Collapse of rotating very massive stellar core to BH + disk system

National Astronomical Observatory of Japan
Yuichiro Sekiguchi
&
Masaru Shibata (Kyoto Univ.)

Motivation

- Very massive stellar core ~ high entropy core ($s/k_B > 1$)
  - GRB progenitor candidate (Collapsar model)
    - Current progenitor models predict 'higher-entropy cores'
      - He star merger model (Fryer & Heger 2005)
      - Binary interaction model (van den Huevel & Yoon 2007)
      - Chemically homogeneous evolution model (Yoon & Langer 2006, Woosley & Heger 2006)
  - Collapse has not been studied in detail
    - Evolution in ρ-T plane is different from that of ordinary SN
- Core rotation
  - Essential for BH + Disk formation (e.g. MacFadyen & Woosley 1999)
  - Poorly known
    - Very rapid rotation is often assumed to guarantee disk formation
    - (Relatively) 'SLOWLY' rotating models are not studied in detail

Motivation

- Very massive stellar core ~ high entropy core ($s/k_B > 1$)
  - GRB progenitor candidate (Collapsar model)
    - Current progenitor models predict 'higher-entropy cores'
      - He star merger model (Fryer & Heger 2005)
      - Binary interaction model (van den Heuvel & Yoon 2007)
      - (Yoon & Langer 2006; Woosley & Heger 2006)
  - Collapse has not been studied in detail
    - Evolution in ρ-T plane is different from that of ordinary SN

In my talk, I present our resent Full-GR-simulation-results of collapse of 'slowly' rotating high entropy core to BH and Disk

Not detailed, but general feature of collapse is described
For detail, see Sekiguchi & Shibata (2010) to be submitted

- Core rotation
  - Essential for BH + Disk formation (e.g. MacFadyen & Woosley 1999)
  - Poorly known
    - Very rapid rotation is often assumed to guarantee disk formation
    - (Relatively) 'SLOWLY' rotating models are not studied in detail

Setting

Basic equations

- Einstein's equations : BSSN formulation
  - 4th order finite difference in space, 3rd order Runge-Kutta time evolution
  - Gauge conditions : 1+log slicing, dynamical shift
- General relativistic hydrodynamics :
  - Tμν for neutrinos is also introduced
  - High resolution shock capturing scheme

$$\nabla_a T_b^{a} = -Q_b^{(\mathrm{leak})}$$

$$\nabla_a T_b^{a\ (\nu,\mathrm{stream})} = Q_b^{(\mathrm{leak})}$$

- Lepton conservation equations :
  - Electron fraction
  - Neutrino fractions

$$\frac{d\,Ye}{dt} = -\gamma_{\mathrm{e-\,cap}} + \gamma_{\mathrm{e+\,cap}}$$

$$\frac{d\,Y\nu_{\mathrm{e}}}{dt} = \gamma_{\mathrm{e-\,cap}} + \gamma_{\mathrm{pair}} + \gamma_{\mathrm{plasmon}} + \gamma_{\mathrm{Brems}} - \gamma_{\nu_{\mathrm{e}}\mathrm{leak}}$$

$$\frac{d\,Y\bar{\nu}_{\mathrm{e}}}{dt} = \gamma_{\mathrm{e+\,cap}} + \gamma_{\mathrm{pair}} + \gamma_{\mathrm{plasmon}} + \gamma_{\mathrm{Brems}} - \gamma_{\bar{\nu}_{\mathrm{e}}\mathrm{leak}}$$

$$\frac{d\,Y\nu_{\mathrm{x}}}{dt} = \gamma_{\mathrm{pair}} + \gamma_{\mathrm{plasmon}} + \gamma_{\mathrm{Brems}} - \gamma_{\nu_{\mathrm{x}}\mathrm{leak}}$$

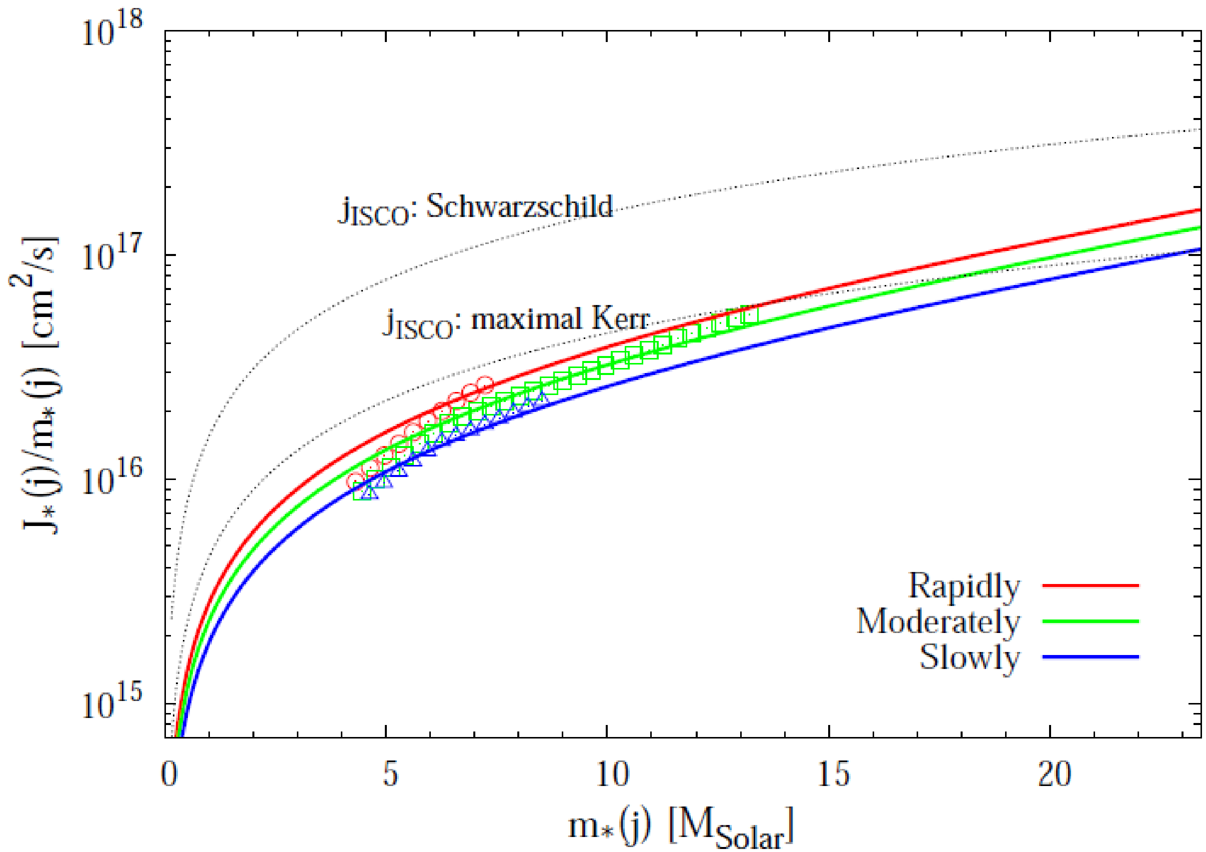
- See Sekiguchi (2010a,b) for detail
- A BH excision technique

Summary of microphysics

- EOS
  - Any tabulated EOS can be used
  - Currently Shen EOS + electrons + radiation + neutrinos
- Weak rates
  - $e^{\pm}$ captures : FFN 1985, rate on NSE back ground
  - $e^{\pm}$ annihilation: Cooperstein et al. 1985, Itoh et al. 1996
  - plasmon decay: Ruffert et al. 1996, Itoh et al. 1996
  - Bremsstrahlung: Burrows et al. 2006, Itoh et al. 1996
- Neutrino emissions
  - GR neutrino leakage scheme (Sekiguchi 2010a,b)
  - Detailed opacities based on Burrows et al. 2006
    - (n, p, A) scattering and absorption
    - with higher order corrections (e.g, Horowiz 2005)

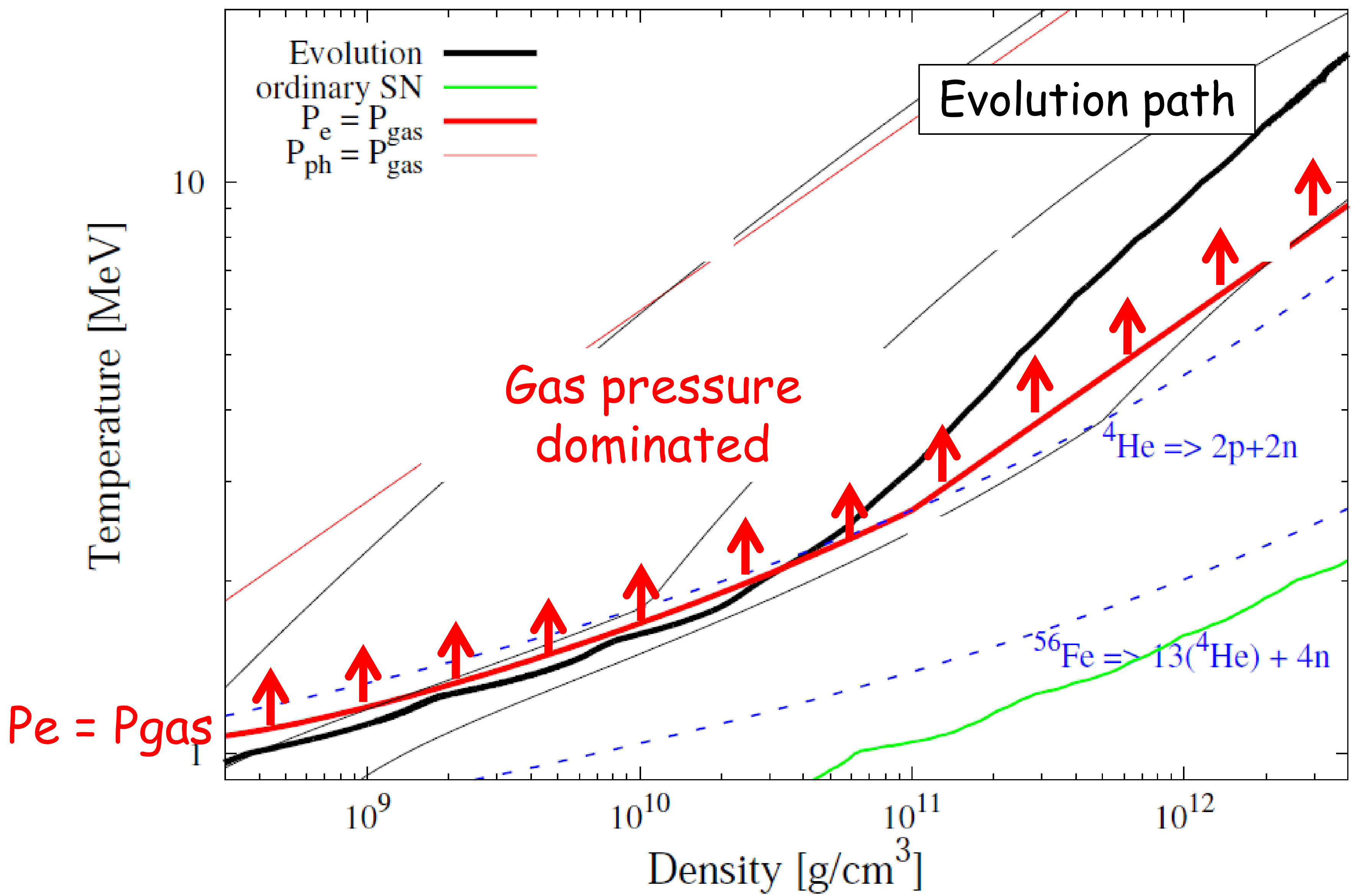
Initial conditions

- Simplified model (s (entropy per baryon) & Ye are constant)
  - **s = (5-)8k_B**, Ye = 0.5, ⇒ core mass ~ (8—)15 Msolar
- Rotation profiles are added (based on Woosley & Heger 2006)
  - 'Slowly', **'moderately'**, and 'rapidly' rotating models
  - Initial models are 'SLOWLY rotating' in the sense $j < j_{ISCO, Sch.BH}$



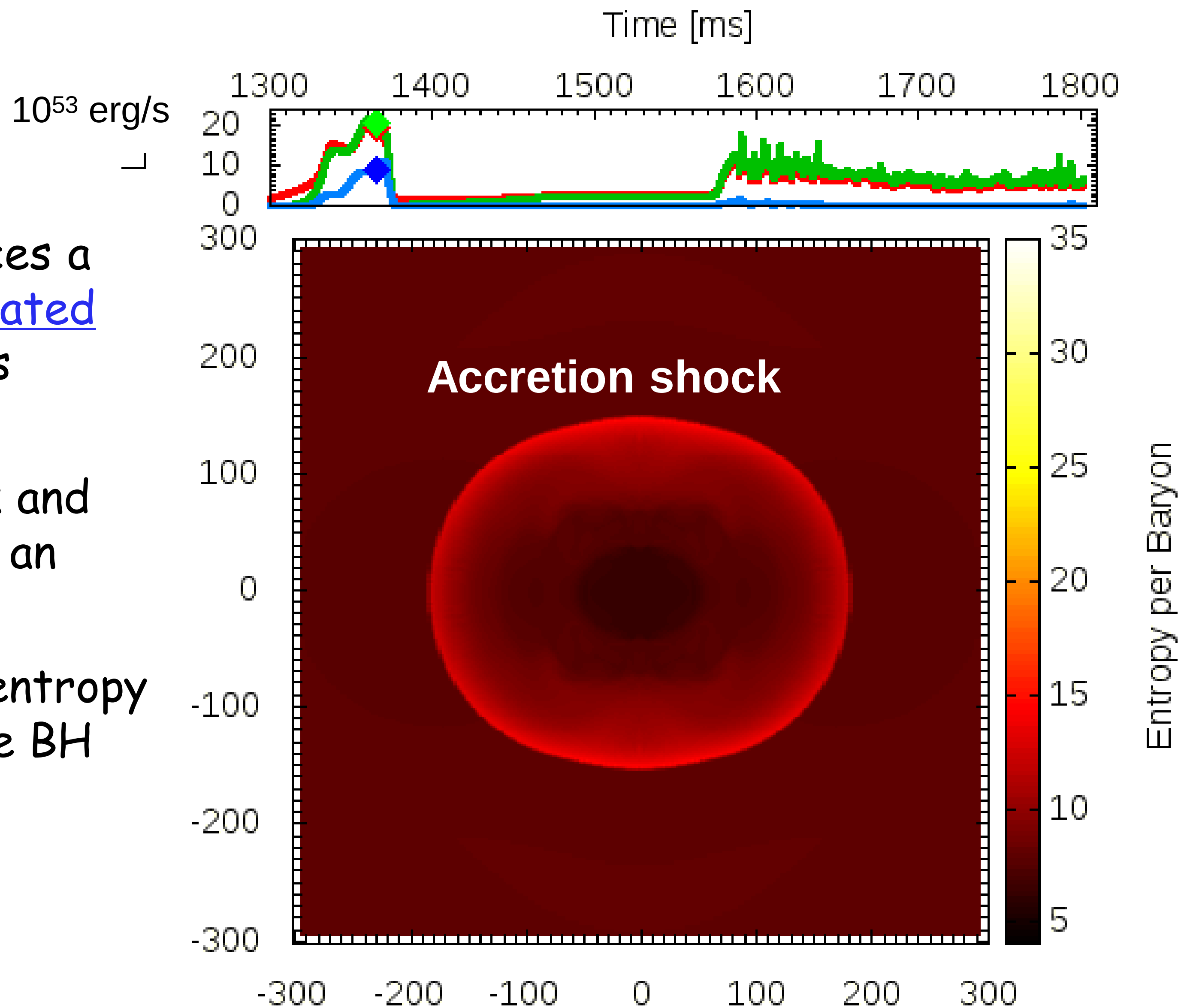
Results

Gas pressure dominated bounce



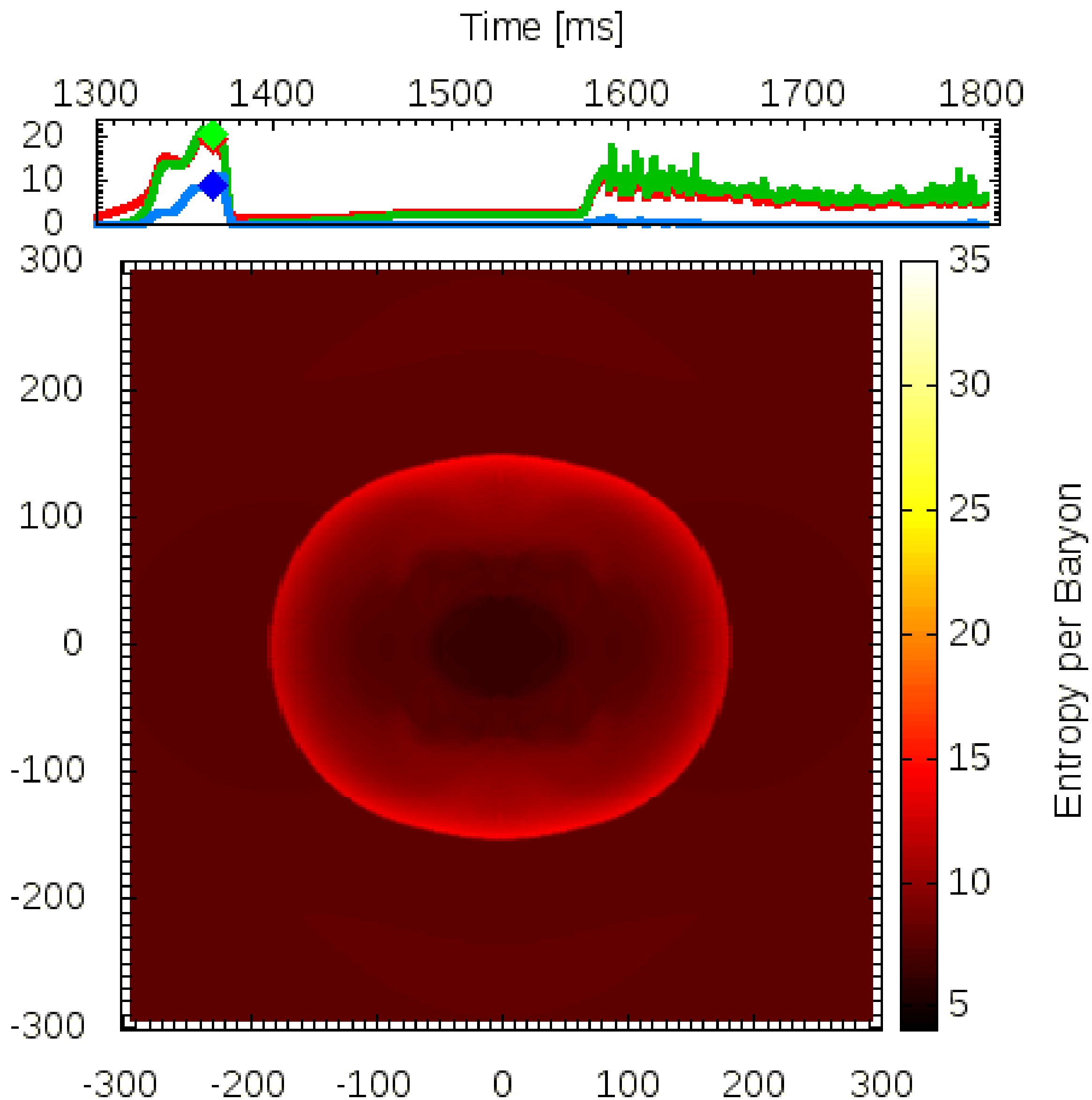
Moderately rotating model

- The core experiences a gas pressure dominated bounce and shock is formed
- The bounce is weak and the shock becomes an accretion shock
- This figure shows entropy contour just before BH formation
- Animation !!

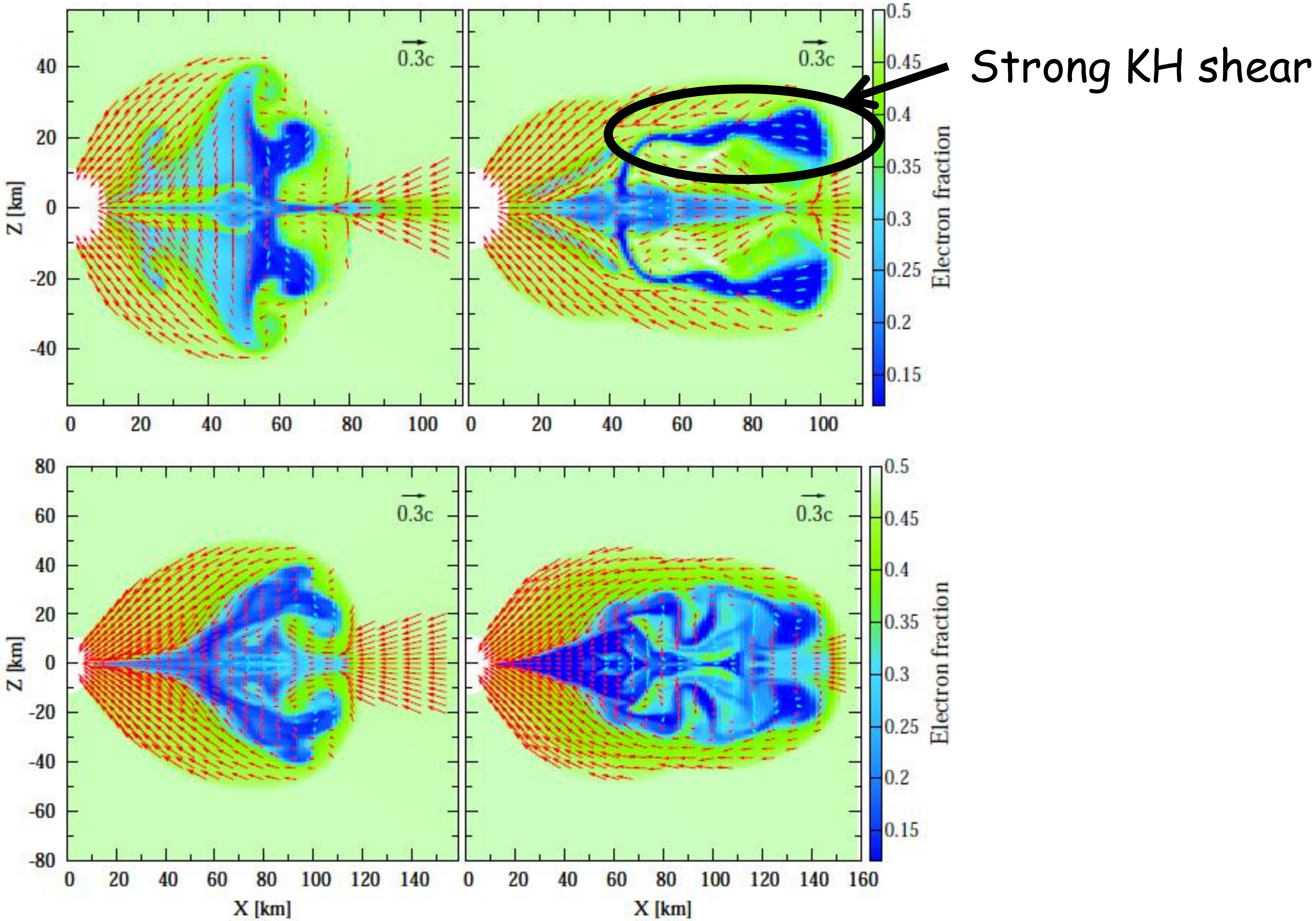


Moderately rotating model

- Geometrically thin disk is formed first
- Shocks are formed in inner region near the surface
- As the matter with higher j falls, P_{disk} and hence, disk height increase
- Ram pressure decreases
- Also, negative entropy gradient is developed (convectively unstable)
    - In inner region, shock heating is stronger and neutrino cooling is less efficient
- Disk expands to be a torus and convection sets in

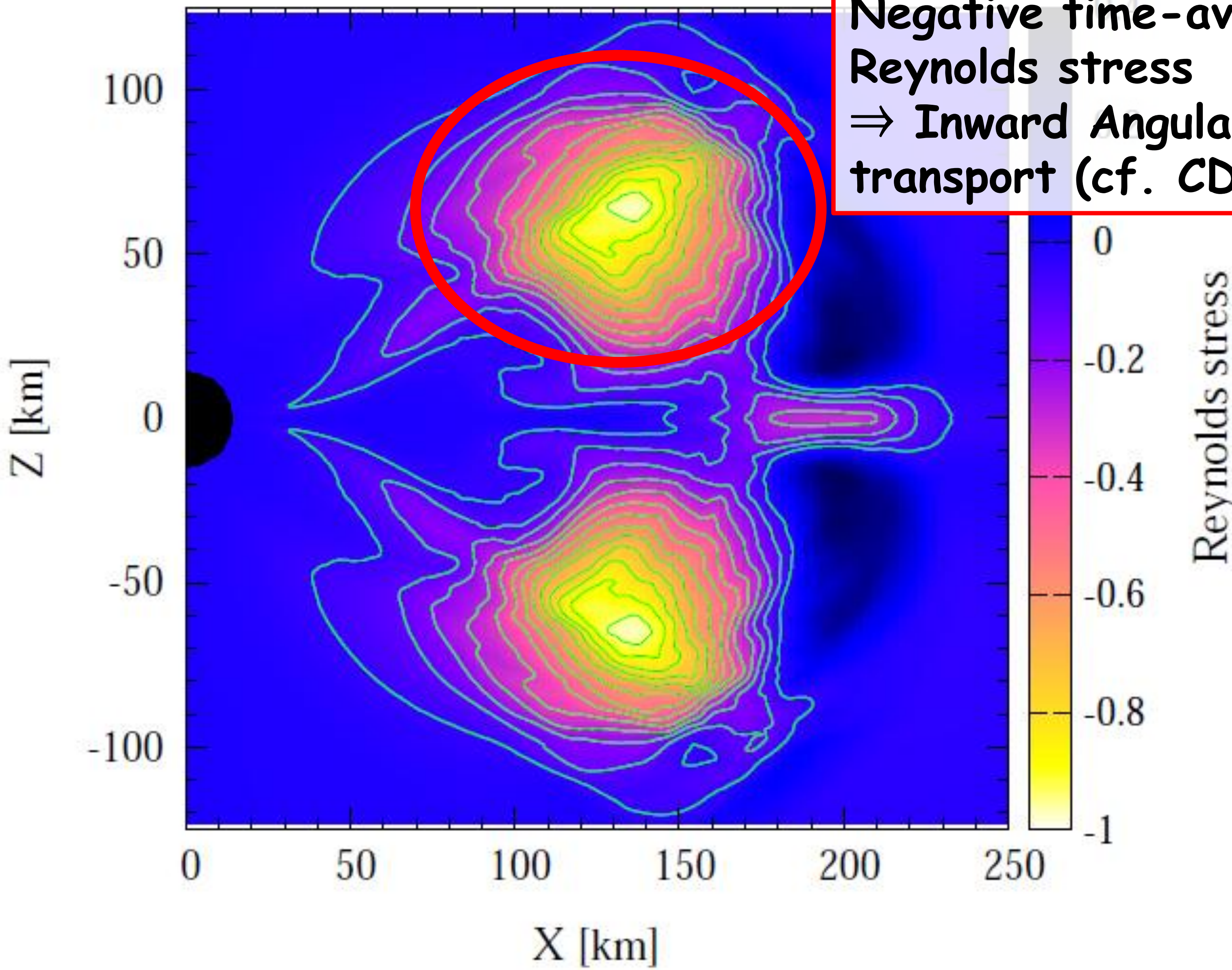


Flow is RT, KH, and convectively unstable

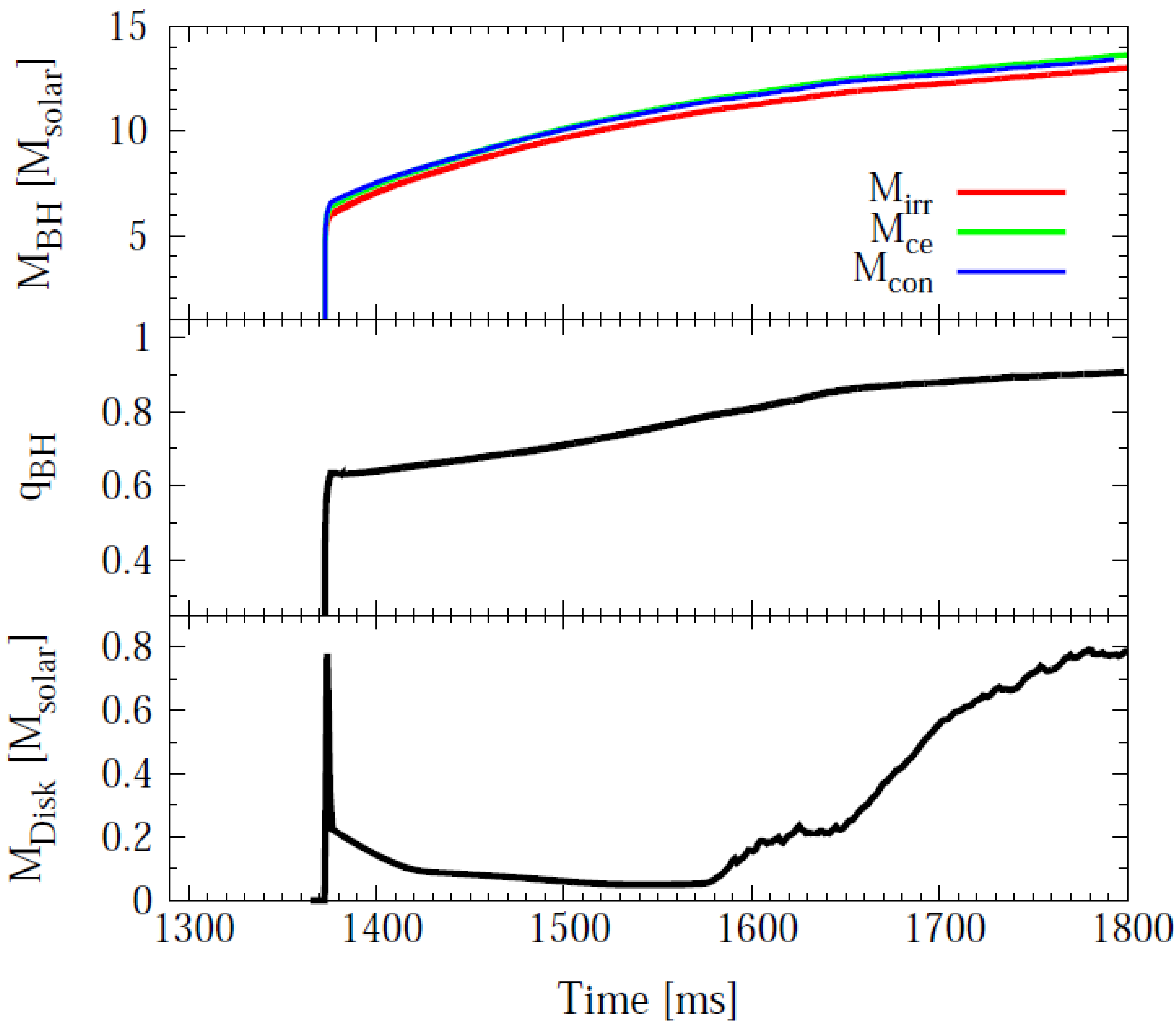


Angular momentum is transported inward

Negative time-averaged Reynolds stress
⇒ Inward Angular momentum transport (cf. CDAF)

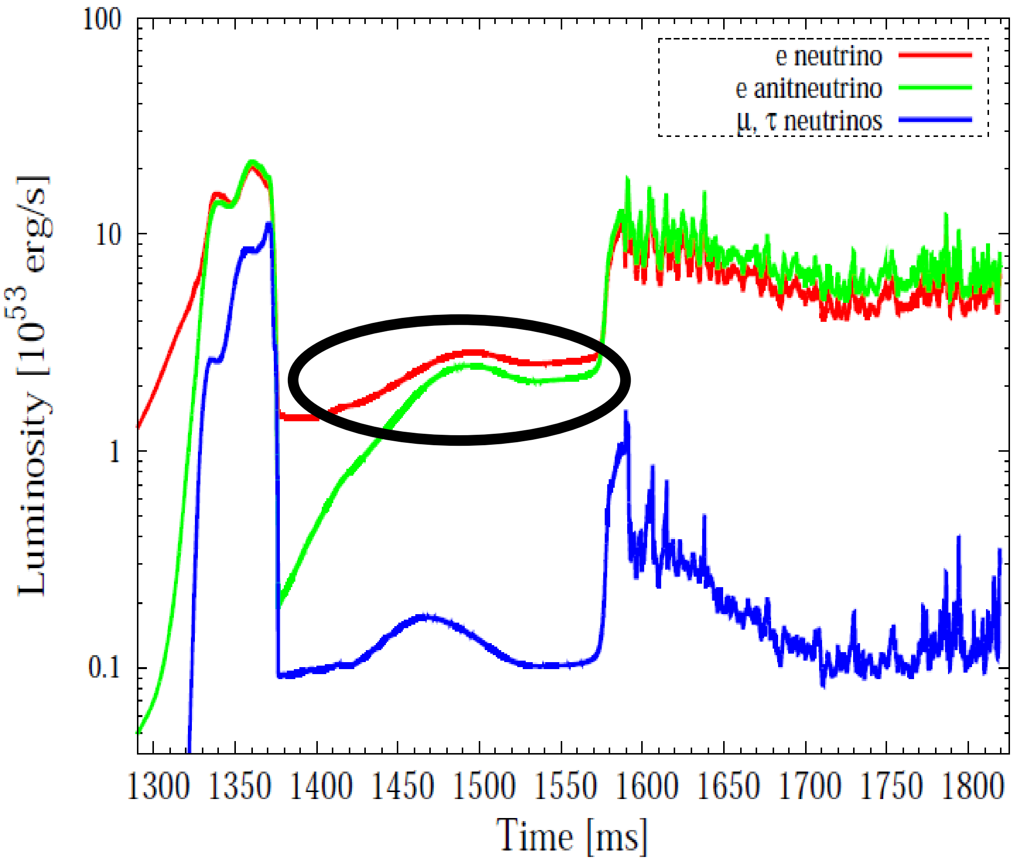


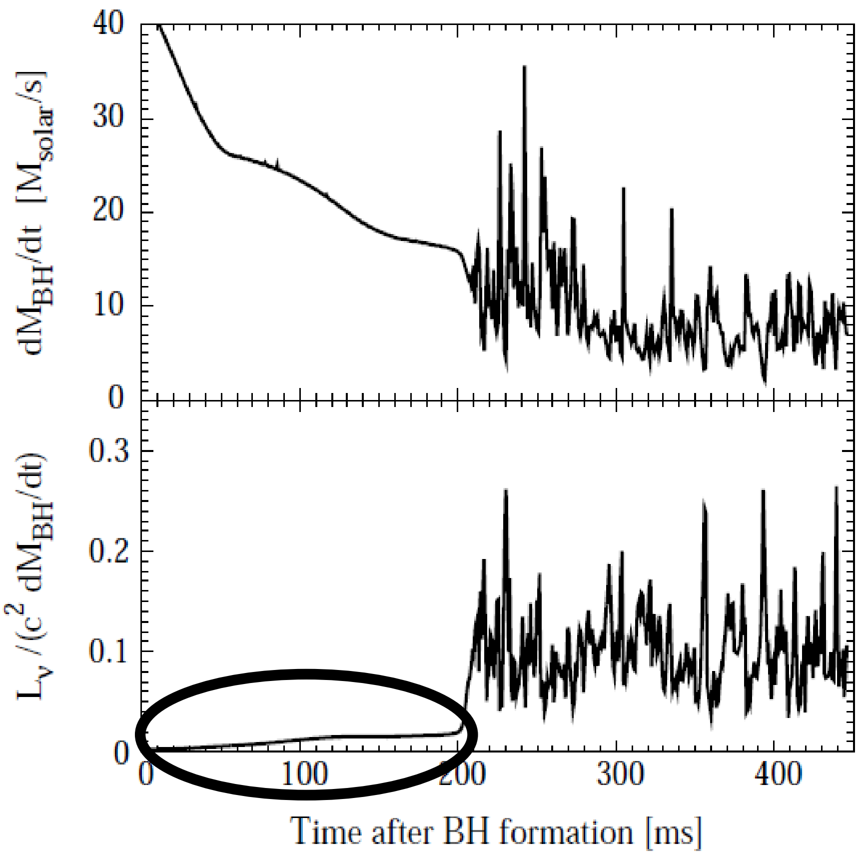
Rapidly rotating BH (q~0.9) is formed



Neutrino luminosity (1)

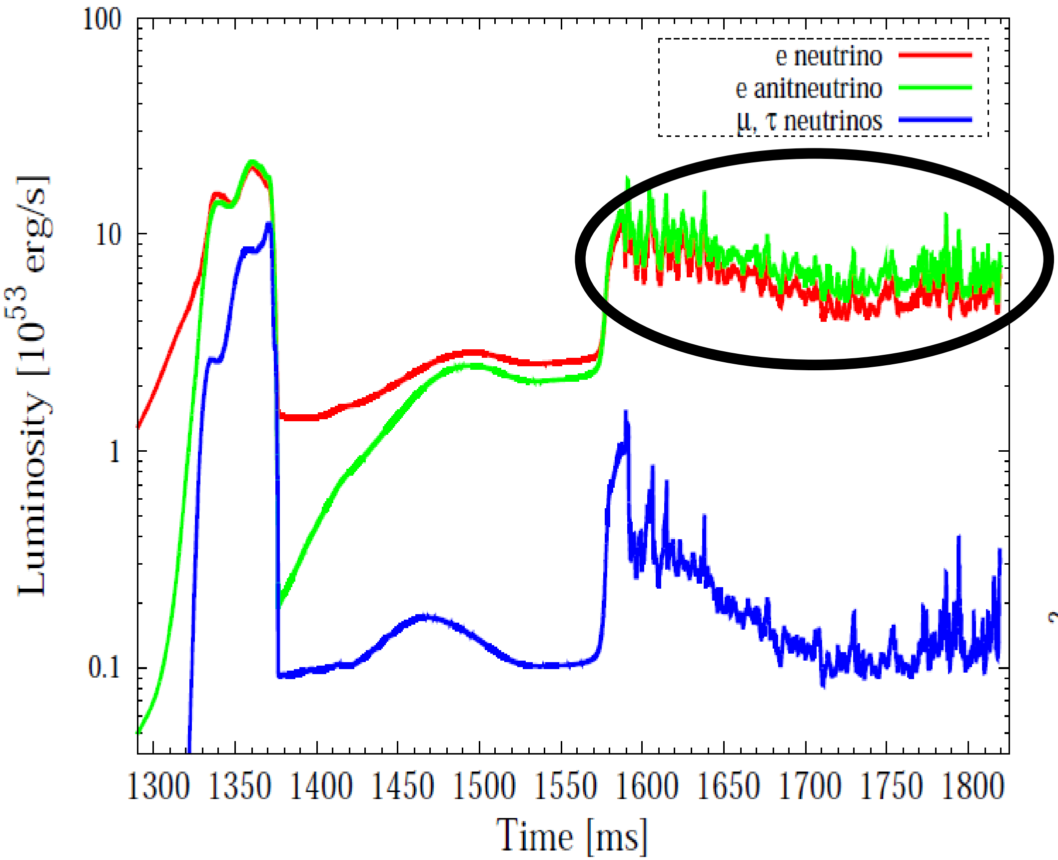
- The thin disk emits neutrinos of ~ 10^{53} erg/s
  - The efficiency is low as ~ 10^{-3} because thermal energy generated at the shocks is advected onto BH before emitted by neutrinos
  - Expected efficiency is $GM_{\rm BH}\dot{M}/r \sim 0.1\dot{M}c^2$

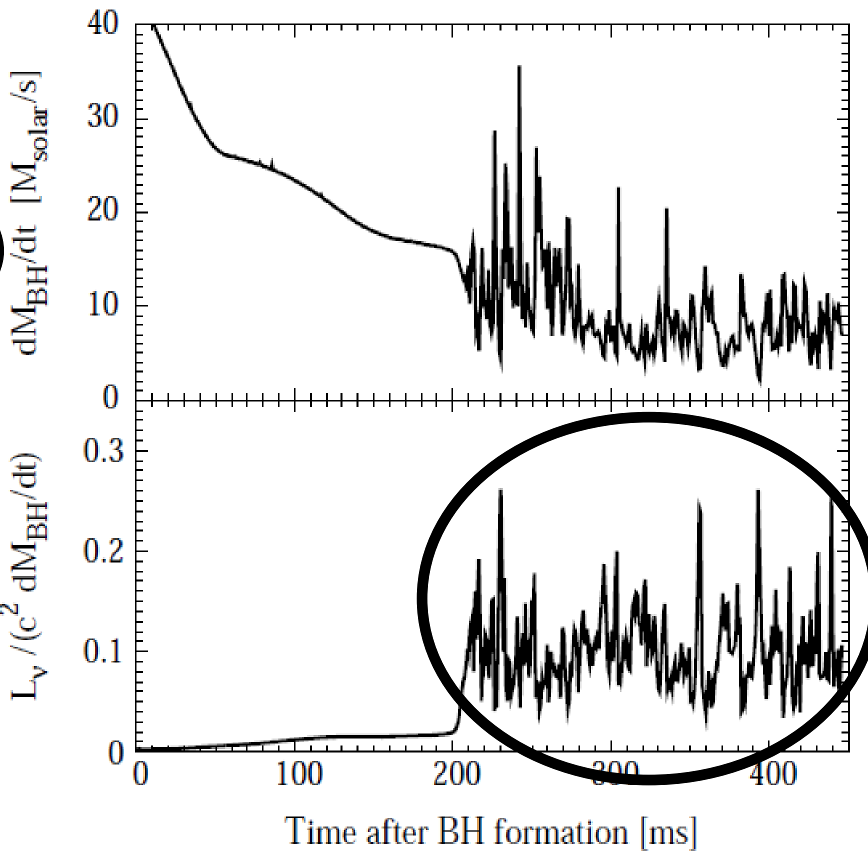




Neutrino luminosity (2)

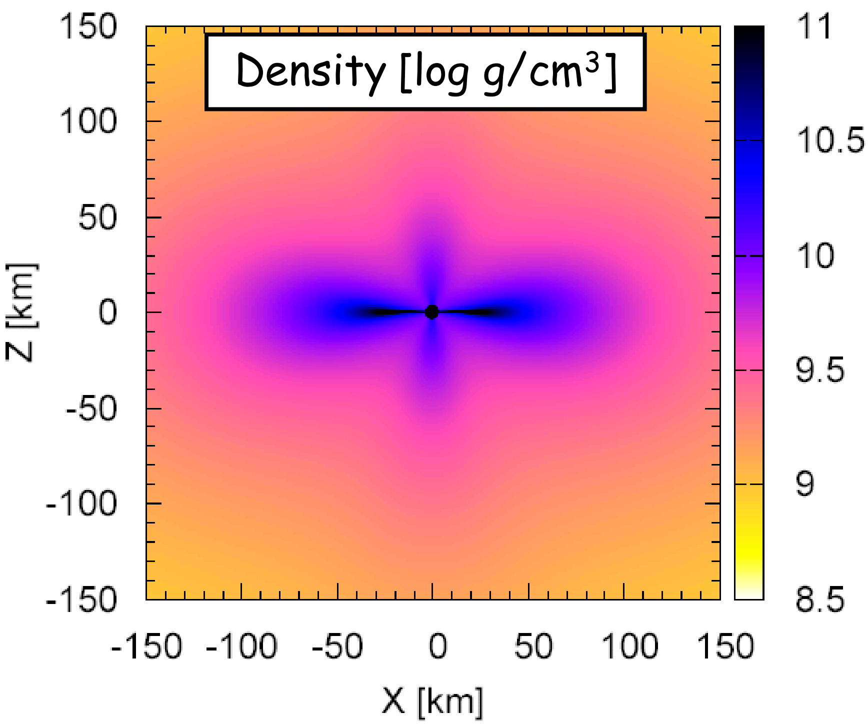
- The convective torus emits neutrinos of ~ 10^{54} erg/s
  - The efficiency is ~ 0.1 which indicates that thermal energy generated at the shocks is efficiently carried away by neutrinos
  - Convective activities induce time-variability in luminosities

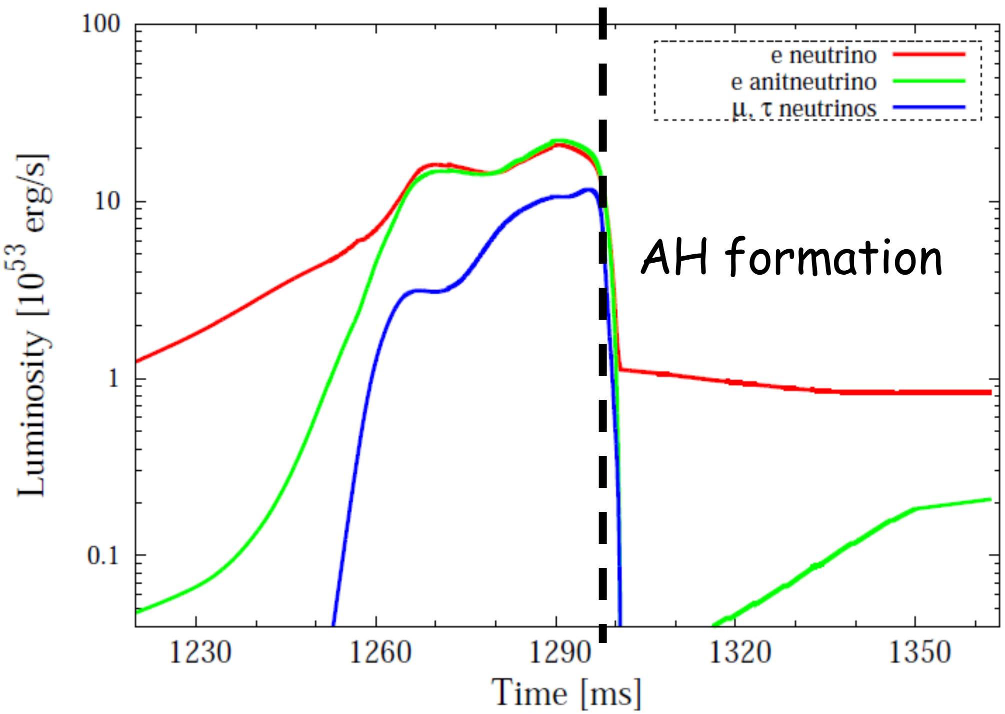




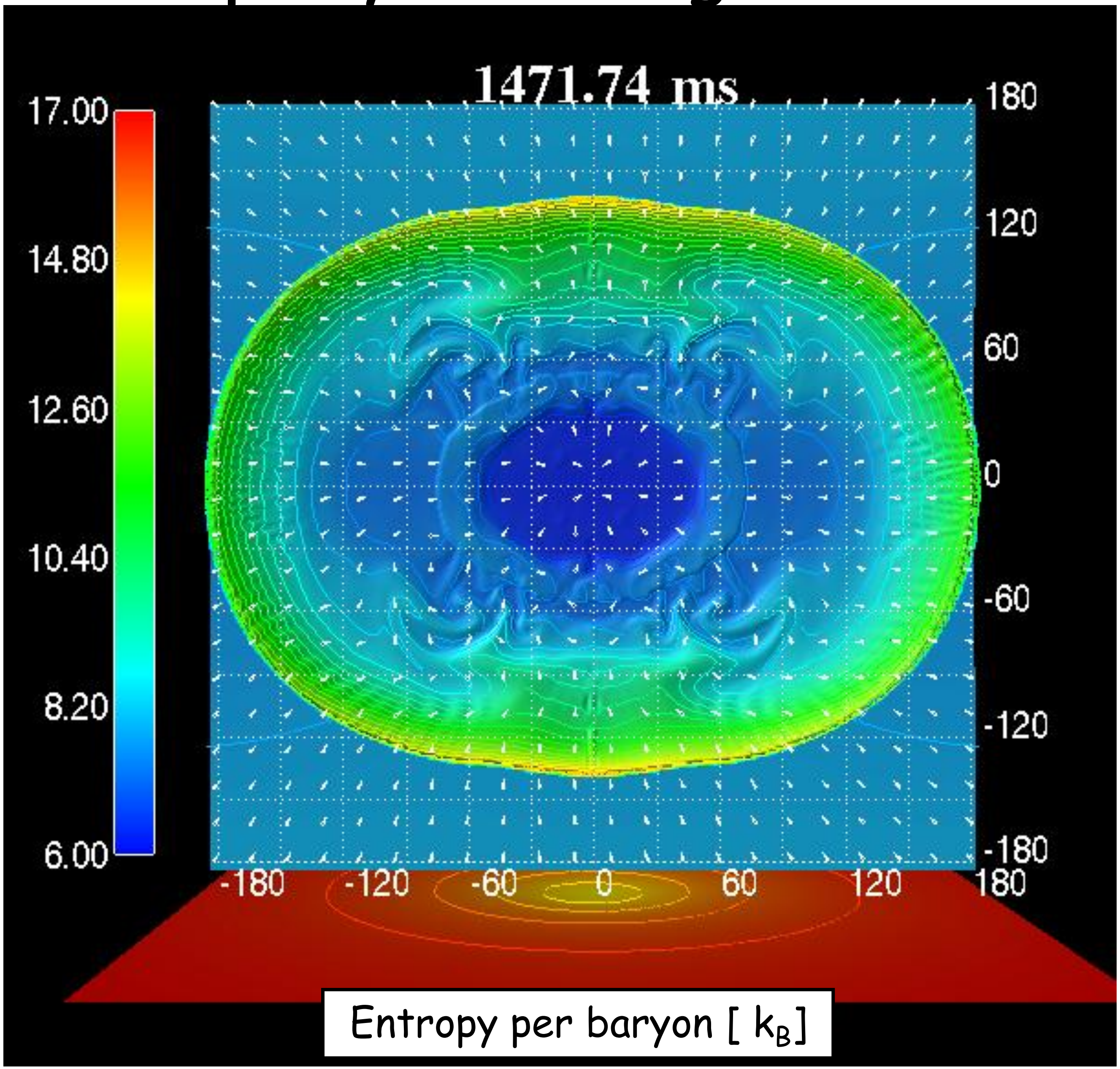
Slowly rotating model

- The thin disk does not expand in our simulation time
  - When fluids with higher *j* fall onto disk in a later phase, the disk will expand to be a thick torus and convection may set in
- Neutrino luminosity is low as ~ 10^{53} erg/s



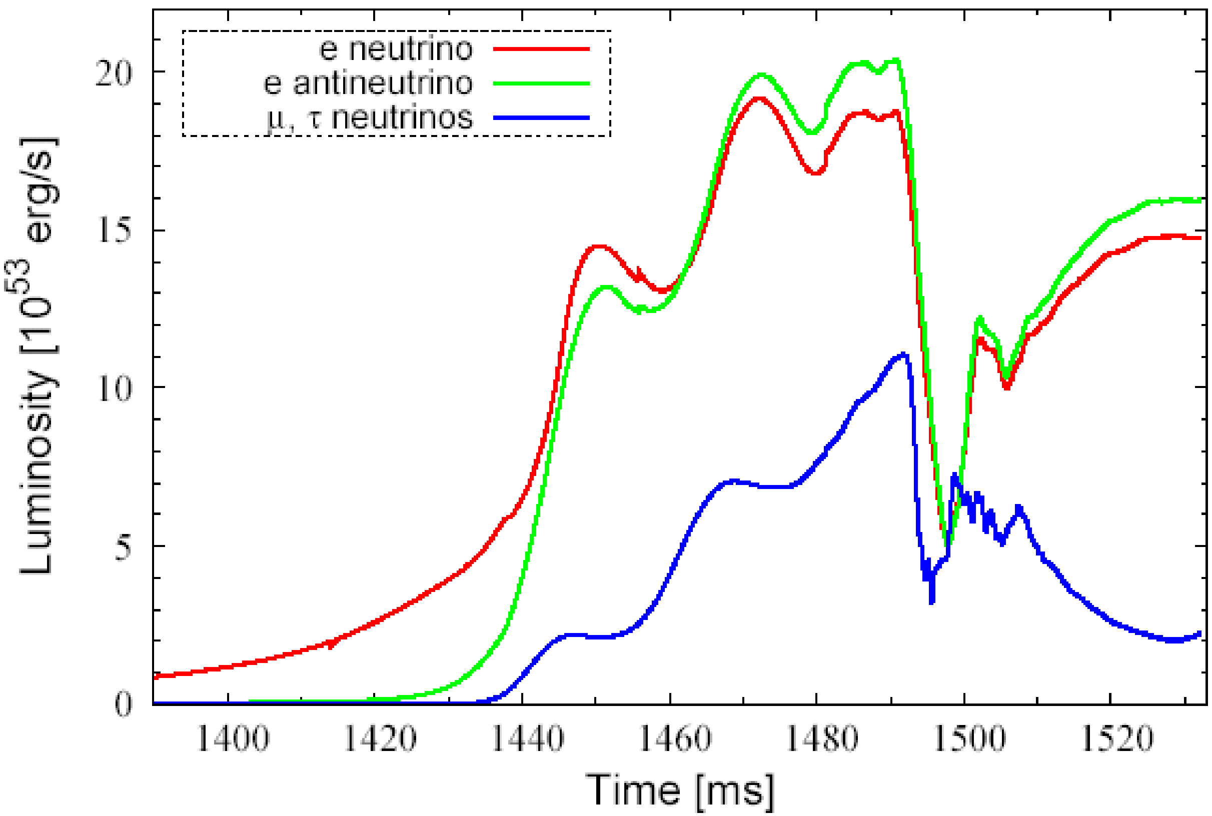


Rapidly rotating model



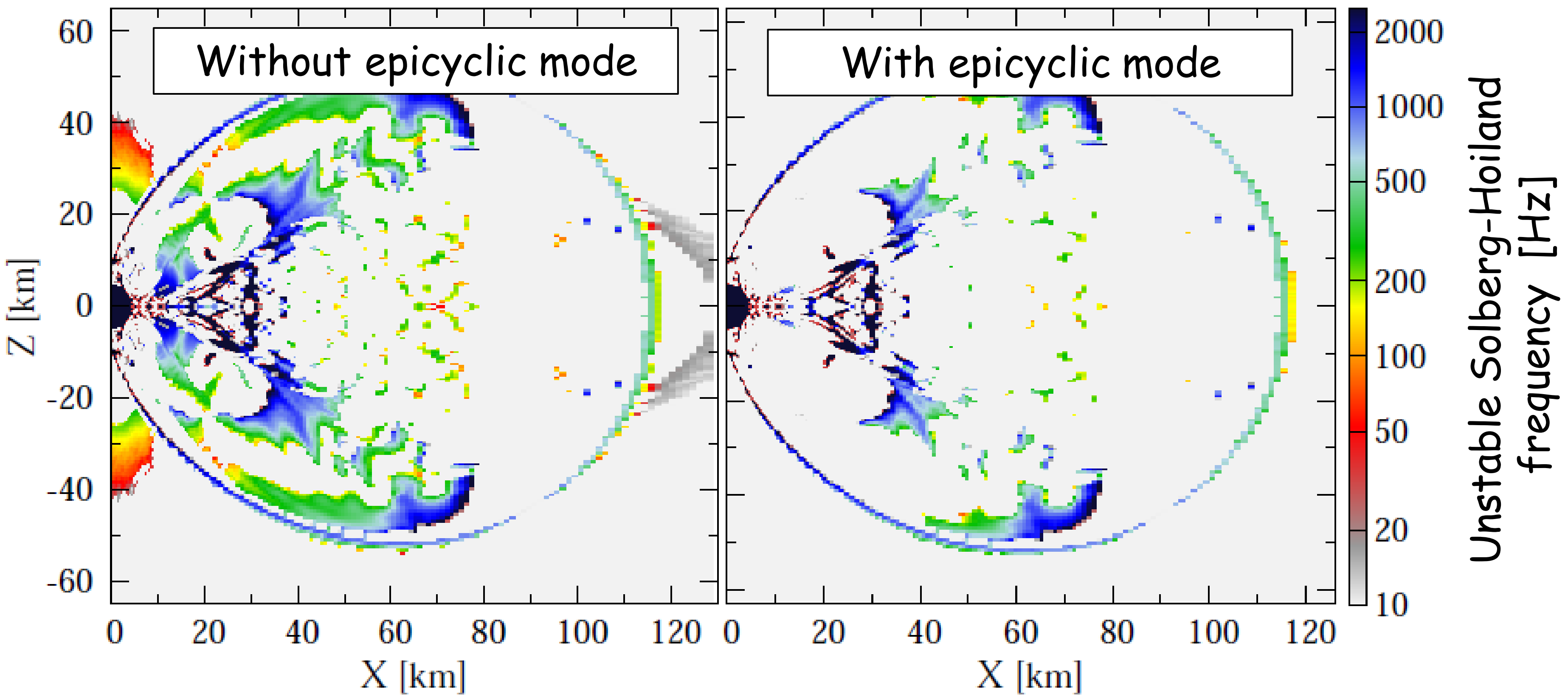
Rapidly rotating model

- Centrifugally supported, geometrically thick torus is immediately formed because of rapid rotation
- Copious neutrino emissions (~ 10^{54} erg/s) from the torus
- Convection is suppressed due to stabilizing epicyclic mode



Rapidly rotating model

- Centrifugally supported, geometrically thick torus is immediately formed because of rapid rotation
- Copious neutrino emissions (~ 10^{54} erg/s) from the torus
- Convection is suppressed due to stabilizing epicyclic mode



Summary

- First full GR simulation of collapse of 'slowly' rotating high entropy core to BH + Disk
- Moderately rotating model
  - **thin Disk ⇒ thick Torus transition**
  - disk emits copious neutrinos
  - accretion flow is convectively unstable (cf. CDAF)
  - **convection induces time-varying neutrino luminosity**
- Slowly rotating model
  - thin disk formation
  - the transition might occur in a later phase
- Rapidly rotating model
  - **thick torus is immediately formed**
  - convection is suppressed due to stabilizing epicyclic mode