Challenge to GW170817 with Numerical Relativity

Kenta Kiuchi (CRA/YITP)
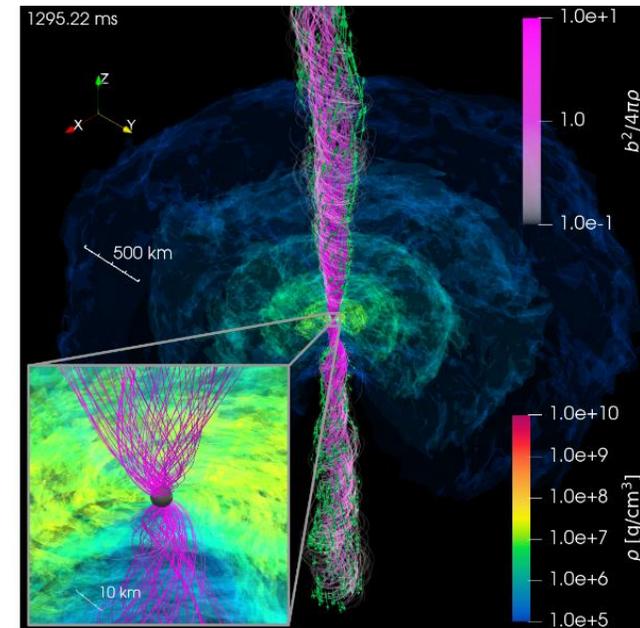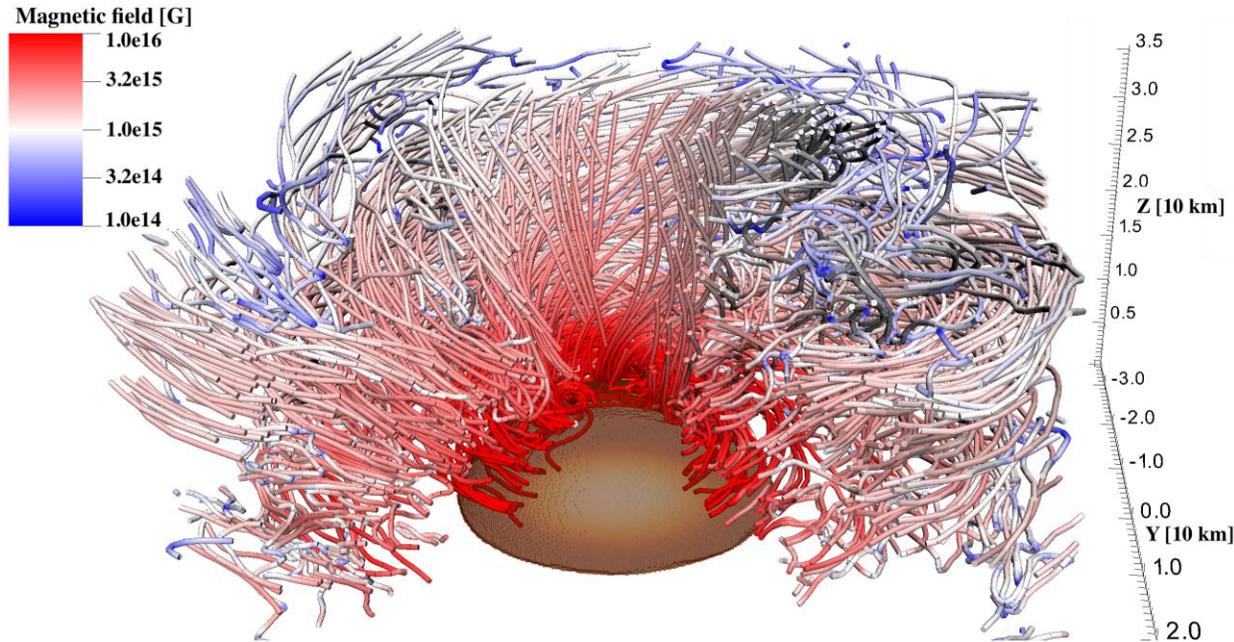
Max-Planck-Institut
für Gravitationsphysik
(Albert-Einstein-Institut)

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

Happy 60th birthday, Shibata san!

@ banquet last week

Japanese quates: 名選手、名監督にあらず
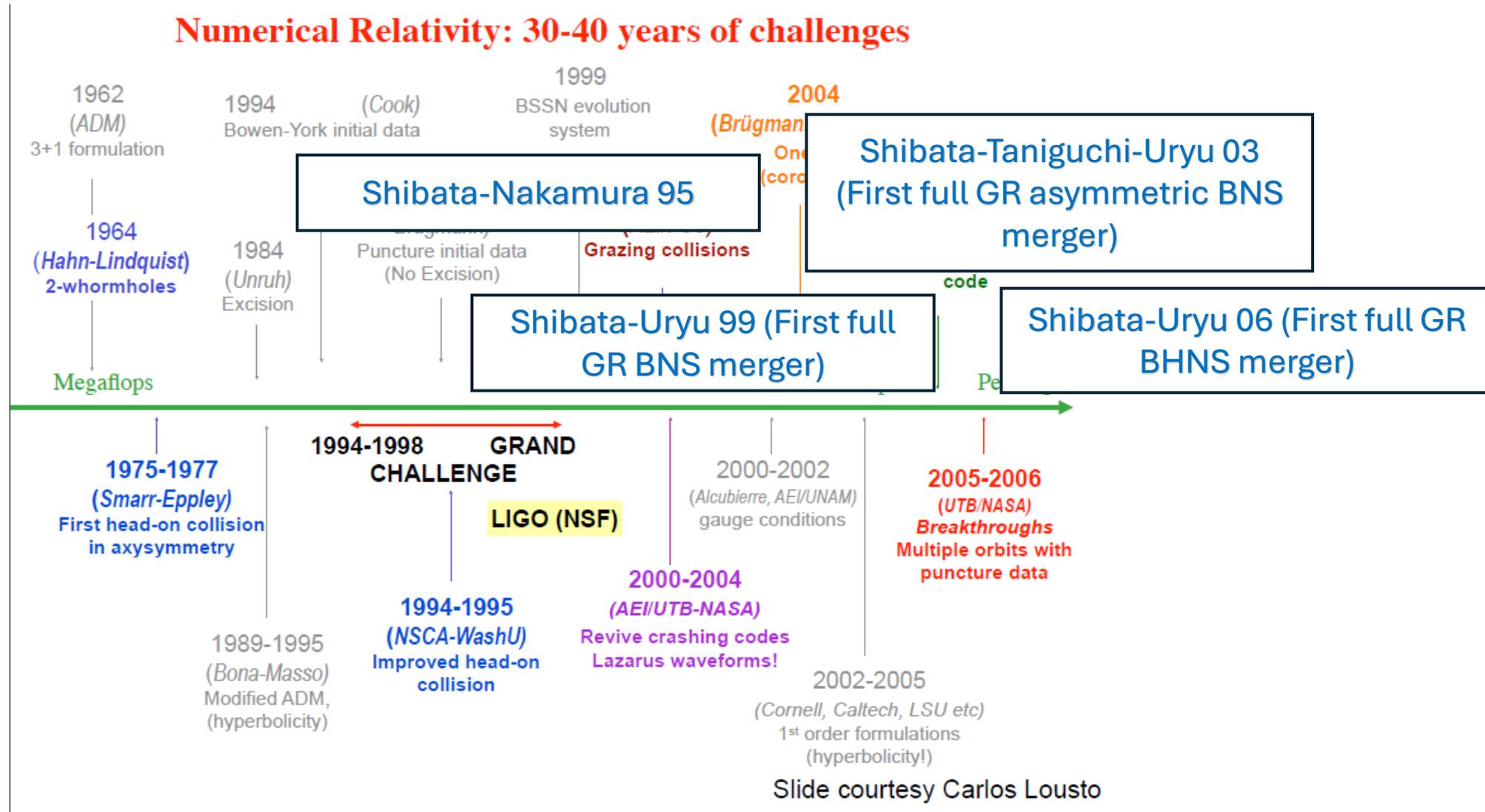⇒ An excellent player is not necessarily an excellent director (supervisor)

Shibata san's contribution to relativistic astrophysics

Timetable of the 2nd week (February 2 - February 6)

| February 2 (Mon.)	February 3 (Tue.)	February 4 (Wed.)	February 5 (Thu.)	February 6 (Fri.)
		9:30-10:20 D. Radice	9:30-10:20 M. Aloy	9:30-10:20 O. Just
10:00-10:55 Registration	10:00-11:00 A. Tanikawa	10:20-11:10 E. Most	10:20-11:10 P. Mösta	10:20-11:10 S. Fujibayashi
10:55-11:00 Opening	11:00-11:30 Coffee	11:10-11:30 Coffee	11:10-11:30 Coffee	11:10-11:30 Coffee
11:00-12:30 T. Piran	11:30-12:30 Discussion (Tanikawa, Morisaki)	11:30-12:30 M. Miravet-Tenes, E. Gutierrez, A. Reboul-Salze	11:30-12:30 T. Kuroda, C. Musolino, A. Mizuta	11:30-12:30 A. Janiuk, D. Desai, A.T.L. Lam
12:30-14:00 Lunch & Poster	12:30-14:00 Lunch & Poster	12:30-14:00 Photos Lunch & Poster	12:30-14:00 Lunch & Poster	12:30-14:00 Lunch & Poster
14:00-15:00 A. Perego	14:00-15:00 M.-R. Wu	14:00-14:50 K. Kawaguchi	14:00-14:50 T. Dietrich	14:00-15:40 A. Agarwal, A. Shankar, P. Hammond, Y. Gao, M. Jacobi
15:00-15:30 Coffee	15:00-15:30 Coffee	14:50-15:50 J. Ehring, L. Longo Micchi, P. Cheong	14:50-15:50 Y. Qiu, H.-J. Kuan, K. Hayashi	15:40-16:10 Coffee
15:30-17:00 Discussion (Perego, Wanajo)	15:30-17:00 Discussion (Wu, Nagakura)	15:50-16:20 Coffee	15:50-16:20 Coffee	16:10- M. Shibata
		16:20-17:50 Poster & Free Discussion	16:20-17:50 Discussion (Radice, Dietrich)	

Please upload the talk slide, Shibata san!

Shibata san's contribution to relativistic astrophysics

Numerical Relativity: 30-40 years of challenges

1962
(ADM)
3+1 formulation

1994
Bowen-York initial data

(Cook)

1999
BSSN evolution system

2004
(Brügman
On
(core

Shibata-Taniguchi-Uryu 03 (First full GR asymmetric BNS merger)

1964
(Hahn-Lindquist)
2-whormholes

1984
(Unruh)
Excision

Puncture initial data
(No Excision)

Grazing collisions

Shibata-Nakamura 95

code

Shibata-Uryu 99 (First full GR BNS merger)

Shibata-Uryu 06 (First full GR BHNS merger)

Megaflops

1975-1977
(Smarr-Eppley)
First head-on collision in axysymmetry

1994-1998   GRAND
CHALLENGE

LIGO (NSF)

2000-2002
(Alcubierre, AEI/UNAM)
gauge conditions

2005-2006
(UTB/NASA)
Breakthroughs
Multiple orbits with puncture data

2000-2004
(AEI/UTB-NASA)
Revive crashing codes
Lazarus waveforms!

1989-1995
(Bona-Masso)
Modified ADM,
(hyperbolicity)

1994-1995
(NSCA-WashU)
Improved head-on collision

2002-2005
(Cornell, Caltech, LSU etc)
1st order formulations
(hyperbolicity!)

Slide courtesy Carlos Lousto

These lists are the tip of the iceberg of Shibata san's pioneering works.

Shibata san's contribution to relativistic astrophysics
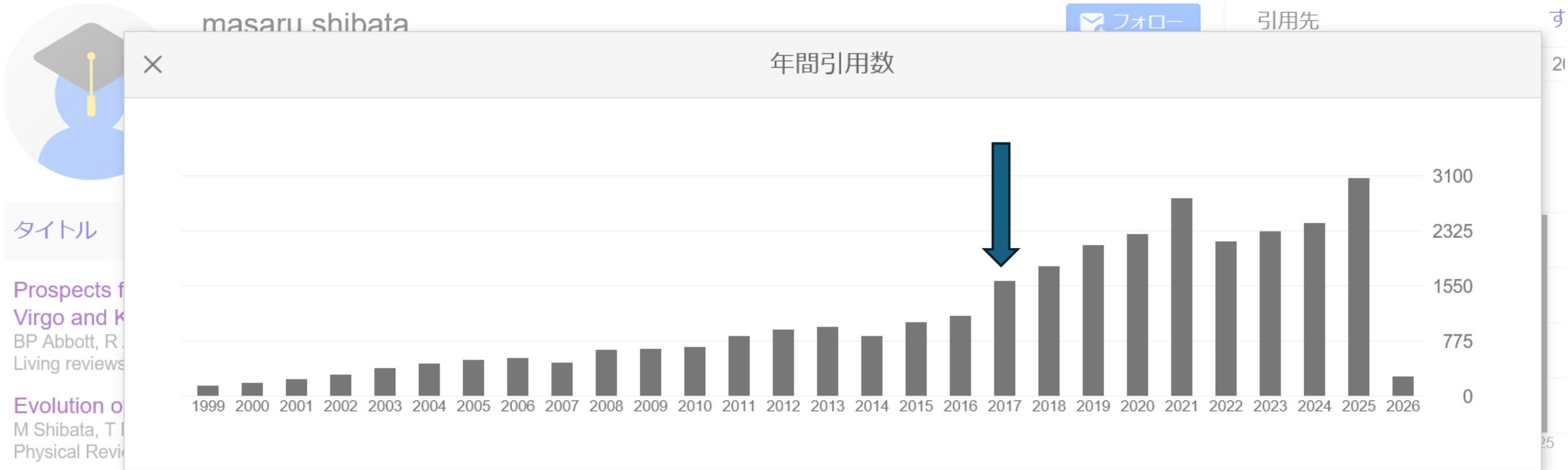
GW170817 + GRB170817A + AT2017gfo

I appreciate Shibata-san's tremendous contributions to relativistic astrophysics, particularly in binary neutron star mergers.

Introduction

Reality ⟷ Imagination

Ascenzi+20
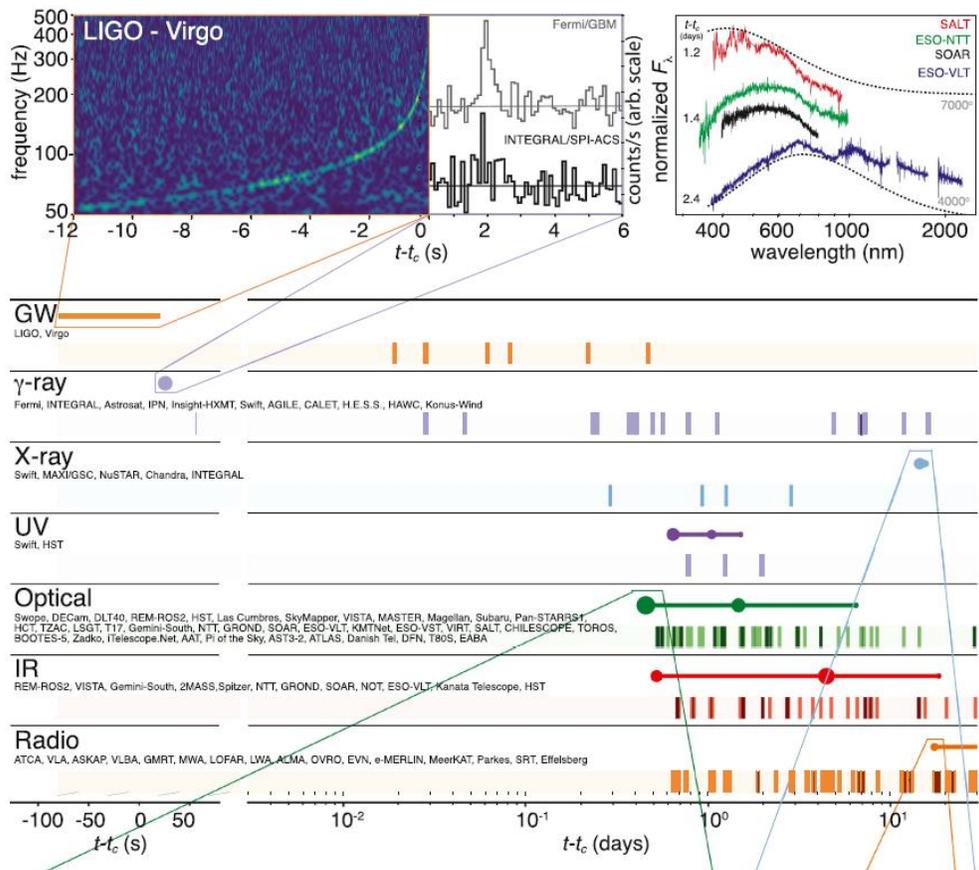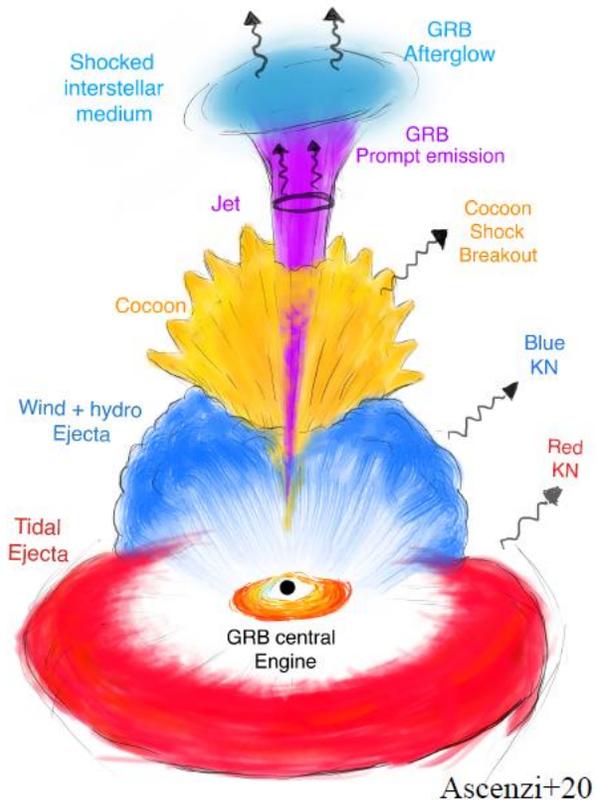
There is no self-consistent model to explain it.

We as numerical relativists must explain

▶SGRB (+Afterglow observations)

▶Kilonova emission:$M_{eje}≈0.05M_\odot$(Hotokezaka & Nakar20), Red+Blue? (Kitamura et al. 25)

at least qualitatively, and quantitatively at the best.

A "package" for EM counterpart modeling

NR simulation

(GR+EOS+ ν -Rad.+MHD)

⇩

R-process nucleosynthesis calculation

⇩

Kilonova/GRB light curve modeling

⇩

Observation
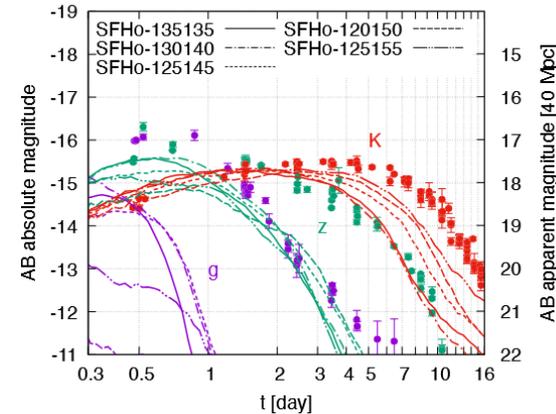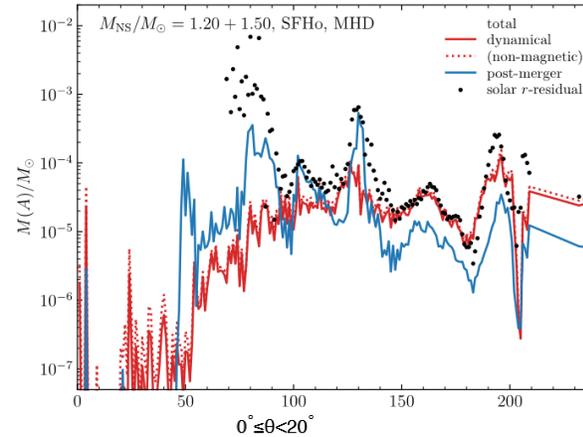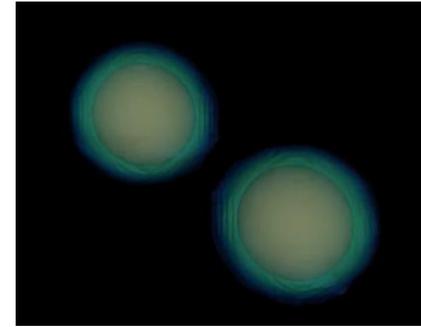
Sys. Err.

▶ Resolution
▶ Approx. GR
▶ Approx. ν -Rad
▶ MHD approx.
...
▶ Reaction rate
▶ Mass model
...

▶ Photon rad. transfer
...
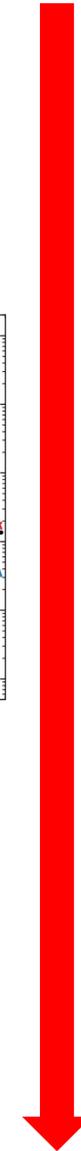
Neutron rich matter ejection mechanism

S. Fujibayashi, KK, et al. 18

$v_{ej} \sim 0.15\,c$
$Y_e = 0.4 - 0.5$

Case I
Long-lived MNS

B-field amplification

Merger   **MNS+Torus**

NS

NS

$v_{ej} \sim 0.05\,c$
$Y_e \sim 0.3 - 0.4$

BH+Torus

BH

$v_{ej} \sim 0.05\,c$
$Y_e < 0.3 - 0.4$

Case II
Delayed collapse

Dynamical mass ejection

Early MHD/viscosity-driven mass ejection

Long-term viscosity & Neutrino-driven mass ejection

0   ~ 1 ms ~ 10 ms ~ 100 ms ~ 1 s

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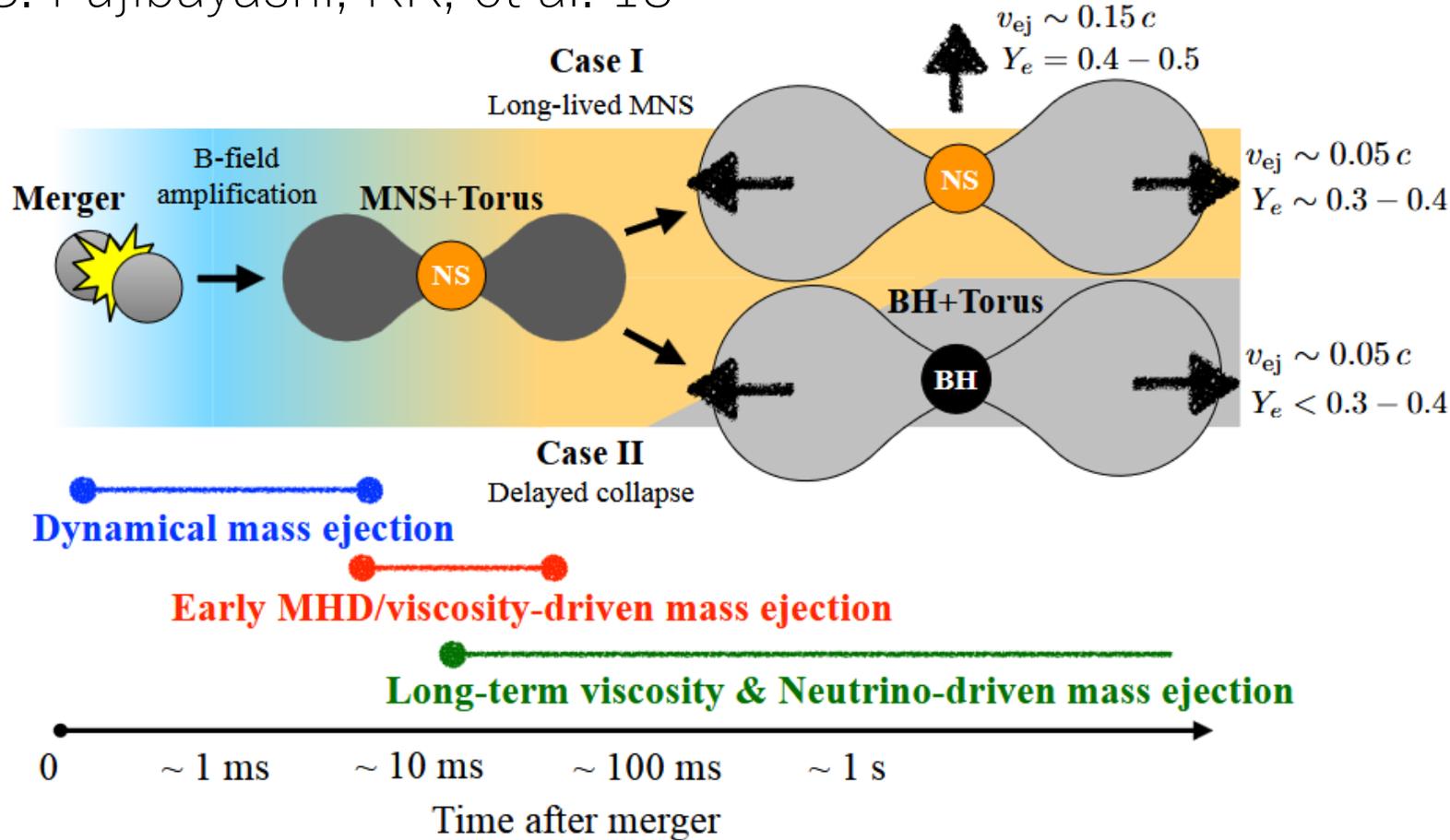
Many Refs.
Hotokezaka et al. 13,
Fujibayshi et al. 18,20,21,22
Bauswein et al. 13, 17
Just et al. 14, 21
Siegel & Metzger, 18
Combi & Siegel, 23
Radice et al. 18
+ more

▶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)

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

$P - \dot{P}$ Diagram

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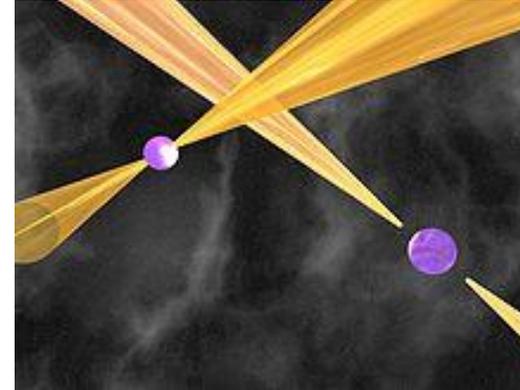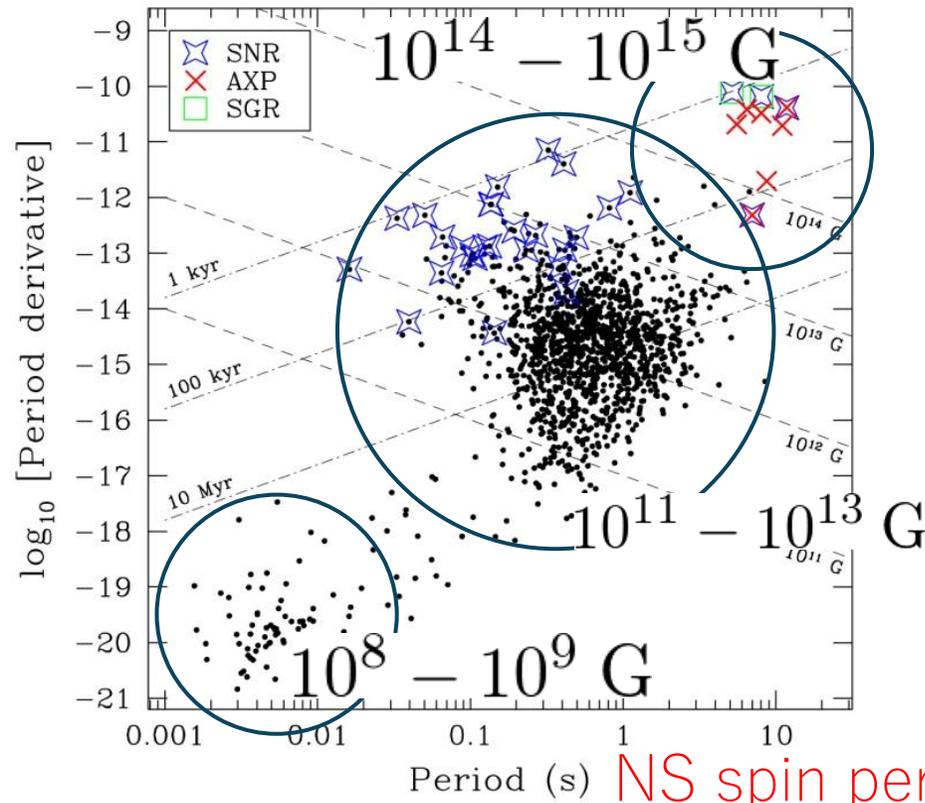
▶ Assumption : Rotational energy is dissipated by the magnetic dipole radiation ⇒ $B \propto (P\dot{P})^{1/2}$

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 $\sim 10^{53}$ g cm^2 s^{-2} $(M/2.7M_{sun})(v/0.3c)^2$

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

B-field is irrelevant in BNS mergers ?

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

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

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

Mean field dynamo theory

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

$$\bar{\mathcal{E}} = \overline{\mathbf{u} \times \mathbf{b}} \qquad \text{u \& b : turbulence of the velocity and b-field.}$$

α Ω dynamo

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

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

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

$$\partial_t \bar{B}_z = -\partial_R \bar{\mathcal{E}}_\varphi \approx \partial_R \left(\alpha_{\varphi\varphi}\bar{B}_\varphi \right)$$
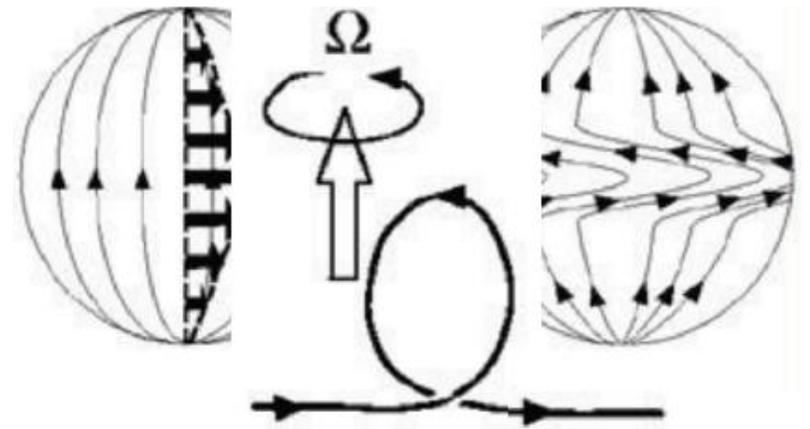
Generation of a large-scale field via $\alpha\,\Omega$ dynamo

$\alpha\,\Omega$ 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 α Ω dynamo

Kelvin Helmholtz instability (Rasio and Shapiro 99, Price & Rosswog 05)
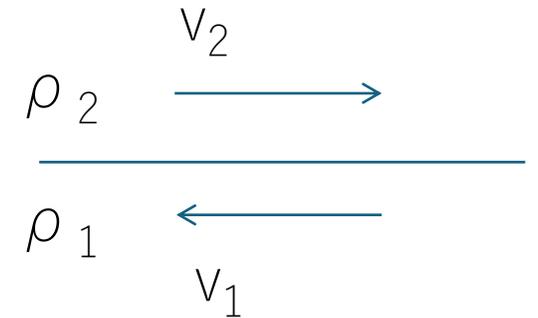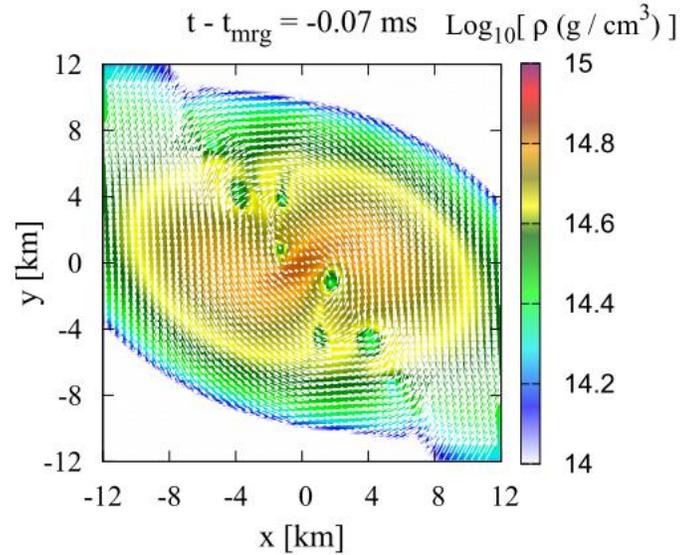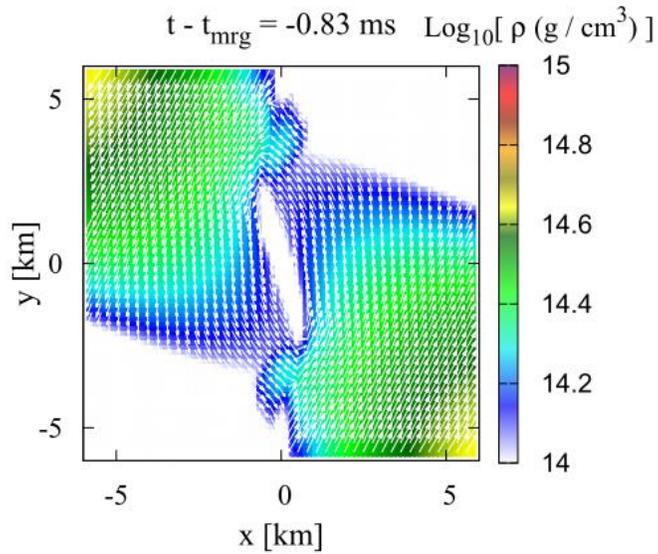
$$\sigma \propto k$$

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

<u>Magneto Rotational Instability (MRI)</u> (Balbus & Hawley 91)

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

$$\lambda_{MRI}^{BH-Disk} \approx 1,000m \left(\frac{B_p}{10^{15}G}\right)\left(\frac{\rho}{10^{13}gcm^{-3}}\right)^{-\frac{1}{2}}\left(\frac{\Omega}{6000rads^{-1}}\right)^{-1}$$
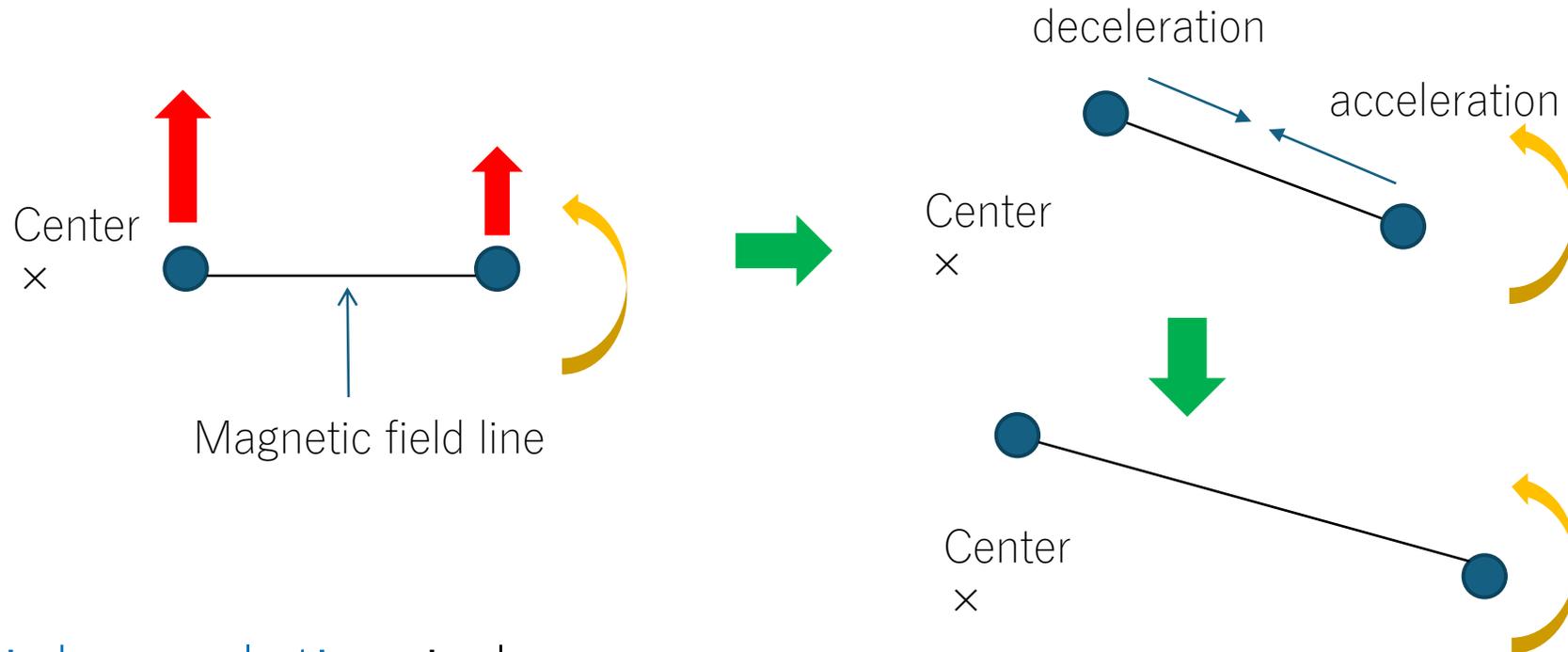
Again, high resolution is key. (Shibata et al. 05, Duez et al. 05, Siegel et al. 13, KK et al. 18,24)

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)

$$\lambda \propto k^{-1}$$
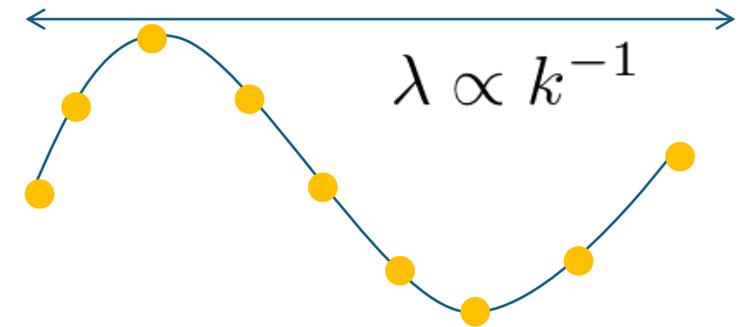
All the works, we quantify the ability of our simulation set up to resolve the KHI and MRI:

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

Code Name

▶ I was asked more than 100 times about which NR code we use.
▶ The code was originally developed by Shibata san, and my colleagues implemented new features, e.g., neutrino, MHD, etc.
▶ It doesn't have a specific name.

Numerical relativity code for Astrophysical and Non-AstrophySIcal objects = No name in Japanese

Computational facilities

Fugaku@Riken (Japan)

Raven@MPCDF (Germany)

Supercomputer = Experimental labo.

Inferring the EOS from ab initio simulations

Lifetime of the remnant massive neutron star

| Prompt $\sim$ 0s | Short-lived $\sim$ O(0.01) s | Intermediate-lived $\sim$ O(0.1)s | Long-lived $\sim$ O(1) s |
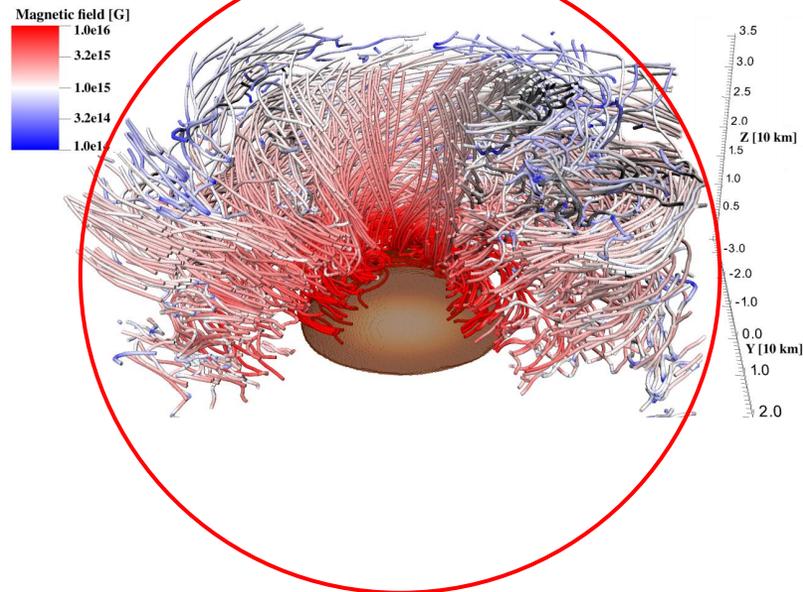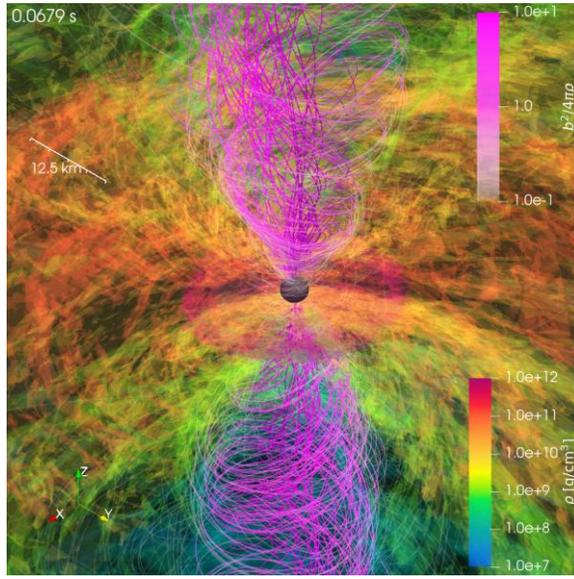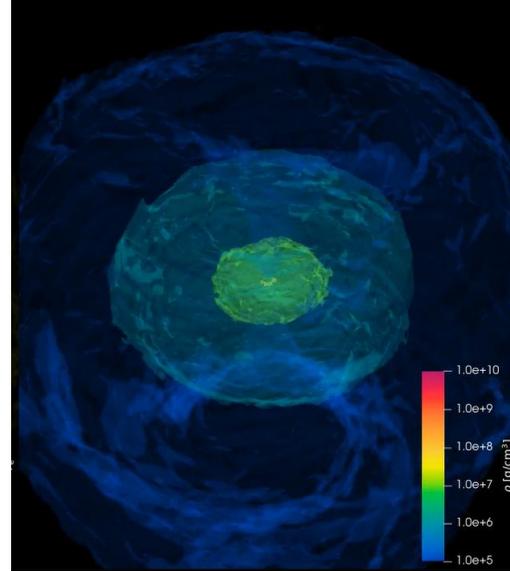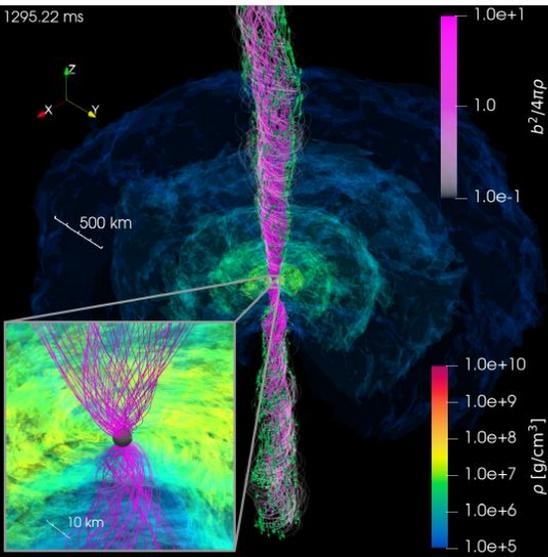
$L_{iso} \sim 10^{49}$ erg/s

Hayashi et al. PRL 25

No jet until 1s at least.

KK PRL 23

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

KK 26 in prep.

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

KK Nature Astro. 24

EOS stiffness: Soft (SFHo) $\longleftarrow\longrightarrow$ Stiff (DD2)

Binary mass: Large $\longleftarrow\longrightarrow$ Small

Long-lived remnant formation (KK et al. Nature Astron. 24)

0.2s simulation, DD2-1.35-1.35M$_\odot$, Δ x$_{finiest}$=12.5 m, B$_{max}$=10$^{15.5}$G, 36M CH

$$Y_e \qquad \rho\,(g\,cm^{-3}) + B - field\;line \qquad B(G)$$

©K. Hayashi
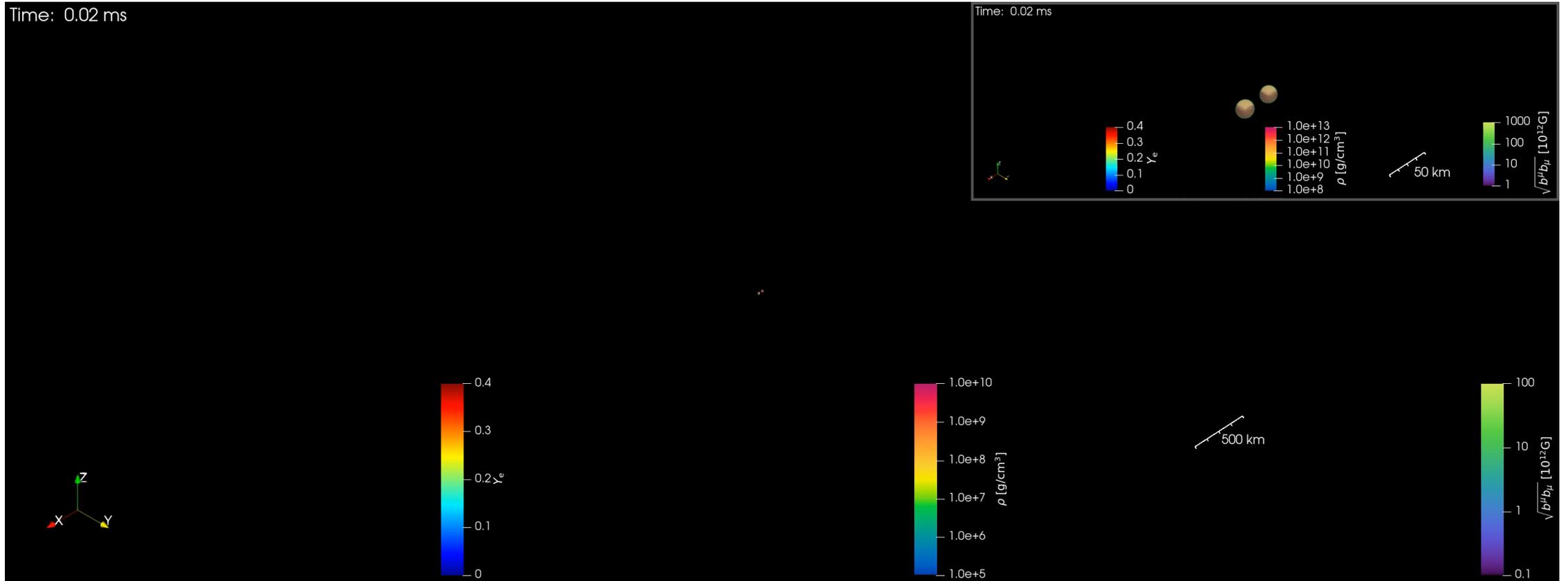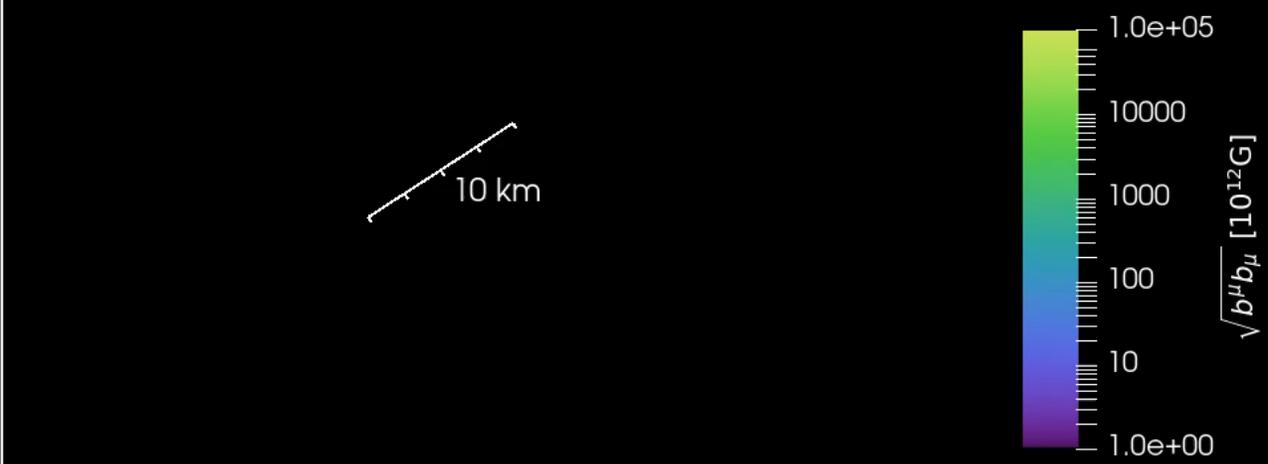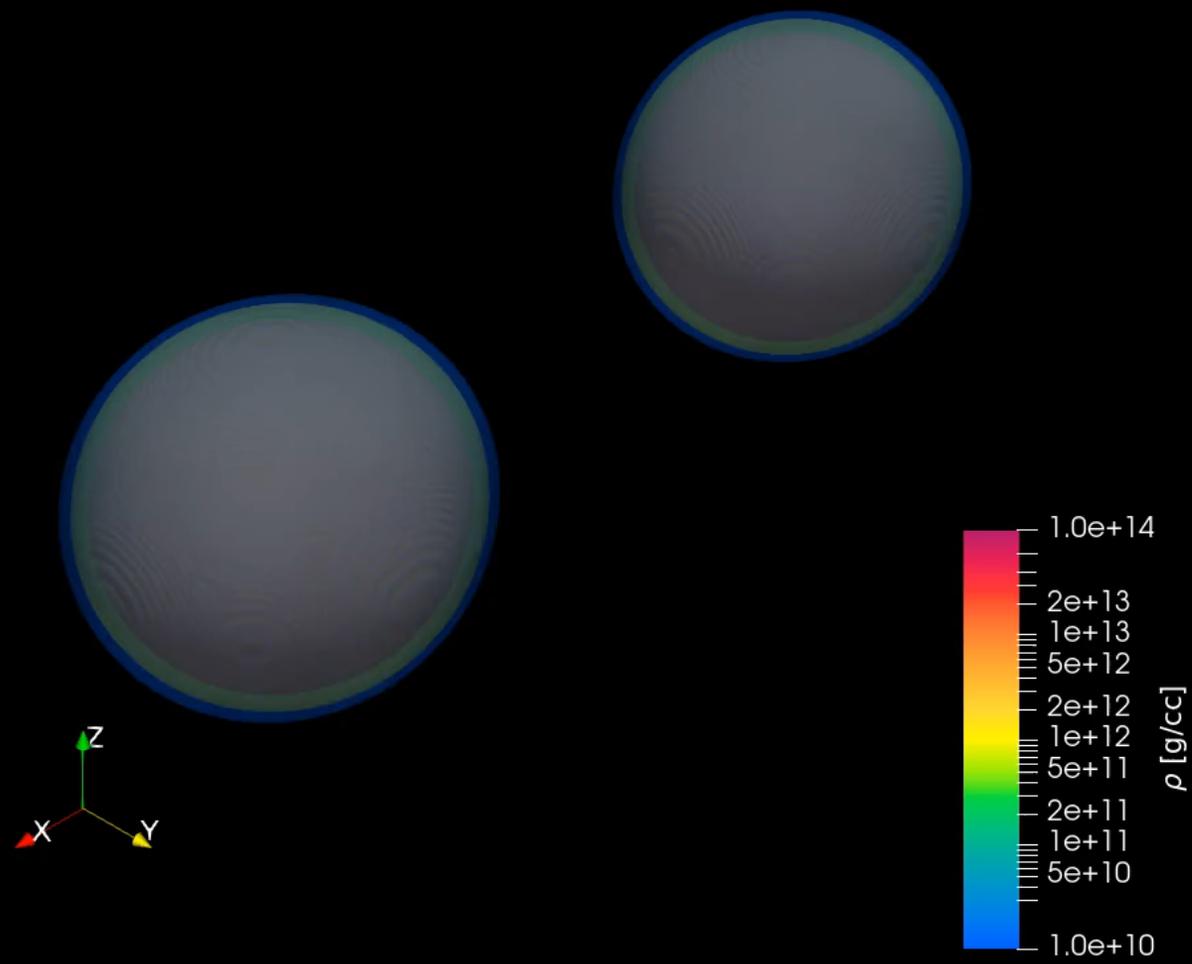
Kelvin-Helmholtz dynamo at the merger

KH amplification at the merger
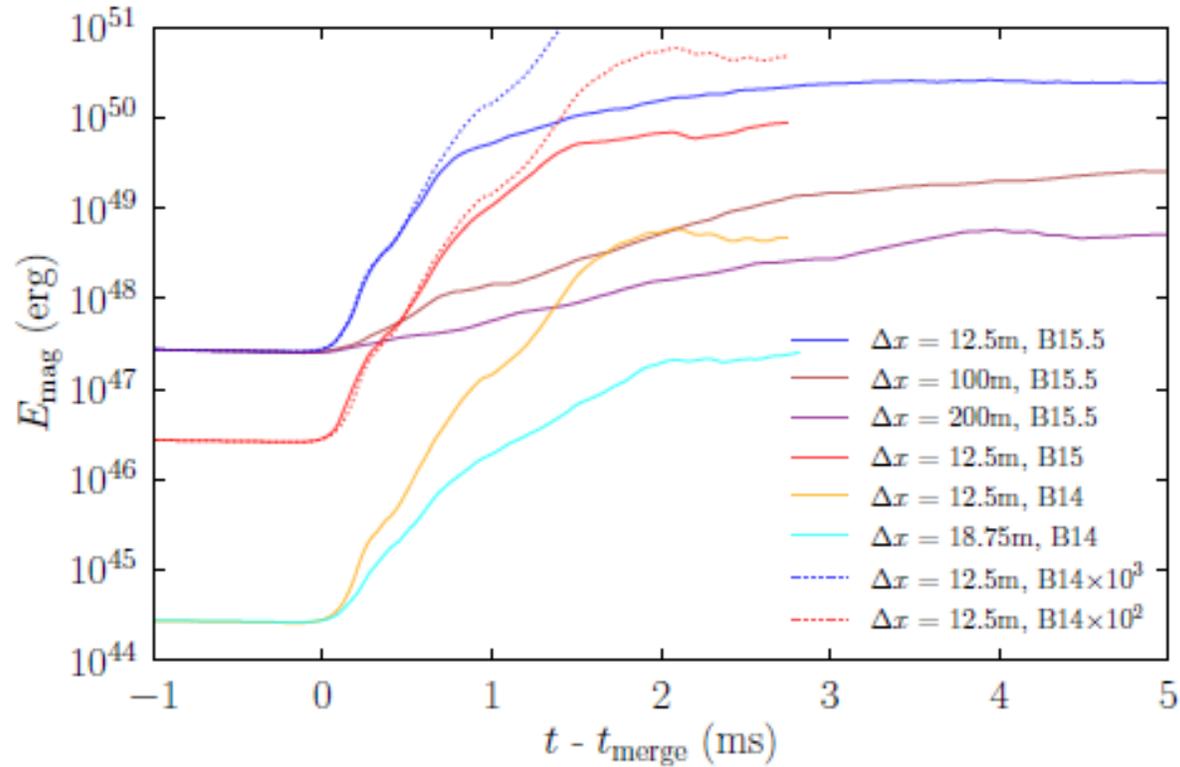
Growth rate vs initial B-field
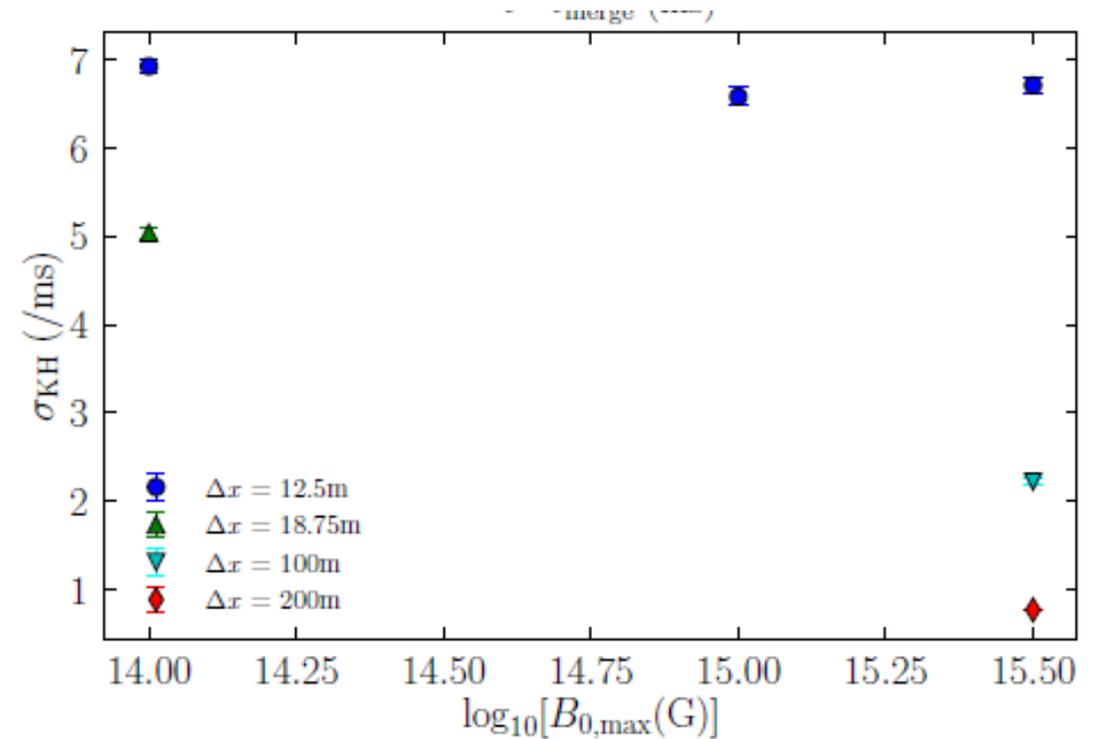
▶ In reality, the KH dynamo would produce a strong, but small-scale magneto turbulence (see also Palenzuera et al. 22, Aguilera-Miret et al. 22, 23).

Neutrino viscosity/drag on MRI

Dispersion relation for MRI with the neutrino viscosity:

$$\left[\left(\tilde{\sigma} + \textcolor{red}{\tilde{k}^2 \tilde{\nu}}\right)\tilde{\sigma} + \tilde{k}^2\right]^2 + \tilde{\kappa}^2\left[\tilde{\sigma}^2 + \tilde{k}^2\right] - 4\tilde{k}^2 = 0,$$

$$\tilde{\sigma} \equiv \frac{\sigma}{\Omega}, \ \tilde{k} \equiv \frac{k v_A}{\Omega}, \tilde{\kappa}^2 \equiv \frac{\kappa^2}{\Omega^2}, \ \tilde{\nu} \equiv \frac{\nu\Omega}{v_A^2}$$

Dispersion relation for the neutrino drag:

$$\left[\left(\tilde{\sigma} + \textcolor{red}{\tilde{\Gamma}}\right)\tilde{\sigma} + \tilde{k}^2\right]^2 + \tilde{\kappa}^2\left[\tilde{\sigma}^2 + \tilde{k}^2\right] - 4\tilde{k}^2 = 0,$$

$$\tilde{\Gamma} \equiv \frac{\Gamma}{\Omega}$$

$$\nu = 1.2 \times 10^{10} \left(\rho/10^{13}\mathrm{gcm}^{-3}\right)^{-2} \left(T/10\mathrm{MeV}\right)^2 \mathrm{cm}^2\mathrm{s}^{-1}$$

$$\Gamma = 6 \times 10^3 \left(T/10\mathrm{MeV}\right)^6 \mathrm{s}^{-1} \quad \text{Guilet et al. 16}$$
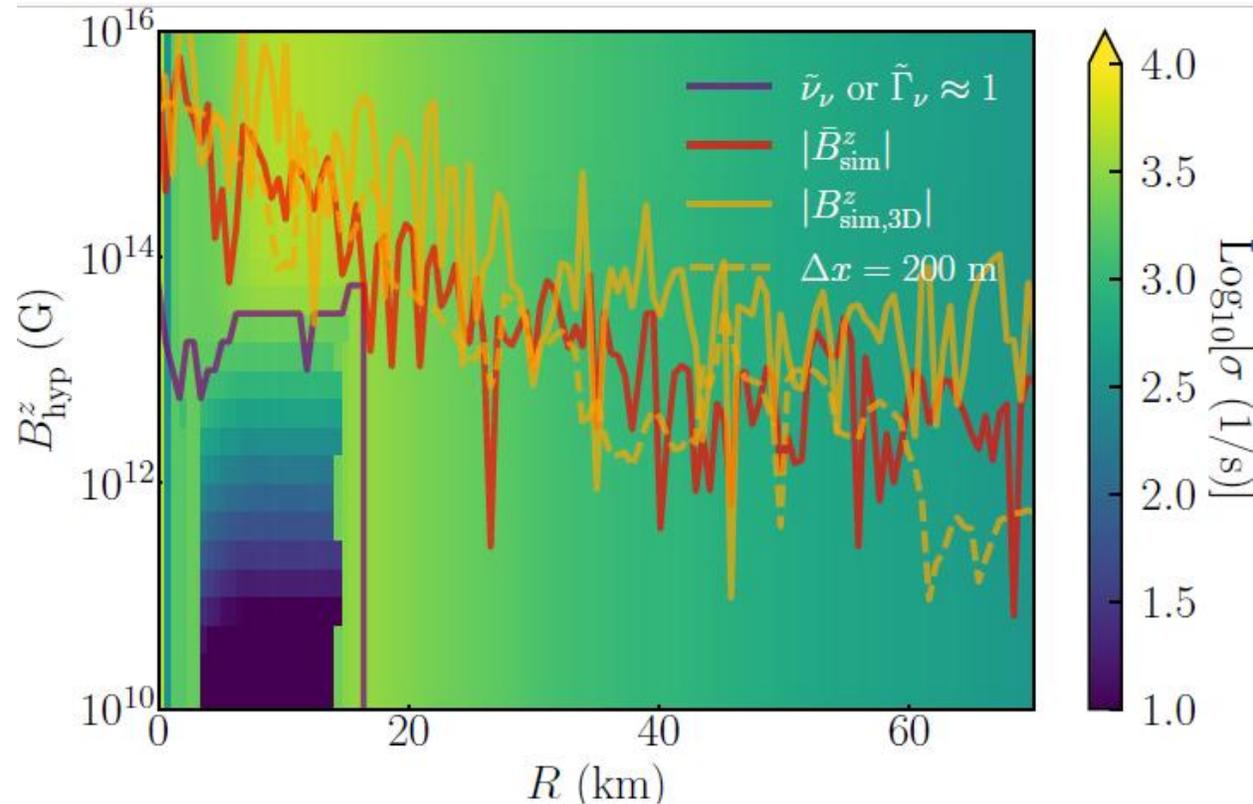
Neutrino viscosity/drag could be irrelevant for MRI.

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

Prerequisite

MRI quality factor: $\dfrac{\lambda_{MRI}}{\Delta x} > 10$
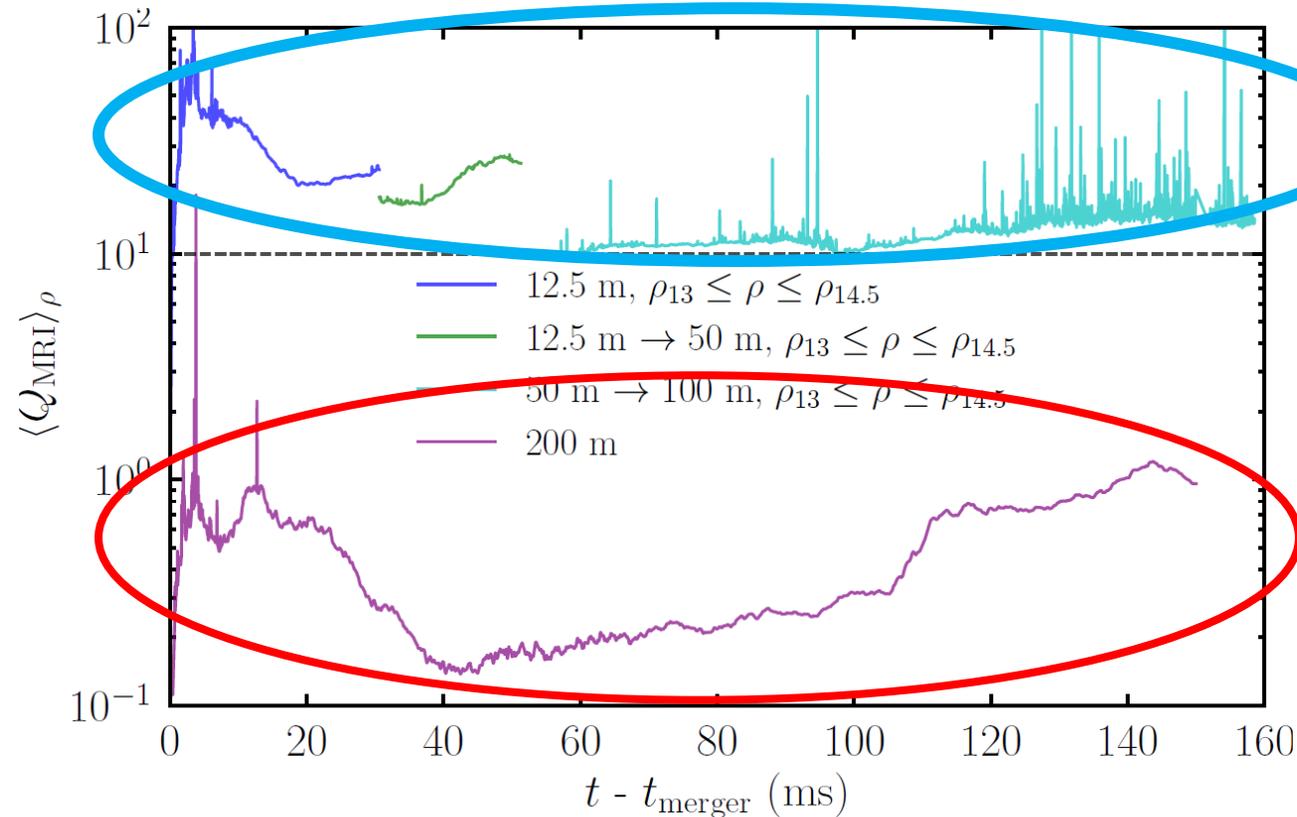
MRI is well resolved in $\triangle x$=12.5m run ⇒ Turbulence is developed
MRI is not resolved in $\triangle x$=200m run ⇒ No turbulence

Generation of a large-scale field via α Ω dynamo
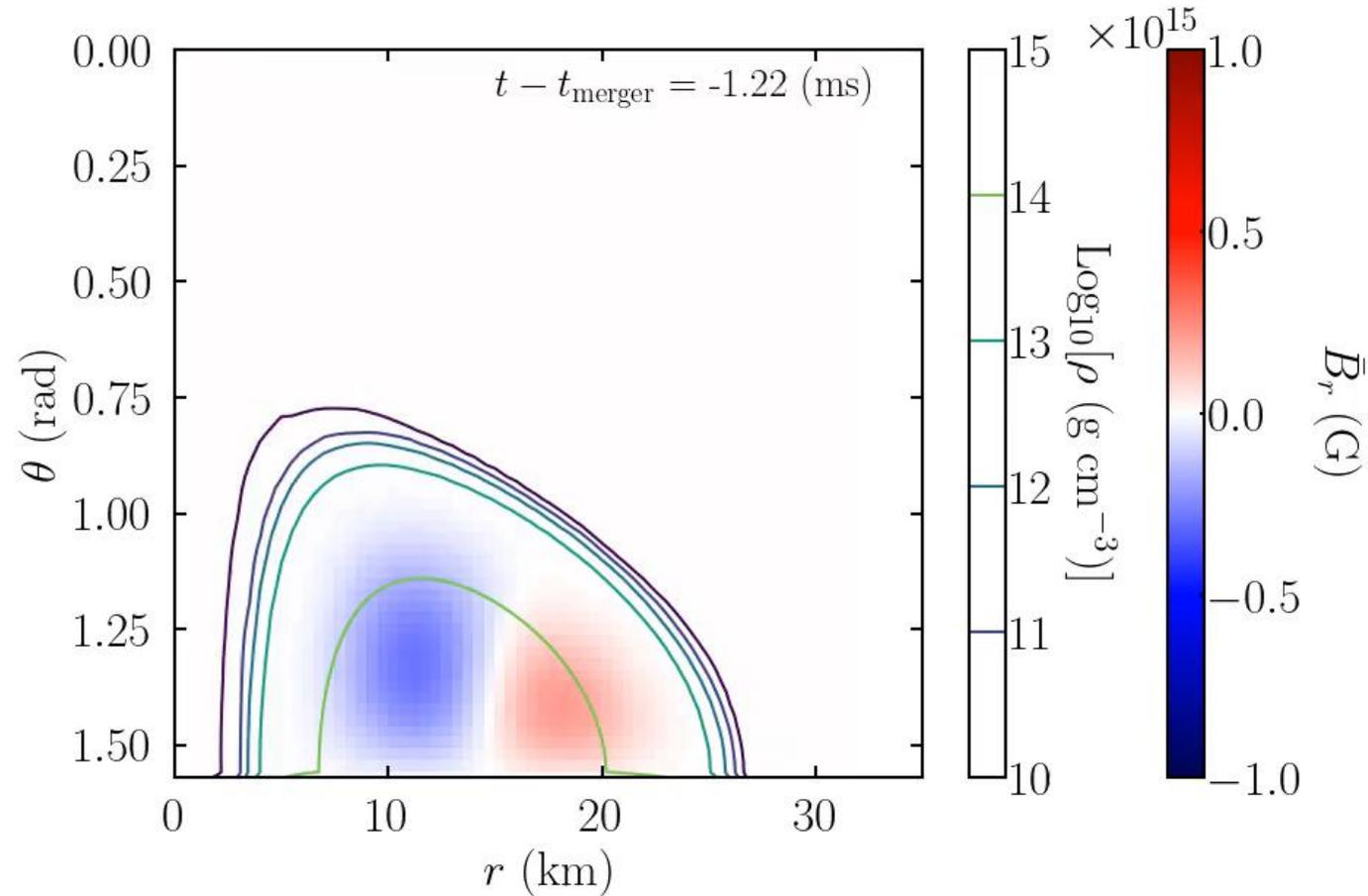
▶ Waves generated in the MRI-active region propagates towards the polar
▶The B-field deep inside the core in the polar region stays buried throughout the simulation

Check list to pin down an $\alpha\,\Omega$ dynamo
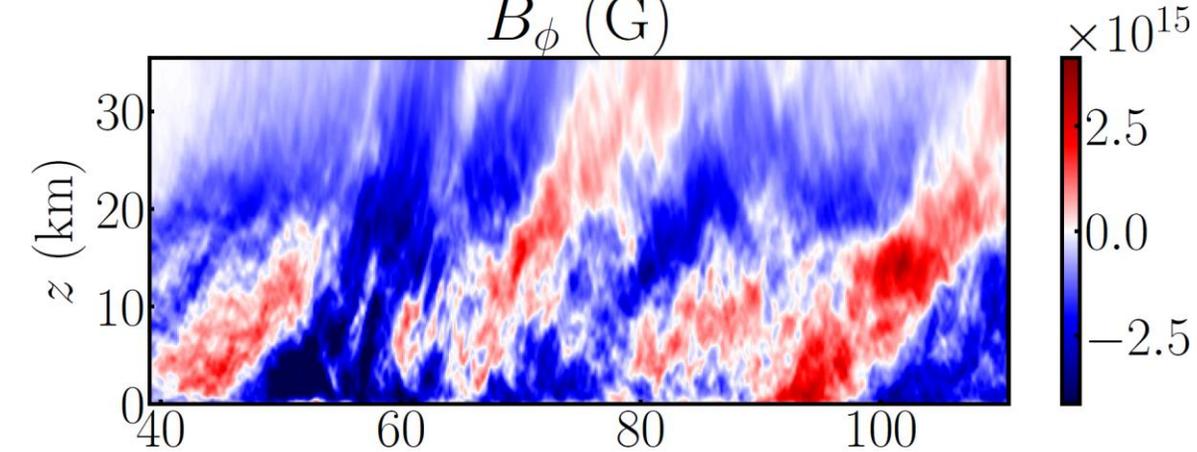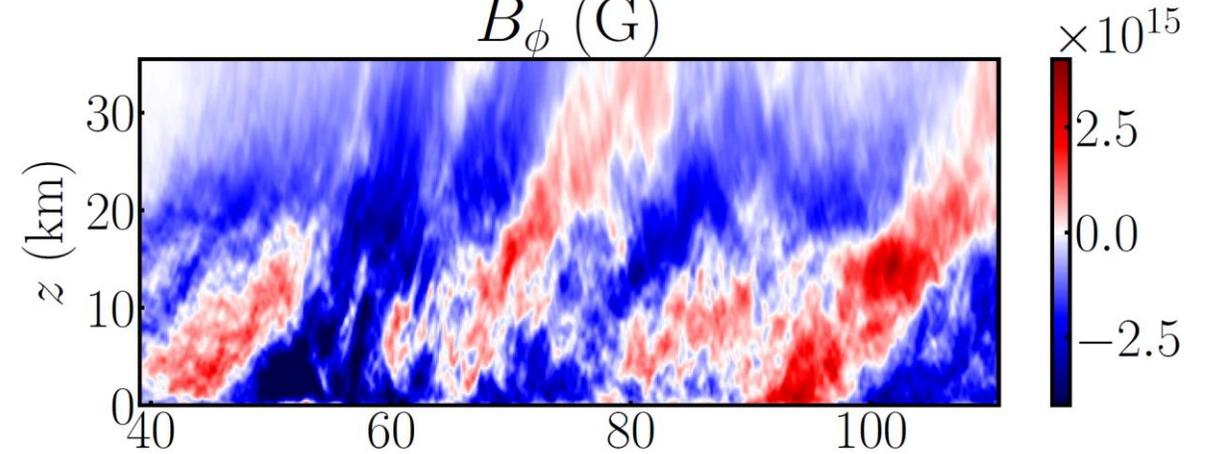
Ω effect

$\bar{B}_\phi$ (G)

$\bar{B}_R$ (G)

α effect

$\bar{B}_\phi$ (G)
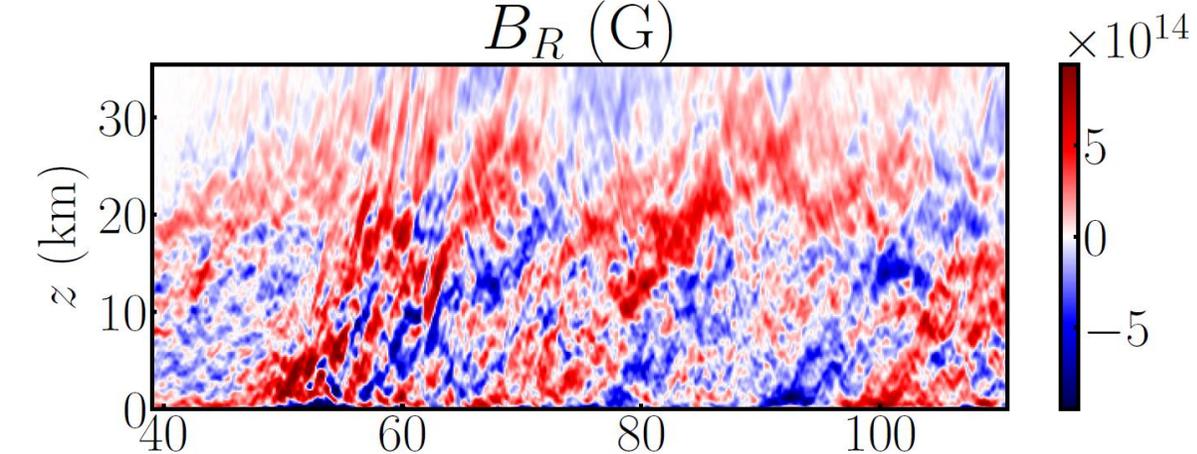
$\bar{\mathcal{E}}_\phi$ (G cm s^{-1})
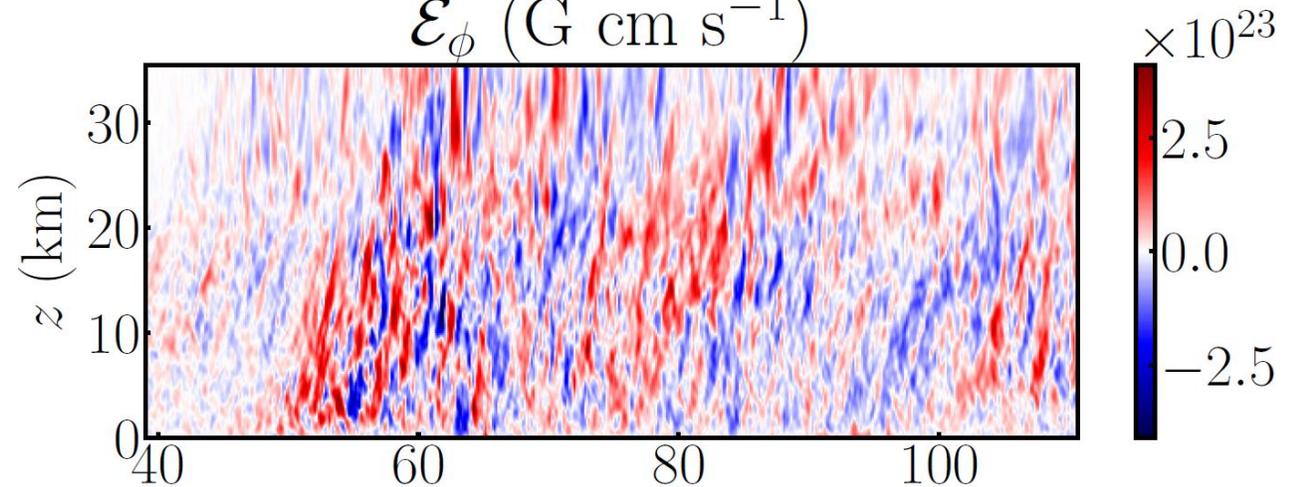
Check list to pin down an $\alpha\ \Omega$ dynamo

Pearson correlation between $\bar{E}_\varphi$ and $\bar{B}_\varphi$
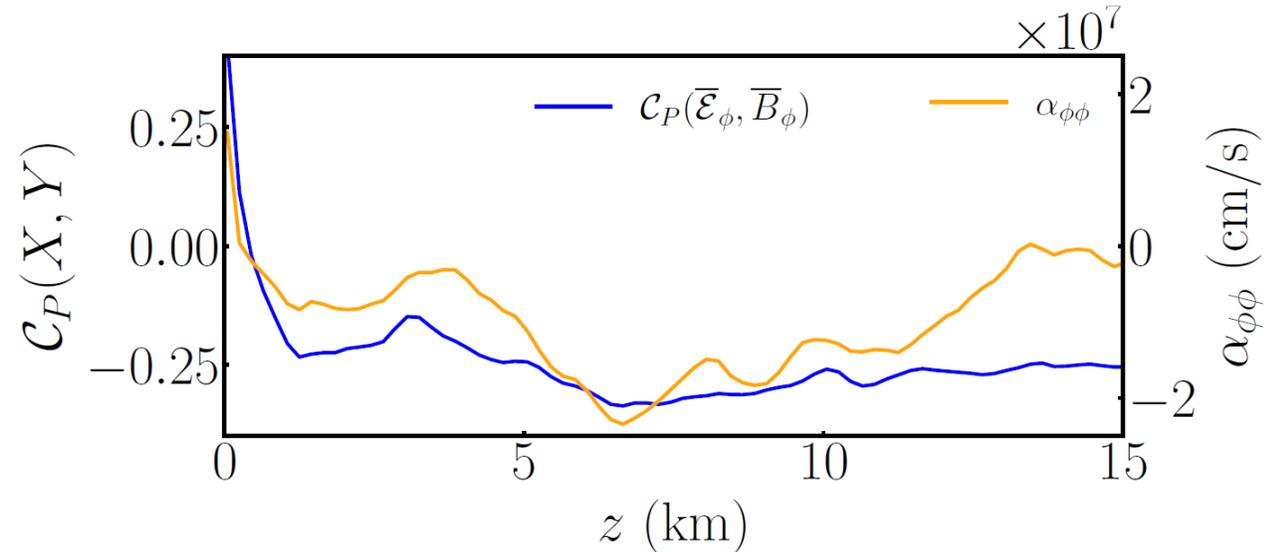
Table 1 The $\alpha\Omega$ dynamo period prediction and simulation data at several radii

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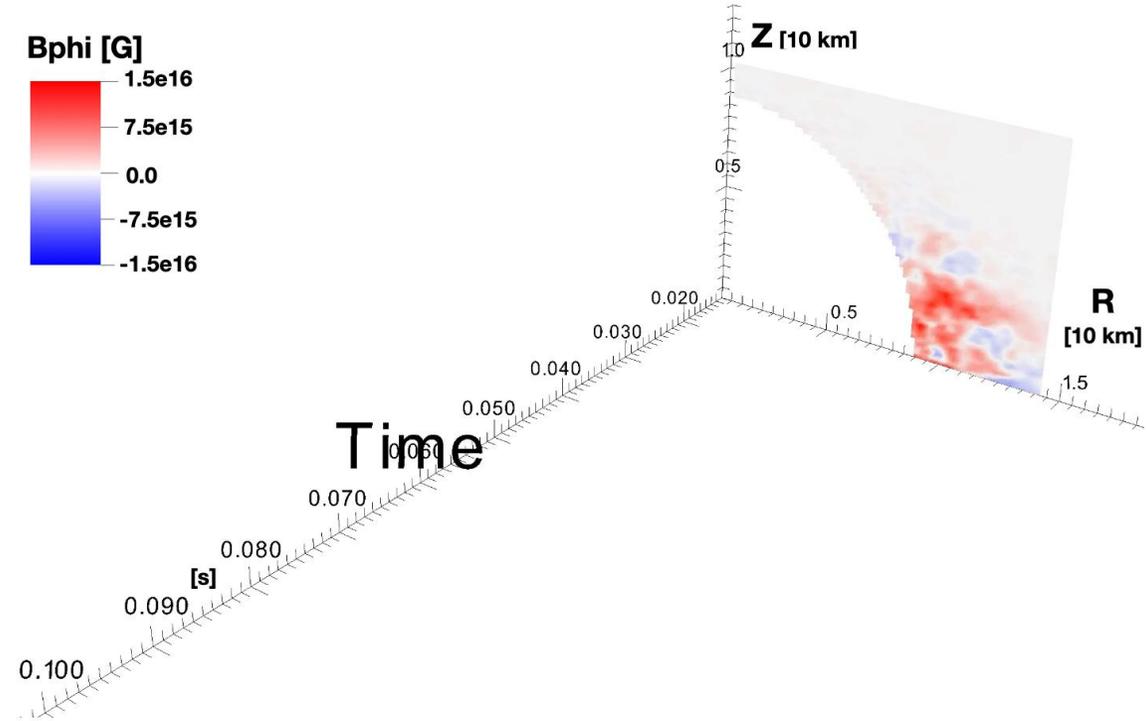
Dynamo wave propagates to the z direction according to the Yoshimura-Parker rule $\alpha_{\phi\phi} \nabla \Omega \times e_{\phi}$

Jet from long-lived remnant formation

t - t_{merger} = 151.66 ms
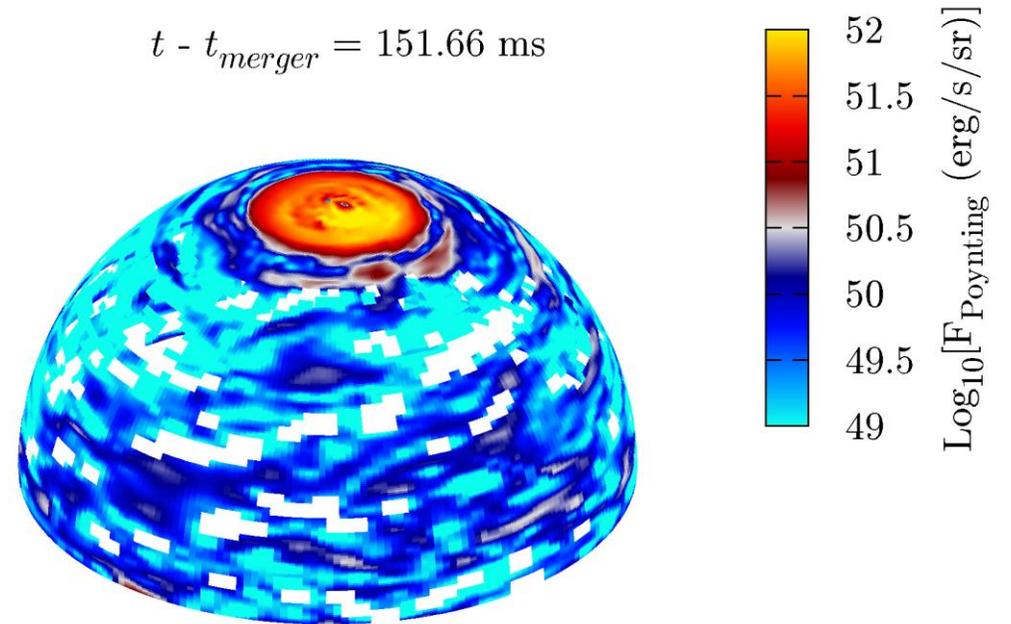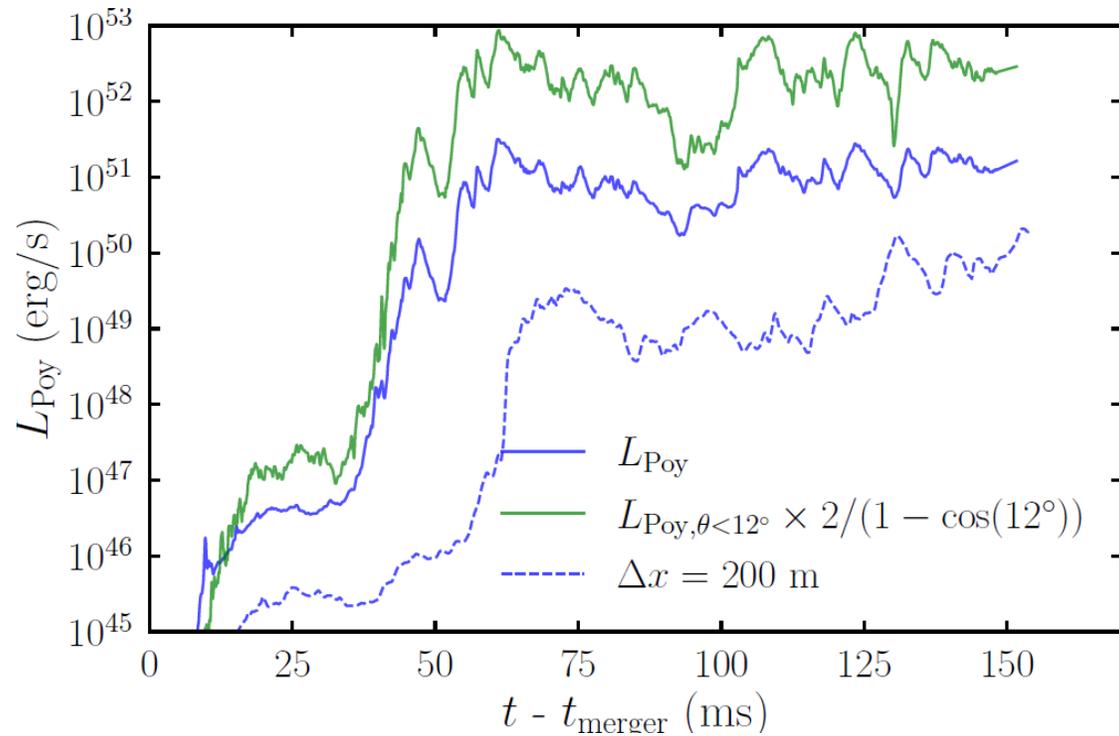
▶ Poynting flux dominated luminosity outflow is $L_{jet}^{iso} \approx 10^{52} erg/s$

▶ Relativistic outflow is confined in a region with $\theta \sim 12°$.

▶ Terminal Lorentz factor $\approx$10-20.

▶ The standard resolution (200m) underestimates the luminosity by a factor of 10-100.

Mass ejection from long-lived remnant formation
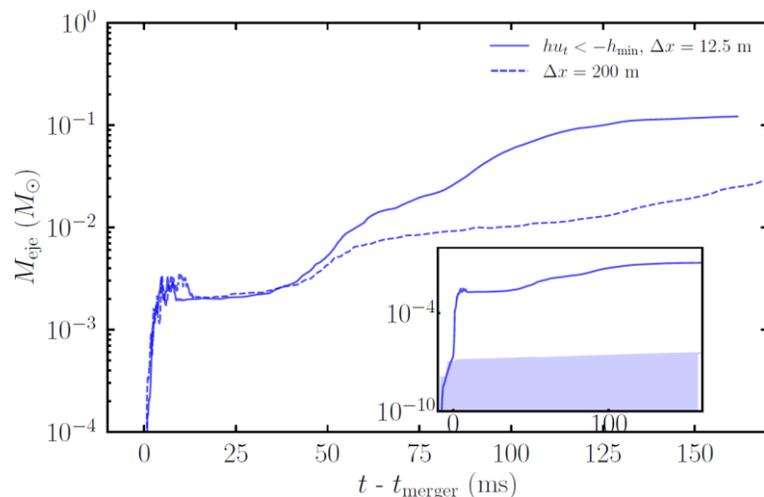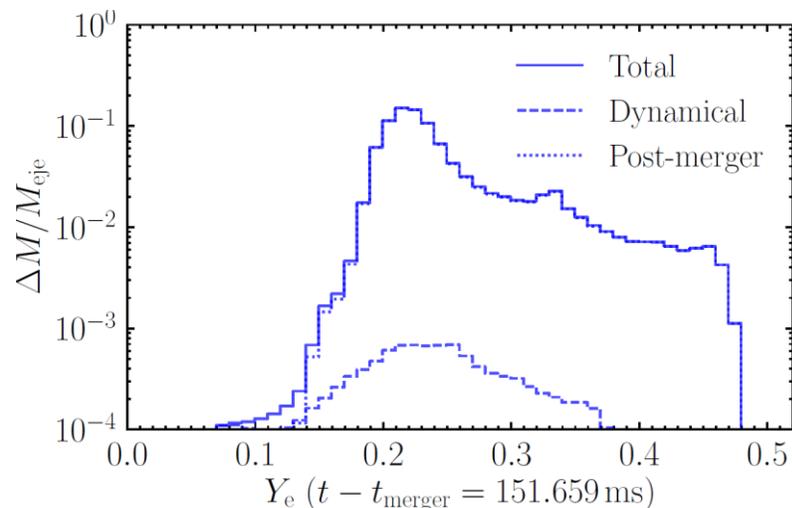
Ejecta mass evolution Mass histogram vs Y_e Mass histogram vs v_∞
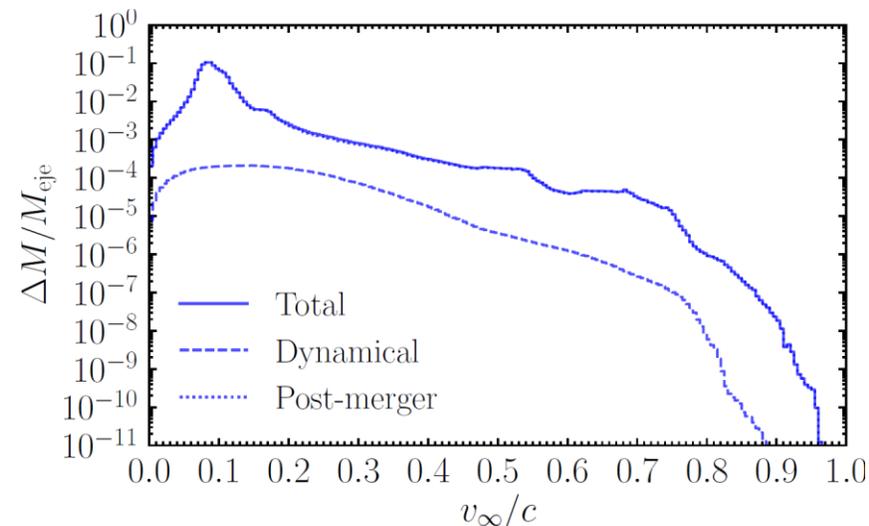
▶ $M_{eje, peak, dyn} \approx 10^{-3}\ M_\odot$, $M_{eje, peak, post}$ (Lorentz force-driven)$\approx 0.1\ M_\odot$,

▶ $Y_{e,peak,dyn} \approx 0.24$, $Y_{e,peak,post} \approx 0.22$,

▶ $v_{\infty,peak,dyn} \approx 0.1\text{-}0.3$ c, $v_{\infty,peak,post} \approx 0.1$c

▶ The standard resolution (200m) underestimates the ejecta mass by a factor of 10 (see also Mösta et al. 20).

# Inferring the EOS from ab initio simulations

Lifetime of the remnant massive neutron star

Prompt ~ 0s	Short-lived $\sim O(0.01)$ s	Intermediate-lived $\sim O(0.1)$s	Long-lived $\sim O(1)$ s
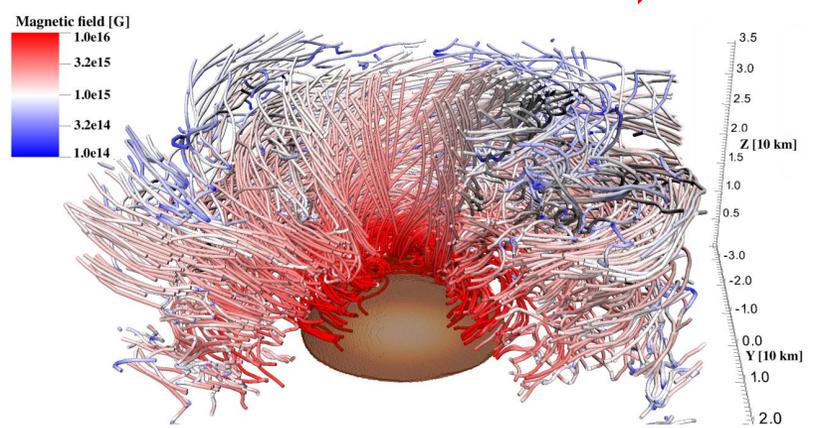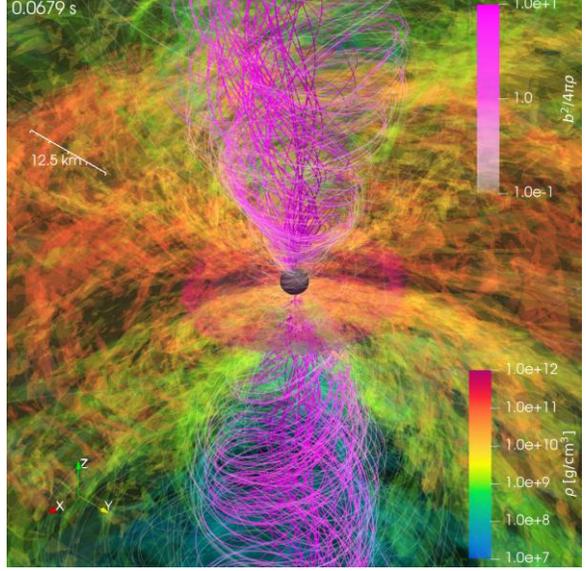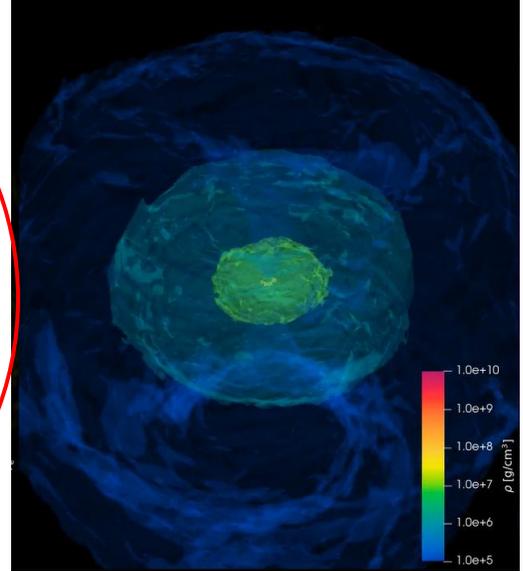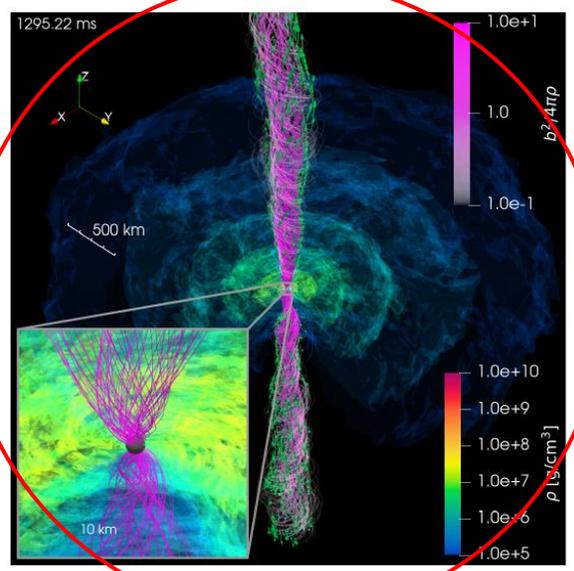
$L_{iso} \sim 10^{49}$erg/s
Hayashi et al. PRL 25

No jet until 1s at least.
KK PRL 23

$L_{iso} \sim 10^{52}$erg/s
KK 26 in prep.

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

EOS stiffness: Soft (SFHo) ⟷ Stiff (DD2)

Binary mass: Large ⟷ Small

Prompt BH formation motivated by GW190425 (Hayashi, KK et al. 24)

1.5s simulation, SFHo-1.25-1.65$M_\odot$, $\Delta x_{finiest}$=150m, B_{max}=10^{15}G, 130M CH

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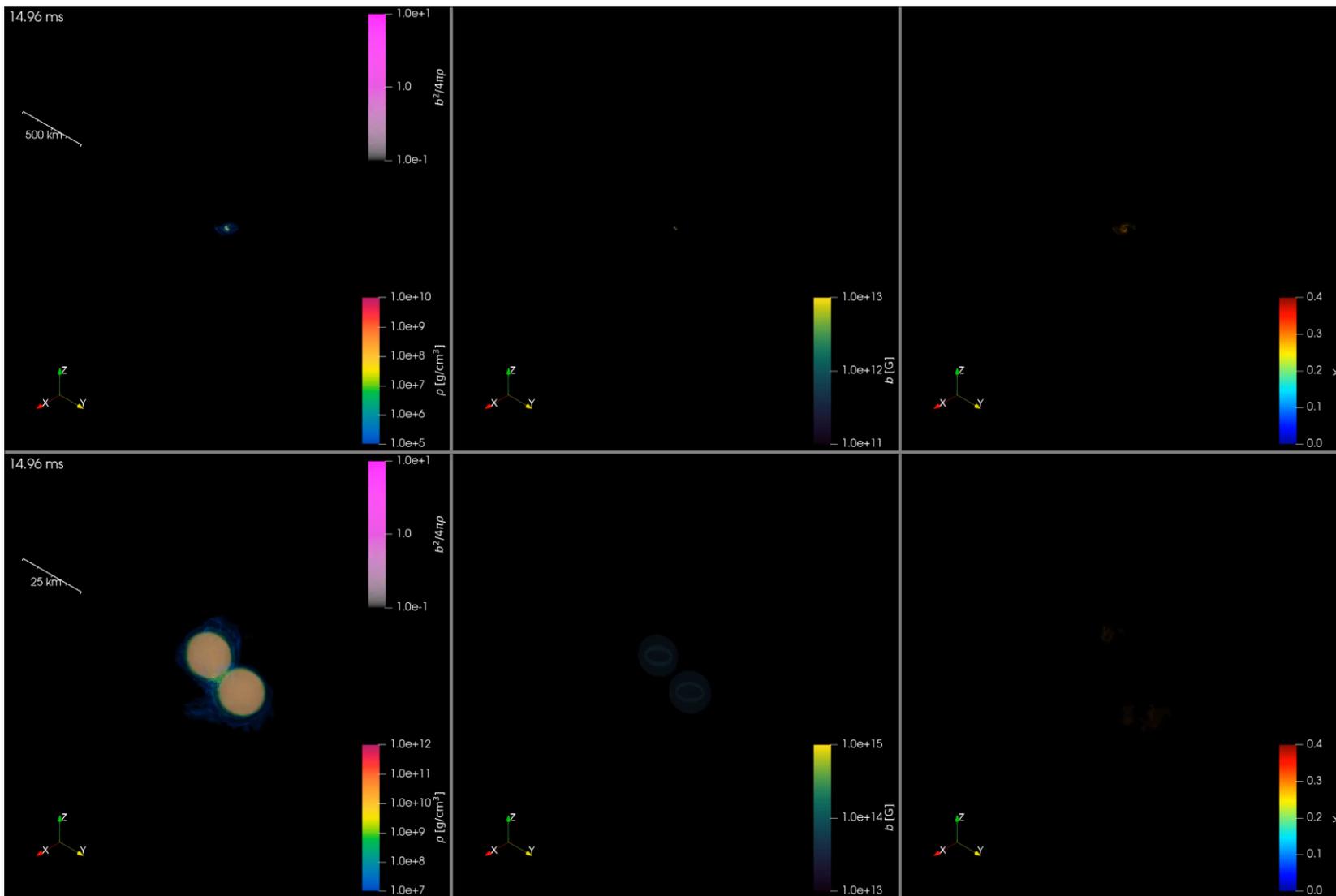
©K. Hayashi

Prompt BH formation
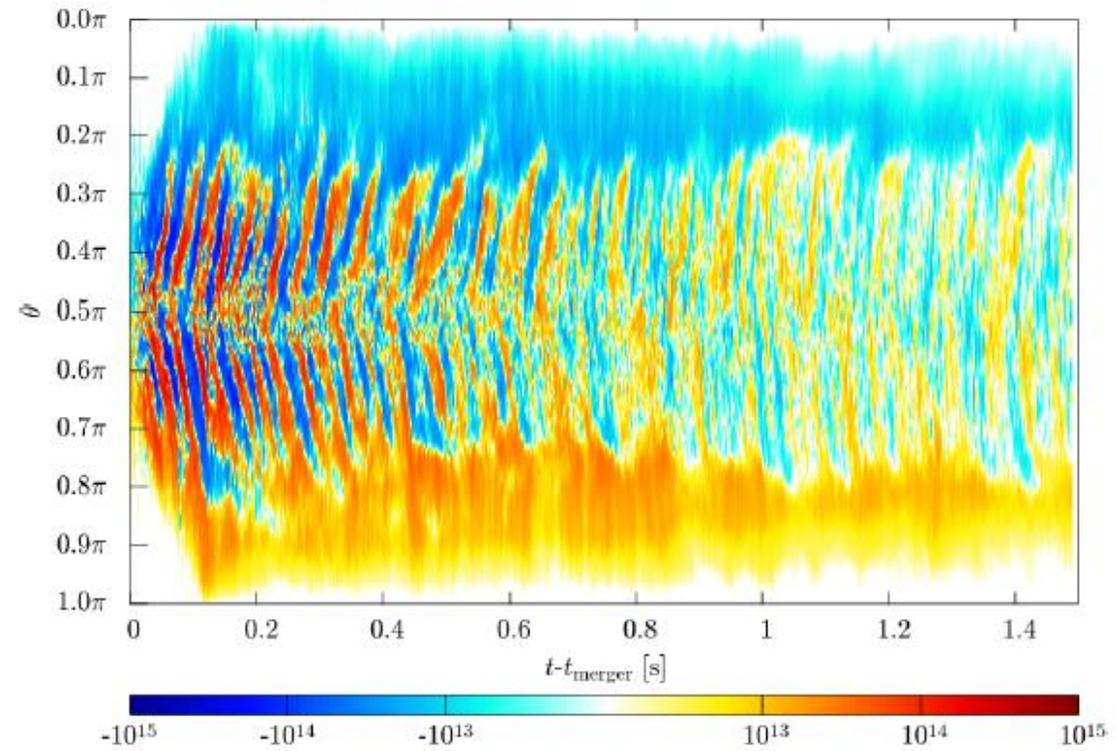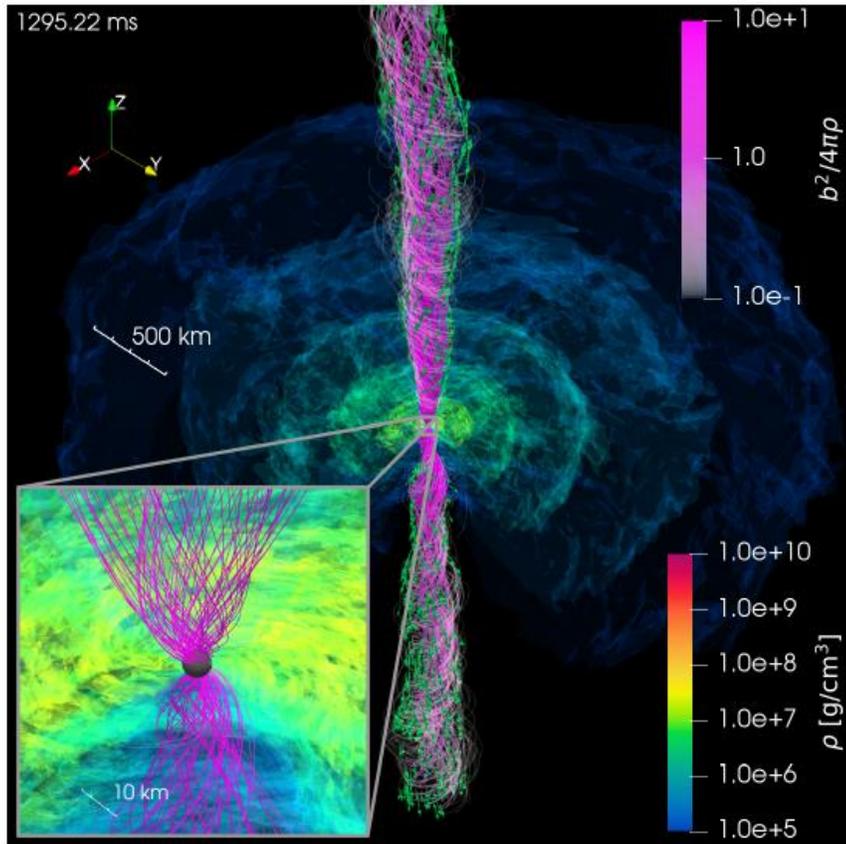
▶ Butterfly diagram suggests MRI-driven $\alpha\,\Omega$ dynamo: $P_{\alpha\,\Omega}$=0.03s vs P_{BF}=0.03-0.04s

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

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

Mass ejection from prompt BH formation
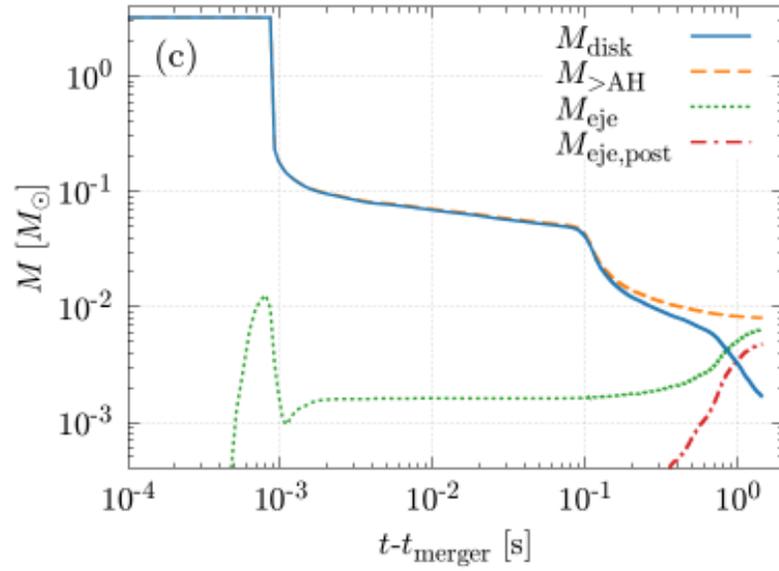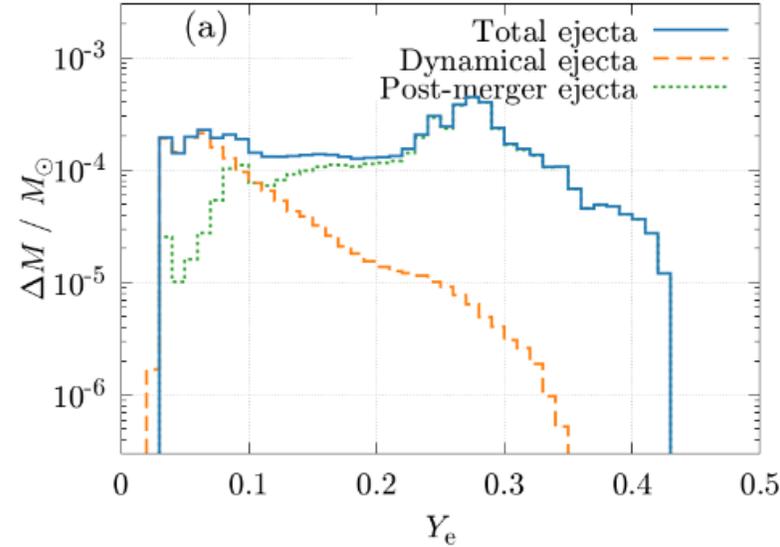
Ejecta mass evolution   Mass histogram vs Y_e Mass histogram vs v_∞
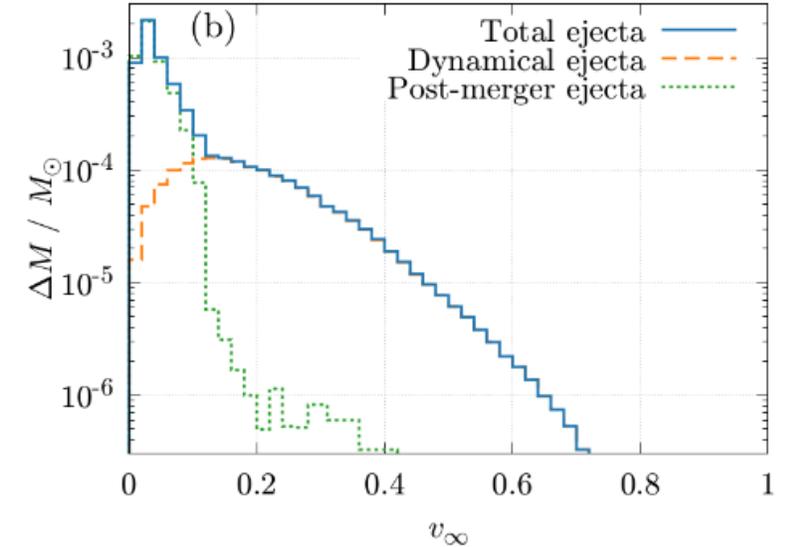
▶ Dynamical ejecta $\approx 1.6 \times 10^{-3}$ $M_\odot$, Post-merger ejecta (MRI-driven turbulent viscosity & Lorentz force) $\approx 4.7 \times 10^{-3} M_\odot$

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

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

Inferring the EOS from ab initio simulations

Lifetime of the remnant massive neutron star

| Prompt $\sim$ 0s | Short-lived $\sim O(0.01)$ s | Intermediate-lived $\sim O(0.1)$s | Long-lived $\sim O(1)$ s |
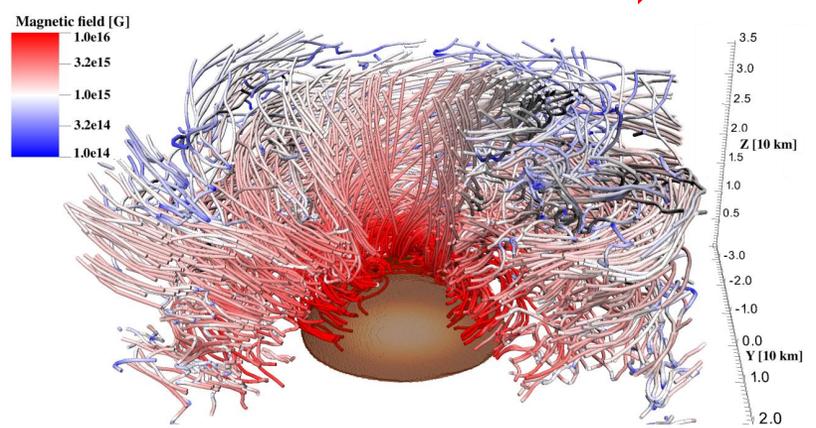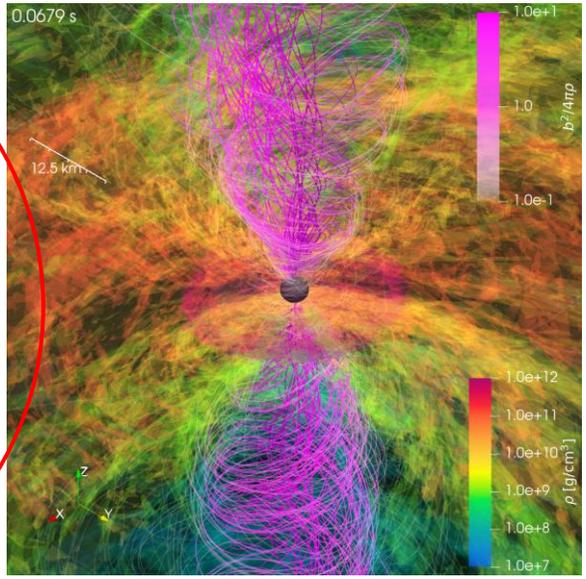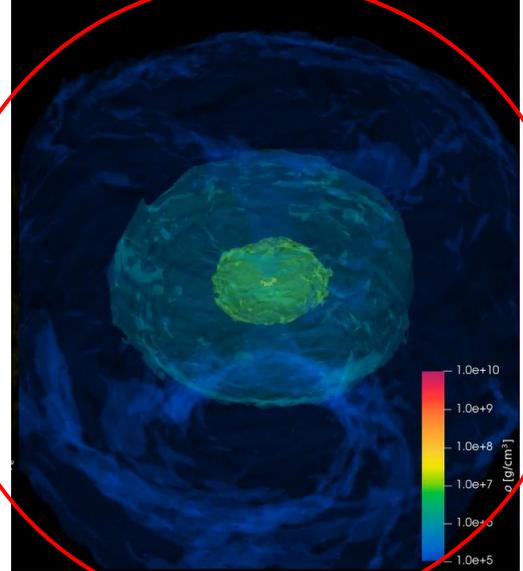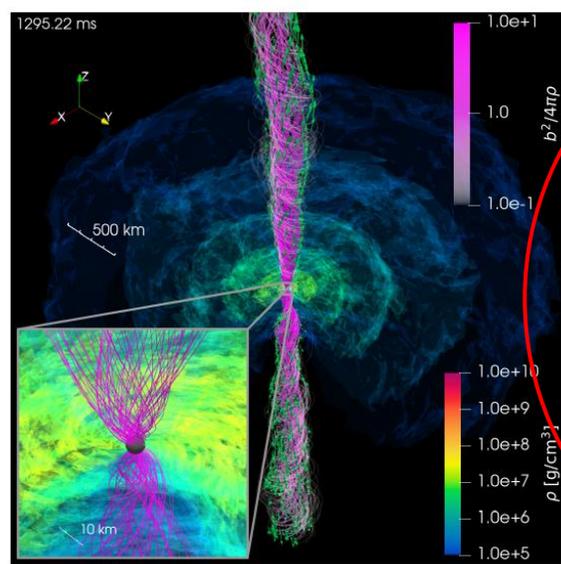
$L_{iso} \sim 10^{49}$erg/s

Hayashi et al. PRL 25

No jet until 1s at least.

KK PRL 23

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

KK 26 in prep.

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

KK Nature Astro. 24

EOS stiffness: Soft (SFHo) $\longleftrightarrow$ Stiff (DD2)

Binary mass: Large $\longleftrightarrow$ Small

Short-lived remnant formation (KK et al. PRL 23)

1.2s simulation, SFHo-1.2-1.5M$_\odot$, $\Delta x_{finiest}$=150m&200m, 85M CH

$\rho\ (g\ cm^{-3})$ $\qquad\qquad$ Y_e $\qquad\qquad$ $B(G)$ $\qquad$ ©K. Hayashi
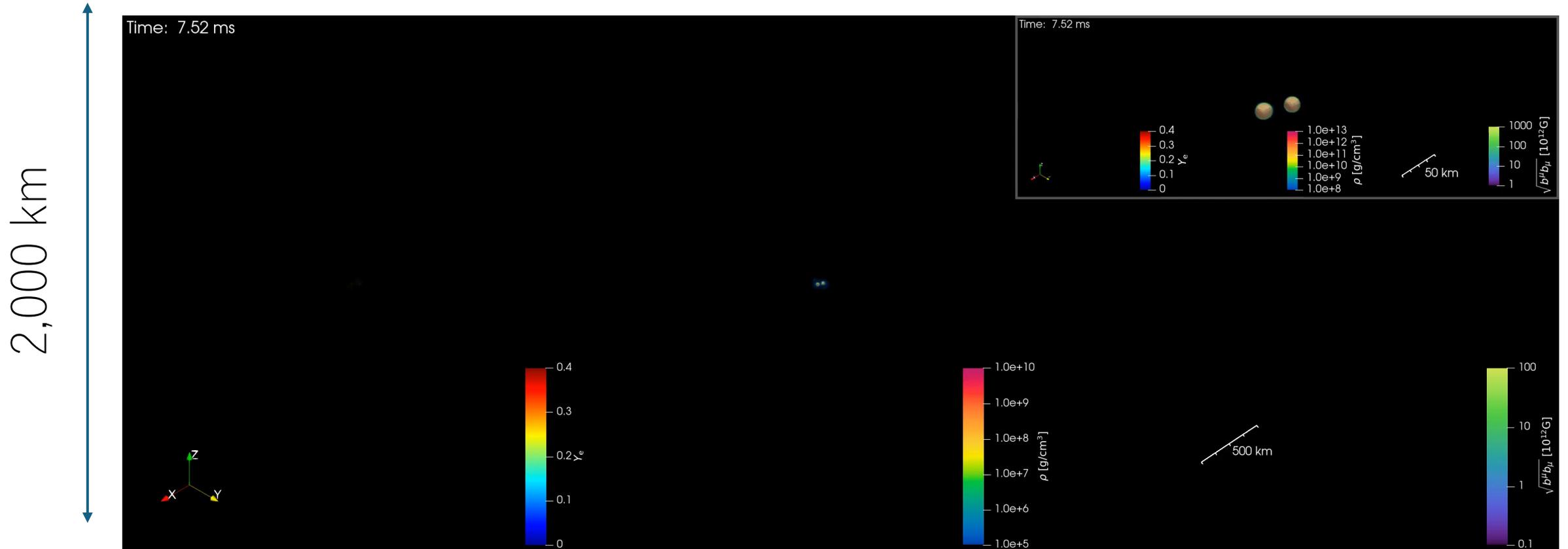
(see also, Just et al. 14, 21)

No "jet" from the short-lived remnant formation

No jet until 1s at least.
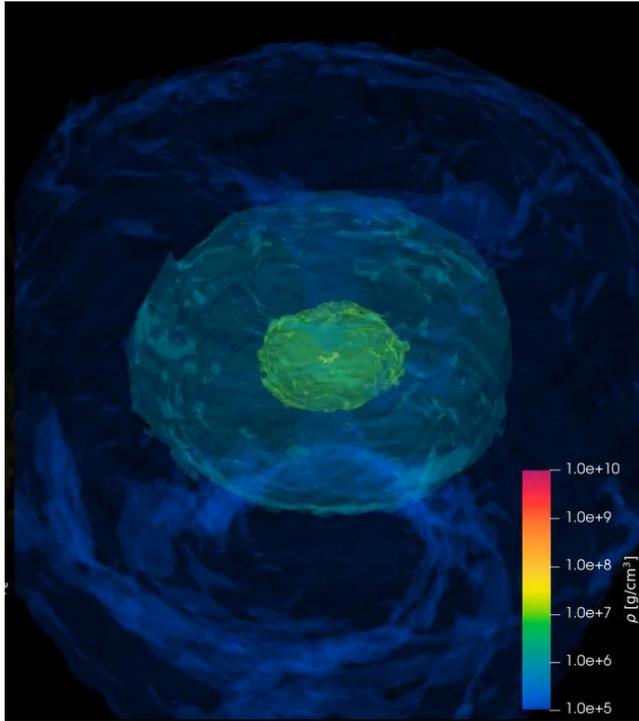
Butter-fly diagram
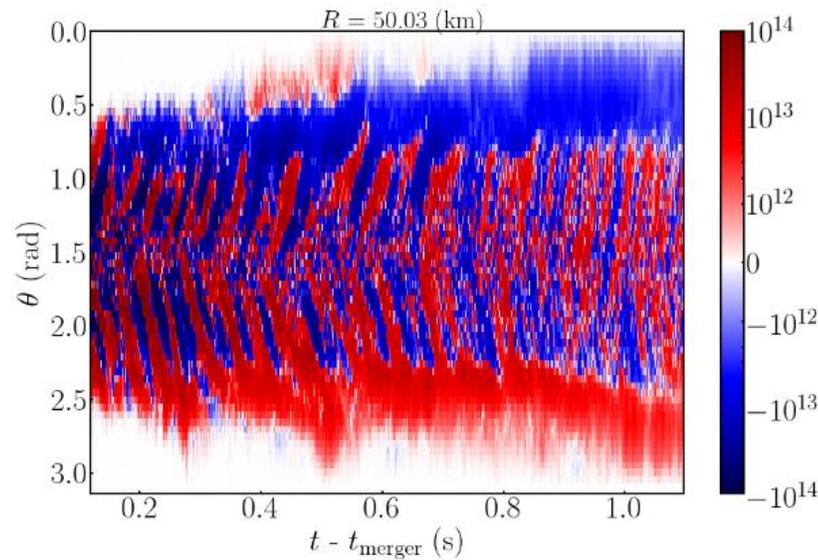
Ram-pressure/Mag-pressure
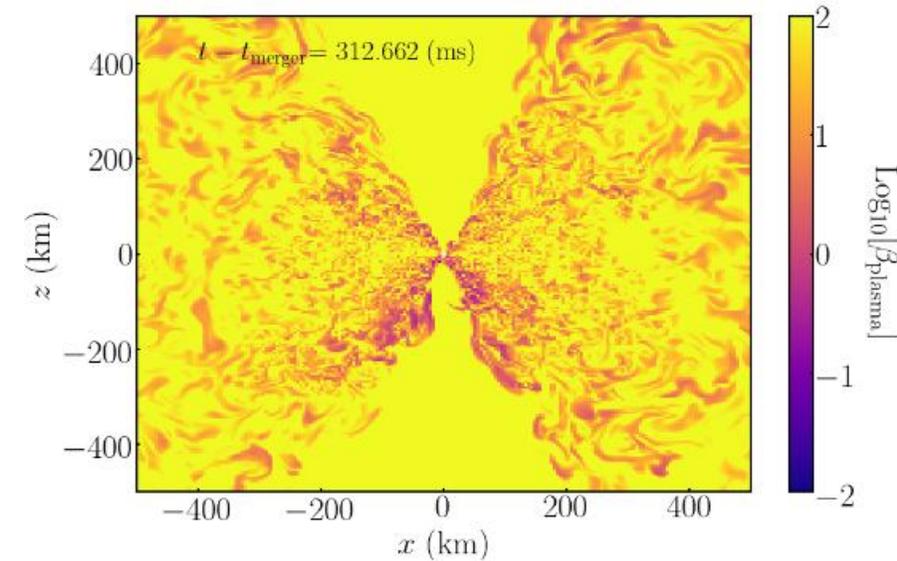
▶ BF diagram indicates the $\alpha\,\Omega$ dynamo generates the large-scale B-field.
▶ Resultant large-scale is not strong enough to overcome the ram-pressure. Why? Disk rotational energy is $\approx 10^{51}$erg, c.f. Remnant NS rotational energy is $\approx 10^{53}$erg.

Mass ejection from the short-lived remnant formation

Ejecta mass evolution
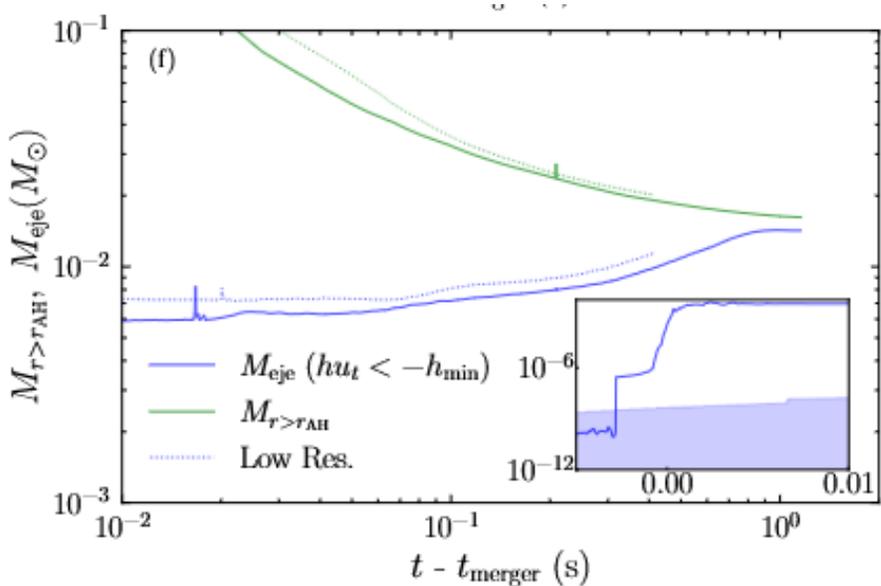
Mass histogram vs Y_e
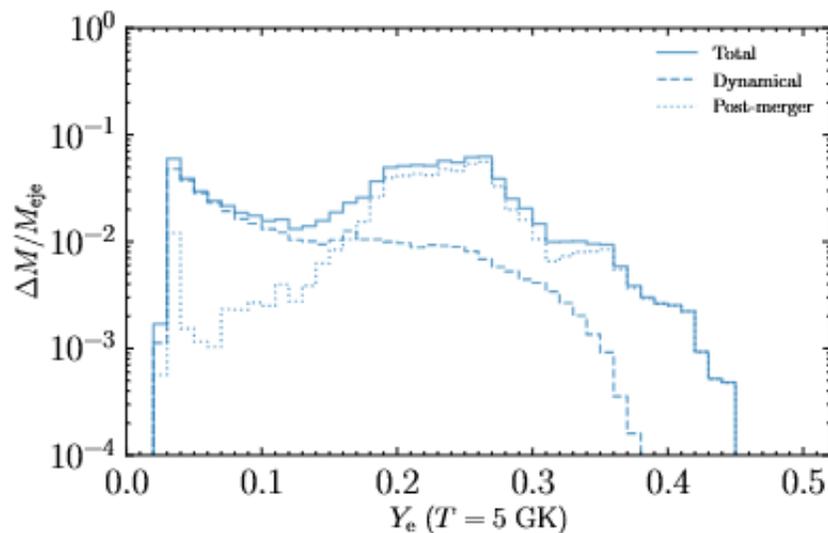
Mass histogram vs v_∞
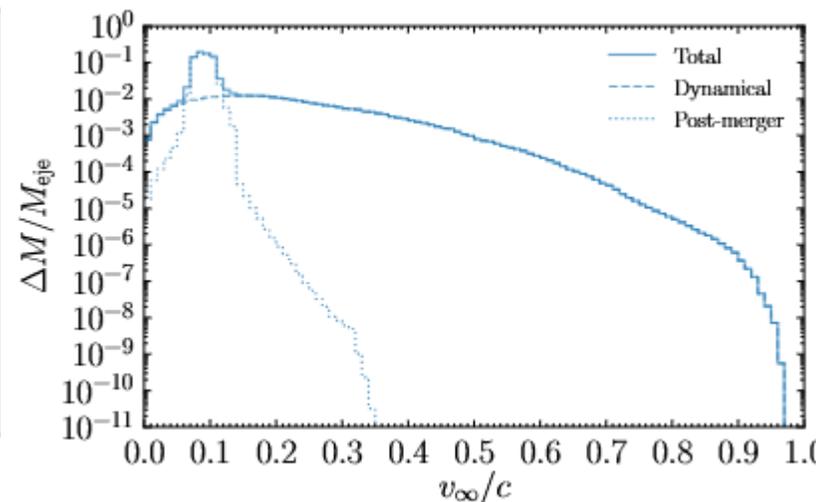
▶ $M_{eje, peak,dyn} \approx 6 \times 10^{-3}\ M_\odot$, $M_{eje, peak,post}$(MRI-driven turbulent viscosity)$\approx$ $8 \times 10^{-3} M_\odot$.

▶ $Y_{e, peak,dyn} \approx 0.03$, $Y_{e, peak, post} \approx 0.26\text{-}0.27$.

▶ $v_{\infty, peak,dyn} \approx 0.2\text{-}0.3c$, $v_{\infty, peak, post} \approx 0.08\text{-}0.10c$.

Inferring the EOS from ab initio simulations

Lifetime of the remnant massive neutron star

| Prompt $\sim$ 0s | Short-lived $\sim O(0.01)$ s | Intermediate-lived $\sim O(0.1)$s | Long-lived $\sim O(1)$ s |
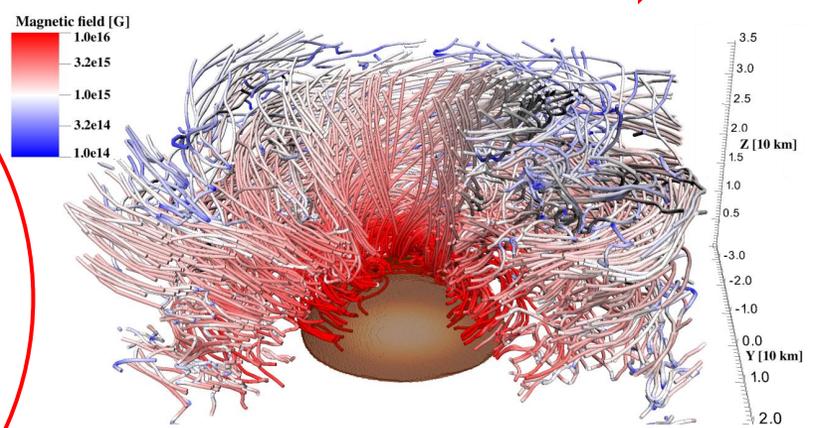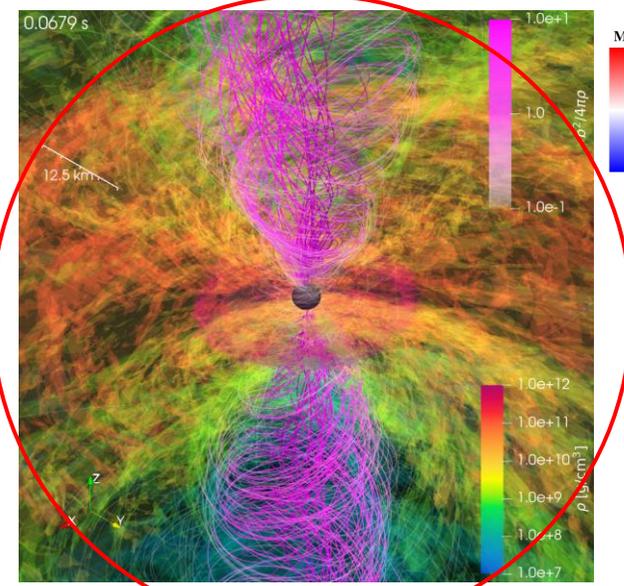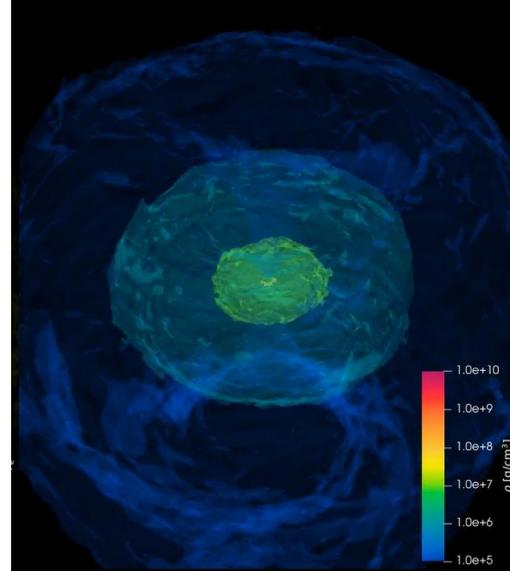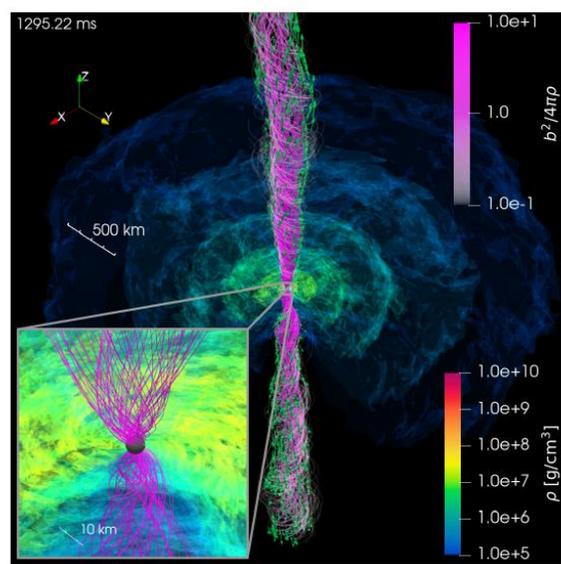
$L_{iso} \sim 10^{49}$erg/s
Hayashi et al. PRL 25

No jet until 1s at least.
KK PRL 23

$L_{iso} \sim 10^{52}$erg/s
KK 26 in prep.

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

EOS stiffness: Soft (SFHo) $\longleftarrow$ $\longrightarrow$ Stiff (DD2)

Binary mass: Large $\longleftarrow$ $\longrightarrow$ Small

Intermediate lived remnant formation case (KK in prep)

$M_{chirp}=1.186M_\odot$, BHB Λ_ϕ, $\Delta x_{finest}=12.5m$, 0.7 second, $B_{max}=10^{15}G$, 150M CH

$\rho\ (g\ cm^{-3})$ $B(G)$ Y_e ©K. Hayashi
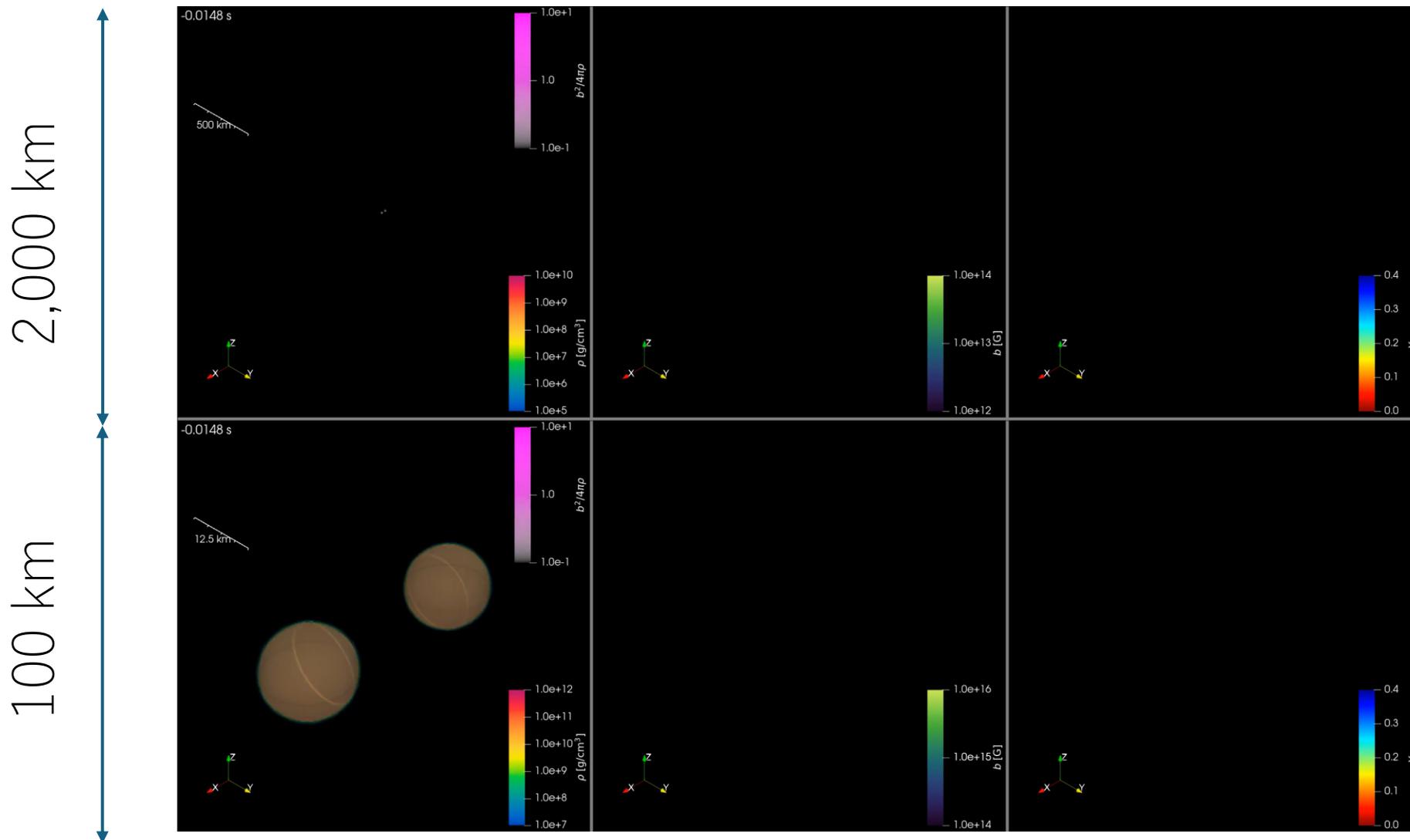
Pinning down the $\alpha\Omega$ dynamo in BNS

Butterfly diagram
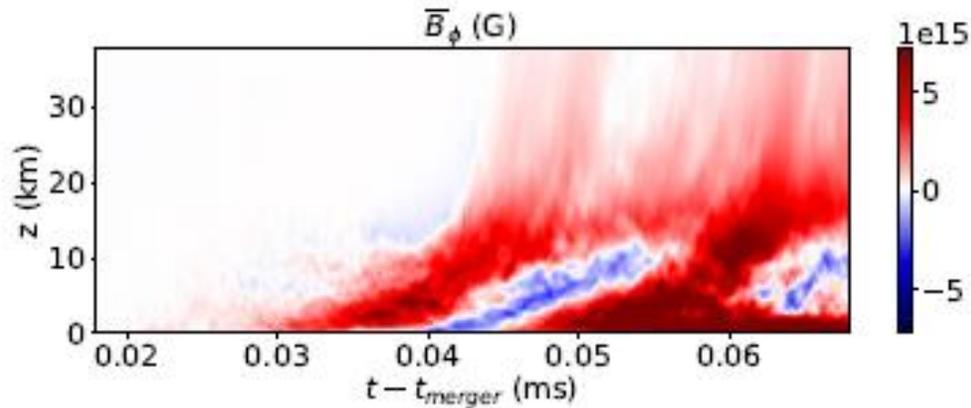
Theory vs simulation

R [km]	$\alpha_{\varphi\varphi}$ [cm/s]	k_z [cm^{-1}]	$d\Omega/d\ln R$ [s^{-1}]	$P_{\alpha\Omega}$ [ms]	P_{BF} [ms]
10	8.0×10^6	2.4×10^{-5}	5359	8.8	12
20	$0.5 - 1.0 \times 10^7$	7.0×10^{-6}	4955	$15 - 25$	17
30	1.5×10^7	3.3×10^{-6}	3505	21	17

▶ A couple of predictions based on the mean-field large-scale dynamo theory (not shown)

▶ The most relevant prediction is

$$P_{\alpha\Omega} = 2\,\pi \left(\alpha_{\phi\phi} d\Omega/d\ln R \, k_z \right)^{-1/2}$$

$$\partial_t \bar{B}_\varphi = R\bar{B}^R \nabla_R \Omega,$$

$$\partial_t \bar{B}_R = \partial_z \bar{\mathcal{E}}_\varphi \approx \partial_z (\alpha_{\varphi\varphi} \bar{B}_\varphi)$$

"Jet" from the intermediate-lived remnant formation

Poynting flux
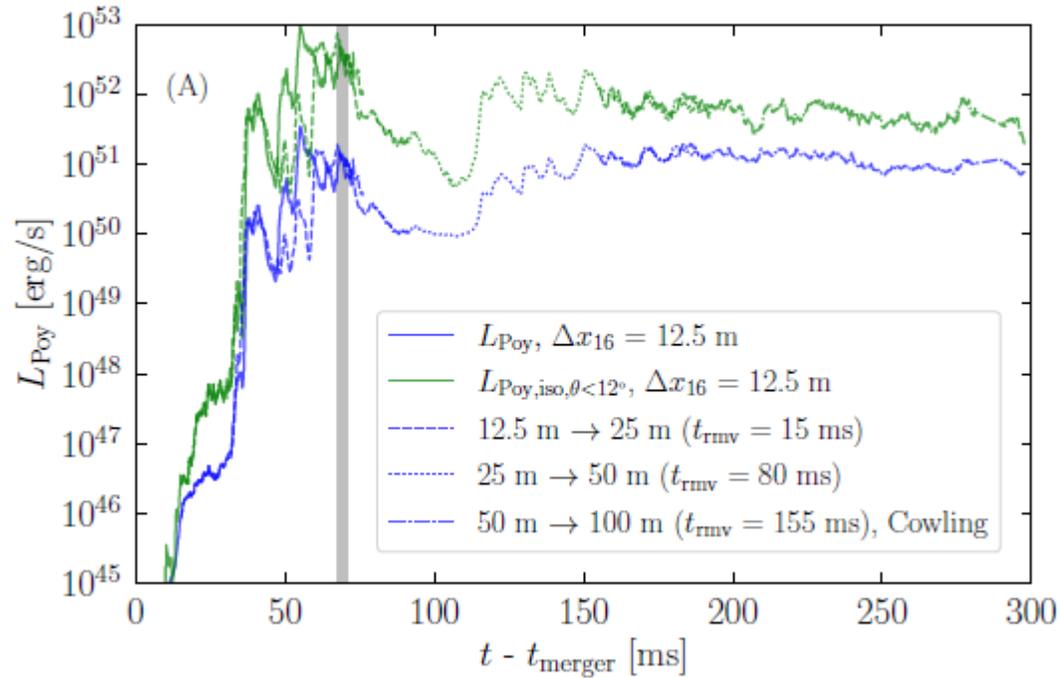
Required jet kinetic energy (GW170817)
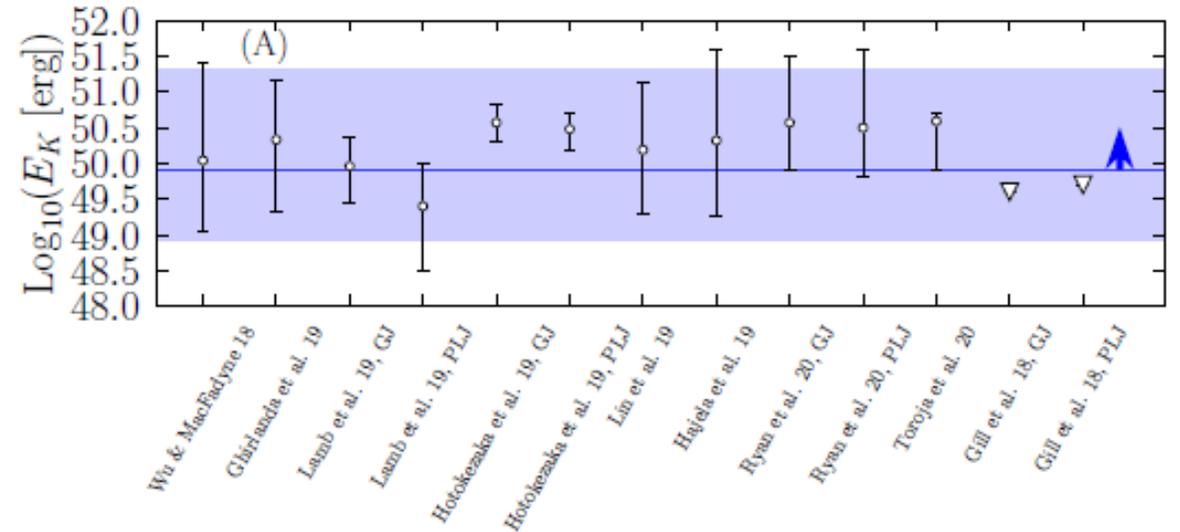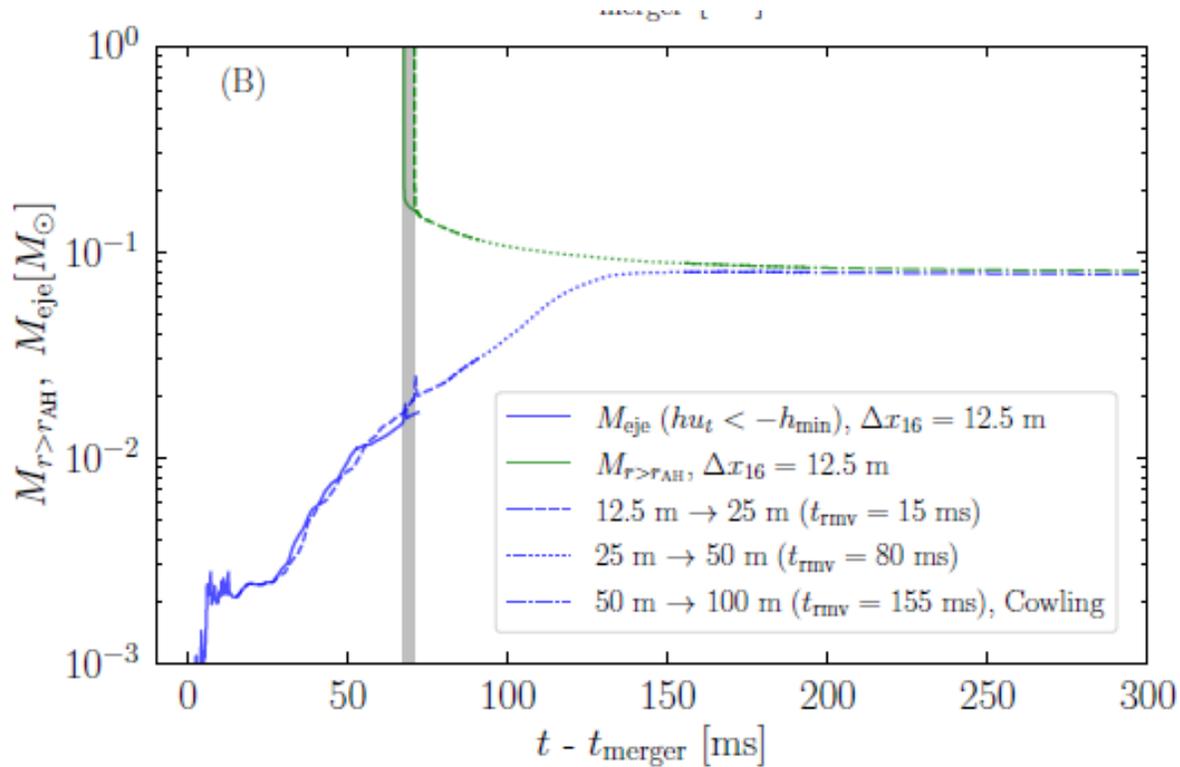

▶ $L_{jet}^{iso} \sim 10^{52} erg/s$ ⇒ If 1 second duration and 10% convergence efficiency are assumed, it is consistent with the required jet kinetic energy in GW170817 (see also Sadeh & Waxman 24).
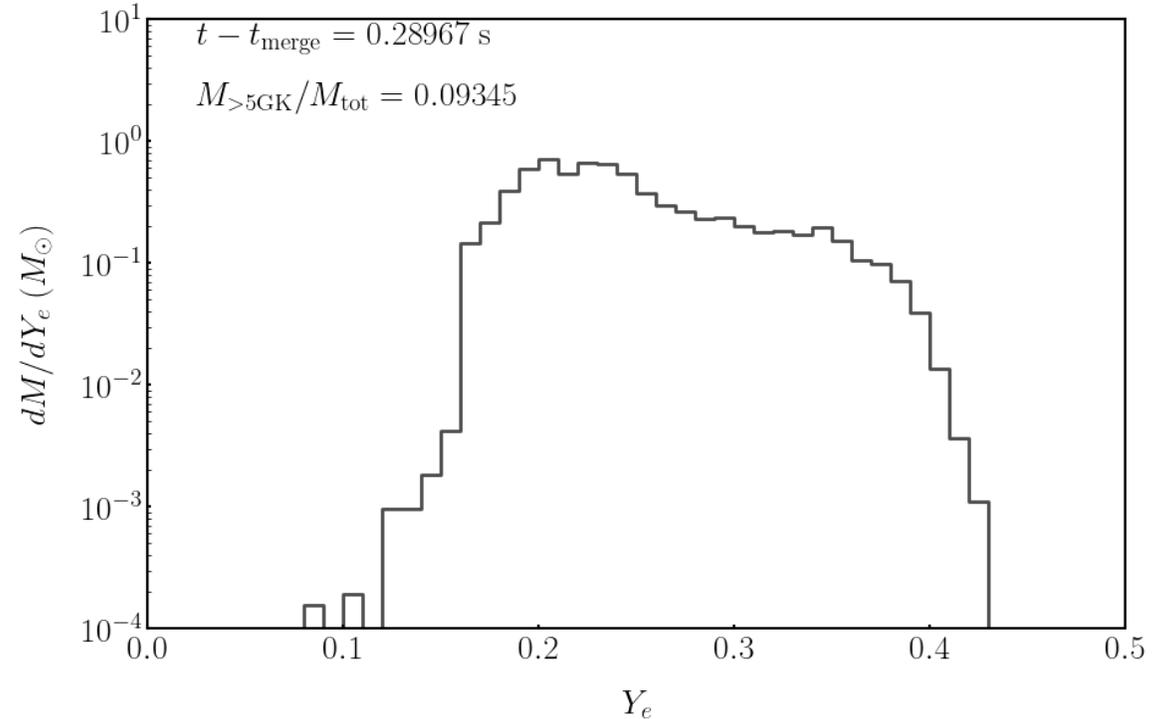
▶ $\Gamma_\infty \approx 30$

Intermediate lived remnant formation case
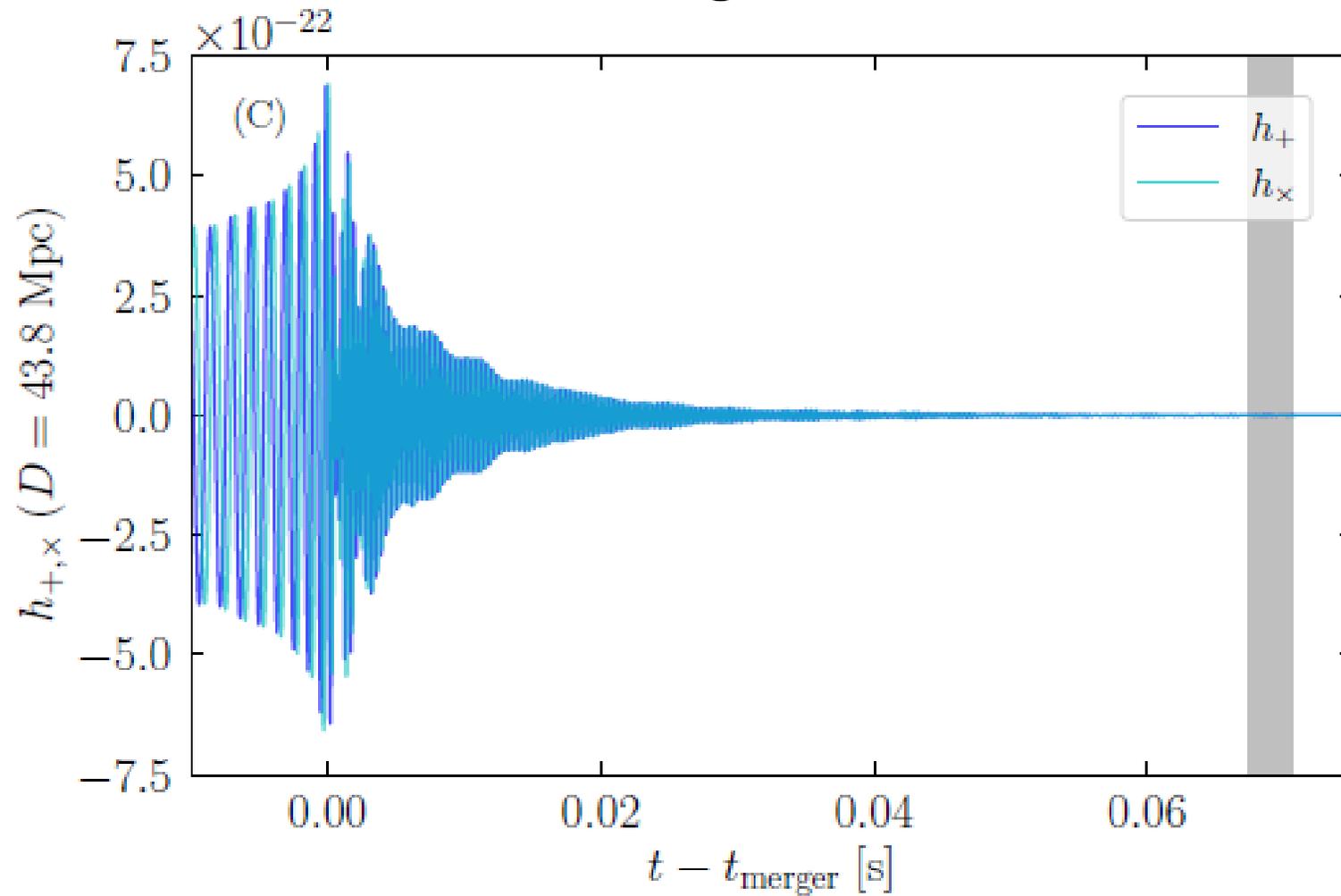
Ejecta mass evolution

Mass histogram vs Y_e

▶ $M_{eje, dyn} \approx 2\times10^{-3} M_\odot$, $M_{eje, post}$(Lorentz-force-driven)$\approx 8\times10^{-2}M_\odot$.

▶ $Y_{e, peak,dyn} \approx 0.03$, $Y_{e, peak, post} \approx 0.2$

Intermediate lived remnant formation case
GW signals

The energy emitted in the post-merger phase is below the observed upper limit (LVK18).
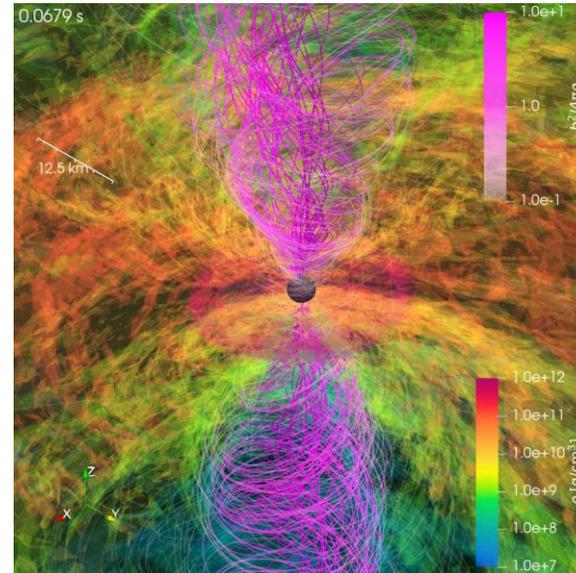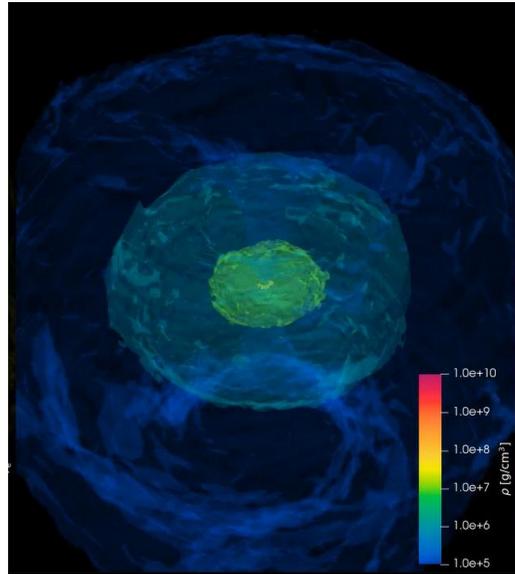
Inferring the EOS from "jet" launching

Lifetime of the remnant massive neutron star

| Prompt ~ 0s | Short-lived $\sim O(0.01)$ s | Intermediate-lived $\sim O(0.1)$s | Long-lived $\sim O(1)$ s |
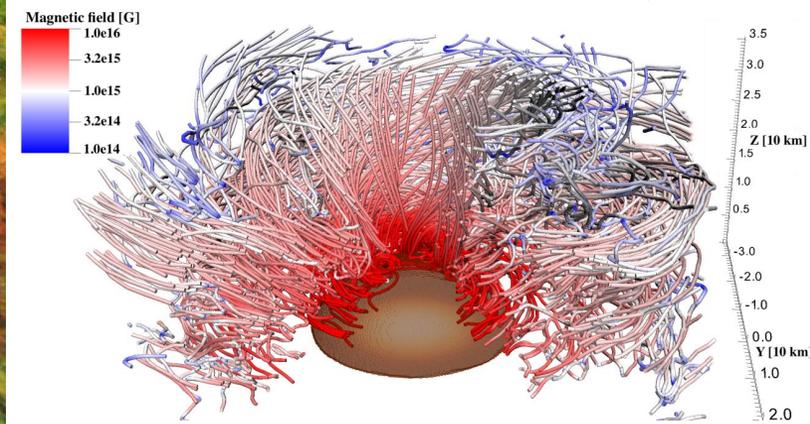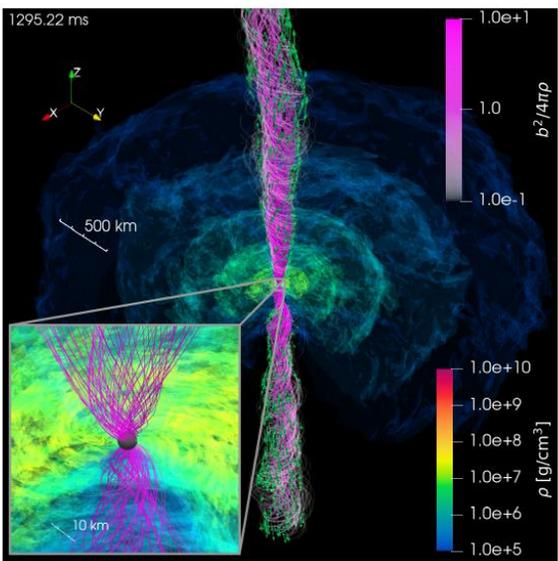
$L_{iso} \sim 10^{49}$erg/s

No jet until 1s at least.

SFHo

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

BHB Λ_ϕ

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

DD2
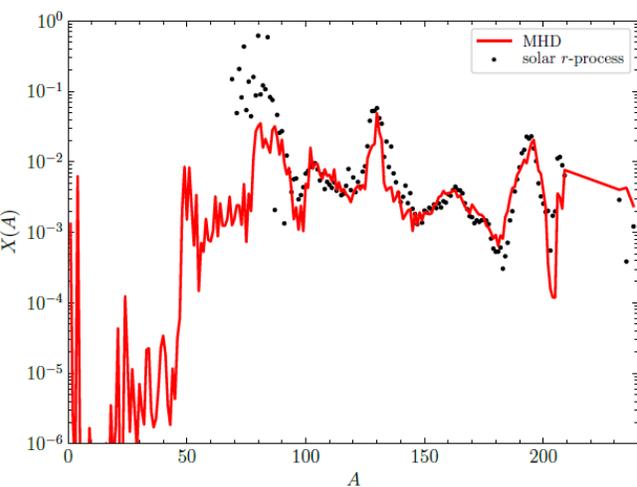
Inferring the EOS from R-process nucleosynthesis

Lifetime of the remnant massive neutron star

Prompt ~ 0s	Short-lived $\sim O(0.01)$ s	Intermediate-lived $\sim O(0.1)$s	Long-lived $\sim O(1)$ s
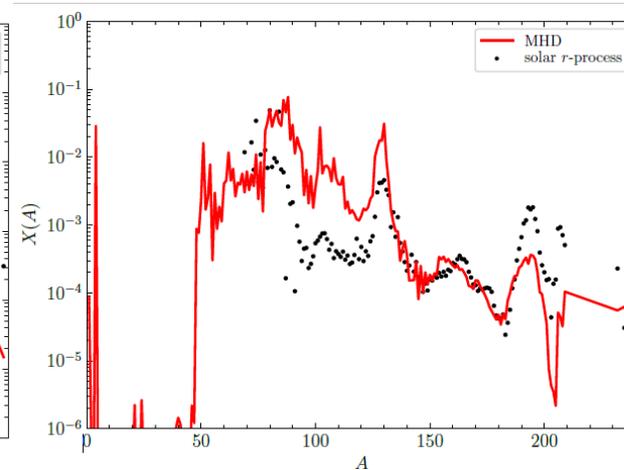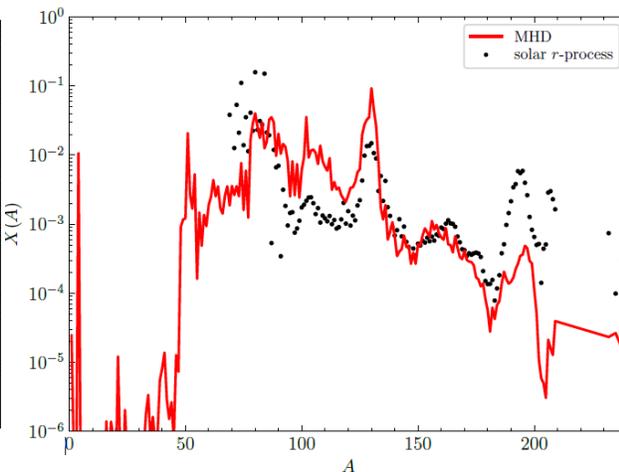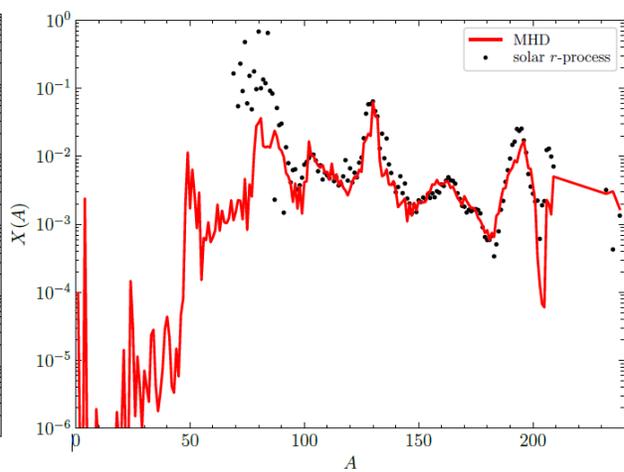
$M_{eje} \simeq 0.006\, M_\odot$ $M_{eje} \simeq 0.014\, M_\odot$ $M_{eje} \simeq 0.08\, M_\odot$ $M_{eje} \simeq 0.1\, M_\odot$

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

R-process universality: SFHo   BHB Λ_ϕ DD2

Kilonova in GW170817:   SFHo   BHB Λ_ϕ DD2

End-to-End modeling of GW170817

$$M_{\text{chirp}}^{\text{GW170817}} = 1.186 M_\odot, q = 0.8 - 1$$
$$M_{\text{eje}}^{\text{GW170817}} = 0.05 M_\odot$$
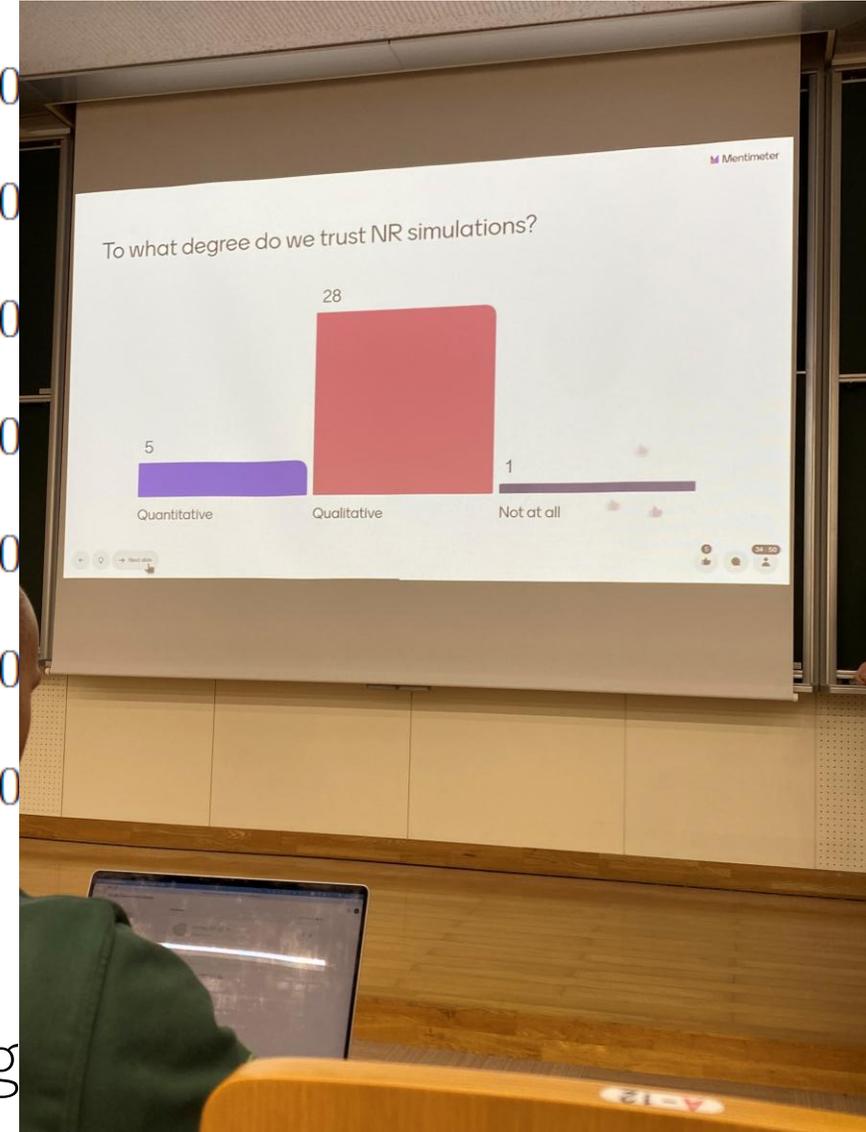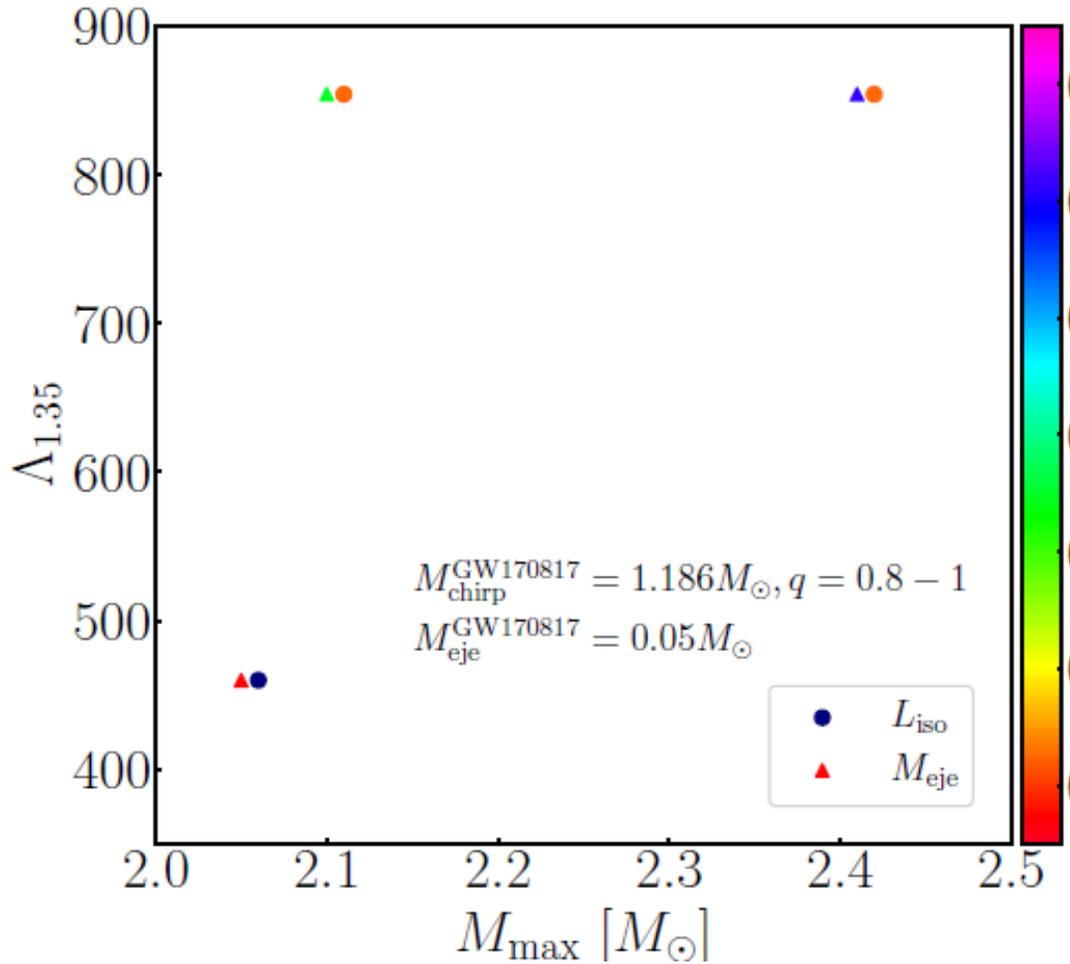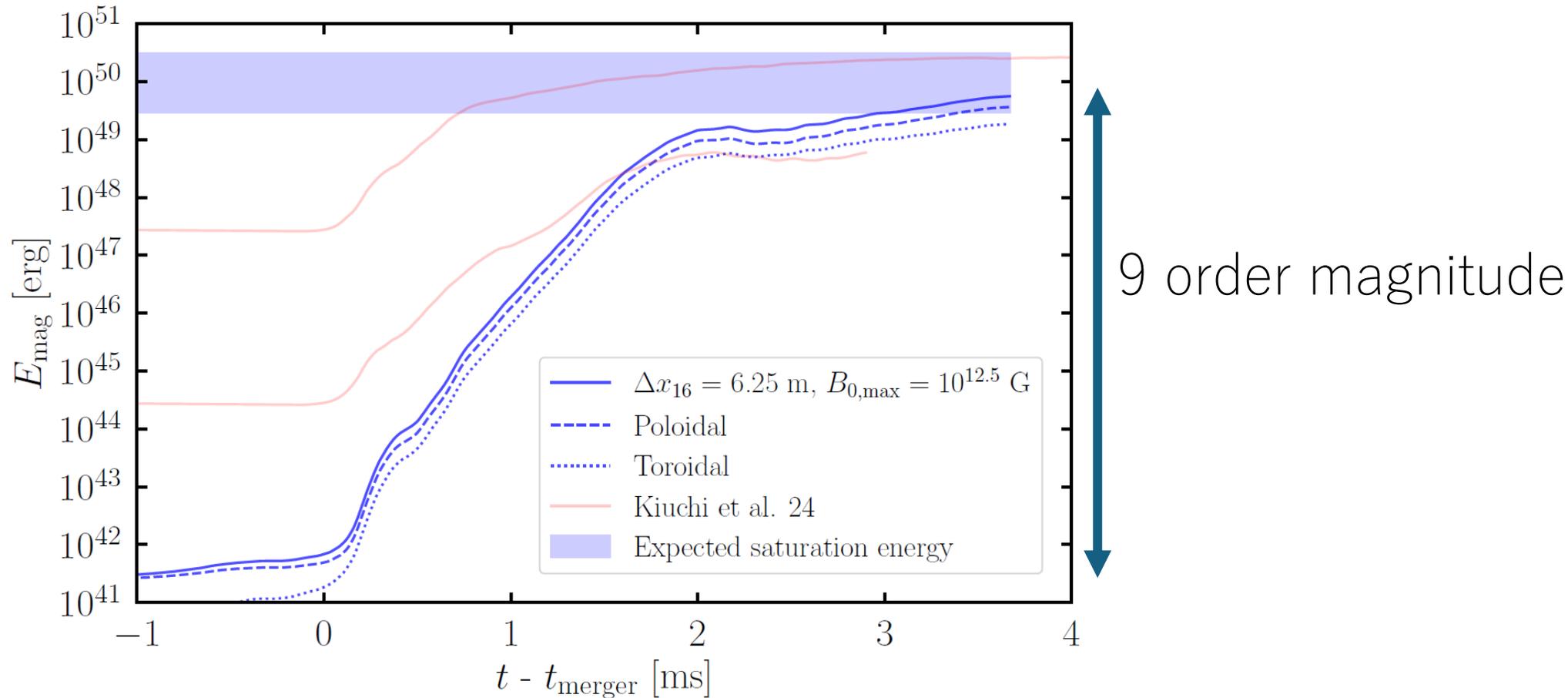
Nuclear EOS predicts a "blind" spot on this diag
Mass asymmetry? Jet-ejecta interaction? Different BNS merger types?

A prelude to magnetar formation in BNS

1.35-1.35M$_\odot$, DD2, Δx=6.25m, B$_{0,max}$ = 3x10^{12} G, 480M CH

9 order magnitude

At least, the EM energy reaches an expected saturation level (see also Gutiérrez et al. 26).
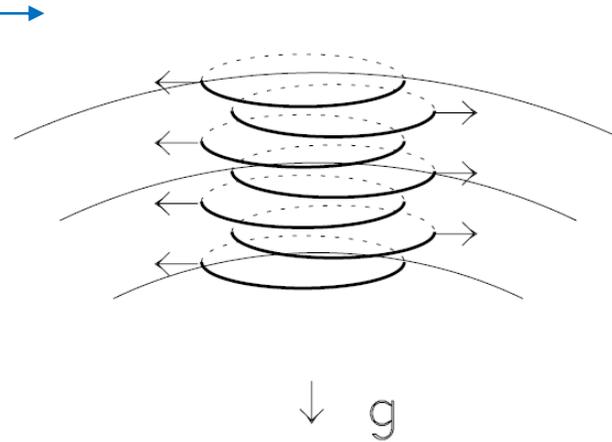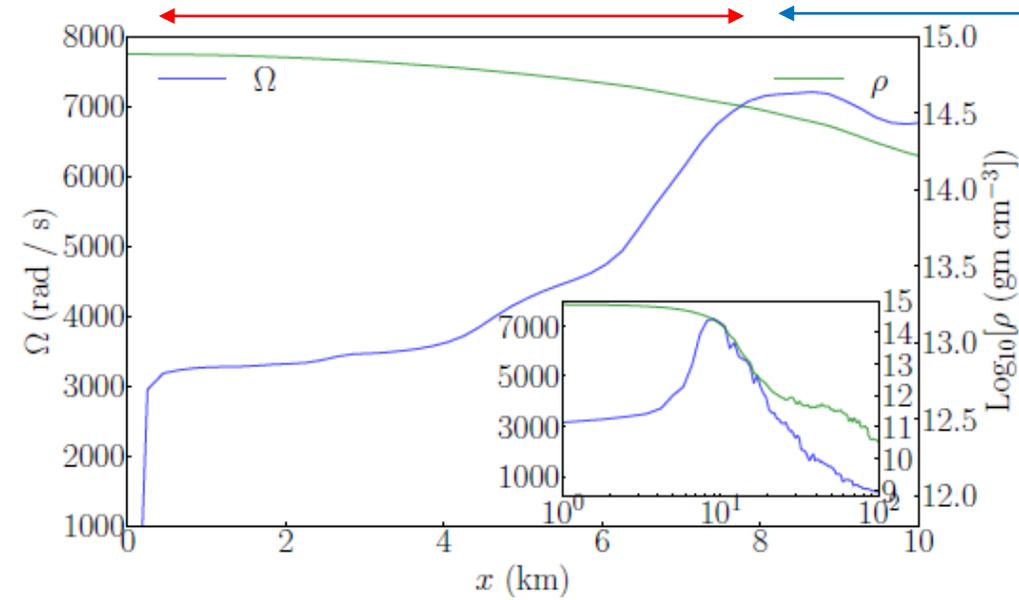
Another potential large-scale dynamo

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

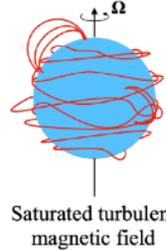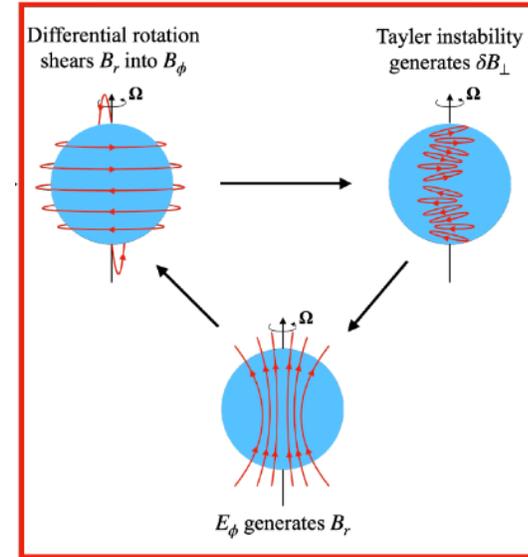$$\bar{\mathcal{E}} = \overline{\mathbf{u} \times \mathbf{b}}$$

MRI-inactive MRI-active

Spruit 98

Tayler-Spruit dynamo loop

Barrère et al. 25

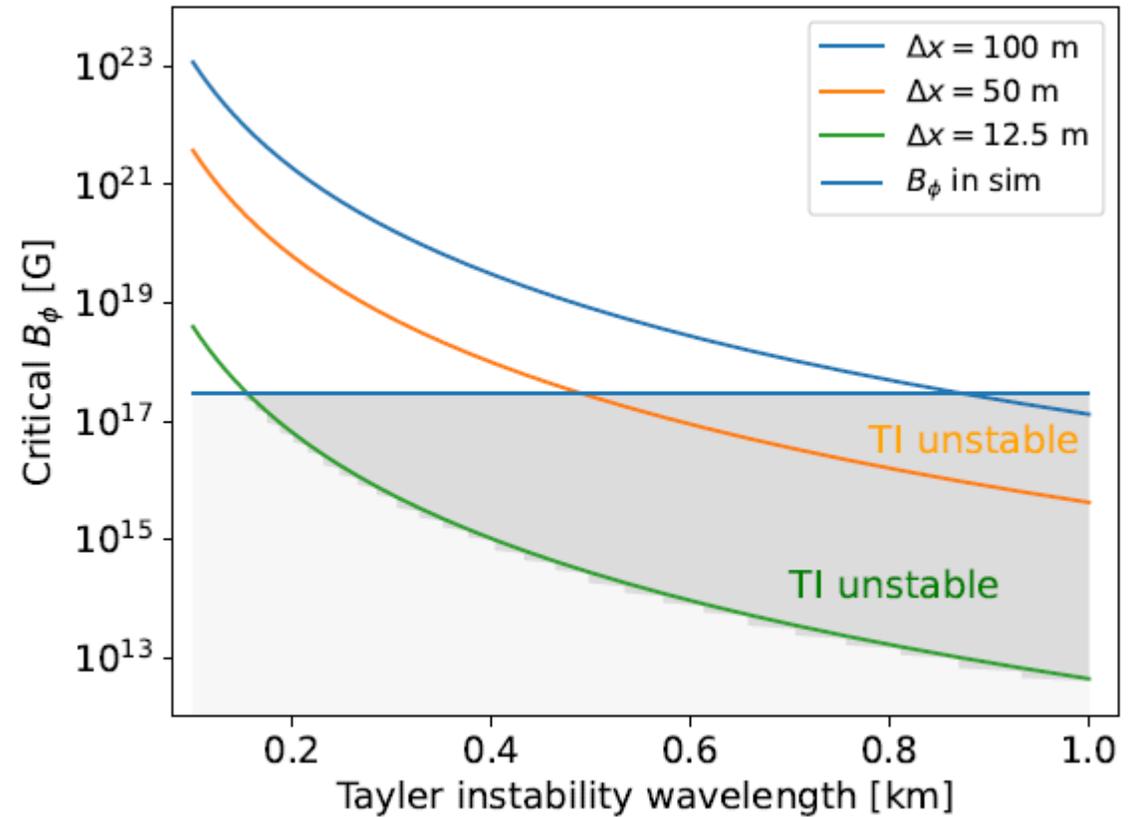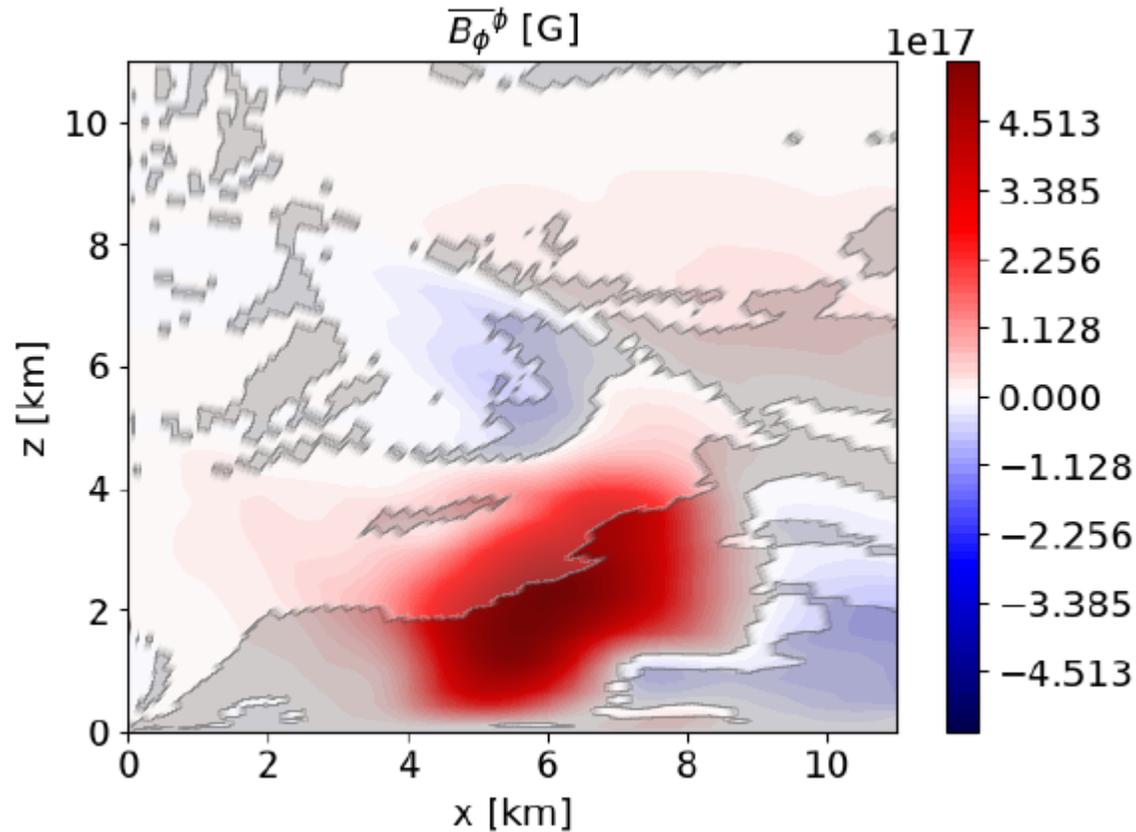▶ Deep inside (Outside) core is MRI-inactive (active) region
▶ Bulk EM energy is contained in the MRI-inactive region.

Tayler-Spruit dynamo could be the case in the core.

Tayler-Spruit dynamo in BNS (Reboul-Salze et al. 25)

▶ Solving the linear perturbation equation on top of the simulation data.
(gray: stable, white unstable)
▶ Numerical viscosity alters the critical strength of the instability
        Tayler-Spruit dynamo is the next challenge.

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, $L_{jet}^{iso} \sim 10^{52} erg/s$, $M_{eje} \approx 0.08 \, M_\odot \sim M_{eje}^{GW170817}$.

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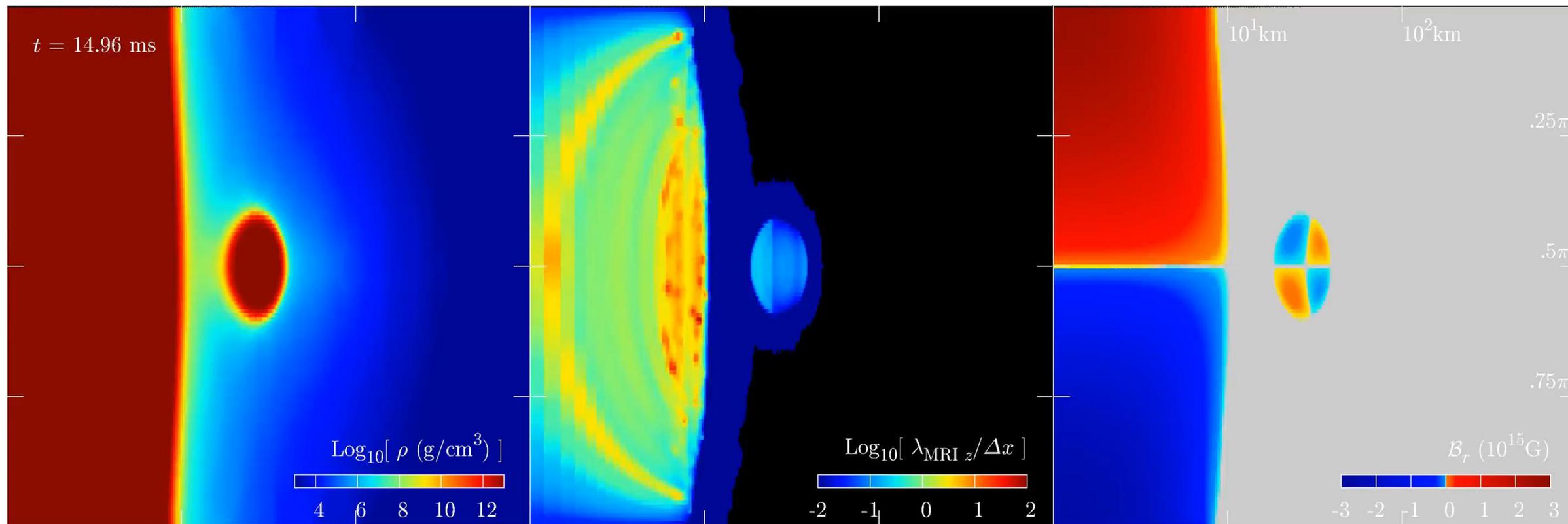
Mean B-field in MRI-active region
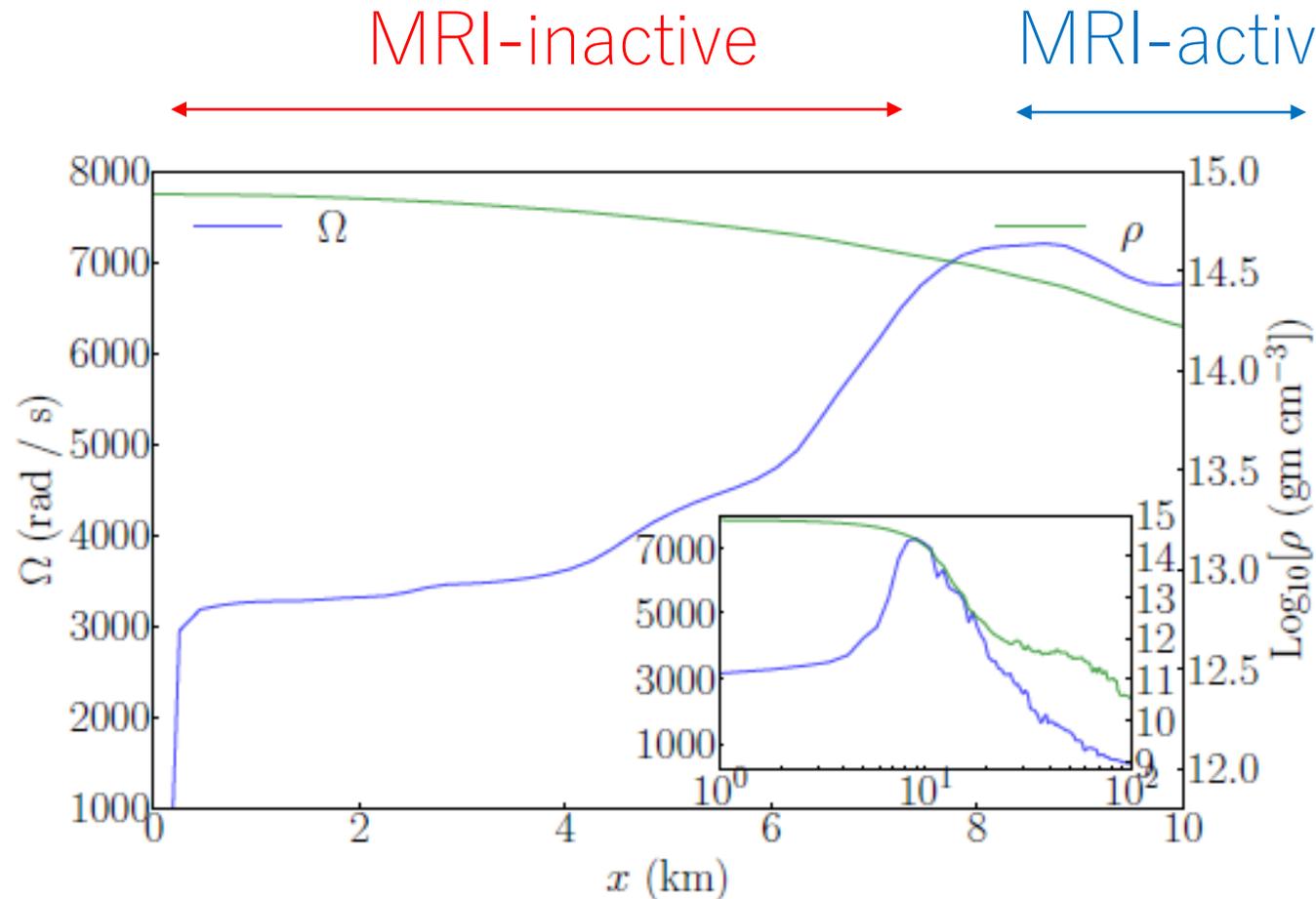
▶ Deep inside (Outside) core is MRI-inactive (active) region
▶ Bulk EM energy is contained in the MRI-inactive region.

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 $P_{BF} = 0.03\text{-}0.04$s

Electromagnetic emission in compact binary mergers

R(paid)-process nucleosynthesis and EM
(Lattimer & Schramm 74, Metzger et al. 10, Li & Paczynski 98)

Role of the r-process elements

▶ Heating source via radio-active decay (Kasen et al. 17)

$$\dot{\epsilon} \approx 10^{10} \text{ erg s}^{-1} \text{ g}^{-1} \left(\frac{t}{\text{day}}\right)^{-1.3}$$

▶ Opacity source (Lanthanide elements)
(Barnes & Kasen 13, Tanaka & Hotokezaka 13)
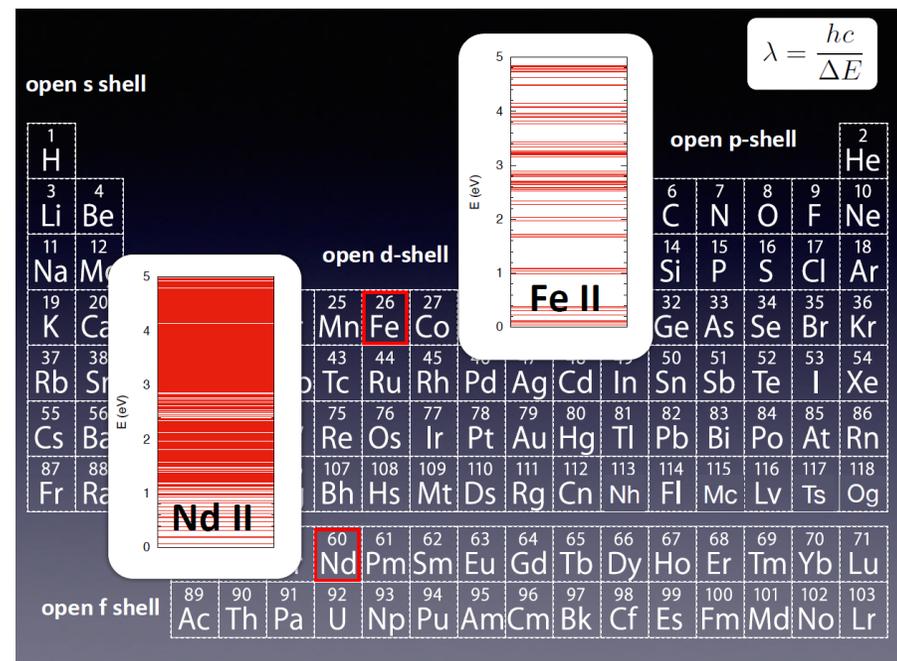
$$\kappa \approx 10 \text{ cm}^2 \text{ g}^{-1}$$

Slide courtesy of M. Tanaka

Properties of electromagnetic emission (Optical-IR)

▶ Peak time (diffusion time = dynamical time)

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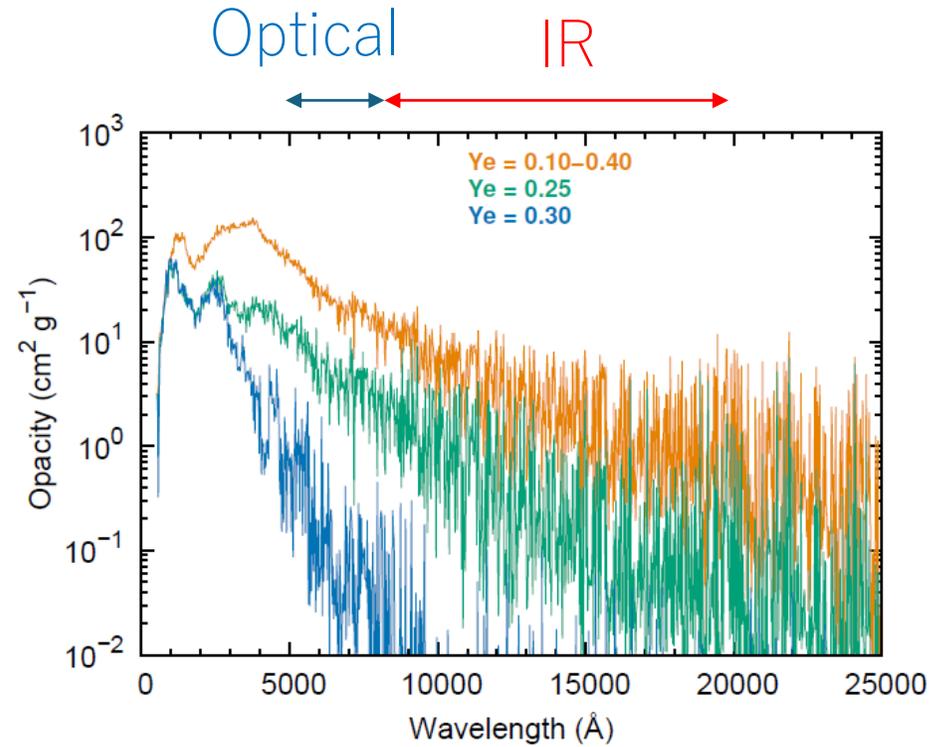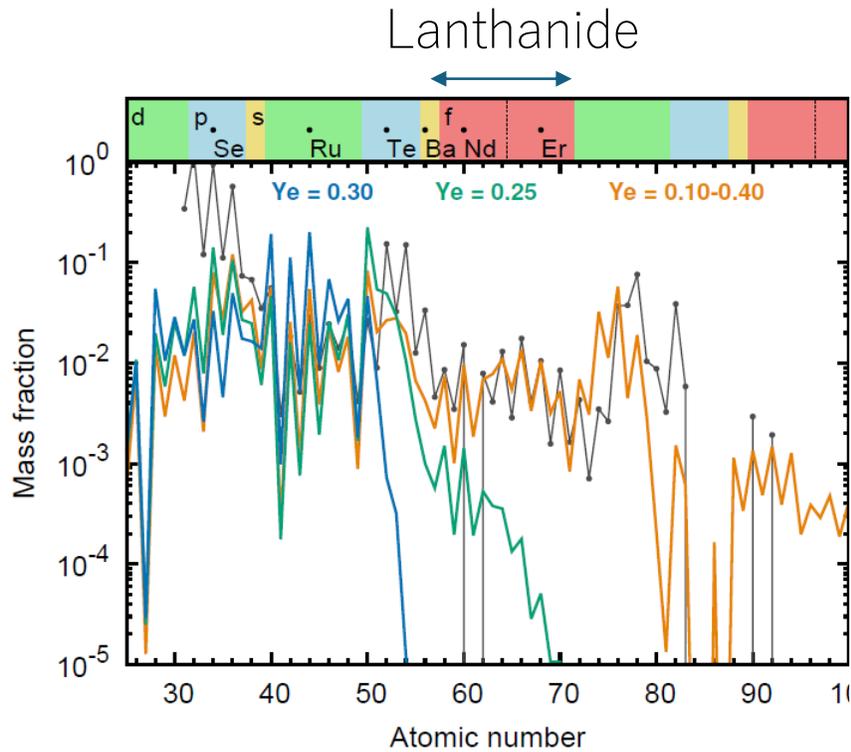
▶ Peak Luminosity

$$L \approx \dot{\epsilon} M_{\text{ej}} \approx 6 \times 10^{41} \text{ erg s}^{-1} \left(\frac{M_{\text{eje}}}{0.03 M_\odot}\right) \left(\frac{t}{\text{day}}\right)^{-1.3}$$
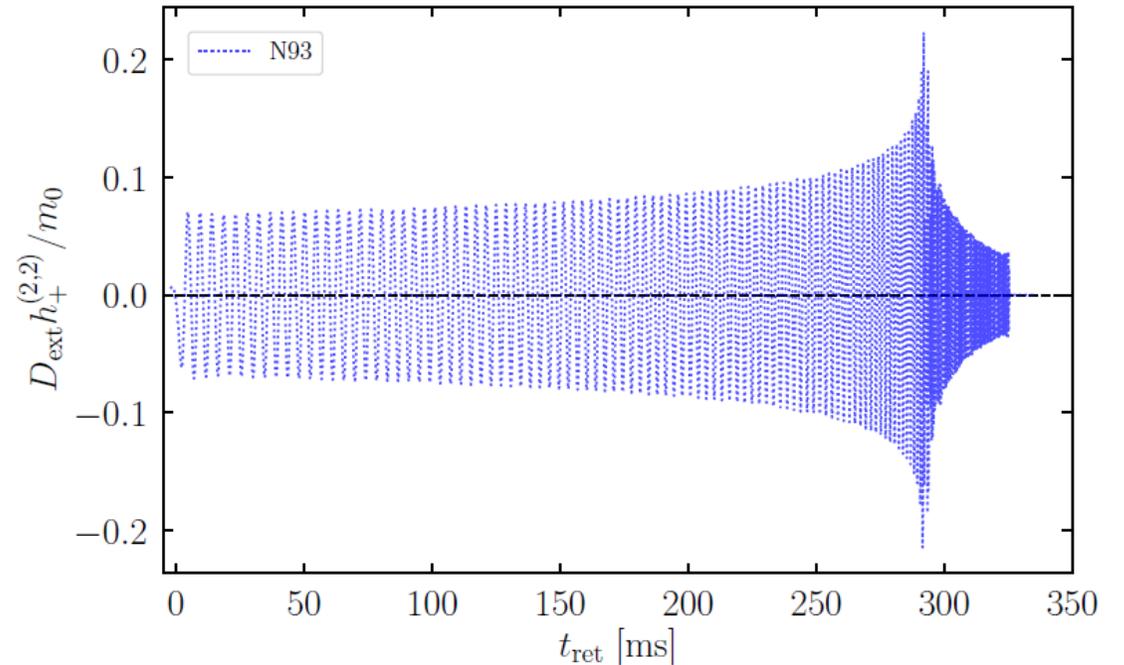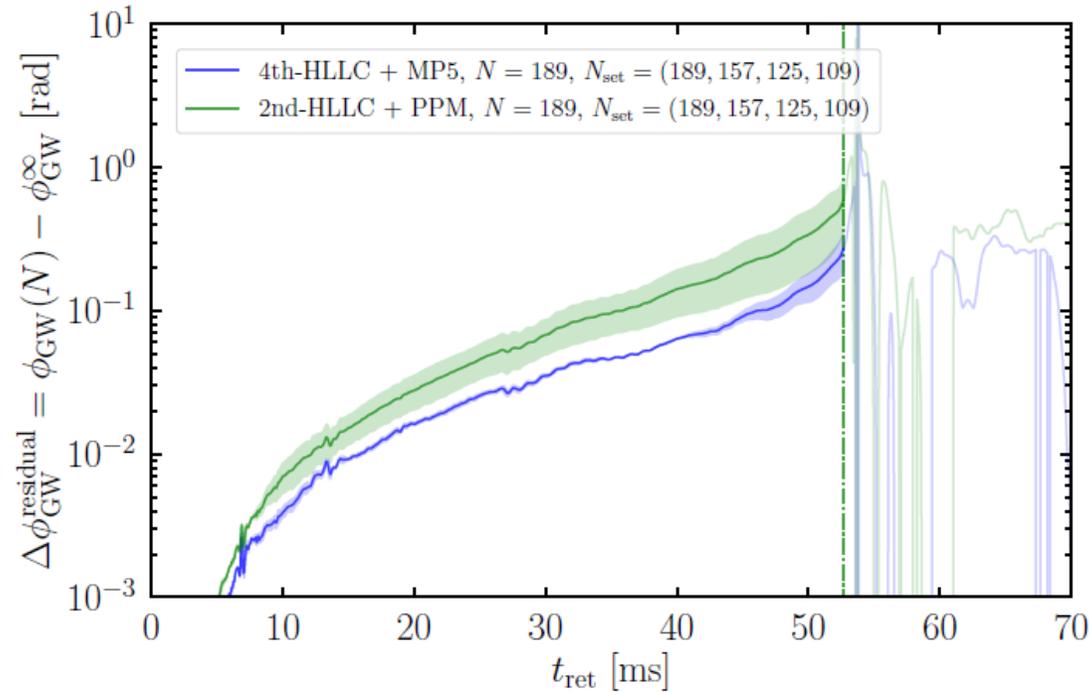
R-process nucleosynthesis and its opacity

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

Super long-term BNS inspiral simulation (KK 25)

Residual phase error

▶ Fourth-order accurate finite volume Riemann solver (KK 25)

▶ $\delta\phi_{error} = 0.27 \pm 0.07\ rad$ (*new solver*) *vs* $\delta\phi_{error} = 0.58 \pm 0.22\ rad$ (*old solver*)

▶ $\approx$100 GW cycles

Black Hole - Neutron Star mergers
Key ingredients for tidal disruption in BH-NS

Tidal force > NS self gravity $\Rightarrow$ r $\lesssim$ $(M_{BH}/M_{NS})^{-2/3} (M_{NS}/R_{NS})^{-1} M_{BH} \equiv r_{tidal}$

If $r_{tidal} > r_{isco} \Rightarrow$ Tidal disruption
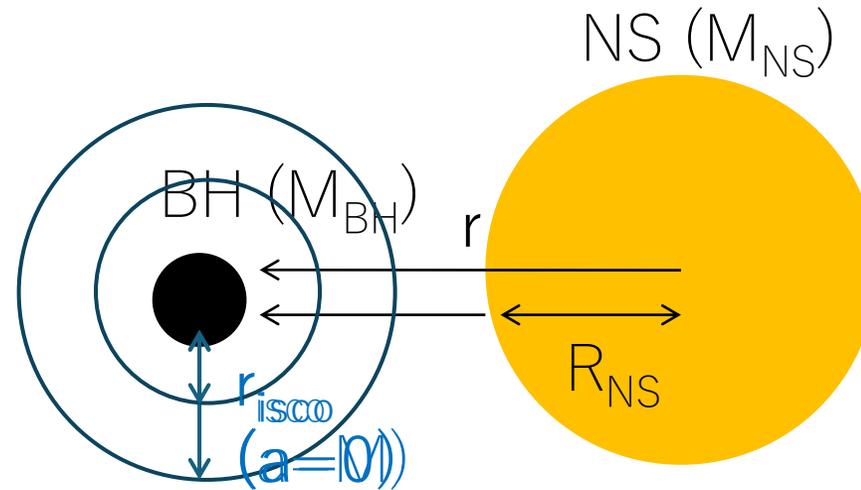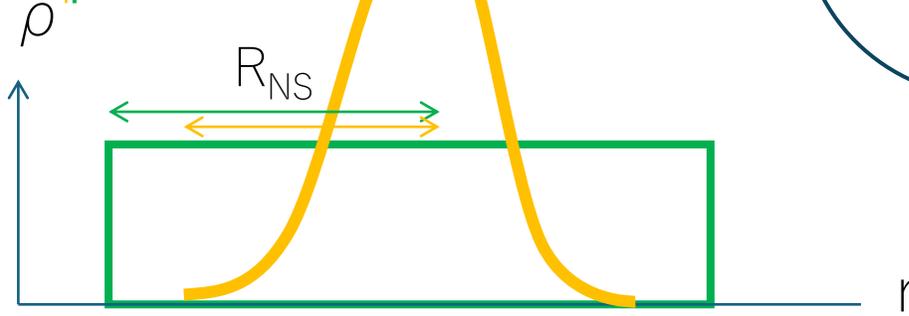
$\quad r_{tidal} < r_{isco} \Rightarrow$ No tidal disruption

*ISCO = Inner Stable Circular Orbit

Key ingredients of the mass ejection in BH-NS are
▶ Spin of BH
▶ Mass ratio (M_{BH}/M_{NS})
▶ Compactness of NS (M_{NS}/R_{NS})

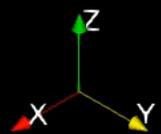NS (M_{NS})

BH (M_{BH})

r

r_{isco}

$(a=0)$
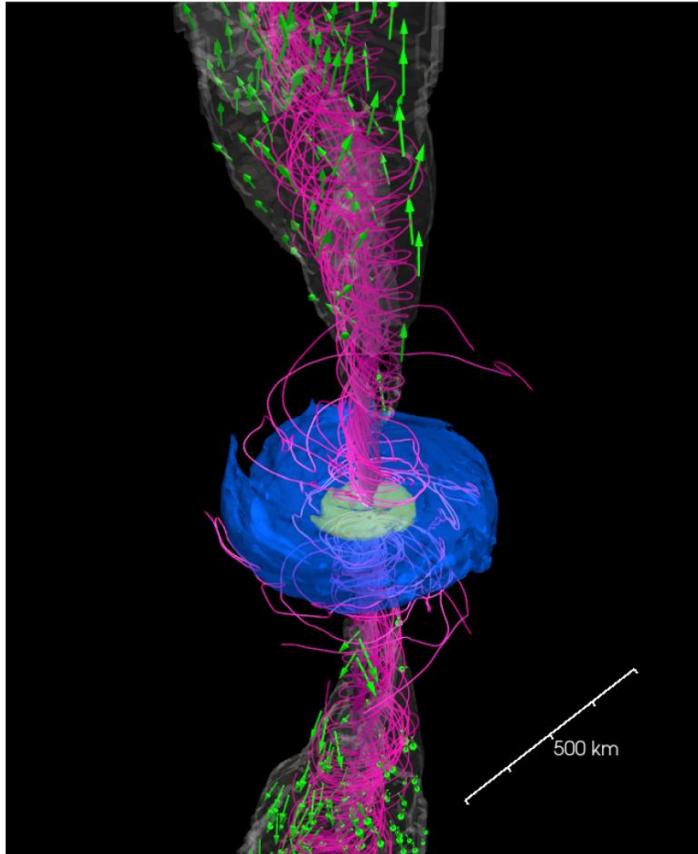
R_{NS}

Stiff EOS = small
Compactness

ρ

R_{NS}

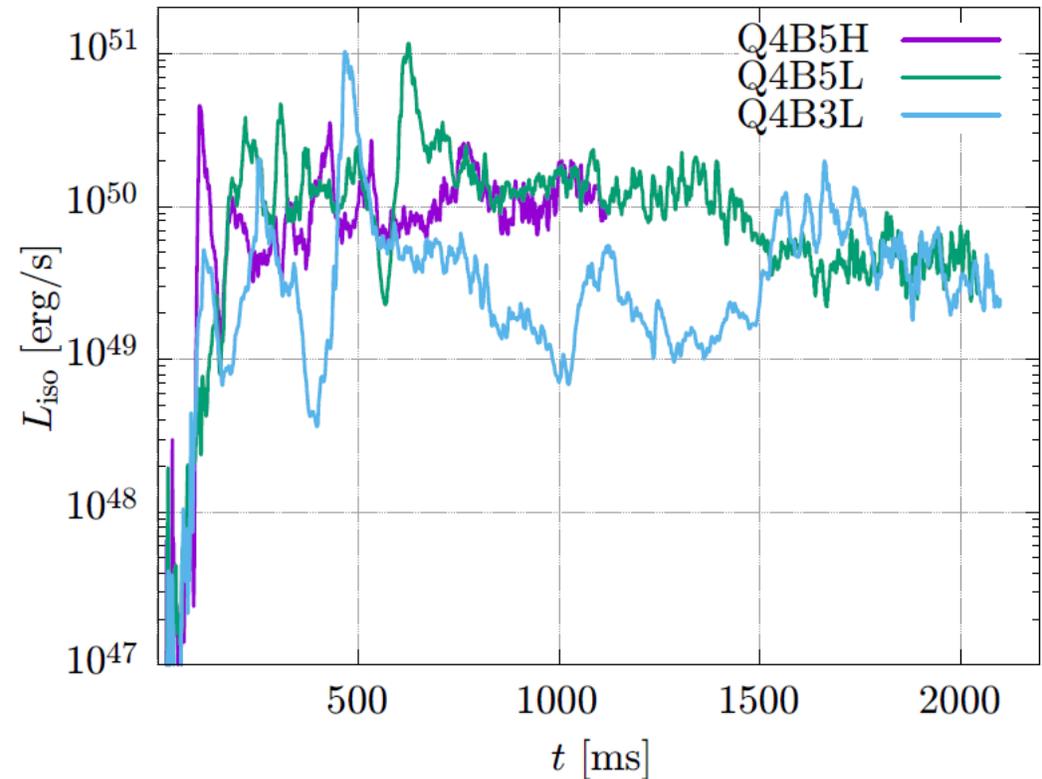Ab initio simulation of BH-NS (K. Hayashi, KK et al. 22,23)
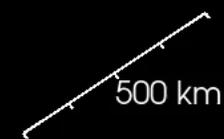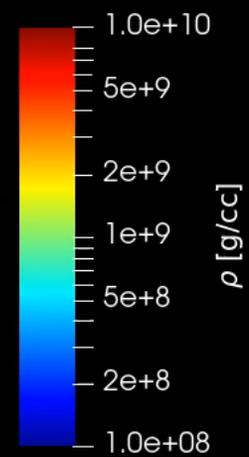
Numerical modeling of BH-NS merger

Magnetically tower "jet"

Isotropic Poynting Luminosity

▶Magnetically tower "jet" builds up magnetosphere
⇒L_{iso} and θ_{jet} are roughly consistent with the observed values.