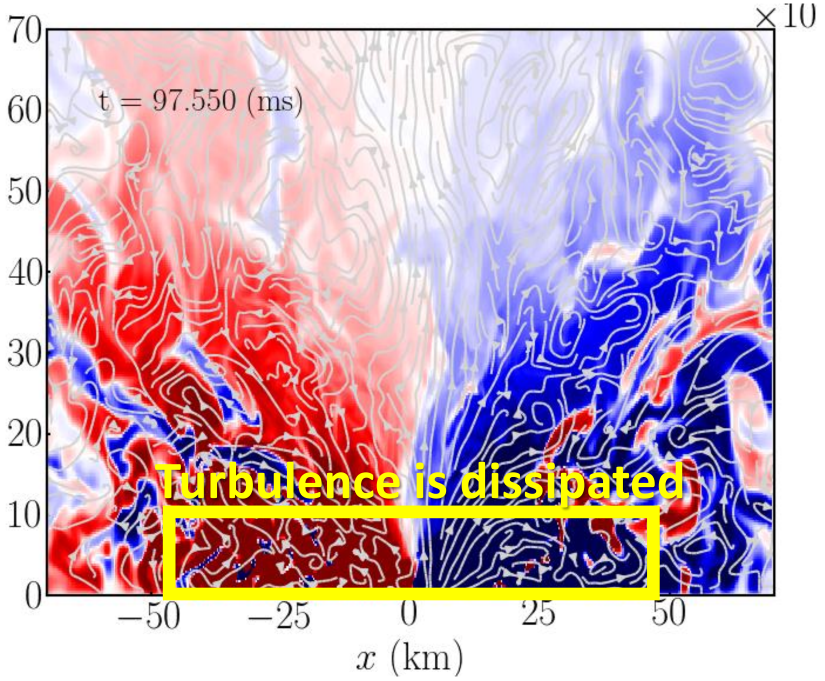
Technical issues to follow small-scale fields

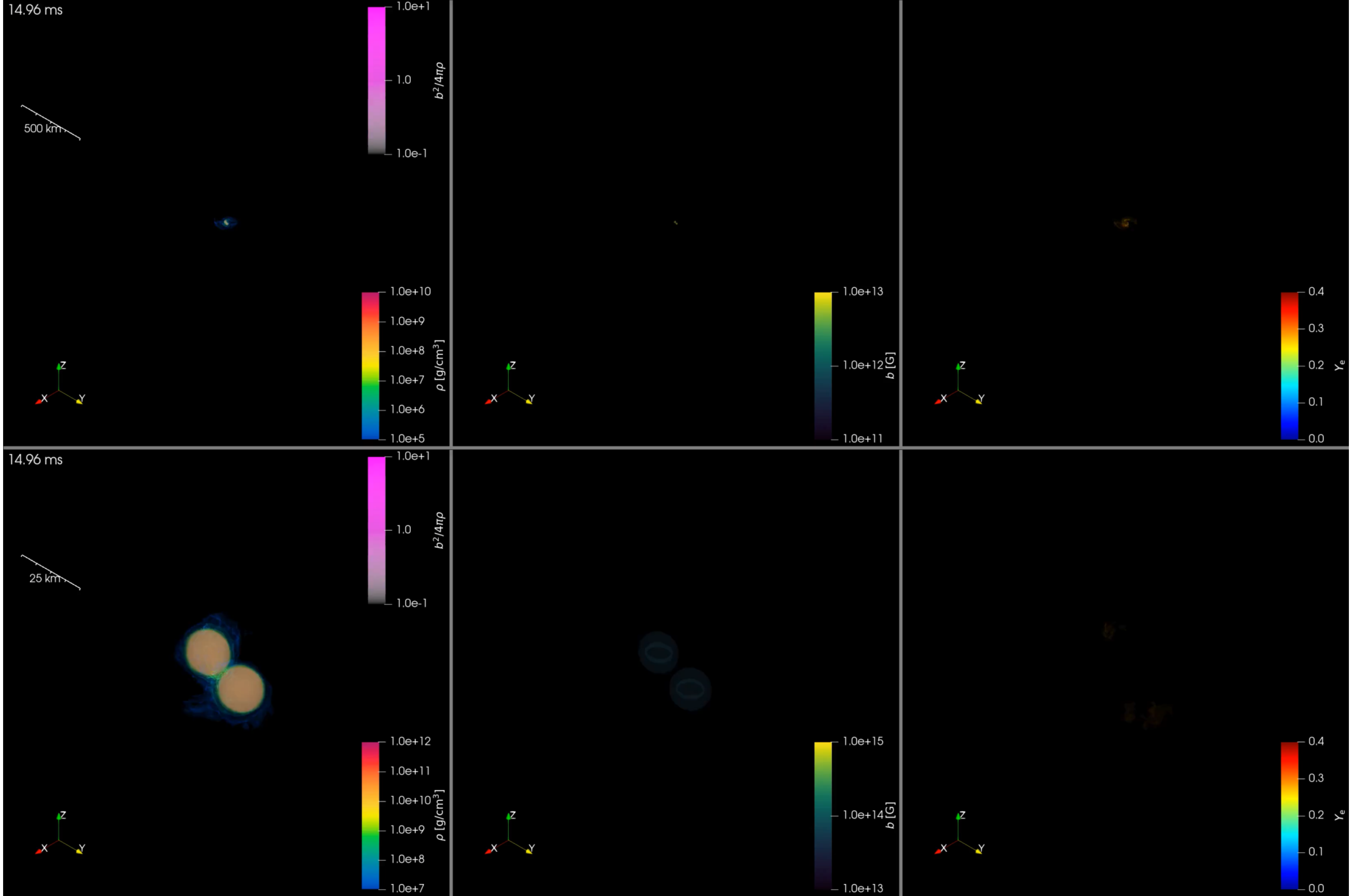
- **High resolution is required**
  - we adopted $\Delta x_{\text{finest}} = 12.5\text{m}$ (previously $\Delta x_{\text{finest}} = 150\text{m}$)to resolve the fastest growing mode of MRI and accurately follow the B-field amplification in KH instability
- **Less dissipative MHD solver is advantegeous**
  - we developed less dissipative HLLD solver (Kiuchi, YS+ 2022) in the framework of NR

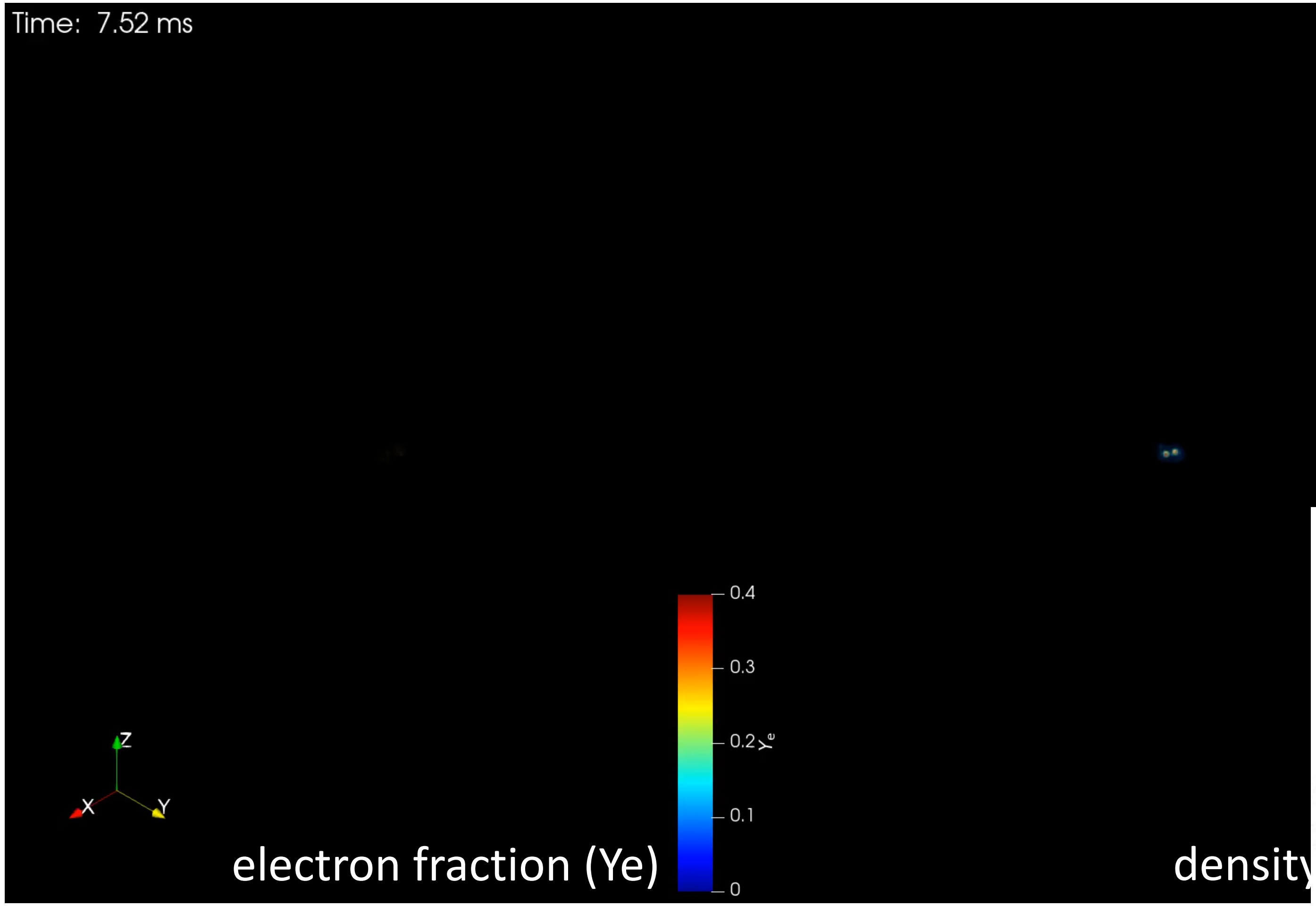
HLLD (new !)

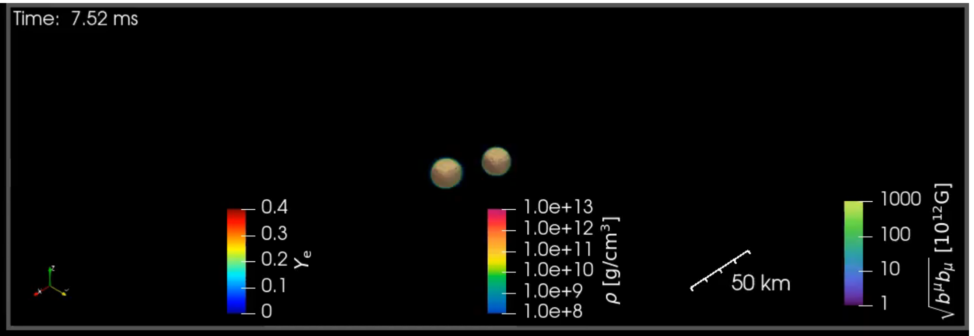


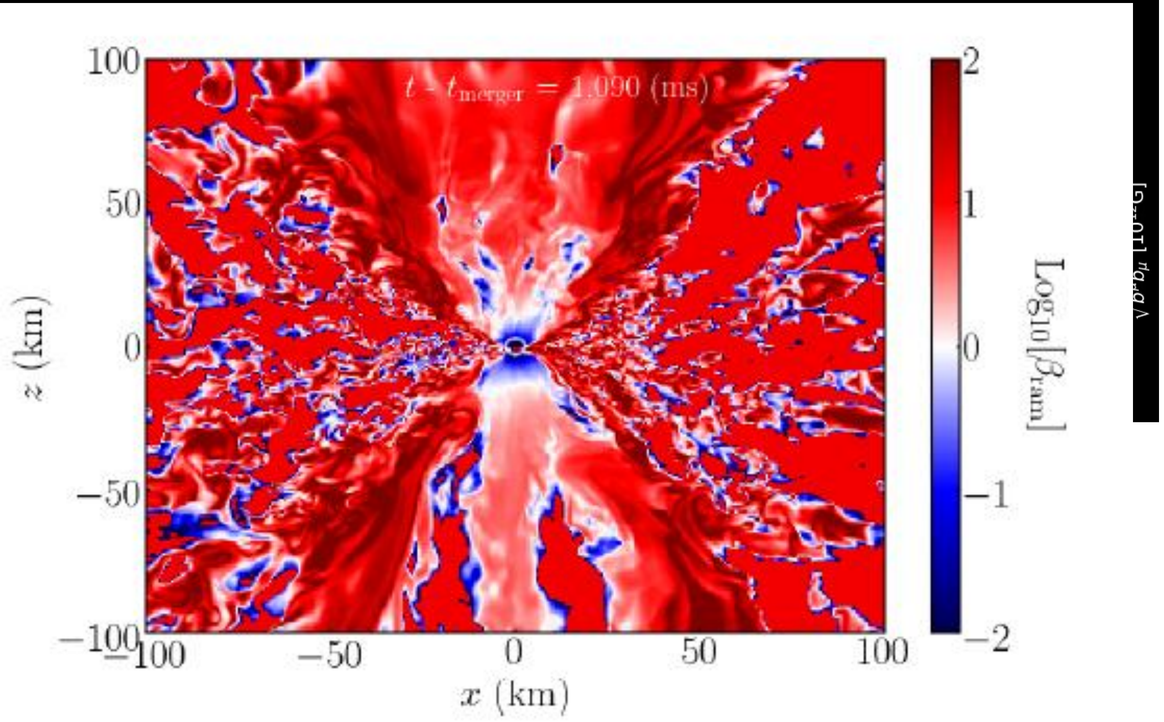
HLLE (previous)

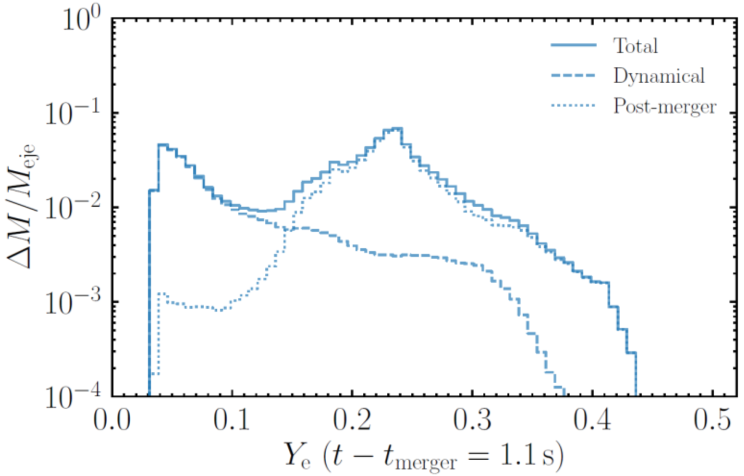



14.96 ms
500 km
1.0e+1
1.0
1.0e-1
$b^2/4\pi\rho$
1.0e+10
1.0e+9
1.0e+8
1.0e+7
1.0e+6
1.0e+5
ρ [g/cm^3]
1.0e+13
1.0e+12
1.0e+11
b [G]
0.4
0.3
0.2
0.1
0.0
Y_e
14.96 ms
25 km
1.0e+1
1.0
1.0e-1
$b^2/4\pi\rho$
1.0e+12
1.0e+11
1.0e+10
1.0e+9
1.0e+8
1.0e+7
ρ [g/cm^3]
1.0e+15
1.0e+14
1.0e+13
b [G]
0.4
0.3
0.2
0.1
0.0
Y_e
Z
X
Y









- ejecta properties (ch
  broadly consistent w
  - ejecta mass may not
- Absence of jet launcl
  - Insufficient coherent B-field ?, too large ram pressure due to shorter simulation time ?

Result for 1.35-1.35$M_\odot$ with DD2 EOS