Hydrodynamics modeling of neutron-star mergers

Masaru Shibata

Max Planck Institute for Gravitational Physics at Potsdam
& Yukawa Institute for Theoretical Physics, Kyoto U.

with the help of **S. Fujibayashi, K. Hayashi**, K. Kiuchi & S. Wanajo

17.10.2022

Outline

I. Introduction

II. Status for NS-merger theory

III. Remaining issues

IV. Conclusion

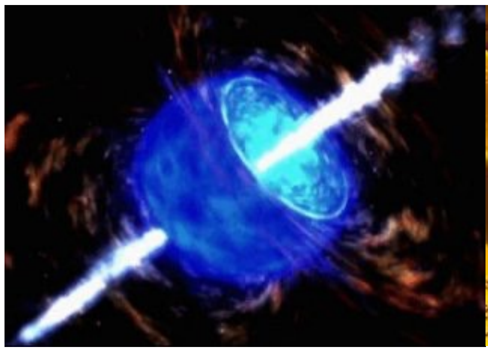
Nucleosynthesis will be talked by the next speaker.

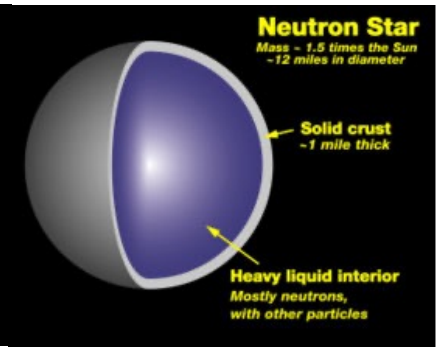
I Introduction

NS merger was predicted to be

- Promising source for short-hard gamma-ray bursts
  (e.g., Eichler et al. 1989)
- Site for *r*-process nucleosynthesis (rapid neutron capture nucleosynthesis) (e.g., Schramm & Lattimer 1974)
- Source for Kilonovae (e.g., Li & Paczynskii 1998)
- Invaluable site for studying nuclear equation of state through GW detection (e.g., Lai et al. 1993, Hinderler 2008,…..)

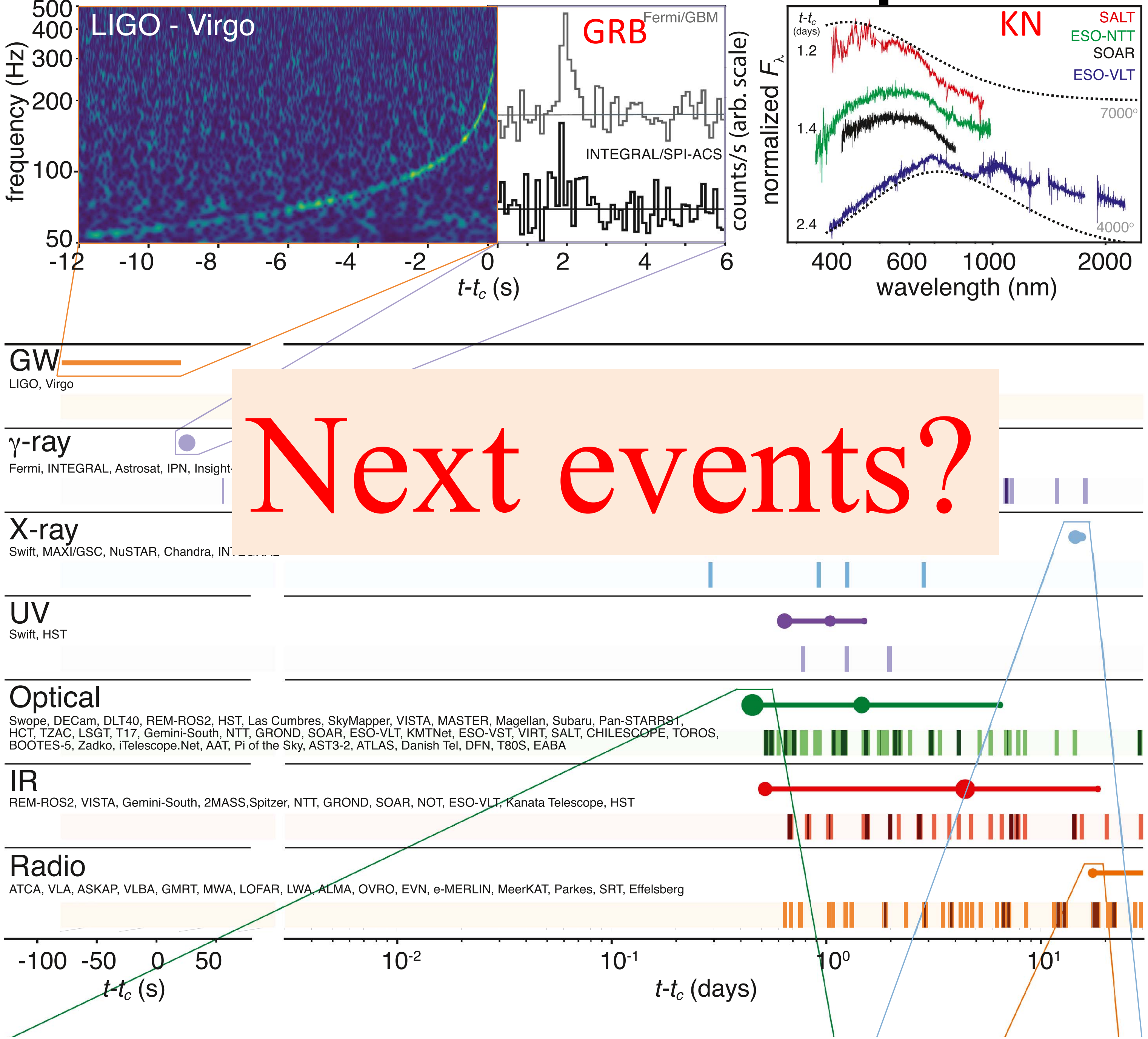
- **GW170817 (1st NS-NS) has shown all these aspects**



GW170817 & EM counterparts

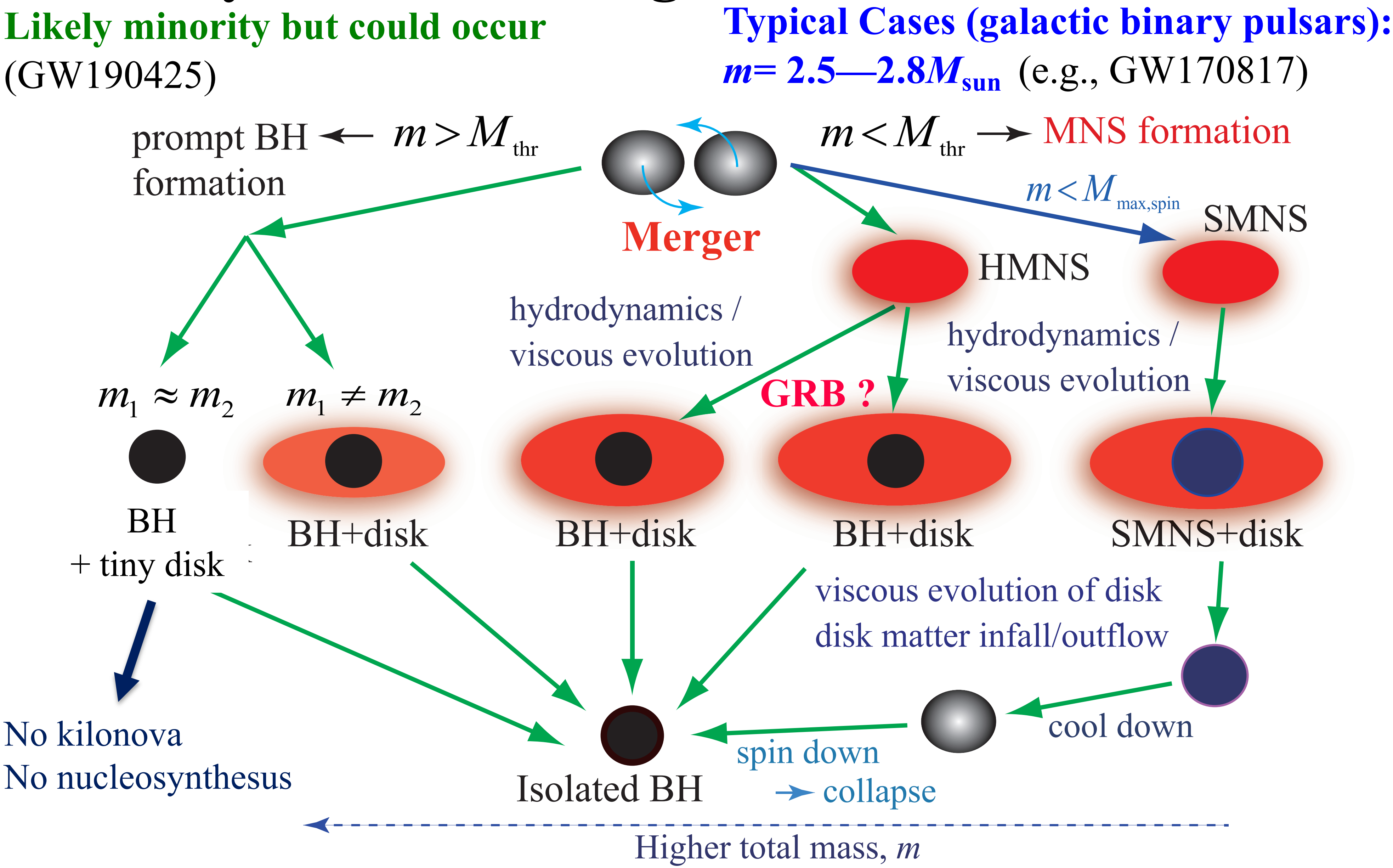
ApJ 848, 3000 authors 2017



Next events?

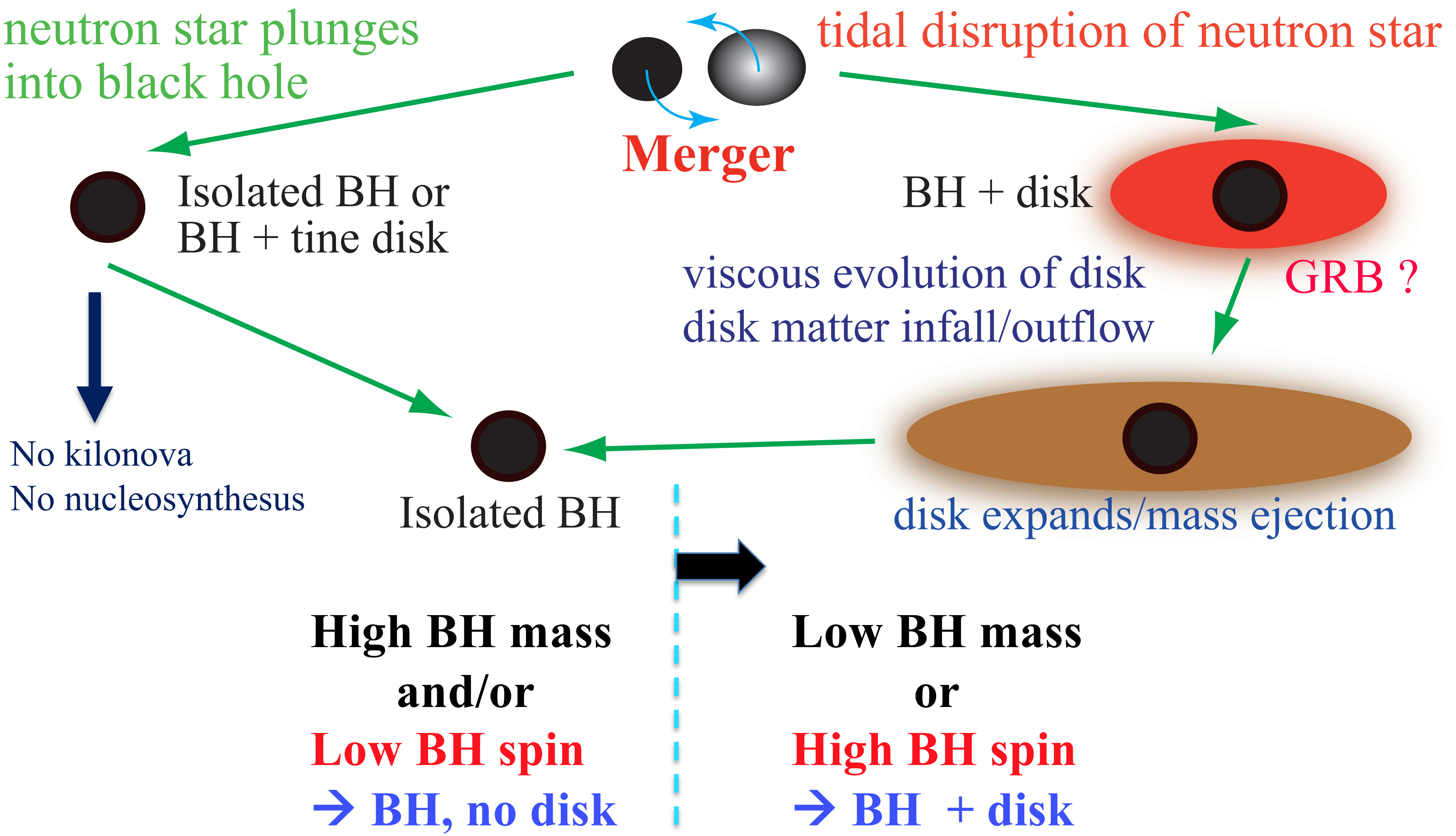
MORE up to > 1500 days

Variety of NS-NS merger remnants based on NR



A wide variety of possibilities exist; need widely exploring

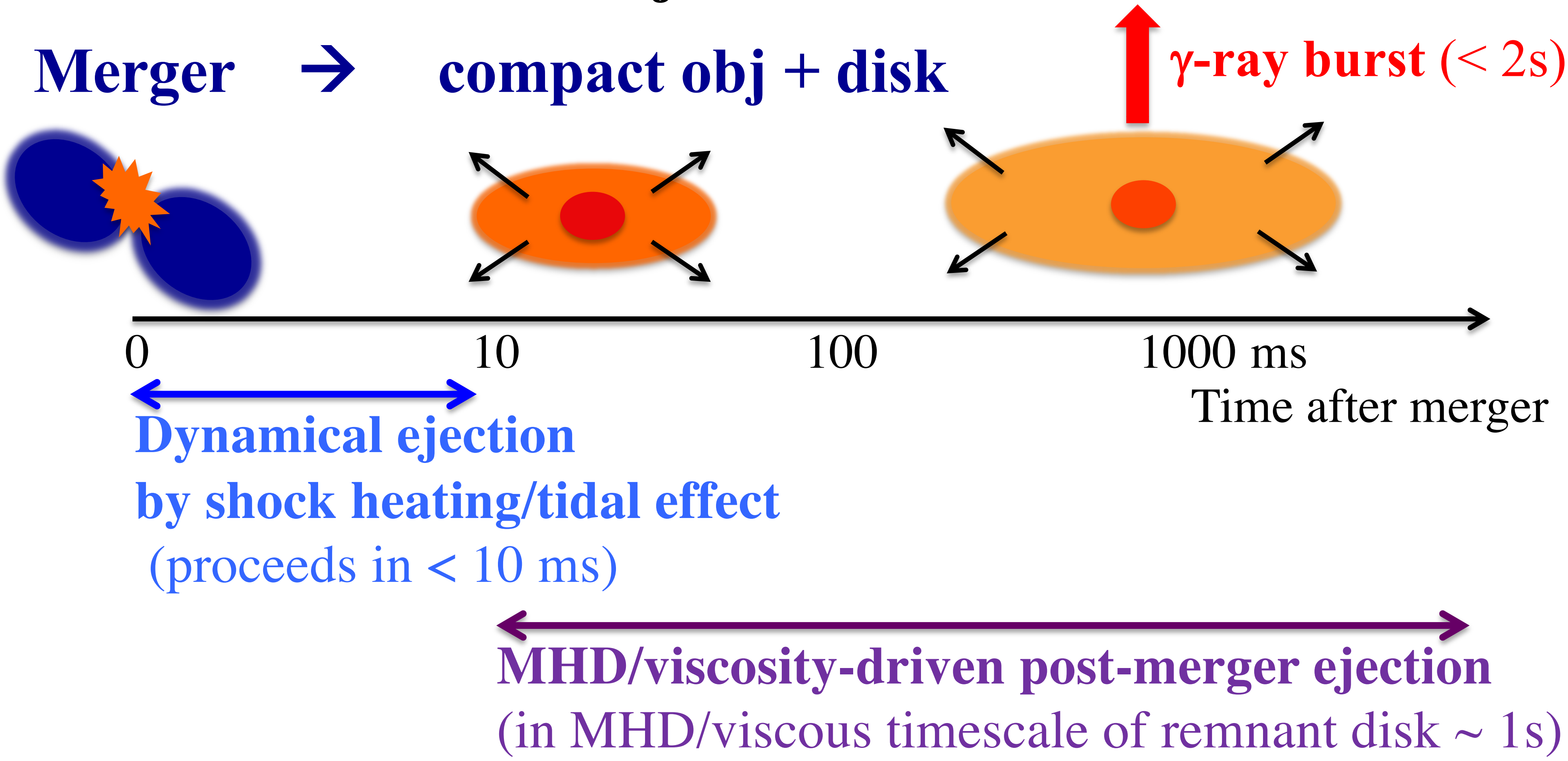
Two fates of BH-NS binaries



II Status of NS merger theory based on numerical relativity simulations

Animation by Fujibayashi & Kiuchi

Mass ejection scenario



- **Weak interaction** determines the property of ejecta:
  Important for nucleosynthesis & kilonovae
- ***Electron fraction, $Y_e(=n_p/(n_n+n_p))$, is key for r-process***

A Dynamical mass ejection from NS-NS

(ejection within ~ 10 ms after the merger)

- Many *numerical-relativity* simulations have been done since 2013 (easy to do now) → **Well understood**

◆What we have learned are

- Mass=10^{-4}~10^{-2} M_{sun} (Hotokezaka, Sekiguchi, Foucart, Radice, Dietrich, Bernuzzi…., now it is routine work): For *low total mass (MNS formation)*, it is <~10^{-3} M_{sun}
- **Electron fraction=0.05~0.4** (show later)
  → suitable for *r*-process nucleosynthesis of **heavy elements** (Wanajo, Sekiguchi, Goriely, Foucart, Roberts, and others)
- Average velocity=0.15~0.25c, but could be up to ~ 0.9c (or more) (Hotokezaka+ '13, many follow-ups, Radice…..)

B Post-merger mass ejection: *more complicated*

- Neutron star is *magnetized* → **Remnants are magnetized**
- The magnetic field is amplified by **MHD instabilities** (Kelvin-Helmholtz instability, MRI, convection, etc)

i. Turbulence & effective viscosity are excited (Fernandez & Metzger+ ‘13, Just et al. ‘15, ‘21, Fujibayashi+ ‘18, ‘20)

ii. Purely MHD effects (e.g., Christie+ ‘19, Just+ ‘21, Shibata+ ‘21)

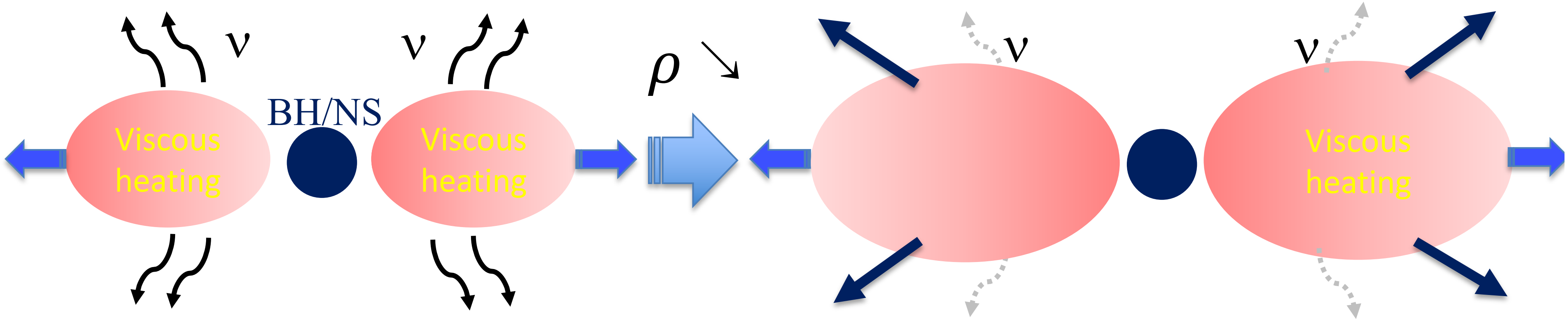
→ **Post-merger mass ejection from disk/torus**

✓ **Ejecta mass depends on the remnant (BH or NS)**

→ Ejecta mass ~ 0.05–0.1 M_{sun} *for long-lived NS formed,* while it is *lower,* ~ 0.01 M_{sun}, *for BH formation*

- **Weak interaction physics (e.g., neutrino reaction) is key for determining electron fraction (Y_e)** (Metzger & Fernandez ‘14, Just+ ‘15, ‘21, Siegel-Metzger ‘18, Fujibayashi+ ‘18, ’20, Miller ‘19)

Basic evolution process of disks by neutrino cooling and (effective) viscous effects



$T_{max} > \sim 3\text{MeV} \rightarrow L_\nu \approx \dot{E}_{vis}$

No viscous mass ejection;
Viscous angular momentum transport → Disk expansion (but no mass ejection)

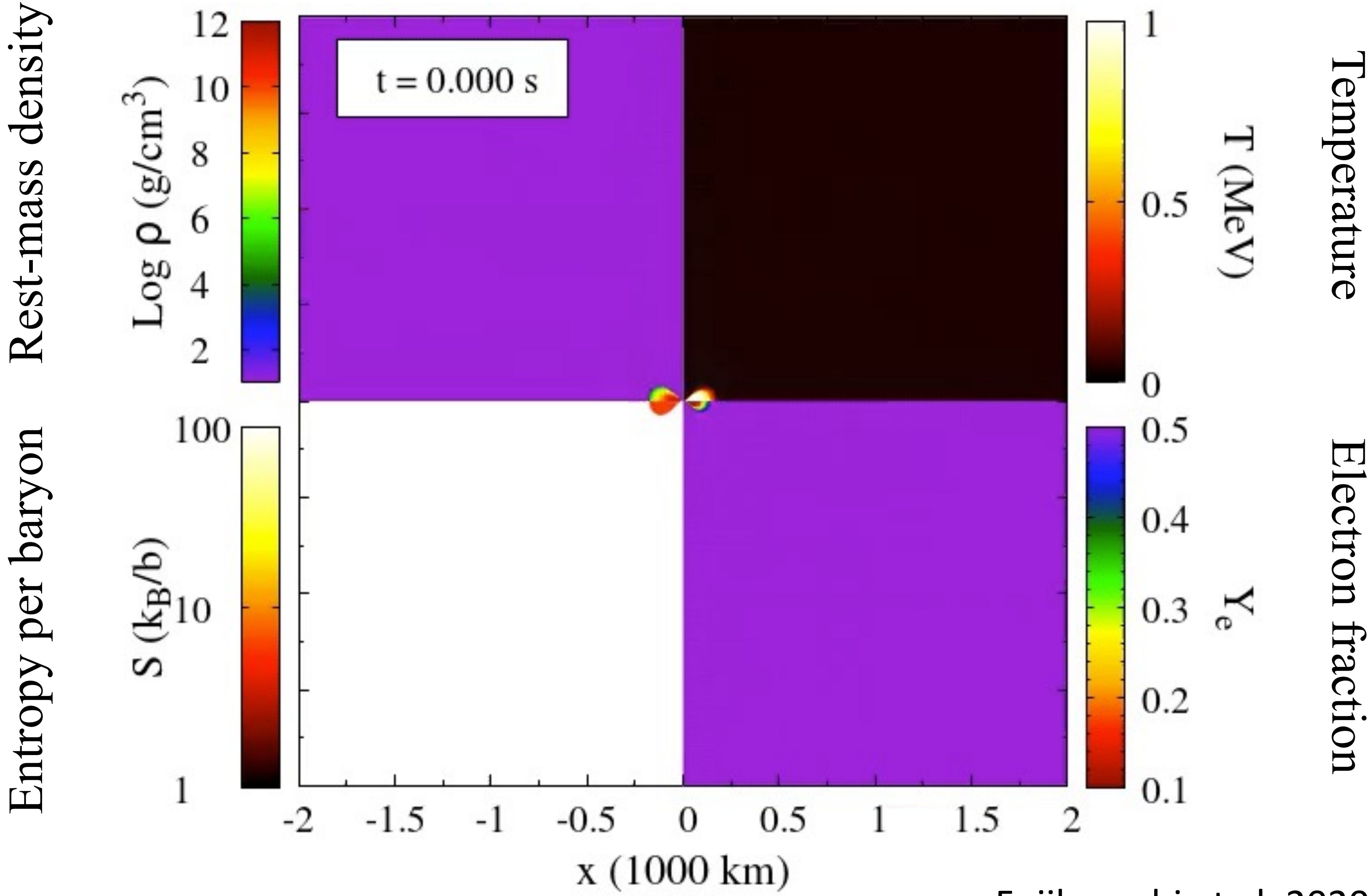
$T_{max} < \sim 3\text{MeV} \rightarrow L_\nu \ll \dot{E}_{vis}$

Viscous heating is fully used for matter expansion →
Onset of viscous mass ejection

Viscous angular momentum transport timescale: ***long***

$$\tau_{\rm vis} \sim 0.55\,{\rm s} \left(\frac{\alpha_{\rm vis}}{0.02}\right)^{-1} \left(\frac{\varpi}{50\,{\rm km}}\right)^{2} \left(\frac{c_s}{0.05c}\right)^{-1} \left(\frac{H}{20\,{\rm km}}\right)^{-1}$$

Viscous hydro simulation in full GR: 3 solar mass BH + 0.1 solar mass disk



Fujibayashi et al. 2020

How Y_e of disks/ejecta is determined?

- β-equilibrium (reaction timescale < disk evolution one)

$$p + \bar{\nu}_e \leftrightarrow n + e^+ \quad \& \quad n + \nu_e \leftrightarrow p + e^-$$

$\rightarrow$ Y_e is determined by $\mu_p + \mu_e = \mu_n + \mu_\nu$

- In typical situations, neutrino captures decouple first, but still **electron & positron capture processes proceed** because of high temperature > MeV

$$p + e^- \rightarrow n + \nu_e \quad \& \quad n + e^+ \rightarrow p + \bar{\nu}_e$$

- For $T_{\mathbf{max}}$< **~3MeV**, the weak interaction decouples and Y_e is determined (Fujibayashi+ '20, Just+ '21)

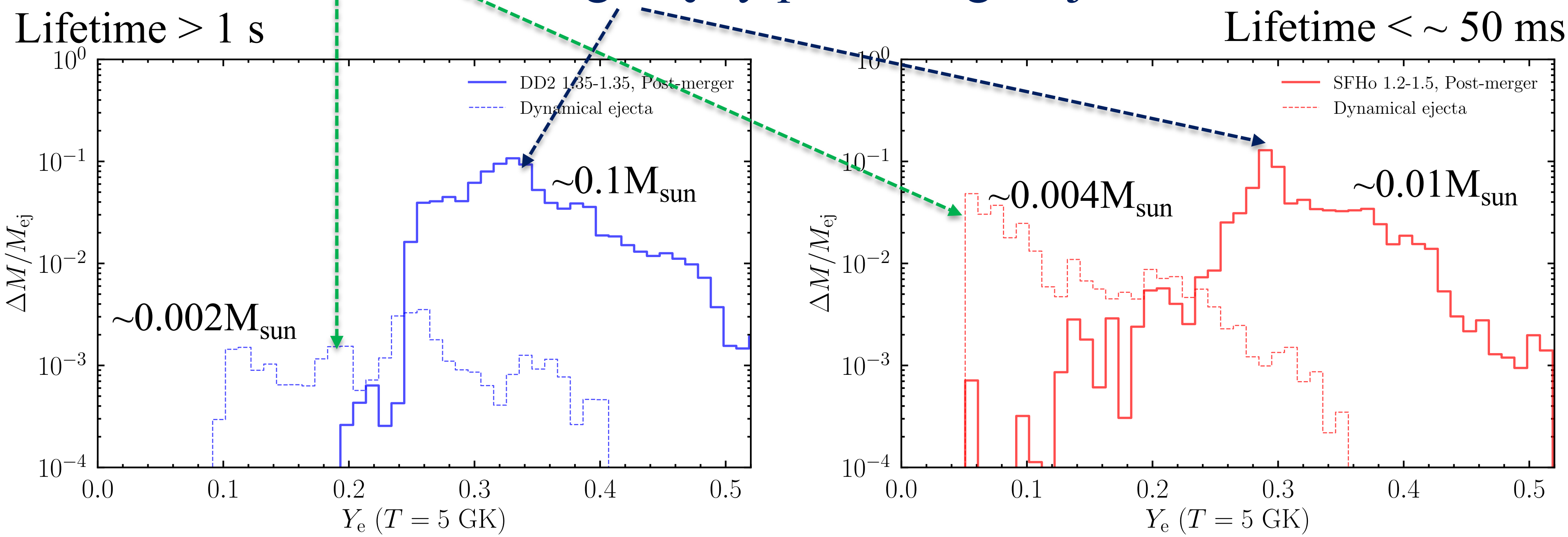
✓ Electron degeneracy is weakened for decreased density, i.e., μ_e decreases with time
→ At mass ejection, moderately neutron rich, $Y_e \sim 0.3$
→ **Heavy *r*-elements production is suppressed**

Y_e distribution: Two components

Results from 3D merger + 2D post merger simulation

Low Y_e (neutron-rich) ejecta by dynamical ejection

High Y_e by post-merger ejection



Long-lived MNS case

Short-lived MNS → BH case

Numerical relativity results by Fujibayashi et al. (2022)

Mass ratios by *dynamical* and *post-merger ejecta* depend significantly on the lifetime of remnant NS

The goal of NS merger simulations

- <u>Important timescales</u>:

➢ Dynamical mass ejection timescale ~ 10 ms

➢ Post-merger mass ejection timescale ~ O(1) s

➢ Short gamma-ray bursts: up to ~2 s

→ Until quite recently, the merger and post-merger simulations are performed *separately*

✓ For *self-consistent studies,* a simulation of **inspiral, merger & post-merger with > 1 s** is required

- ***MHD effects*** *are likely to be the key*
- ***Weak processes*** *are the key for nucleosynthesis*

→ **Seconds-long GR+rad+MHD simulation with weak physics input (e.g., neutrino transfer) is needed**

Second-long self-consistent simulations for BH-NS & NS-NS mergers are now feasible!

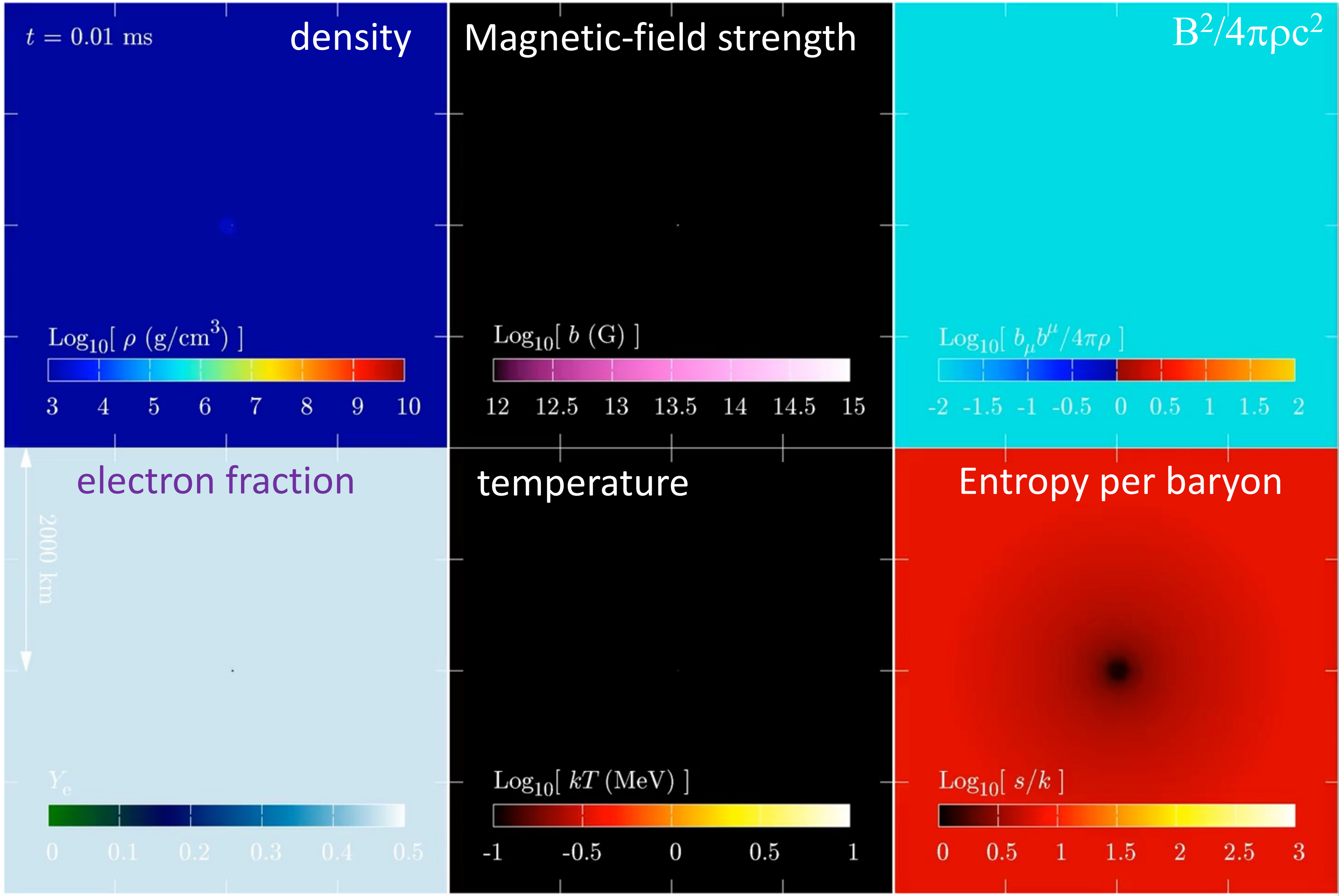
K. Hayashi et al. PRD 106, 023008, 2022
K. Kiuchi et al. in preparation

2 steps mass ejection scenario is reconfirmed

BH-NS merger for 2 seconds: GR + ν–rad + MHD

NS with strong dipole field initially

K. Hayashi et al. PRD106 (2022)



BH mass $=5.4M_{sun}$

χ(spin) $=0.75$

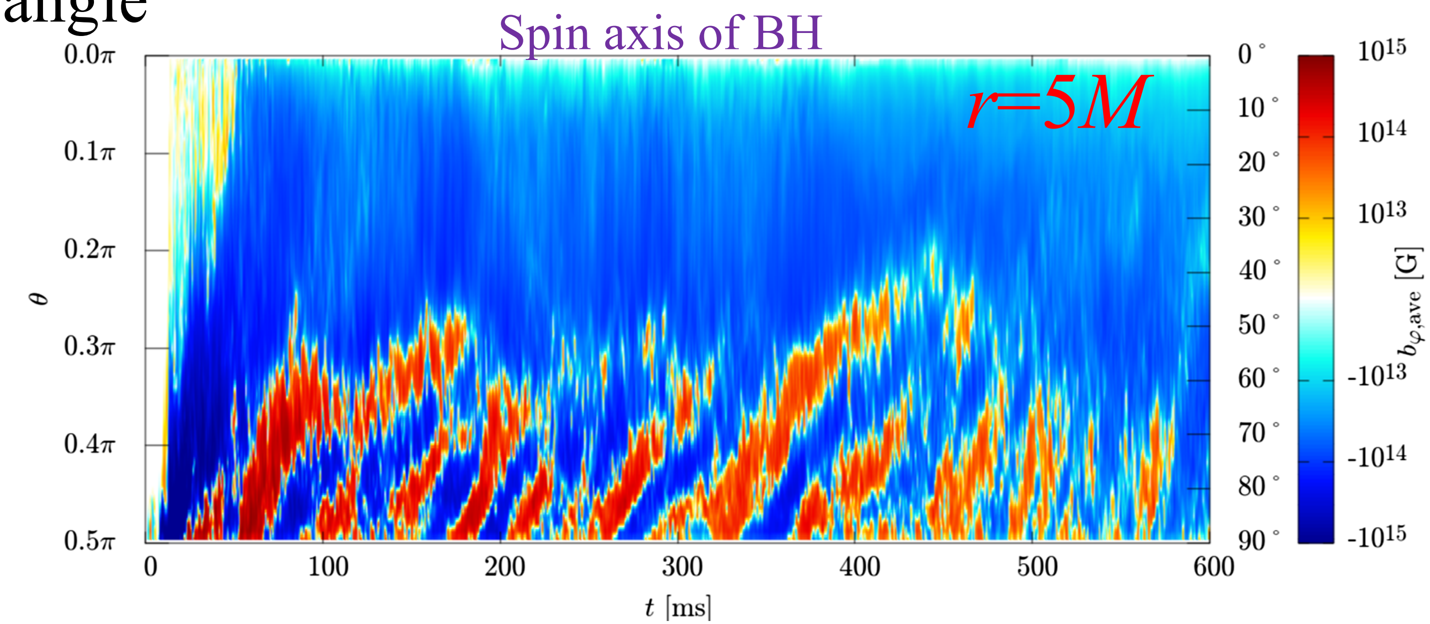
NS mass $=1.35M_{sun}$

y=0 plane is displayed: [-2000,2000] km

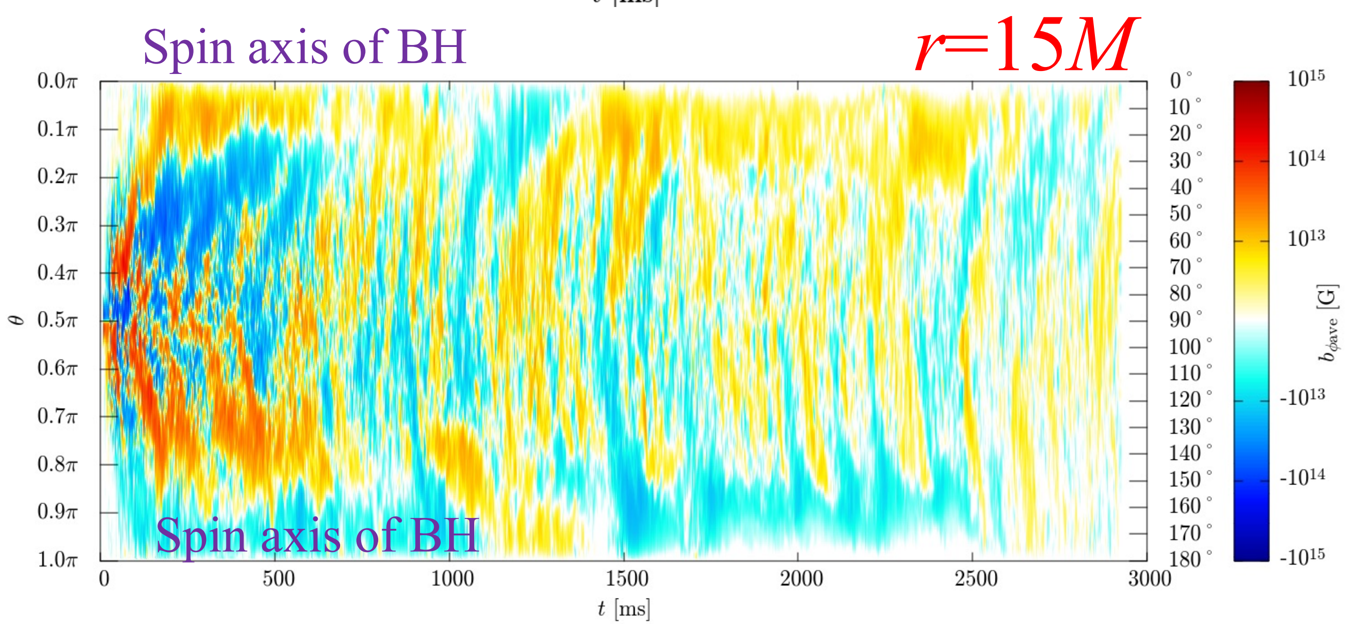
Δx=400 m; Fix mesh refinement with ~400*400*200 grid * 9 levels

Butterfly diagram at fixed *r*: toroidal field

Polar angle



Equatorial symmetric case

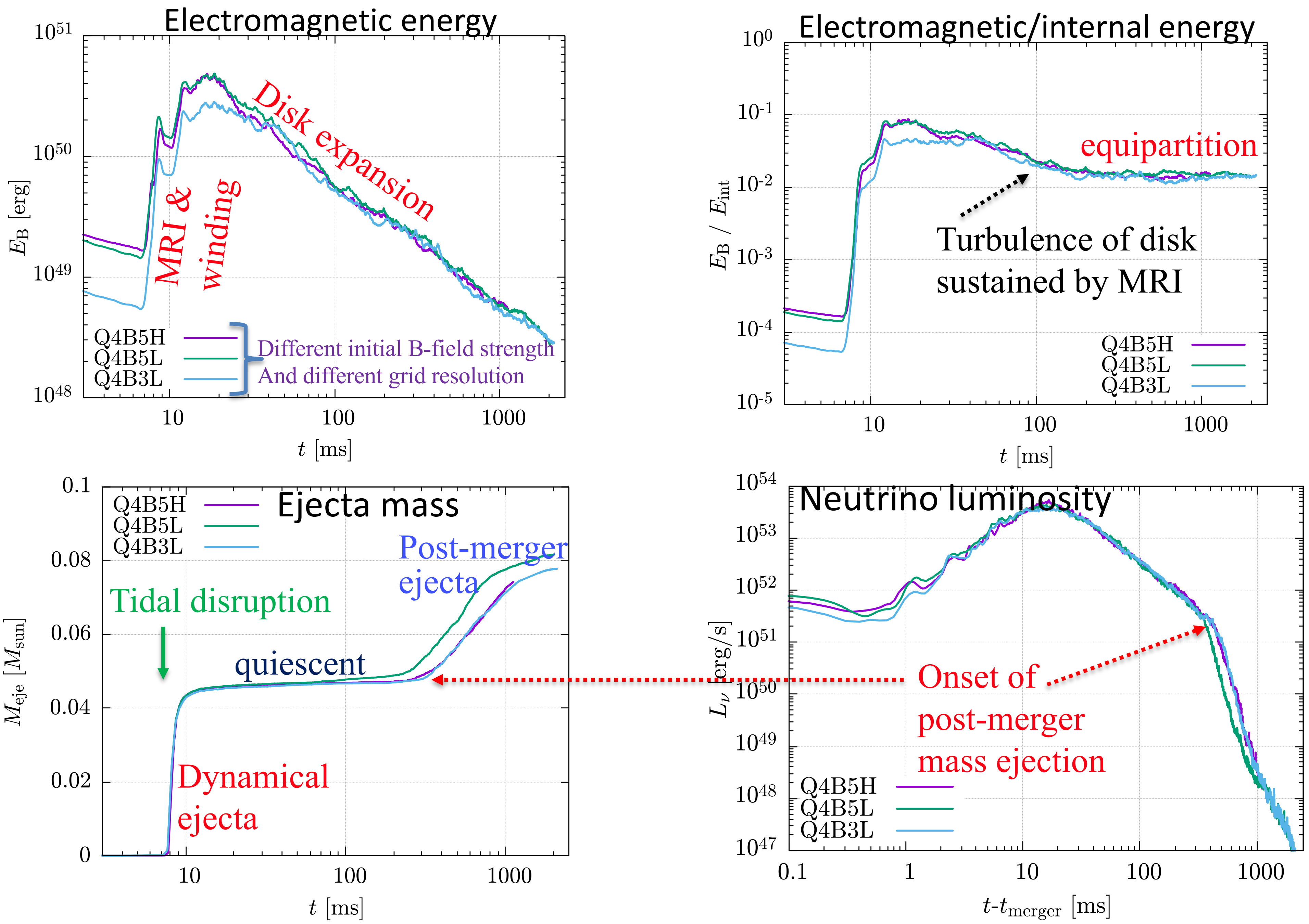


Equatorial asymmetric case

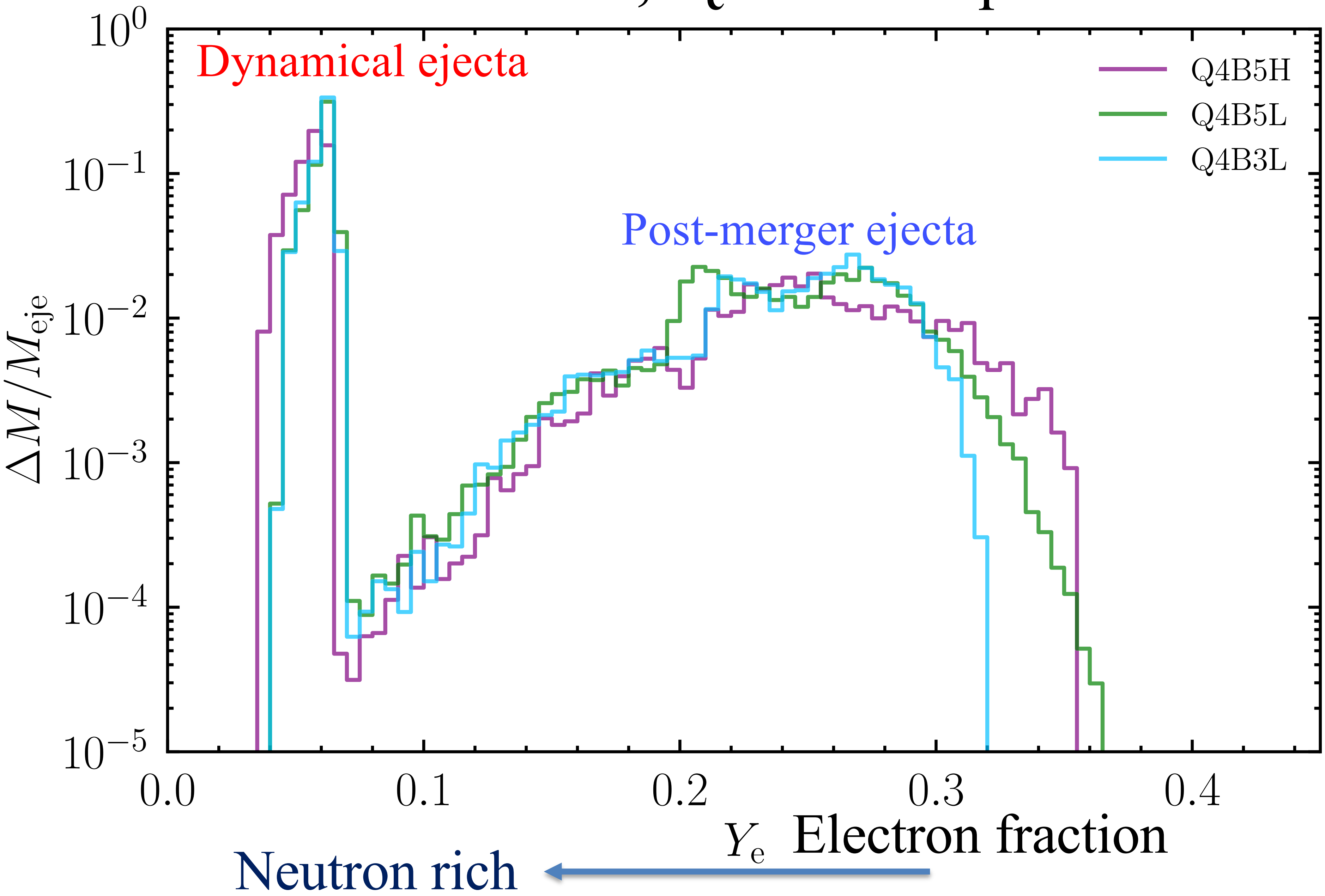
New

Time (ms)

Electromagnetic energy, mass ejection, neutrinos

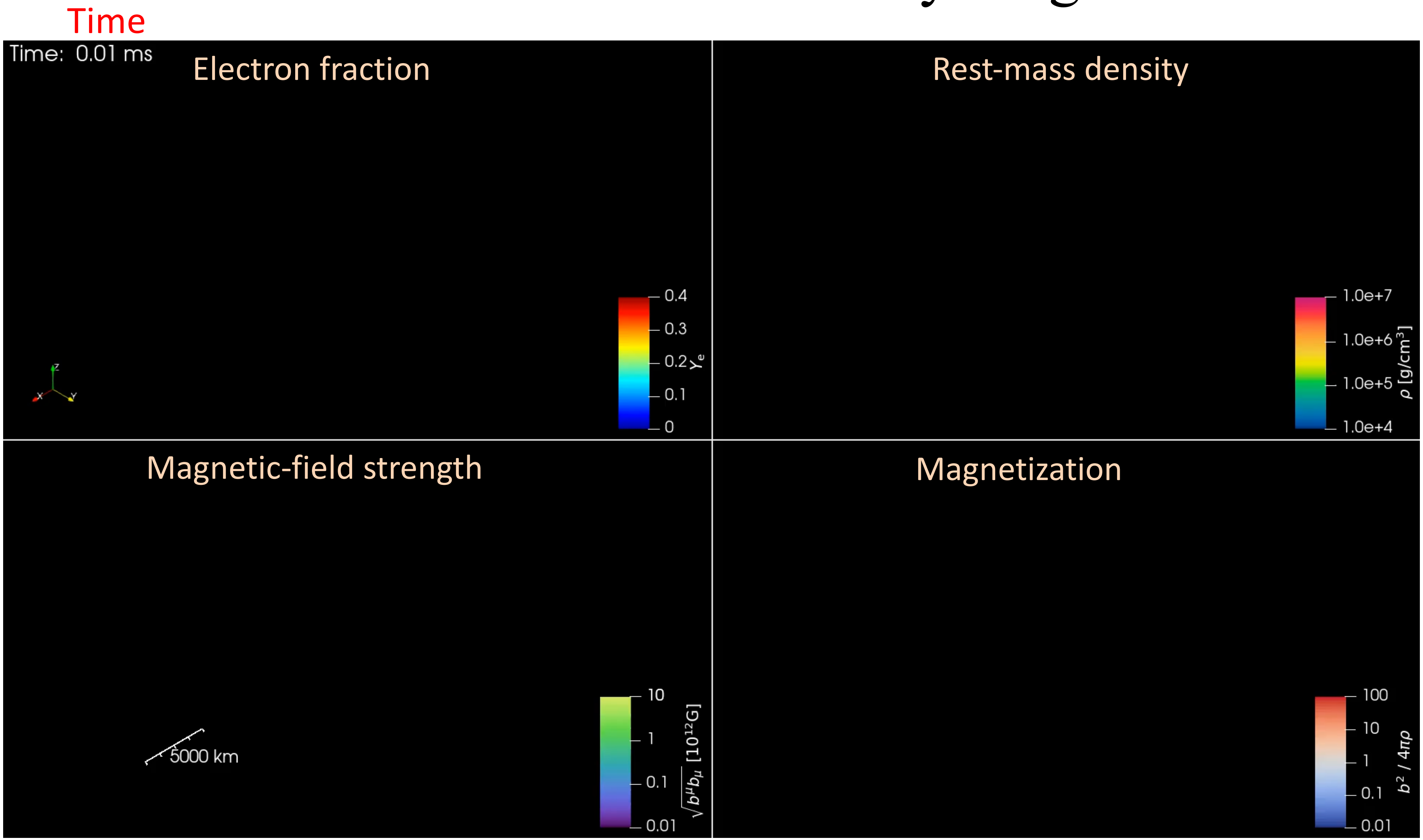


Electron fraction, Y_e: two components



Consistent with the merger + post-merger studies

Formation of collimated Poynting flux



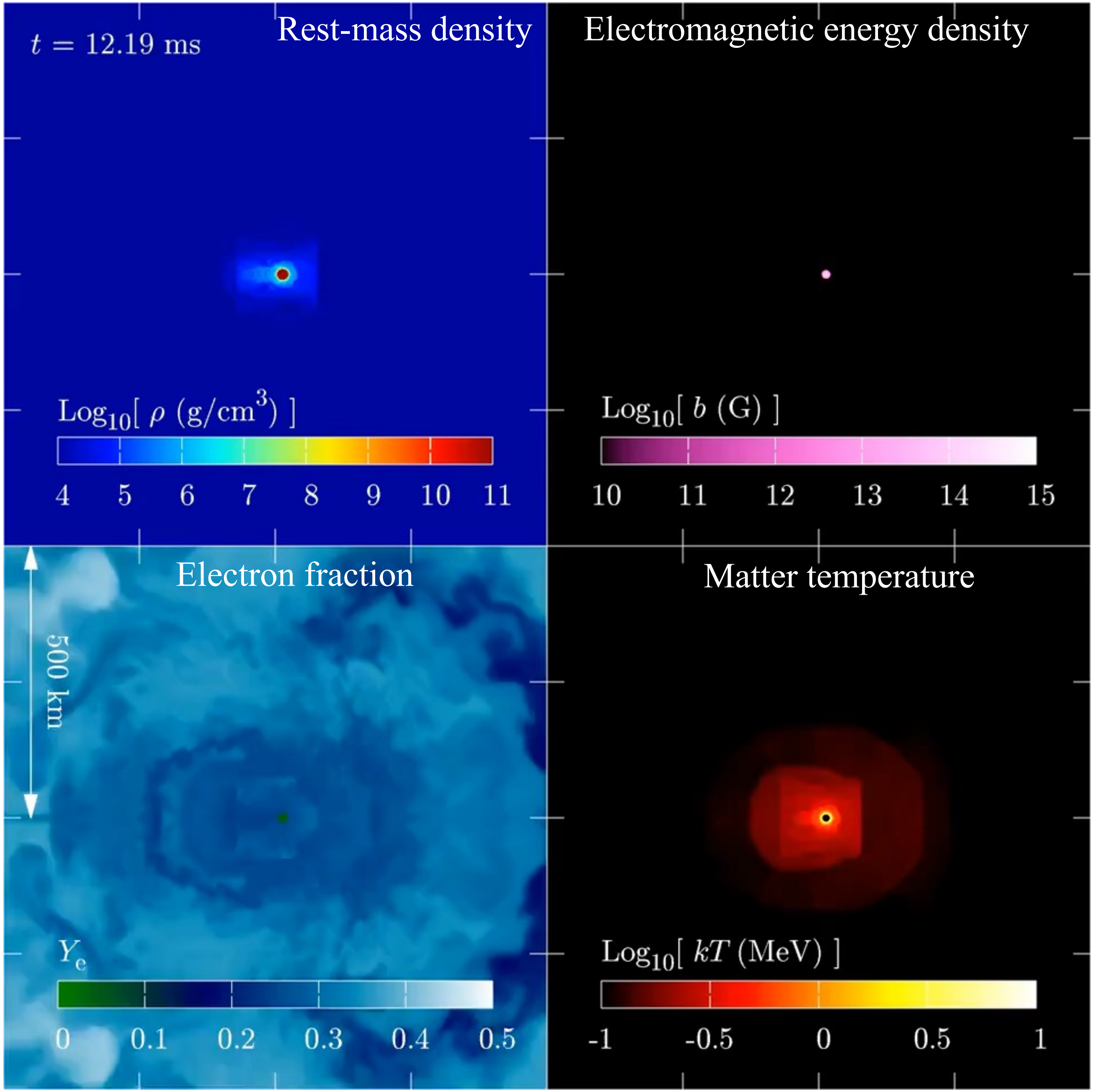
y=0 plane is displayed: [-2000,2000]km

Δx=400m; Fix mesh refinement with ~400*400*200 grid * 9 levels

1.2-1.5 solar mass NS-NS merger to a BH + disk: *New*

Time→

Kiuchi et al. in preparation



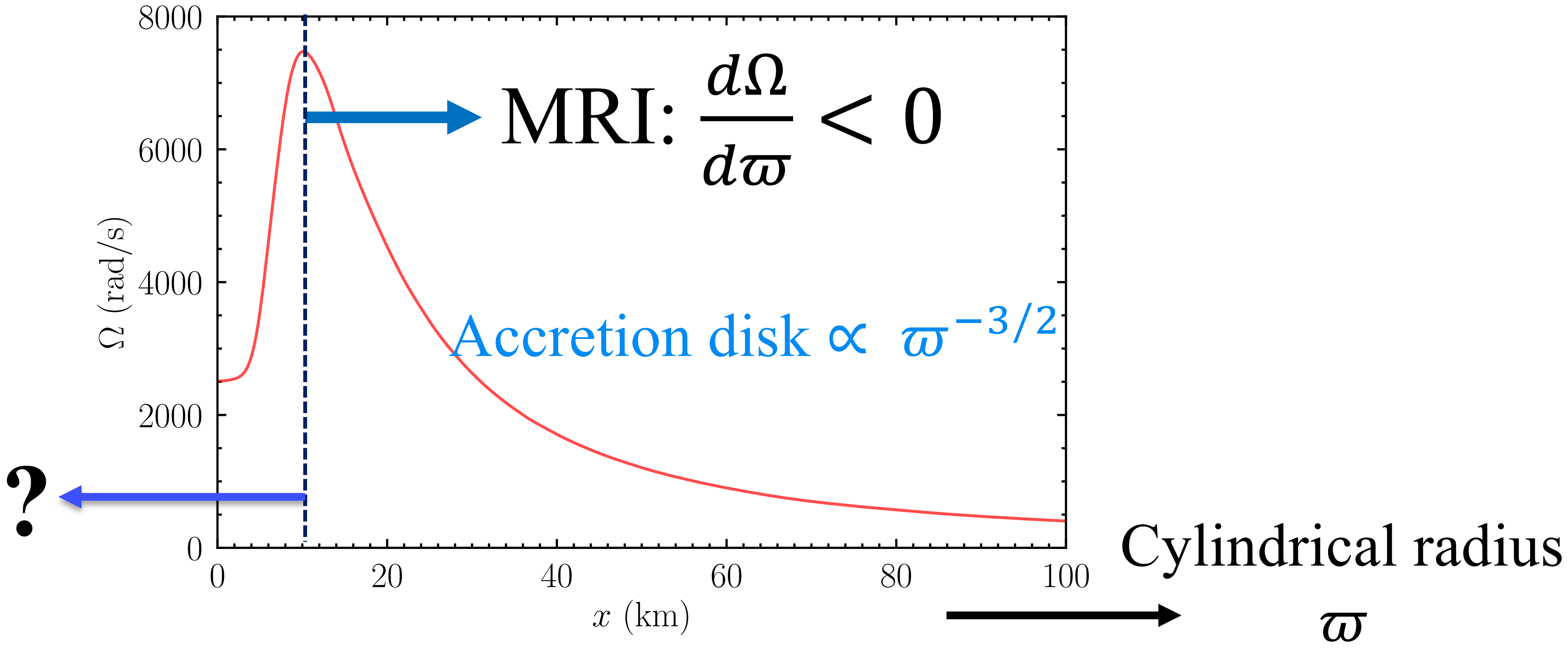
III Remaining issues

- What happens for ***long-lived neutron star formation***?

✓ Differential rotation is present both in NS and disk

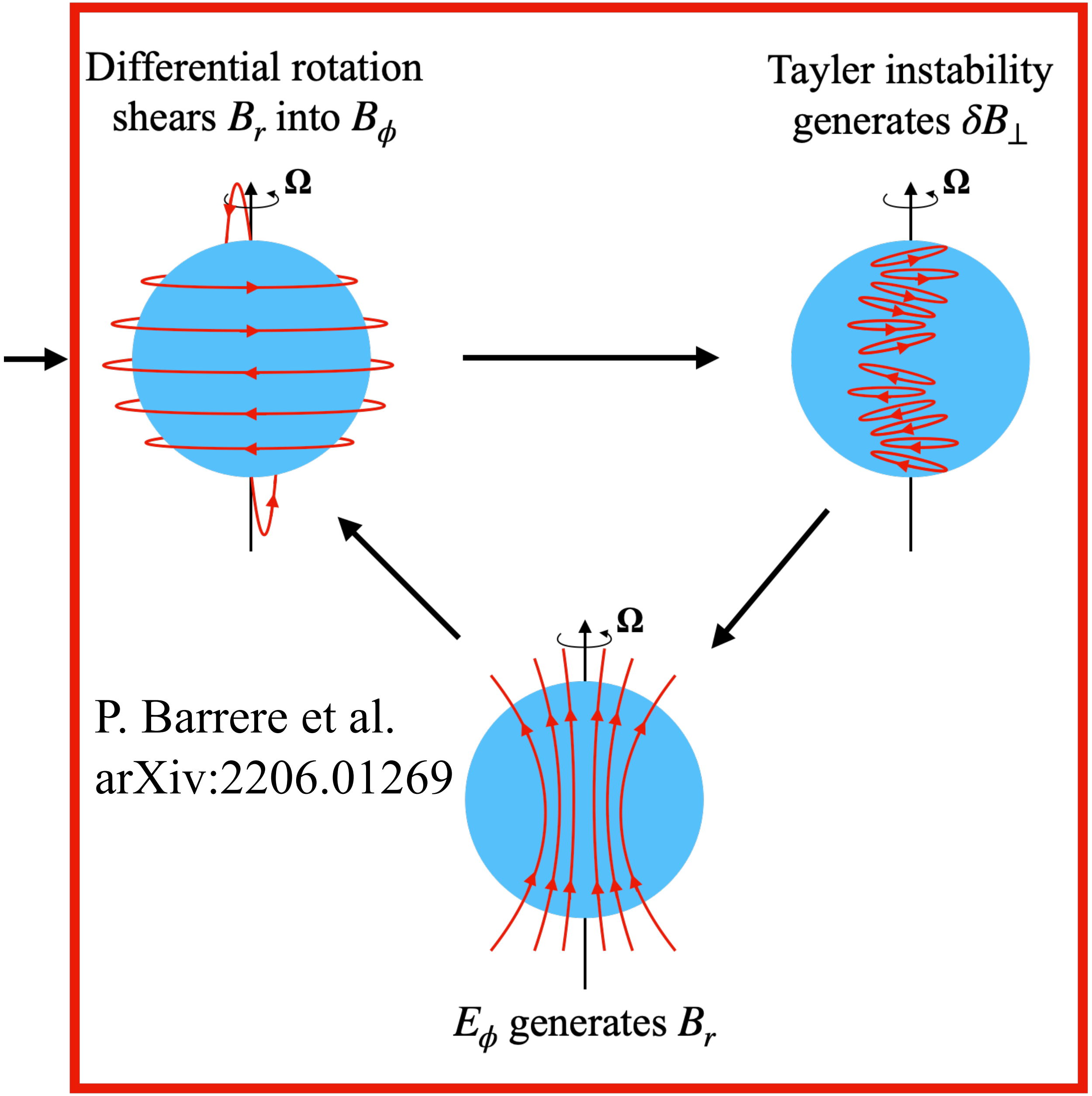
→A strong magnetic field is likely to be developed

- **Magnetic-field amplification by dynamo proceeds not only in disk but also in NS??**



Magnetic -field amplification in MNS?

Tayler-Spruit dynamo loop



Differential Rotation
+
Tayler-Spruit Dynamo
⇩
Formation of global magnetic field

A very phenomenological approach as an experiment

- **α–Ω Dynamo** is likely to play a crucial role in magnetic-field (B-field) amplification not only for the disk but also for remnant NS

→ *Need 3D high-resolution MHD with microphysics for remnant neutron star*

- However, it is not an easy task; Simple modeling?
- A *phenomenological* approach that explores possible effects by amplified B-field in the remnant NS:
  Shibata, Fujibayashi, Sekiguchi PRD 104, 063026 (2021)
- ***This can perhaps give the most extreme possibility***

Basic equations for resistive MHD + dynamo

- $F^{\mu\nu} = n^\mu E^\nu - n^\nu E^\mu + n_\beta \epsilon^{\beta\mu\nu\alpha} B_\alpha$
- $\mathcal{E}^\mu = \sqrt{\gamma} E^\mu,\ \mathcal{B}^\mu = \sqrt{\gamma} B^\mu$

$$\partial_t \mathcal{E}^i = -\partial_k\left(\beta^i \mathcal{E}^k - \beta^k \mathcal{E}^i + \alpha \epsilon^{kij} \mathcal{B}_j\right) - 4\pi J^i$$

$$\partial_t \mathcal{B}^i = -\partial_k\left(\beta^i \mathcal{B}^k - \beta^k \mathcal{B}^i - \alpha \epsilon^{kij} \mathcal{E}_j\right)$$

where $J^i = Qv^i + \alpha\sigma_c\left[\alpha u^t A^i{}_j \mathcal{E}^j + \epsilon^{ijk} u_j \mathcal{B}_k - \alpha_d\left(-\alpha u^t A^i{}_j \mathcal{B}^j + \epsilon^{ijk} u_j \mathcal{E}_k\right)\right]$

and $A^i{}_j = \delta^i{}_j - \gamma^{ik} u_k u_j / (\alpha u^t)^2$

- The term associated with α_d is related to dynamo *for hypothetical amplification of fields.*
- The term associated with (a finite value of) σ_c is related to resistive dissipation present in dynamo.

An isotropic turbulent theory tells

(e.g., Brandenburg and Subramanian, Phys. Rep. '05)

- $\alpha_d = -\frac{1}{3c}\tau_{cor}\langle u_i \cdot \nabla \times u^i \rangle \sim \frac{v_A^2}{3cL}\tau_{cor} \sim \mathrm{O}(10^{-4})$
- $\eta = \frac{c^2}{4\pi\sigma_c} = \frac{1}{3}\tau_{cor}\langle u_i \cdot u^i \rangle \sim \frac{v_A^2}{3}\tau_{cor}$

$$\rightarrow \sigma_c \sim 10^7 - 10^8\ \mathrm{s}^{-1}$$

where we assume $\tau_{cor} \sim \Omega^{-1}$ (Ω: angular vel.)

- Fastest growing rate of dynamo mode:

$$\omega_{max} = \frac{3}{4}\left(\frac{\pi\alpha_d^2\sigma_c S}{4}\right)^{1/3} =$$

$$46\ \mathrm{s}^{-1}\left(\frac{|\alpha_d|}{10^{-4}}\right)^{2/3}\left(\frac{\sigma_c}{3\times10^7\ \mathrm{s}^{-1}}\right)^{1/3}\left(\frac{S}{10^3\ \mathrm{rad/s}}\right)^{2/3}$$

where $S = \frac{\partial\Omega}{\partial \ln\varpi}$

→ Growth time ~ 10/ ω_{max} ~ O(100) ms

Check & setup for simulation

- Does this treatment *qualitatively* reproduce the results of viscous hydrodynamics for disks around BH?

✓ Yes.

- Does this treatment *qualitatively* reproduce MRI dynamo in disks around BH?

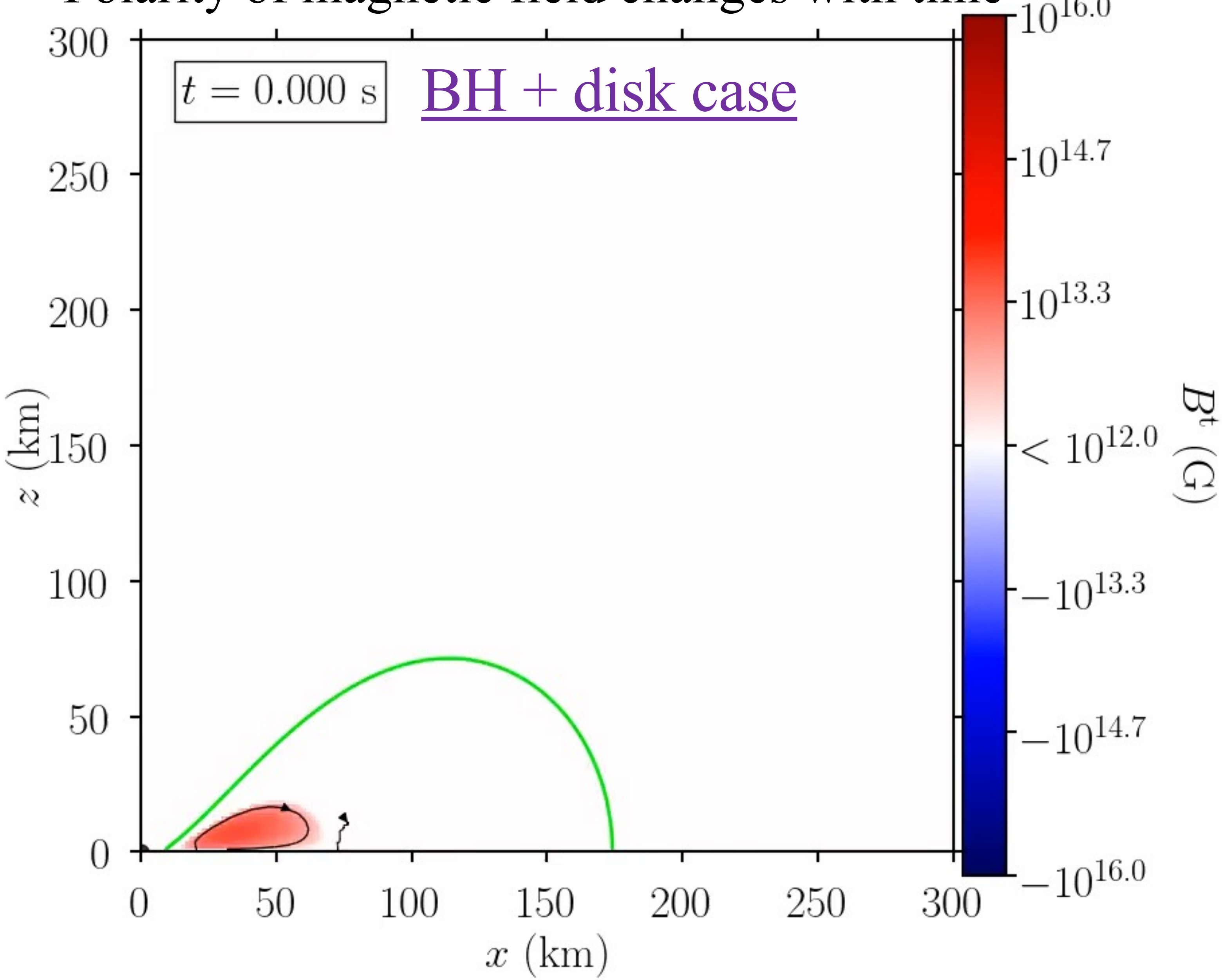
✓ Yes.

see, Shibata, Fujibayashi, Sekiguchi PRD 104, 063026 (2021)

- All the following simulations were done in axial and *z*-plane symmetries with a small toroidal magnetic field as an initial seed

Poloidal lines and toroidal strength (color)

Polarity of magnetic field changes with time



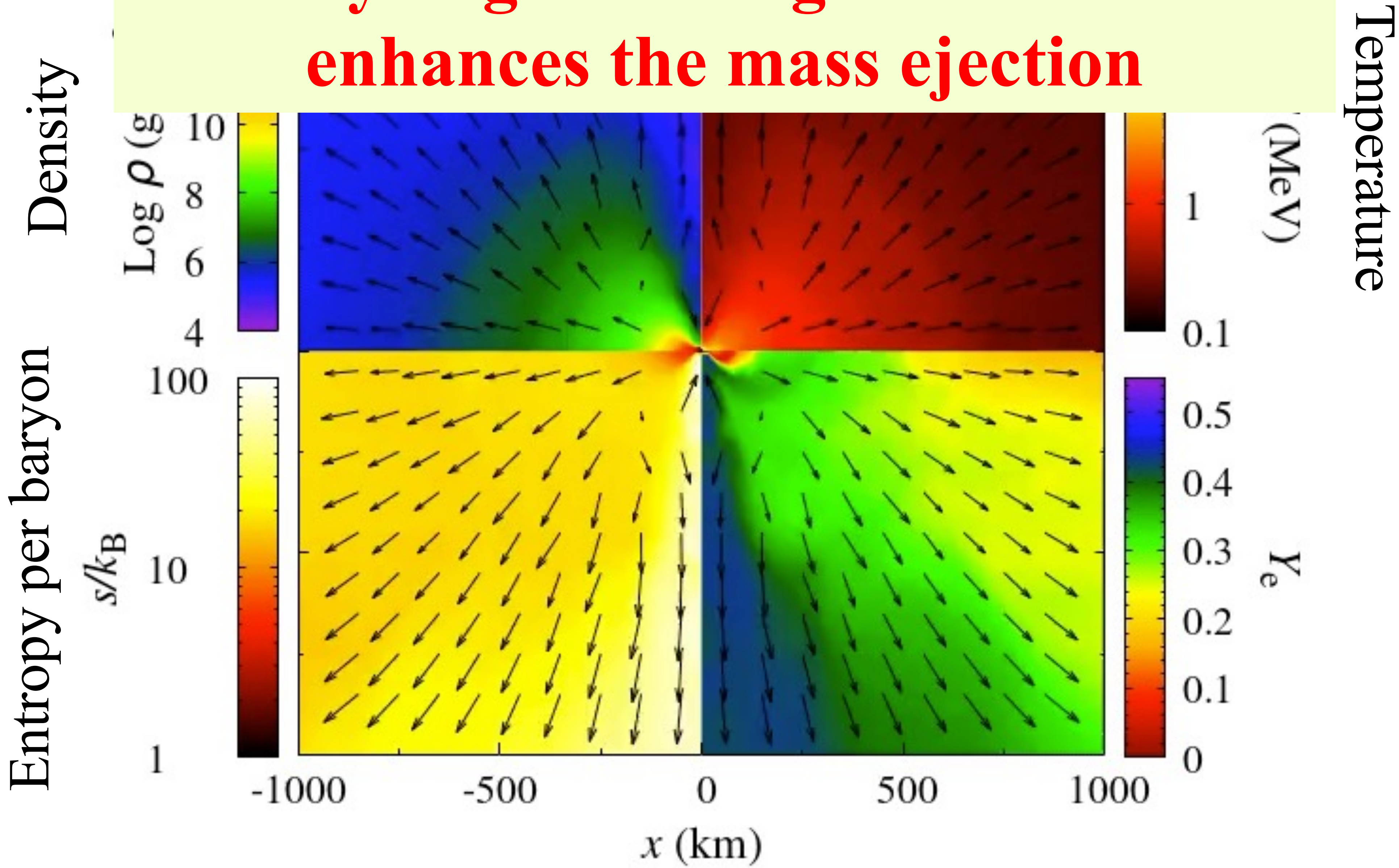
Result is similar to Christie et al. (2019)

Evolution of remnant NS + disk

- Remnant of 1.35-1.35 solar mass merger model is used as an initial condition
- Same simulation was performed in viscous hydrodynamics (Fujibayashi+ ApJ 901, '21)

Remnant NS + disk

Activity of global magnetic field lines enhances the mass ejection



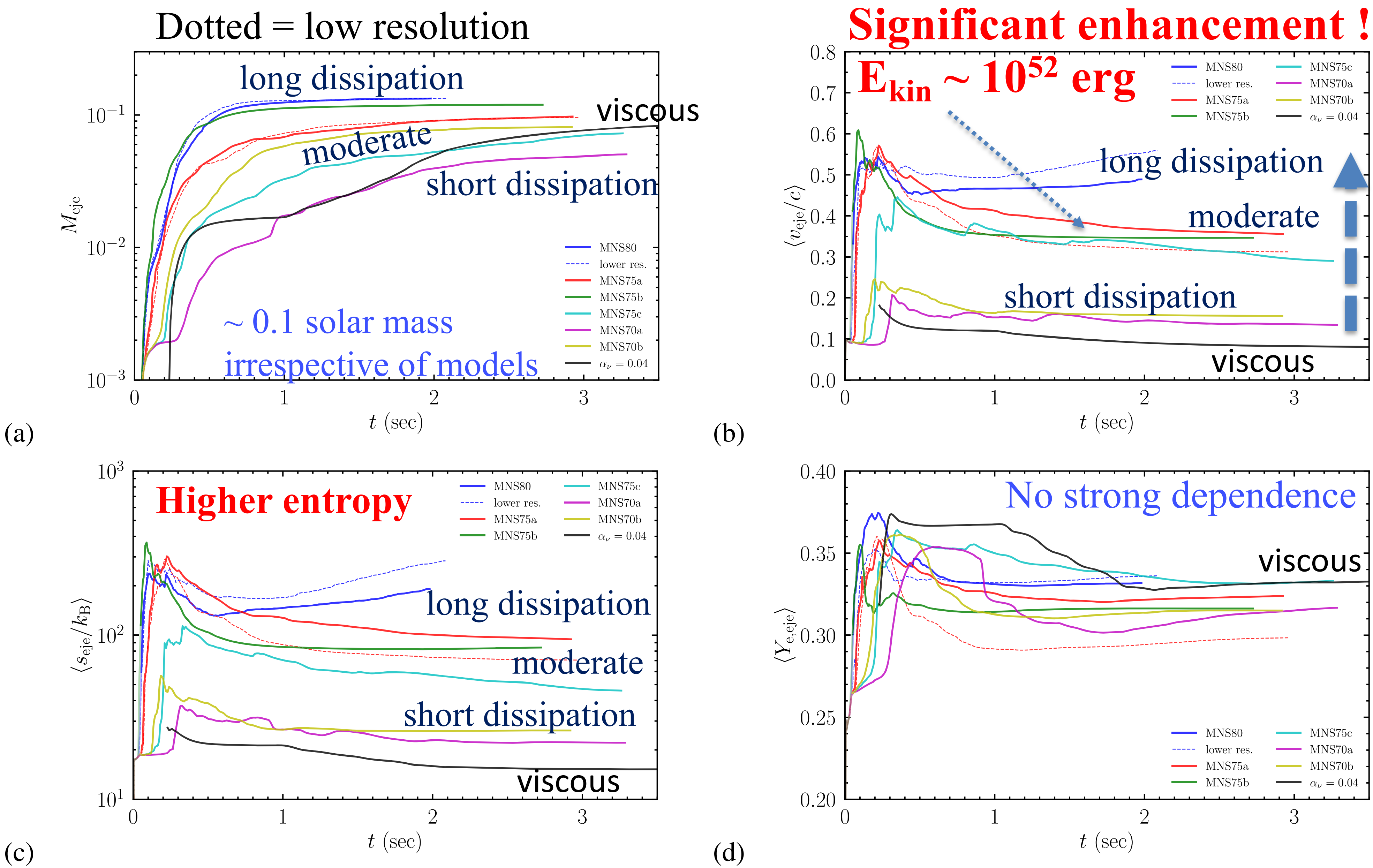
Initial expansion is due to dynamical mass ejection

Effect of magnetic fields developed by dynamo

- By dynamo action, magnetic fields are amplified
- **Some of field loops are ejected from the NS & global fields with high field strength are developed**
  → Some of field lines have an anchor at the NS
- Angular velocity of NS is larger than of disk/ejecta
- **Magnetocentrifugal force associated with NS** plays an significant role for surrounding matter and ejecta *if dissipation timescale of B-fields in NS is not short*
- **Mass ejection and ejecta kinetic energy are enhanced significantly**

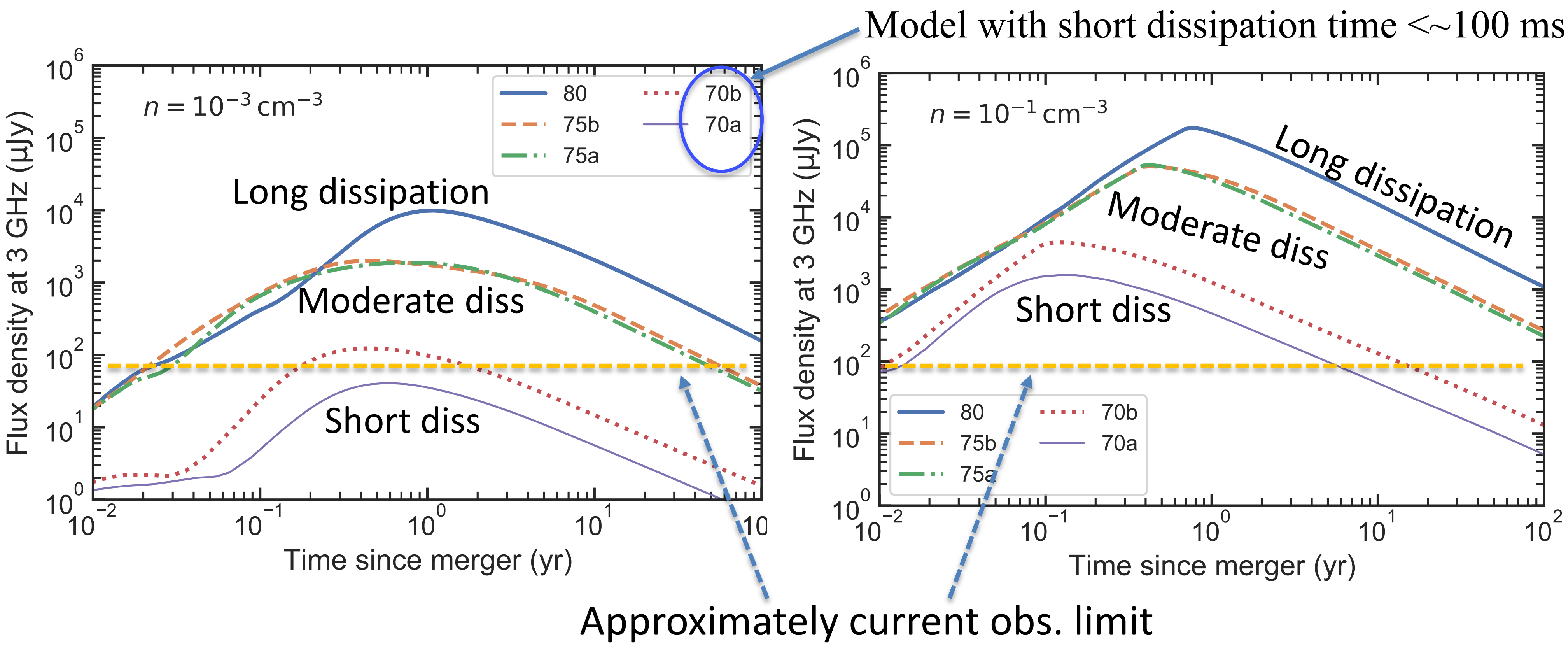
Maybe, the most extreme possibility

Quantities for ejecta



Black: viscous, others: MHD with different choice of parameters

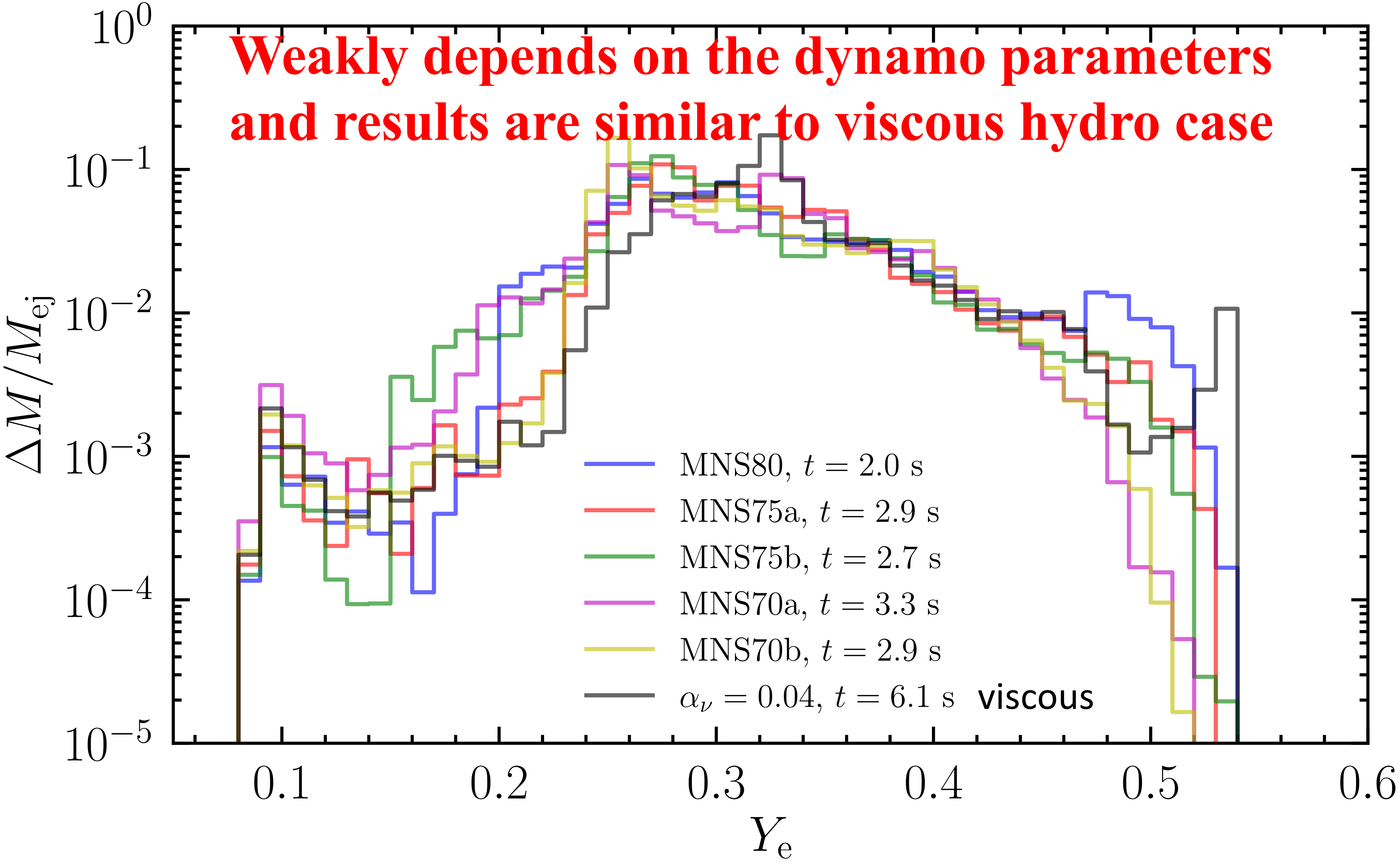
Radio light curve model (Kawaguchi et al. ApJ, 933, '22)



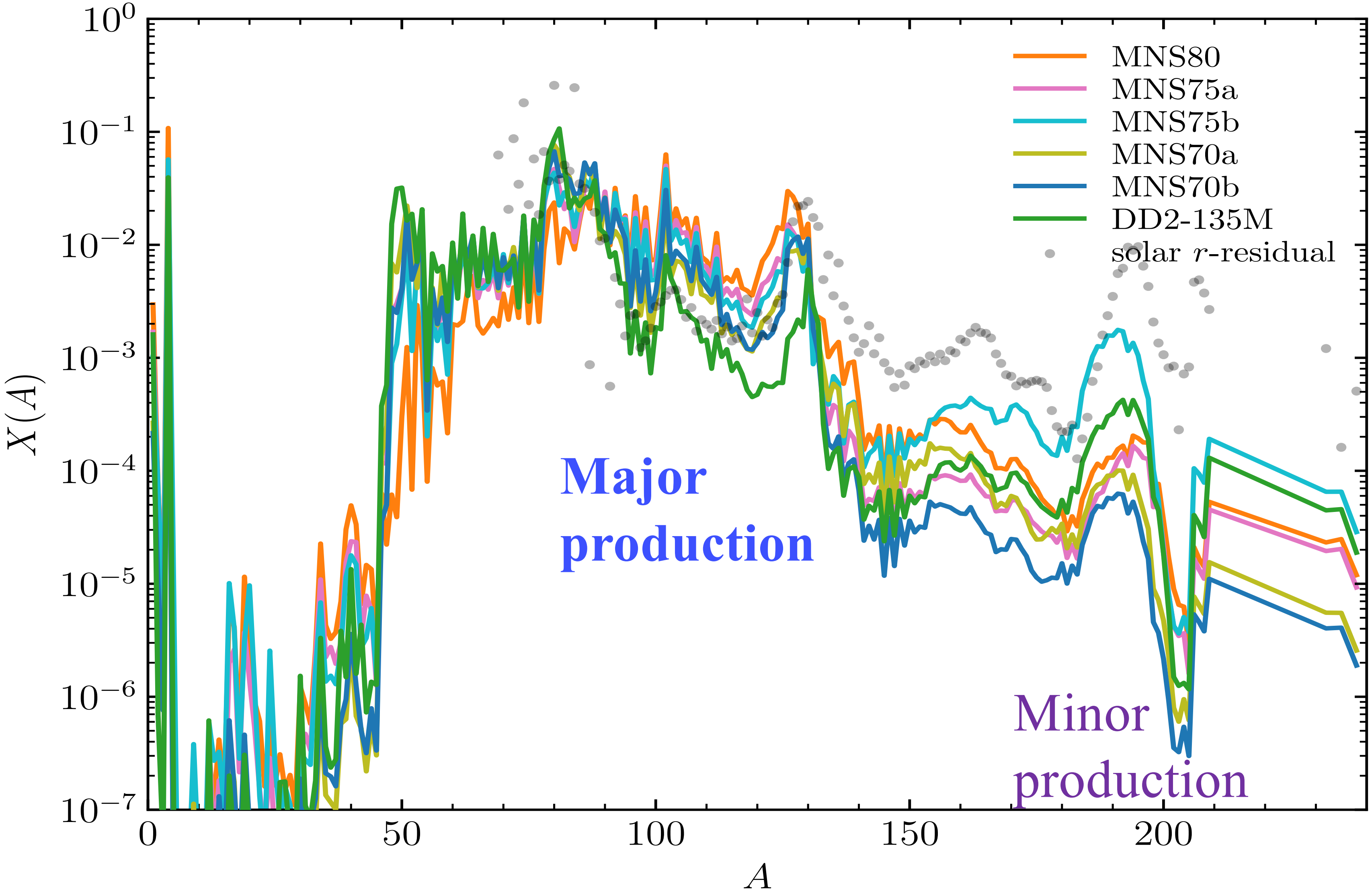
Synchrotron radiation models with
ε_e=0.1, ε_B=0.01, p=2.2, and D=200Mpc

Could be very bright for >~ 10 days if strong global B-fields are present for > 100—200 ms after merger

Electron fraction



Nucleosynthesis result by Wanajo



✓ **Overproduction of light elements with A < 100**

➔Abundance pattern does not agree with solar one

✓ **Unlikely to be a typical remnant**

IV Conclusion

- Long-term numerical-relativity simulation from late inspiral to merger & post-merger is feasible now
  → "Standard scenarios for merger & post merger"
- Properties of dynamical and post-merger ejecta can be studied in a self-consistent way by GRRMHD
  if the merger remnant is a black hole
- Remaining task 1: In the presence of a remnant NS, we still do not understand the details, but something violent may happen
- Remaining task 2: Sophisticated radiation transfer code is necessary to better quantify the post-merger ejecta property

Thank you very much!