

Jet from Binary Neutron Star Merger with Prompt Black Hole Formation



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PRL 134, 211407

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Collaborators :

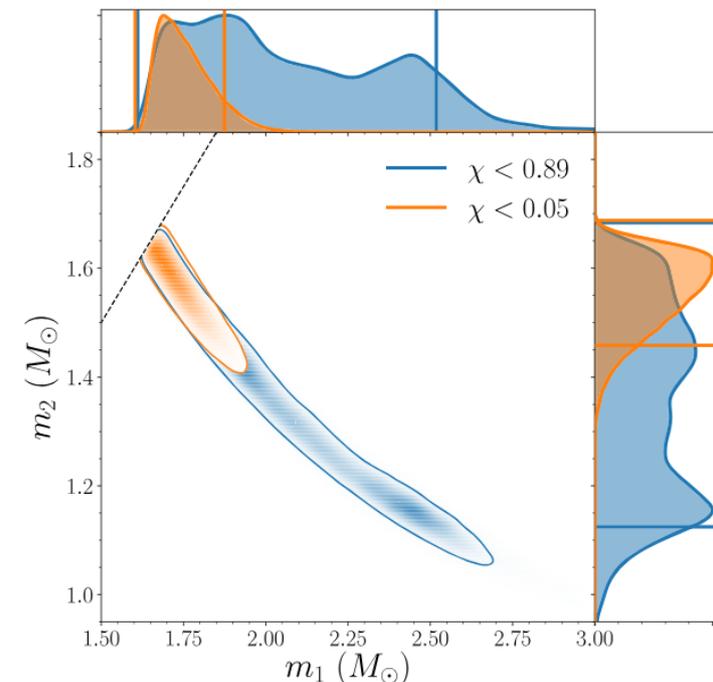
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Introduction

Observing Compact Binary Merger using Gravitational Wave

GW190425:

- GW event from the BNS merger with **total mass $3.4M_{\text{sun}}$**
- Promptly collapses to BH
- EM counterpart from similar source could be detected if **mass asymmetry is large** and **sky localization is better**



Method

Method

3D NRRMHD simulations of binary neutron star merger with prompt black hole formation

- Time scale of the Dynamical mass ejection is $< 10\text{ms}$
 - Time scale of the Post-merger mass ejection is $\sim 1\text{s}$
 - Time scale of sGRB is $\sim 1\text{-}2\text{s}$
- ↓
- **We calculated the evolution of the system from inspiral stage (15ms) to post merger stage (1.5s)**

BNS -Model parameters-

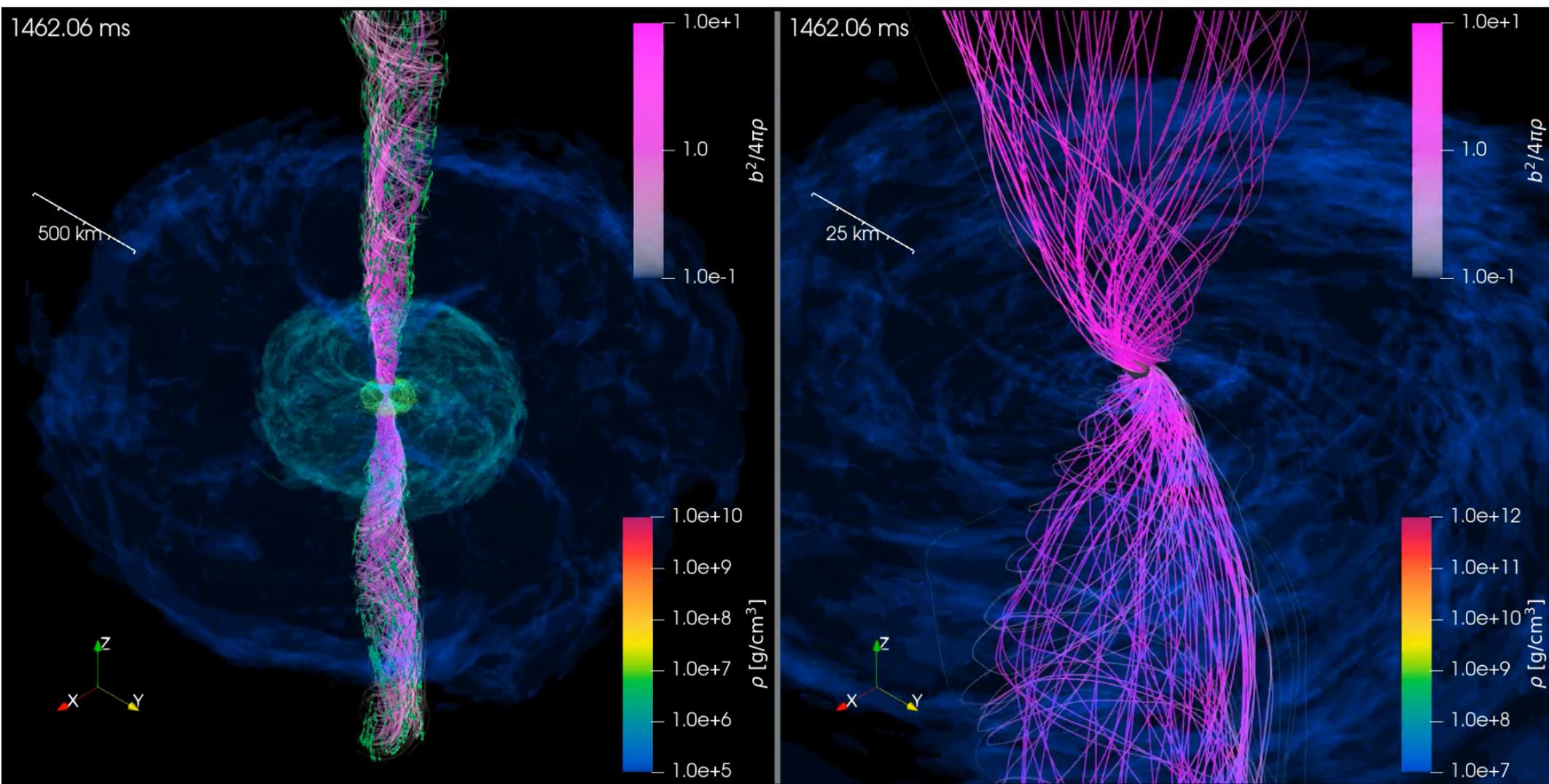
- Neutron star mass: $1.25M_{\text{sun}}$ and $1.65M_{\text{sun}}$
- Neutron star EOS: SFHo
- Max resolution: 150m

- Max Magnetic field strength: 10^{15}G
- **Confined poloidal magnetic field** is superimposed on neutron star initially
- Vector potential $\propto (\text{Pressure})^{0.5}$

- **Equatorial symmetry is not imposed**

Result

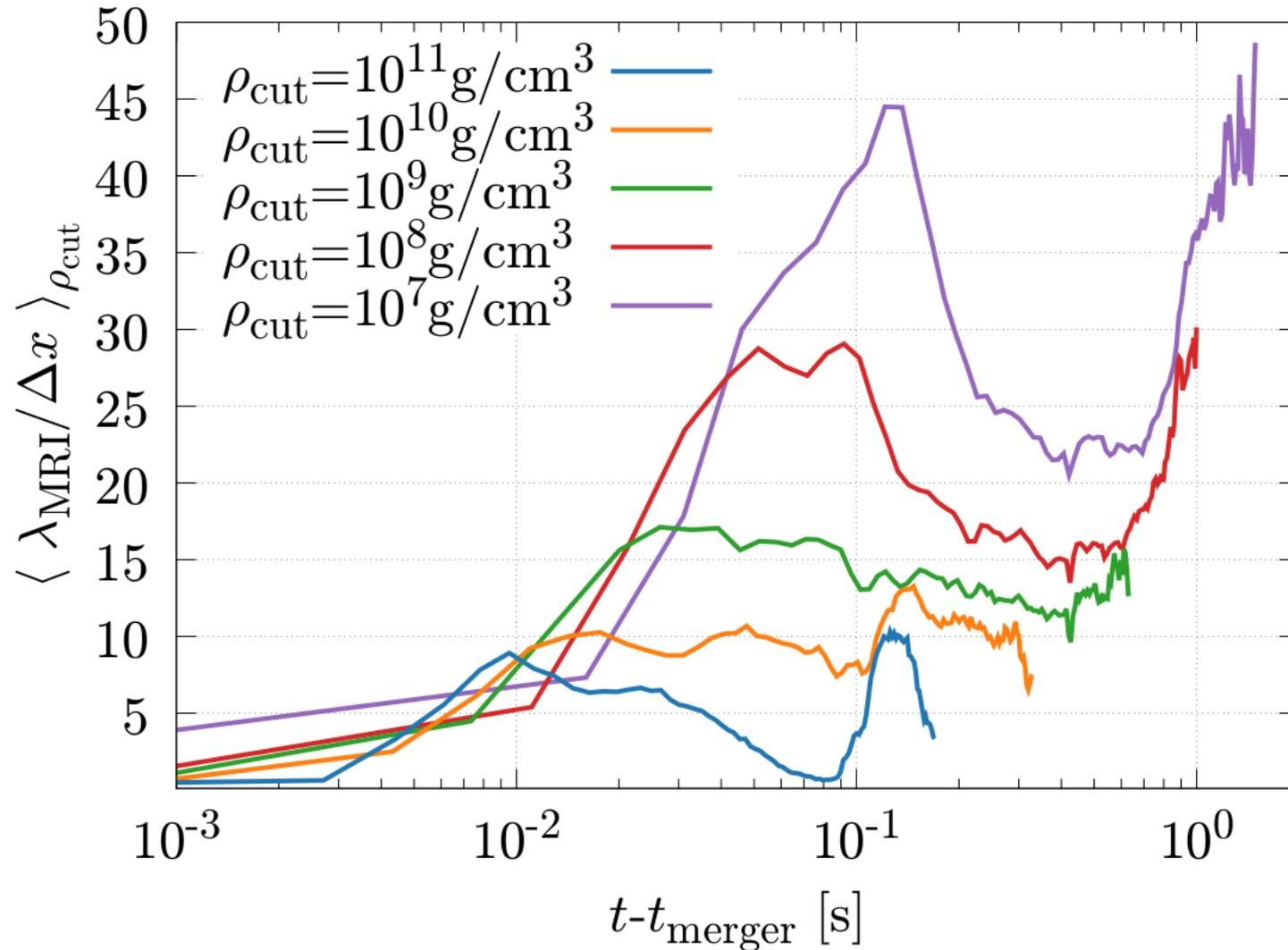
- Contour: Rest-mass density
- Line: magnetic field line penetrating AH
- Arrow: Magnetically driven unbound matter



Animation: <https://www.youtube.com/watch?v=ehZTVPU04wE>

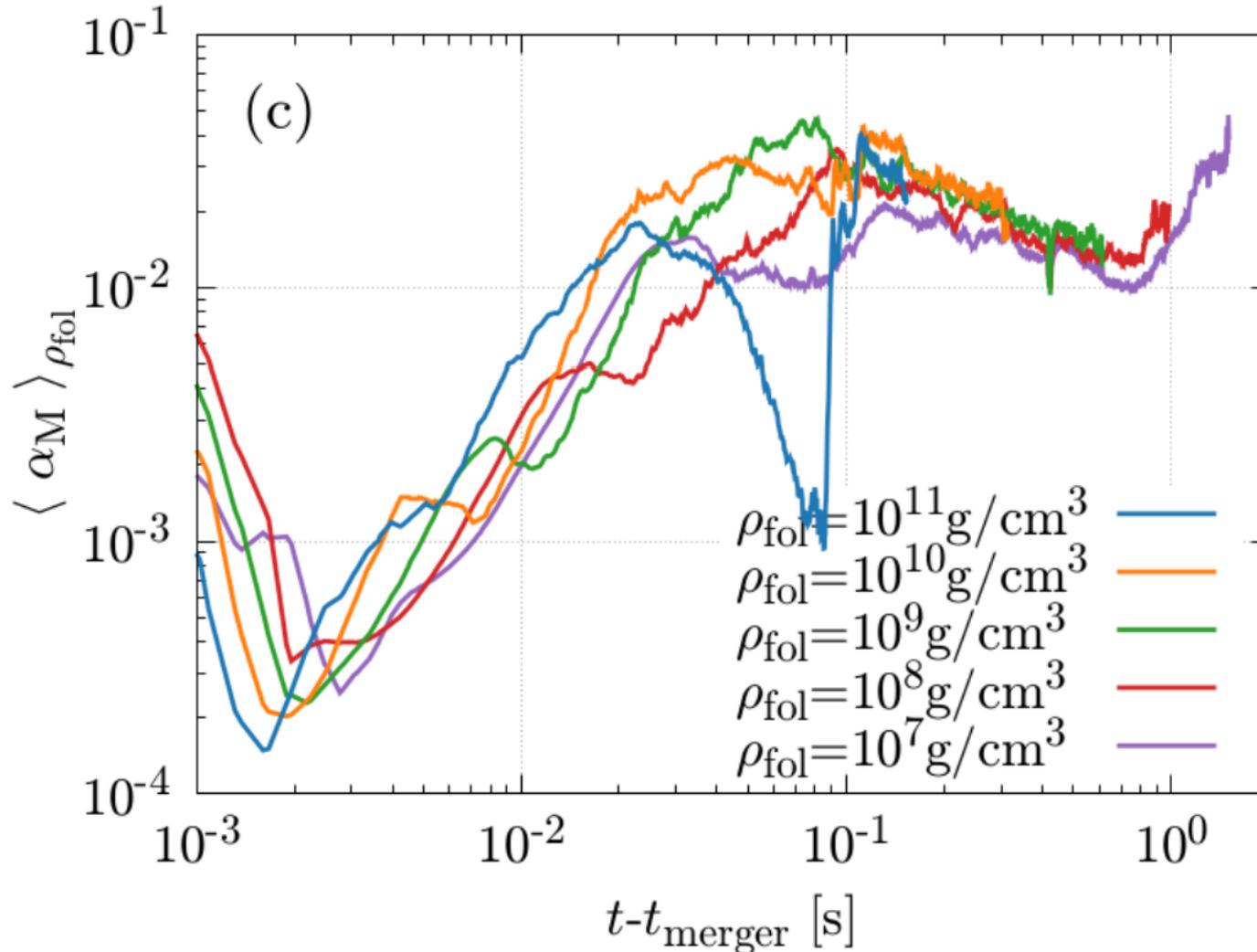
Interactive snapshot: <https://www2.yukawa.kyoto-u.ac.jp/~kota.hayashi/SFHo125165-3Dvtkjs.html>

MRI quality factor



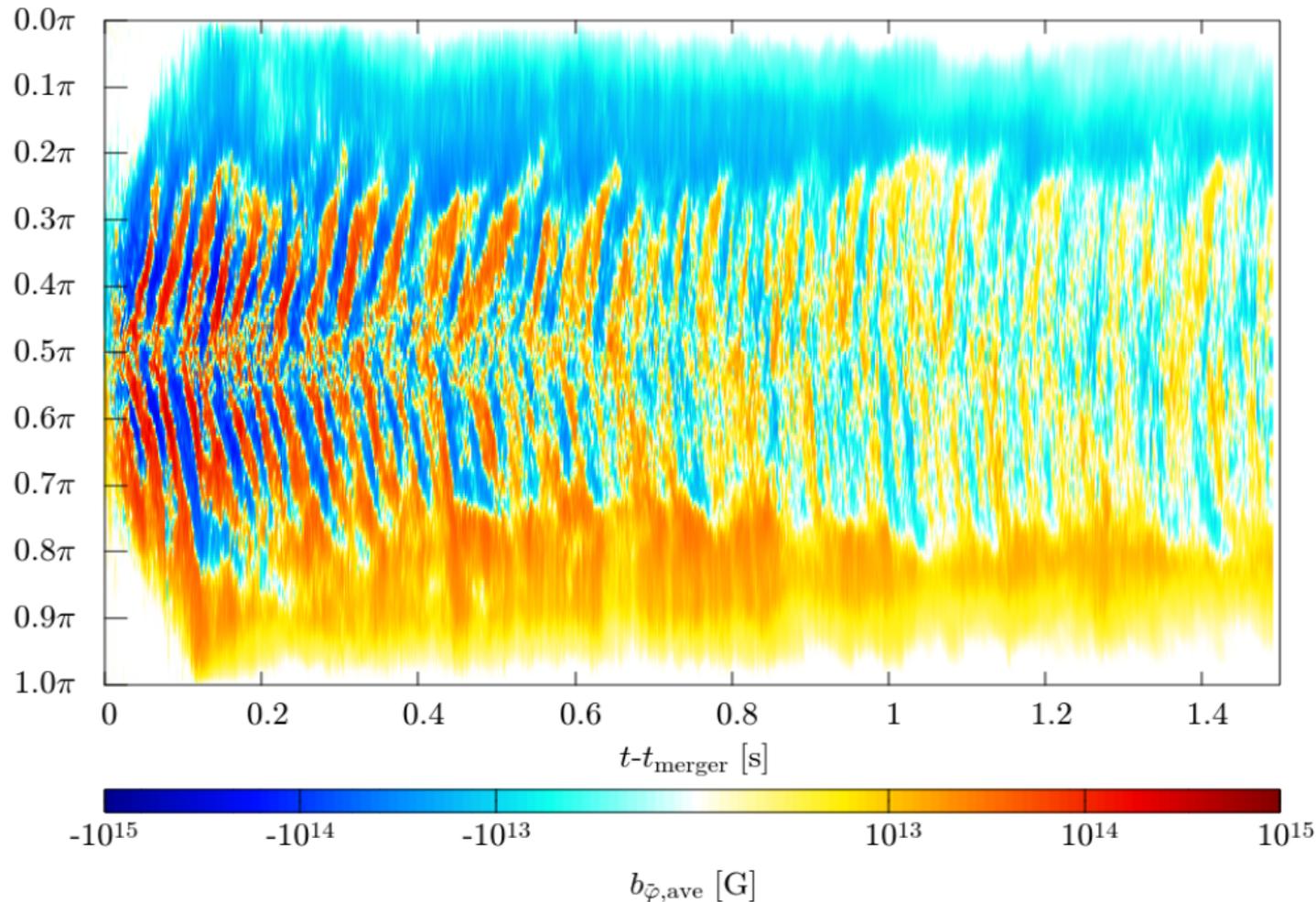
- Fastest growing mode fully resolved at 0.1s after merger.
- Resolved at 0.02s after merger for $\rho < 10^{10} \text{ g/cm}^3$ region

Shakura-Sunyaev parameter



- As the MRI is activated, α_M reaches 0.01-0.03 inducing effective viscosity and drive disk evolution

Toroidal field butterfly diagram



- Evaluated at 50km
- Period of diagram: 0.03-0.04s
- Period derived from $\alpha\Omega$ dynamo theory: 0.03s

Generation of Mean poloidal field

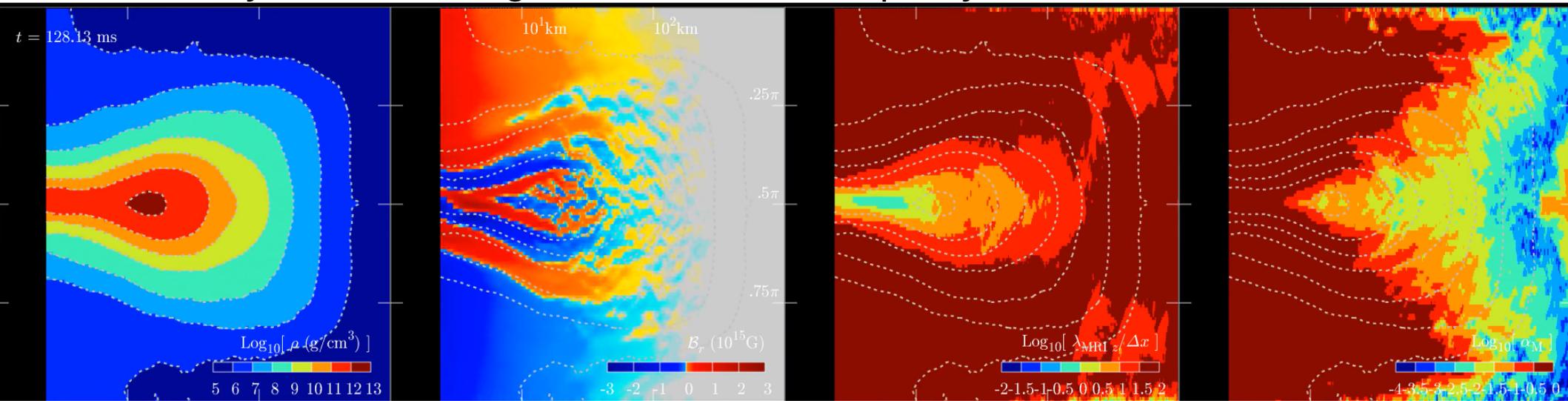
- Azimuthally-averaged quantities on the $\log_{10}(r)-\theta$ plane.

Rest-mass
density

Poloidal
magnetic field

MRI
quality factor

Maxwell
stress



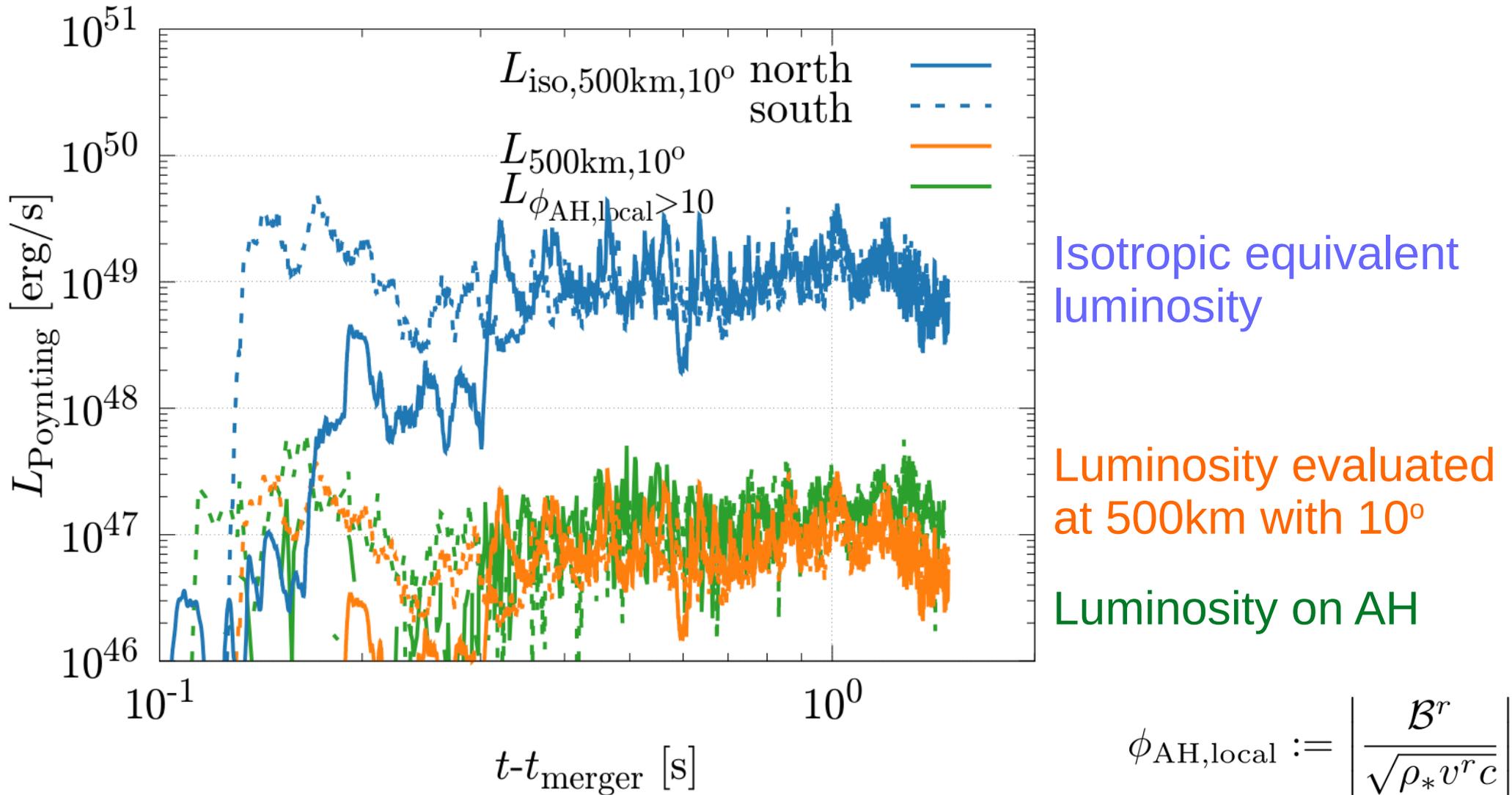
animation: <https://www2.yukawa.kyoto-u.ac.jp/~kota.hayashi/SFHo125165-2Drt.mp4>

At the evaluation radius of 50km...

- Period of mean magnetic field polarity flip: 0.03-0.04s
- Period derived from $\alpha\Omega$ dynamo theory: 0.03s

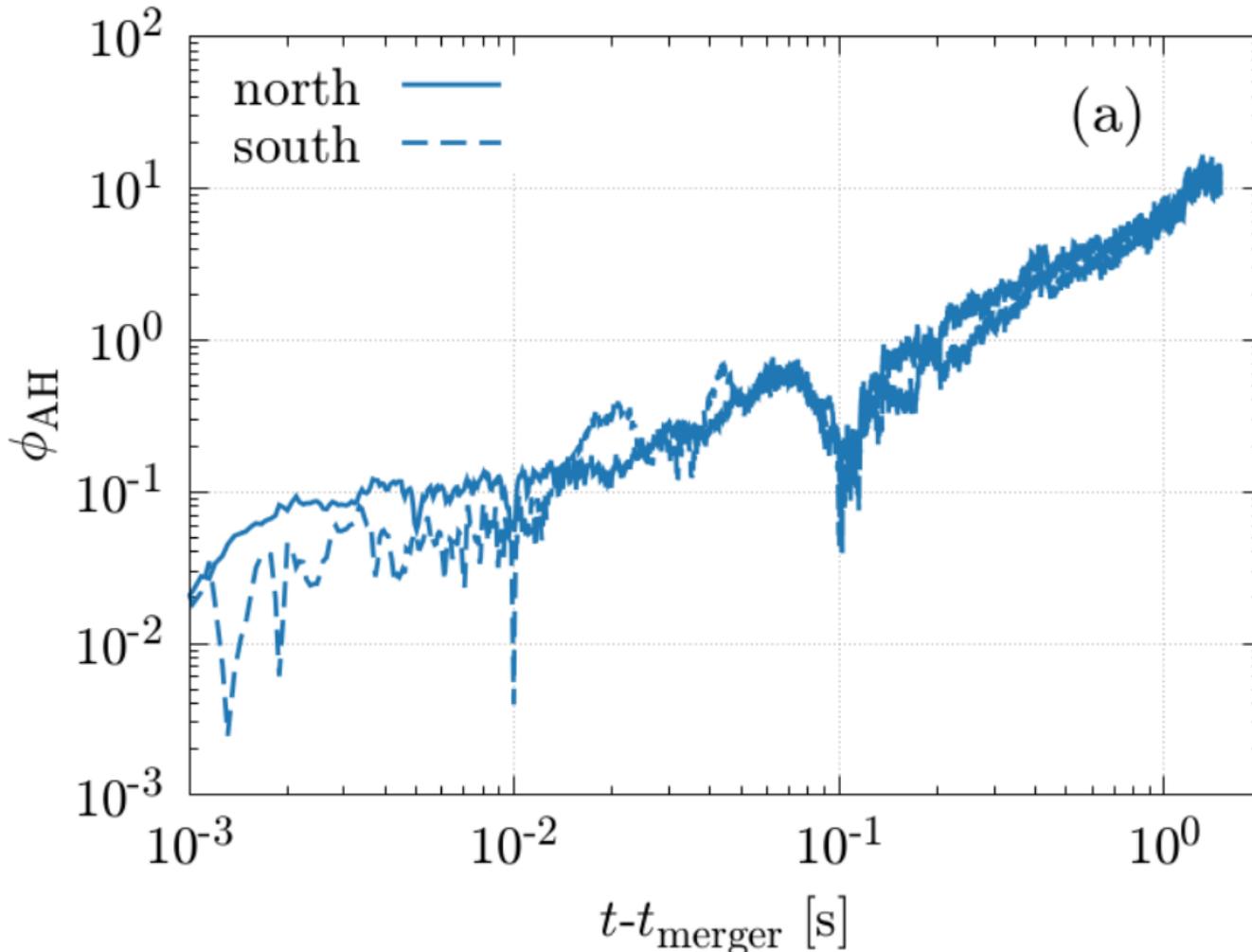
$\alpha\Omega$ dynamo generates the large-scale magnetic field

Poynting flux launch



- $\phi_{\text{AH,local}} > 10$ region on AH is responsible for the Poynting flux launch
- L_{iso} starts decreasing after $\sim 1\text{s}$ as the disk mass is ejected

MADness parameter

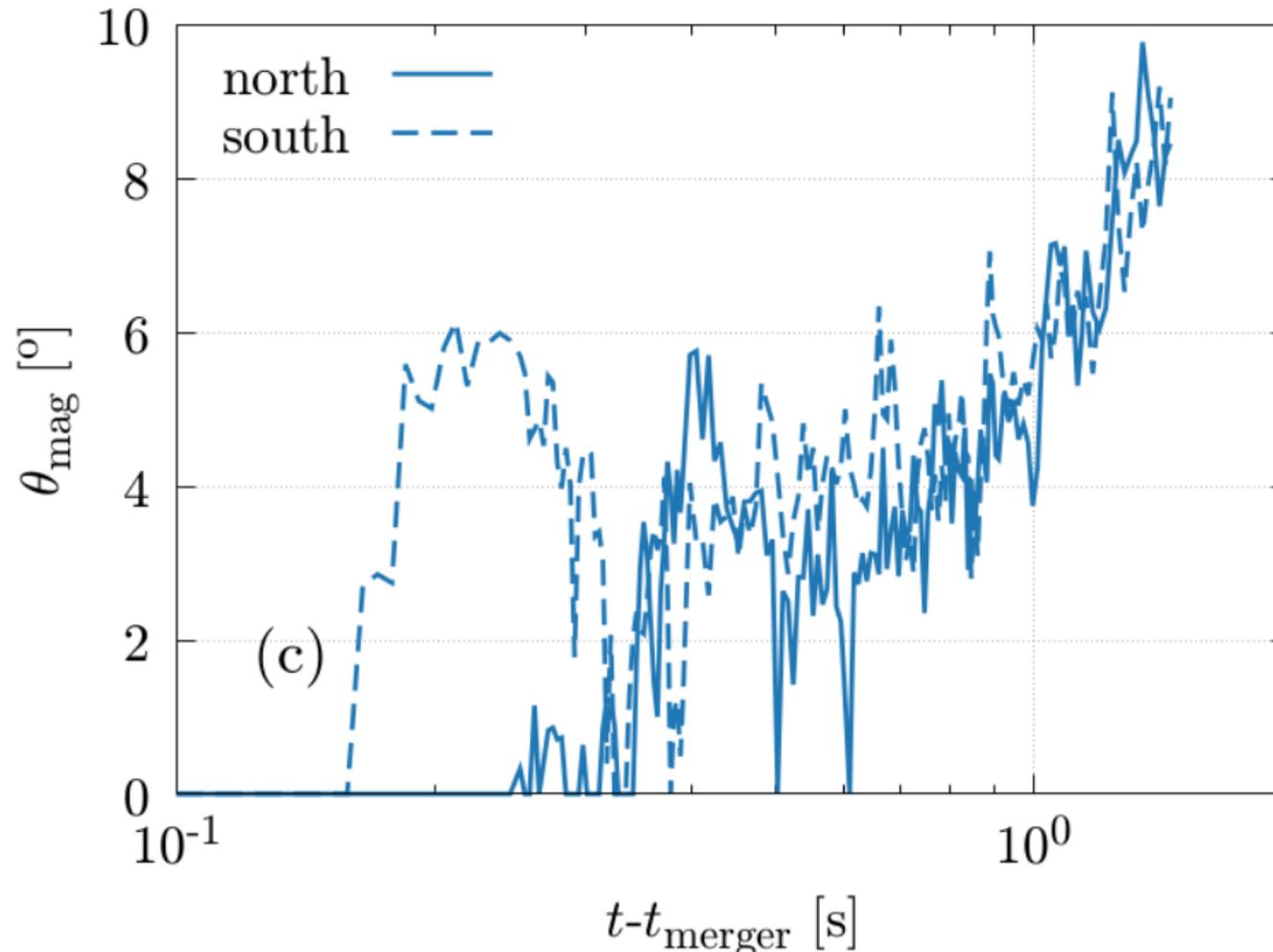


$$\phi_{\text{AH}} := \frac{\Phi_{\text{AH}}}{\sqrt{\dot{M}_{\text{AH}} r_{\text{AH}}^2 c}},$$

$$\begin{aligned} \Phi_{\text{AH}} &:= \oint_{\text{AH}} B^i \sqrt{\gamma} dS_i \\ &\approx \oint_{r=\max(r_{\text{AH}})} B^r r^2 \sin \theta d\theta d\varphi, \\ \dot{M}_{\text{AH}} &:= \oint_{\text{AH}} \rho \sqrt{-g} u^i dS_i \\ &\approx \oint_{r=\max(r_{\text{AH}})} \rho_* v^r r^2 \sin \theta d\theta d\varphi, \end{aligned}$$

- Not yet reaches MAD state [Tchekhovskoy+11]
- Energy supply from BH will be kept [Christie+19, Gottlieb+23]

Opening Angle of Magnetosphere



- Decrease of the disk mass due to the post-merger mass ejection leads to loss of the gas pressure support for magnetosphere resulting in the increase of the opening angle at ~ 1 sec after merger.

Summary

- The longest 3D NRRMHD simulations of BNS merger that self-consistently solve from the inspiral stage
- Large-scale magnetic field generated by the $\alpha\Omega$ dynamo in the black hole-accretion disk system after the merger and forms magnetically dominated region along the BH spin axis
- Collimated outflow with luminosity $\sim 10^{49}$ erg/s is driven by the Blandford-Znajek mechanism and propagates through magnetosphere