Outflow from post-merger system of binary neutron star

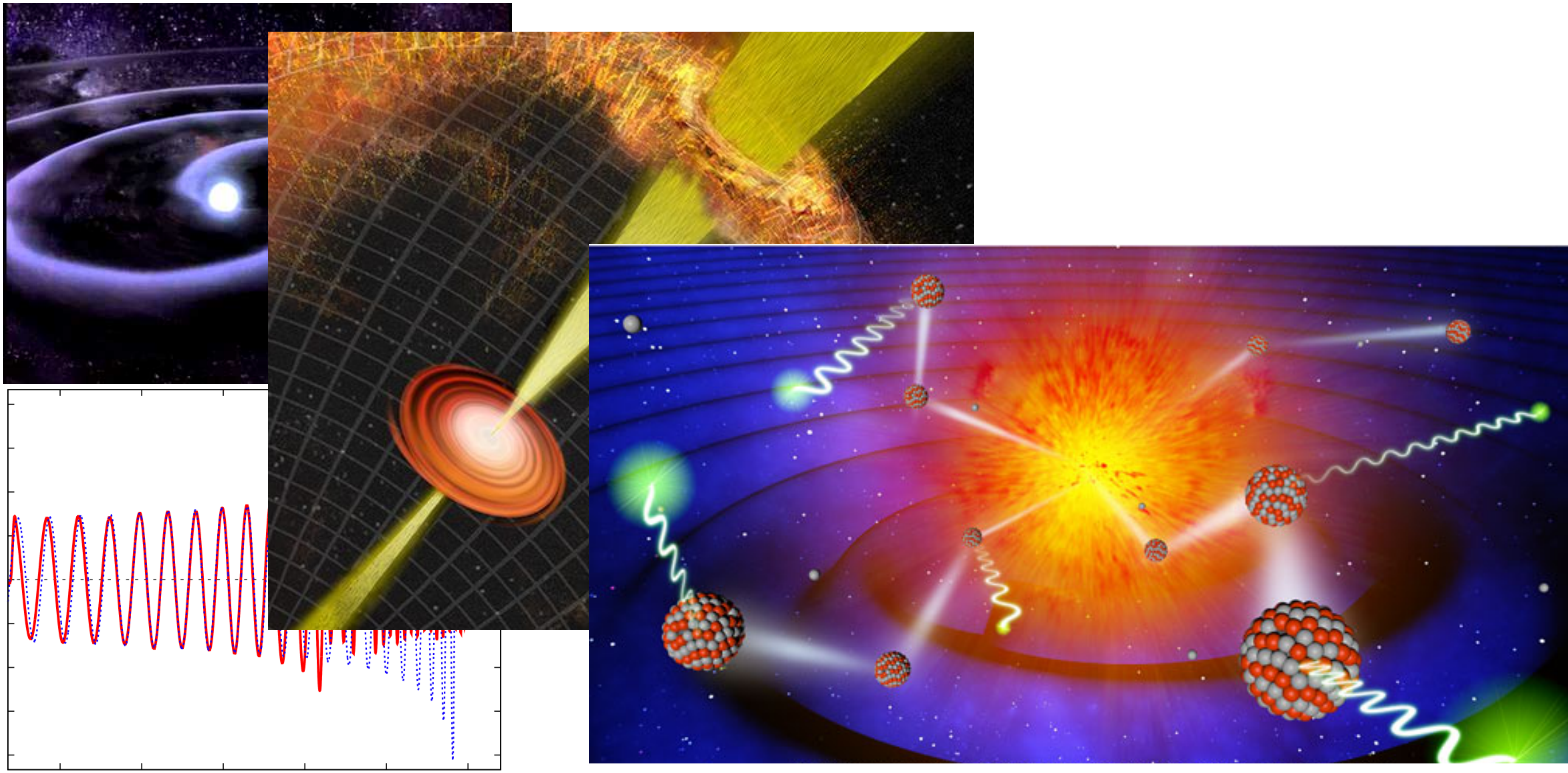
Sho Fujibayashi （藤林　翔）
(Max-Planck-Institute for Gravitational Physics; AEI)

in collaboration with
Shinya Wanajo, Kenta Kiuchi, Kyohei Kawaguchi, Koutarou Kyutoku,
Yuichiro Sekiguchi, and Masaru Shibata

Extreme Outflows in Astrophysical Transients
@YITP (+online), 2021.08.26

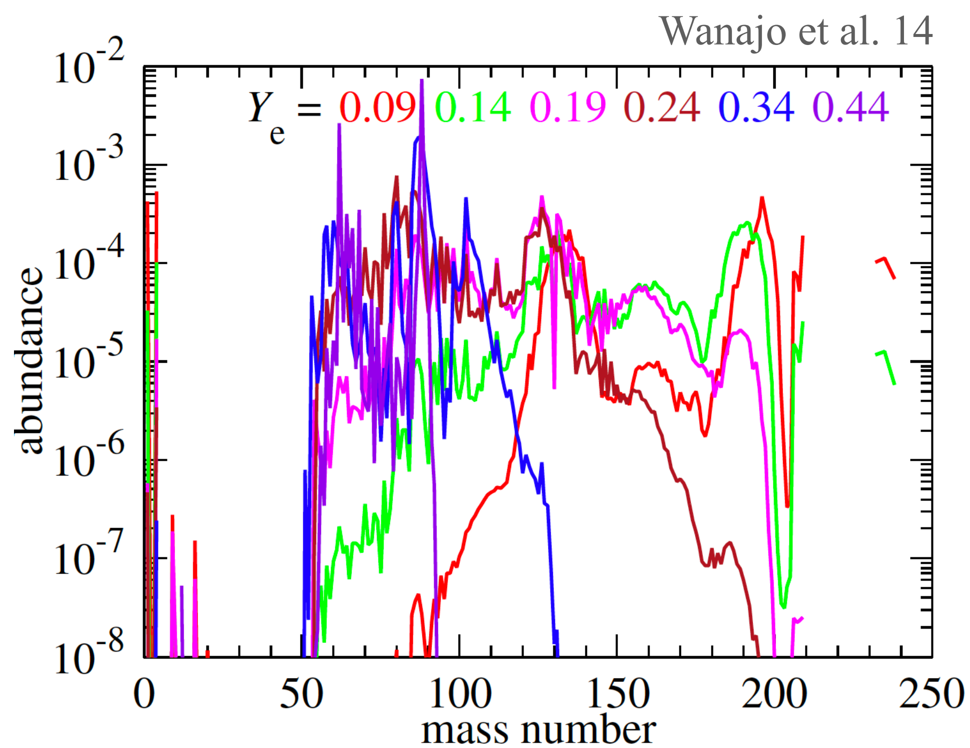
Max-Planck-Institut
für Gravitationsphysik
(Albert-Einstein-Institut)

Binary Neutron Star Merger



- One of the primary targets of ground based GW detector
- (Short) Gamma-ray bursts
- Site of heavy-element synthesis, EM transient

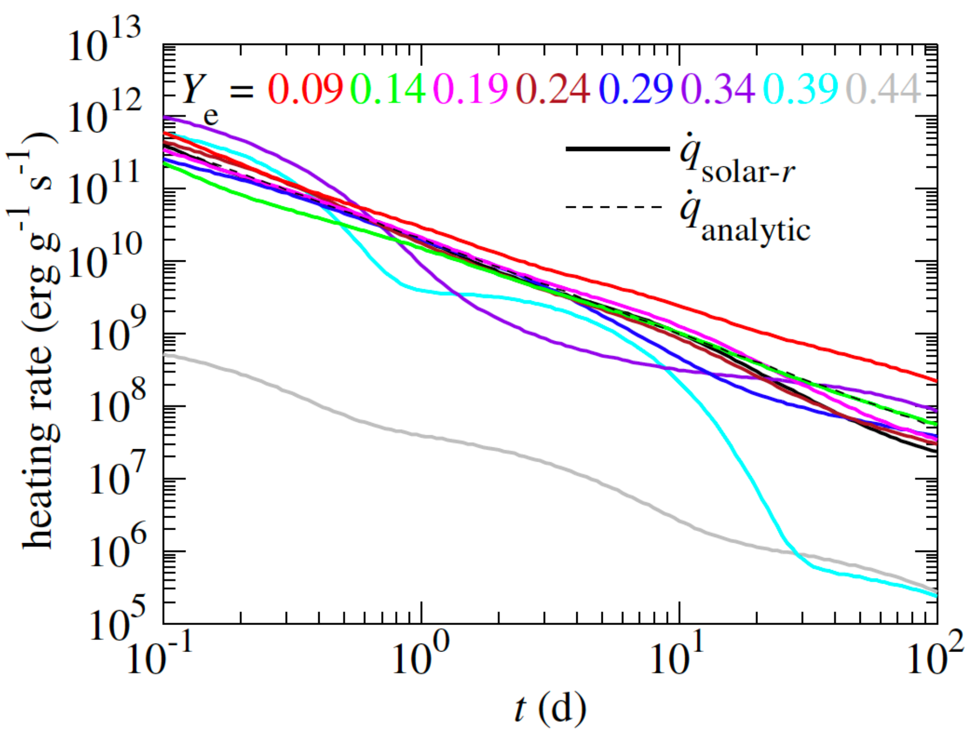
Effects of Neutron richness



Electron fraction $Y_e = \frac{n_e}{n_B} = \frac{n_p}{n_p + n_n}$

【Products】

Lower Ye ↔ more neutron-rich
stronger r-process



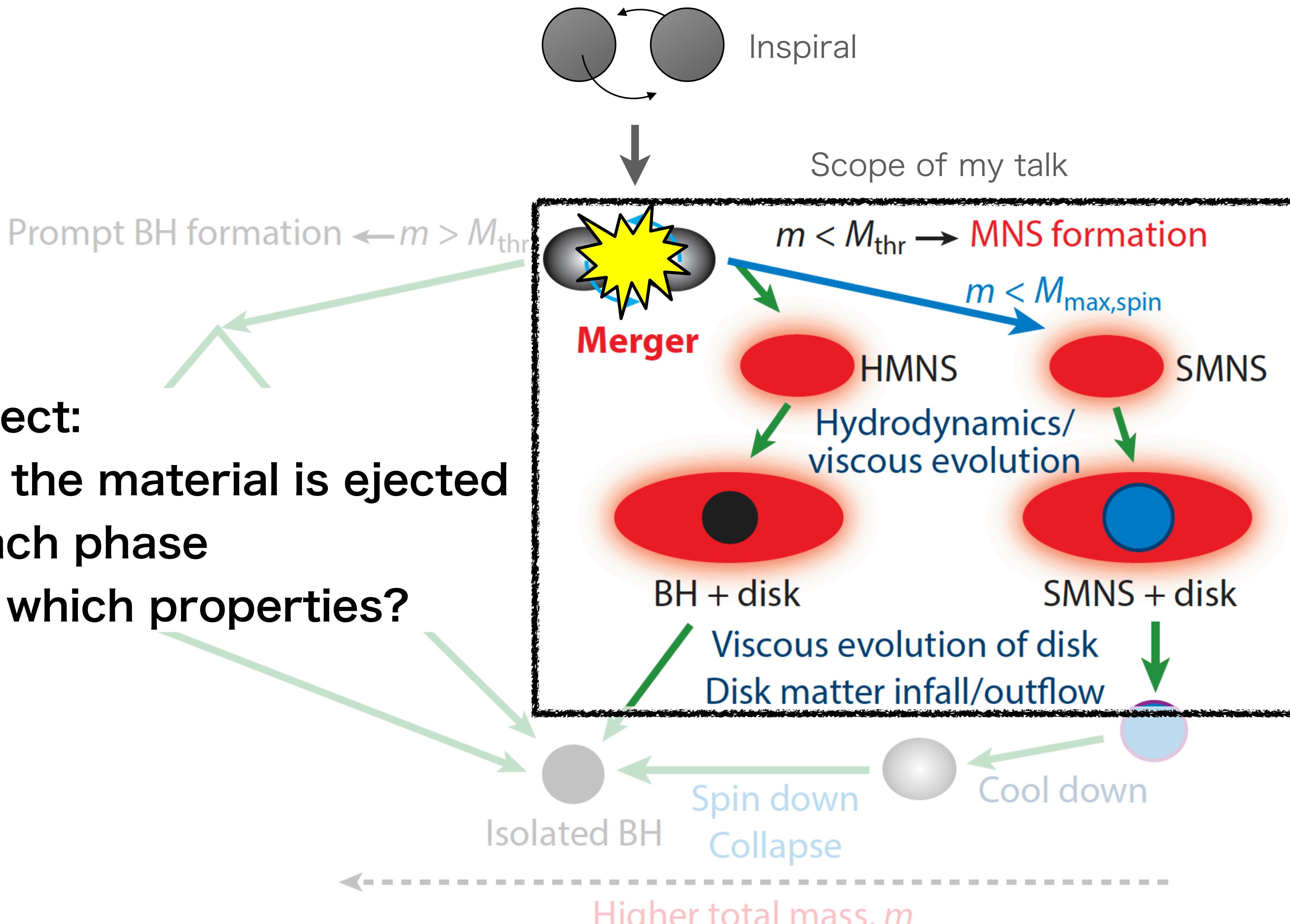
【Electromagnetic signal】

Matter with different composition has different heating rate and opacity.

Lanthanides have a very large opacity.

see talks by Kawaguchi san, Tanaka san, Domoto san

Timeline of NS-NS Merger

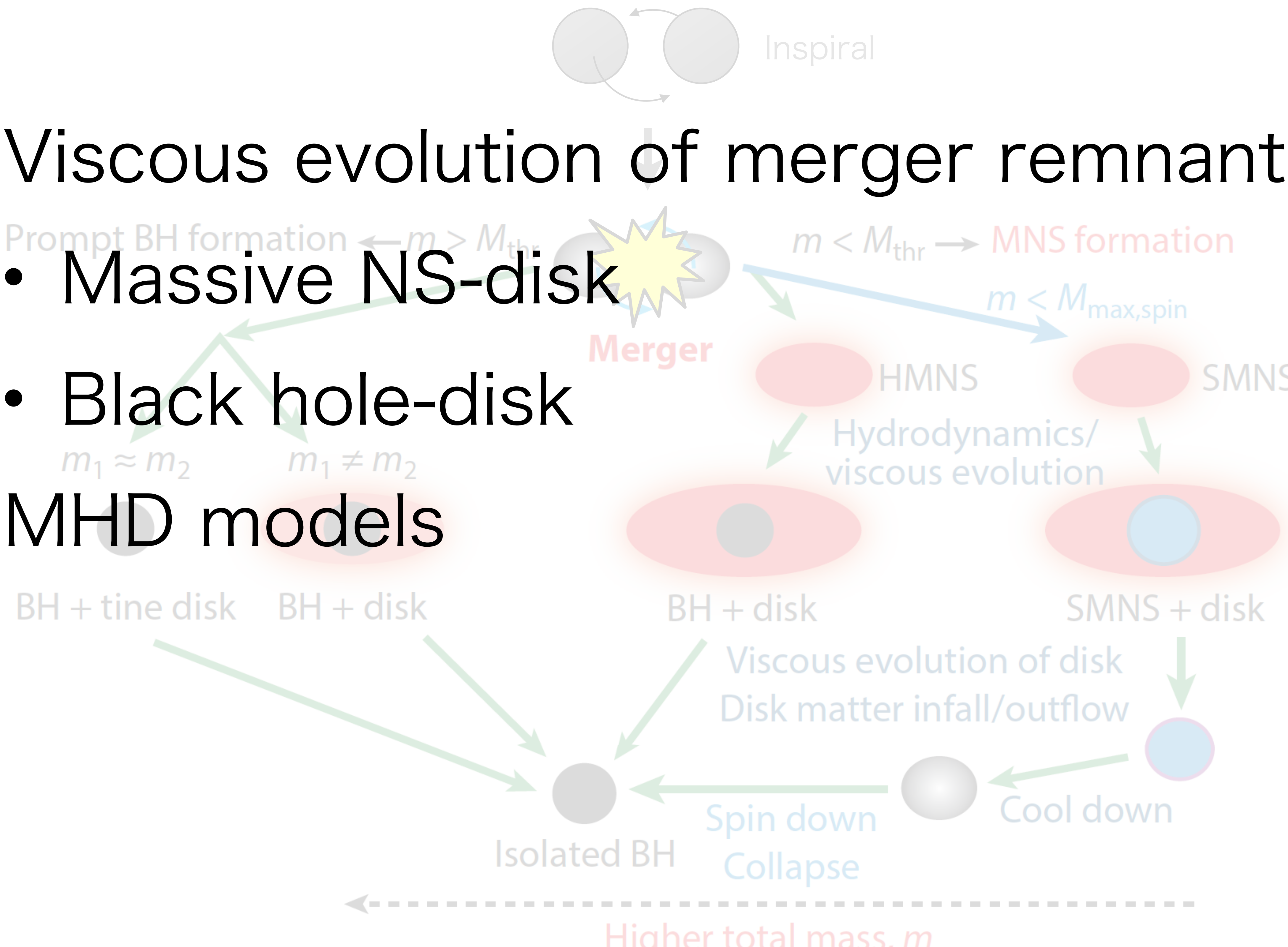


Subject:
How the material is ejected in each phase with which properties?

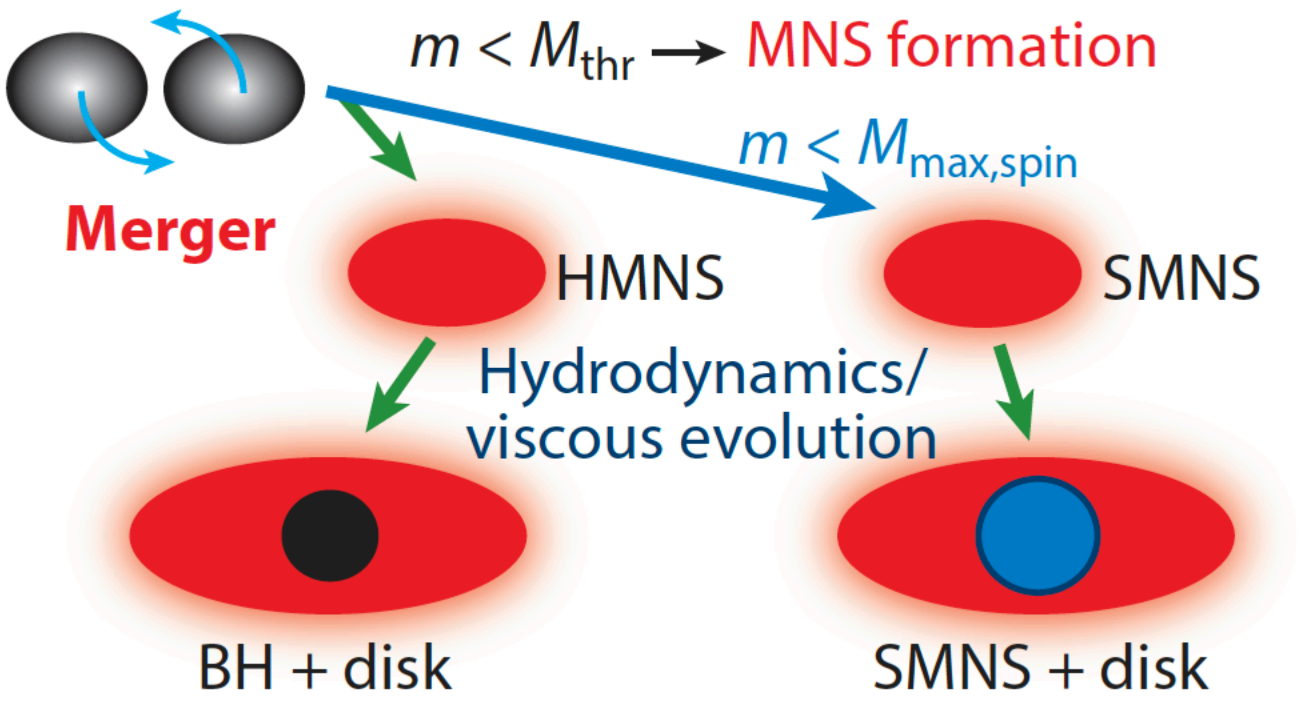
taken from Shibata & Hotokezaka 2019

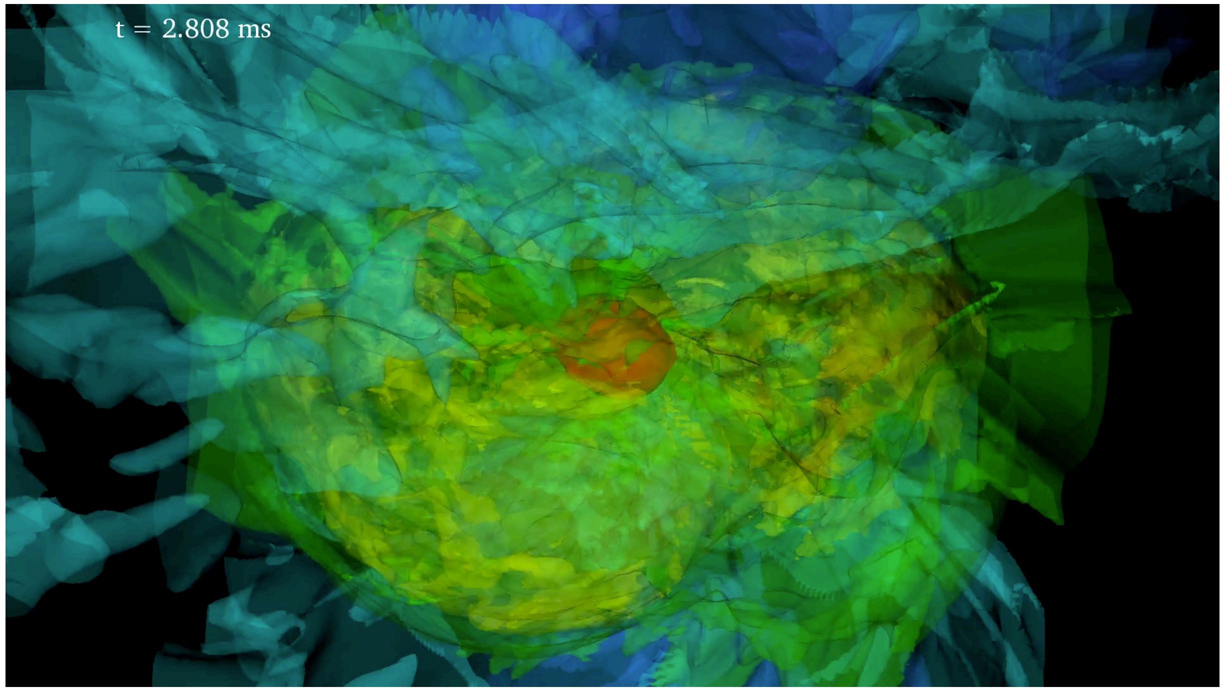
Contents

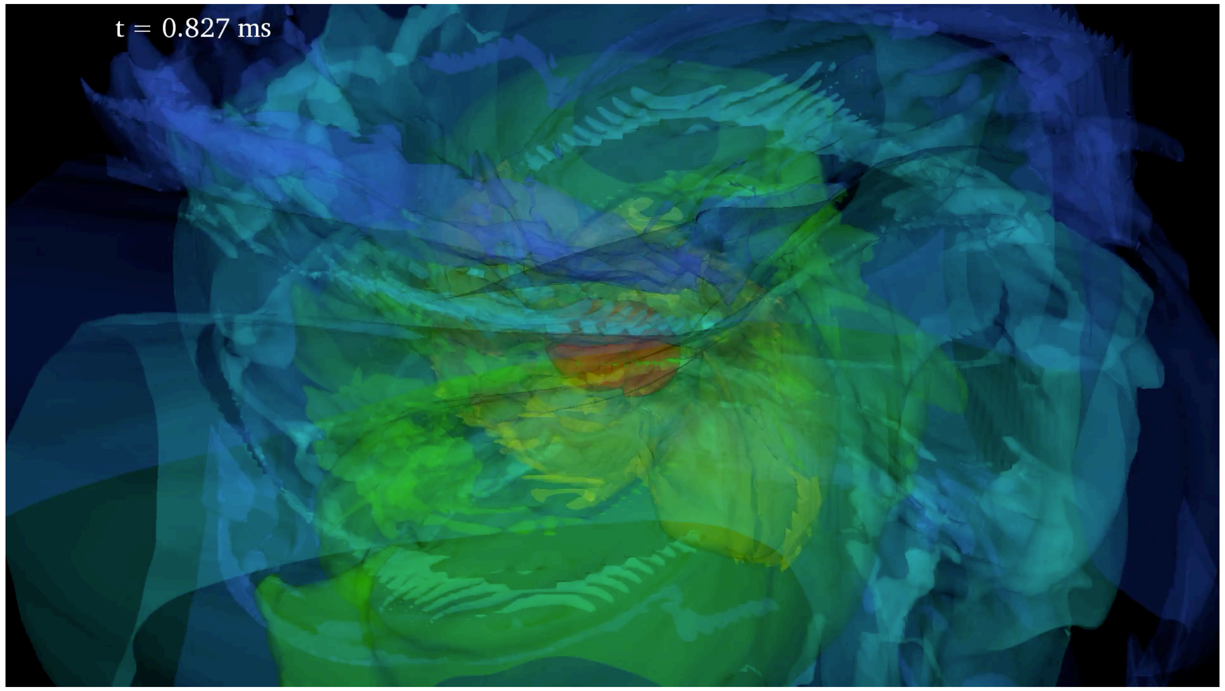
- Viscous evolution of merger remnants
  - Massive NS-disk
  - Black hole-disk
- MHD models



Evolution in Post-merger Phase







Mass ejection in Post-merger phase

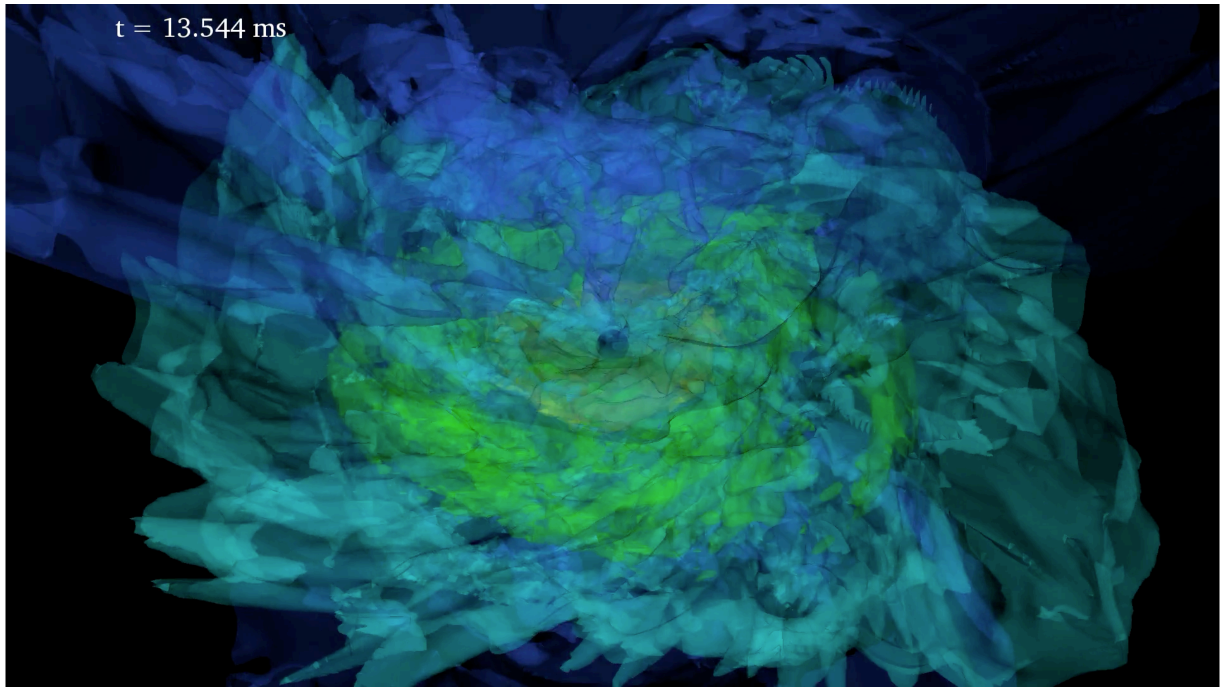
In post-merger phase. . .

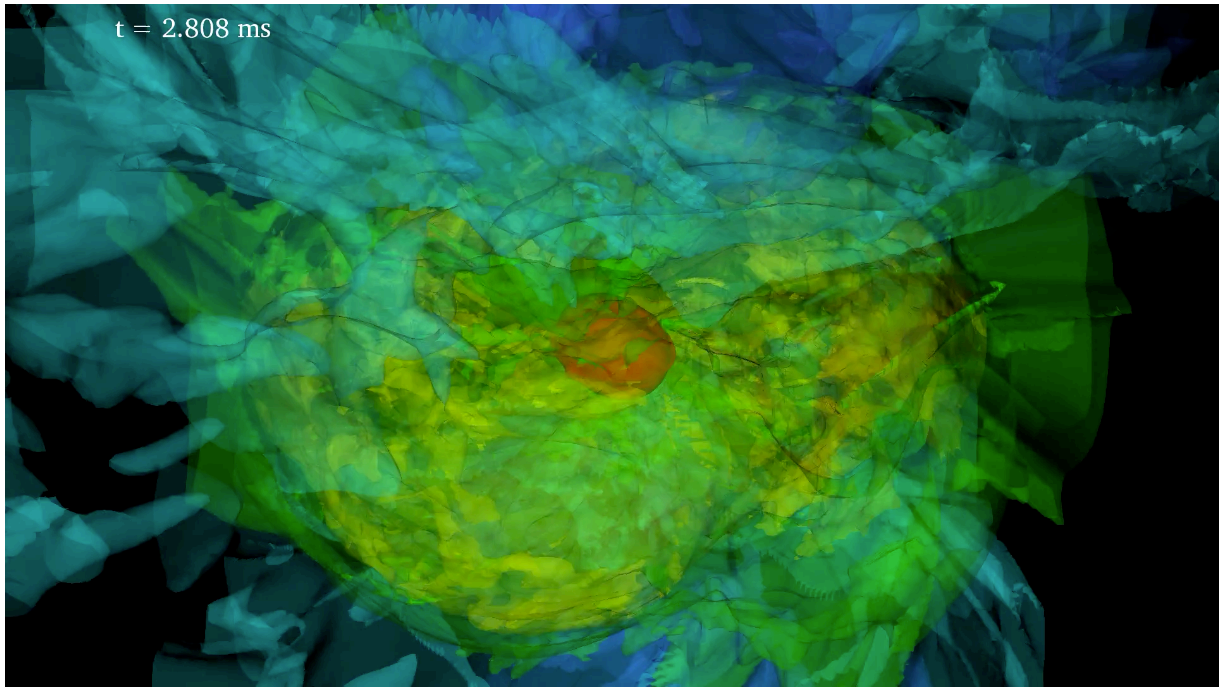
- High temperature → weak interaction plays an important role

  $t_{\mathrm{weak}} \sim 1\,\mathrm{ms}\left(\frac{T}{5\,\mathrm{MeV}}\right)^{-5}$ << 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





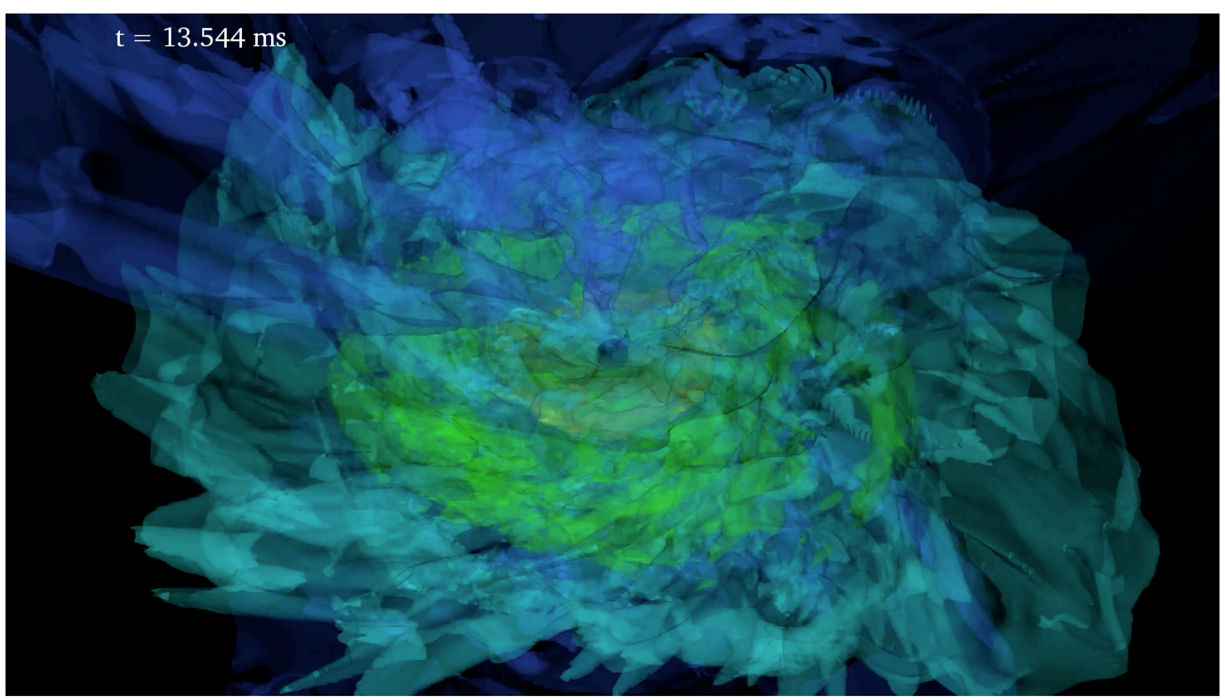
Mass ejection in Post-merger phase

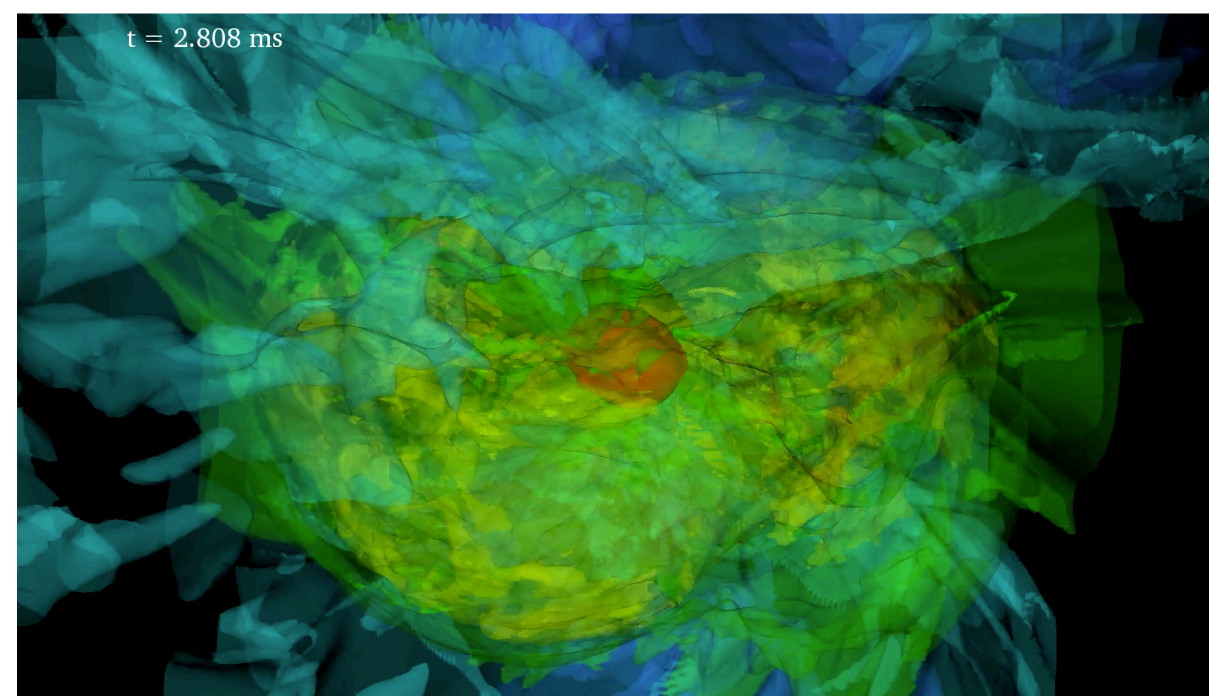
In post-merger phase. . .

- Magnetic field is amplified due to MHD processes.

- MRI in the disk → Viscosity (by turbulent motion) emergence
- Viscous angular momentum transport/heating → mass ejection

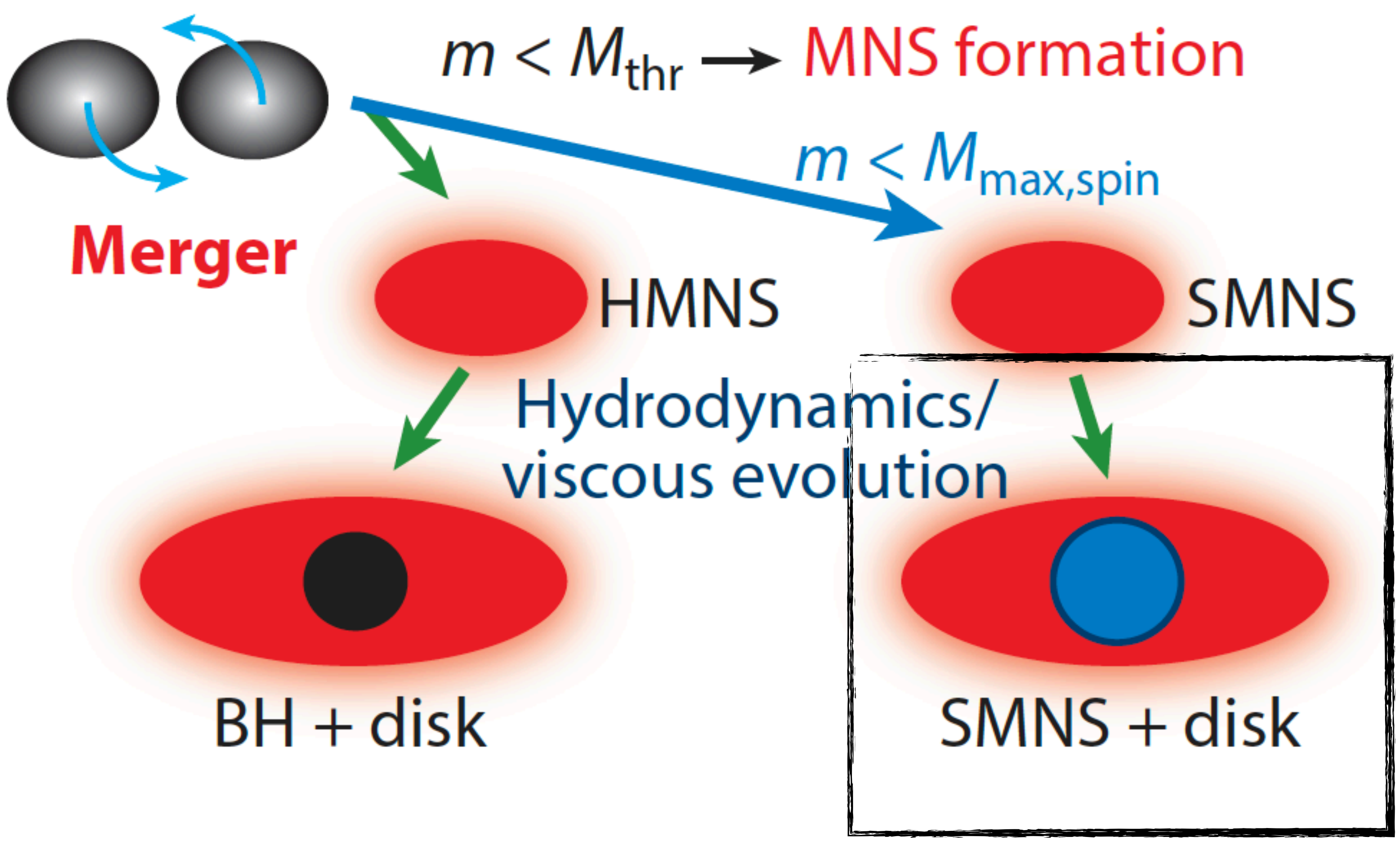
- Mass ejection by (purely) MHD processes (due to aligned global B-field)





Viscous hydrodynamics case

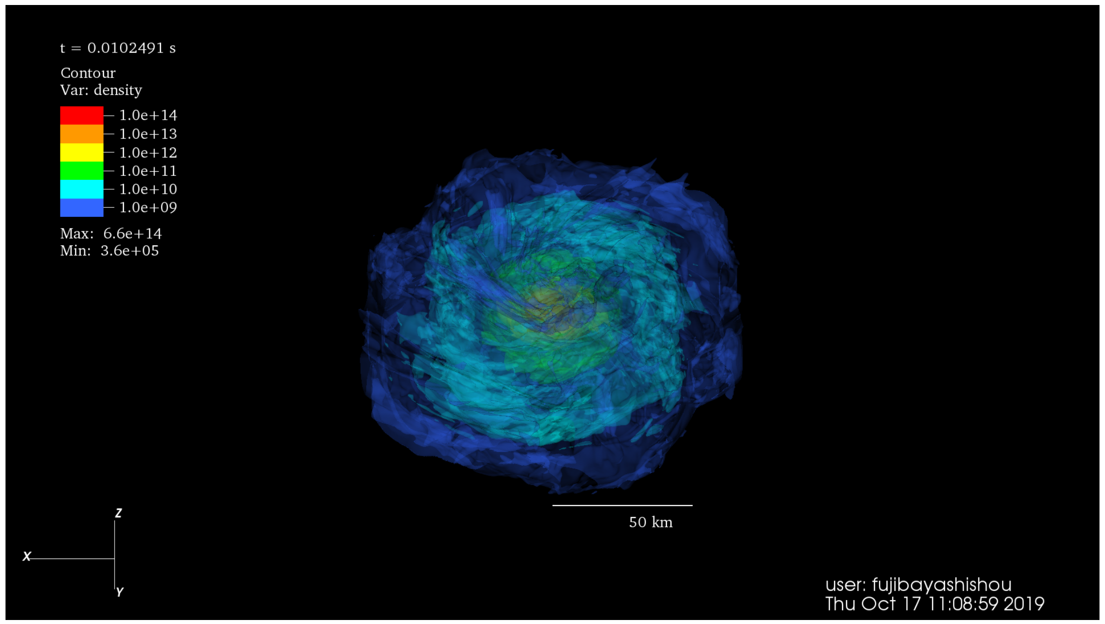
1. Mass ejection from long-lived NS–disk system

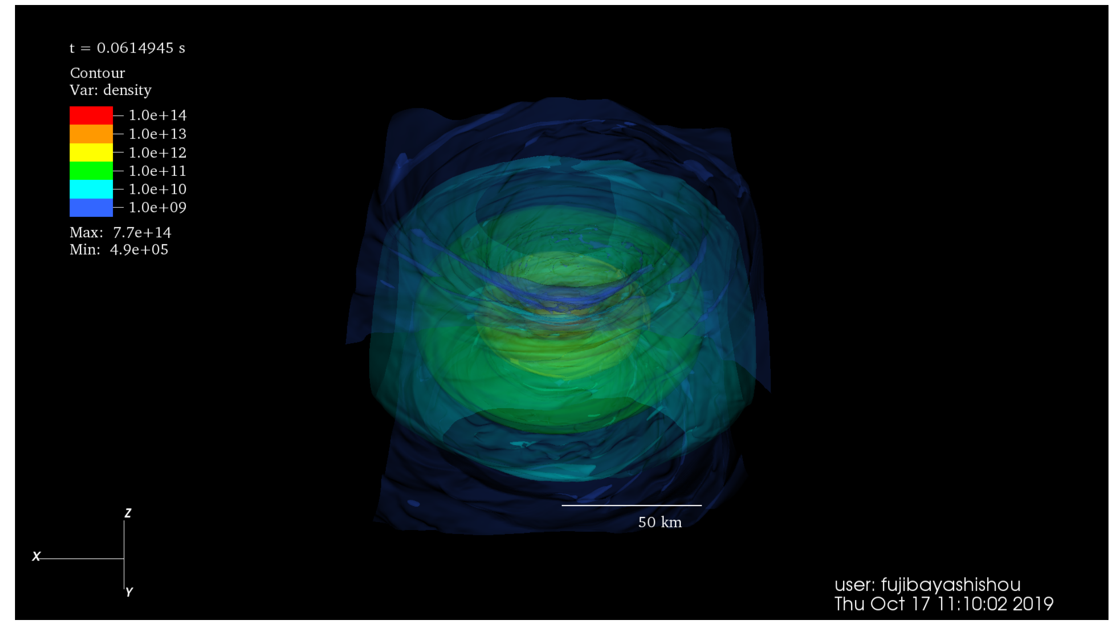


Viscous Evolution of the Merger remnant.

i) Simulate the NS-NS merger with 3D full GR code

Sekiguchi et al. 15
Kiuchi et al. in prep.





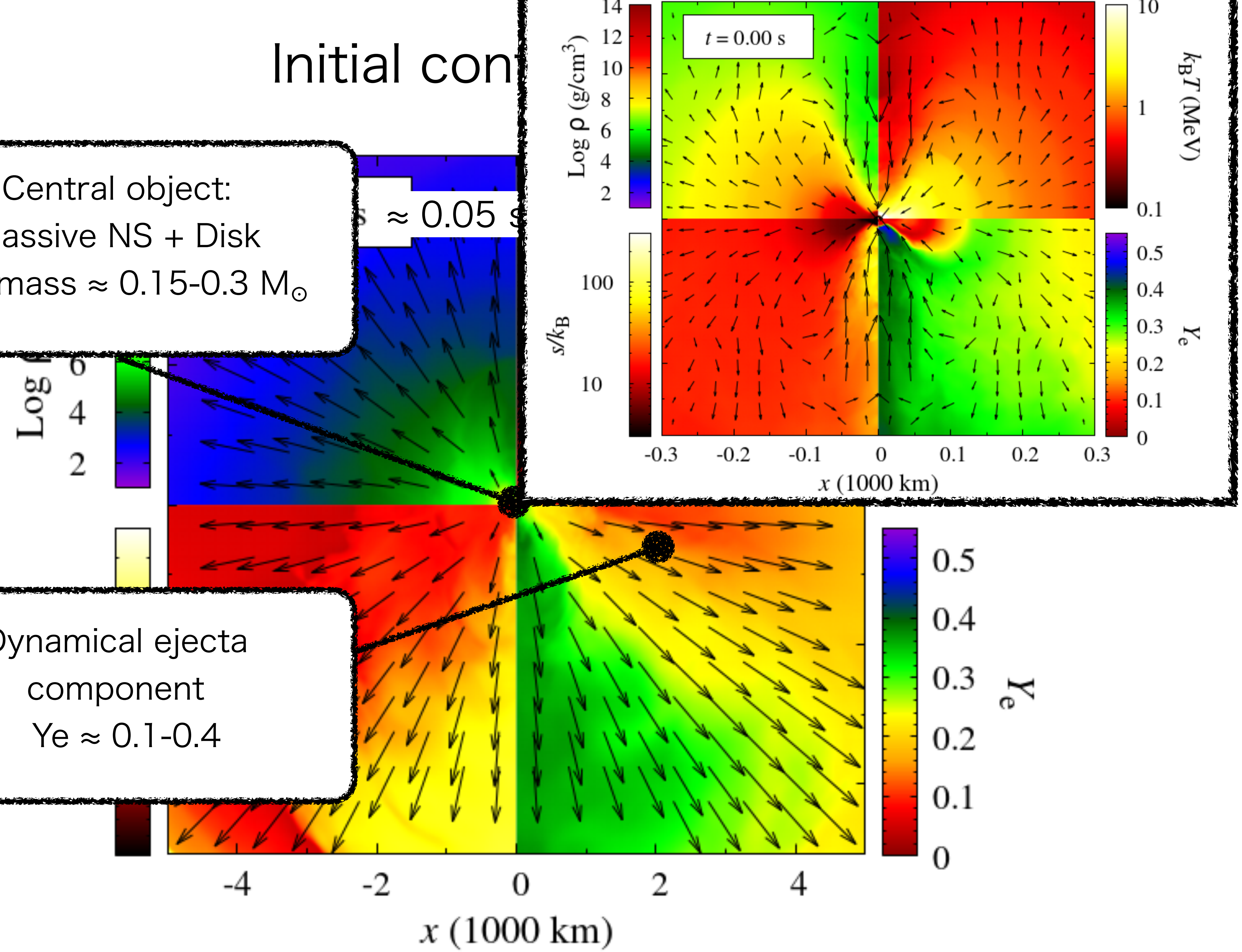
Average over azimuthal angles around the rotational axis after ~50 ms after the merger, when the system settles into quasi-axisymmetic configuration.

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

SF et al. 17, 18, and 20

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

Initial con



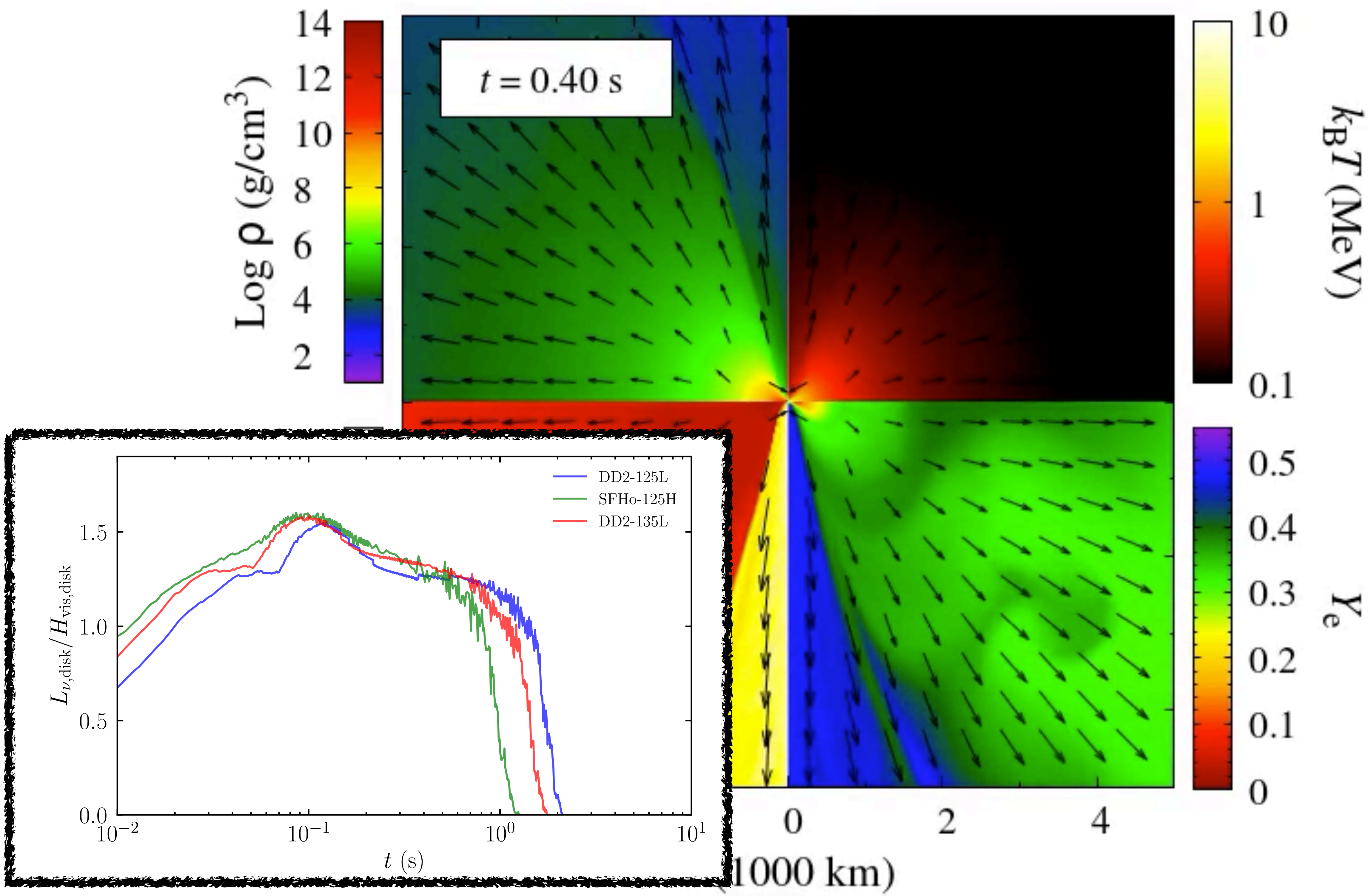
Central object:
Massive NS + Disk
Disk mass ≈ 0.15-0.3 $M_\odot$

Dynamical ejecta
component
Ye ≈ 0.1-0.4

DD2-125

Other models are very similar to this.

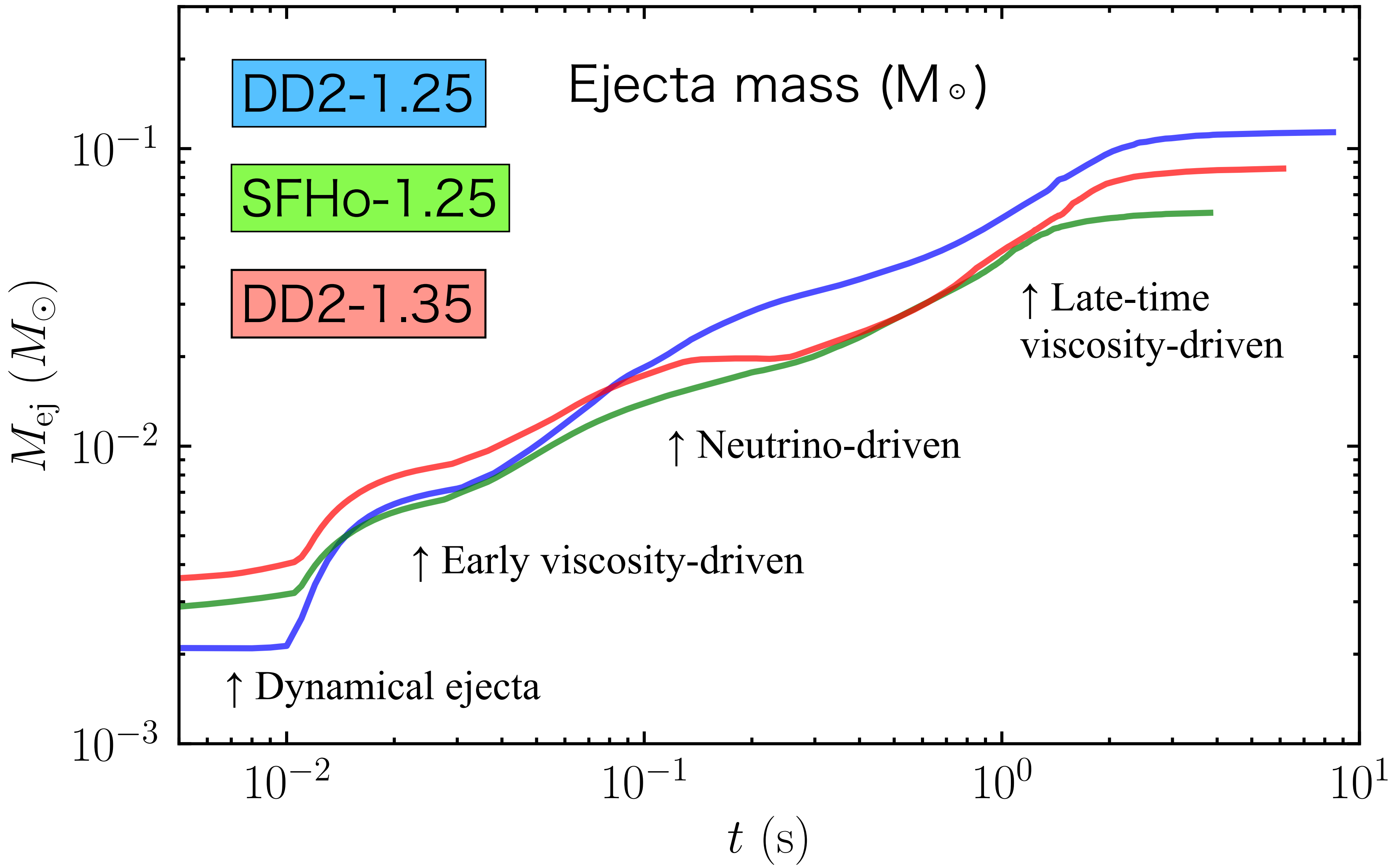
Evolution



In the early phase, cooling is efficient.

Secular mass ejection sets in after the cooling of the disk becomes inefficient.

Mass Ejection

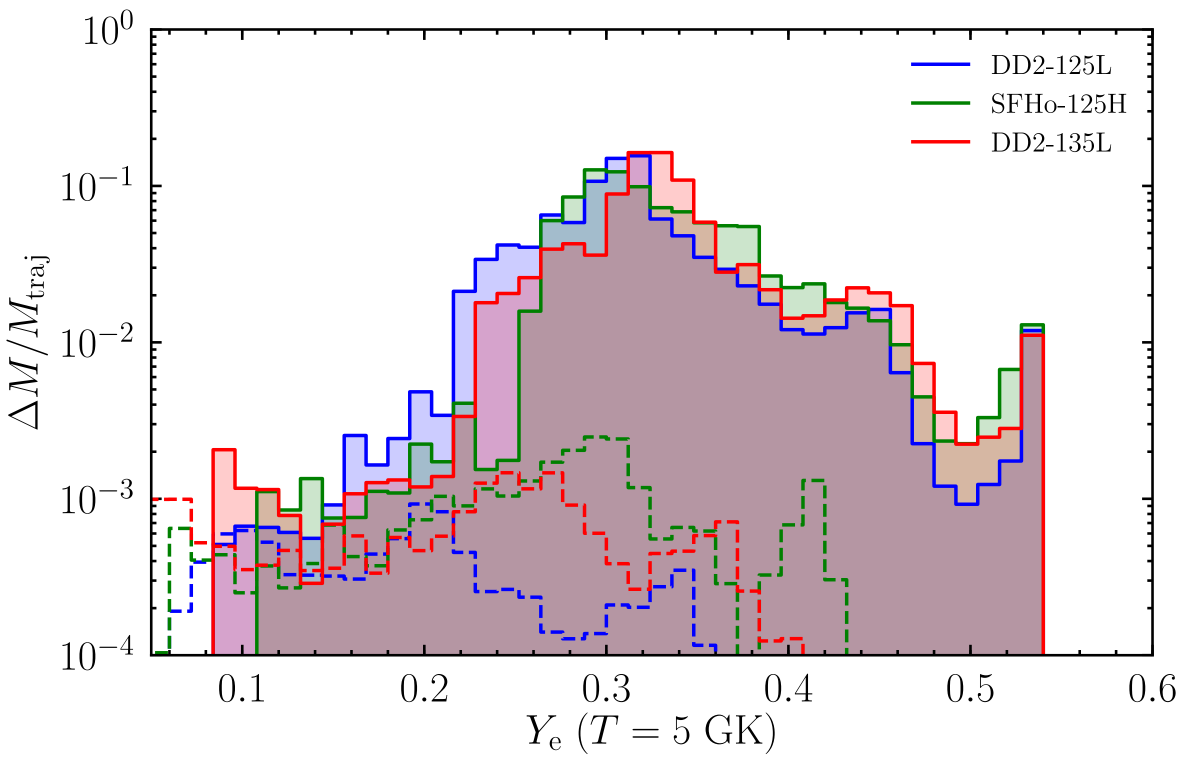


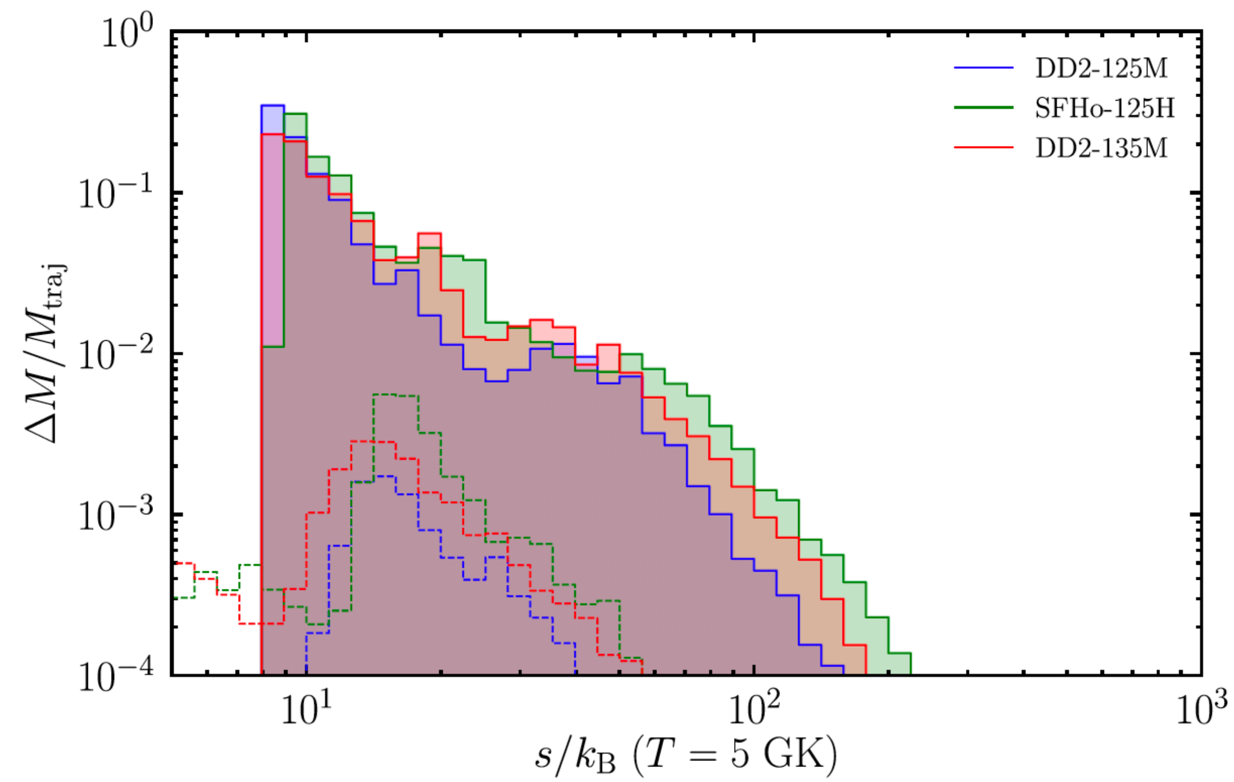
Mass ejection rate becomes large three times: at t~0.01, 0.1, 1 sec.

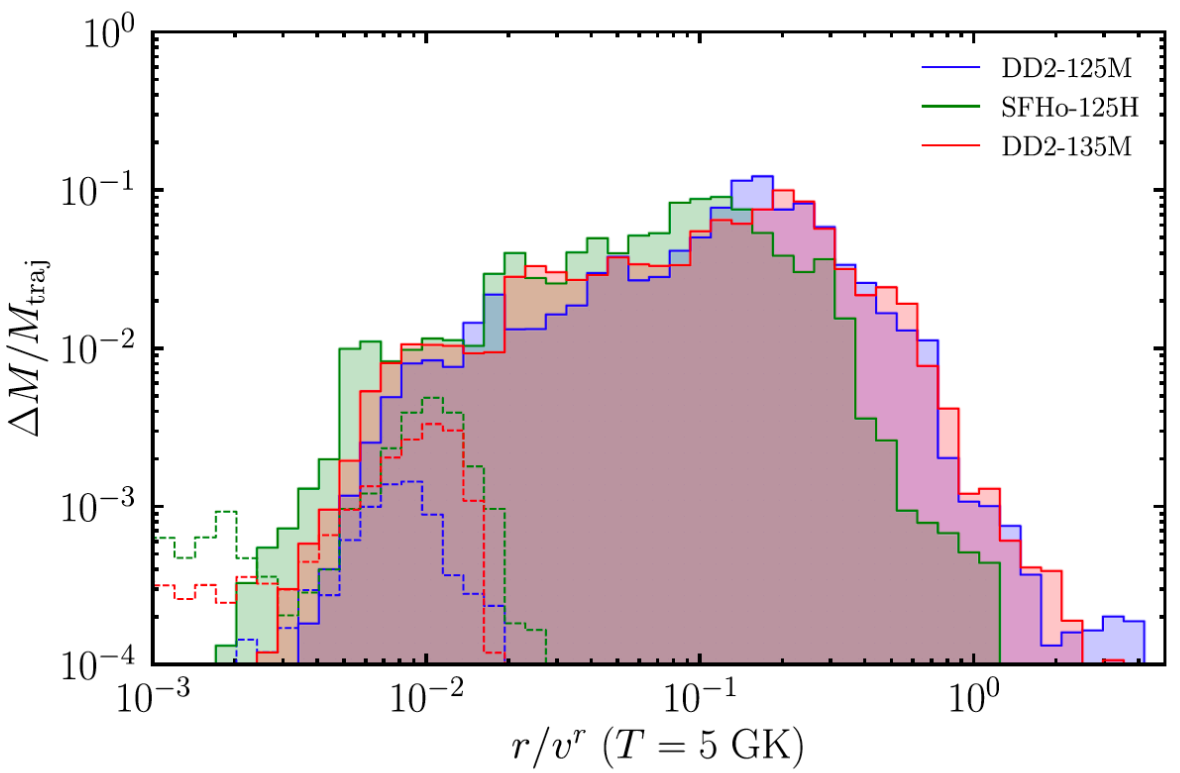
1. Early viscosity-driven ejecta
2. Neutrino-driven ejecta (neutrino luminosity enhanced by viscous heating)
3. Late-time viscosity-driven ejecta

Ejecta mass is large = 0.6 - 0.11 M☉, depending on the initial disk mass
~30% of the disk material is ejected.

Ejecta Properties







Post-merger ejecta:

Ye peaks at ~0.3

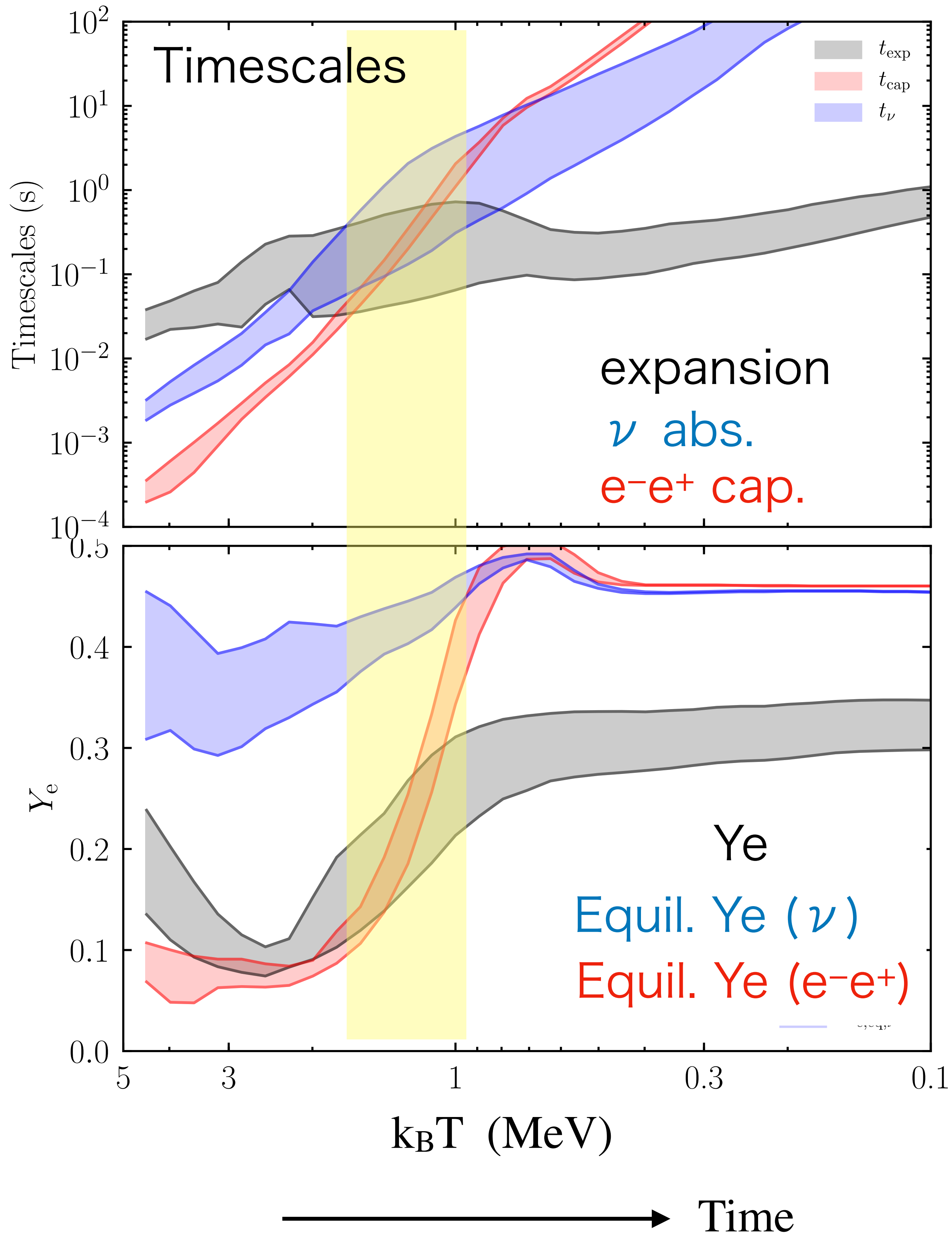
S/k peaks at ~10 with tail

expansion time ~ 0.1 s

Low-Ye, fast-expansion end is determined by the dynamical ejecta

Processes which determine Ye of post-merger ejecta

SF et al. 20, Just et al. 21

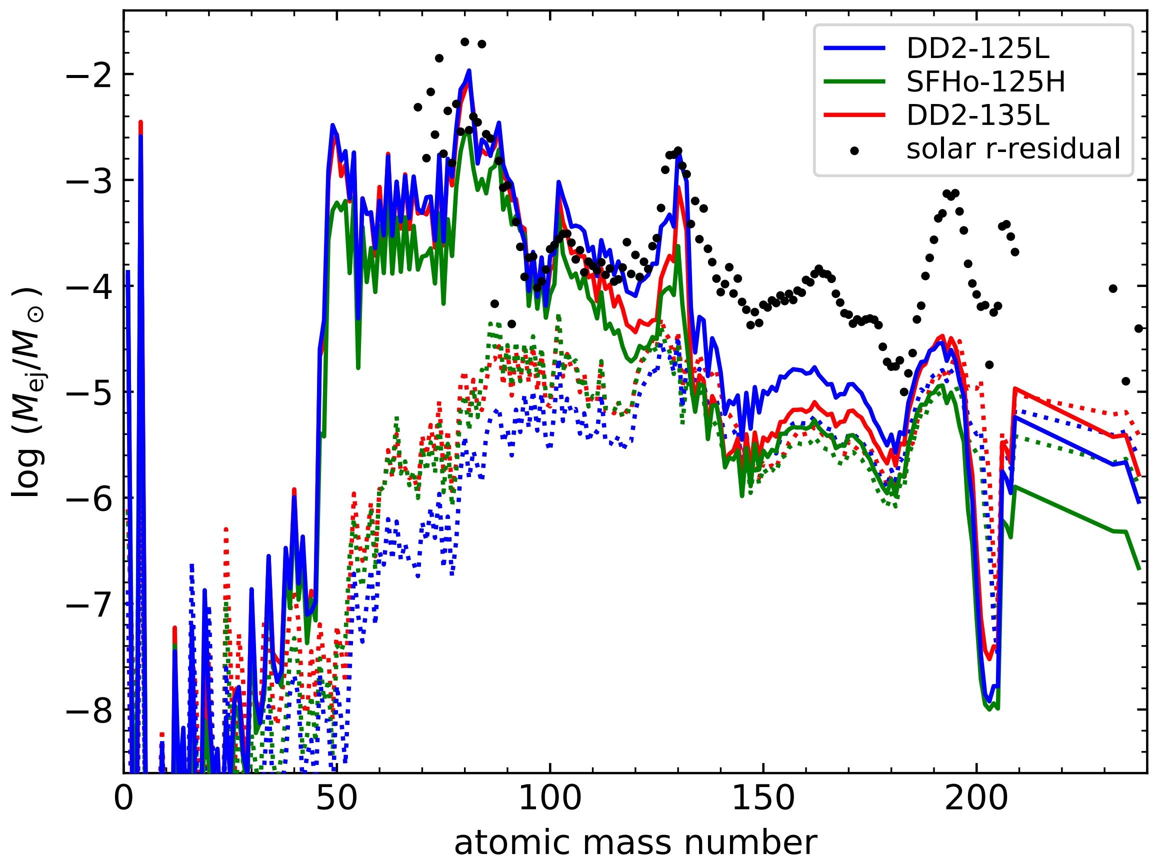


Ejecta non-polar direction dominates.

Until the freeze out,
the e⁻e⁺ capture predominantly
determines the Ye.

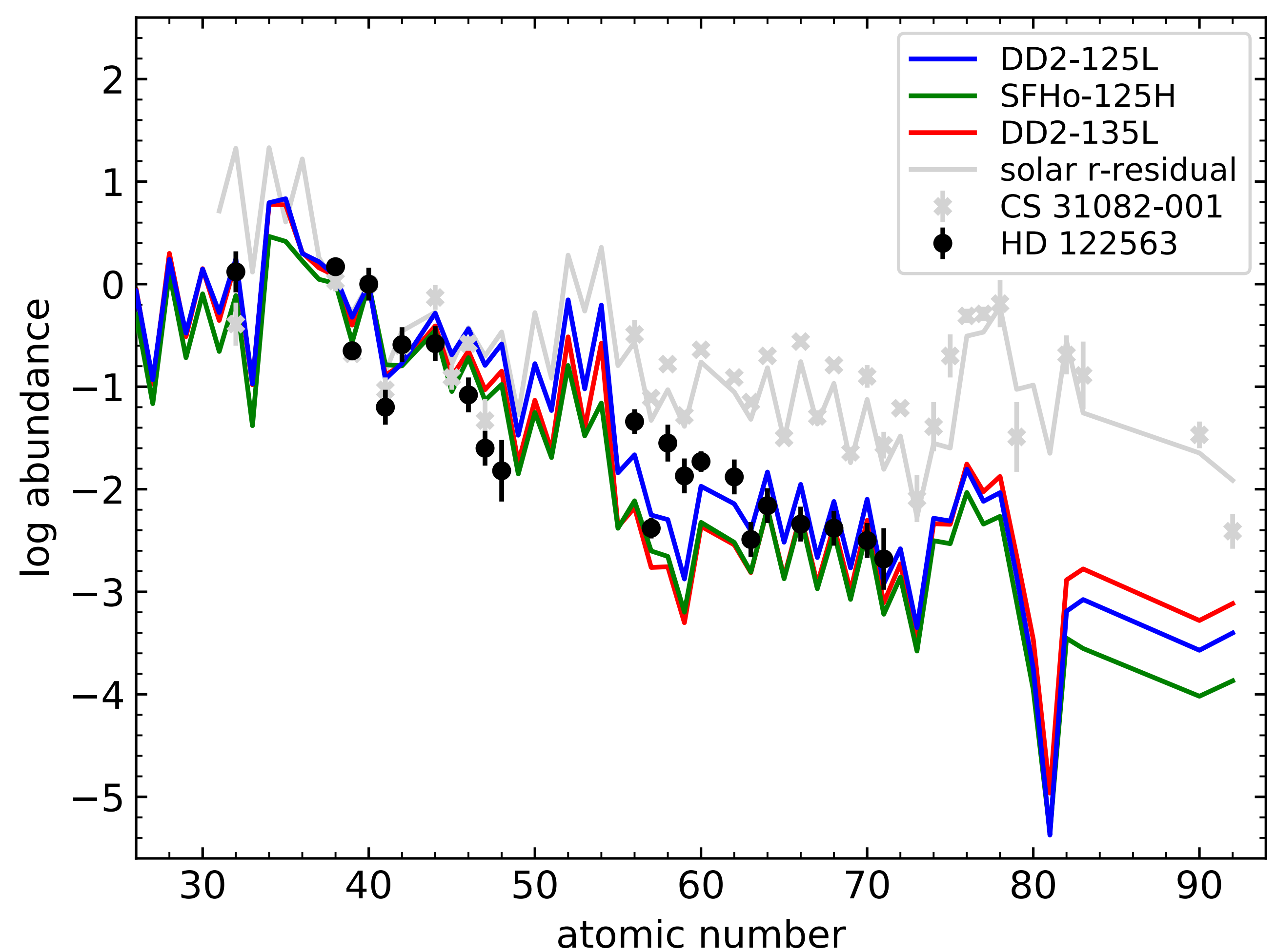
At the freeze-out, neutrino
irradiation additionally enhances Ye.

Nucleosynthesis results



The results are similar.
The post-merger ejecta contributes up to 2nd peak nuclei.

Conflicts with the robust elemental pattern observed in the r-process-enhanced star.

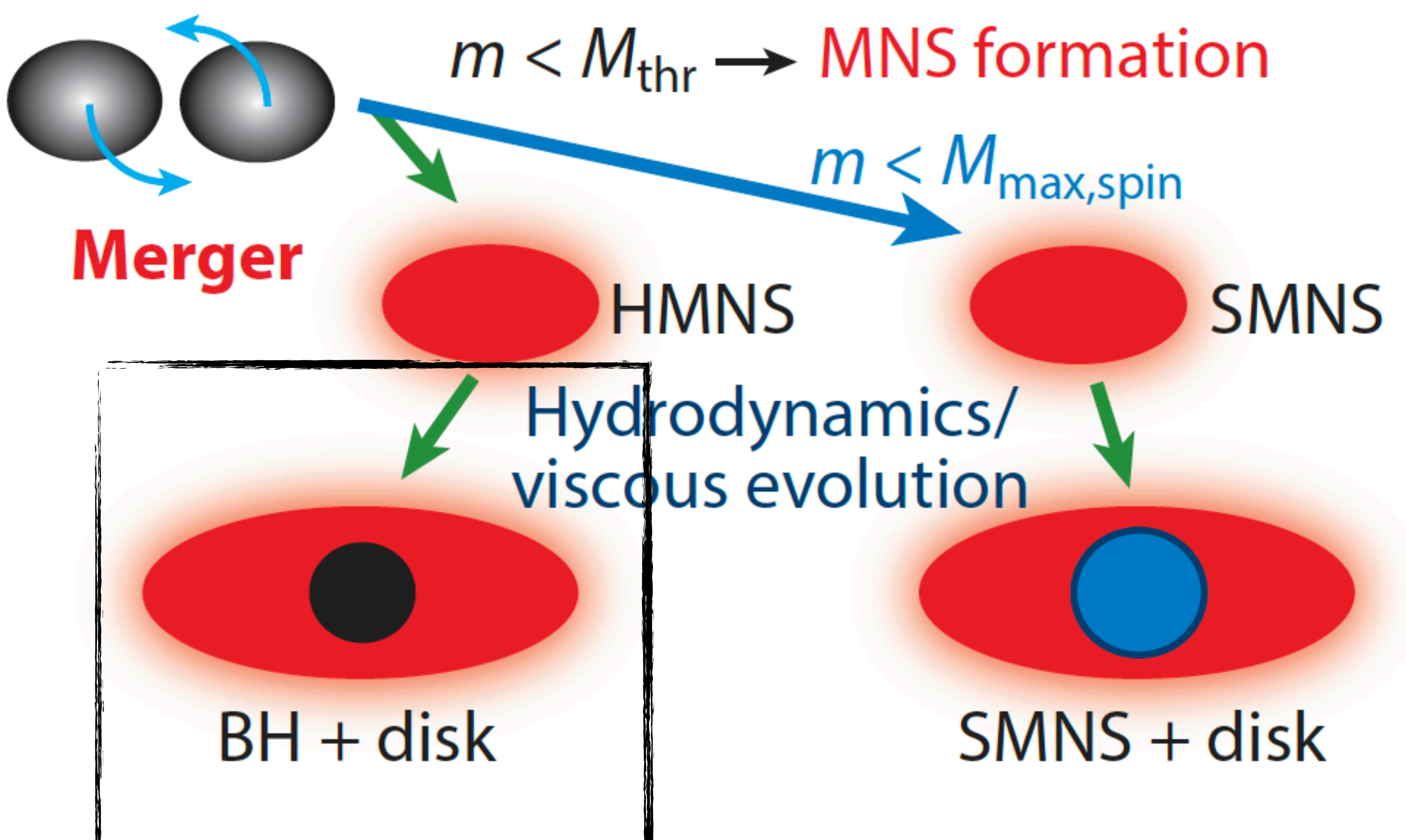


Such low-mass NS-NS merger events should be rare.

Agrees rather with the pattern of "weak" r-process star

Viscous hydrodynamics case

2. Mass ejection from BH-disk system



Set up

SF et al. 20

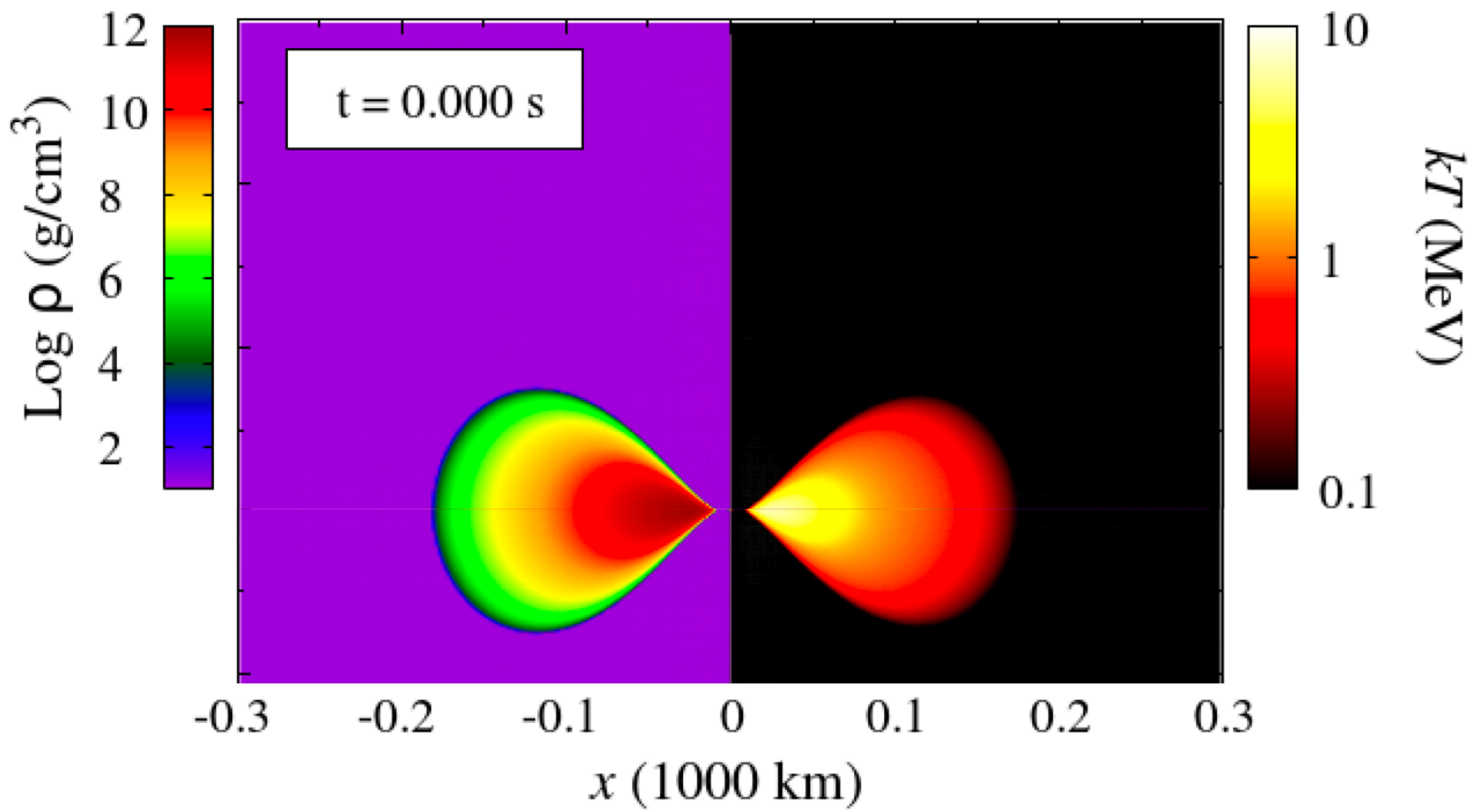
Initial condition: equilibrium disk configuration surrounding a BH

BH: 3 $M_\odot$, χ = 0.8

Disk mass: 0.1 $M_\odot$

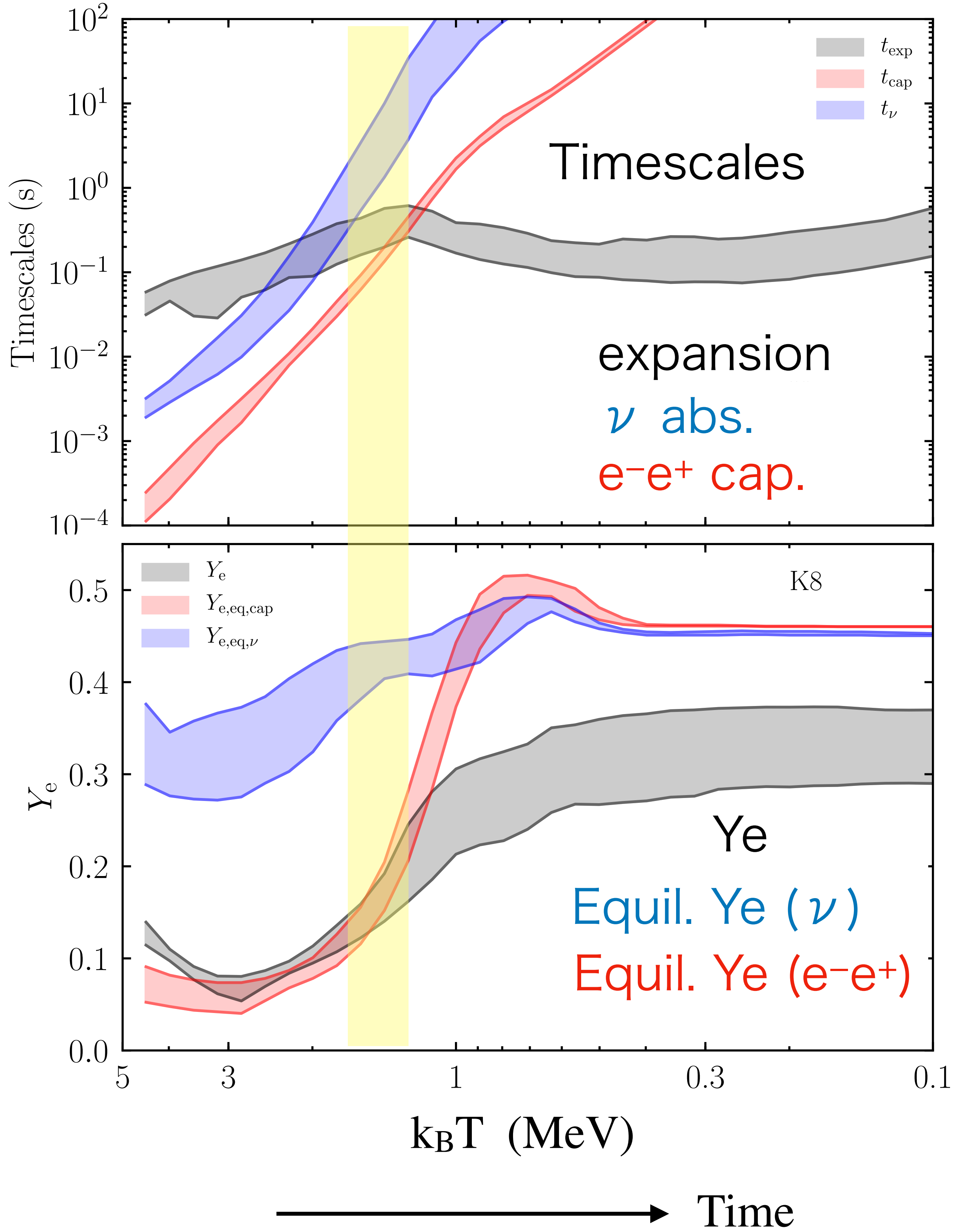
Viscous parameter: α = 0.05 - 0.15 $\nu = \alpha \cdot c_s H_{\rm tur}$

with $H_{\rm tur} = 2M_{\rm BH} \approx 9$ km (Const.)



Physics which determines Ye of BH-disk ejecta

SF et al. 20, Just et al. 21



$M_{BH} = 3M_\odot$, $M_{disk} = 0.1M_\odot$

α=0.05 model

Ye is determined in the same manner as NS-disk

Until the freeze out, the e⁻e⁺ capture predominantly determines the Ye.

Neutrino irradiation does not play significant role.

MHD models

Effects of Magnetic Field

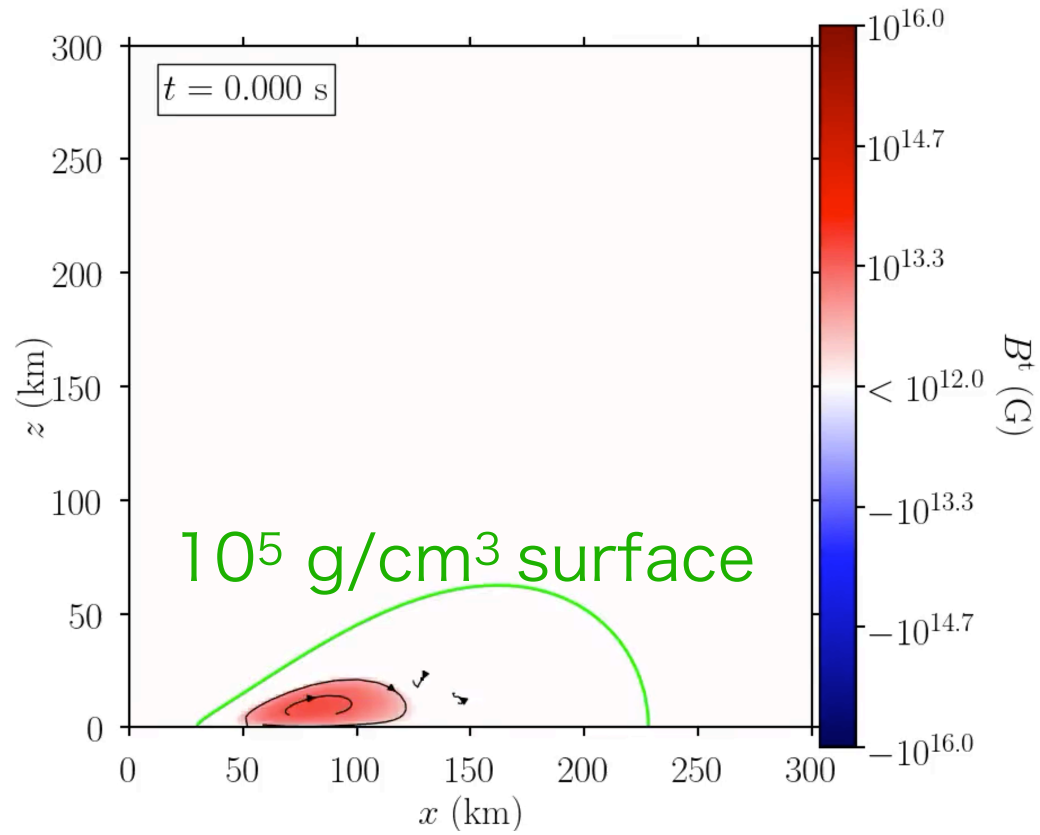
- Shown are the results of viscous-hydrodynamics.
- Strong large-scale magnetic field could modify the ejecta dynamics

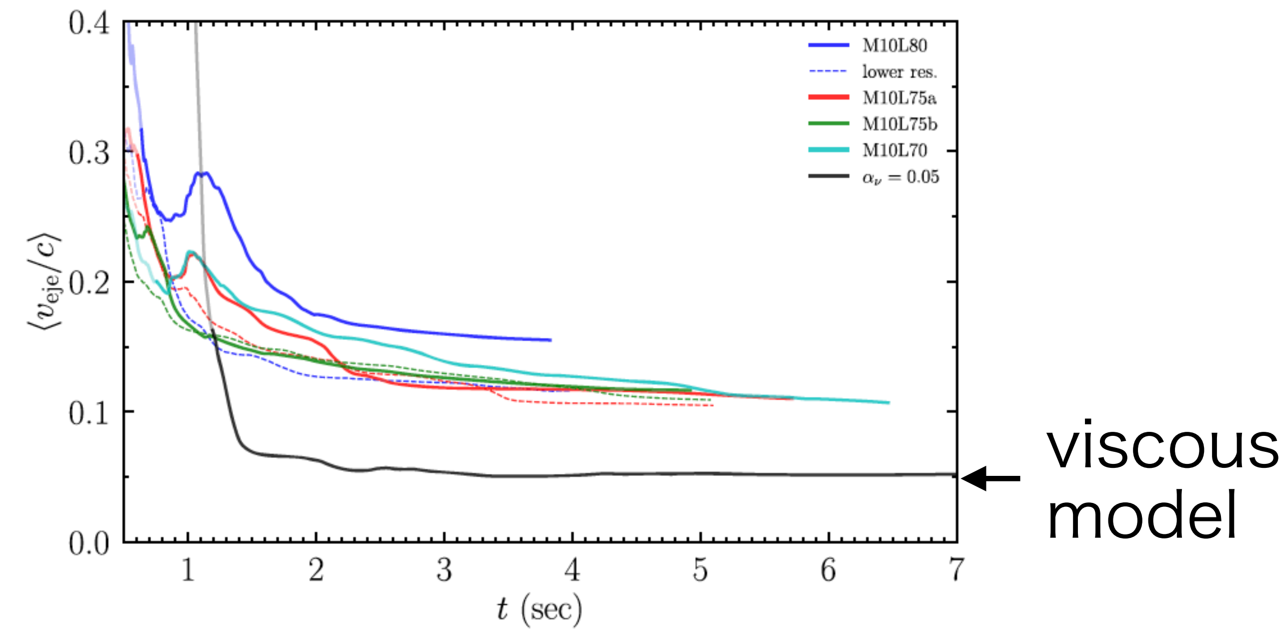
1. Lorentz force could drive the ejecta in shorter timescale
   Faster freeze out → lower Ye

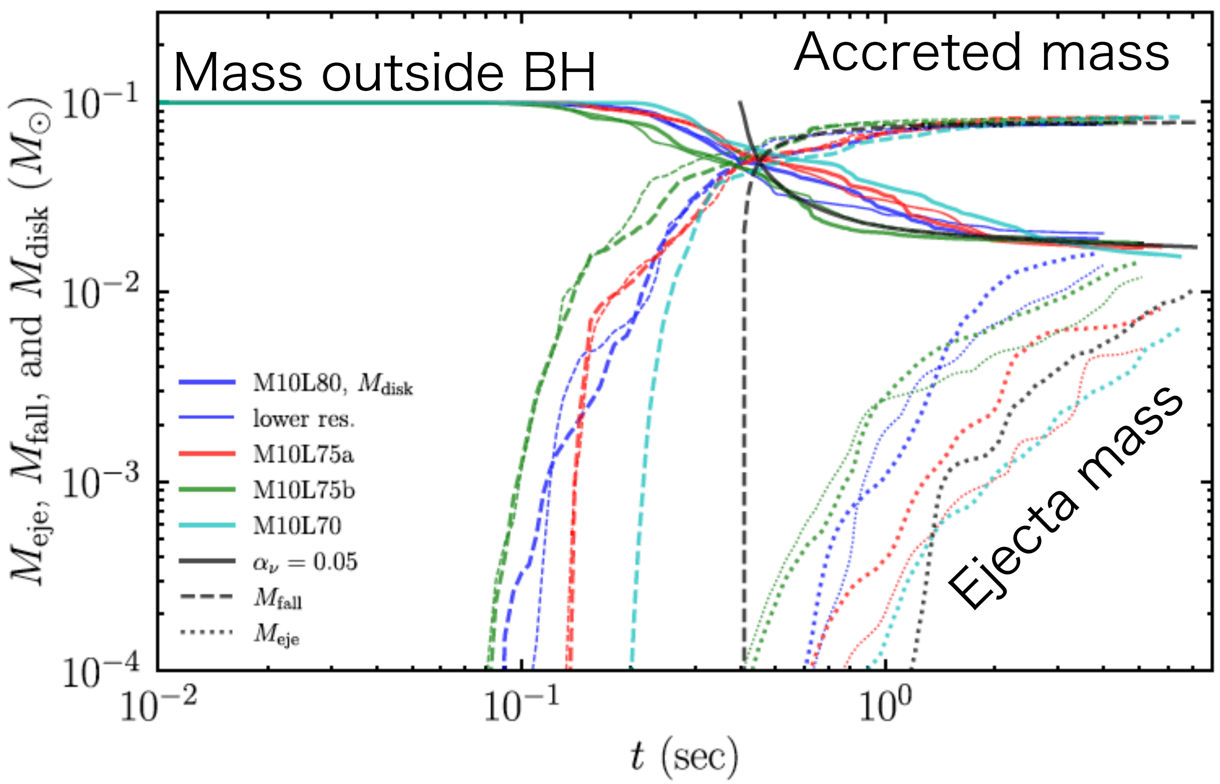
2. If the remnant NS develops strong B-filed, the ejecta would be strongly affected by the B-field.

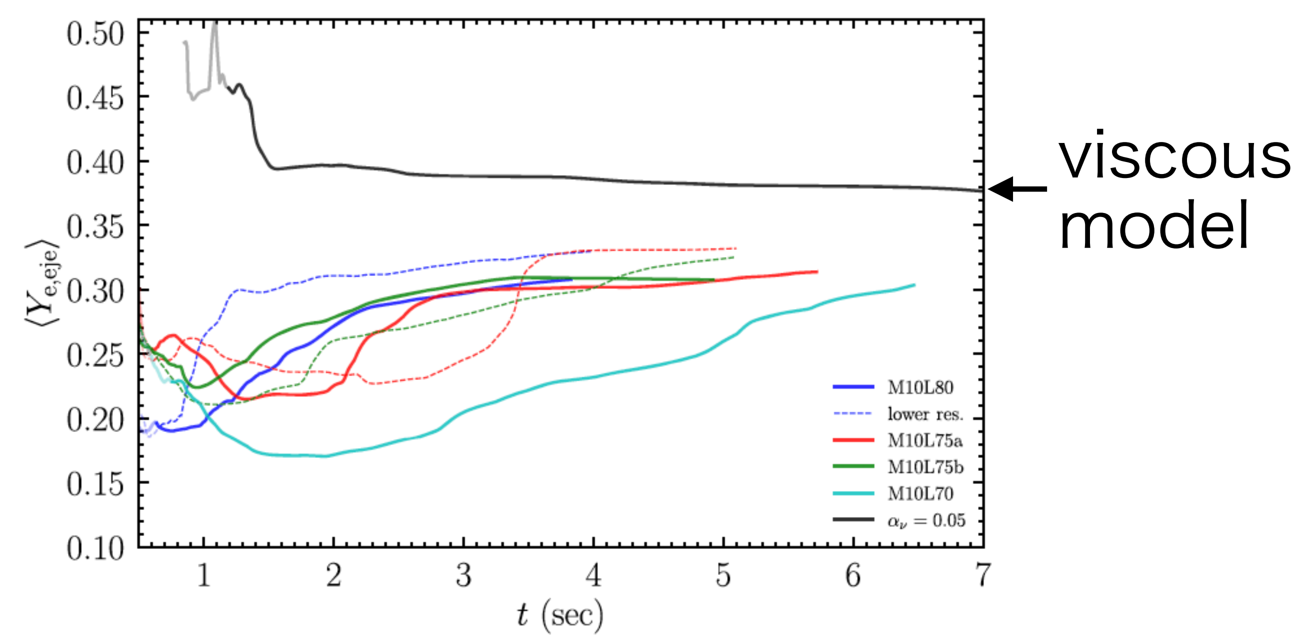
RMHD simulation with effective dynamo term for **BH-disk**

Shibata, SF, and Sekiguchi, accepted





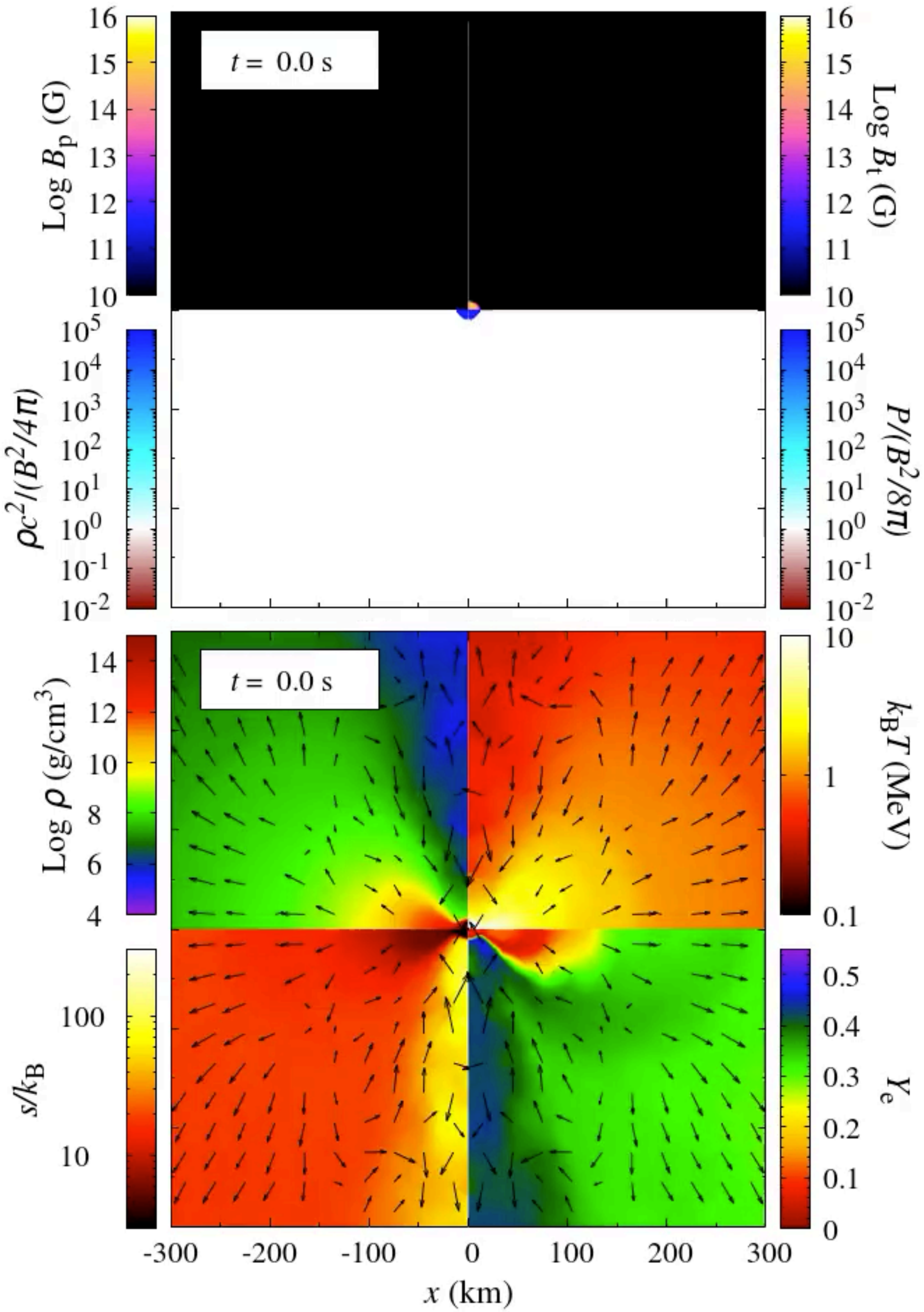


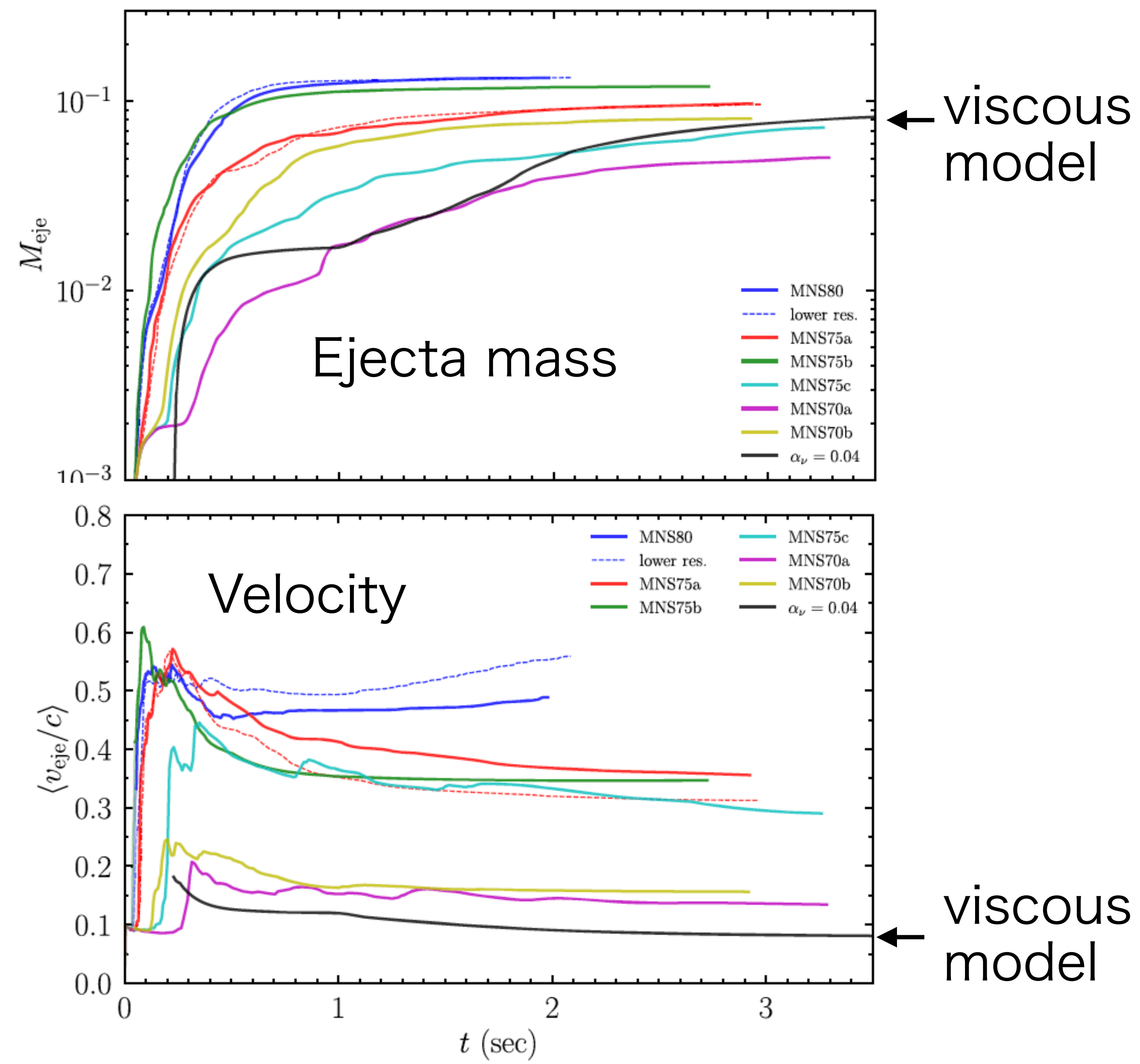


(Roughly speaking) consistent with viscous hydrodynamics case.

RMHD with dynamo simulation for merger remnant (**MBH-disk**)

Shibata, SF, and Sekiguchi, accepted





(Depending on the parameters)
Mass ejection is more violent than in viscous hydro model.
Imprints of long-lived MNS would be in Kilonova and radio emission.

Kawaguchi+ in prep.

Summary

- Viscous hydrodynamics simulations have been performed
  - (Irrespective of NS-disk/BH-disk) Ejecta Ye is determined predominantly by the freeze-out value of $e^- e^+$capture equilibrium.
  - Ye ~ 0.3 → Light r-process nuclei are main products

- MHD simulations (with effective dynamo term)
  - If the neutron star survives for a long time,
    MHD effect would drive a strong outflow.
    It can be a bright radio counterpart.