連星中性子星合体後の系からの質量放出

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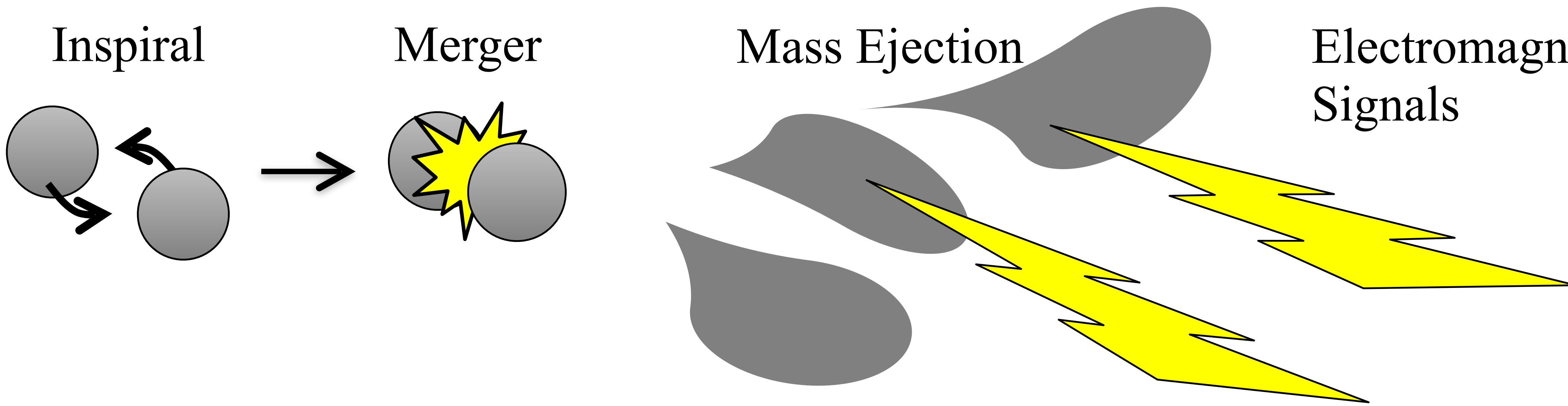
SF et al. 17 (arXiv:1711.02093)

～中性子星の観測と理論～ 研究活性化ワークショップ 2017, 国立天文台, 17.11.23

Introduction

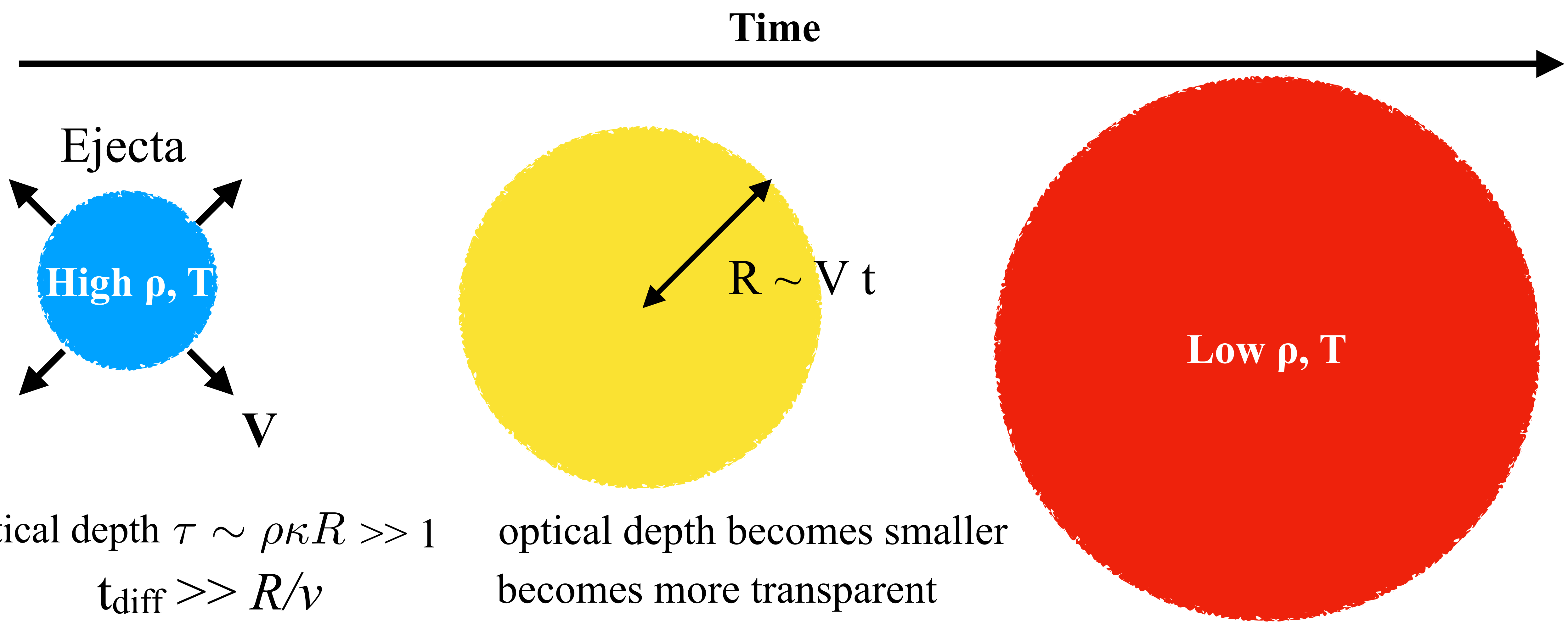
Kilonova/Macronova



- Two NSs approach due to GW emission → Merger
- A part of the NS matter is ejected by several processes
- Unstable nuclei are synthesized via *r*−process
- Radioactive decay (and fission) heats up the ejecta
  → Thermal emission (Kilonova/Macronova)

Simple Model for Kilonova

Li & Paczynski 98, Metzger et al. 10, …



optical depth $\tau \sim \rho\kappa R >> 1$

$t_{\rm diff} >> R/v$

Photons leak-out very slowly

~ Adiabatic expansion

optical depth becomes smaller

becomes more transparent

peak of the photon emission :

$$t_{\rm diff} \sim R/v$$

Kilonova/Macronova Model

○ <u>Mass</u>, <u>velocity</u>, and **<u>opacity</u>** of the ejecta are key quantities **Li & Paczynski 98, Metzger 08**

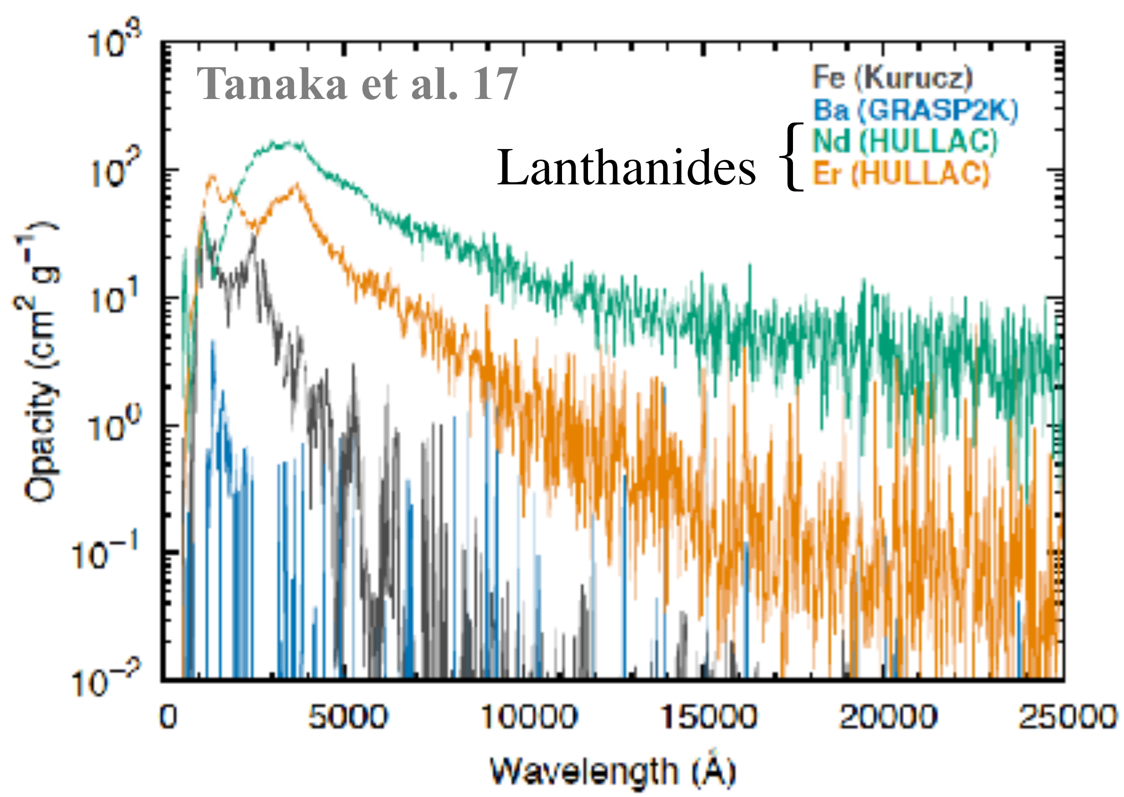
$$t_{\rm peak} \sim 10\,{\rm days} \left(\frac{v}{0.3c}\right)^{-1/2} \left(\frac{M}{0.01M_{\rm solar}}\right)^{1/2} \left(\frac{\kappa}{10\,{\rm cm}^2/g}\right)^{1/2}$$

$$L_{\rm peak} \sim 10^{41}\,{\rm erg/s} \left(\frac{f}{10^{-6}}\right)\left(\frac{v}{0.3c}\right)^{1/2} \left(\frac{M}{0.01M_{\rm solar}}\right)^{1/2} \left(\frac{\kappa}{10\,{\rm cm}^2/g}\right)^{-1/2}$$

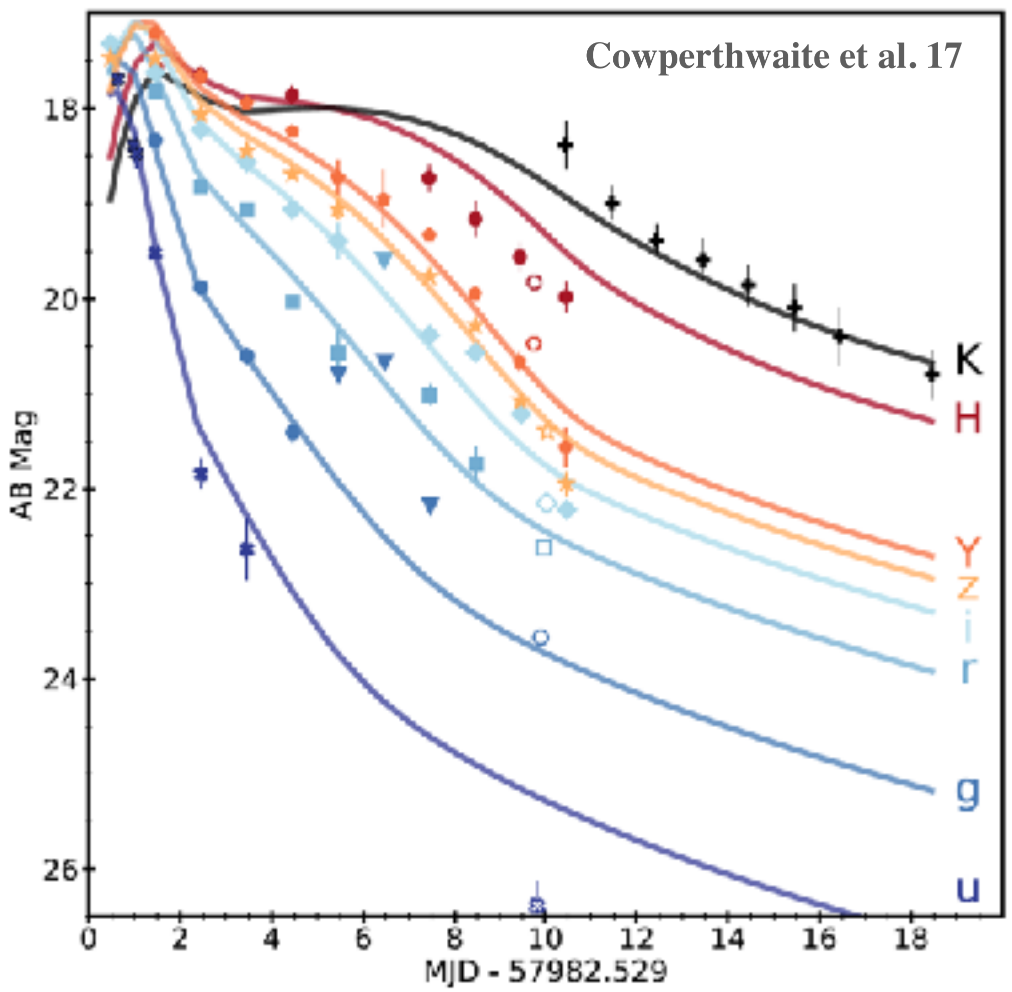
$$T^{\rm eff}_{\rm peak} \sim 2\times10^{3}\,{\rm K} \left(\frac{f}{10^{-6}}\right)^{1/4}\left(\frac{v}{0.3c}\right)^{-1/8} \left(\frac{M}{0.01M_{\rm solar}}\right)^{-1/8} \left(\frac{\kappa}{10\,{\rm cm}^2/g}\right)^{-3/8}$$

○ Lanthanides have significantly high opacity **Kasen et al. 13, Tanaka & Hotokezaka 13** (Z=57-71)

- In Lanthanide-rich ejecta, $\kappa \sim 10\ {\rm cm}^2/{\rm g}$



Electromagnetic Signal Associated with GW170817



○ **Optical - NIR light curve**

- Consistent with Kilonova/Macronova model.

- Many work suggest

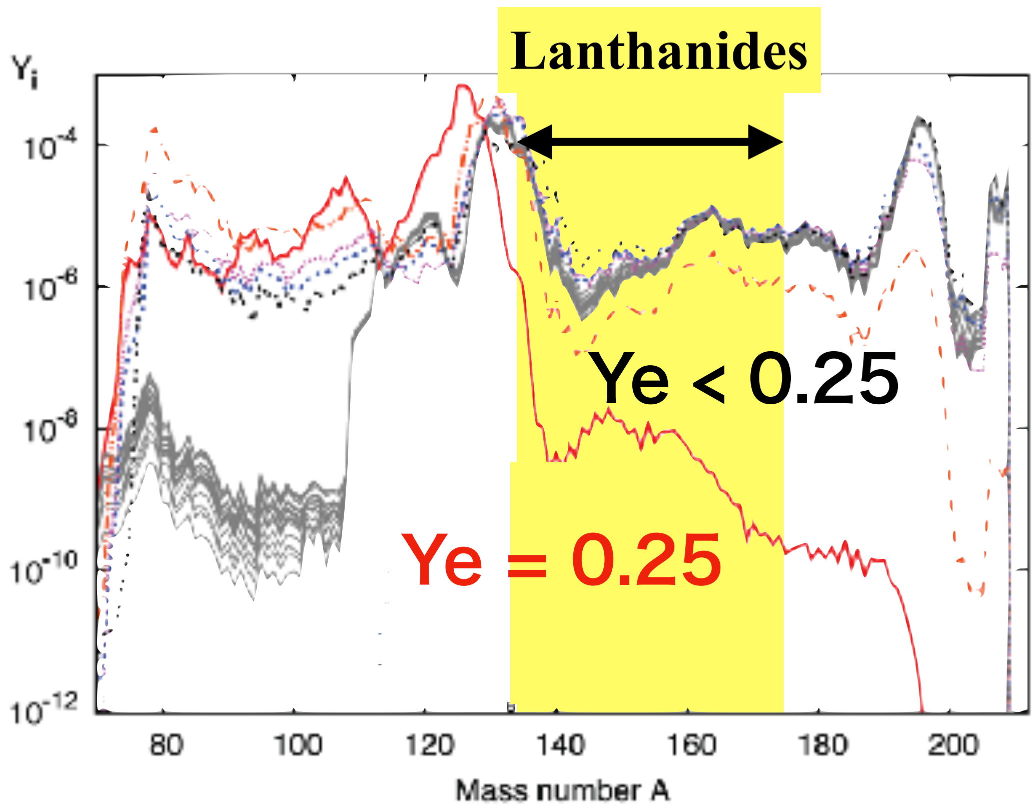
"red" component of Mej ~ 0.02-0.04 Msun (v ~ 0.1 c)
(Lanthanide-rich , κ ~ 10 cm^2/g)

"blue" component of Mej ~ 0.01 Msun (v ~ 0.2-0.3 c)
(Lanthanide-poor , κ ~ 0.1−1 cm^2/g)

Villar et al. 17, Kasen et al. 17, Nicholl et al. 17, Chornock et al. 17, …

Can we derive such values from latest simulation for NS−NS merger ?

Lanthanide Fraction in the Ejecta



Korobkin et al. 12 (For dynamical ejecta)

○ **Key quantity for Lanthanide production**

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

Ye < 0.5 ↔ proton # < neutron #

Ye > 0.25
➔ Lanthanides are not synthesized efficiently.

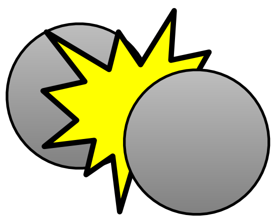
◎ **Relevant reactions :**

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

Initially low Ye can becomes large due to

1) Neutrino irradiation
2) High temperature (positron capture sets in)

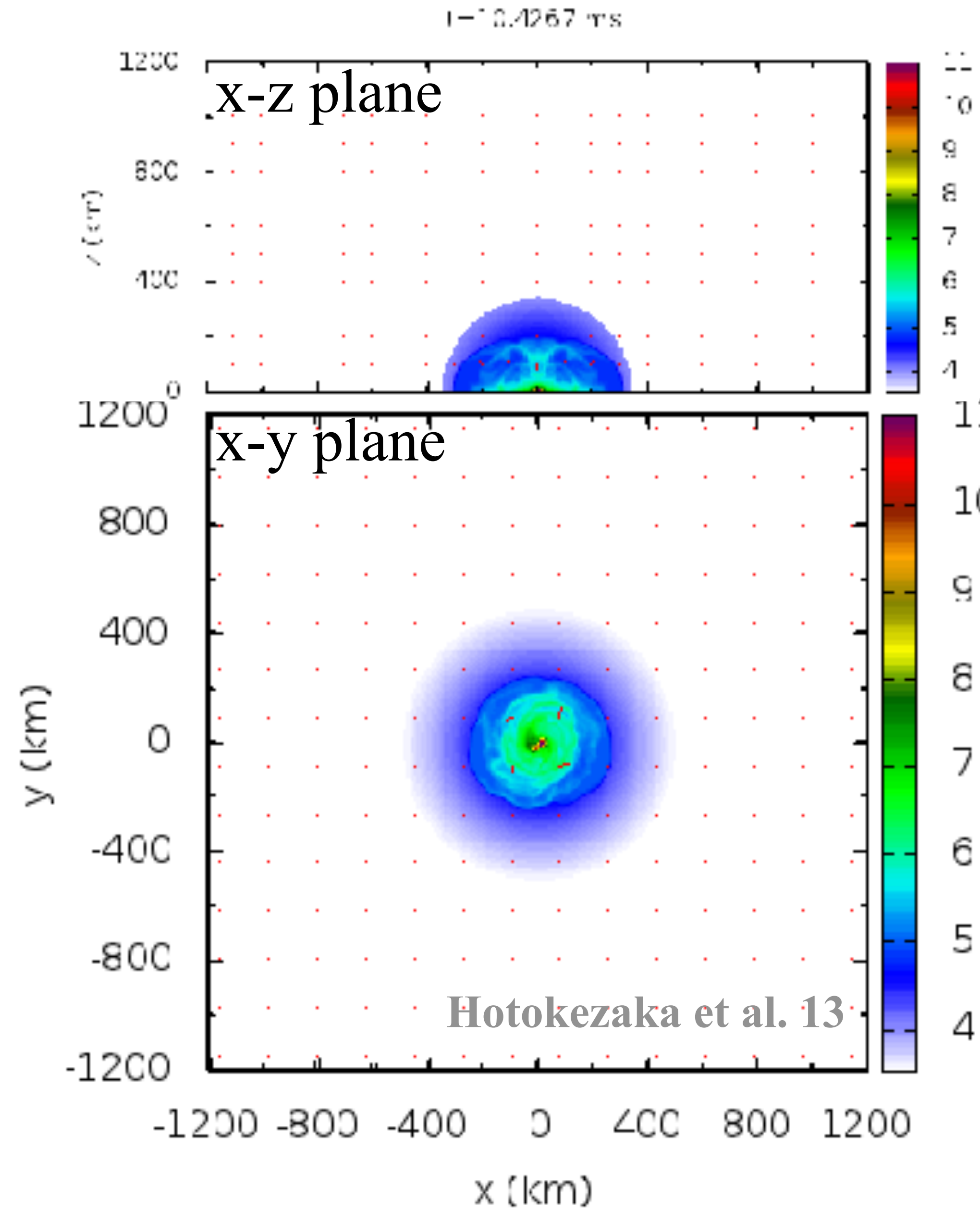
Dynamical Mass Ejection



Merger

Dynamical ejection

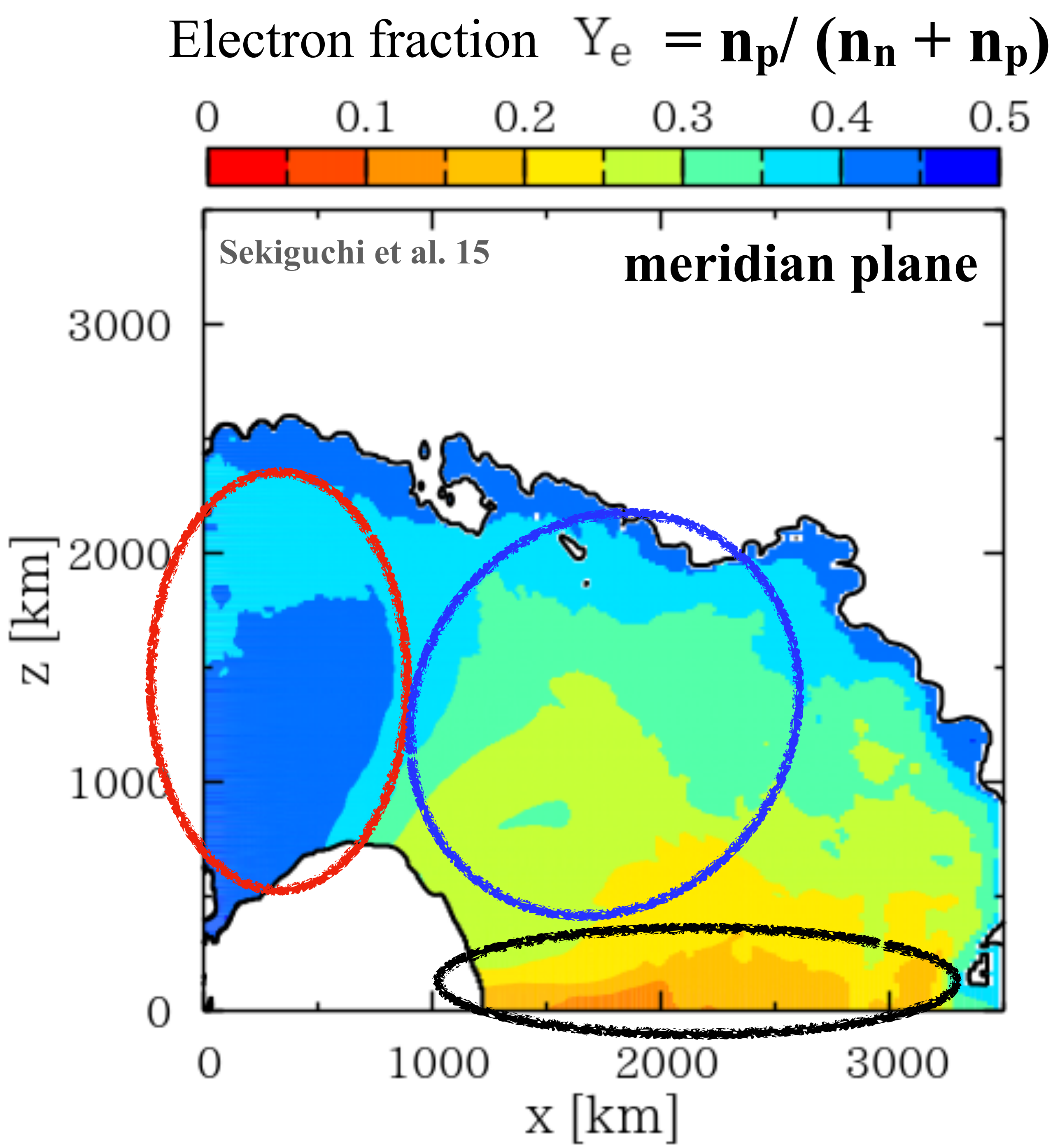
- Due to tidal force and shock heating
- Well studied (mass, EOS dependence)



0 ~ 1 ms ~ 10 ms ~ 100 ms ~ 1 s ~ 10 s

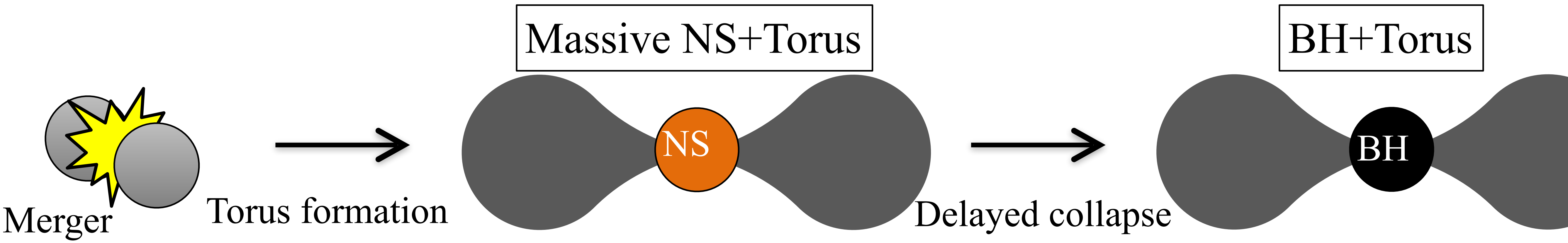
Time after merger

Morphology of Dynamical Ejecta



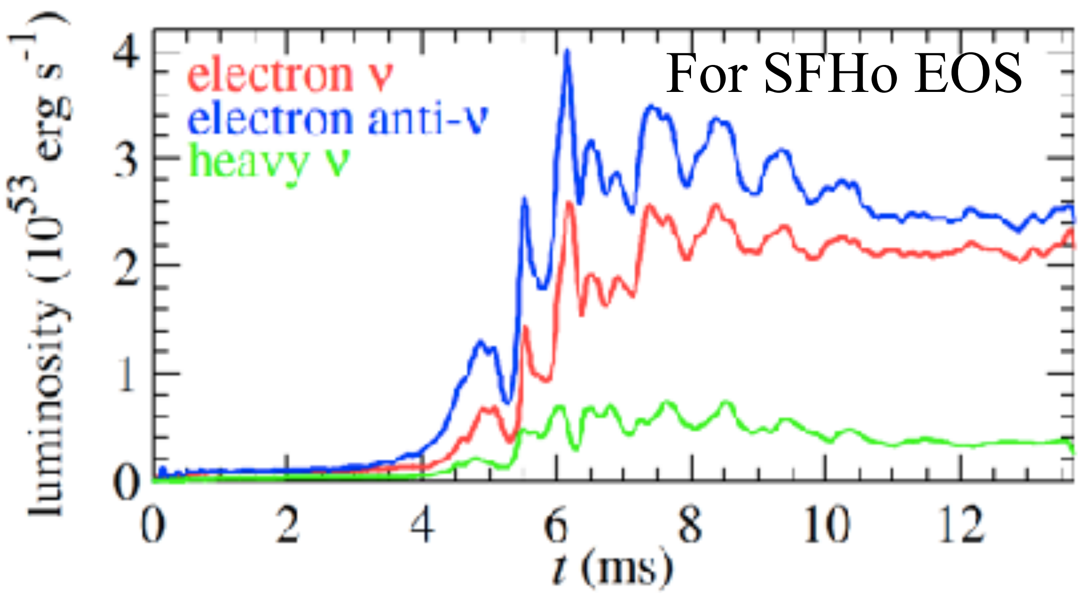
- $M_{ej} \sim 0.001\text{-}0.02\ M_{sun}$
  - depends on EOS & mass ratio
- Nearly isotropic
- Tidally driven ejecta
  - Ye < 0.2
- Thermal driven ejecta
  - Ye = 0.2−0.4 (due to positron capture)
- Neutrino irradiated ejecta
  - Ye > 0.4 (due to ν-absorption)

Evolution of the Typical Merger Remnant

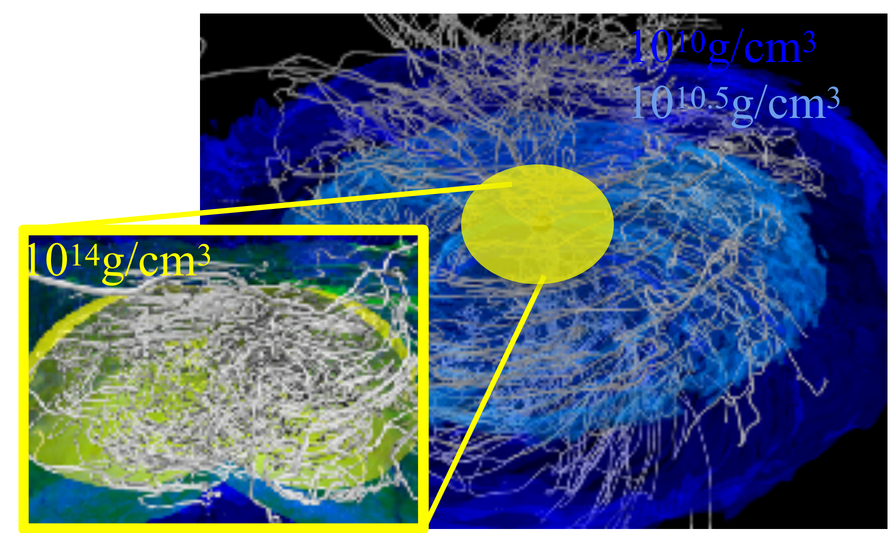


$t_{collapse}$ depends on M_{tot} & EOS

Neutrino emission Sekiguchi et al. 15



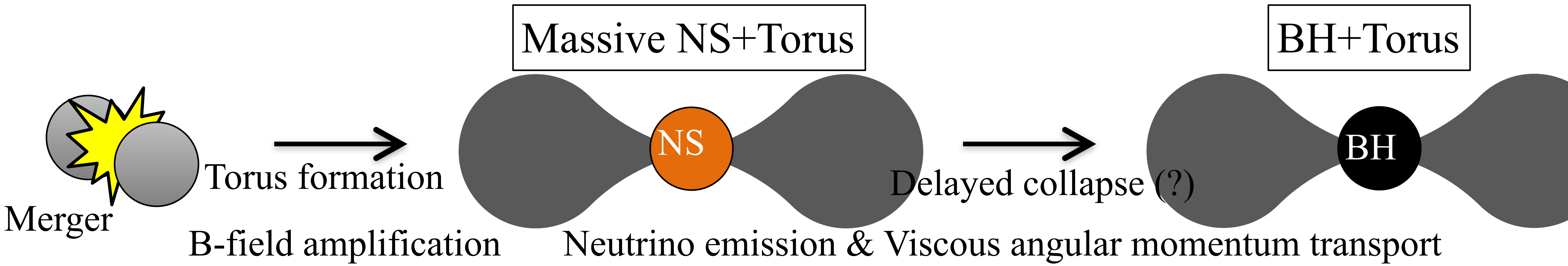
B-field amplification Kiuchi et al. 14, 15



0 ~ 1 ms ~ 10 ms ~ 100 ms ~ 1 s ~ 10 s

Time after merger

Post-merger Mass Ejection



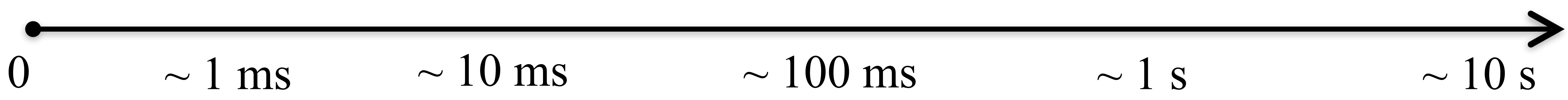
Viscosity & Neutrino-driven ejection

Heating by neutrinos and viscosity

The ejecta mass can exceed (significantly!) the dynamical ejecta

Currently extensively studied

Fernandez & Metzger 13, Metzger & Fernandez 14, Perego et al. 14
Siegel et al. 17, Lippuner et al. 17, SF et al. 17



Time after merger

Our Research

To connect the ejecta properties and the physics of the merger, it is needed to construct reliable physical model of the binary NS merger remnant and mass ejection from it

- ○ Ejecta properties (mass, Ye, velocity)
- ○ Morphology

We perform long-term (> second) simulations for NS-NS merger remnant including relevant physics:

- General relativity
- Neutrinos
- Viscous angular momentum transport

Previous Works

	Gravigy	Initial condition	NS	Neutrino	Hydrodynamics
Metzger & Fernandez 14 Lippuner et al. 17,	Pseudo-Newtonian	J=Const. equiv. torus	Reflection boundary	Leakage + light bulb	Viscous fluid
Perego et al. 14, …	Newtonian	Based on Newtonian simulation	Not resolved	Leakage + absorption	Ideal fluid
SF et al. 17 (Our work)	**Full GR**	**Based on Full GR simulation**	**Resolved**	**Leakage + M1-scheme**	**Ideal fluid**

Method

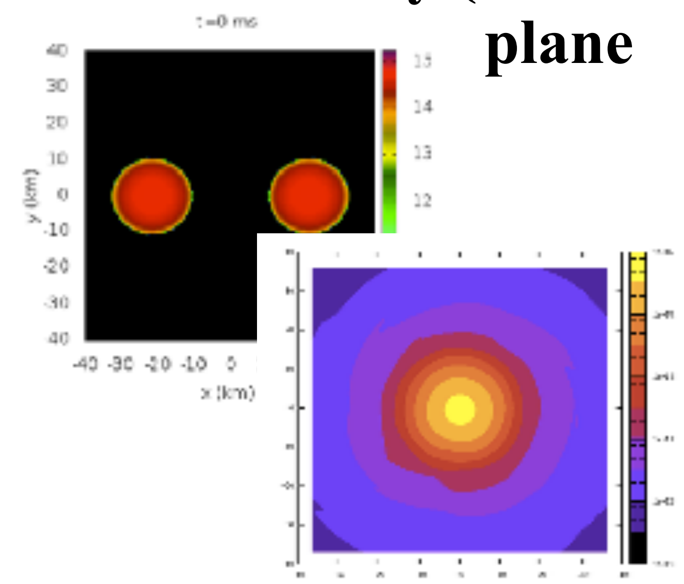
Method

◎ Strategy

i) Merger of NS−NS and massive NS formation by 3-D full GR simulation

Sekiguchi et al. 15

x-y (rotational) plane



Equation of state : DD2

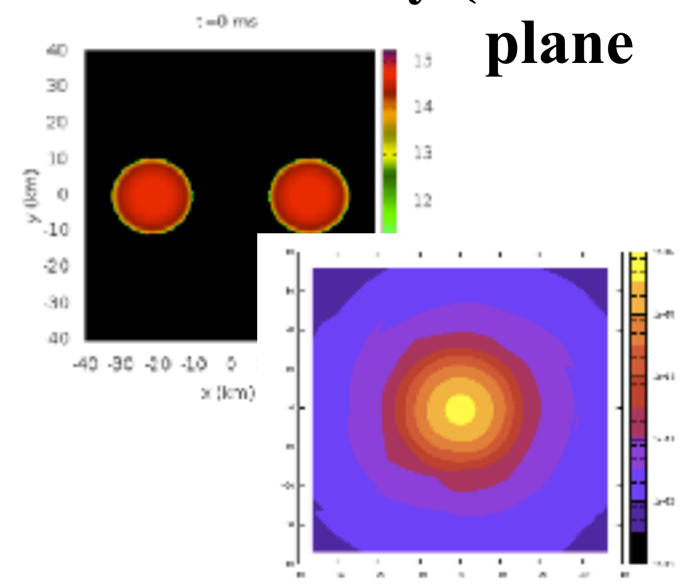
(→ The remnant is long-lived massive NS)

Method

◎ Strategy

i) Merger of NS−NS and massive NS formation by 3-D full GR simulation

x-y (rotational) plane

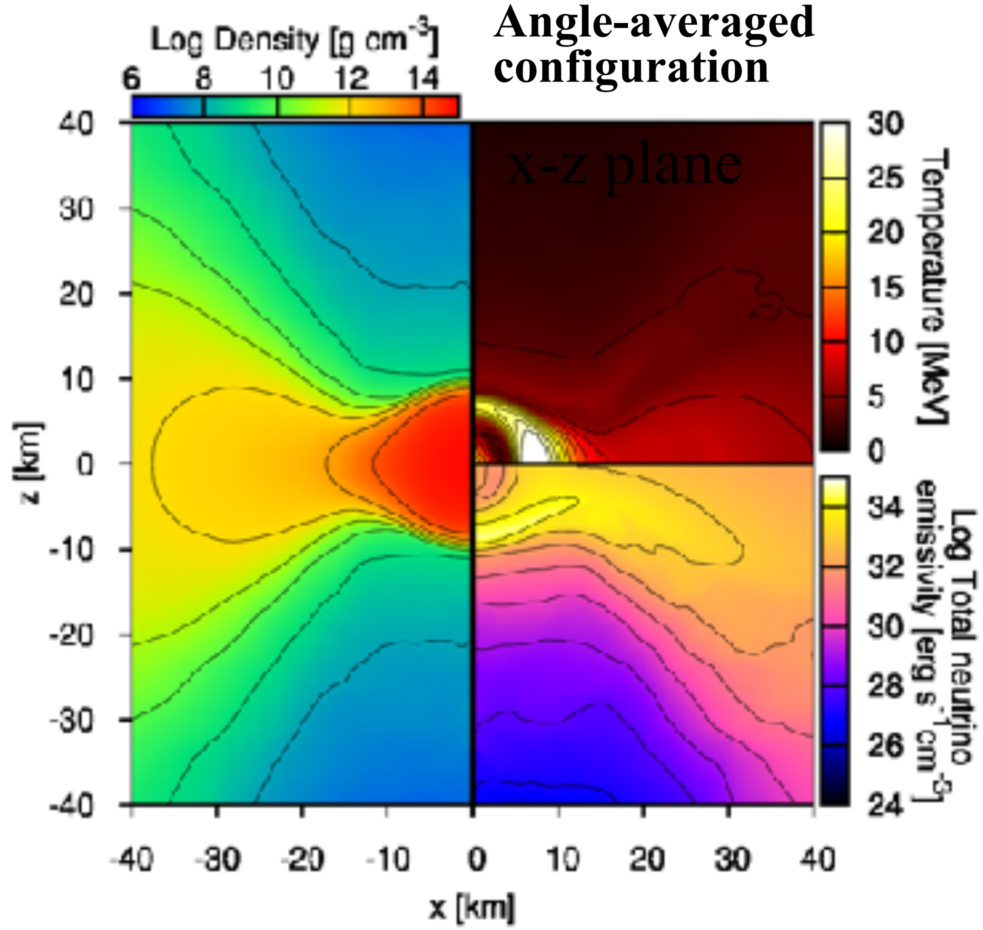


Sekiguchi et al. 15

Equation of state : DD2
(→ The remnant is long-lived massive NS)

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

Angle-averaged configuration



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

Method

◎ **Basic Equations**

- Full GR neutrino radiation viscous hydrodynamics

• Einstein's equation

• Neutrino radiation transfer equation

Leakage+ scheme incorporating Moment formalism **Thorne 81, Shibata et al. 11**

• Viscous hydrodynamics equation

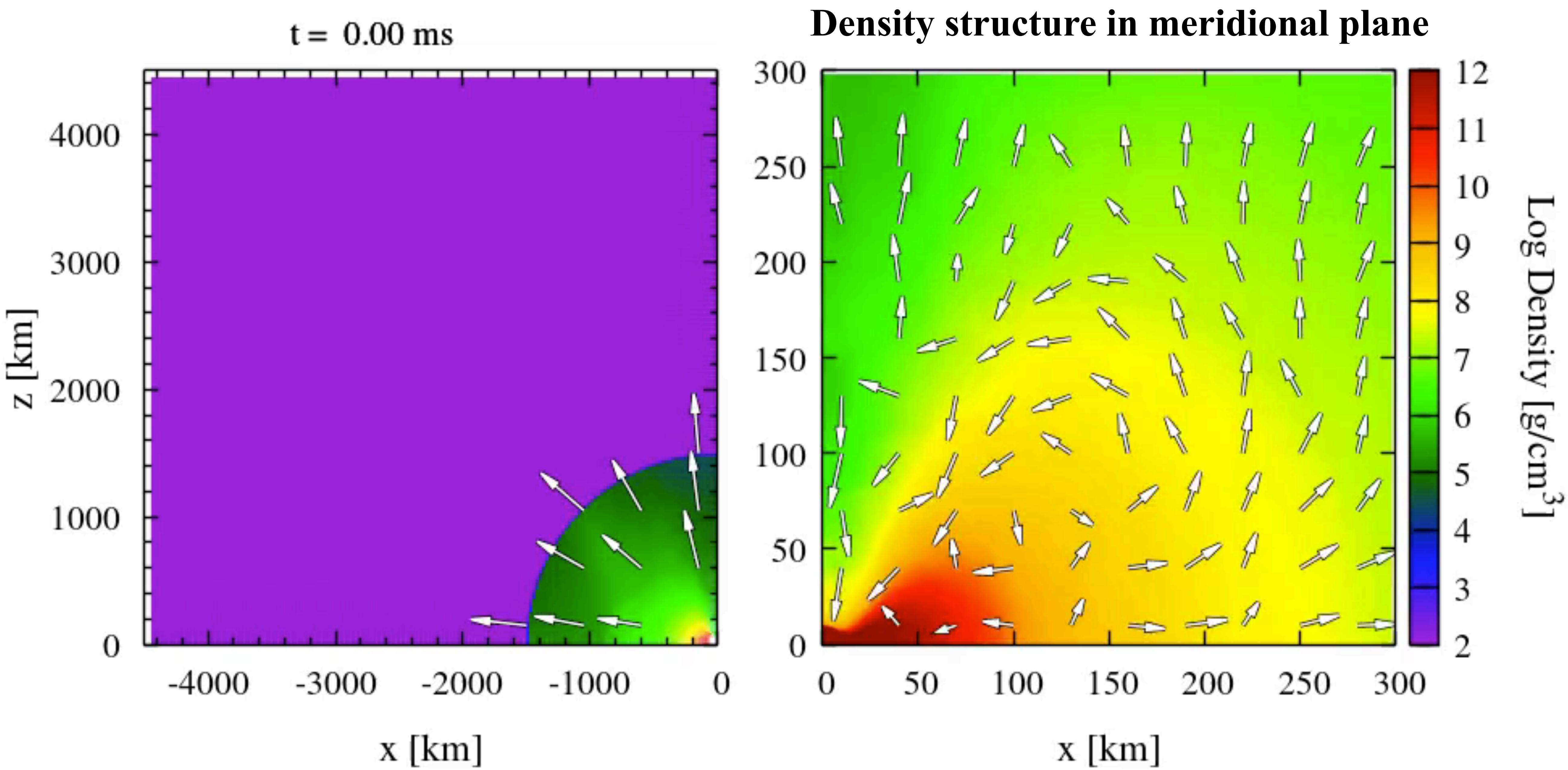
In order to mimic the effective viscosity due to MHD turbulence,
We solve viscous hydrodynamics equation. **Israel & Stuart 79,**
The code was developed by Sekiguchi-san. **Shibata et al. 17, Shibata & Kiuchi 17**

Shakura–Sunyaev "alpha" parametrization : $\nu = \alpha \cdot c_s H_{\rm tur}$

Models : α = 0, 0.01, 0.02, **0.04**

Result

Dynamics for $\alpha = 0.04$ model



Torus :

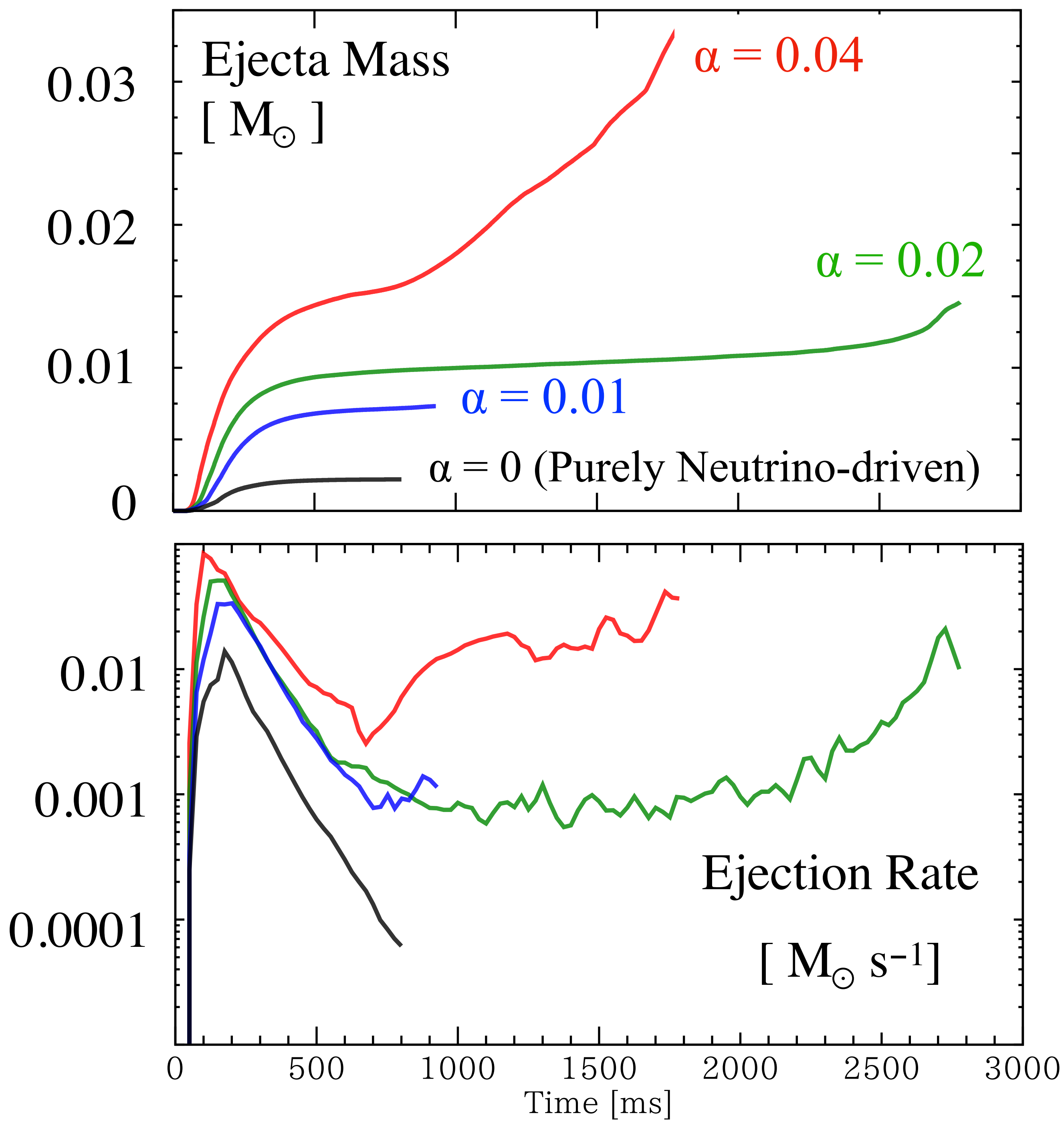
Gradually expands
→ Ejected

Ejecta :

~ 10 ms : ejection by a shock
After that : viscosity-driven ejection

Mass Ejection from Merger Remnant

Mass Ejection



◯ Integral of unbound mass flux at r = 4000 km

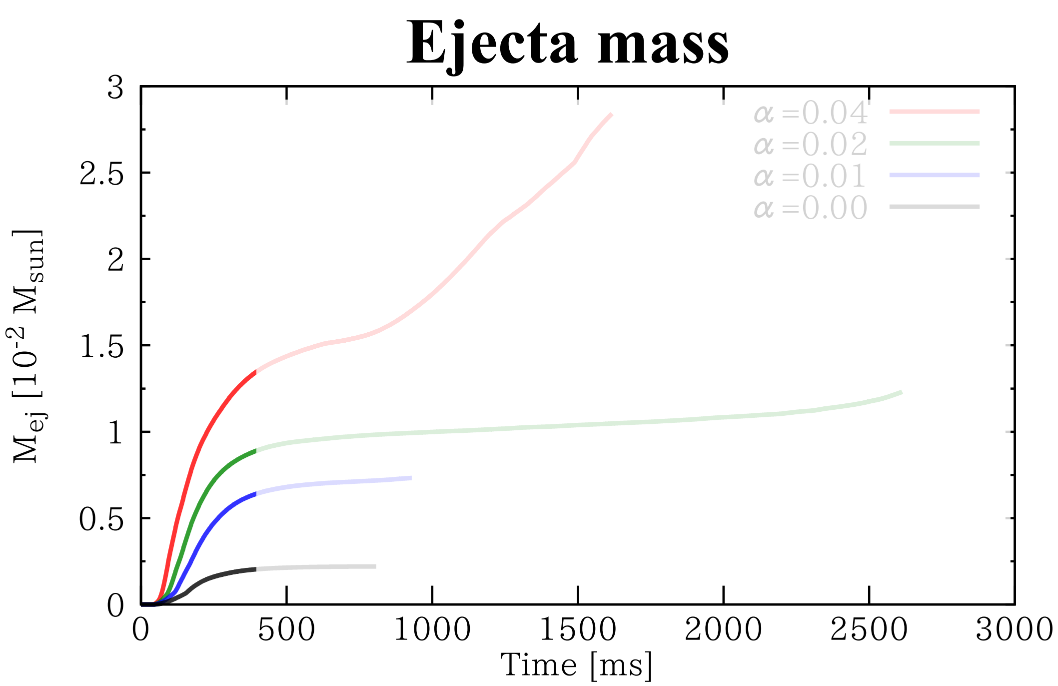
◯ $\alpha = 0.04$

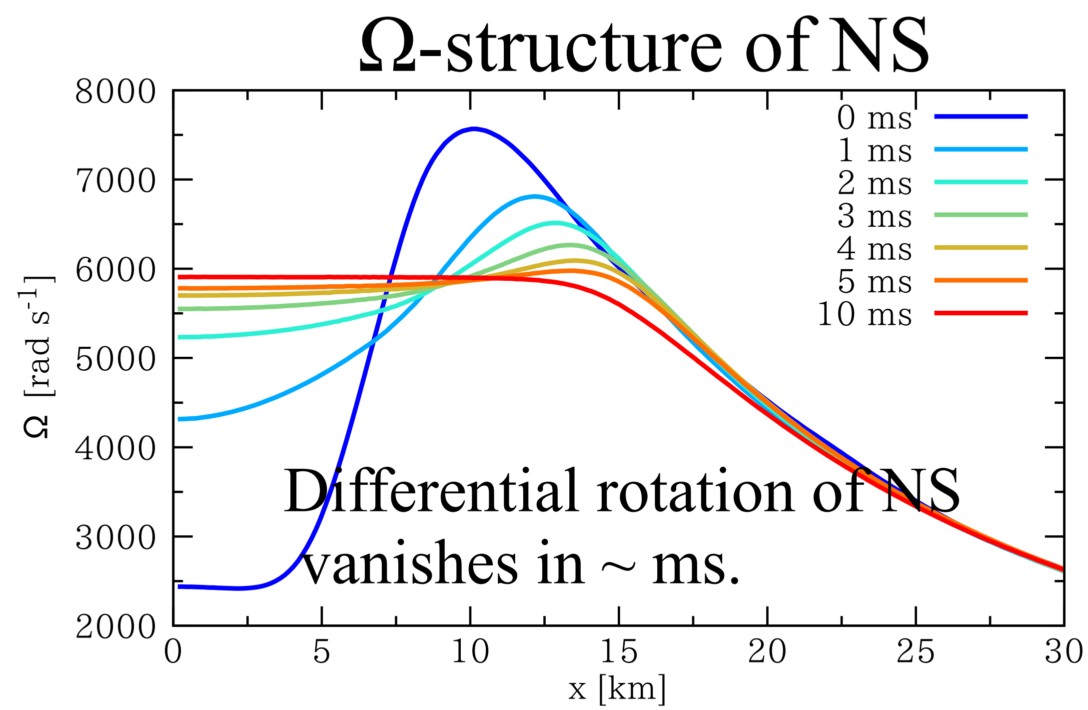
High mass ejection rate
for early phase $t < 400$ ms & late phase $t > 1$ s

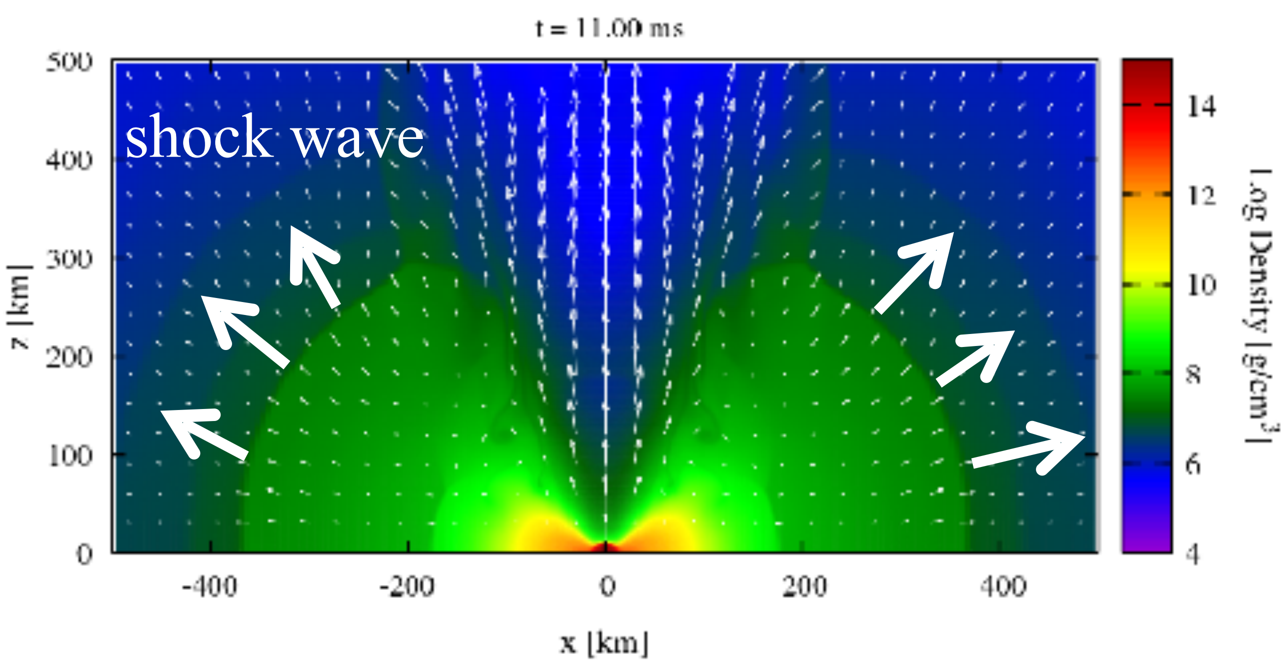
◯ $\alpha = 0.02$

Same feature for t < 400 ms,
but late-time ejection rate increases for $t > 2$ s

Early Viscosity-driven Ejecta







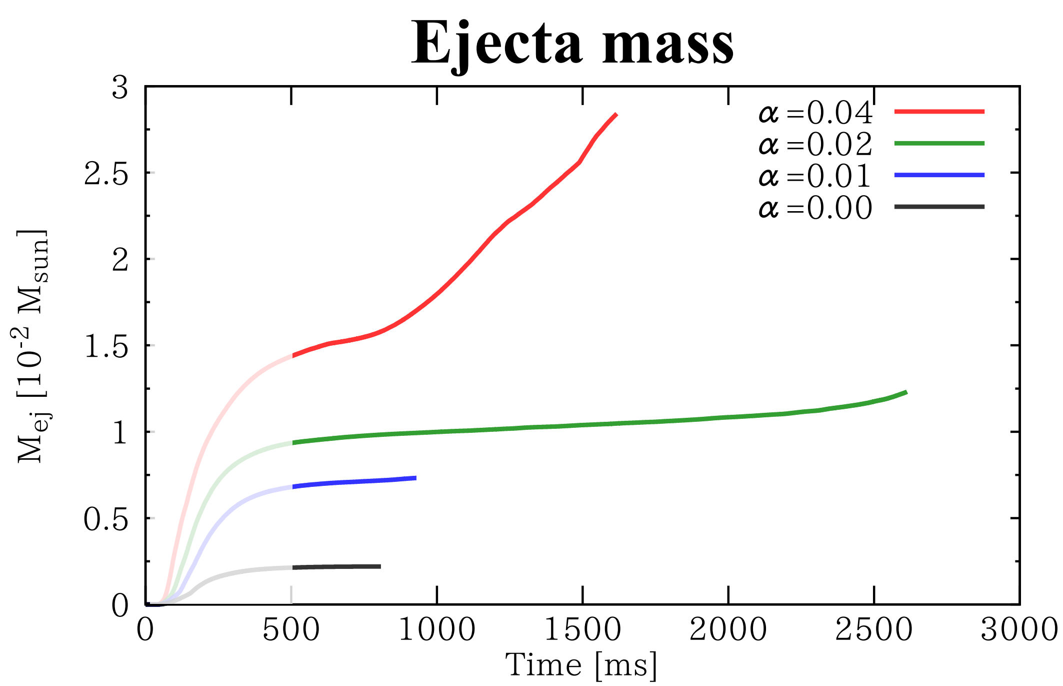
The MNS settles into rigidly rotation state due to viscous angular momentum transport.

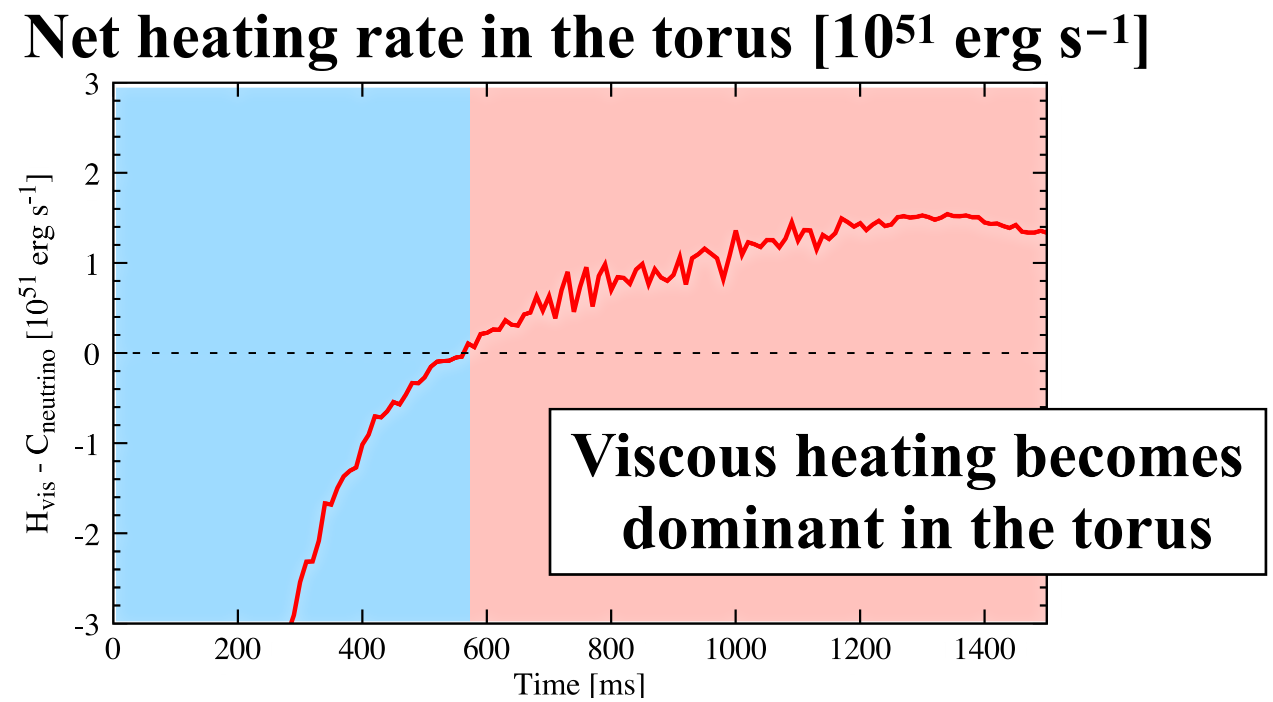
Change of the equilibrium state of NS

→ A sound wave is formed in the vicinity of the NS, and it becomes a shock wave.

→ The torus is swept-up by the shock wave and becomes unbound.

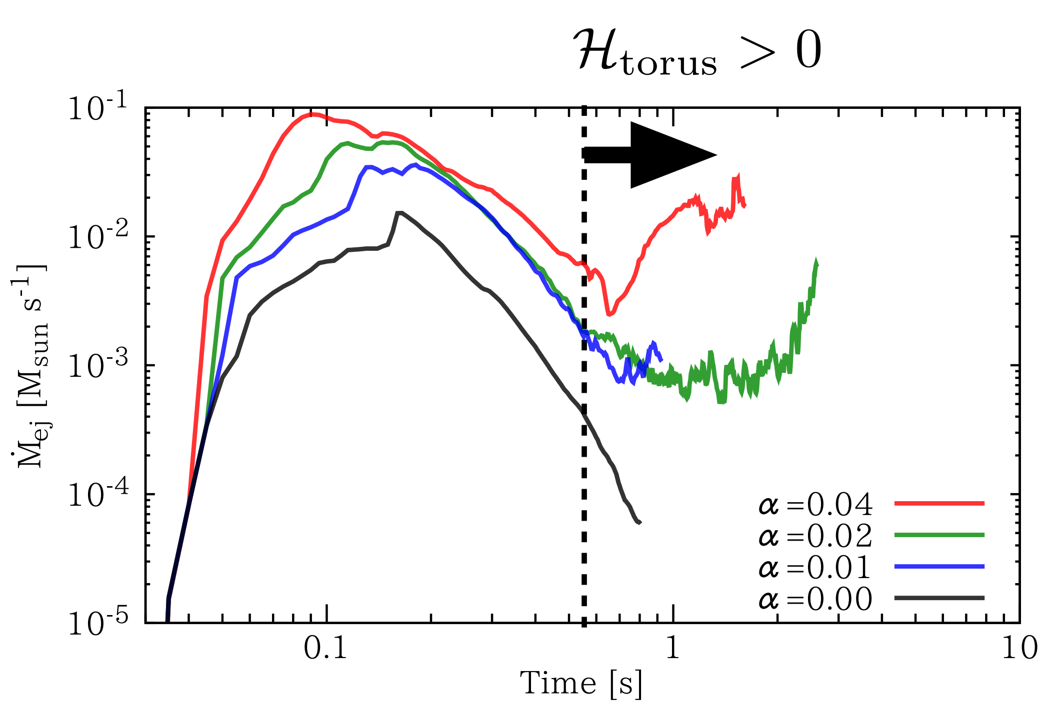
Late-time Ejecta (t > 500 ms)





After t>600 ms, viscous heating becomes dominant in the torus

The torus material is ejected in the viscous timescale in the torus (~ 1 s)



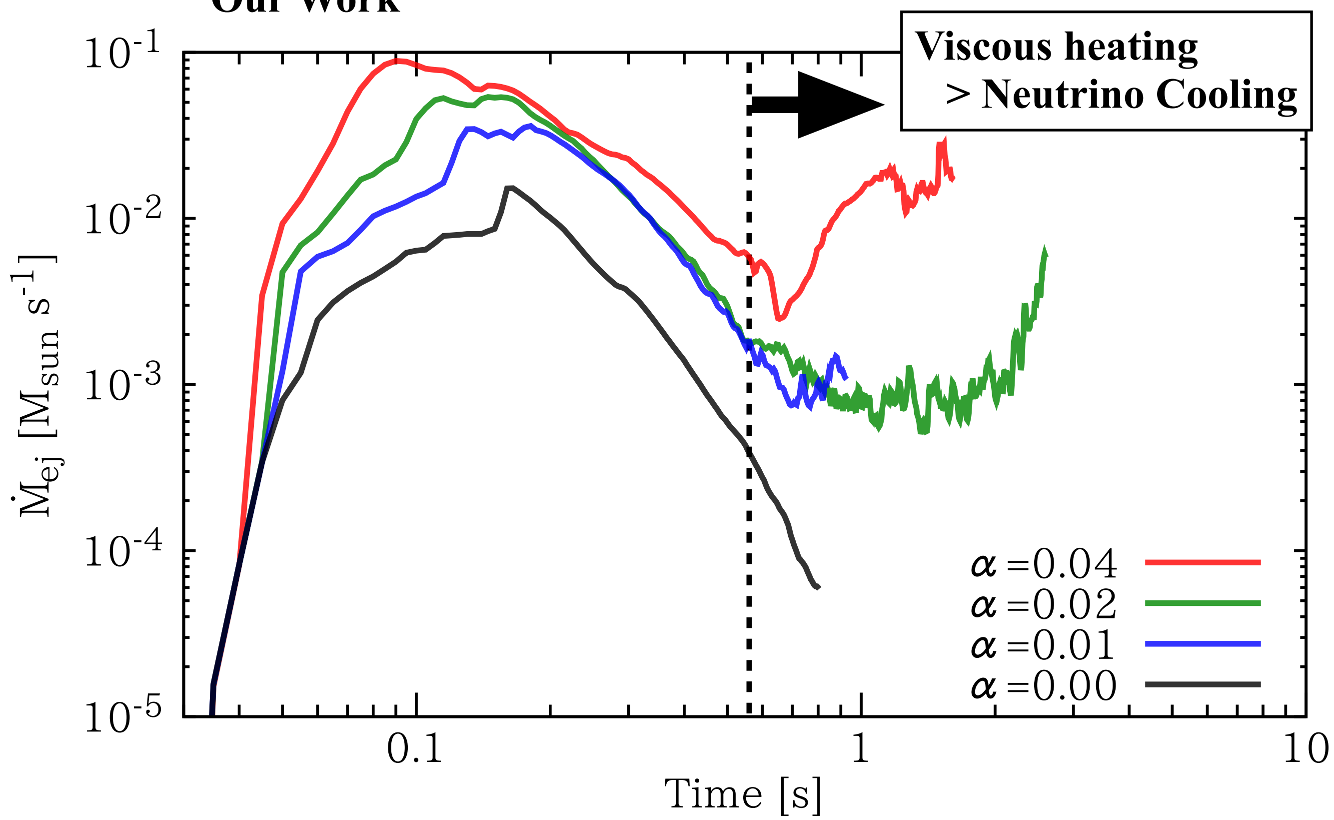
Mass ejection rate is estimated by (heating rate) / (specific binding energy)

$$\dot{M}_{\rm ej} \sim \frac{\mathcal{H}_{\rm torus}}{GM_{\rm MNS}/r}$$

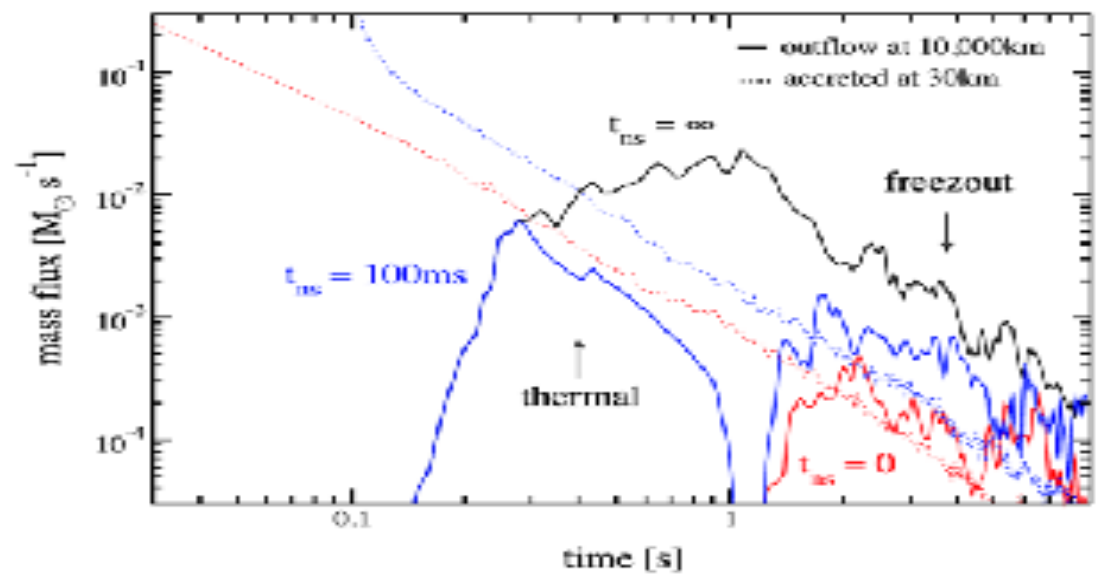
$$\sim 10^{-2} M_\odot\,{\rm s}^{-1} \left(\frac{\mathcal{H}_{\rm torus}}{10^{51}{\rm erg\,s^{-1}}}\right)^{-1} \left(\frac{M_{\rm MNS}}{2.6M_\odot}\right)^{-1} \left(\frac{r}{100{\rm km}}\right)$$

Total Amount of Viscosity-driven Ejecta

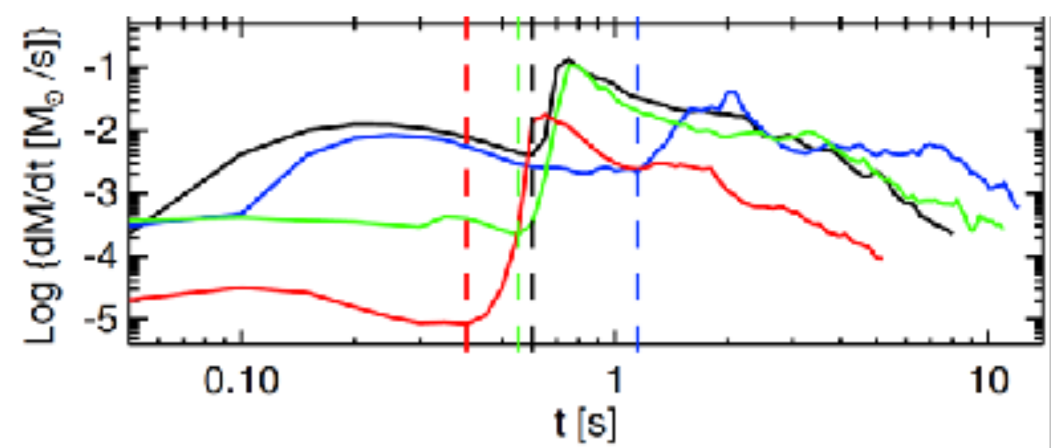
Our Work



Metzger & Fernandez 14



Just et al. 15 (BH-torus)



◯ **Late-time mass ejection rate**

consistent with the model in Metzger & Fernandez 14 and Just et al. 15.

Even for low-α models, such mass ejection is likely to occur in ~ seconds.

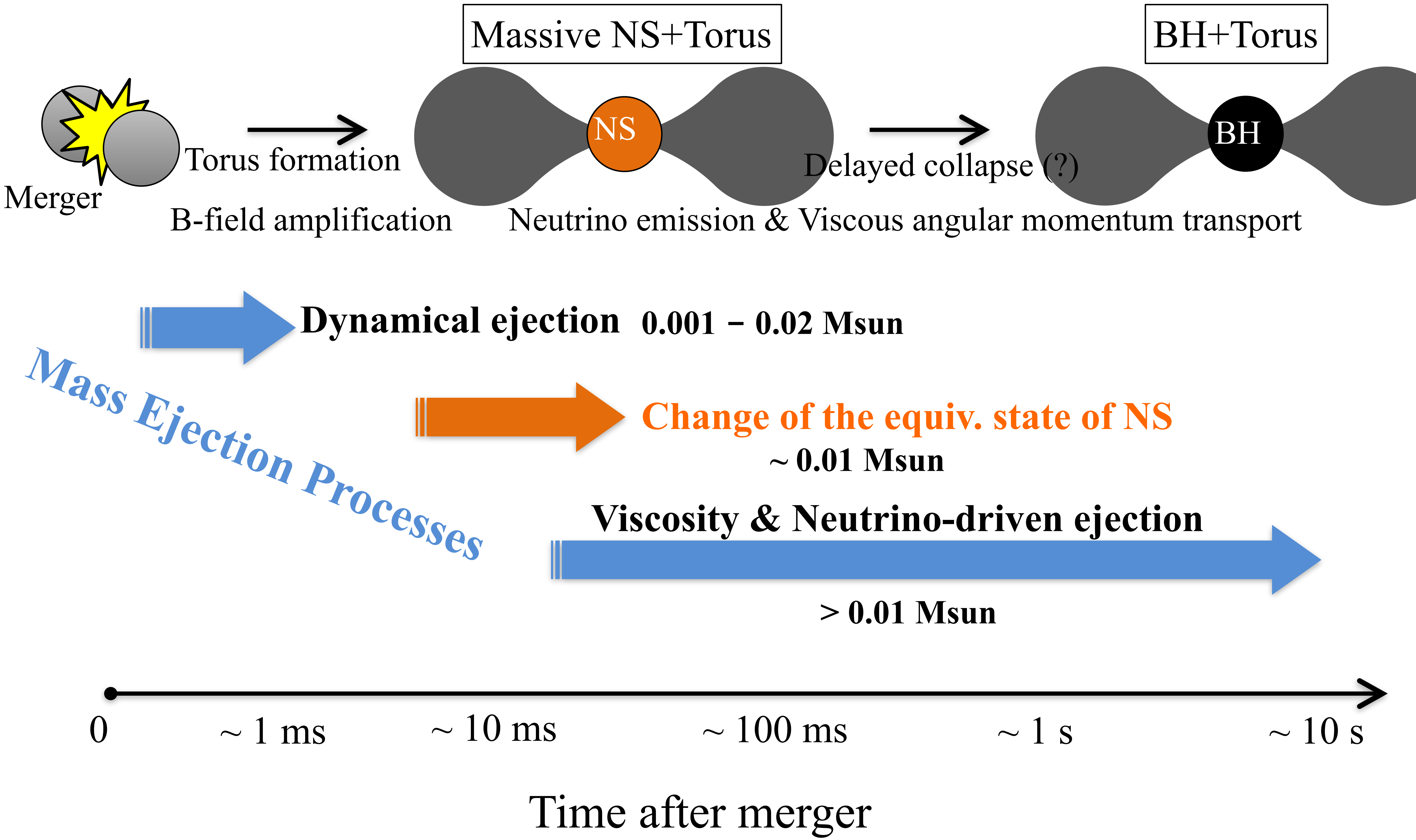
we confirmed their work by the most realistic simulation so far.

After ~1s, The mass accretion is negligible compared with the mass ejection.

Significant fraction of the torus (~ 90 %) could be ejected (in the case of long-lived NS).

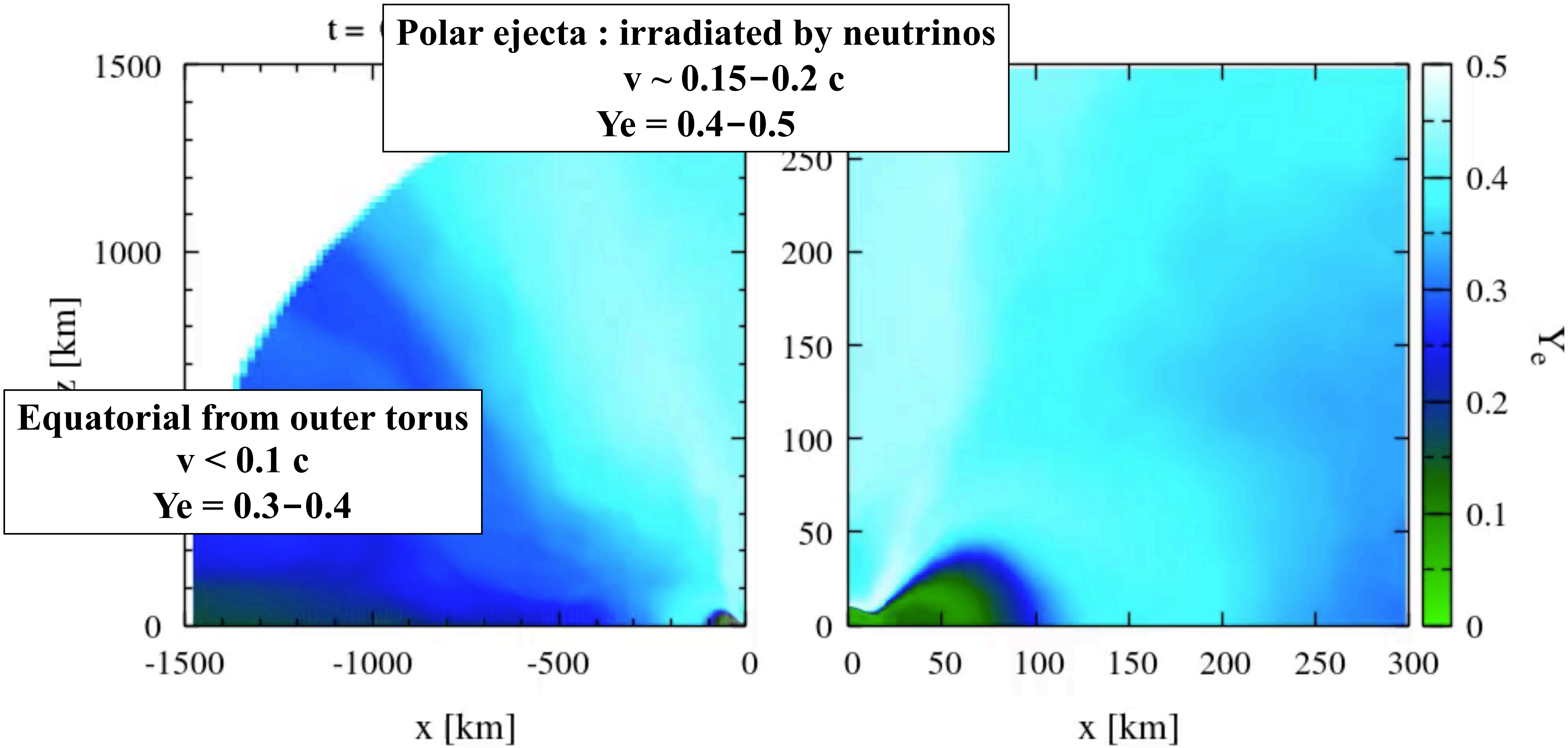
Torus mass at *t* = 1 s is ~ 0.05 Msun ➔ ejecta mass could be ~ 0.04 Msun ?

Mass Ejection Processes in Canonical Merger Remnant

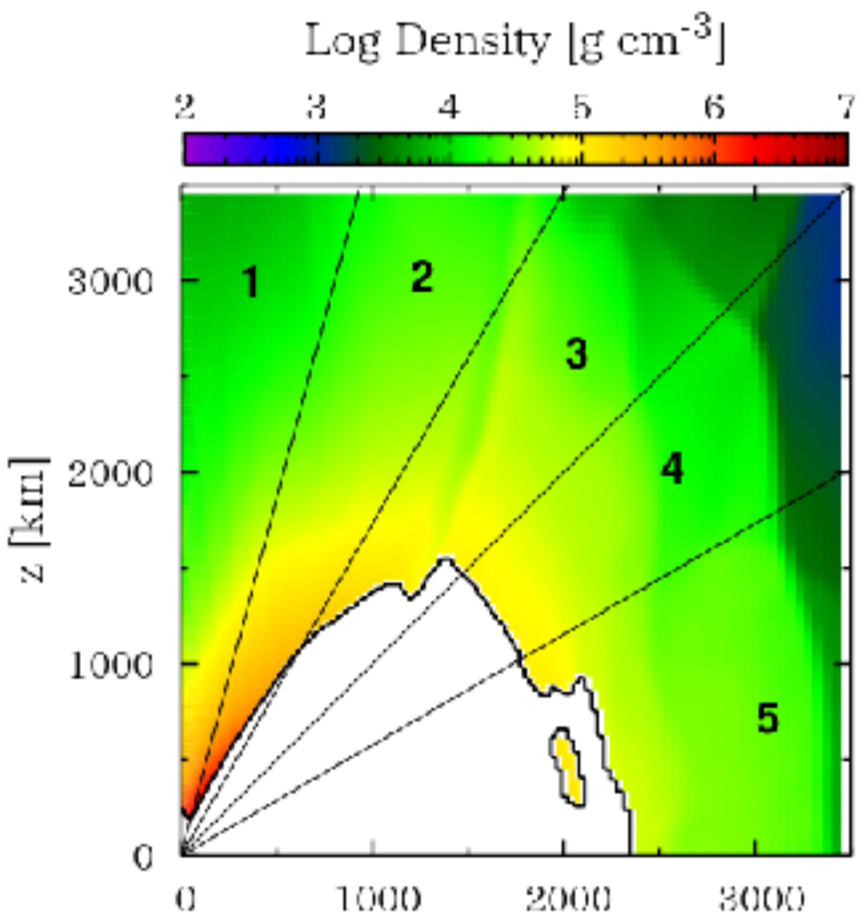


Elemental Abundance and Implication of Electromagnetic Signal

Electron Fraction (Y_e) of the Ejecta



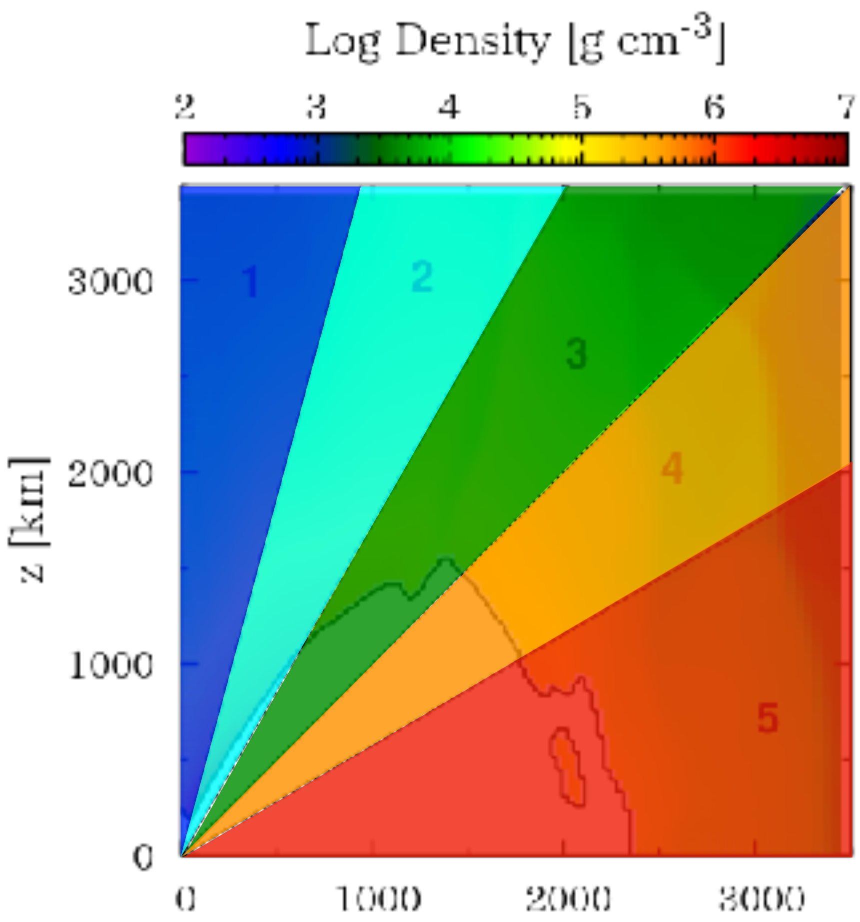
Elemental Abundance in the Ejecta from the Merger Remnant

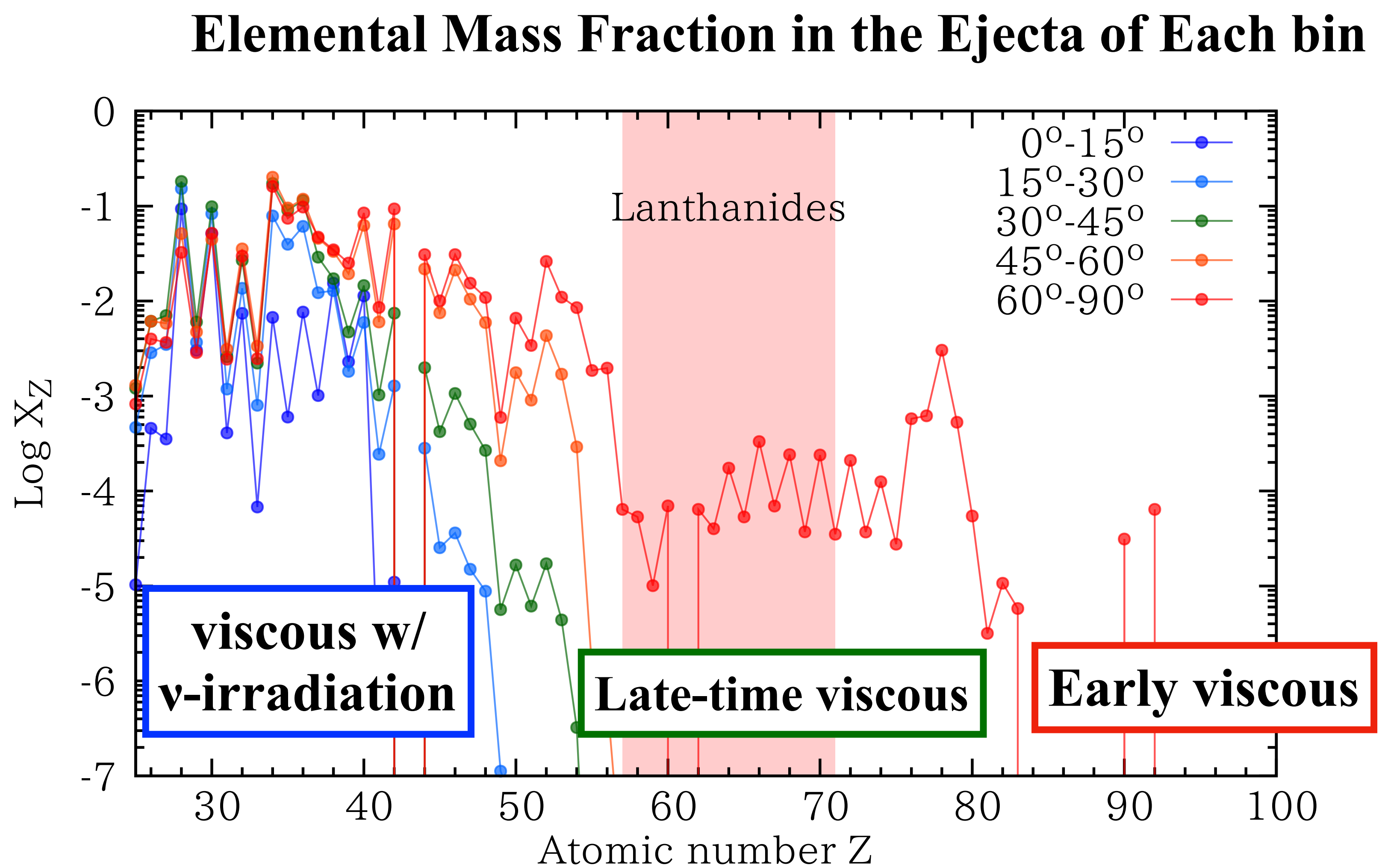


We performed nucleosynthesis calculations for the ejecta.

We investigate the angle-dependence of the elemental abundance.

Elemental Abundance in the Ejecta from the Merger Remnant





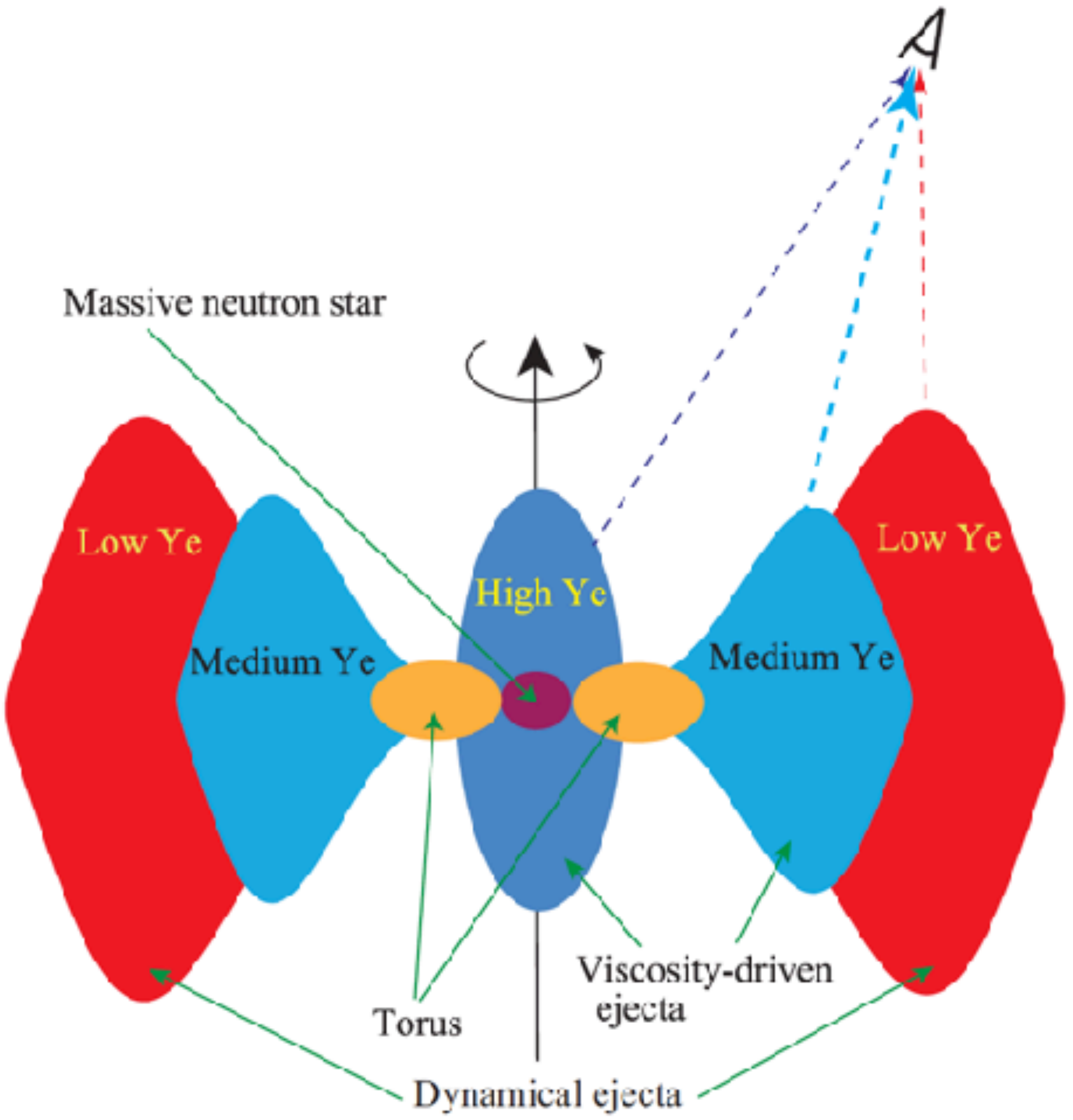
The late-time viscous ejecta dominates the total ejecta.

The ejecta from the merger remnant is (nearly) lanthanide-free.
Therefore we can see more rapidly evolving, brighter emission with higher effective temperature.

Scenario for (early) EM signal associated with GW170817

○ **Due to moderate neutrino irradiation, the late-time viscosity-driven ejecta (>0.01 Msun) has medium Ye (0.3-0.4).**

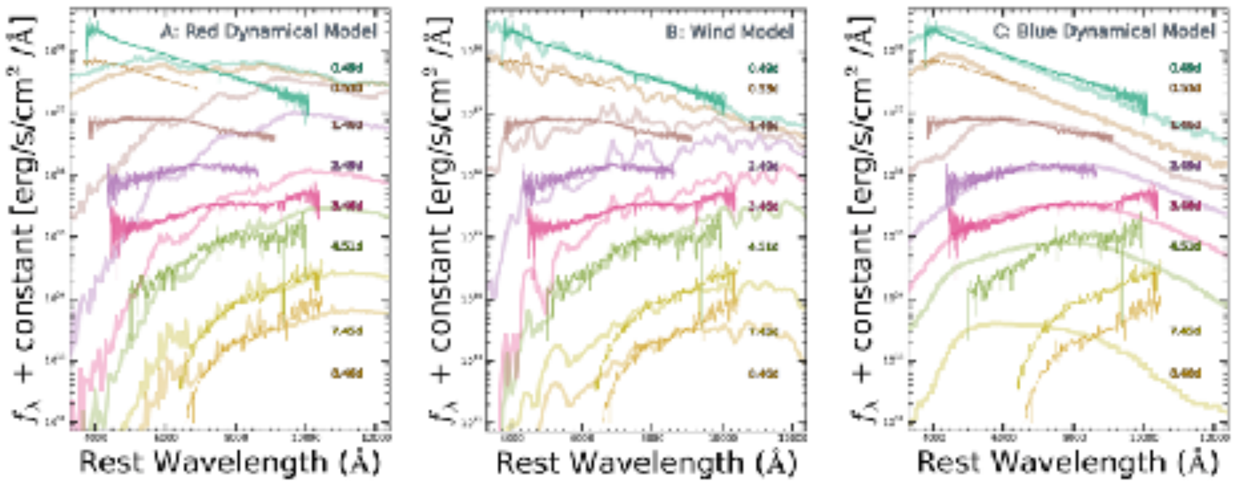
○ **This component would explain the fast-evolving and blue EM signal in in the early phase (< 5 days), if we observe the system from small viewing angle (θ<45°) to avoid Lanthanide curtain of dynamical ejecta.**



Observational Implication

○ Early Spectrum of Kilonova associated with GW170817 Shappee et al. 17, Kasen et al. 17

Lanthanide-rich ~ 0.2 c | Lanthanide-poor ~ 0.03 c | Lanthanide-poor ~ 0.3 c



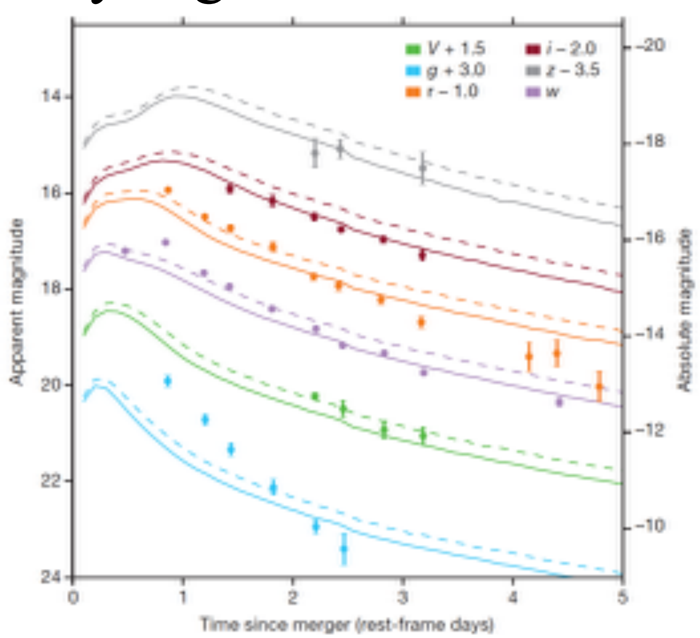
○ Featureless

→ Fast-expanding (~0.3c) ejecta is preferred for blue component.

↔ Viscosity-driven ejecta is slow (<~ 0.1 c)

Some acceleration mechanism of viscosity-driven ejecta is needed.

○ Early Light Curve Arcavi et al. 17



Best-fit parameters of the light curve for < 3−4 days (corresponding to blue component)

$M_{ej} \sim 0.02-0.025\ M_\odot$

$V_{ej} \sim 0.3$ c

$X_{Lanthanide} \sim 10^{-4.5}$ (not completely Lanthanide-free)

↔ Ejecta from MNS-torus : $X_{Lanthanide} < 10^{-8}$ (Too blue)

If the MNS collapses into a BH in a short (~100 ms) timescale, The ejecta may be more neutron-rich, and the lanthanide fraction would be higher.

Possible Constraint on Maximum Mass of NS

○ If magnetized NS survives for a long time, the rotational kinetic energy

$$T_{\rm rot} \approx 1.1 \times 10^{53}\,{\rm erg} \left(\frac{M_{\rm MNS}}{2.5 M_\odot}\right) \left(\frac{R}{15\,{\rm km}}\right)^2 \left(\frac{\Omega}{7000\,{\rm rad/s}}\right)^2,$$

could be injected into the ejecta by electromagnetic processes.

Since $T_{\rm rot} > M_{\rm ej}\, c^2$, if a fraction of the rotational energy is injected into the ejecta, the ejecta velocity cound increases to ~ c , but such feature is not observed.
→ The MNS should collapse into a BH before its spin-down time.

$$\tau_B \approx 650\,{\rm s} \left(\frac{B_p}{10^{15}\,{\rm G}}\right)^{-2} \left(\frac{M_{\rm MNS}}{2.5 M_\odot}\right) \left(\frac{R}{15\,{\rm km}}\right)^{4} \left(\frac{\Omega}{7000\,{\rm rad/s}}\right)^{2}$$

(If γ-rays detected by Fermi and INTEGRAL comes from BH+torus system, the MNS should collapse in ~ sec.)

The gravitational mass of the MNS ~ sec after the merger : ~ 2.6 Msun
(~ 0.15Msun is reduced due to GW & ν emission)

This should be
the maximum mass of the rigidly rotating mass, which is ~ 0.4 Msun larger than that of spherical cold NS

→ The maximum mass of the spherical cold NS ~ 2.6−0.4 = 2.2 Msun.

Summary

- We performed GR radiation viscous-hydrodynamics simulation of the remnant of the binary NS merger.
  - Variation of the equiv. state of the NS can be used for mass ejection.
  - Viscosity-driven ejecta would be dominant at $t \sim 1$ s.
  - Late time ejecta will be nearly lanthanide-free.

→ Short , **Bright**, and Blue emission could be explained by this ejecta component

- Future prospects
  - Dependence on the binary system (masses) and nuclear EOSs.
  - Mass ejection from (MNS→BH)−torus system
  - Photon radiation transfer to obtain theoretical light curves.