Dynamics and nucleosynthesis of neutron star mergers and collapsars

Sho Fujibayashi （藤林　翔）

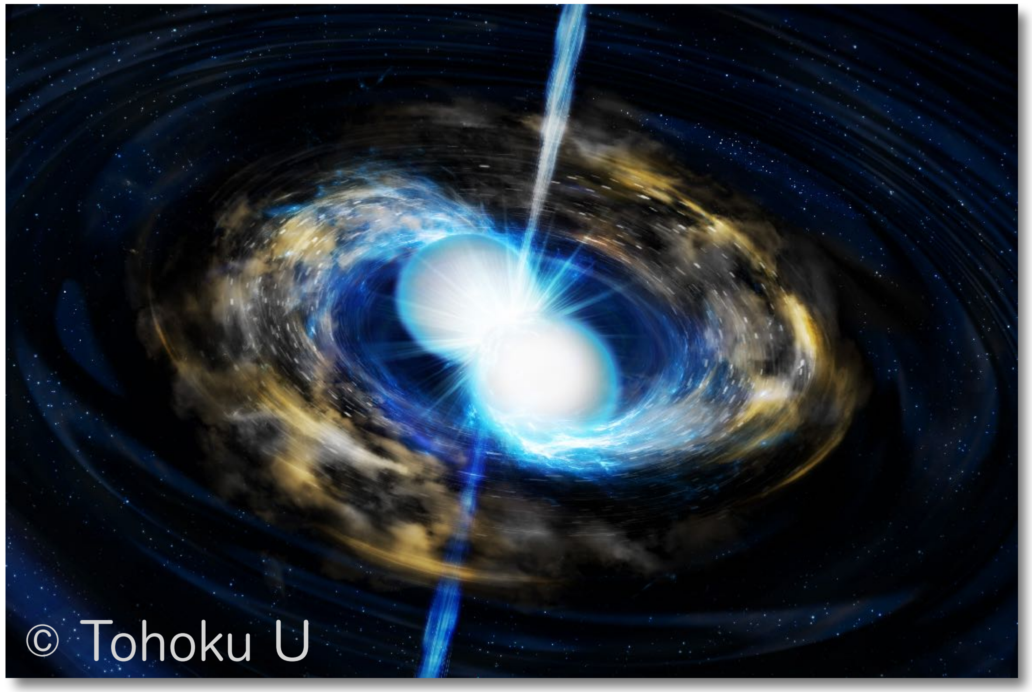
Tohoku U

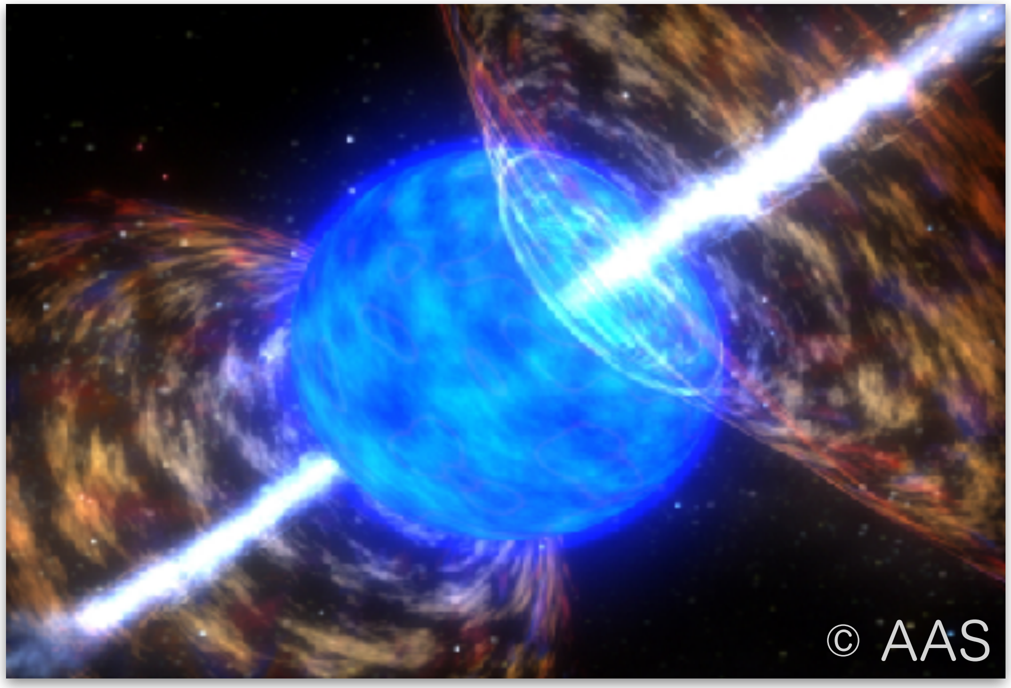
MPI for Gravitational Physics

OMEG17, 2024.9.10, Chengdu, China

FRIS

Outline



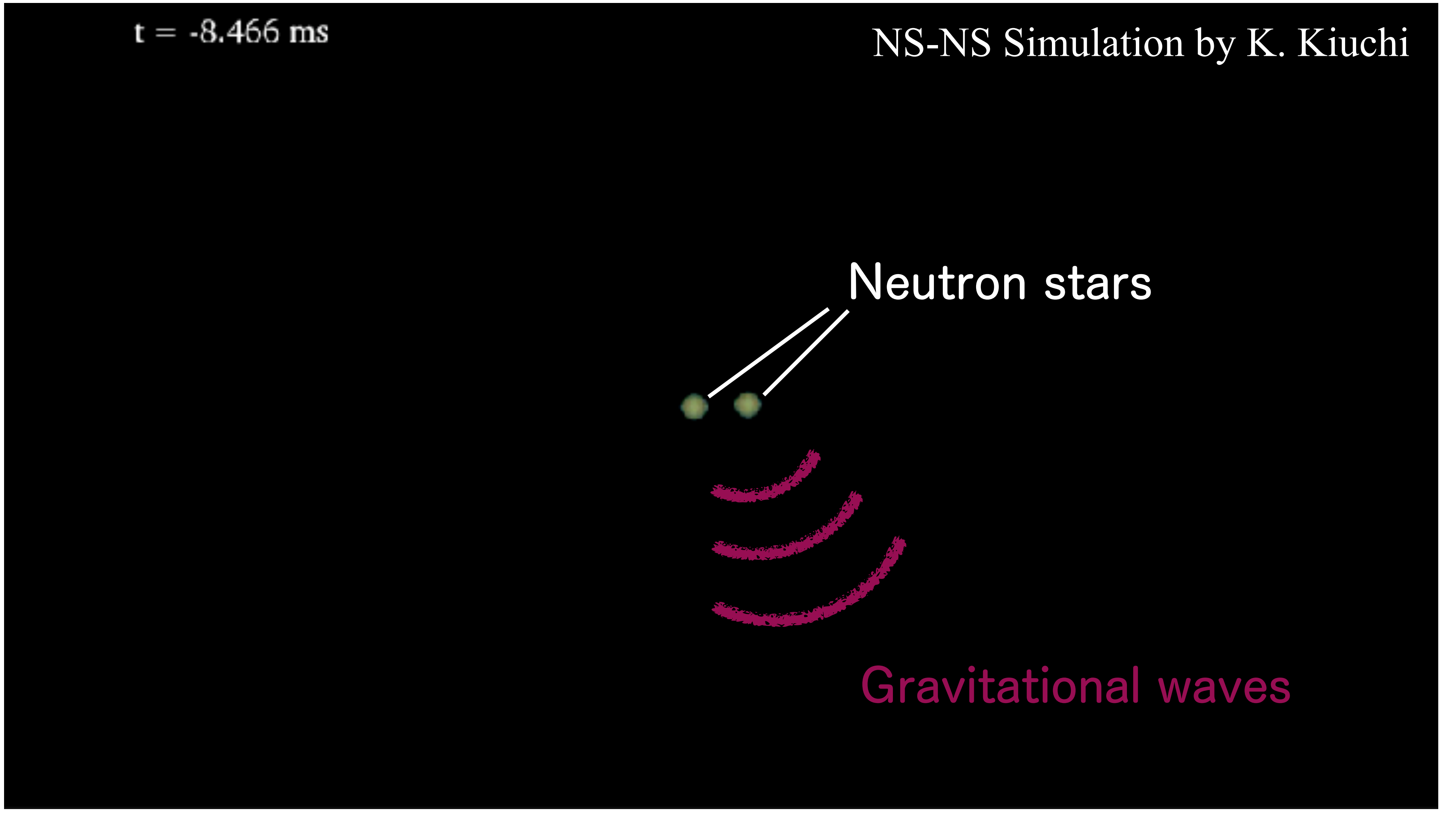


- NS binary merger
  - (a) Introduction
  - (b) Dynamical/Post-merger ejecta
  - (c) Nucleosynthesis
  - (d) Dependence on NS lifetime
- Collapsar
  - (e) Introduction
  - (f) Disk outflow scenario
  - (g) Nucleosynthesis
- Summary

Ask me later if you are interested in their details!

Binary NS merger

Binary NS merger



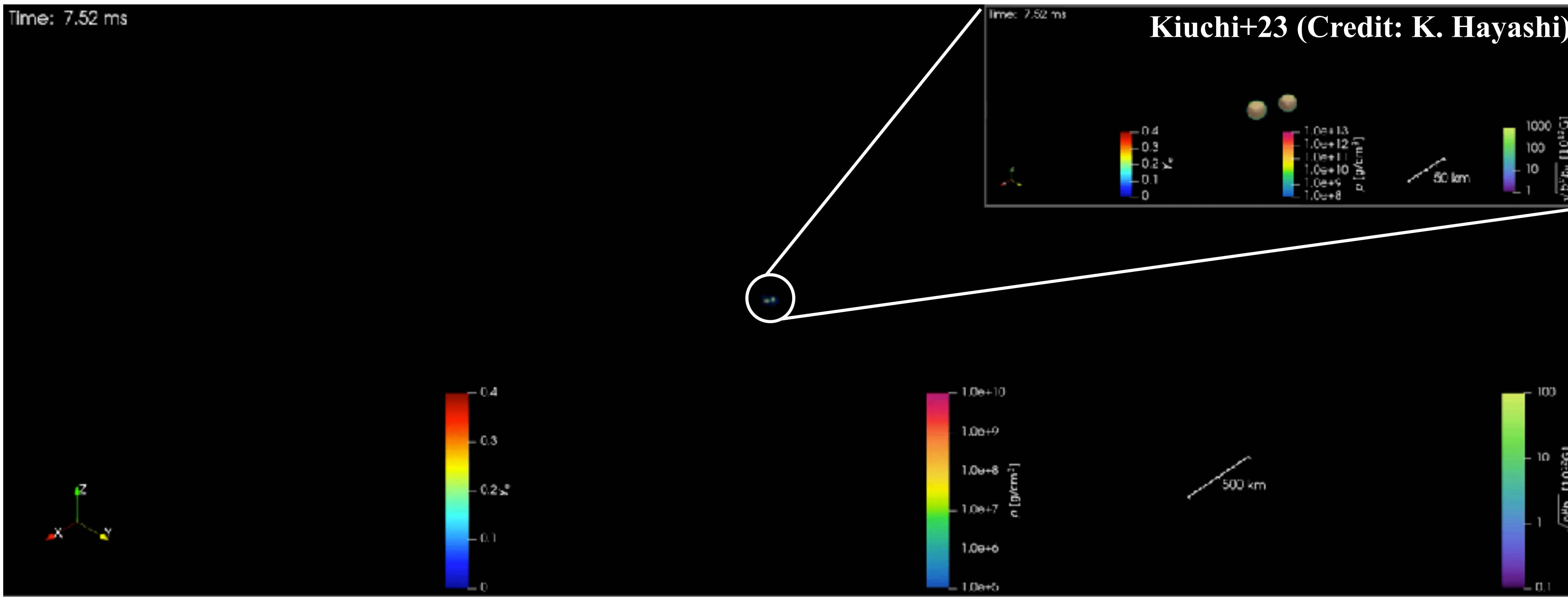
Binary NS merger

- 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

Mass ejection activities of merger: Dynamical phase



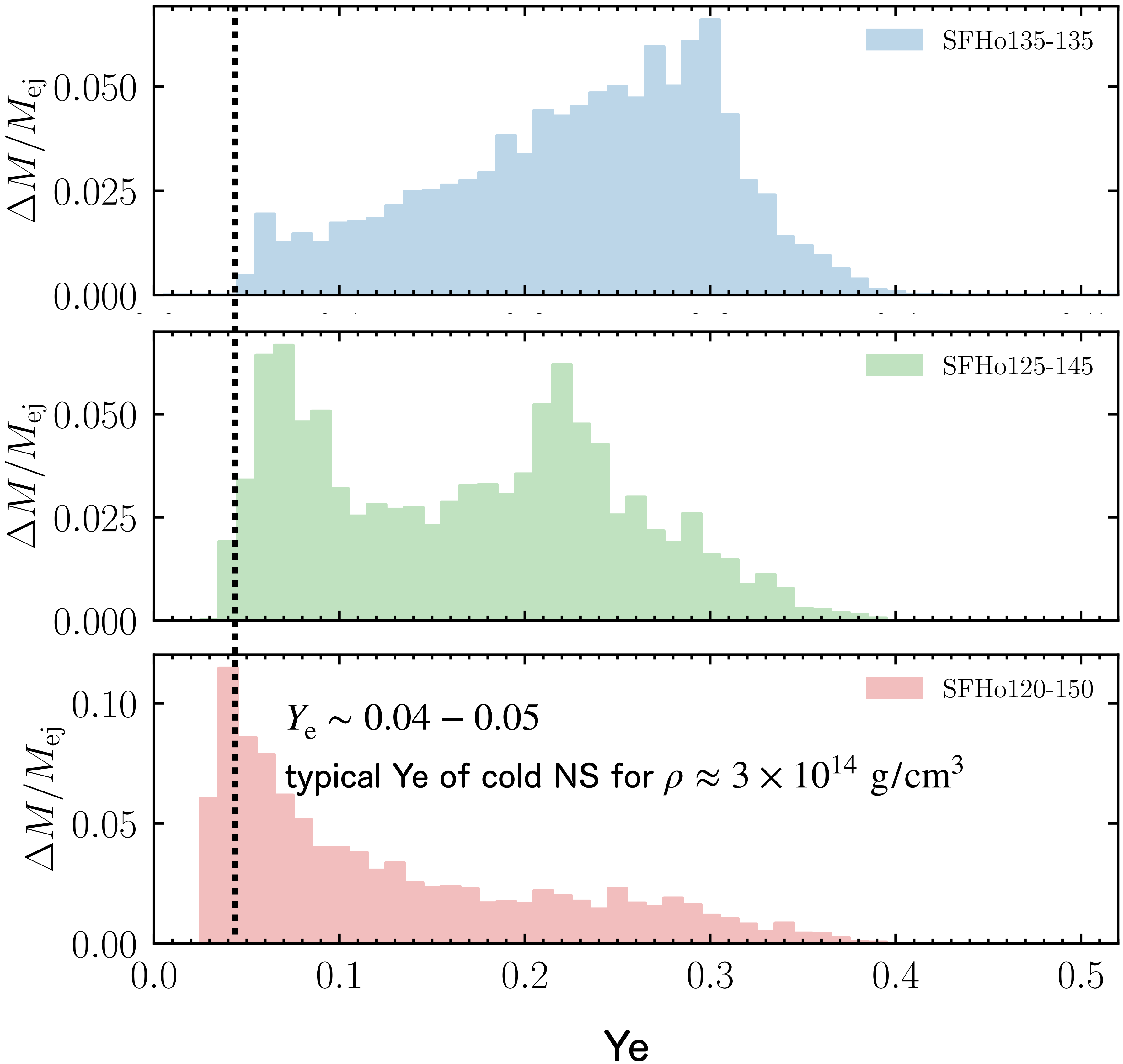
Dynamical mass ejection
(tidal force, shock heating) ~ 10 ms

Neutron-richness of dynamical ejecta

~ controls efficiency of r-process

SF+23

also Radice+18, Just+23



Electron fraction

$$Y_{\rm e} := \frac{n_e}{n_B} = 1 - \frac{n_n}{n_B}$$

Lower Ye

↔ higher n-richness

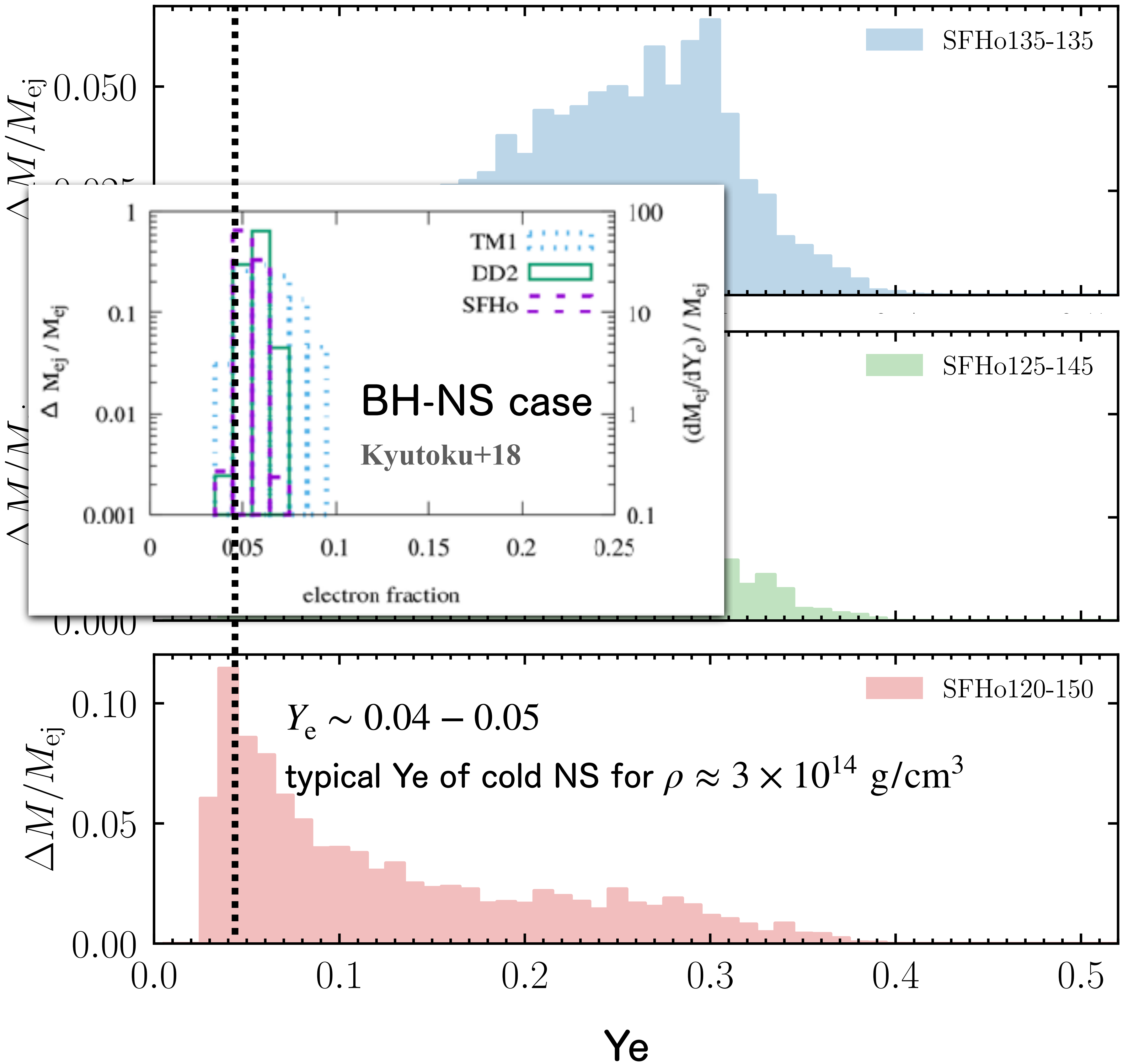
More asymmetric

more neutron-rich

Neutron-richness of dynamical ejecta

SF+23

also Radice+18, Just+23



Electron fraction

$$Y_e := \frac{n_e}{n_B} = 1 - \frac{n_n}{n_B}$$

Lower Ye

↔ higher n-richness

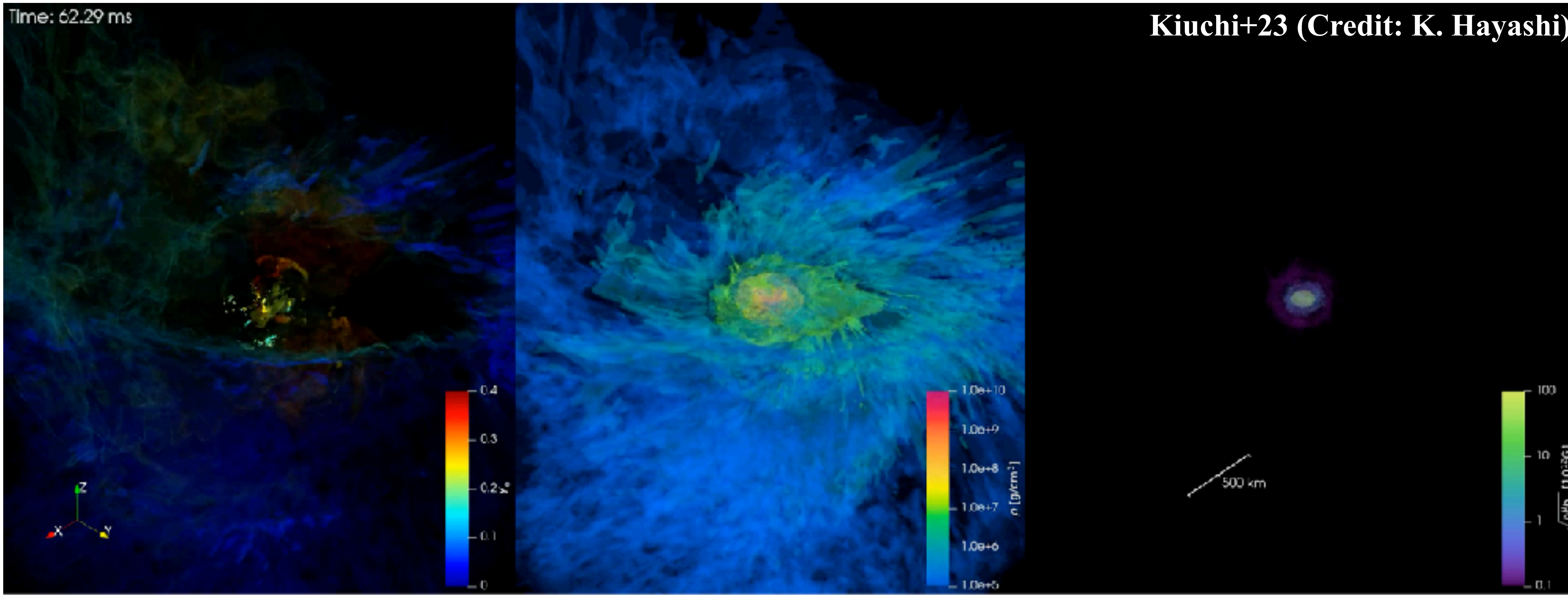
More asymmetric

more neutron-rich

more BH-NS-like

(shock heating not important)

Mass ejection activities of merger: 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)

- High temperature → weak interaction plays an important role

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

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

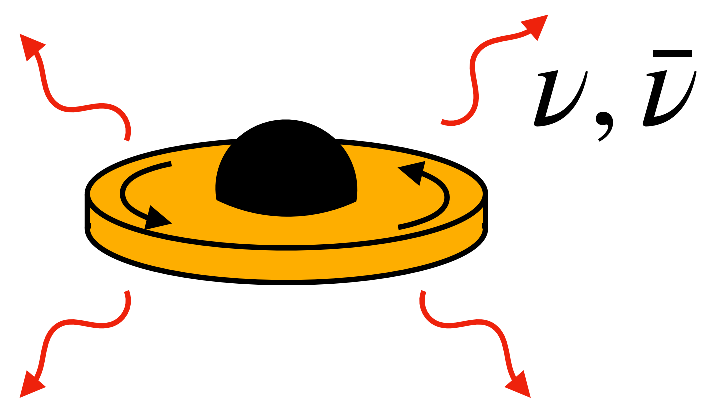
- Neutrino emission cooling evolves the system
- Determine the neutron richness

Neutrino cooling vs viscous heating

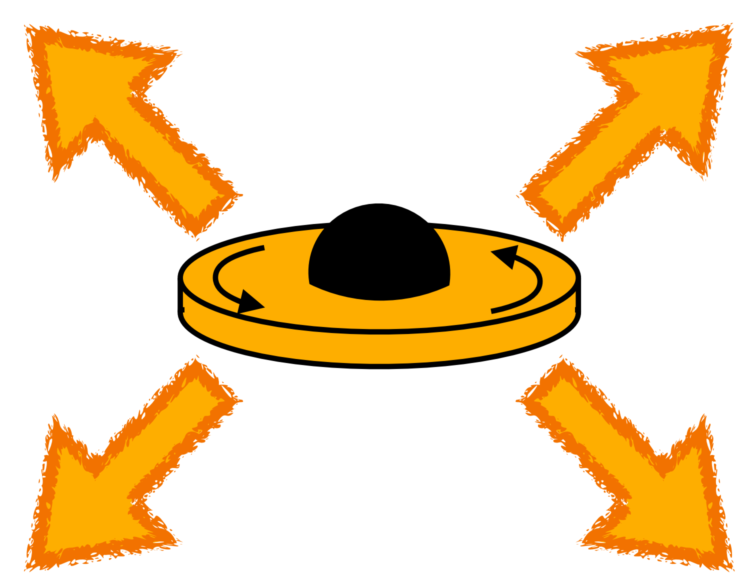
For high temperatures, ($kT \gtrsim 1\,\mathrm{MeV}$) neutrino emission cools down the disk.

Neutrino emission timescale : $t_{\mathrm{weak}} \sim 1\,\mathrm{s}\left(\dfrac{kT}{1\,\mathrm{MeV}}\right)^{-5}$

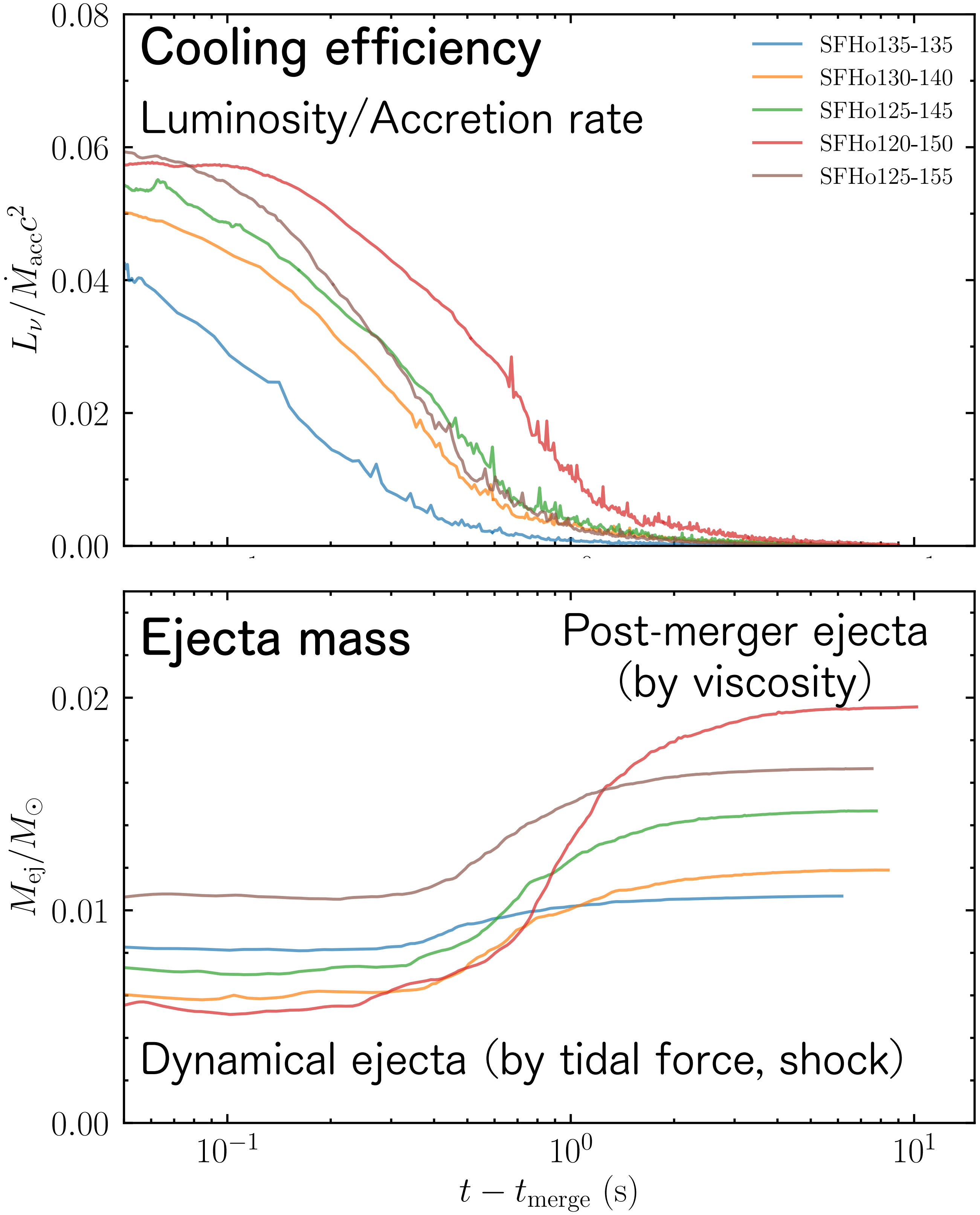
$t_{\mathrm{weak}} \lesssim t_{\mathrm{vis}}$ (NDAF) phase: weak/no outflow



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



Post-merger mass ejection



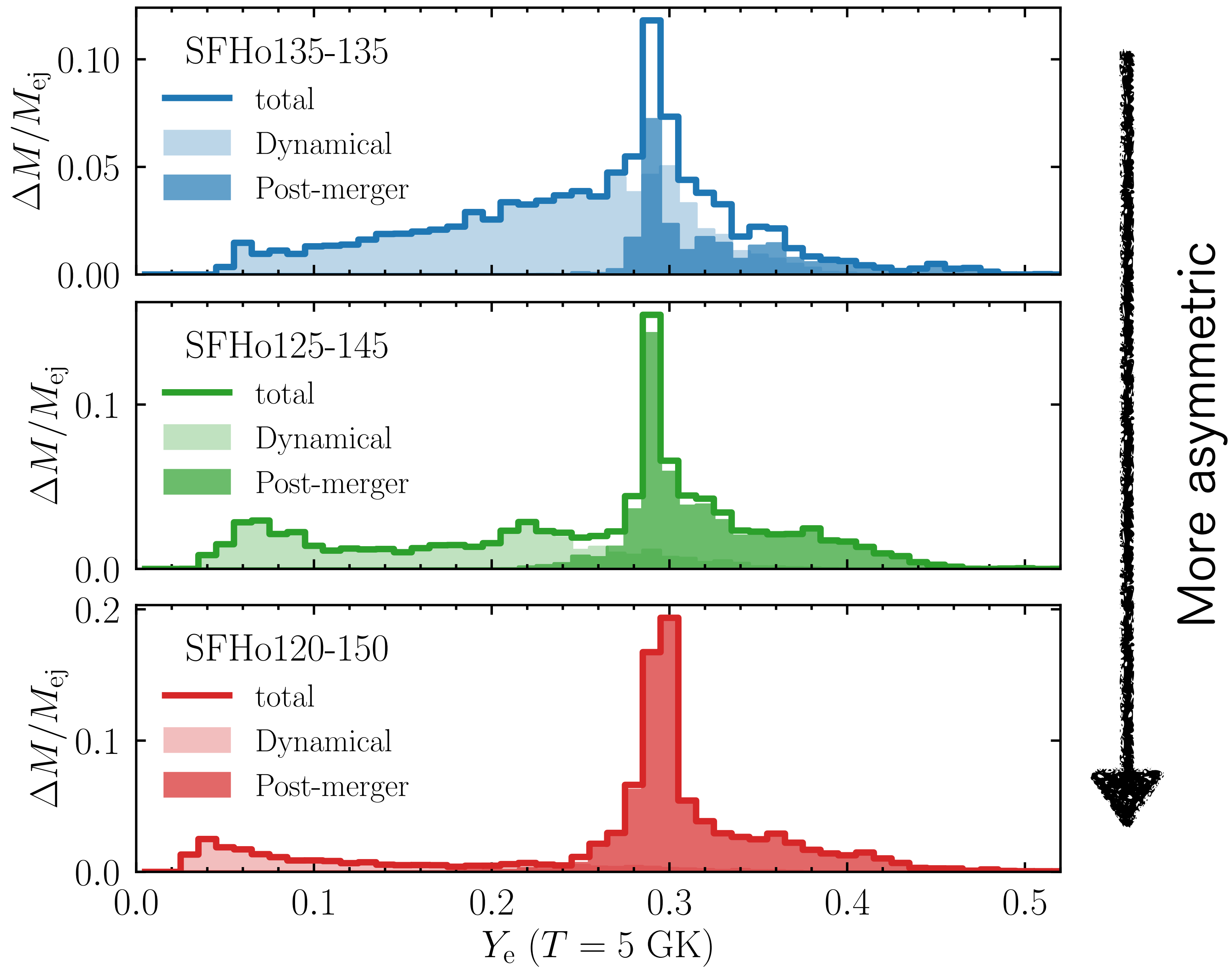
<u>Mass-ejection mechanism</u>

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

Neutron-richness of post-merger ejecta



Post-merger ejecta is more massive for more asymmetric case
because of the larger disk mass.

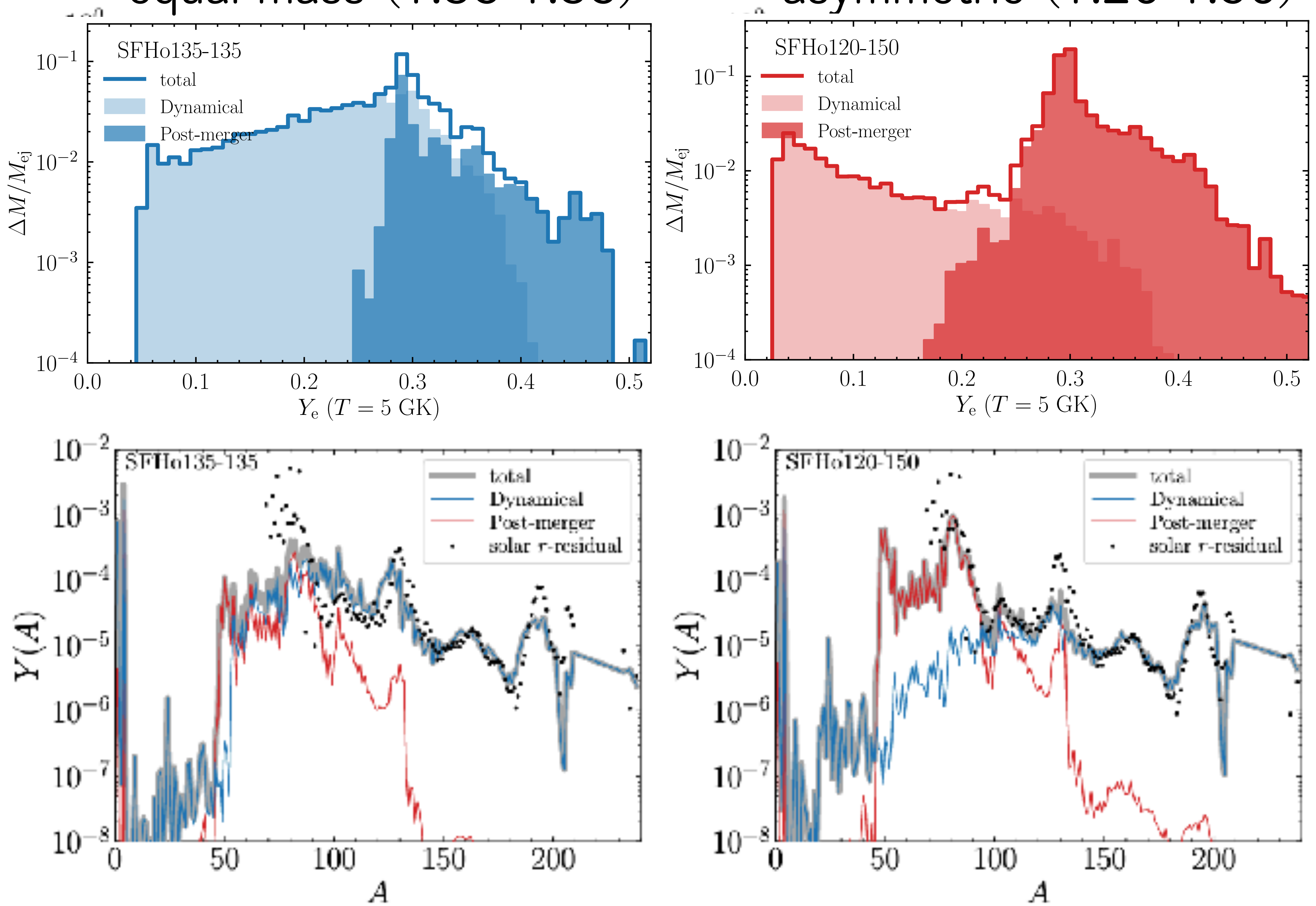
The peak at Ye ≈ 0.3 ← Freeze-out value of electron/positron capture equilibrium.

*Important: The value depends on the strength of the viscosity

Composition of the ejecta

Short-lived massive NS

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



Dynamical ejecta's broad Ye distribution
→ Solar r-abundance

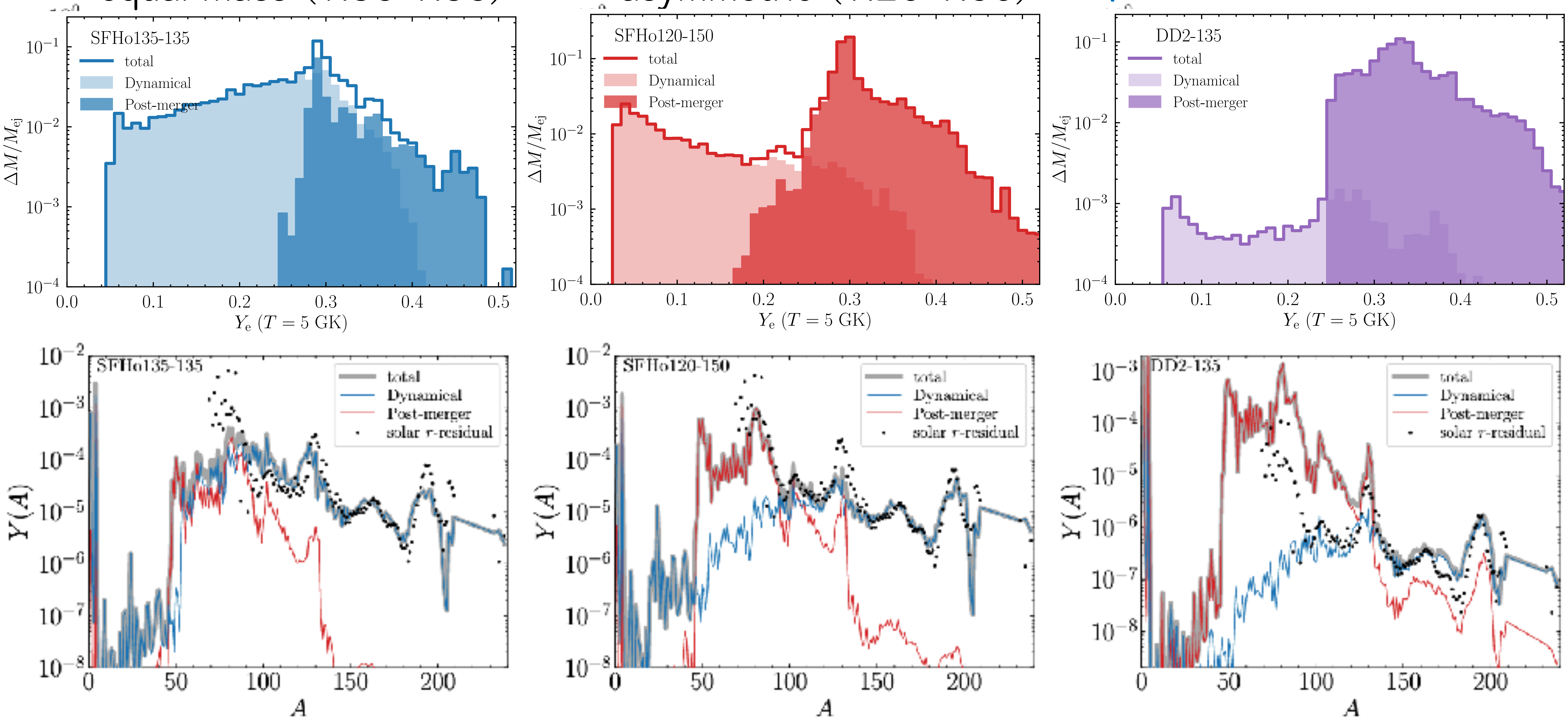
Dynamical (heavy-r)+Post-merger (light-r)
→ Solar r-abundance

Long-lived massive NS cases

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)

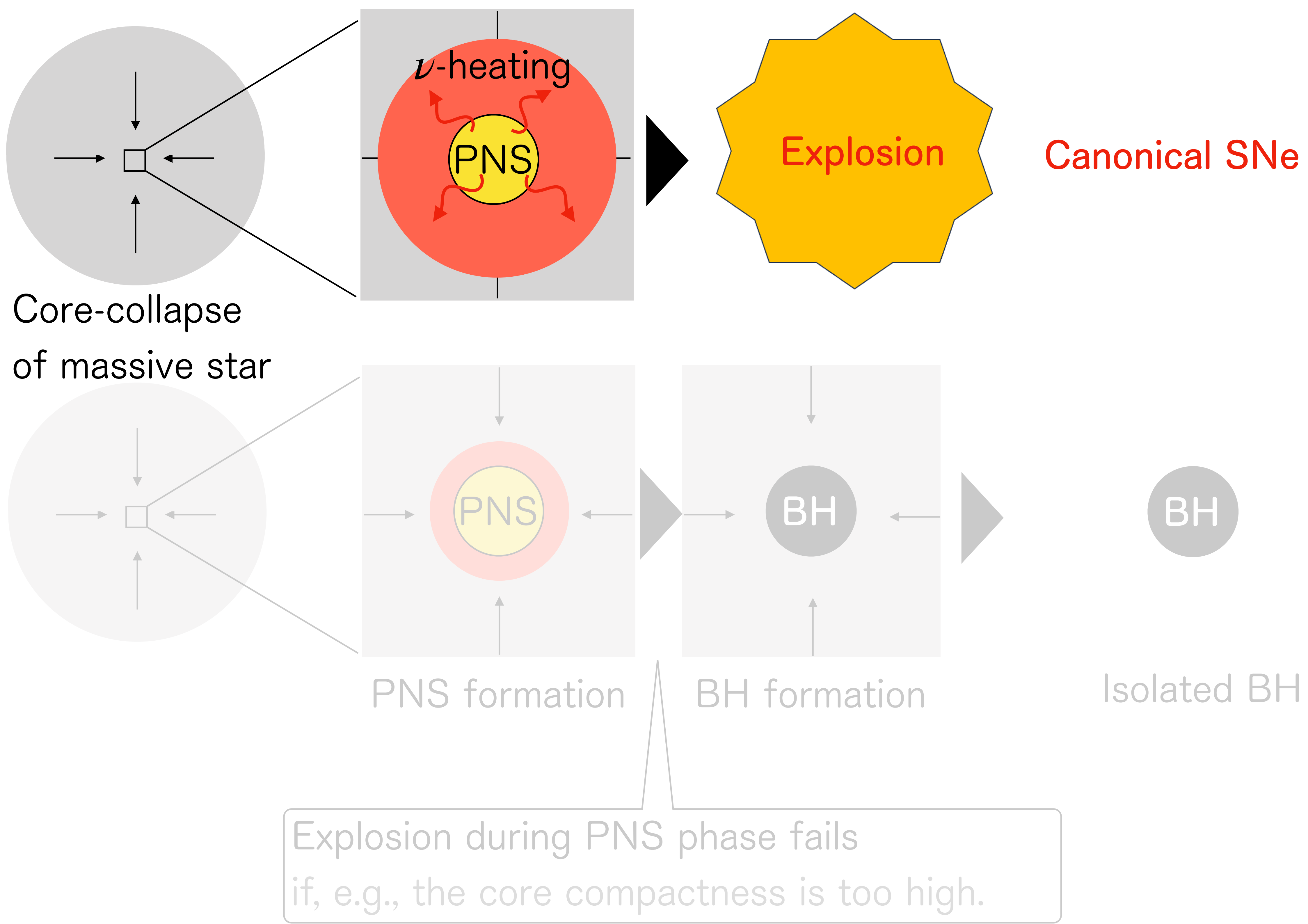


Post-merger ejecta is too massive.

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

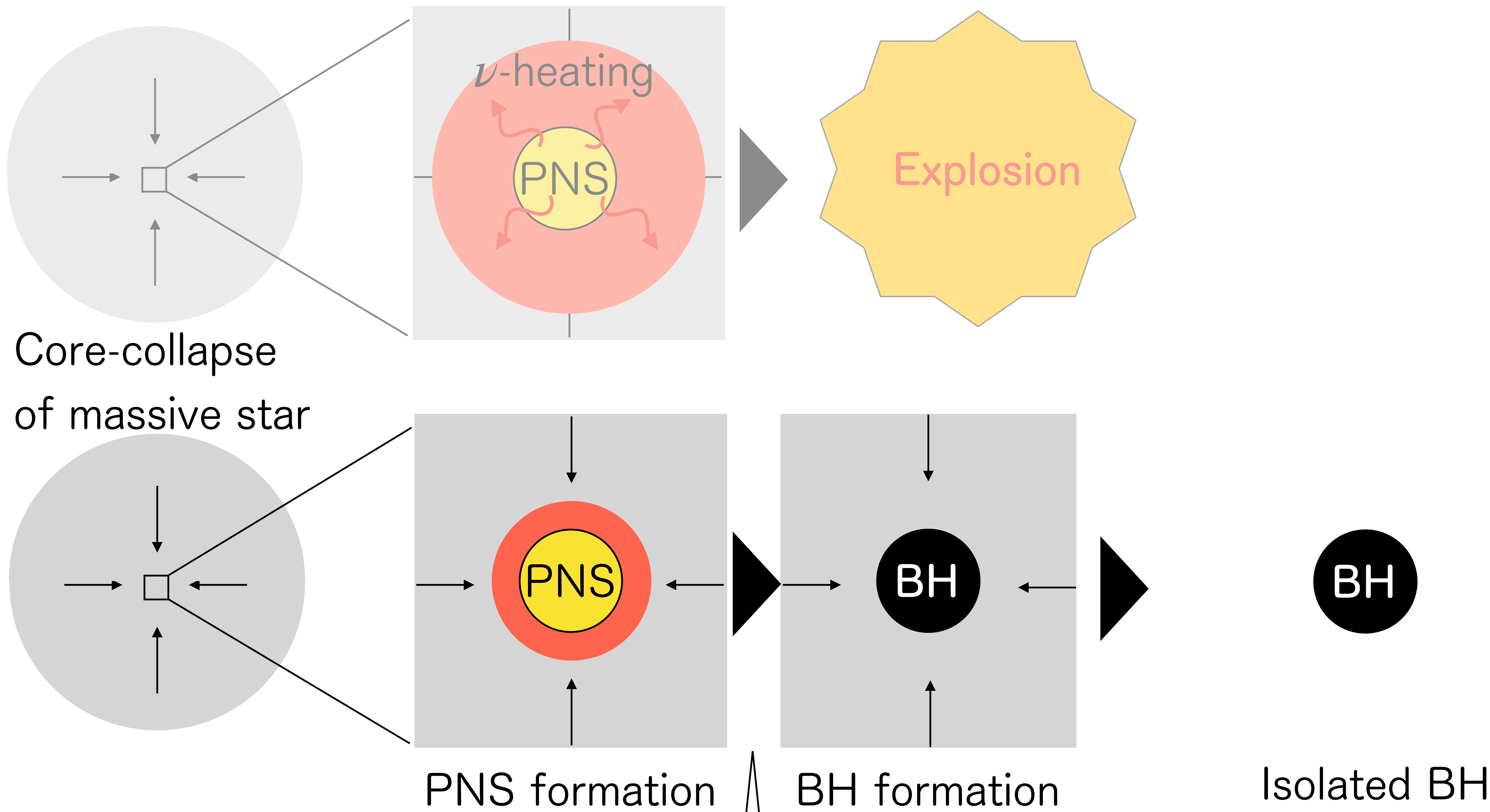
Collapsar

Collapsar



ν-heating
PNS
Explosion
Canonical SNe
Core-collapse
of massive star
PNS
BH
BH
PNS formation
BH formation
Isolated BH
Explosion during PNS phase fails
if, e.g., the core compactness is too high.

Collapsar

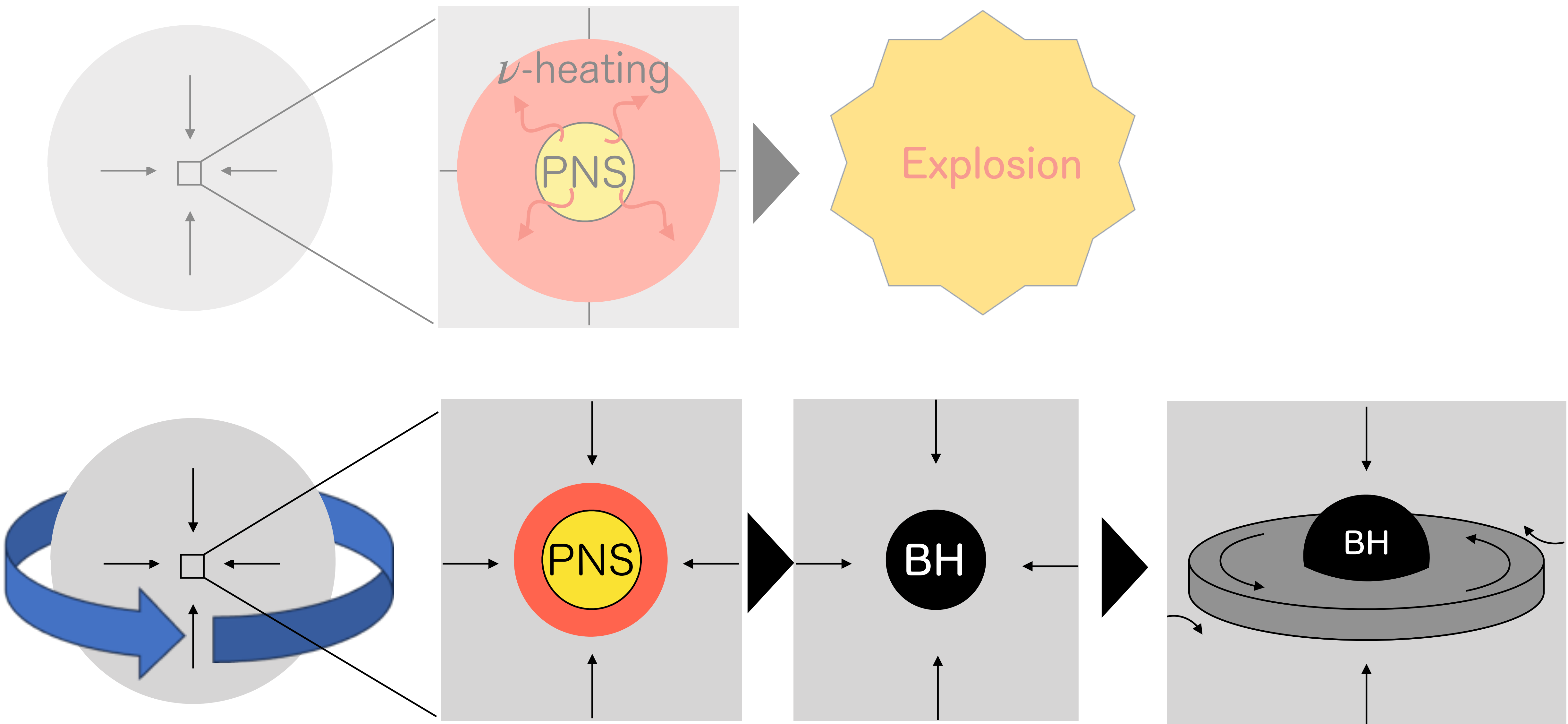


Explosion during PNS phase fails
if, e.g., the core compactness is too high.

Note: MHD process can help explosion

Obergaulinger & Aloy

Collapsar



Core-collapse of rotating star

PNS formation

BH formation

Disk formation

Further activities!

Explosion during PNS phase fails

if, e.g., the core compactness is too high.

BH-disk activities and GRB-SN

Gamma-ray bursts (GRBs)

BH-disk is one of the promising central engines (e.g., Woosley et al. 1993...)

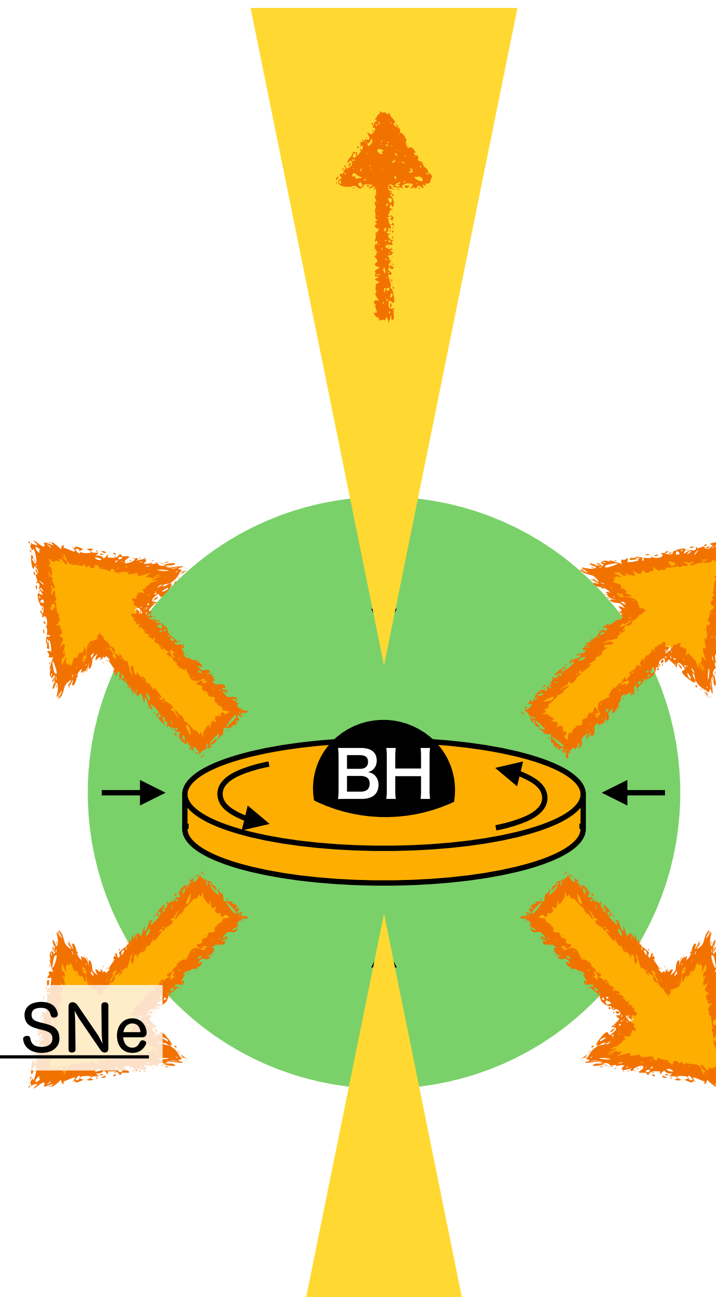
Disk outflow (as post-merger system!) (MacFadyen & Woosley 1999)

Energy generated by viscous accretion:

$$GM_{\rm BH}M_{\rm disk}/r_{\rm disk} \approx 3 \times 10^{52}\,{\rm erg}\left(\frac{M_{\rm BH}}{10M_\odot}\right)\left(\frac{M_{\rm disk}}{0.1M_\odot}\right)\left(\frac{r_{\rm disk}}{10^7{\rm cm}}\right)^{-1}$$

Long GRBs are accompanied by energetic SNe (Ic-BL)

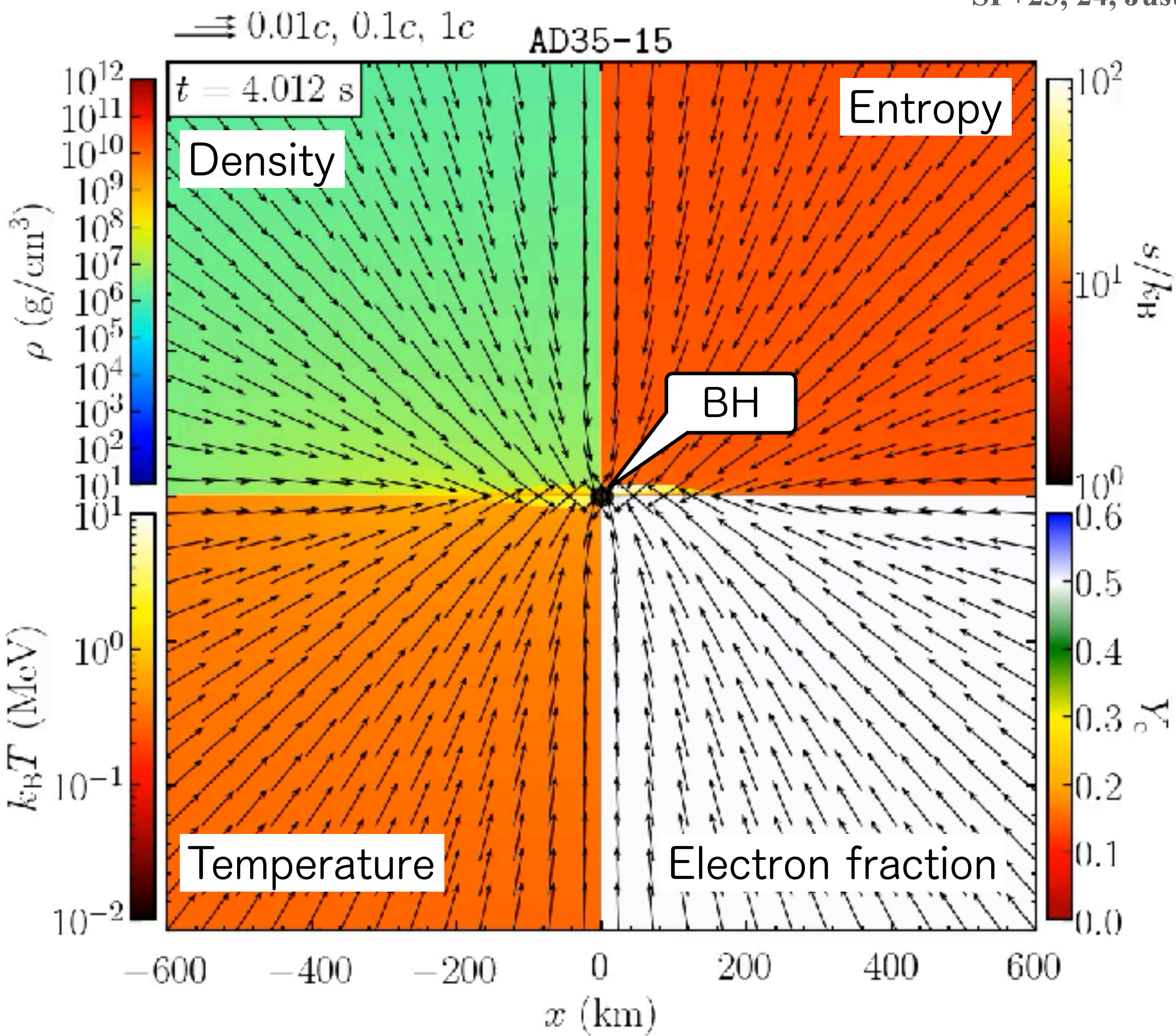
- Explosion energy $E_{\rm K} = (0.8 - 4.4) \times 10^{52}\,{\rm erg}$
- ^{56}Ni mass $M_{\rm Ni} = (0.2 - 0.5)\,M_\odot$ (Cano et al. 17)



Viscosity-driven outflow from disk would naturally explain such SNe

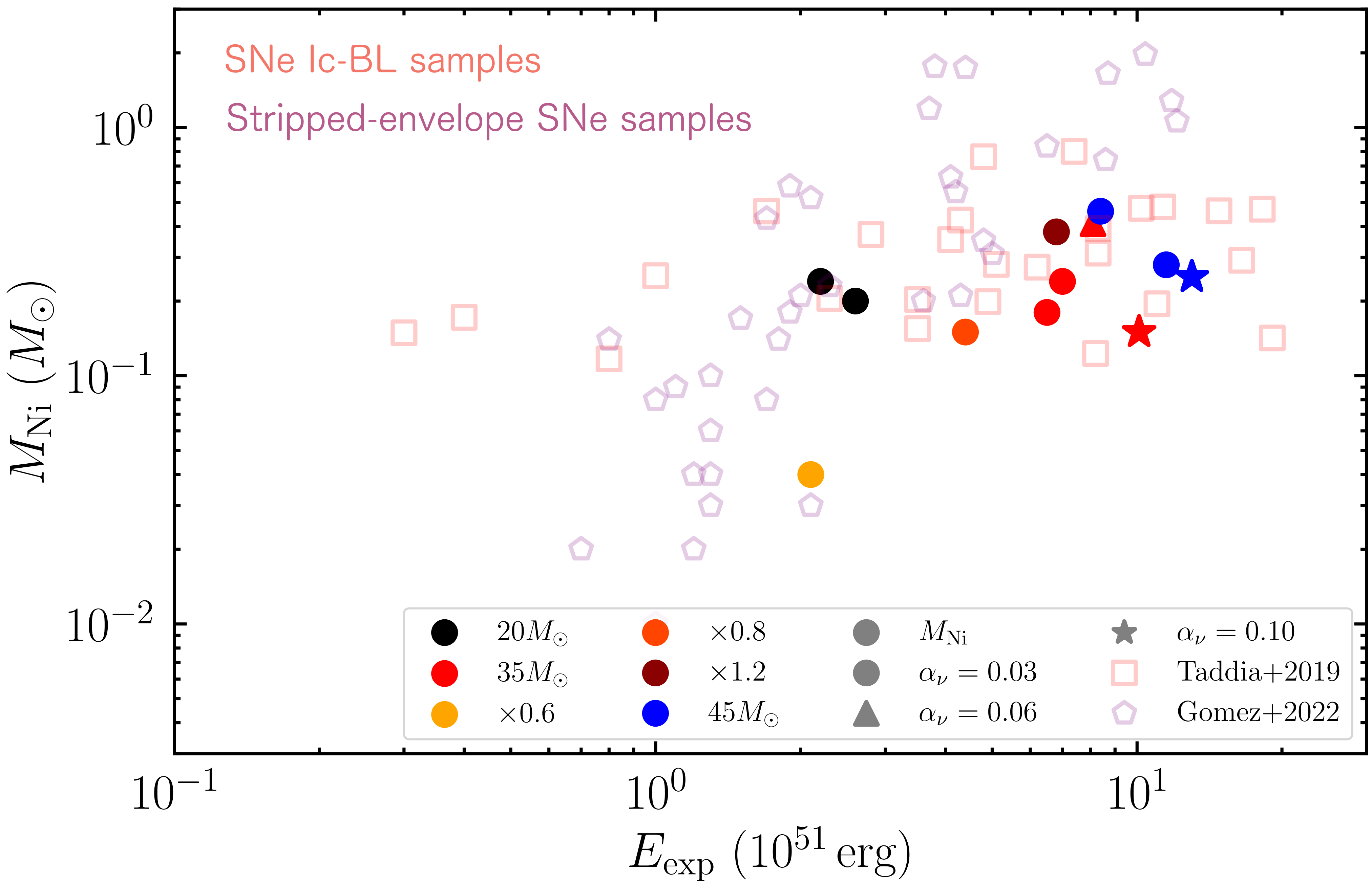
Disk formation→neutrino-cooled disk→Outflow

SF+23, 24, Just+22, Dean+24



Progenitor models from Aguilera-Dena+20 (This is a 35 solar mass model)

Comparison with observations



Nucleosynthesis calculation in the ejecta → $M_{\rm Ni} \gtrsim 0.1 M_\odot$

BH-disk can be an engine of the energetic explosion.

Effects of jets

NS binary merger and Collapsar: promising system for GRBs

NS binary merger (short GRBs) (also some long GRBs...?)

Jet propagates through the dynamical ejecta modifies the ejecta structure

Abundance changes in the shocked dynamical ejecta Granot+24

Collapsar (long GRBs)

Jet may make the SN component e.g., Tominaga+07, Barnes+18, Leung+23,...

^{56}Ni may be synthesized in the shocked matter.

A high energy deposition (rate) is necessary.

Inconsistent with observed velocity distribution? Eisenberg+22

Summary

NS-NS merger

Short-lived NS case:

Equal-mass → **Asymmetric**

Broad Ye distribution

Lower typical Ye (→ limit: BH-NS)

Larger disk mass

→ More massive post-merger ejecta

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

Collapse of rotating massive star

BH formation → Disk formation → Disk outflow (after neutrino-cooling phase)

Promising energy & ^{56}Ni sources for SNe Ic BL.

(depends on progenitor profile → More systematic study is necessary)

Thank you for your attention!