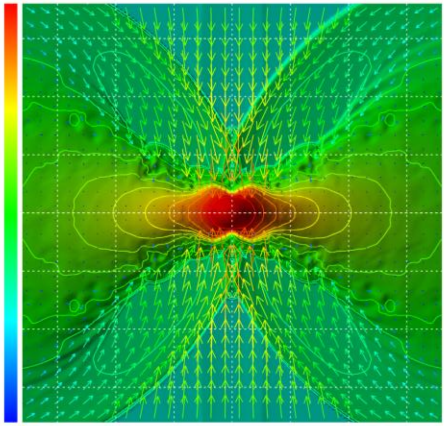

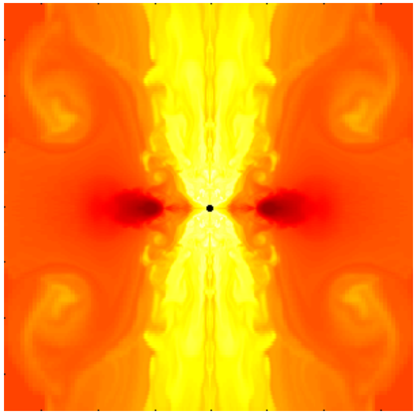

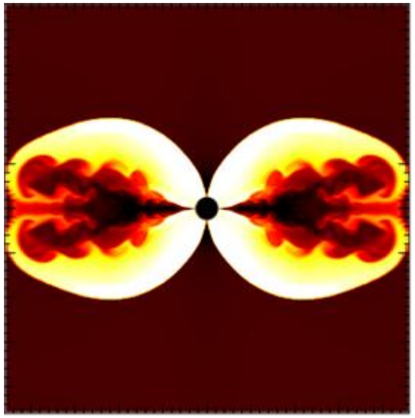

Formation and Evolution of BH-Disk System in Collapse of Massive Stellar Core

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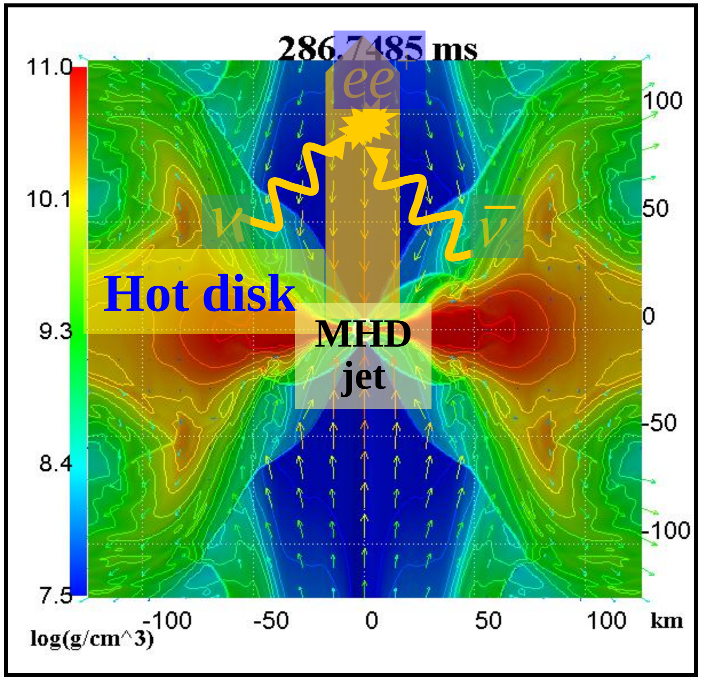
IAU Sym 279 Death of Massive Stars
@ Nikko, Japan, Mar, 12-16, 2012

K computer

Dilemma in LGRB progenitor model

- **Rapid rotation is required**
  - Collapsar (central engine: BH + Disk)
    - Possible energy sources
      - Gravitational energy of disk ⇒ neutrinos
      - Rotational energy of BH⇒Poynting flux
  - Rotation is important in other models
    - E.g. magnetar model (more severe due to strong B fields)



Sekiguchi & Shibata 2007

- **Association of Type-Ic(b) SNe**
  - Progenitor must have been 'lost' H and/or He envelopes
  - **Angular momentum loss at the same time of mass loss**
    - ⇒ slow rotator (e.g. Yoon et al. 2005, Woosley & Heger 2006)
  - How to produce energetic SNe at all when BH is formed ?

Dilemma in LGRB progenitor model

- Peculiar progenitor models are necessary
  - LGRBs are anomalous events: Progenitor cores may also be anomalous
    - He star merger model (Fryer & Heger 2005)
    - Tidal spun up star model (van den Huevel & Yoon 2007)
    - Chemically homogeneous evolution model (Woosley & Heger 2006, Yoon et al. 2006)
  - These models predict formation of core different from ordinary SN
    - **Accompanied by strong mixing which tends to lead to high entropy core**
- **Suggestion: LGRB-progenitor core may have higher entropy**
  - Massive (& compact) : BH formation,   Rapid Rot. : Disk formation
  - That's all ???   Further novel consequences ???
  - Different evolution pass in density-temperature plane
  - Less investigated ⇒ **Numerical Relativity simulation !**

Summary of Code

Sekiguchi (2010) Progress of Theoretical Physics **124**, 331

- Einstein's equations: Puncture-BSSN formalism
  - 4^{th} order finite difference in space, 4^{th} order Runge-Kutta time evolution
  - Gauge conditions : 1+log slicing, dynamical shift
- GR ν-Hydrodynamics with ***GR Leakage Scheme*** (Sekiguchi 2010)
  - **EOM of Neutrinos and Lepton Conservations**
  - **Nuclear-theory-based EOS (Shen et al. 1998, 2011)**
  - **Weak Interactions**
    - $e^{\pm}$ captures (Fuller et al 1985),
    - $e^{\pm}$ pair annihilation (Cooperstein et al. 1986)
    - plasmon decay (Ruffert et al. 1996)
    - Bremsstrahlung (Burrows et al. 2006)
  - **Neutrino opacities (Burrows et al. 2006)**
    - **Ion screening effect (Itoh et al. 2004)**
    - **Nucleon recoil corrections (Horowitz 2002)**
  - High-resolution-shock-capturing scheme
  - **BH excision technique (long term (~ 1s) simulation)**

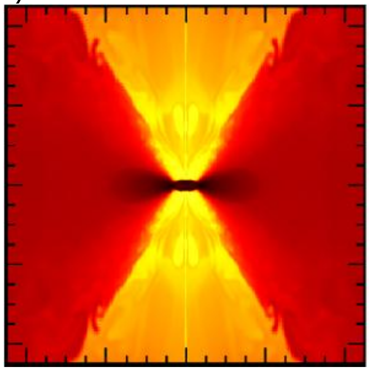
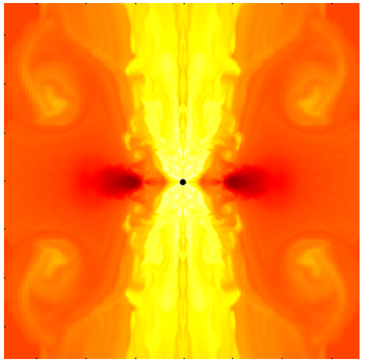
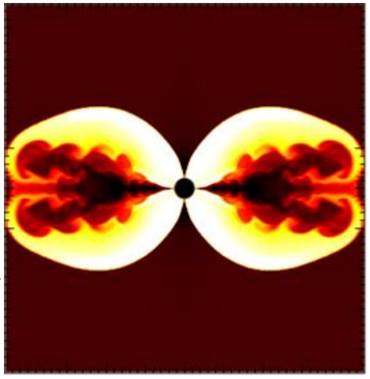
$$\nabla_a (T_{\rm Fluid})^a_b = -Q_b$$
$$\nabla_a (T_{\rm Neutrino})^a_b = Q_b$$

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

Adopted initial models

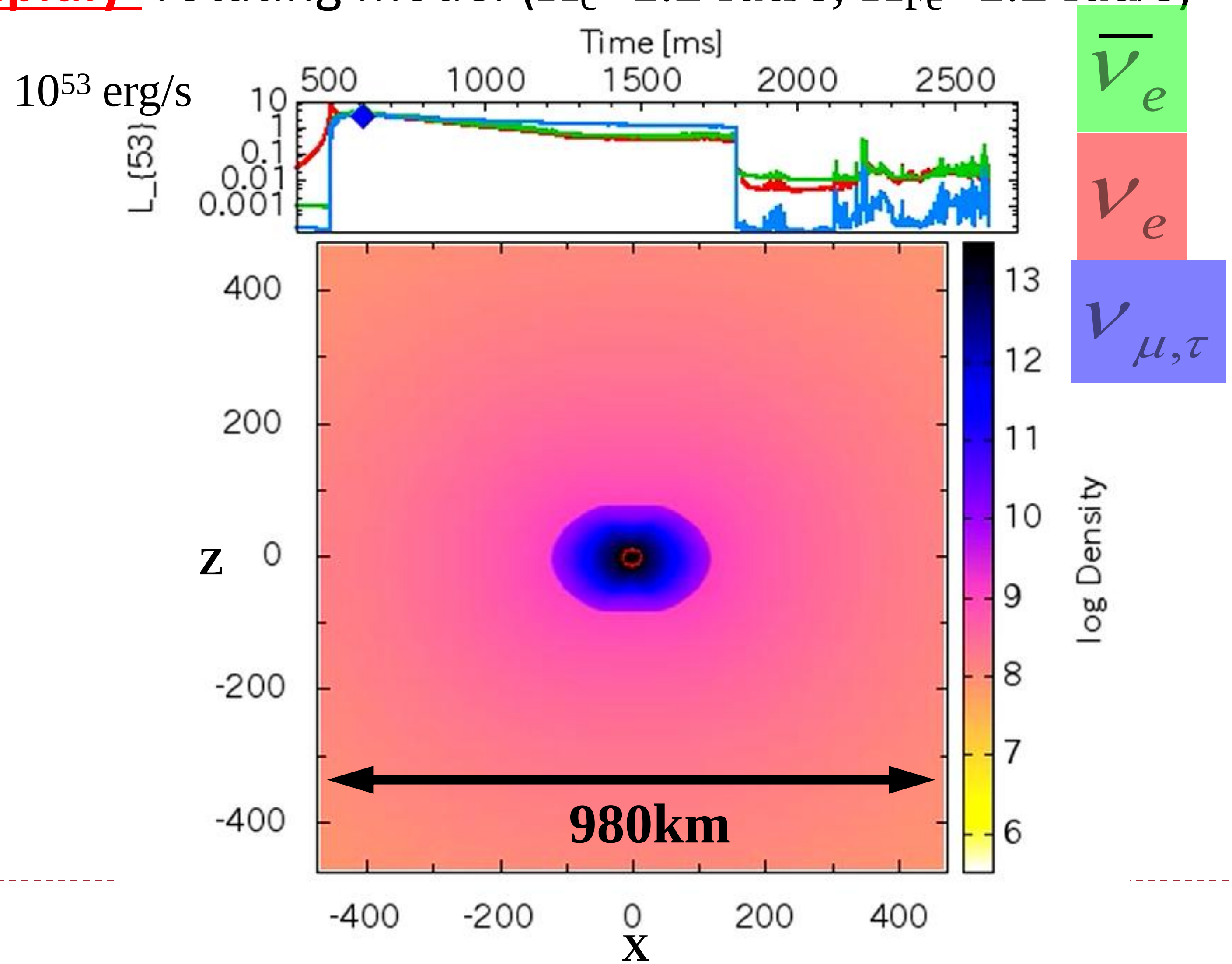
- **100Msolar presupernova model** (Umeda & Nomoto 2008)
  - Central entropy/baryon **~ 4kB**
  - Iron core mass : 3Msolar
  - As a representative model of high entropy core
  - **This talk** (Sekiguchi & Shibata 2012)
- **Core of 500Msolar PopIII star** (Ohkubo et al. 2006)
  - Central entropy/baryon **~ 8kB**
  - Core mass : ~10Msolar
  - Sekiguchi & Shibata in prep.
- **High entropy cores** (GR equilibrium configuration)
  - Central entropy/baryon : **5-8kB**
  - Core mass : 6-13Msolar
  - Sekiguchi & Shibata 2011, ApJ

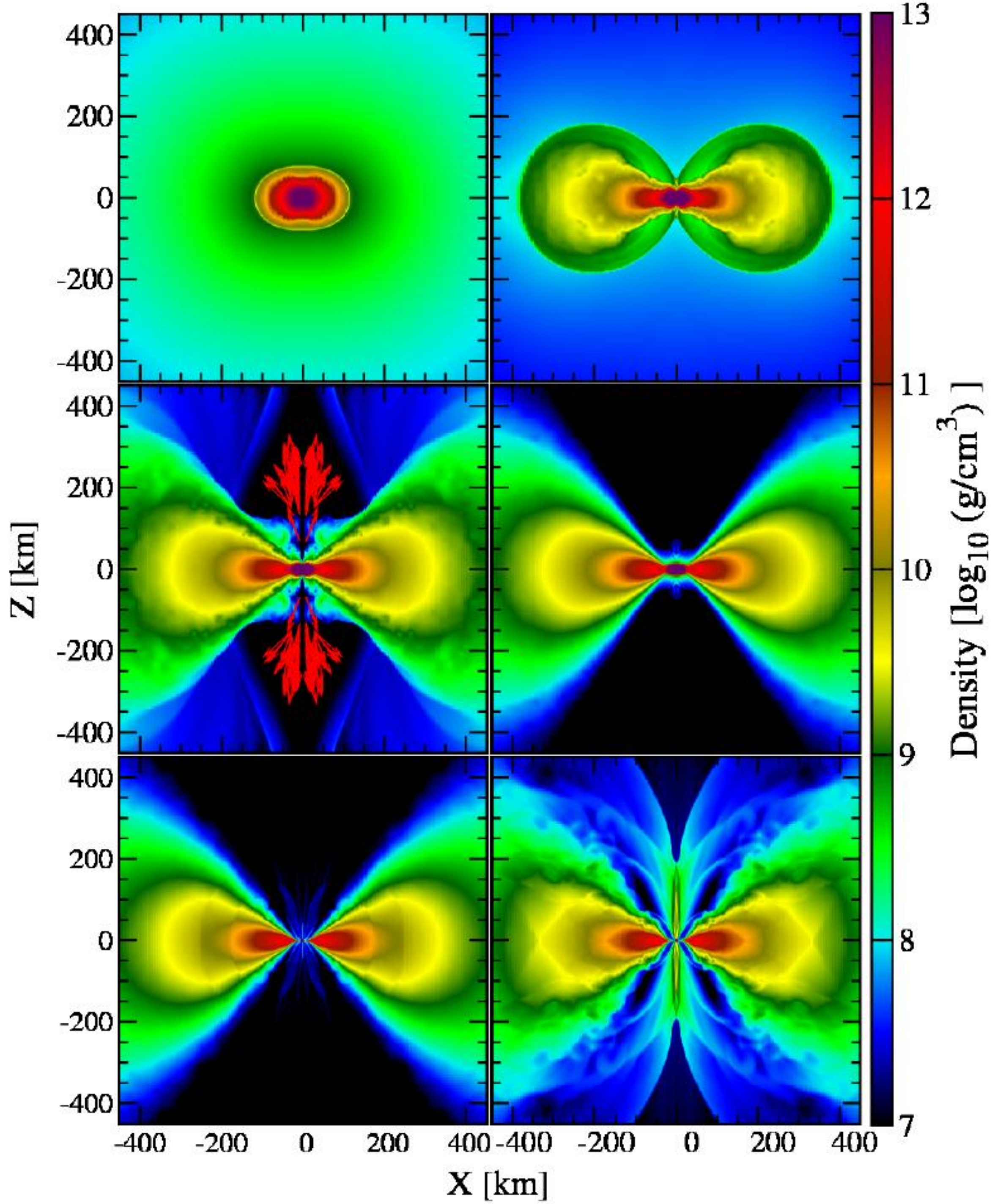
Rotational Profiles are added

Collapse of 100Msolar presupernova model: rapid (but not very rapid) rotation case

- **'Rapidly'** rotating model (Ω_c=1.2 rad/s, Ω_{Fe}=1.2 rad/s)

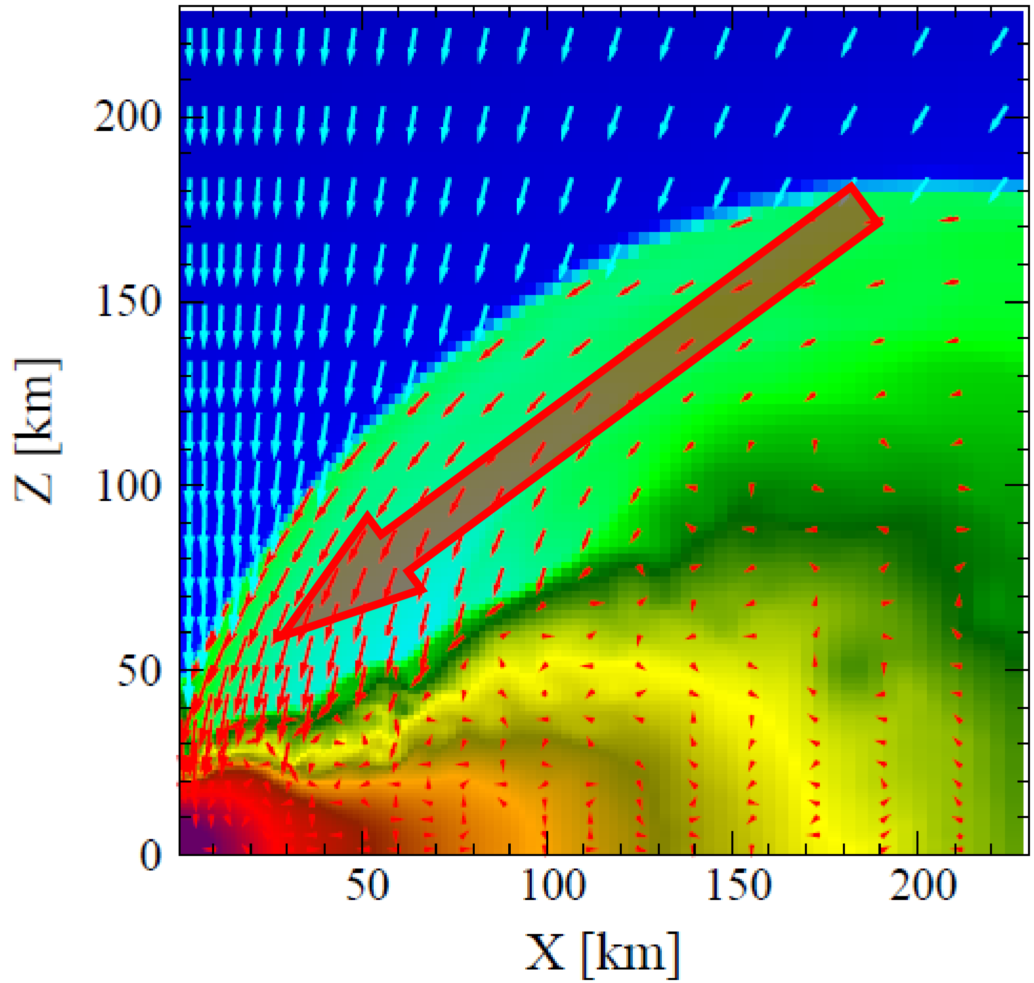




Z [km]
X [km]
Density [log10 (g/cm3)]
400
200
0
-200
-400
13
12
11
10
9
8
7

Importance of **Rotation**: Oblique Shock

- Torus-structured shock
- Infalling materials are accumulated into the PNS due to the **oblique shock**
- **Thermal energy is efficiently stored in the pole of PNS**
  - Ram pressure ↓
  - **⇒Outflow**
- **Flows hit central PNS**
  - NS oscillation
  - ⇒ **PdV work** , Lν ↑



Importance of **High Entropy/Rotation :** Energy balance

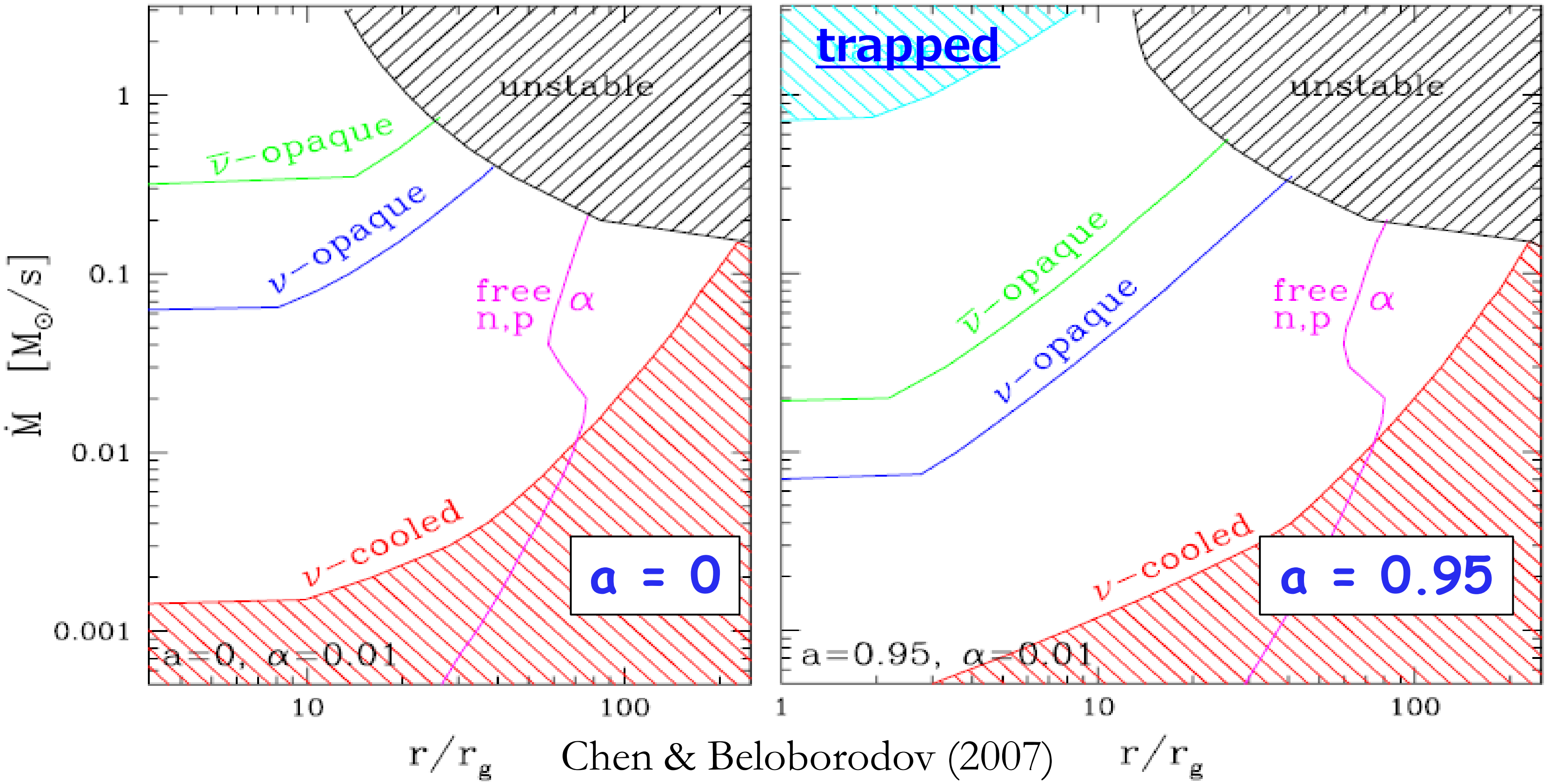
- Compact core / Oblique shock ⇒ **high mass accretion rate**
- Energy balance may not be satisfied ……
  - **Rotation decreases |Qadv| & |Qv| (dense disk)**
  - **Additional 'cooling' sources required**

$$\dot{Q}^{+}_{\rm acc} = \dot{Q}^{-}_{\rm adv} + \dot{Q}^{-}_{\nu}$$
$$\Rightarrow \dot{Q}^{+}_{\rm acc} = \dot{Q}^{-}_{\rm adv} + \dot{Q}^{-}_{\nu} + \dot{Q}^{-}_{\rm outflow/expansion} + \dot{Q}^{-}_{\rm convection}$$

  - **Strong dependence of Qv (ν-cooling) on T (and ρ)**
    ⇒ slight change of configuration leads to dynamically large change
    - **Torus is partially supported by the (thermal) pressure gradient**
- **Smaller amount of heavy nuclei ⇒ more energetic SNe ?**
  - **Dissociation of 0.1 Msolar Fe costs ~ 10^{51} erg**
- Higher temperature : Less Pauli blocking in neutrino pair annihilation

Importance of **Rotation**: BH spin

- **Energy conversion efficiency can change two orders of magnitude**
- **Disk properties to neutrinos strongly depend on BH spin**
  - **Slow rot. BH ⇒ ISCO (disk edge) located far ⇒ low density / opacity ⇒ Efficient cooling ⇒ the local valance satisfied ⇒ weak/no time variability**

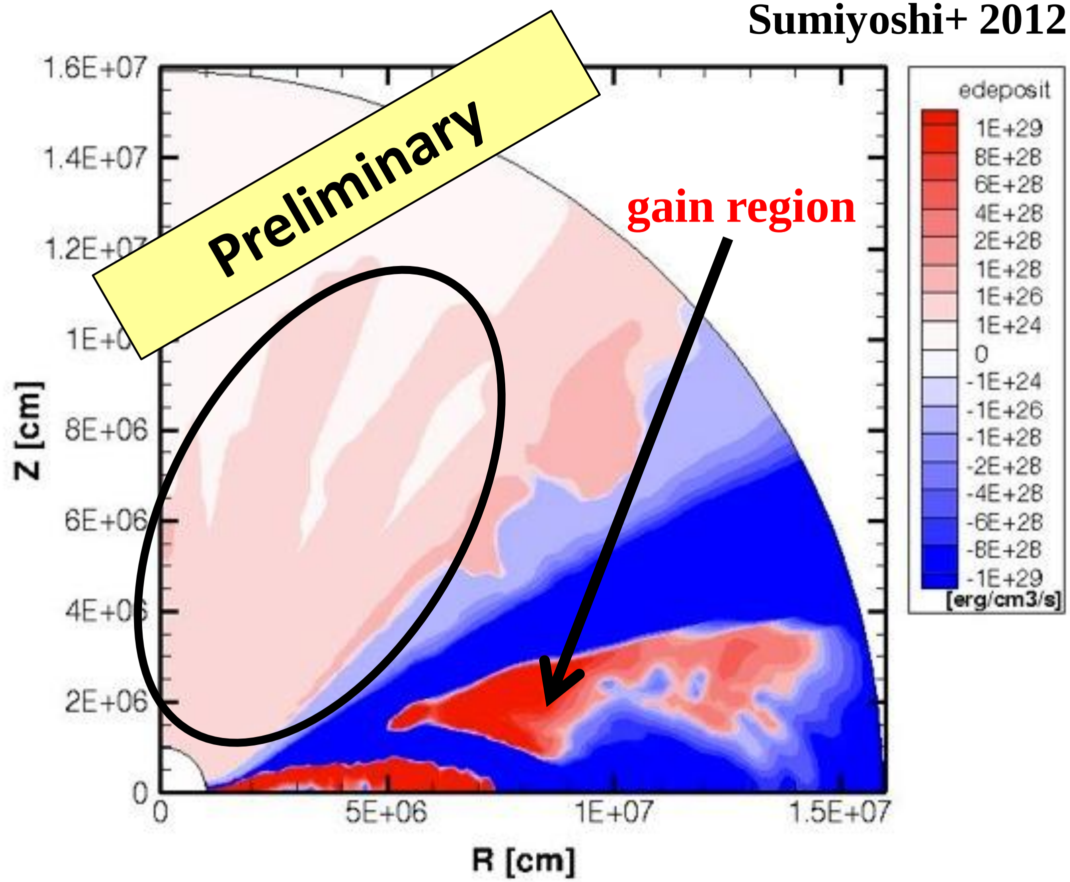


Chen & Beloborodov (2007)

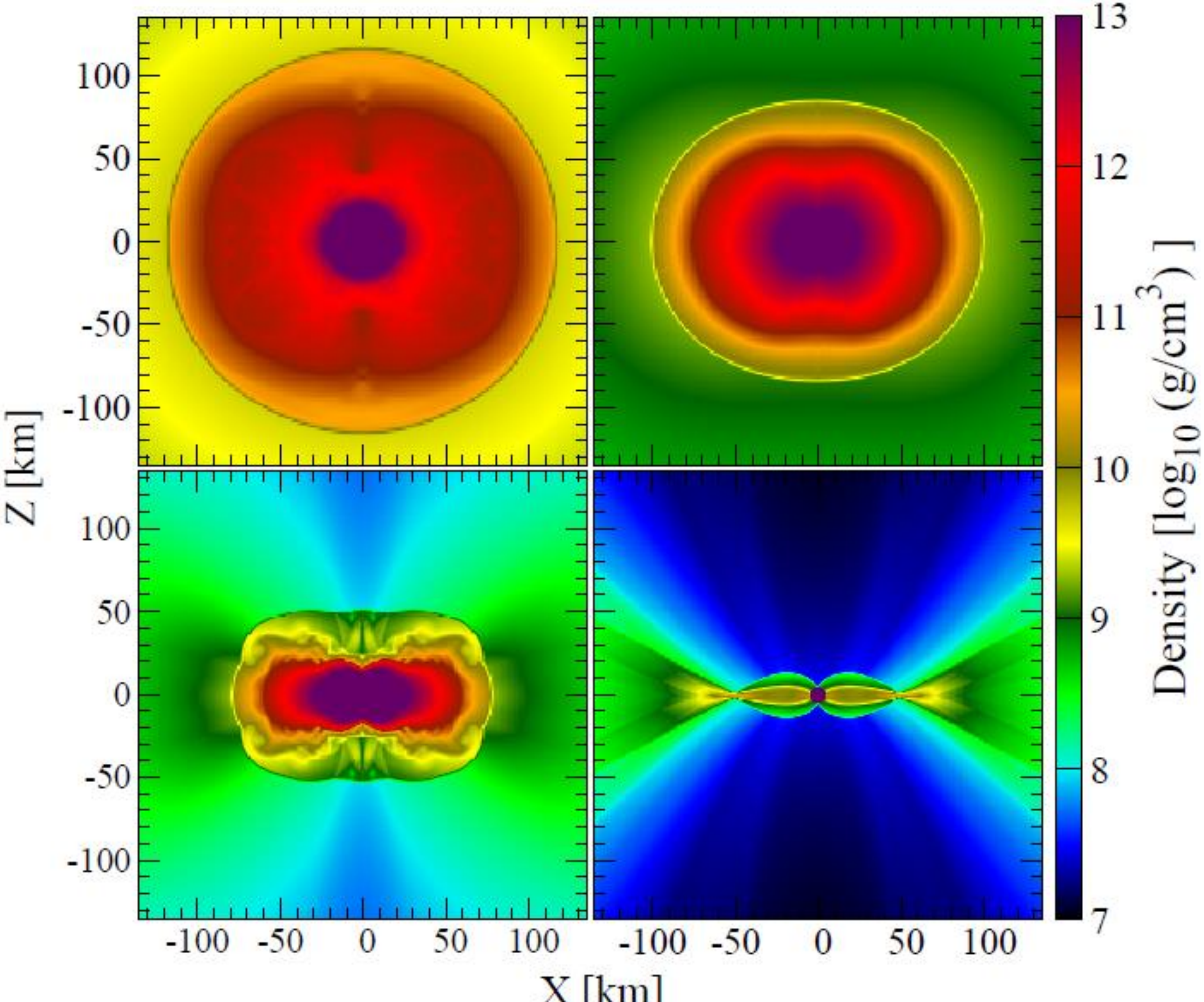
Similarities to ordinary SN

- Same components: ‘stalled’ shock + neutrino sphere/torus
  - **SASI-like activities are likely to occur** (Sekiguchi+ 2012)
  - **The gain (neutrino-heated) regions do exist** (Sumiyoshi+ 2012)
- Only topology is different
  - How will this system evolve in the presence of ν-heating
  - The next study using **GR-νRad-Hydro Code** (recently developed)

Sumiyoshi+ 2012

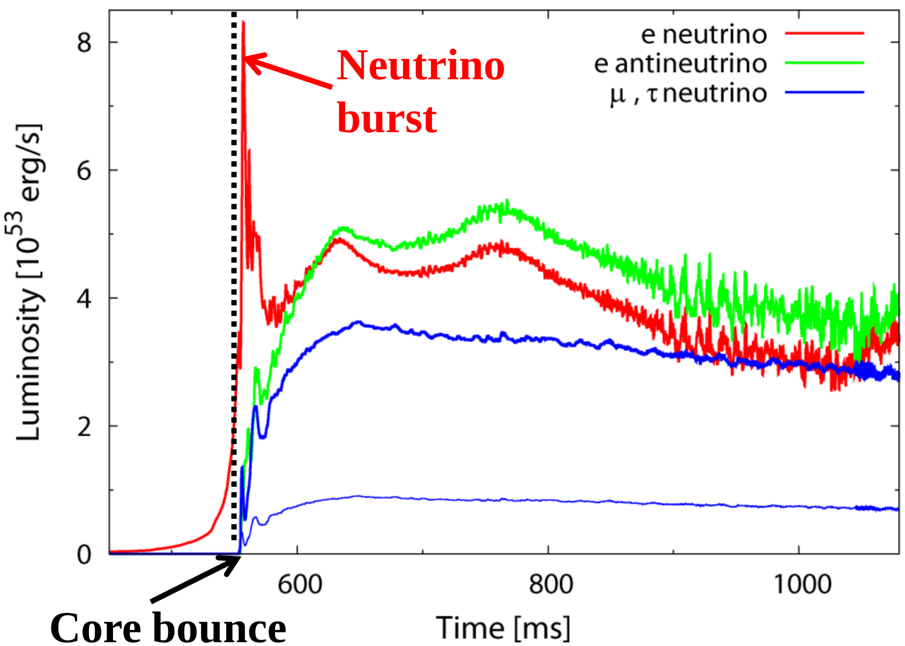


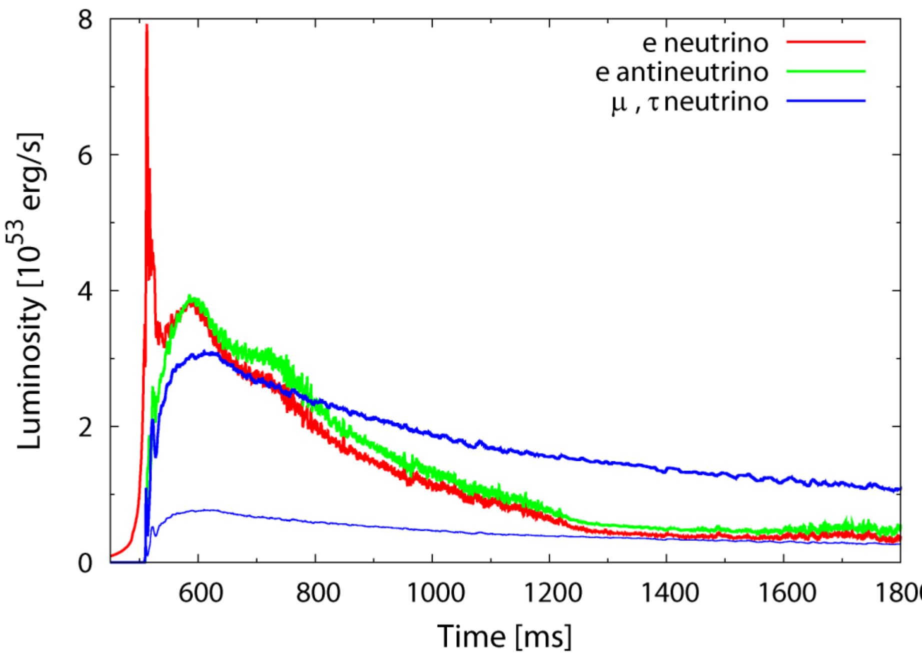
Slower (still moderate) Rotation Case:
Spheroidal configuration, No time variability



Neutrino Luminosity (PNS Phase)

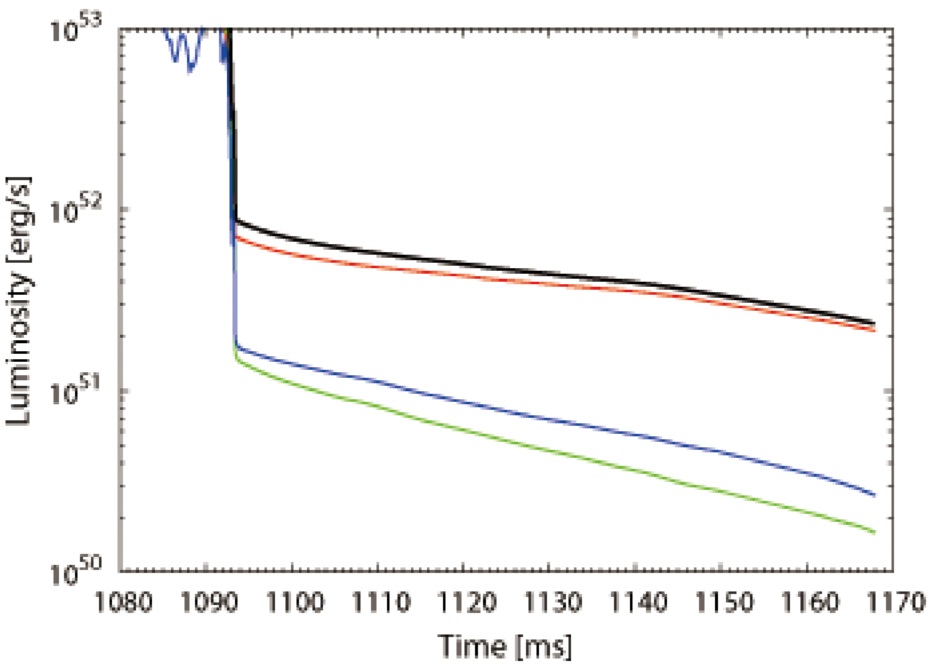
- **Moderate rotation**
  - Higher luminosity
  - Time variability due to convective activity
- **Rapid rotation**
  - Lower luminosity
  - Neutrino pair production processes are dominant

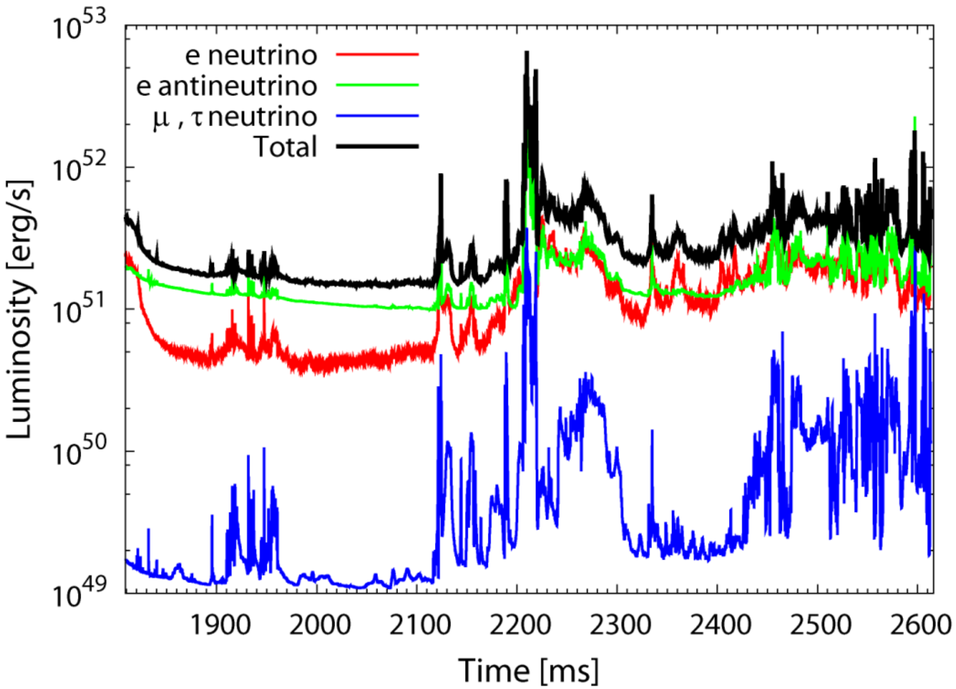




Neutrino Luminosity (BH Phase)

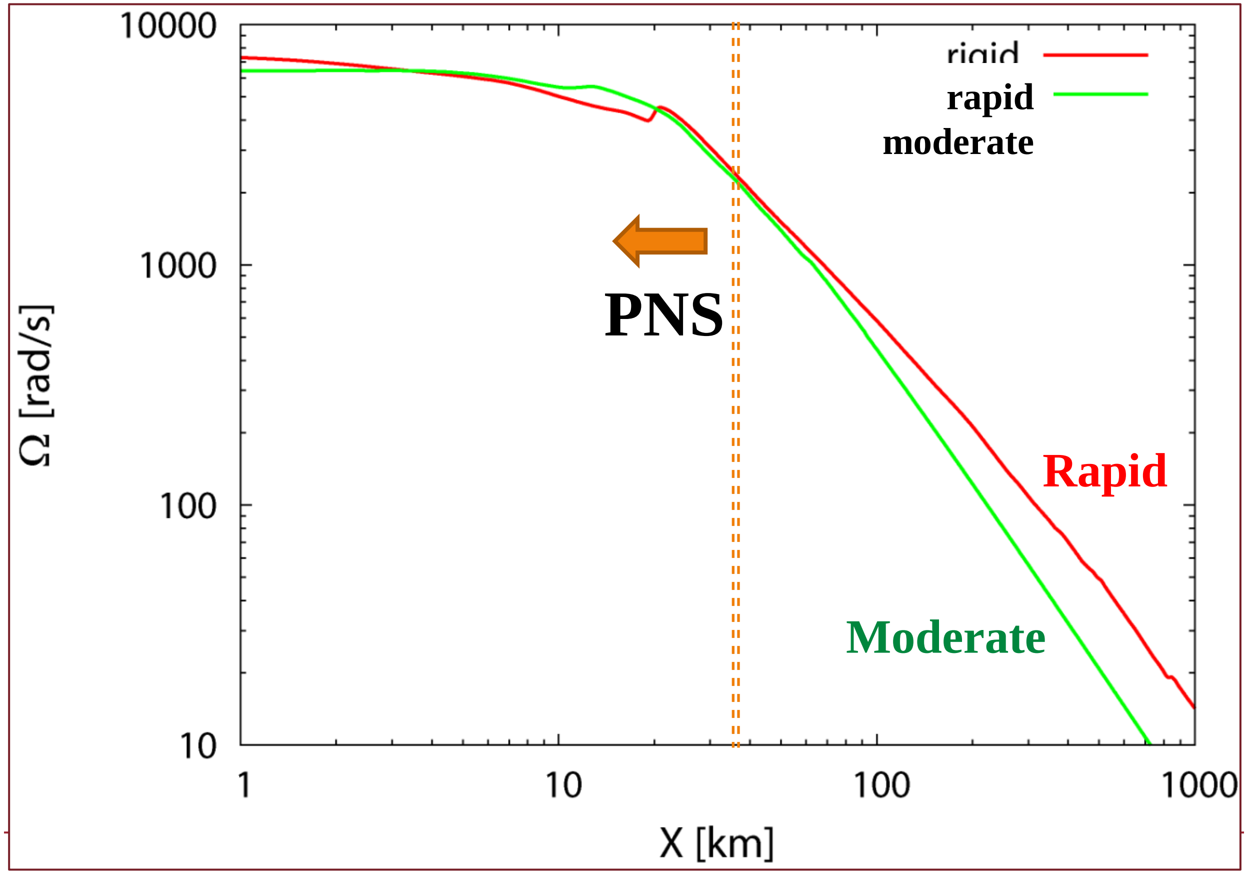
- **Slower (moderate) rotation**
  - $L_{tot} \sim 10^{51\text{-}52}$ erg/s
  - No time variability
- **Rapid rotation**
  - $L_{tot} \sim 10^{51\text{-}52}$ erg/s
  - **Violent time variability**
  - Preferable feature for GRB



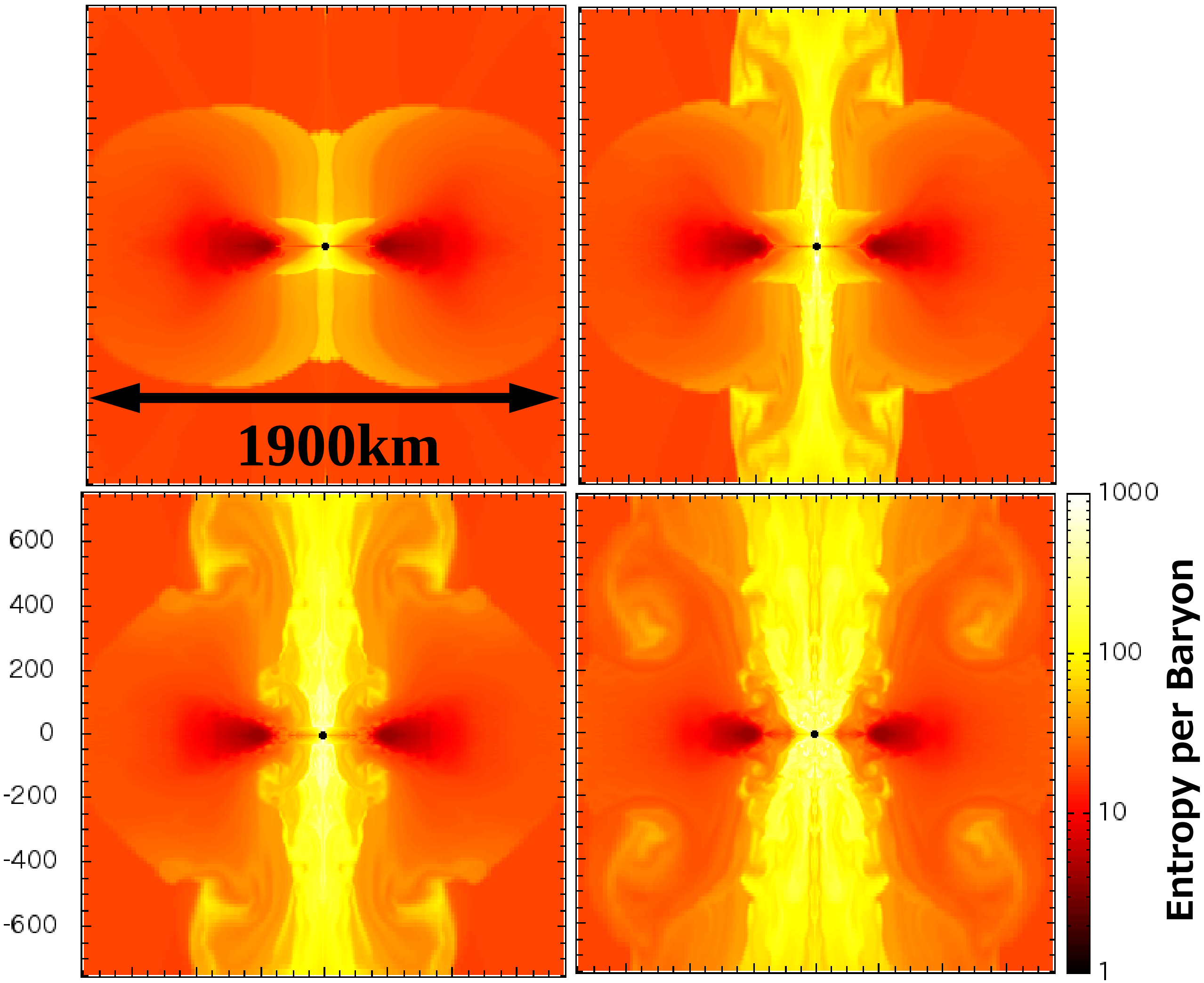


Comparison of Rotational Profile

- Rotational profiles of **<u>Proto-Neutron Star</u>** are similar
- **<u>Small difference in rotational profile of outer region results in large difference in dynamics</u>**



500Msolar-PopIII core collapse: Outflow appears even when BH is formed directly



- Matter accumulation into the central region due to the oblique shock
- **Shock wave formation in the pole region of the BH**
- Efficient dissipation of kinetic energy
- Inefficient advection cooling
- Thermal energy is stored
- Outflow

Summary

- The first full GR simulations, incorporating microphysics, of stellar core collapse are performed, adopting high entropy models (only showing you one model)
- **BH formation process is quite dynamical, accompanying oblique shock, convection, KH instability and outflows**
  - **The dynamics is very sensitive to the initial rotational profile which is poorly known**
  - **Accumulation of material (energy) into the pole region of the central object is a key feature for driving an outflow**
    - **Outflows can be driven even when BH is directly formed**
- **The resulting system has preferable features for LGRBs**
  - **More systematic studies are necessary**