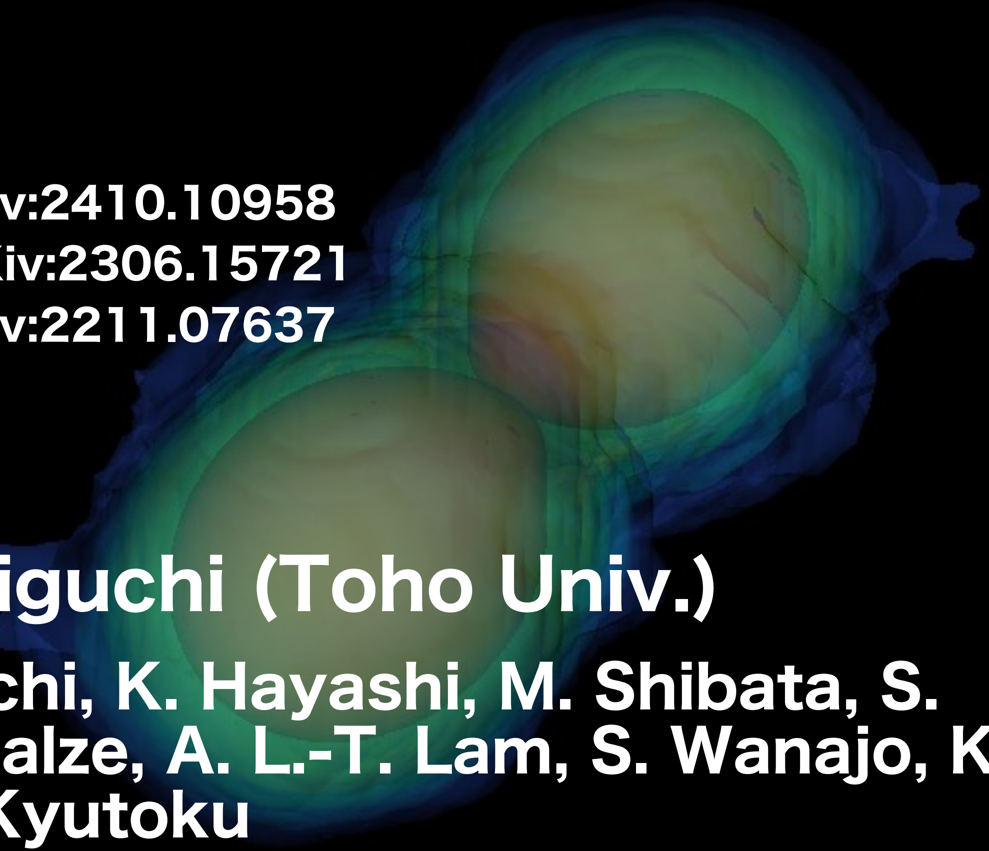
General Relativistic neutrino-Radiation MagnetoHydroDynamics (GRRMHD) simulations of binary neutron star mergers



Phys. Rev. Lett. 134, 211407 (2025), arXiv:2410.10958
Nature Astronomy 8, 298 (2024), arXiv:2306.15721
Phys. Rev. Lett. 131, 011401 (2023), arXiv:2211.07637

Yuichiro Sekiguchi (Toho Univ.)

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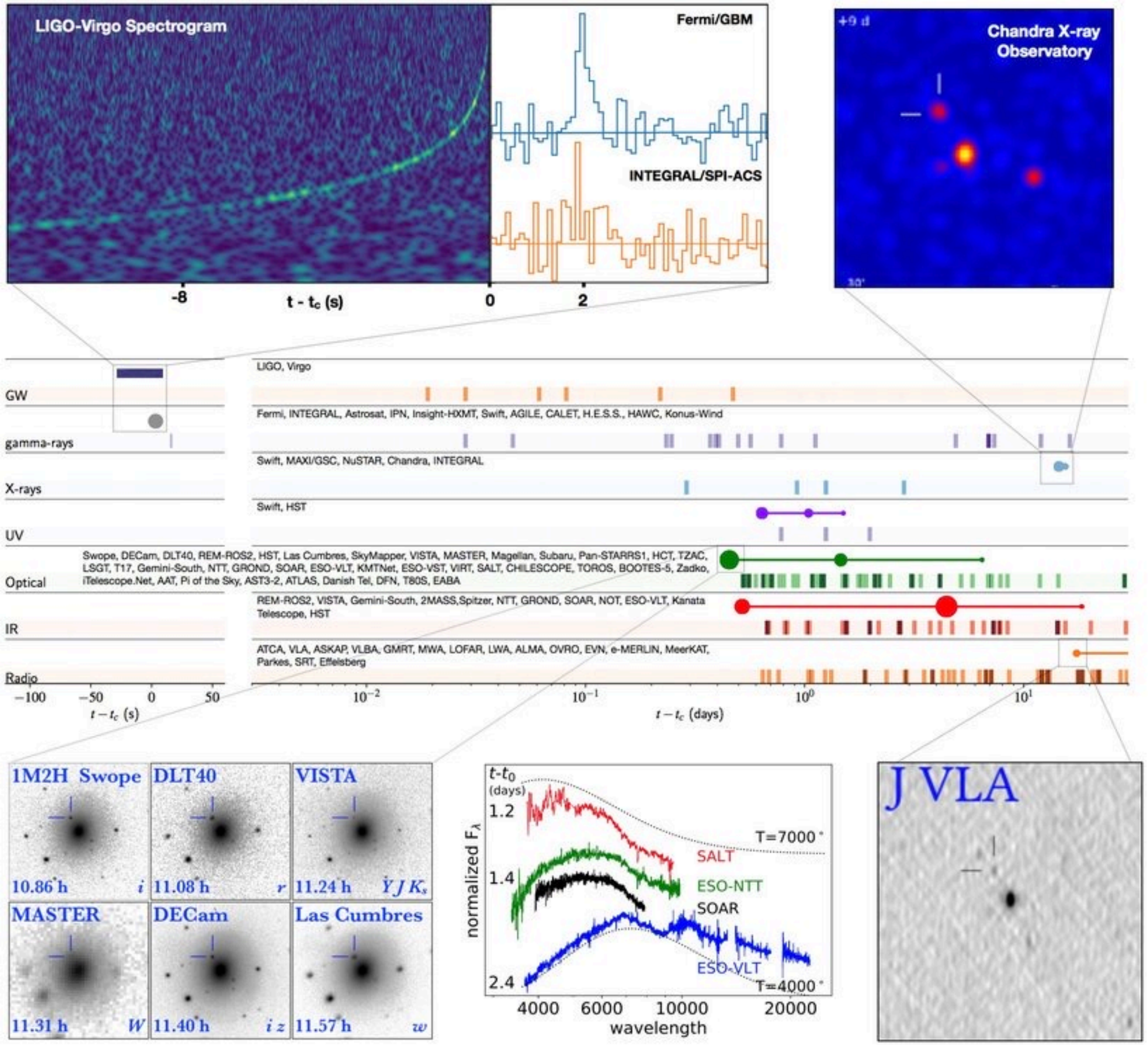
GW170817: dawn of Multi-messenger astrophysics with GW

- **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 way to launch the short GRB jet
- **Strong** ($\gtrsim 10^{14-15}$ G) **and coherent (global) magnetic fields** which thread the BH horizon are necessary to launch an energetic jet

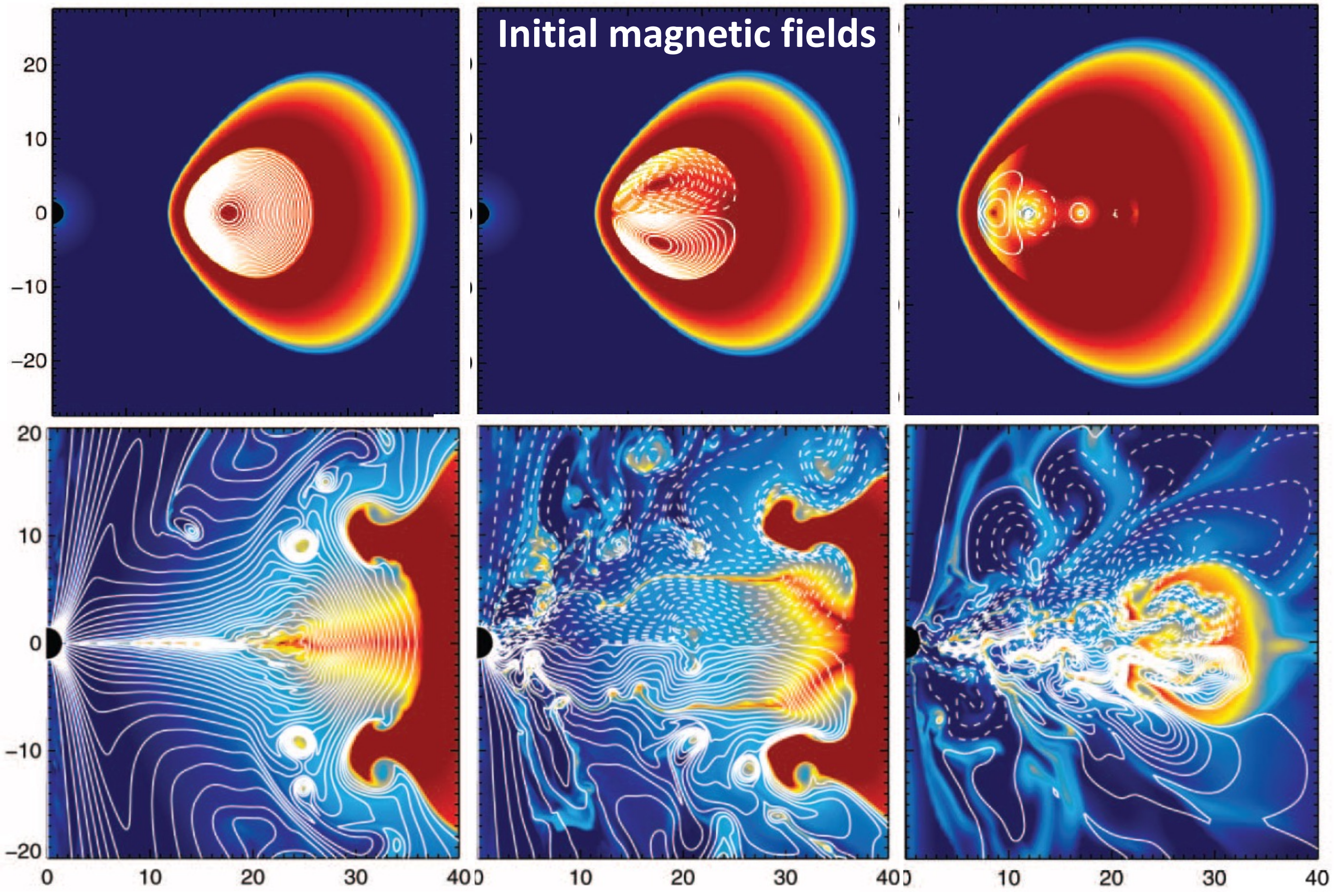
- Poloidal magnetic fields of binary pulsars estimated by the spin-down period : $B_p \sim 10^{8-12}$ G $\ll 10^{14-15}$ G

Tauris et al. 2017

Key question

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

Beckwith et al. 2008



Generation of coherent magnetic fields

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

The averaged induction equation

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

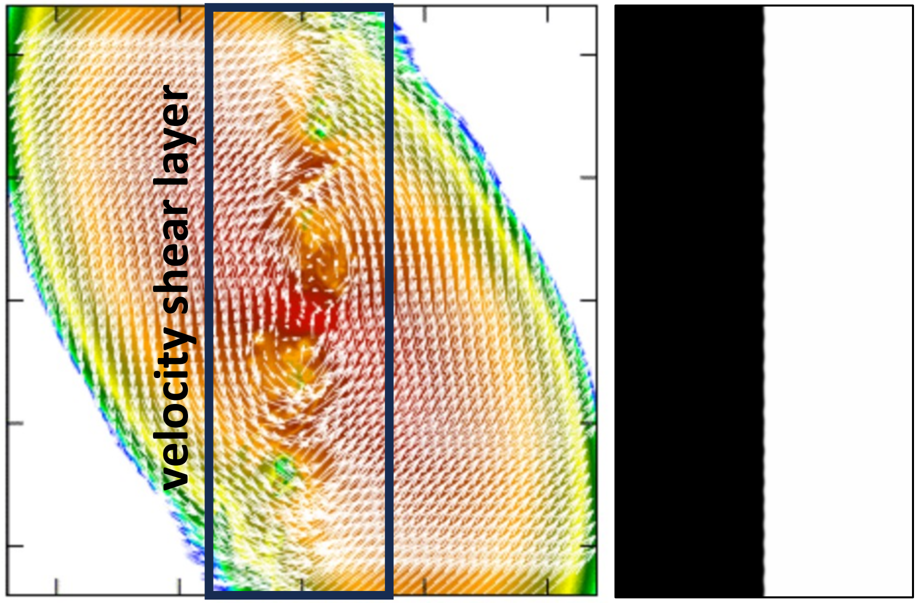
Electromotive force

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

$$\boldsymbol{Q} = \overset{\text{mean field}}{\overline{\boldsymbol{Q}}} + \overset{\text{random field}}{\boldsymbol{q}}$$

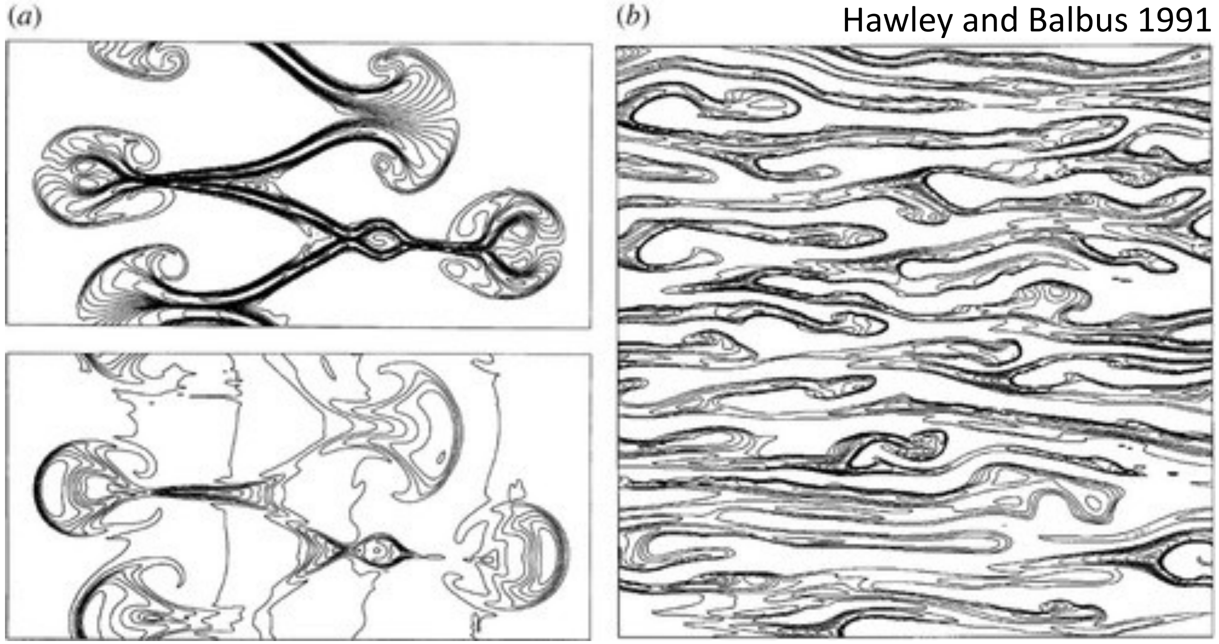
⇒ small scale turbulent velocity and magnetic fields can generate coherent fields

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

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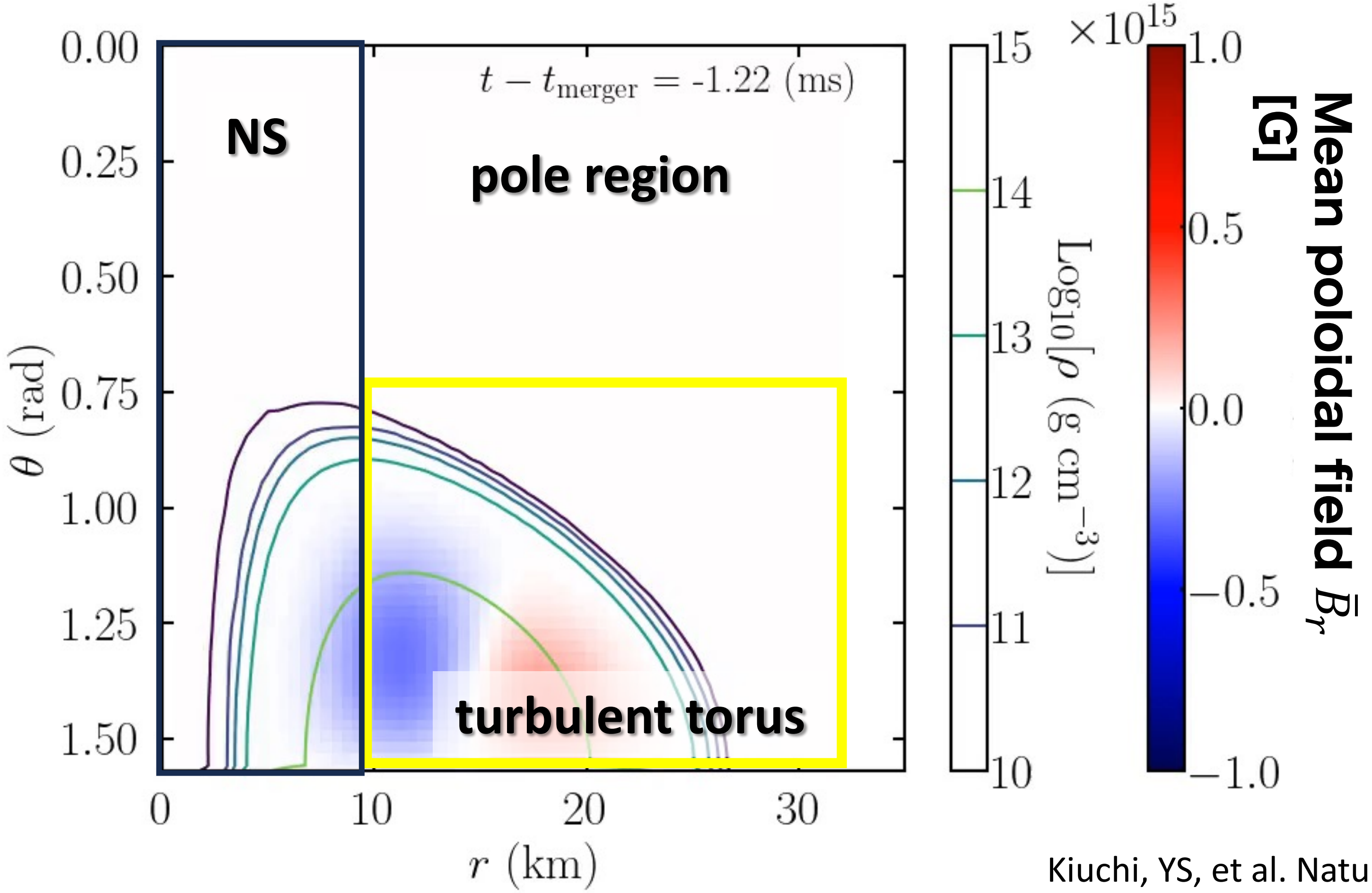

Kiuchi, YS, et al. Nature Astronomy 8, 298 (2024)

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Phenomenological Prescription

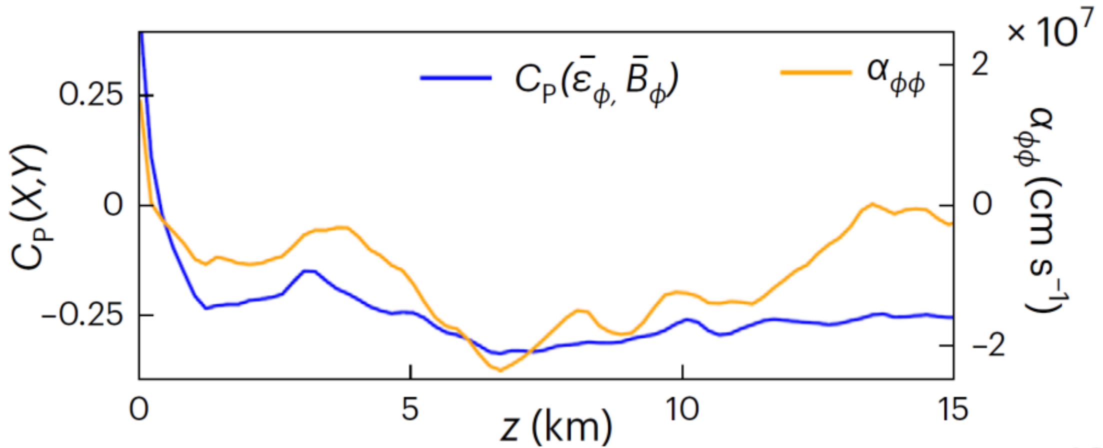
$$\bar{\mathcal{E}}_i = \alpha_{ij}\bar{B}_j + \beta_{ij}(\overline{\nabla\times B})_j$$

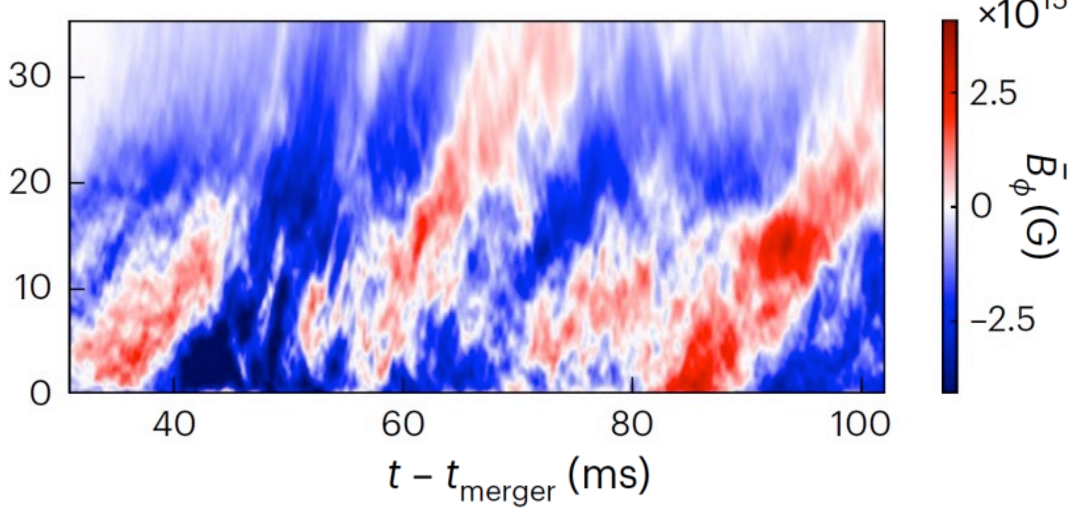
$$\partial_t \bar{B}_R = -\partial_z(\alpha_{\varphi\varphi}\bar{B}_\varphi) \qquad R = \sqrt{x^2+y^2}$$

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

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



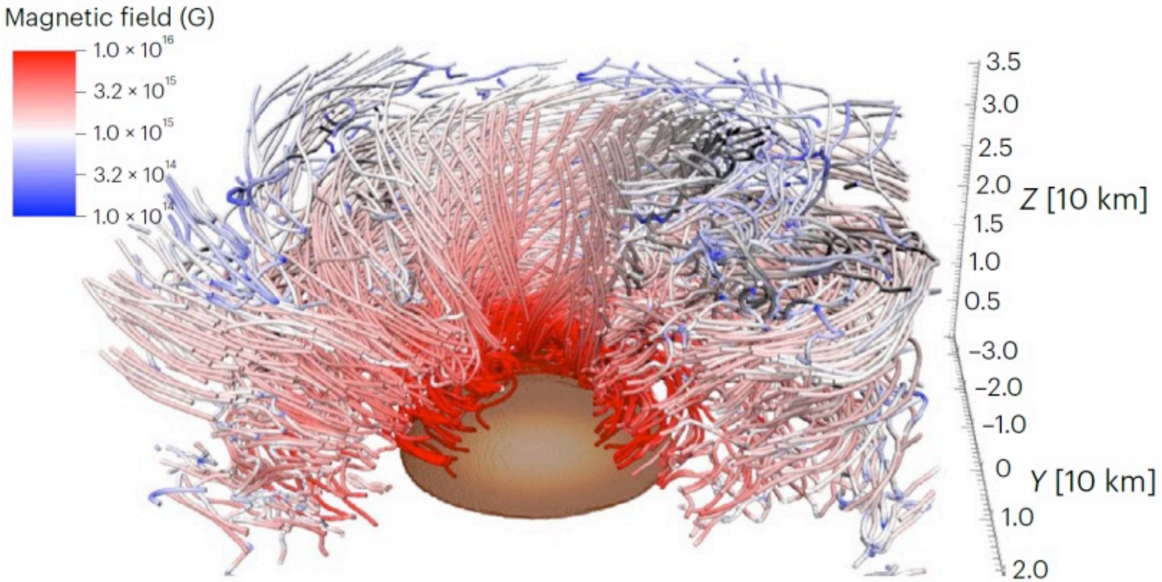


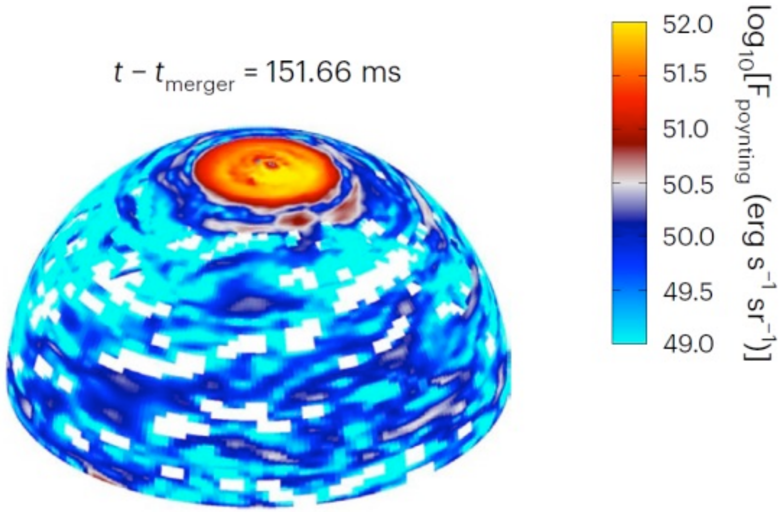
Kiuchi, YS, et al. Nature Astronomy 8, 298 (2024)

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 (**finest grid = 12.5m**)
- ✓ 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)

Kiuchi, YS, et al. Nature Astronomy 8, 298 (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

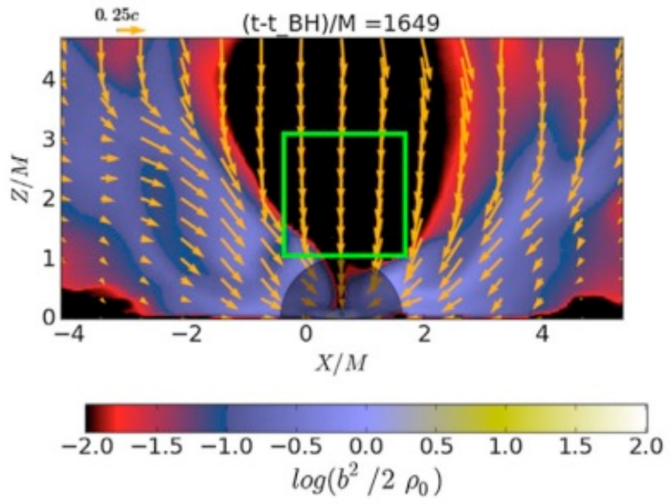
Source Properties for GW190425

	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}	$3.3^{+0.1}_{-0.1}$ $\mathrm{M}_{\odot}$	$3.4^{+0.3}_{-0.1} M_{\odot}$
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

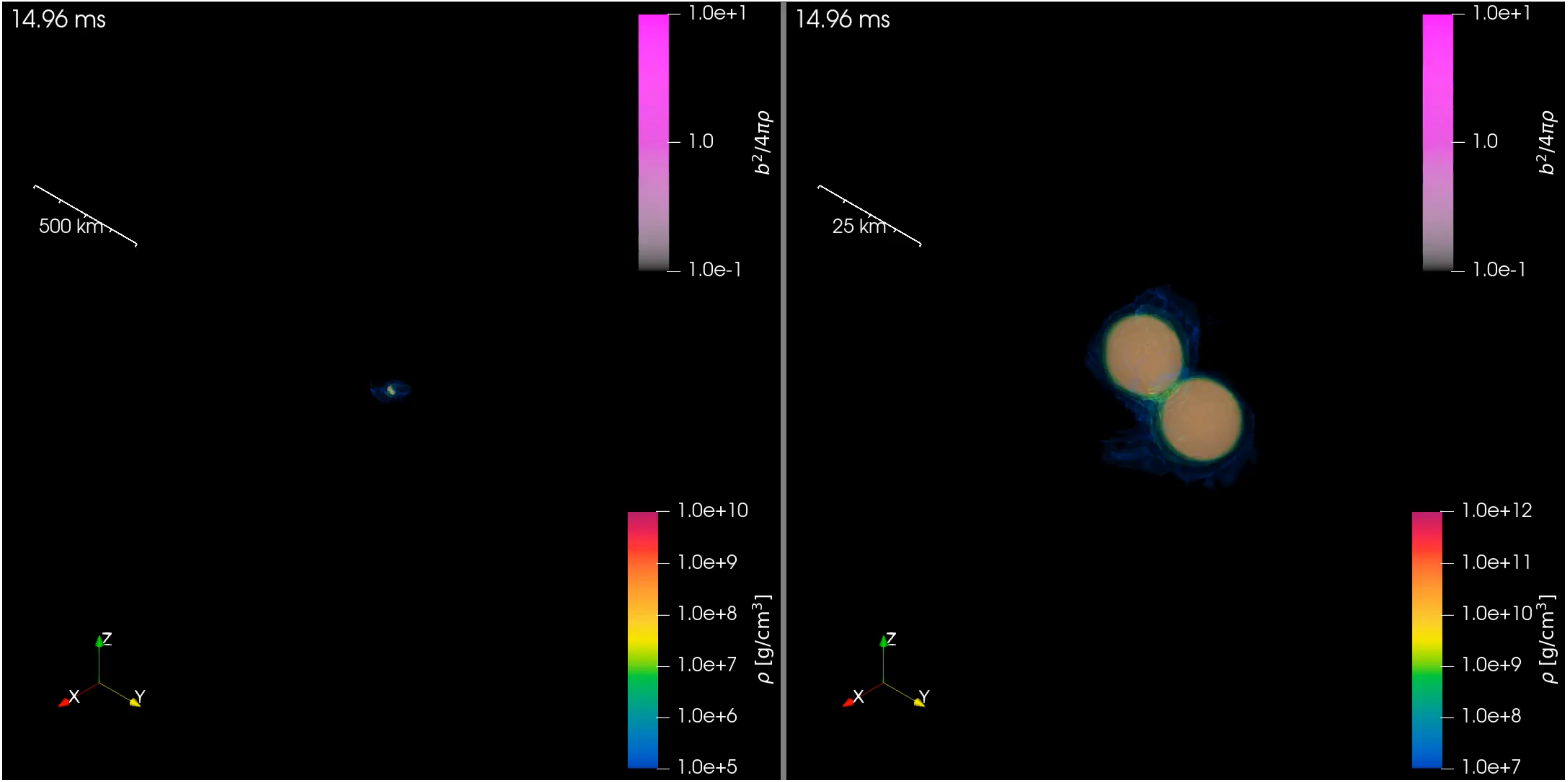
- **Einstein's equations :**
  - BSSN formalism (Shibata and Nakamura 1995; Baumgarte and Shapiro 1998)
  - Moving puncture method (Campanelli et al. 2006; Baker et al. 2006)
  - Z4c constraint propagation (Hilditch et al. 2013)
- **Magnetohydrodynamics :**
  - Tetrad ⇔ global coordinate transformation
  - 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. 2010, 2012)
  - M1 closure (Shibata et al. 2011)
  - Neutrino heating (Fujibayashi et al. 2017)

- **Prescription of BNS parameter :**
  - 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 $\approx 10^{15}\ \rm G \ \rightarrow B_p \approx 10^{13}\ G$
- **Grid set-up and timescale :**
  - 13-level fixed mesh refinement
  - finest grid resolution : $\Delta x = 150\ \rm m$ 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 (130,000,000 CPU hour on Fugaku)

animation by K.

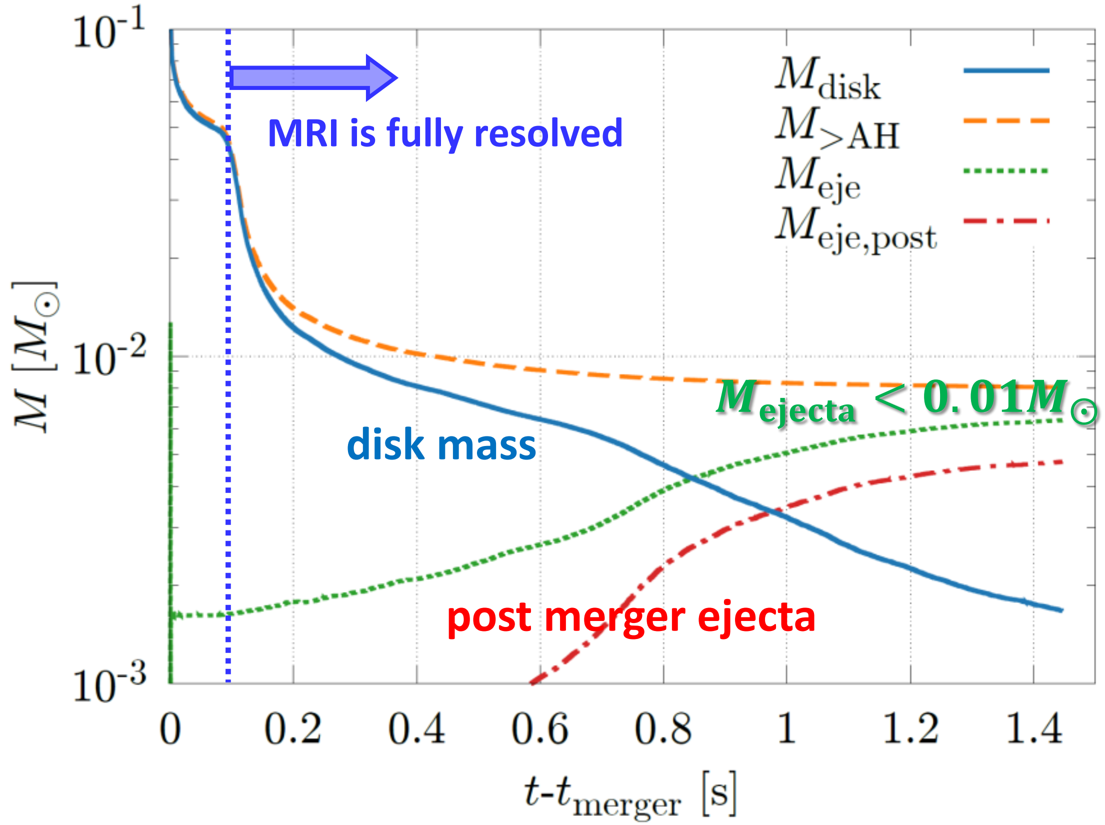


Hayashi, YS, et al, Phys. Rev. Lett. 134, 211407 (2025)

MRI induced viscosity and dynamo

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

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

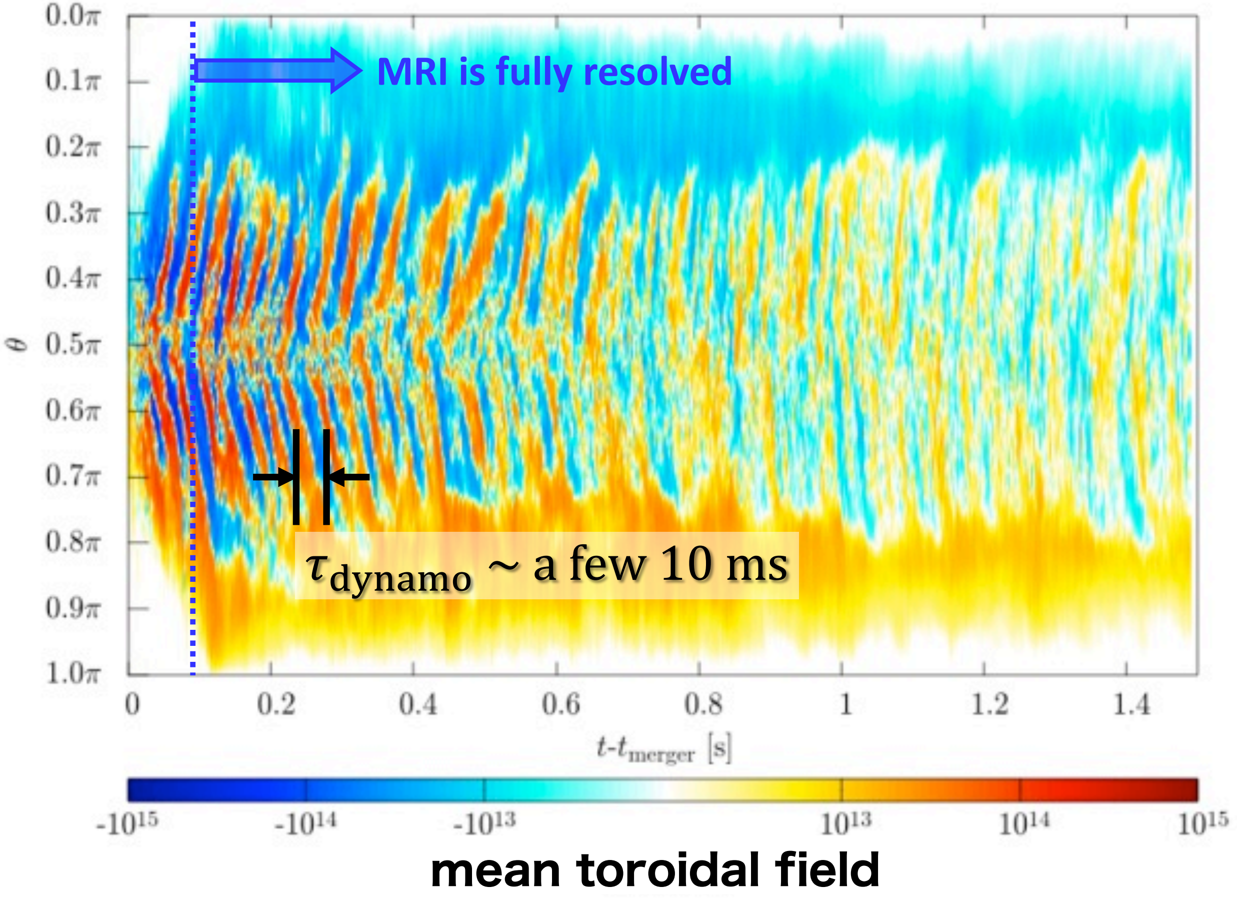


MRI is fully resolved

$M_{\mathrm{ejecta}} < 0.01 M_\odot$

disk mass

post merger ejecta



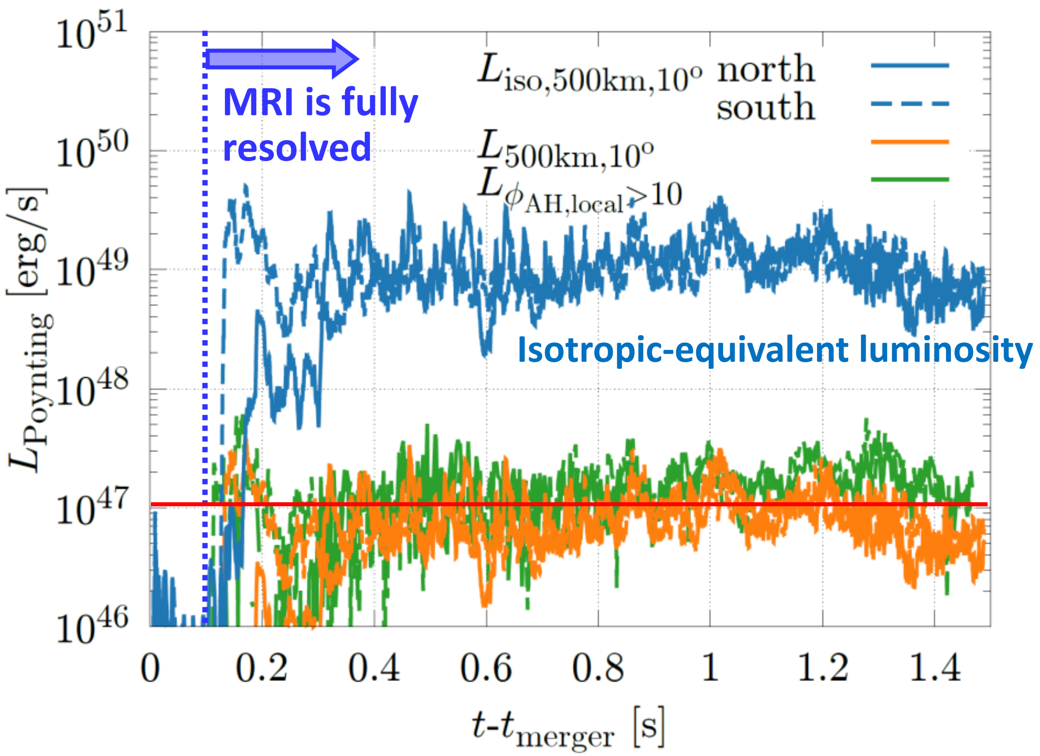
MRI is fully resolved

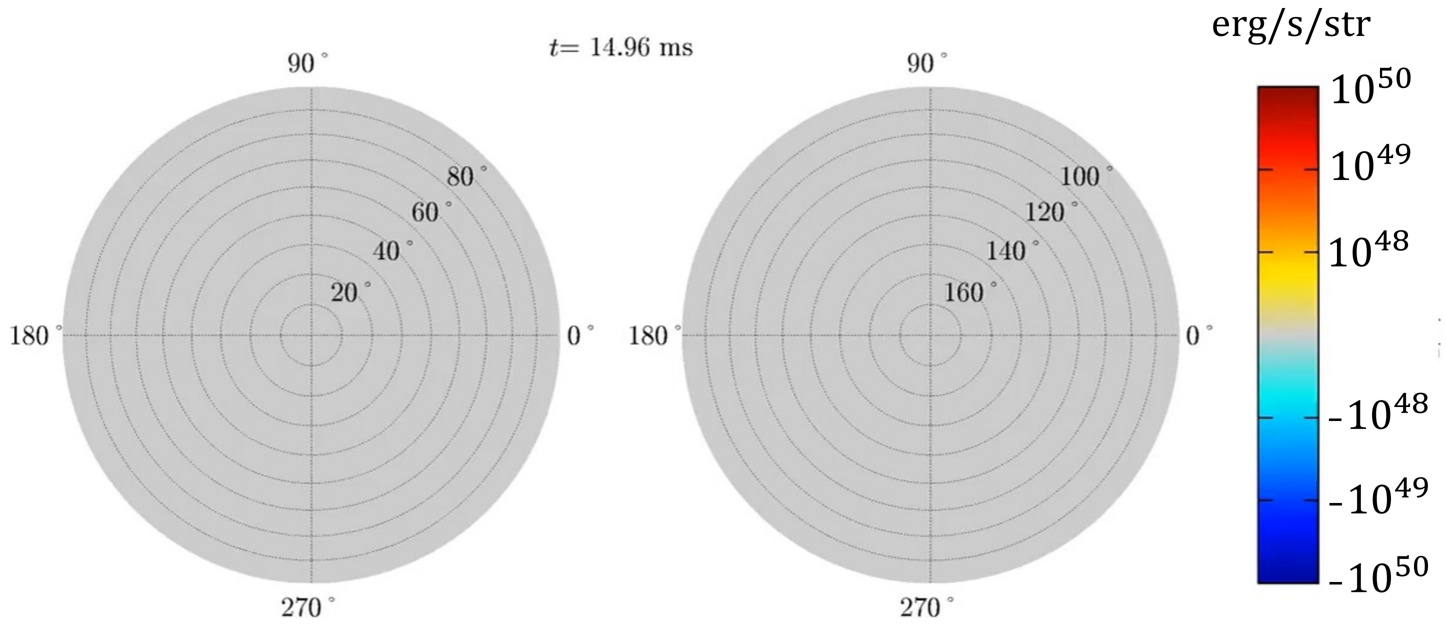
$\tau_{\mathrm{dynamo}} \sim$ a few 10 ms

Hayashi, YS, et al, Phys. Rev. Lett. 134, 211407 (2025)

(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
  - ✓ Prompt BH formation ⇒ (relatively) small torus mass + small ram pressure => weak jet





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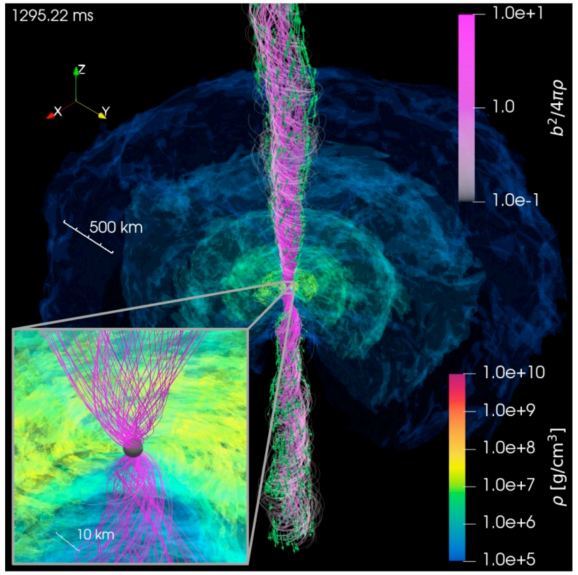
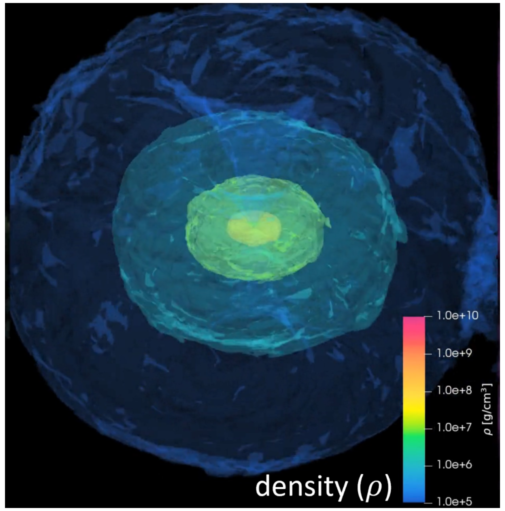


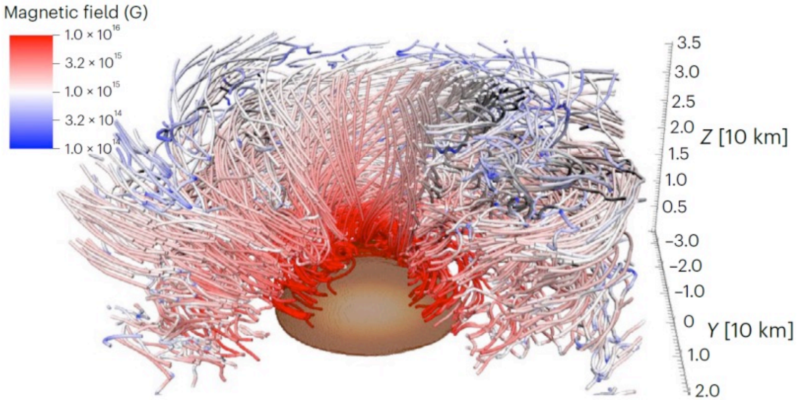
- ✓ Prompt BH formation
- ✓ mean field generation by MRI-induced dynamo
- ✓ ram pressure is smaller
- ✓ $L_{\rm Poy} \sim 10^{47}$ erg/s , $\theta_{\rm jet} \sim 10°$
- ✓ $M_{\rm ej} \lesssim 0.01 M_\odot$

Hayashi et al. PRL 2025



- ✓ 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

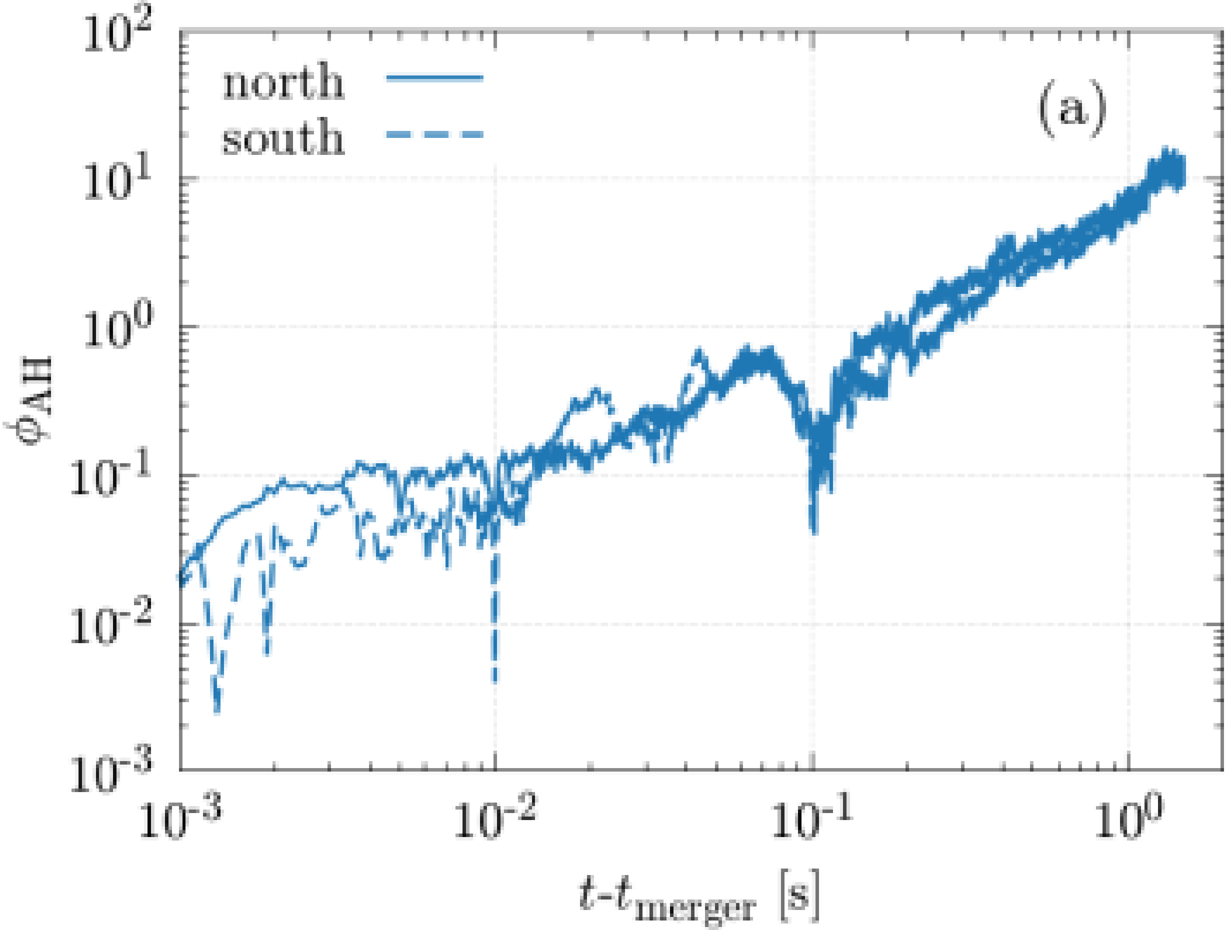


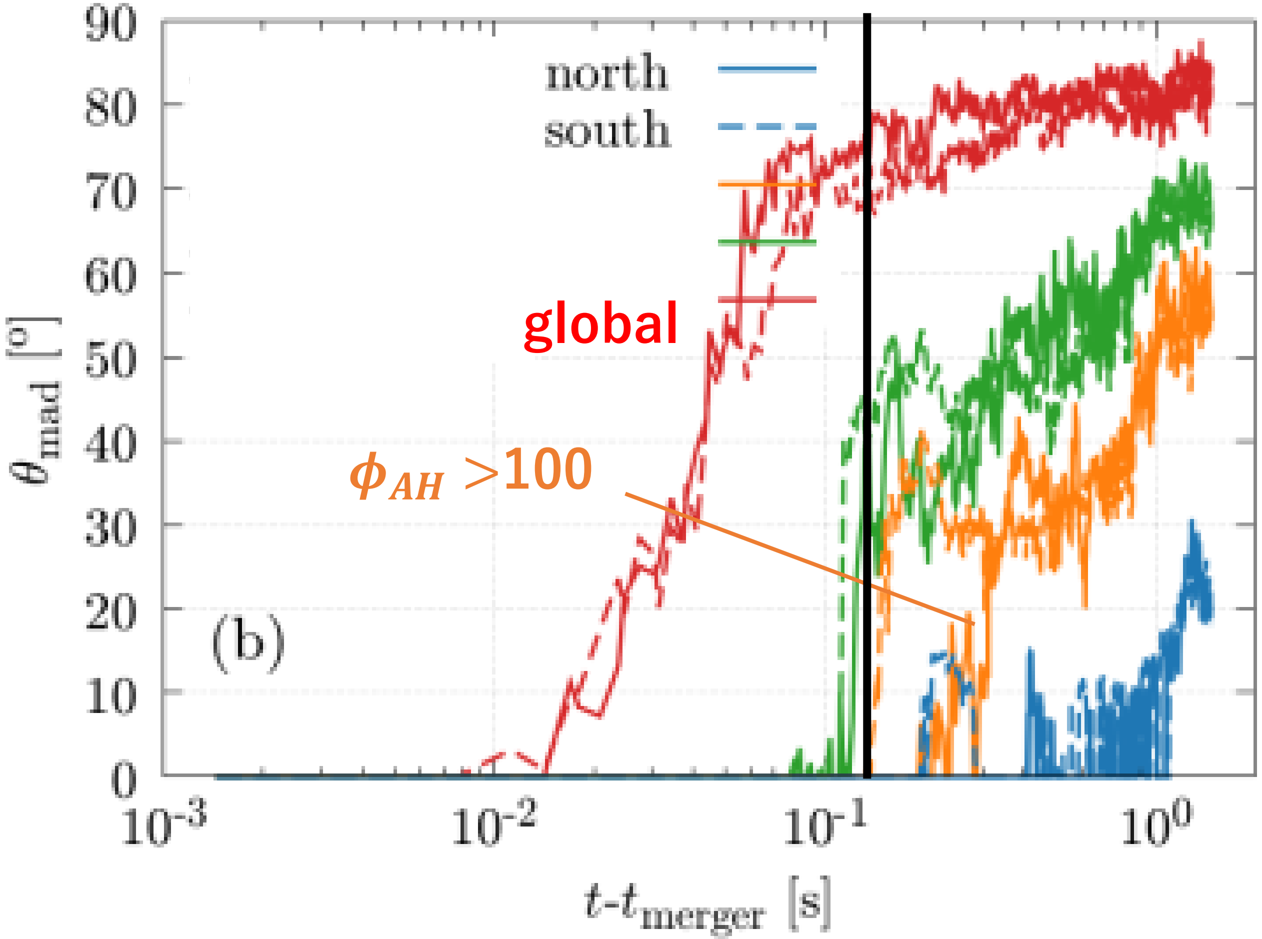
- ✓ Long-lived NS : amplification by KH instability and MRI
- ✓ mean field generation by $\alpha\Omega$ dynamo
- ✓ $L_{\rm Poy} \sim 10^{51}$ erg/s , $\theta_{\rm jet} \approx 12°$
- ✓ $M_{\rm ej} \geq 0.1 M_\odot$ $(X_{n,\rm ave} \sim 0.7)$

Kiuchi et al. Nature Astronomy 2024

The global and local MADness parameters

✓ The global MADness parameter : $\phi_{\rm AH} = \dfrac{\Phi_{\rm AH}}{\sqrt{\dot{M}_{\rm AH} r_{\rm AH}^2 c}}$, $\Phi_{\rm AH} = \int_{\rm AH} B^i \sqrt{\gamma} dS_i$





Jet launched

global

ϕ_{AH} >100

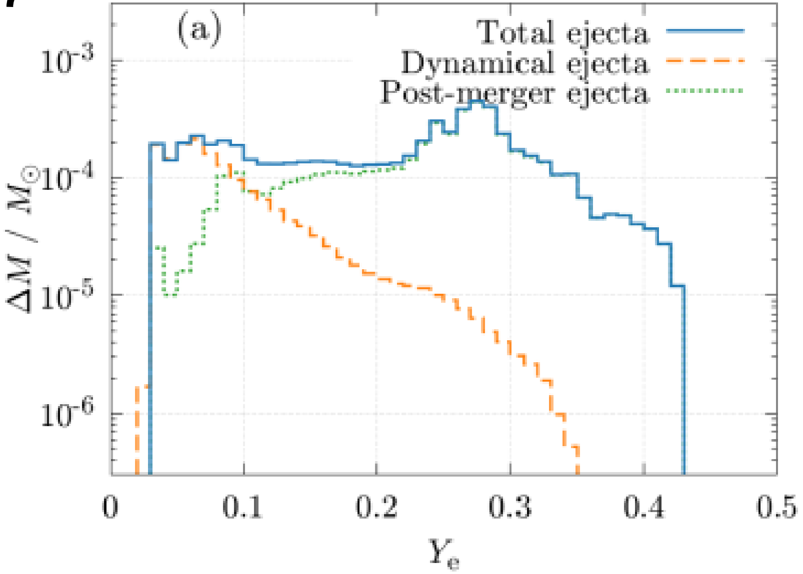
prompt collapse

$O(0.01\ \mathrm{sec})$

$O(0.1\ \mathrm{sec})$

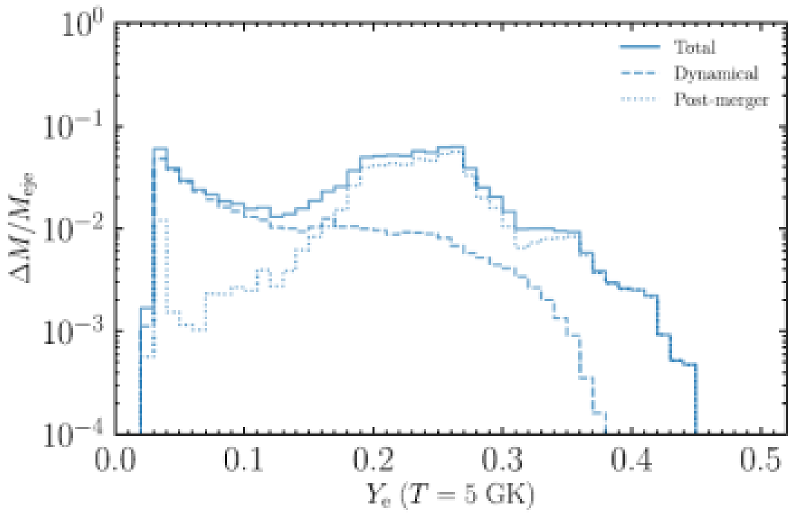
$< O(1\ \mathrm{sec})$

Remnant NS lifetime



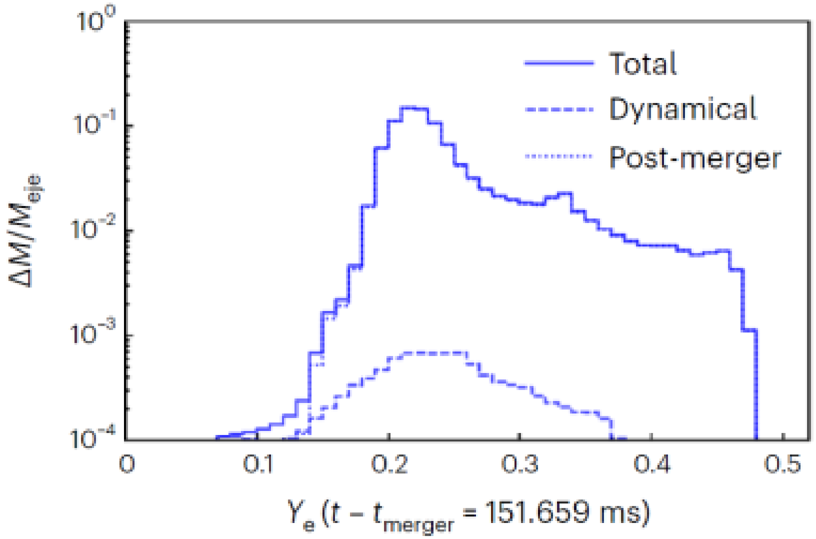
- ✓ **Prompt BH formation**
- ✓ mean field generation by MRI-induced dynamo
- ✓ ram pressure is smaller
- ✓ $L_{\mathrm{Poy}} \sim 10^{47}\ \mathrm{erg/s}$, $\theta_{\mathrm{jet}} \sim 10°$
- ✓ $M_{\mathrm{ej}} \lesssim 0.01 M_\odot$

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



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Kiuchi et al. Nature Astronomy 2024

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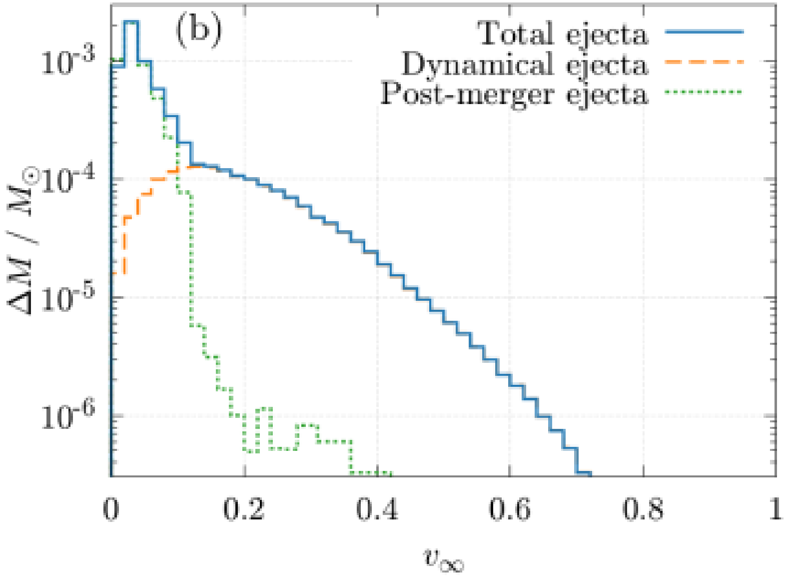

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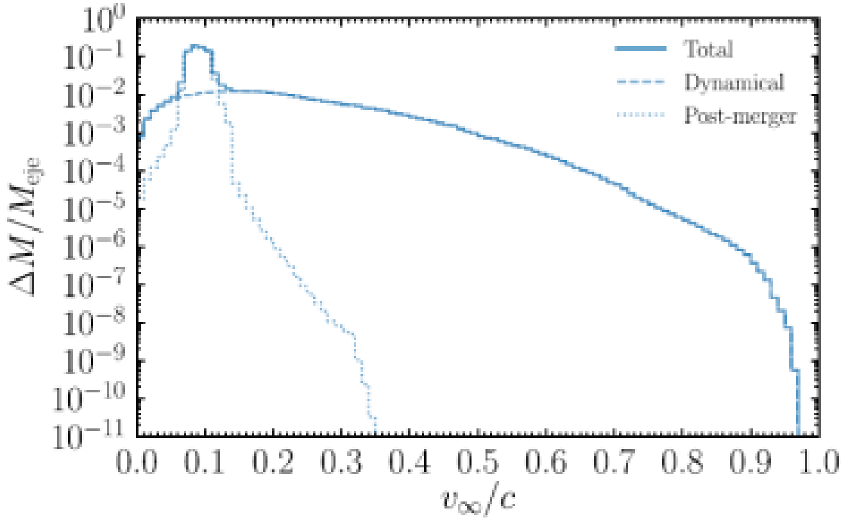
Hayashi et al. PRL submitted



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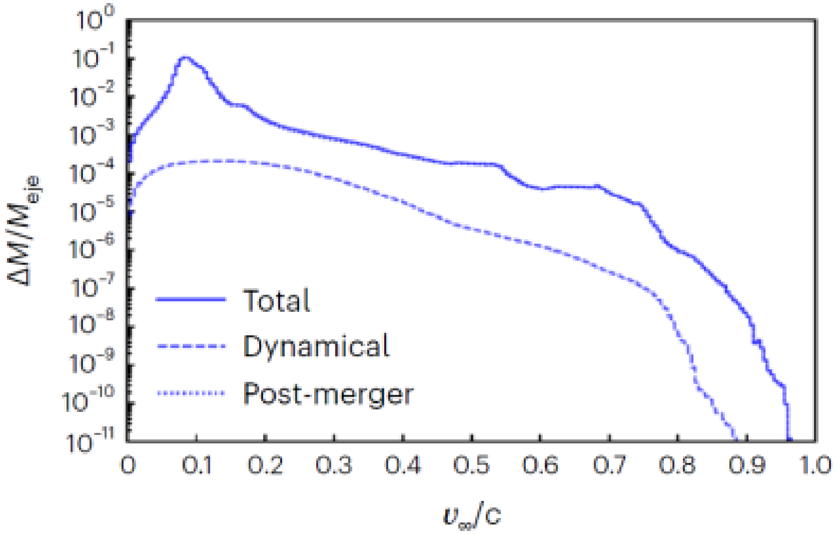
Kiuchi et al. PRL 2023



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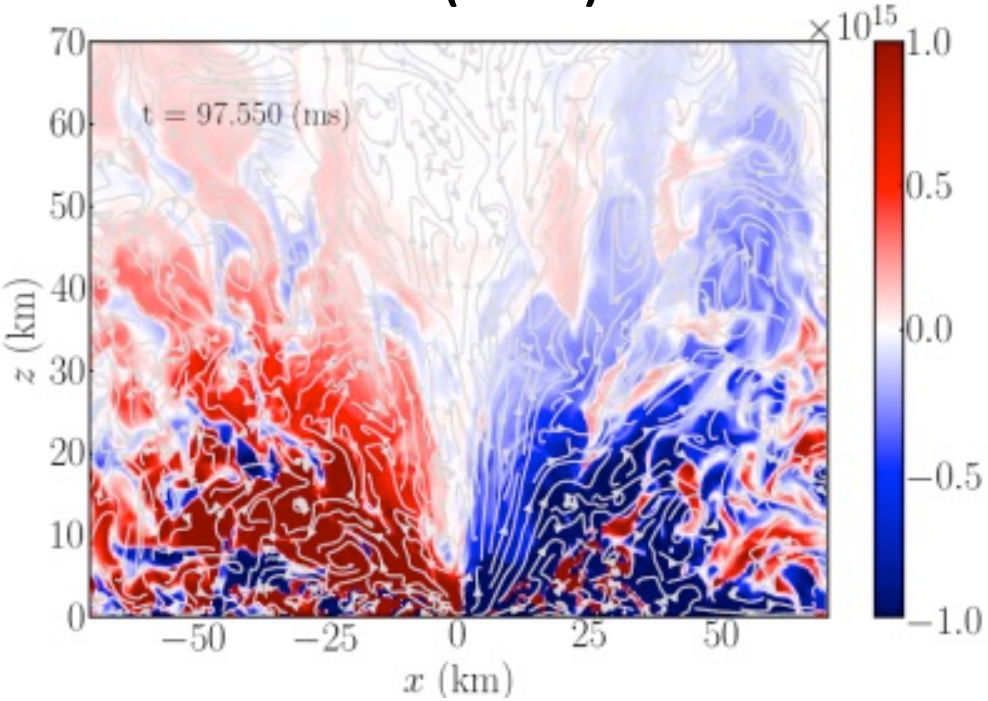
Technical issues to follow small-scale fields

- High resolution is required
  - we adopted $\Delta x_{\rm finest} = 12.5{\rm m}$ (previously $\Delta x_{\rm finest} = 150{\rm m}$)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)