Long-term evolution of binary neutron star merger and nucleosynthesis

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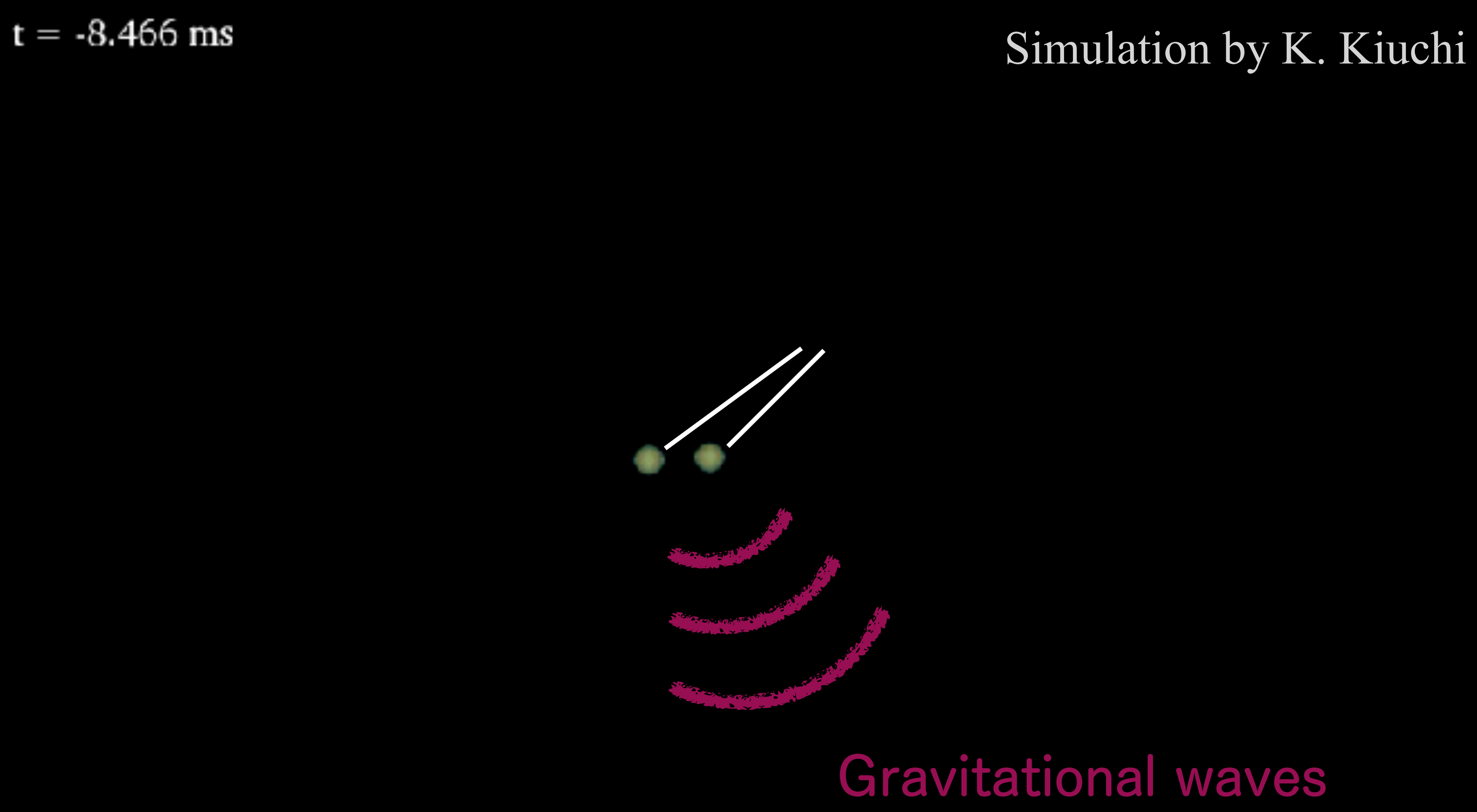
FRIS

Outline

1. NS mergers and nucleosynthesis
2. Time evolution and mass ejection
3. Implications of numerical simulations
4. Summary

NS-mergers and nucleosynthesis

Introduction



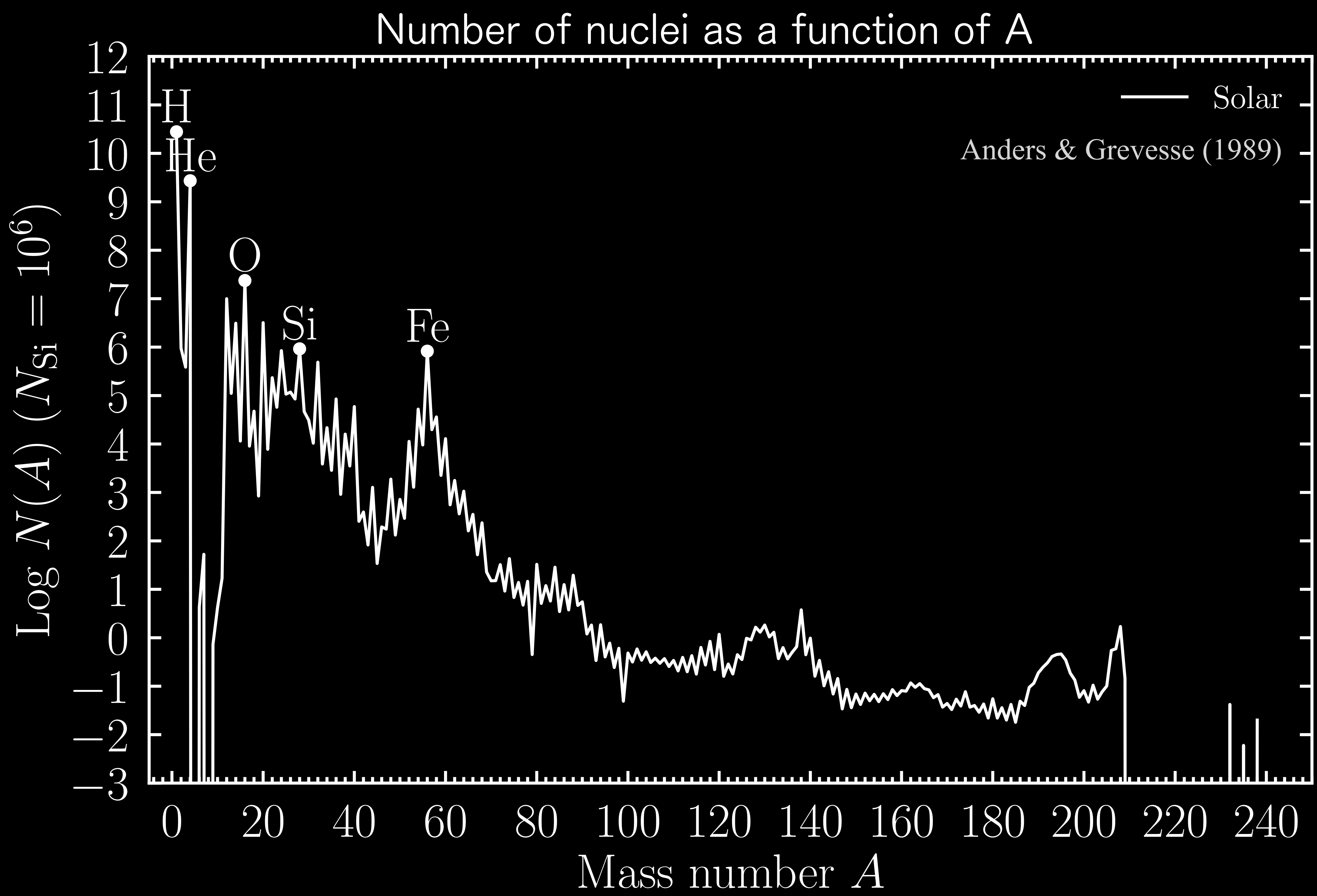
Binary NS is ...

- One of the primary sources of GWs (targeted by ground-based detectors)
    - Constituent masses
    - Nuclear matter properties
- Promising source of (short-hard) gamma-ray bursts
    - Mechanism of the bursts
- Promising site of heavy-element synthesis

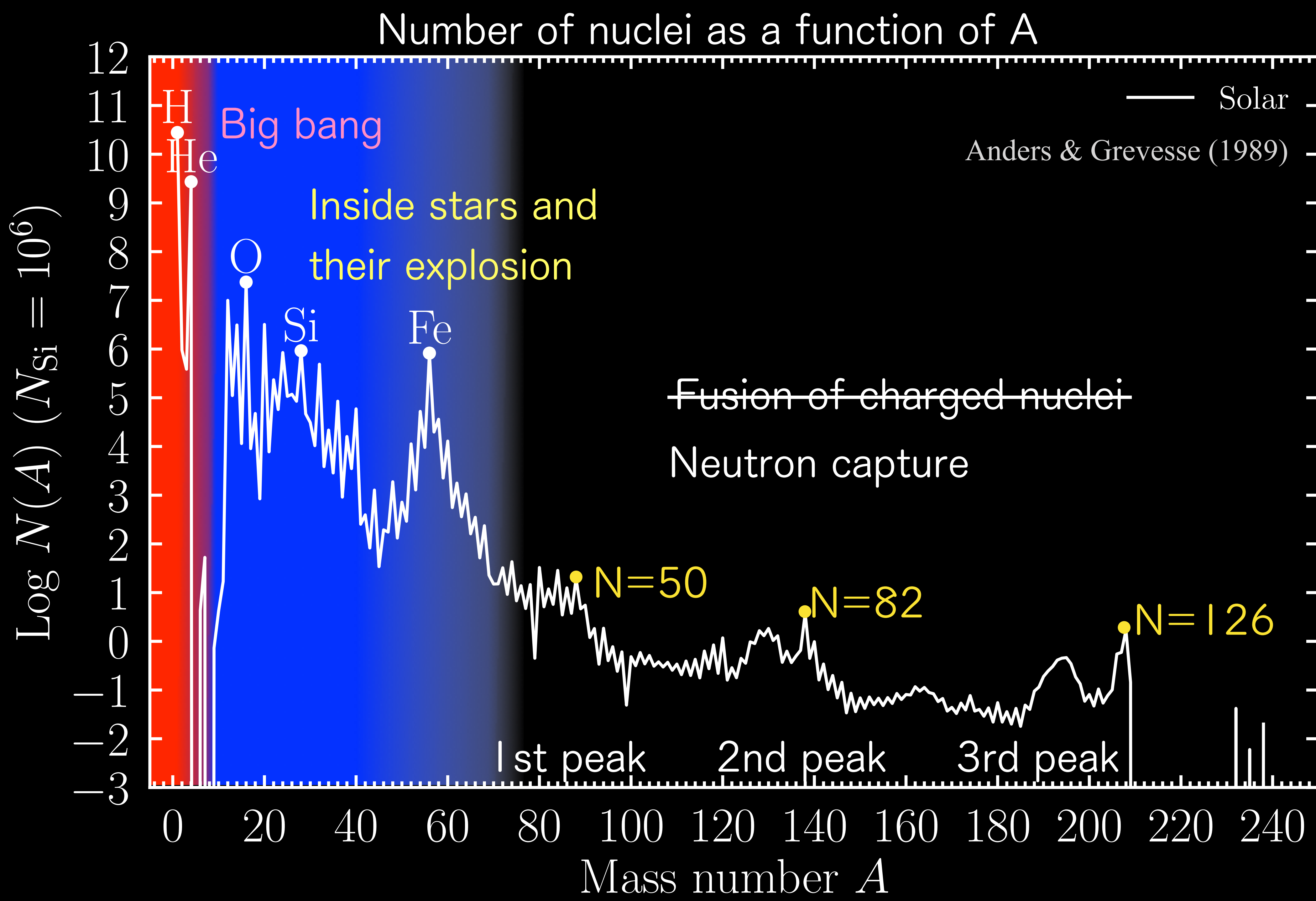
  Origin of elements

  Electromagnetic signal (kilonova)
    - Dynamics of the merger, post-merger activities

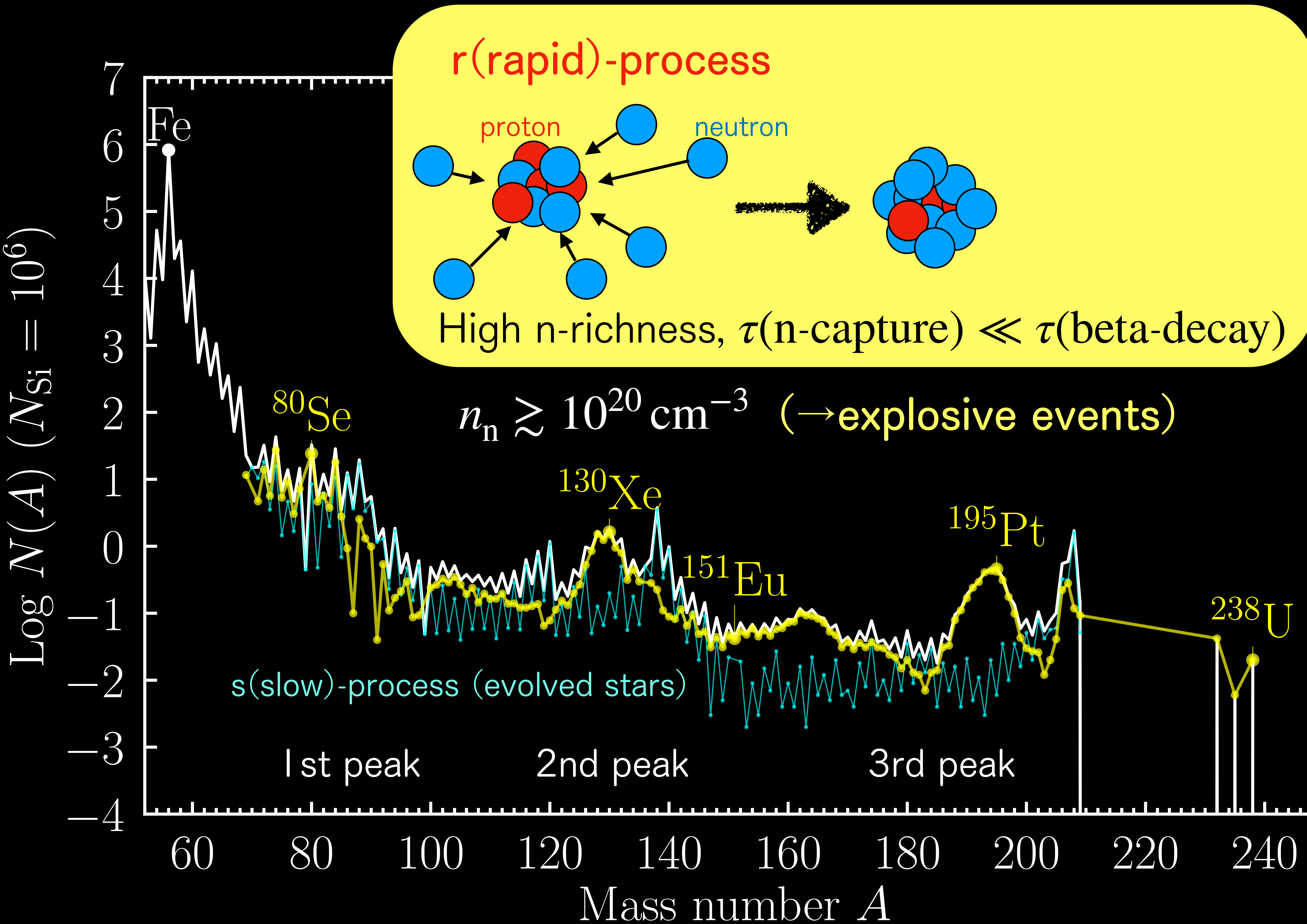
Solar nuclear pattern



Solar nuclear pattern



r-process


r(rapid)-process
proton
neutron
High n-richness, τ(n-capture) ≪ τ(beta-decay)
$n_n \gtrsim 10^{20}\,\mathrm{cm}^{-3}$ (→explosive events)
Fe
^{80}Se
^{130}Xe
^{151}Eu
^{195}Pt
^{238}U
s(slow)-process (evolved stars)
1st peak
2nd peak
3rd peak
Log $N(A)$ ($N_{\mathrm{Si}} = 10^6$)
Mass number A
7
6
5
4
3
2
1
0
−1
−2
−3
−4
60
80
100
120
140
160
180
200
220
240

r-process in NS-NS merger

Symbalisty & Schramm 82, Eichler+ 89, …

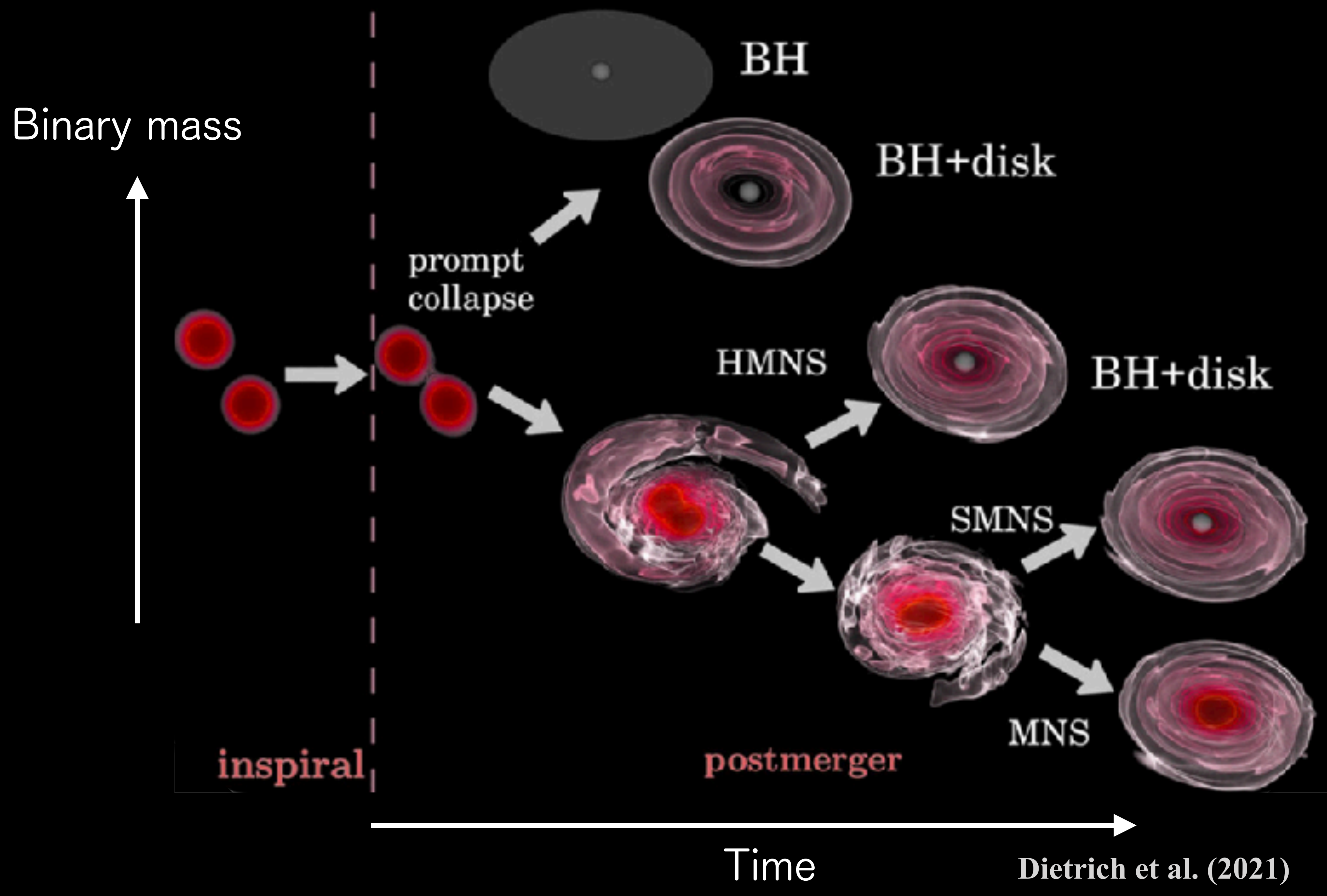
Simulation by K. Kiuchi

A fraction of matter becomes unbound.

Likely neutron-rich → r-process nucleosynthesis!

Time evolution and mass ejection

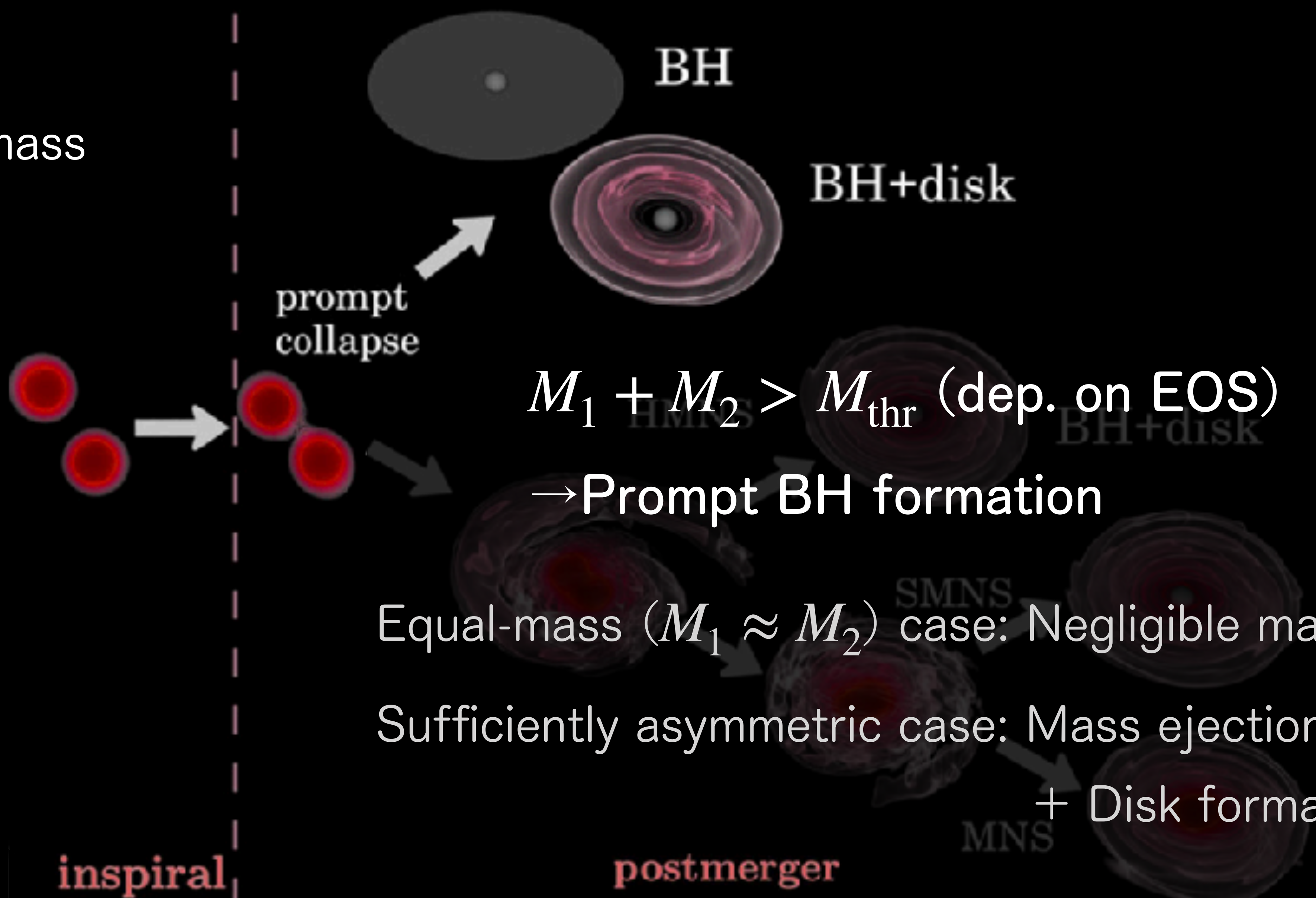
Evolution path of mergers



Dietrich et al. (2021)

Evolution path of mergers

Binary mass



$M_1 + M_2 > M_{\rm thr}$ (dep. on EOS)

→Prompt BH formation

Equal-mass ($M_1 \approx M_2$) case: Negligible mass ejection

Sufficiently asymmetric case: Mass ejection by tidal force

+ Disk formation

Time

Dietrich et al. (2021)

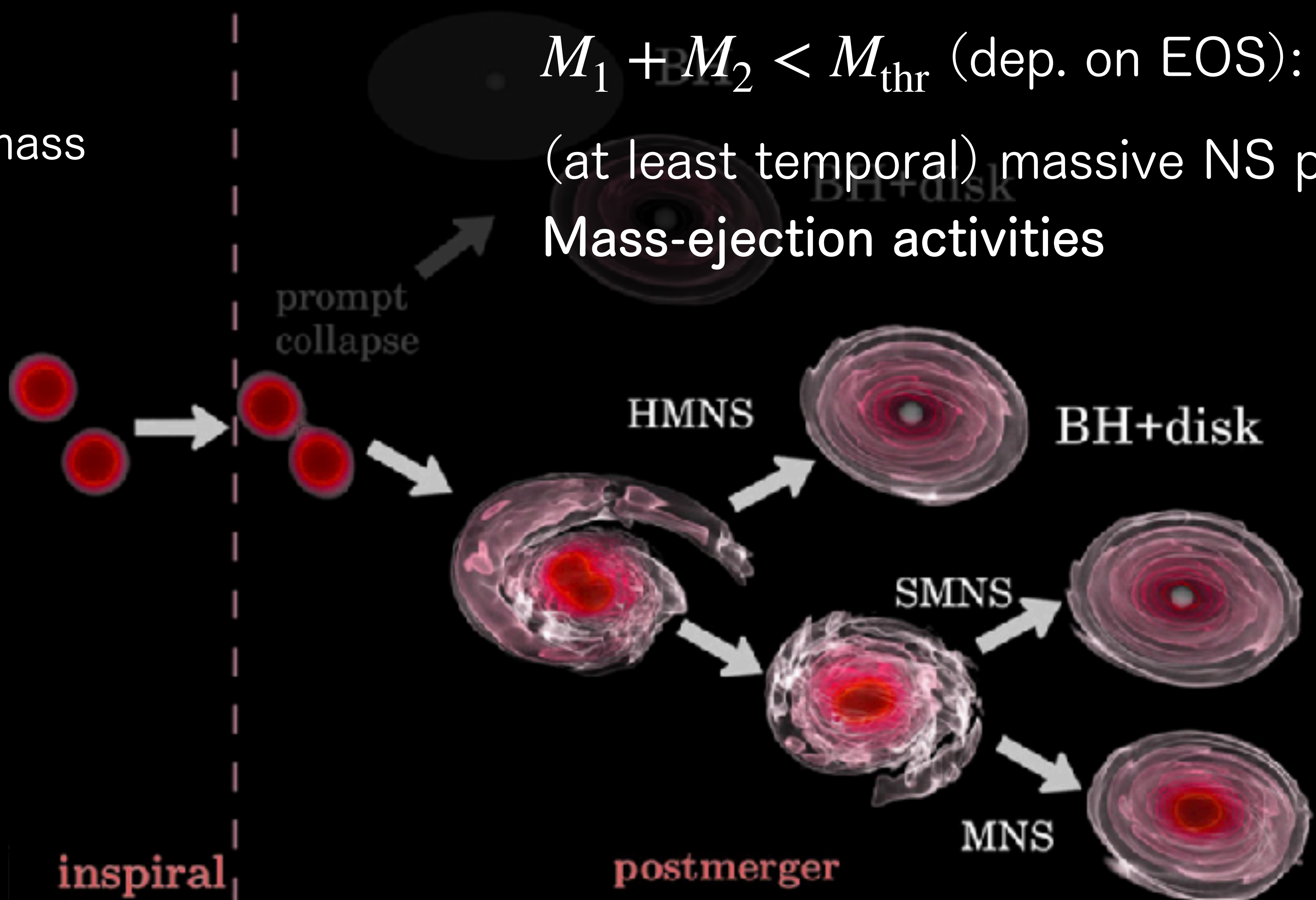
Evolution path of mergers

$M_1 + M_2 < M_{thr}$ (dep. on EOS):

(at least temporal) massive NS phase

Mass-ejection activities

Binary mass

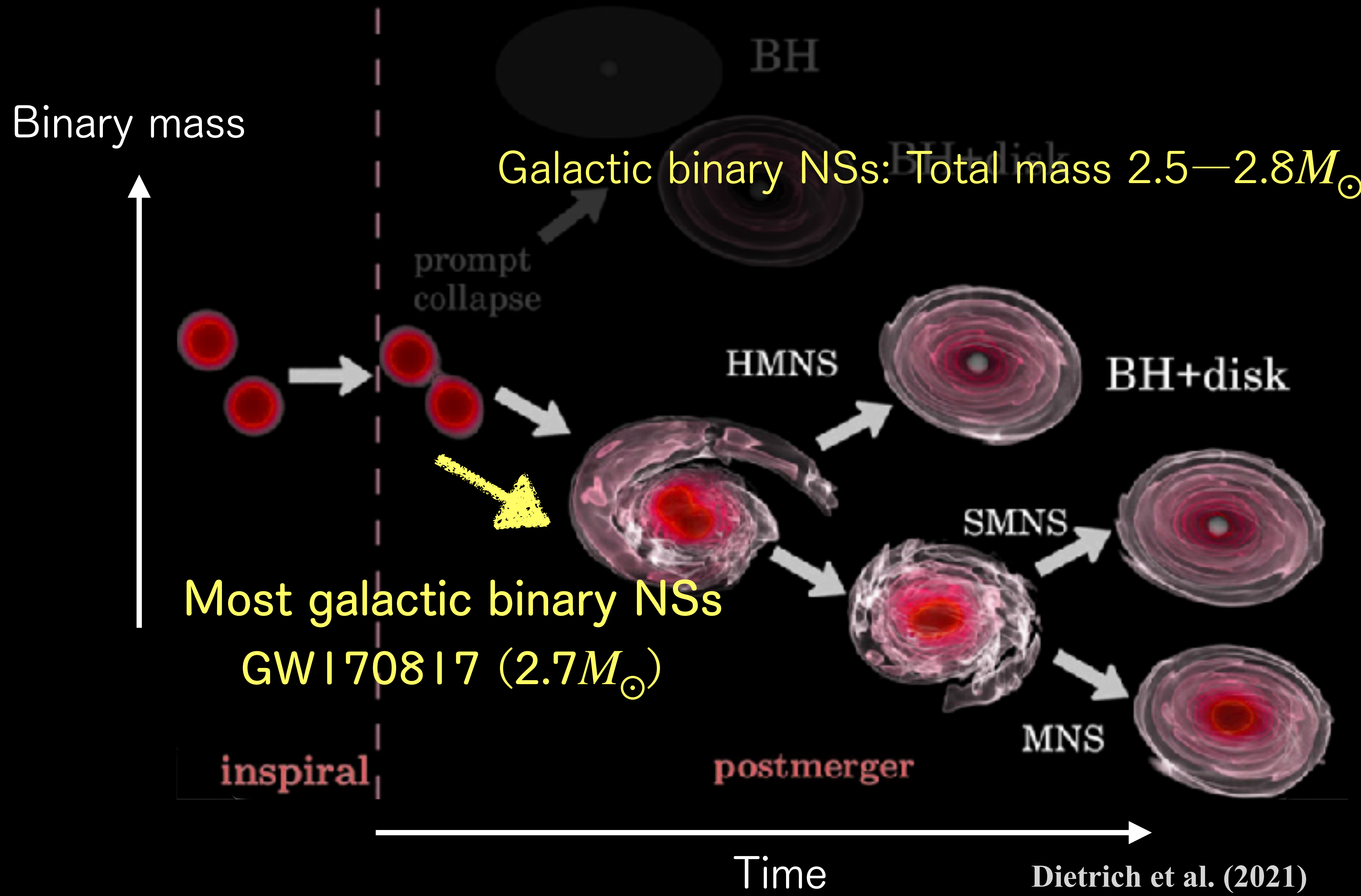


Time

Dietrich et al. (2021)

Evolution path of mergers

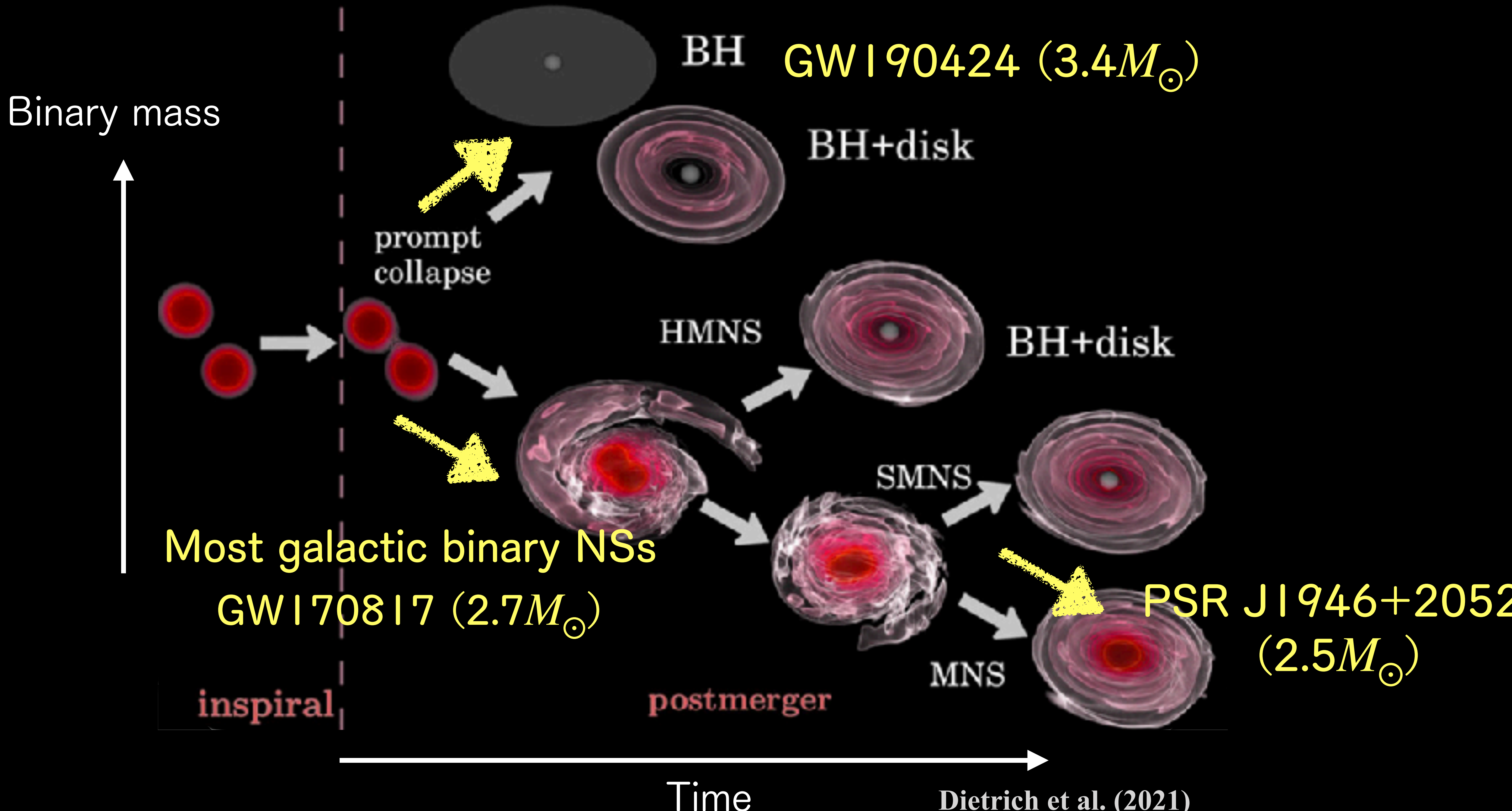
EOS that can support $2M_\odot$ NS → $M_{\rm thr} \gtrsim 2.8M_\odot$ Hotokezaka+11 Dietrich+17



Dietrich et al. (2021)

Evolution path of mergers

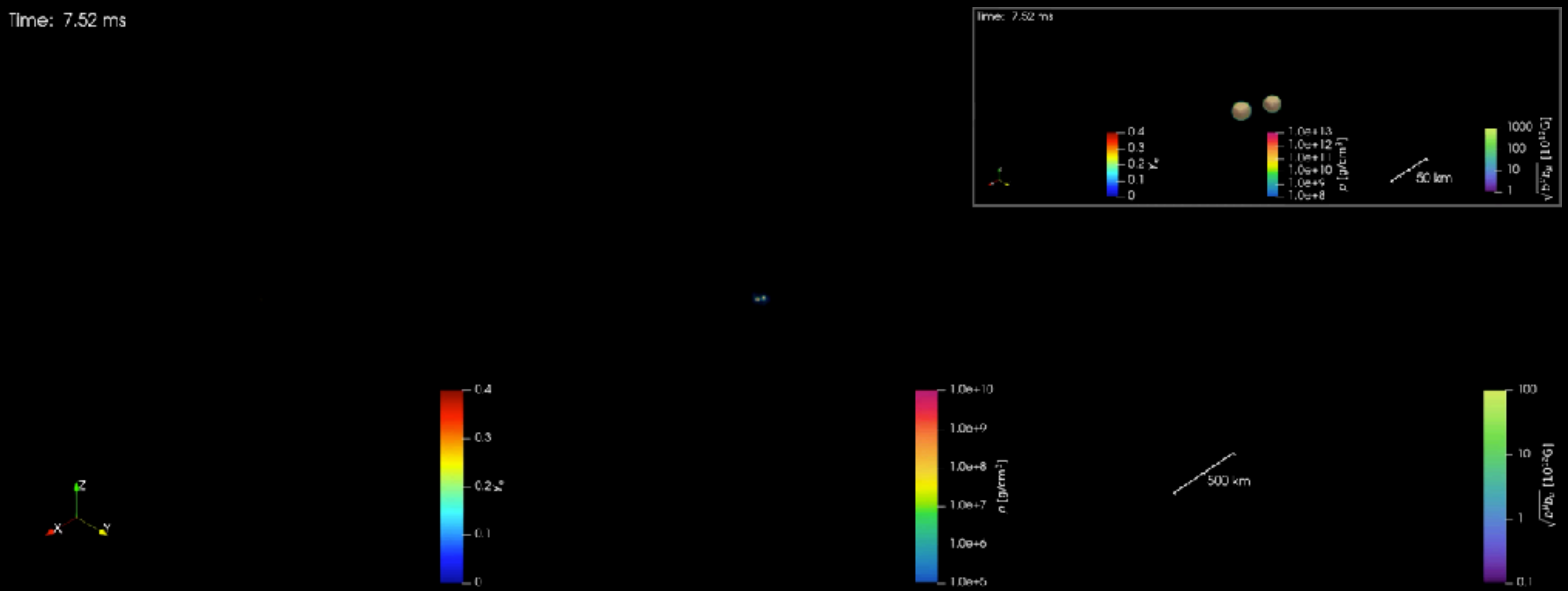
EOS that can support $2M_\odot$ NS → $M_{\rm thr} \gtrsim 2.8M_\odot$



Dietrich et al. (2021)

Mass ejection activities of merger

Kiuchi, SF+23 (visualized by K. Hayashi)



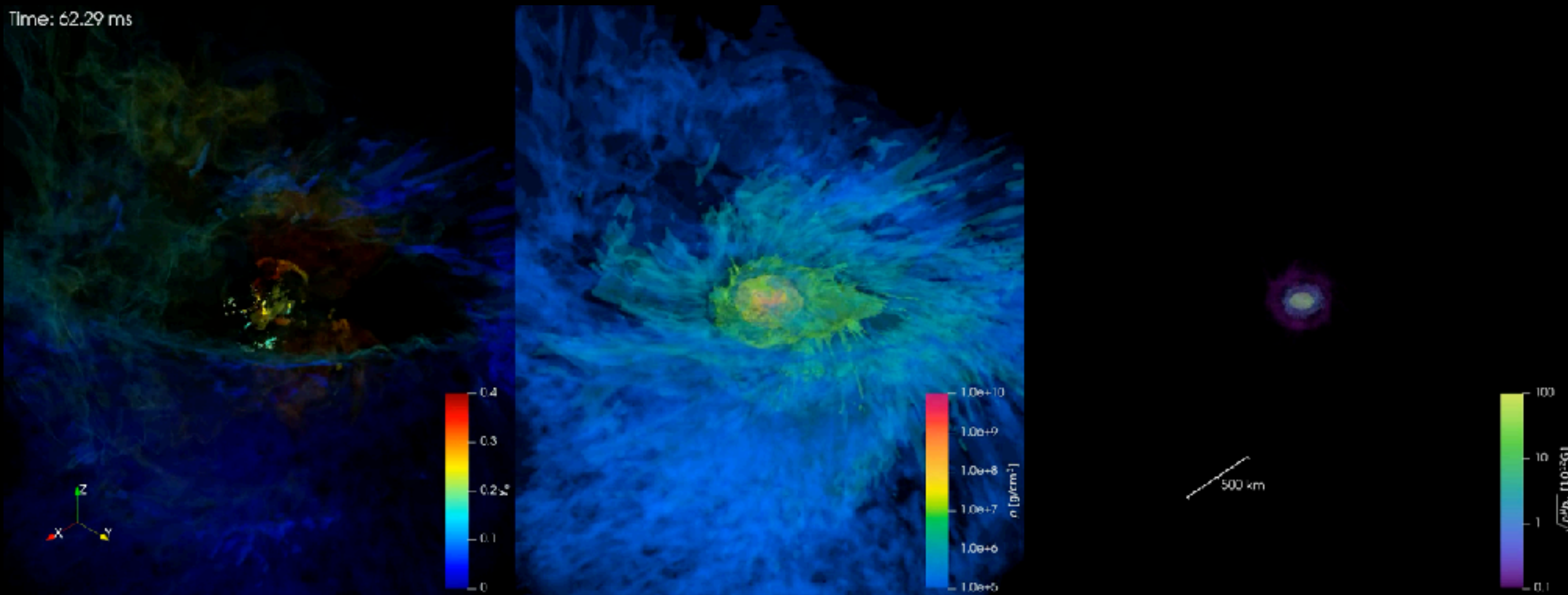
Dynamical mass ejection

(tidal force, shock heating) ~ 10 ms

→ Disk formation

Mass ejection activities of merger

Kiuchi, SF+23 (visualized by K. Hayashi)



- High temperature → weak interaction plays an important role
- $t_{\rm weak} \sim 1\,{\rm ms}\left(\frac{kT}{5\,{\rm MeV}}\right)^{-5} \lesssim$ 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

- 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)

Implications of numerical simulation: Dynamical Ejecta

To understand what happens in NS merger...

Performing numerical simulations solving is essential

Highly non-linear system with
- Strong and dynamical gravity
- Neutrino radiation (highly coupled to nearly free-streaming)
- Possible MHD effects

- Full GR radiation hydrodynamics code **Sekiguchi 10, Sekiguchi & Shibata 11, Sekiguchi+12**

- Einstein's equation **Nakamura & Shibata 95, Baumgarte & Shapiro 99**
- Neutrino radiation transfer equation **Thorne 81, Shibata et al. 11**
- 3D: Ideal-gas hydrodynamics equation

- 2D: Viscous hydrodynamics equation **Israel & Stuart 79, Shibata et al. 17, Shibata & Kiuchi 17**

Neutron-richness

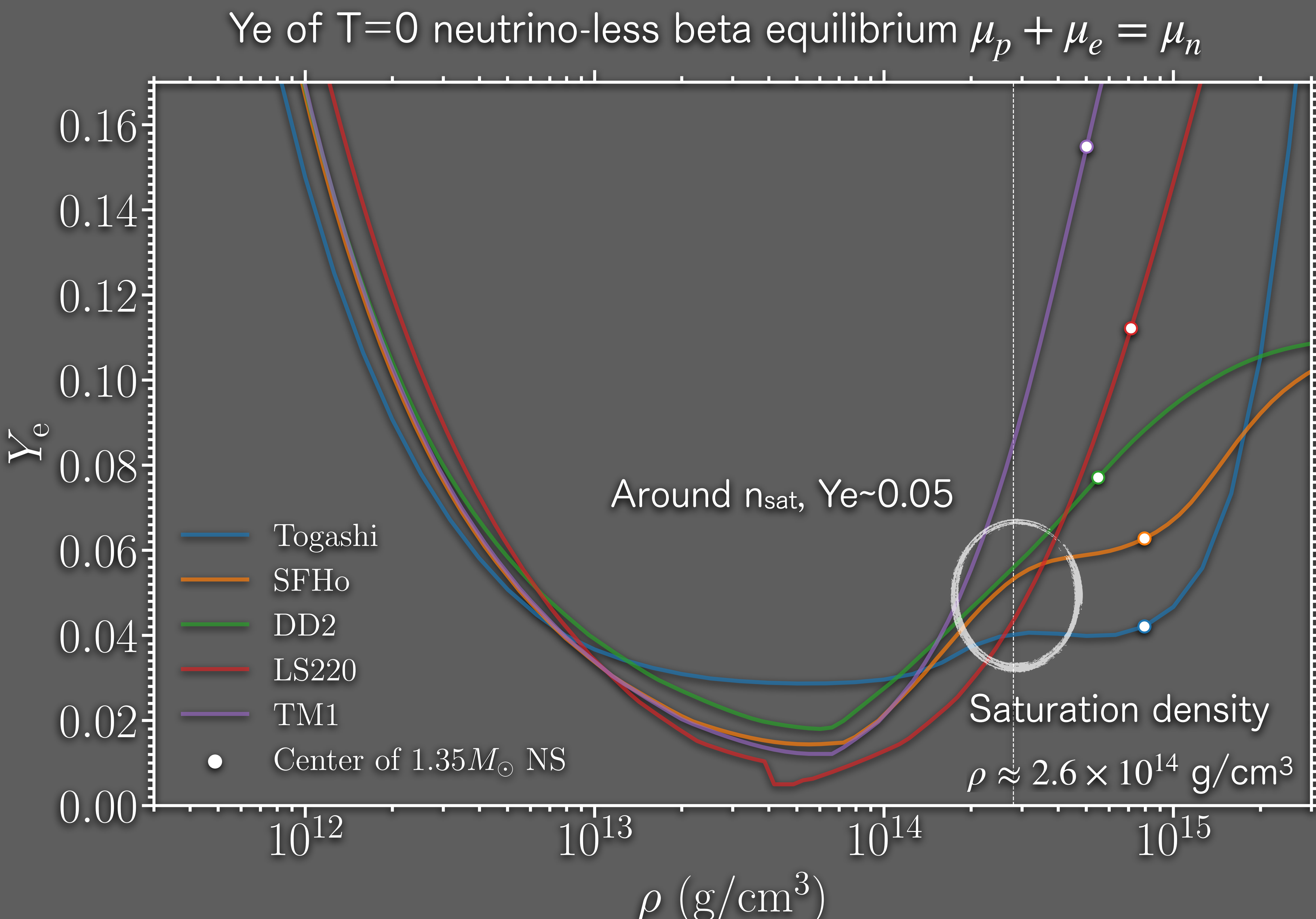
Controls efficiency of r-process

"Electron fraction" $Y_e := \frac{n_e}{n_{\rm baryon}} = 1 - \frac{n_n}{n_{\rm baryon}}$

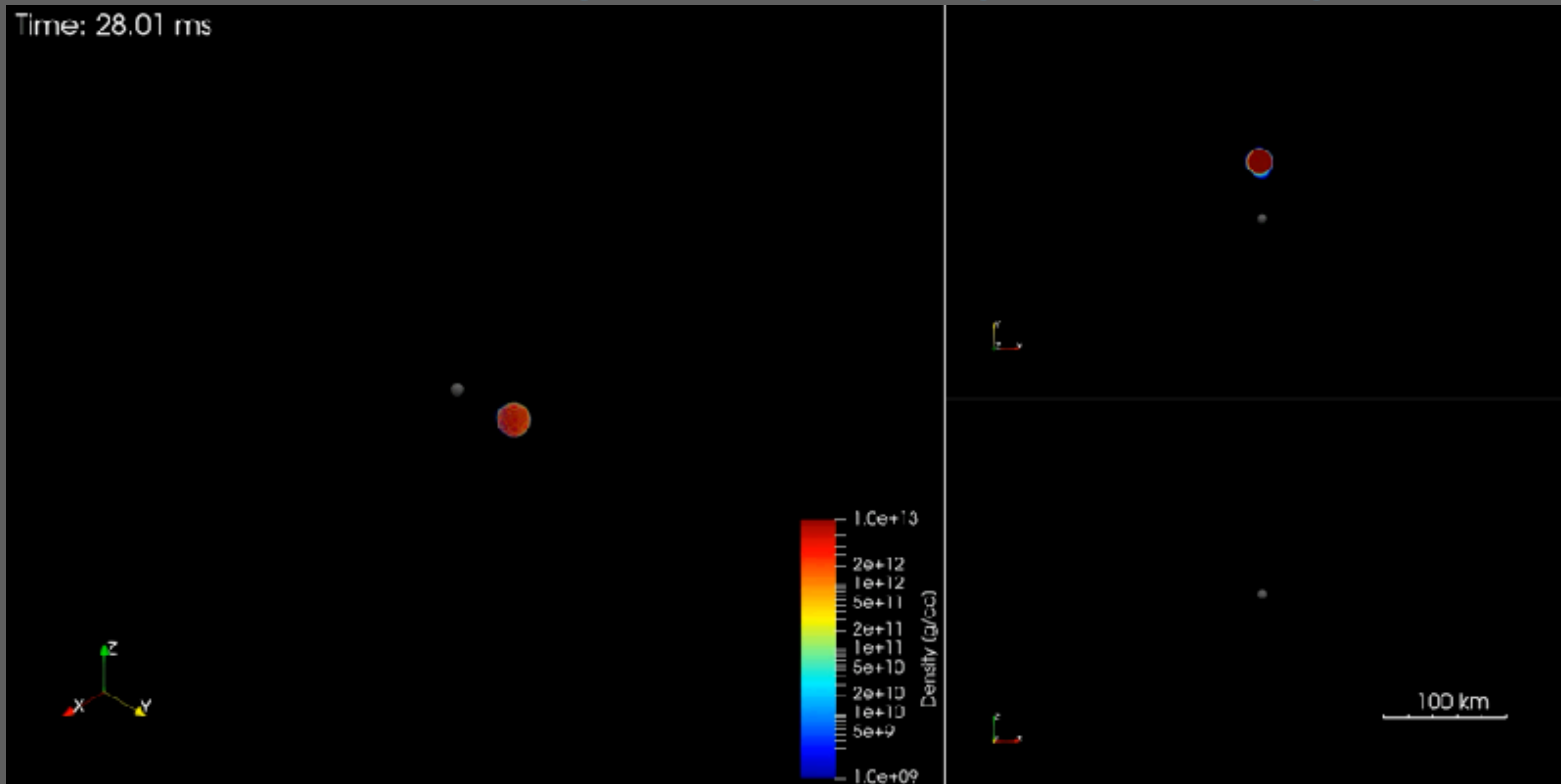
(= proton fraction)

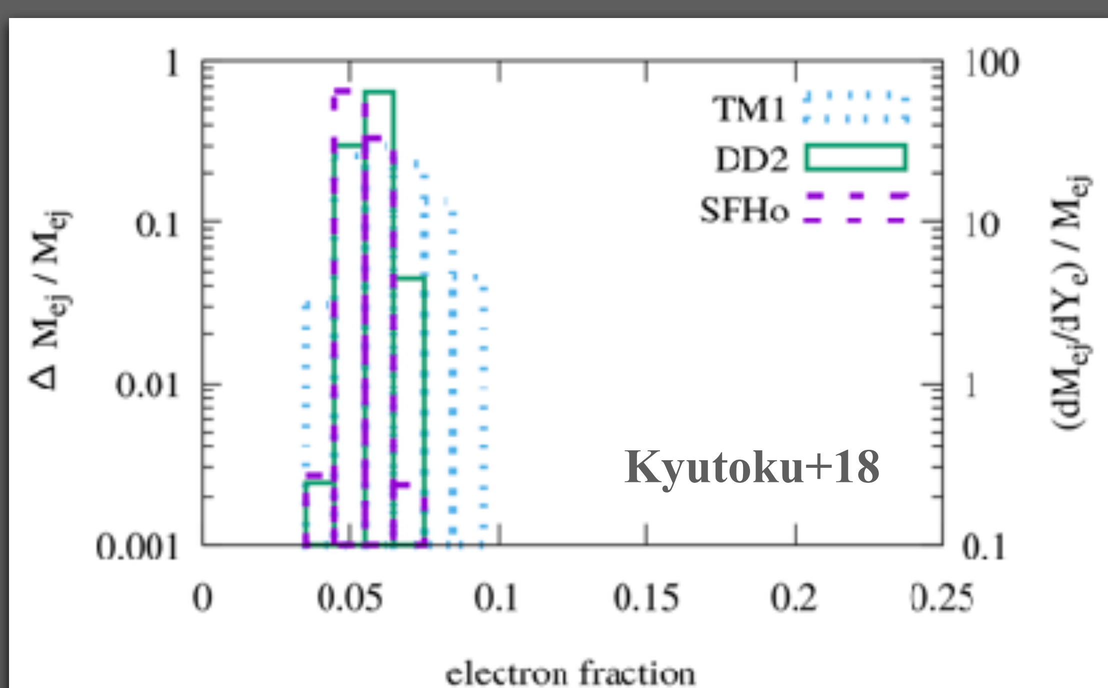
Lower-Y_e ↔ more neutron-rich

Neutron-richness



BH-NS merger: Purely tidal ejecta



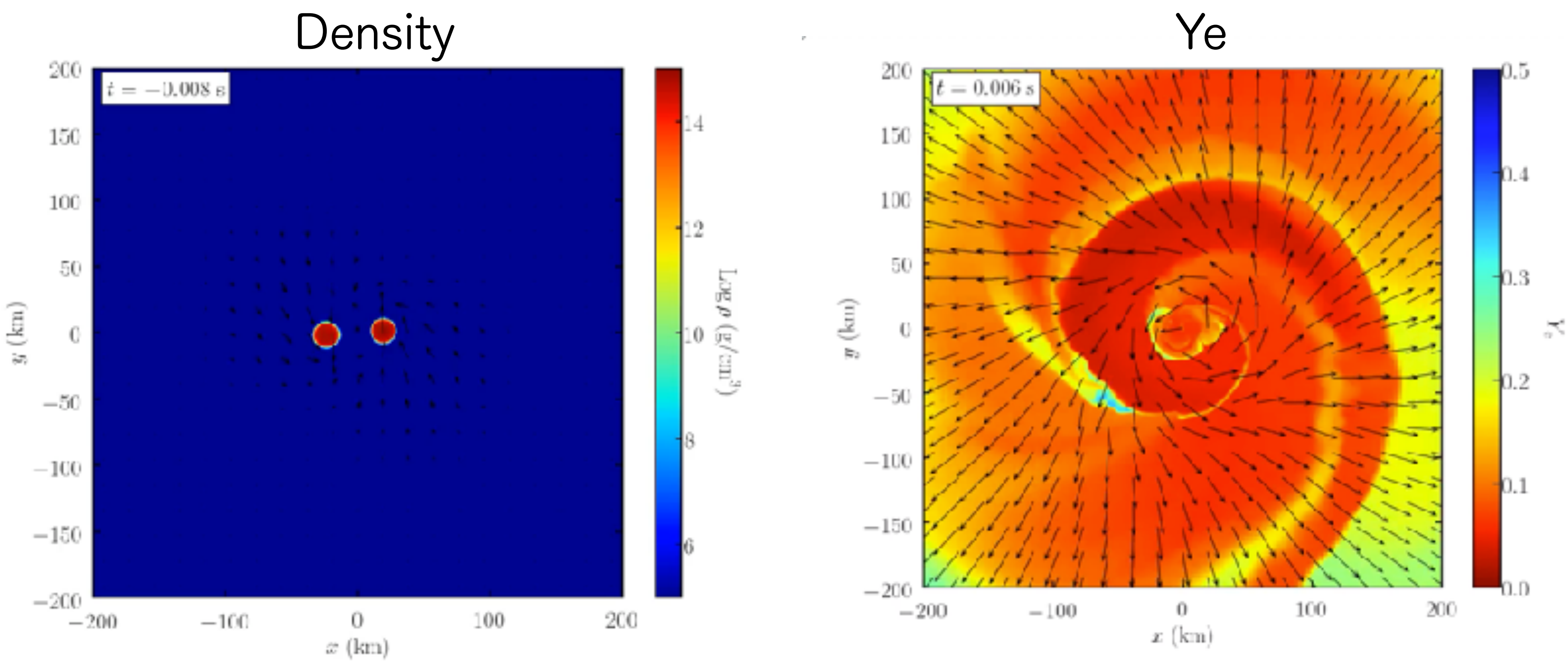


- Tidal effect only
- Original Ye preserved.

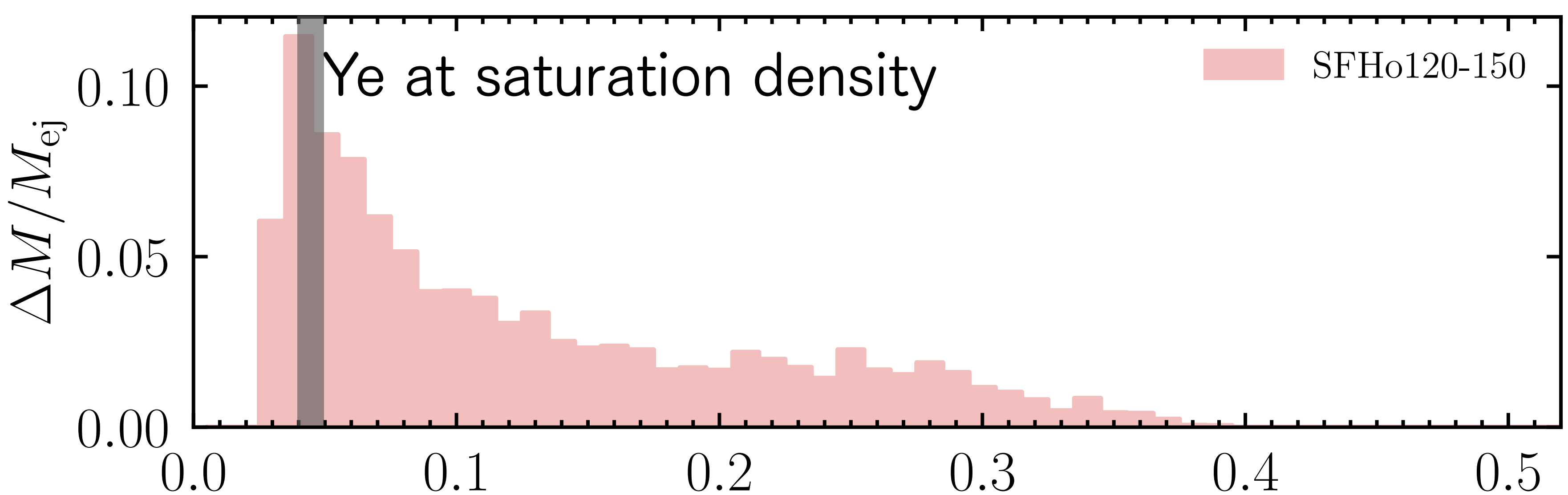
N-richness of Dynamical ejecta

$m_1 \neq m_2$

$1.20 - 1.50 M_\odot$



Unequal-mass (asymmetric) merger → more BH-NS-like.



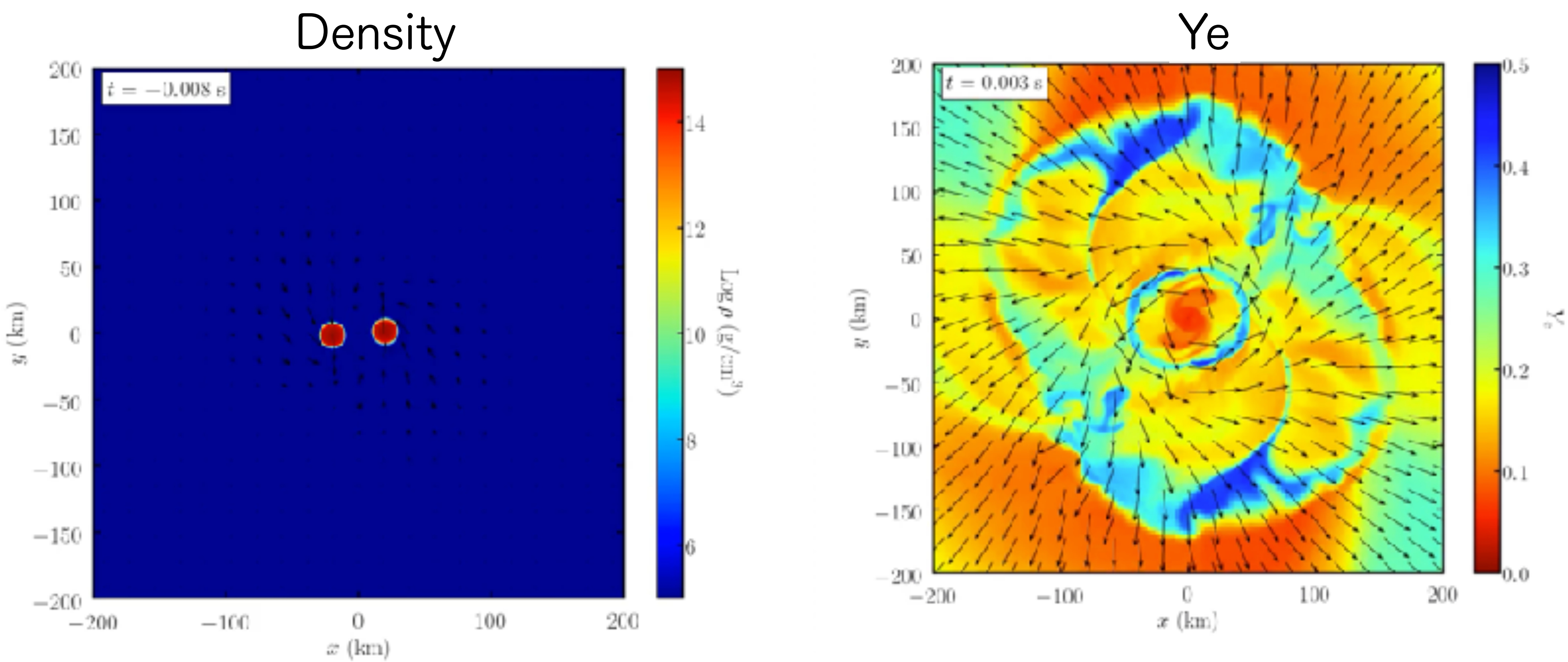
Electron fraction $Y_e := \frac{n_e}{n_{\rm baryon}} = 1 - \frac{n_n}{n_{\rm baryon}}$

(2.70 Msun in total, SFHo EOS adopted.)

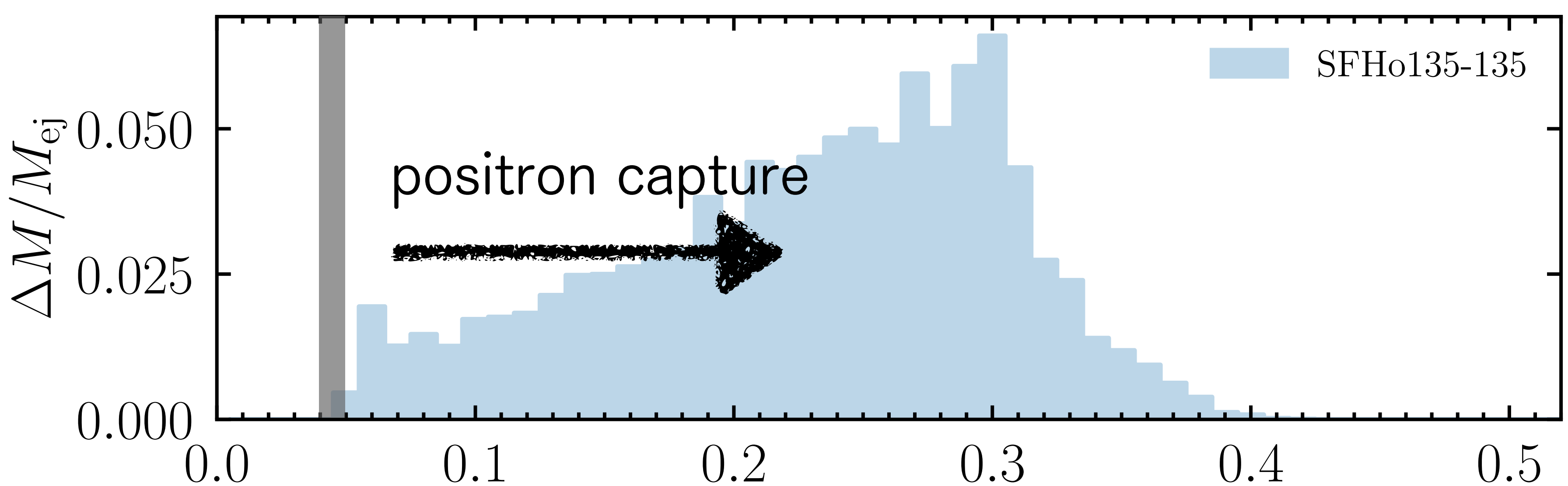
N-richness of Dynamical ejecta

$m_1 = m_2$

$1.35 - 1.35 M_\odot$



Equal-mass merger: matter reprocessed → higher Ye (lower n-richness)



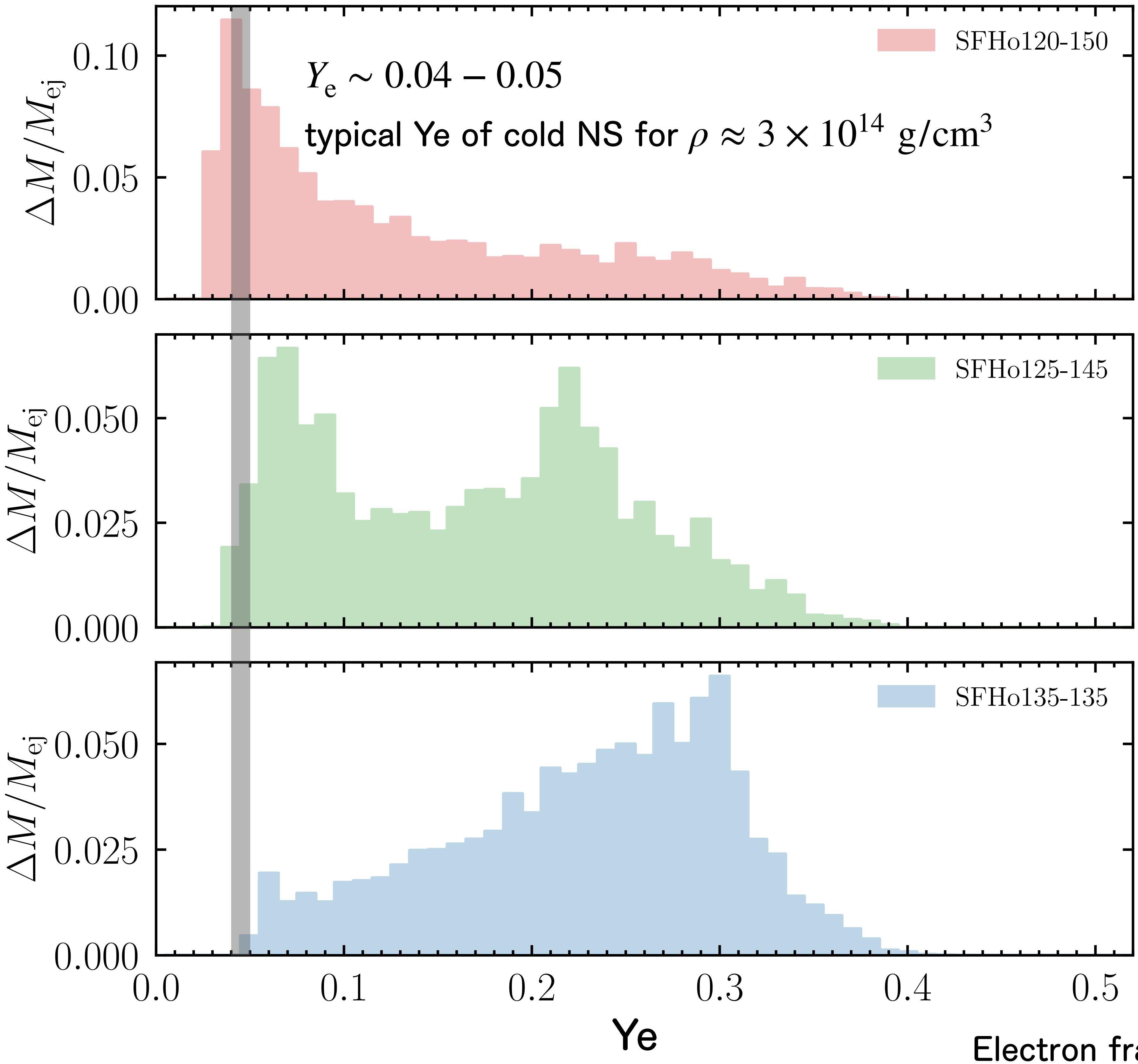
Electron fraction $Y_e := \frac{n_e}{n_{\rm baryon}} = 1 - \frac{n_n}{n_{\rm baryon}}$

(2.70 Msun in total, SFHo EOS adopted.)

N-richness of dynamical ejecta

SF+23

also Radice+18, Just+23



(2.70 Msun in total, SFHo EOS adopted.)

Asymmetric merger

- Mainly tidal effect
- ~Original Ye preserved (More BH-NS like)

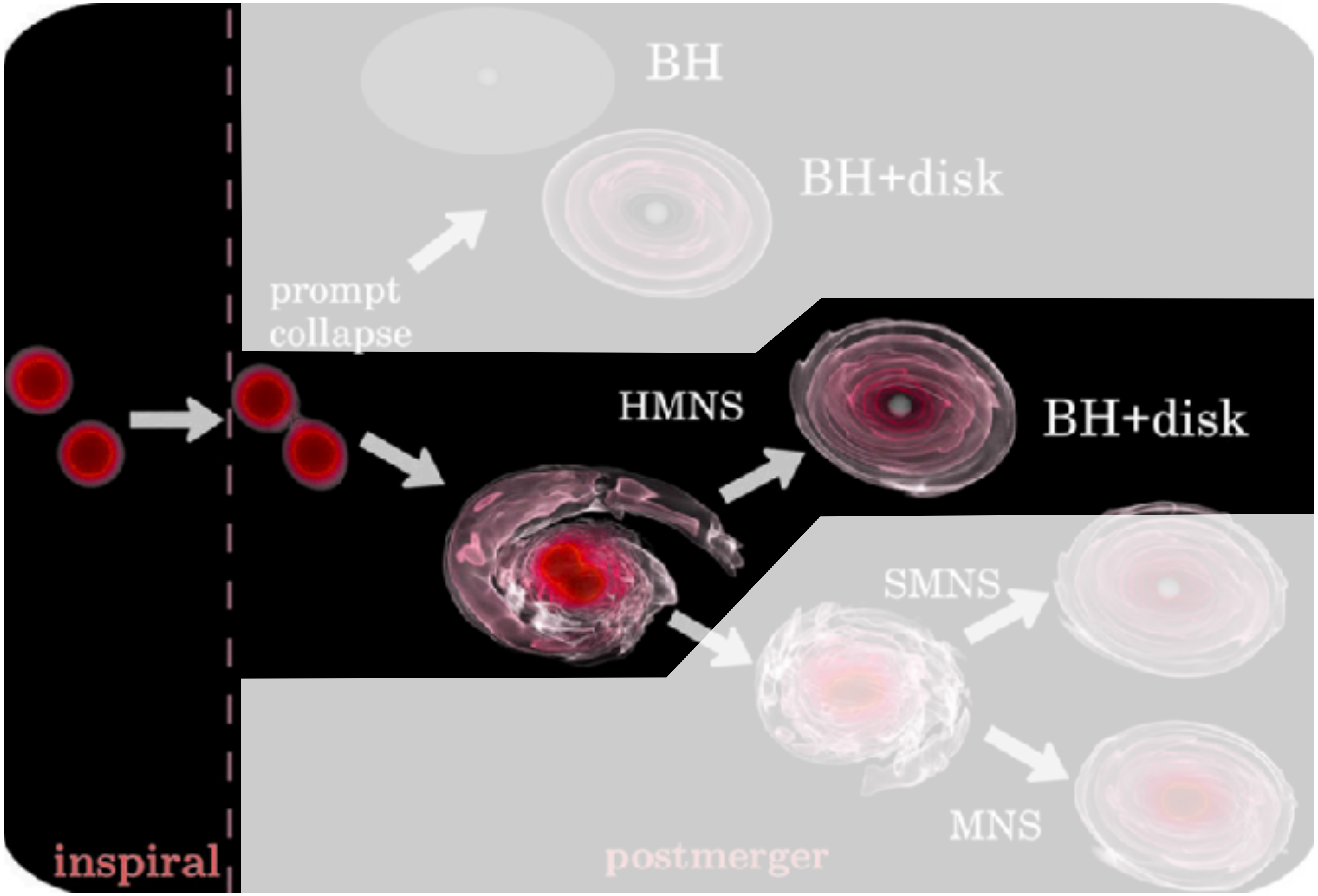
Symmetric merger

- Stronger shock effects
- higher Ye (less n-rich)

Electron fraction $Y_e := \frac{n_e}{n_{\rm baryon}} = 1 - \frac{n_n}{n_{\rm baryon}}$

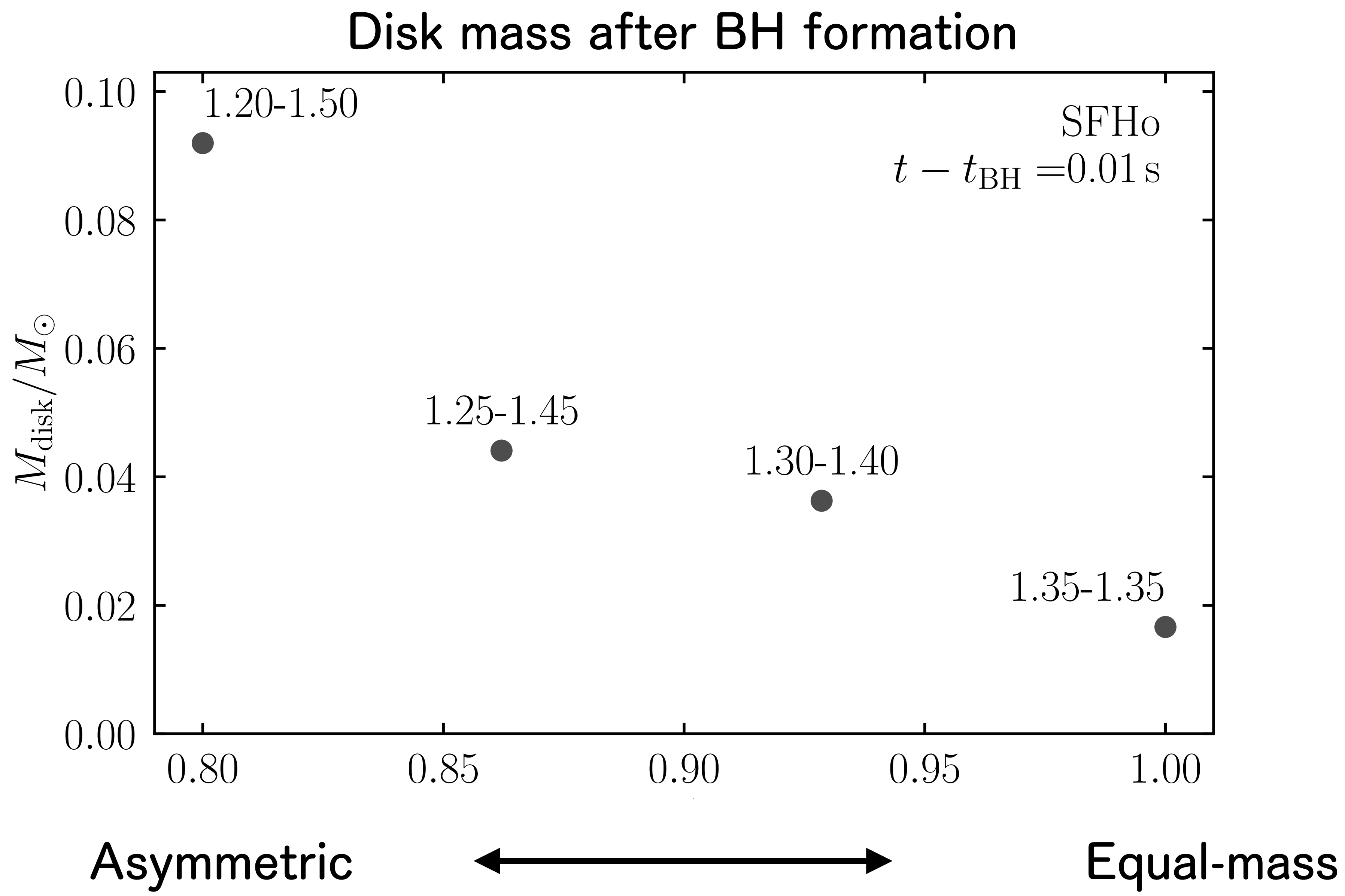
Implications of numerical simulation: Post-merger Ejecta

Short-lived massive NS



- SFHo EOS, Total mass $2.7M_{\odot}$ with different mass ratios
- Collapse into a BH in 20 ms

Mass-ratio dependence of disk mass

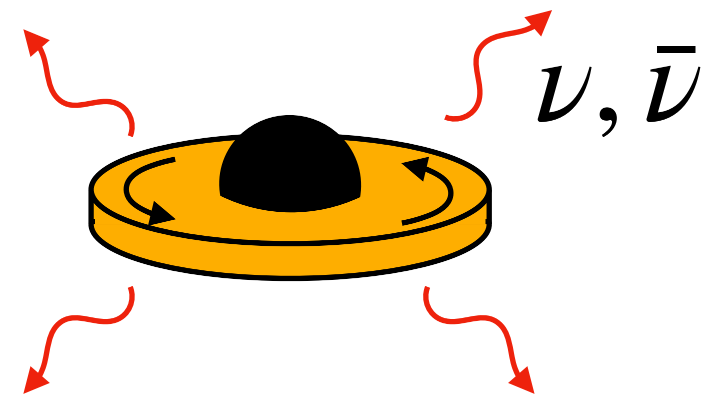


Disk mass (↔ Importance of post-merger ejecta)
is larger for the merger of more asymmetric binary (more tidal effect)

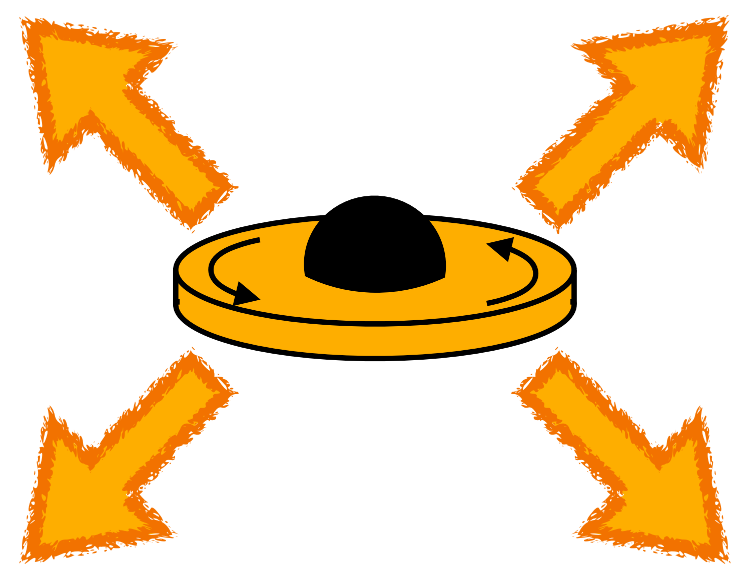
Neutrino cooling vs viscous heating

- Neutrino emission cooling
- MHD turbulence → Viscous angular momentum transport/heating

$t_{\mathrm{weak}} \lesssim t_{\mathrm{vis}}$ phase: weak/no outflow

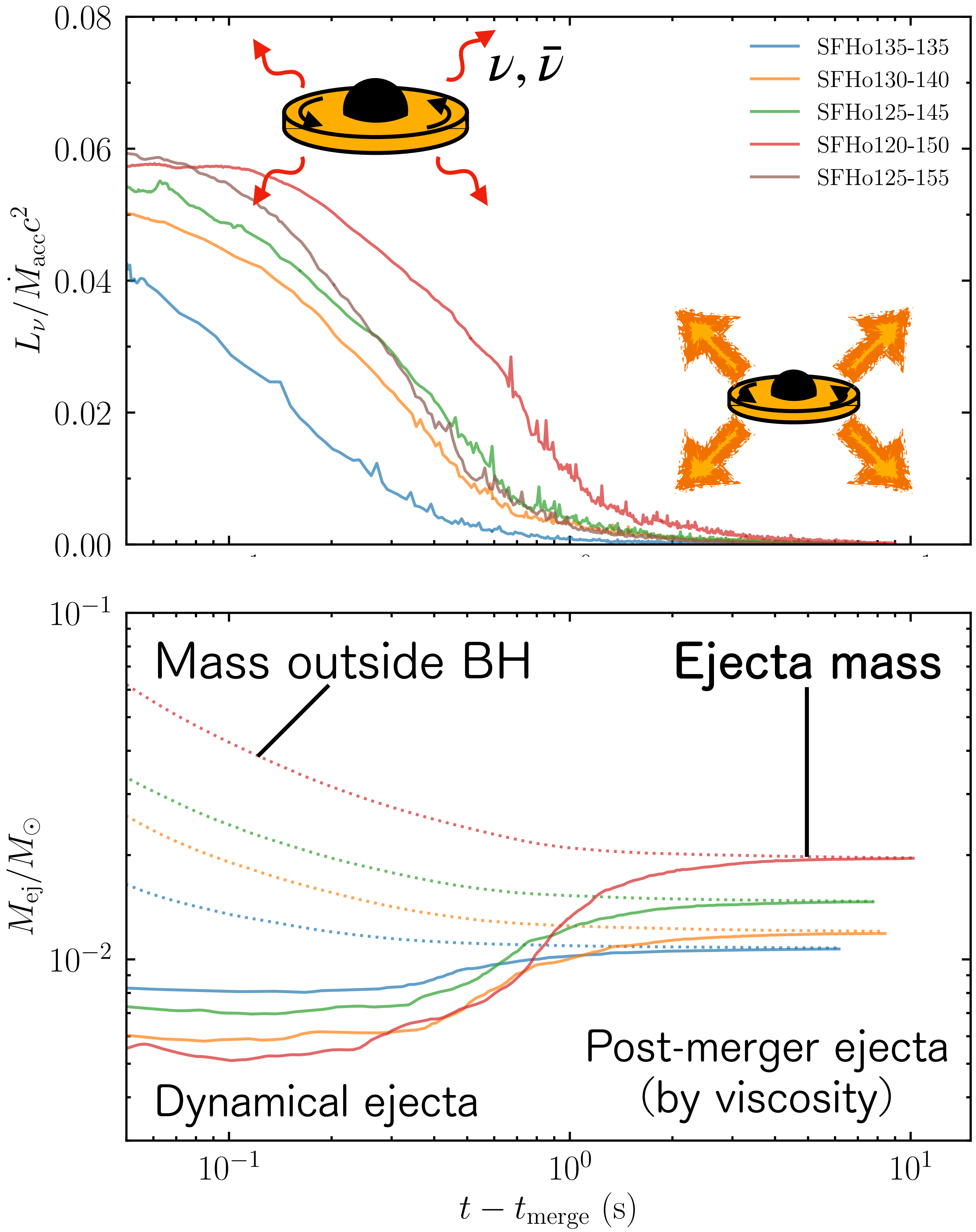


$t_{\mathrm{weak}} \gg t_{\mathrm{vis}}$ phase: viscosity can drive outflow



Post-merger mass ejection

Cooling efficiency = Luminosity/Accretion rate

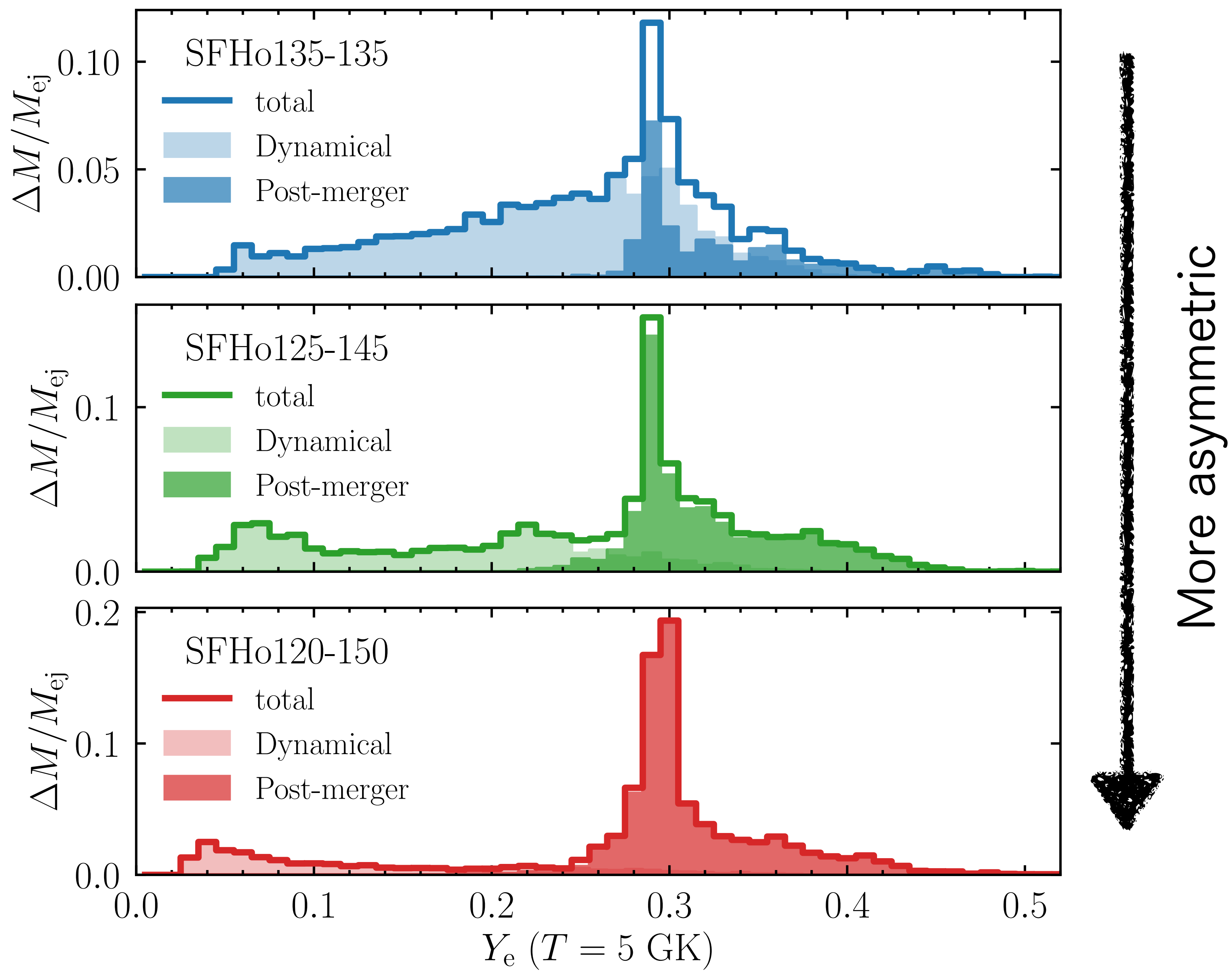


<u>Mass-ejection mechanism</u>

Disk temperature decreases
due to the drop of accretion rate

Cooling efficiency drops
→Mass ejection by viscous heating

Neutron-richness of the ejecta



- Larger post-merger contribution in more asymmetric case ← Larger disk mass.
- The peak at Ye ≈ 0.3 irrespective of mass ratio.

Electron fraction $Y_e := \frac{n_e}{n_{\rm baryon}} = 1 - \frac{n_n}{n_{\rm baryon}}$

Neutron-richness of the ejecta

SF+20, 23
see also Just+22

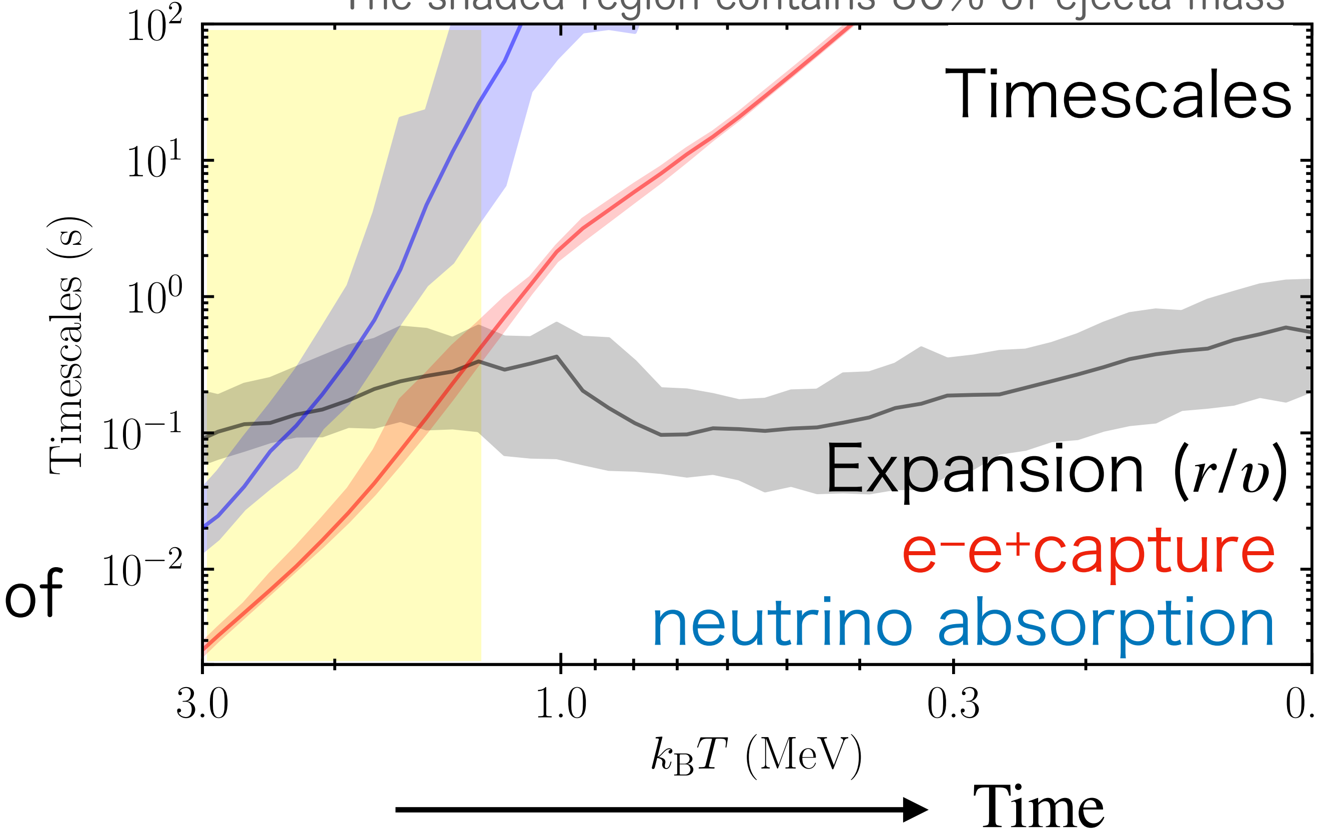
At high temperature $T \gtrsim 1-2$ MeV,

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

timescale is shorter than dynamical time.

Ye settles into a (dynamical) equilibrium of these reactions

Post-merger ejecta of SFHo 1.2-1.5 case
The shaded region contains 80% of ejecta mass



Neutron-richness of the ejecta

SF+20, 23
see also Just+22

At high temperature $T \gtrsim 1 - 2$ MeV,

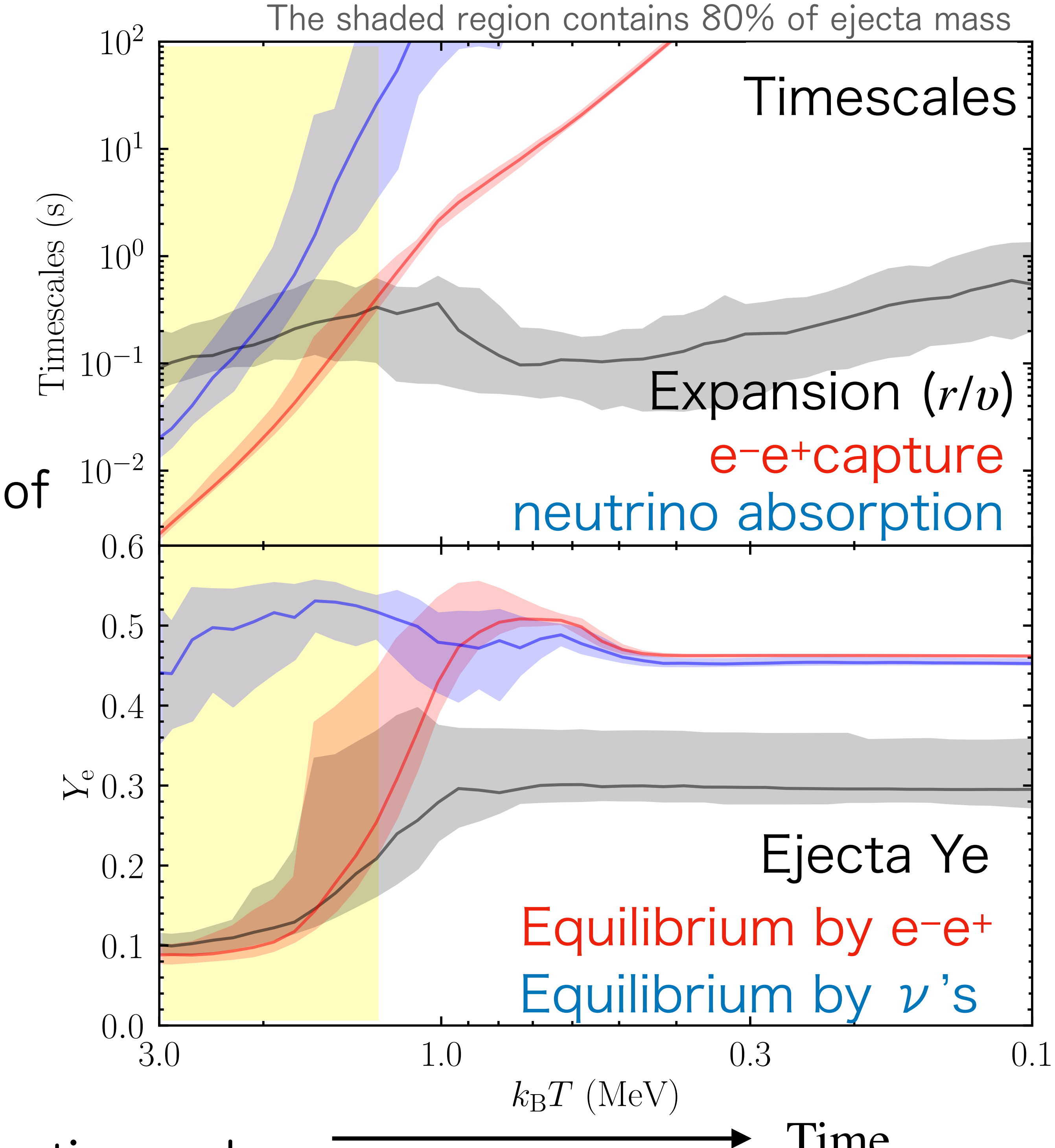
$$e^- + p \to \nu_e + n$$
$$e^+ + n \to \bar{\nu}_e + p$$

timescale is shorter than dynamical time.

Ye settles into a (dynamical) equilibrium of these reactions

Ye freezes out when

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

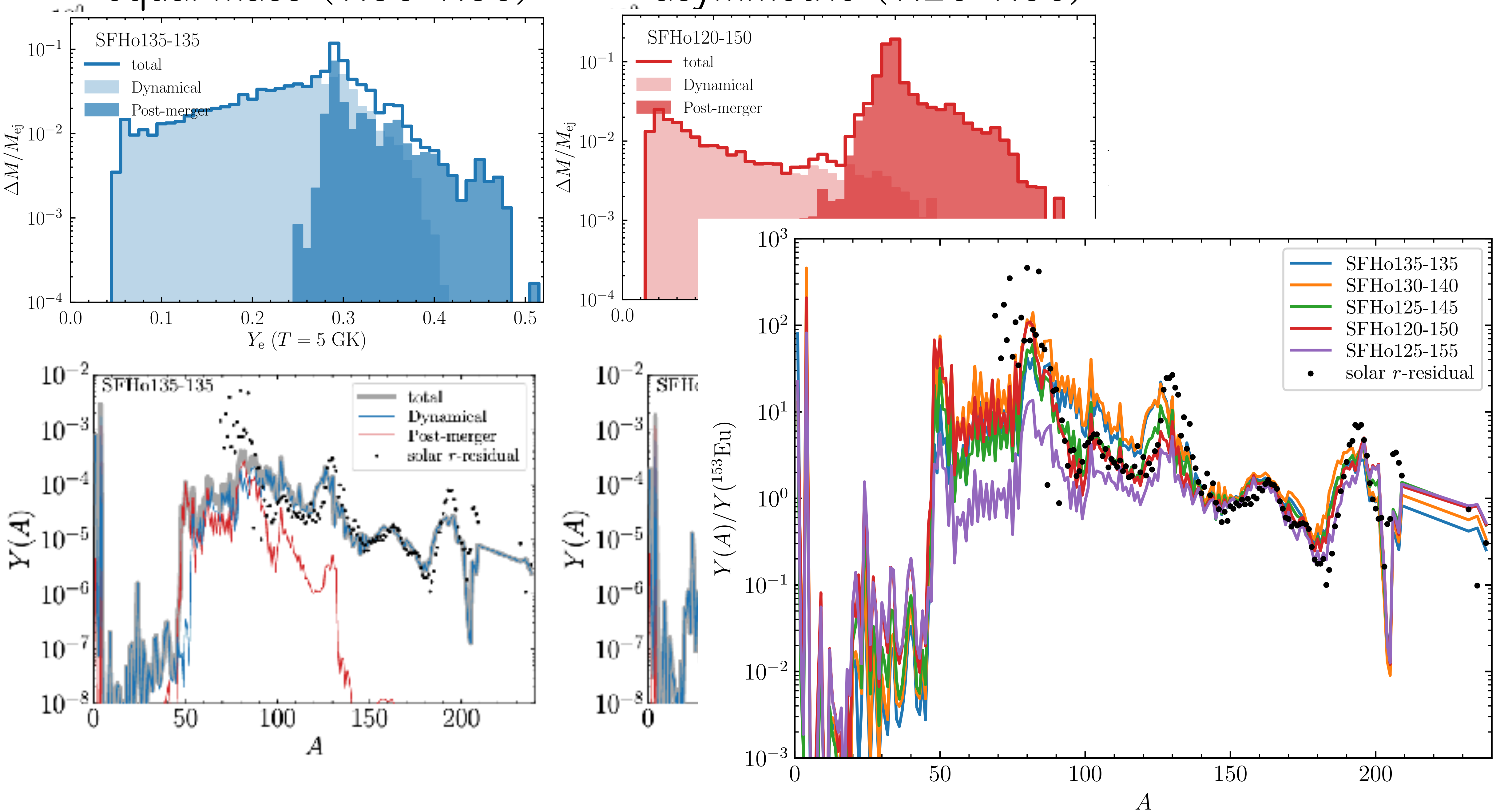


- In this case, $Y_e \approx 0.3$.
  Resulting Y_e depends on the expansion timescale (strength of the viscosity).

Composition of the ejecta

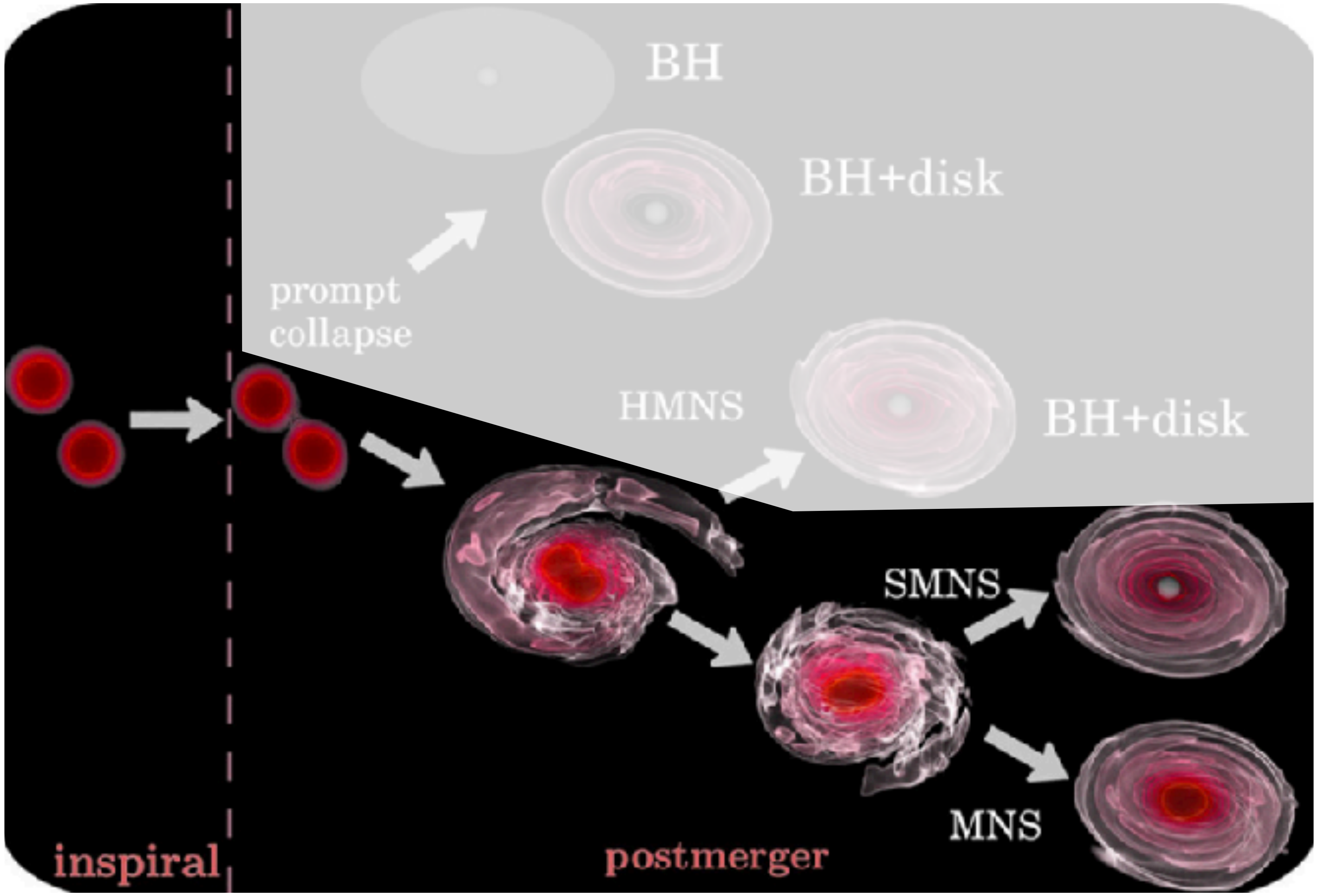
Short-lived massive NS

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



Solar-like r-process pattern can be approximately reproduced irrespective of the binary mass ratio for short-lived NS cases.

Long-lived massive NS case



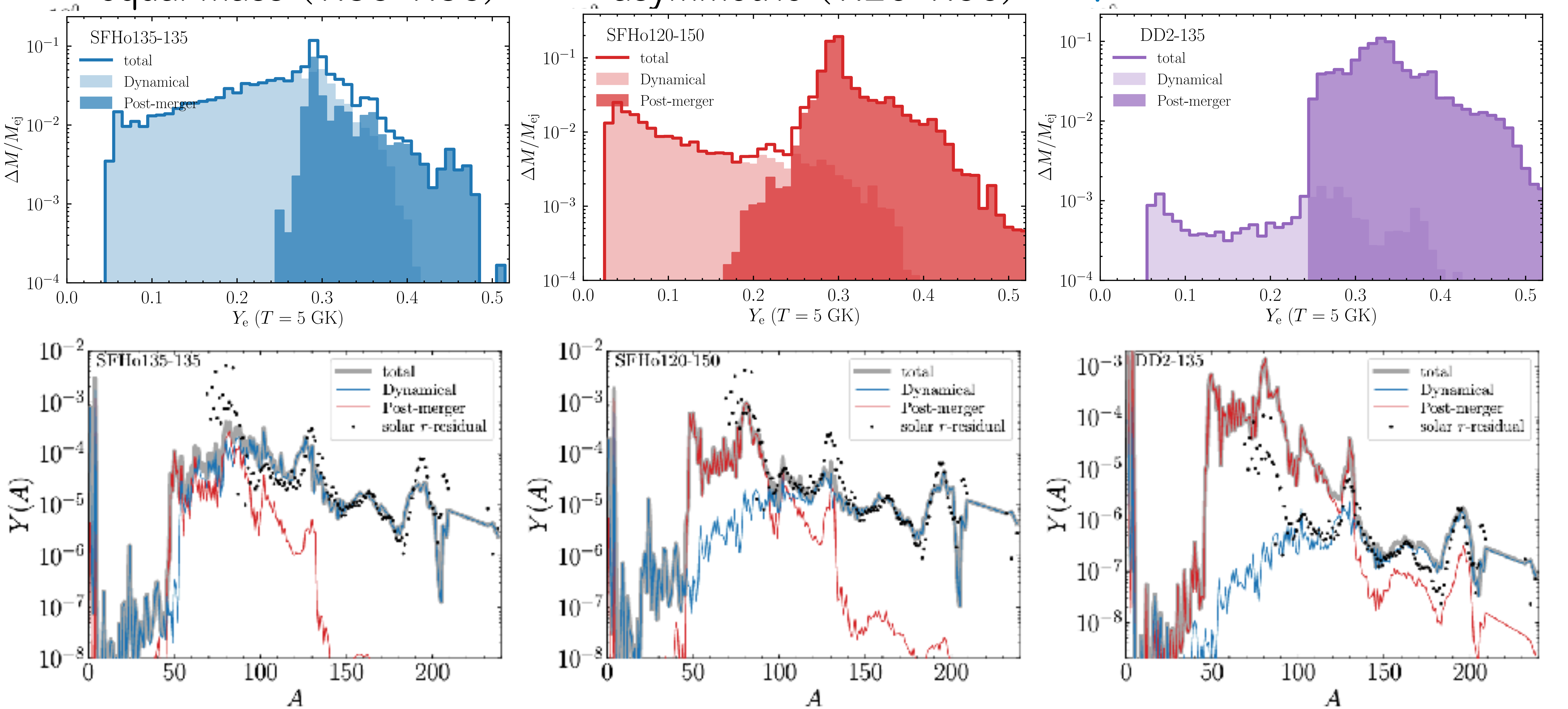
- DD2 EOS, $1.35 - 1.35 M_{\odot}$
- NS lifetime >10 sec.

Long-lived massive NS case

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)



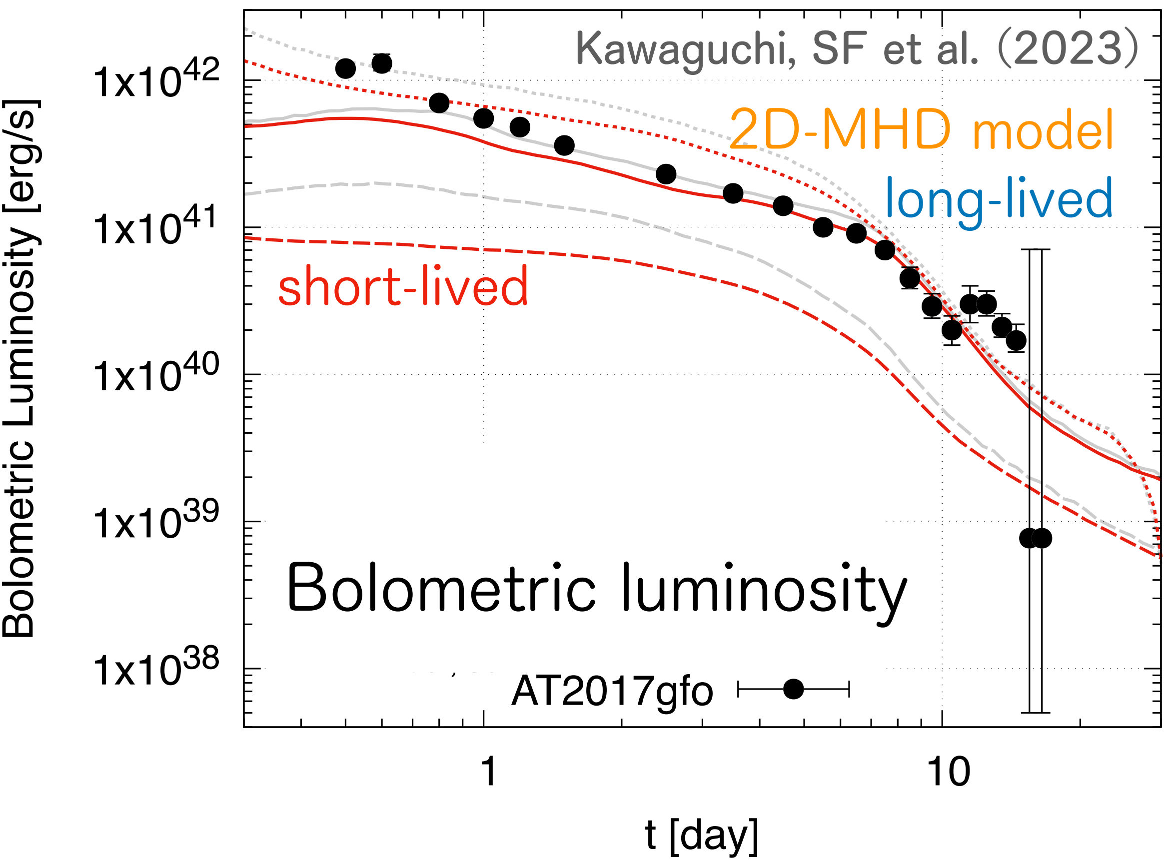
Post-merger ejecta is too massive.

(If binary NS merger is the main r-process site)

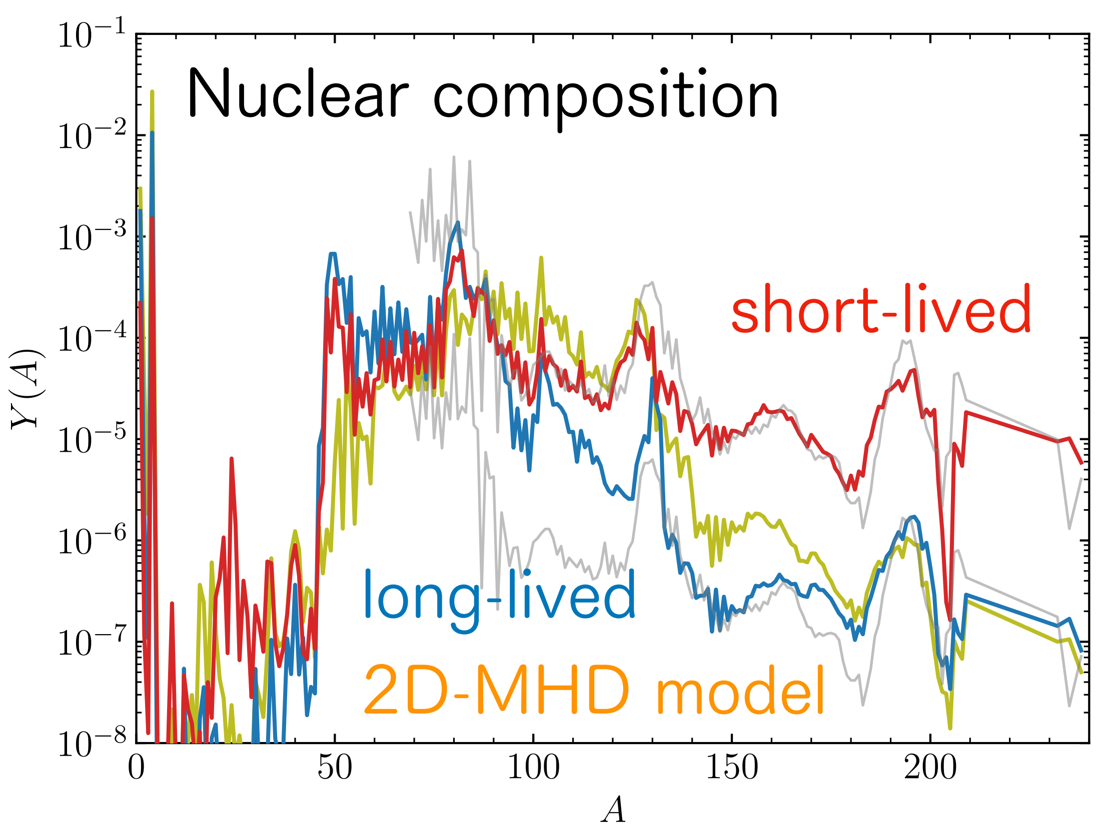
Mergers leaving long-lived NSs should be minor.

Kilonova

Kawaguchi, SF+22, 23



	Kilonova GW170817?	Solar r-process?
Short-lived cases:	✗ small total ejecta mass	✓
Long-lived cases:	✓	✗ too massive post-merger ejecta



- We saw a rare event in GW170817, for which remnant NS survived for a long time (most of kilonovae are dim)?
- Some effects missing in simulation, and solar pattern can be achieved even for long-lived cases?
- NS mergers are not main r-process site?

Beyond viscous hydrodynamics model

- MHD: the most consistent way to model angular momentum transport.

- Disk dynamics: Viscous hydro is a good approximation

  e.g., Just+22, Fernandez+19, Hayashi+22, Kiuchi, SF+23 Wanajo, SF+ in prep.

- MHD effect may be underestimated in the presence of a long-lived NS.

- Strongly magnetized massive neutron star may drive a strong wind.

  e.g., Ciolfi+17, Mösta+20, Shibata+21, Combi & Siegel 23, Most & Quataert 23

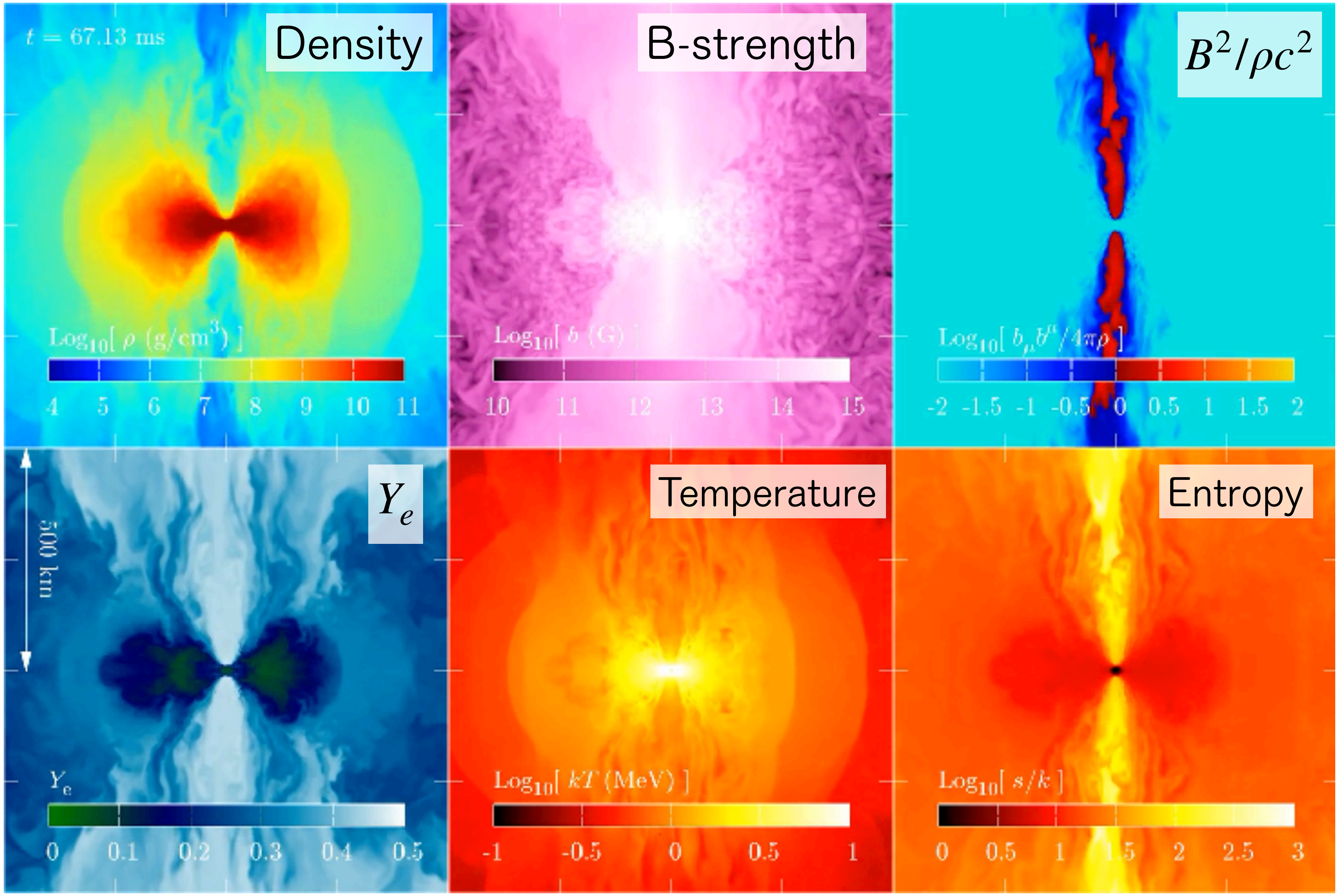
- The ejecta profile may be significantly modified

  Effects on kilonova lightcurves Kawaguchi+22

MHD effects for long-lived NS case

Strongly magnetized massive neutron star drives a strong wind.

Kiuchi+24 (Visualized by K. Hayashi)



Summary

- Galactic BNS distribution $(M_{\rm tot} \lesssim 2.8 M_\odot)$ → Temporal formation of massive NS
- Other paths: GW190424 → Prompt collapse, PSR J1946+2052 → long-lived NS

Short-lived NS case:

Asymmetric ⟶ **Equal-mass**

Asymmetric:
- Dyn. ejecta has Ye closer to original NS (→ limit: BH-NS)
- More post-merger ejecta
  → solar r-process abundance

Equal-mass:
- Dyn. ejecta reprocessed
  → Higher Ye, broader distribution
  → solar abundance
- Post-merger ejecta sub-dominant

Long-lived NS case:

- Post-merger ejecta too massive.
- Fail to reproduce solar r-process abundance
- MHD may be more important for long-lived cases

Thank you for your attention!