Mass ejection and nucleosynthesis in binary neutron star mergers leaving short-lived massive neutron stars

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in collaboration with

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Based on: SF et al. arXiv2205.05557

SF et al. (2020) ApJ 901, 122

Shibata, SF, Sekiguchi (2021) PRD 104, 063026

Kawaguchi, SF et al. (2021) arXiv:2202.13149

INT Workshop INT-20R-1B

“The r-process and the nuclear EOS after LIGO-Virgo’s third observing run” 2022.05.25

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

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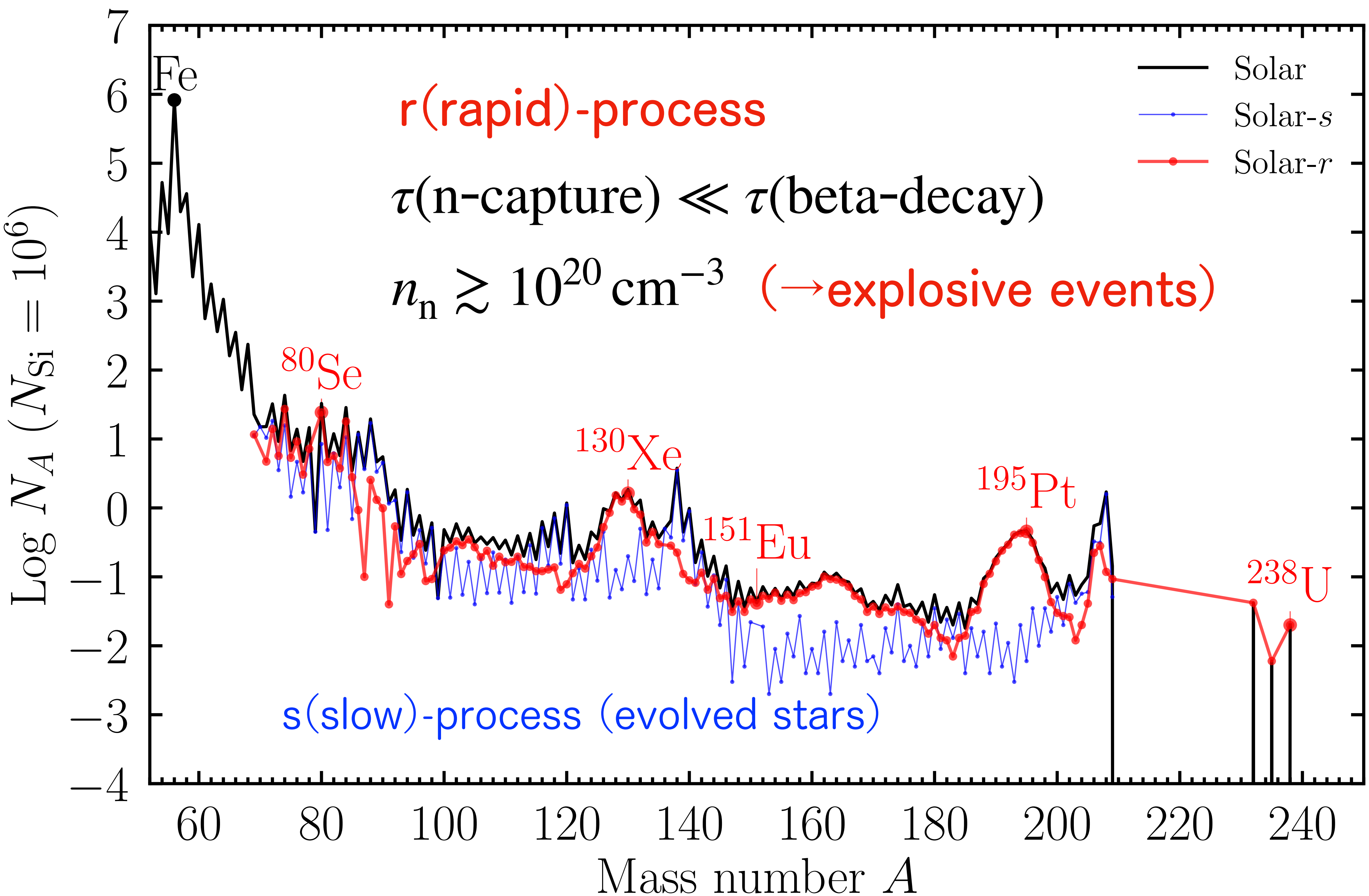
2. Simulations for NS-NS mergers
    - Short-lived massive NS cases
        - Dynamical ejecta
        - Post-merger ejecta
        - Composition
    - Long-lived massive NS case
3. Summary

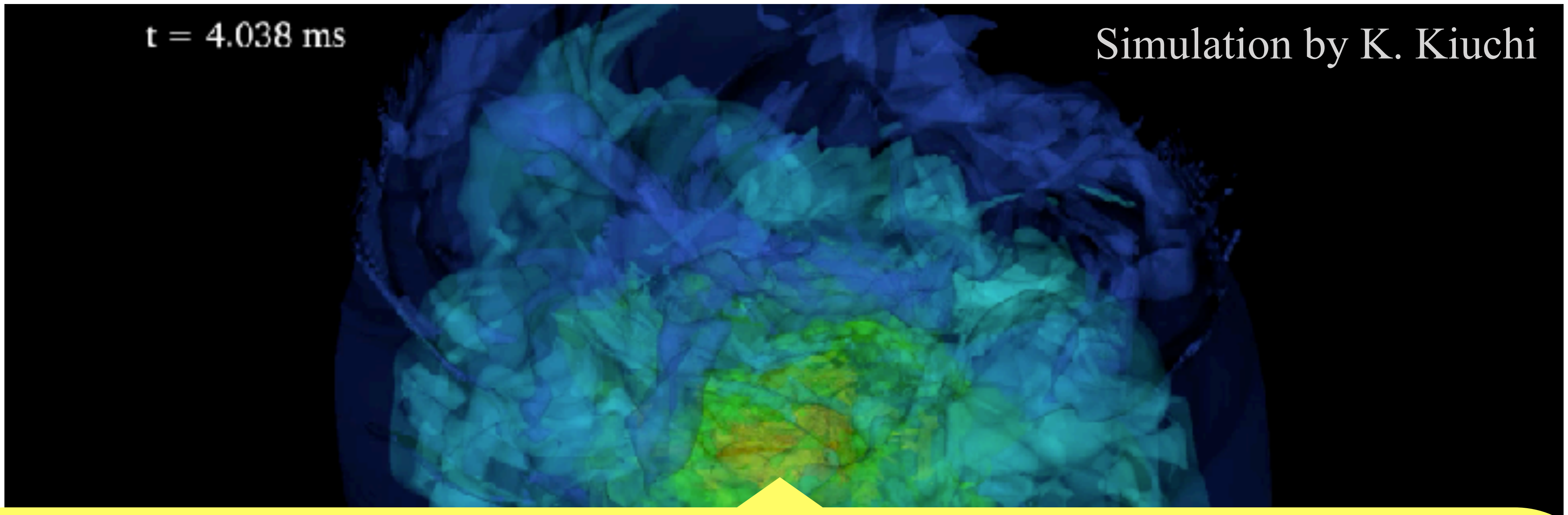
I. Introduction

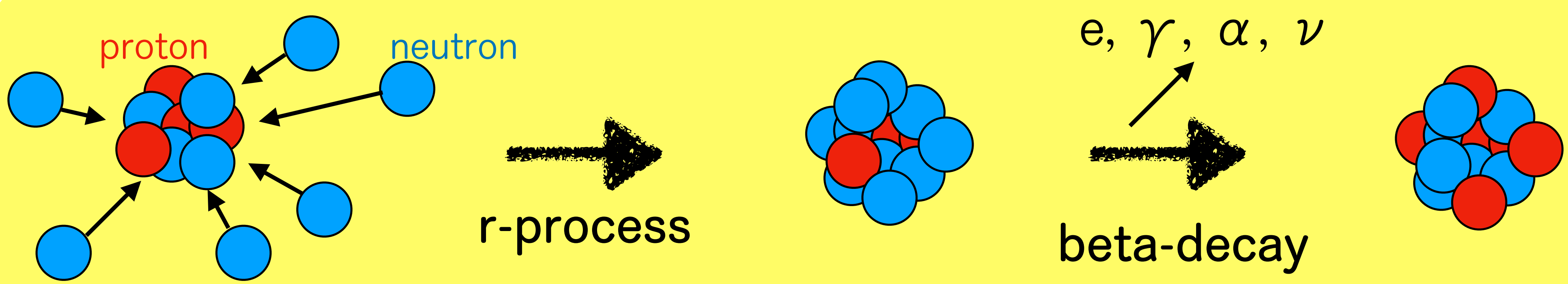
Processes making nuclei heavier than iron



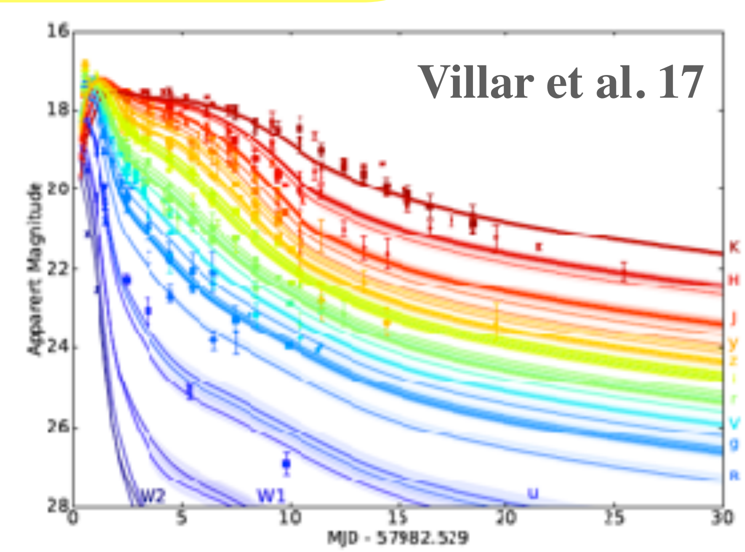
r-process in NS-NS merger

Symbalisty & Schramm 82, Eichler+ 89, …
Li & Paczynski 98, Kulkarni 05, Metzger 10



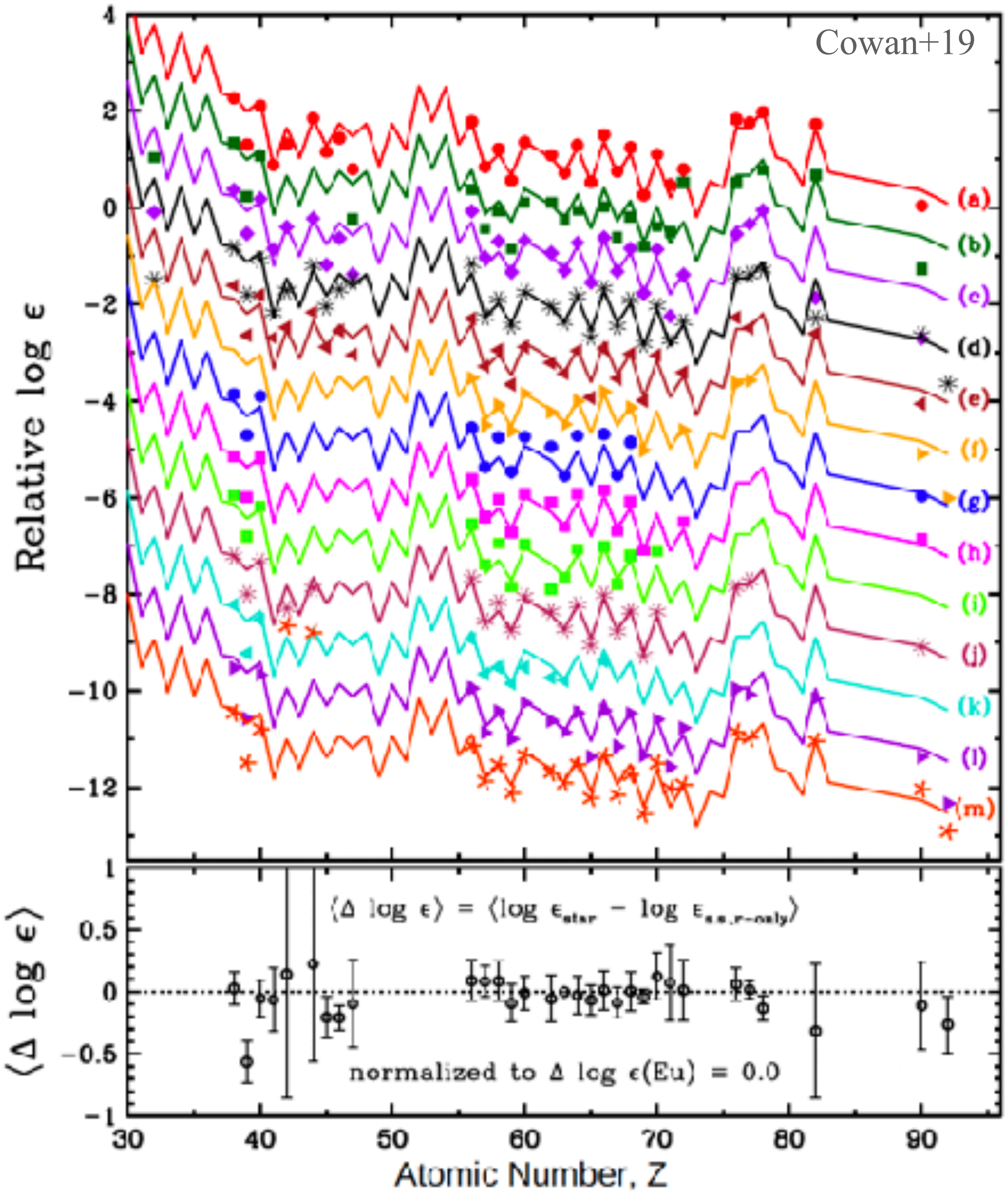


High n-richness → τ(n-capture) ≪ τ(beta-decay)



“Universality” of the r-process

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



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.

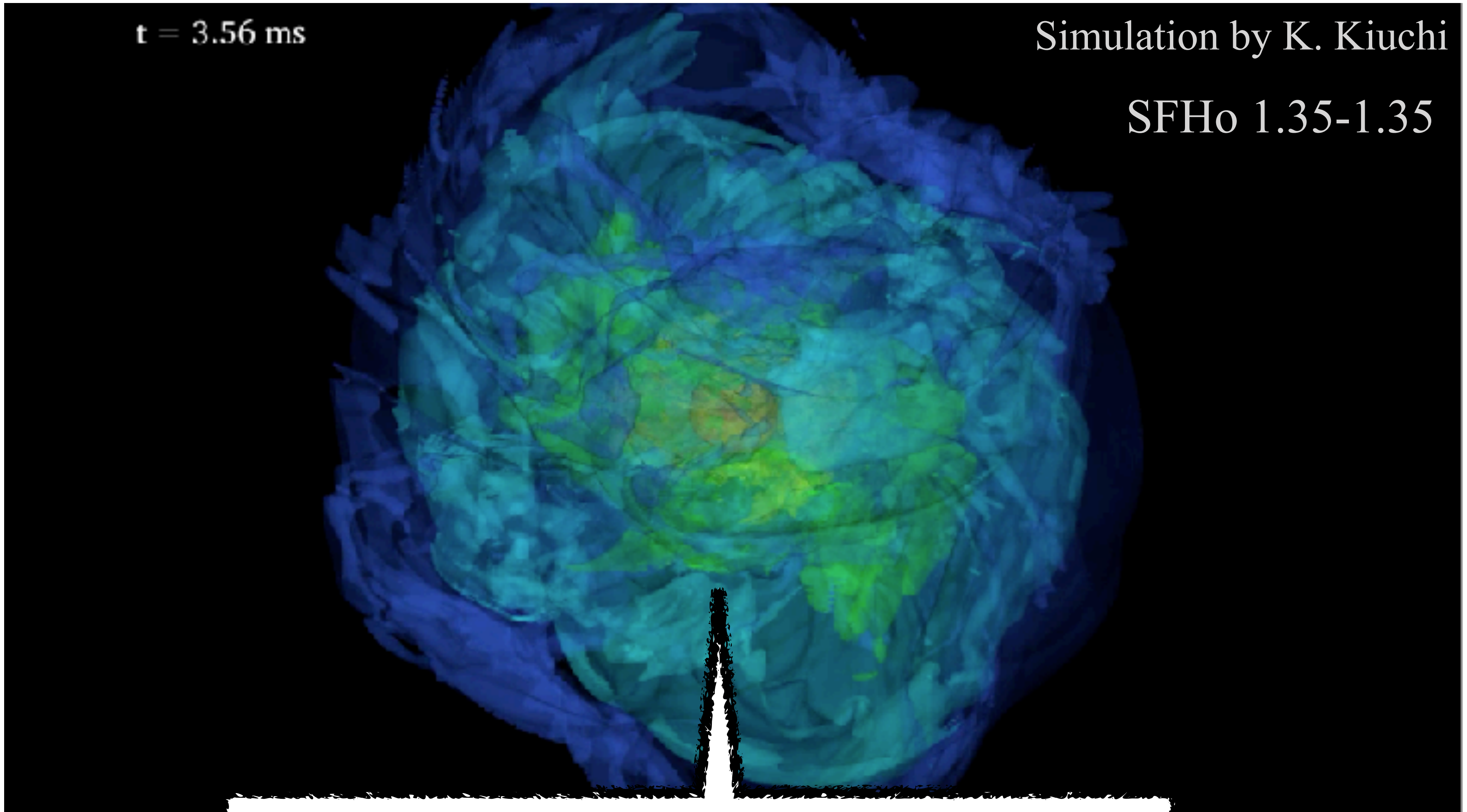
Constraint:
Each r-process enrichment event has to provide the solar pattern.

(elements with Z<50 have some scatter)

(There are some outliers with non-solar pattern)

Honda+ 06

Mass ejection in different phases

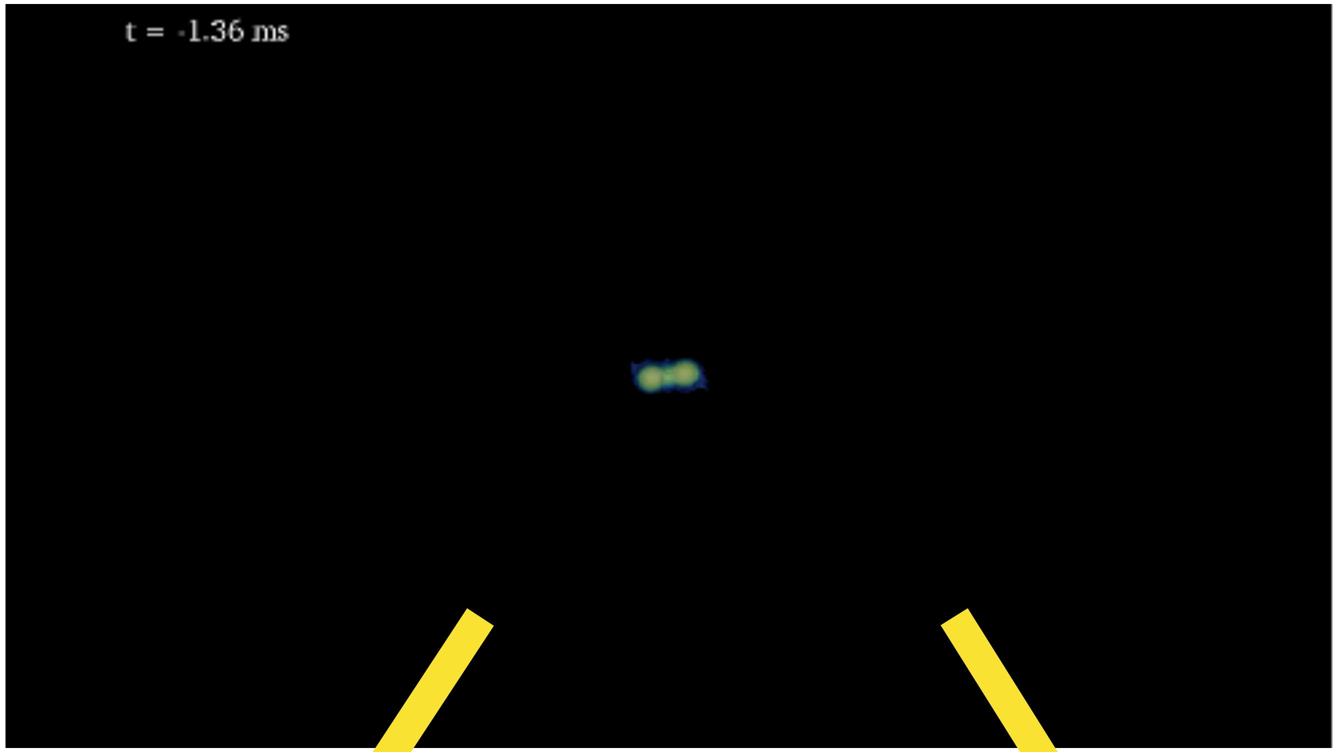


Dynamical ejecta

Due to tidal force and shock heating

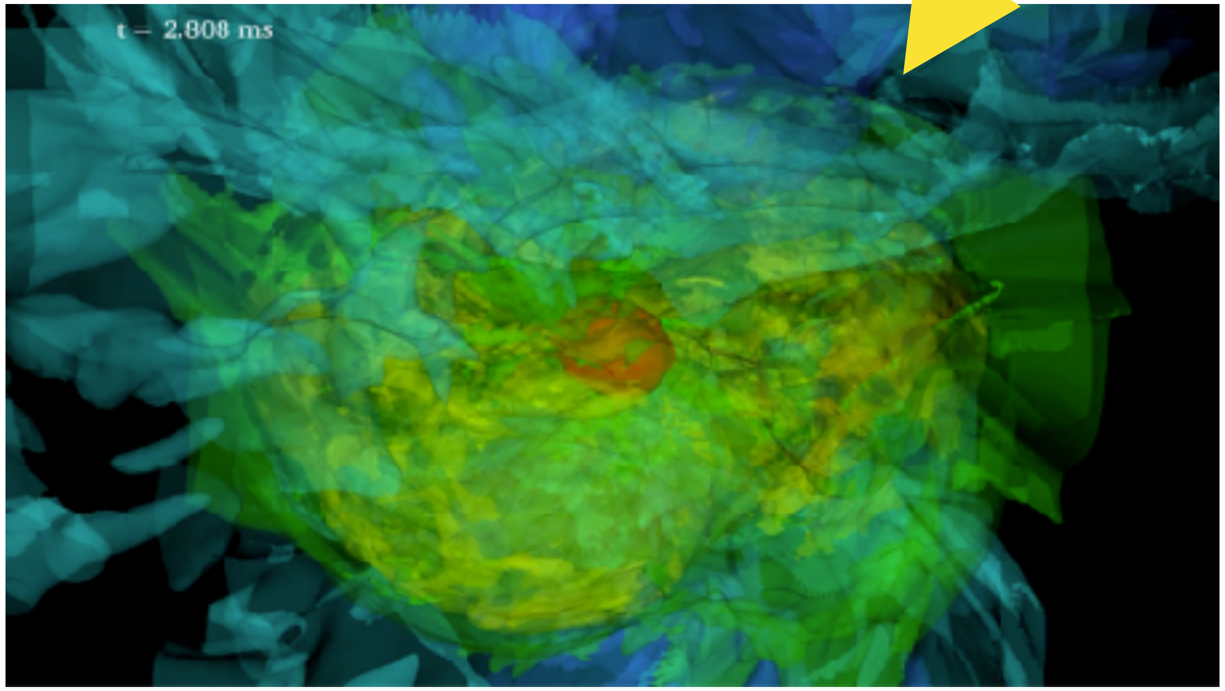
e.g., Rosswog+ ’99,
Hotokezaka+ 13, Bauswein+ 13; Palenzuela+ 15,
Sekiguchi+ 15,16, Foucart+ 15, Radice+ 18, Kullmann+ 21

Evolution in Post-merger Phase

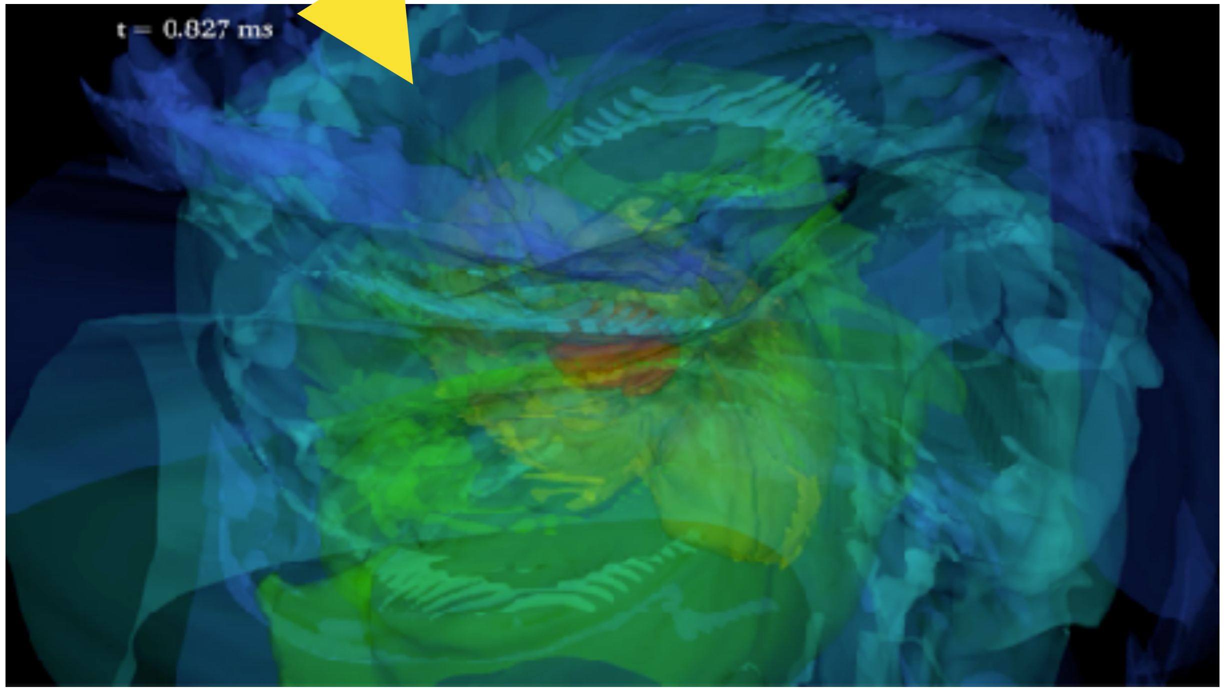


$M_{\mathrm{tot}} > M_{\mathrm{thr}}$

$M_{\mathrm{tot}} < M_{\mathrm{thr}}$(given EOS)



BH formation



long-lived massive NS

Mass ejection in Post-merger phase

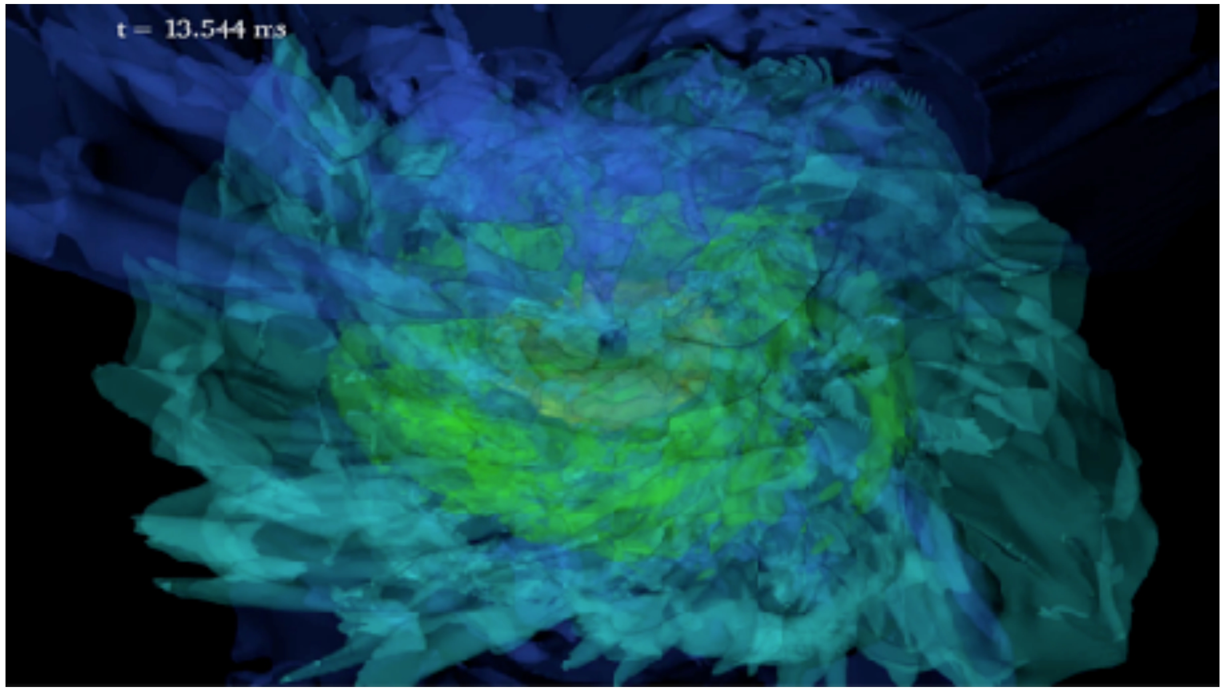
In post-merger phase. . .

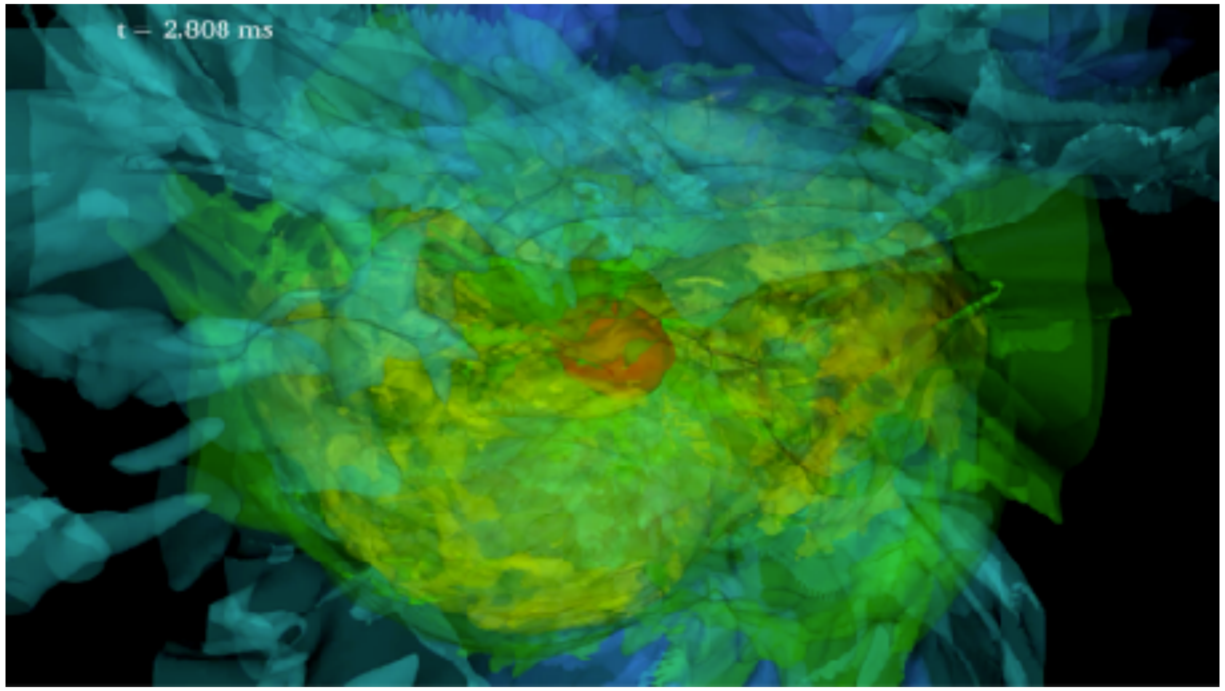
- High temperature → weak interaction plays an important role

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

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

- 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

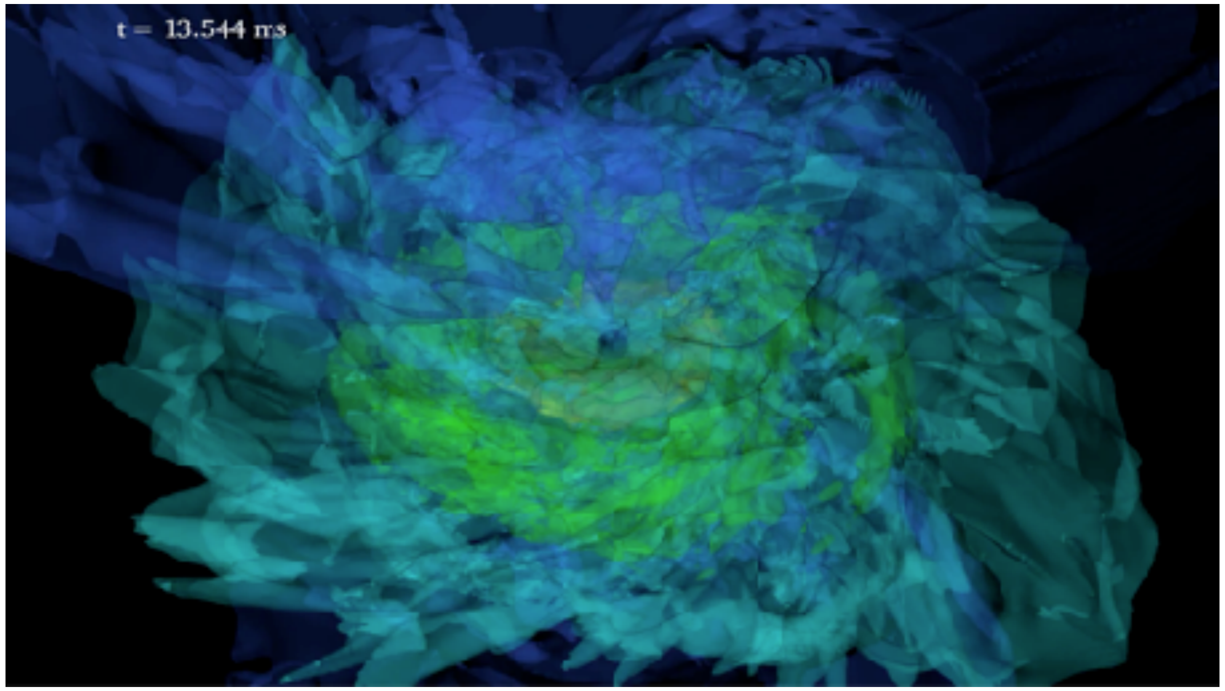
Mass ejection in Post-merger phase

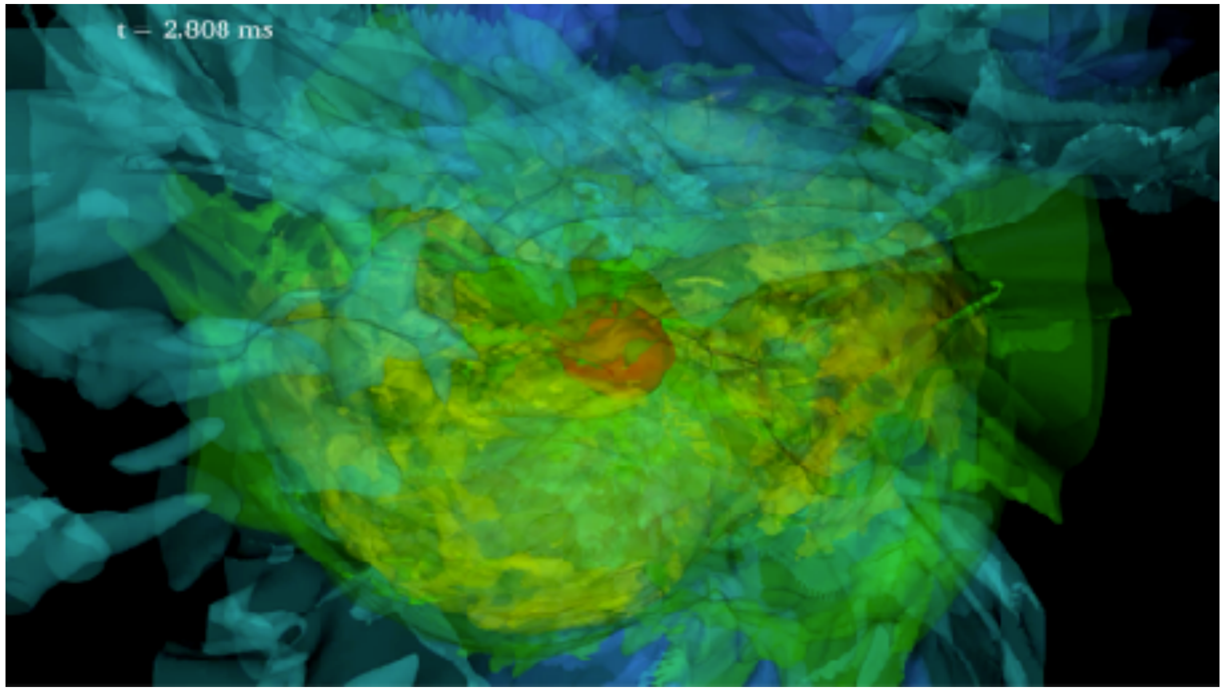
In post-merger phase. . .

- 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, Hayashi+ 21,…

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, SF+20a, 20b, Just+ 21

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

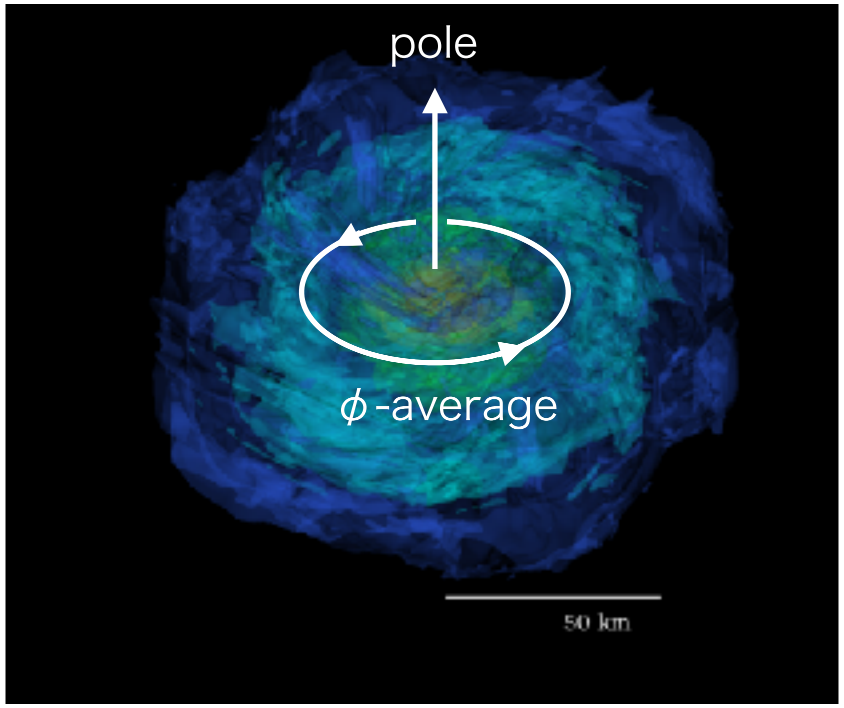
Out previous work:
Equal mass (M1=M2) case leaving a long-lived massive NS

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

Our procedure

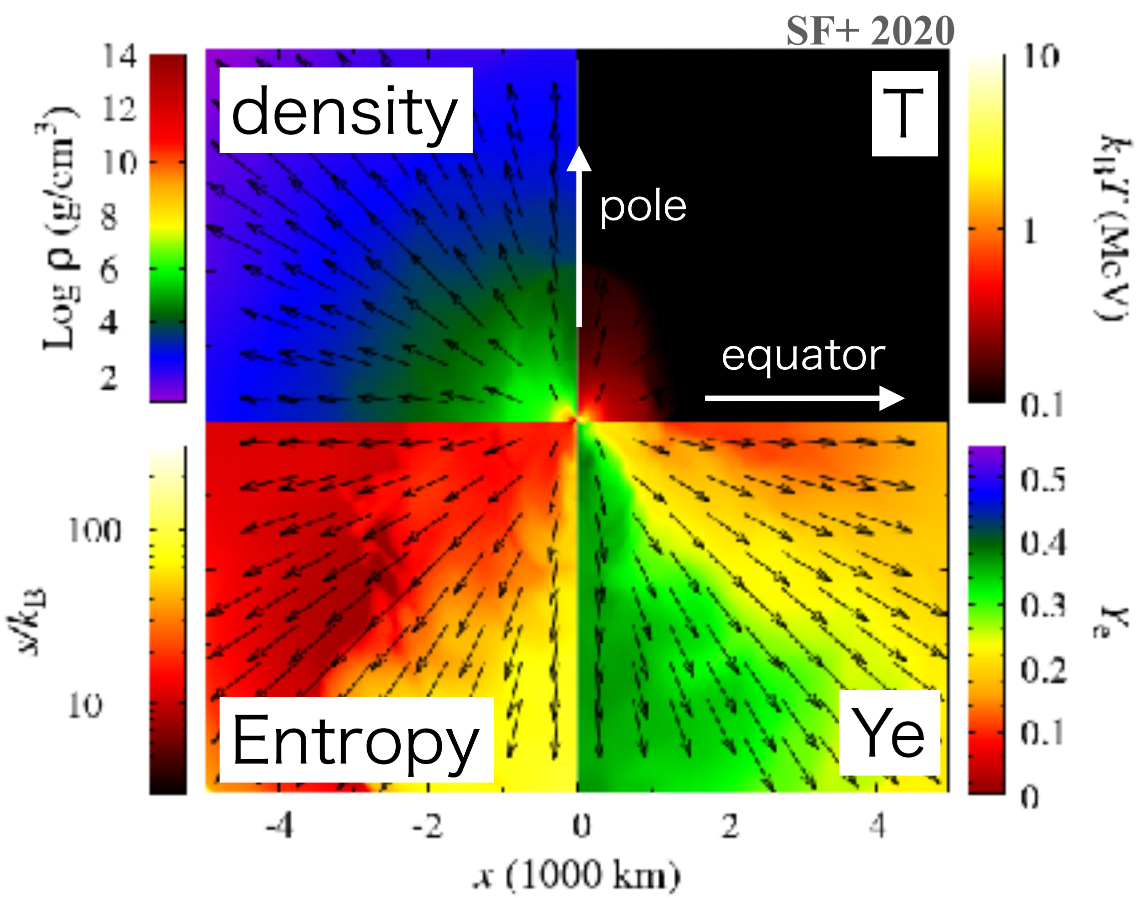
i) Perform NS-NS merger simulation (3D)

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

$$\nu = \alpha c_s H_{\rm tur} \quad \text{with } \alpha H_{\rm tur} = 400\,{\rm m}\,(=\text{Const.}).$$

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	$6.9\times10^{-3}M_\odot$
SFHo 1.30-1.40	0.93	$4.6\times10^{-3}M_\odot$
SFHo 1.25-1.45	0.86	$5.4\times10^{-3}M_\odot$
SFHo 1.20-1.50	0.80	$3.7\times10^{-3}M_\odot$
SFHo 1.25-1.55	0.81	$8.6\times10^{-3}M_\odot$

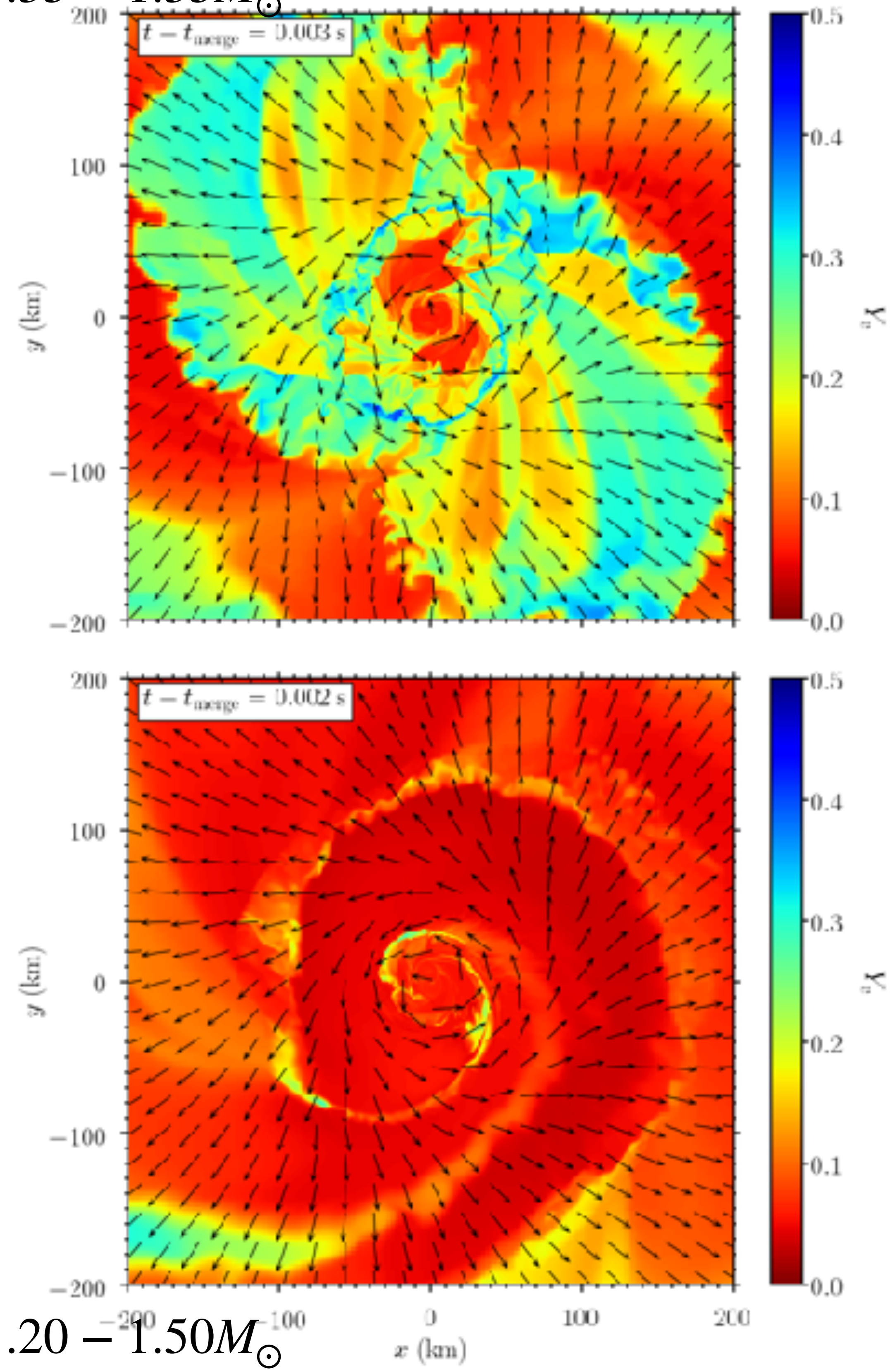
SFHo EOS, Total mass 2.7 and 2.8$M_\odot$ with different mass ratios.

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

Ye distribution on x-y plane

$1.35-1.35M_\odot$

Ye low↔high



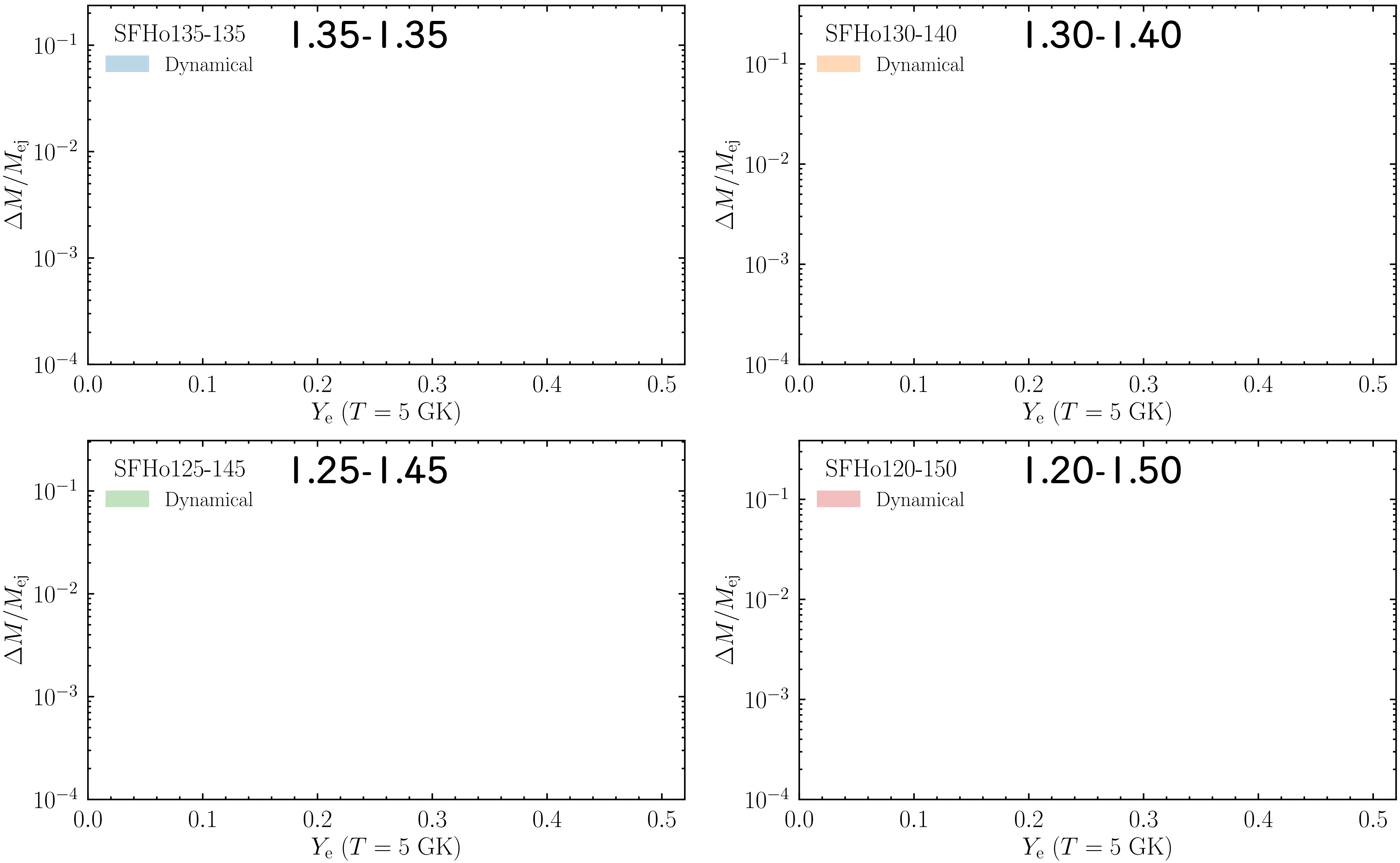
$1.20-1.50M_\odot$

<u>Ejecta Ye</u>

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

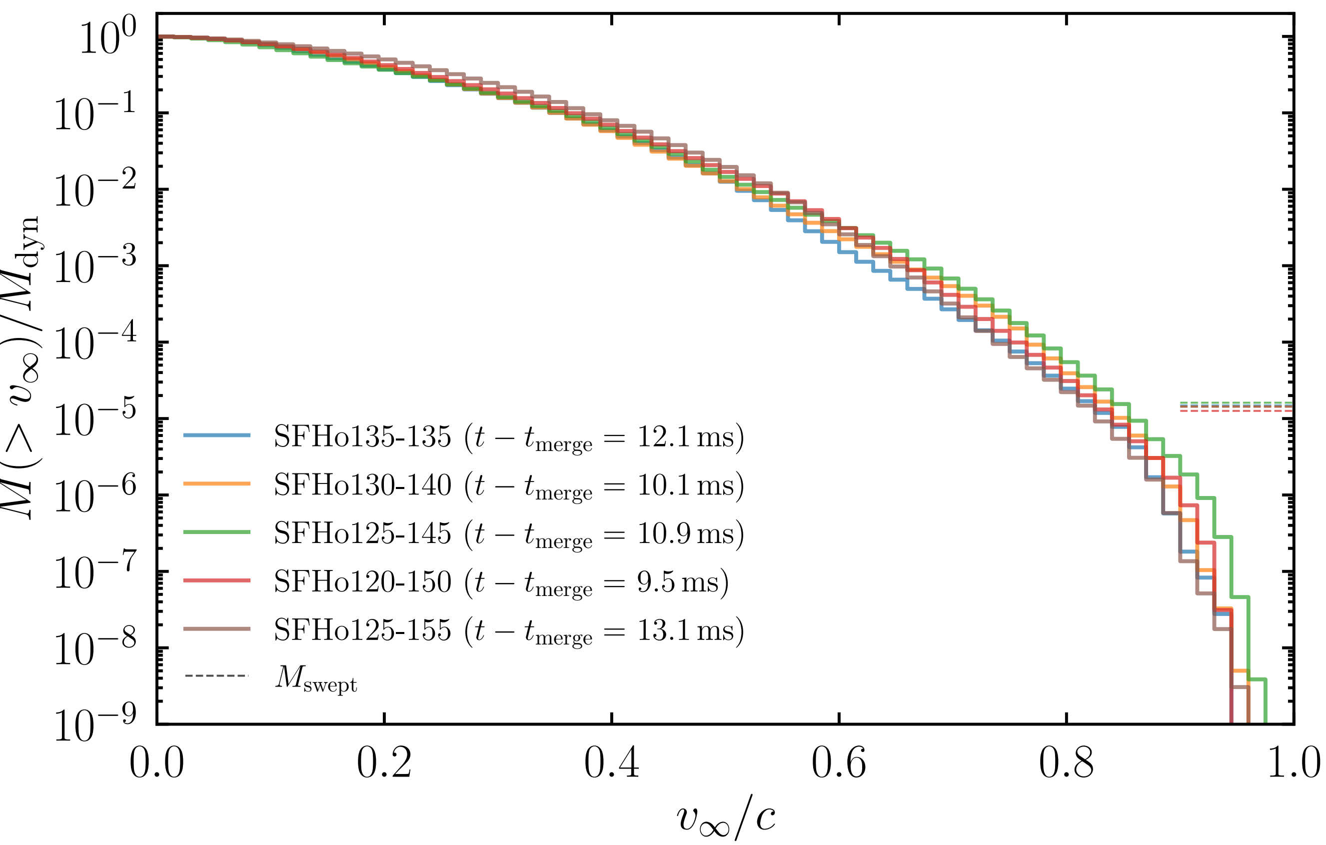
Asymmetric：Mainly by tidal interaction
→ low Ye

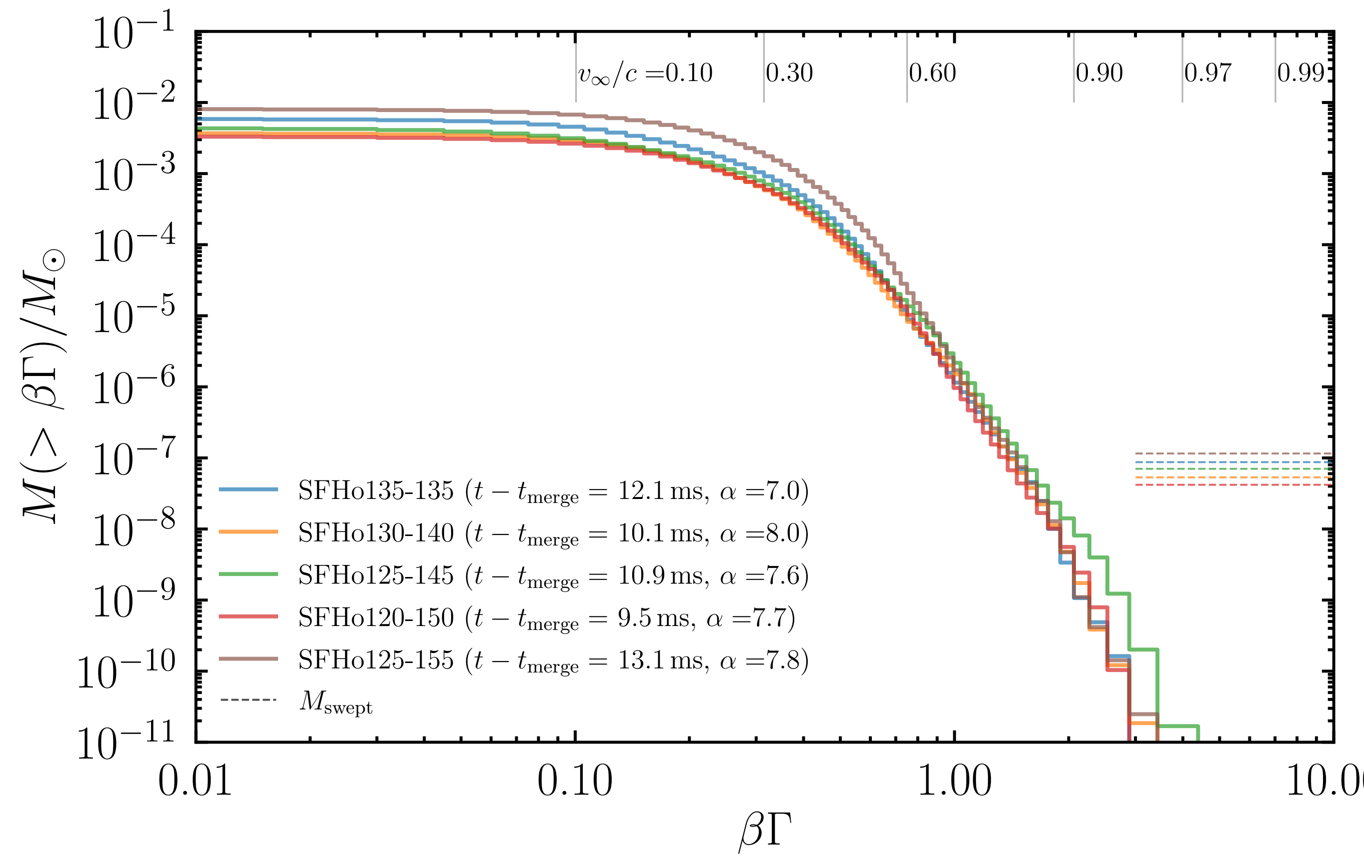
Mass-ratio dependence of n-richness



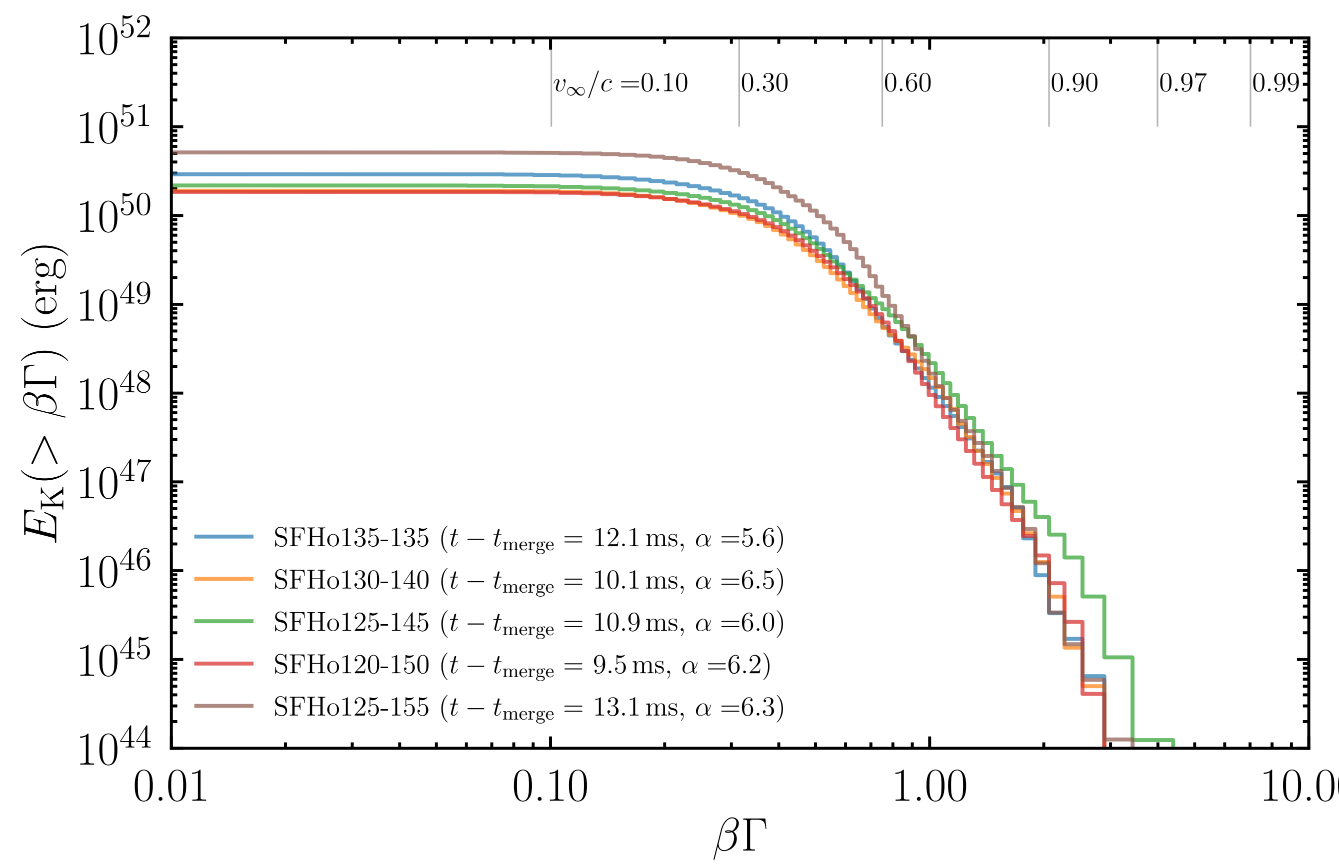
More asymmetric merger results in more n-rich dynamical ejecta

High-velocity Component



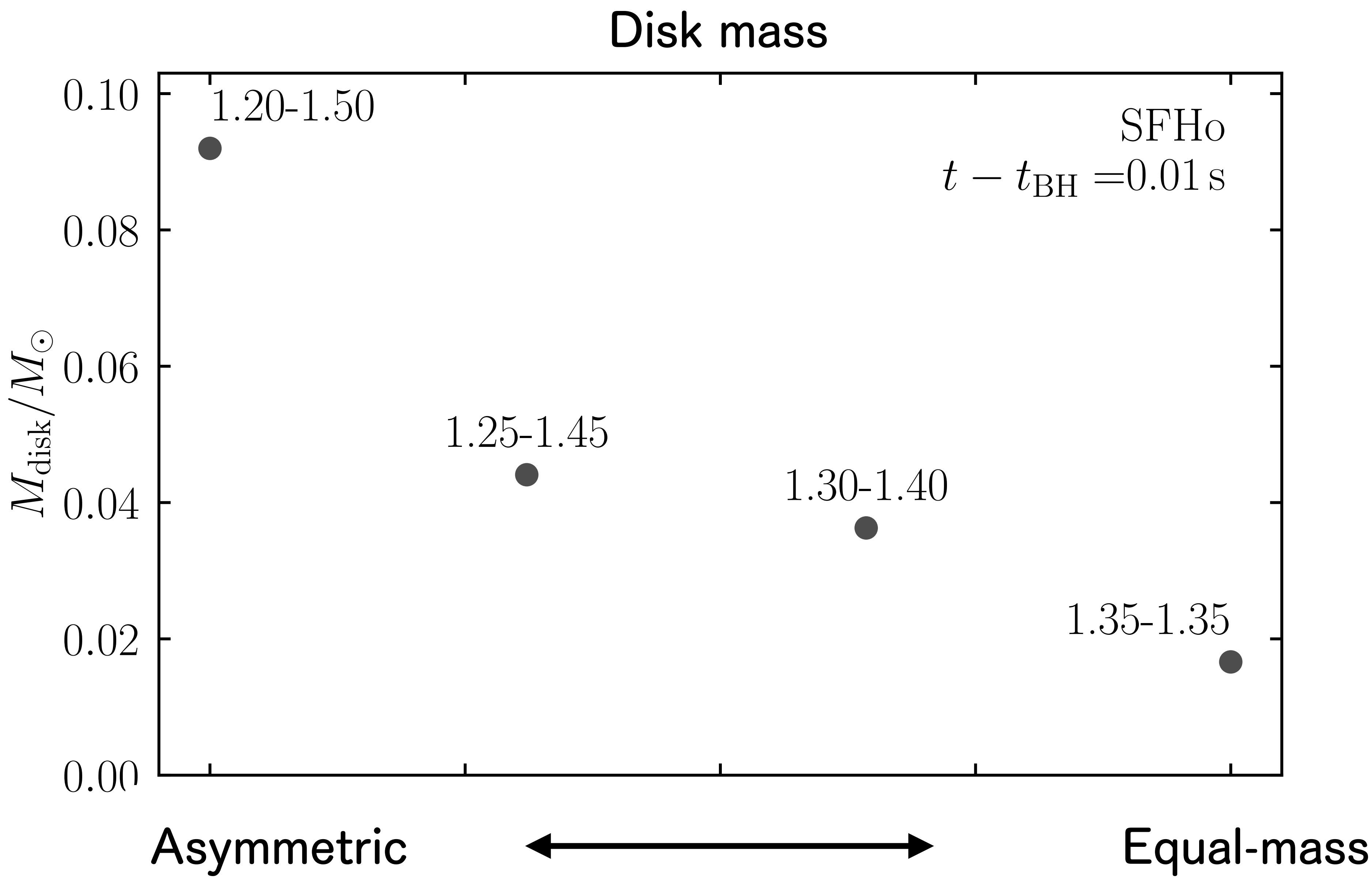


Highest velocity > 0.9 c
irrespective of the total mass, mass ratio.
M(v/c > 0.5) ~ 1e-4 Msun.



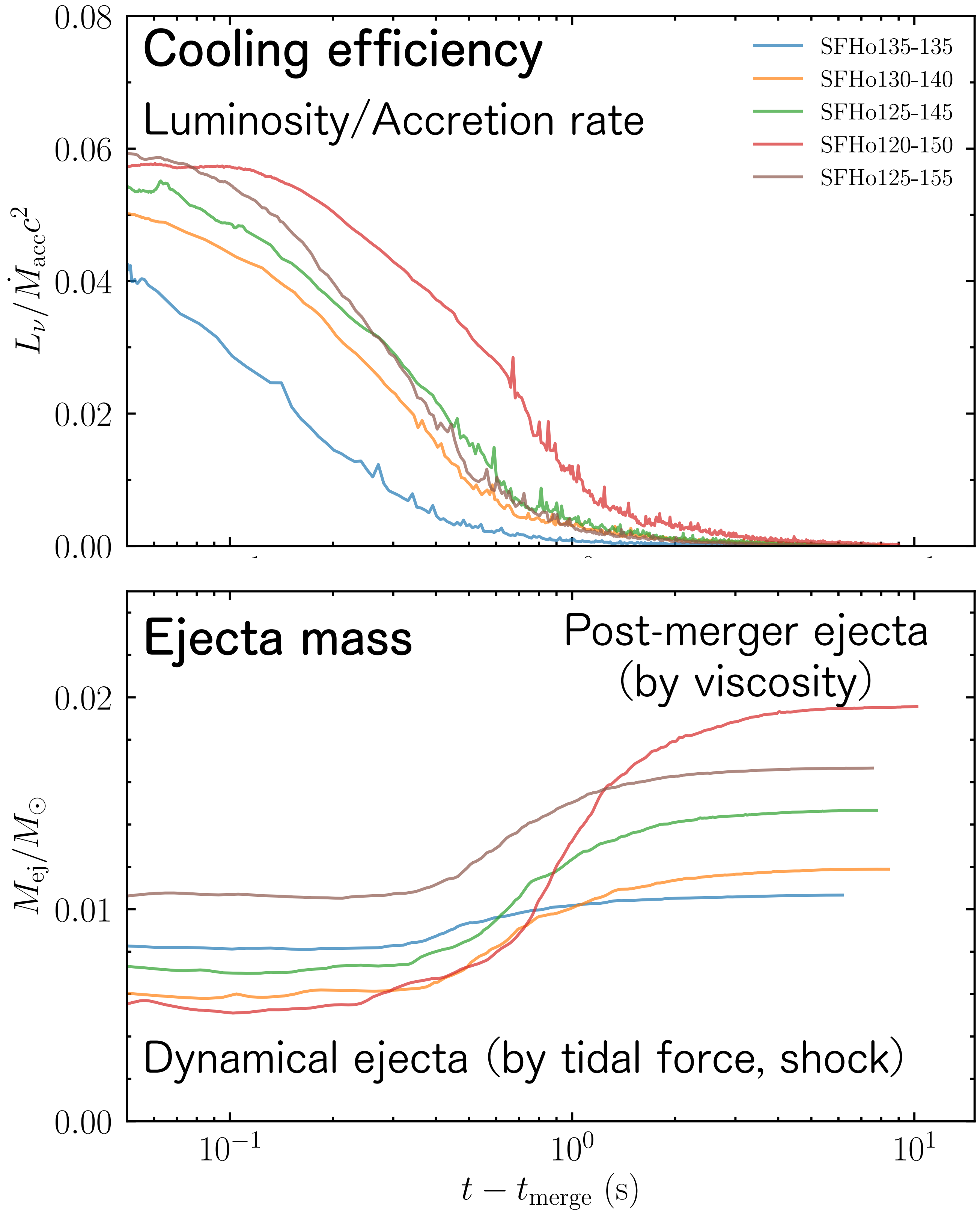
Post-merger ejecta

Mass-ratio dependence of disk 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 $t_{\rm weak} \sim 1\,{\rm ms}\left(\frac{kT}{5\,{\rm MeV}}\right)^{-5}$
→Mass ejection by viscous heating

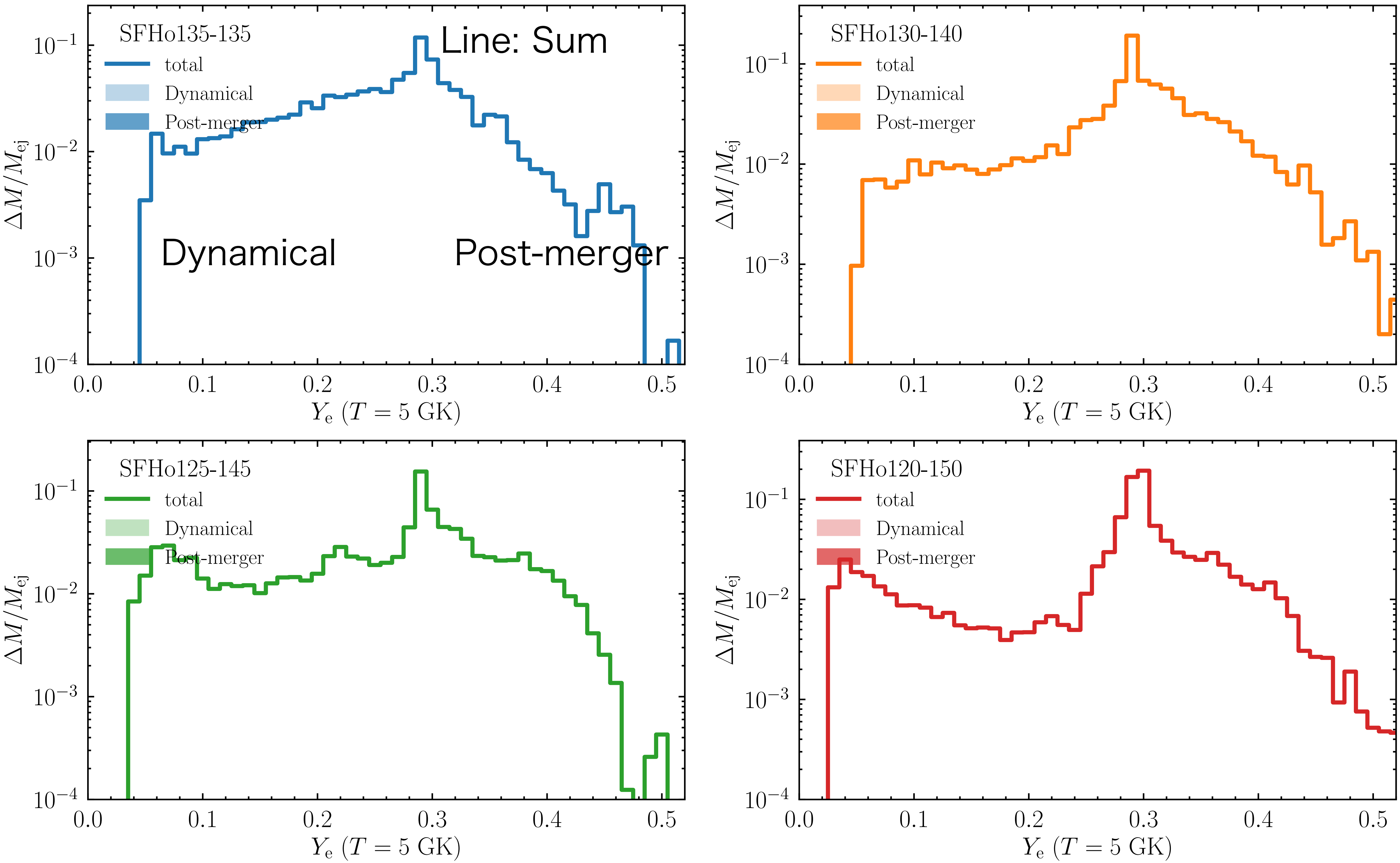
Mass-ratio dependence

Equal-mass: Lower disk mass
→ Dynamical ejecta dominates

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

Ejecta composition

Composition of the ejecta

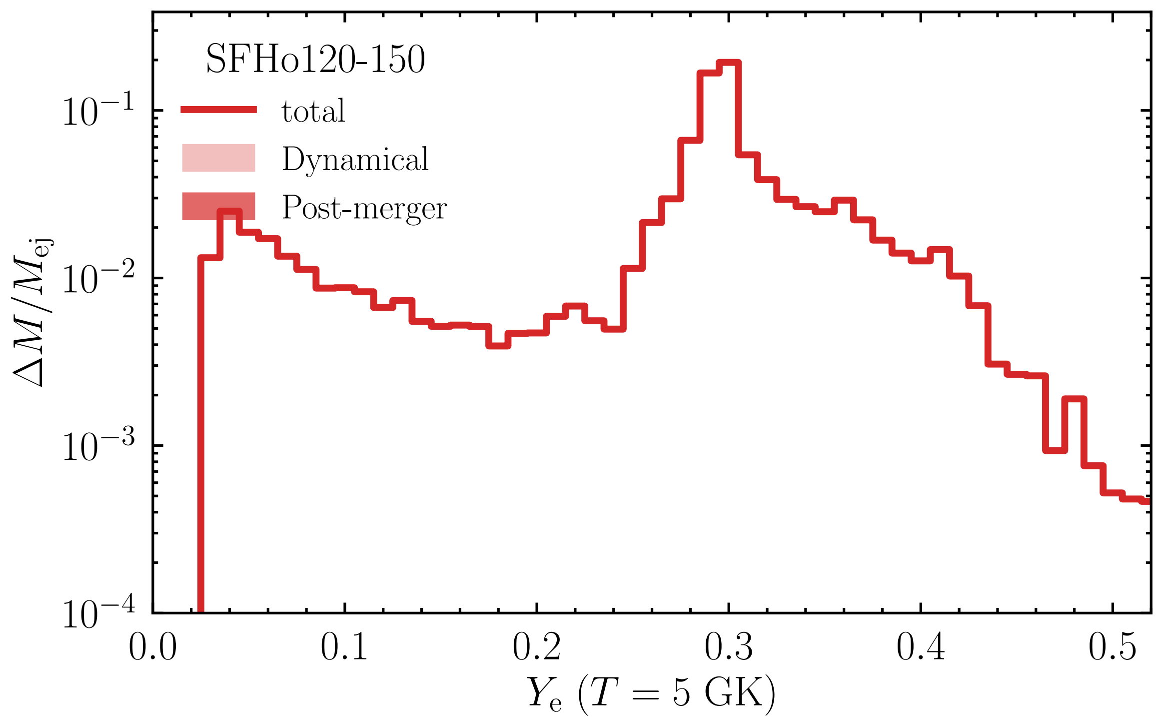


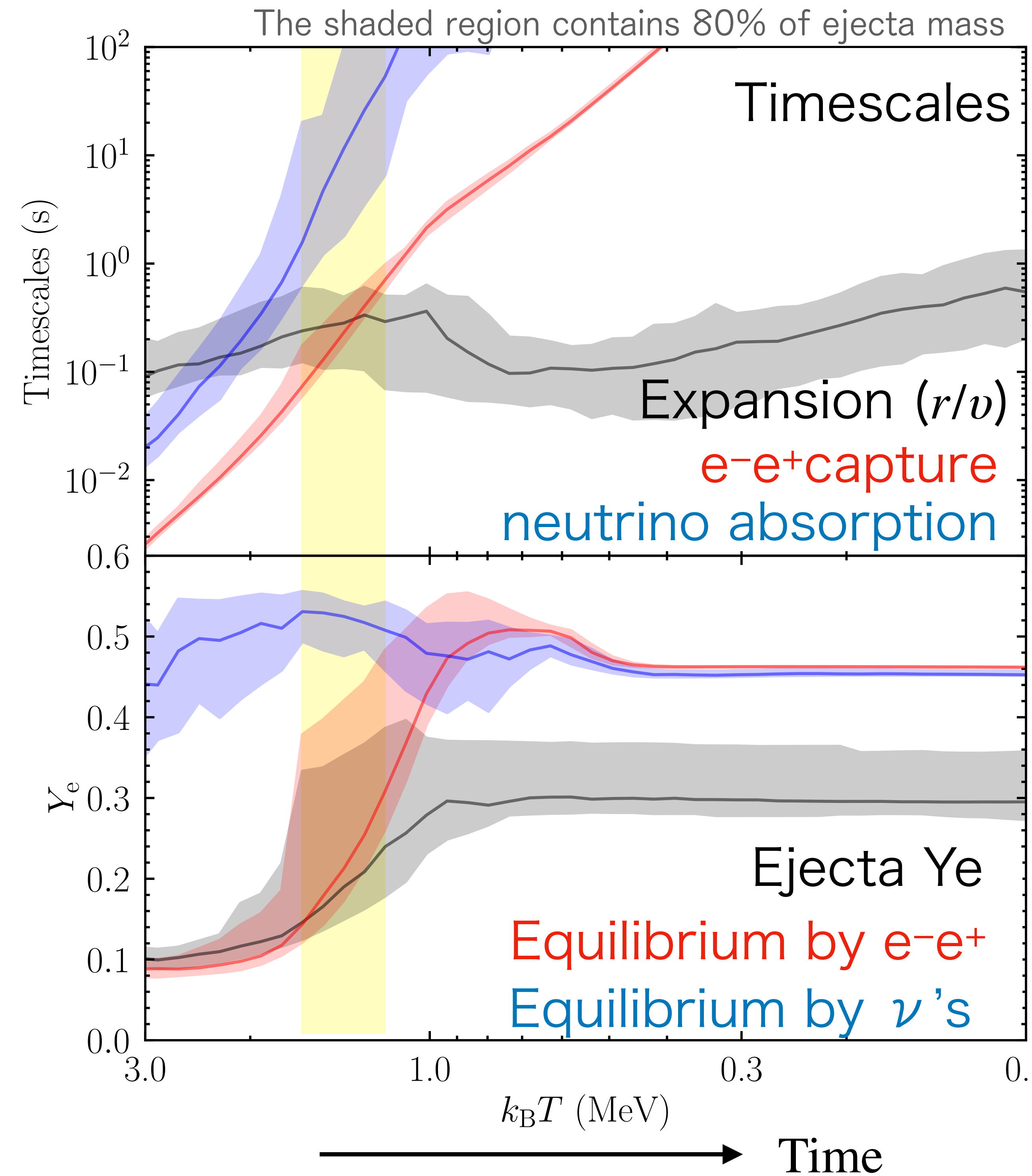
Contribution of the post-merger ejecta is larger for more asymmetric case

The peak at Ye ≈ 0.3 irrespective of mass ratio

Composition of the ejecta

see also Just+22





Distribution peaks at $Y_e \approx 0.3$
(irrespective of mass ratio)

At high temperature

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

determines Y_e , which freezes out when

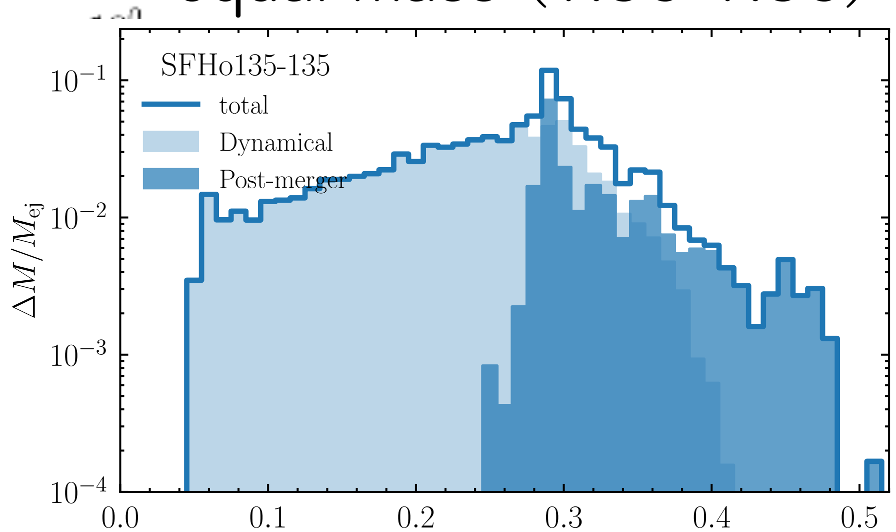
$$t_{\text{expansion}} \sim t_{\text{weak}} \quad (k_B T \sim 1 - 2\,\text{MeV})$$

※ Resulting Y_e depends on the strength of the viscosity (or expansion timescale).

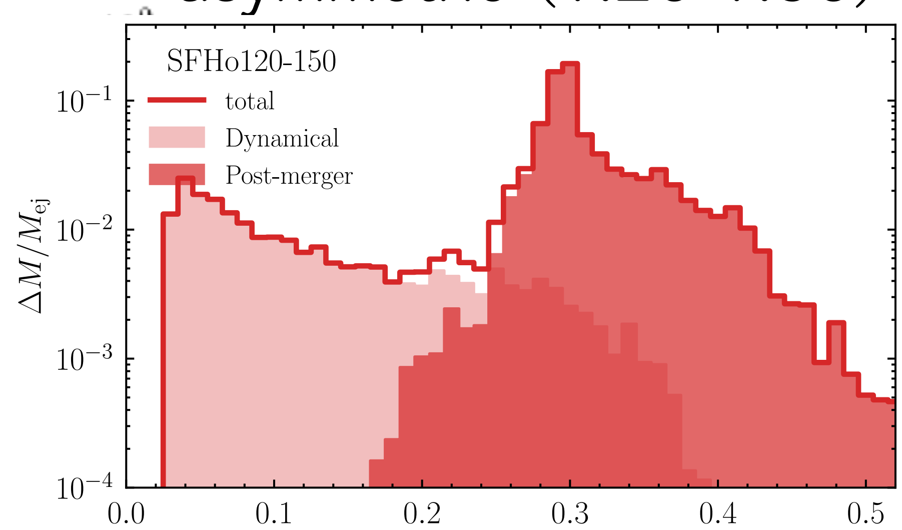
Composition of the ejecta

Short-lived massive NS

equal-mass (1.35-1.35)

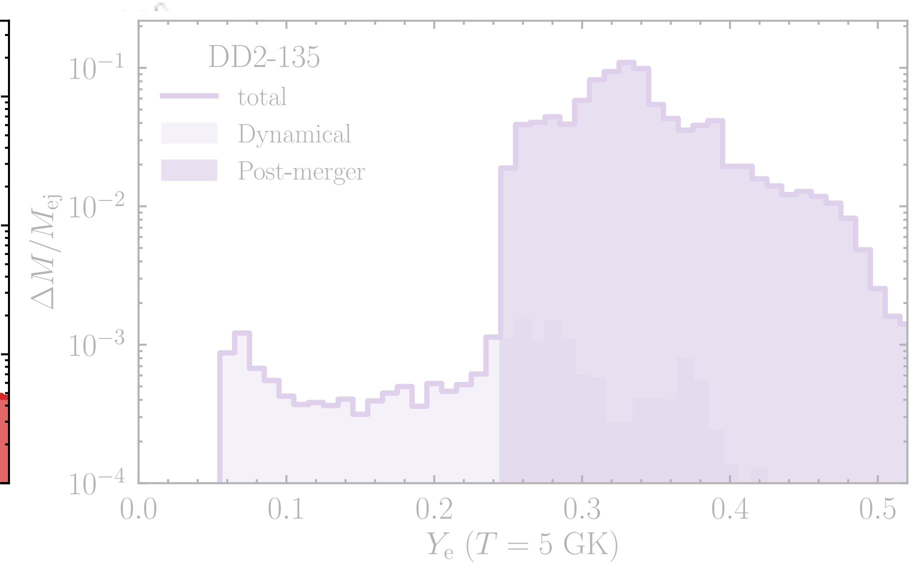


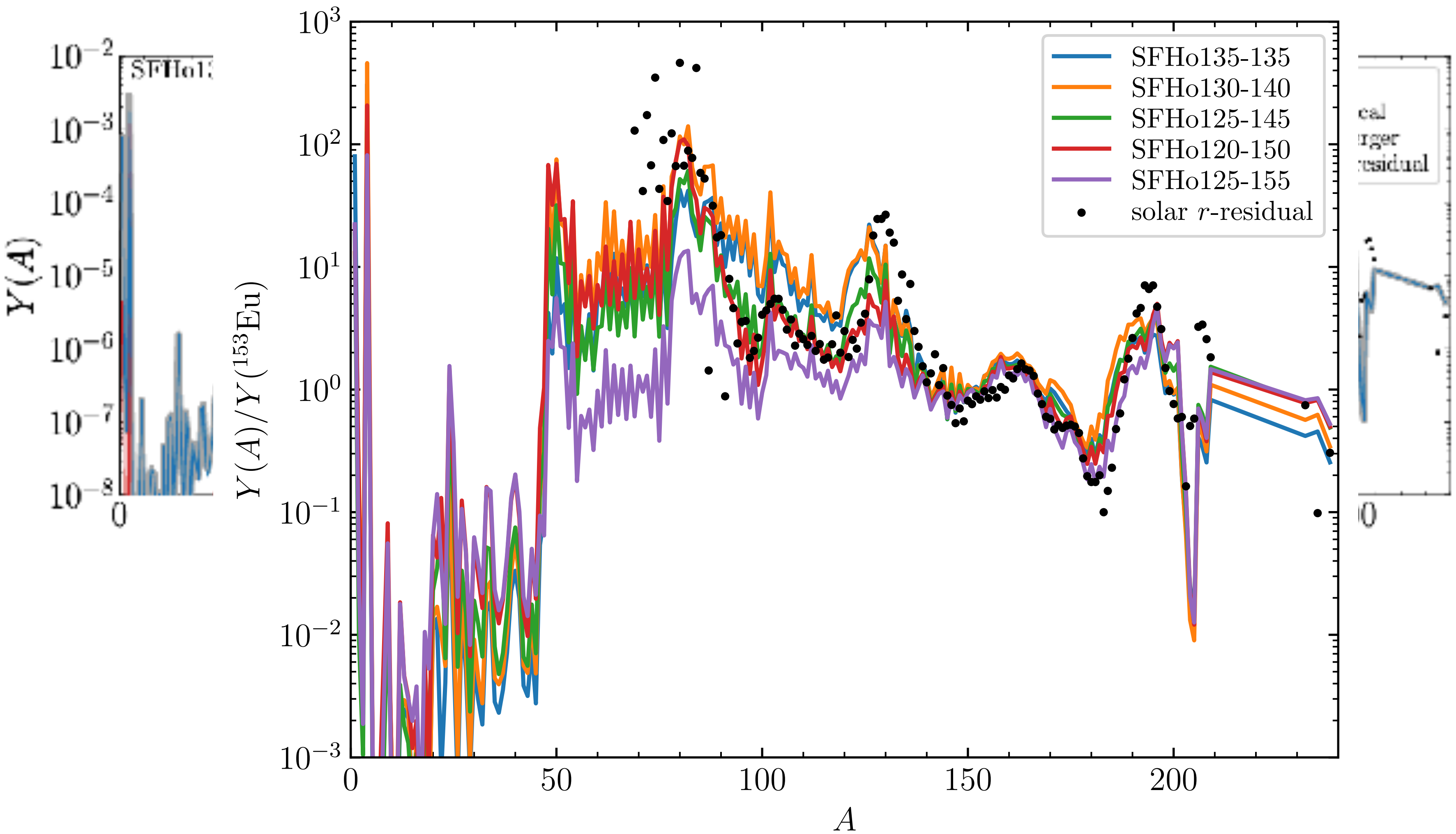
asymmetric (1.20-1.50)

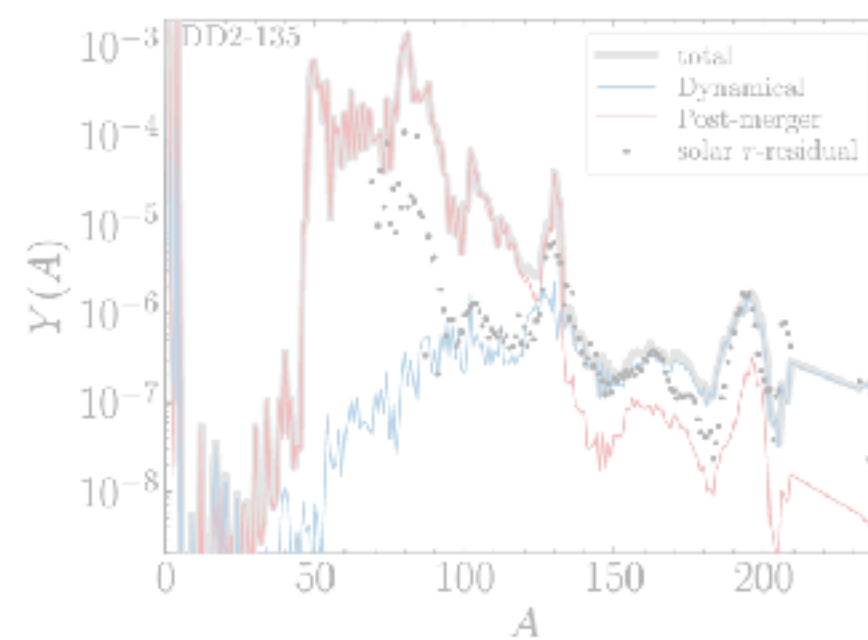


Long-lived massive NS

equal-mass (DD2 1.35-1.35)







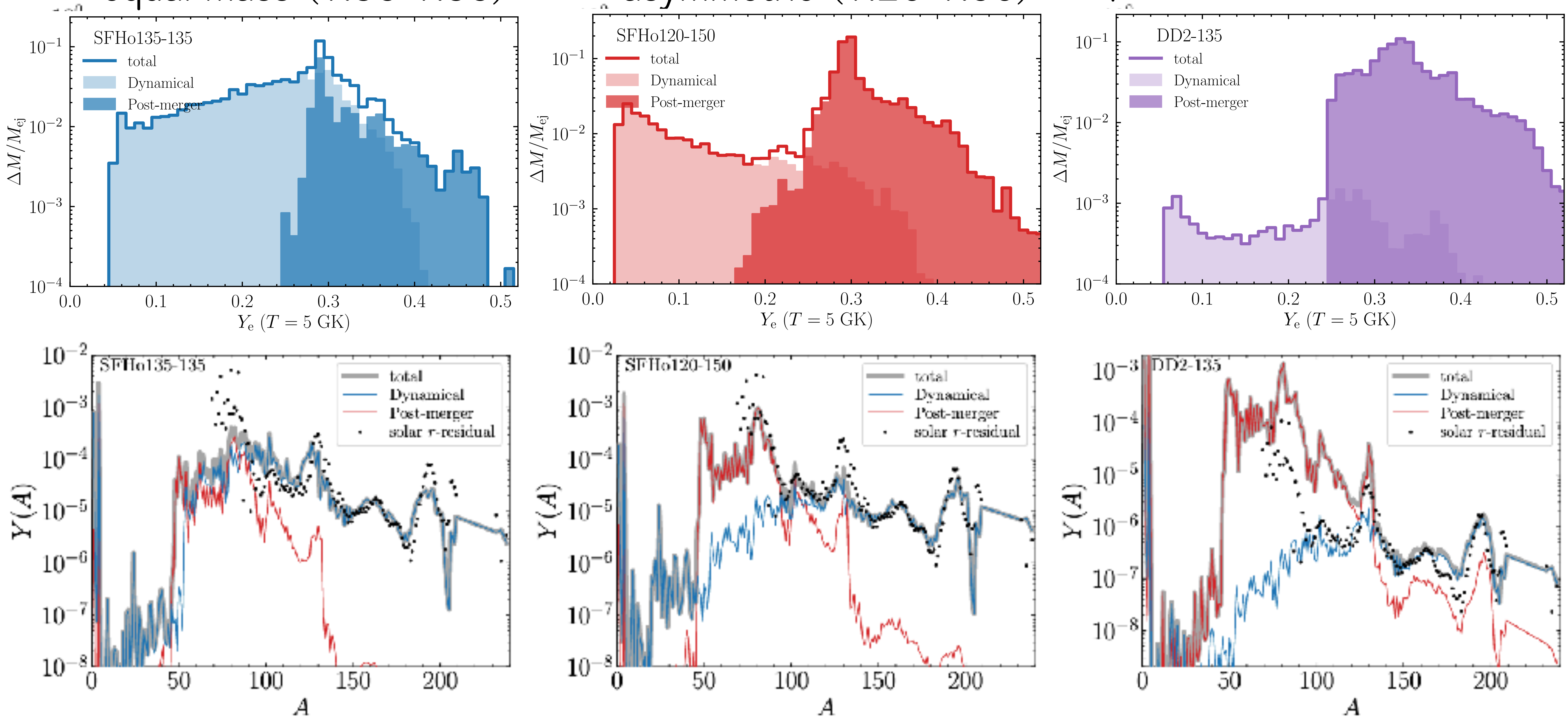
Long-lived massive NS case

Composition of the ejecta

Short-lived massive NS

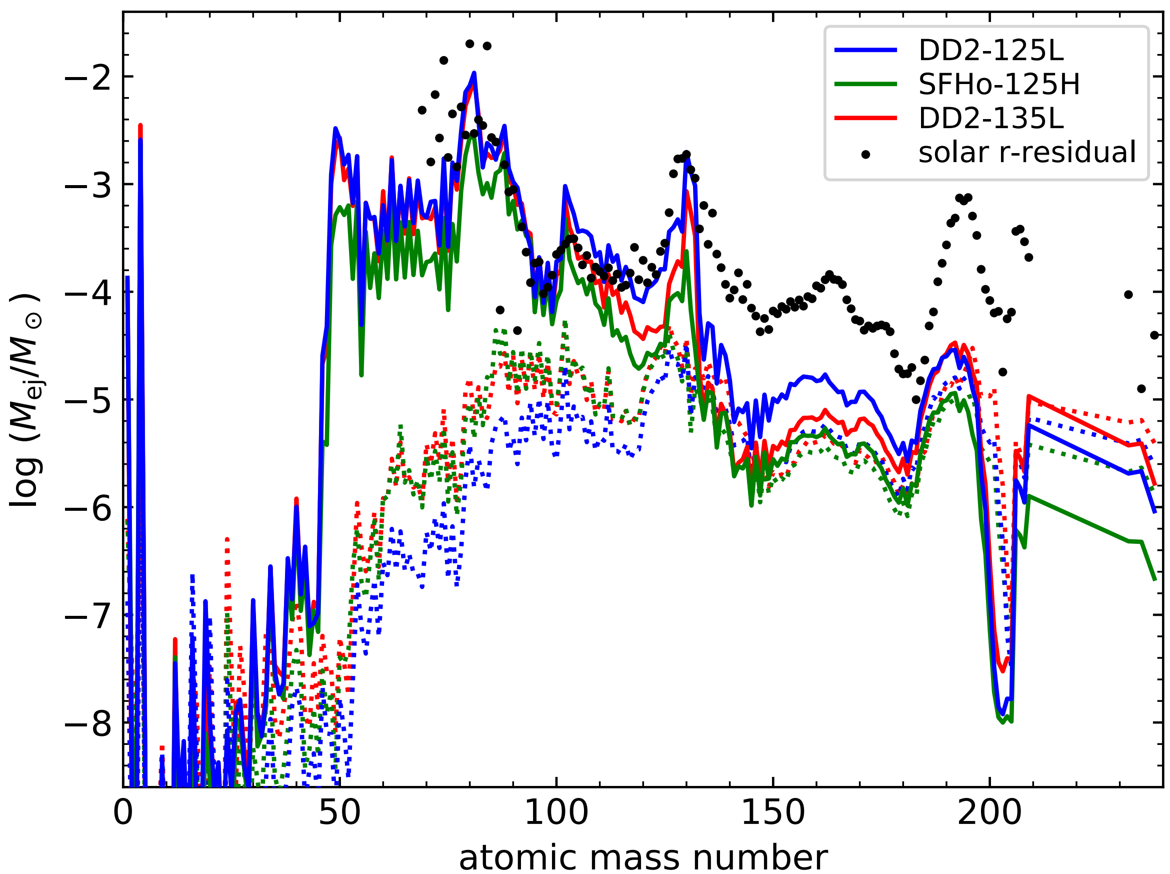
equal-mass (1.35-1.35) asymmetric (1.20-1.50)

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.

RMHD simulation with effective dynamo term for merger remnant

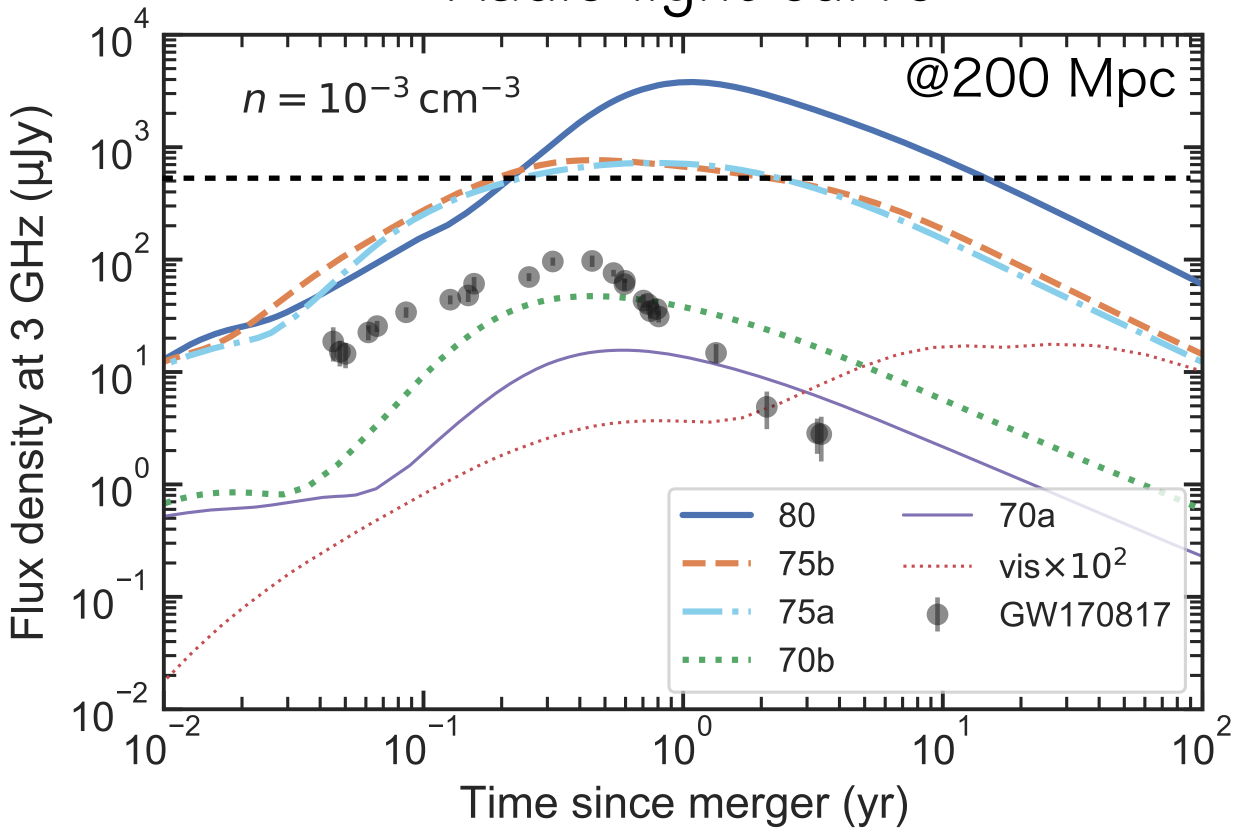
Shibata, SF, and Sekiguchi 21,
Kawaguchi, SF+22 (submitted)

We investigated the possible amplification of B-field inside the long-lived massive NS by performing 2D MHD simulations for merger remnant with effective dynamo term.

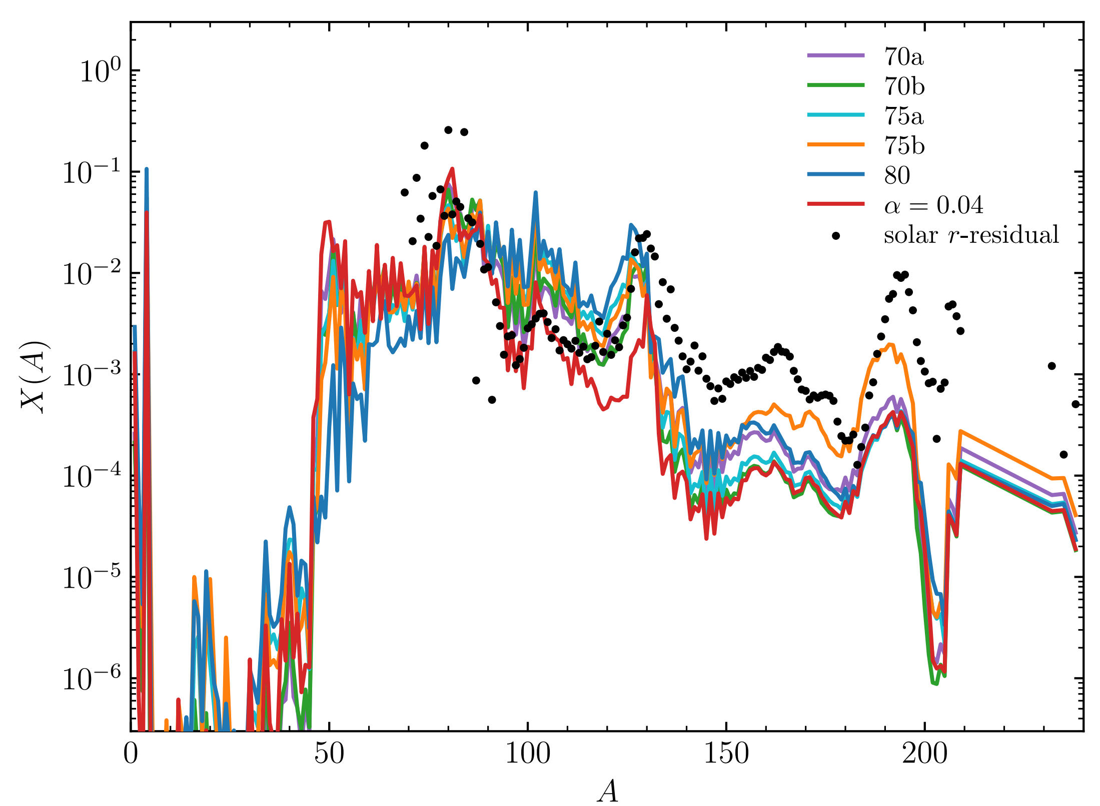
(Depending on the growth timescale of B-field in the NS)

- Mass ejection is more violent with large kinetic energy.
  → Very bright radio emission (event rate already constrained?).
- MHD effect makes Ye lower, but not sufficient.
  → Underproduction for A>140 is still present.

Radio light curve

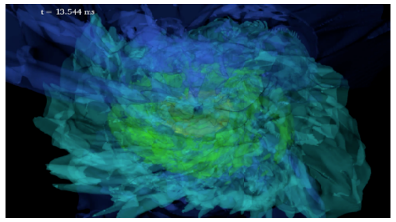


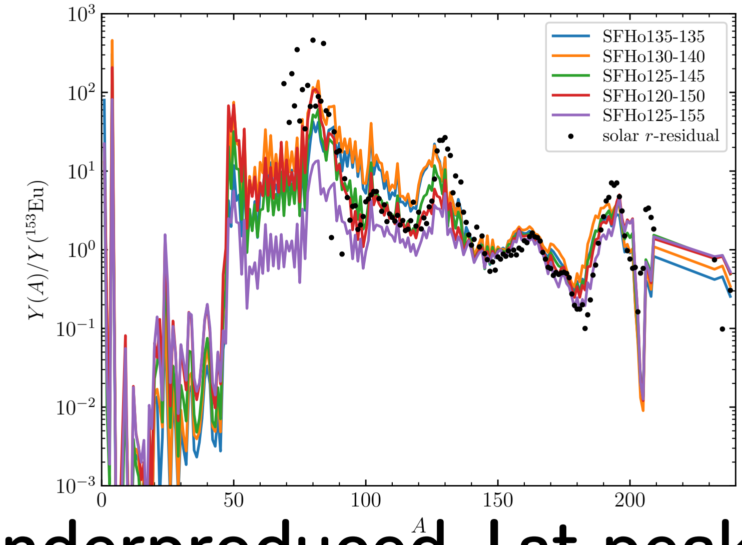
Nuclear abundance



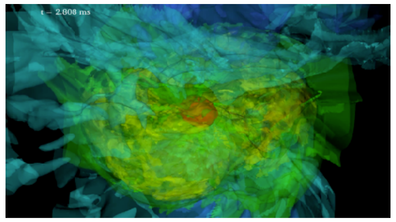
Summary

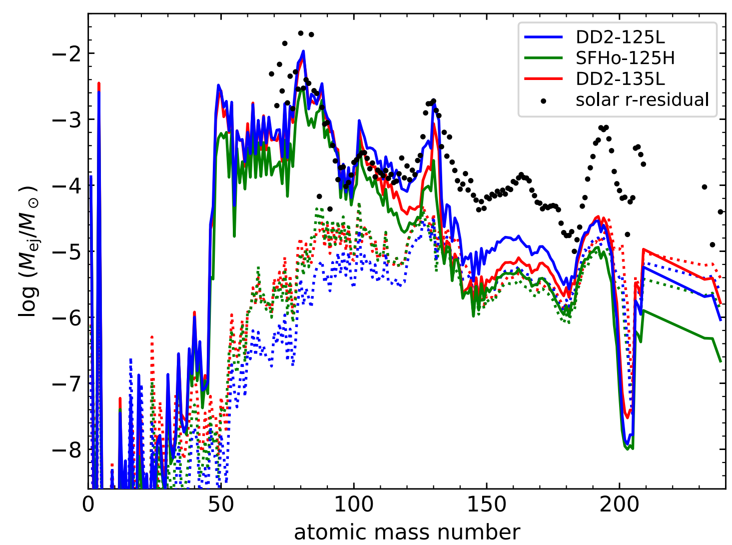
★Numerical simulation of NS-NS mergers and its remnants
(merger in 3D, post-merger in 2D with approx. neutrino transport)





- 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.

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