中性子星連星合体後の粘性による質量放出

Viscosity-driven Mass Ejection from NS-NS merger remnant

藤林翔, 木内建太, 柴田大, 西村信哉（基研）,

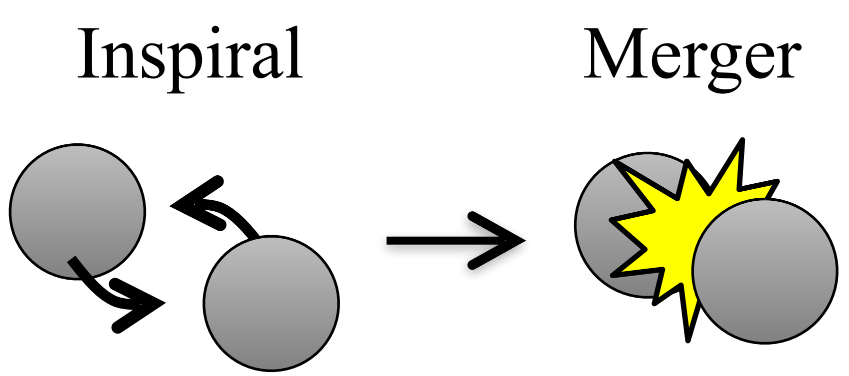
Sho Fujibayashi, Kenta Kiuchi, Masaru Shibata, Nobuya Nishimura (YITP)

関口雄一郎（東邦大）

Yuichiro Sekiguchi (Toho U.)

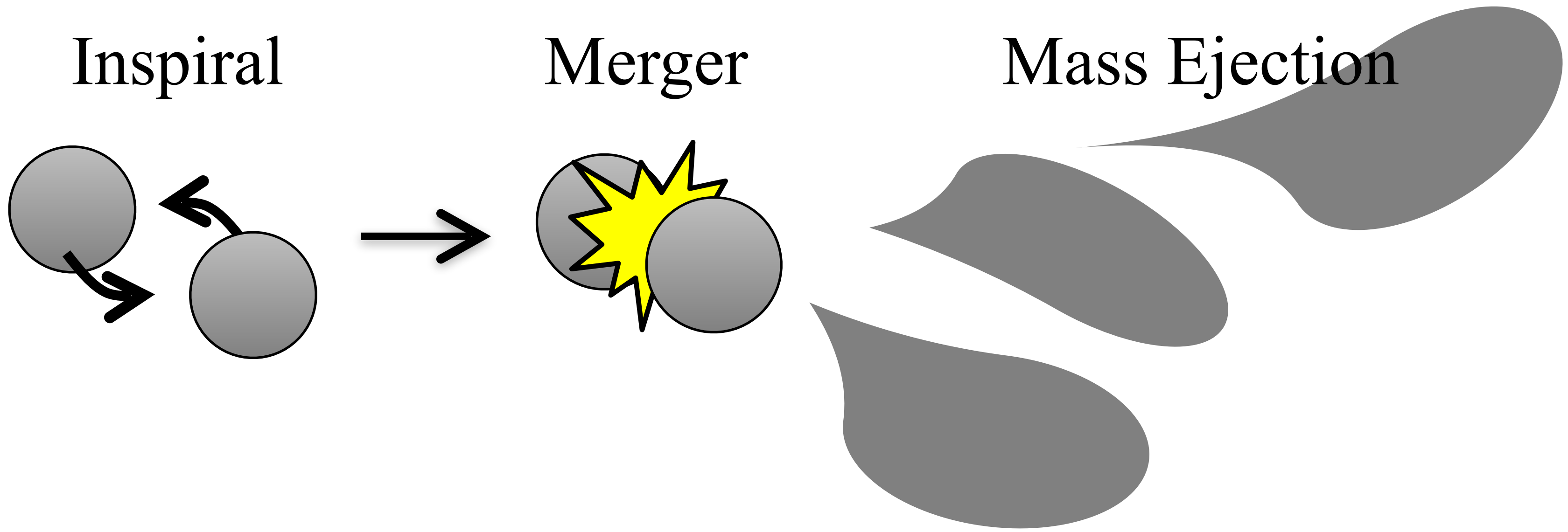
SF et al. will be submitted in ~20 days…

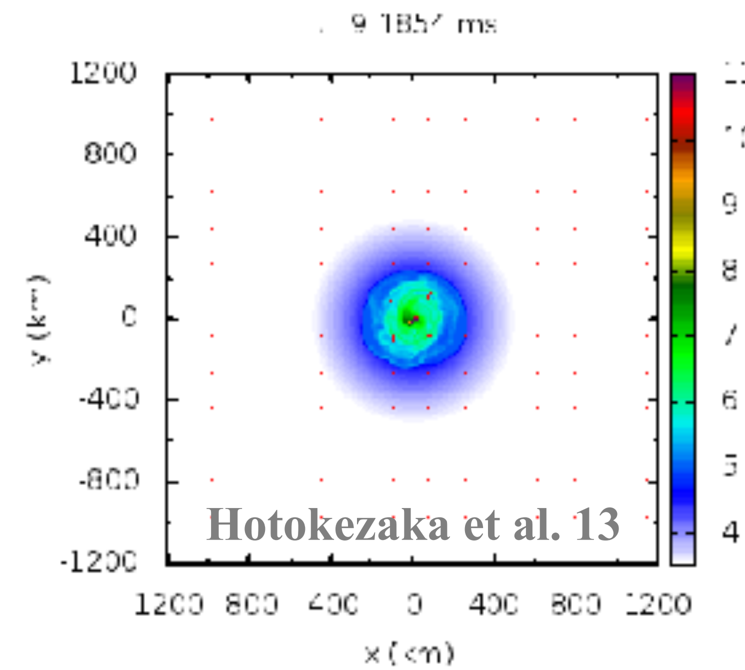
Binary Neutron Star (NS) Merger



Two NSs approach due to GW emission → Merger

Mass Ejection from Merger

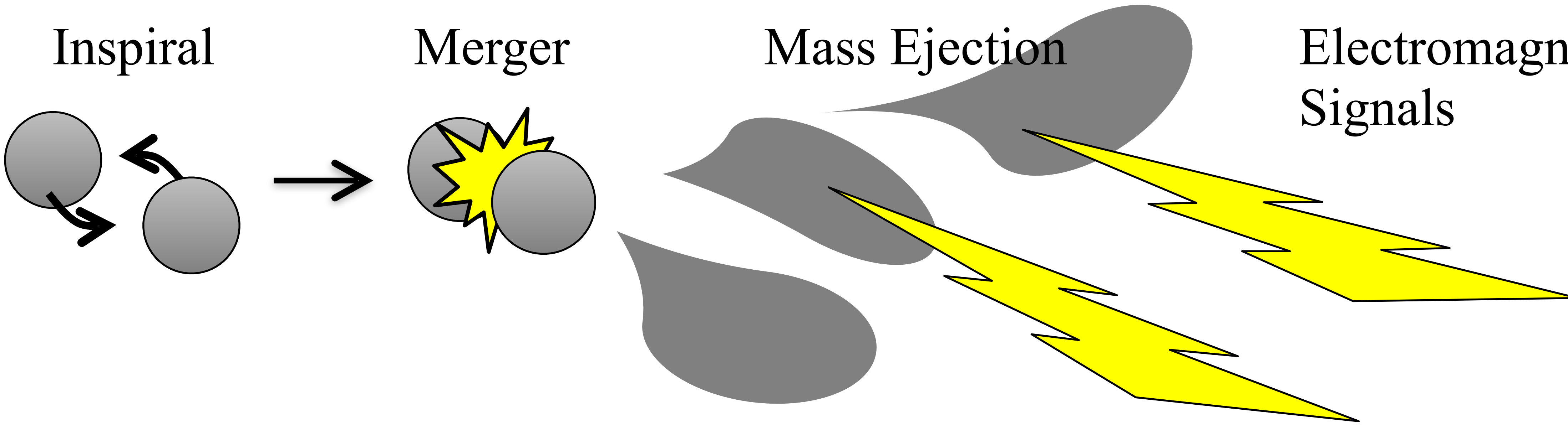




Two NSs approach due to GW emission → Merger

A part of the NS matter is ejected by several processes

Electromagnetic Emission from the Ejecta



Two NSs approach due to GW emission → Merger

A part of the NS matter is ejected by several processes

Unstable nuclei are produced via neutron-capture process.
(Origin of *r*-process elements?)

Radioactive decay (and fission) heats up the ejecta
→ Thermal emission (Kilonova/Macronova)

Important electromagnetic signal ~week after the merger

Electromagnetic Emission from the Ejecta

◎ Sky localization

Only GW → we cannot find the host-galaxy where the merger occurs.
Search of the electromagnetic signal is important to find the host-galaxy.

◎ Properties of electromagnetic signal depends on

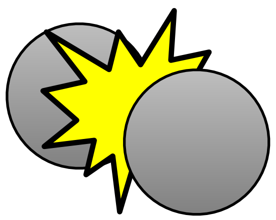
the properties of ejected material.
(Mass, Expansion velocity, Chemical composition)

◎ They may have information of

the binary system and the physics of extreme environment.
(e.g., Nuclear matter EOS)

Nuclear matter physics could be constrained with
the observation of the electromagnetic signals from the merger.

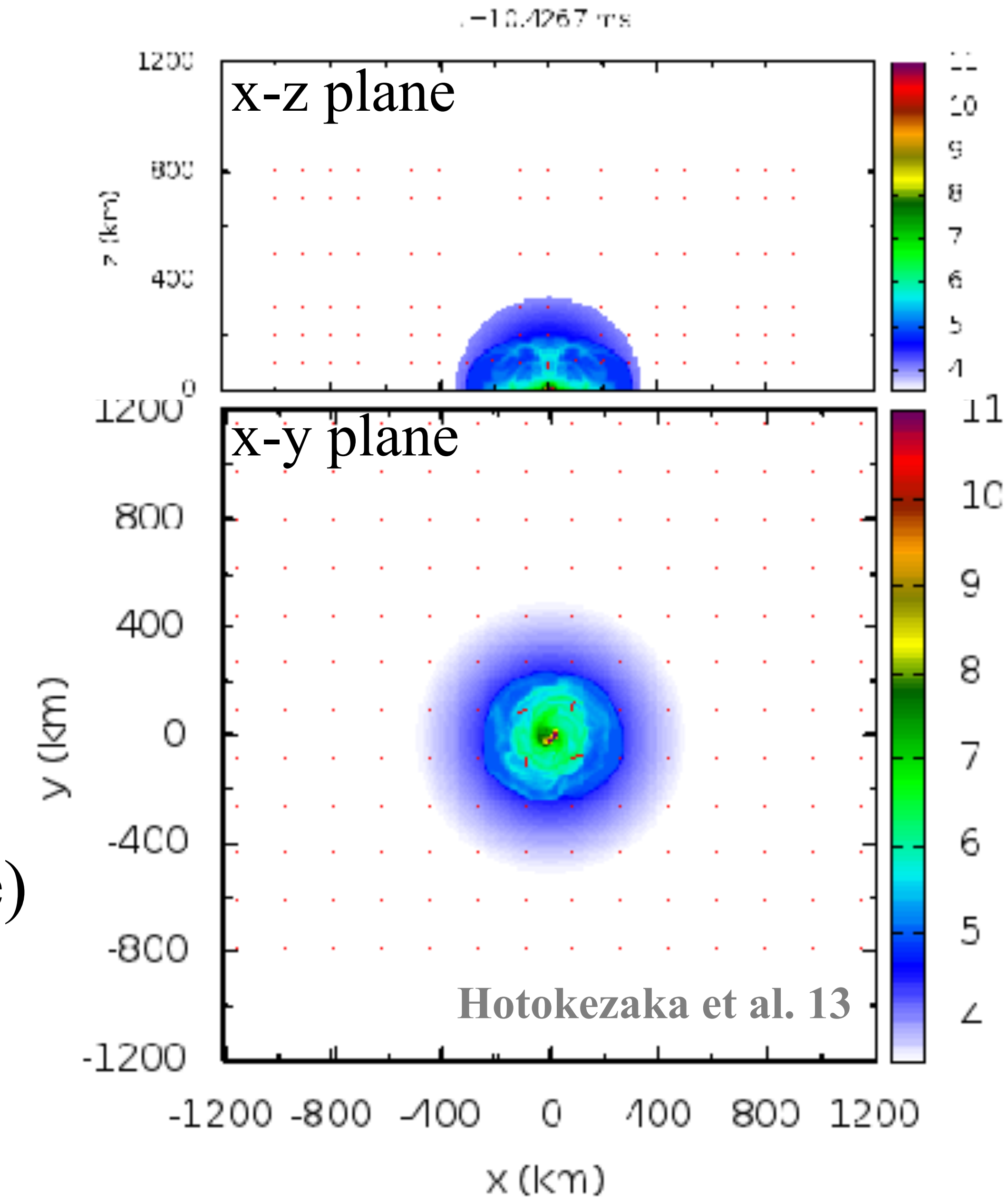
Mass Ejection Processes in Canonical Merger



Merger

Dynamical ejection

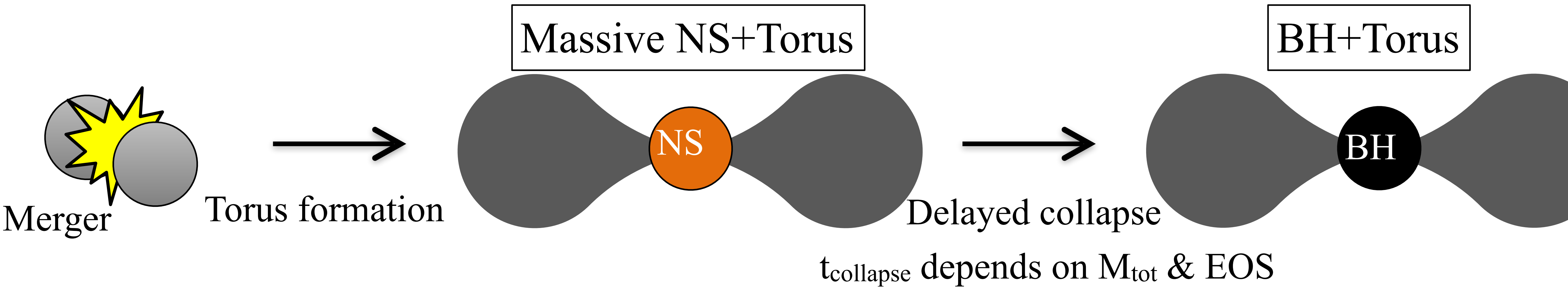
- Due to tidal force and shock heating
- Well studied (mass, EOS dependence)



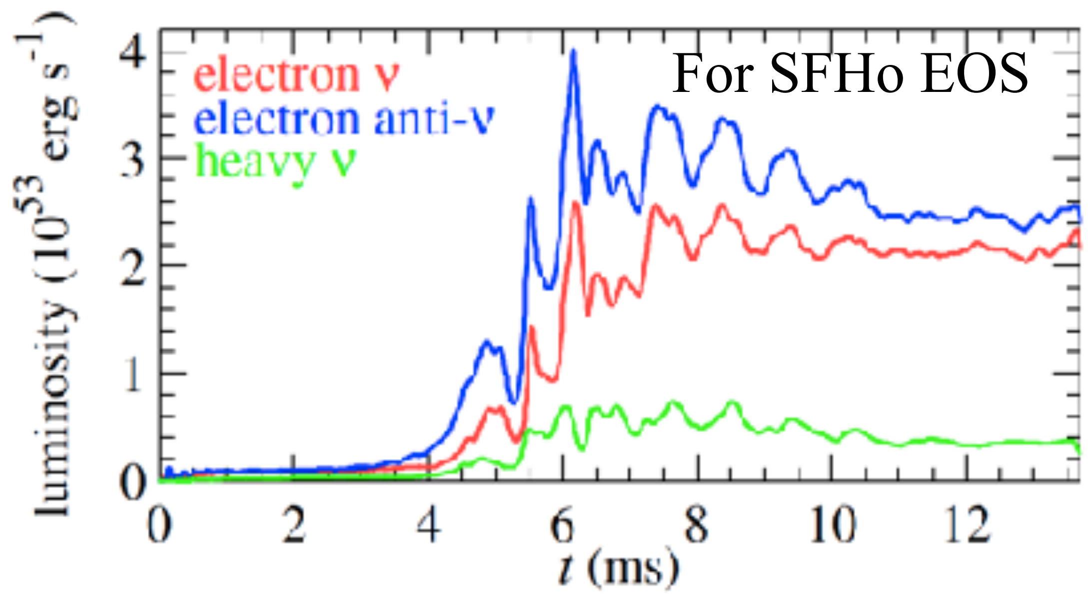
0 ~ 1 ms ~ 10 ms ~ 100 ms ~ 1 s ~ 10 s

Time after merger

Mass Ejection Processes in Canonical Merger



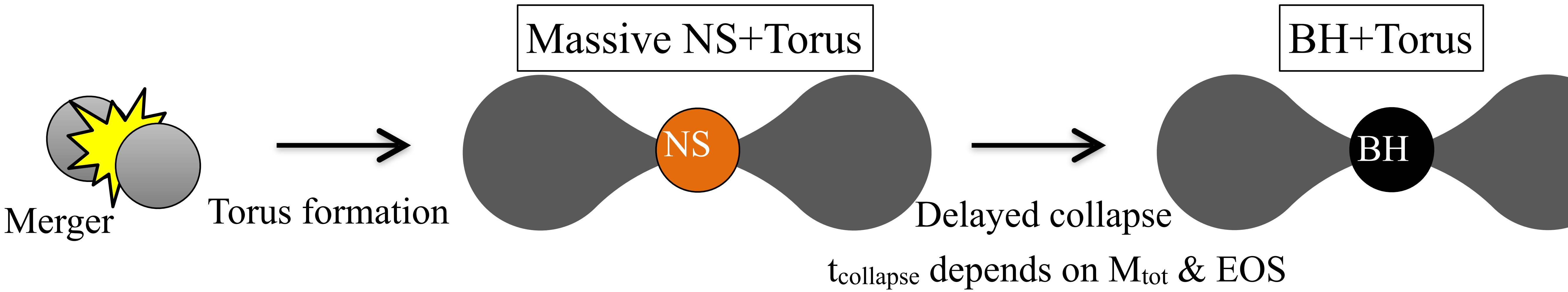
Neutrino emission Sekiguchi et al. 15



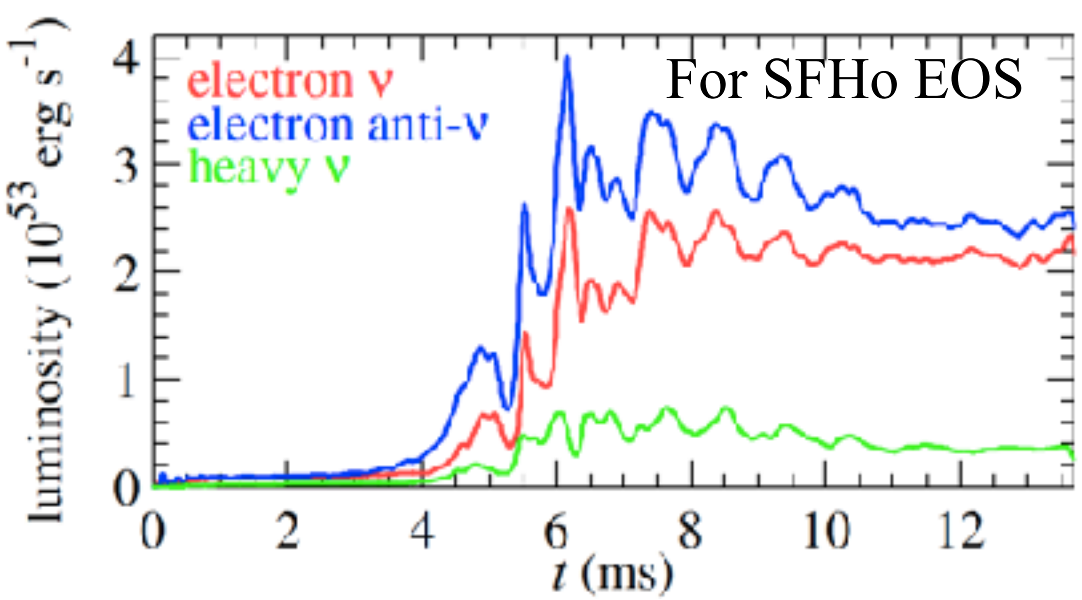
0 ~ 1 ms ~ 10 ms ~ 100 ms ~ 1 s ~ 10 s

Time after merger

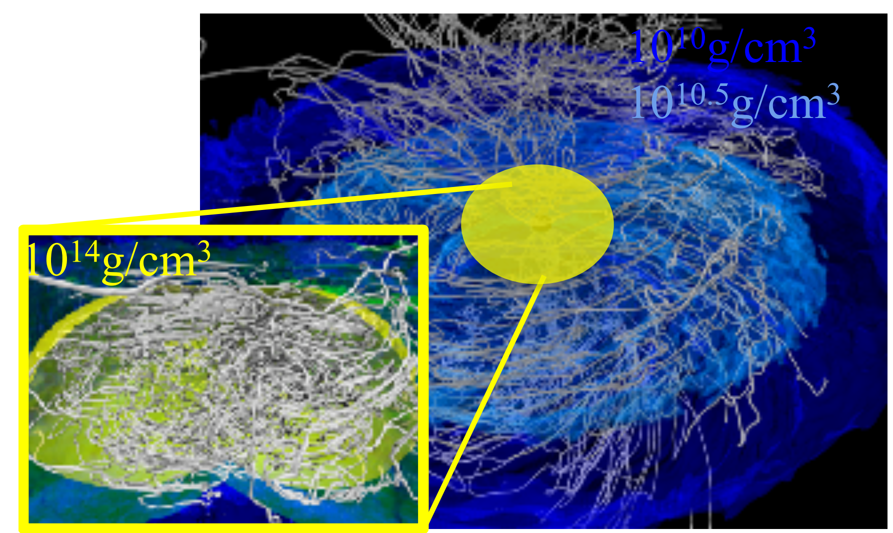
Mass Ejection Processes in Canonical Merger



Neutrino emission Sekiguchi et al. 15



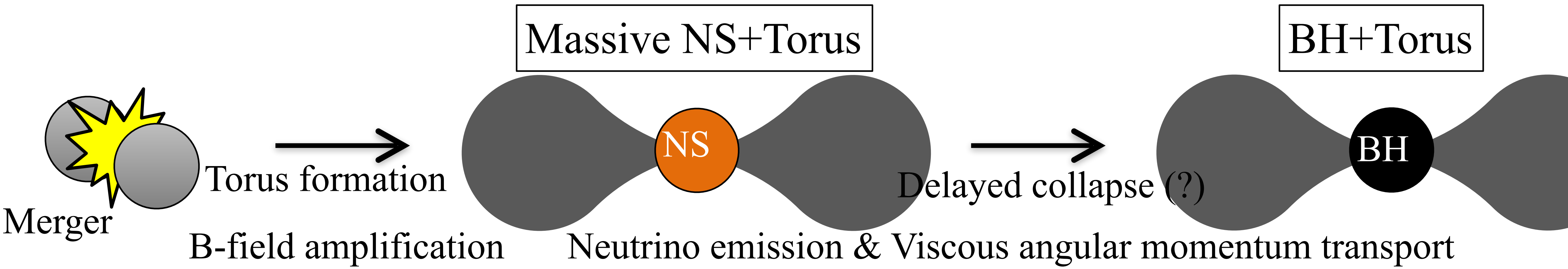
B-field amplification Kiuchi et al. 14, 15



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

Time after merger

Mass Ejection Processes in Canonical Merger



Viscosity & Neutrino-driven ejection

Heating by neutrinos and viscosity
Effective viscosity caused by MHD turbulence
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

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

Time after merger

Our Research

Constructing reliable physical model of
the binary NS merger remnant and mass ejection from it.

We perform long-term simulations for NS-NS merger remnant including relevant physics:

- General relativity
- Neutrinos
- Magnetic field

Our Research

Constructing reliable physical model of
the binary NS merger remnant and mass ejection from it.

We perform long-term simulations for NS-NS merger remnant including relevant physics:

- General relativity
- Neutrinos
- Magnetic field $\rightarrow$ (effective) Viscosity
  due to MHD turbulence

Method

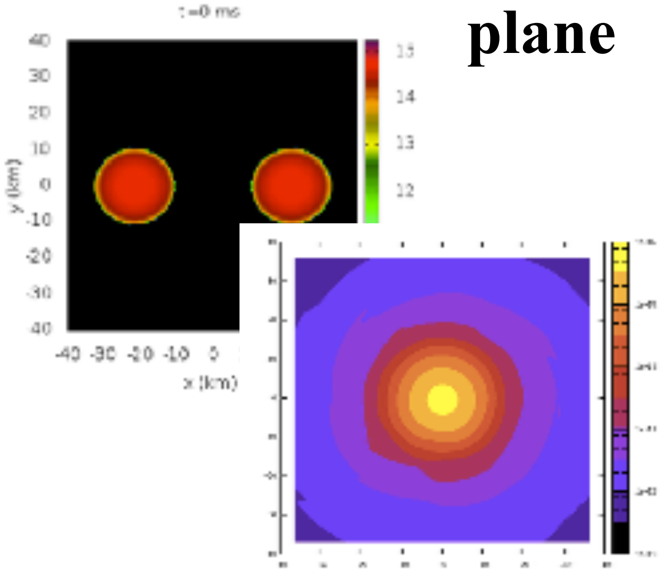
Method

◎ 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

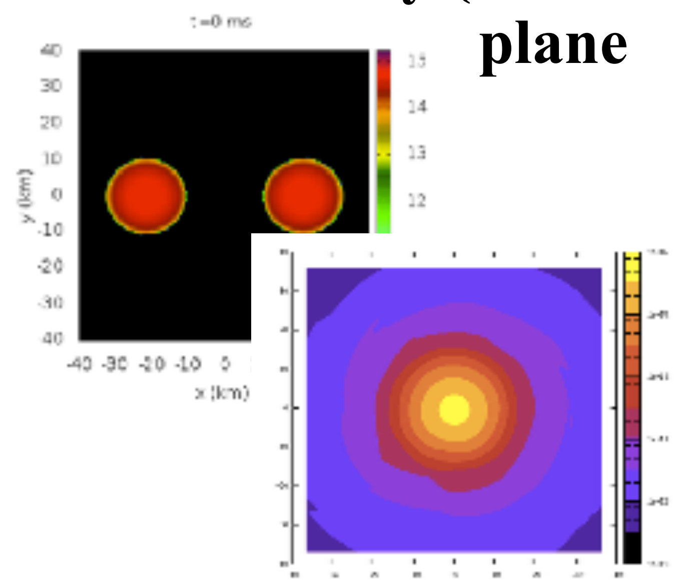
i) Merger of NS−NS and massive NS formation by 3-D full GR simulation

Sekiguchi et al. 15

Equation of state : DD2

(→ The remnant is long-lived massive NS)

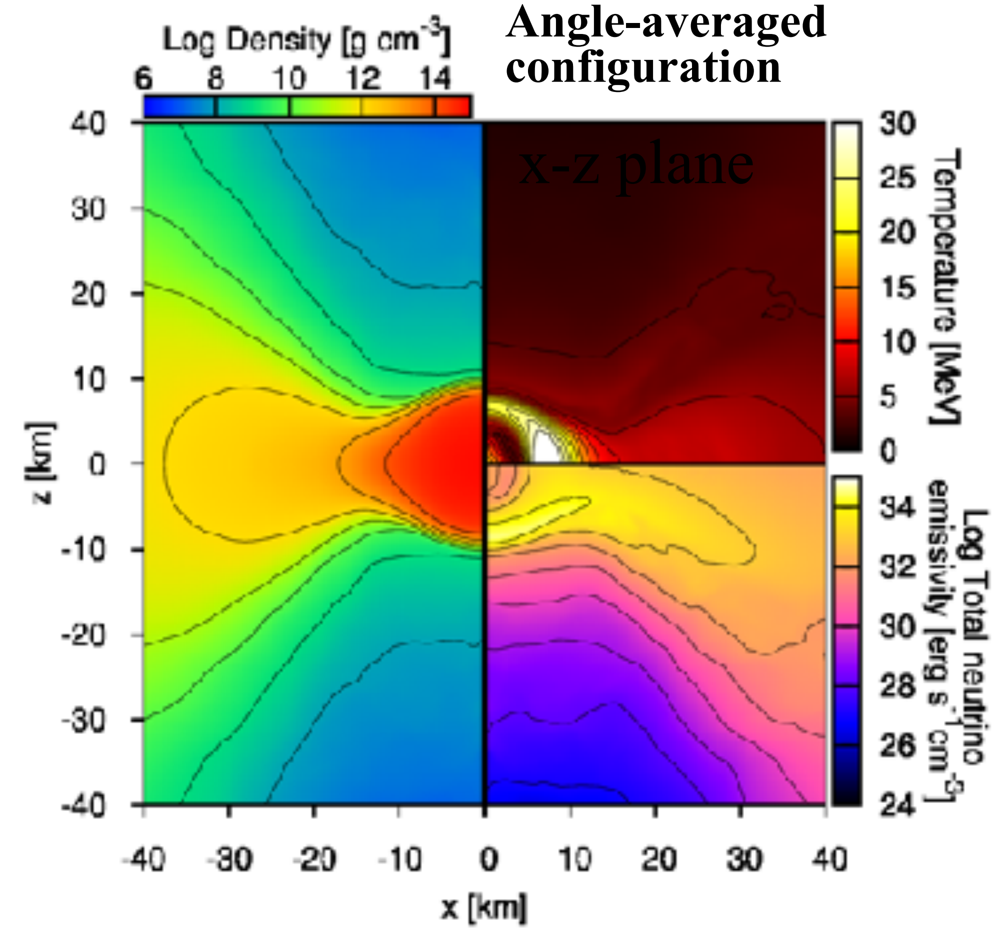
x-y (rotational) plane



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 2-D simulation using angle-averaged configuration as a initial condition

Angle-averaged configuration



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**

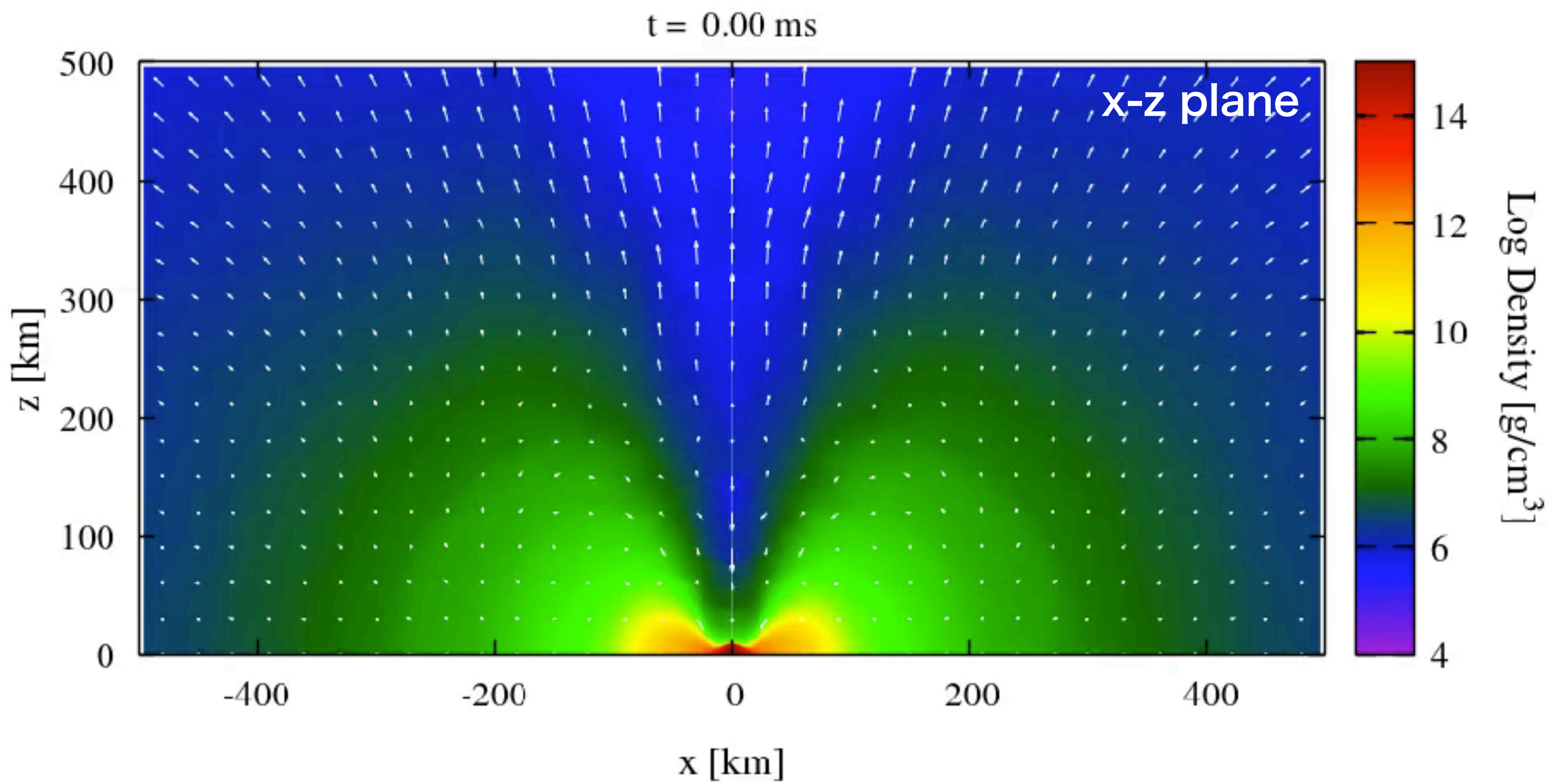
- Viscous hydrodynamics equation

  In order to mimic the effective viscosity due to MHD turbulence,
  We developed GR viscous hydrodynamics code
  based on a version of Israel-Stuart formalism. **Shibata et al. 17, Shibata & Kiuchi 17**

Models : $\alpha = 0, 0.01, 0.02$

Result

Dynamics



Disk :

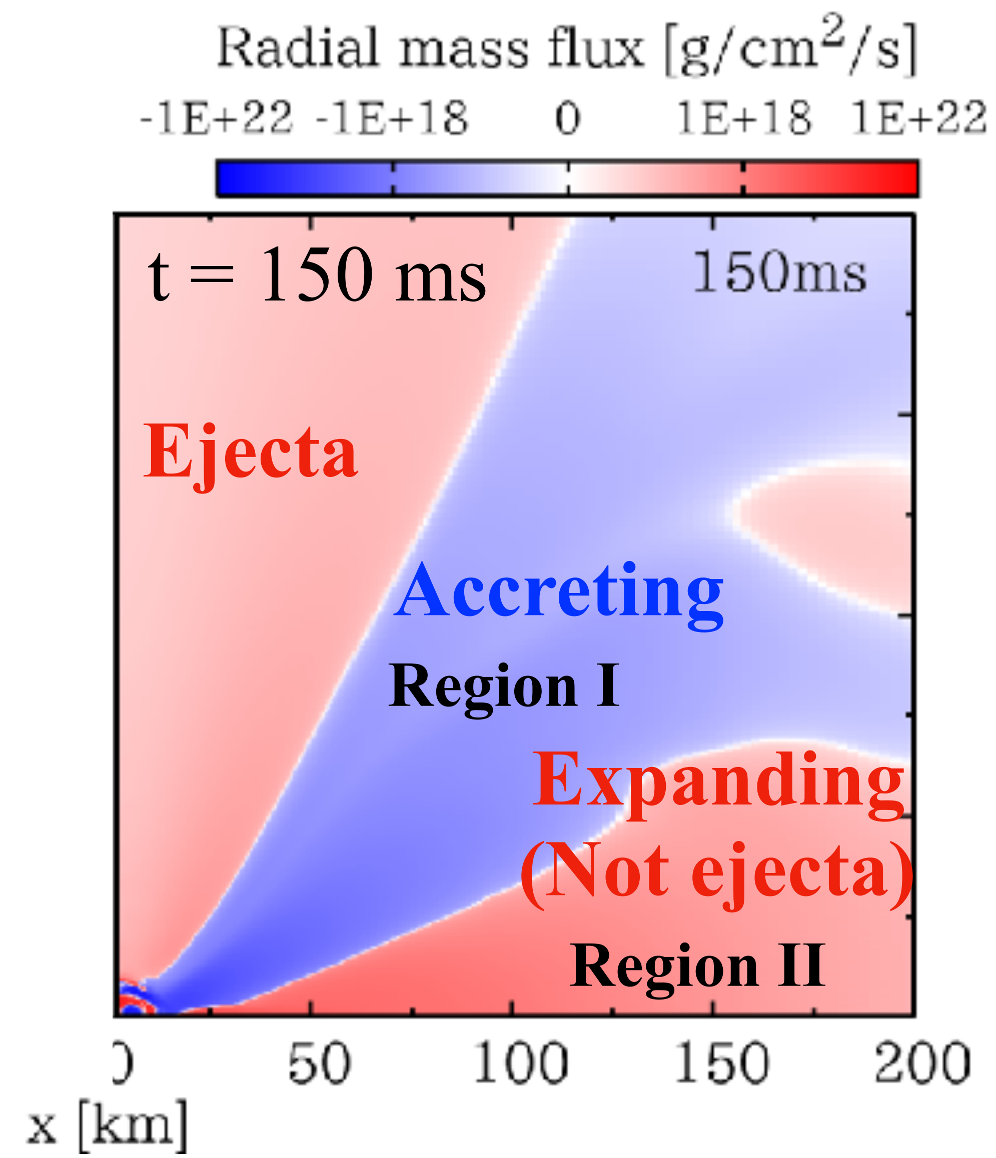
Gradually expands

Ejecta :

~ 10 ms : ????-driven ejecta
< 200 ms : neutrino-driven
> 200 ms : viscosity-driven

Accretion

Accretion Structure



Torus is divided into two parts : **Accreting part** and **Expanding part**

Accretion Structure

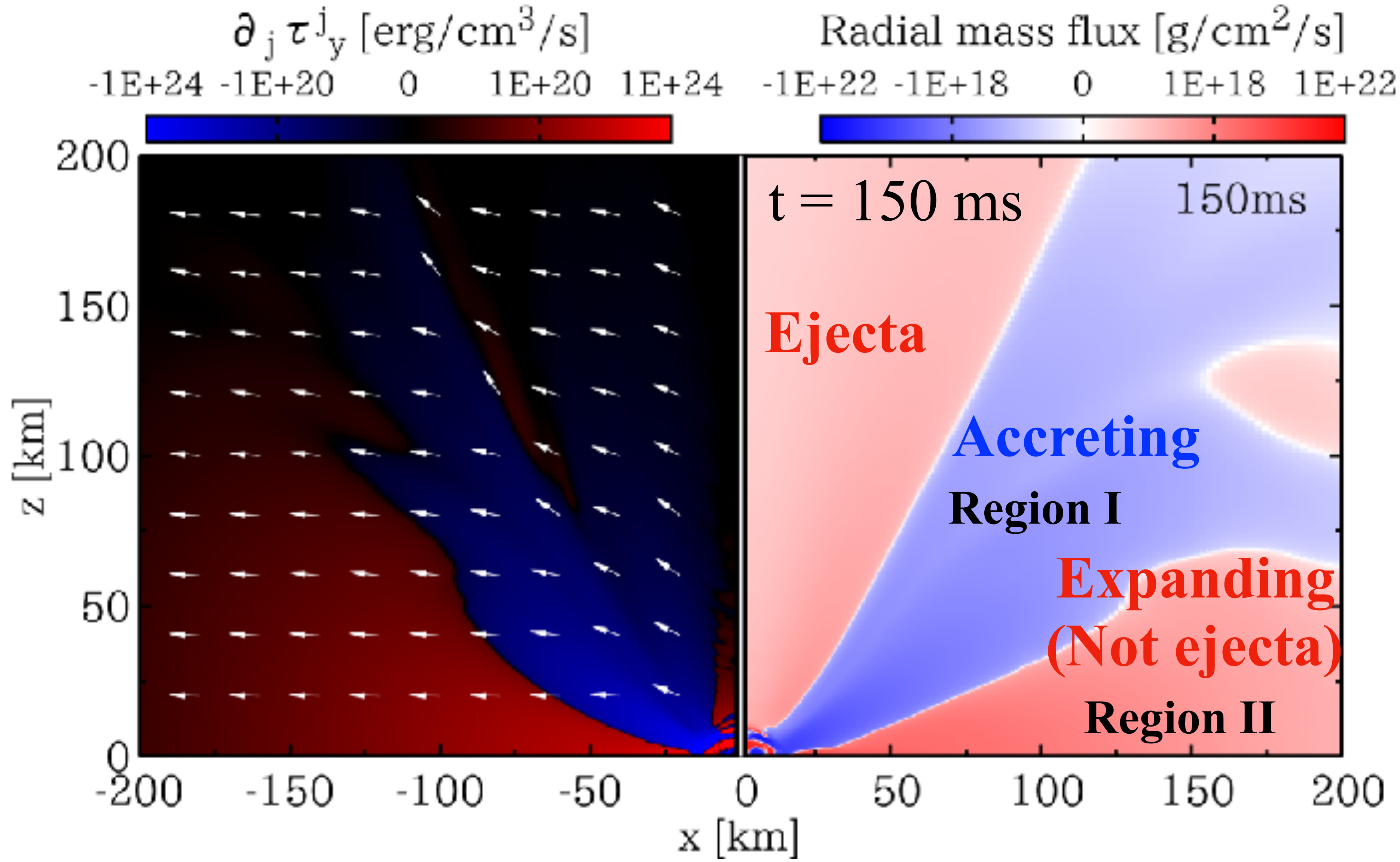
τ : **viscous tensor**

Vector : $\tau^k{}_y$

Angular momentum flux due to viscosity (only direction)

Color : $\nabla_k \tau^k{}_y$

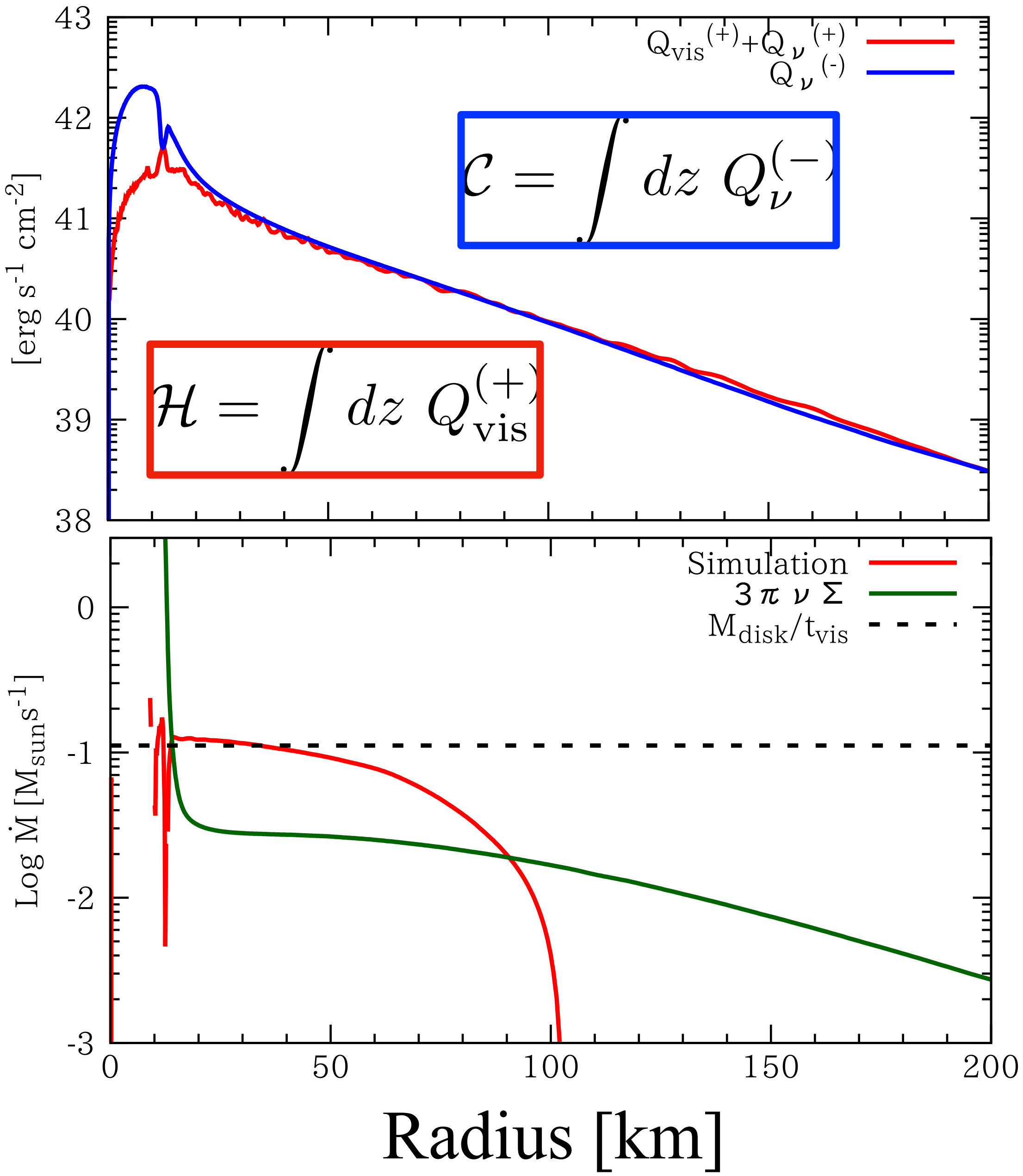
Angular momentum source



Angular momentum in **Region I** is transported to **Region II** due to the viscosity.

(Vertically integrated) Accretion Structure

Structure @ t=300 ms



H = C is satisfied in the disk.
NDAF is achieved.

$$\int dz\ 2\pi R\ \rho v^R$$

$$\dot{M} \sim \frac{M_{\rm disk}}{t_{\rm vis}}$$

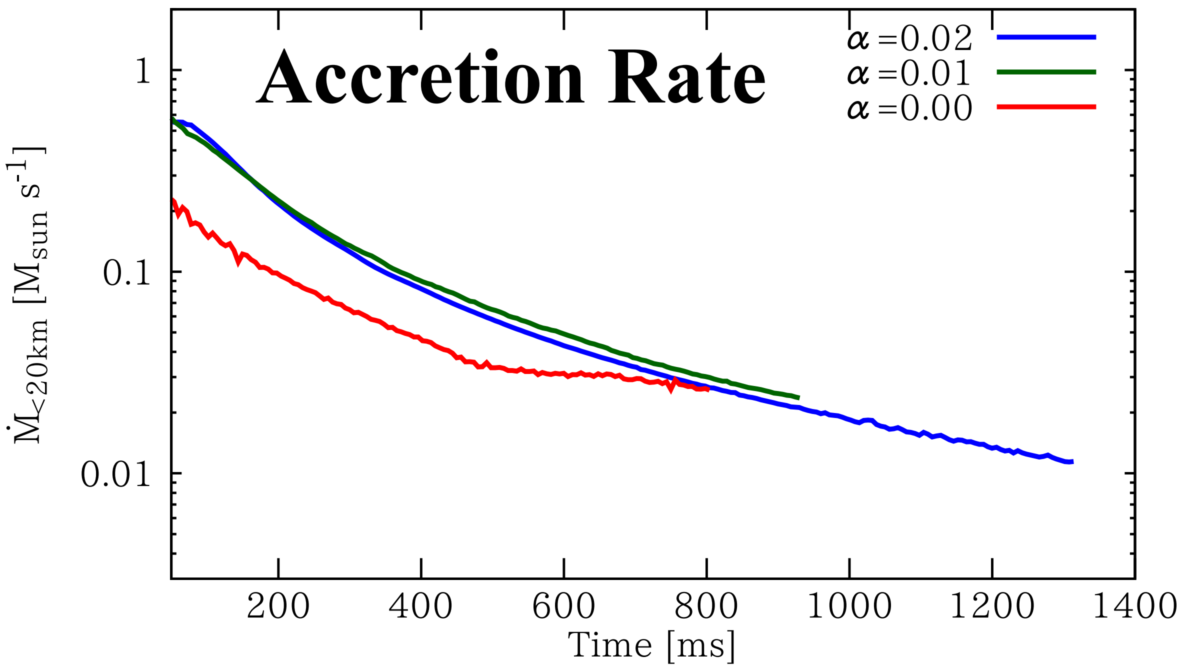
$$\sim 0.2\ M_\odot\ {\rm s}^{-1} \left(\frac{M_{\rm disk}}{0.1\ M_\odot}\right)\left(\frac{R_{\rm disk}}{50\ {\rm km}}\right)^{-3/2}$$

$$\times \left(\frac{M_{\rm NS}}{2.6\ M_\odot}\right)^{1/2}\left(\frac{\alpha}{0.01}\right)\left(\frac{H/R}{1/3}\right)^2$$

$$R_{\rm disk} = \frac{J_{\rm disk}^2}{M_{\rm disk}^2}\frac{1}{M_{\rm NS}}$$

Accretion structure of NS+torus is well described by the standard NDAF.

Accretion Rate



Accretion rate: > 1e-1 $M_\odot$ s^{-1} for t < 400ms and decreases with time.

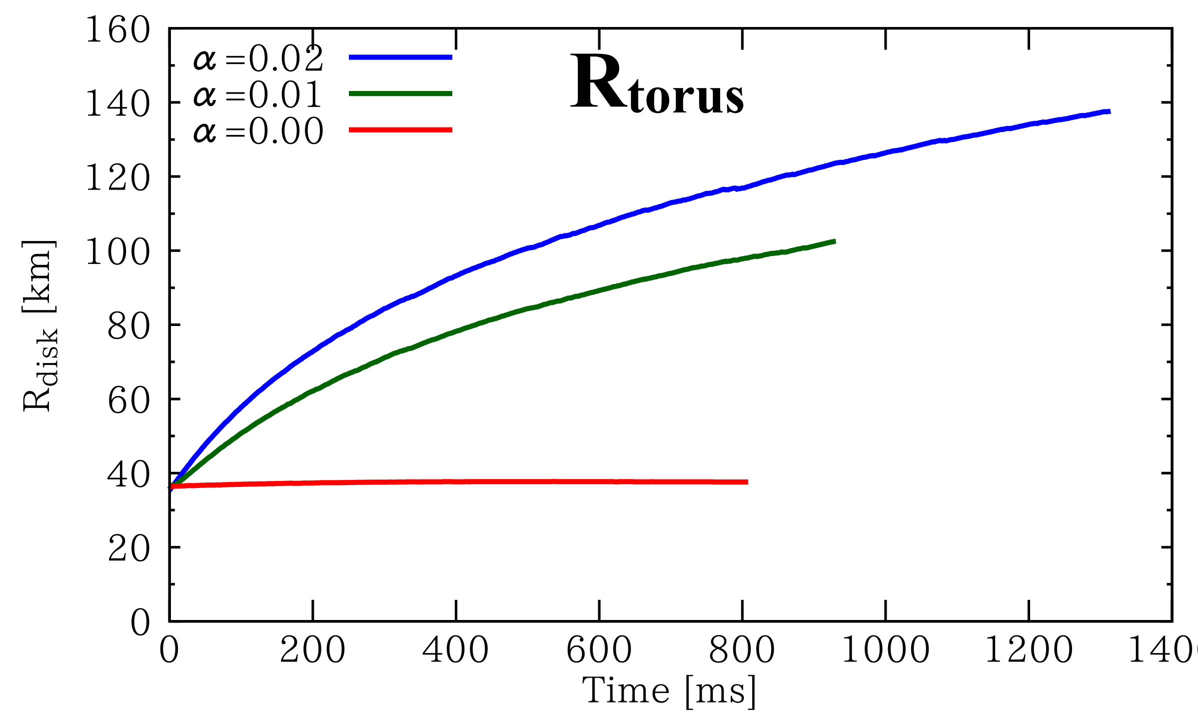
Viscosity parameter-dependence of the accretion rate (and neutrino luminosity) is not strong.

This is due to the expansion of the torus.

$$\dot{M} \sim \frac{M_{\rm disk}}{t_{\rm vis}}$$

$$\sim 0.2\ M_\odot\ {\rm s}^{-1} \left(\frac{M_{\rm disk}}{0.1\ M_\odot}\right)\left(\frac{R_{\rm disk}}{50\ {\rm km}}\right)^{-3/2}$$

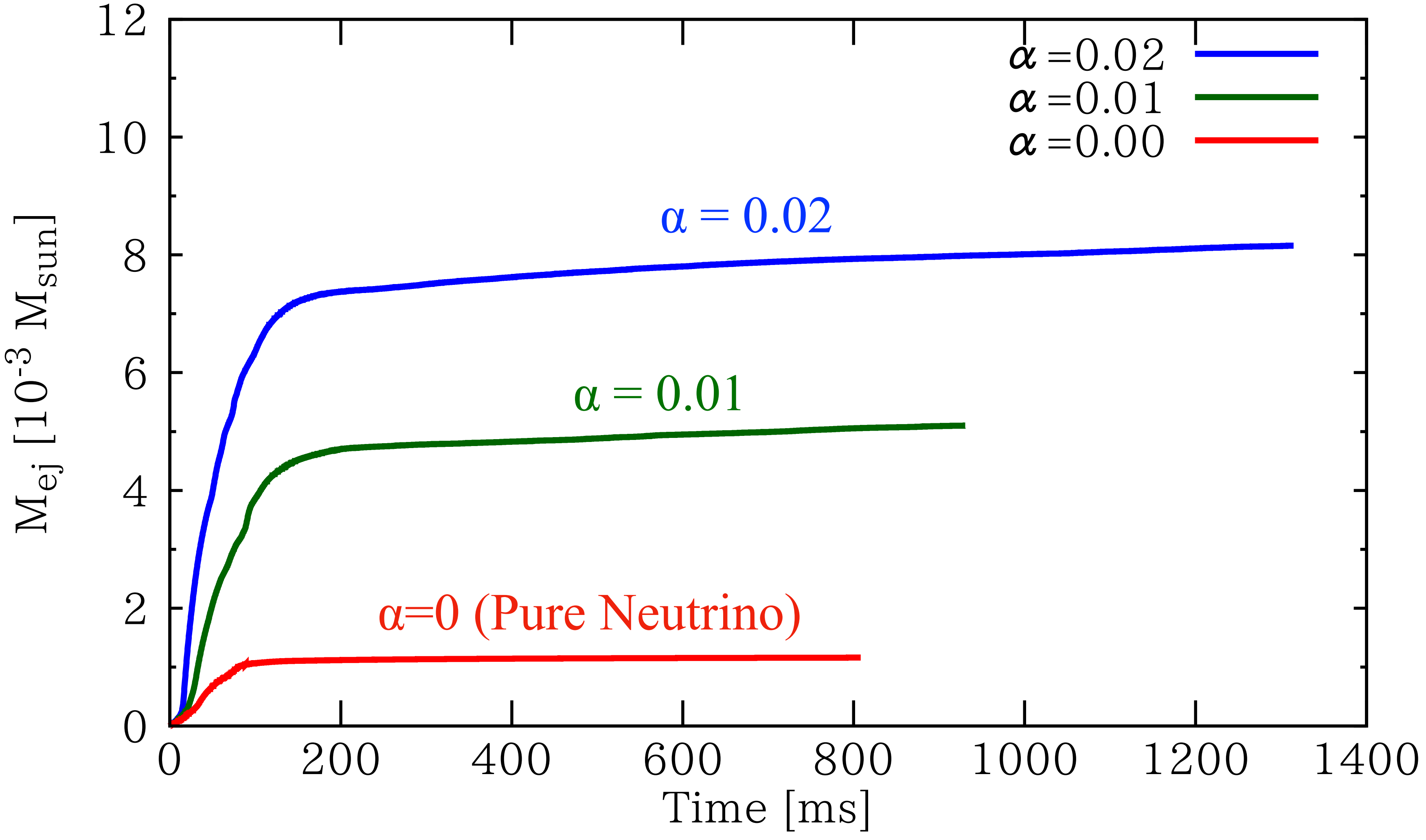
$$\times\left(\frac{M_{\rm NS}}{2.6\ M_\odot}\right)^{1/2}\left(\frac{\alpha}{0.01}\right)\left(\frac{H/R}{1/3}\right)^2$$



Accretion rate becomes larger as R_{torus} increases.

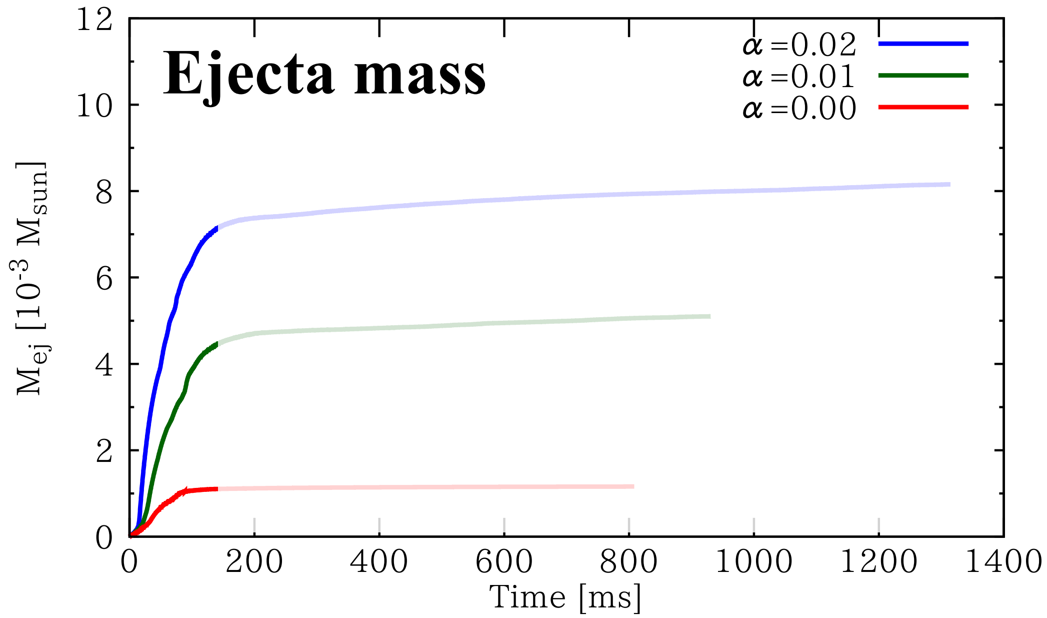
Mass Ejection from Merger Remnant

Ejecta Mass

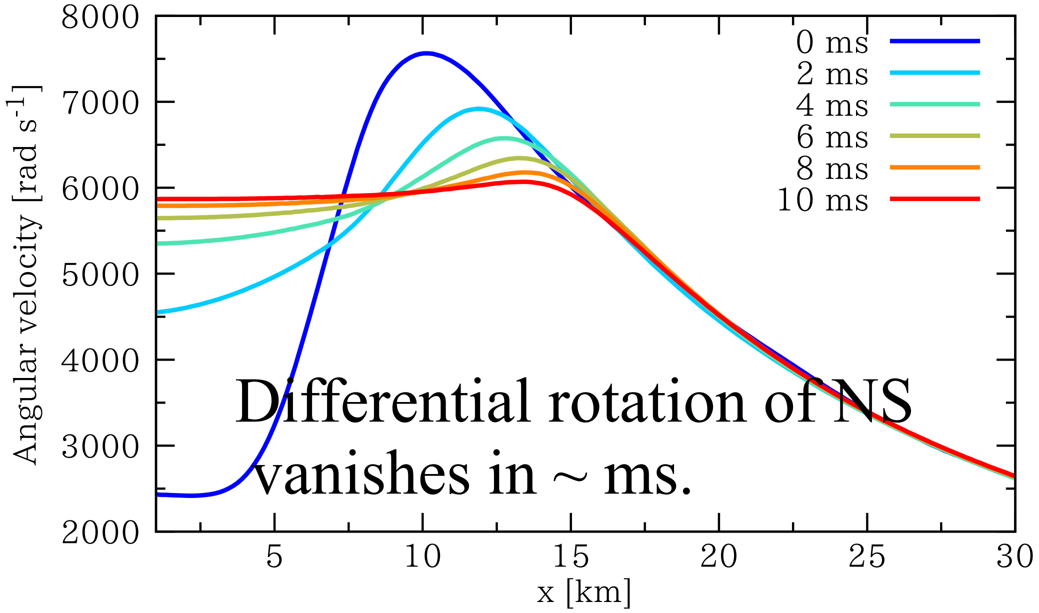


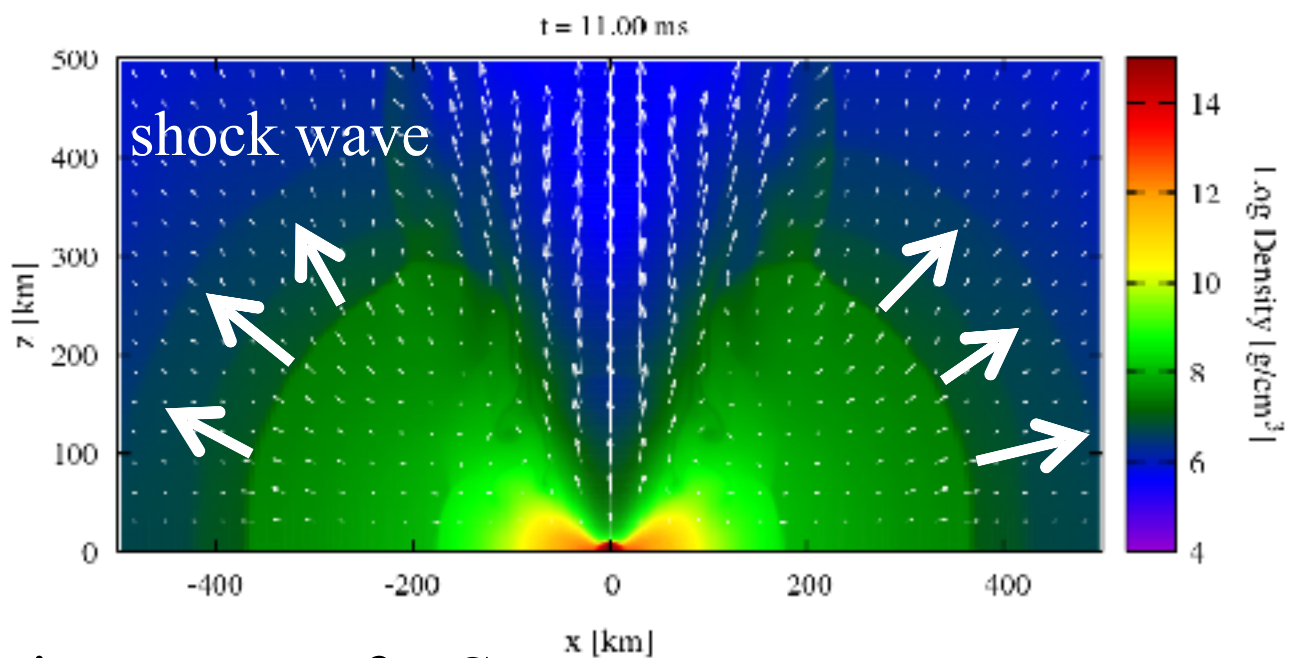
c.f.) Dynamical ejecta is ~ 10^{-3} Msun for DD2 EOS

Early Viscosity-driven Ejecta



Ω-structure of NS



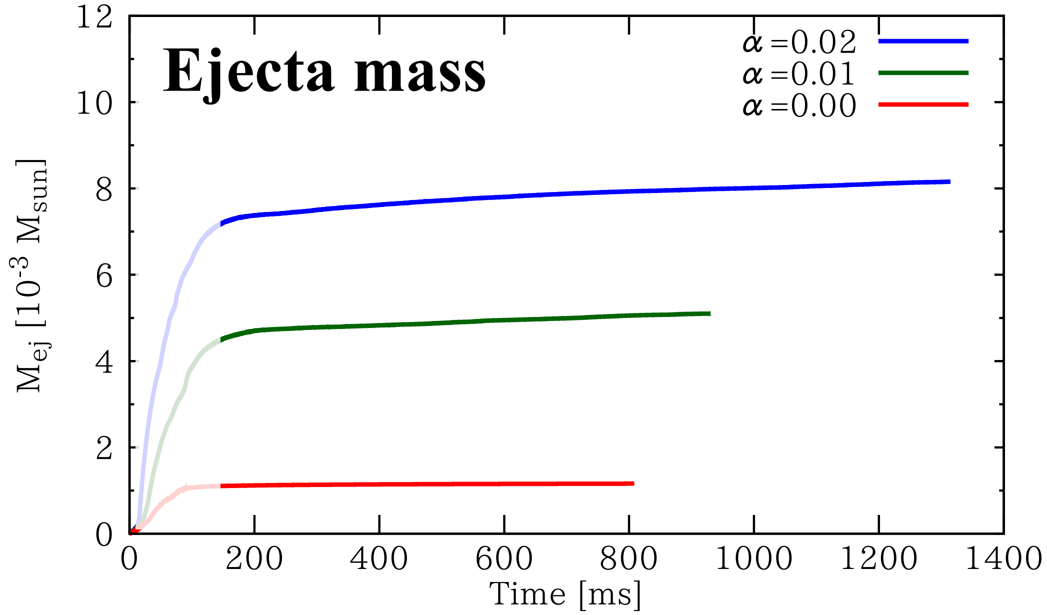


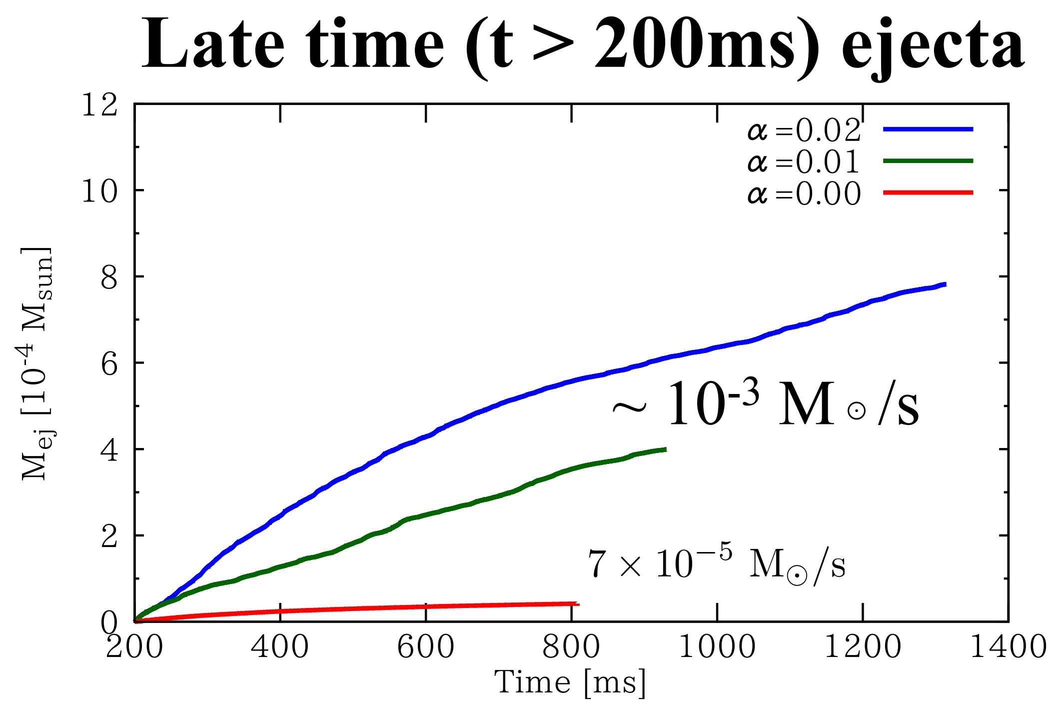
Change of the equilibrium state of NS

→ 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.

Viscosity-driven Ejecta (t>200 ms)





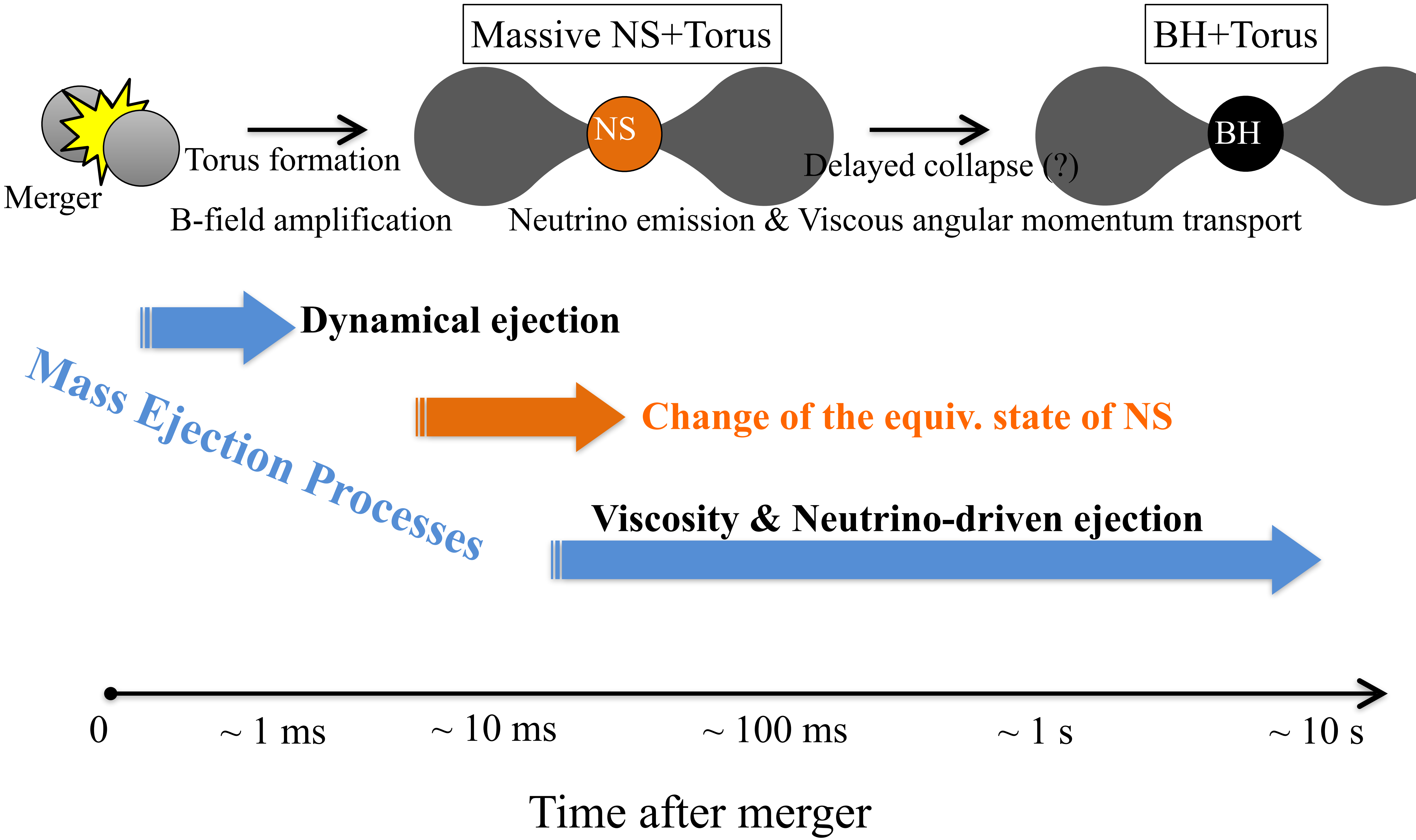
○ Change of the equilibrium state of massive NS → Ejecta @ t ~ 10 ms

○ Viscosity-driven ejecta : t > 200 ms

Viscosity-driven ejecta could be M_{ej} ~ 1e-2 M☉ if the ejection is sustained for ~10 s.

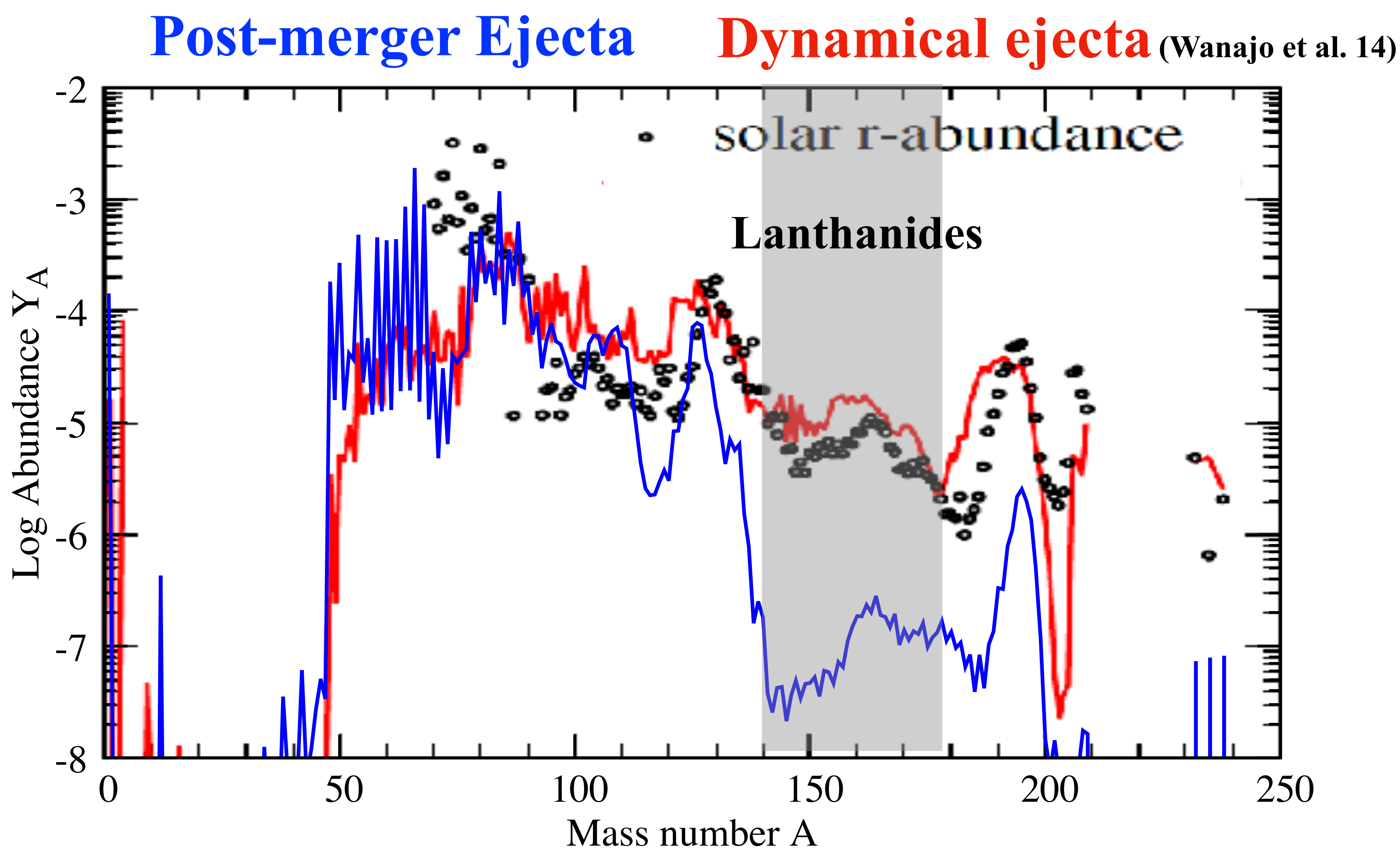
(Unlike the mass accretion rate,) Mass ejection rate is highly dependent on the viscosity parameter

Mass Ejection Processes in Canonical Merger Remnant



Elemental Abundance in the Ejecta from the Merger Remnant

See also N.Nishimura's talk



The ejecta from the merger remnant is (nearly) lanthanide-free !
If this component dominates the total ejecta, we can see more rapidly evolving, brighter emission with higher effective temperature.

Summary

- We performed GR radiation viscous-hydrodynamics simulation of the remnant of the binary NS merger.
  - Change of the equiv. state of the NS can be used for mass ejection.
  - Viscosity-driven ejecta could be significant after ~10 s.
  - Late time ejecta will be lanthanide-free.

$\rightarrow$ Short , **Bright**, and Blue emission ?

$$t \propto \kappa^{1/2} v^{-1/2} M_{\rm ej}^{1/2}$$

$$L \propto \kappa^{-1/2} v^{1/2} M_{\rm ej}^{1/2}$$

- Future prospects
  - Dependence on the binary system (masses) and nuclear EOSs.
  - Nucleosynthesis and electromagnetic signals due to radioactive decay.