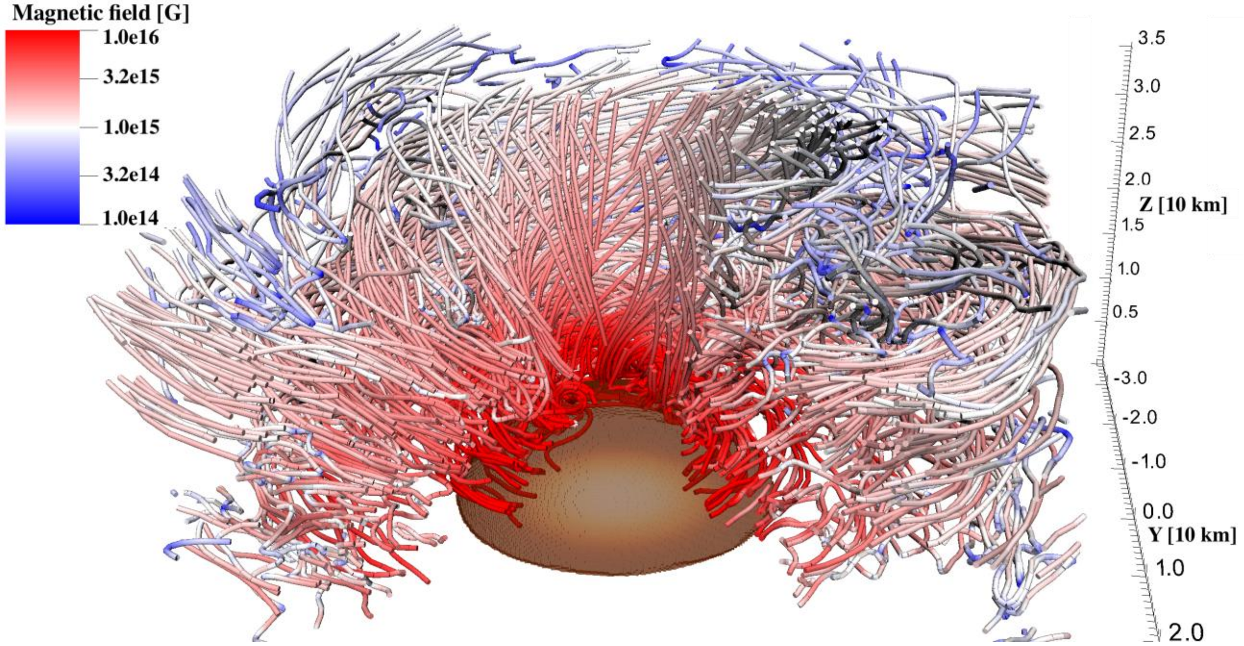
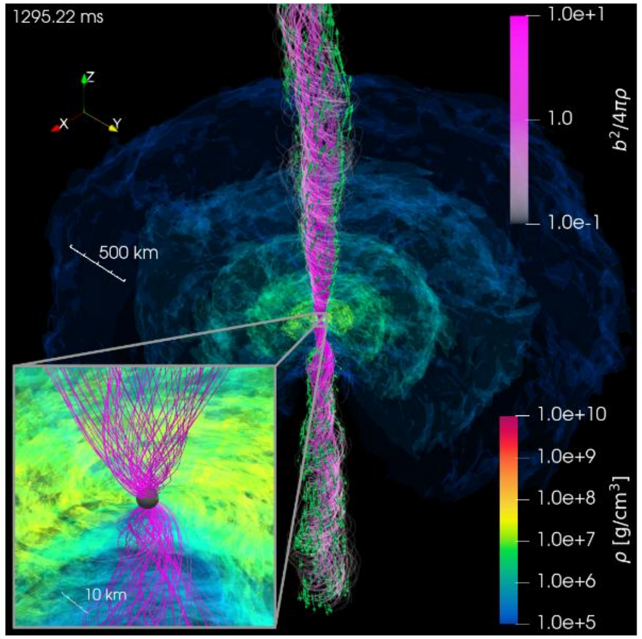
Inferring the nuclear equation of state from binary merger simulations





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

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A “package” for EM counterpart modeling

NR simulation
(GR+EOS+ ν -Rad.+MHD)

⇩

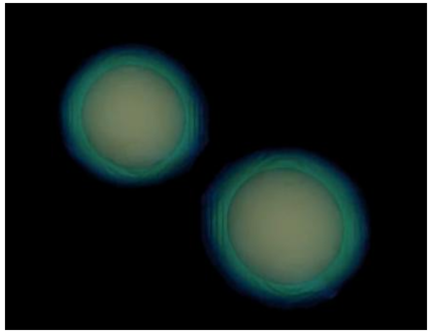
R-process nucleosynthesis calculation

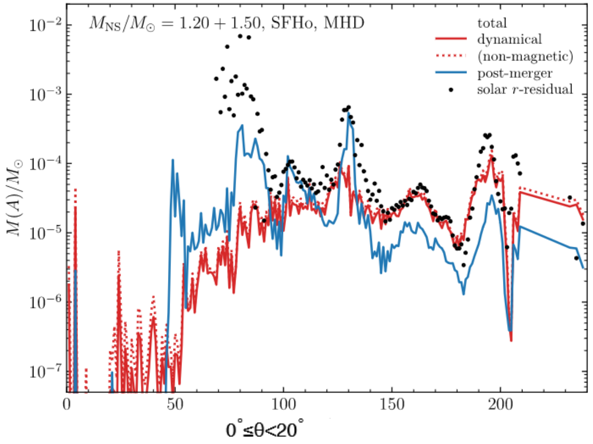
⇩

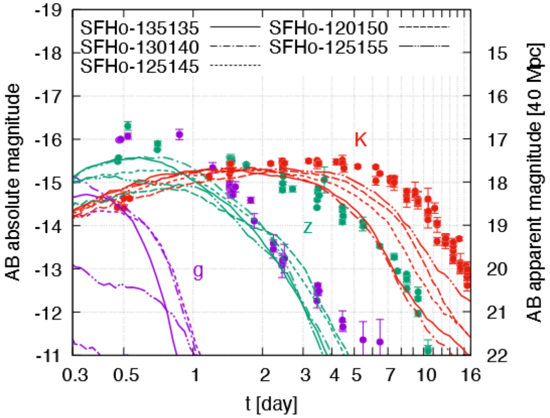
Kilonova/GRB light curve modeling

⇩

Observation







Sys. Err.

- ▶ Resolution
- ▶ Approx. GR
- ▶ Approx. ν -Rad
- ▶ MHD approx.

…

- ▶Reaction rate
- ▶Mass model

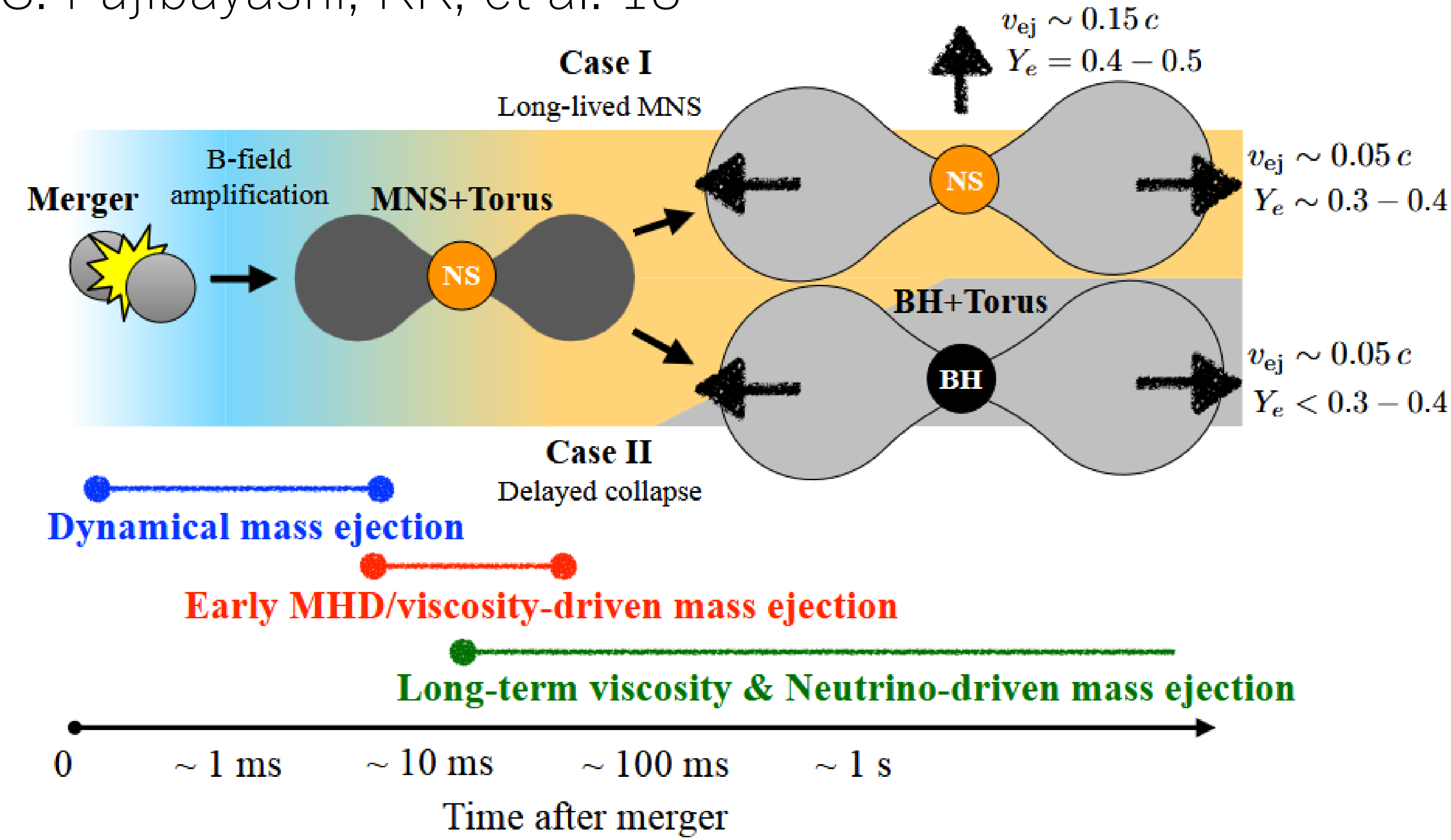
…

- ▶Photon rad. transfer

…

Neutron rich matter ejection mechanism

S. Fujibayashi, KK, et al. 18



Many Refs.

Hotokezaka et al. 13,
Fujibayshi et al. 18,20,21,22
Bauswein et al. 13, 17
Just et al. 14, 21
Siegel & Metzger, 18
Combi & Siegel, 23
Radice et al. 18
+ more

▶One missing mass ejection channel = Lorentz force-driven ejecta

Recent progress indicates its relevance. (Mösta et al. 20, Combi & Siegel 23, KK et al. 24, Most 23)

Lorentz force(MHD)-driven ejecta as a "new" channel

Question: How can be a large-scale field established?

Mean field dynamo theory

$$\partial_t \bar{\mathbf{B}} = \nabla \times (\bar{\mathbf{U}} \times \bar{\mathbf{B}} + \bar{\mathcal{E}}), \quad \mathbf{Q} = \bar{\mathbf{Q}} + \mathbf{q},\ \bar{\mathbf{Q}} = \text{Axisym. Ave.}$$

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

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

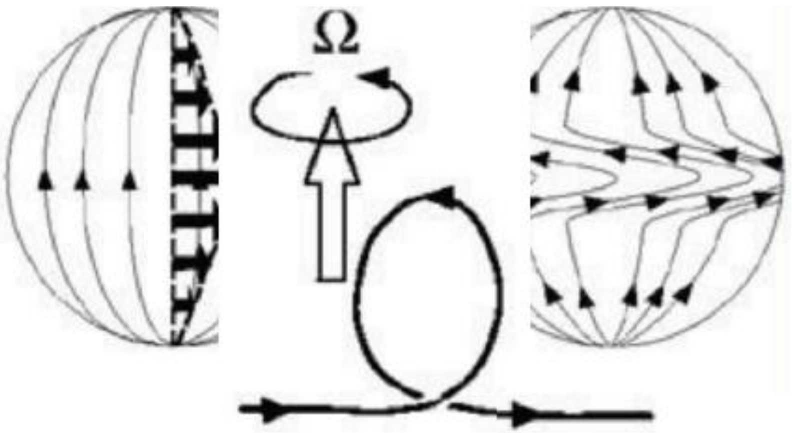
$\alpha\ \Omega$ dynamo

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

$$\partial_t \bar{B}_\varphi = R\bar{B}^A \nabla_A \Omega\ (A = R, z,\ \Omega - \text{effect})$$

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

$$\partial_t \bar{B}_z = -\partial_R \mathcal{E}_\varphi \approx \partial_R \left(\alpha_{\varphi\varphi}\bar{B}_\varphi\right)$$



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

$\alpha\ \Omega$ dynamo theory prediction (Check list)

1. $\bar{B}_{\varphi}$ should be anticorrelated with $\bar{B}_{R/z}$.

2. $\bar{E}_{\varphi}$ should be correlated or anti-correlated with $\bar{B}_{\varphi}$.

3. Dynamo cycle period $P_{theory} = 2\pi\,(\alpha_{\phi\phi}\, d\Omega/d\ln R\ k_z/2)^{-1/2}$

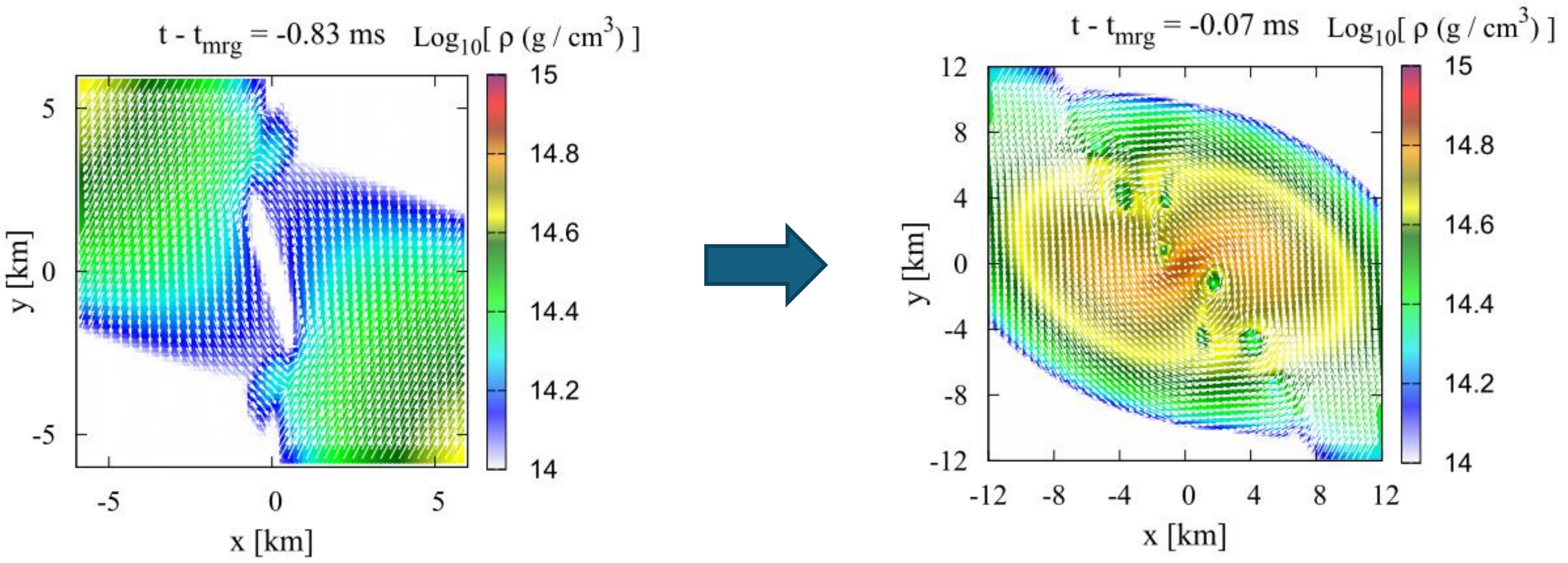
4. Dynamo wave propagation direction according to the Yoshimura-Parker rule $\alpha_{\phi\phi} \nabla \Omega \times e_{\phi}$

Question: What generate electromotive force (EMF), i.e., fluctuation component of velocity and magnetic field?

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

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

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



$$\sigma \propto k$$

High grid resolution is key.

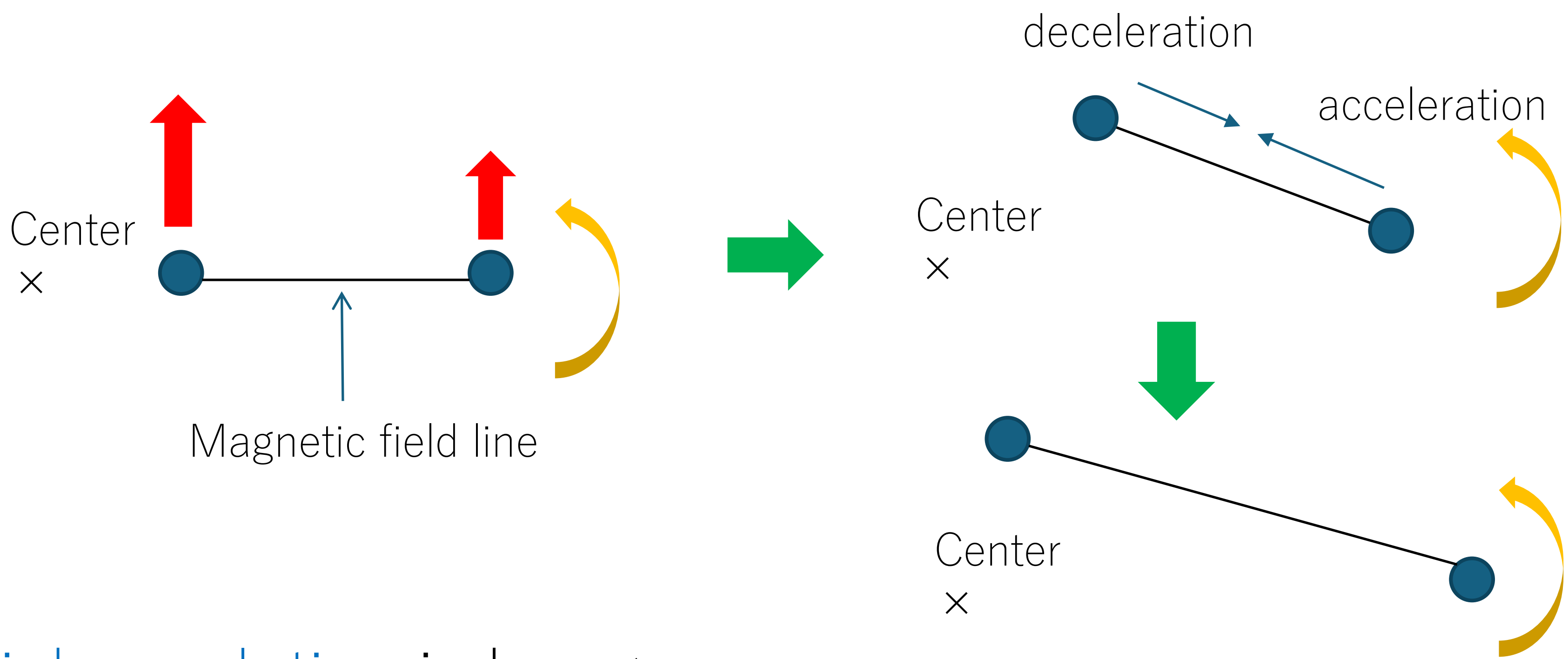
(KK et al. 14,15,18,24, Palenzuela et al. 22, Aguilera-Miret et al. 20, 22, 23)

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

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

▶Differential rotation: $\nabla\Omega < 0, \lambda_{MRI}^{\mathrm{RNS}} \approx 80m \left(\frac{B_P}{10^{15}G}\right)\left(\frac{\rho}{10^{15}g\ cm^{-3}}\right)^{-\frac{1}{2}}\left(\frac{\Omega}{8000rads^{-1}}\right)^{-1}$

$$\lambda_{MRI}^{BH-Disk} \approx 1{,}000m \left(\frac{B_p}{10^{15}G}\right)\left(\frac{\rho}{10^{13}gcm^{-3}}\right)^{-\frac{1}{2}}\left(\frac{\Omega}{6000rads^{-1}}\right)^{-1}$$



Again, high resolution is key. (Shibata et al. 05, Duez et al. 05, Siegel et al. 13, KK et al. 18,24)

Methodology

▶ 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/BHBLp /DD2) (Steiner et al. 13, 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)

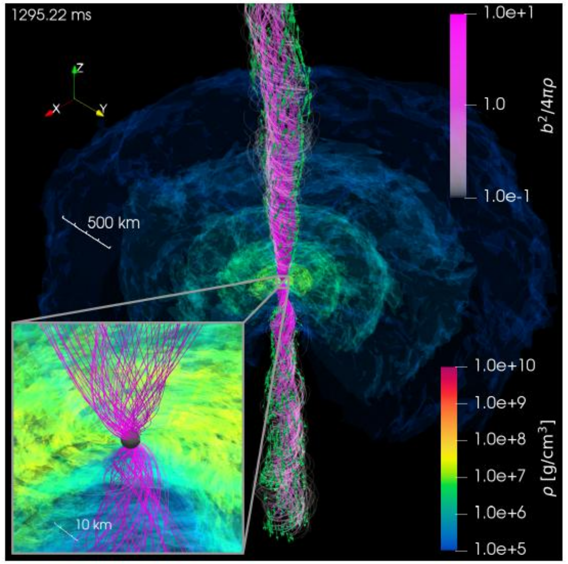
All the works, we quantify the ability of our simulation set up to resolve the KHI and MRI:

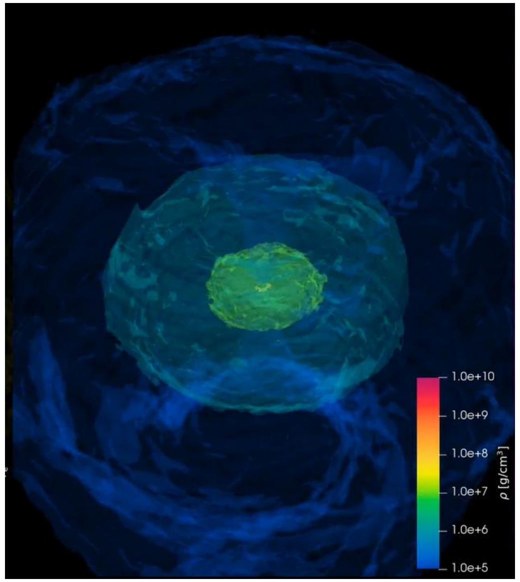
$$Q_{MRI} \equiv \frac{\lambda_{MRI}}{\Delta x} \geq 10$$

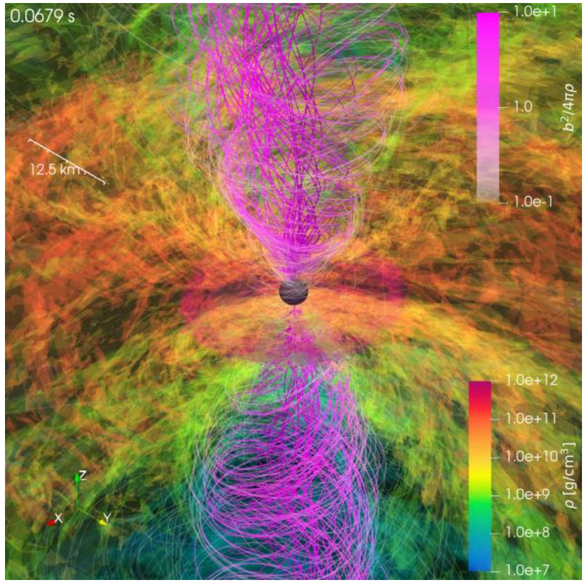
Inferring the EOS from ab initio simulations

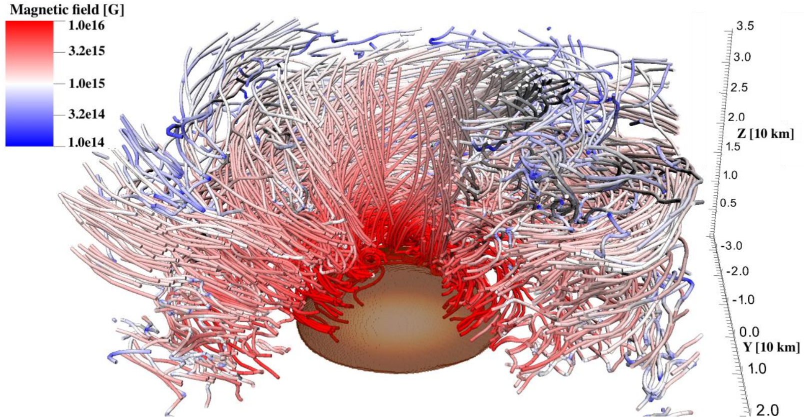
Lifetime of the remnant massive neutron star

Prompt	Short-lived	Intermediate-lived	Long-lived
$\sim$ 0s	$\sim$O(0.01) s	$\sim$O(0.1)s	$\sim$O(1) s









$L_{iso} \sim 10^{49}$erg/s
Hayashi et al. PRL 25

No jet until 1s at least.
KK PRL 23

$L_{iso} \sim 10^{52}$erg/s
KK 25 in prep.

$L_{iso} \sim 10^{52}$erg/s
KK Nature Astro. 24

EOS stiffness: Soft ⟷ Stiff

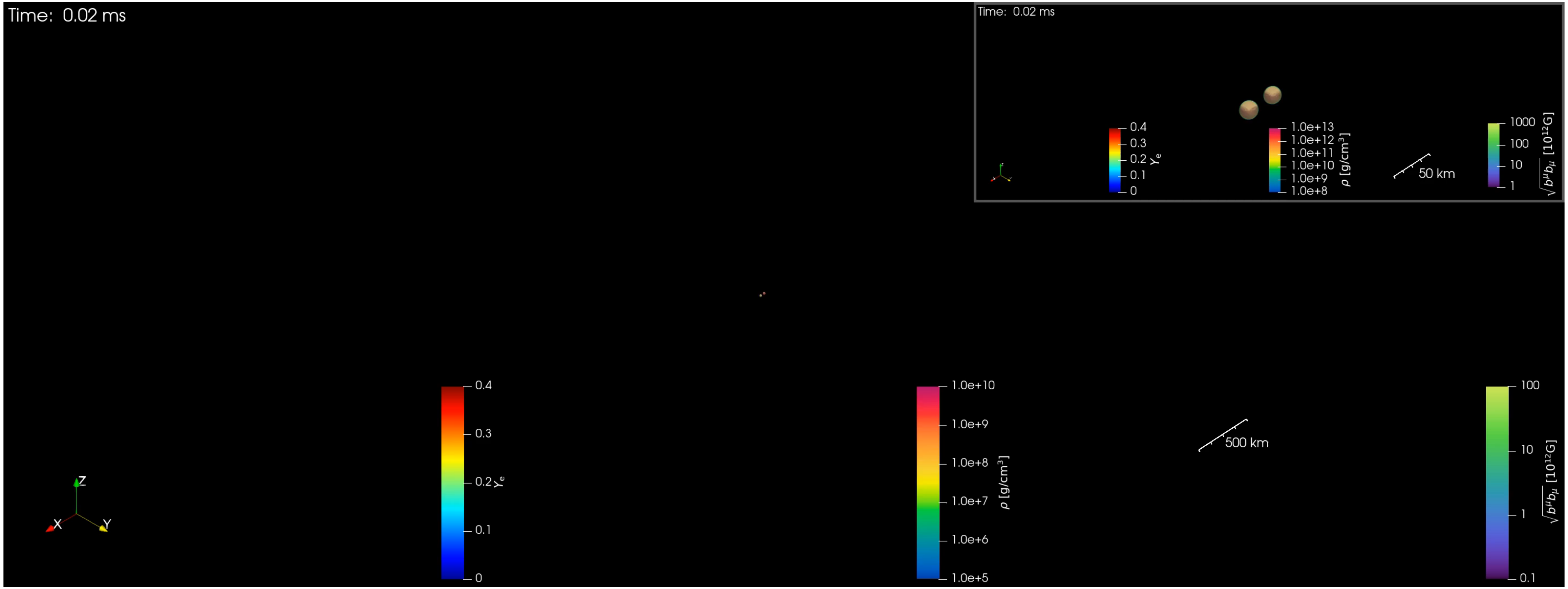
Binary mass: Large ⟷ Small

Long-lived remnant formation

0.2s simulation, DD2-1.35-1.35$M_\odot$, $\Delta x_{finiest}$=12.5 m (KK et al. Nature Astron. 24)

Y_e $\rho\ (g\ cm^{-3}) + B - field\ line$ $B(G)$ ©K. Hayashi

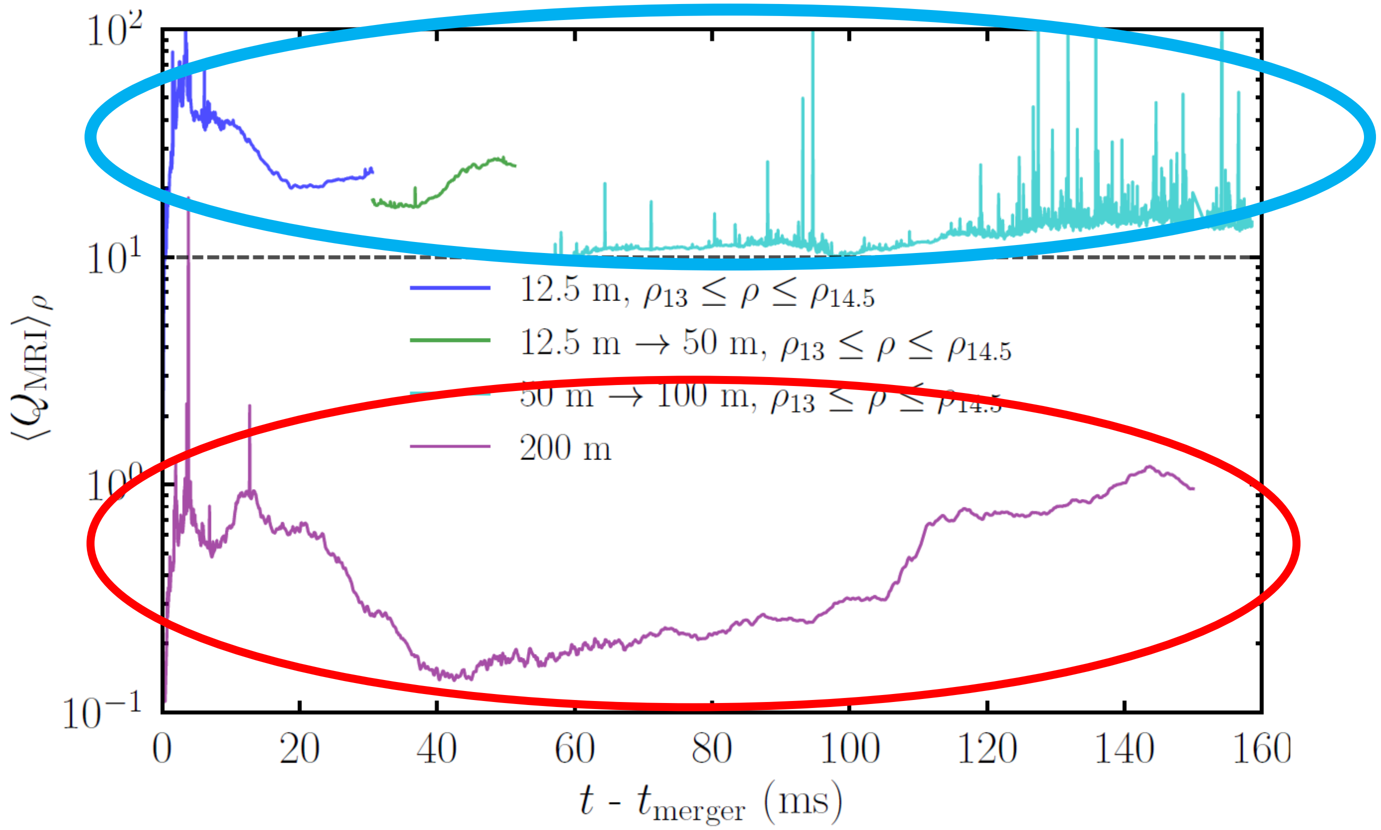
2,000 km



Check list to pin down an $\alpha\ \Omega$ dynamo

Prerequisite

MRI quality factor: $\frac{\lambda_{MRI}}{\Delta x} > 10$

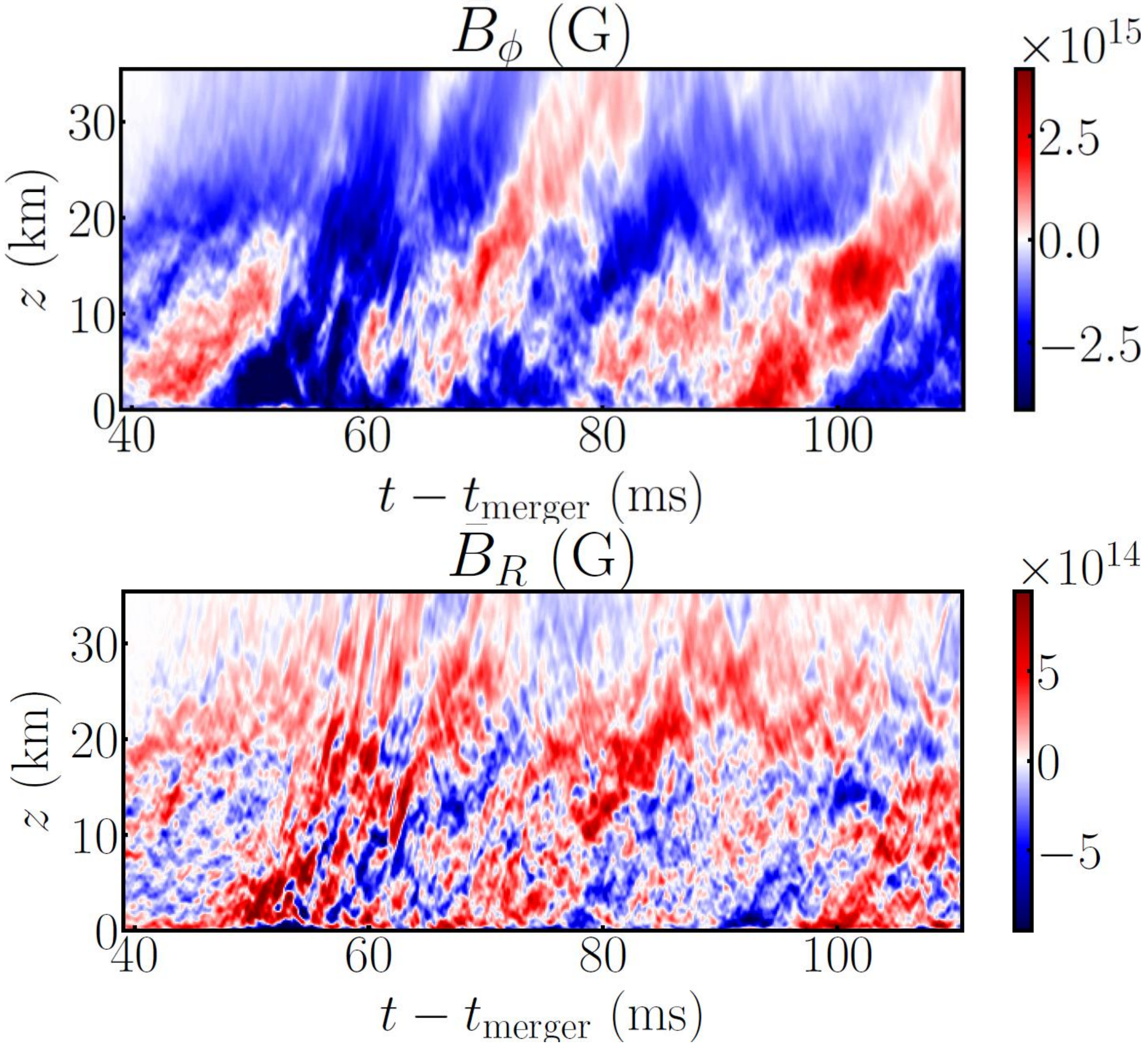


MRI is well resolved in Δx=12.5m run⇒Turbulence is developed

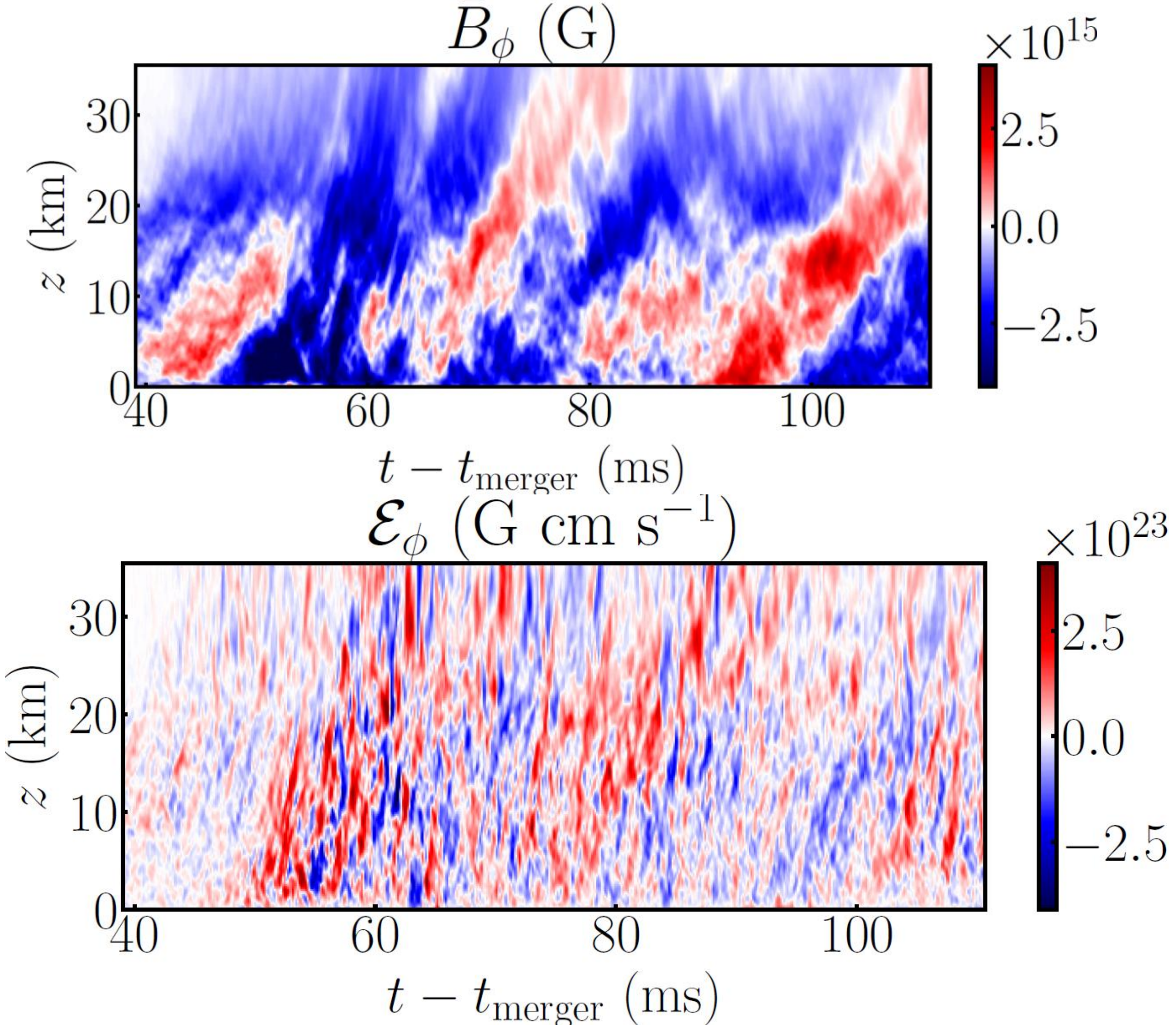
MRI is not resolved in Δx=200m run⇒ No turbulence

Check list to pin down an $\alpha\ \Omega$ dynamo

Ω effect



α effect



Check list to pin down an $\alpha\ \Omega$ dynamo

Pearson correlation between $\bar{E}_\varphi$ and $\bar{B}_\varphi$

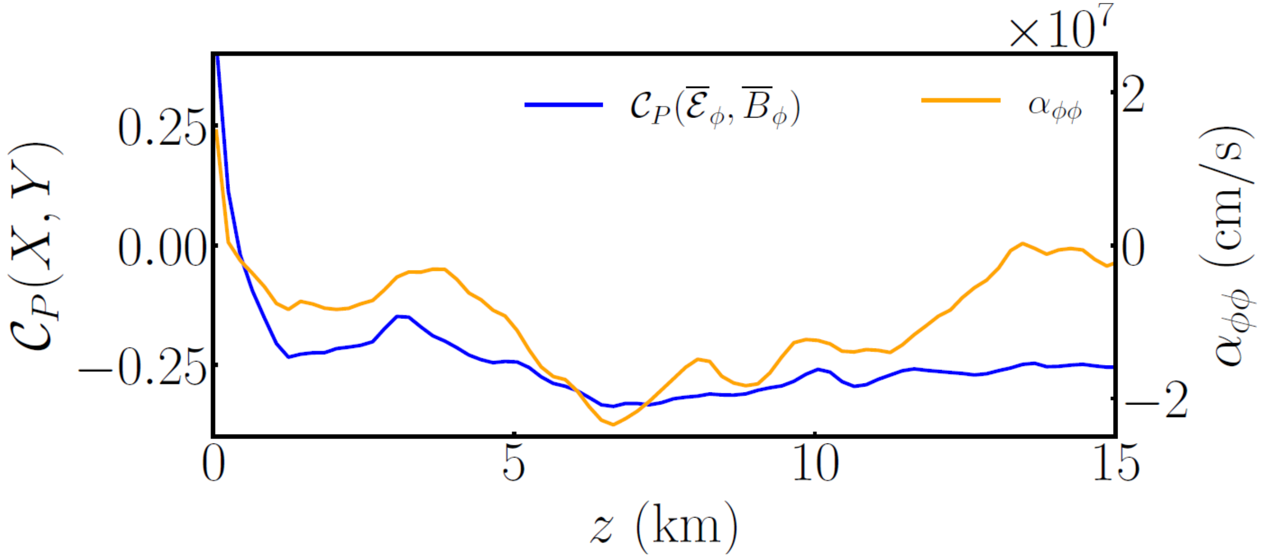
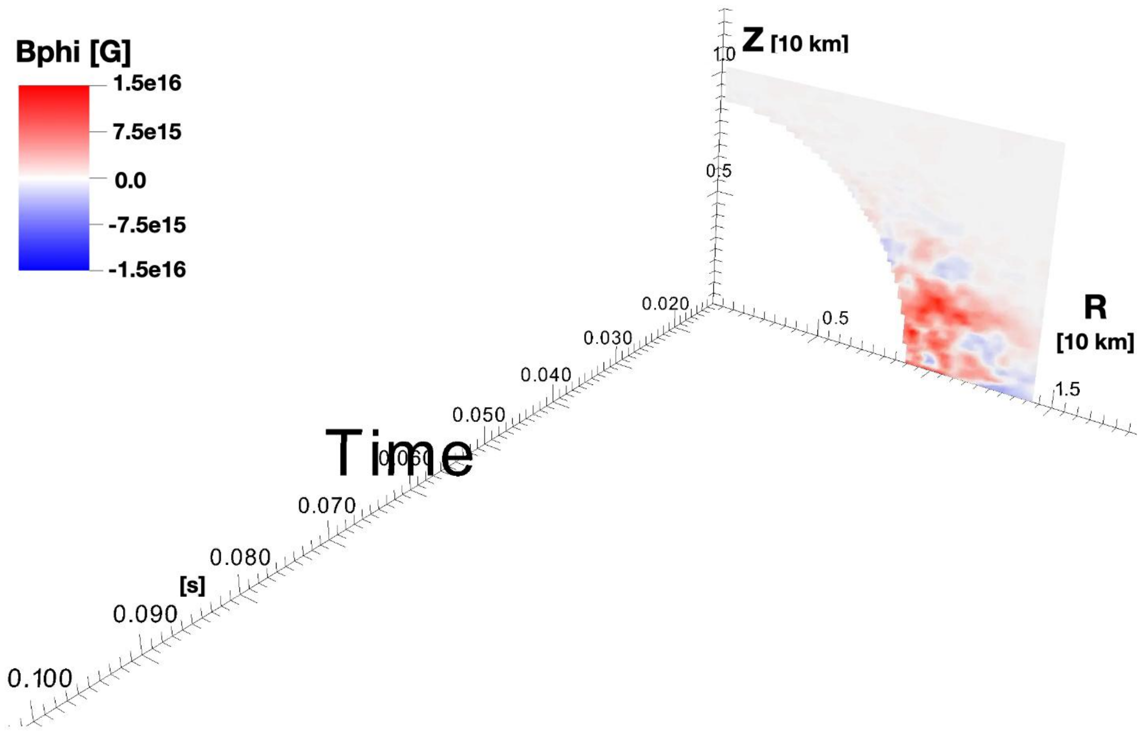


Table 1 The $\alpha\Omega$ dynamo period prediction and simulation data at several radii

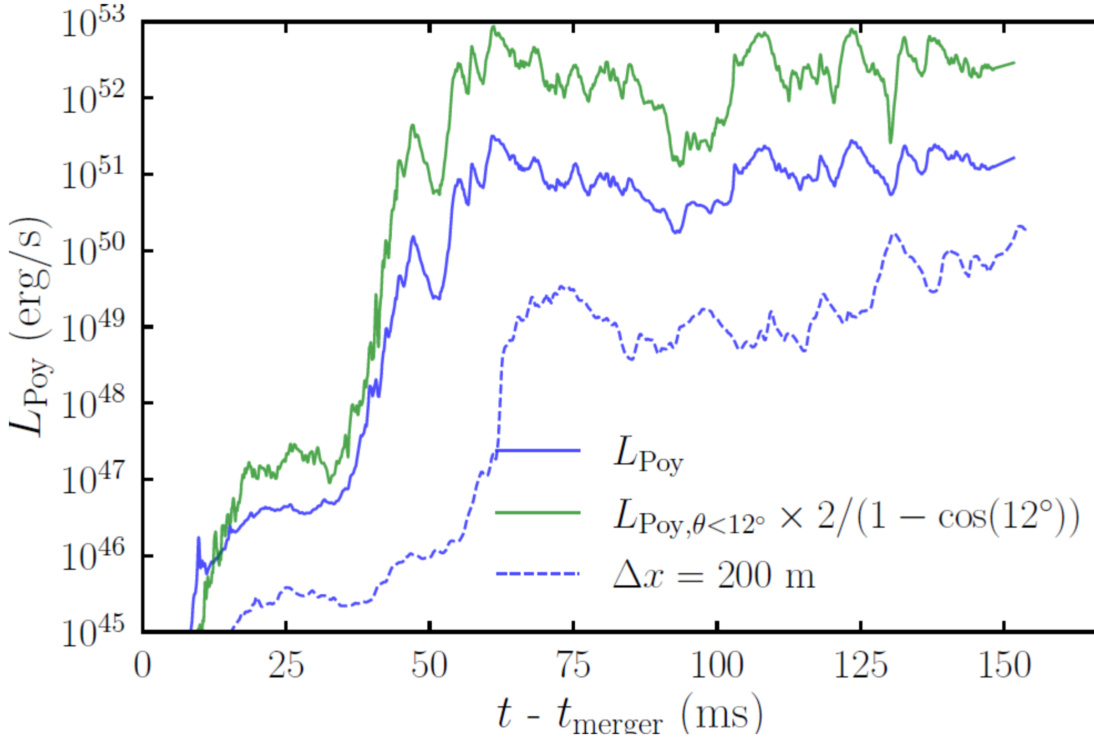
R (km)	$\alpha_{\phi\phi}$ (cm/s)	Ω (rad/s)	Shear rate	k_z (/cm)	P_{theory} (s)	P_{sim} (s)
20	-8.1×10^6	4025	$q = -1.0$	6.3×10^{-6}	0.020	0.018
30	-1.0×10^7	2515	$q = -1.34$	4.2×10^{-6}	0.021	0.018–0.024
40	-1.0×10^7	1688	$q = -1.44$	3.3×10^{-6}	0.037	0.018–0.030
50	-4.4×10^6	1200	$q = -1.50$	2.6×10^{-6}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

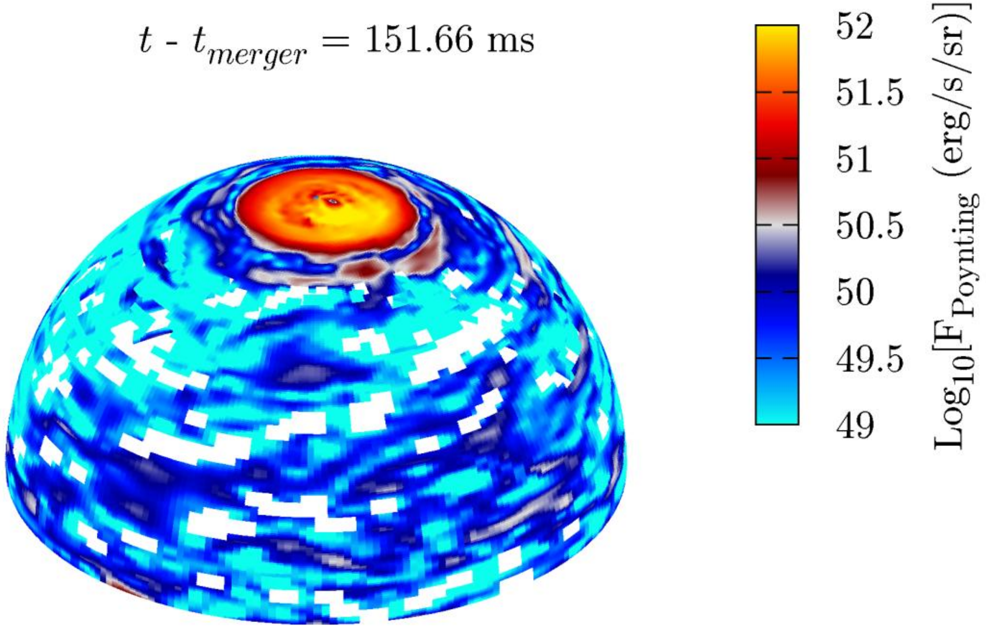
Check list to pin down an $\alpha\ \Omega$ dynamo



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

Jet from long-lived remnant formation

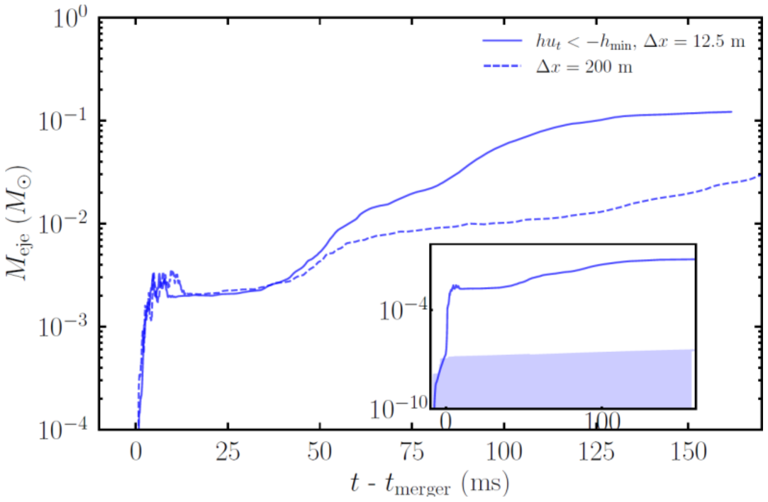




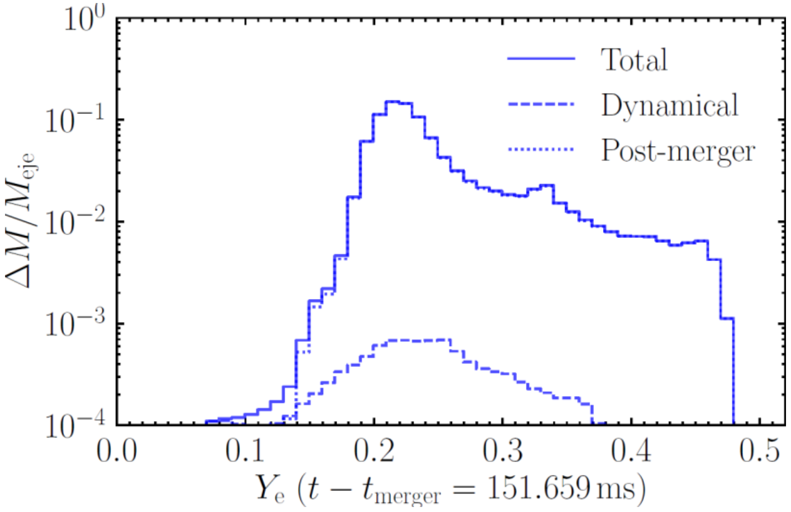
- ▶ Poynting flux dominated luminosity outflow is $L_{jet}^{iso} \approx 10^{52} erg/s$
- ▶ Relativistic outflow is confined in a region with $\theta \sim 12°$.
- ▶ Terminal Lorentz factor ≈10-20.
- ▶ The standard resolution (200m) underestimates the luminosity by a factor of 10-100.

Mass ejection from long-lived remnant formation

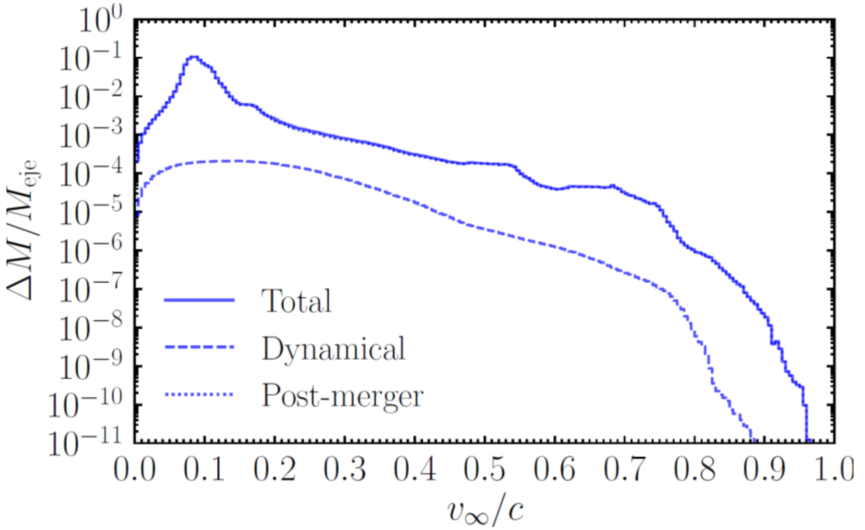
Ejecta mass evolution



Mass histogram vs Y_e



Mass histogram vs v_∞

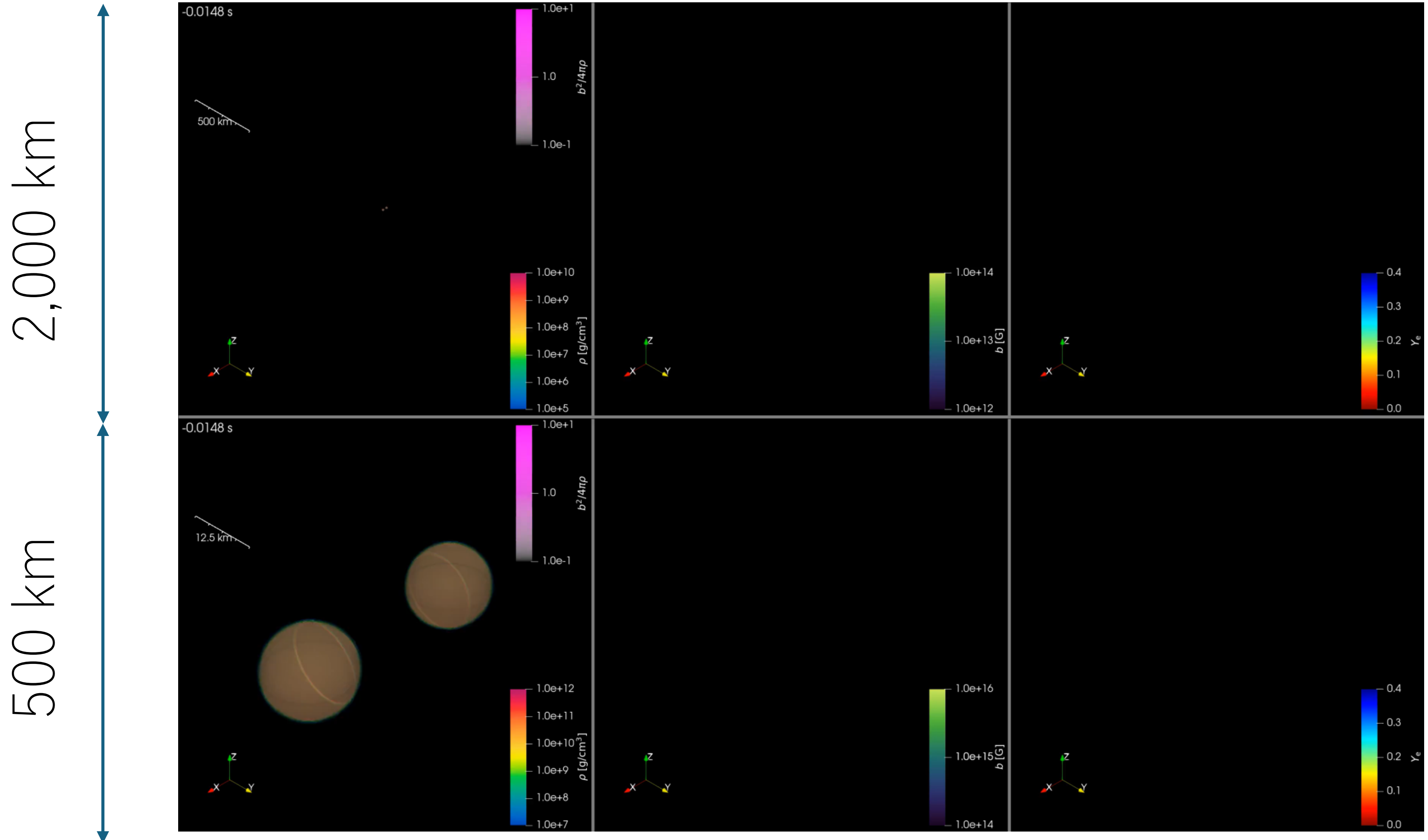


- ▶ $M_{\rm eje,\ peak,dyn}$ ≈10^{-3} $M_\odot$, $M_{\rm eje,\ peak,post}$ (Lorentz force-driven)≈0.1 $M_\odot$,
- ▶ $Y_{\rm e,peak,dyn}$≈0.24, $Y_{\rm e,peak,post}$≈0.22,
- ▶ $v_{\infty,\rm peak,dyn}$ ≈0.1-0.3 c, $v_{\infty,\rm peak,post}$ ≈ 0.1c
- ▶The standard resolution (200m) underestimates the ejecta mass by a factor of 10 (see also Mösta et al. 20).

Intermediate lived remnant formation case

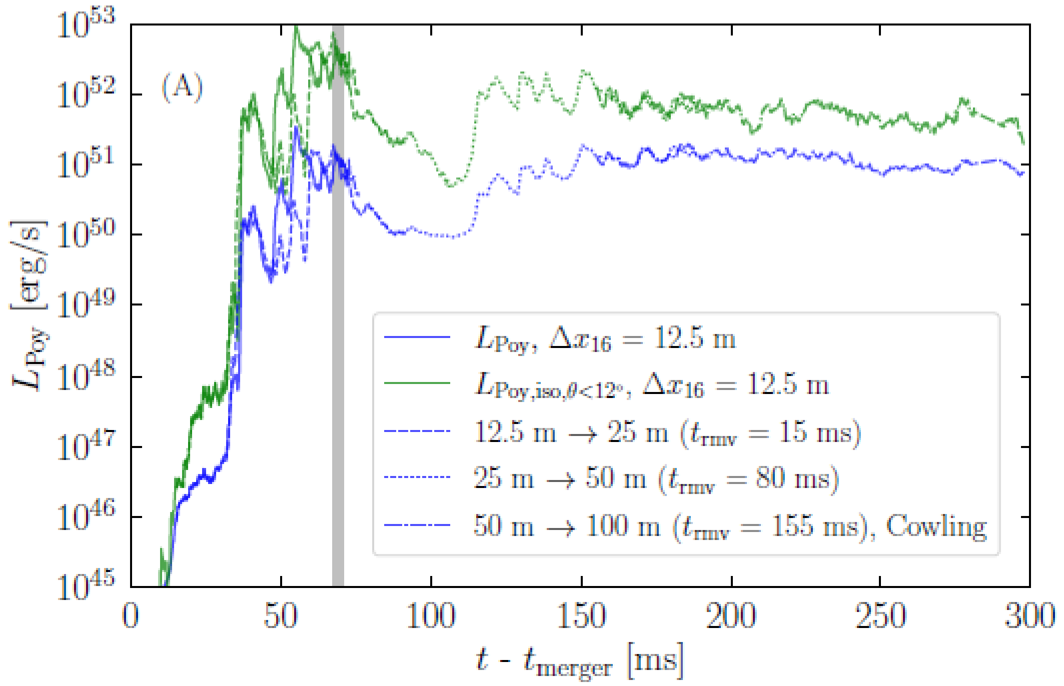
M_{chirp}=1.186$M_\odot$, BHBΛ_ϕ, Δx_{finest}=12.5m, 0.3 second simulation (KK in prep.)

$\rho\ (g\ cm^{-3})$ $B(G)$ Y_e ©K. Hayashi

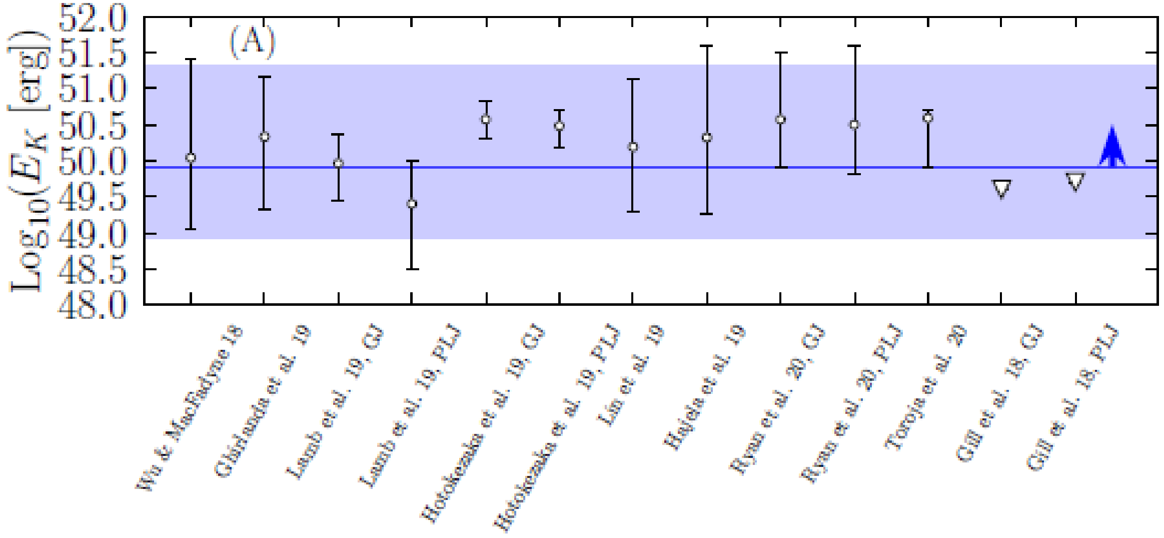


“Jet” from the intermediate-lived remnant formation

Poynting flux



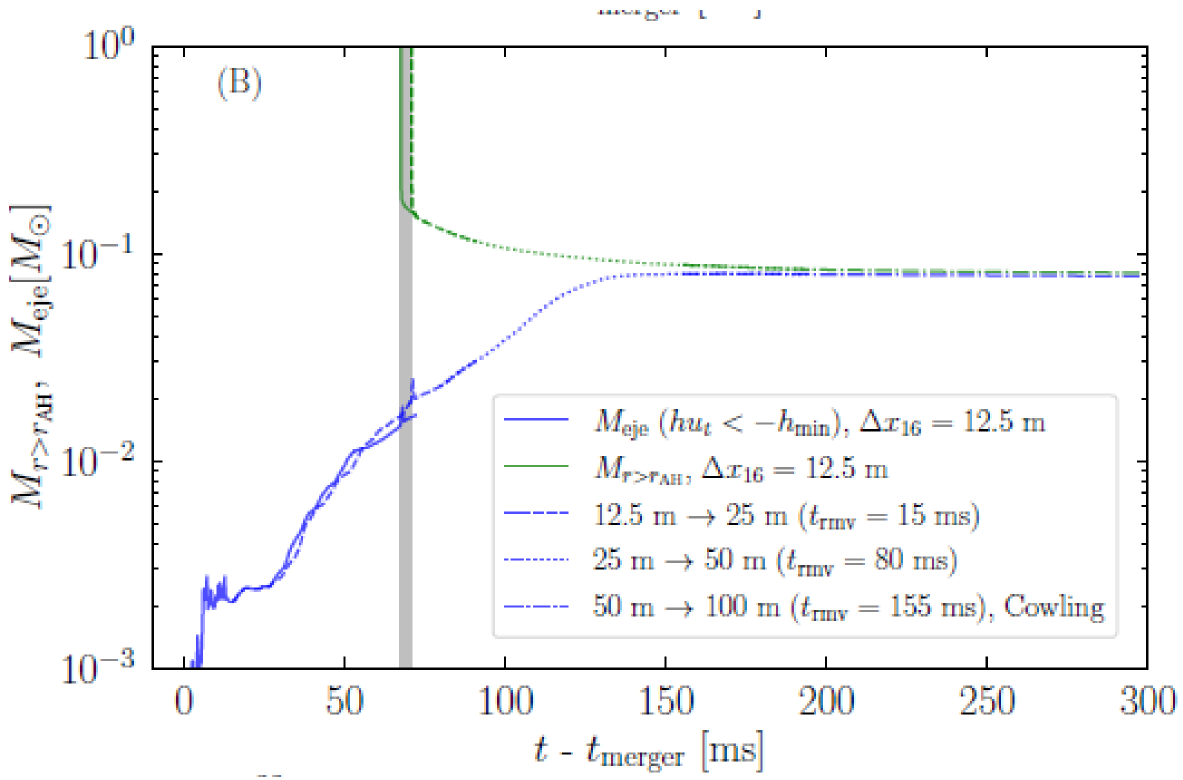
Required jet kinetic energy (GW170817)



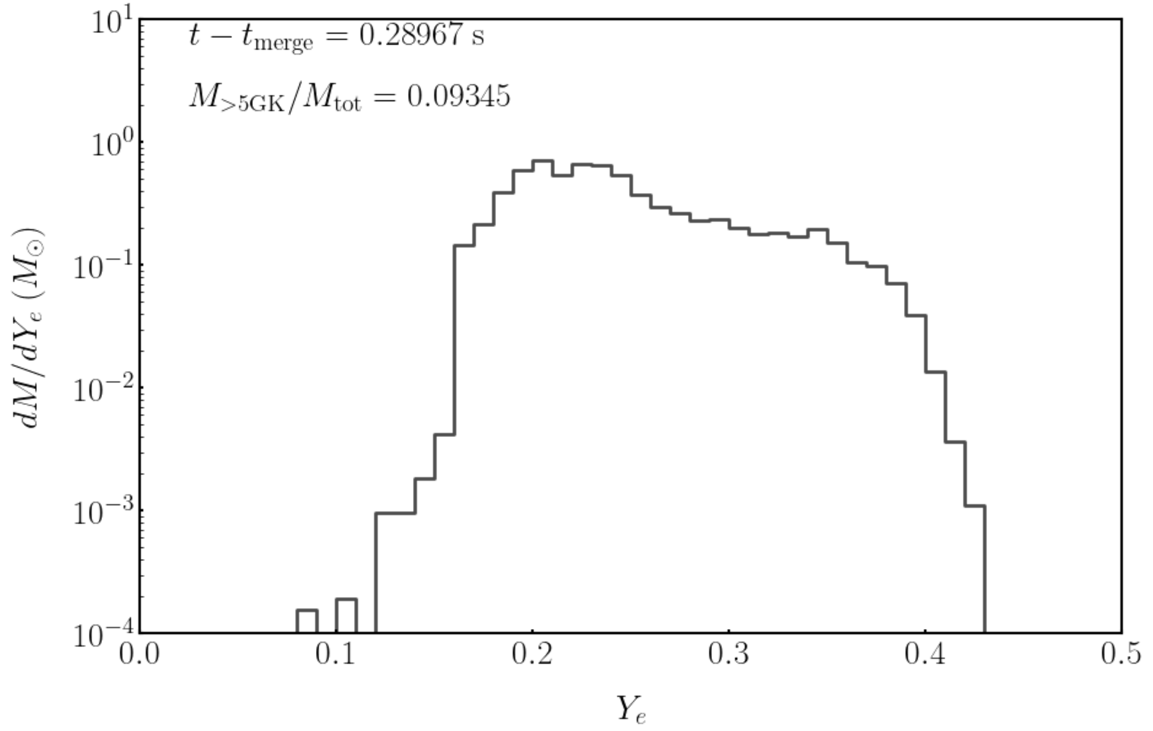
▶ $L_{jet}^{iso} \sim 10^{52} erg/s \Rightarrow$ If 1 second duration and 10% convergence efficiency are assumed, it is consistent with the required jet kinetic energy in GW170817.

Intermediate lived remnant formation case

Ejecta mass evolution



Mass histogram vs Y_e

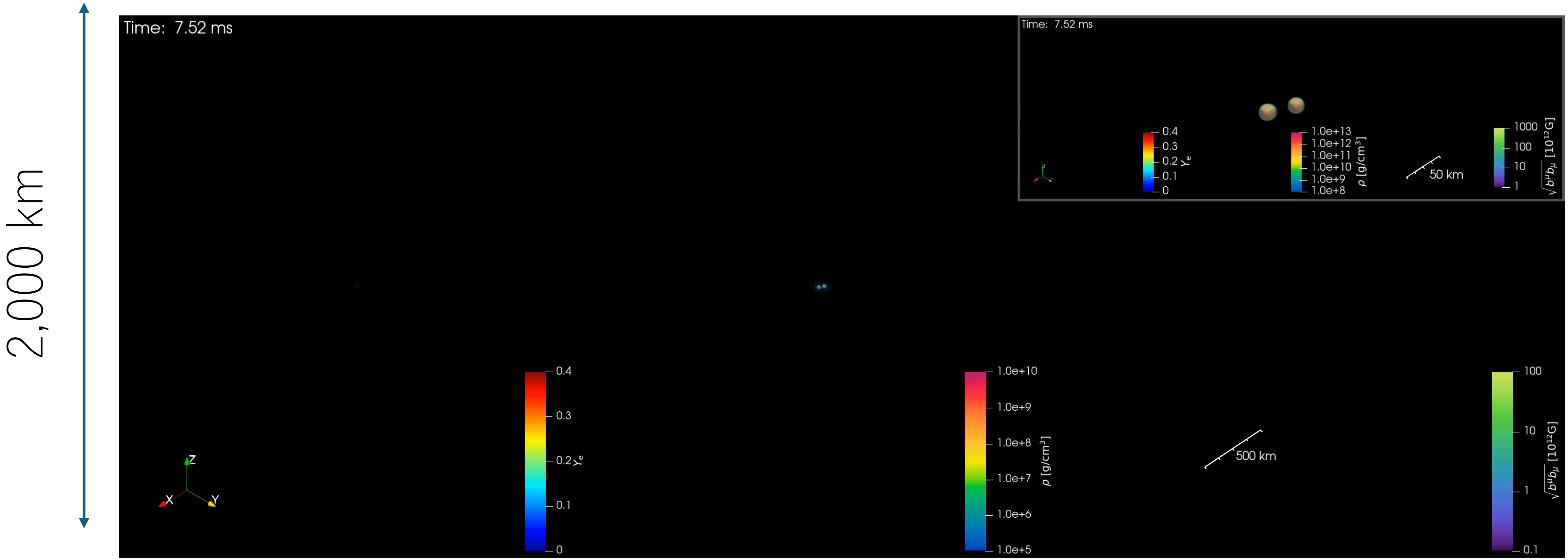


- $M_{\rm eje,\,dyn} \approx 2\times10^{-3}\ M_\odot$, $M_{\rm eje,\,post}$(Lorentz-force-driven)$\approx 7\times10^{-2} M_\odot$.
- $Y_{\rm e,\,peak,dyn} \approx 0.03$, $Y_{\rm e,\,peak,\,post} \approx 0.2$.

Short-lived remnant formation

1.2s simulation, SFHo-1.2-1.5$M_\odot$, $\Delta x_{finiest}$=150m&200m (KK et al. PRL 23)

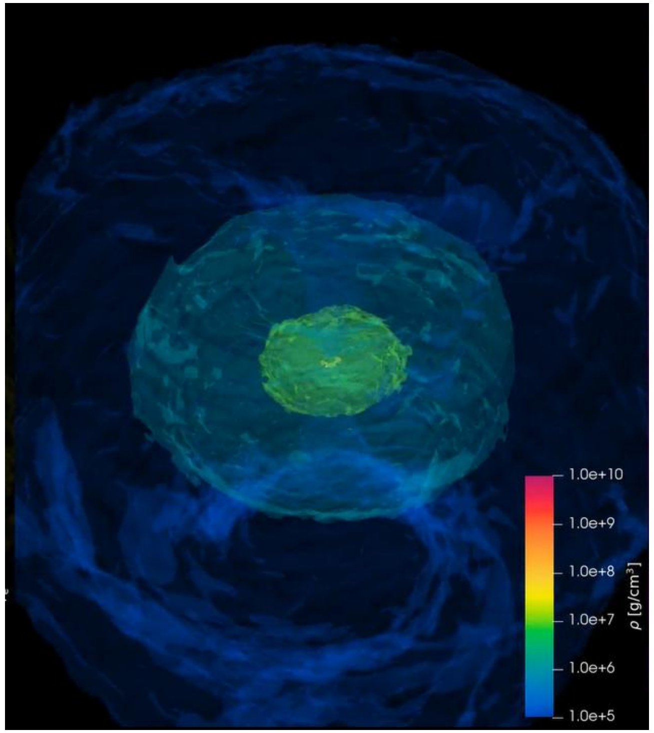
$\rho\ (g\ cm^{-3})$ Y_e $B(G)$ ©K. Hayashi



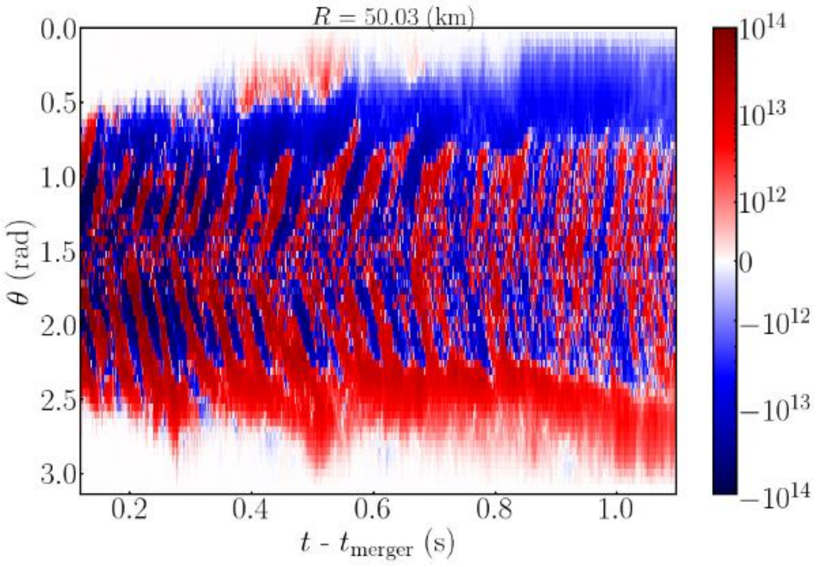
(see also, Just et al. 14, 21)

No "jet" from the short-lived remnant formation

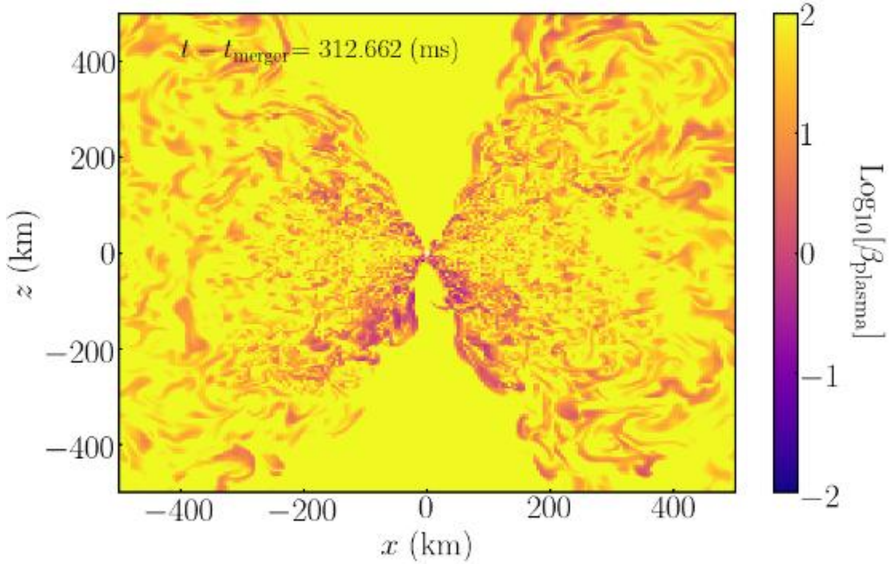
No jet until 1s at least.



Butter-fly diagram



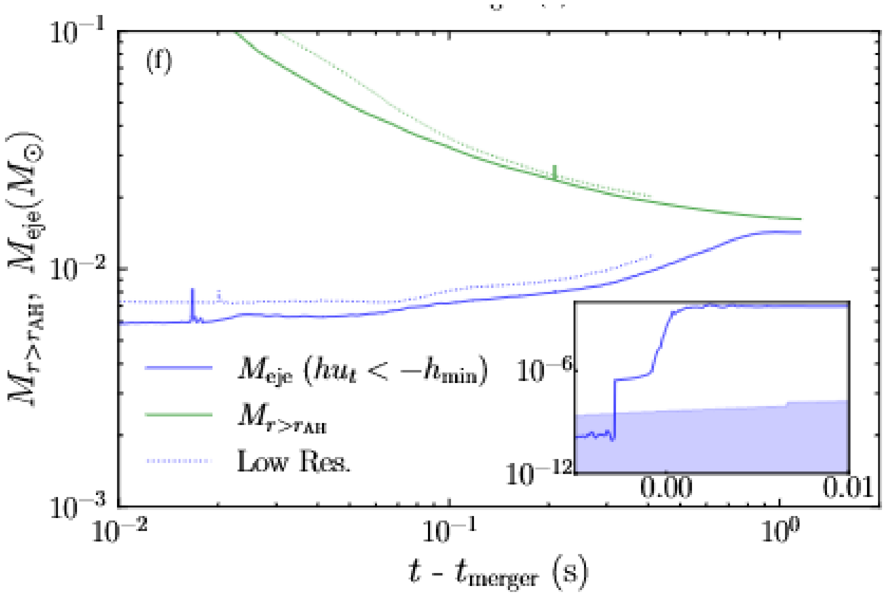
Ram-pressure/Mag-pressure

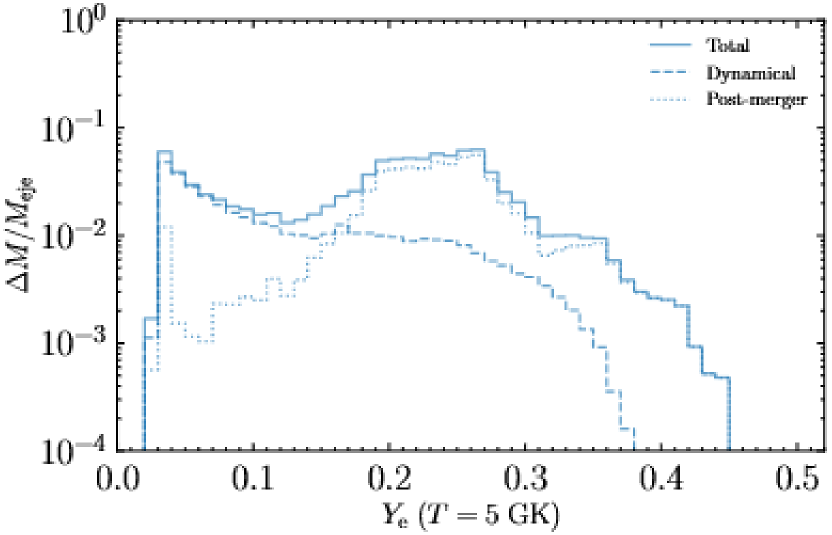


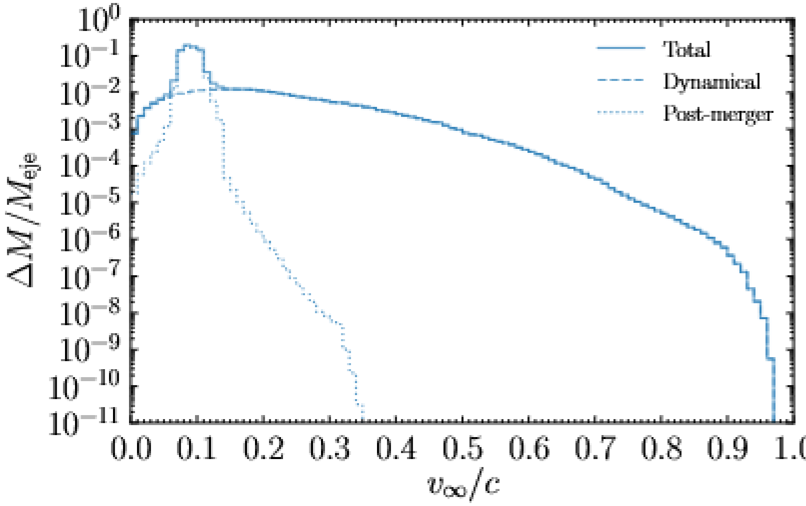
▶ BF diagram indicates the $\alpha\,\Omega$ dynamo generates the large-scale B-field.
▶ Resultant large-scale is not strong enough to overcome the ram-pressure.
Why? Disk rotational energy is $\approx \mathbf{10^{51}}$erg, c.f. Remnant NS rotational energy is $\approx \mathbf{10^{53}}$erg.

Mass ejection from the short-lived remnant formation

Ejecta mass evolution | Mass histogram vs Y_e | Mass histogram vs v_∞







- ▶ $M_{eje,\ peak,dyn} \approx 6\text{x}10^{-3}\ M_\odot$, $M_{eje,\ peak,post}$(MRI-driven turbulent viscosity)$\approx 8\text{x}10^{-3} M_\odot$.
- ▶ $Y_{e,\ peak,dyn} \approx 0.03$, $Y_{e,\ peak,\ post} \approx 0.26\text{-}0.27$.
- ▶ $v_{\infty,\ peak,dyn} \approx 0.2\text{-}0.3c$, $v_{\infty,\ peak,\ post} \approx 0.08\text{-}0.10c$.

R-process nucleosynthesis calculation will be shown later on.

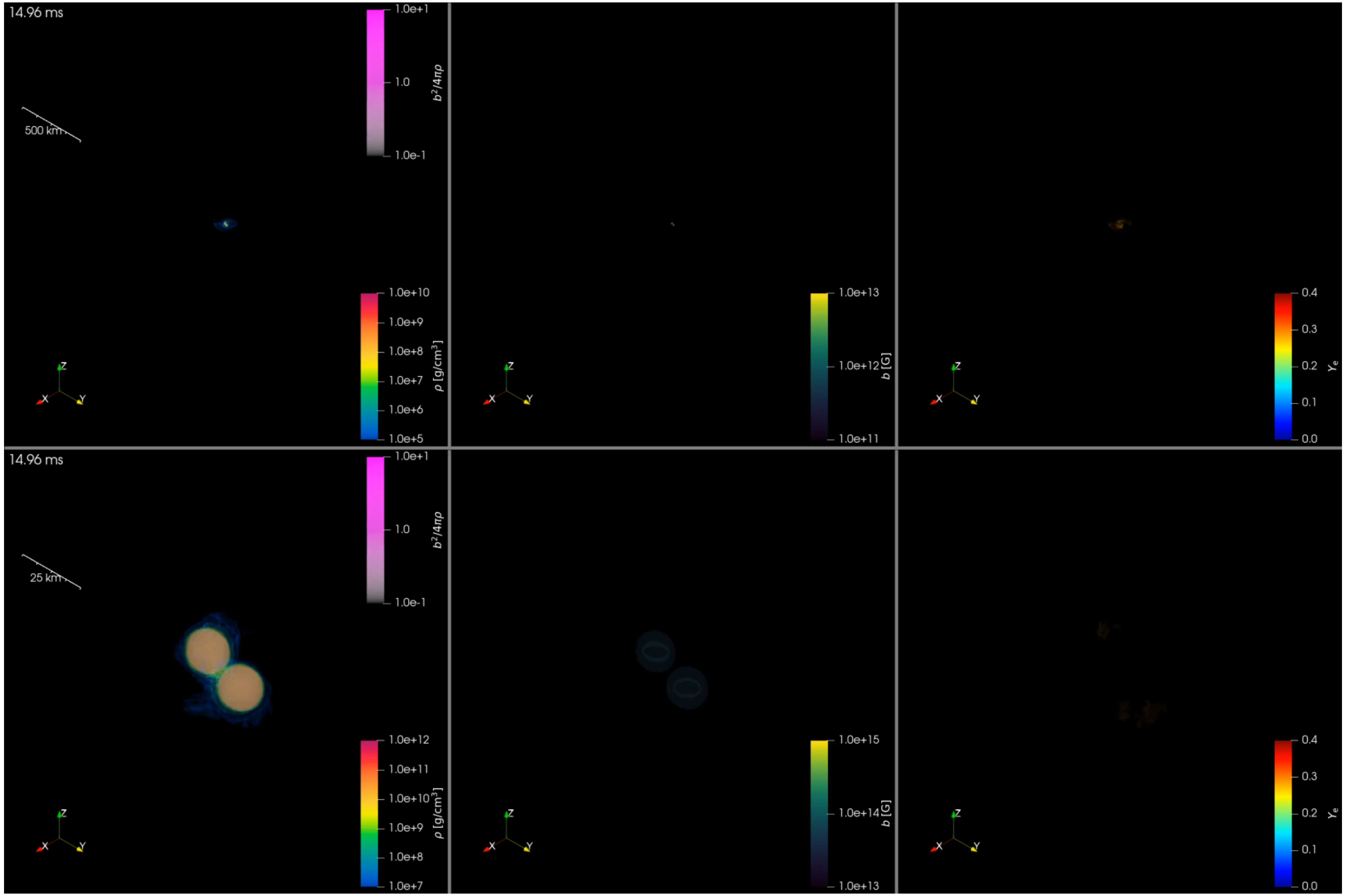
Prompt BH formation motivated by GW190425

1.5s simulation, SFHo-1.25-1.65$M_{\odot}$, $\Delta x_{finiest}$=150m (Hayashi, KK et al. 24)

ρ $(g\ cm^{-3}) + B - field\ line$ $B\ (G)$ Y_e

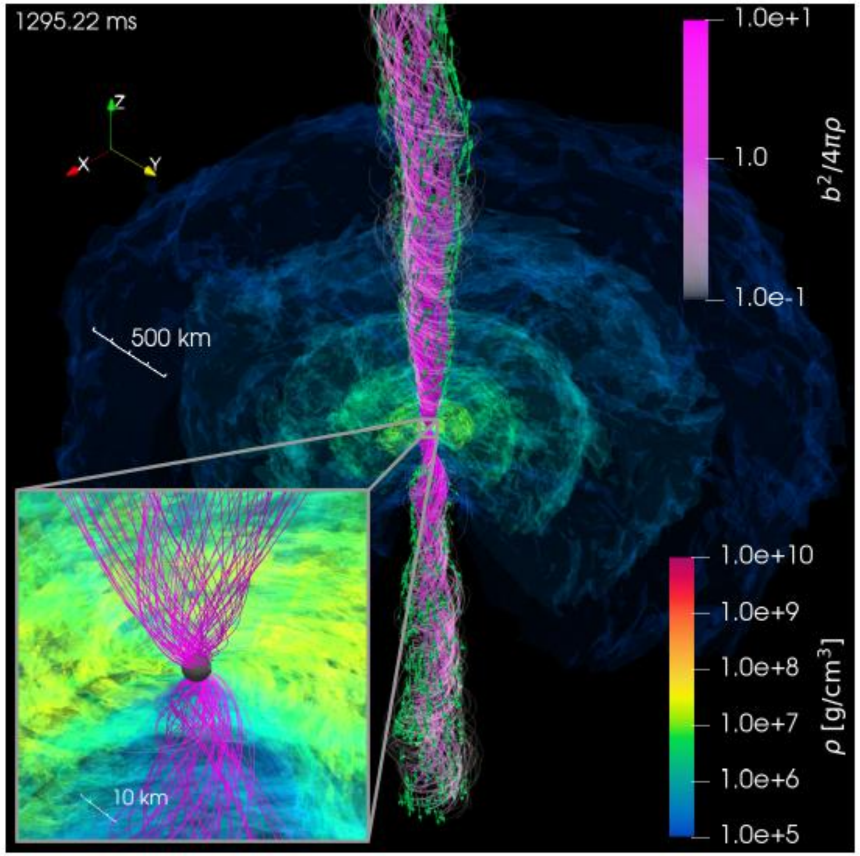
2,000 km

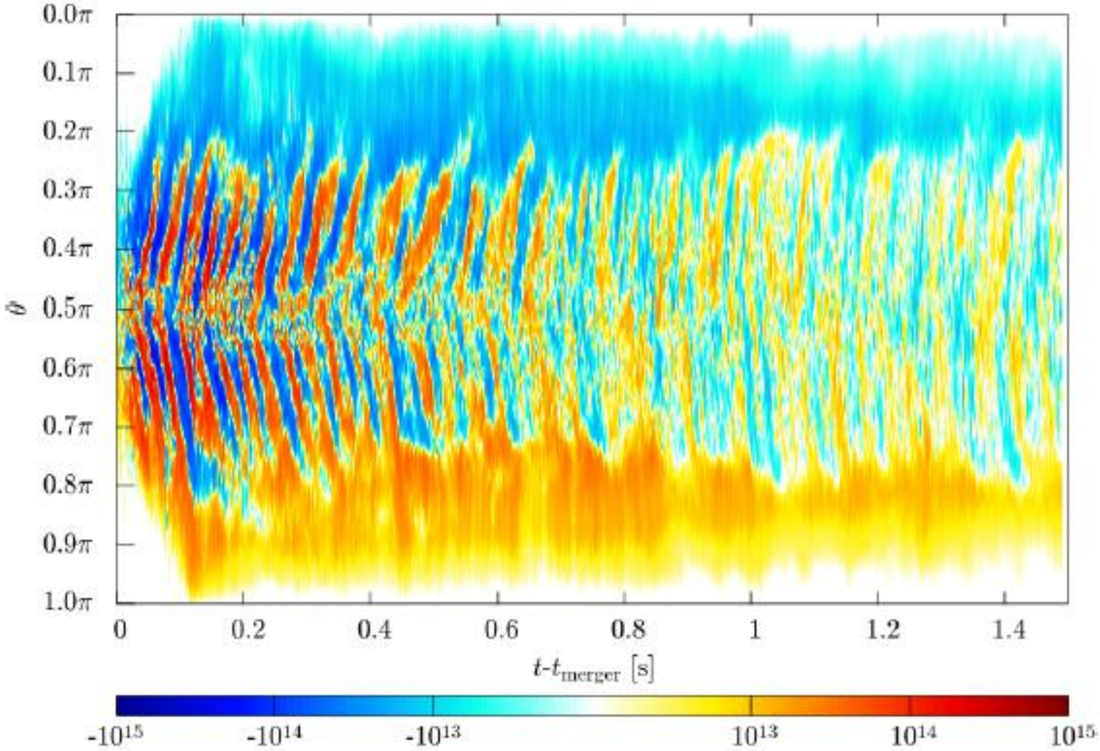
100 km



©K. Hayashi

Prompt BH formation





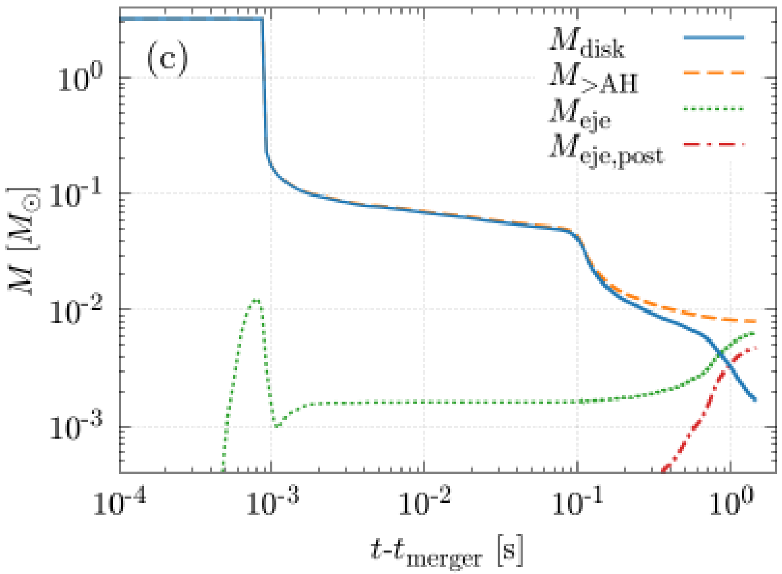
- ▶ Generation of large-scale B-field ⇒ Blandford-Znajek mechanism.

$$L_{jet} \sim 10^{49} erg/s$$

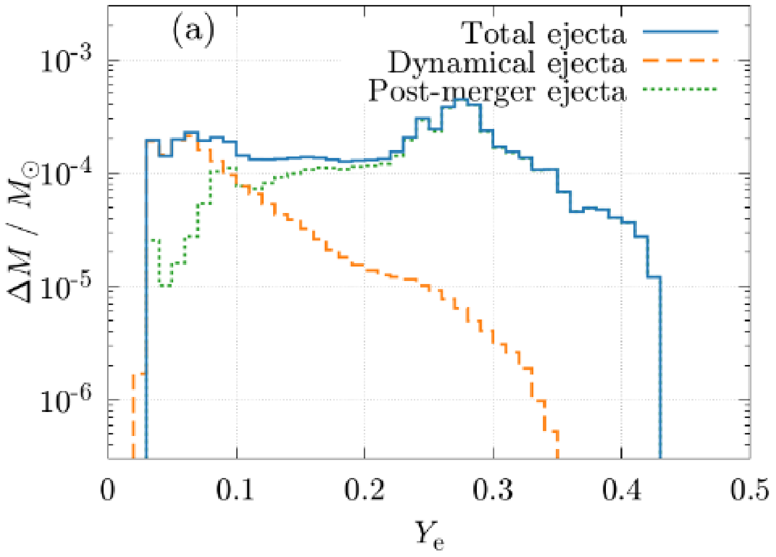
- ▶ Butterfly diagram suggests MRI-driven $\alpha\,\Omega$ dynamo.

Mass ejection from prompt BH formation

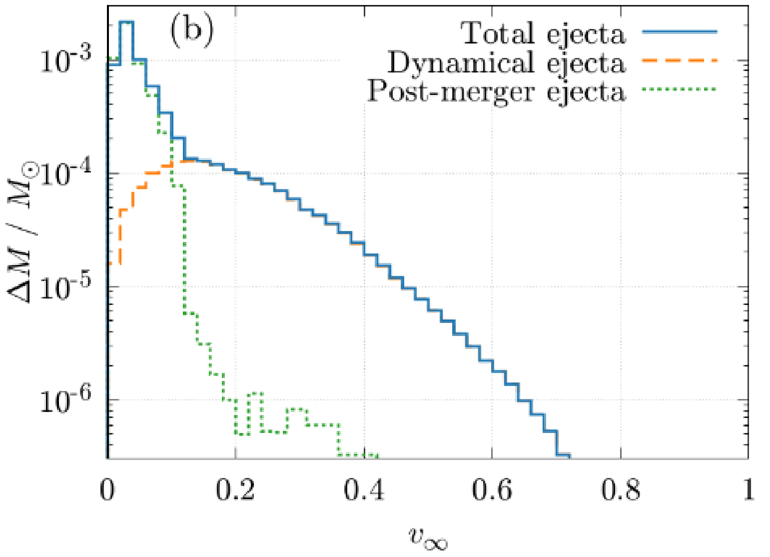
Ejecta mass evolution



Mass histogram vs Y_e



Mass histogram vs v_∞



▶ Dynamical ejecta ≈$1.6\times10^{-3}\ M_\odot$, Post-merger ejecta (MRI-driven turbulent viscosity & Lorentz force) ≈ $4.7\times10^{-3} M_\odot$

▶ $Y_{e,\ peak,dyn}$ ≈ 0.08, $Y_{e,\ peak,\ post}$ ≈ 0.28

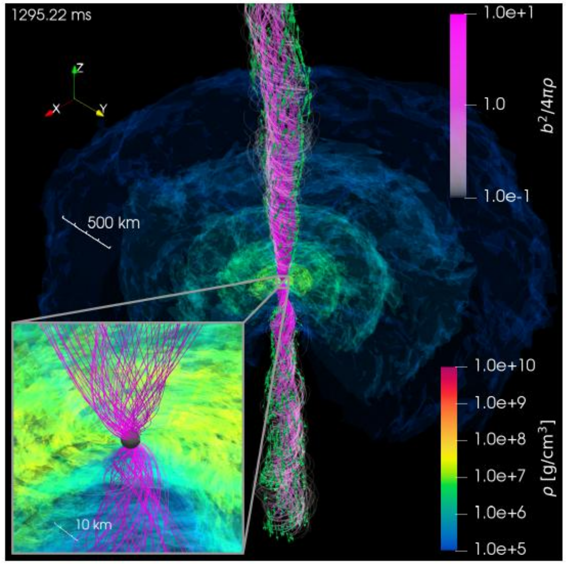
▶ $v_{\infty,\ peak,dyn}$ ≈ 0.2c, $v_{\infty,\ peak,\ post}$ ≈ 0.08c

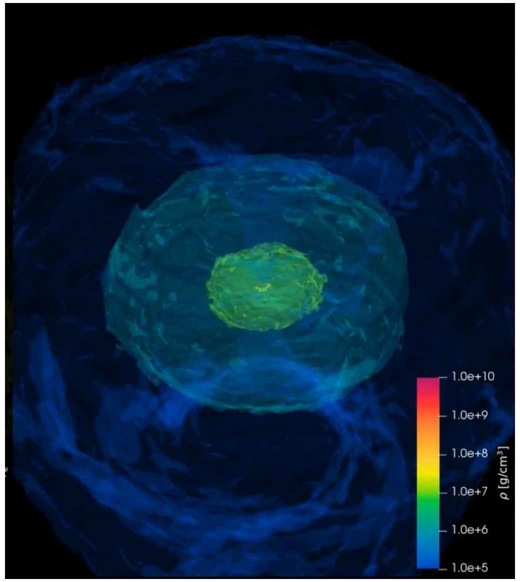
Nucleosynthesis calculation is on going.

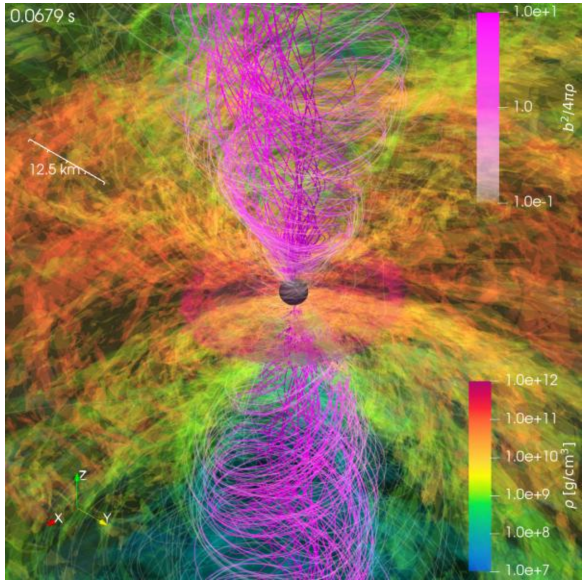
Inferring the EOS from "jet" launching

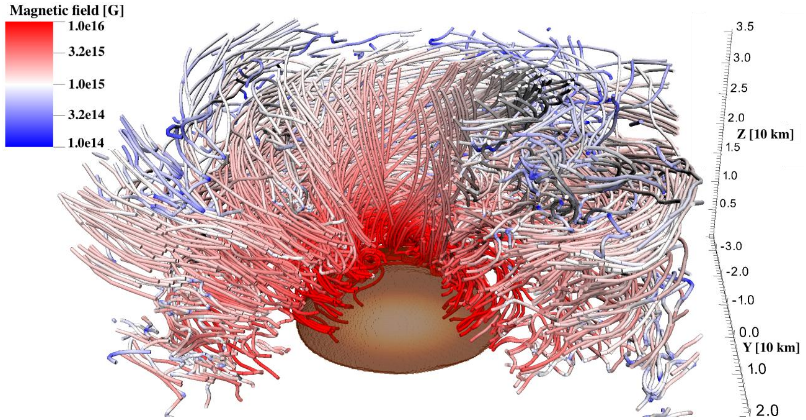
Lifetime of the remnant massive neutron star

Prompt	Short-lived	Intermediate-lived	Long-lived
~ 0s	~O(0.01) s	~O(0.1)s	~O(1) s









$L_{iso} \sim 10^{49}$erg/s

No jet until 1s at least.

$L_{iso} \sim 10^{52}$erg/s

$L_{iso} \sim 10^{52}$erg/s

SFHo

BHB Λ_{ϕ}

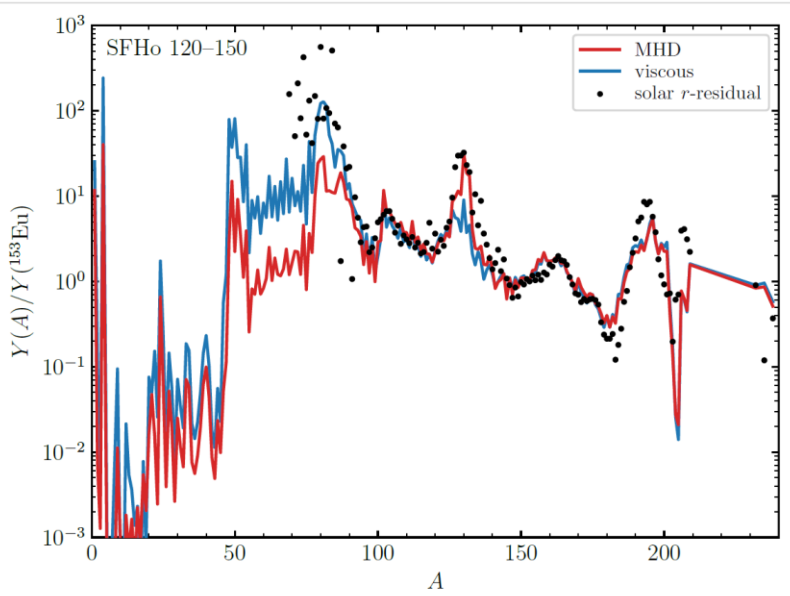
DD2

Inferring the EOS from R-process nucleosynthesis

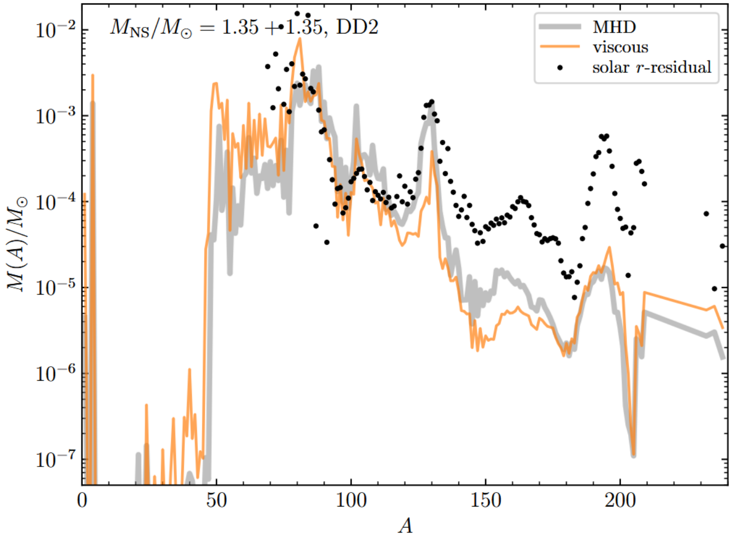
Lifetime of the remnant massive neutron star

Prompt	Short-lived	Intermediate-lived	Long-lived
~ 0s	~O(0.01) s	~O(0.1)s	~O(1) s

On-going



On-going



$M_{eje} \simeq 0.006\, M_\odot$ $M_{eje} \simeq 0.014\, M_\odot$ $M_{eje} \simeq 0.07\, M_\odot$ $M_{eje} \simeq 0.1\, M_\odot$

$M_{eje}^{GW170817} \simeq 0.05\, M_\odot$

R-process universality:	SFHo	BHB $\Lambda\ \phi$	DD2
Kilonova in GW170817:	SFHo	BHB $\Lambda\ \phi$	DD2

Conclusion

▶ A self-consistent direct modelling of BNS merger is feasible.

▶ For the long-lived case, $L_{jet}^{iso} \sim 10^{52} erg/s$, $M_{eje} \approx 0.1\ M_{\odot} \gg M_{eje}^{GW170817}$, and the solar R-process can not be reproduced.

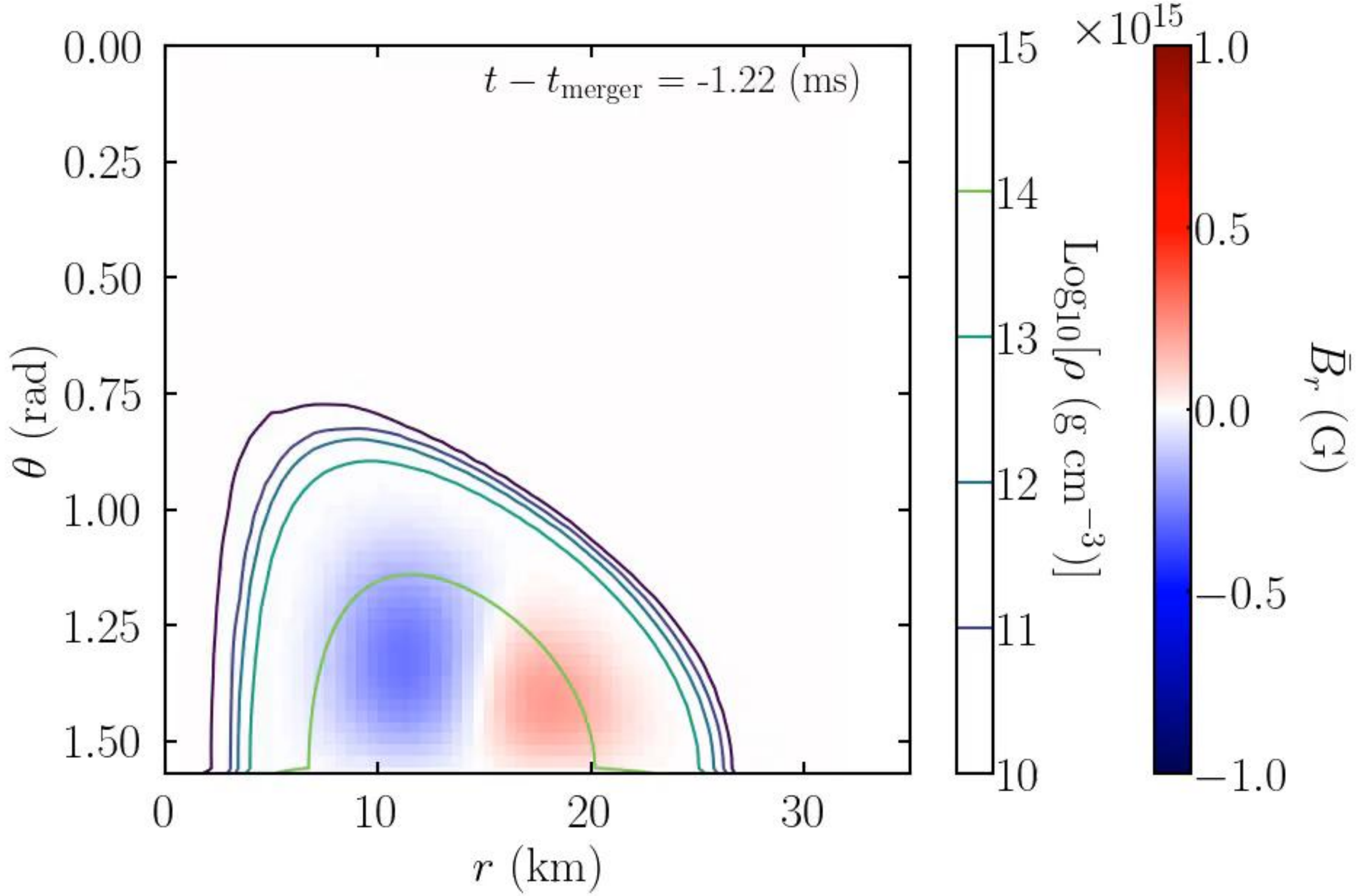
▶ The intermediate case, $L_{jet}^{iso} \sim 10^{52} erg/s$, $M_{eje} \approx 0.07\ M_{\odot} \sim M_{eje}^{GW170817}$.

▶ For the short-lived case, no strong jet, $M_{eje} \approx 0.014 M_{\odot} \ll M_{eje}^{GW170817}$, and the solar R-process is reproduced.

▶ For the prompt collapse case, $L_{eje}^{iso} \sim 10^{49} erg/s$, $M_{eje} \approx 0.006 M_{\odot}$.

Caveat: A large systematics in hydro. simulation, in particular, MHD-turbulent case.

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

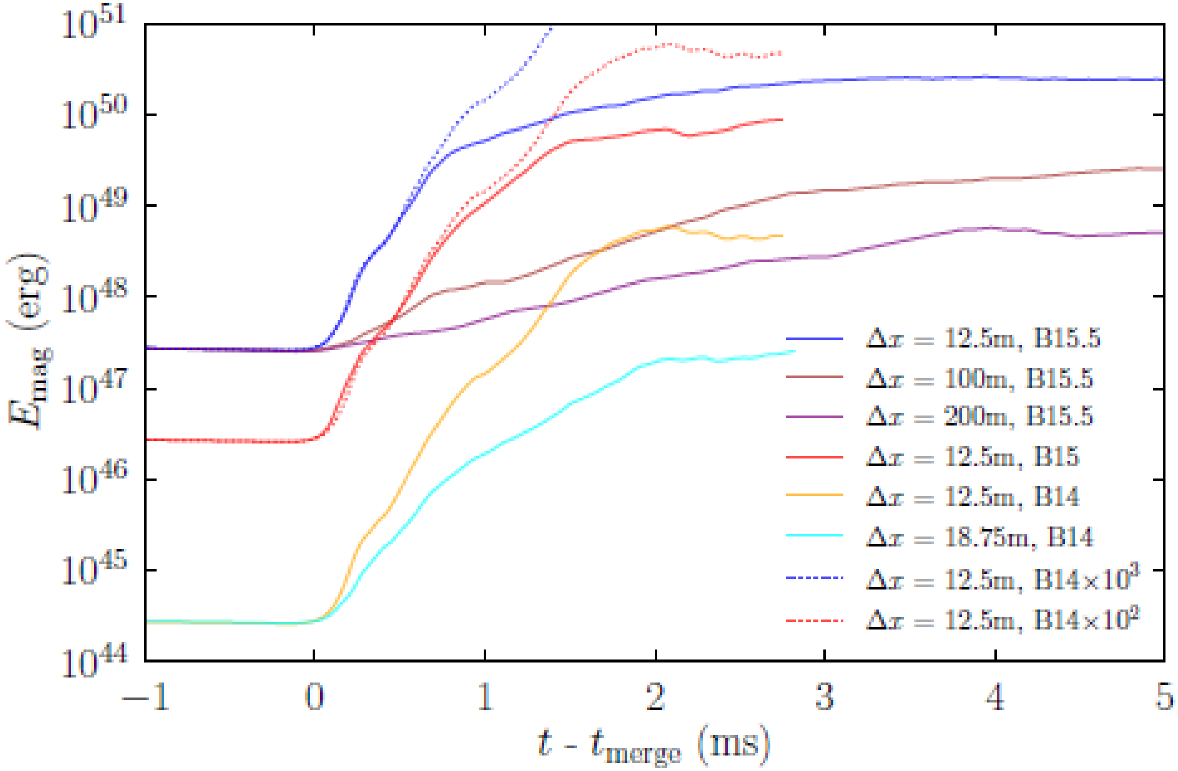


▶ Waves generated in the MRI-active region propagates towards the polar

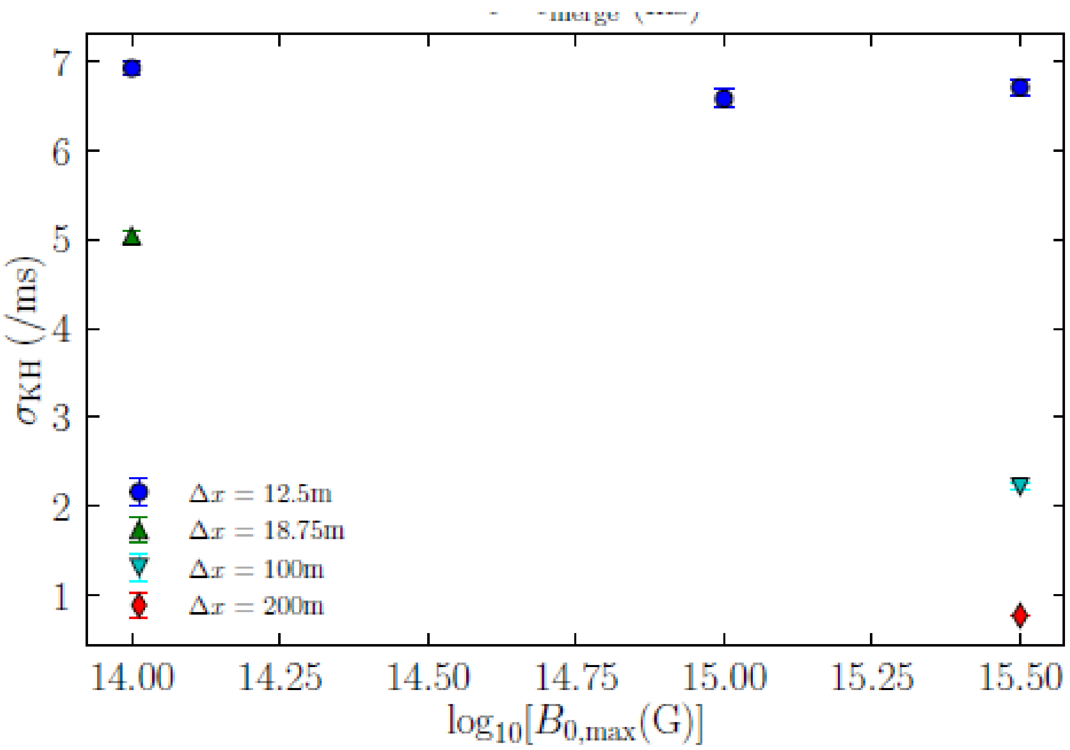
▶The B-field deep inside the core in the polar region stays buried throughout the simulation

Kelvin-Helmholtz dynamo at the merger

KH amplification at the merger

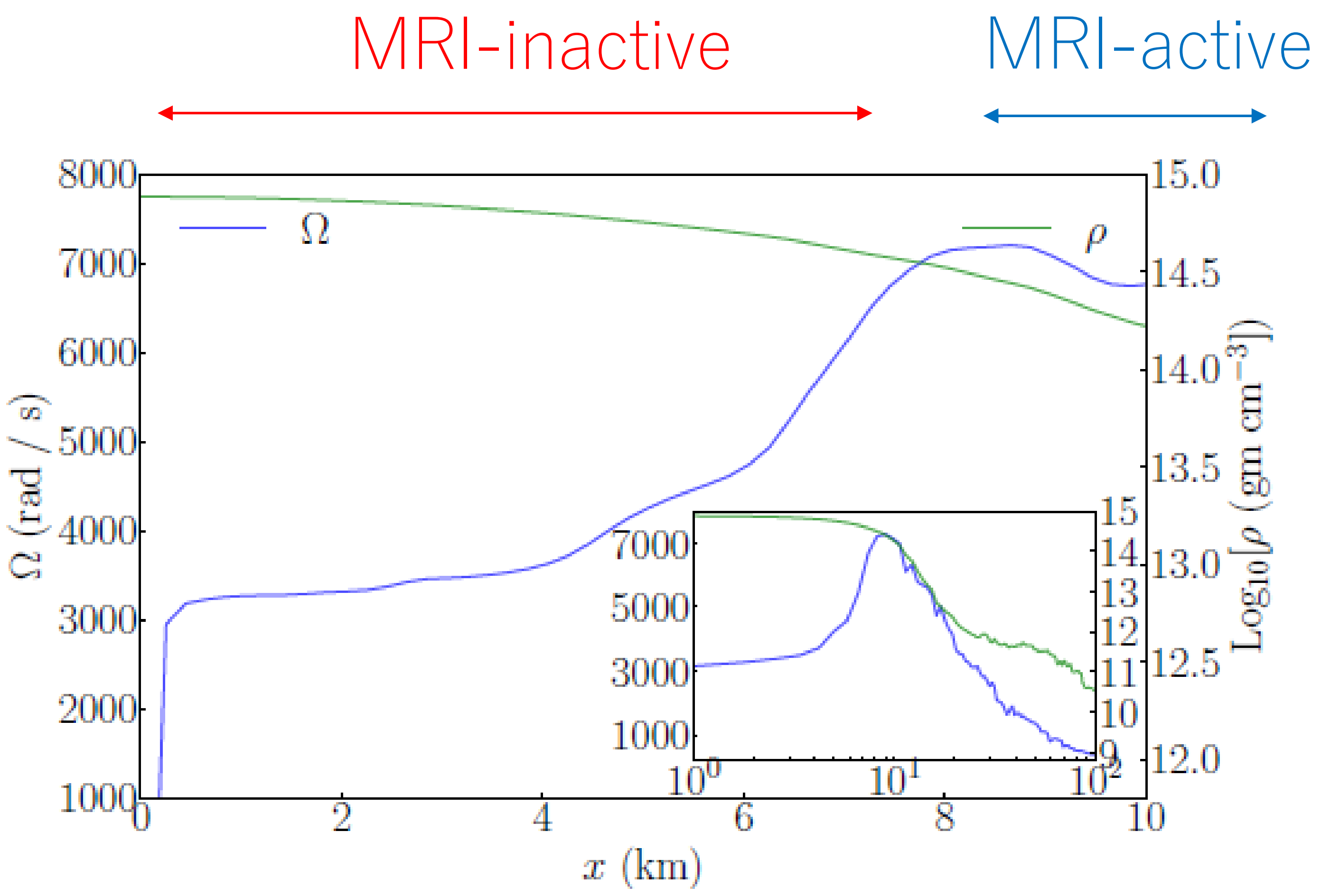


Growth rate vs initial B-field



▶ 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.

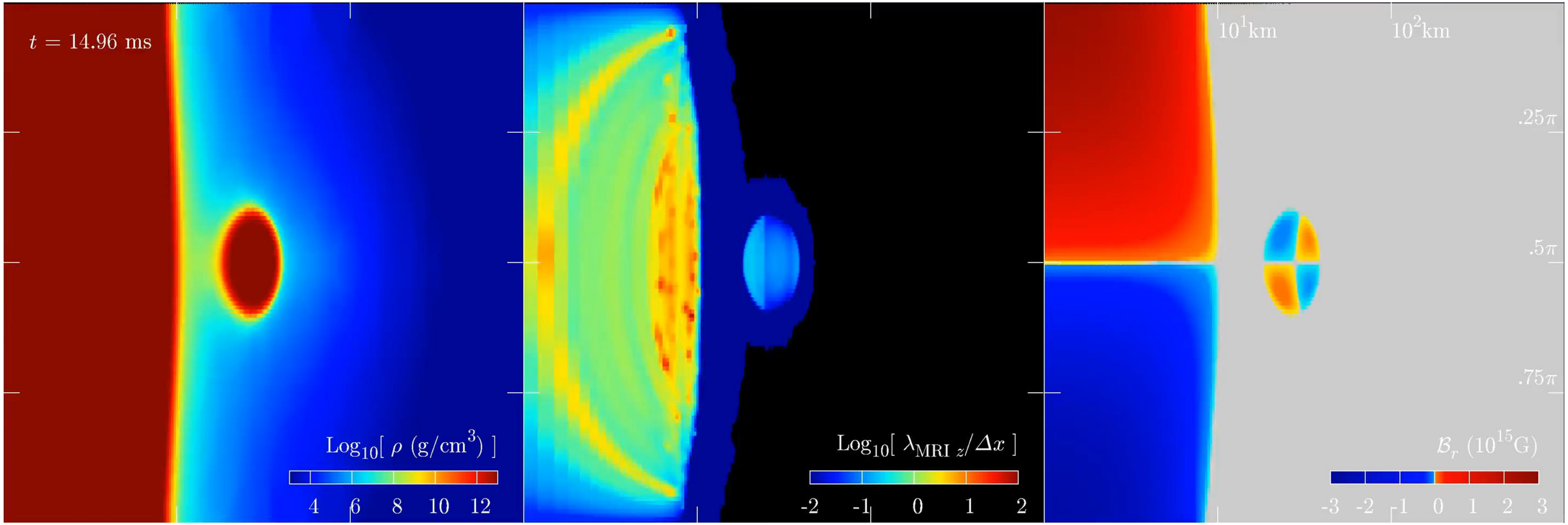
Mean B-field in MRI-active region



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

Prompt BH formation

Rest-mass density MRI-quality factor Mean poloidal B-field



Once the MRI starts to be resolved, the mean poloidal B-field is generated.

P_{theory} = 0.03 s vs P_{BF} = 0.03-0.04s