Constraints to the GRB central engine from jet penetrability to massive stars

(Neutrino-driven collapsar model)

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Talk Plan

1. Introduction

2. Methods and Models

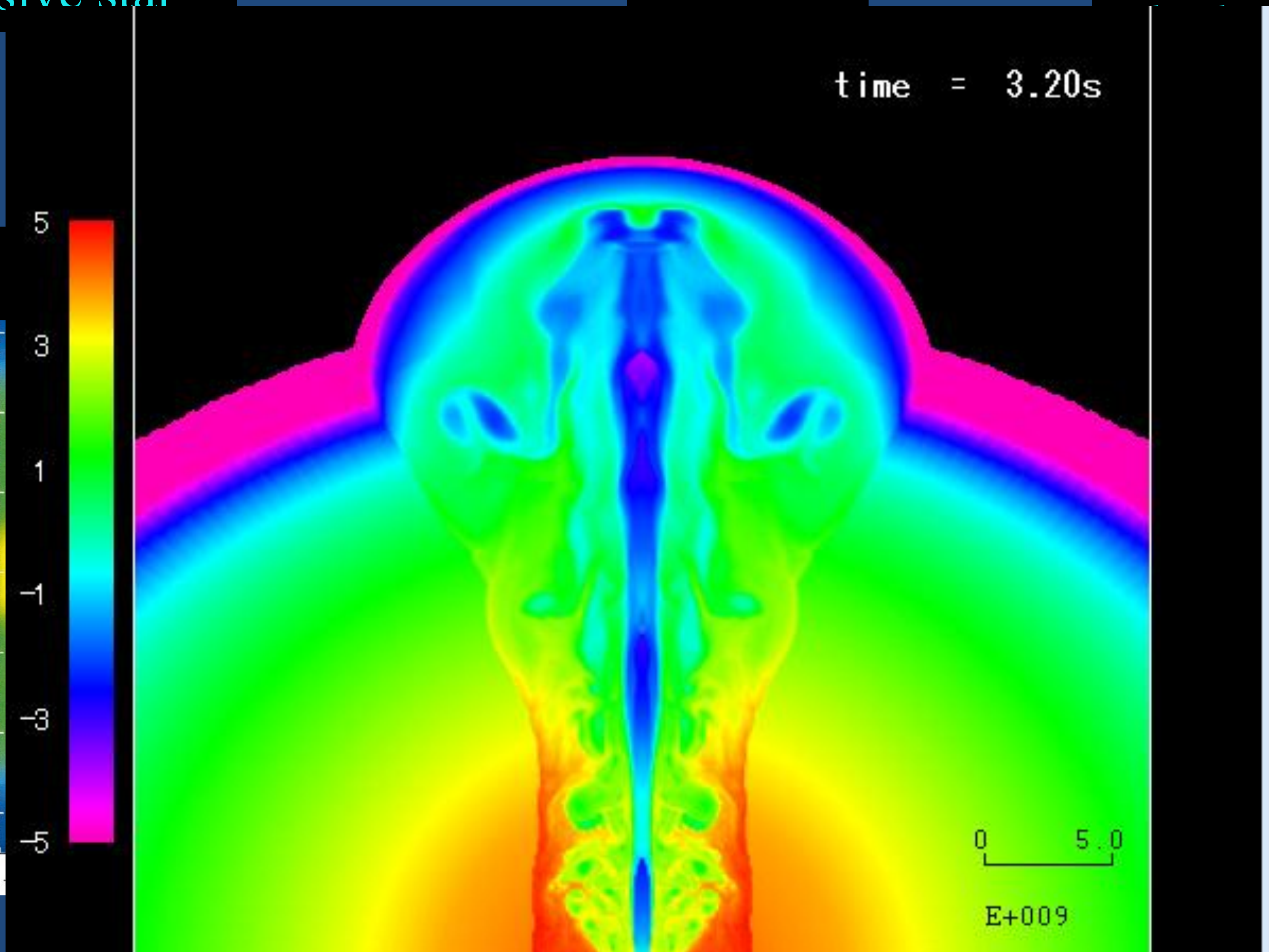
3. Results

4. Summary

Rapidly rotating massive star

Collapsar Model

Nagakura et al. 2011



ted Jet

arov (2008)

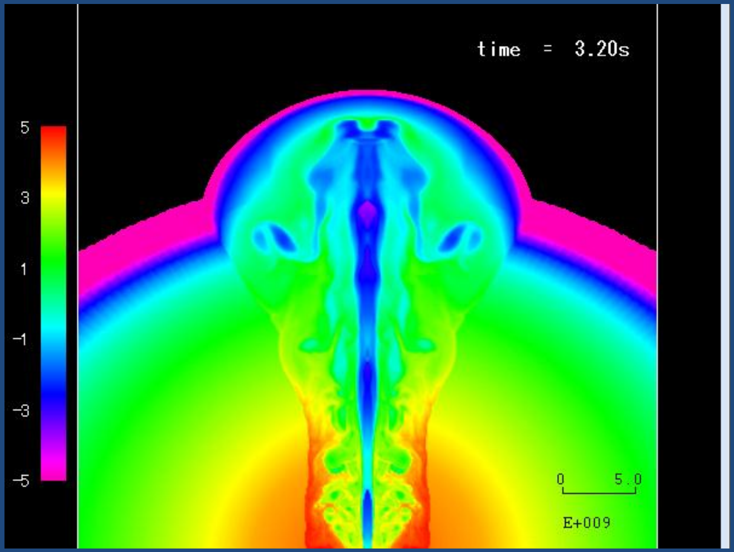
The jet penetration to the star is trivial??

Off-course **No!!**

Operation of Central Engine

≠

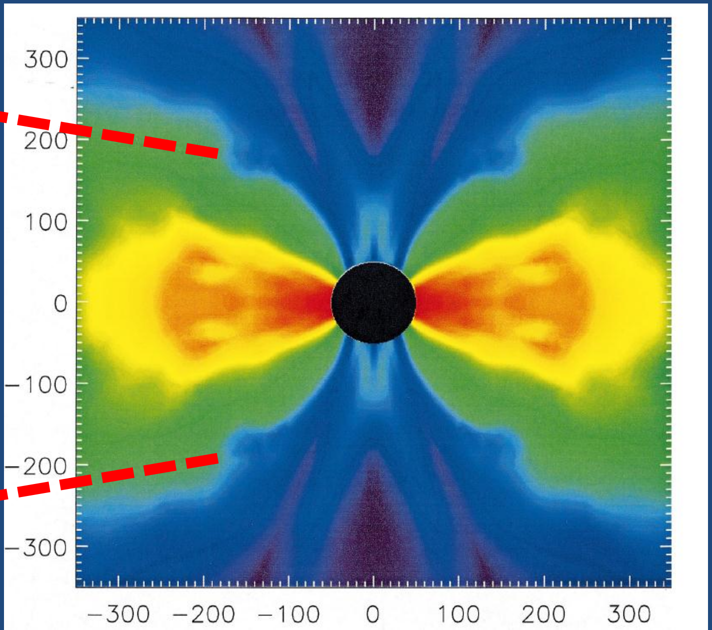
Success of GRB



The jet should break out the star before the engine die!

- Can the neutrino-driven jet break out the star?
- What progenitor or how fast rotation is required to succeed the jet break out?

- Einstein Equation
- General Relativistic Neutrino Transfer (7D Boltzmann equation)
- 3D Hydro or Magneto-Hydro
- Nucleosynthesis



Black Hole Accretion Model with Steady State Approximation (Neutrino-Dominated Accretion Flows)

Narayan 1994, Popham et al. 1999, Kohri & Mineshige 2002, Matteo et al. 2002, Kohri et al. 2005, Liu & Lu 2006, Chen & Beloborodov 2007, Liu et al. 2010, Zalamea & Beloborodov 2010

Neutrino heating near hyper-accreting black holes

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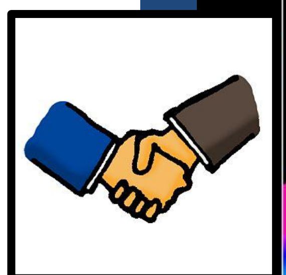
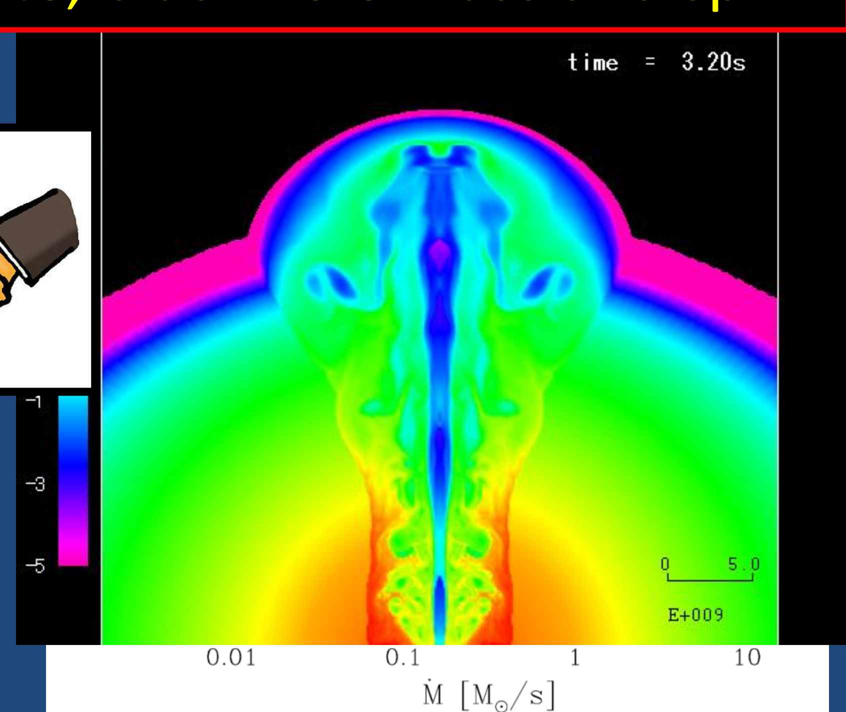
I numerically investigate jet propagation by using the neutrino energy deposition rate with taking into account the evolution of mass accretion rate, black hole mass and spin.

$$\dot{E}_{\nu\bar{\nu}} \approx 1.1\times10^{52}\, x_{\rm ms}^{-4.8}\left(\frac{M}{3M_\odot}\right)^{-3/2} \times \left\{\begin{array}{ll} 0 & \dot{M}<\dot{M}_{\rm ign} \\ \dot{m}^{9/4} & \dot{M}_{\rm ign}<\dot{M}<\dot{M}_{\rm trap} \\ \dot{m}_{\rm trap}^{9/4} & \dot{M}>\dot{M}_{\rm trap} \end{array}\right\}$$

$$x_{ms}(a) = r_{ms}(a, M)/r_s(M)$$





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Special Relativistic Hydrodynamic Code with Weak Gravitational Field Limit

Basic Equations

High Resolution Shock Capturing Scheme

$$\partial_t \rho_* + \partial_j \left(\rho_* v^j\right) = 0$$

$$\partial_t S_r + \partial_j \left(r^2 \sin\theta \, T^j_{\ r}\right) = r^2 \sin\theta \left\{ -T^{00} \psi_{,r} + r\, T^{\theta\theta} + r \sin^2\theta \, T^{\phi\phi} \right\}$$

$$\partial_t S_\theta + \partial_j \left(r^2 \sin\theta \, T^j_{\ \theta}\right) = r^2 \sin\theta \left\{ -T^{00} \psi_{,\theta} + r^2 \sin\theta \cos\theta \, T^{\phi\phi} \right\}$$

$$\partial_t S_\phi + \partial_j \left(r^2 \sin\theta \, T^j_{\ \phi}\right) = 0$$

$$\partial_t \tau + \partial_j \left(r^2 \sin\theta \, T^{0j} - \rho_* v^j\right) = -r^2 \sin\theta \, T^{0i} \psi_{,i}$$

$$\partial_t \left(\rho_* A\right) + \partial_j \left(\rho_* A v^j\right) = 0$$

$$\rho_* \equiv r^2 \sin\theta \rho_0 u^t$$

$$S_i \equiv r^2 \sin\theta T^0_{\ i}$$

$$\tau \equiv r^2 \sin\theta T^{00} - \rho_*$$

$$D_i D^i \psi = 4\pi \rho_0 \left\{ 2h \left(u^t\right)^2 - h + 2\frac{p}{\rho_0} \right\}$$

A: mean molecular weight

D: 3D covariant derivative

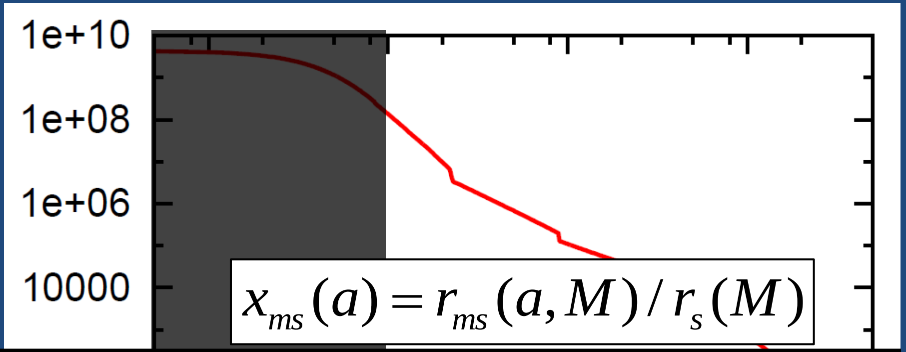
MICCG (Conjugate Gradient Method)

EOS : gamma-law

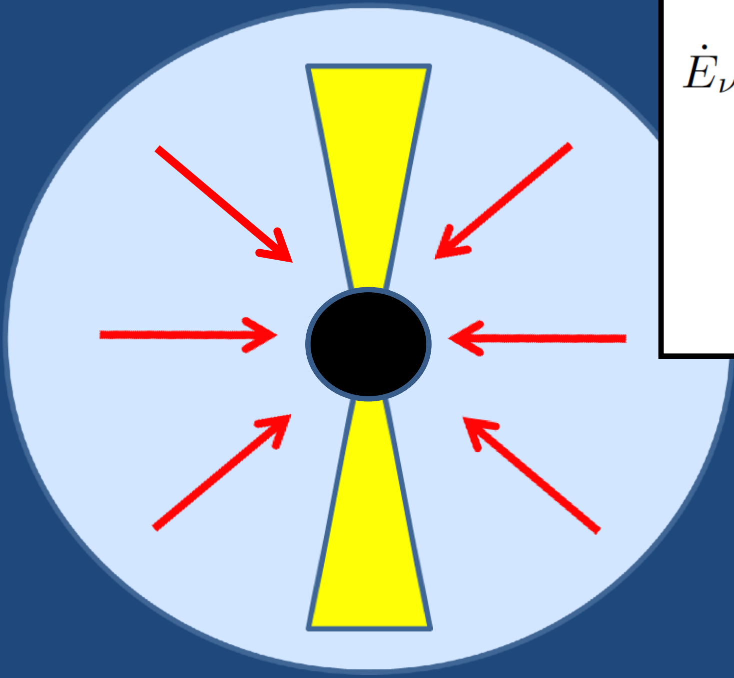
Methods and Models

- Compact-Wolf-Rayet Progenitor
  (16TI model of Woosley & Heger 2006)

$R \approx 4 \times 10^{10}\,cm$ $M \approx 14 M_{sun}$



$x_{ms}(a) = r_{ms}(a, M) / r_s(M)$

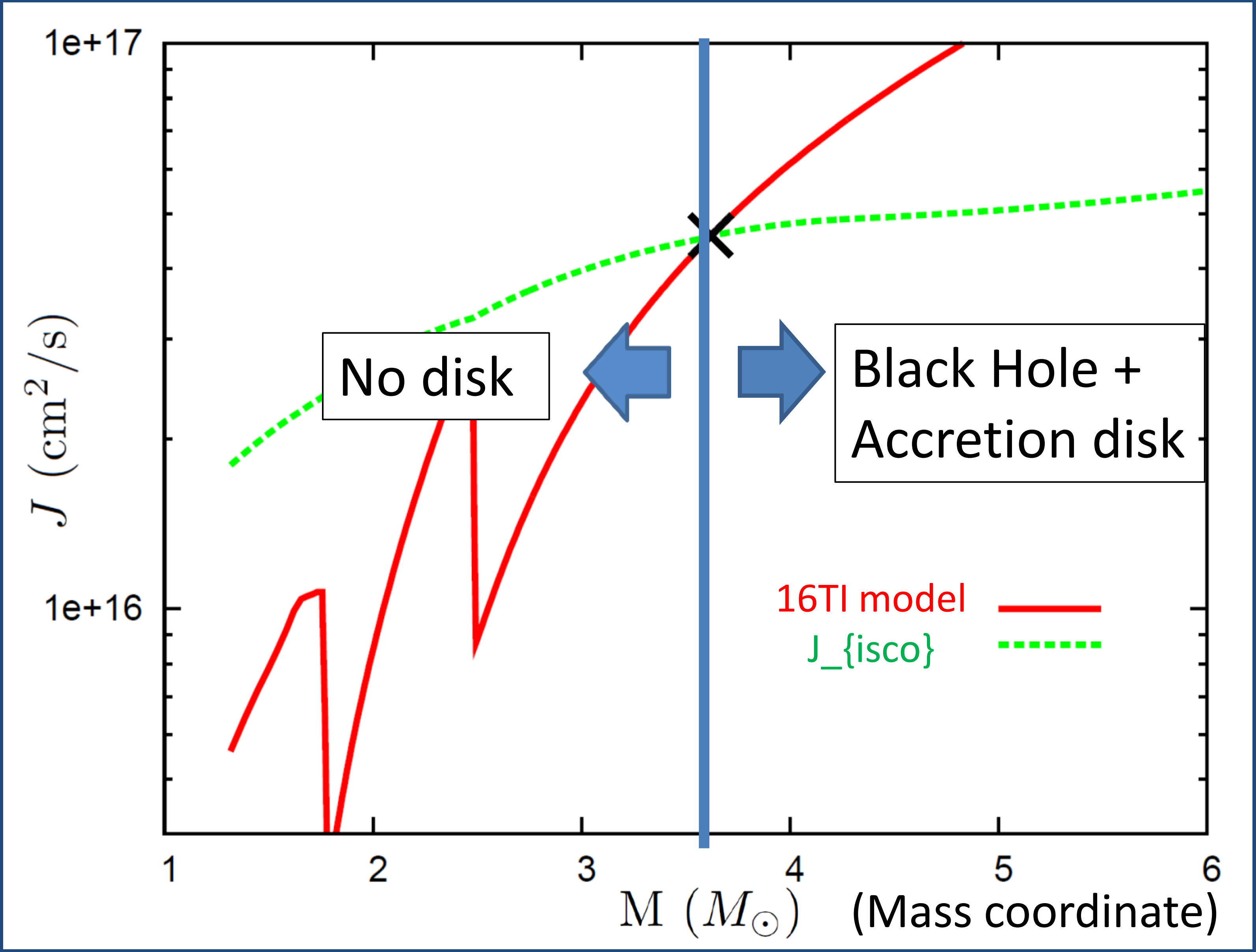


$$\dot{E}_{\nu\bar{\nu}} \approx 1.1 \times 10^{52}\, x_{\rm ms}^{-4.8} \left(\frac{M}{3M_\odot}\right)^{-3/2} \times \left\{ \begin{array}{ll} 0 & \dot{M} < \dot{M}_{\rm ign} \\ \dot{m}^{9/4} & \dot{M}_{\rm ign} < \dot{M} < \dot{M}_{\rm trap} \\ \dot{m}_{\rm trap}^{9/4} & \dot{M} > \dot{M}_{\rm trap} \end{array} \right\} {\rm erg\ s^{-1}}$$

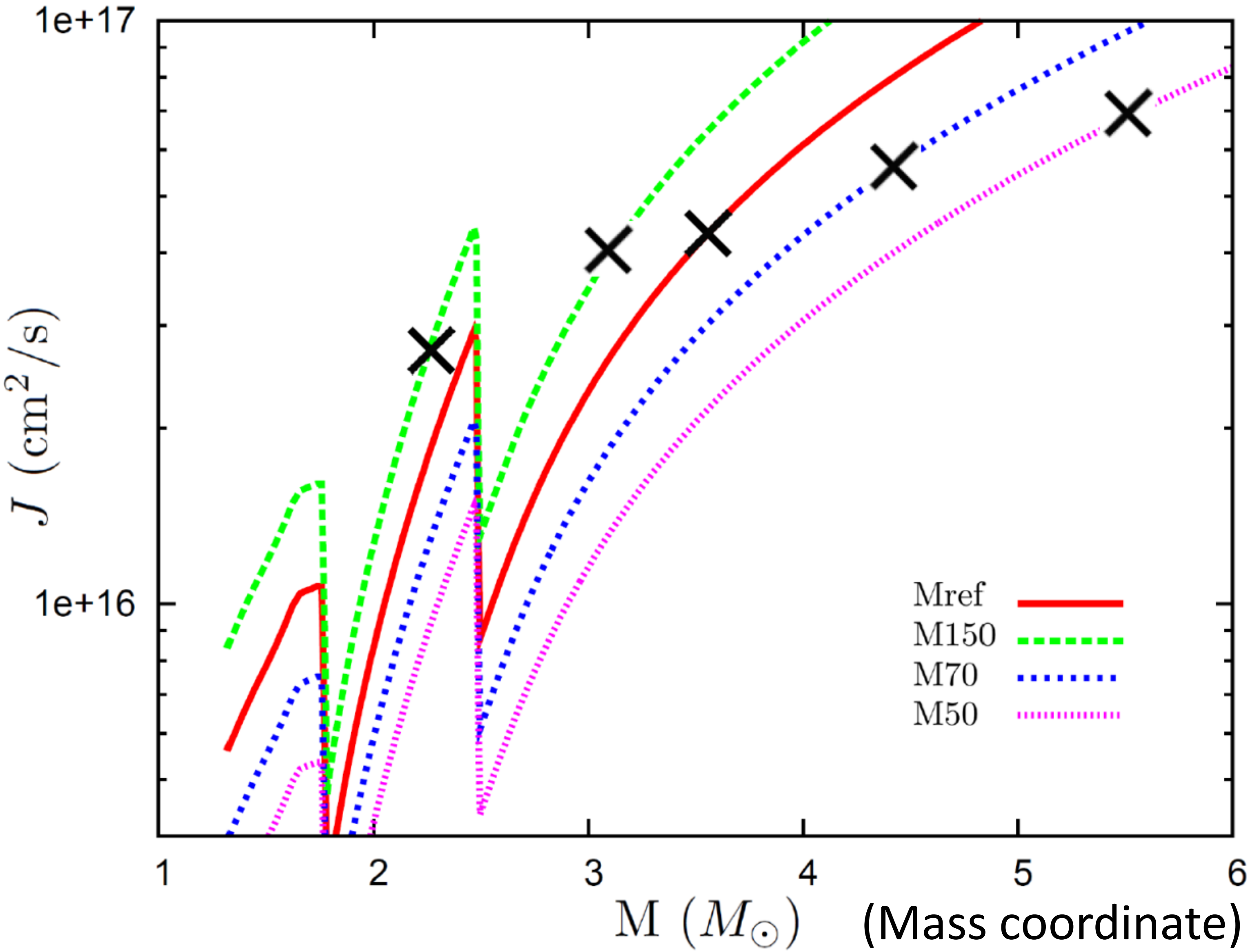
We can get the time evolution of

- Mass Accretion Rate
- Black Hole Mass
- Black Hole Spin

Angular Momentum Distributions (16 TI model)



Angular Momentum Distributions (4 models)



(Mass coordinate)

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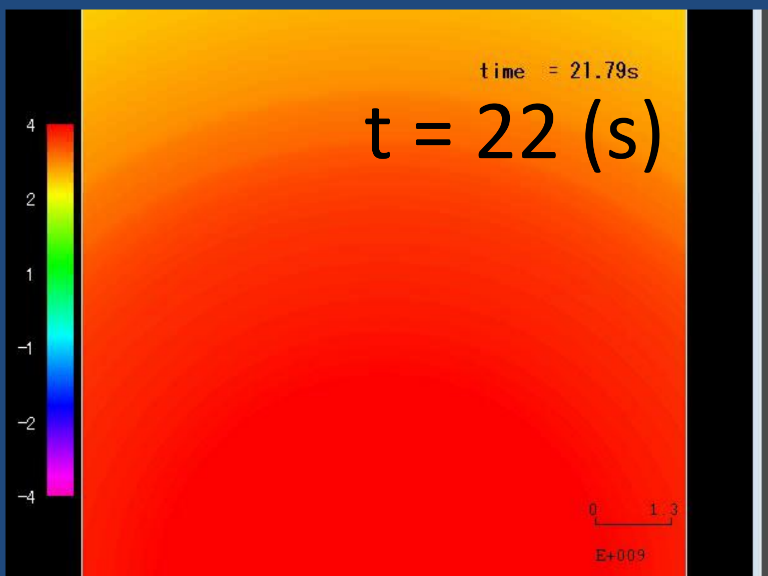
TABLE I: Summary of our models

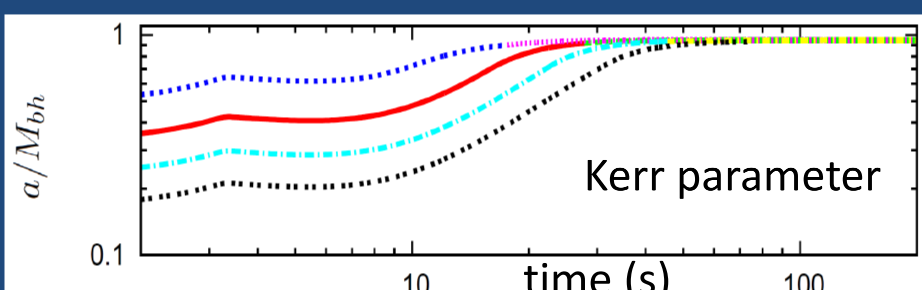
Model	Breakout	t_i (s)	t_{br} (s)	L_p (10^{50} erg/s)	E_{dg} (10^{51}erg)	E_j (10^{51}erg)	$E_{j>L_{50}}$ (10^{51}erg)	$E_{j>L_{49.5}}$ (10^{51}erg)	$T_{j>L_{50}}$ (s)	$T_{j>L_{49.5}}$ (s)
Mref	yes	10.9	27.8	1.9	1.4	7.4	4.4	5.6	27.8	46.2
M150	yes	2.2	17.6	3.2	1.6	11.7	8.8	9.8	40.0	55.0
M70	yes	15.5	45.5	1.0	0.9	3.6	-	1.7	-	21.7
M50	no	21.6	-	0.6	-	-	-	-	-	-



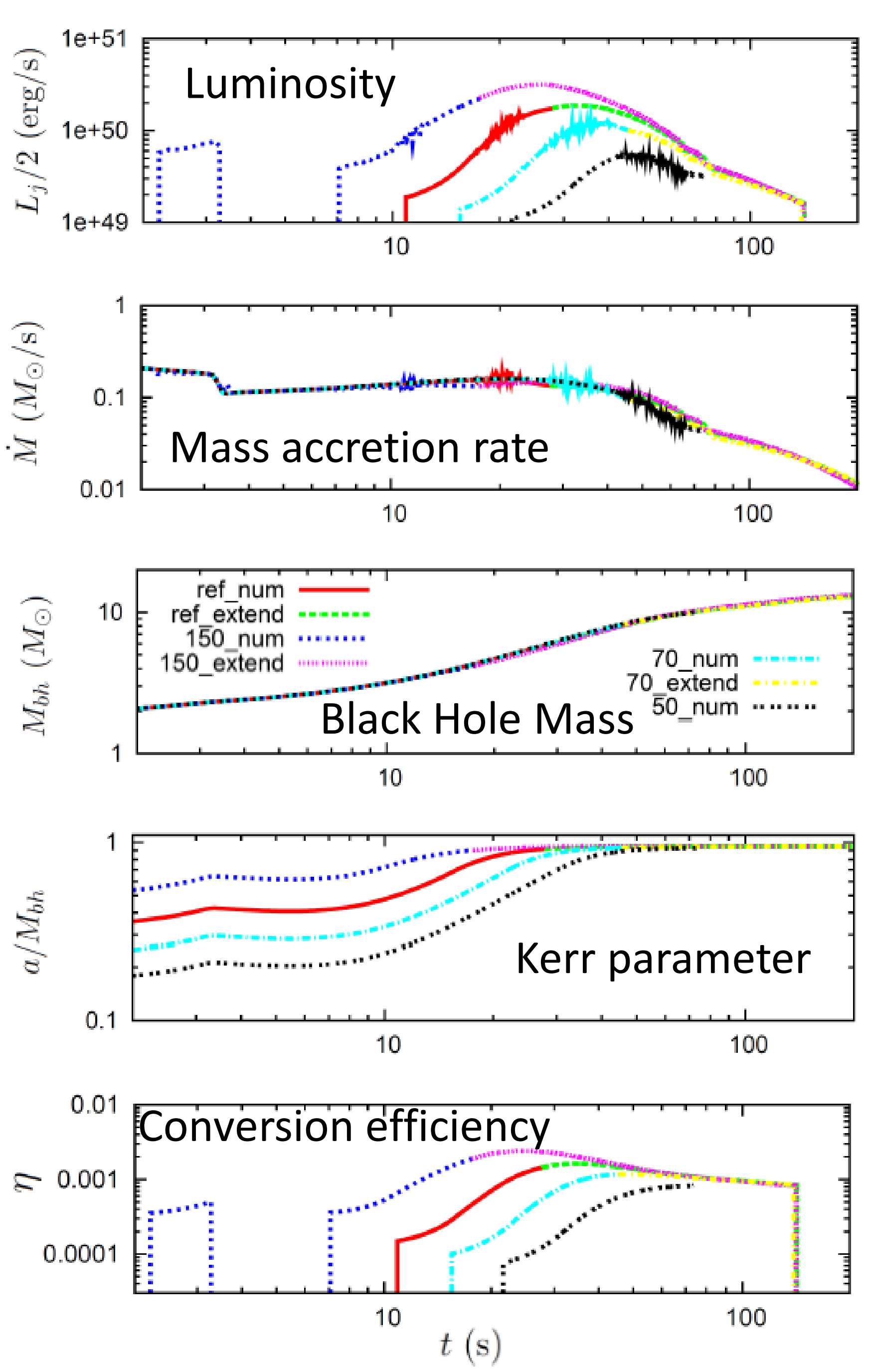
- The jet succeeds to break out the star (for 16 TI original model).

  Propagation time ～ 17 (s)

- Forward shock wave does not propagate until t= 22 (s).
  (Ram pressure > jet luminosity)



- Black hole rotates faster and faster with time
  (Ram pressure < jet luminosity)



Red: Mref (original) ○
Blue: M150 ○
Light Blue: M70 ○
Black : M50 ×

Faster rotation

↓

Disk is formed at early time

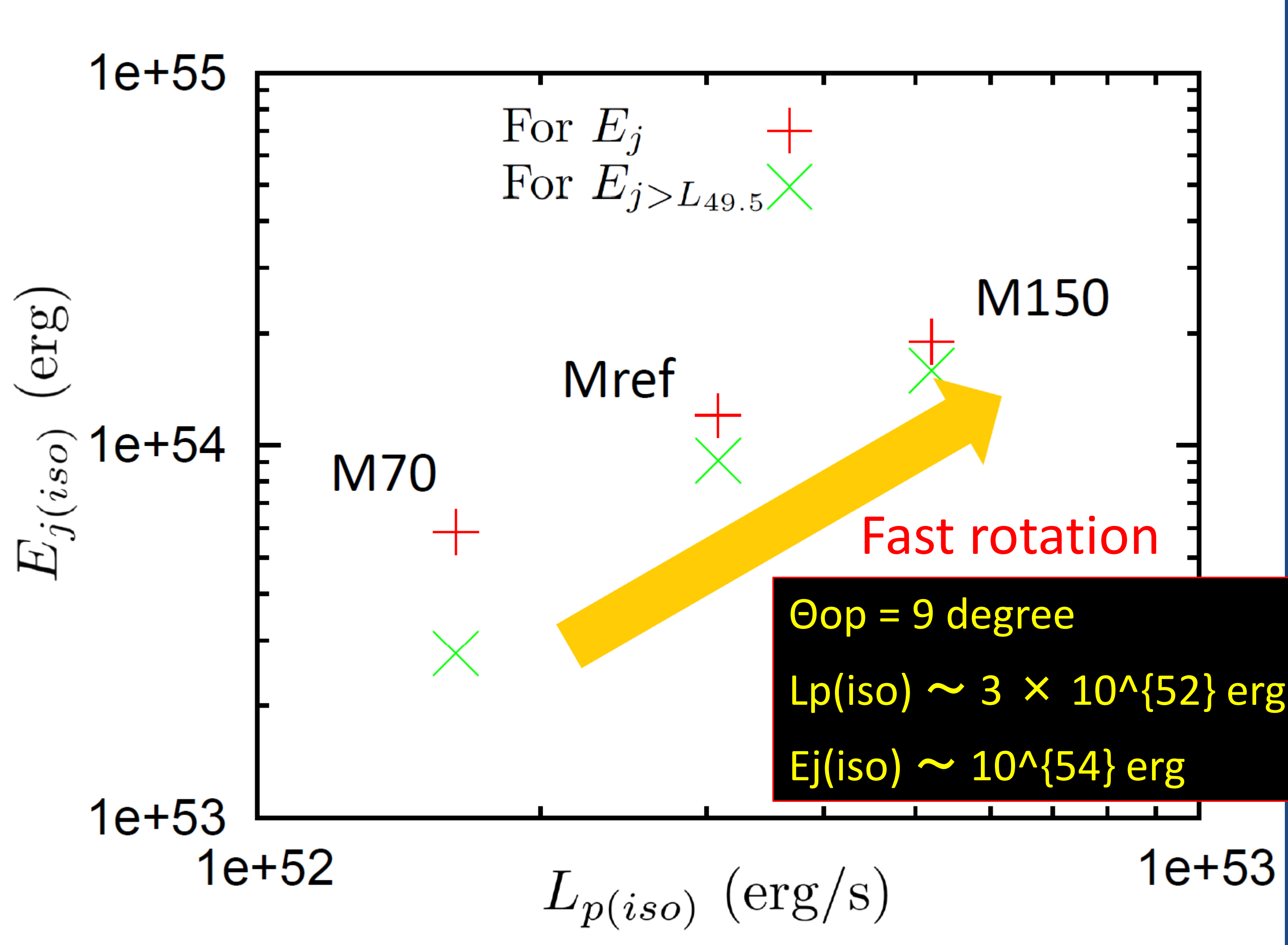
↓

Mass Accretion rate : ↗

Black hole mass : ↘

Black hole spin : ↗

Istropic energy – istoropic peak luminosity



Θop = 9 degree

Lp(iso) ～ 3 × 10^{52} erg/s

Ej(iso) ～ 10^{54} erg

Summary

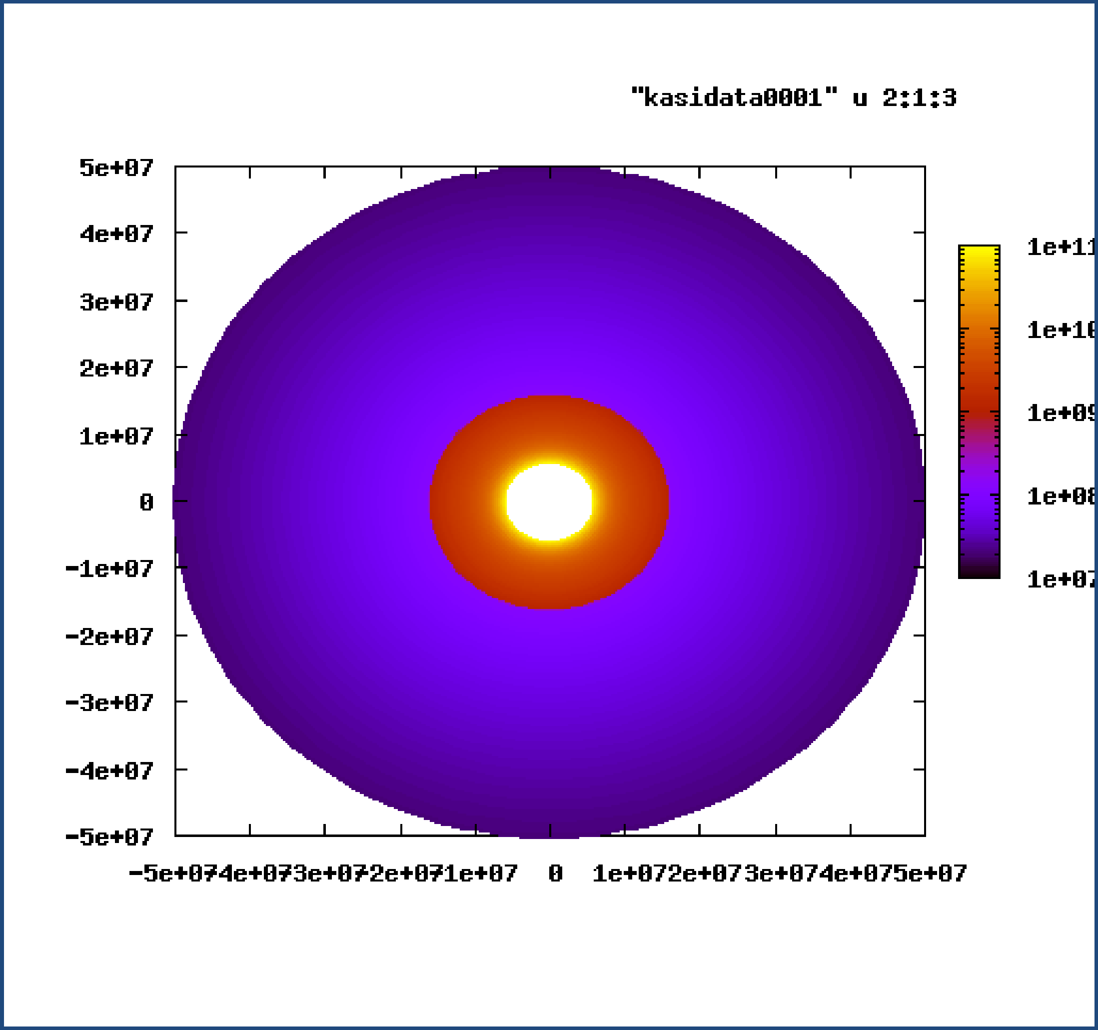
1. I numerically investigate jet propagation through the stellar mantle based on the neutrino-driven collapsar model.

2. My calculation takes into account the evolution of mass accretion rate, black hole mass and spin, all of which are necessary to estimate the power of jet.

3. The current elaborate model of neutrino energy deposition provides us good condition for the success of jet breakout.

4. Rapidly rotating core would provide the condition for large explosion energy (for both GRBs and SNe), while ～50% reduction of angular momentum from original angular momentum would be the threshold rotation to have the jet breakout.

Towards Multi-D Neutrino Radiation Hydrodynamic Simulations for Core-Collapse of Massive Stars



Still on going project (tests for multi-d simulation)