Explosion and Gravitational Wave Emission from Gravitational Collapse of Super Massive Star

Haruki Uchida, Masaru Shibata(YITP)

YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

Introduction

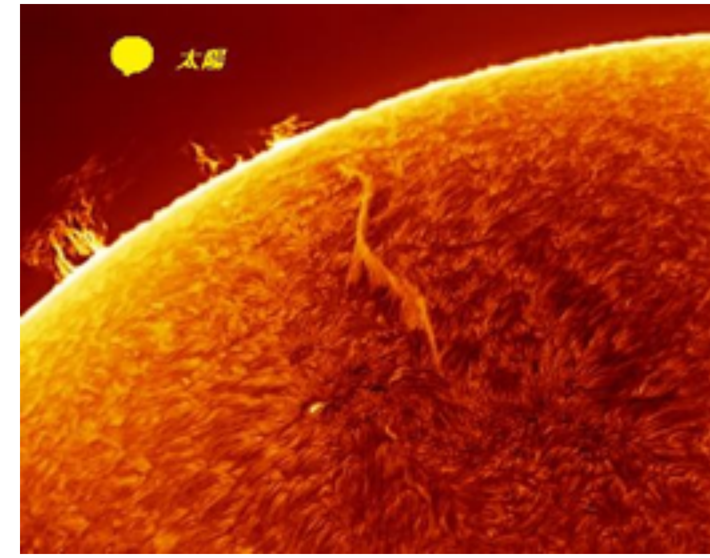
SMBH formation

Recent discovery of luminous quasars at z > 6 suggests the existence of black holes with mass exceeding 10^9 M⊙ when the age of the Universe was less than one billon years

e.g.) $M \sim 10^9 M_{\rm sun}$ at z ~ 6 Mortlock et al.(2011)

A supermassive star (SMS) with mass $M \sim 10^5 M_{\rm sun}$ is a possible progenitor for the formation of a seed of a supermassive blackhole(SMBH)

property of SMSs



- Very massive $M \sim 10^5 M_{\rm sun}$

  Metal poor $Z_{\rm CNO} \sim 10^{-9} \quad ({\rm c.f.}\ Z_{\rm sun} \sim 0.02)$

- SMSs have not been observed yet

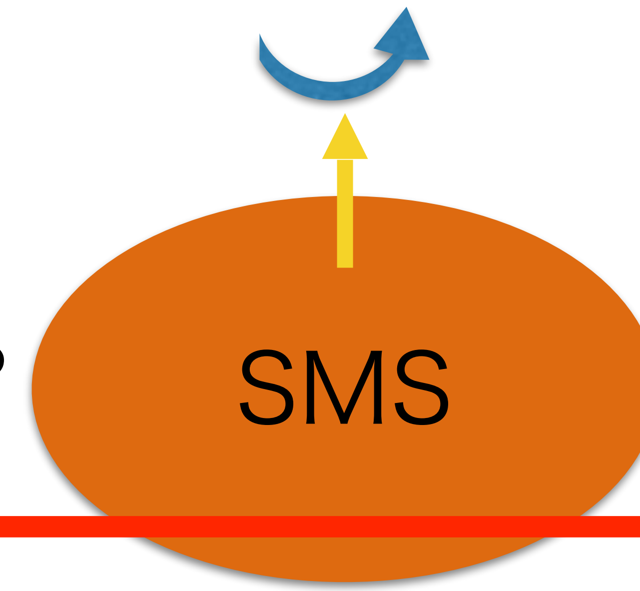
- SMSs may undergo a general-relativistically induced quasi-radial collapse (e.g. Chandrasekhar 1964)

- If SMSs are rapidly rotating, 4-5 percent of their mass will remain as the surrounding disk (Shibata,Uchida,Sekiguchi 2016)

$$\frac{T}{|W|} > 2.0 \times 10^{-3}$$

T : rotational kinetic energy
W : gravitational potential energy

How to observe SMSs ?



It is difficult to directly observe SMSs

➡ **Can collapse of SMSs be observed?**

<u>During collapse</u>

Nuclear burning may introduce high energy emissions

Montero et al. (2012),Chen et al. (2014)

SMSs emit GWs during formation of the BHs

(Shibata,Sekiguchi,Uchida,Umeda 2016)

<u>After collapse</u>

BH + Disk will form (Shibata,Uchida,Sekiguchi 2016)

➡ Viscous heating and nuclear burning

→**electromagnetic waves**

Deformation of the disks→**GWs** Kiuchi et al.(2011)

Today's talk

We simulated the gravitational collapse of one SMS model which is helium burning phase and rapidly rotating as a test calculation.

↓

I will talk about

- Overview of gravitational collapse
- Effect of nuclear burning
- Property of outflow
- Gravitational wave emission

Set up

Set Up

$$\frac{T}{|W|} \sim 0.009$$

T : rotating kinetic energy

W : gravitational energy

Initial condition

Rapidly rotating

Helium burning phase

Unstable against general-relativistic gravitational collapse

(Shibata,Uchida,Sekiguchi 2016)

Mass

$$M \sim 1.6 \times 10^5 M_\odot$$

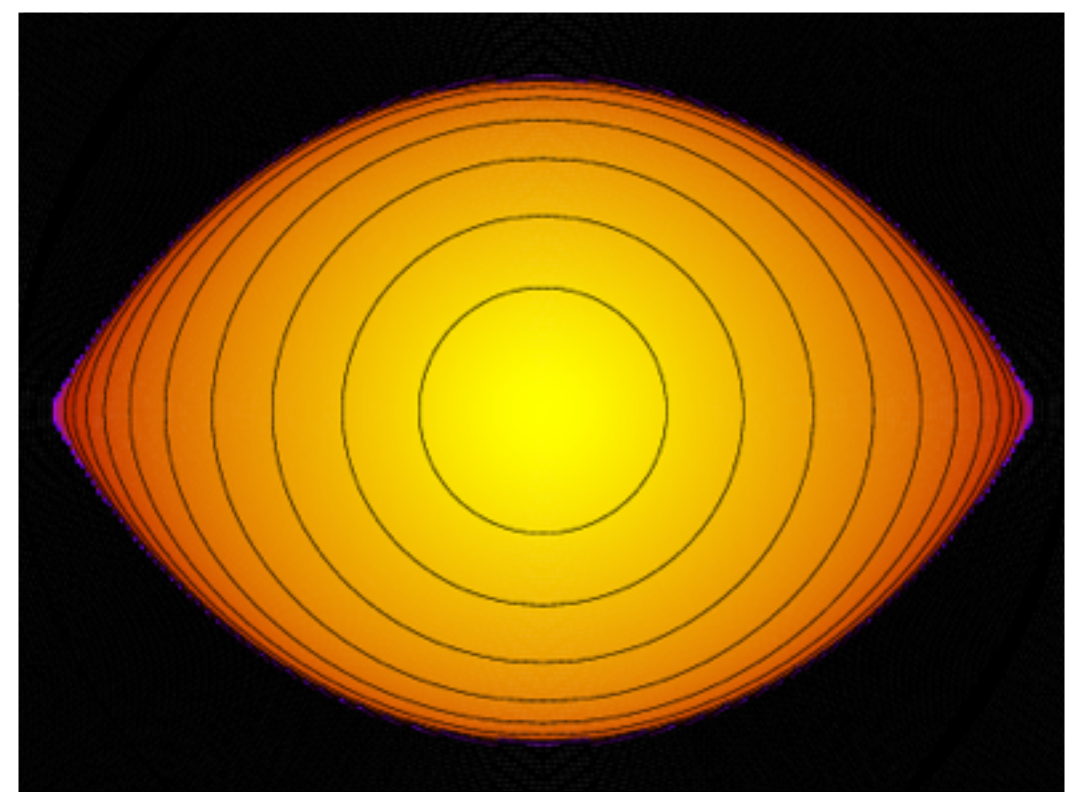
Composition

$$X_{\mathrm{He}} = 1$$

Central density,temperature

$$\rho_{\mathrm{c}} \sim 11[\mathrm{g/cm^3}]$$

$$T_{\mathrm{c}} \sim 3.2 \times 10^8 [\mathrm{K}]$$



Set Up(2)

EOS … Ideal gas + radiation

$$P = \frac{Y_{\rm T} k_{\rm B}}{m_{\rm B}} \rho T + \frac{1}{3} a T^4$$

$$e = \frac{3}{2} \frac{Y_{\rm T} k_{\rm B}}{m_{\rm B}} \rho T + a T^4$$

$Y_{\rm T}$: the number of particles per baryon (=0.75)

Perturbation

Temperature is uniformly decreased by 0.5%

(~2% of pressure)

Assumption

- axisymmetric (Shibata & Sekiguchi 2005)
- viscosity is negligible

Numerical Calculation

Spacetime：Einstein equation

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{8\pi G}{c^4}T_{\mu\nu}$$

ρ ：density

u^μ ：four-velocity

h ：enthalpy per a unit mass

Fluid：EOC、Energy momentum conservation

$$T_{\mu\nu} = h\rho c^2 u_\mu u_\nu + P g_{\mu\nu}$$ ：perfect fluid

$$\nabla_\mu(\rho u^\mu) = 0$$ ：EOC

$$\nabla_\mu T^{\mu\nu} = 0$$ ：Energy momentum conservation

Nuclear burning

We are only interested in the effect of heating by nuclear burning
→ calculate small nuclear reaction networks

①solve advection term $\nabla_\mu(\rho_{\rm i} u^\mu) = 0$ (i=p,a,c)

②calculate nuclear reaction networks at fluid local frame
by using energy generation rates $\dot{q}$ (depend on T, ρ)

$$\frac{dY_{\rm p}}{d\tau} = -m_{\rm u}\left(\frac{\dot{q}_{\rm CNO}}{Q_{\rm c}}\right)$$

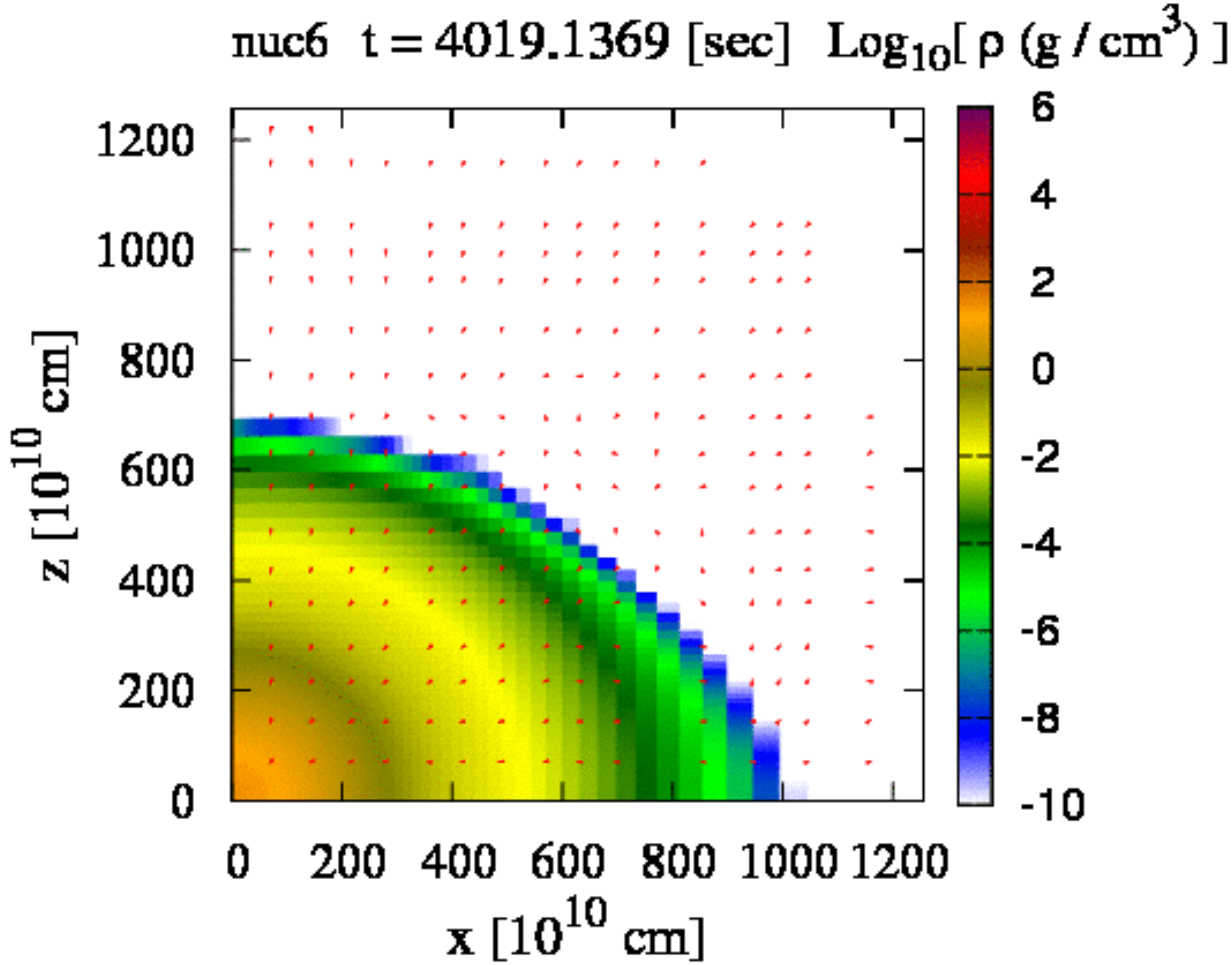
$$\frac{dY_\alpha}{d\tau} = \frac{m_{\rm u}}{4}\left(\frac{\dot{q}_{\rm CNO}}{Q_{\rm c}} - \frac{\dot{q}_{3\alpha}}{Q_{3\alpha}}\right)$$

$$\frac{dY_{\rm c}}{d\tau} = \frac{m_{\rm u}}{12}\left(\frac{\dot{q}_{3\alpha}}{Q_{3\alpha}}\right)$$

$Y_{\rm i}$: $n_{\rm i}/n_{\rm B}$
τ : proper time
$m_{\rm u}$: atomic mass unit
$\dot{q}$: energy generation rate[erg/g/s]
Q : liberated energy per baryon

Result

Overview



- about 4-5% of mass remained as the surrounding disk
- about 1 % of mass is ejected
- The effect of nuclear burning is negligible in this model

  reason : nuclear energy < gravitational bounding energy

Disk formation

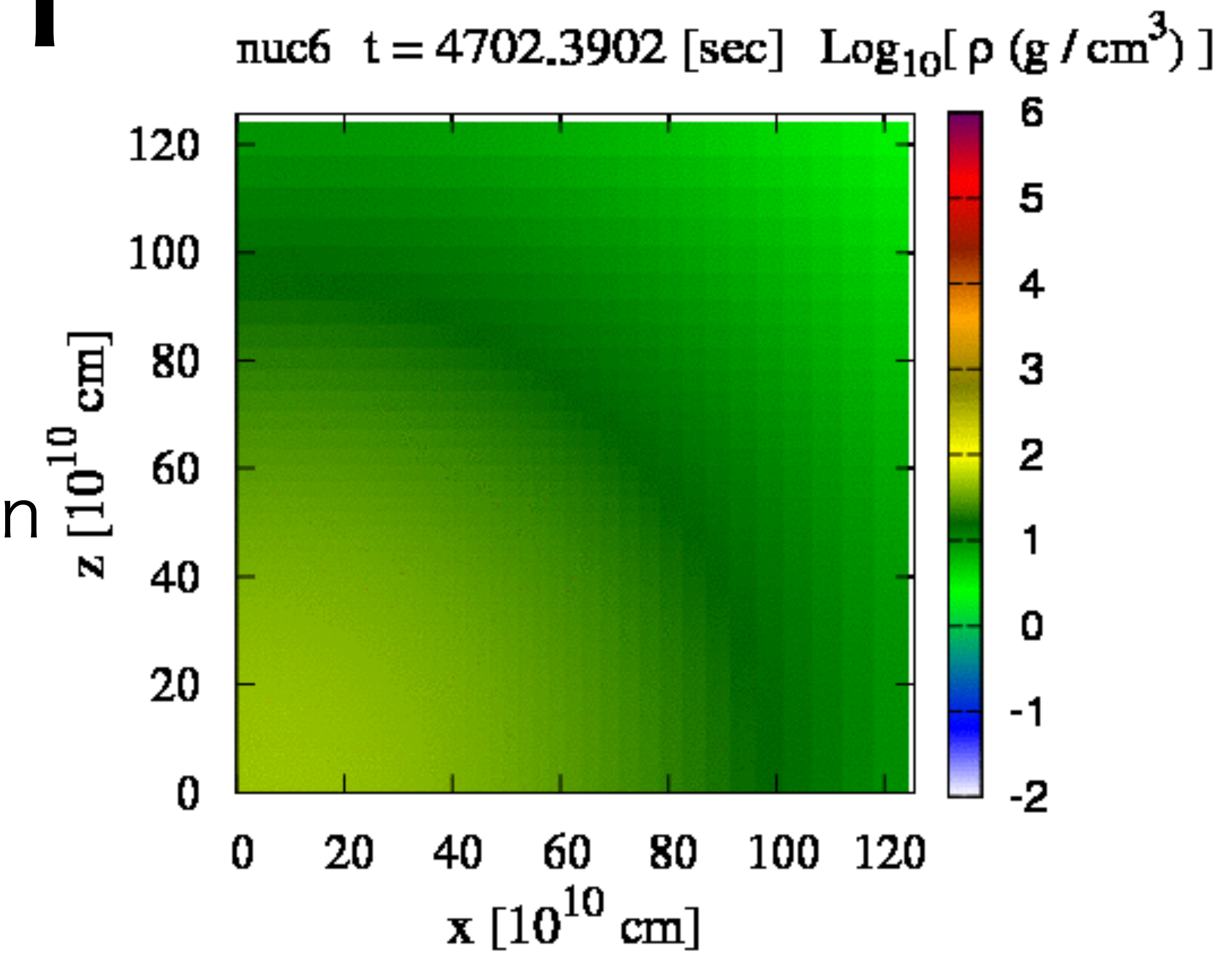
- about 4% mass forms disk

$$M_{\rm disk} \sim 6000 M_\odot$$

- The disk's T, ρ are higher than the initial SMS

$$T_{\rm max} \sim 10^9 [{\rm K}]$$

$$\rho_{\rm max} \sim 300 [{\rm g/cm^3}]$$

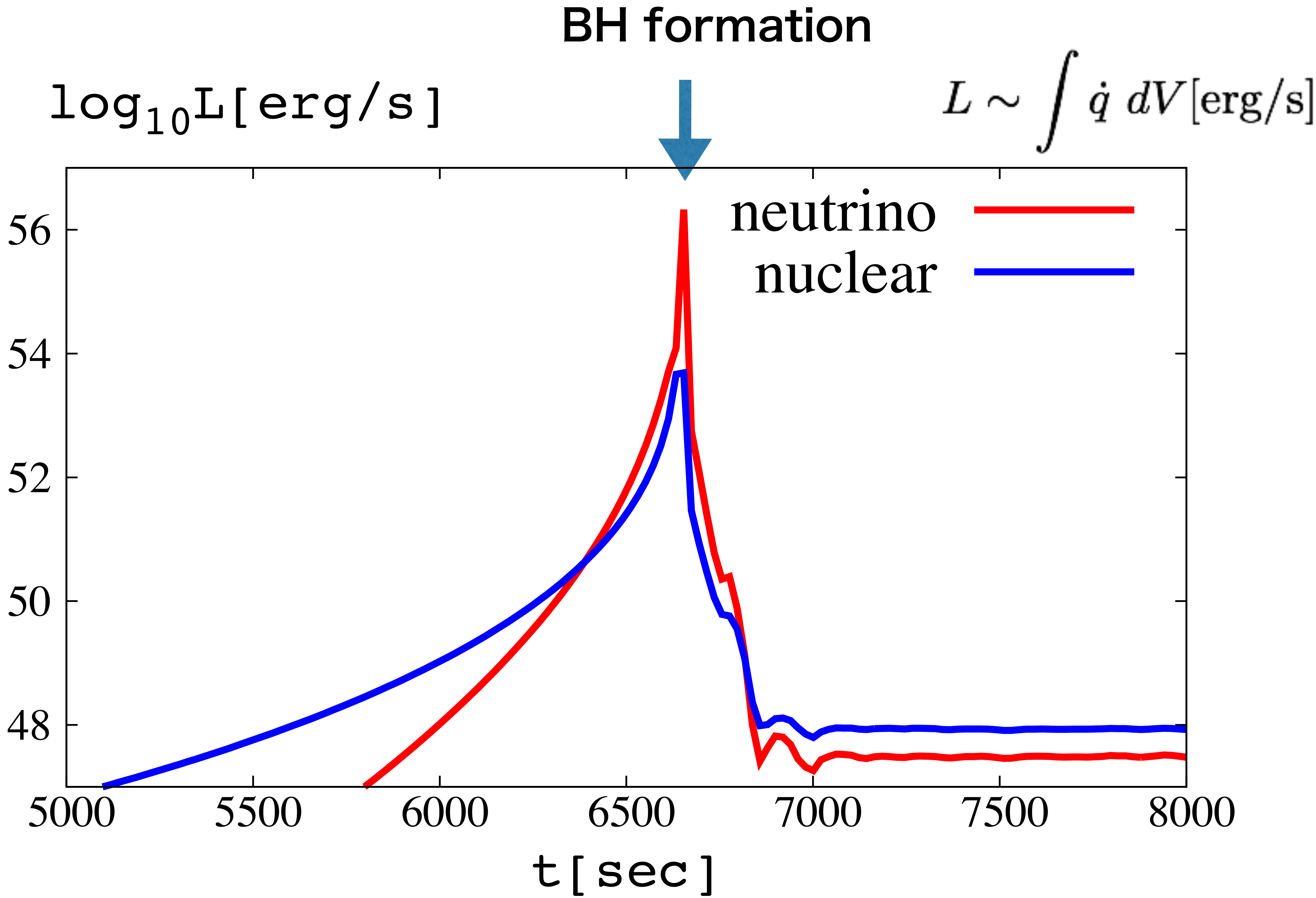


- The effect of nuclear burning is also negligible
  (the difference of T, ρ are at most 1 %)

Reason : the total released energy by nuclear burning during collapse is much less than the total inertial energy of the disk

Result : The effect of nuclear burning is negligible in this model

Energy generation rate



Disk Evolution

- nuclear energy generation rate

$$L \sim 10^{48} [\mathrm{erg/sec}]$$

- internal energy of the disk

$$E_{\mathrm{int}} \sim 10^{56}\ [\mathrm{erg}]$$

timescale

$$t = E_{\mathrm{int}}/L \sim 10^{8} [\mathrm{sec}]$$

- total nuclear energy (He→C)

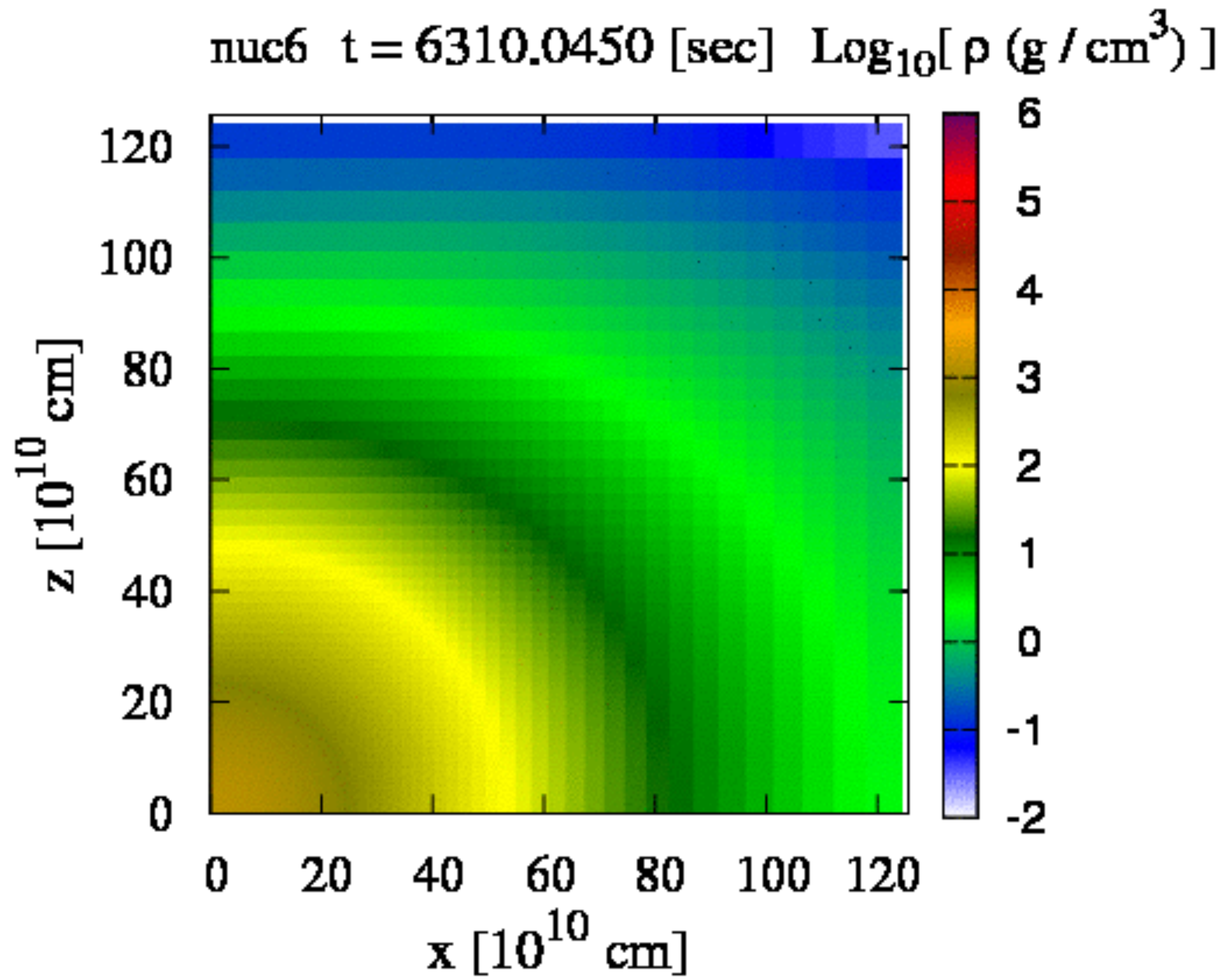
$$E_{\mathrm{nuc}} \sim 6 \times 10^{54} [\mathrm{erg}]$$

$$t = E_{\mathrm{nuc}}/L \sim 10^{6-7} [\mathrm{sec}]$$

$$E_{\mathrm{int}} > E_{\mathrm{nuc}}$$

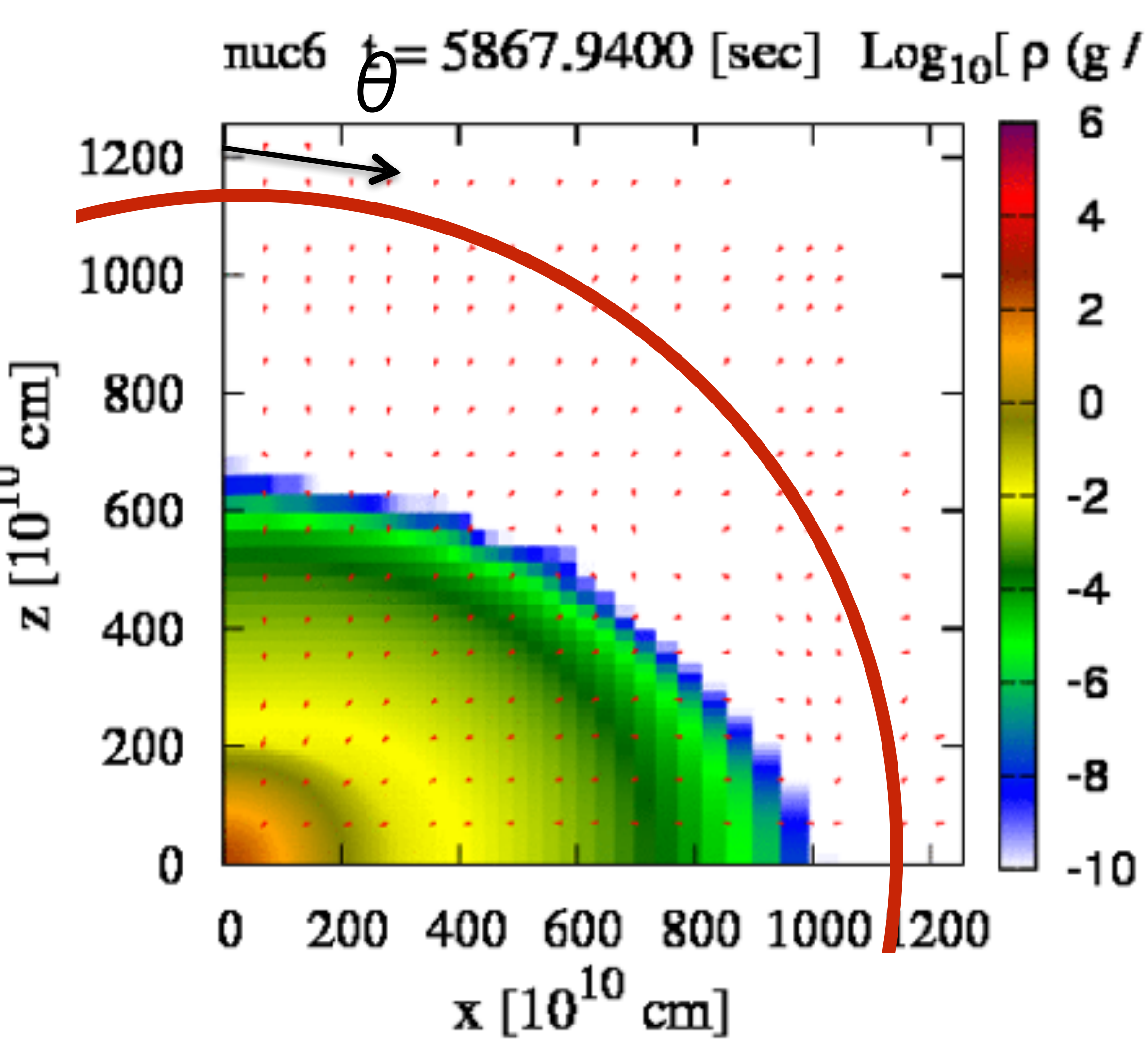
⇒ **Viscous heating is more important**

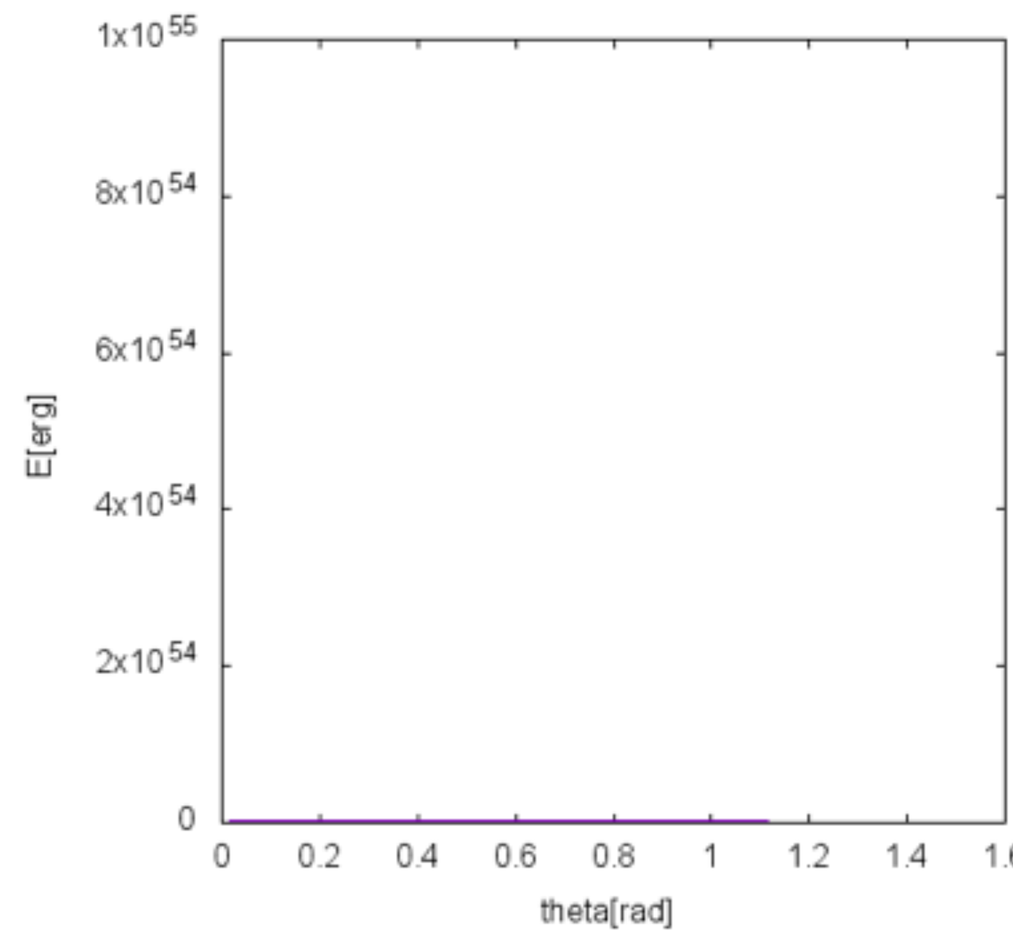
Outflow



nuc6 t = 6310.0450 [sec] Log10[ρ (g / cm3)]
z [10^10 cm]
x [10^10 cm]
0
20
40
60
80
100
120
6
5
4
3
2
1
0
-1
-2

Energy of the outflow





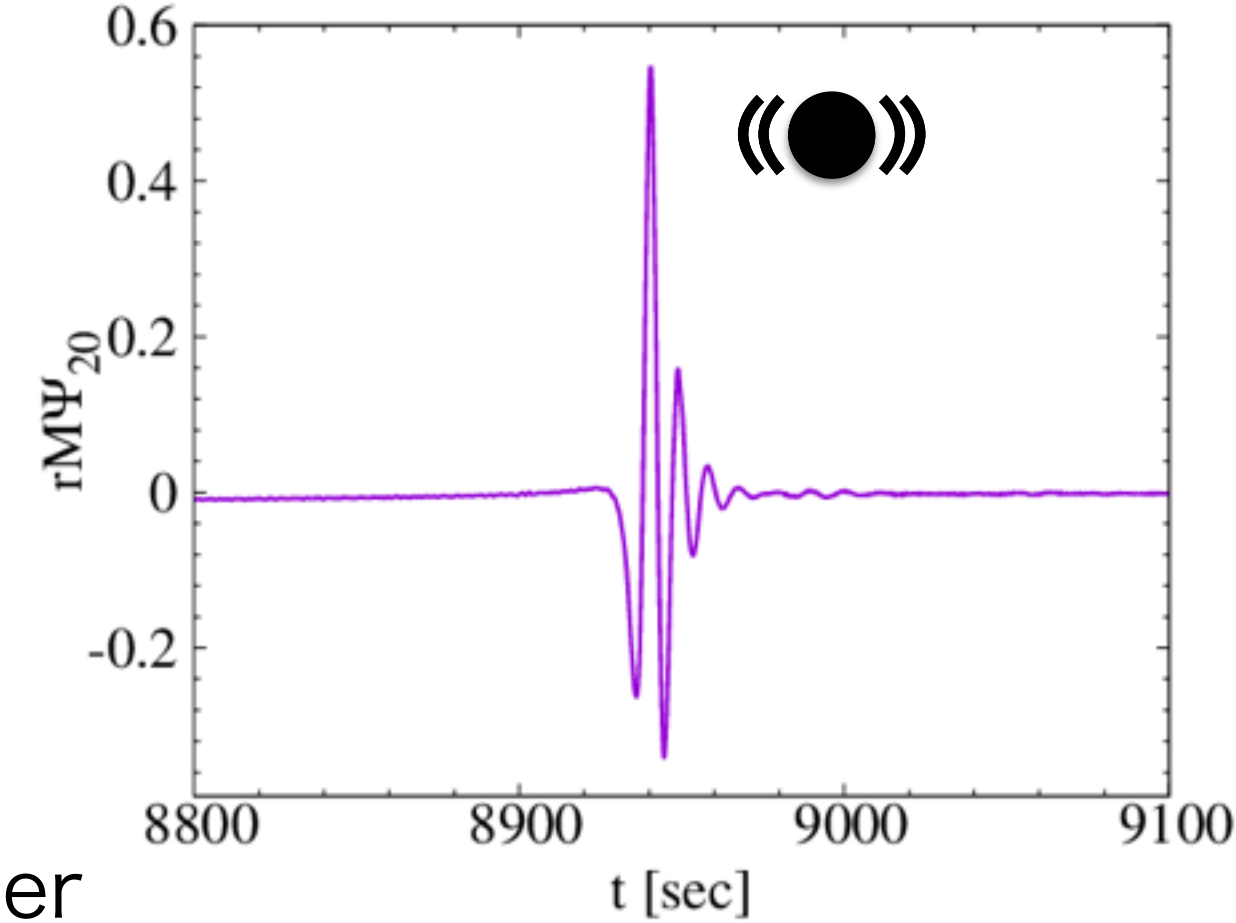
- Total energy of the outflow (except rest mass energy) is about 10^{55} [erg] (~explosion ?)

GWs emission

- GWs are emitted during the BH formation

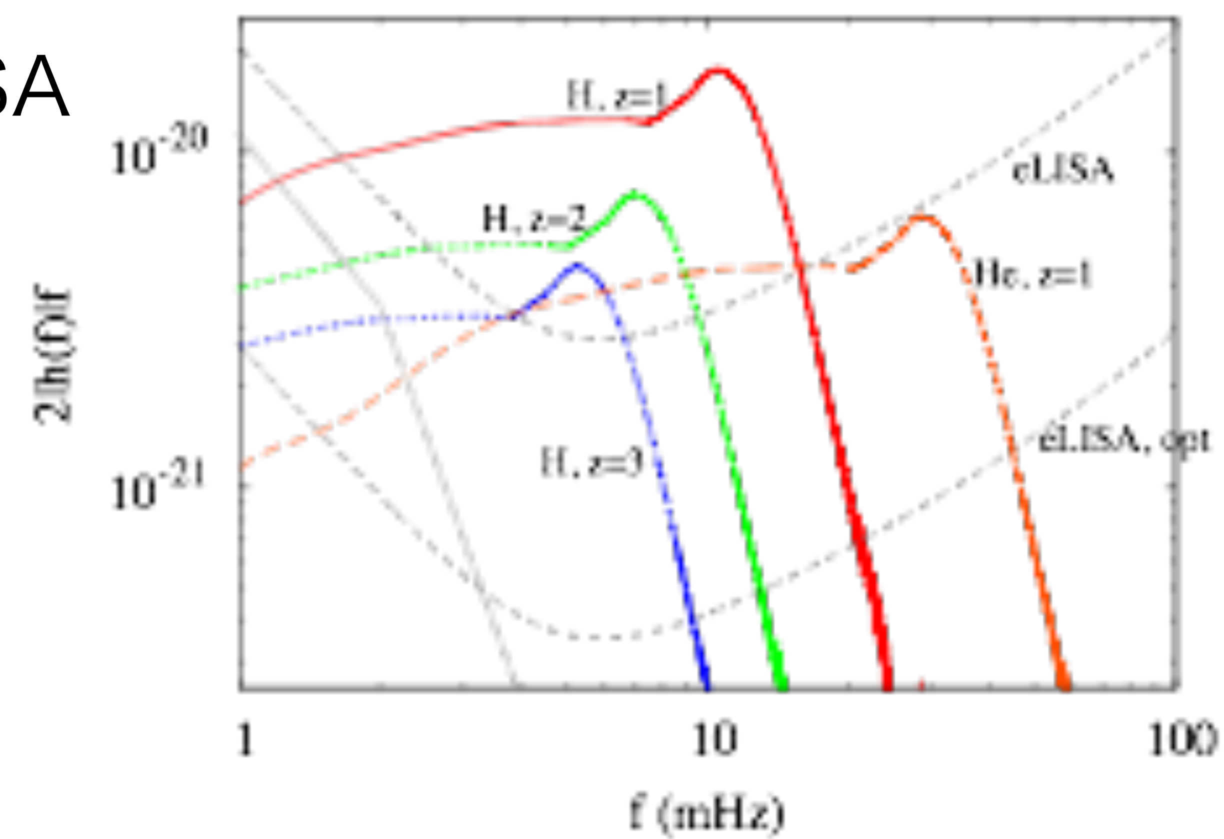
$$\Psi_4 = \ddot{h}_+ - i\ddot{h}_\times$$

$$\Psi_4 = \sum_{l,m} \Psi_{lm} \ {}_{-2}Y_{lm}$$



- They will be detectable by space laser interferometric detectors like eLISA

Shibata,Sekiguchi,Uchida,Umeda(2016)



Summary

・初期宇宙には超大質量星が存在する可能性がある
・超大質量星の重力崩壊の観測可能性について調べたい
・テスト計算として高速回転するヘリウム燃焼期の超大質量星の重力崩壊をシミュレーションした
・結果としてこのモデルでは核融合反応は重力崩壊にほとんど影響を与えなかった
・重力崩壊後、質量の数%がディスクとして残り、ほとんどがBHになった
・BH形成時に重力波が放出され、LISA等で検出できる可能性がある
・崩壊後、outflowが高速で出るのでその観測可能性についても興味がある

future work

・**より多くのモデルで核融合の効果を見る**
・**outflowの観測可能性について外層との相互作用も考慮に入れて調べる**
・粘性を入れたディスクの長時間発展を行う

ありがとうございました