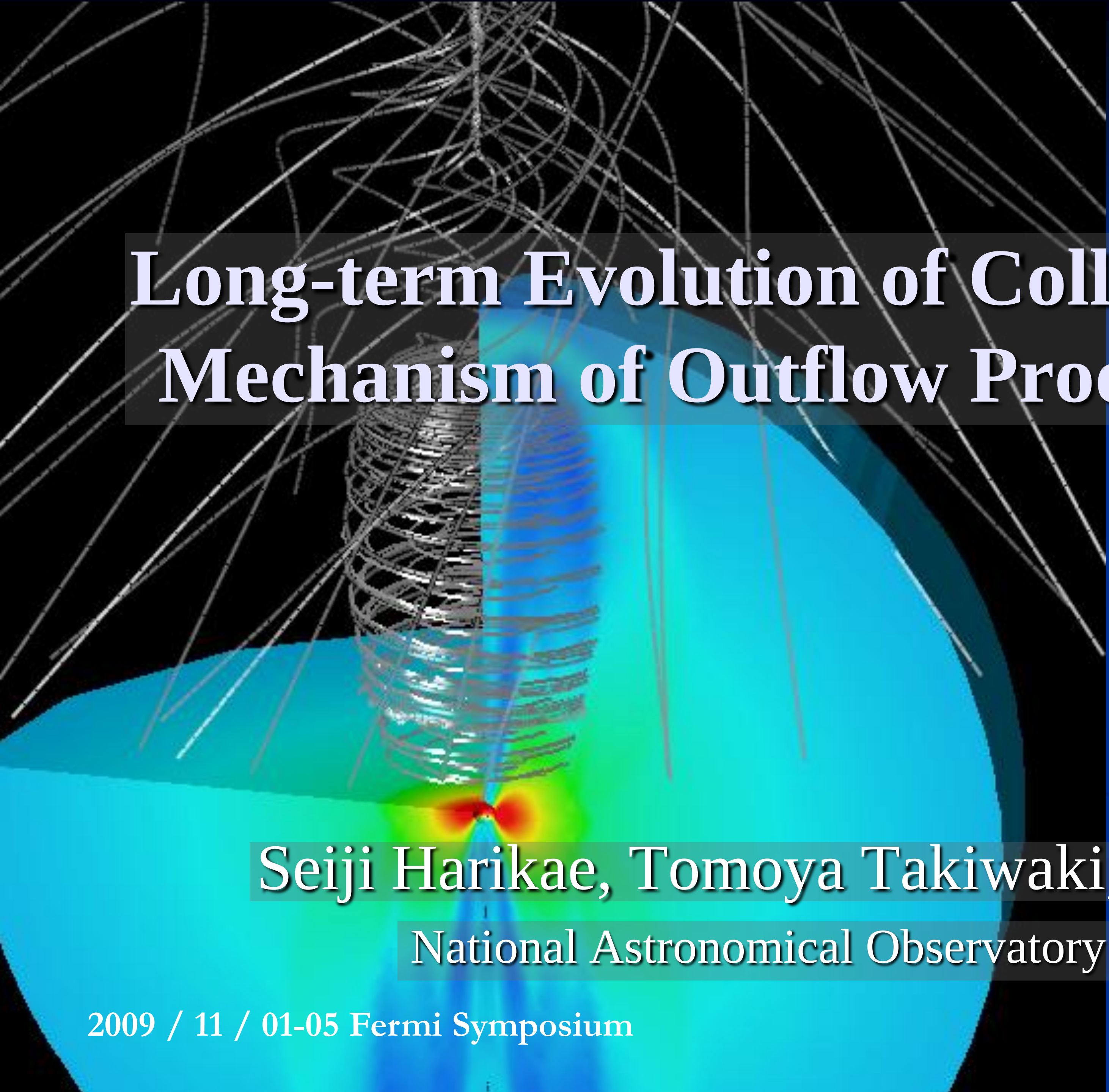
Long-term Evolution of Collapsars : Mechanism of Outflow Production



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Abstract

We present our numerical results of two-dimensional hydrodynamic (HD) and magnetohydrodynamic (MHD) simulations of the collapse of rotating massive stars in light of the collapsar model of gamma-ray bursts (GRBs). Pushed by recent evolution calculations of GRB progenitors, we focus on lower angular momentum of the central core than the ones taken mostly in previous studies. By performing special relativistic simulations including both realistic equation of state and neutrino cooling, we follow a unprecedentedly long-term evolution of the slowly rotating collapsars up to 10 s, accompanied by the formation of jets and accretion disks. We find the formation of thick disk in the equatorial plane and the launch of both the MHD jets and the HD jet at several seconds after core-collapse. We discuss the formation mechanism of each outflow and their connection to GRBs.

Outline

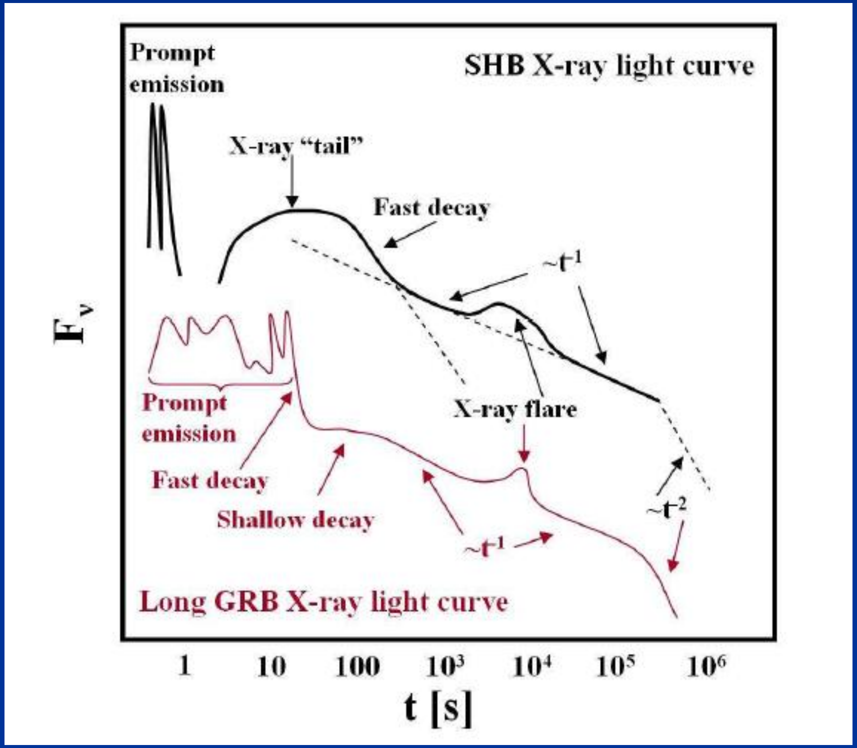
- Introduction
- Numerical methods for magneto-driven outflow and neutrino-driven outflow
- Results
- Summary and conclusion

Intro

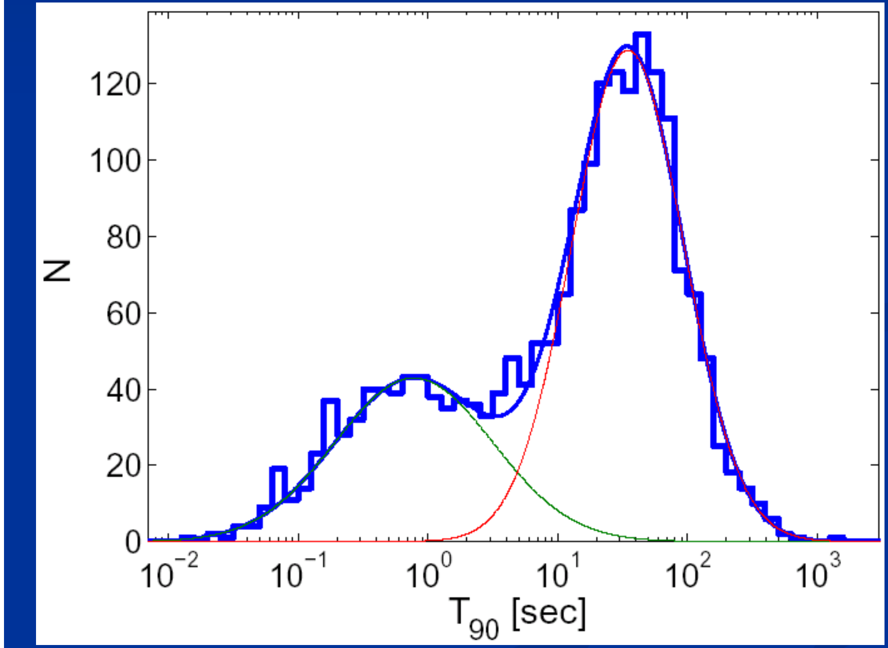
Properties of LGRB

Nakar (2007)

Typical light curve



Duration time vs Observed number (yr^{-1})



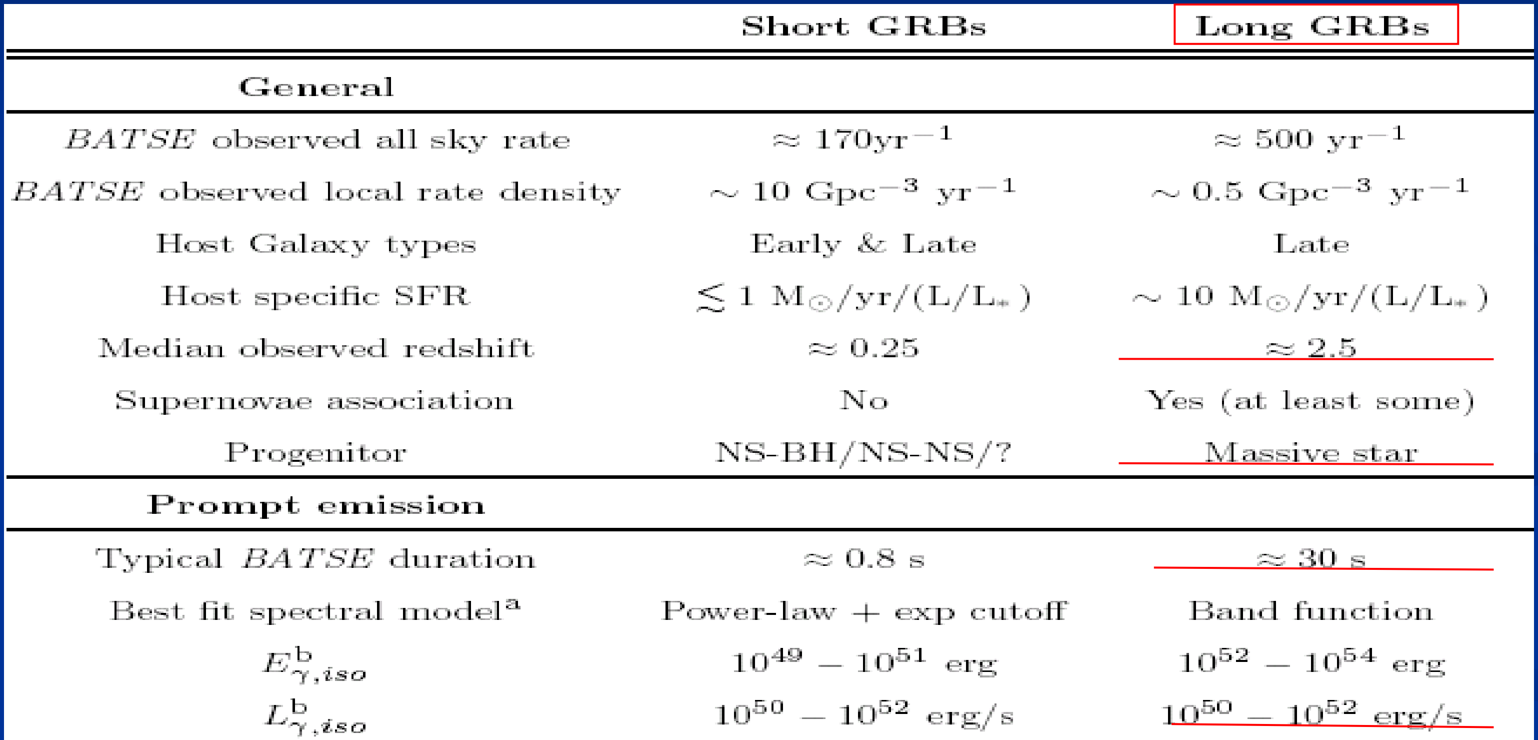
Long duration of prompt emission ⇒ Long GRB (LGRB)

Intro

Properties of LGRB

Nakar (2007)

General feature of GRBs



	Short GRBs	Long GRBs
General		
BATSE observed all sky rate	$\approx 170\text{yr}^{-1}$	$\approx 500\ \text{yr}^{-1}$
BATSE observed local rate density	$\sim 10\ \text{Gpc}^{-3}\ \text{yr}^{-1}$	$\sim 0.5\ \text{Gpc}^{-3}\ \text{yr}^{-1}$
Host Galaxy types	Early & Late	Late
Host specific SFR	$\lesssim 1\ \text{M}_{\odot}/\text{yr}/(\text{L}/\text{L}_*)$	$\sim 10\ \text{M}_{\odot}/\text{yr}/(\text{L}/\text{L}_*)$
Median observed redshift	≈ 0.25	≈ 2.5
Supernovae association	No	Yes (at least some)
Progenitor	NS-BH/NS-NS/?	Massive star
Prompt emission		
Typical *BATSE* duration	≈ 0.8 s	≈ 30 s
Best fit spectral model[a]	Power-law + exp cutoff	Band function
$E^{\text{b}}_{\gamma,iso}$	$10^{49} - 10^{51}$ erg	$10^{52} - 10^{54}$ erg
$L^{\text{b}}_{\gamma,iso}$	$10^{50} - 10^{52}$ erg/s	$10^{50} - 10^{52}$ erg/s

Requirements for LGRB progenitor：

①jet-like explosion (with rotation)

②low metallicity massive star

③energy emission with $10^{50\sim52}$erg/s

④duration time ～ 30 s

Intro

Path for Collapsar

Massive star

Collapse
(direct black hall)

Collapse

PNS

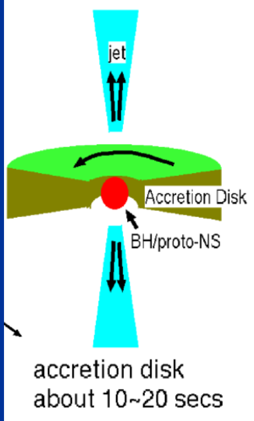
BH

Fa

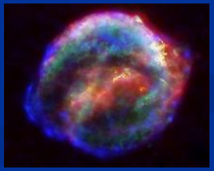
explosion

explo on

PATH for LGRB



LGRB



SN

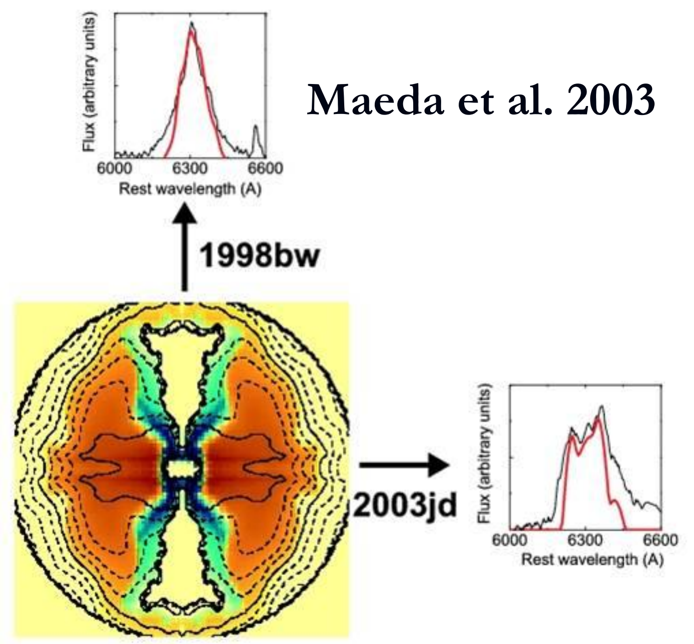
Intro

Collapsar

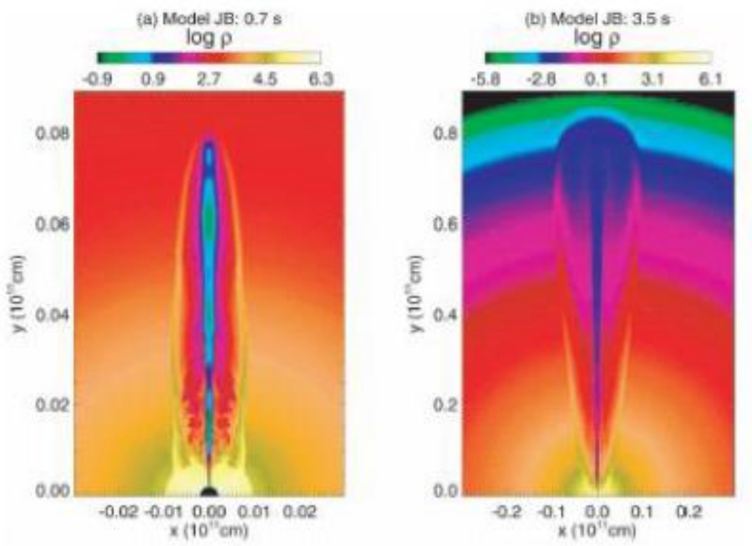
- After the identification of GRB/SN (SN1998bw, SN2003dh) 、collapsar model becomes the most plausible model for LGRB(+SN).

wind from torus ⇒ SN　？

jet on the axis ⇒ LGRB　？



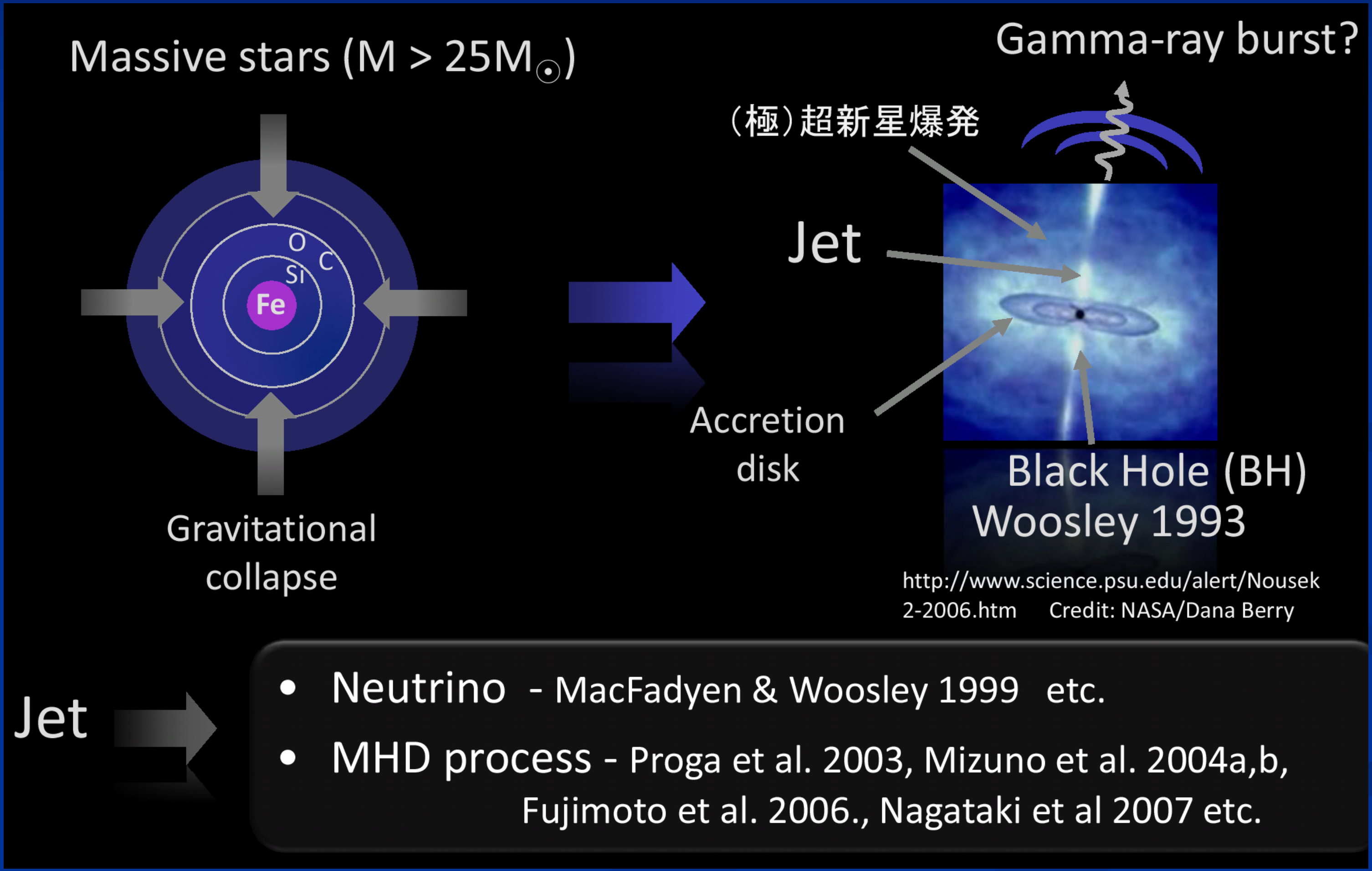
Maeda et al. 2003



Zhang et al. 2003

Intro

Collapsar



Massive stars ($M > 25M_\odot$)

Gravitational collapse

Gamma-ray burst?

（極）超新星爆発

Jet

Accretion disk

Black Hole (BH)

Woosley 1993

http://www.science.psu.edu/alert/Nousek2-2006.htm Credit: NASA/Dana Berry

Jet

- Neutrino - MacFadyen & Woosley 1999 etc.
- MHD process - Proga et al. 2003, Mizuno et al. 2004a,b, Fujimoto et al. 2006., Nagataki et al 2007 etc.

(Figure in presentation file of Mizuno)

Intro
Previous studies

MHD(magnetohydrodynamic) process or neutrino process. So far, a lot of MHD simulations have been performed by many groups (e.g., Proga (2003); Proga et al. (2003); Mizuno et al. (2006); Fujimoto et al. (2006); Sekiguchi & Shibata (2007); Nagataki et al. (2007); Nagataki (2009))

Neutrino driven outflow still remains preliminary ones, such as evaluation in post-processing step (e.g., Ruffert et al. (1997); Ruffert & Janka (1998)) or artificial injection of thermal energy (e.g., MacFadyen & Woosley (1999)). One of the most advanced work has been done by Nagataki et al. (2007), who followed the time evolution with neutrino heating by neutrino-nucleon interaction ($ve + n \rightarrow e^- + p$, $\overline{ve} + p \rightarrow e^+ + n$) *and neutrino pair annihilation* ($v + \overline{v} \rightarrow e^- + e^+$), although they could not observe any neutrino driven outflow.

No one has succeeded to reproduce GRBs from stellar core-collapse in a consistent manner.

Intro

Our purpose

- We focus of the long-term evolution, since almost all of simulations have been performed in so short time (～ 1 s) compared to LGRB(～30 s).
- We perform HD and MHD simulations to determine the formation mechanism of the LGRBs.
- For HD simulation, we include neutrino-antineutrino pair annihilation.

Numerical methods

(1) MHD simulation

- MHD simulation without neutrino heating
  - Special relativistic MHD code (Takiwaki et al 2009)
  - Neutrino cooling is calculated by leakage scheme.
  - Realistic EOS of Shen et al (1998) is implemented.
  - Initial data is taken from 35OC model (Woosley&Heger 2006)
  - Initial rotation and magnetic field is set with analytical form.

$$j = \alpha j_{\rm Iso}(M(R)) \qquad A_r = A_\theta = 0 \qquad A_\phi = \frac{B_0}{2}\frac{r_0^3}{r^3 + r_0^3} r \sin\theta$$

  - Numerical domain covers 50km < r < 30000km, 0 < θ < π/2 with 300(r) × 40(θ)

Numerical methods

(2) HD simulation

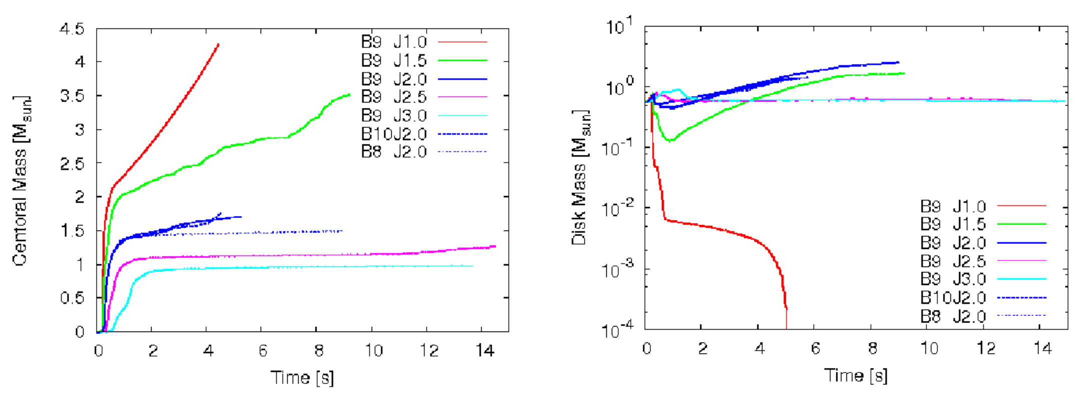
- HD simulation with neutrino heating
  - Special relativistic MHD code (Takiwaki et al 2009)
  - Neutrino cooling is calculated by leakage scheme.
  - Neutrino heating is calculated by ray-tracing in flat space-time.
  - Realistic EOS of Shen et al (1998) is implemented.
  - Initial data is taken from 35OC model (Woosley&Heger 2006)
  - Initial rotation is set with analytical form.

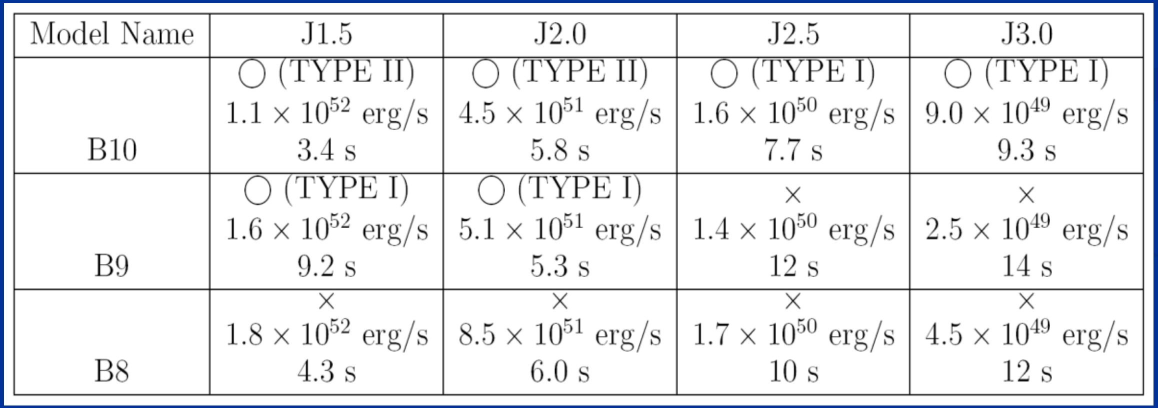
$$\Omega(r,\theta) = \frac{\Omega_0 X_0^4 + \alpha \Omega_{\rm lso}(M(X)) X^4}{X_0^4 + X^4}$$

  - Numerical domain covers $\max(10\mathrm{km}, 2r_g) < r < 30000\mathrm{km}$, $0 < \theta < \pi/2$, $0 < \varphi < 2\pi$ with $300(r) \times 40(\theta) \times 32(\varphi)$

Azimuthal mesh is used only when we calculate neutrino pair annihilation.

Results (MHD simulation)



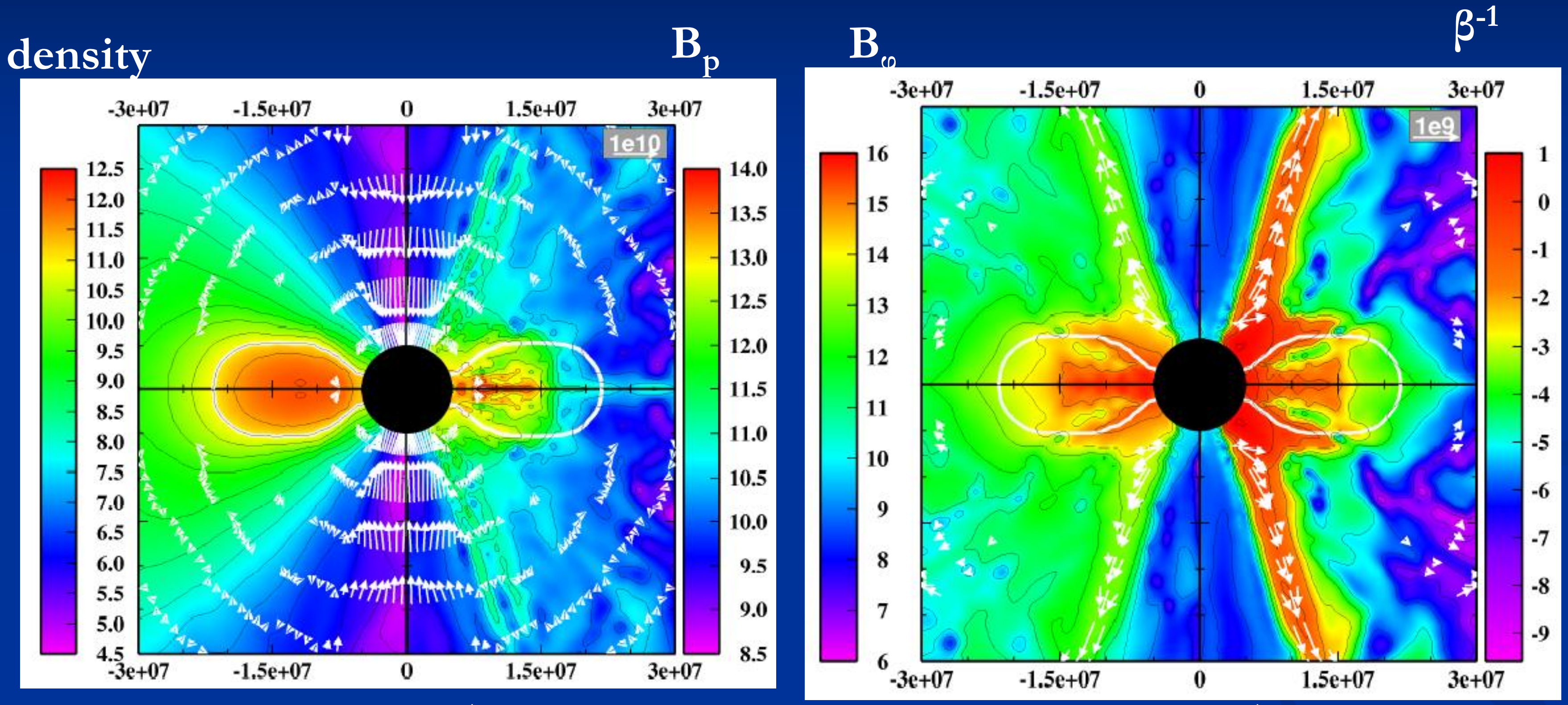


Model Name	J1.5	J2.0	J2.5	J3.0
B10	○ (TYPE II) 1.1×10^{52} erg/s 3.4 s	○ (TYPE II) 4.5×10^{51} erg/s 5.8 s	○ (TYPE I) 1.6×10^{50} erg/s 7.7 s	○ (TYPE I) 9.0×10^{49} erg/s 9.3 s
B9	○ (TYPE I) 1.6×10^{52} erg/s 9.2 s	○ (TYPE I) 5.1×10^{51} erg/s 5.3 s	× 1.4×10^{50} erg/s 12 s	× 2.5×10^{49} erg/s 14 s
B8	× 1.8×10^{52} erg/s 4.3 s	× 8.5×10^{51} erg/s 6.0 s	× 1.7×10^{50} erg/s 10 s	× 4.5×10^{49} erg/s 12 s

Existence of outflow、
neutrino luminosity、
and time when disk becomes stationary.

i) Outflow is formed for models with strong magnetic field and slow rotation.
ii) The type of outflow can be divided into two (TYPE I and TYPE II).
iii) Neutrino luminosity reached 10^{52}erg/s, depending on the initial rotation.

Results (MHD simulation)



（Figure for model with 10^9G, j=1.5j_{lso}(7.99 s)）

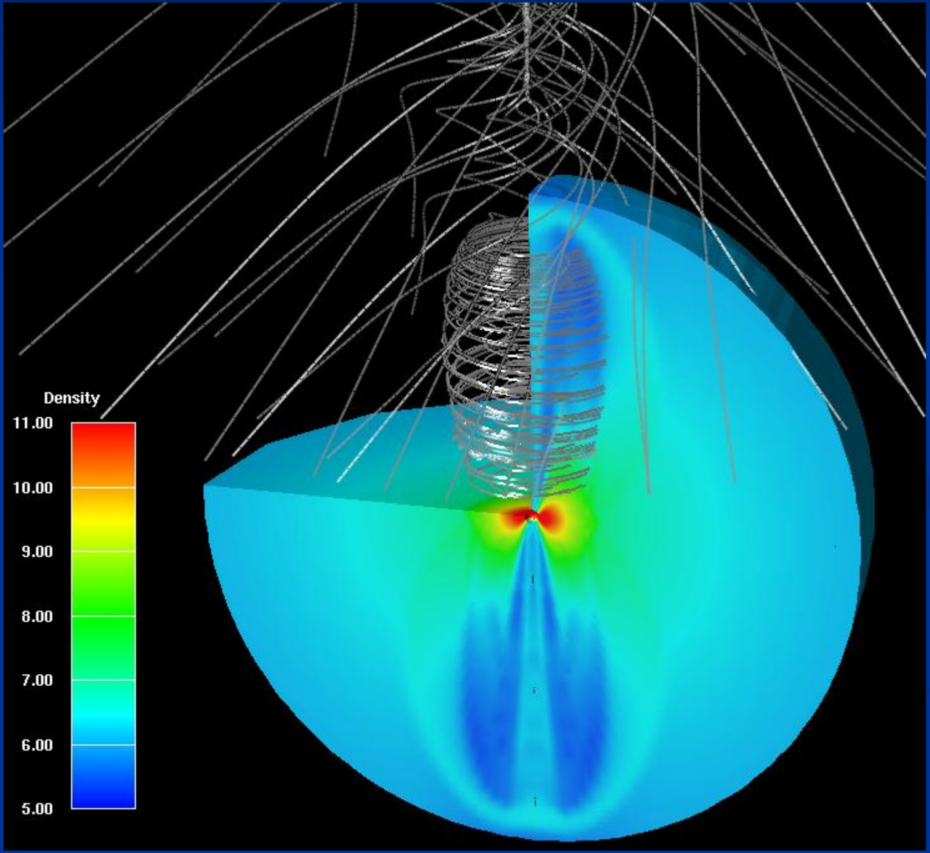
Slow rotation ⇒ Amplification of poloidal field by compression

⇒ Amplification of toroidal field by winding

⇒ Off-axis outflow production by magneto pressure

Results (MHD simulation)

Magneto driven jet

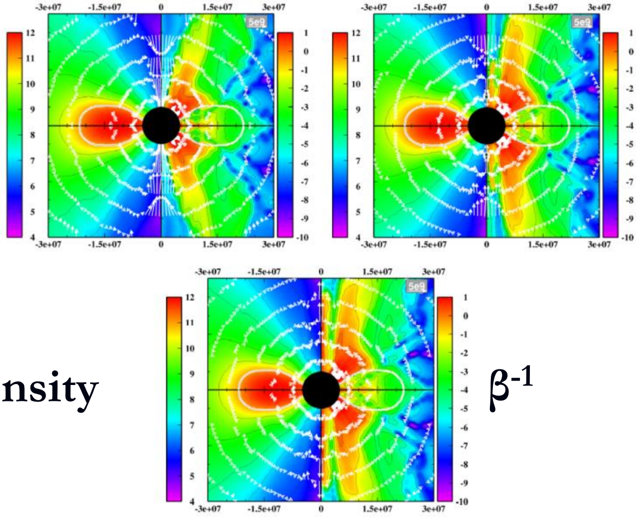


Magnetic field line (line)
and density (contour)

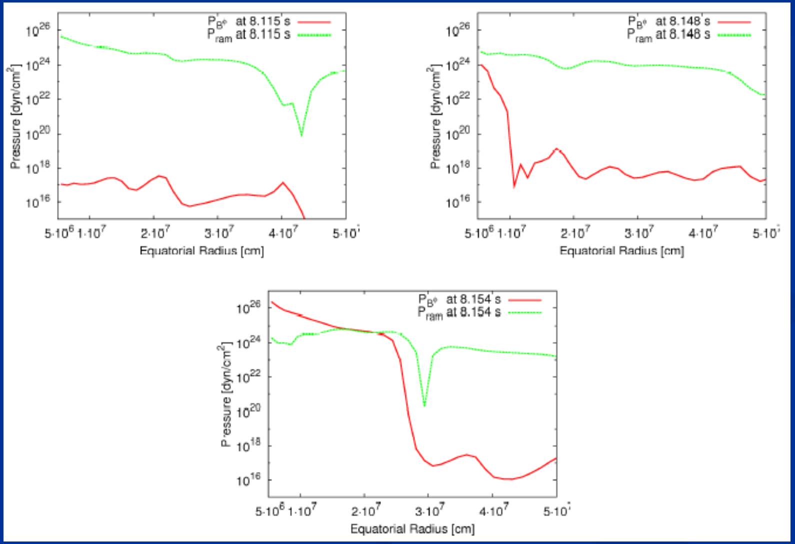
collimated outflow is formed due to the winding around the polar axis.

Results (MHD simulation)
Advection induced MHD jet (TYPE I)
(in weakly magnetized model)

jet formation(8.115 s, 8.148 s, 8.154 s)



Magneto pressure and ram pressure along the axis(8.115 s, 8.148 s, 8.154 s)

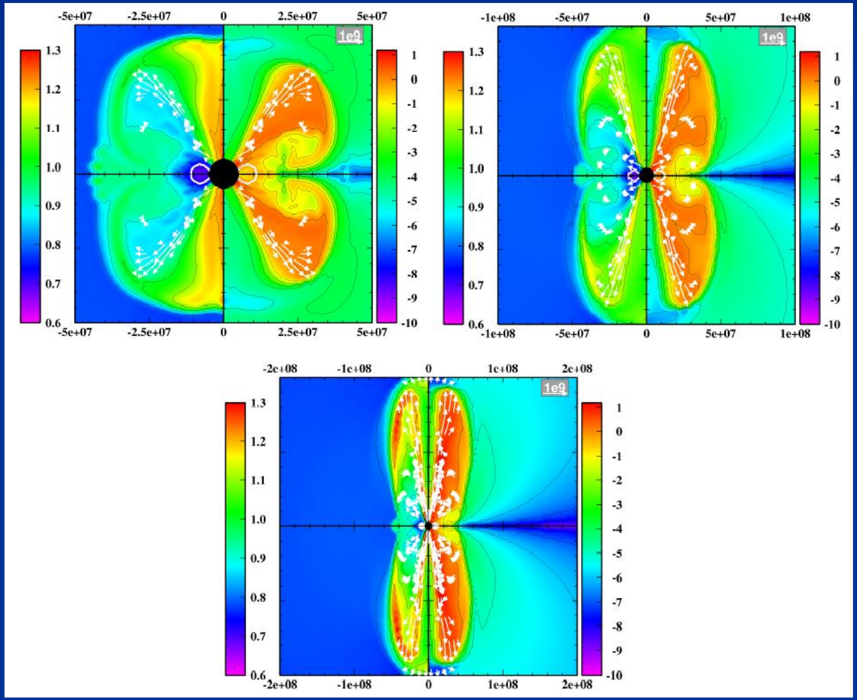


In the case of weak initial magnetic field(10^9G)、
When ram pressure decreases, strongly magnetized region moves onto the polar axis .
The magneto pressure rapidly increases due to the strong differential rotation, resulting in the outflow formation.

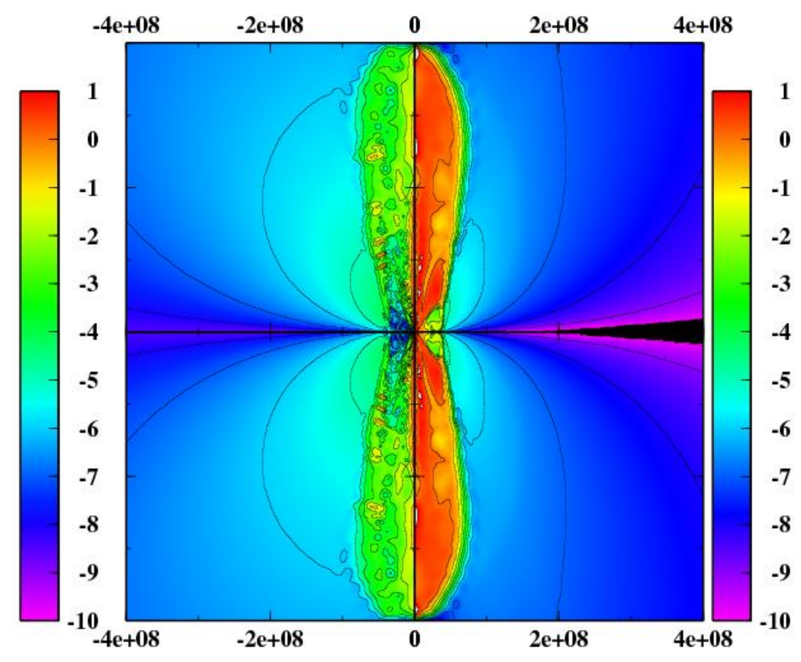
Results (MHD simulation) Magnetic tower jet (TYPE II)

(in strongly magnetized model)

jet formation (1.43 s, 1.87 s, 2.11 s)



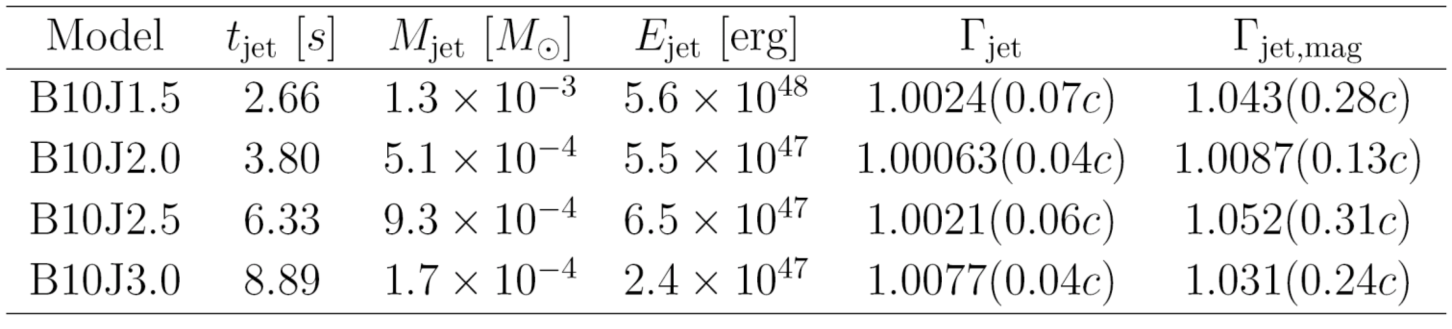
jet propagation (2.2 s)



External pressure suppresses the side spreading motion of jet. If the initial magnetic field is stronger than 10^{10}G、Outflow would be formed at more or less 2 s.

Outflow is collimated by the hoop stress.

Results (MHD simulation)
Properties of jets



Model	$t_{\rm jet}$ [s]	$M_{\rm jet}$ [$M_\odot$]	$E_{\rm jet}$ [erg]	$\Gamma_{\rm jet}$	$\Gamma_{\rm jet,mag}$
B10J1.5	2.66	1.3×10^{-3}	5.6×10^{48}	$1.0024(0.07c)$	$1.043(0.28c)$
B10J2.0	3.80	5.1×10^{-4}	5.5×10^{47}	$1.00063(0.04c)$	$1.0087(0.13c)$
B10J2.5	6.33	9.3×10^{-4}	6.5×10^{47}	$1.0021(0.06c)$	$1.052(0.31c)$
B10J3.0	8.89	1.7×10^{-4}	2.4×10^{47}	$1.0077(0.04c)$	$1.031(0.24c)$

Explosion energy is of order of 10^{48}erg/s.
Only mildly relativistic jet is formed.

This outflow would not become GRBs.

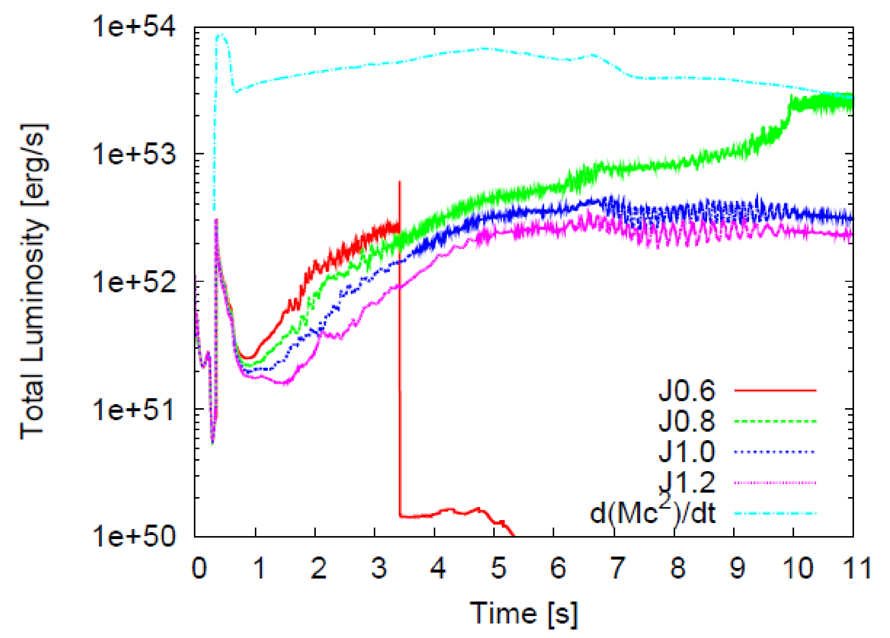
However, since our model has relatively large inner boundary and limited parameters, further study is necessary.

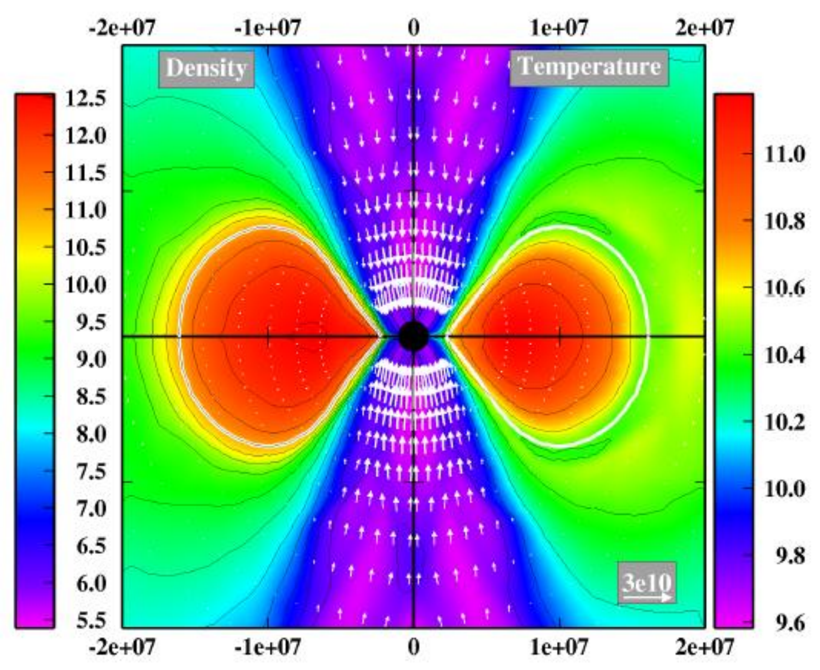
Summary and conclusion of MHD simulation

- **Two types of MHD outflows are observed** in long-term evolution from core-collapse.
- **Both outflows are mildly relativistic and less energetic.**
- **Slower rotation is most plausible for MHD outflow.**

Results (HD simulation)

Dynamical evolution without neutrino heating





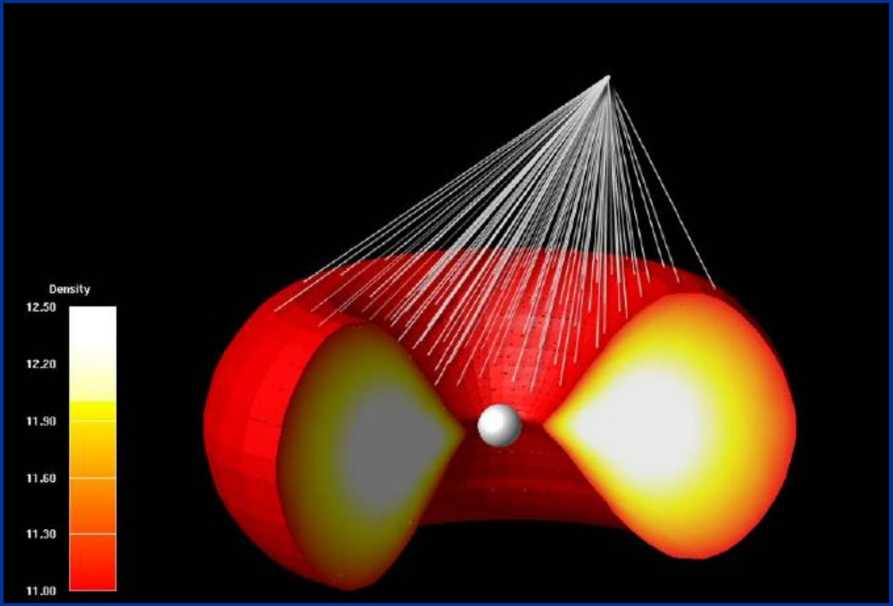
9.1 s of J0.8 model

Neutrino luminosity becomes comparable to $L_E \sim 10^{53}$erg/s at $\sim$ 10 s in model with $j = 0.8j_{lso}$.

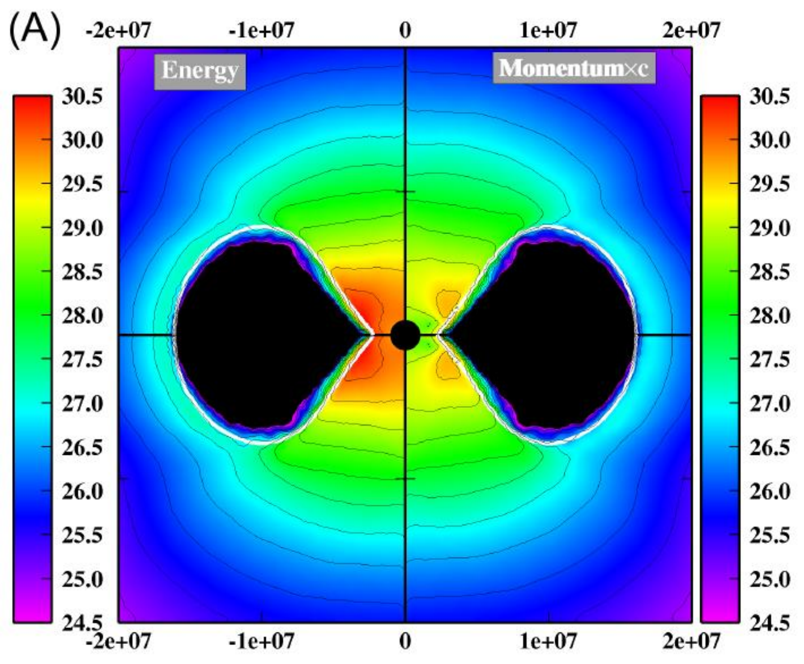
Results (HD simulation)

Heating rate by pair annihilation

We calculate heating rate by neutrino pair annihilation in post-processing step.



Sample image of neutrino pair annihilation.



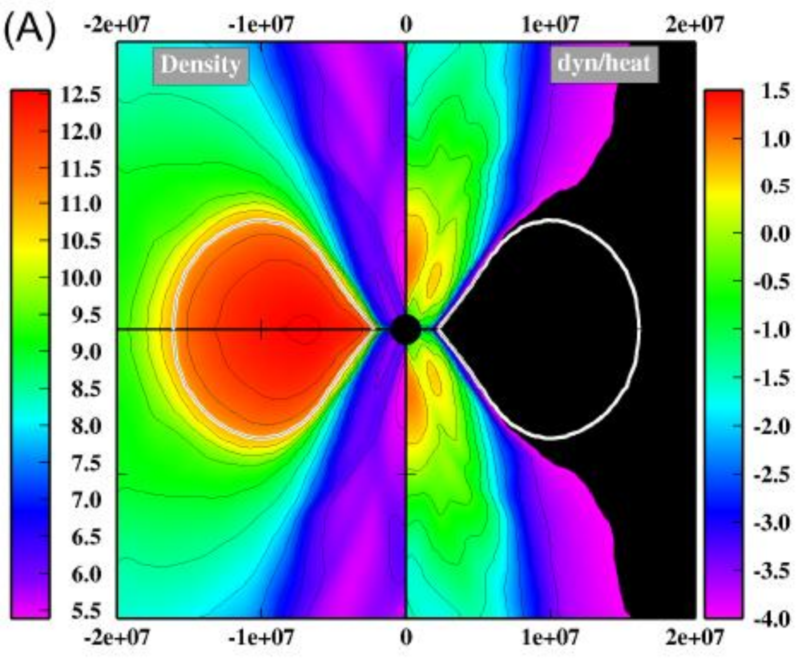
Energy deposition rate is the largest on the surface of the disk.

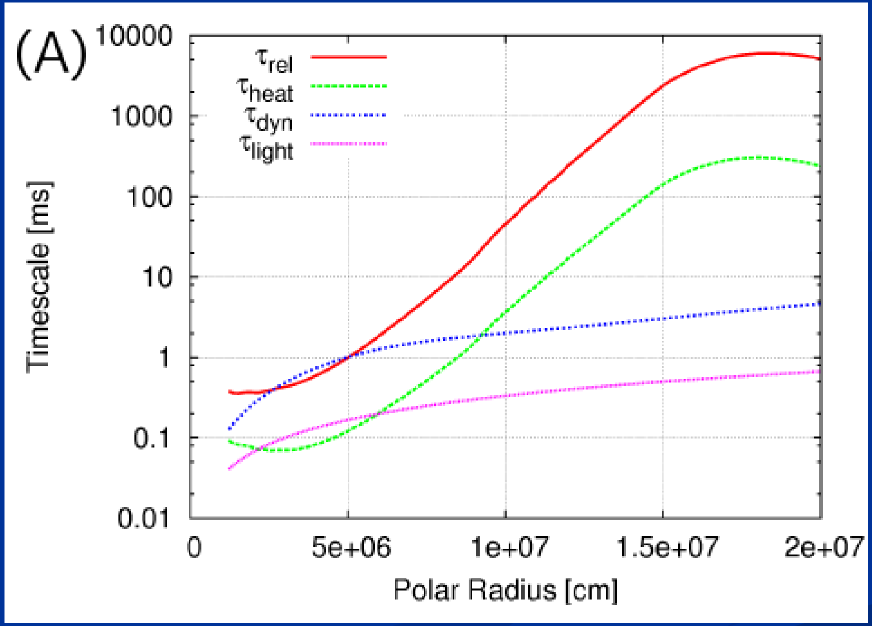
Results (HD simulation)

Comparison of timescales

Criterion for outflow production by neutrino : $\tau_{dyn}/\tau_{heat} >> 1.$

$(\tau_{dyn} \sim (G\varrho)^{-1/2}\ ,\ \tau_{heat} \sim \Phi/q^{+})$





τ_{dyn}/τ_{heat} becomes greater than 1 around 70 km on the axis.

Outflow would be formed inside 100 km.
That outflow might become relativistic.

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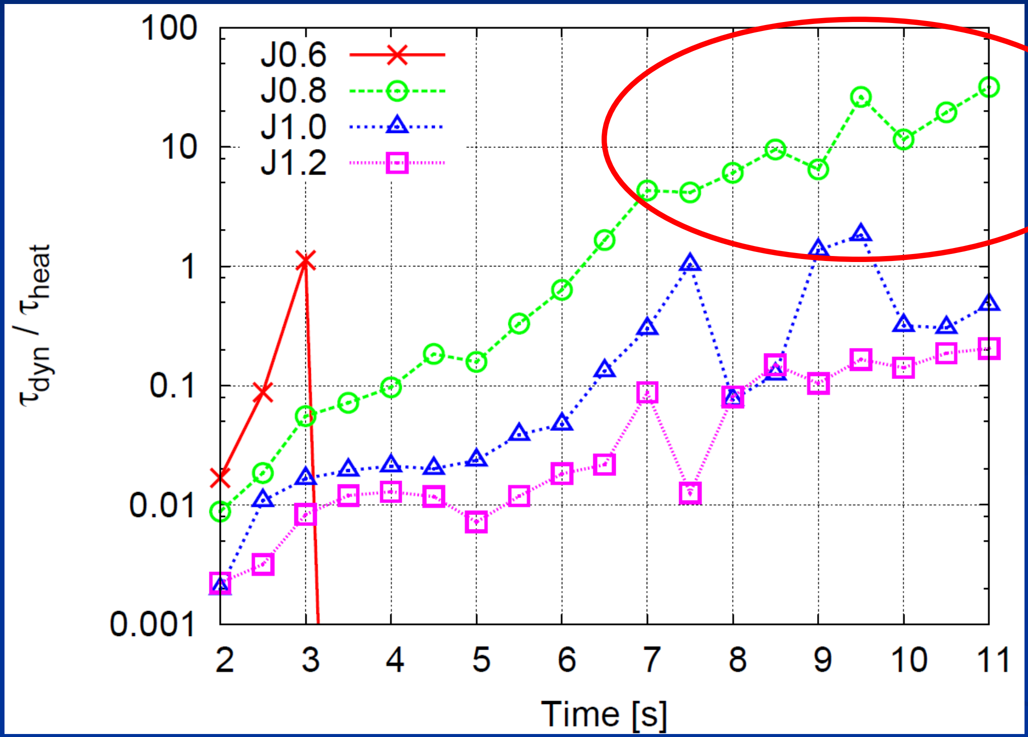
Results (HD simulation)

Time evolution of heating timescale



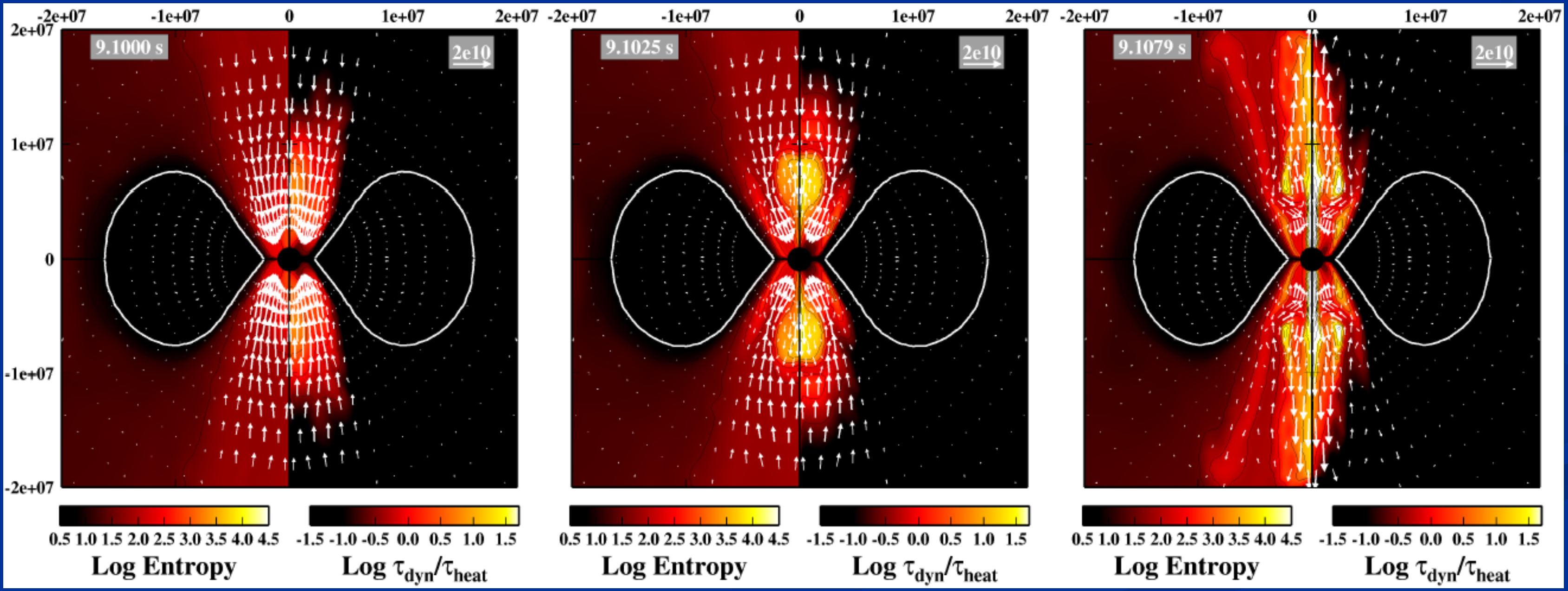
Outflow would be Formed !!

- We calculate neutrino heating and evaluate τ_{dyn}/τ_{heat} every 0.5 s.
- We find that the condition $\tau_{dyn}/\tau_{heat} >> 1$ is safely satisfied <u>after 8.0 s</u>.

Results (HD simulation)

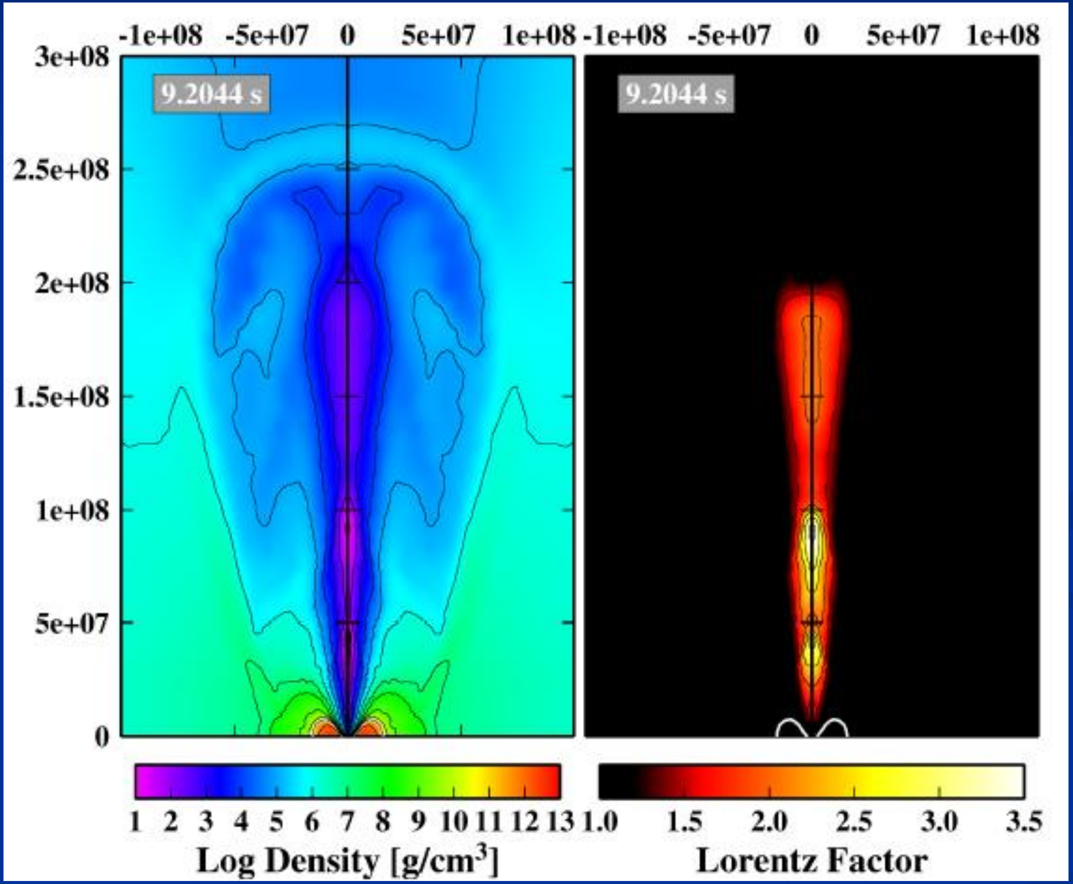
Formation of neutrino-driven outflow

- We restart our simulation from 9.1 s **including neutrino heating**.
- An outflow is formed from the region where $\tau_{dyn}/\tau_{heat} >> 1$ as expected.
- **This outflow is neutrino-driven !!**



Results (HD simulation)

Properties of neutrino-driven outflow



When outflow reaches the edge of Fe core (～3000km),

$\rho = 10 \sim 10^3$ g/cm^3

and **$\Gamma = 2.0 \sim 3.0$**.

This outflow is relativistic and energetic (**$dE/dt \sim 4 \times 10^{49}$ erg/s**).

Summary and conclusion of HD simulation

- We find that the neutrino luminosity becomes comparable to L_E after about 10 s after core-collapse.
- We also find that the condition for the outflow production by neutrino-antineutrino pair annihilation is fulfilled inside 100 km on the axis at 9 s after core-collapse.
- Including the energy deposition by neutrino, we find that neutrino-driven outflow is formed along the rotational axis.
- In addition, the outflow becomes relativistic. Such relativistic outflow can keep collimated till it penetrate the outer layer.