Neutrino-driven Mass Ejection from the Remnant of Binary Neutron Star Merger

Sho Fujibayashi (Kyoto U),
Yuichiro Sekiguchi (Toho U),
Kenta Kiuchi (YITP), and Masaru Shibata (YITP)

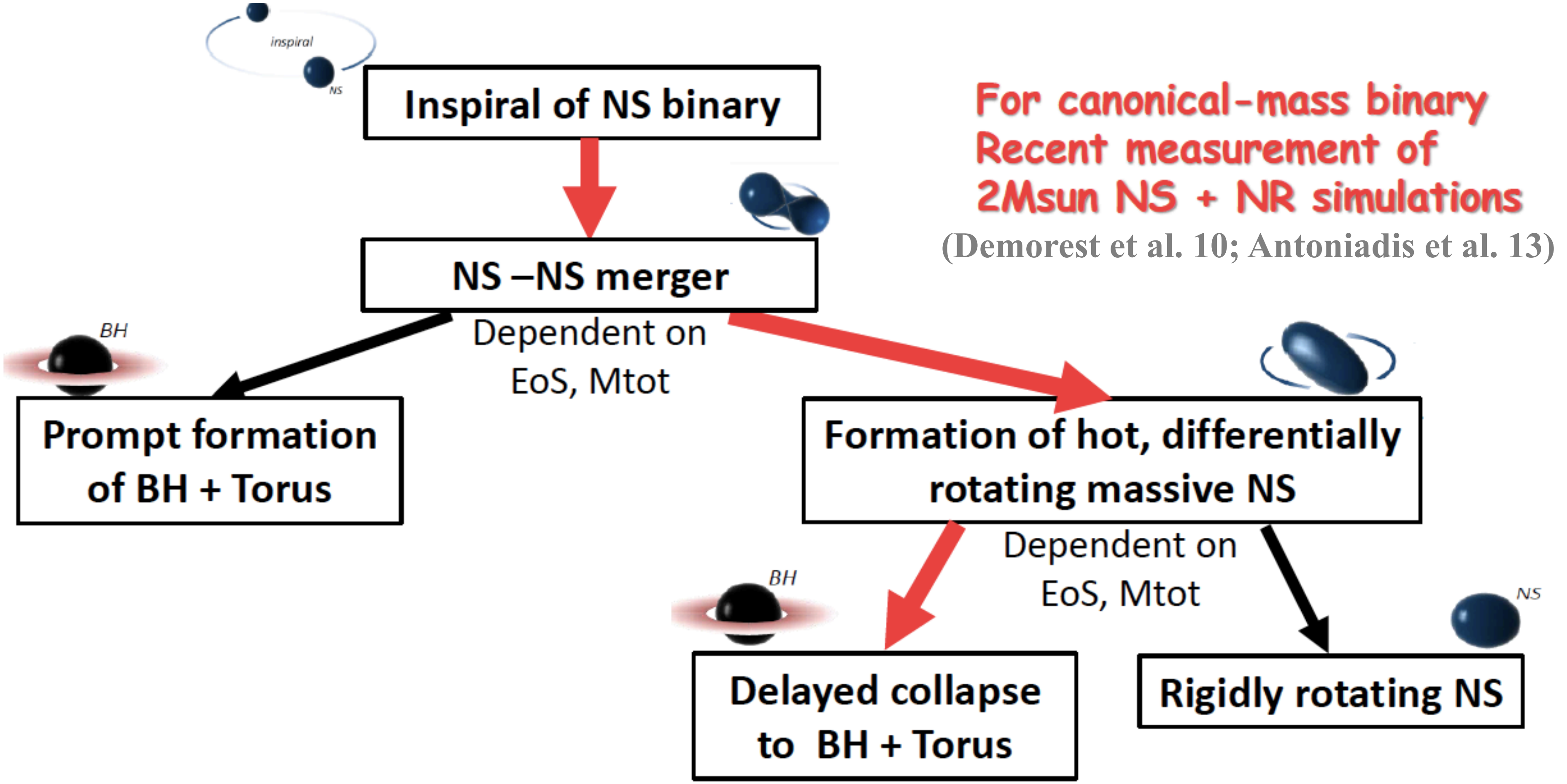
GRADUATE SCHOOL OF SCIENCE
FACULTY OF SCIENCE
KYOTO UNIVERSITY

TOHO UNIVERSITY
NATURE LIFE MAN

YITP
YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

Evolution After Remnant of Binary NS Merger

Shibata et al. 2005,2006
Sekiguchi et al, 2011
Hotokezaka et al. 2013



Inspiral of NS binary

NS –NS merger

Dependent on
EoS, Mtot

Prompt formation of BH + Torus

Formation of hot, differentially rotating massive NS

Dependent on
EoS, Mtot

Delayed collapse to BH + Torus

Rigidly rotating NS

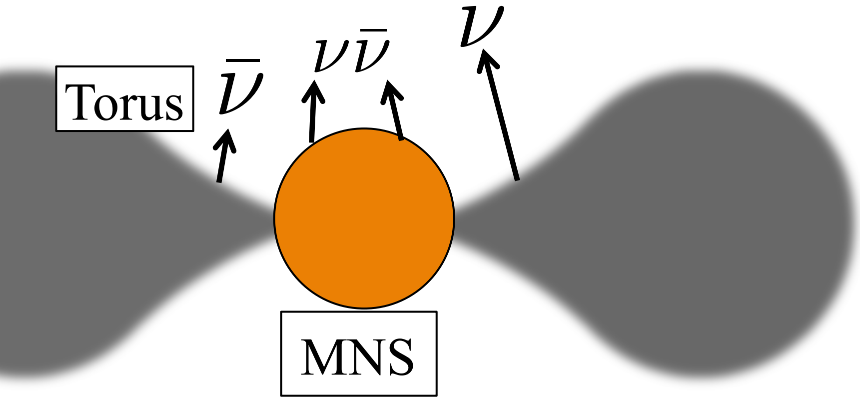
For canonical-mass binary
Recent measurement of
2Msun NS + NR simulations
(Demorest et al. 10; Antoniadis et al. 13)

Neutrino-driven Outflow in MNS Phase

◎ **MNS phase**

- Large neutrino luminosity from the MNS and torus (~10^{53} erg/s)

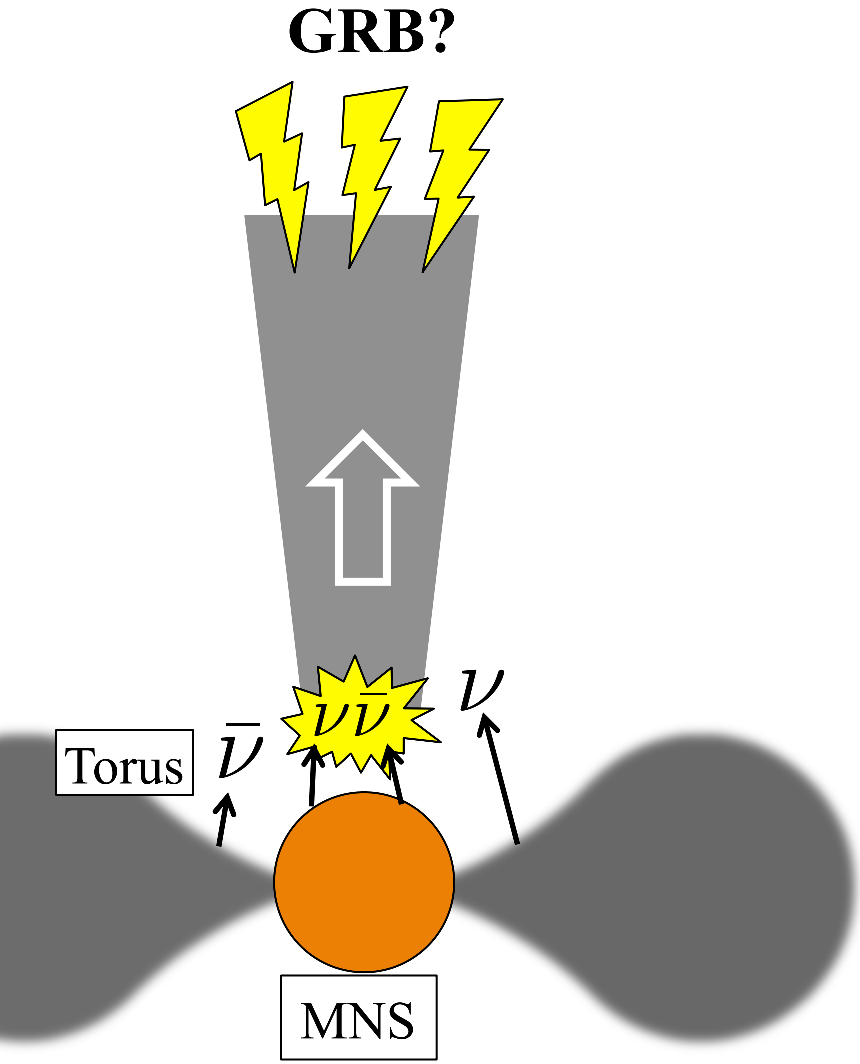
- The effect of neutrinos would be significant.



Neutrino-driven Outflow in MNS Phase

◎ Relativistic jet for short GRBs?

Due to neutrino pair-annihilation heating



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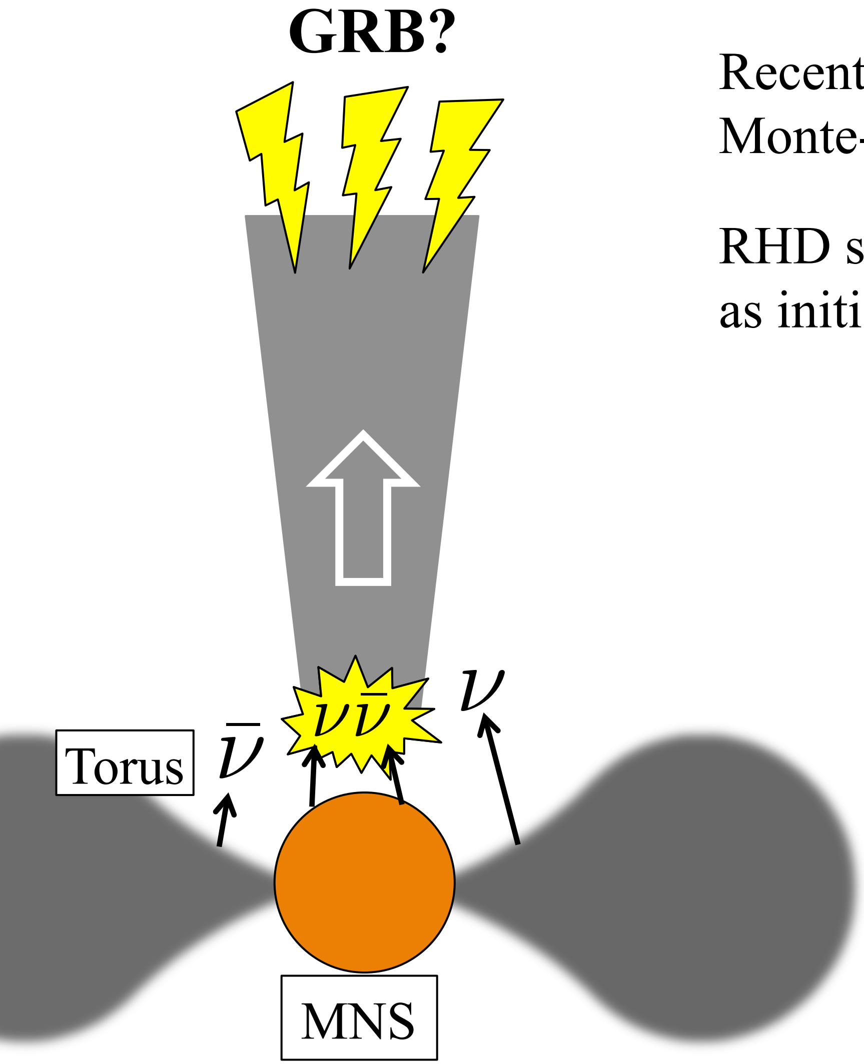
Recent studies :

Monte-Carlo method using Newtonian simulation

Richers et al. 15,

RHD simulations for BH-torus using equilibrium torus as initial conditions **Just et al. 16**



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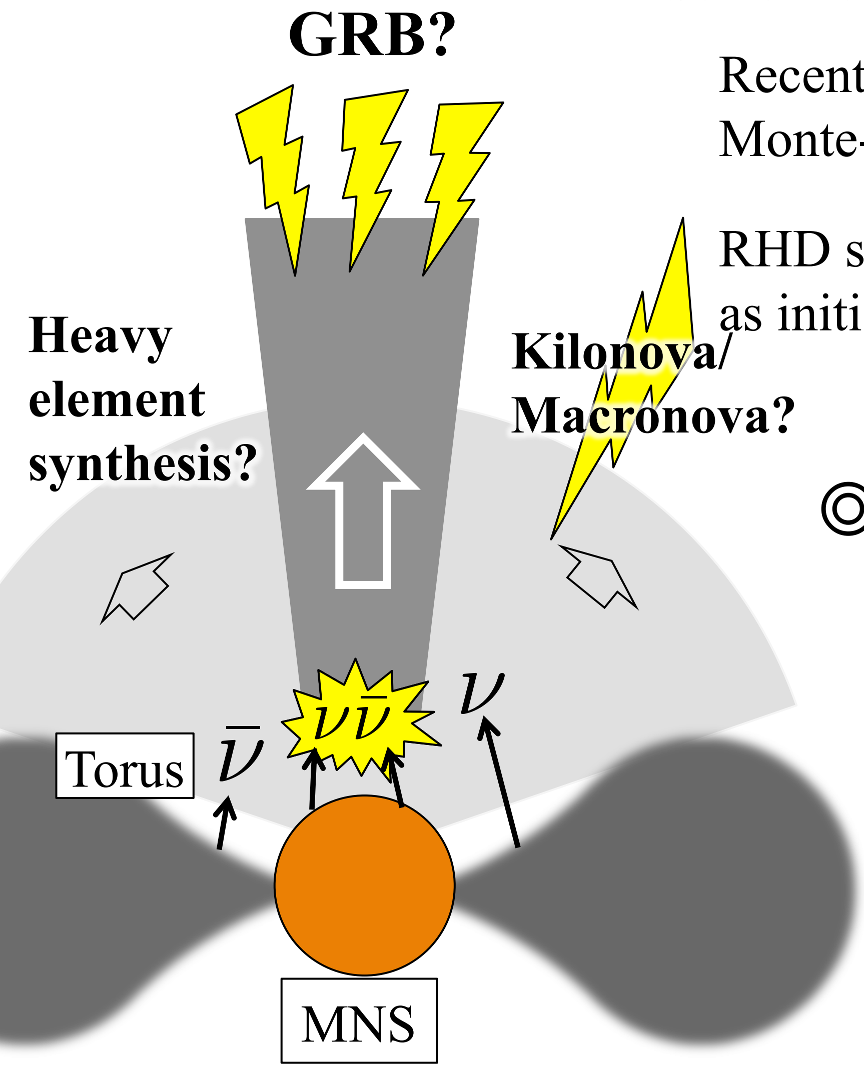

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◎ Neutrino-driven winds

Fernandez & Metzger 13, Perego et al. 14
Metzger & Fernandez 14, Just et al. 15
Fernandez et al. 15

This component would contributes to heavy element nucleosynthesis and electromagnetic signals

Viscosity-driven wind : Fernandez's talk

Neutrino-driven Outflow in MNS Phase

◎ Relativistic jet for short GRBs?

Due to neutrino pair-annihilation heating

Recent studies :
Monte-Carlo method using Newtonian simulation
Richers et al. 15,

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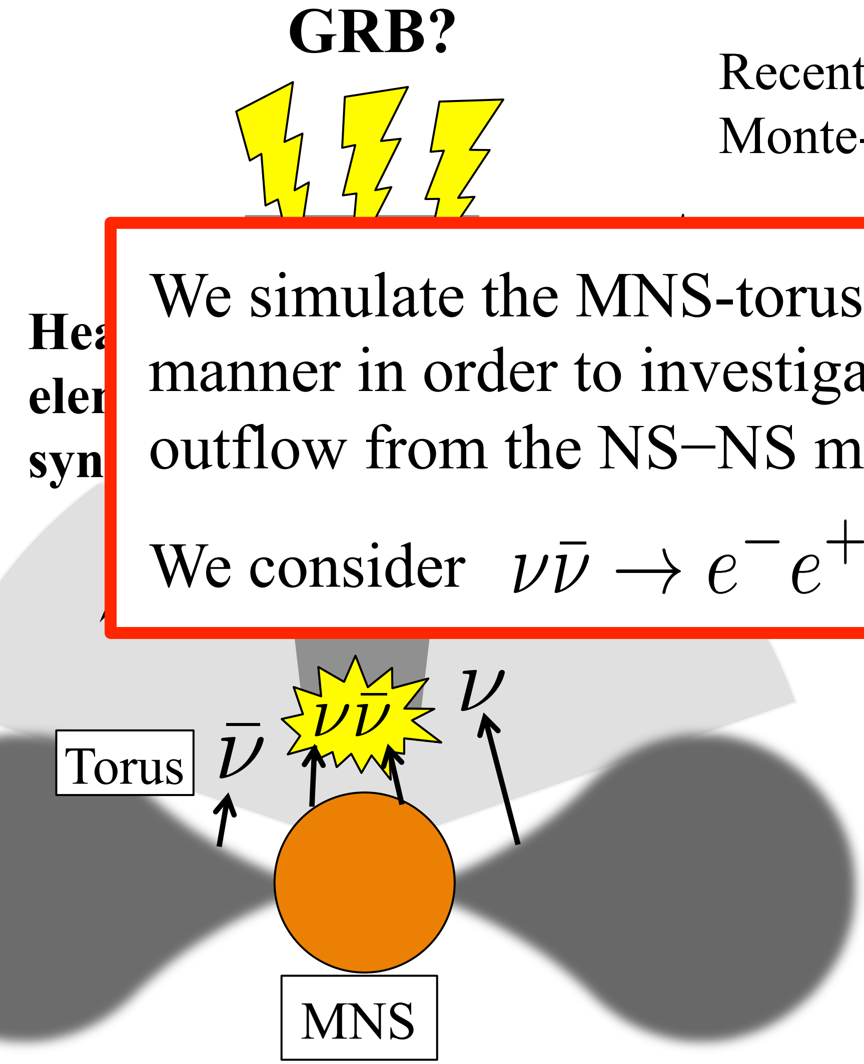
We simulate the MNS-torus system in fully general relativistic manner in order to investigate the properties of neutrino-driven outflow from the NS−NS merger remnant.

We consider $\nu\bar{\nu} \rightarrow e^- e^+$ reaction and investigate the effects.

Metzger & Fernandez 14, Just et al. 15
Fernandez et al. 15



This component would contributes to heavy element nucleosynthesis and electromagnetic signals

Viscosity-driven wind : Fernandez's talk

Method

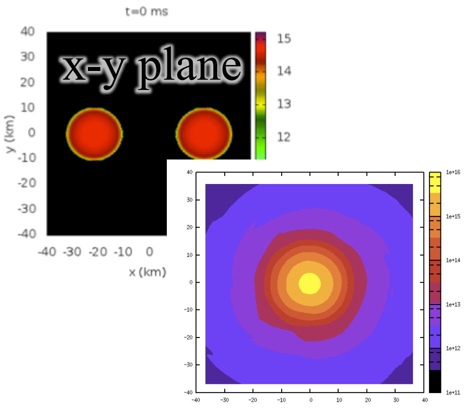
◎ Strategy

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

(Sekiguchi et al. 15)

Equation of state : DD2

(→ The remnant is long-lived MNS)



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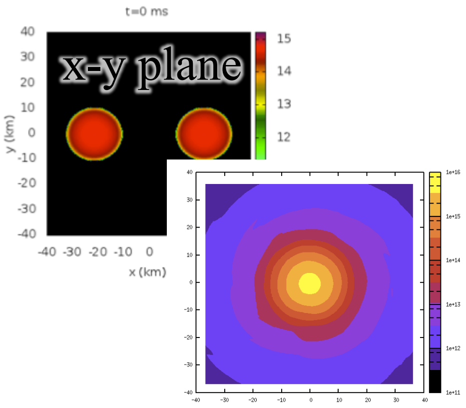
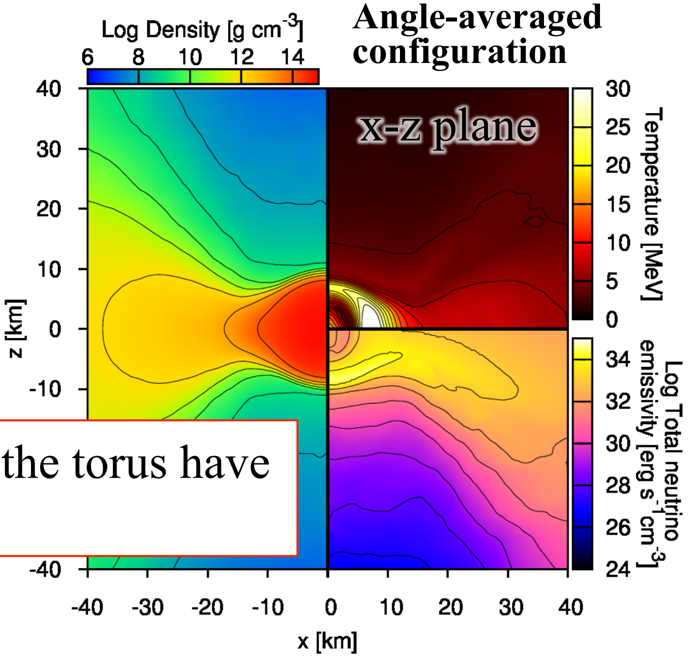


Average over azimuthal angles around the rotational axis after ~50 ms after the merger, when the system settles into quasi-axisymmetic configuration.

Angle-averaged configuration



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

MNS & innermost part of the torus have large neutrino emissivity !

Method

◎ Basic Equations

- Full GR axisymmetric neutrino radiation hydrodynamics simulation

- Einstein's equation : BSSN formalism

  We use Cartoon method to impose axially symmetric conditions.

- General relativistic radiation hydrodynamics :

  Leakage+ scheme incorporating Moment formalism

  Thorne 81
  Shibata et al. 11

  baryons, electrons, trapped neutrinos $\nabla_\alpha T^{\alpha}{}_{\beta} = -Q_{(\mathrm{leak})\beta}$

  streaming neutrinos $\nabla_\alpha T_{(\mathrm{S},\nu)}{}^{\alpha}{}_{\beta} = Q_{(\mathrm{leak})\beta}$

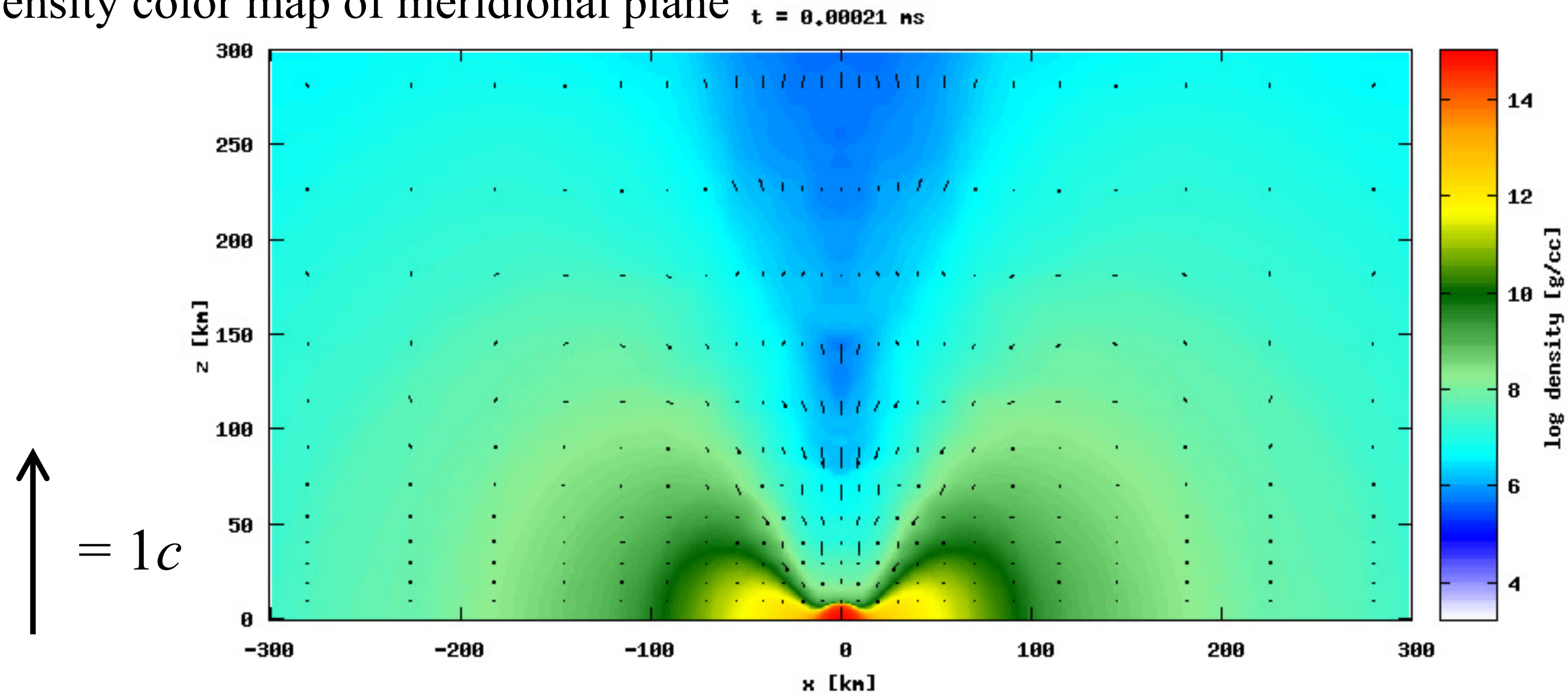
  † We solve neutrino radiation transfer using Moment formalism with M1-closure.

  ††We do not consider the viscosity in this simulation.
  Thus we focus only on purely radiation-hydrodynamical effects on the system.

- Lepton fraction equations

Results : Dynamics of Fluid

Density color map of meridional plane



The density around the rotational axis falls rapidly.
Outflow with ~0.5 c. Relativistic outflow is not seen.

Results : Dynamics of Fluid

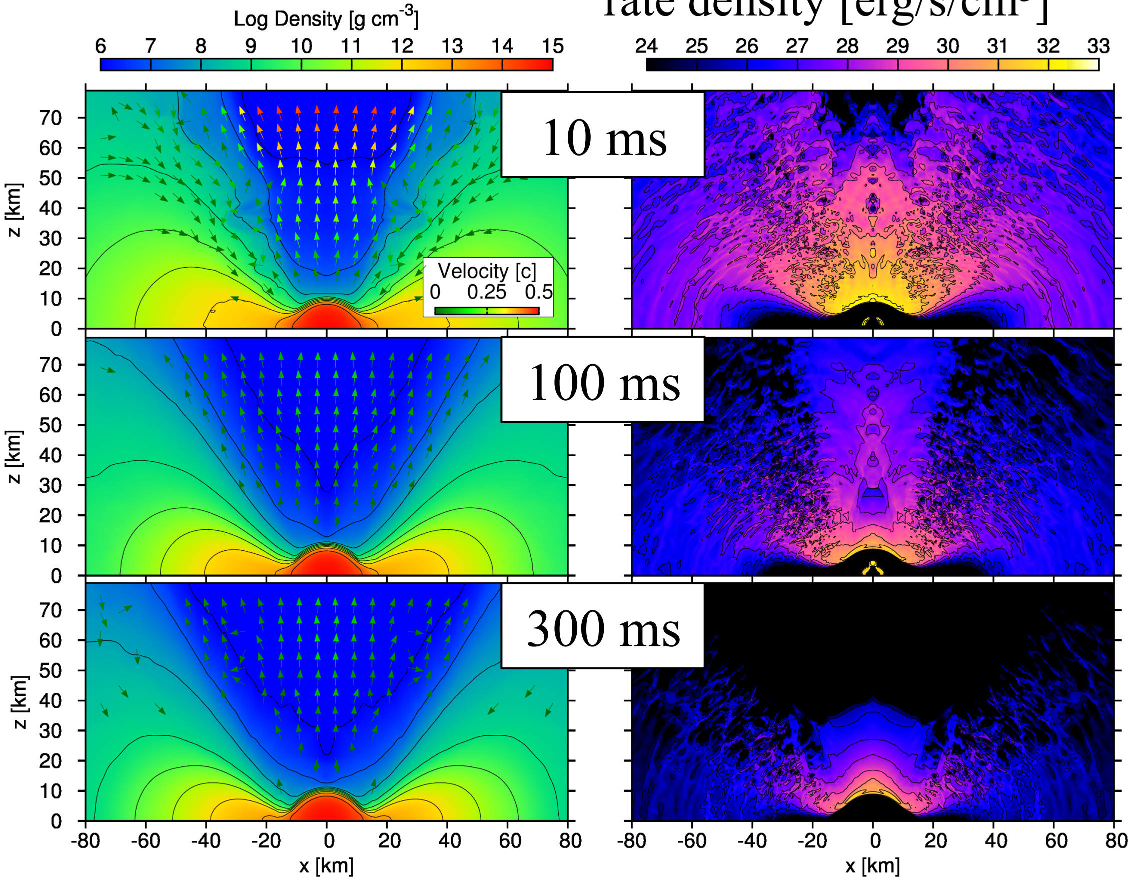
- First ~50 ms

  Strong outflow due to Pair-annihilation heating

- ~100 ms later

  Heating rate decrease
  → outflow becomes weak
  ~ 0.2 c

Log Pair-annihilation heating rate density [erg/s/cm^3]



Relativistic outflow is not observed in this setup

Results : Dynamics of Fluid

- First ~50 ms

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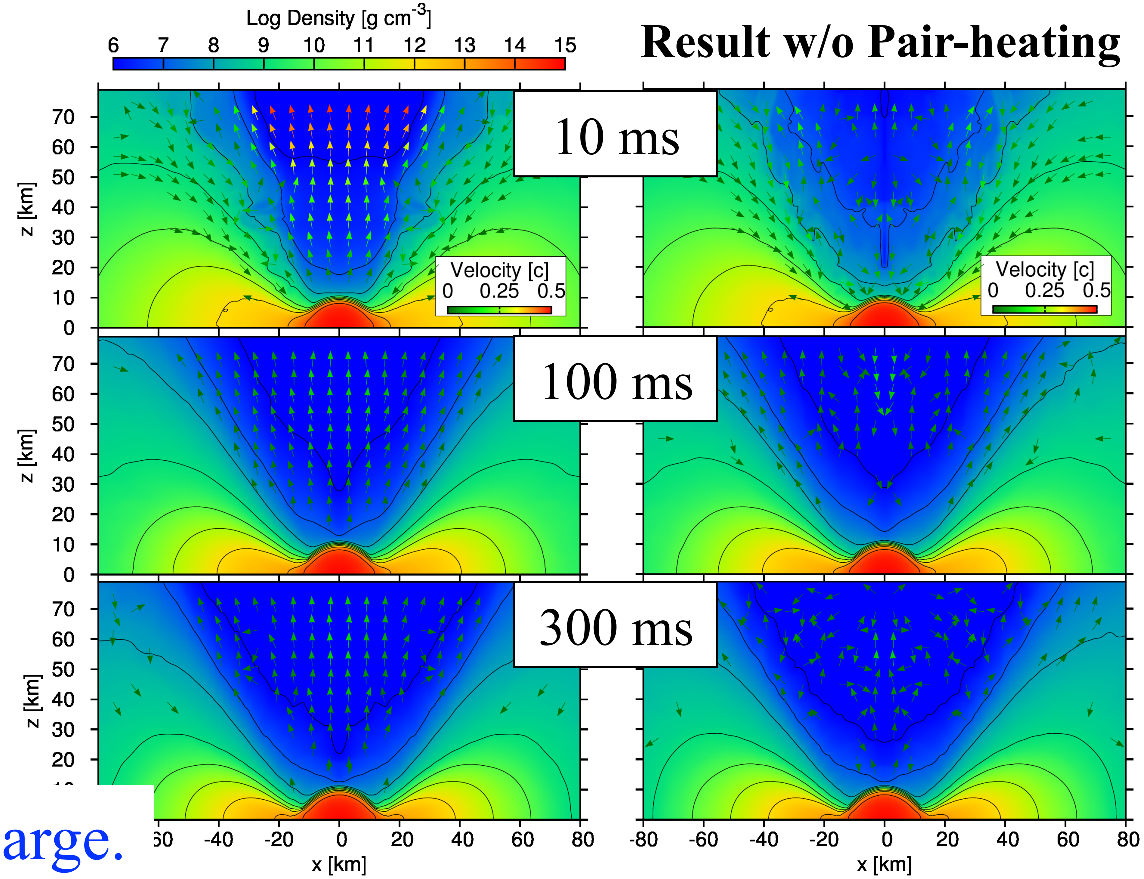
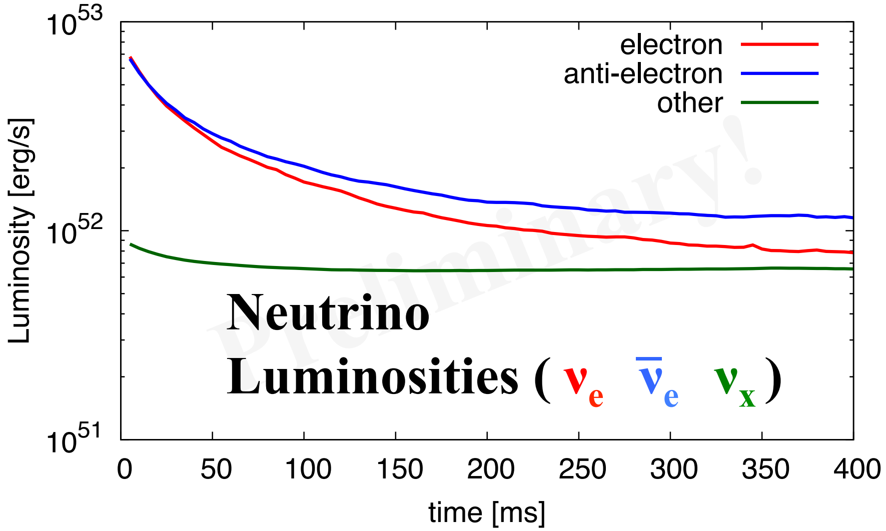
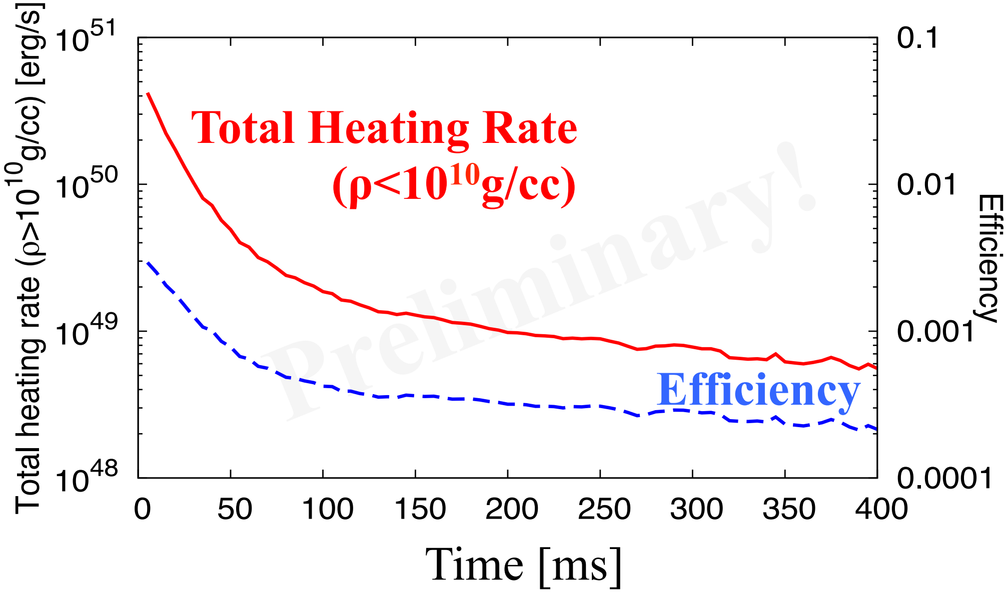

Result w/o Pair-heating

※ Effect of Pair-heating is large.

Strong outflow is not seen in the result without $\nu\,\bar{\nu}$ pair-annihilation.

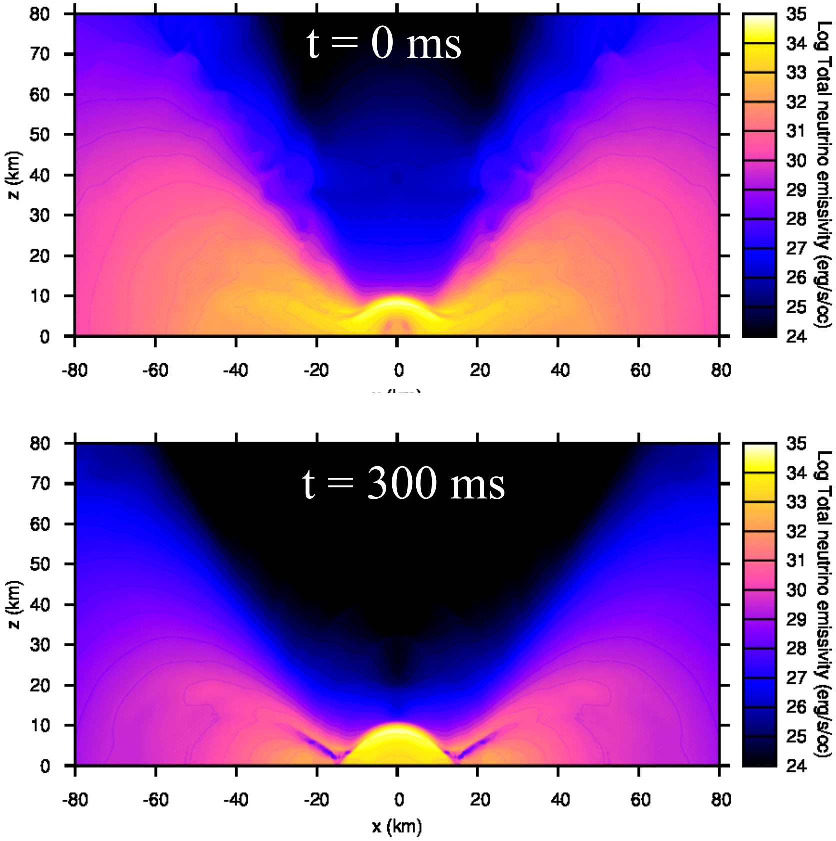
Results : Luminosity & Pair-annihilation heating rates



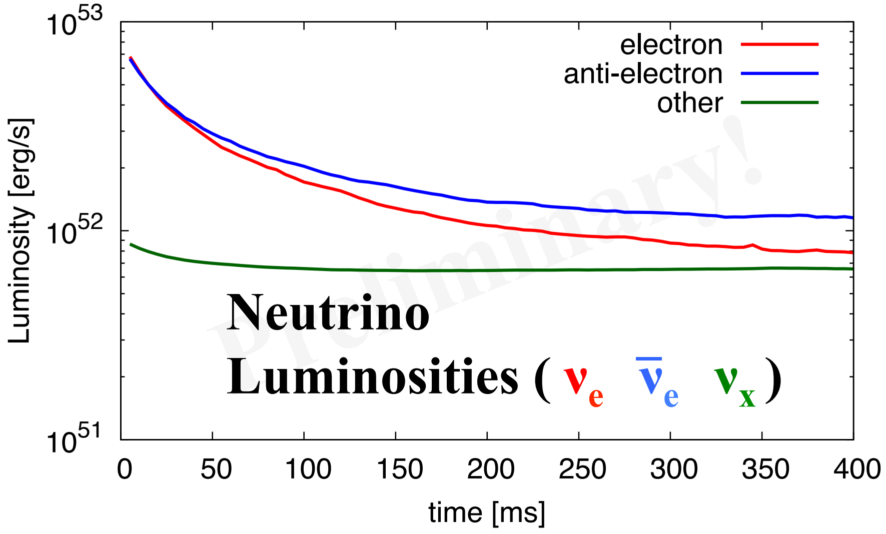


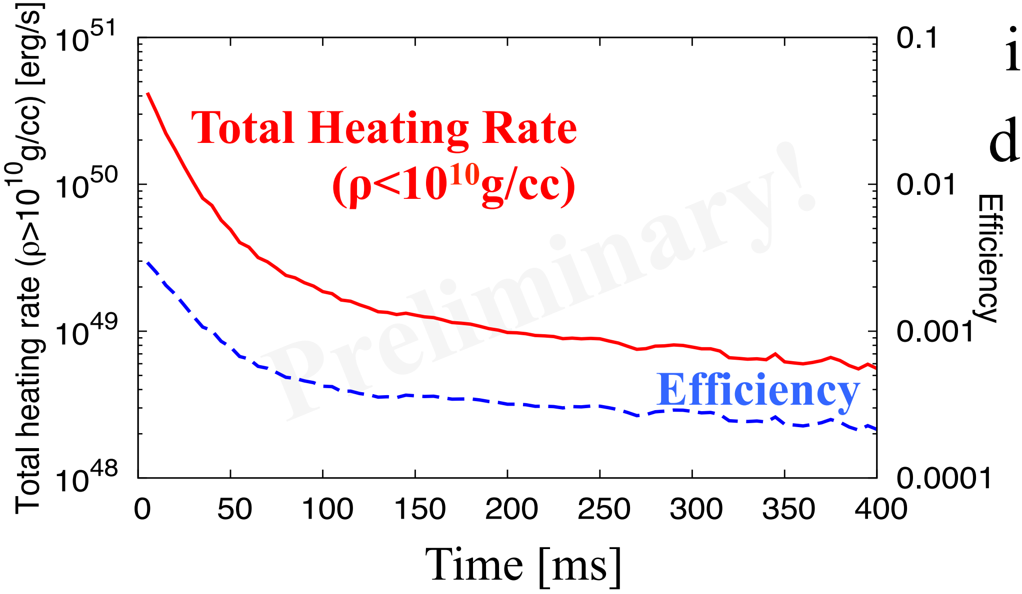
◎ <u>Luminosity</u>

decreases to ~10^{52} erg/s in ~300ms.
and get quasi-stationary.



Results : Luminosity & Pair-annihilation heating rates





◎ <u>Luminosity</u>

decreases to ~10^{52} erg/s in ~300ms.
and get quasi-stationary.

◎ <u>Total pair-annihilation heating rate</u>

$$\dot{E}_{\rm pair} = \int_{\rho<10^{10}{\rm g/cm^3}} d^3x \dot{Q}_{\rm pair}$$

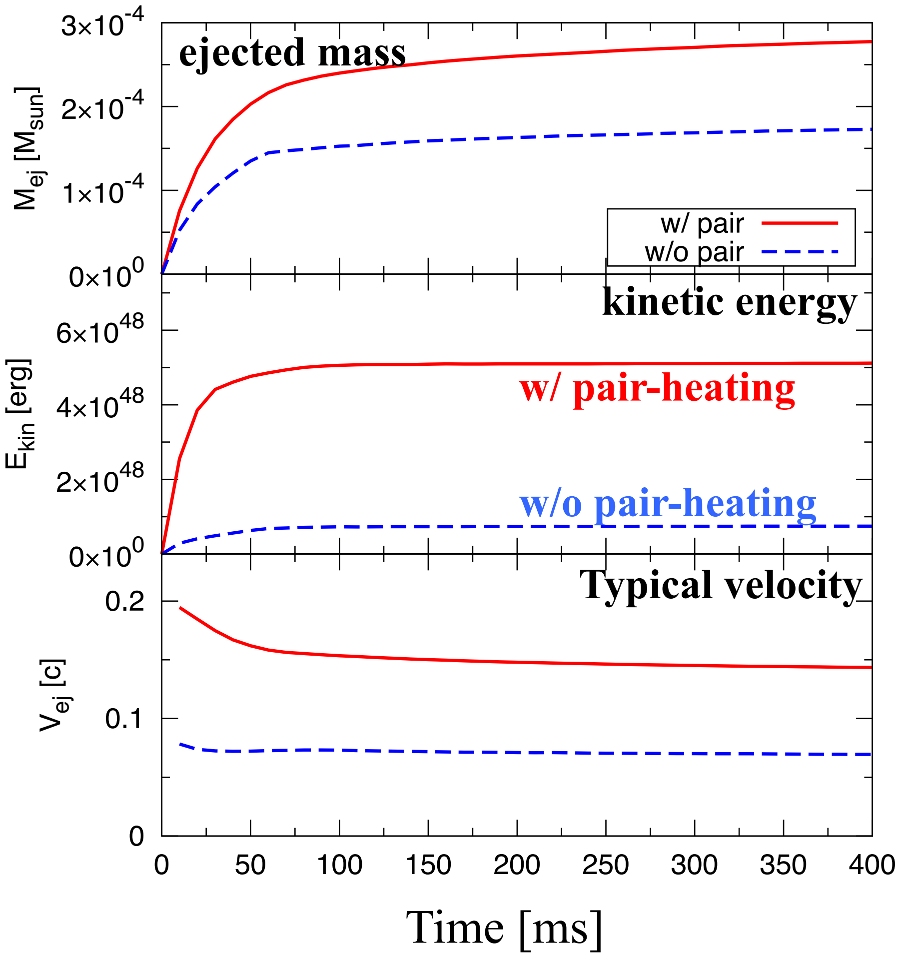
is $>10^{50}$ erg/s in first 50 ms, but decreases to ~10^{49} erg/s in ~300 ms

<u>Efficiency</u> :

$$\eta = \frac{\dot{E}_{\rm pair}}{L_{\nu,{\rm tot}}} \sim 0.3\% \rightarrow 0.03\ \%$$

$$\dot{E}_{\rm pair} \propto {L_\nu}^2 \ \rightarrow\ \text{efficiency} \propto L_\nu$$

Results: The Properties of the Ejecta



- Unbound mass ~ $3\times10^{-4}\ M_\odot$
- Kinetic energy ~ 5×10^{48} erg

Subdominant compared to dynamical ejecta
(~$10^{-3}\ M_\odot$, 2×10^{49} erg for DD2 EOS)

(Sekiguchi et al. 15)

- Average velocity

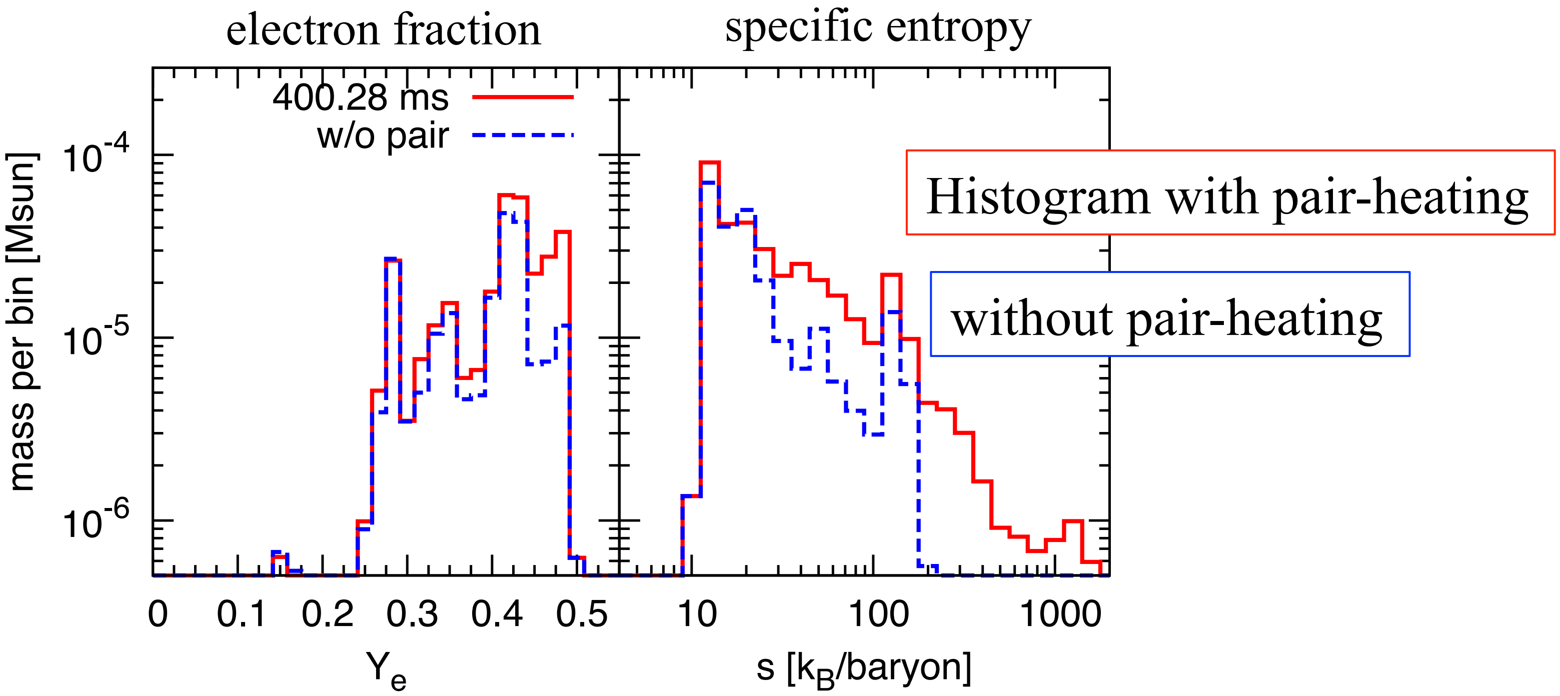
$$V_{\rm ej} = \sqrt{\frac{2E_{\rm kin}}{M_{\rm b,ej}}} \sim 0.1 - 0.2\ \mathrm{c}$$

※ Effect of Pair-heating is large.

Without pair-heating process, we underestimate the amount and kinetic energy of the neutrino-driven outflow.

Results : Electron fraction & Entropy distribution

◎ Mass histogram of ejected material @ t=400 ms



Histogram with pair-heating

without pair-heating

- Material of Y_e>0.25 is mainly ejected. Typical value : ~0.4.
- A small amount (~$10^{-6}M_\odot$) of material has very large specific entropy.

Pair-annihilation process ($\nu + \bar{\nu} \rightarrow e^- + e^+$) can inject energy regardless of baryon density.

r-process in ν-driven outflow

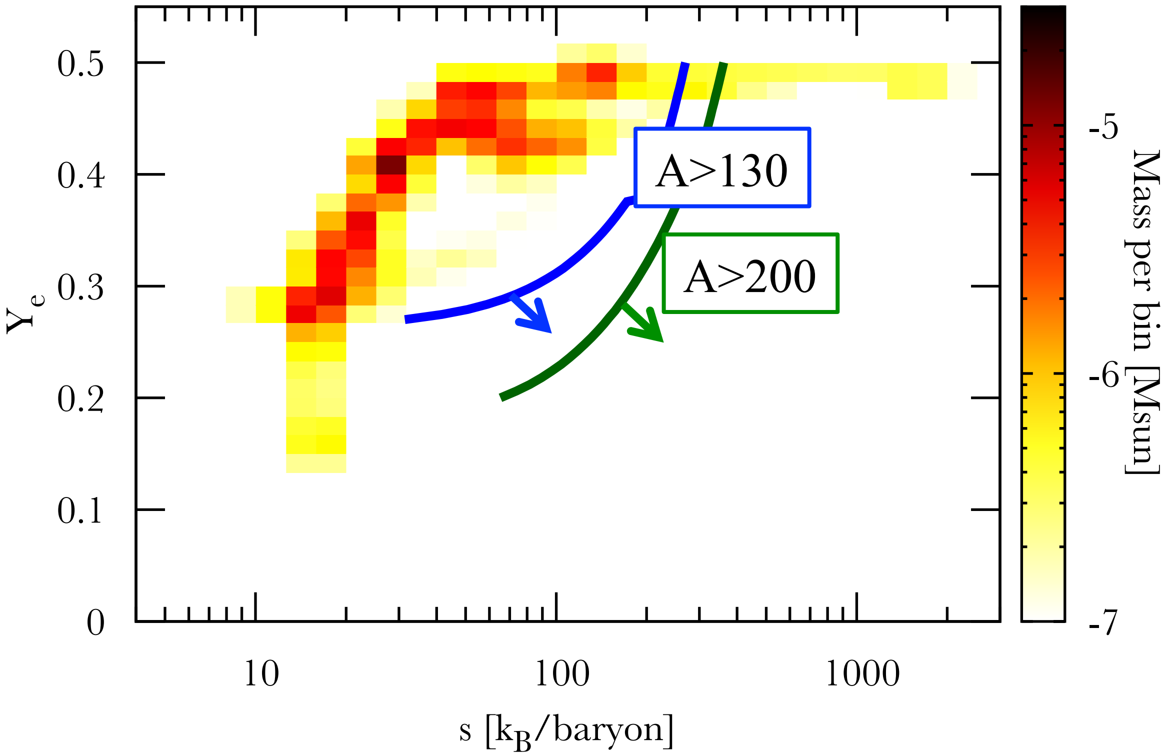
◎ Estimate following Hoffman et al. 97.

(assuming $\tau_{exp} \sim 50$ ms)

— A>130

— A>200

nuclei are produced via the r-process



Mass distribution in Entropy – Electron fraction plane

In the most of the neutrino-driven outflow, heavy nuclei of A>130 are hardly produced via r-process.

Detailed nucleosynthesis study → Next work

Pair-annihilation Heating by Ray-tracing Method

Current treatment of neutrino transfer:
Moment formalism with M1-closure relation **(Shibata et al. 11)**

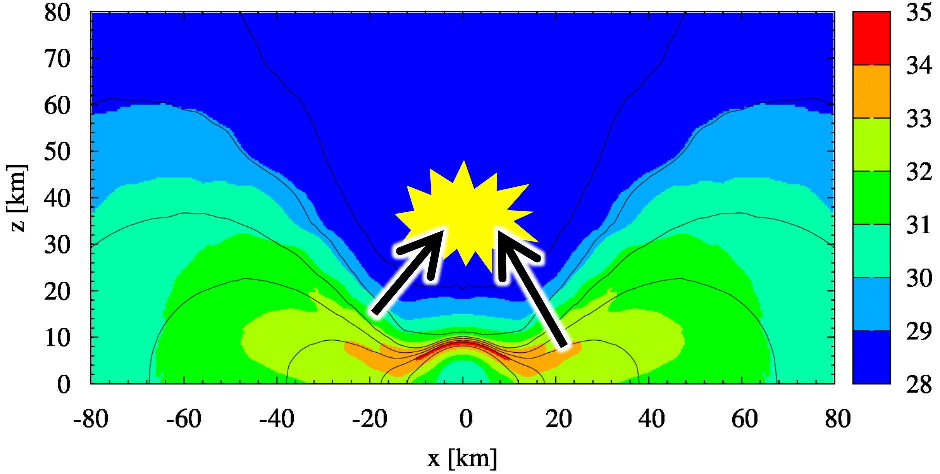
This method cannot treat the crossing of two beams.
Pair-annihilation heating rate should be compared to more Ab initio calculation.

Calculate the pair-annihilation heating rate by ray-tracing method using snapshots of the simulation. **(Ruffert et al. 97)**

$$Q_{\nu\bar{\nu}} = \frac{1}{4}\frac{\sigma_0}{c(m_e c^2)^2}\frac{C_1+C_2}{3}\int d\Omega I_\nu \int d\Omega' I_{\bar{\nu}}[\langle\epsilon\rangle_\nu + \langle\epsilon\rangle_{\bar{\nu}}](1-\cos\theta_{\nu\bar{\nu}})^2$$

$$d\Omega I_\nu = Q_\nu^{\mathrm{eff}}\frac{d^3x'}{\pi|\boldsymbol{x}-\boldsymbol{x}'|^2}$$

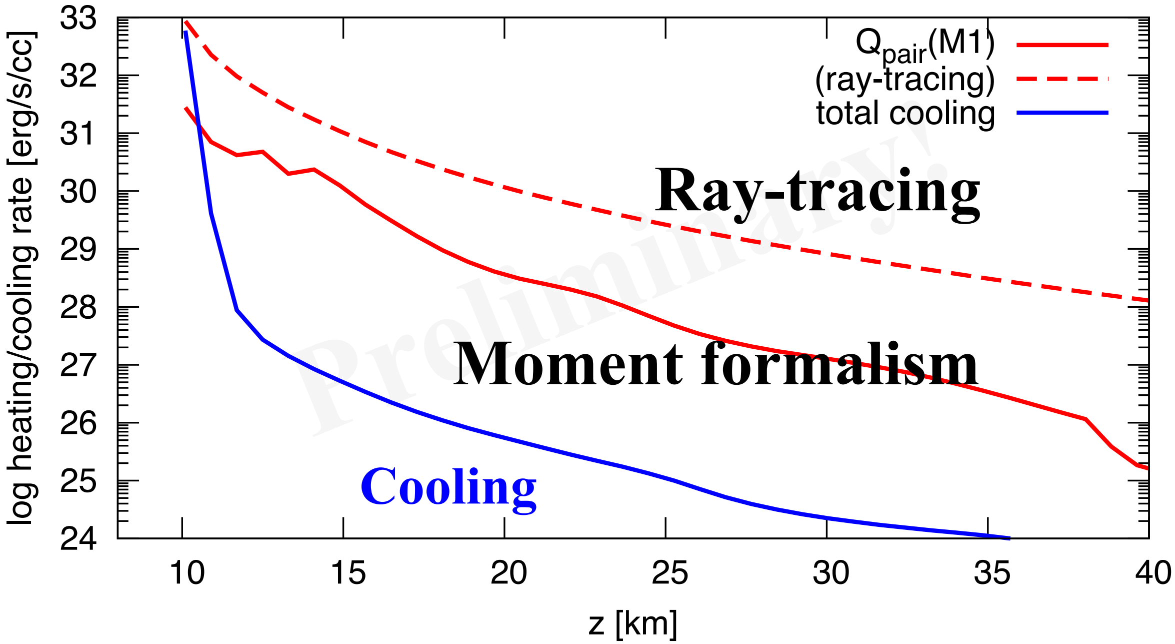
Log Total neutrino emissivity [erg/s/cm3]



*We ignore general relativistic effects.

Pair-annihilation Heating Rate by Ray-tracing method

Pair-annihilation heating rate along z-axis
using snapshot at t = 100ms



Heating rate estimated with (simple) ray-tracing method
~10 times larger that that with moment formalism.
Heating rate would be underestimated.

Summary

Long-term simulations for MNS-torus system to investigate the neutrino-driven mass ejection from the system.

- Neutrinos
  - Luminosity $\sim 10^{53} \rightarrow 10^{52}$ erg/s in ~100ms.
  - Pair-annihilation heating > 10^{50} erg/s at first ($\eta \sim 0.3\%$), but decreases to $\sim 10^{49}$ erg/s ($\eta \sim 0.03\%$).
  - heating rate would be underestimated.
- Ejected mass
  - Unbound mass : $M_{ej} \sim (10^{-4}–10^{-3})\ M_{\odot}$.
  - The kinetic energy : $E_{kin} \sim 10^{48} - 10^{49}$ erg.
  - Subdominant compared to dynamical component.

† Investigating viscosity-driven wind : near future!

Moment Formalism

Thorne 81, Shibata et al. 11

- **Variables**

$$M^{\alpha\beta} = \int dV_p p^\alpha p^\beta f(p,x)$$

(Energy-momentum tensor of neutrino)

$$= E n^\alpha n^\beta + F^\alpha n^\beta + F^\beta n^\alpha + P^{\alpha\beta}$$

n^α : normal of the time slice

- **Evolution Eqs.** (3+1 decomposition of $\nabla_\beta M^{\alpha\beta} = (\text{Source Terms})^\alpha$)

$$\partial_t(\sqrt{\gamma}E) + \partial_j[\sqrt{\gamma}(\alpha F^j - \beta^j E)] = \alpha\sqrt{\gamma}[P^{ij}K_{ij} - F^j\partial_j \ln\alpha - S^\alpha n_\alpha],$$

$$\partial_t(\sqrt{\gamma}F_i) + \partial_j[\sqrt{\gamma}(\alpha P_i{}^j - \beta^j F_i)] = \sqrt{\gamma}\Big[-E\partial_i\alpha + F_k\partial_i\beta^k + \frac{\alpha}{2}P^{jk}\partial_i\gamma_{jk} + \alpha S^\alpha\gamma_{i\alpha}\Big],$$

- **Closure relation (M1-closure)**

opt. thin → $P^{ij} = E\dfrac{F^iF^j}{\gamma_{kl}F^kF^l}$

opt. thick→ $P^{ij} = \dfrac{E}{2w^2+1}\left[(2w^2-1)\gamma^{ij} - 4V^iV^j\right] + \dfrac{1}{w}\left[F^iV^j + F^jV^i\right] + \dfrac{2F^ku_k}{w(2w^2+1)}\left[-w^2\gamma^{ij} + V^iV^j\right]$

$= \dfrac{1}{3}E\gamma^{ij}$ (if $u^i = 0$)

- Energy loss rate due to reaction (opt-thin limit)

$$Q^{\mathrm{reac}} = Q^{\mathrm{reac}}(\rho, Y_e, T) =$$ (electron, positron-capture of nuclei)
+ (pair-production)

- due to diffusion (opt-thick limit)

$$Q^{\mathrm{leak}} = \int dE \frac{En(E)}{\tau_{\mathrm{diff}}(E)}$$

diffusion time

$$\tau_{\mathrm{diff}}(E) = \frac{\tau^2(E)}{c} l_{\mathrm{mfp}}(E)$$

- Effective energy loss rate

$$Q^{\mathrm{eff}} = (1 - e^{-\tau})Q^{\mathrm{leak}} + e^{-\tau} Q^{\mathrm{reac}}$$

$$\epsilon = (1 - e^{-\tau})\epsilon^{\mathrm{leak}} + e^{-\tau}\epsilon^{\mathrm{reac}}$$
$$\epsilon^{\mathrm{leak}} = Q^{\mathrm{leak}}/R^{\mathrm{leak}}$$
$$\epsilon^{\mathrm{reac}} = Q^{\mathrm{reac}}/R^{\mathrm{reac}}$$

Solving this Eq.
→ obtain ε