Mass ejection from binary neutron star merger and nucleosynthesis

Sho Fujibayashi

(Max Planck Institute for Gravitational Physics; AEI)

in collaboration with

Shinya Wanajo, Kenta Kiuchi, Koutarou Kyutoku,

Yuichiro Sekiguchi, and Masaru Shibata

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SF et al. (2020) ApJ 901, 122

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

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     - Dynamical ejecta
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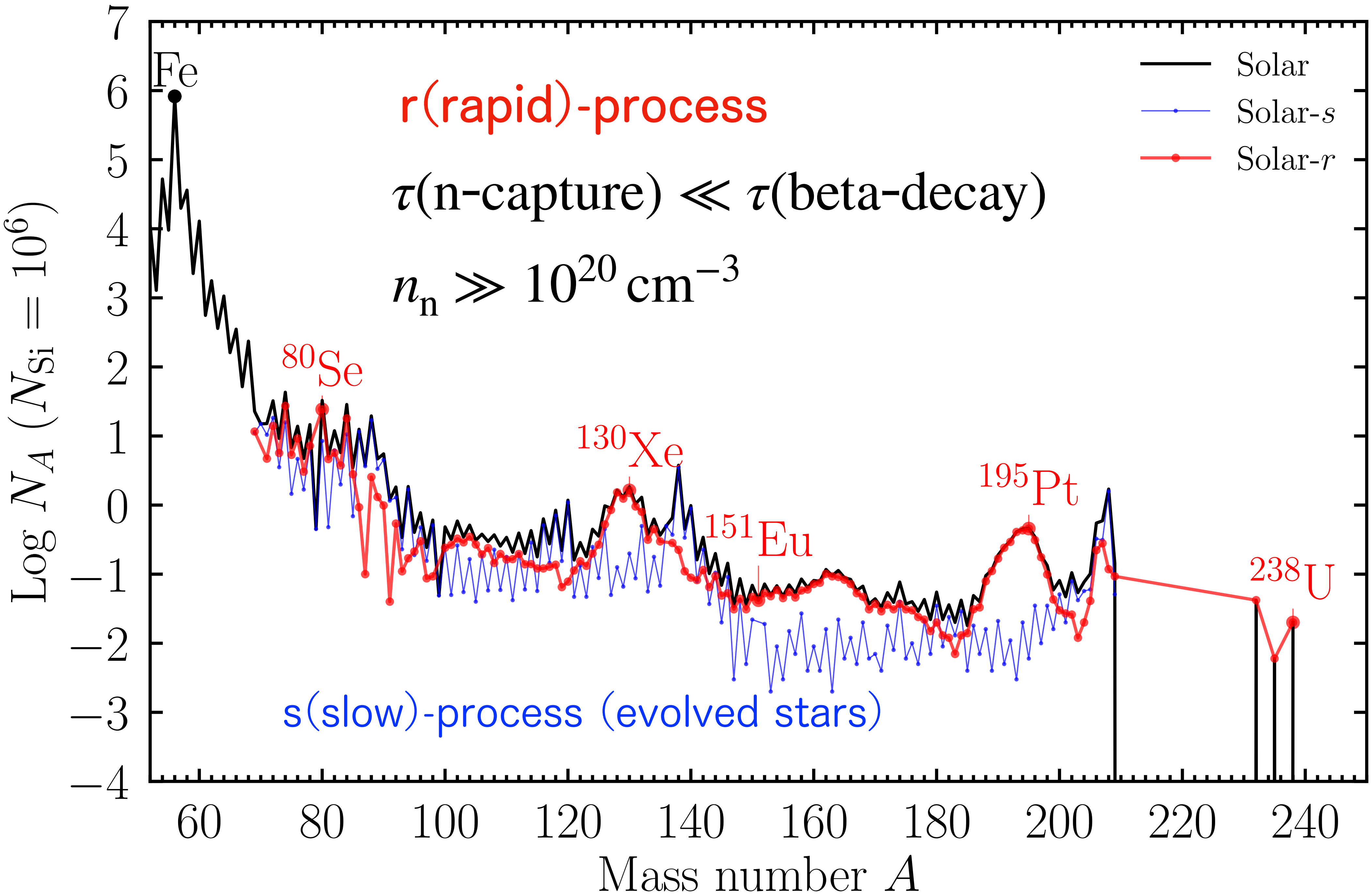
   - Long-lived massive NS case
3. (in short) BH-NS mergers
4. Summary

I. Introduction

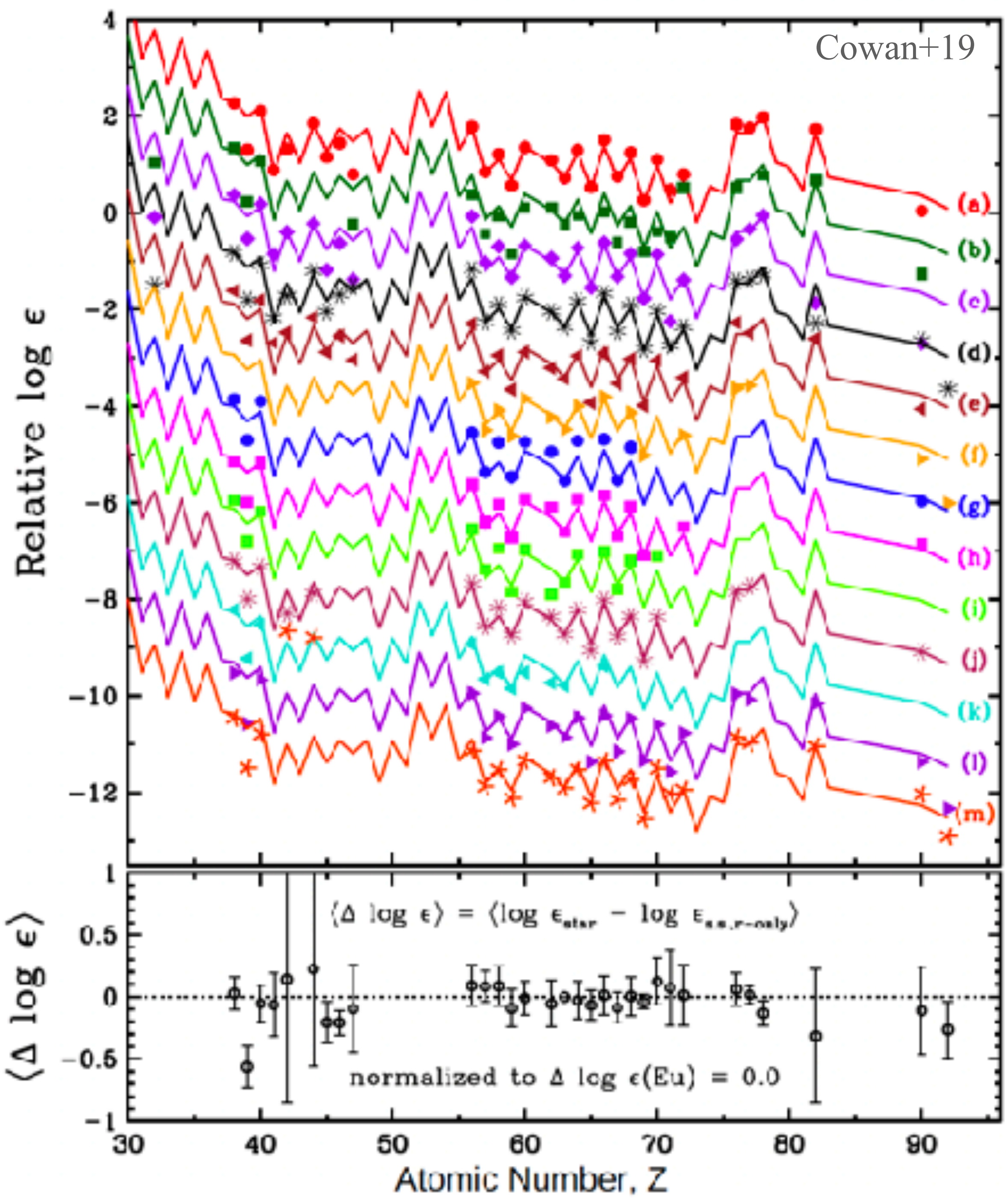
Processes making nuclei heavier than iron



NS mergers are ideal places for the process

Robust pattern of the r-process in metal-poor stars

Abundance pattern in metal-poor stars $[\mathrm{Fe/H}] \lesssim -3$



Some metal-poor stars with enhanced r-process elements have a similar pattern to solar r-process pattern

Very old stars experienced only a few nucleosynthesis events.
They may have imprint of a single event.

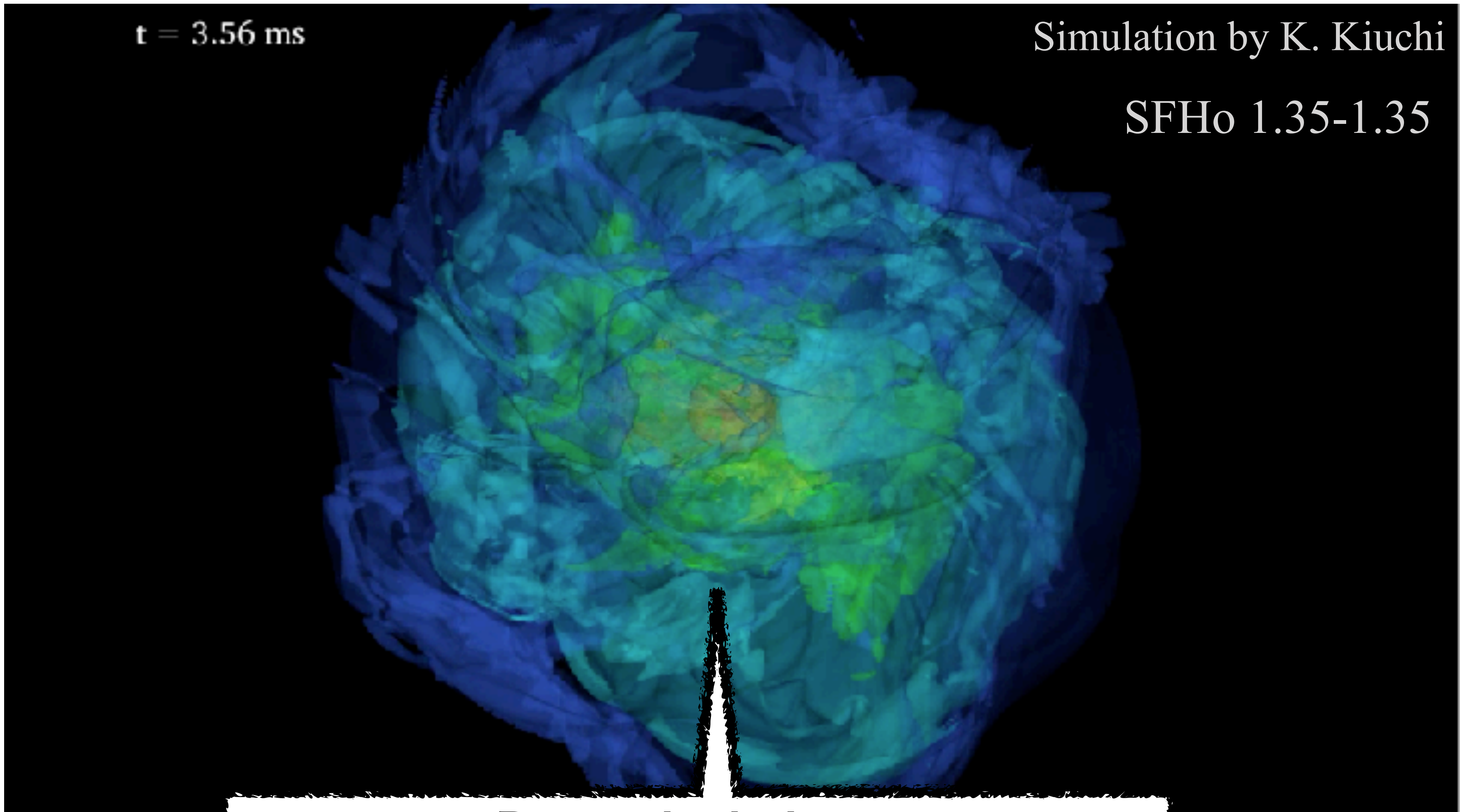
Constraint:
Each r-process enrichment event has to provide the solar pattern.

(elements with Z<50 have some scatter)

(There are some outliers with non-solar pattern)

Honda+ 06

Mass ejection in different phases



Dynamical ejecta

Due to tidal force and shock heating

e.g., Rosswog+ '99,
Hotokezaka+ 13, Bauswein+ 13; Palenzuela+ 15,
Sekiguchi+ 15, Foucart+ 15, Radice+ 18, Kullmann+ 21

Activities in Post-merger phase

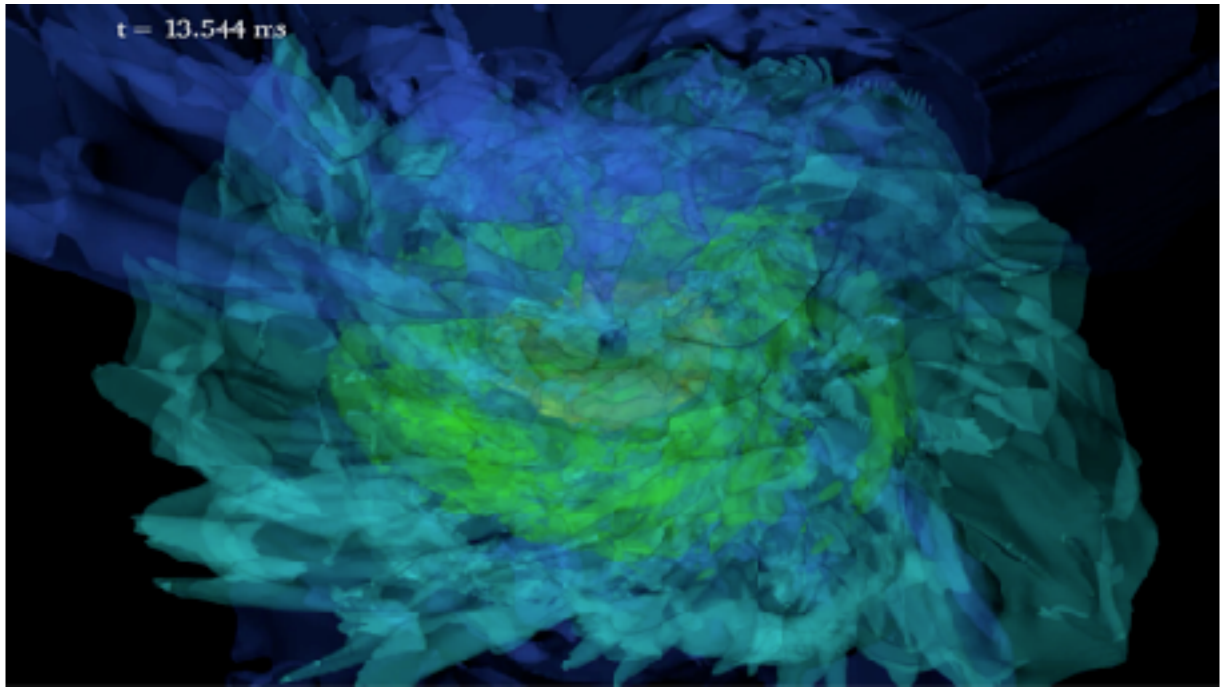
In post-merger phase. . .

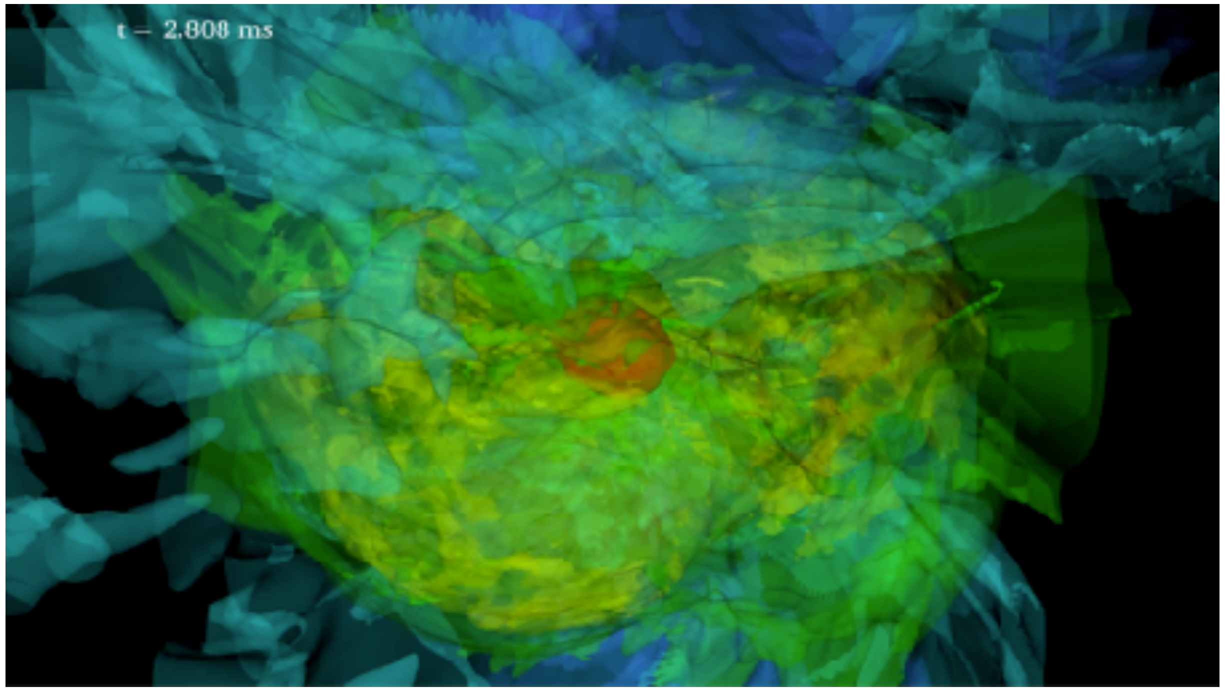
- High temperature → weak interaction plays an important role

$$t_{\rm weak} \sim 1\,{\rm ms}\left(\frac{kT}{5\,{\rm MeV}}\right)^{-5} << \text{timescale of the evolution}$$

$$e^- + p \rightleftarrows \nu_e + n$$
$$e^+ + n \rightleftarrows \bar{\nu}_e + p$$

- Neutrino emission cooling evolves the system
- Determine the neutron-richness (Ye)
- Heating by neutrino irradiation→ **mass ejection**





e.g., Surman & McLaughlin 08, Wanajo & Janka 12, Perego+14, SF+ 17

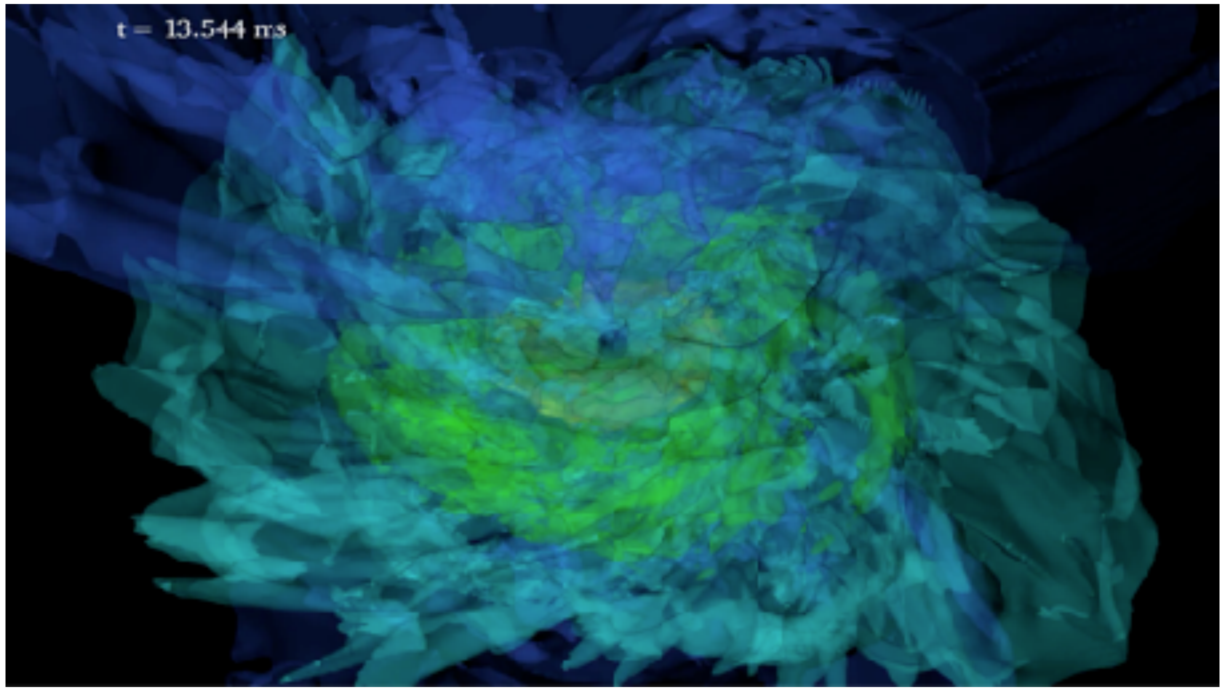
Activities in Post-merger phase

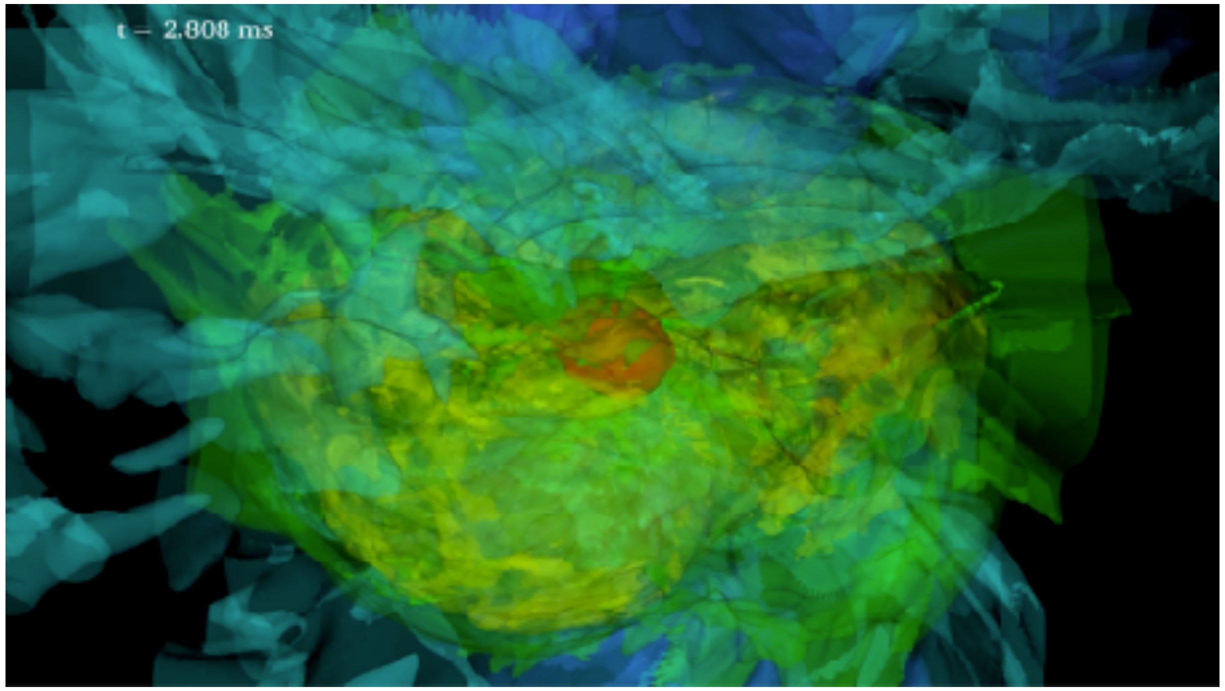
In post-merger phase. . .

- Magnetic field is amplified due to MHD processes.
- MRI in the disk → Viscosity (by turbulent motion) emergence
- Viscous angular momentum transport/heating → **mass ejection**

$$t_{\rm vis} \sim 1\,{\rm s} \left(\frac{\alpha_{\rm vis}}{0.03}\right)^{-1} \left(\frac{R_{\rm disk}}{50\,{\rm km}}\right)^{3/2} \left(\frac{M_*}{3M_\odot}\right)^{1/2} \left(\frac{3H_{\rm scale}}{R_{\rm disk}}\right)^{-2}$$ (assuming standard disk)

- Mass ejection by (purely) MHD processes (due to aligned global B-field)





e.g., Surman & McLaughlin 04, Metzger+08, Fernandez & Metzger 13, Just+ 15, SF+ 18, Lippuner+ 17, Just+ 21, …
Siegel+ 18, Fernandez+ 19, Miller+ 19, Hayashi+ 22, Fahlman & Fernandez 22, …

2. Simulations for NS-NS Mergers

Dynamical ejecta

Post-merger ejecta

Composition

Mass ejection in Post-merger phase

In many work for mass ejection in the post-merger phase,
the initial conditions are the equilibrium disks (tori) around BHs.
(with fixed mass, radius···)

e.g., Fernandez & Metzger 13, Just+ 15, Lippuner+ 17, Siegel+ 18, Fernandez+ 19, Christie+19, Miller+19, Just+ 21, Fahlman & Fernandez 22

The properties of the disk should depend on those of merging binaries (mass ratio, total mass, ···)

Our Purpose:

To model the post-merger mass ejection consistently with the merger

for (I) modeling lightcurves of Kilonovae, (II) Inputs of galactic chemical evolution

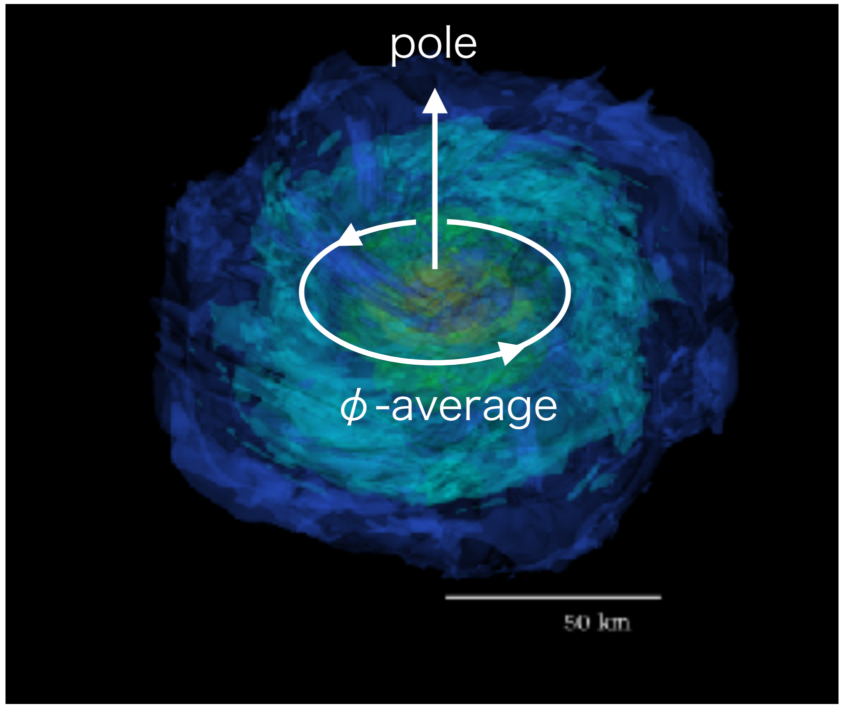
Here we investigated the cases in which the massive NS is short-lived (<20 ms).

Out previous work:
Equal mass (M1=M2) case leaving a long-lived massive NS

Our procedure

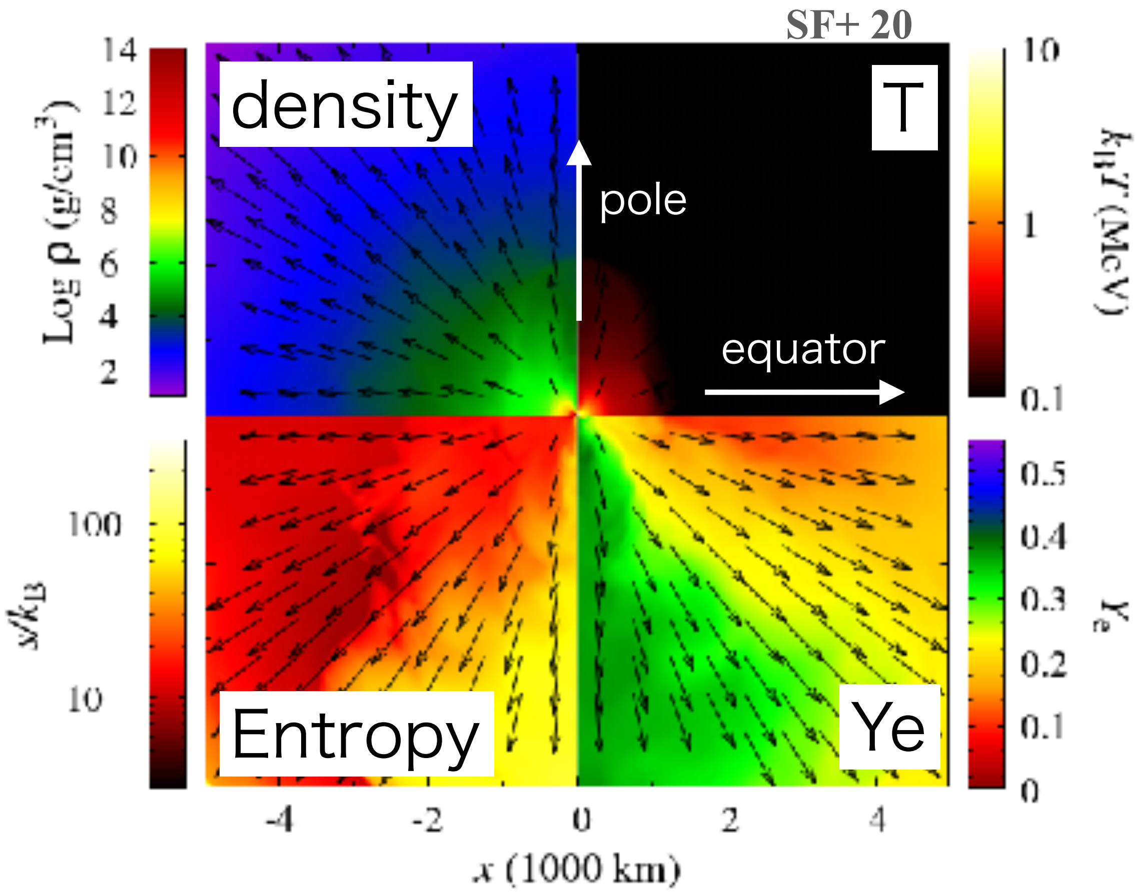
i) Perform NS-NS merger simulation (3D)

Sekiguchi+ 15, 16 Kiuchi+22



Take an average over the azimuthal angle around the rotational axis.

ii) Long-term Axisymmetric 2D simulation using angle-averaged configuration as the initial condition



This enable us to model the post-merger phase consistent with merger simulation (important for later study of Kilonova with photon-radiation transfer)

Method

- Fully general relativistic radiation hydrodynamics code.
- Original code is developed by Y. Sekiguchi

- **Einstein's equation**

  BSSN formalism — Nakamura & Shibata 95, Baumgarte & Shapiro 99

- **Neutrino radiation transfer equation**

  A leakage-based scheme incorporating a moment formalism — Sekiguchi 15, Thorne 81, Shibata et al. 11

- **3D: Ideal-gas hydrodynamics equation**

- **2D: Viscous hydrodynamics equation**

  A effective model for causal viscous hydrodynamics

  Israel & Stuart 79, Shibata et al. 17, Shibata & Kiuchi 17

$$\nu = c_s l_{\mathrm{tur}} \qquad \text{with } l_{\mathrm{tur}} = 400\,\mathrm{m}\,(=\mathrm{Const.}).$$

Dynamical ejecta

Mass-ratio dependence of dynamical ejecta

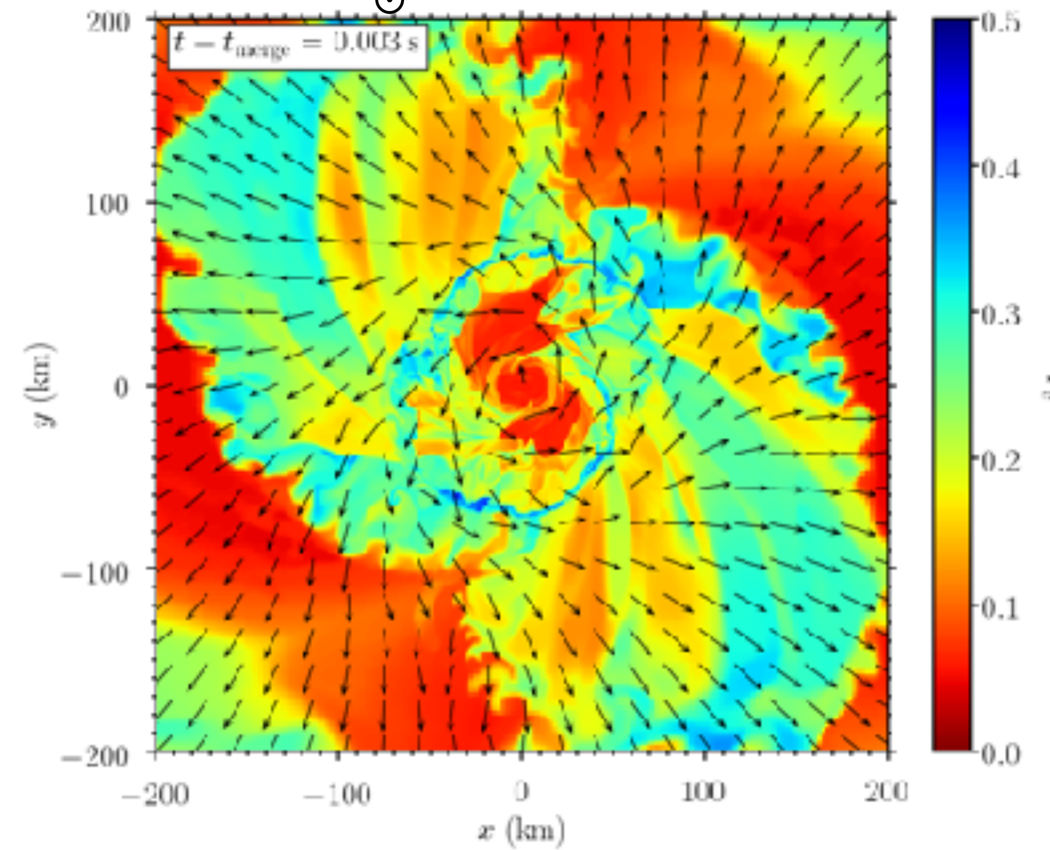
EOS, Mass($M_\odot$)	M_2/M_1	M_{ej}(Dynamical)
SFHo 1.35-1.35	1.0	$6.9 \times 10^{-3} M_\odot$
SFHo 1.30-1.40	0.93	$4.6 \times 10^{-3} M_\odot$
SFHo 1.25-1.45	0.86	$5.4 \times 10^{-3} M_\odot$
SFHo 1.20-1.50	0.80	$3.7 \times 10^{-3} M_\odot$
SFHo 1.25-1.55	0.81	$8.6 \times 10^{-3} M_\odot$

SFHo EOS, Total mass 2.7 and 2.8$M_\odot$ with different mass ratios.

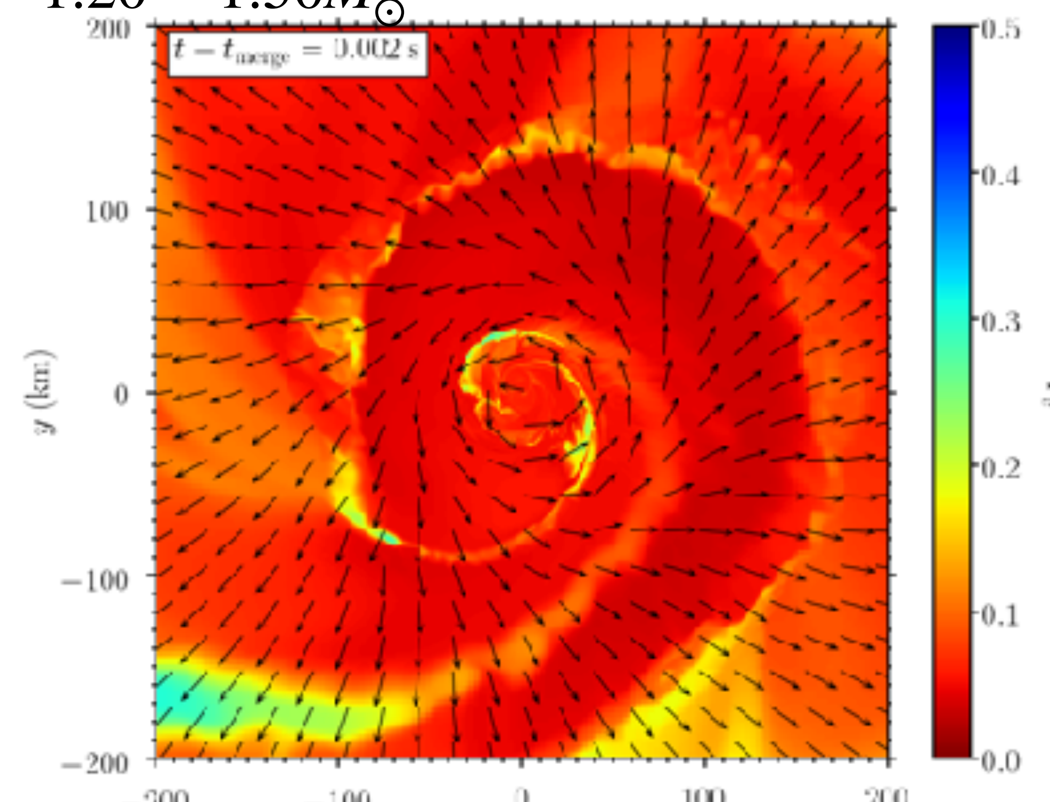
After the merger, massive NS collapses in 3-20 ms.

Ye distribution on x-y plane

$1.35 - 1.35 M_\odot$



$1.20 - 1.50 M_\odot$



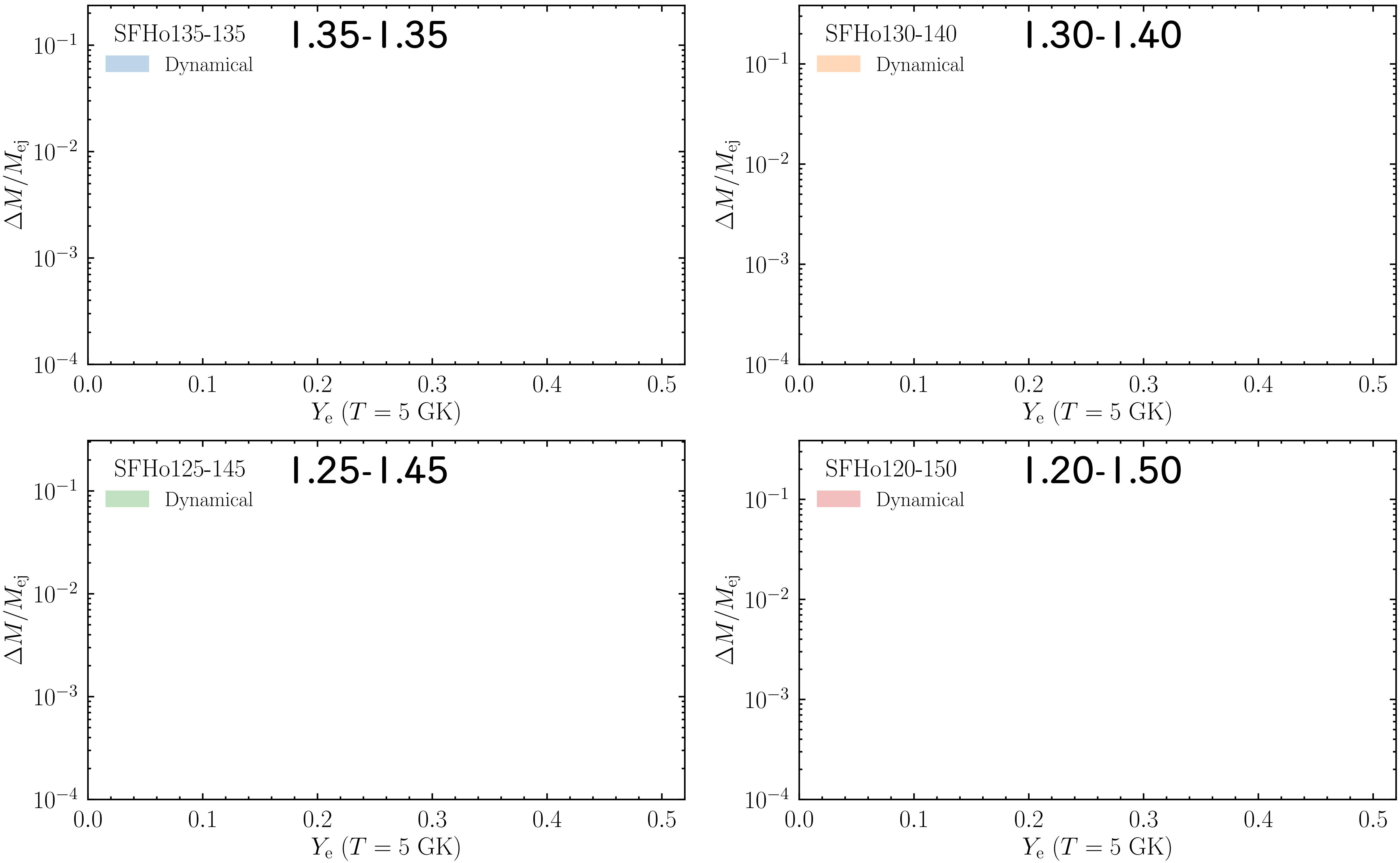
Ye high↔low

<u>Ejecta Ye</u>

Equal-mass：Mainly by shock heating
→ high Ye $(e^+ + n \rightarrow \bar{\nu}_e + p)$

Asymmetric：Mainly by tidal interaction
→ low Ye

Mass-ratio dependence of n-richness

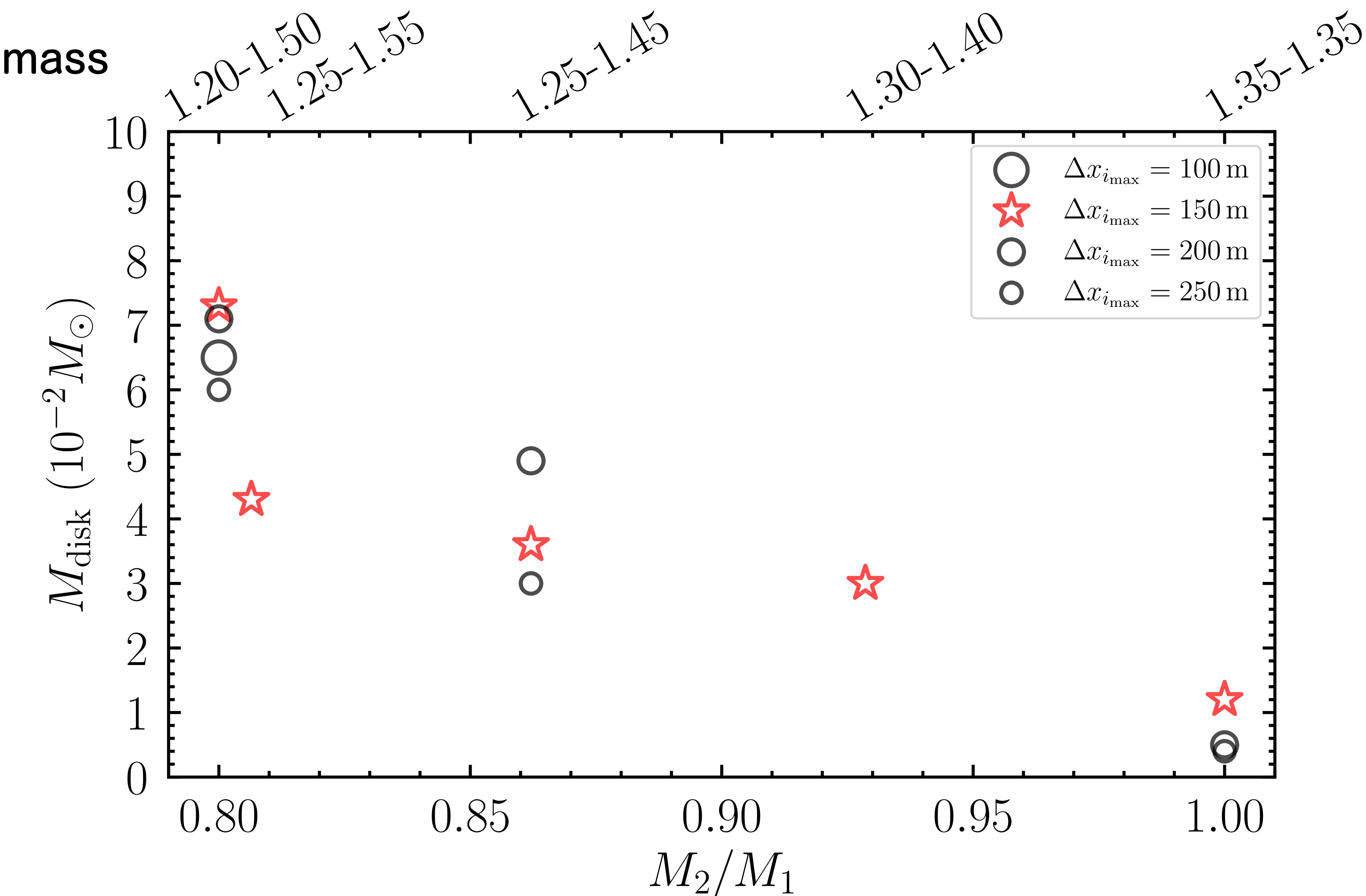


More asymmetric merger results in more n-rich dynamical ejecta

Post-merger ejecta

Mass-ratio dependence of disk mass

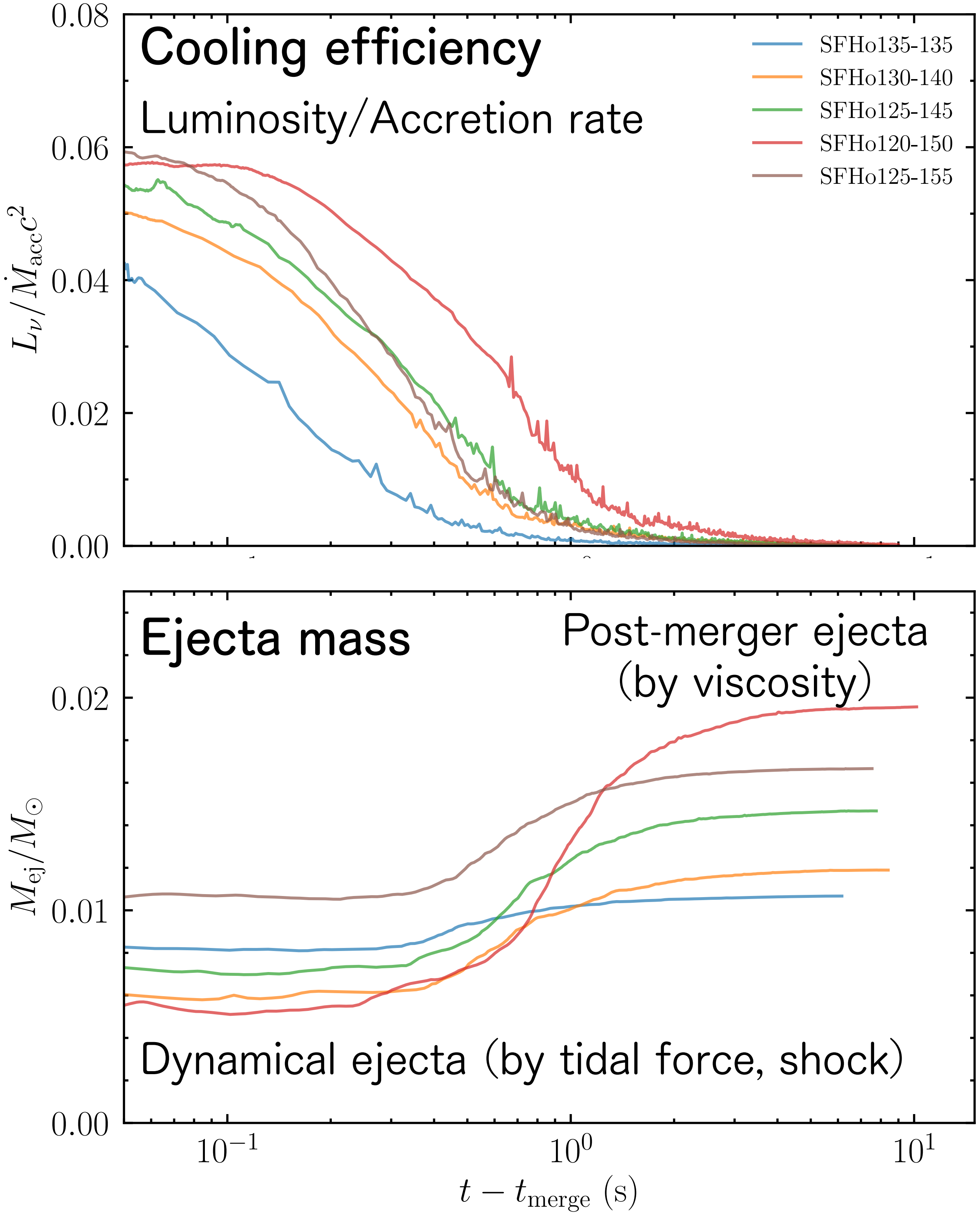
Constituent mass



Asymmetric ⟷ **Equal-mass**

Disk mass（↔ Importance of post-merger ejecta）
is larger for the merger of more asymmetric binary

Post-merger mass ejection



Mass-ejection mechanism

Disk temperature decreases
due to the drop of accretion rate

Cooling efficiency drops $t_{\rm weak} \sim 1\,\mathrm{ms}\left(\frac{kT}{5\,\mathrm{MeV}}\right)^{-5}$
→Mass ejection by viscous heating

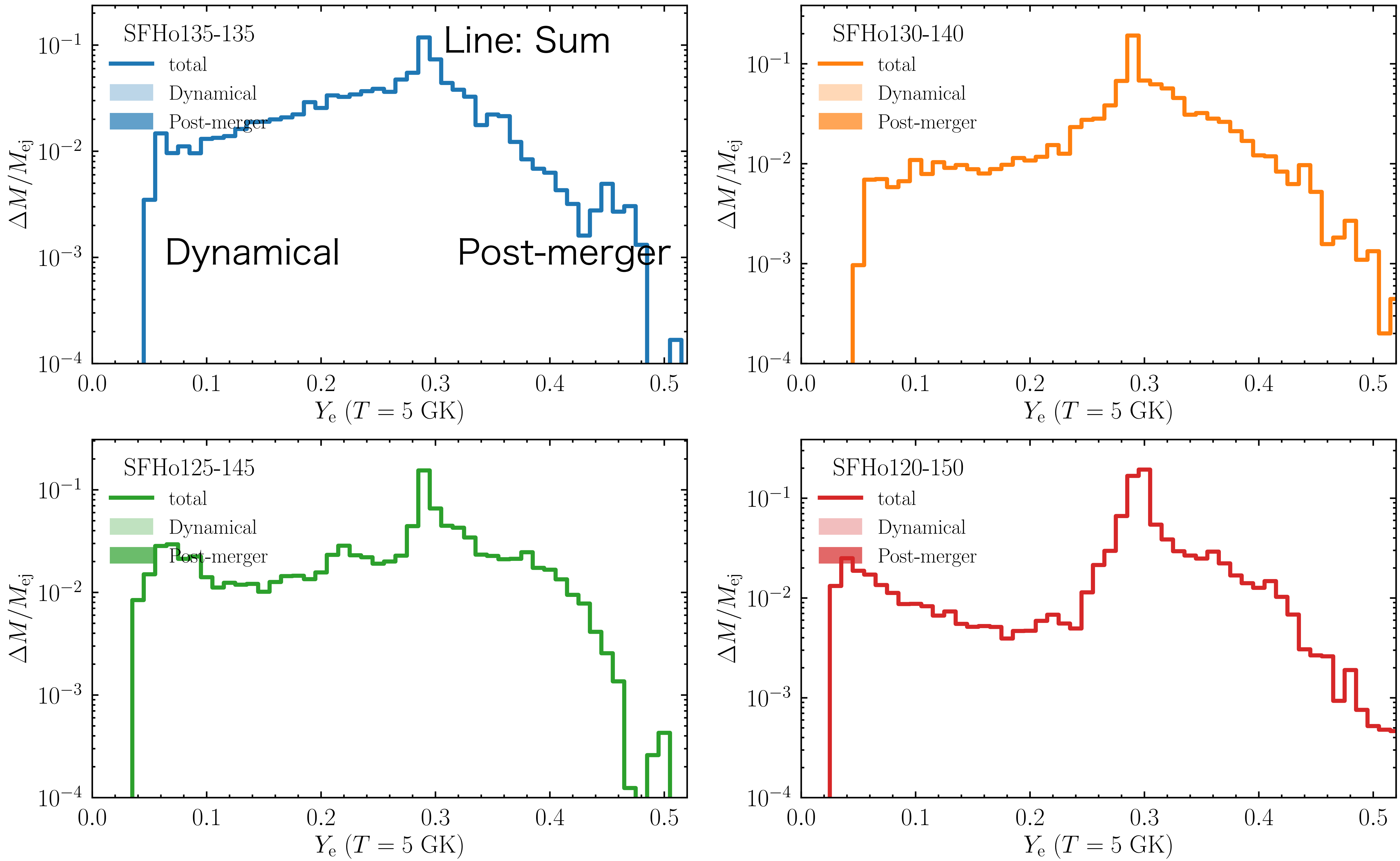
Mass ejection not visible in high-L_ν phase
→Neutrino irradiation plays subdominant
role for mass ejection

Mass-ratio dependence

Equal-mass: Lower disk mass
→ Dynamical ejecta dominates

Asymmetric mergers leave
more massive disks
→ Post-merger ejecta dominates

Composition of the ejecta

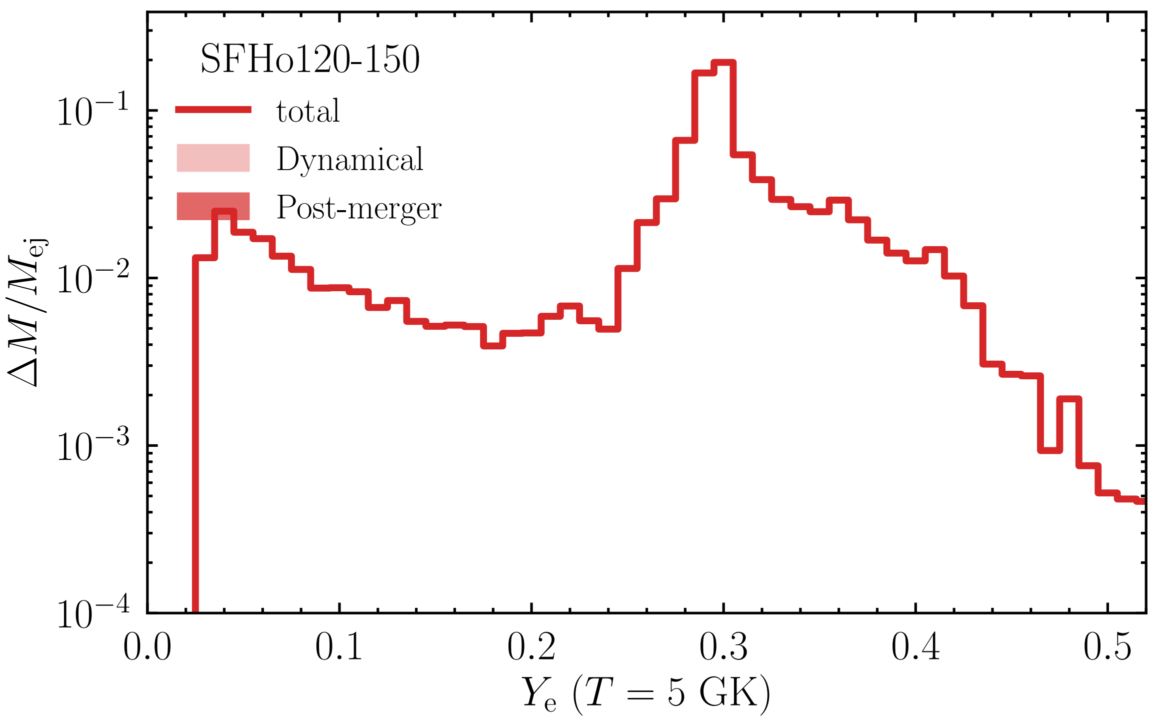


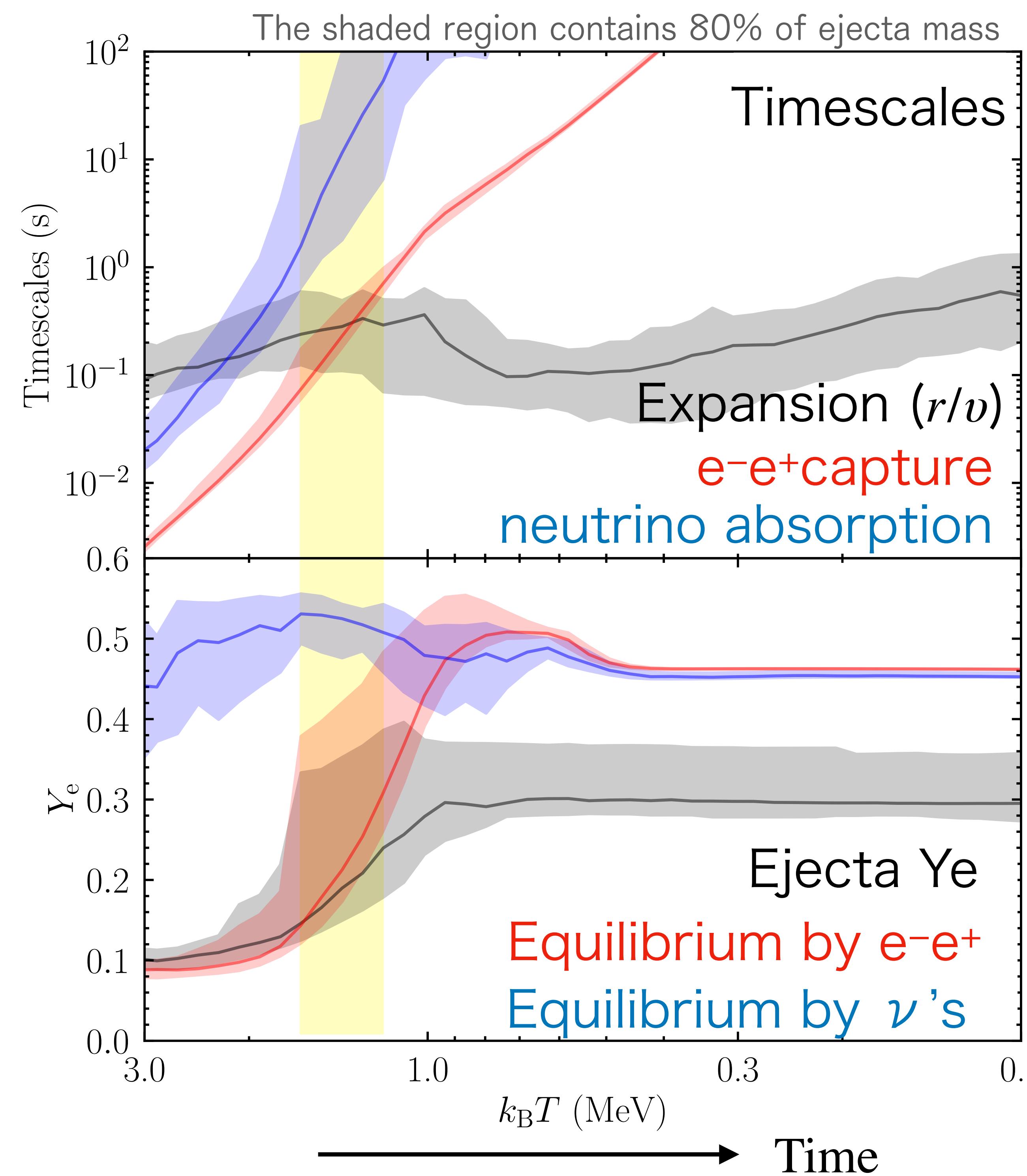
Contribution of the post-merger ejecta is larger for more asymmetric case

The peak at Ye ≈ 0.3 irrespective of mass ratio

Composition of the ejecta

see also Just+22





Distribution peaks at $Y_{\rm e} \approx 0.3$
(irrespective of mass ratio)

At high temperature

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

determines $Y_{\rm e}$, which freezes out when

$$t_{\rm expansion} \sim t_{\rm weak} \quad (k_{\rm B}T \sim 1 - 2\,{\rm MeV})$$

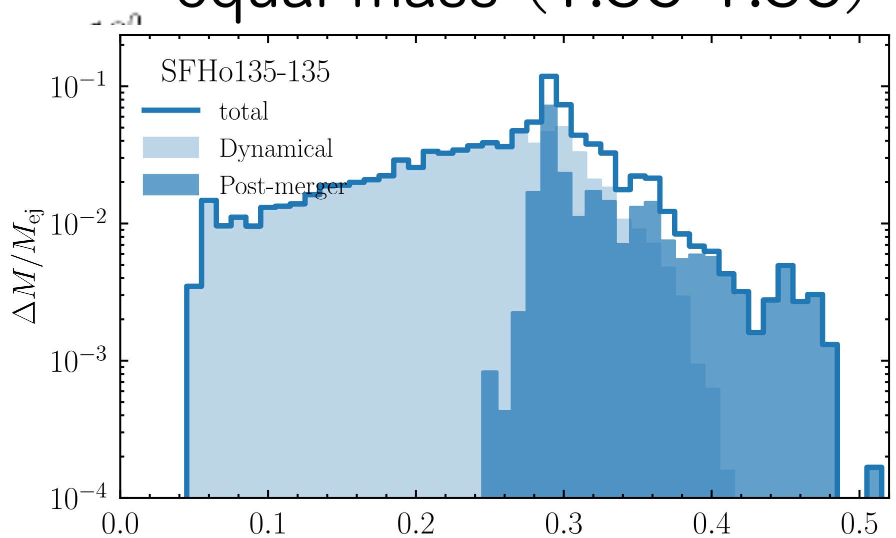
※ Resulting $Y_{\rm e}$ depends on the strength of the viscosity (or expansion timescale).

Ejecta composition

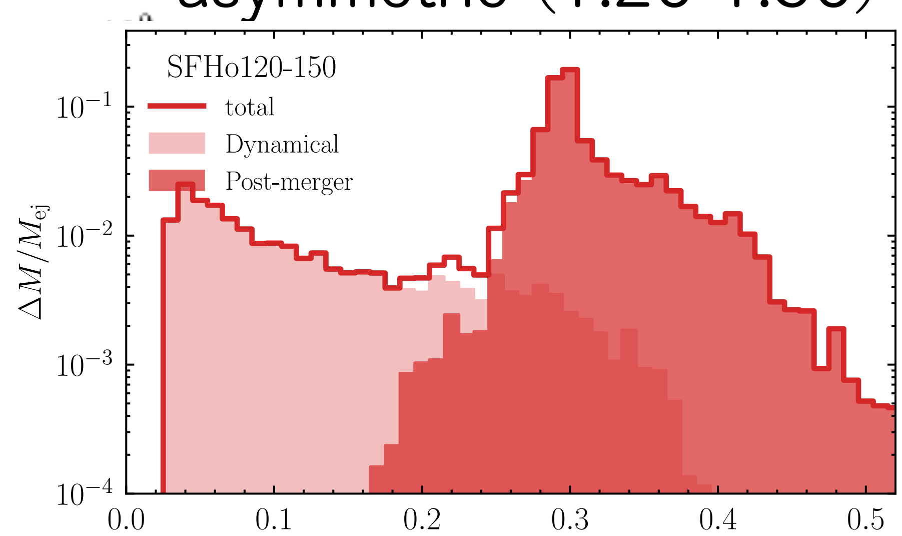
Composition of the ejecta

Short-lived massive NS

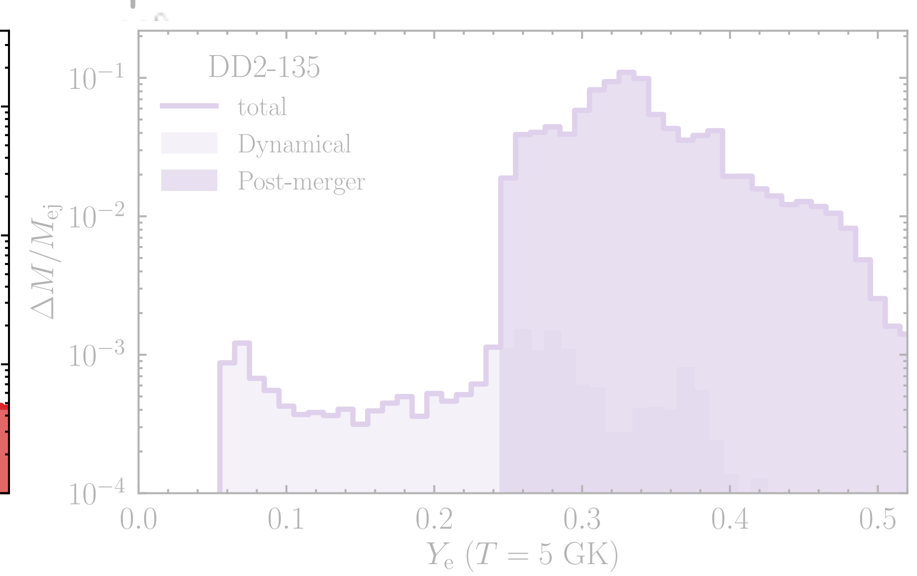
equal-mass (1.35-1.35)

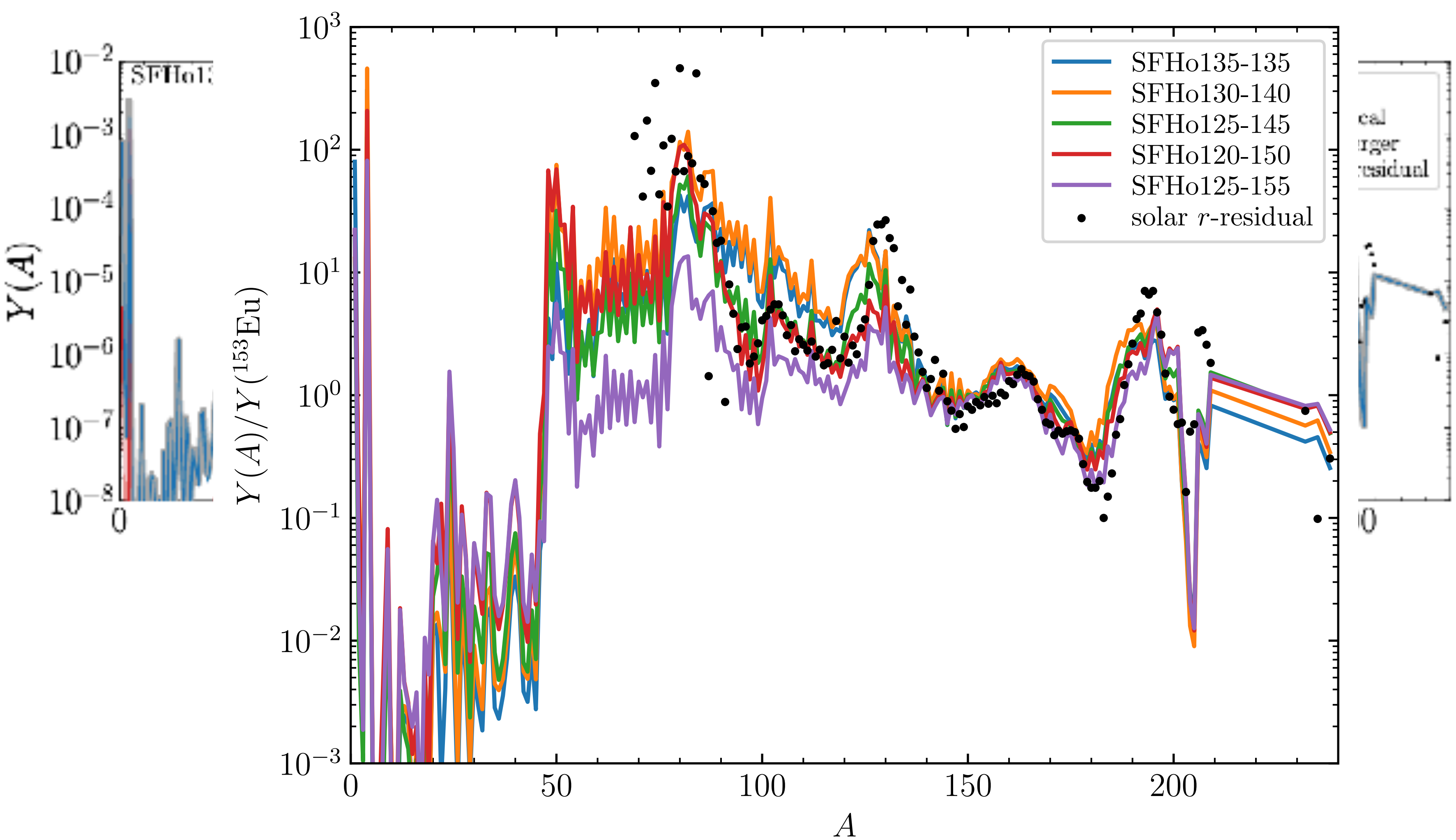


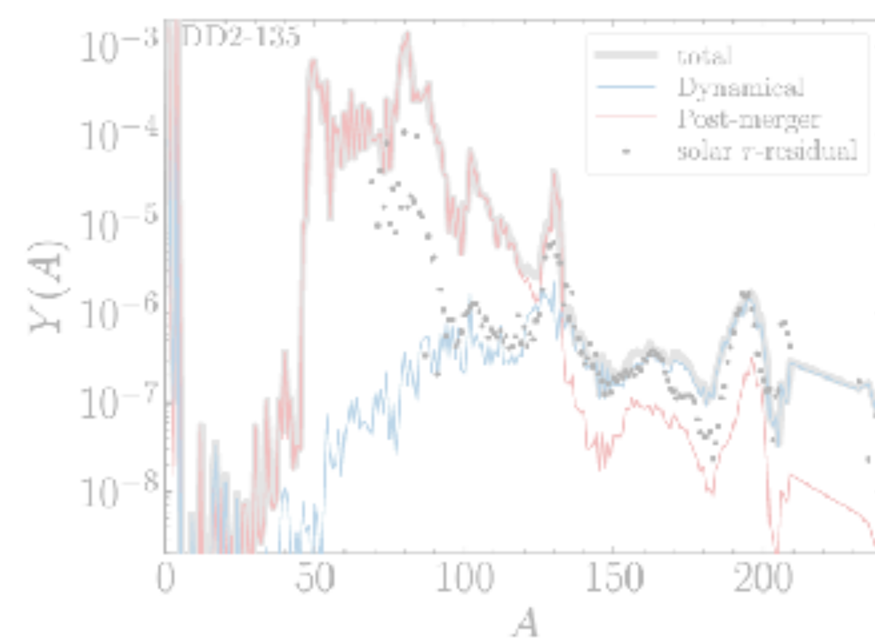
asymmetric (1.20-1.50)



Long-lived massive NS
equal-mass (DD2 1.35-1.35)







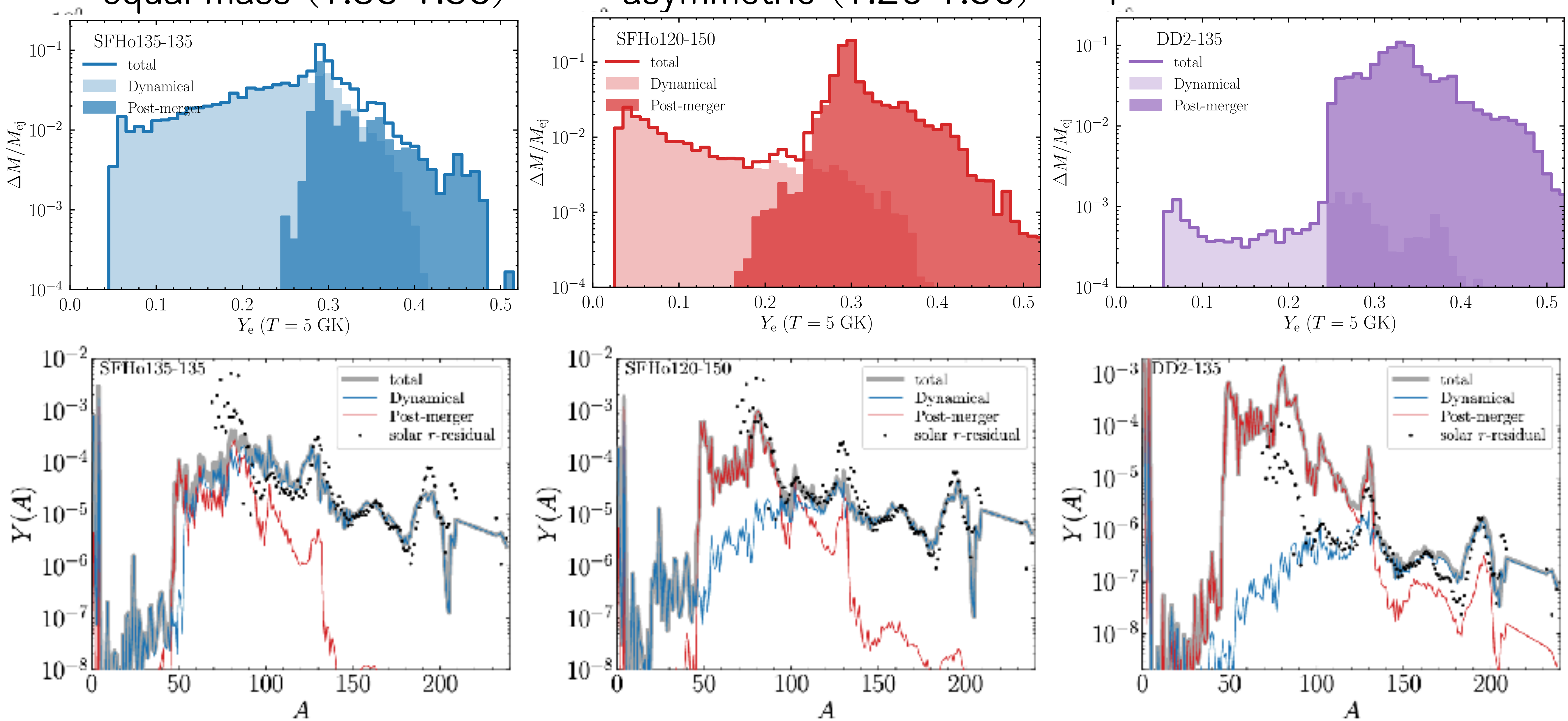
Long-lived massive NS case

Composition of the ejecta

Short-lived massive NS

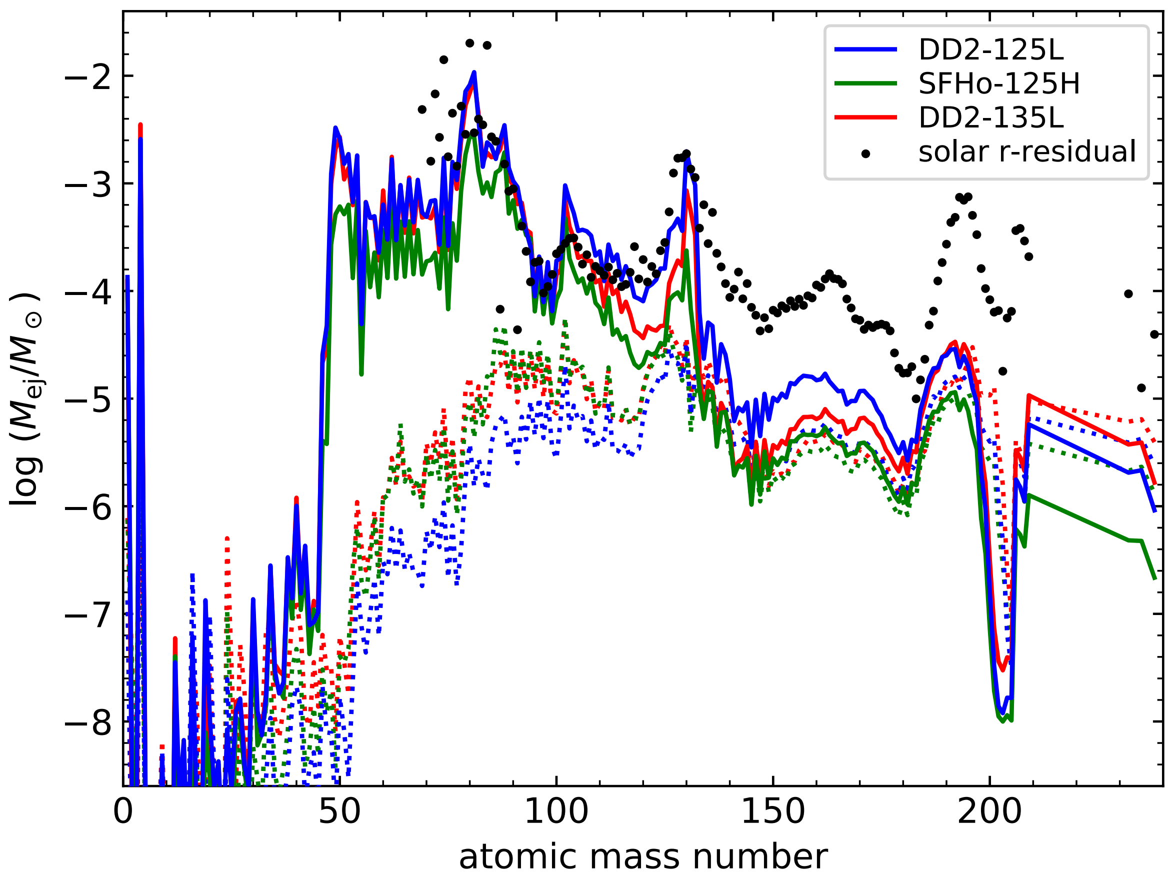
equal-mass (1.35-1.35) | asymmetric (1.20-1.50)

Long-lived massive NS
equal-mass (DD2 1.35-1.35)



Long-lived massive NS cases

	EOS, Mass($M_\odot$)	M_{ej}(Dynamical)	M_{ej}(Post merger)	$\frac{M_{ej}\text{(Post merger)}}{M_{ej}\text{(Dynamical)}}$
(stiff EOS)	DD2 1.25-1.25	$1.0 \times 10^{-3} M_\odot$	$0.113 M_\odot$	113
	DD2 1.35-1.35	$1.5 \times 10^{-3} M_\odot$	$0.085 M_\odot$	57
(soft EOS but smaller total mass)	SFHo 1.25-1.25	$1.3 \times 10^{-3} M_\odot$	$0.060 M_\odot$	46



Post-merger ejecta dominates

$$\frac{M_{ej}\text{(Post merger)}}{M_{ej}\text{(Dynamical)}} \sim 50 - 100$$

Severe underproduction for A>140.

(If binary NS merger is the main r-process site)
Mergers leaving long-lived NSs should be minor.

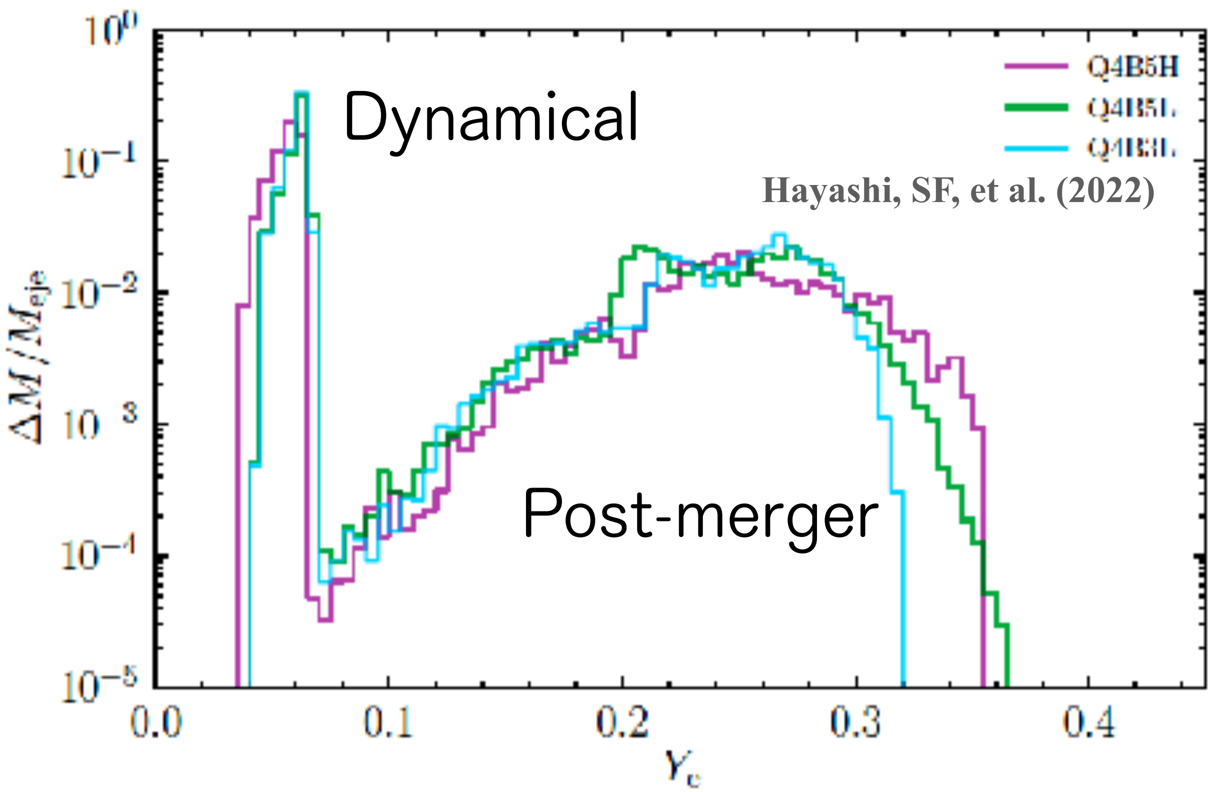
Talk by Kawaguchi for possible constraints based on EM signals

Seconds-long BH-NS merger simulations

1.35 Msun NS with DD2 EOS
and BH with mass ratio 4 (BH mass : 5.4 Msun); MHD simulation.

Talk by Shibata for its dynamics

Wanajo, SF, et al. in prep.



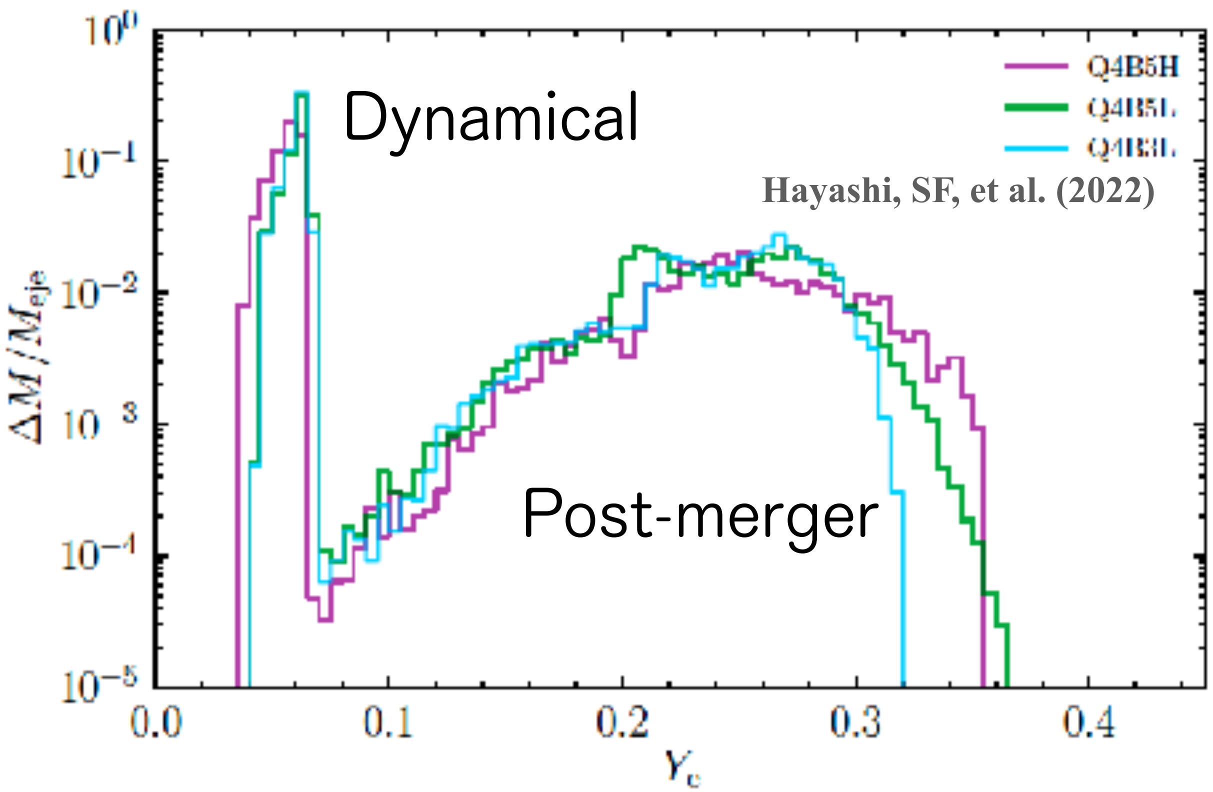
Preliminary

- Post-merger ejecta have similar typical Ye (~0.25-0.3) to that in viscous model.
- M(dynamical) ~ M(post-merger)
  → Nuclear abundance with similar pattern to the solar pattern.

Seconds-long BH-NS merger simulations

- Also for different mass ratio (MBH/MNS=6) and different EOS (SFHo), solar pattern is reasonably reproduced.

Wanajo, SF, et al. in prep.



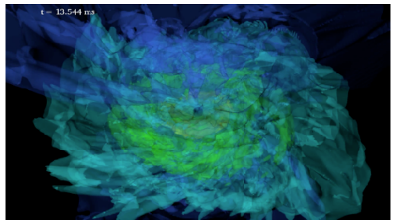
Preliminary

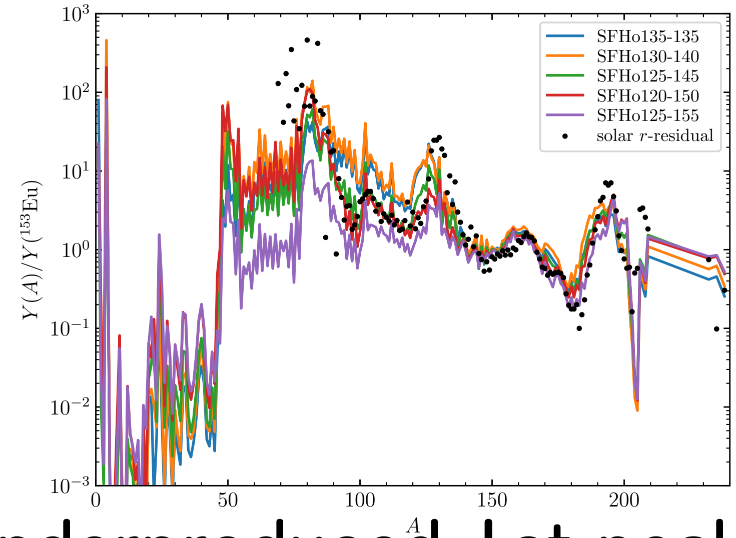
Average logarithmic deviation ~ 0.3

Summary

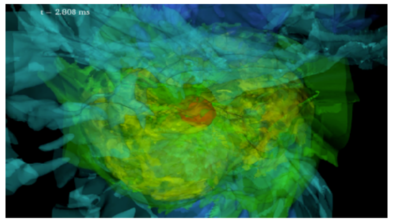
NS-NS

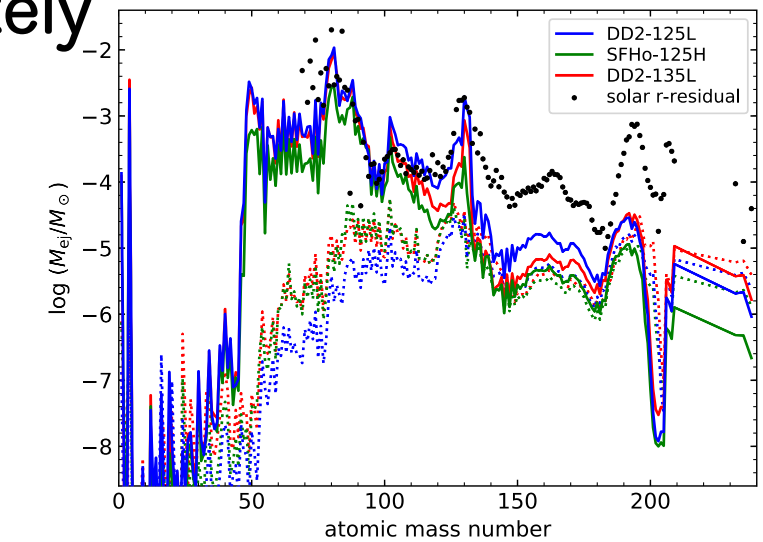
- Short-lived (~10 ms) massive NS cases:
  - Dynamical ejecta is more n-rich for the more asymmetric merger.
  - Post-merger ejecta (mildly n-rich) is more massive for the more asymmetric merger, which compensate underproduced 1st peak.
  - can reproduce solar r-process abundance approximately





- Long-lived (>seconds) massive NS cases:
  - Post-merger ejecta dominates → Nucleosynthesis result deviates from the solar r-process pattern.





BH-NS

- Dynamical + post-merger ejecta can reproduce the solar pattern.