Neutron Star Merger Simulation
- our latest progress -

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Outline

I. Introduction

II. NS-merger & post-merger simulations separately

III. Seconds-long BHNS-merger simulations

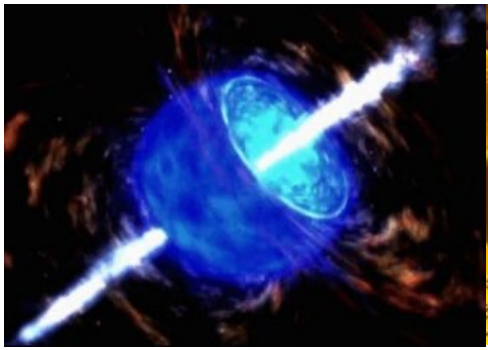
IV. Issues

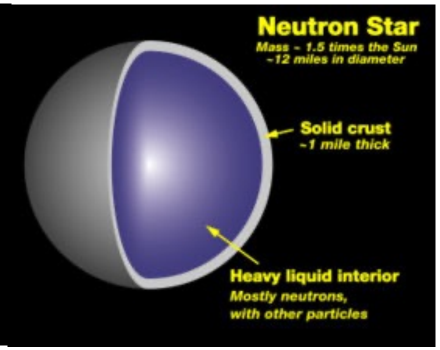
I Introduction

Neutron star mergers are 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/macronovae (e.g., Li & Paczynskii, 1998)
- Invaluable site for studying nuclear equation of state through GW detection (e.g., Lai et al. '93, Hinderler, '08,…..)

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

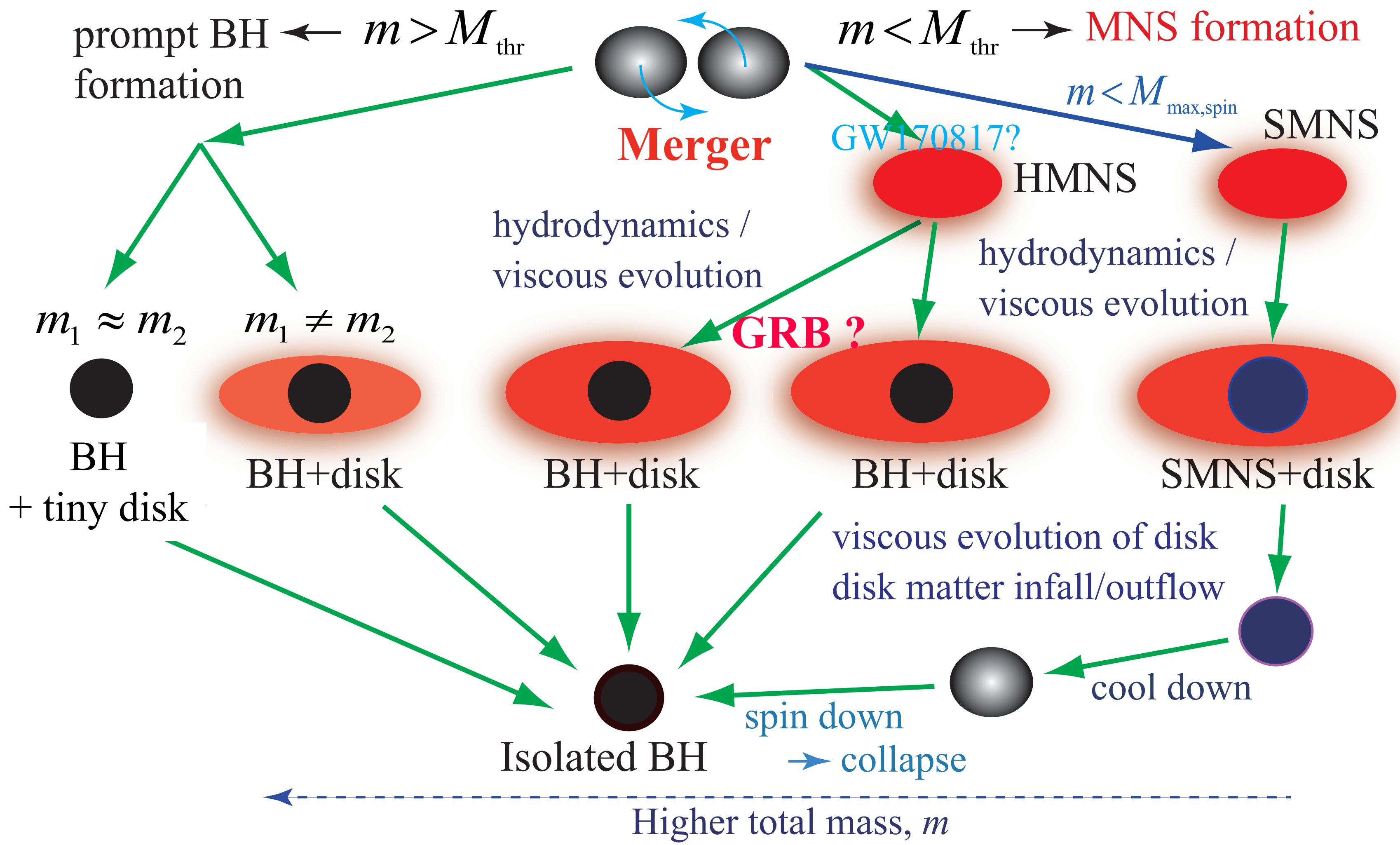


Variety of NS-NS merger process

Likely minority but could occur
(GW190425)

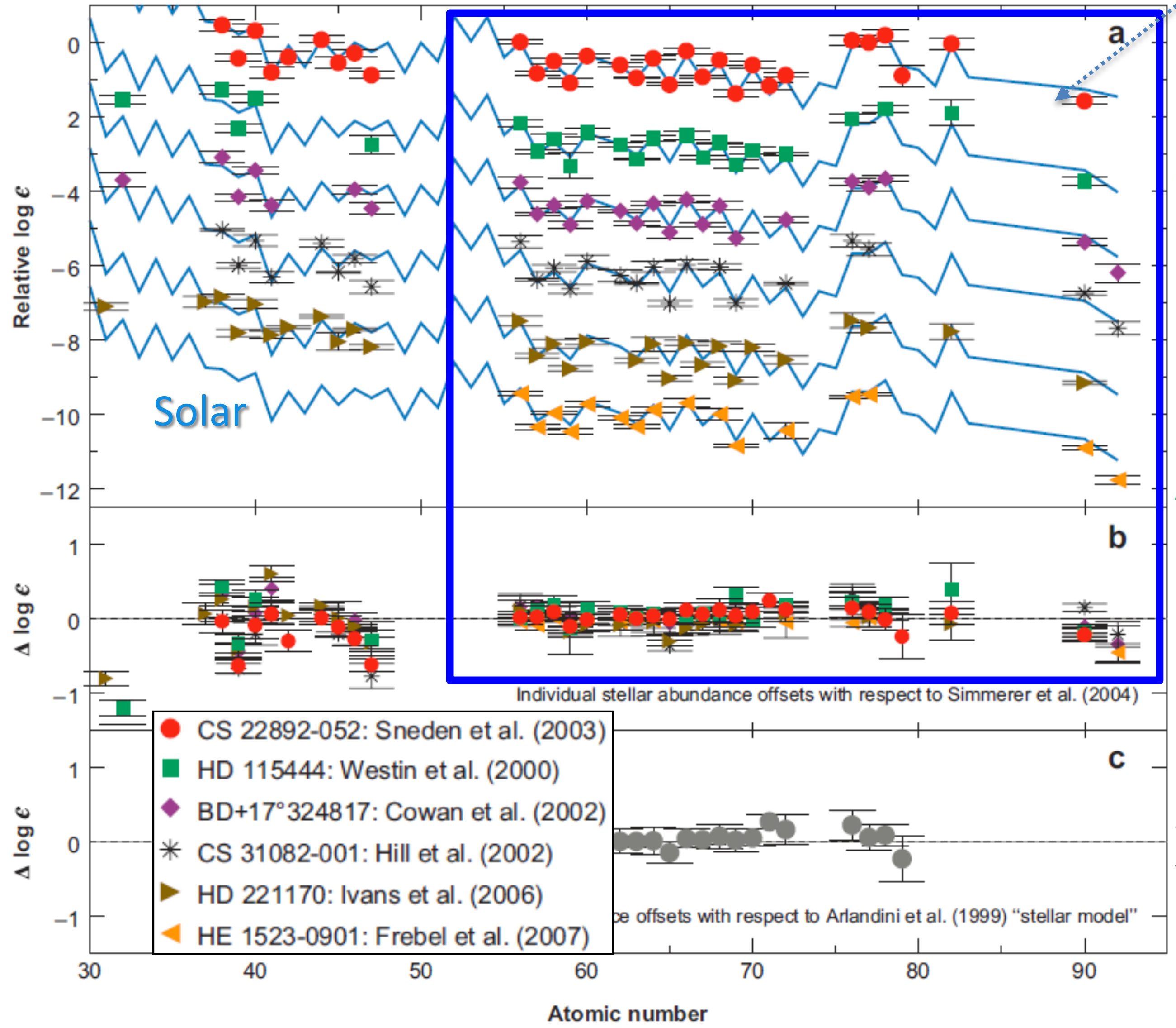
Typical Cases (galactic binary pulsars):
***m*= 2.5—2.8*M*$_{\text{sun}}$** (e.g., GW170817)



Naively thinking, there should exist a variety of electromagnetic counterparts

Universality

Solar-abundance pattern of *r*-process elements



The abundance patterns agree with each other for Z>~55 irrespective of the observed stars:

This suggests that the *r*-process events synthesize heavy elements with a pattern similar to the solar patter

But, note the fluctuation around the light elements

Sneden et al. (2008):

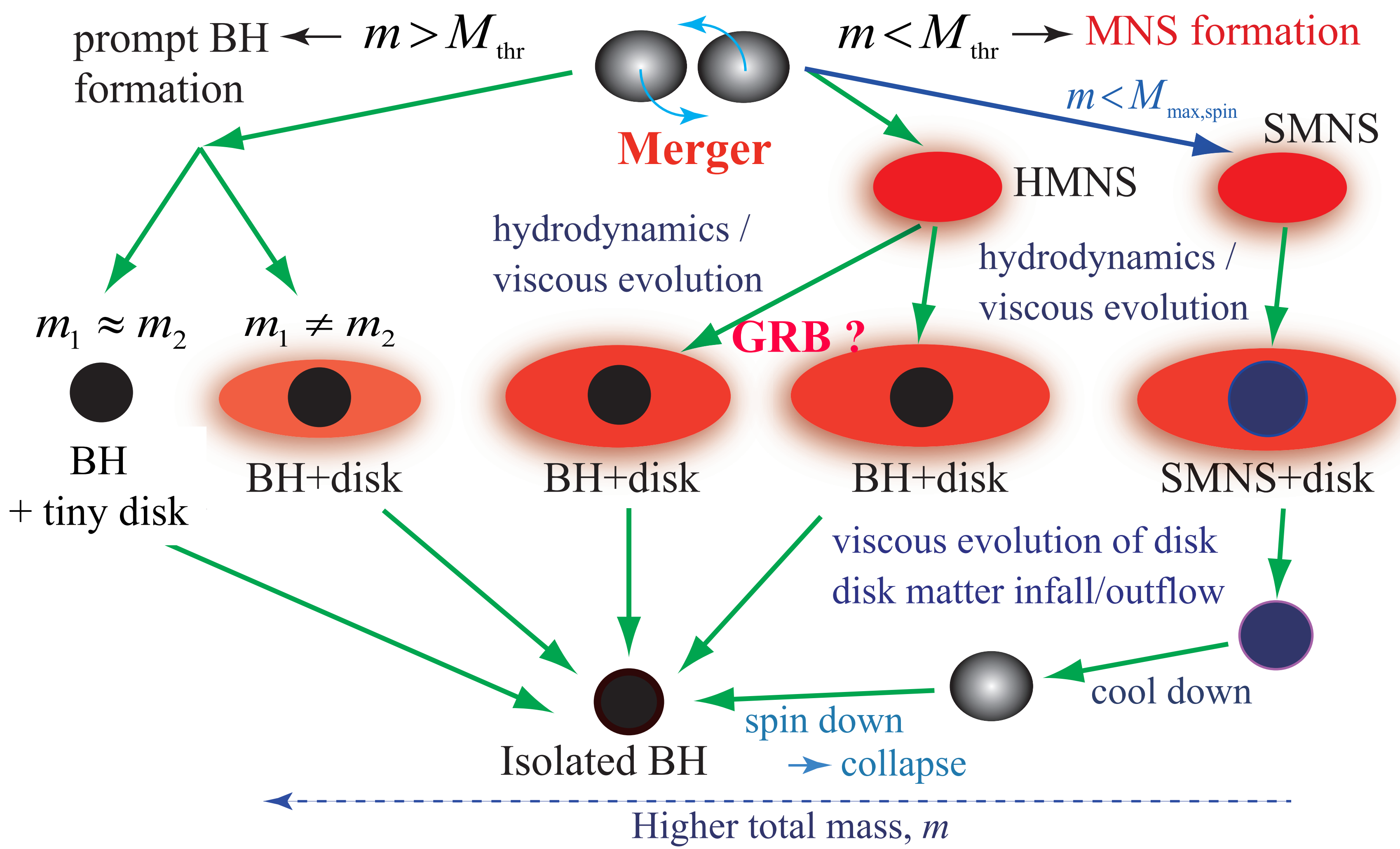
Courtesy of Sekiguchi's presentation

Can NS merger reproduce this?

Variety of NS-NS merger process

Likely minority but could occur (GW190425)

Typical Cases (galactic binary pulsars): $m = 2.5$—$2.8 M_{sun}$ (e.g., GW170817)



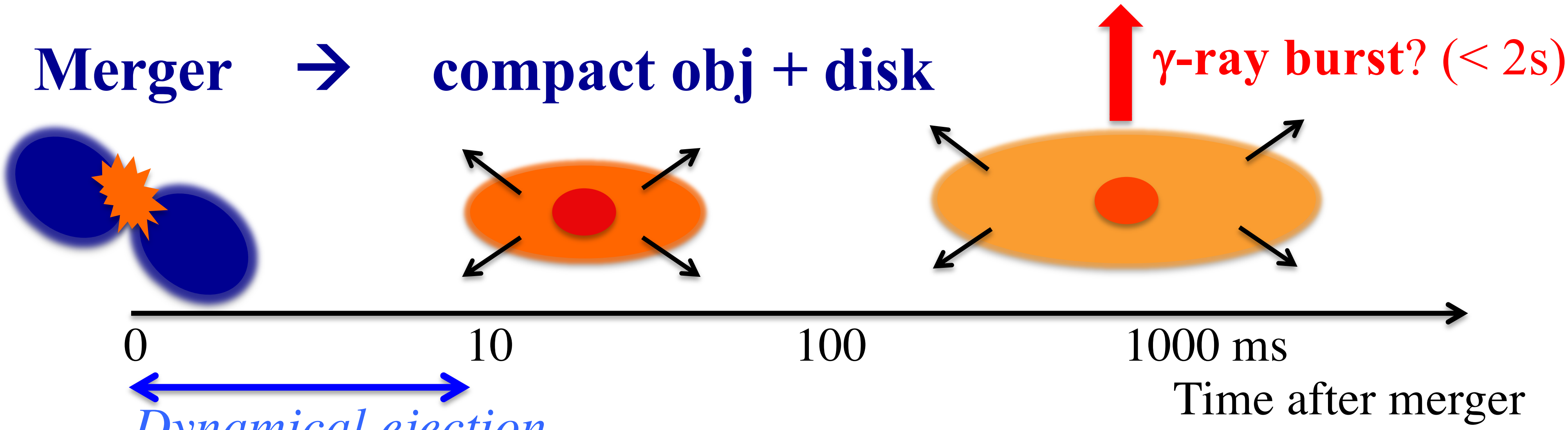
Naively thinking, there should exist a variety of nucleosynthesis abundance pattern

Roles of merger simulations in NR

1. To provide information to predict signals (EM, GW, CR, ν) associated with mergers for the future events
2. To explore nucleosynthesis: e.g, whether the universality is reproduced & what are observable lines for heavy elements? (talk by Hotokezaka)
3. To prepare a setup for the post-process simulations; e.g., long-term evolution of ejecta associated with kilonova & its afterglow, jet simulations, etc.

Time line after the merger: *to be studied*

Merger → compact obj + disk



Dynamical ejection
by shock heating/tidal effect
(proceeds in < 10 ms)

Key: Angular momentum transport

MHD/viscosity-driven post-merger ejection
(in MHD/viscous timescale of remnant disk ~ 1s)

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

A milestone goal of NS merger simulations

- <u>Important timescales</u>:

1. Dynamical mass ejection timescale ~ 10 ms
2. Post-merger mass ejection timescale ~ O(1) s
3. Short gamma-ray bursts: typically 1~2 s

→ **We need to evolve the post-merger system at least for ~10 sec**

➢ Input physics is also important

- ***MHD/viscous effects*** *are the key to PM evolution*
- ***Weak processes*** *are the key to nucleosynthesis*

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

Two ways

1. Merger (<~100 ms) + post-merger simulations separately (e.g., talk by Francois)
2. Seconds-long self-consistent simulation

✓ Nucleosynthesis, kilonova & its afterglow, GRB jets are analyzed as a post-process

II Merger & post-merger separately

- We have been working on this for the last five years: Popular way currently
- A solid way to specifically explore two mass ejection mechanisms

A Dynamical mass ejection from NS-NS

(ejection within ~ 10 ms after the merger)

- Many *numerical-relativity* simulations have been done since 2013 → **Well understood besides quantitative details**

◆ What we have learned are

- Mass=10^{-4}~10^{-2} M_{sun} (Hotokezaka, Sekiguchi, Foucart, Radice…., now it is routine work): For *low total mass (MNS formation)*, it is <~10^{-3} M_{sun} but could be higher for HMNS case
- **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)

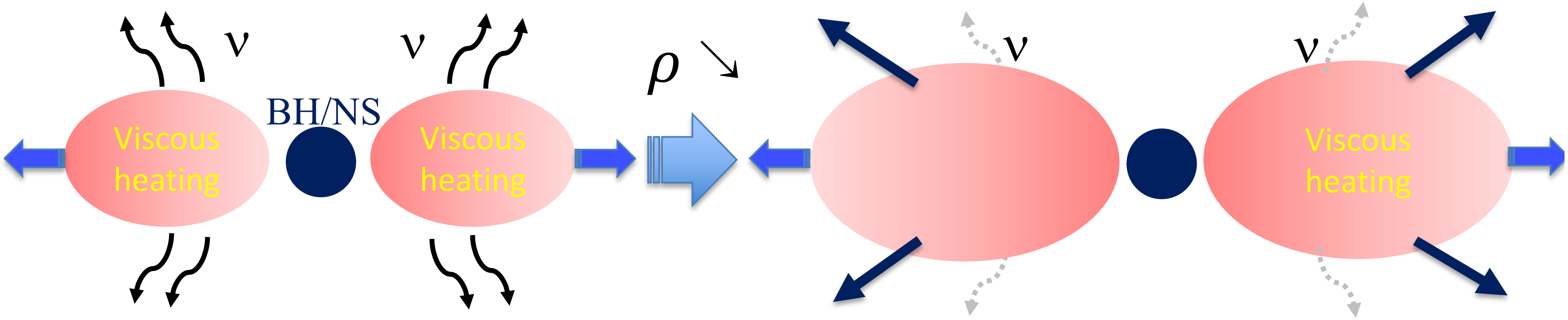
→ **Post-merger mass ejection from disk/torus**

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

→ ***M_{eje}* ~ 0.05–0.1 M_{sun} *for long-lived NS formation*, 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*)** (e.g., Metzger & Fernandez '14, Just+ '15, '21, Fujibayashi+ '18, '20, Miller '19)

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



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

No viscous mass ejection;

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

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

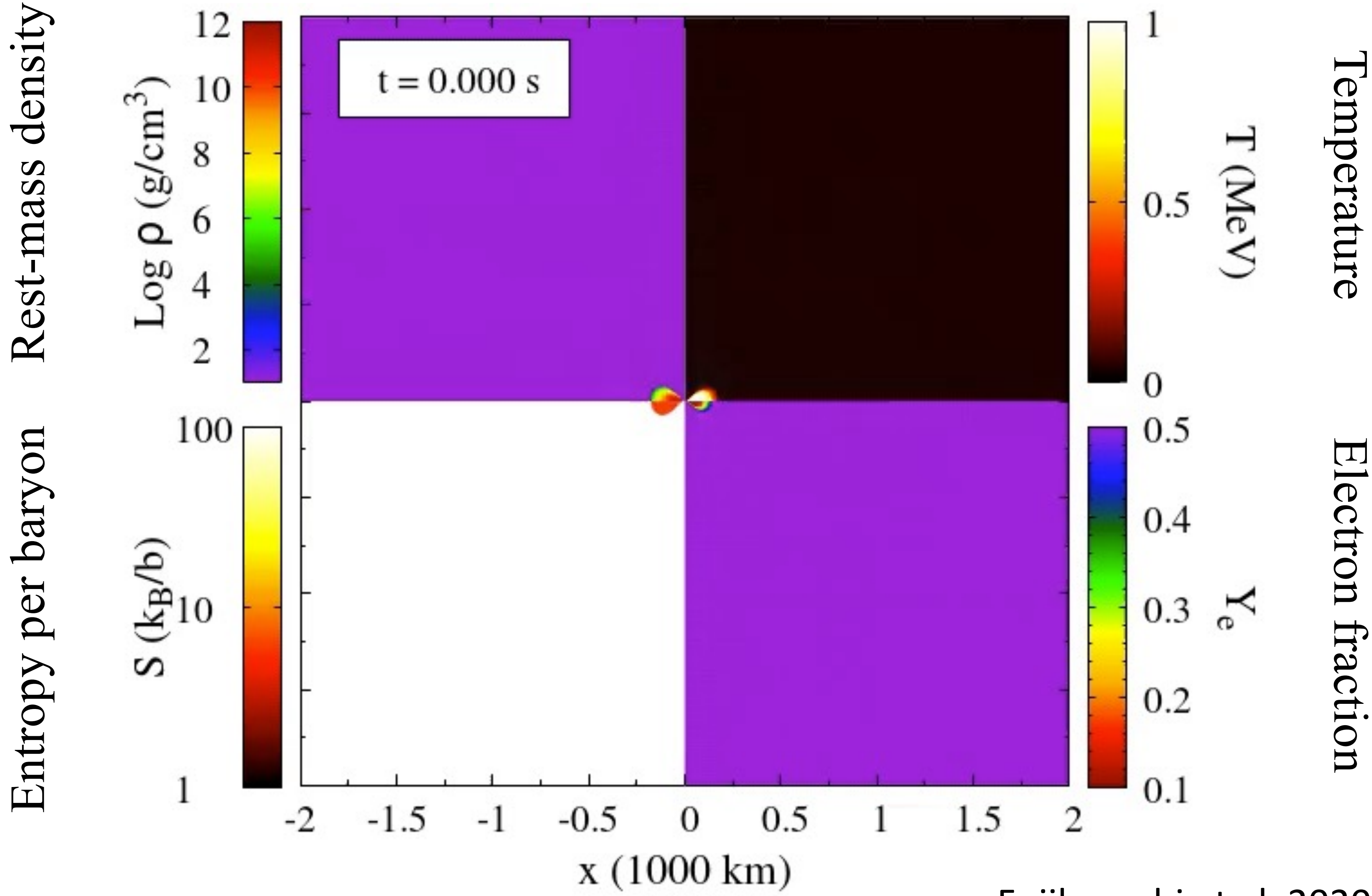
Viscous heating is fully used for matter expansion →

Onset of viscous mass ejection

Viscous angular momentum transport timescale ~ sec

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

Viscous hydro simulation in full GR: 3 solar mass BH + 0.1 solar mass disk (α=0.05)



Fujibayashi et al. 2020

How Y_e of disks/ejecta is determined?

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

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

→ Y_e is determined by $\mu_p + \underline{\mu_e} = \underline{\mu_n} + \cancel{\mu_\nu}$

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

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

- For $\boldsymbol{T_{max}}$**< ~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, $\boldsymbol{Y_e \sim 0.3}$

→ **Heavy *r*-elements production is suppressed**

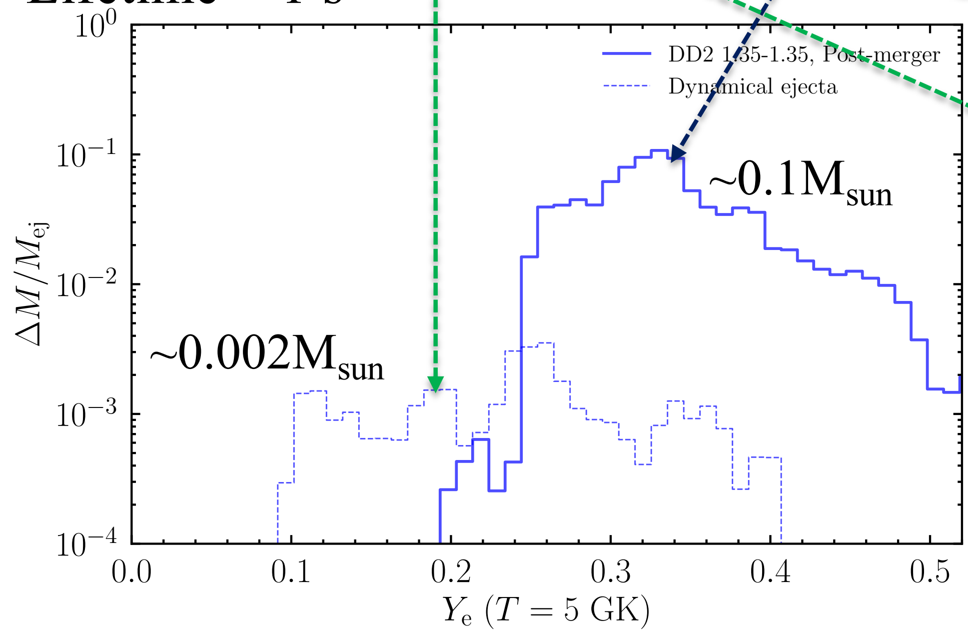
Y_e distribution: Two components

Results from 3D merger + 2D post merger simulation

Low Y_e (neutron-rich) ejecta by dynamical ejection

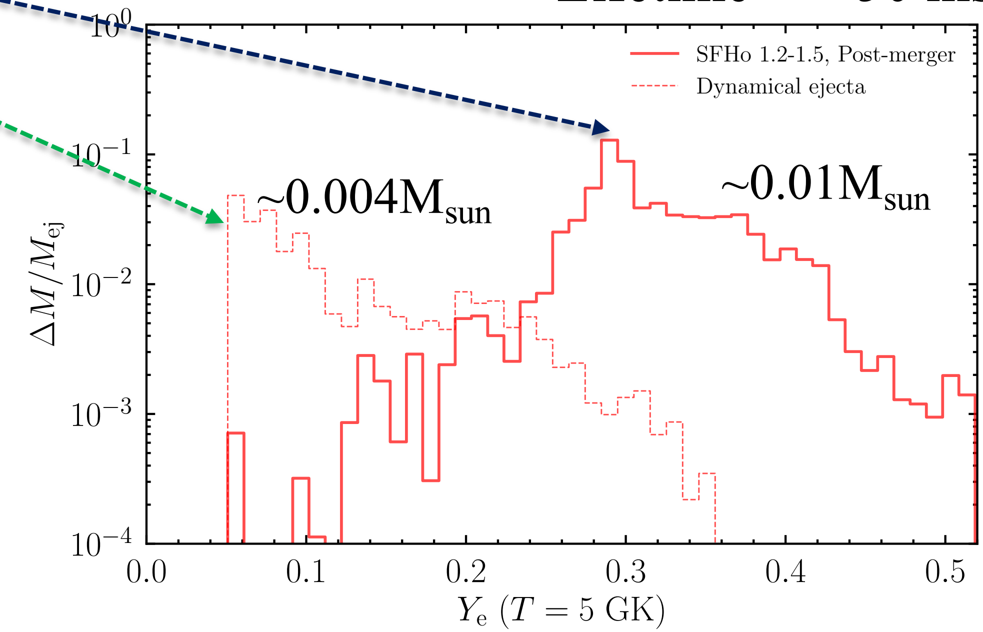
High Y_e by post-merger ejection

Lifetime > 1 s



Long-lived MNS case

Lifetime < ~ 50 ms

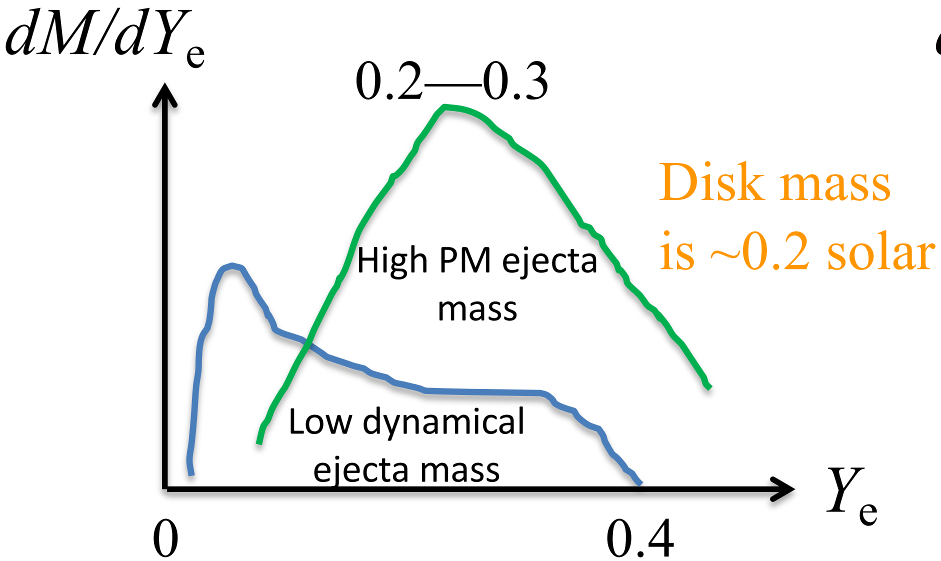


Short-lived MNS → BH case

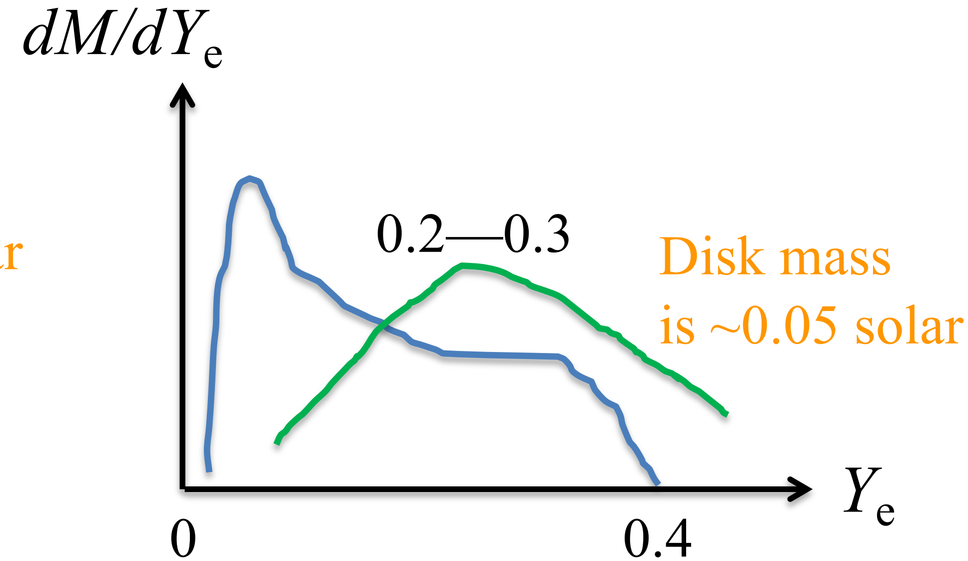
Numerical relativity results by Fujibayashi et al. arXiv: 2205.05557

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

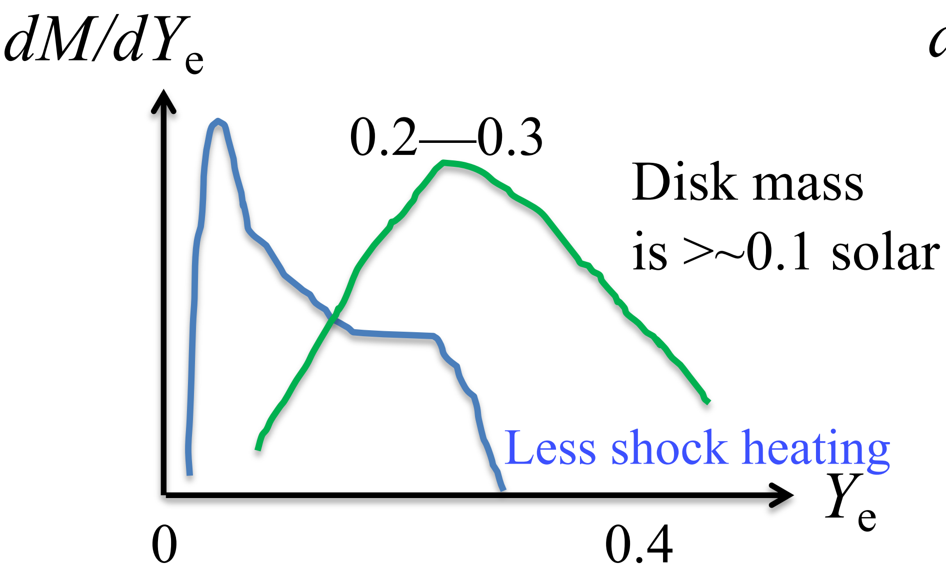
Broadly speaking there are four patterns



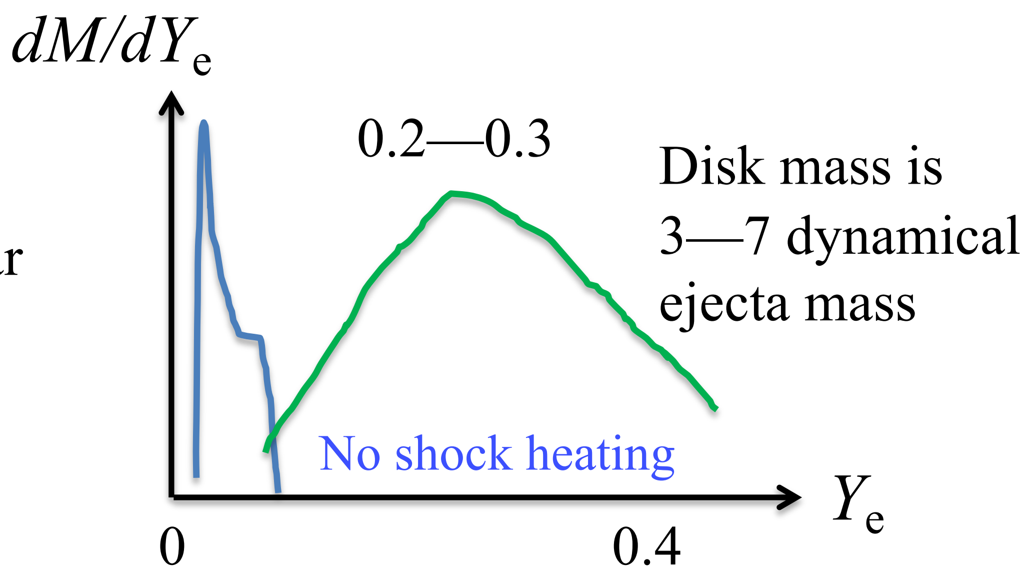
NS-NS→ long-lived NS (Magnetar)



Symmetric NS-NS→ short-lived NS



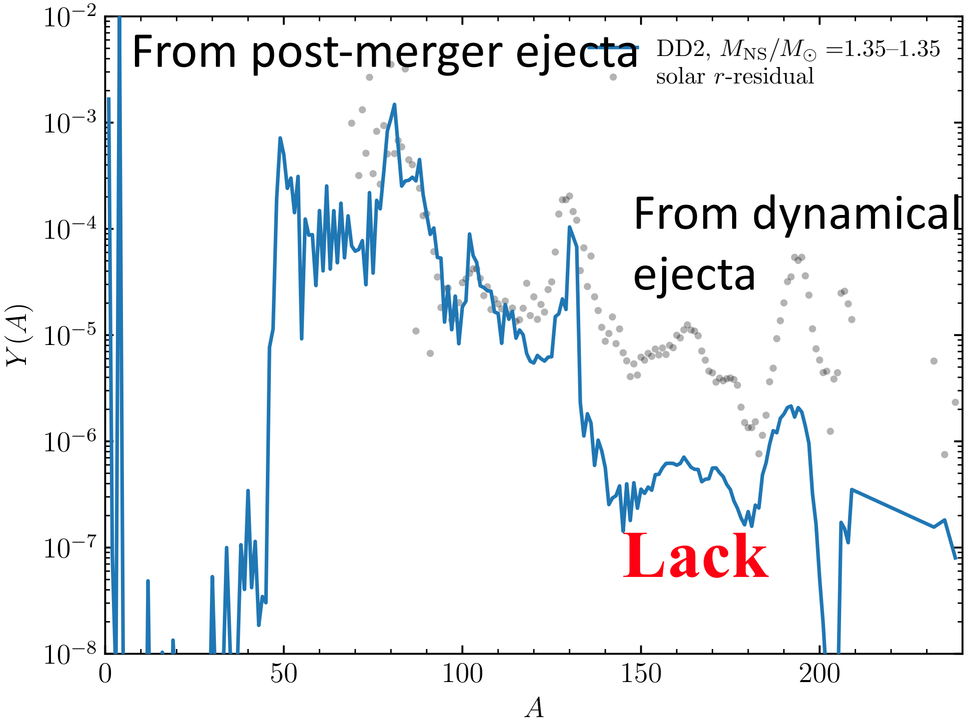
Asymmetric NS-NS→ short-lived NS



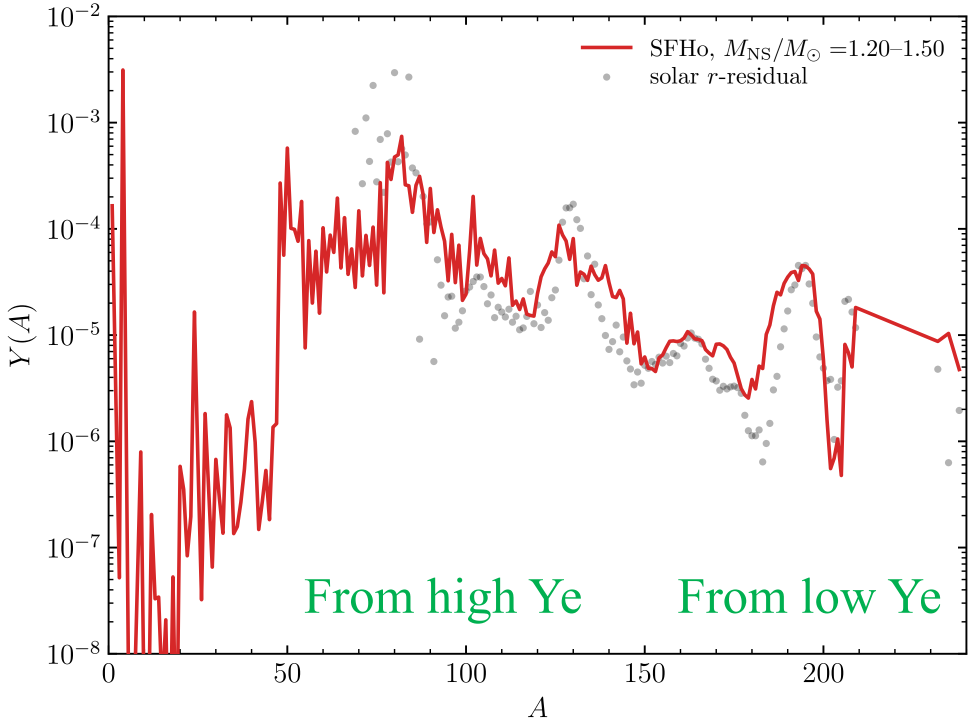
BH-NS→ BH + disk

Nucleosynthesis for MNS vs BH formation

See Fujibayashi et al. 2022; arXiv: 2205.05557



Circles: solar abundance



<u>Long-lived MNS case</u>

Under-production of heavy elements;

Over-production of light elements

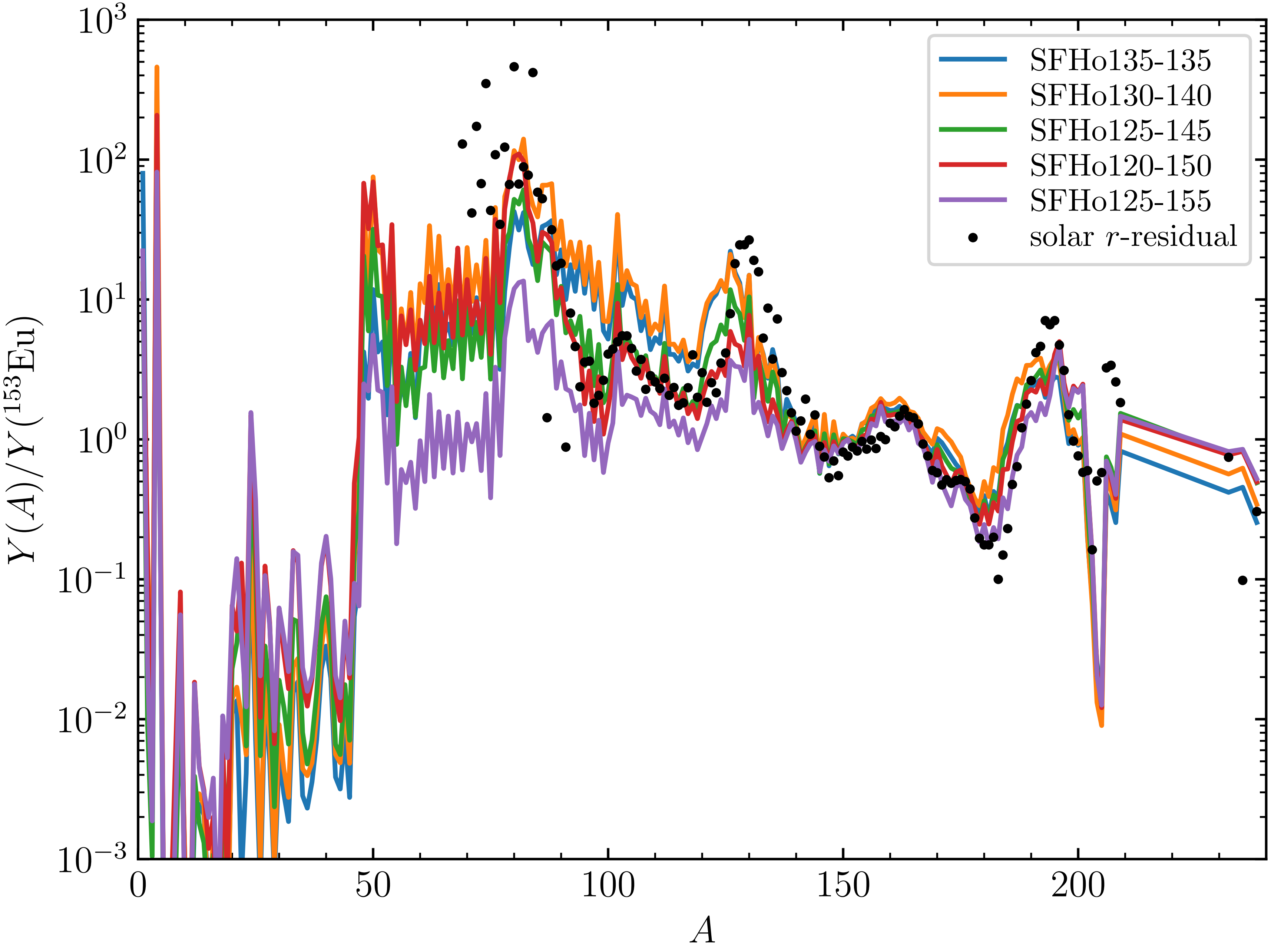
Too much post-merger ejecta

<u>Short-lived MNS → BH case</u>

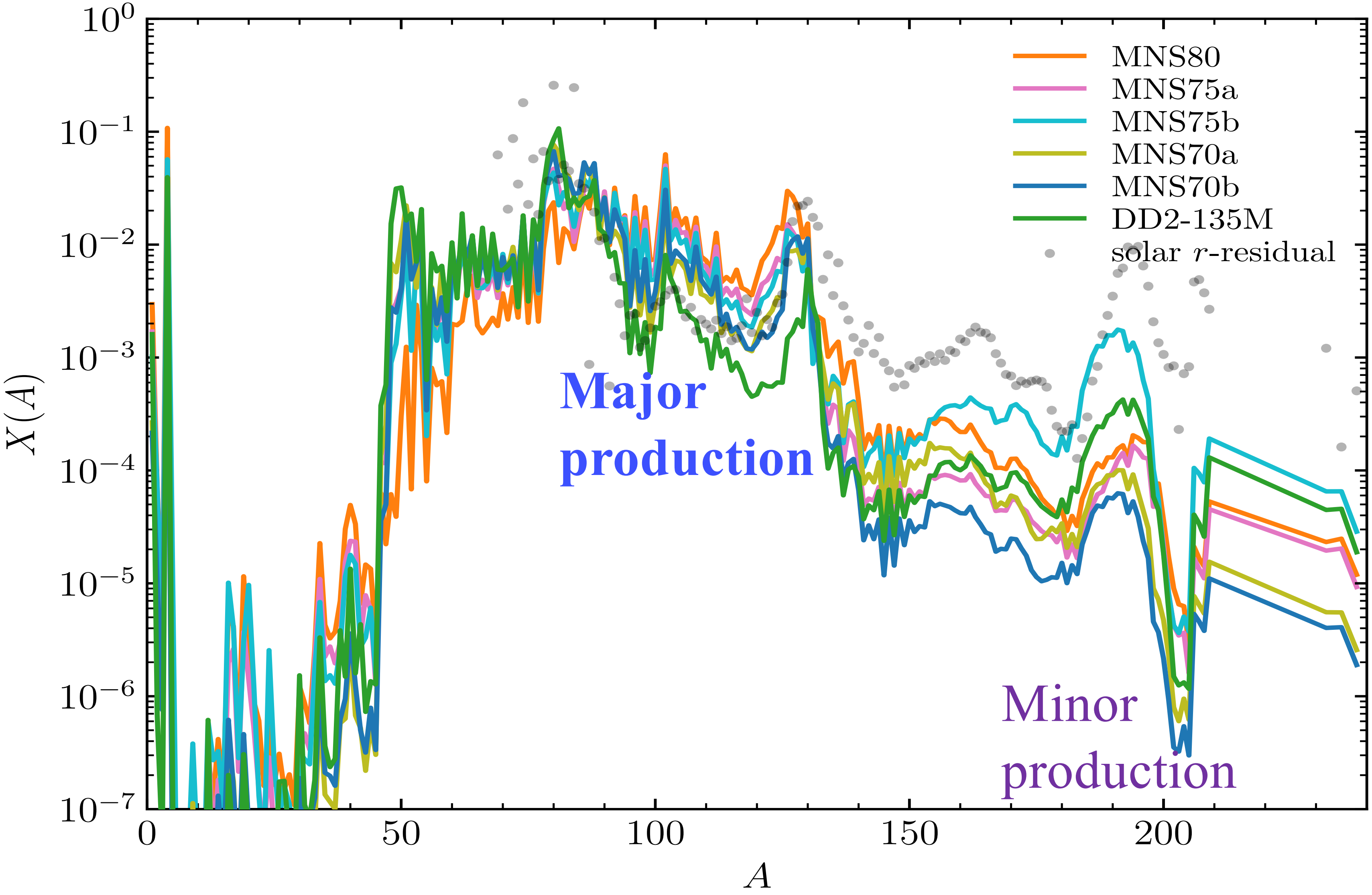
Good agreement with solar abundance!

Good blending of two comp.

A *fair* agreement with the solar abundance for the case that HMNS is short-lived



MHD effect does not significantly change the abundance pattern for long-lived MNS formation case



Shibata et al. PRD 104, 063026 (2021); Kawaguchi et al. ApJ in press

Prediction

- Only when the remnants of NS-NS mergers collapse to a BH in a short timescale (~10—100ms) after the merger, the *universality* can be reproduced
- Suppose that the NS-NS merger is the main site for the *r*-process nucleosynthesis. Then, **long-lived MNS formation should be a minority**

→ Short-GRBs from a remnant magnetar should be rare; consistent with the absence of radio sources (talk of KH)

In other words,

- In case many long-lived MNS formations are observed in the near future, the NS-NS merger scenario of the *r*-process nucleosynthesis may be excluded.

See Fujibayashi et al. 2022; arXiv: 2205.05557

III Seconds-long BH-NS merger simulation

K. Hayashi et al. arXiv: 2111.04621; PRD in press

- With the current computational resources, self-consistent simulations are feasible at least for BH-NS binaries because the length scale is larger than the NS-NS case:

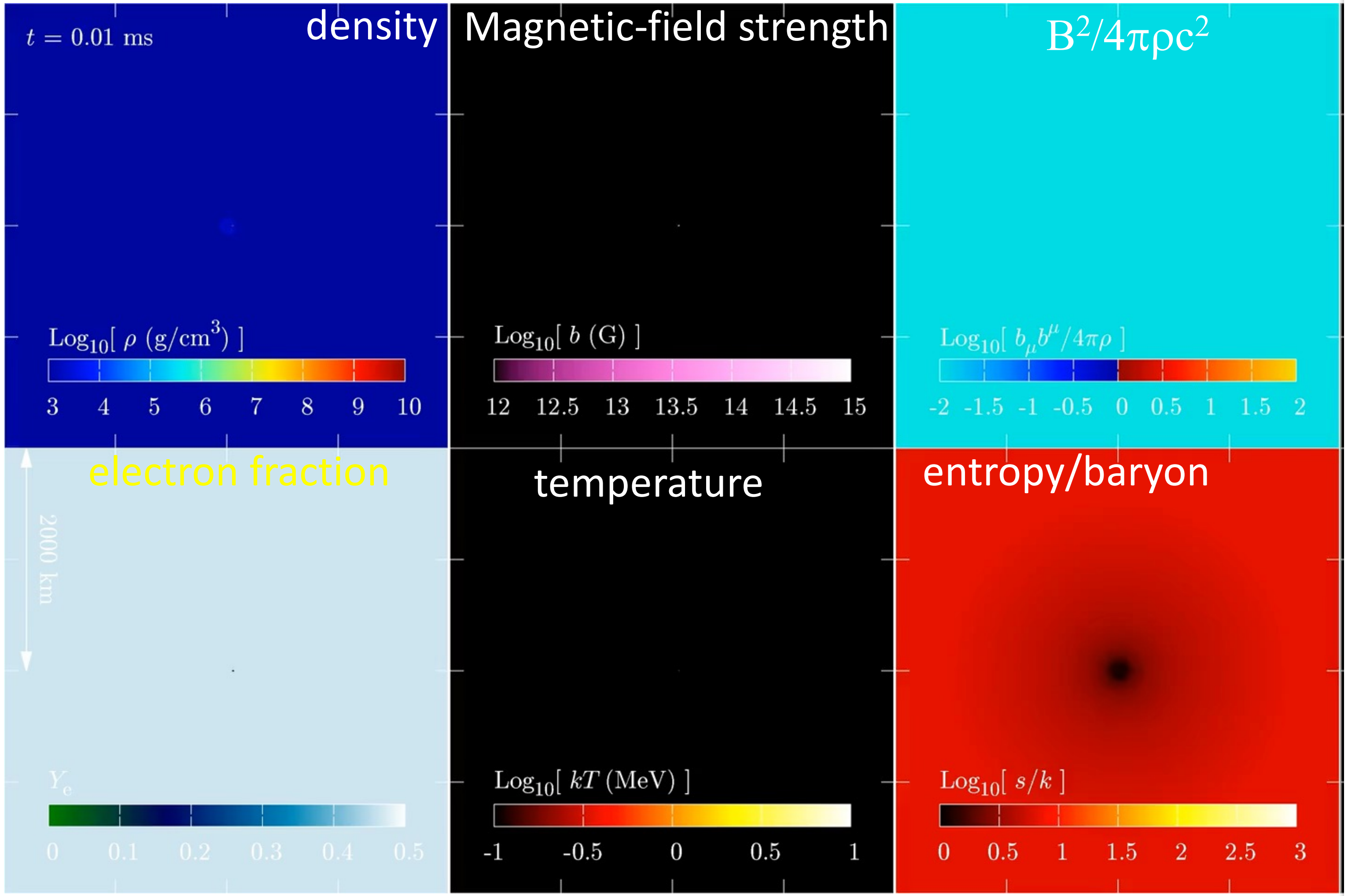
$$\Delta t \propto \Delta x \propto M_{BH}(< \sim 10 M_{\odot})$$

Focusing only on the case that NS is tidally disrupted

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

NS with strong dipole field initially

K. Hayashi et al. arXiv: 2111.04621



BH mass=5.4M_{sun}

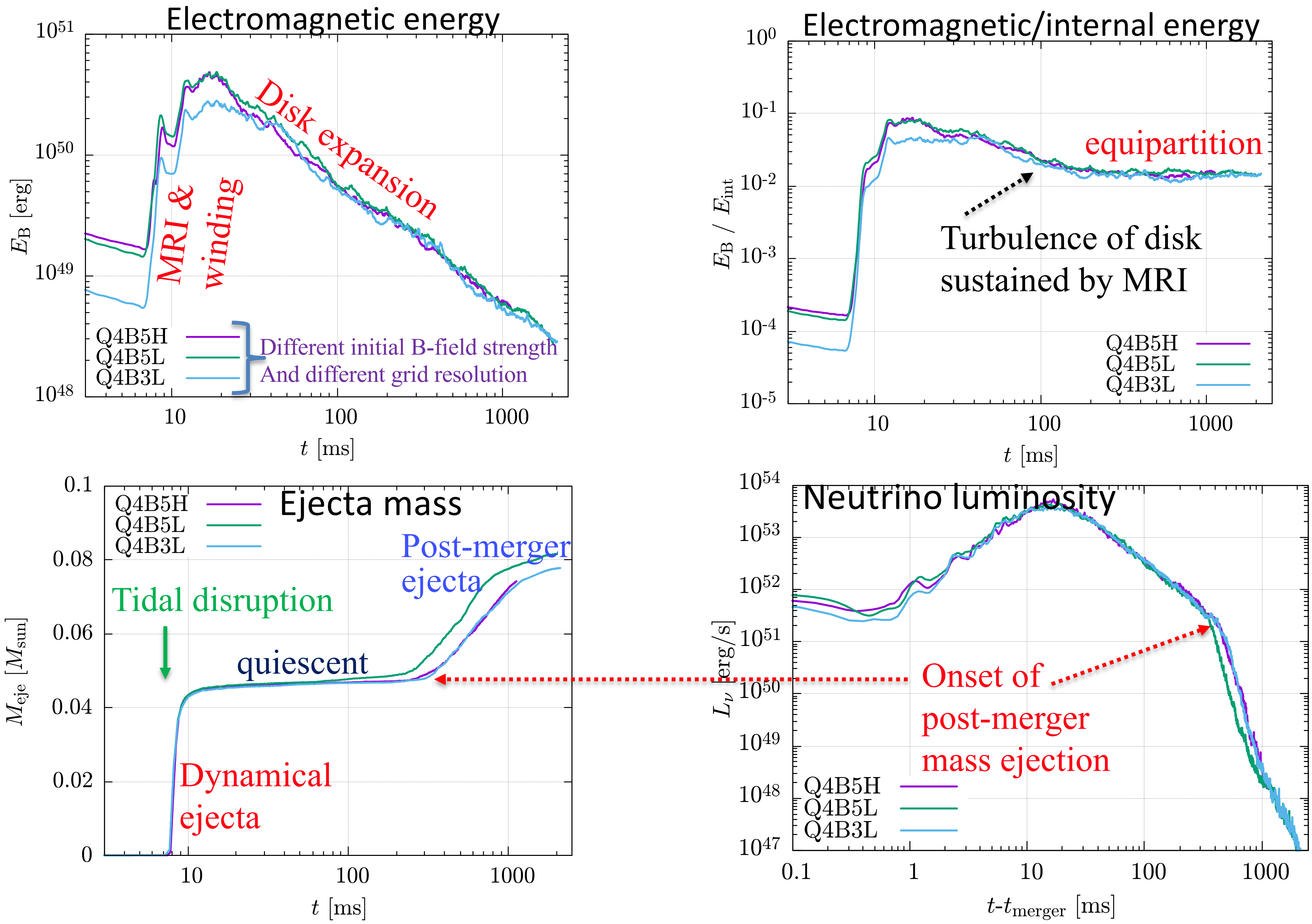
χ(spin)=0.75

NS mass=1.35M_{sun}

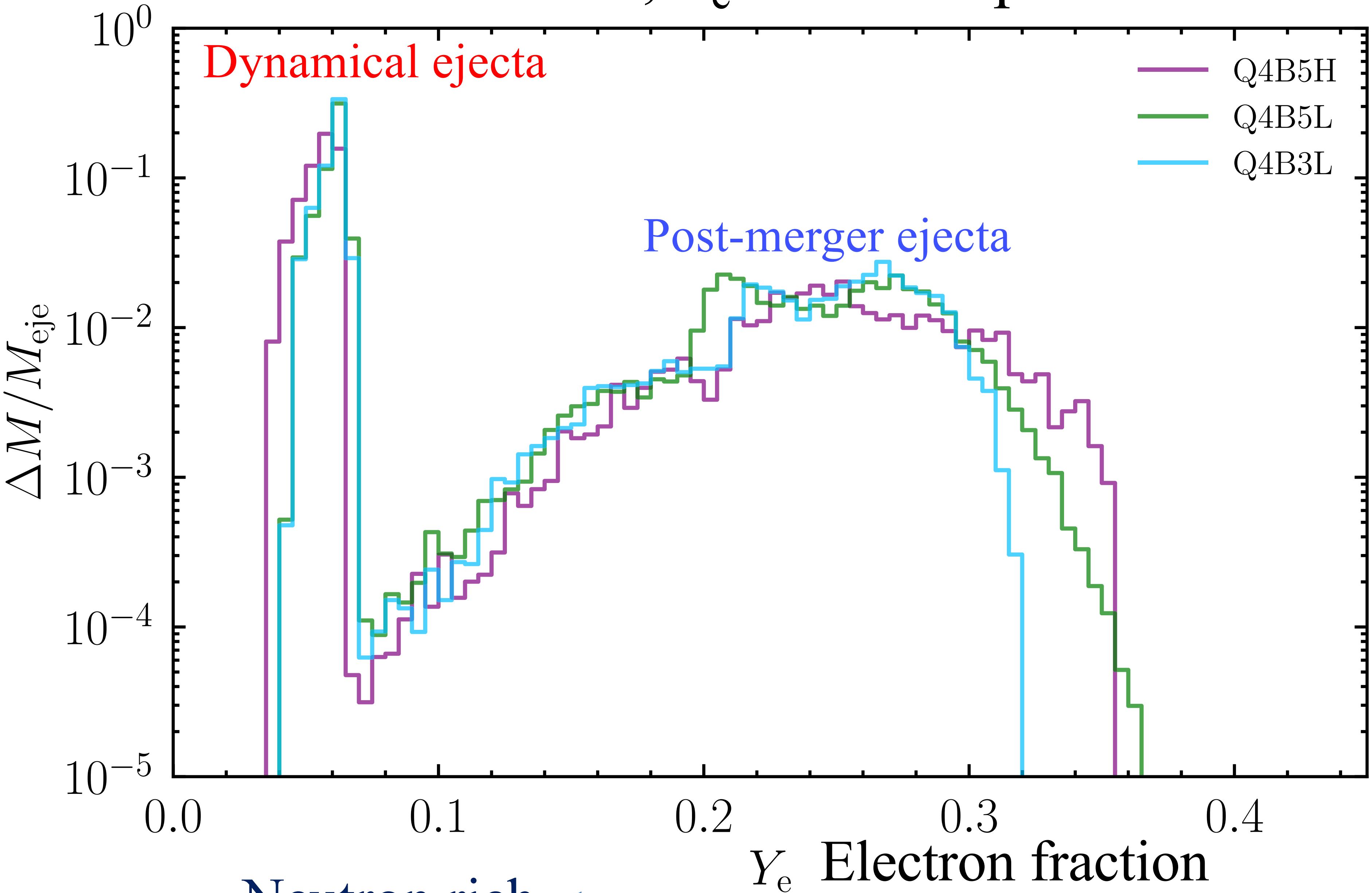
y=0 plane is displayed: [-2000,2000]km

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

Electromagnetic energy, mass ejection, neutrinos



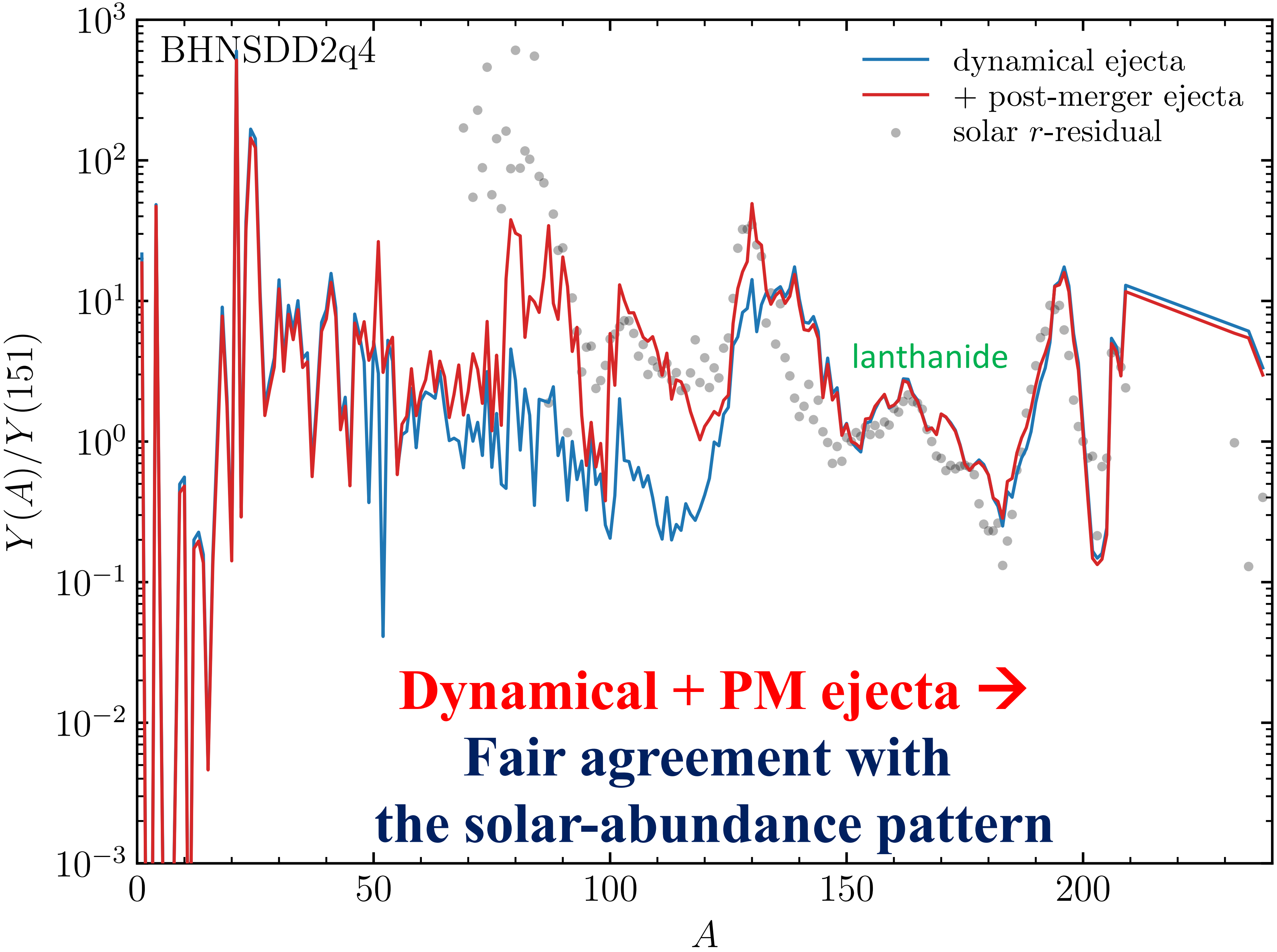
Electron fraction, Y_e: two components



Neutron rich

Consistent with the merger + post-merger studies

Nucleosynthesis: *Preliminary* by S. Wanajo

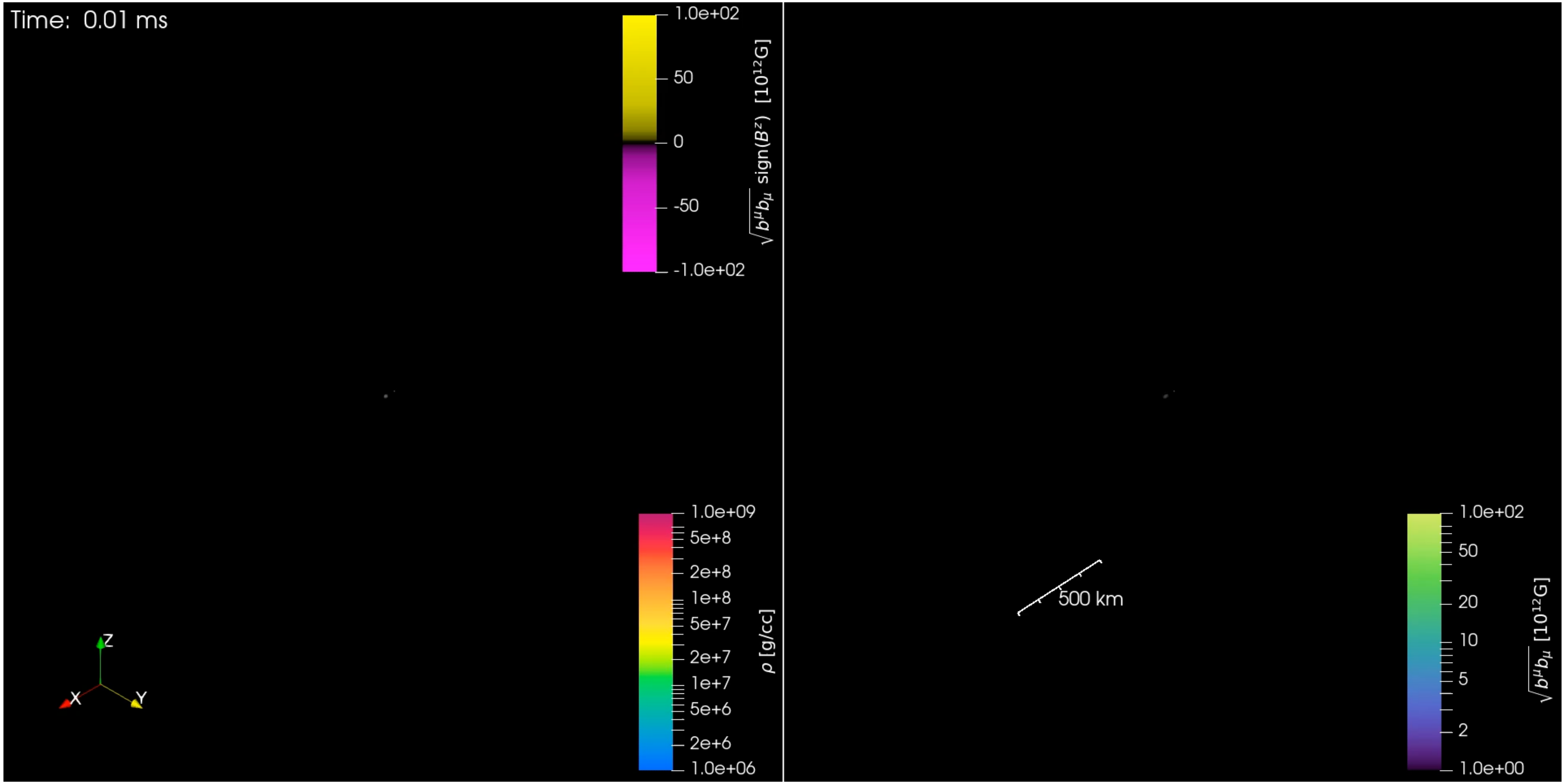


Dynamical + PM ejecta →

Fair agreement with the solar-abundance pattern

3D view: By Kota Hayashi

NEW: Absence of equatorial-plane symmetry



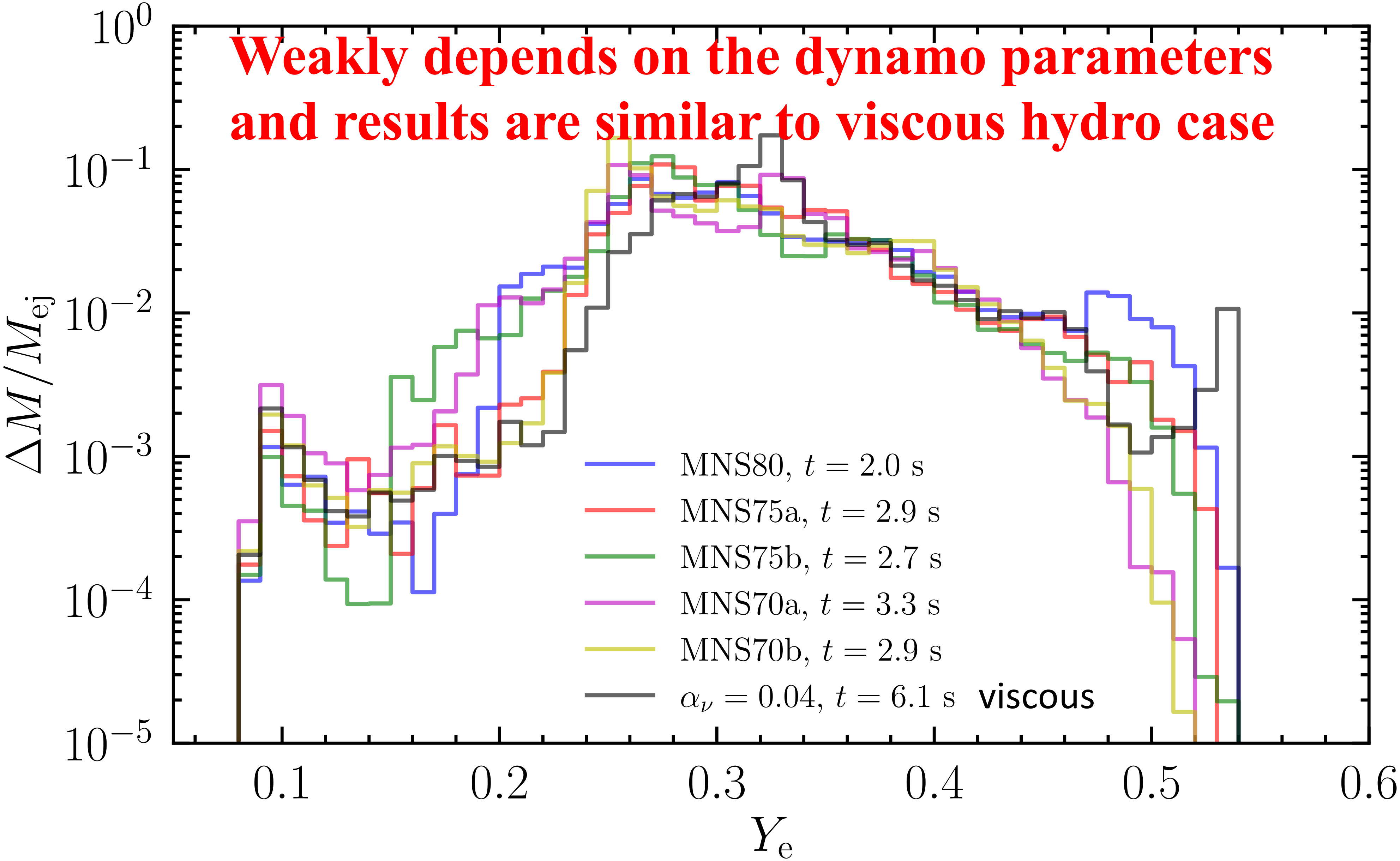
Rest-mass density + magnetic field lines

Magnetic-field strength

IV Issues

- ➢ Next step: Perform seconds-long simulations for binary neutron stars: Kiuchi is working on this now
- Improve weak interaction
- ✓ Better neutrino radiation transfer (never-ending issue)
- ✓ Neutrino oscillation (only qualitative study possible)
- Improve angular momentum transport
- ✓ MHD with high resolution (never-ending issue)
- Dynamo in remnant neutron stars (long-term simulation is needed; not yet seriously attacked)
- ✓ How global magnetic fields are developed in the presence of remnant neutron stars?

Electron fraction in resistive MHD+ dynamo terms



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