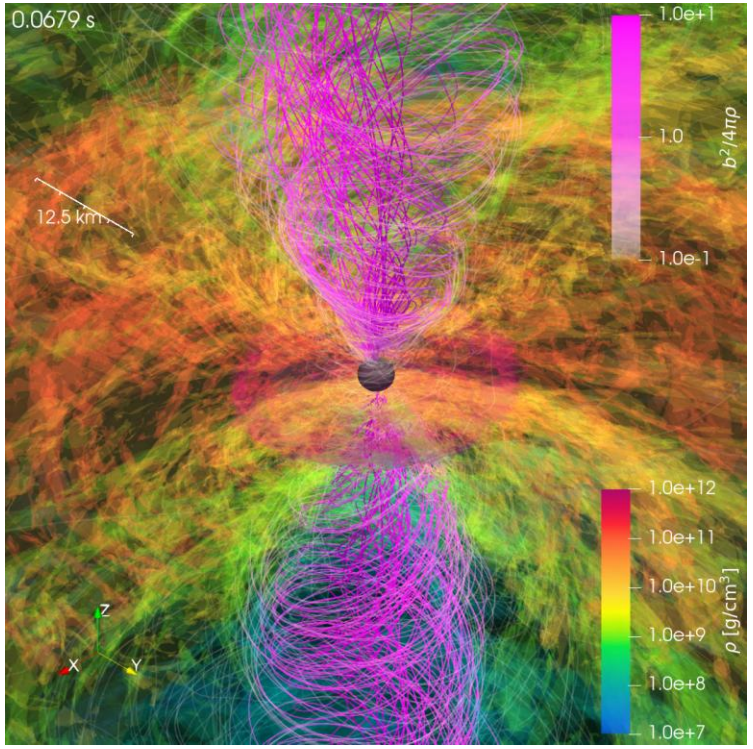
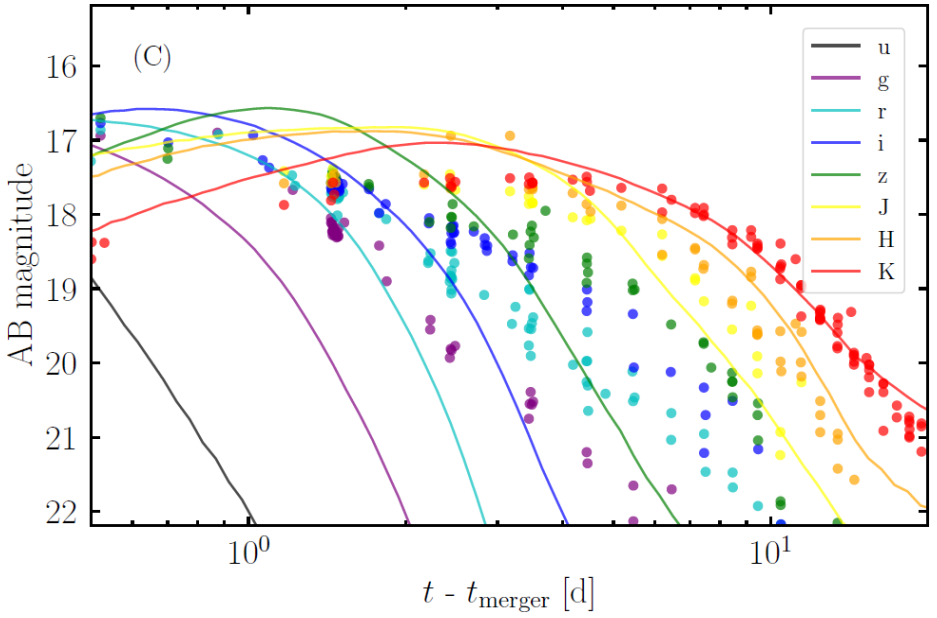
A first-principles binary neutron star model for GW170817, GRB2170817A, and AT2017gfo





KK et al. 26 in submission

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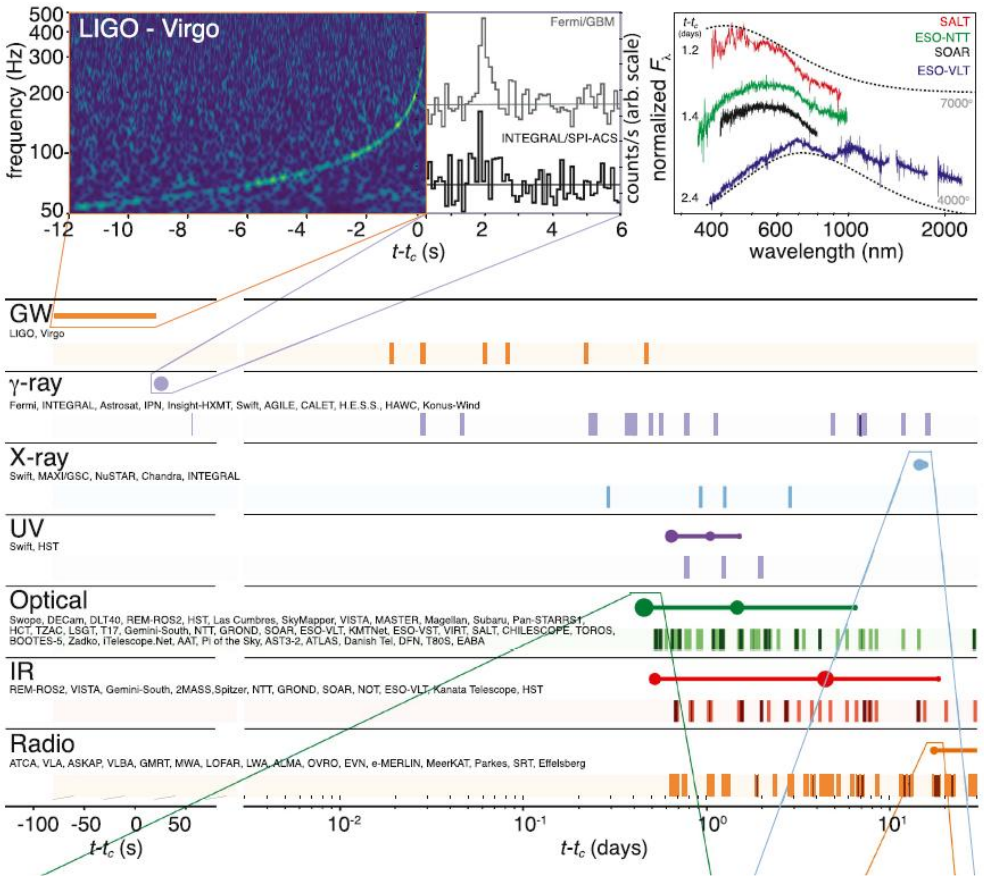
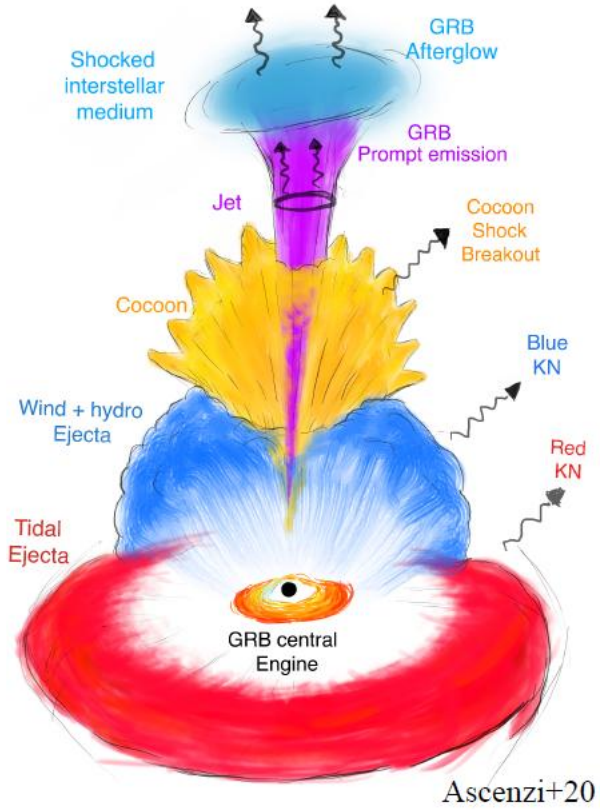
Introduction

Reality



Imagination



There is no self-consistent model to explain it.

We as numerical relativists must explain

▶SGRB (+Afterglow observations)

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

at least qualitatively, and quantitatively at the best.

End-to-End BNS model

NR simulation

(GR+EOS+ ν -Rad.+MHD)

⇩

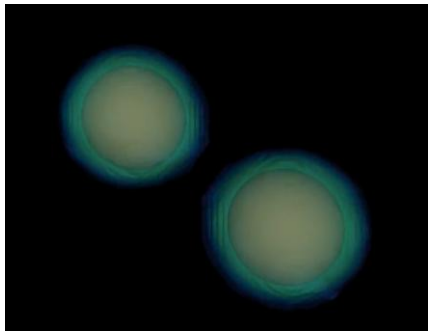
R-process nucleosynthesis calculation

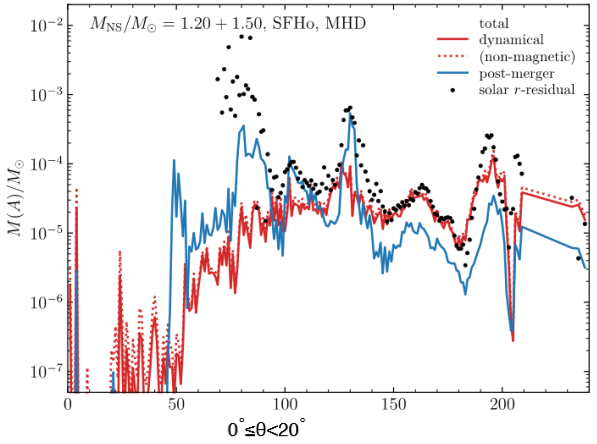
⇩

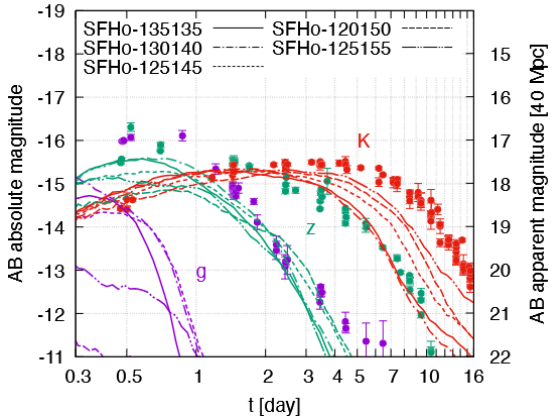
Kilonova/GRB light curve modeling

⇩

Observation





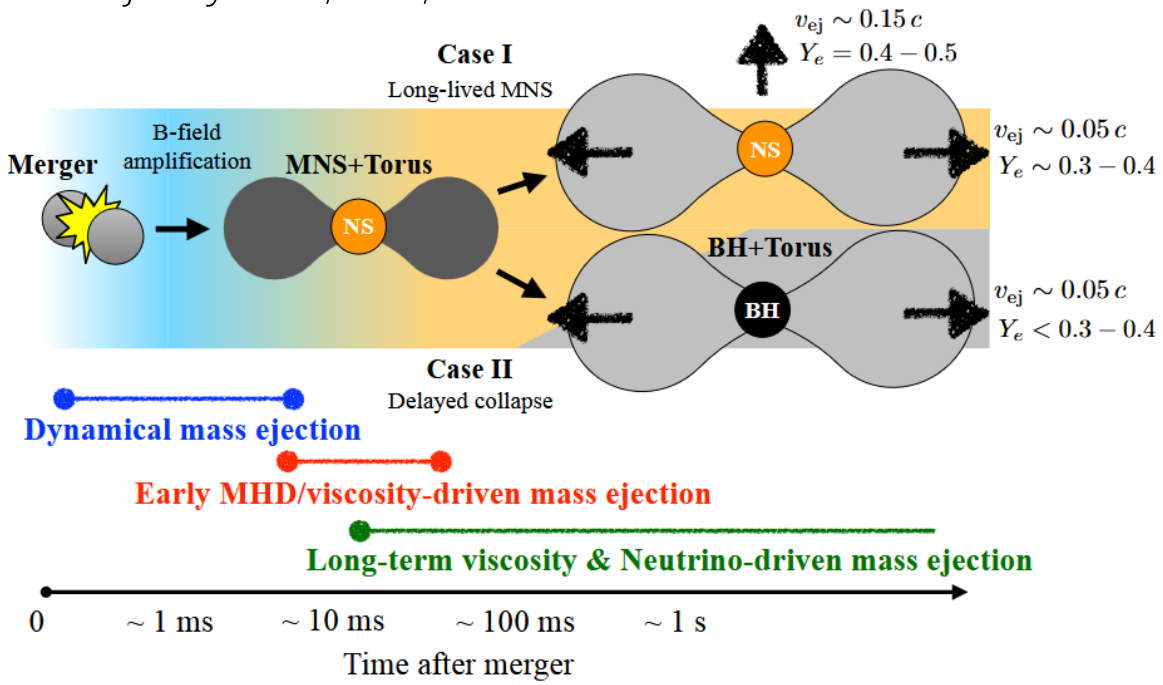


Sys. Err.

- ▶ Resolution
- ▶ Approx. GR
- ▶ Approx. ν -Rad
- ▶ MHD approx.
- …
- ▶Reaction rate
- ▶Mass model
- …
- ▶Photon rad. transfer
- …

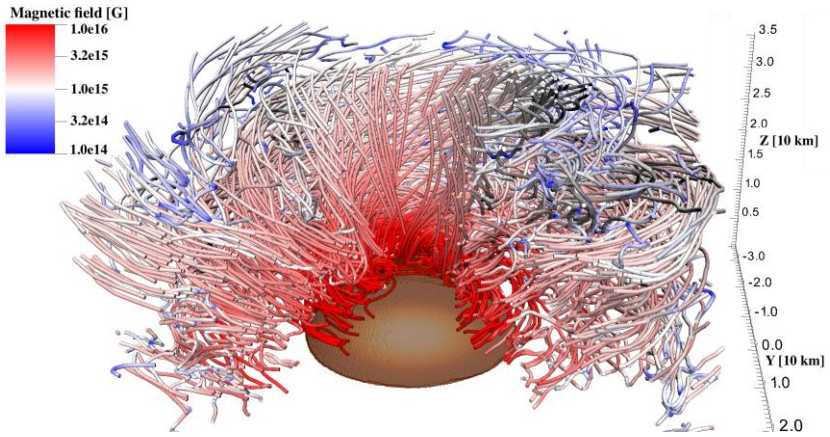
Necessary for large-scale B-field

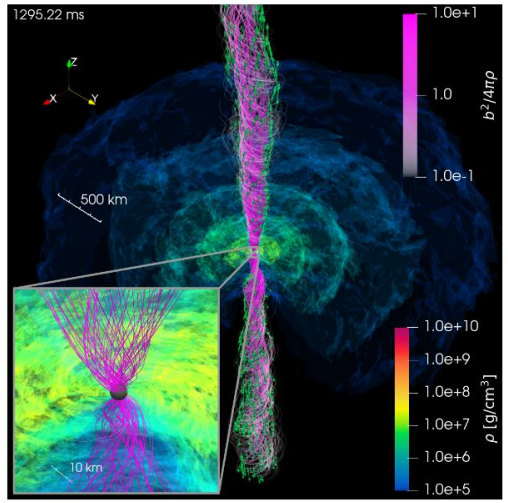
S. Fujibayashi, KK, et al. 18



Hotokezaka et al. 13, Fujibayashi 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 (critical) missing mass ejection channel = Lorentz force-driven ejecta (Mösta et al. 20, Combi & Siegel 23, KK et al. 24, 26, Most 23)





Either the magnetar or the Blandford-Znajek mechanism requires a large-scale field for jet launching. (KK et al. 24, Hayashi, KK et al. 25)

From small- to large-scale B-field

Mean field dynamo theory

$\partial_t \bar{B}^i = \nabla \times (\bar{V} \times \bar{B} + \bar{E})^i, \bar{E}^i = (\overline{v \times b})^i$

where $Q = \bar{Q} + q$ and $\vec{v}(\vec{b})$ notes the velocity (B-field) turbulence.

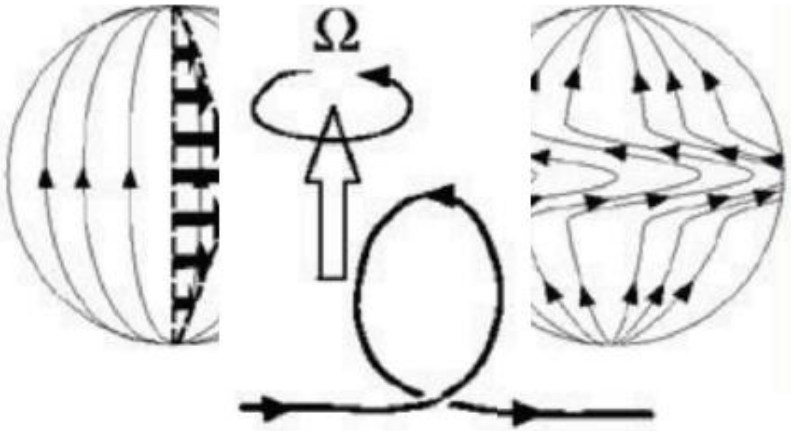
α Ω dynamo (Parker 55)

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

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

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

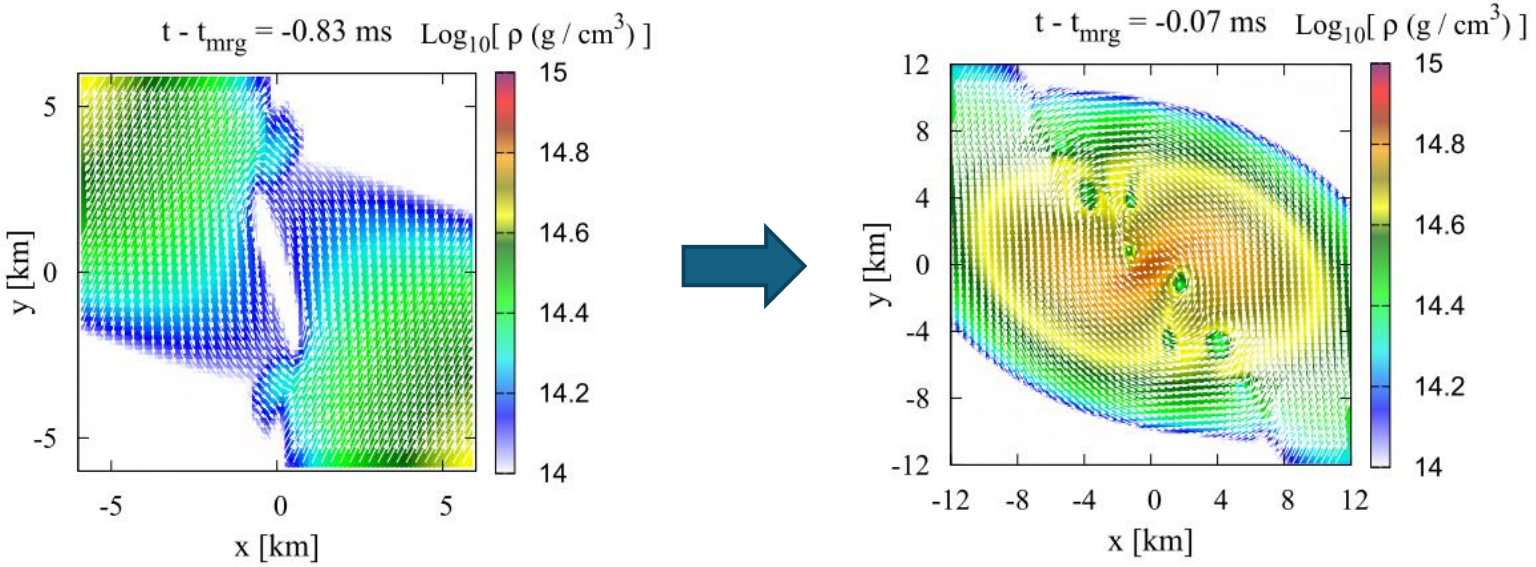
$$\partial_t \bar{B}_z = -\partial_R \mathcal{E}_\varphi \approx \partial_R \left(\alpha_{\varphi\varphi}\bar{B}_\varphi\right)$$



Kelvin-Helmholtz instability & Magneto Rotational Instability are responsible for generating the fluctuation $\vec{v}$ and $\vec{b}$.

Necessary high-resolution simulation

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



$$\sigma \propto k$$

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

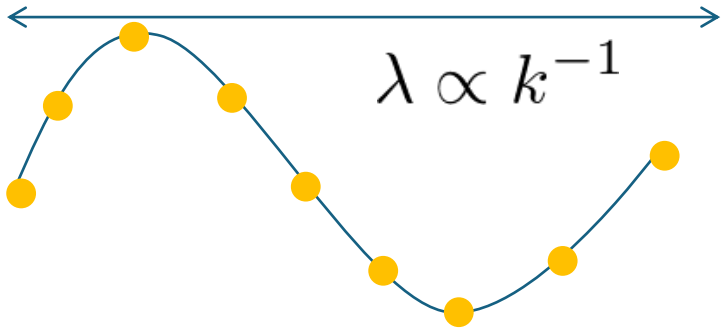
Magneto Rotational Instability (MRI) (Balbus & Hawley 91)

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

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

NANASI (No name in Japanese) description

- 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 aspects (see KK et al. 22)

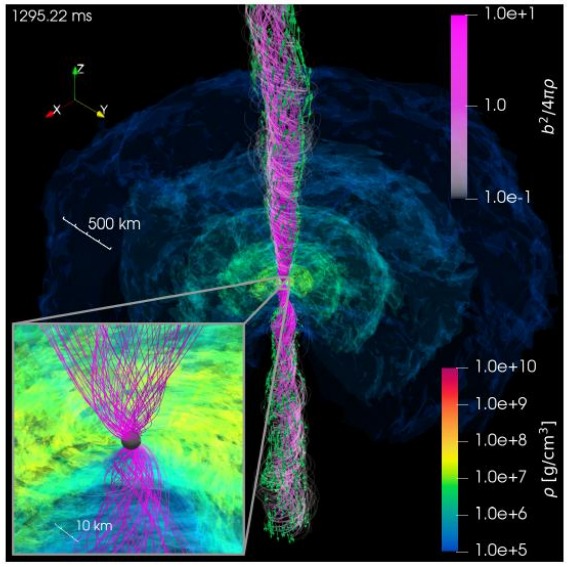
All the works, we quantify the ability of our simulation setup to resolve the KHI and MRI:

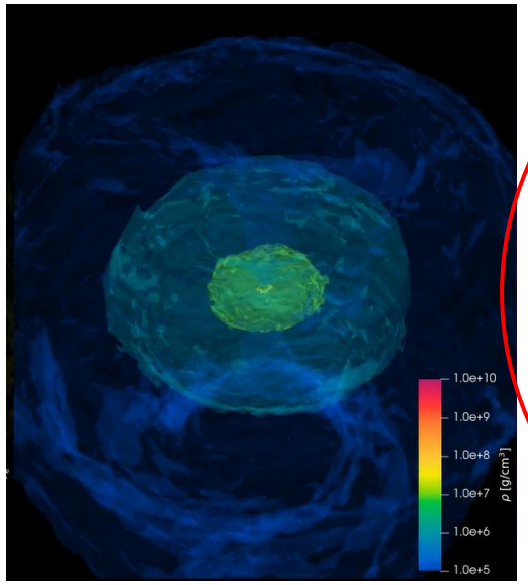
$$Q_{MRI} \equiv \frac{\lambda_{MRI}}{\Delta x} \geq 10$$

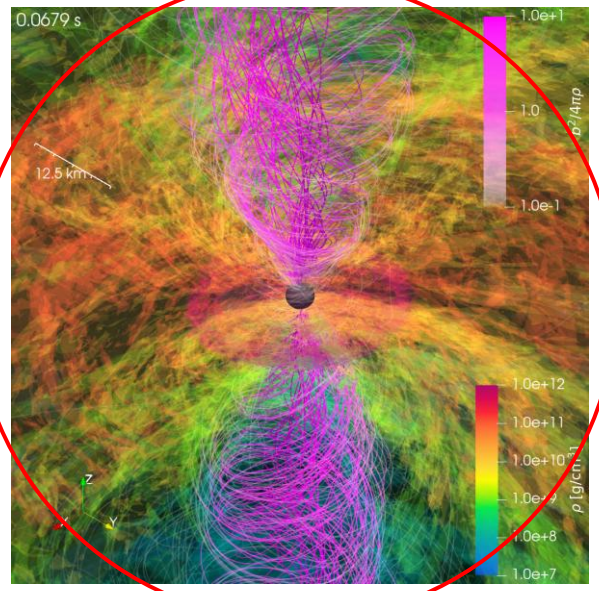
Inferring the EOS from ab initio simulations

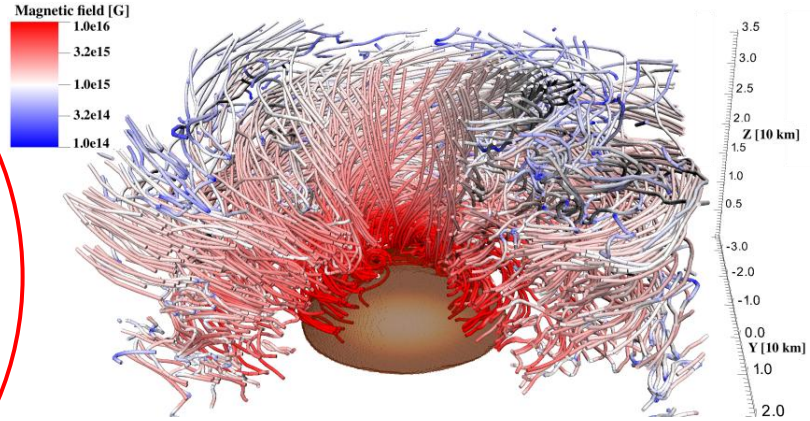
Lifetime of the remnant massive neutron star

Prompt ~ 0s | Short-lived ~O(0.01) s | Intermediate-lived ~O(0.1)s | Long-lived ~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 et al. 26

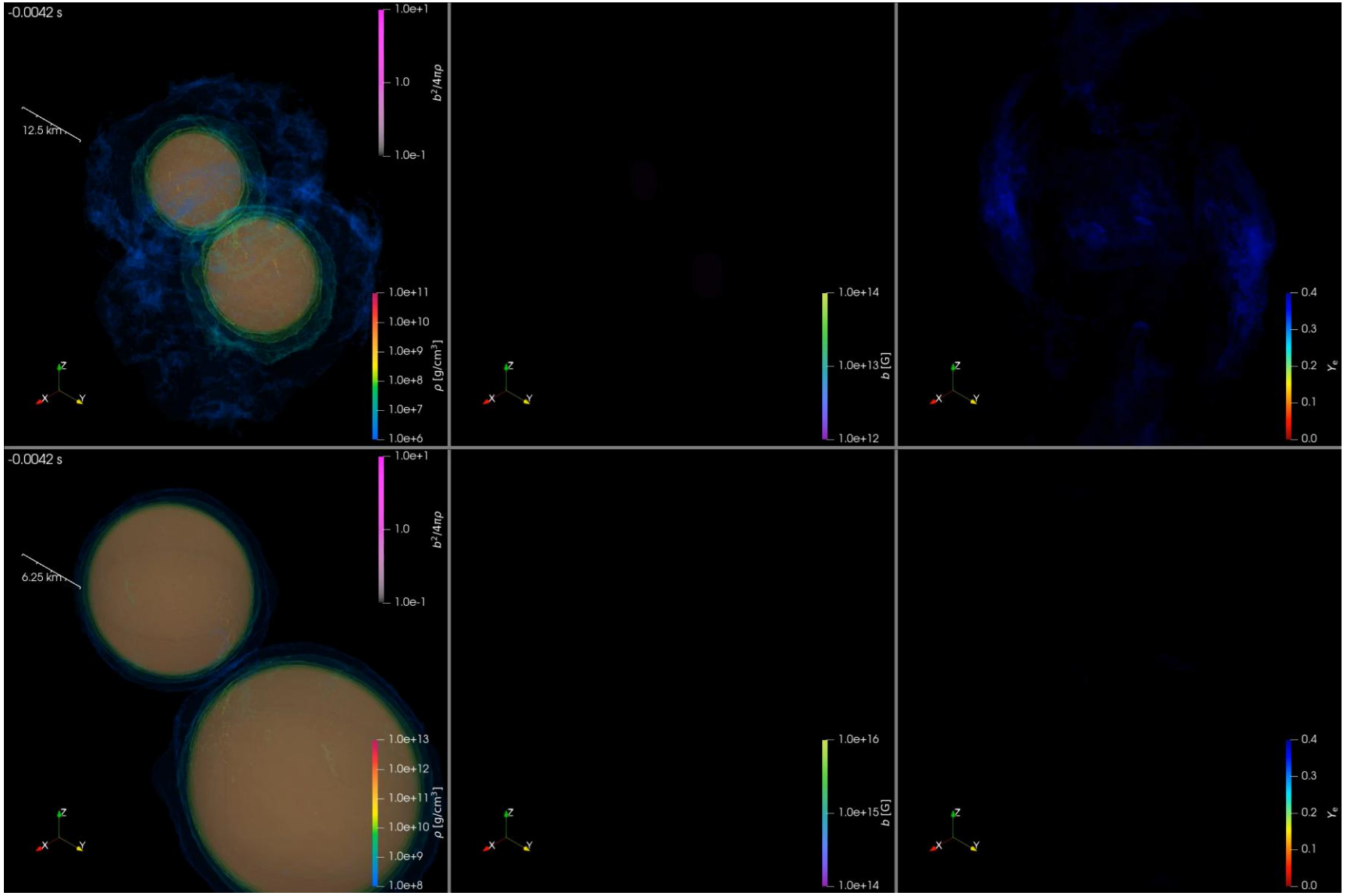
$L_{iso} \sim 10^{52}$erg/s
KK Nature Astro. 24 (see talk by Quentin)

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

Binary mass: Large ⟷ Small

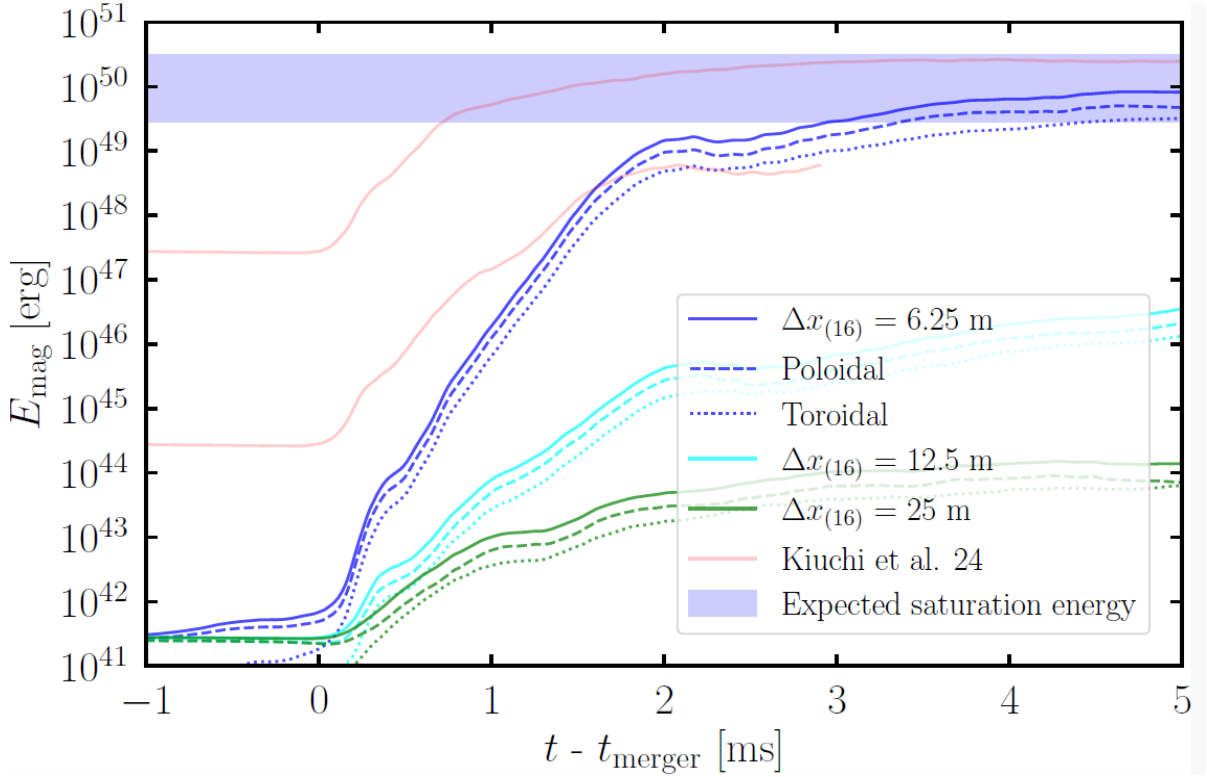
Episode I for “From small- to large-scale B-field”

1.35-1.35$M_\odot$, DD2, Δx=6.25m, $B_{0,max} = 3\times10^{12}$ G, 500M CH

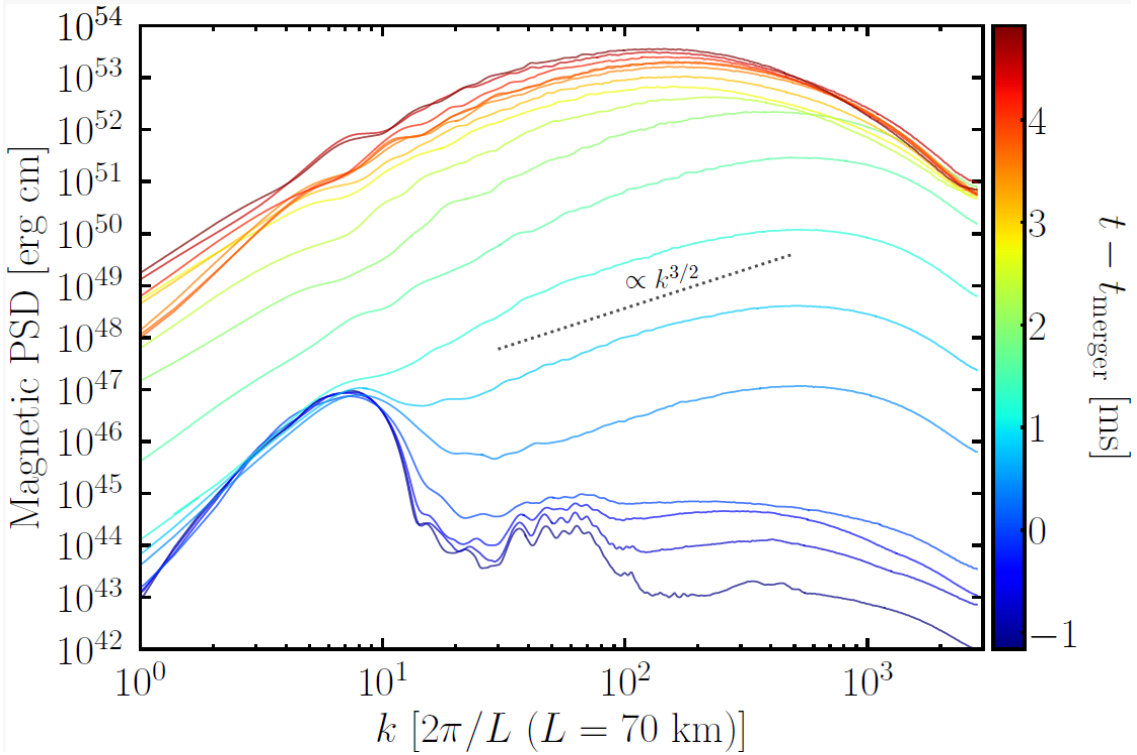


Episode I for “From small- to large-scale B-field” (KK et al. PRL in press)

EM energy



Magnetic PSD



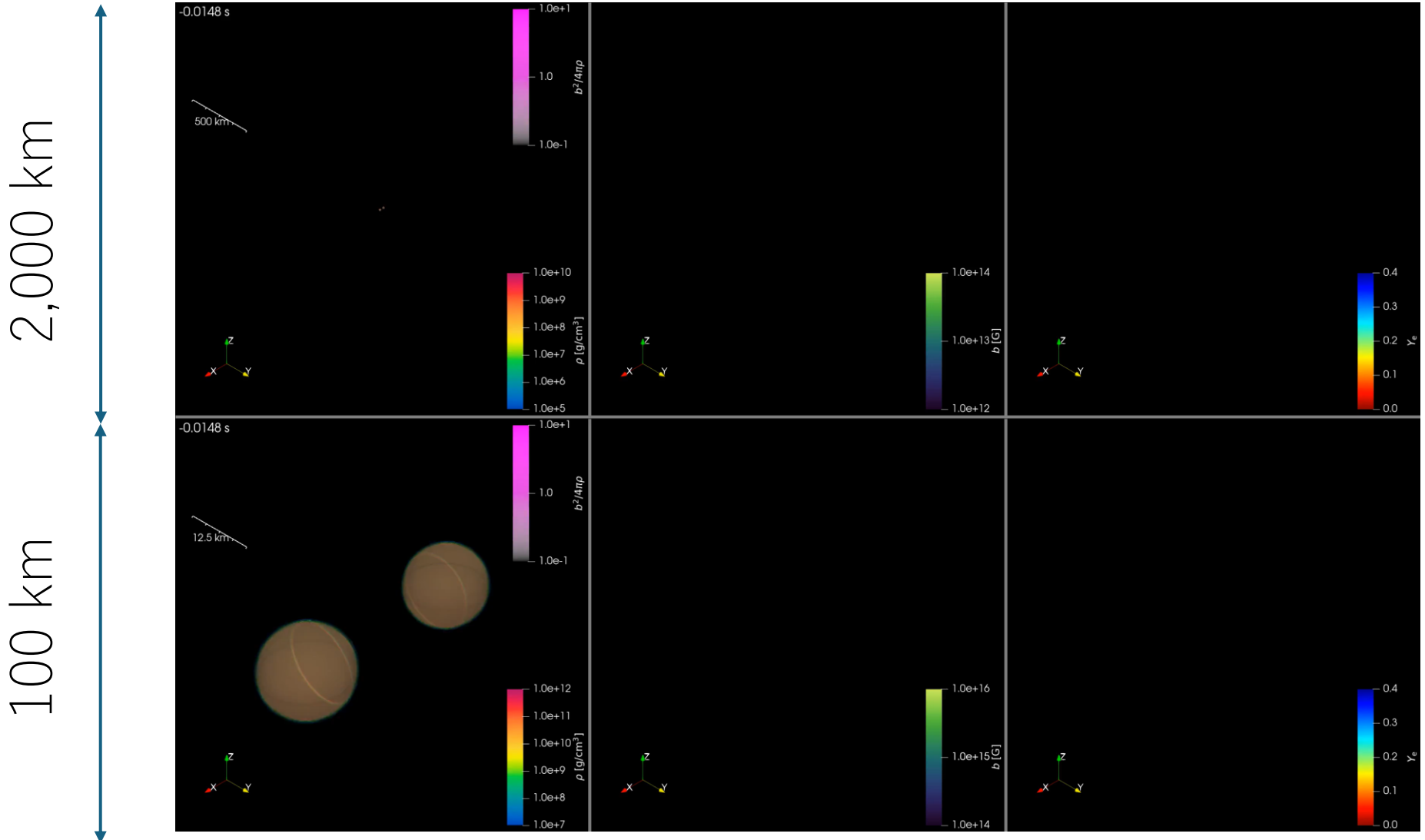
▶ Kinematic dynamo leads super-efficient B-field amplification (see also Gutiérrez et al. 26).

▶ Stellar-scale B-field strength is amplified (at least) up to $\approx 10^{15}$G (good news for global simulation people).

Episode II for “From small- to large-scale B-field” (KK et al. 26)

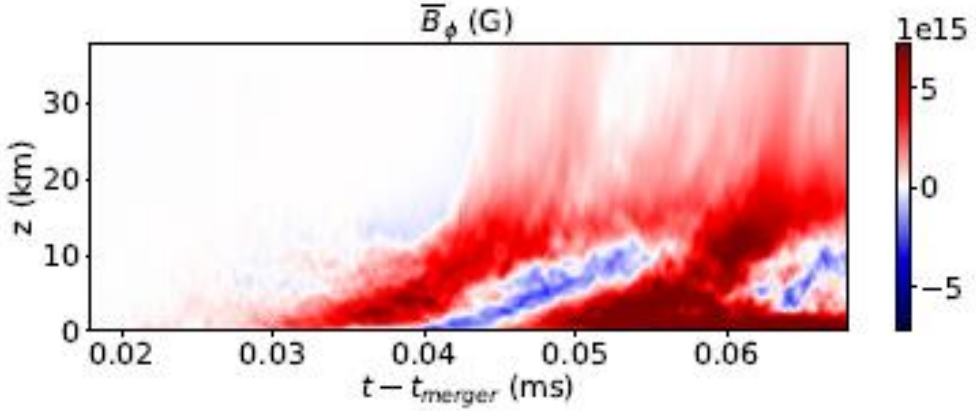
M_{chirp}=1.186$M_{\odot}$, BHB Λ_{ϕ}, Δx_{finest}=12.5m, 0.7 second, B_{max}=10^{15}G, 150M CH

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



Pinning down the $\alpha\Omega$ dynamo in BNS

Butterfly diagram



Theory vs simulation

R [km]	$\alpha_{\varphi\varphi}$ [10^6 cm s^{-1}]	k_z [10^{-6}cm^{-1}]	$d\Omega/d\ln R$ [s^{-1}]	$P_{\alpha\Omega}$ [s]	$P_{\rm BF}$ [s]
10	2.6 (1.4)	24 (26)	5359 (5397)	0.015 (0.02)	0.012 (0.02)
20	8.6 (6.2)	5.6 (5.9)	4911 (4534)	0.018 (0.027)	0.017 (0.024)
30	9.6 (3.8)	3.4 (3.4)	3505 (3326)	0.026 (0.043)	0.017 ($\geq$ 0.03)

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

▶ The most relevant prediction is

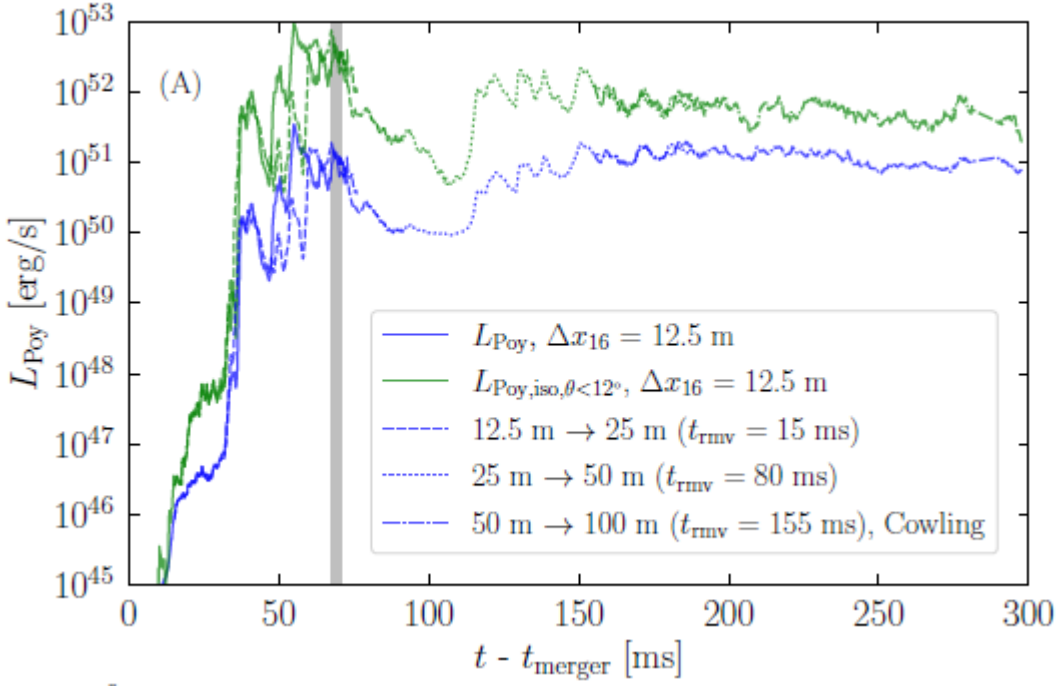
$$P_{\alpha\Omega} = 2\,\pi\left(\alpha_{\phi\phi}\, d\Omega/d\ln R\; k_z/2\right)^{-1/2}$$

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

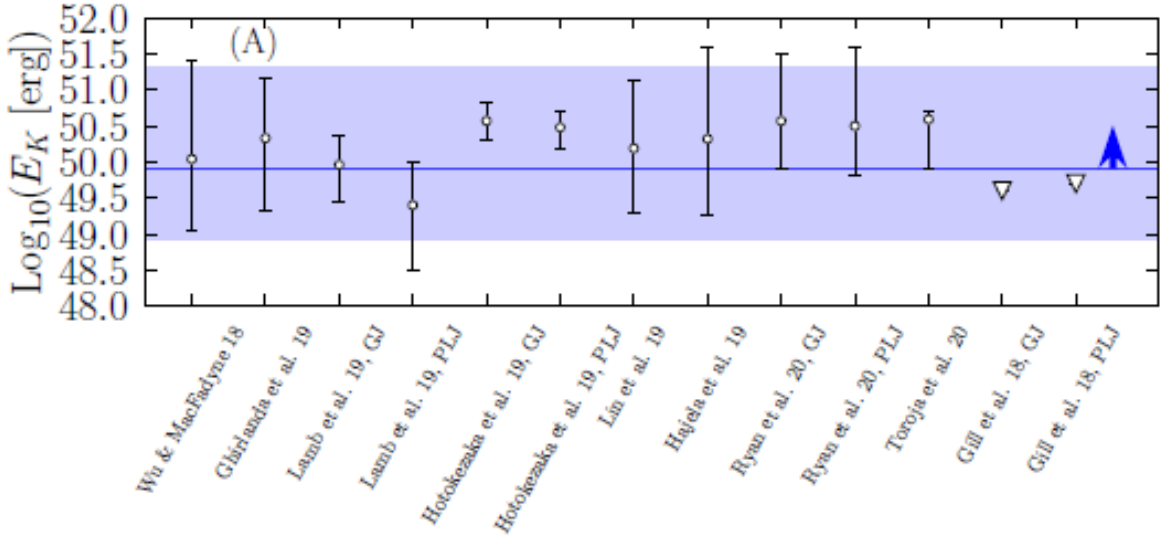
$$\partial_t \bar{B}_R = \partial_z \bar{\mathcal{E}}_\varphi \approx \partial_z(\alpha_{\varphi\varphi}\bar{B}_\varphi)$$

“Jet” from the intermediate-lived remnant formation

Poynting flux



Required jet kinetic energy (GW170817)

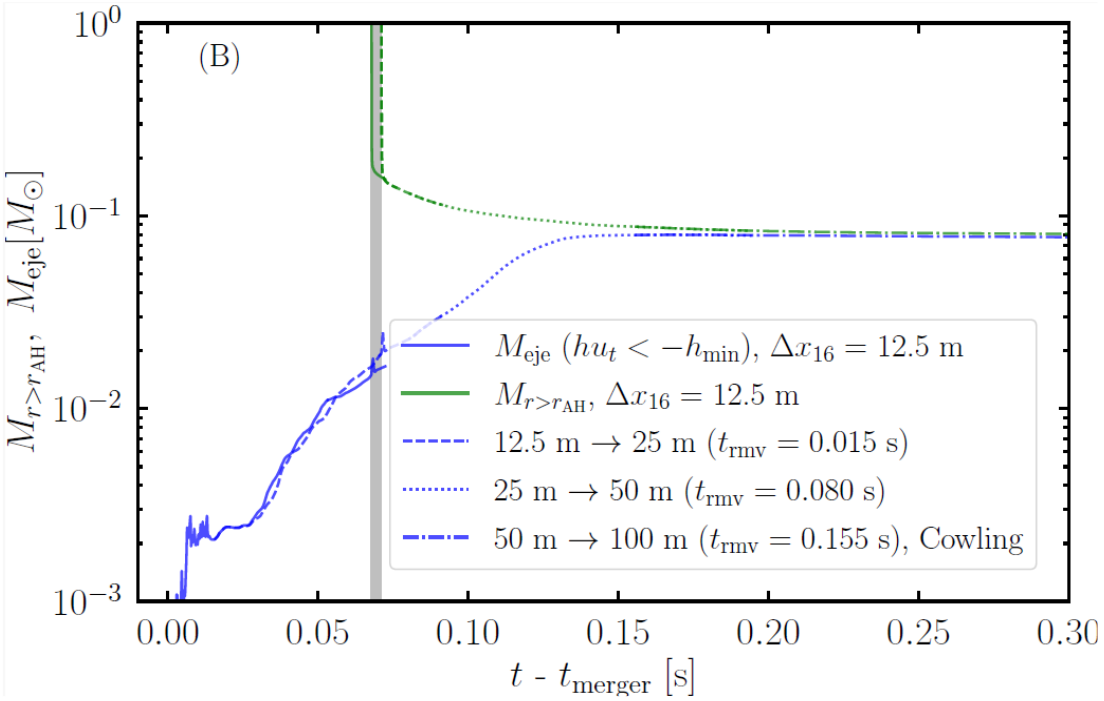


▶ $L_{jet}^{iso} \sim 10^{52} erg/s$ ⇒ If 1 second duration and 10% convergence efficiency are assumed, it is consistent with the required jet kinetic energy in GW170817 (see also Sadeh & Waxman 24).

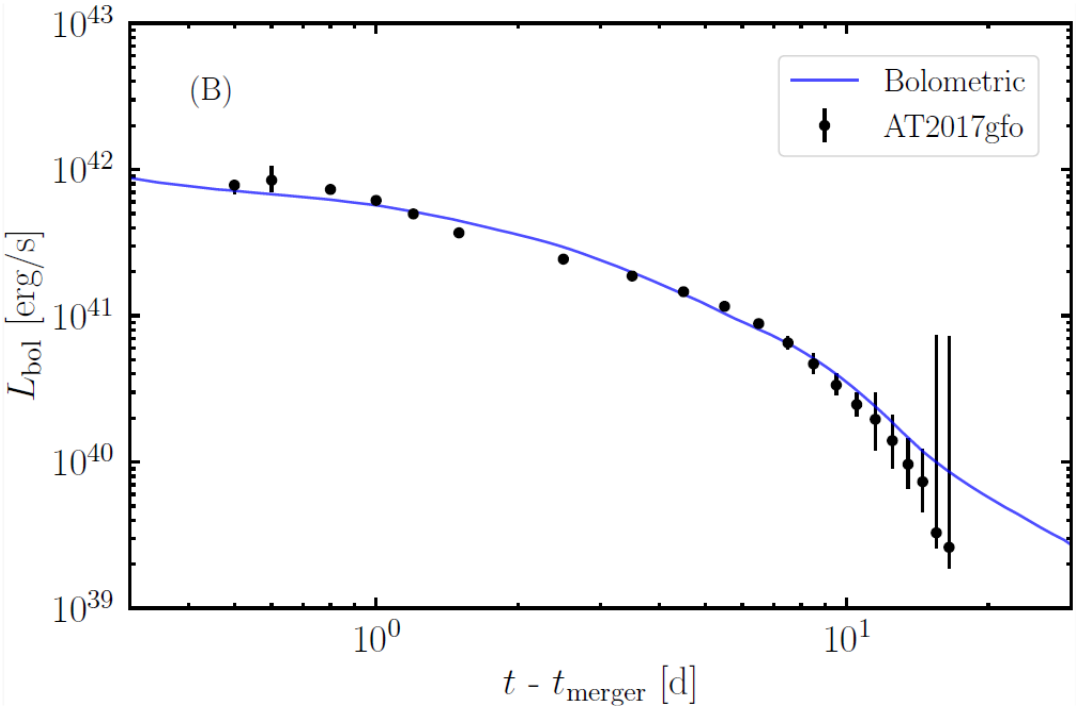
▶ $\Gamma_\infty \approx 30$

Kilonova light curve vs AT2017gfo

Ejecta mass evolution

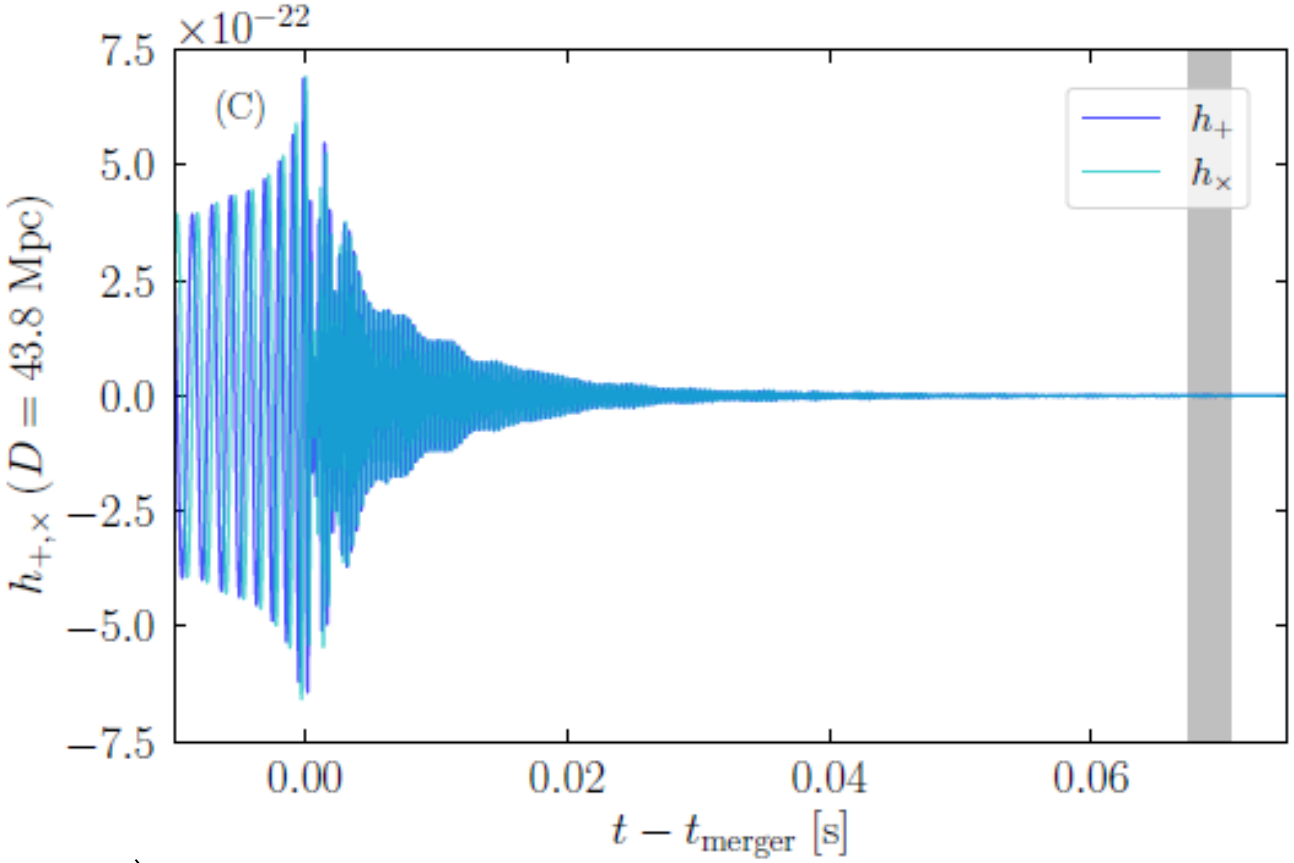


LC vs AT2017gfo



- $M_{eje,\ dyn}$ ≈2x10^{-3} $M_\odot$, $M_{eje,\ post}$(Lorentz-force-driven)≈ 8x10$^{-2}M_\odot$.
- Bolometric LC reproduces the AT2017gfo observation (see talk by Kyohei).

Post-merger GW signals



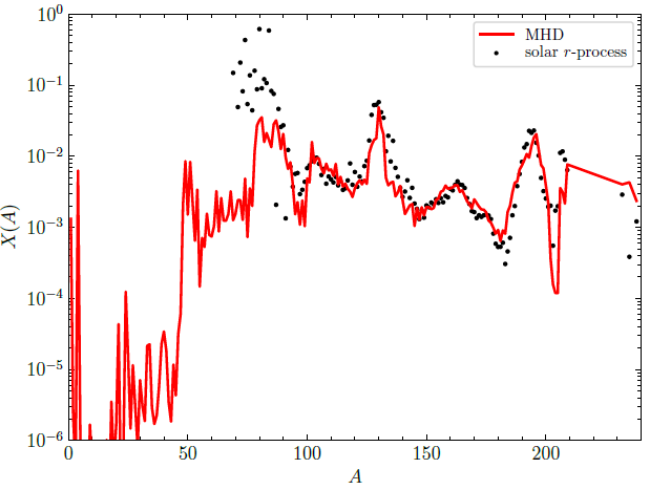
▶Our EOS (BHB Λ_ϕ) satisfies the tidal deformability constraint by LVK. But, it is non-trivial whether this EOS satisfies the post-merger GW upper limit or not.

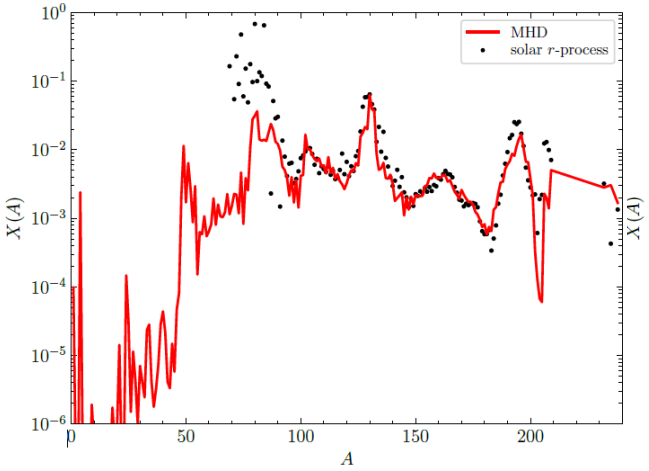
▶The emitted energy is well below the observed upper limit (LVK18).

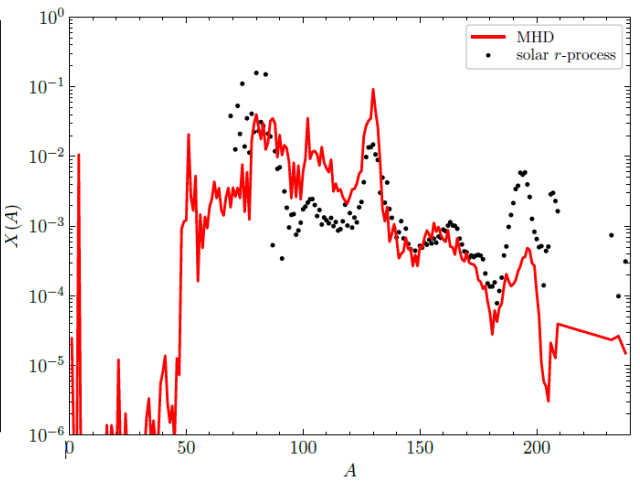
Inferring the EOS from R-process nucleosynthesis

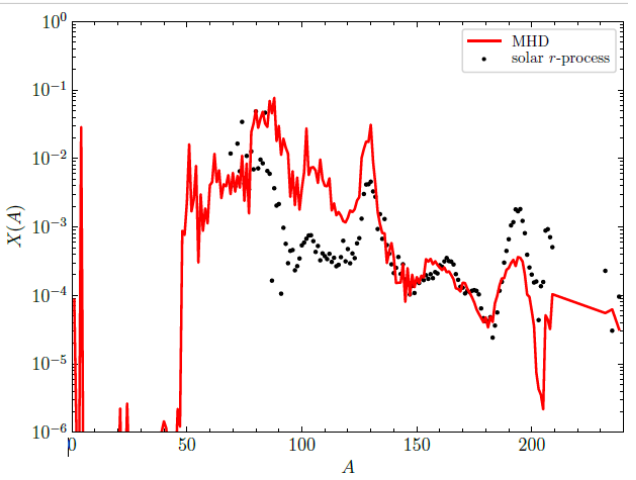
Lifetime of the remnant massive neutron star

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









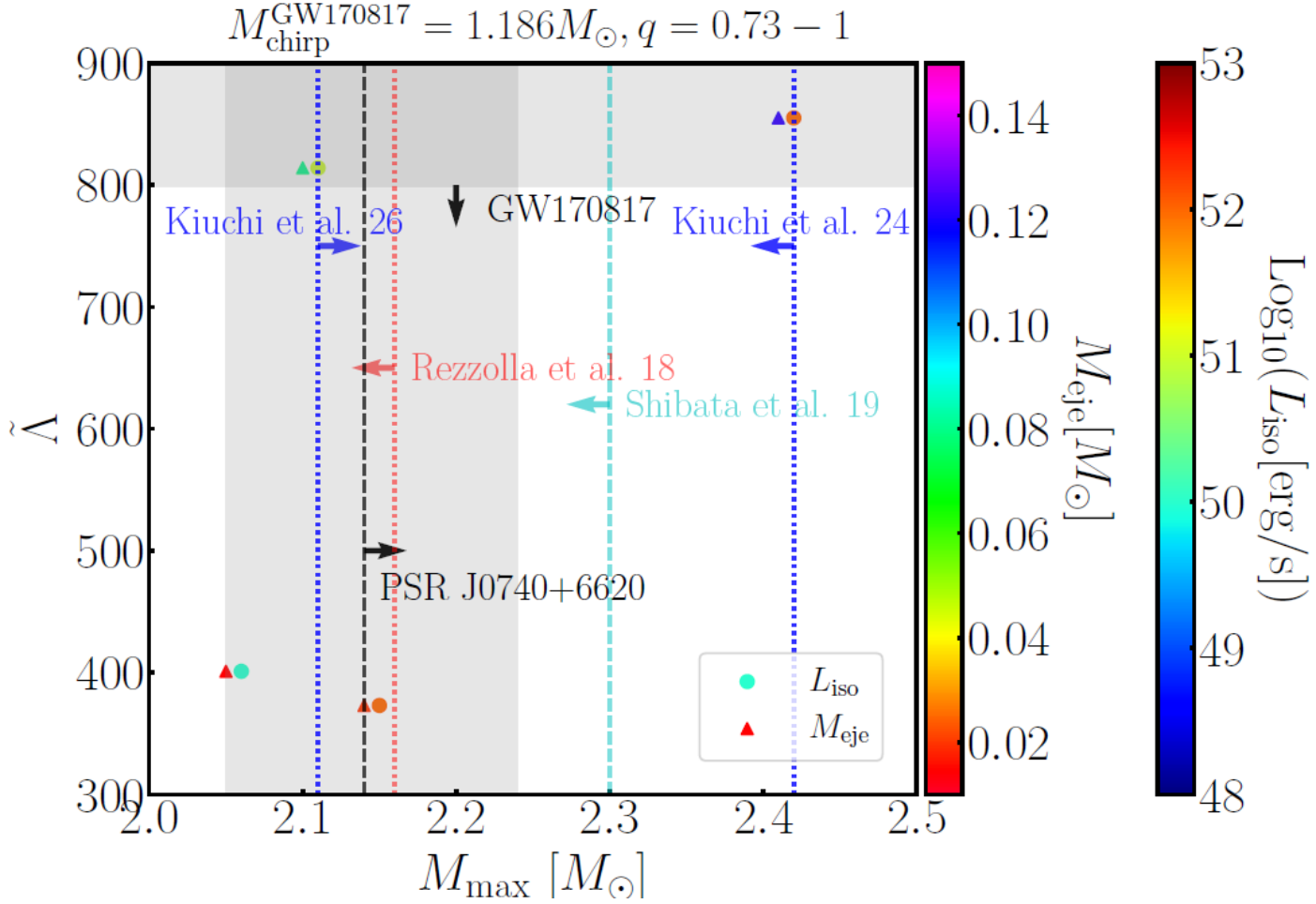
$M_{eje} \simeq 0.006\, M_\odot$ | $M_{eje} \simeq 0.014\, M_\odot$ | $M_{eje} \simeq 0.08\, M_\odot$ | $M_{eje} \geq 0.1\, M_\odot$

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

(see Kyohei's talk) | (see Quentin's talk)

Kilonova in GW170817:	SFHo	BHB Λ_ϕ	DD2
R-process universality:	SFHo	BHB Λ_ϕ	DD2

End-to-End modeling of GW170817



Nuclear EOS predicts a “blind” spot on this diagram?
Mass asymmetry? Jet-ejecta interaction? Different BNS merger types?

Conclusion

▶End-to-End BNS model based on the first-principles simulation is feasible.

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

The bolometric (and broad band) LC reasonably reproduce the AT2017 gfo.

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

6.25m/12.5m should not be an ultimate resolution!!

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?

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