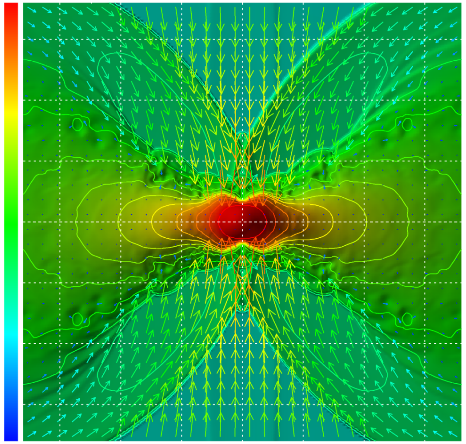
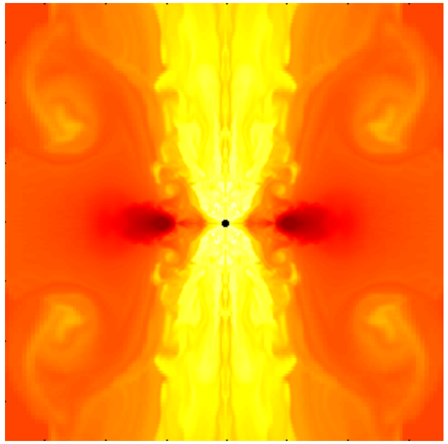
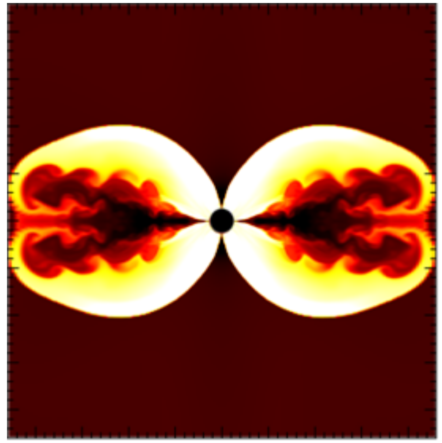




大質量星の重力崩壊における ブラックホール形成

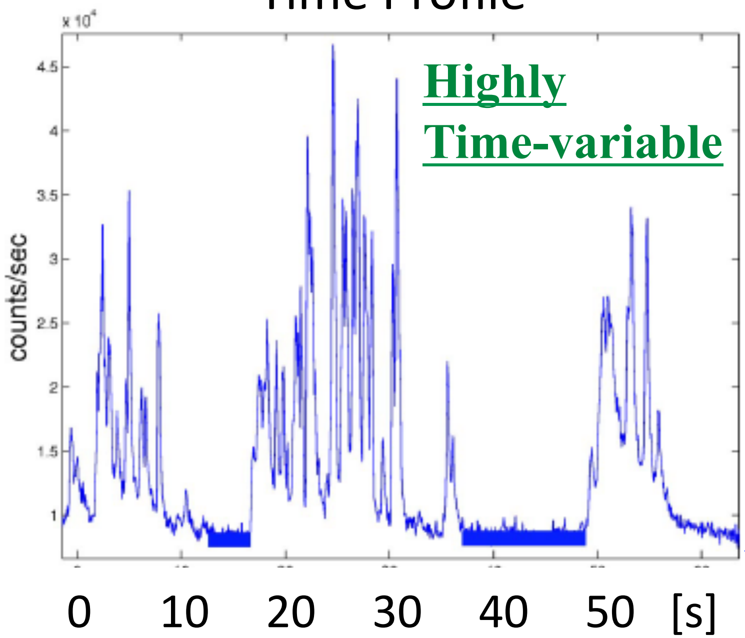
関口雄一郎（京都大学基礎物理学研究所）

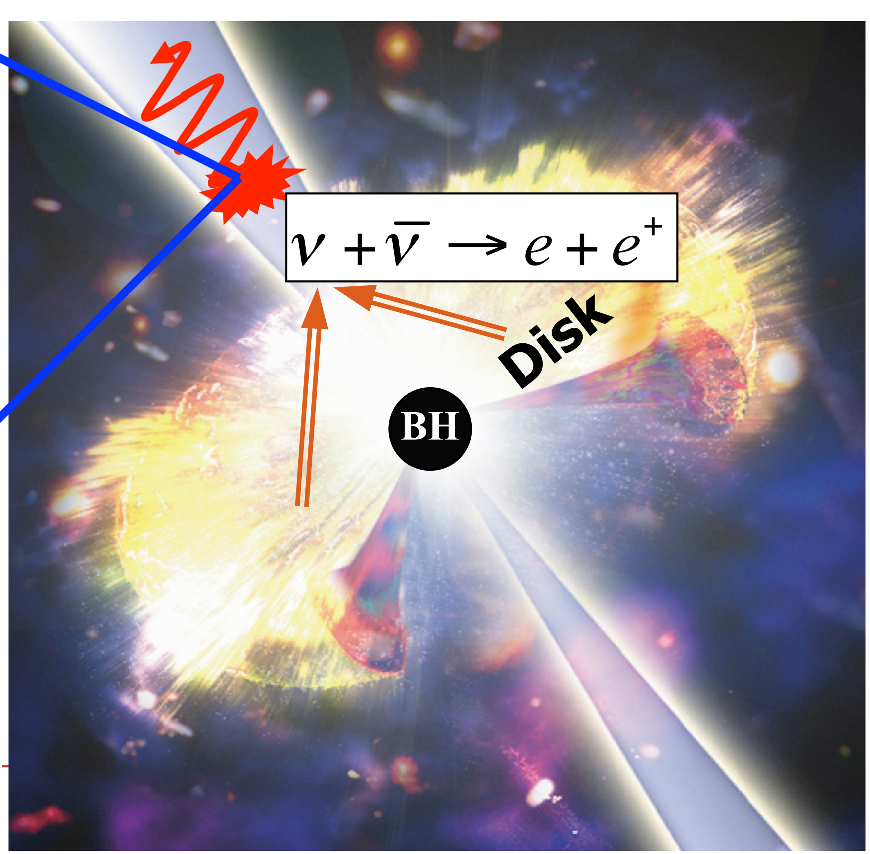
K computer

BH formation and Long GRBs

- Collapse of massive stellar core to BH + Disk
  - Promising theoretical candidate of central engine of **Long Gamma-ray Bursts (LGRBs)**

Time Profile





10^{50}erg/s $<$ $L_{\gamma} < 10^{52}$erg/s

Most violent explosion in the universe

To produce LGRB

- If the LGRB jet is produced by neutrino pair annihilation
  - **Huge amount of neutrinos should be emitted**
  - **in a highly time-variable manner**

Basic Equations and Physics

- Solve Einstein's equation with eqs. for source fields

$$G_{ab} = \frac{8\pi G}{c^4} T_{ab}$$

$$\nabla_a T^{ab} = 0 \quad (T^{ab} = (T_{\text{Fluid}} + T_{\text{EM}} + T_{\nu} + \ldots)^{ab})$$

$$\nabla_a J^{a} = 0 \quad (J^{a} \sim (n_{\text{baryon}},\ n_{\text{lepton}}(n_e, n_{\nu}, \ldots),\ \ldots)u^{a})$$

- All four known interactions play important roles
  - Gravity : GR, BH formation, ISCO, etc
  - Strong : EOS (equation of state) of dense nuclear/hadronic matter
  - EM : MHD phenomena, EOS of dense matter
  - Weak : Electron capture, Neutrino production
    - 99% gravitational binding energy released is carried away by neutrinos in SNe

Previous full GR numerical studies

- 実はあまりシミュレーションは行われていない
- 球対称 w. Boltzmann transfer & microphysics
  - Sumiyoshi et al. 2006,2007,2008,2009,2010
  - Nakazato et al. 2006,2007,2010,2011
  - Fisher et al. 2009 BH 形成後の時空は追えない
- 軸対称 w.o. microphysics
  - Shibata & Shapiro 2002
  - Sekiguchi & Shibata 2005, 2007
  - Liu et al. 2007 BH 形成後の時空を多少追跡
- **Long term 軸対称 w. GR neutrino leakage & microphysics**
  - **Sekiguchi & Shibata 2011, in prep.**
- 3D w.o. microphyics
  - Ott et al. 2011 BH 形成後の時空を多少追跡

Remark

- 一般相対論的強重力の重要性

GENERAL RELATIVISTIC HYDRODYNAMICS AND THE ADIABATIC COLLAPSE OF STELLAR CORES[1]

KENNETH A. VAN RIPER
Department of Physics, University of Illinois at Urbana-Champaign
Received 1978 September 18; accepted 1979 March 7

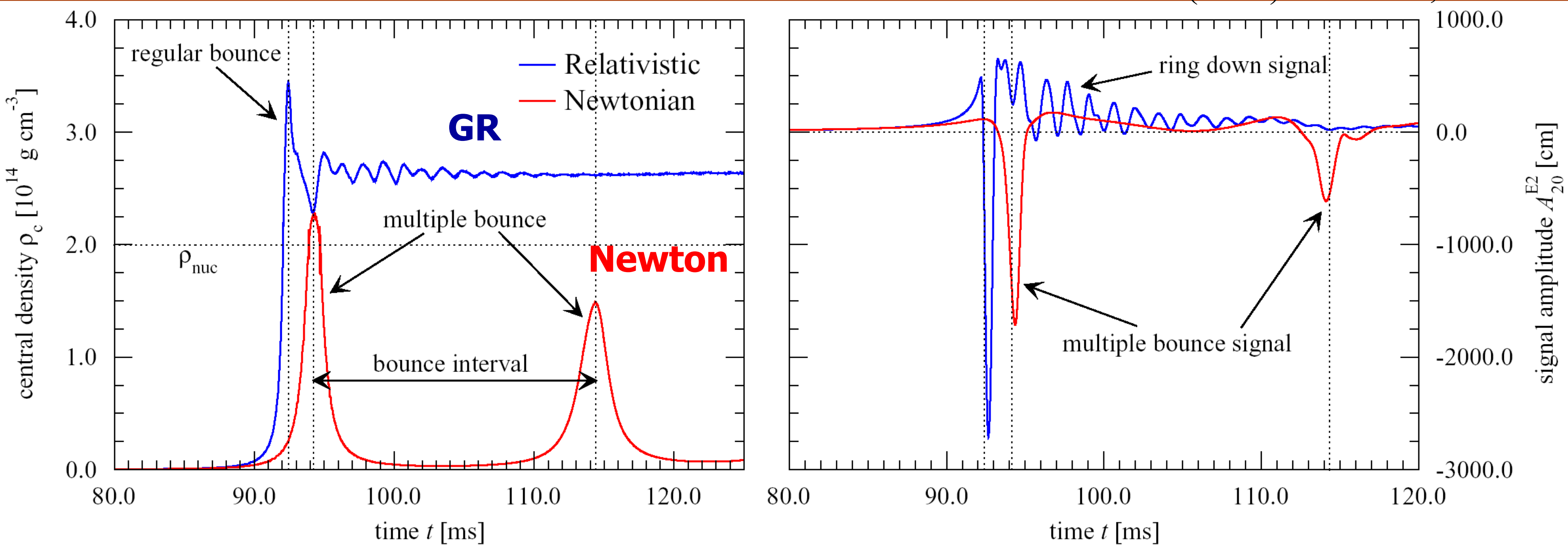
It is incorrect to conclude that GR corrections to the evolution will always be as small as R_g/R; because of the more restrictive dynamic stability criteria in GR the evolution can be substantially altered, even though the GR terms appear small. The critical adiabatic index in GR is greater than 4/3 by an amount that depends on how relativistic the star is.[2] For cores bouncing at

$$\gamma_{\mathrm{crit,\,GR}} = \frac{4}{3} + 2.78\frac{P}{\rho c^2} \sim \frac{4}{3} + 2.78 \times O(1)\frac{GM}{Rc^2}$$

Chandrasekhar 1964, 1965

回転重力崩壊からの重力波

Dimmelmeier et al (2002) A&A 393, 523



- **Rotational frequency increases** during collapse

$$\rho^{-1}\nabla P \sim \rho^{-1}\frac{1}{R}(\rho^{\gamma}) \sim \rho^{-1}\rho^{1/3}\rho^{\gamma} \sim \rho^{\gamma-2/3}$$

$$R\Omega^2 \sim R(R^{-4}) \sim R^{-3} \sim \rho$$

$$j = R^2\Omega \sim \text{const} \Rightarrow \Omega \sim R^{-2}$$

$$\gamma_{\text{rot, eff}} \sim 5/3$$

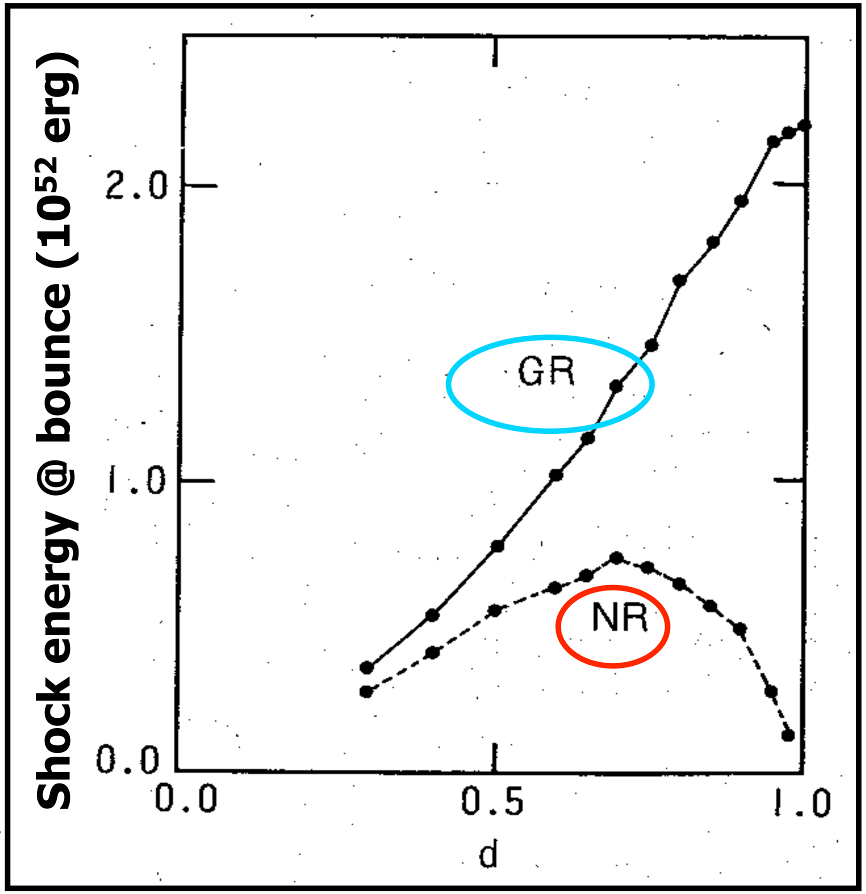
Stable in Newtonian if the centrifugal term is dominant

- **Qualitative difference** in collapse dynamics and thus in waveforms

電子捕獲反応(弱い相互作用)

- 電子の縮退圧：P ∝ $\rho^{4/3}$ ニュートン重力では臨界安定
  - 電子捕獲反応によって、実効的に $\gamma < 4/3$
- 弱い相互作用への応答が違う
  - 電子捕獲反応率
  - ニュートリノ散乱断面積
    - ニュートリノトラッピング
  - 衝撃波のエネルギー
    - ∝ バウンス時のコアの大きさ
    - ∝ バウンス時の $(Ye)^2$

Takahara & Sato (1984) PTP 72, 978

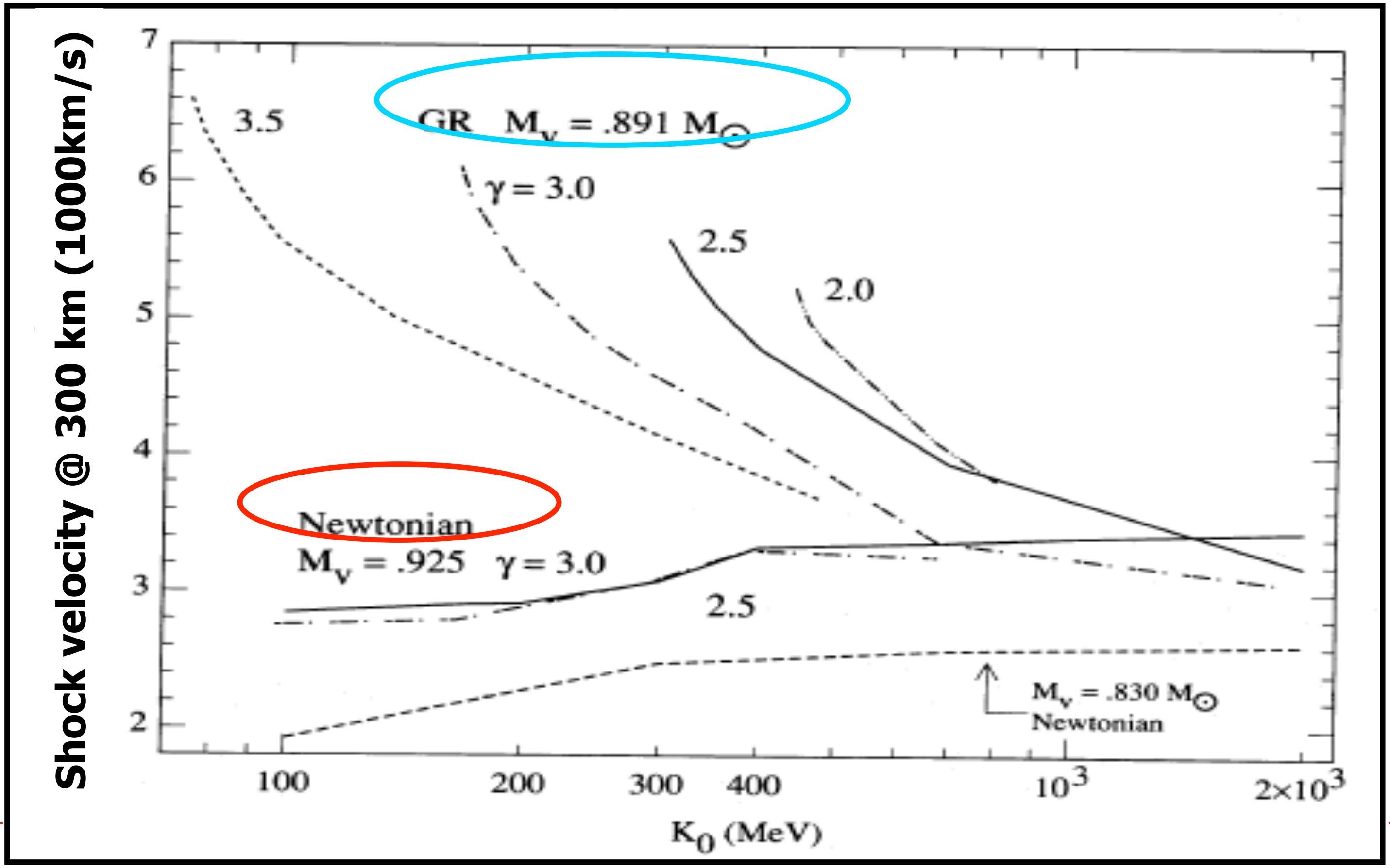


$$d \sim \left(\frac{Y_{\text{lepton,bounce}}}{Y_{\text{lepton,init}}} \right)^{4/3} \quad : \text{depends on weak rates}$$

状態方程式(強い相互作用)

- 核力： P ～ K $\rho^{2\text{-}3} \propto \rho^{2\text{-}3}$ と非常に「かたい」
  - ニュートン重力では 2.5 も 3 も十分に「かたい」ため違いが顕著に現れない

Van Riper (1988) ApJ 326, 235



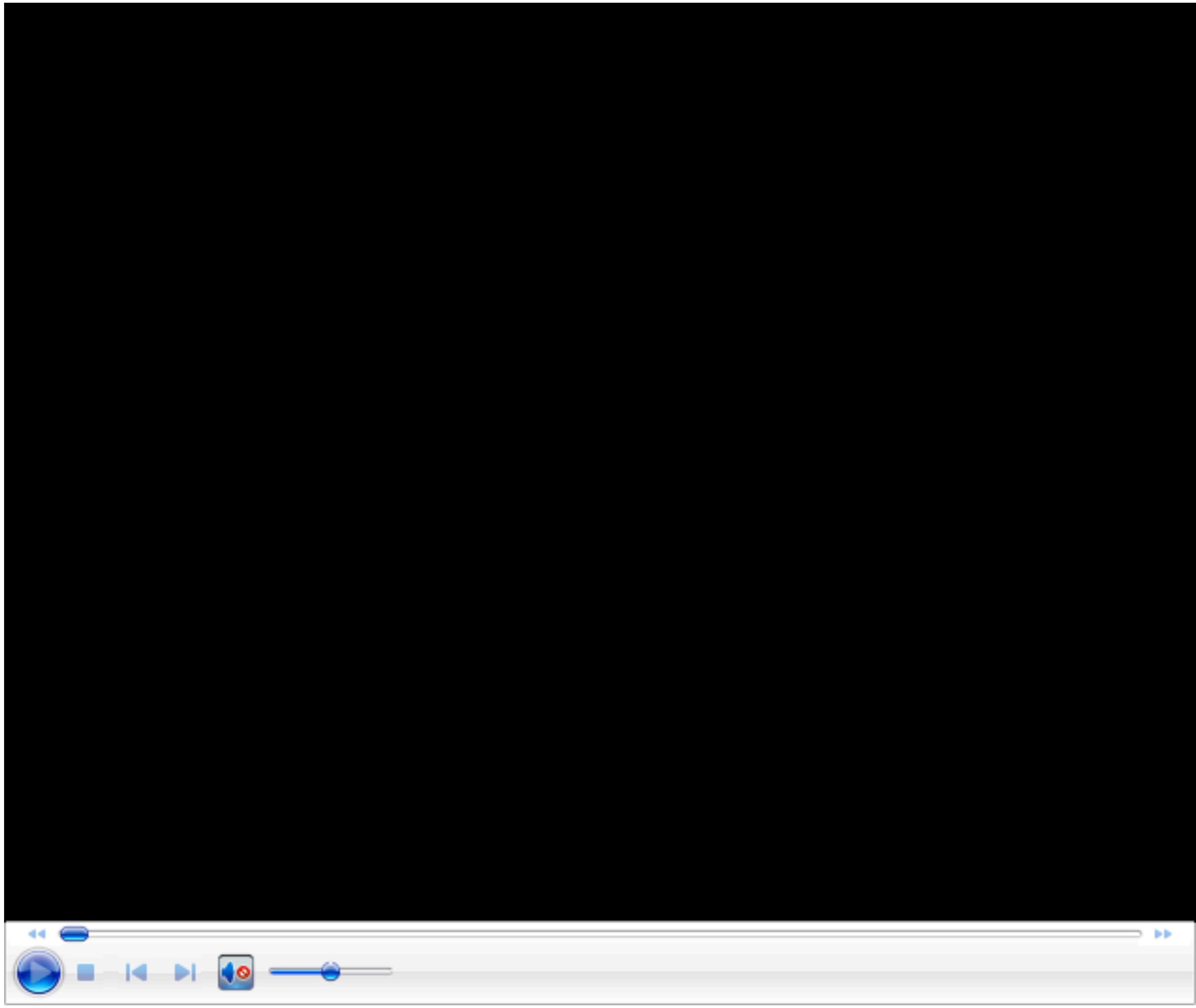
Results

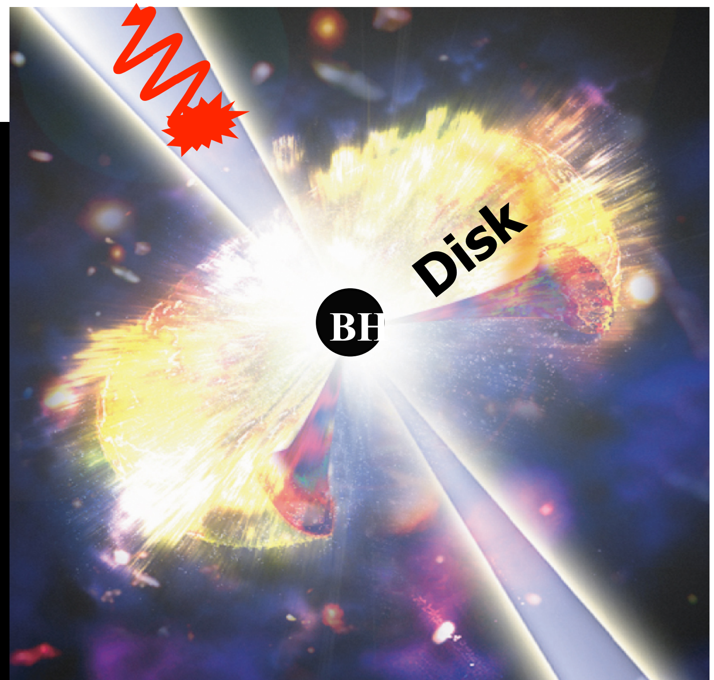
- アニメーションを中心に

BH formation 2005

- Initial condition : rotating polytrope
- **Microphysics was not included**
- The simulation was terminated shortly after the BH formation

BH formation 2005





BH formation 2010-2011: Setting

- (Very) Brief summary of simulation code
- Initial conditions

Summary of Code

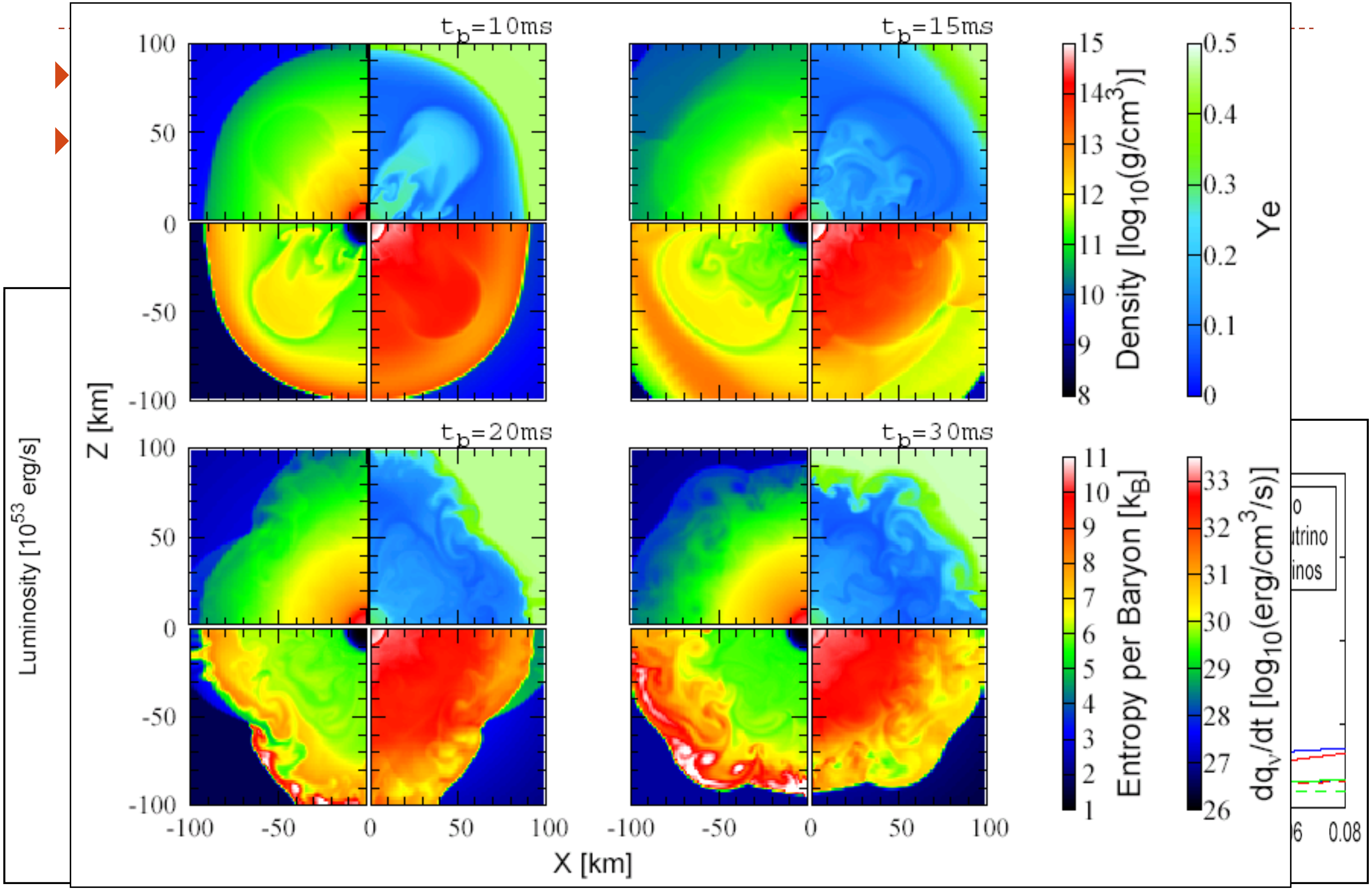
Sekiguchi (2010) Progress of Theoretical Physics **124**, 331

- 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 Hydrodynamics with ***GR Leakage Scheme*** (Sekiguchi 2010)
  - EOM of Neutrinos and Lepton Conservations
  - Nuclear-theory-based EOS (Shen et al. 1998)
  - 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)
    - (n,p,A)-scattering and absorption
    - Ion-ion screening, **nucleon recoil**
  - High-resolution-shock-capturing scheme
  - **BH excision technique**

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

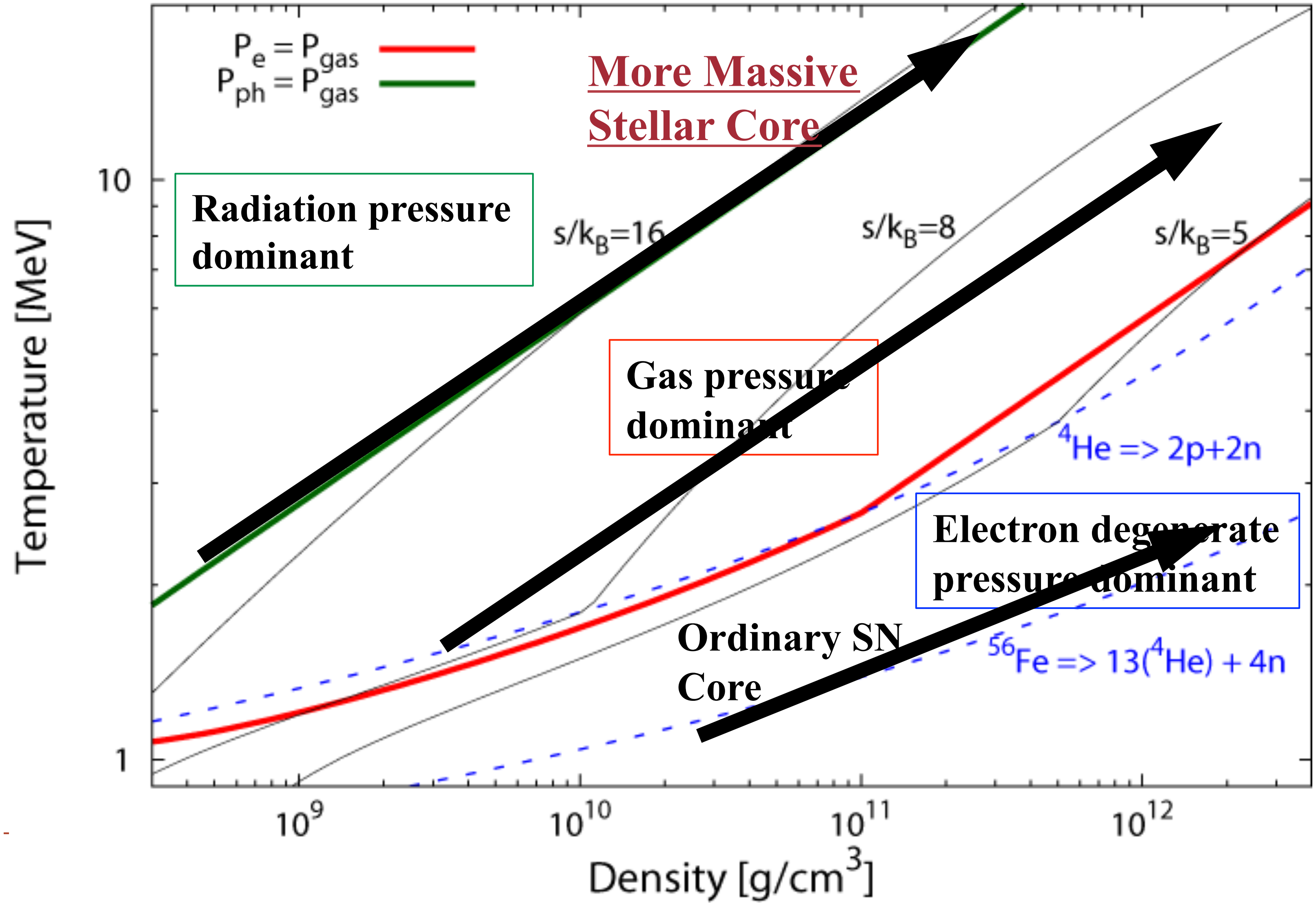
$$\frac{d\,Ye}{dt} = -\gamma_{\rm e-\,cap} + \gamma_{\rm e+\,cap}$$
$$\frac{d\,Y\nu_{\rm e}}{dt} = \gamma_{\rm e-\,cap} + \gamma_{\rm pair} + \gamma_{\rm plasmon} + \gamma_{\rm Brems} - \gamma_{\nu_{\rm e}\rm leak}$$
$$\frac{d\,Y\bar{\nu}_{\rm e}}{dt} = \gamma_{\rm e+\,cap} + \gamma_{\rm pair} + \gamma_{\rm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

Code Validity (球対称崩壊)



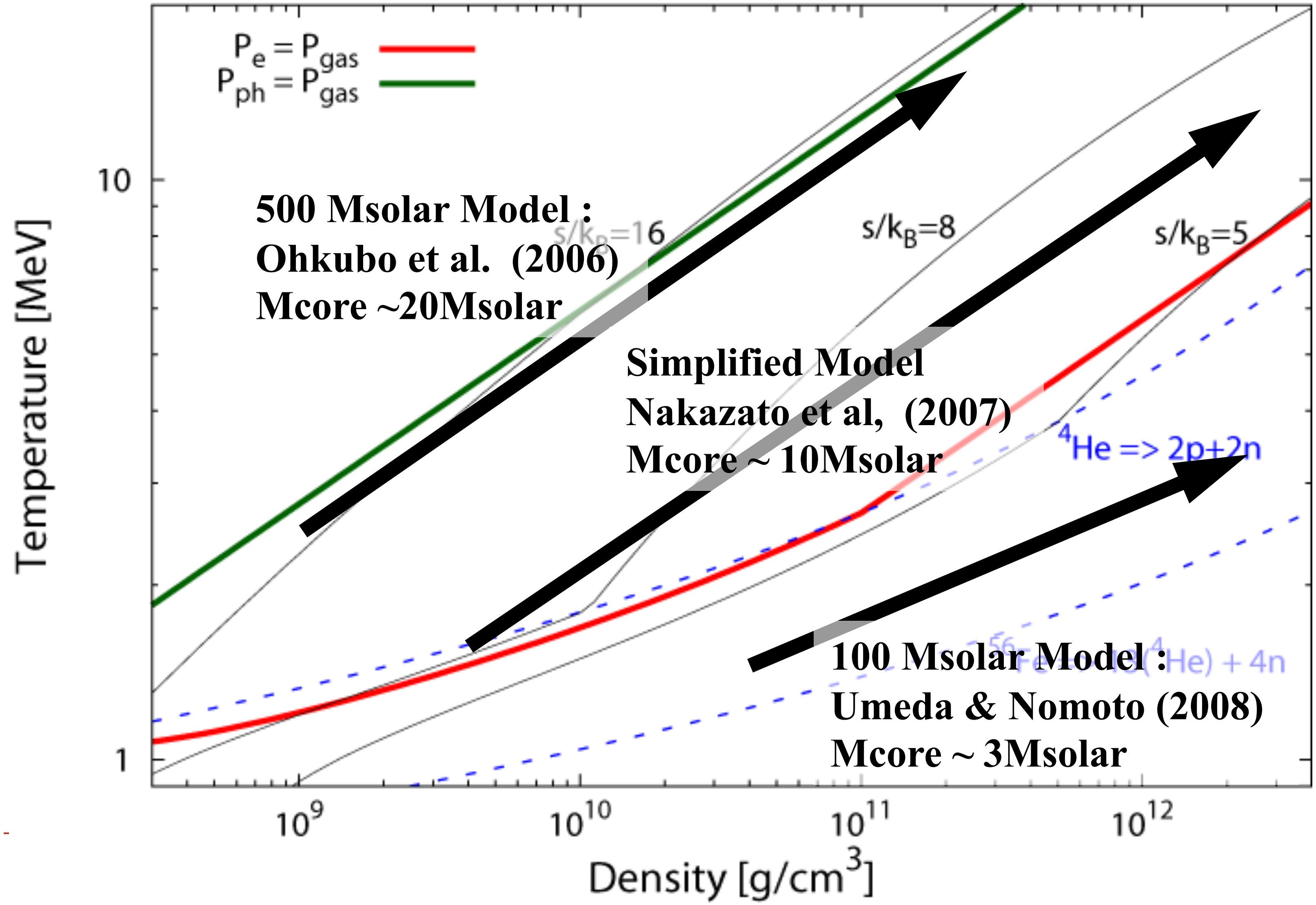
Three Initial Models

- Evolution path is characterized by central entropy (mass)



Three Initial Models

- Rotational Profiles are added by hand



Comments on progenitor model of GRB

- 中心動力源：ブラックホール＋ディスク
  - 高速回転する親星コアが必要
  - ⇔ Type-Ic SN の付随: H, He を失うに伴いに回転が遅くなる
- 要：角運動量を保持しつつ外層をなくす特殊な親星モデル
    - He星合体モデル (Fryer & Heger 2005)
    - Tidal spin up モデル (van den Huevel & Yoon 2007)
    - Chemically homogeneous evolution (Woosley & Heger 2006, Yoon et al. 2006)
  - いずれのモデルも親星コアでの強いmixingを伴う
    - 中心エントロピーが高くなる傾向がある
- GRBの親星コアは 高いエントロピー を持つ可能性を示唆

高速回転・高エントロピーコアの重力崩壊

- 高エントロピーコアの重力崩壊で期待されること
  - 高エントロピー ⇒ 大質量のコア ⇒ BH形成
  - 鉄の光分解がより進んだコア
    - 主な衝撃波冷却源である重元素光分解が少ない
    - 10^{51} erg per $0.1M_{solar}$ Fe
  - より(大質量で)コンパクトなコア ⇒ 高い質量降着率
  - 高エネルギー爆発（Hypernova）が期待できる？ (山田さん'talk)

- 高速回転で期待されること
  - ディスク形成
  - 衝撃波面の変形 (斜め衝撃波)

- 実際のところは数値相対論シミュレーションをしてみるしかない

BH formation 2010-2011: Results

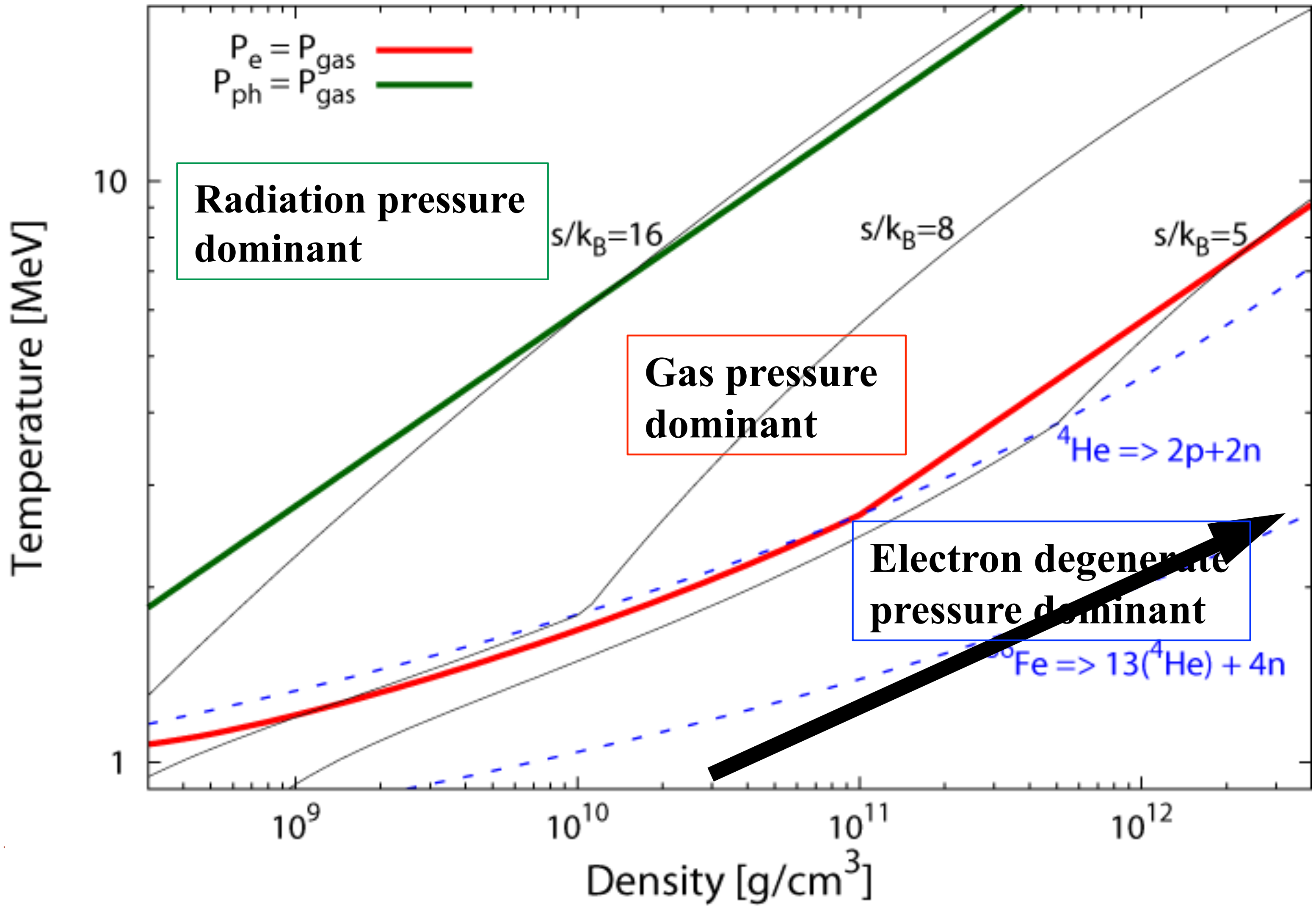
- Sekiguchi & Shibata , ApJ **737**, 6 (2011)
- Sekiguchi & Shibata , in preparation

- Without Magnetic fields

- **Please see how NR simulations have been developed since 2005.**

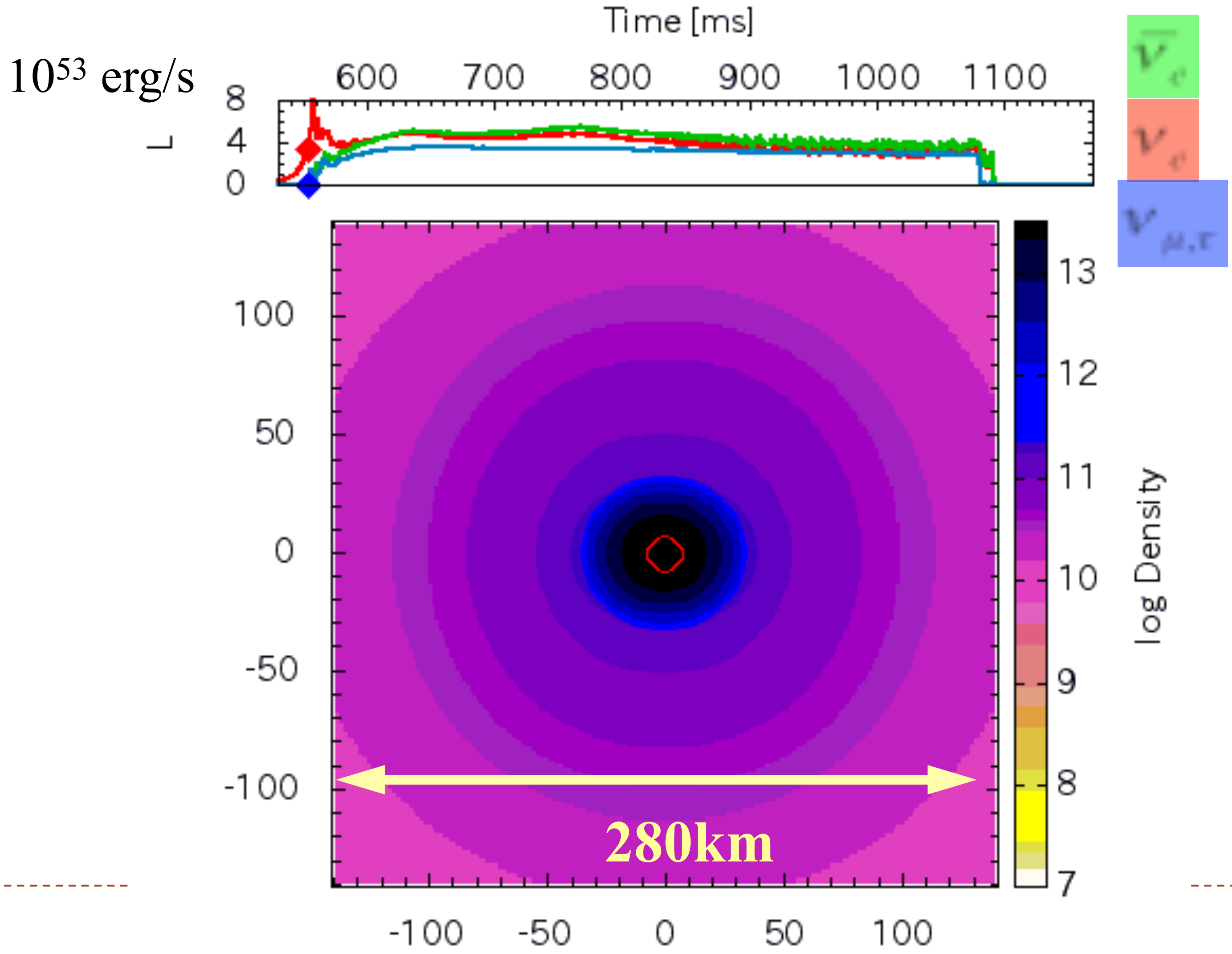
Collapse of 100Msolar presupernova model

- **Two rotation models (Moderate and Rapid rotation)**



Collapse of 100Msolar presupernova model

- **'Moderately'** rotating model (Ω_c=1.2 rad/s, Ω_{Fe}=0.6 rad/s)



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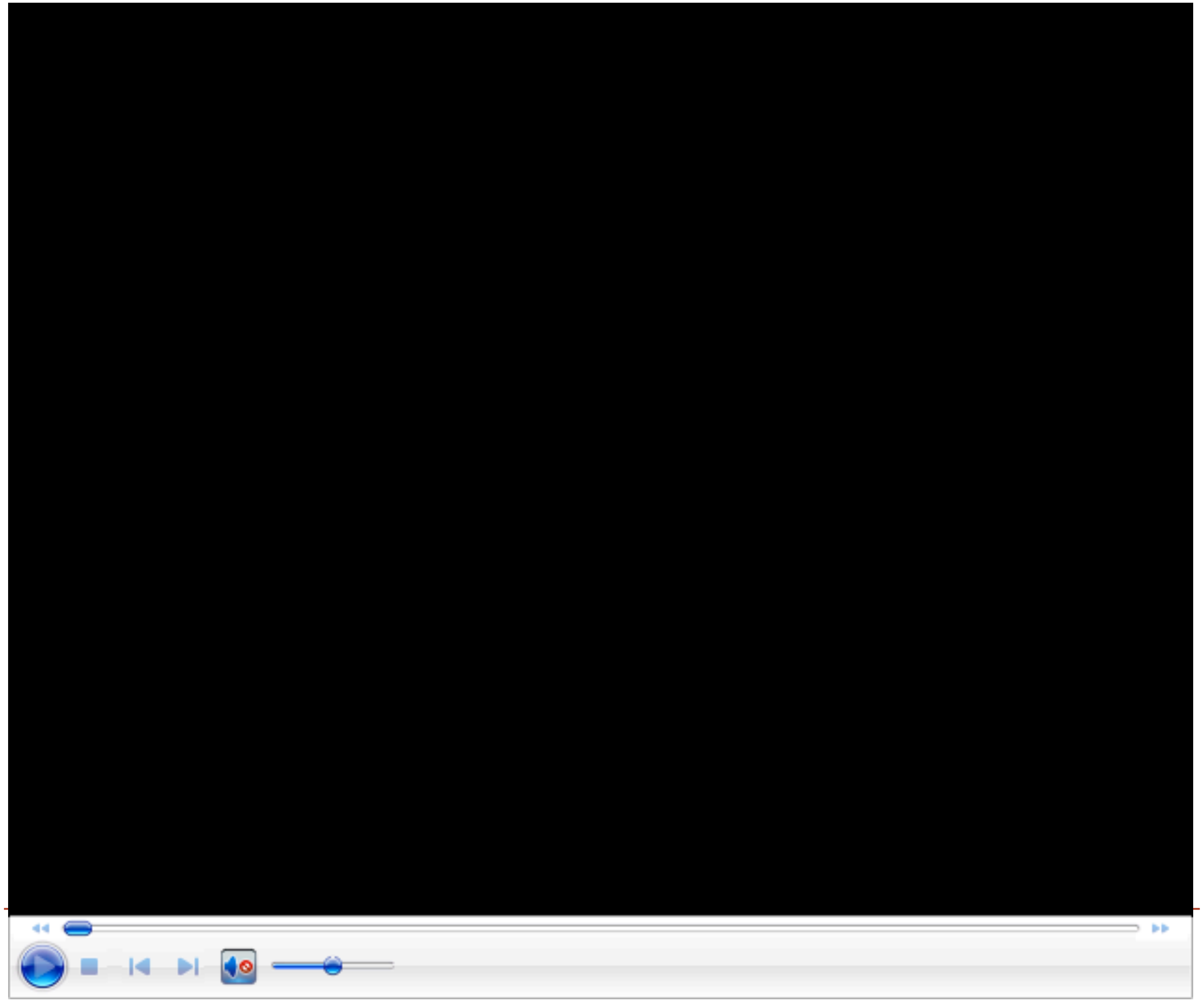
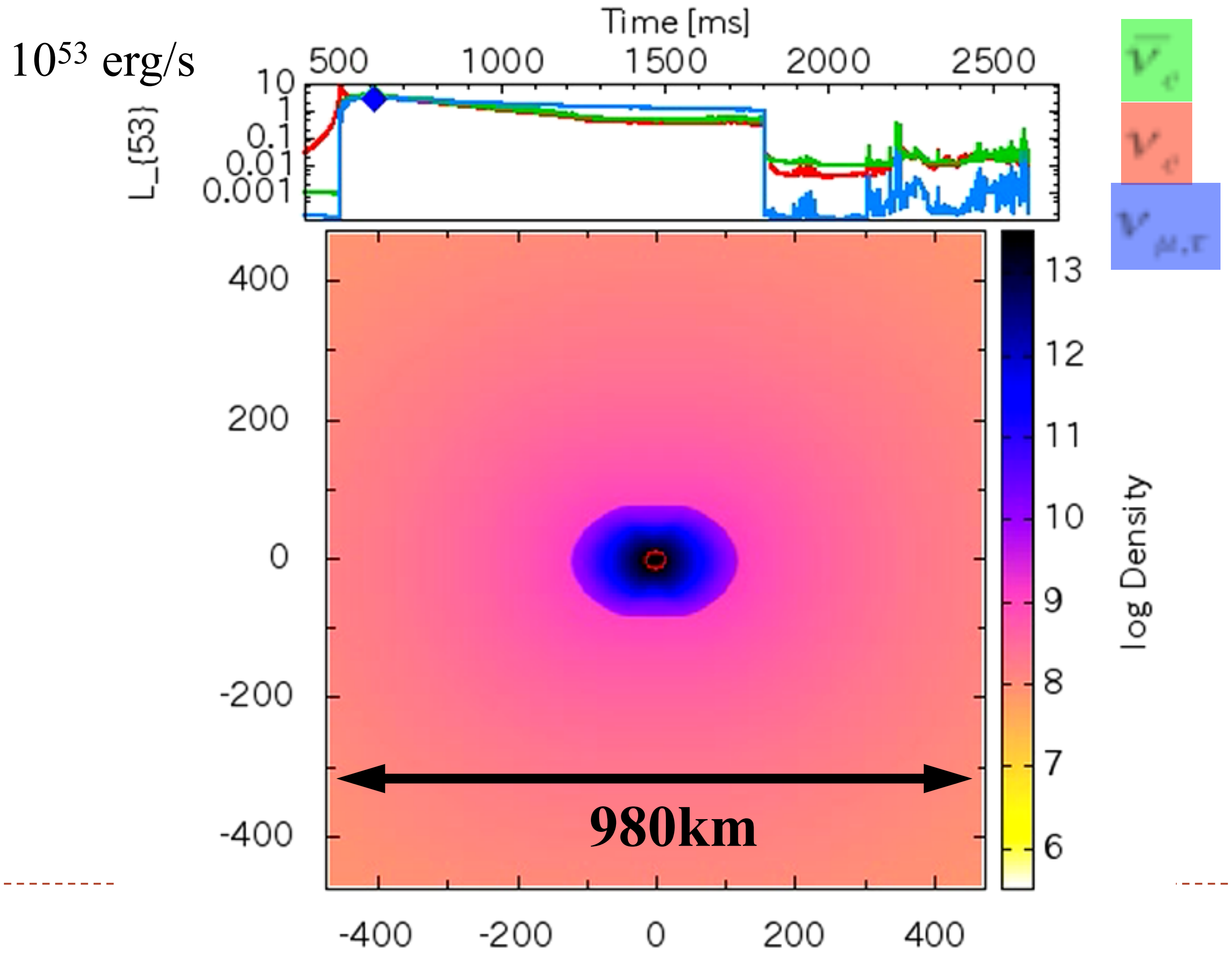


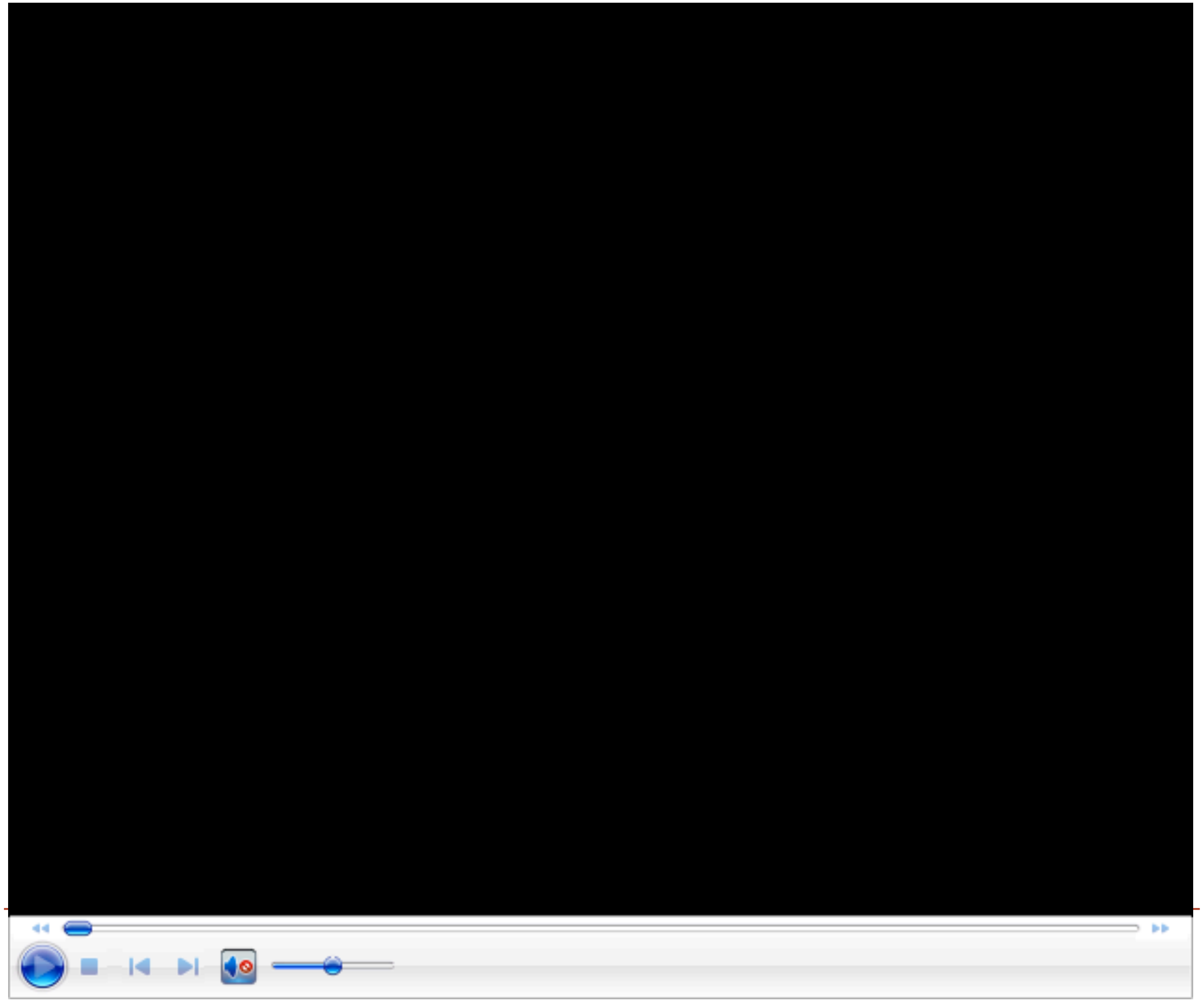
Collapse of 100Msolar presupernova model

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



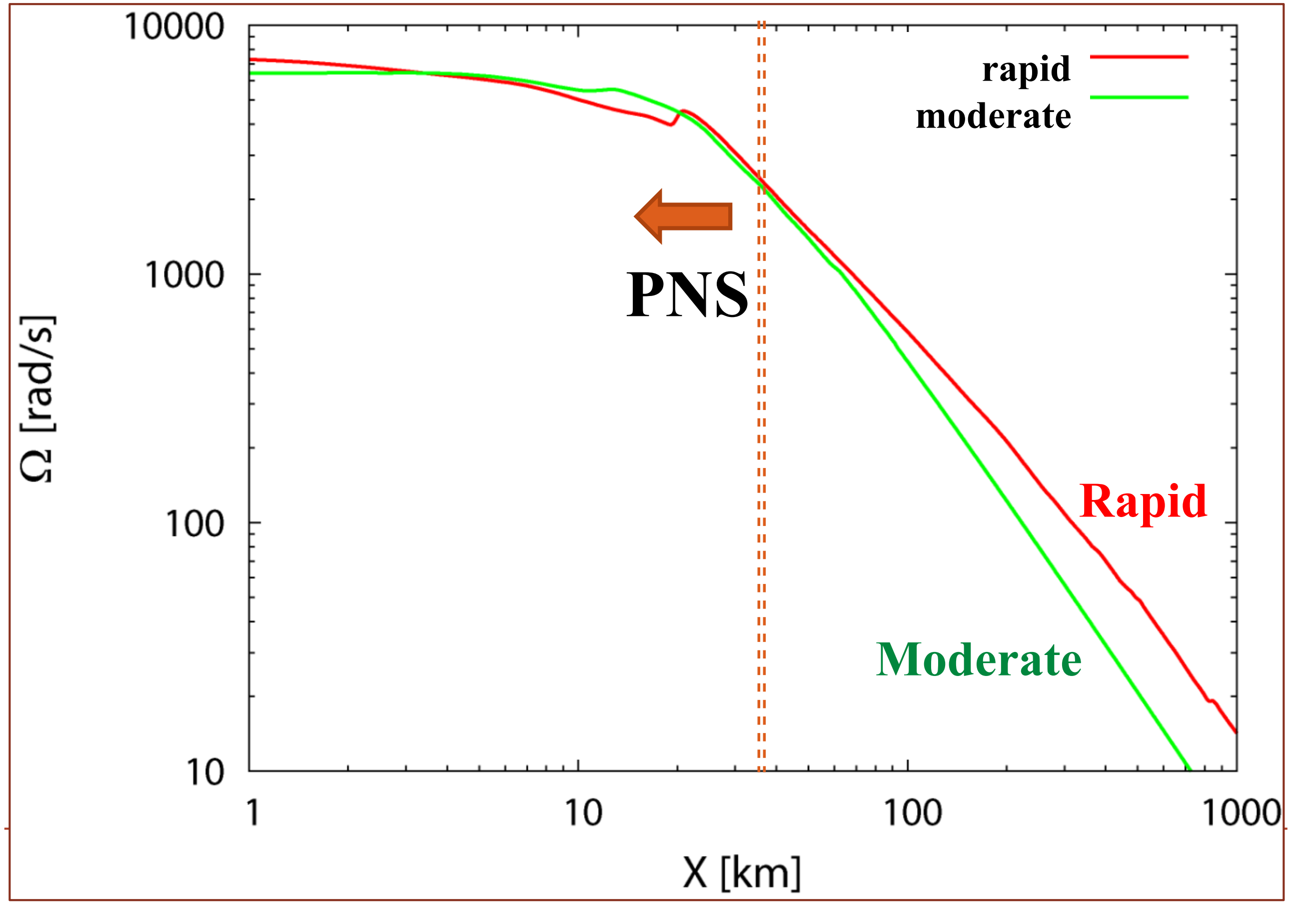
Collapse of 100Msolar presupernova model

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



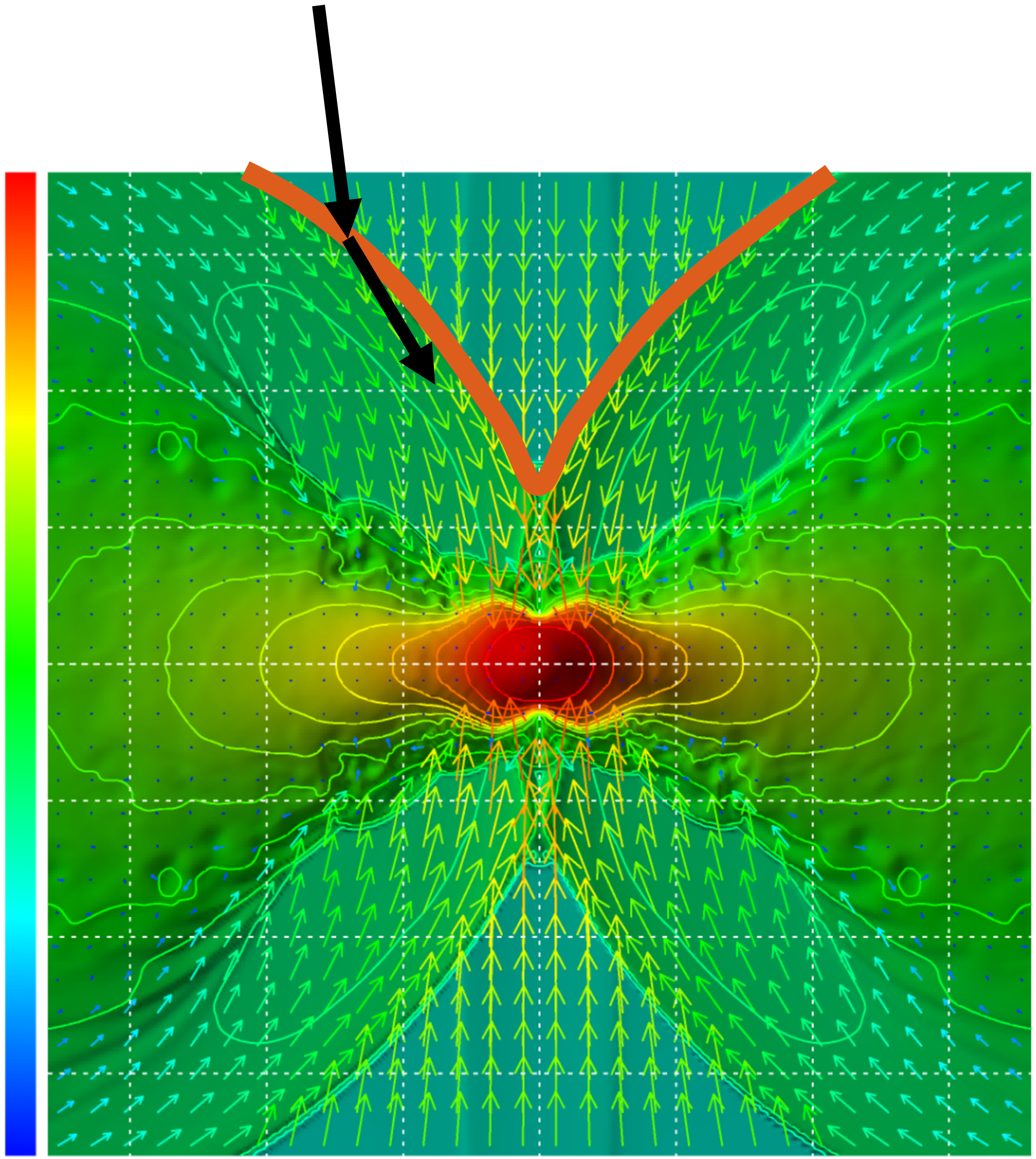
Rotational Profile of PNS

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



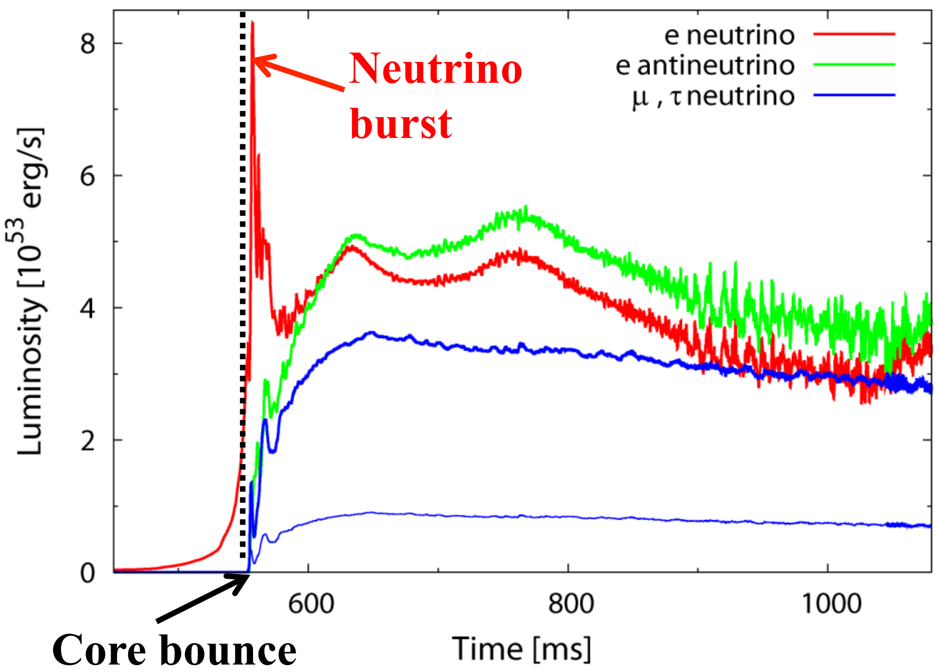
Oblique Shock

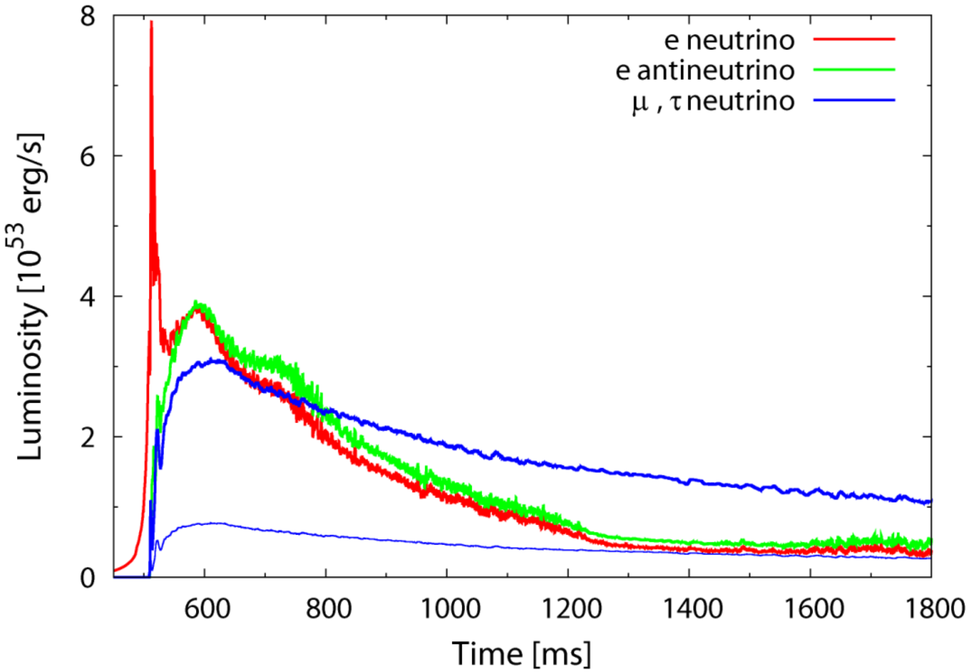
- **Rapid rotation:**
- Torus-structured shock
- Infalling materials are accumulated into the PNS due to the **oblique shock**
- Thermal energy is efficiently stored near the pole of PNS
- Ram pressure is decreasing
- ⇒Outflow



Neutrino Luminosity (PNS Phase)

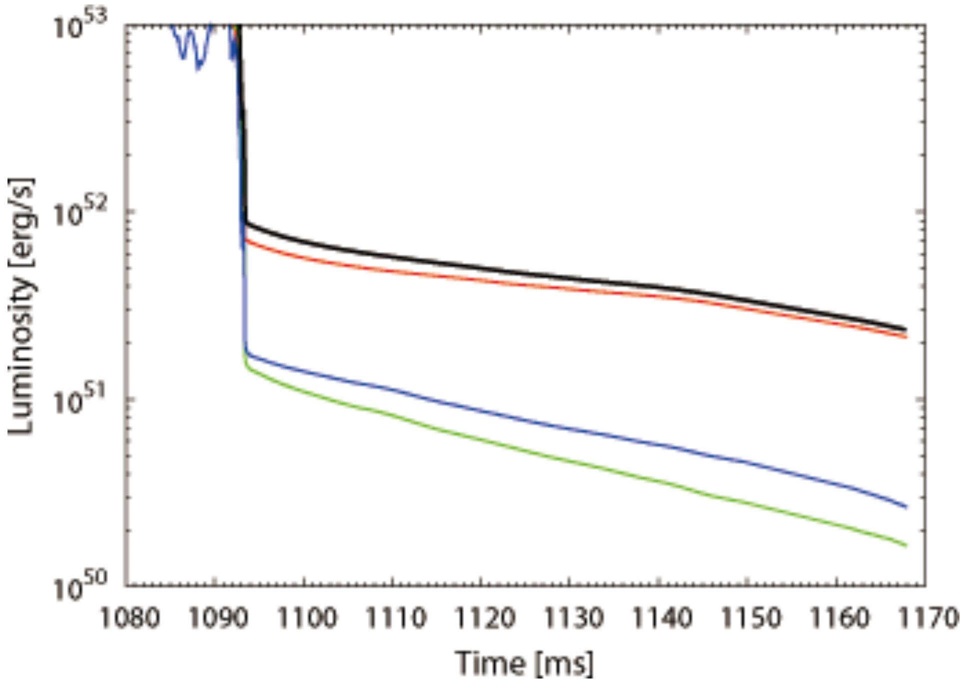
- **Moderate rotation**
  - Higher luminosity
  - Time variability due to convective activity
- **Rapid rotation**
  - Lower luminosity
  - Neutrino pair production processes are dominant



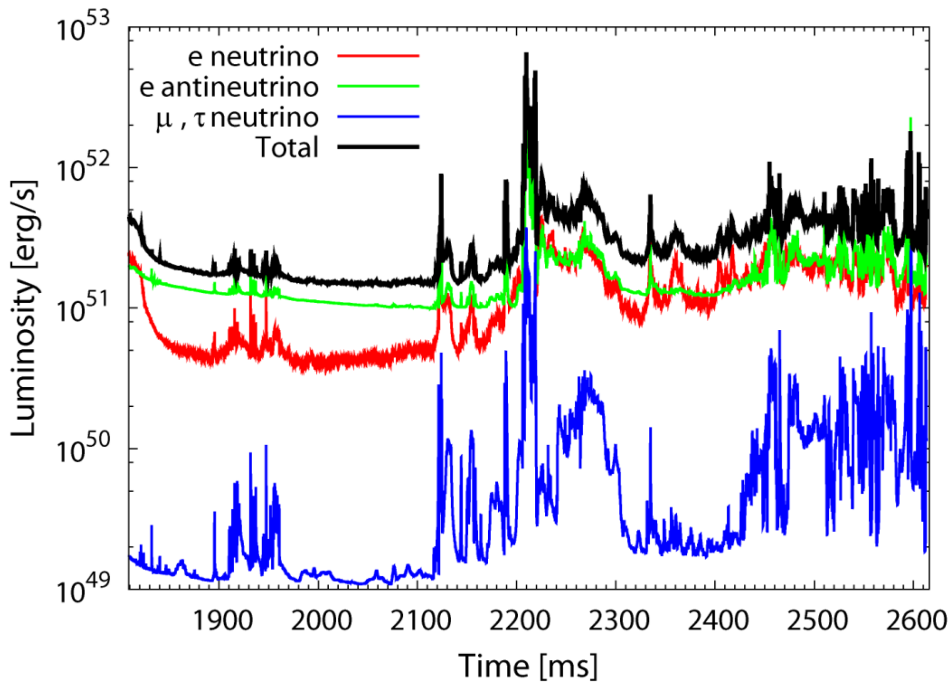


Neutrino Luminosity (BH Phase)

- **Moderate rotation**
  - $L_{tot} \sim 10^{51\text{-}52}$ erg/s
  - No time variability

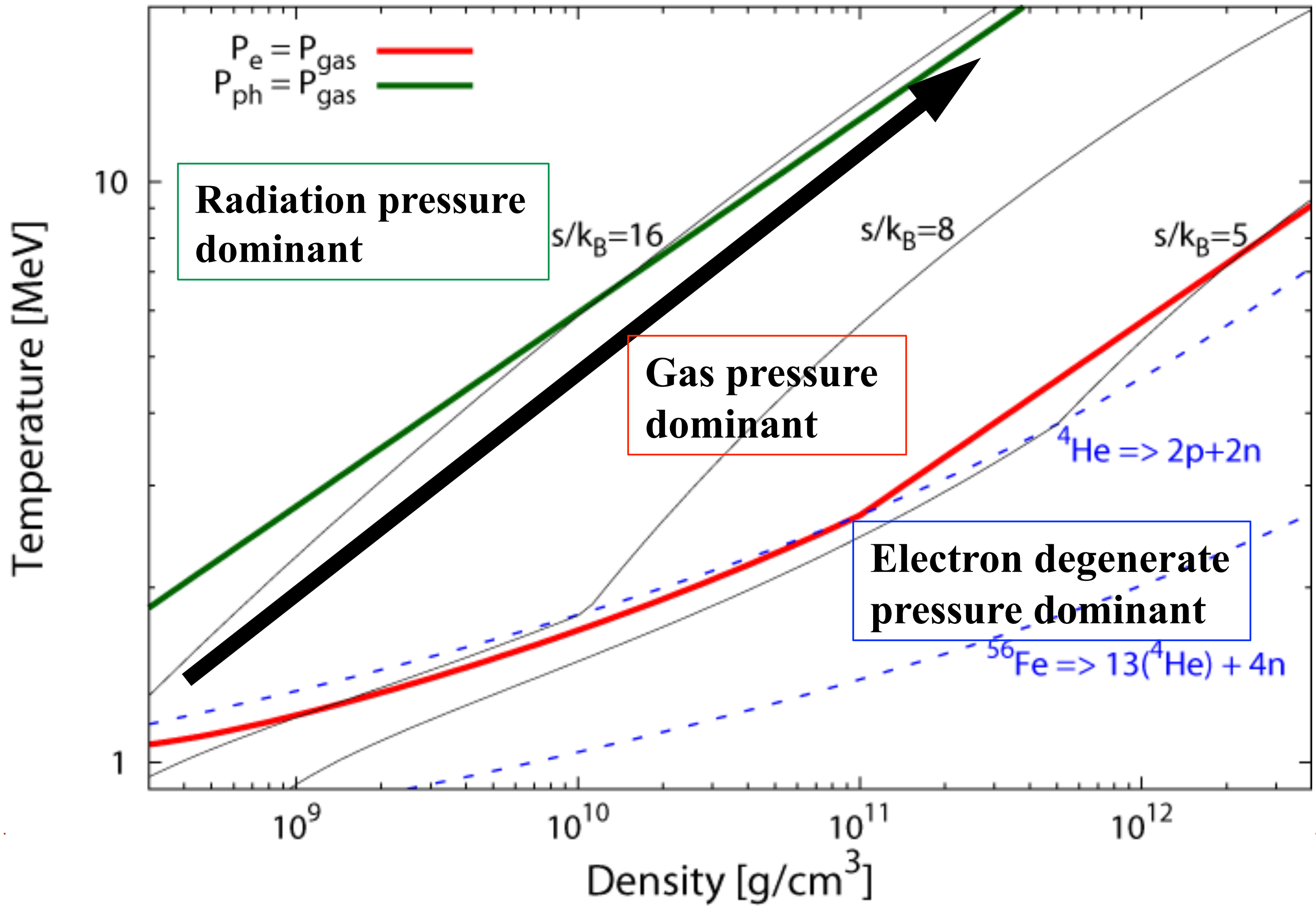


- **Rapid rotation**
  - $L_{tot} \sim 10^{51\text{-}52}$ erg/s
  - **Violent time variability**
  - Preferable feature for GRB



Collapse of 500M_{solar} PopIII stellar core

- **Rapidly rotating model** (Ω_c=**0.5** rad/s) : Direct BH formation



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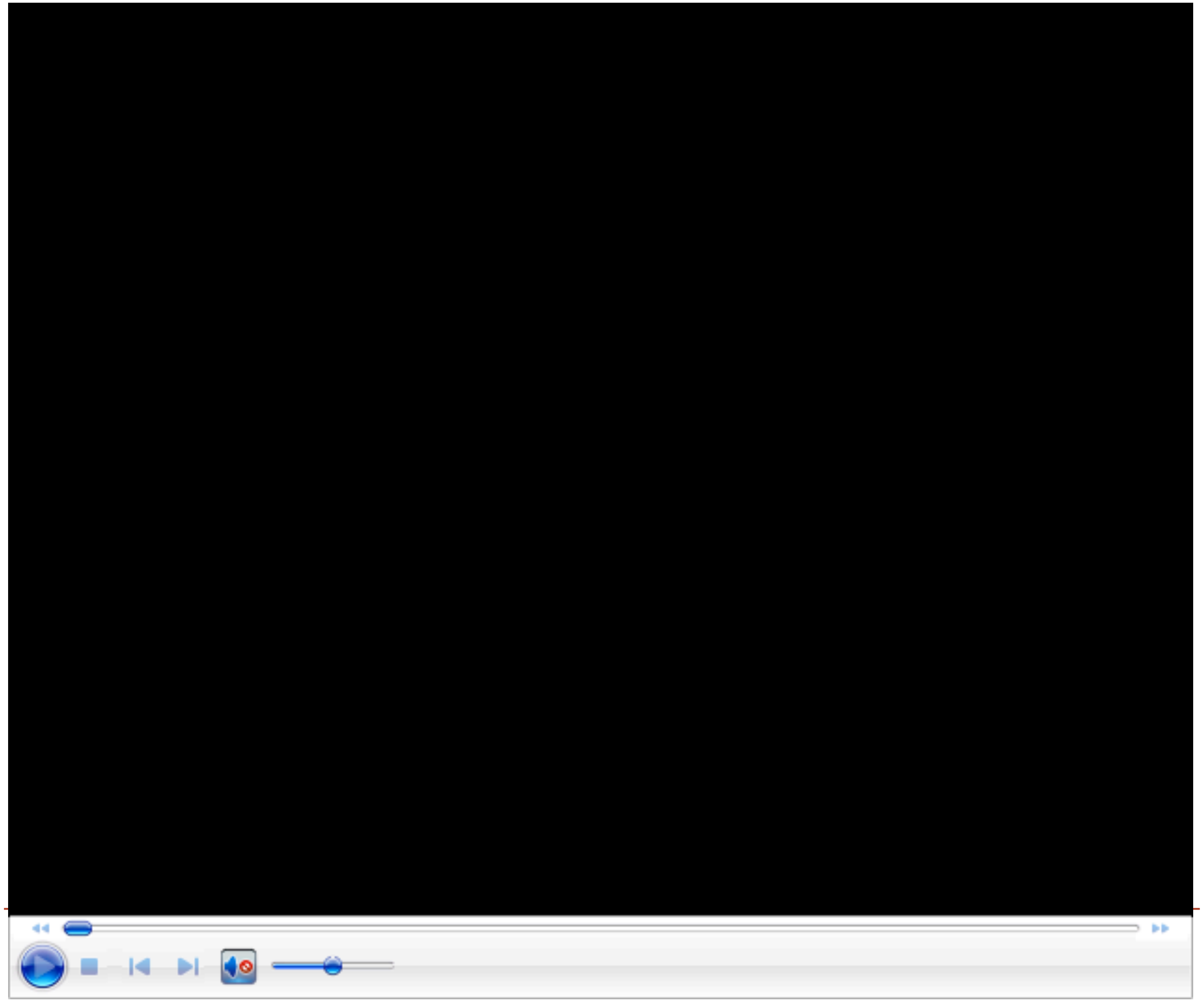
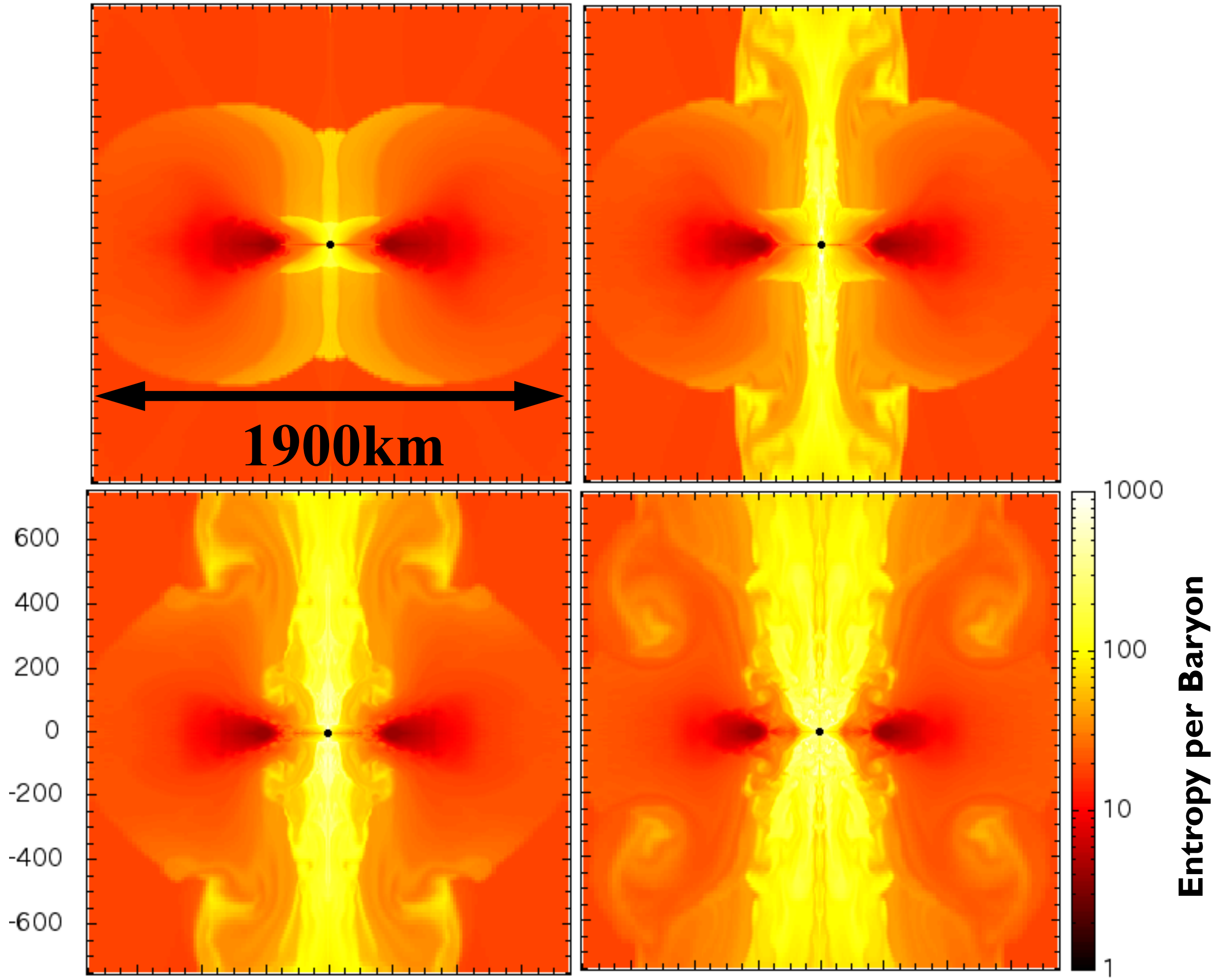


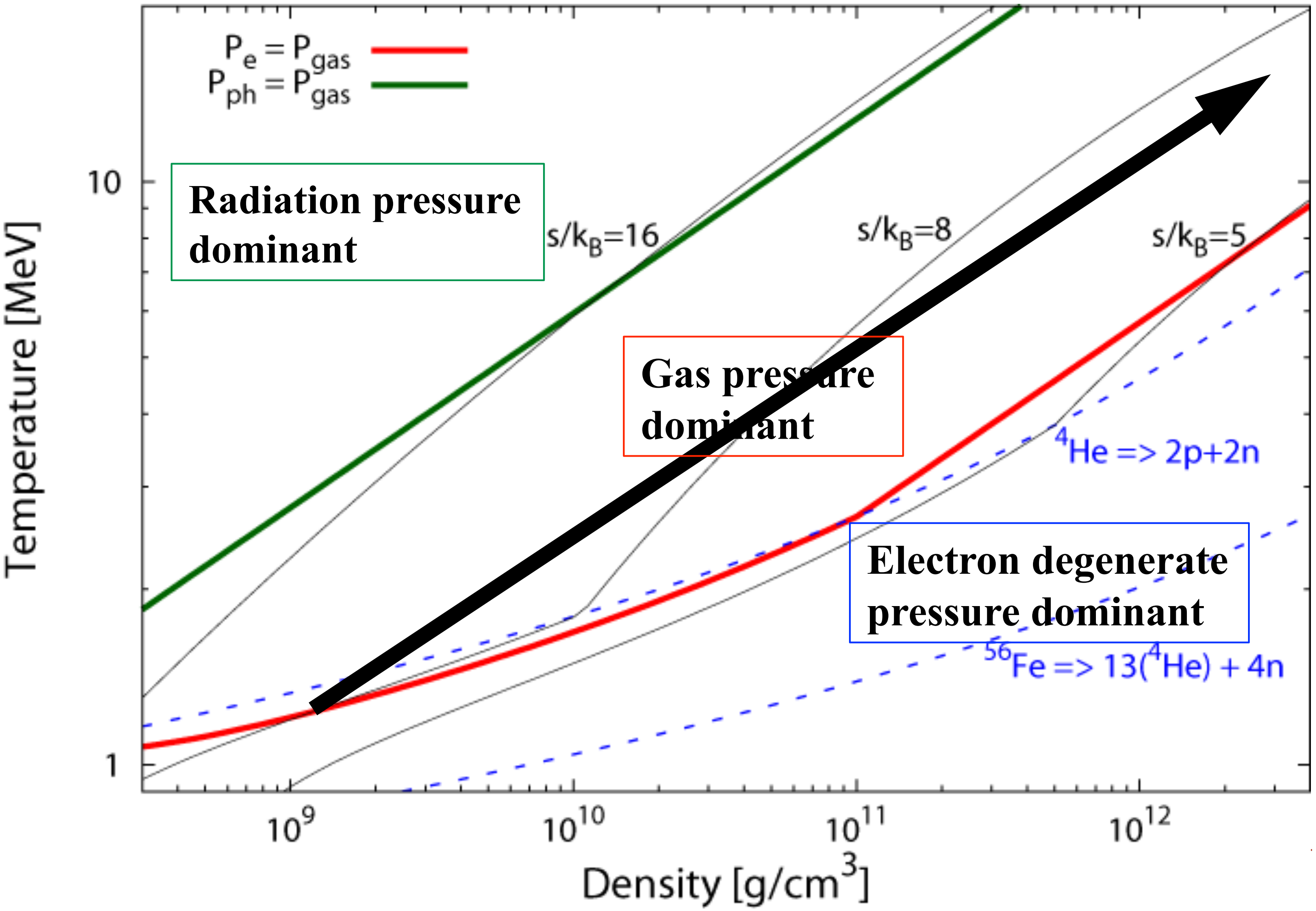
Outflow appears even when BH is formed



- Infalling materials are accumulated into the central region due to the oblique shock
- At a later phase BH is surrounded by shock waves
- Advection of energy into BH becomes less efficient
- Thermal energy is stored
- Outflow

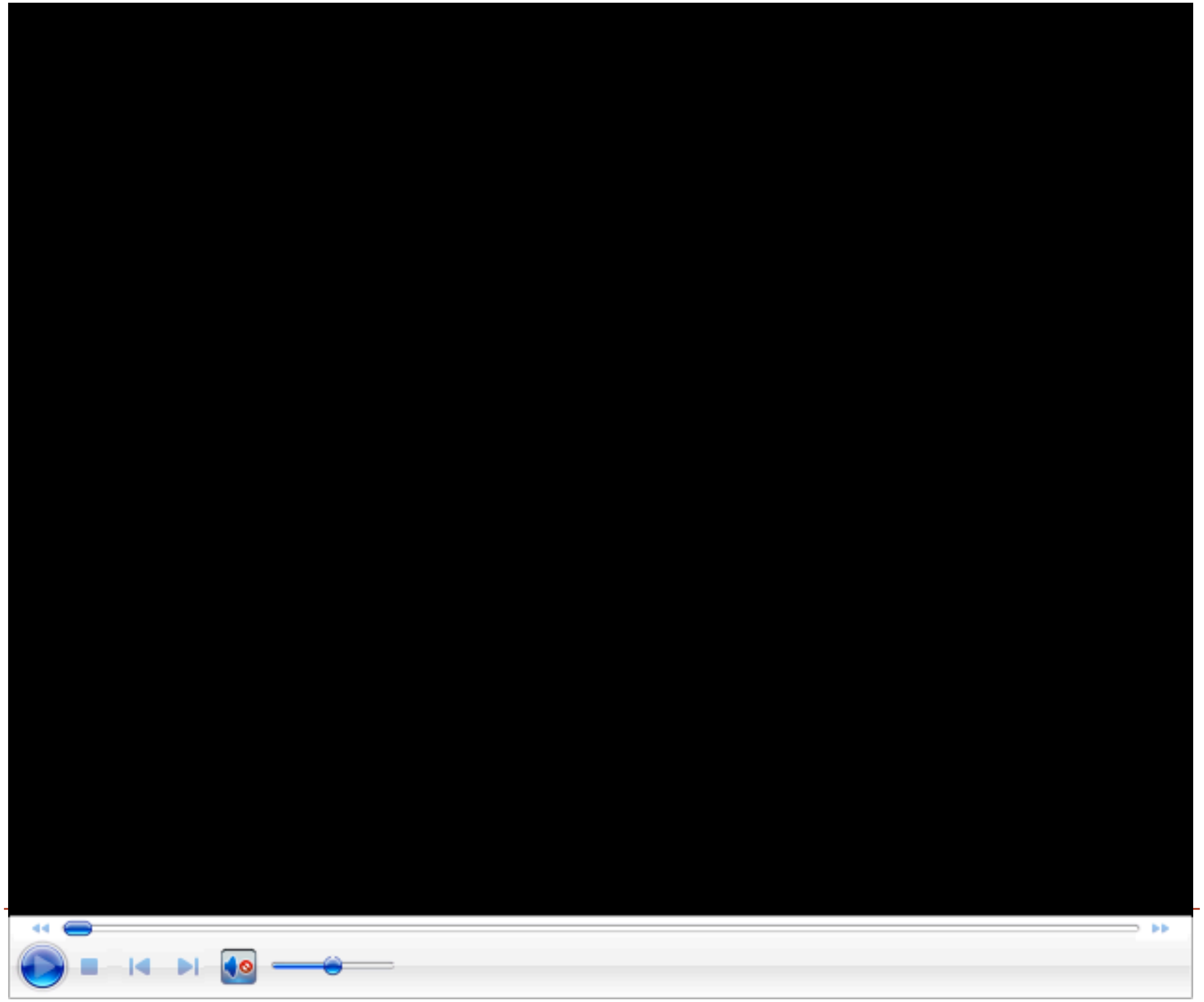
Moderately High entropy core

- **Moderate rotation** (Ω_c=**0.5** rad/s)

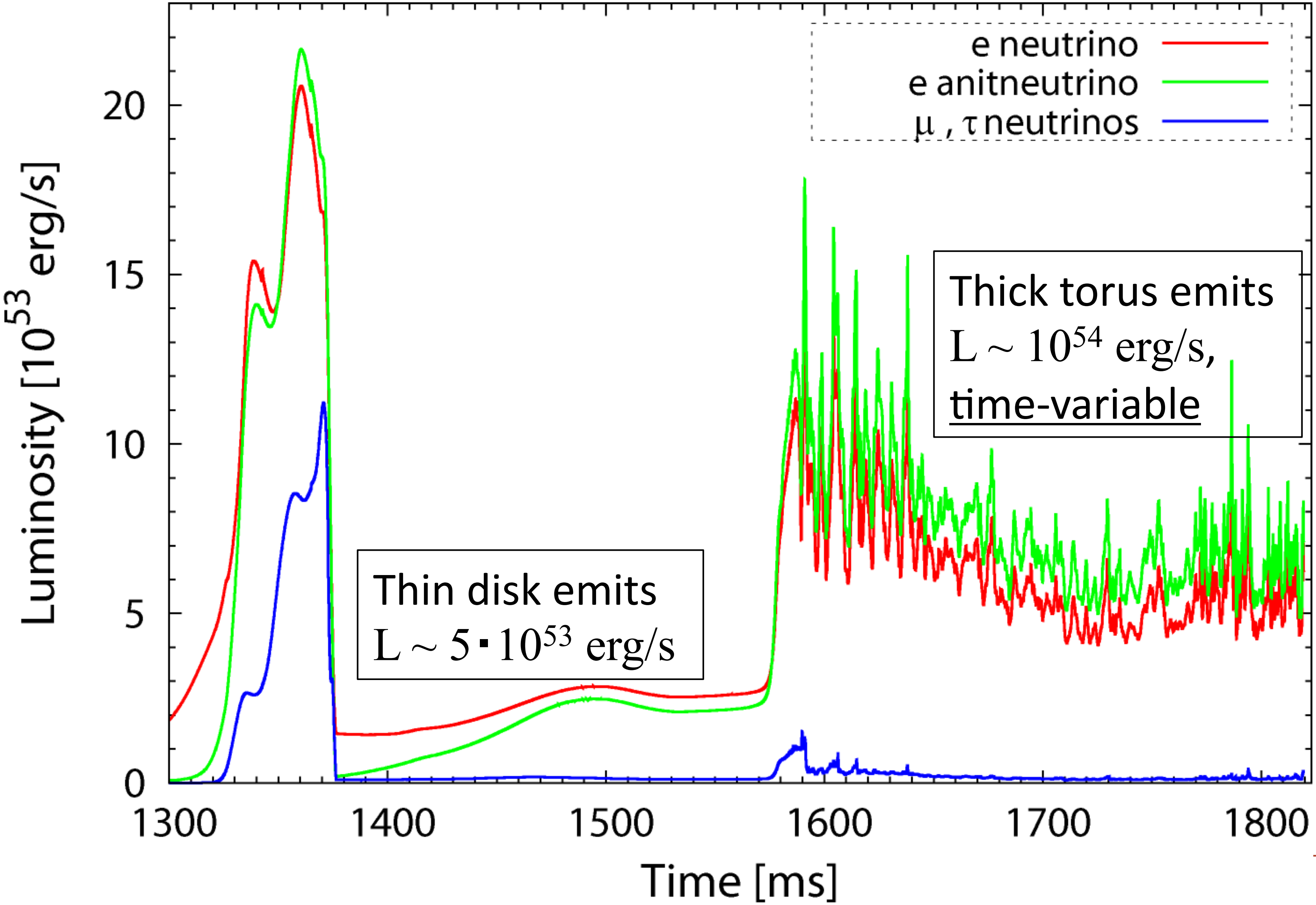


Moderately High entropy core

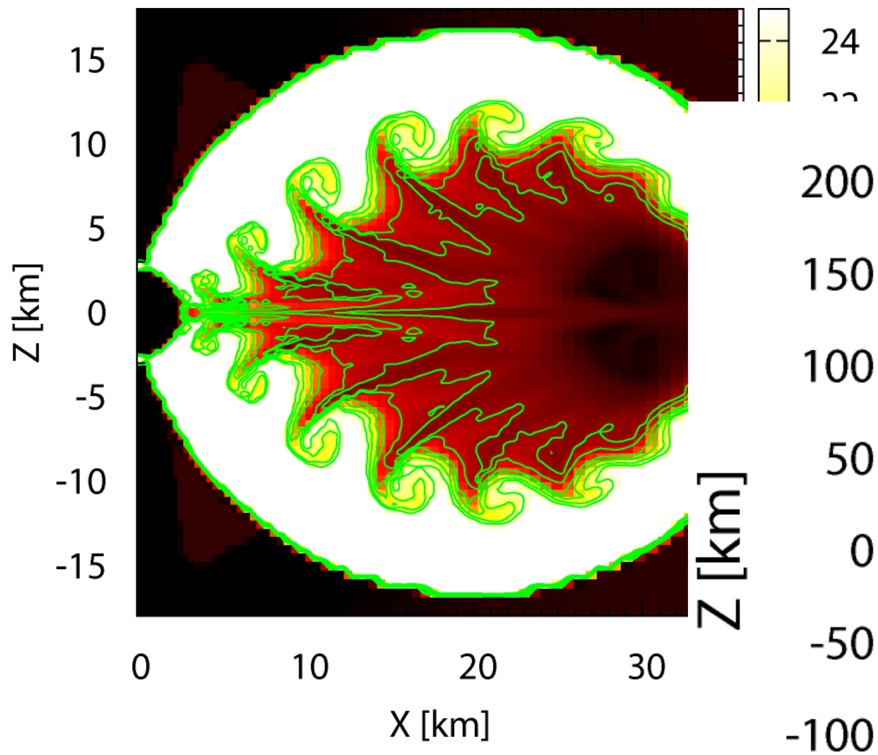
- **Moderate rotation** (Ω_c=**0.5** rad/s)

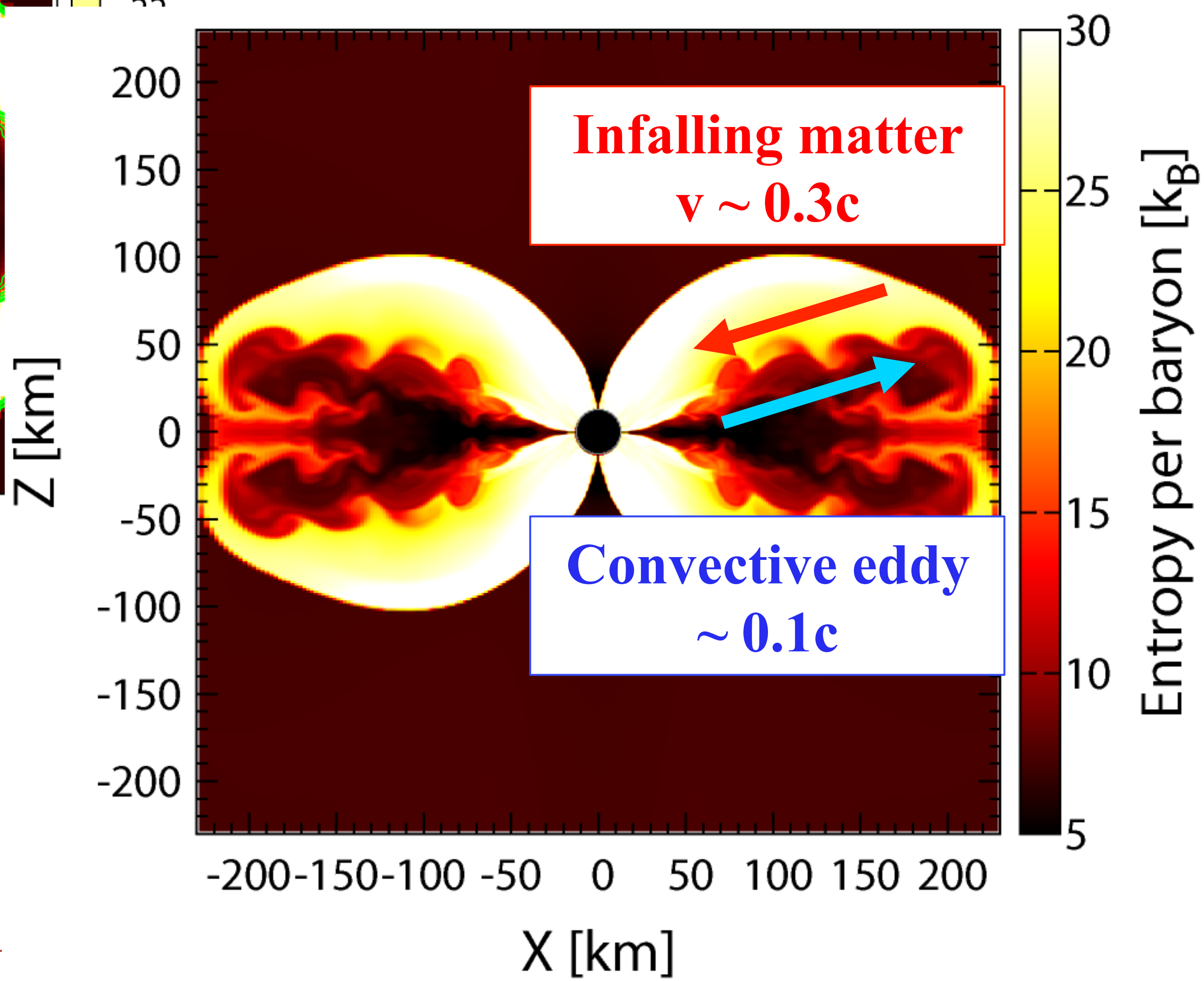


Neutrino luminosity



KH instability





Summary

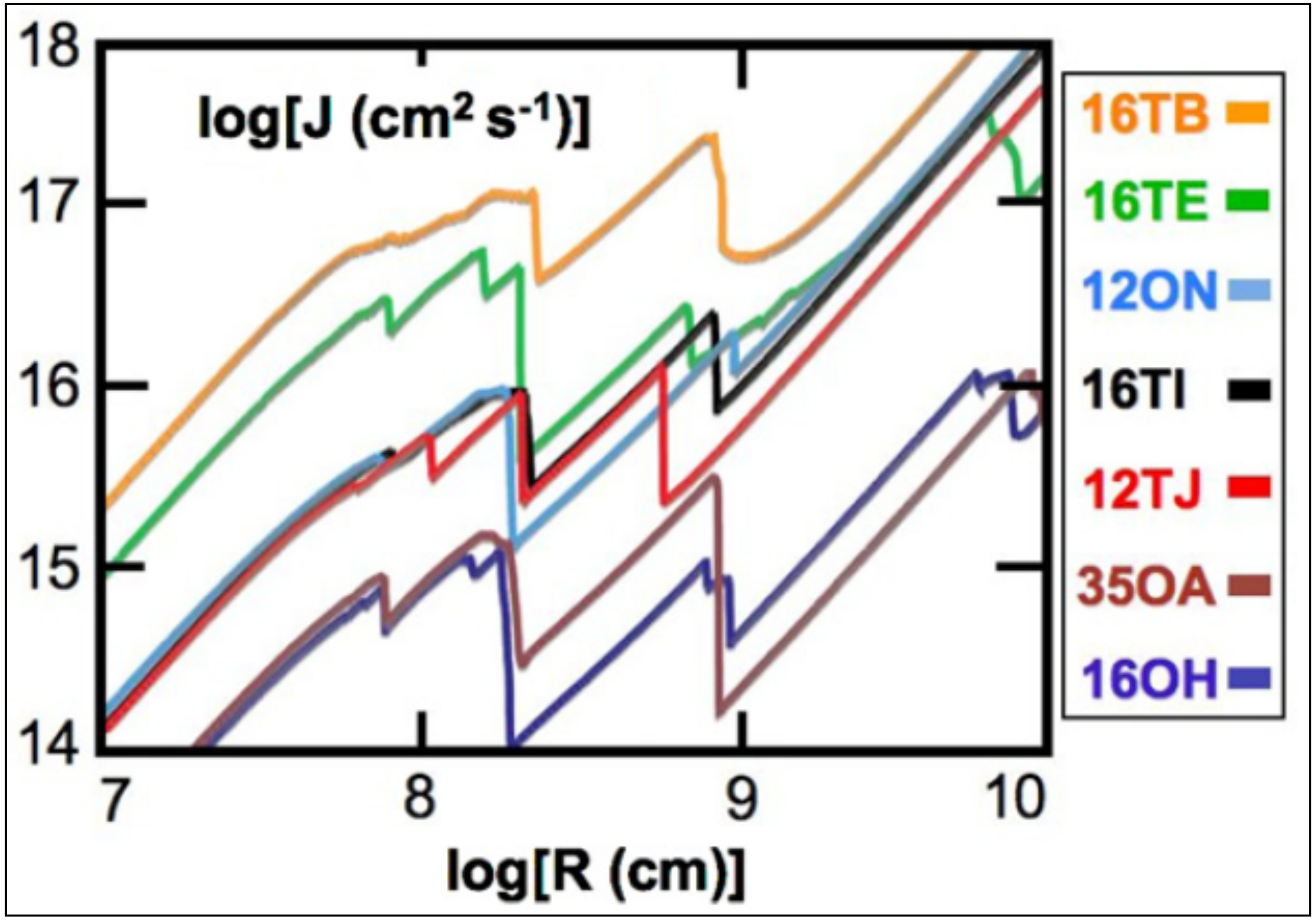
- The first full GR simulations, incorporating microphysics, of stellar core collapse are performed, adopting various initial models
- **BH formation process is quite dynamical, accompanying oblique shock, convection, KH instability and outflows**
  - The dynamics is very sensitive to the initial rotational 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
  - Connection between variation in LGRB and variation in dynamics ?

今後の展望

- GR leakage scheme からの脱却、Thorne's moment formalism に基づくGR-Radiation-Hydrodynamics へ
  - 定式化 : Shibata et al. 2011
  - BH -Disk の GR-Rad-MHD (simplified) : Shibata & Sekiguchi 2012
  - Detailed microphysics ver. ほぼ完成しつつある
    - 爆発計算 ⇒ SN groups のシミュレーションコードの図に参入
- 3D simulation
  - BH 周りの massive disk の Papaloizou-Pringle不安定性 Kiuchi et al. 2011
  - Torus-Shaped shock の SASI は起こるか？
- Convection と MHD processes (e.g. MRI) の関係
  - 競合する可能性も (c.f. CDAF)
  - GR-Rad/ν-MHD

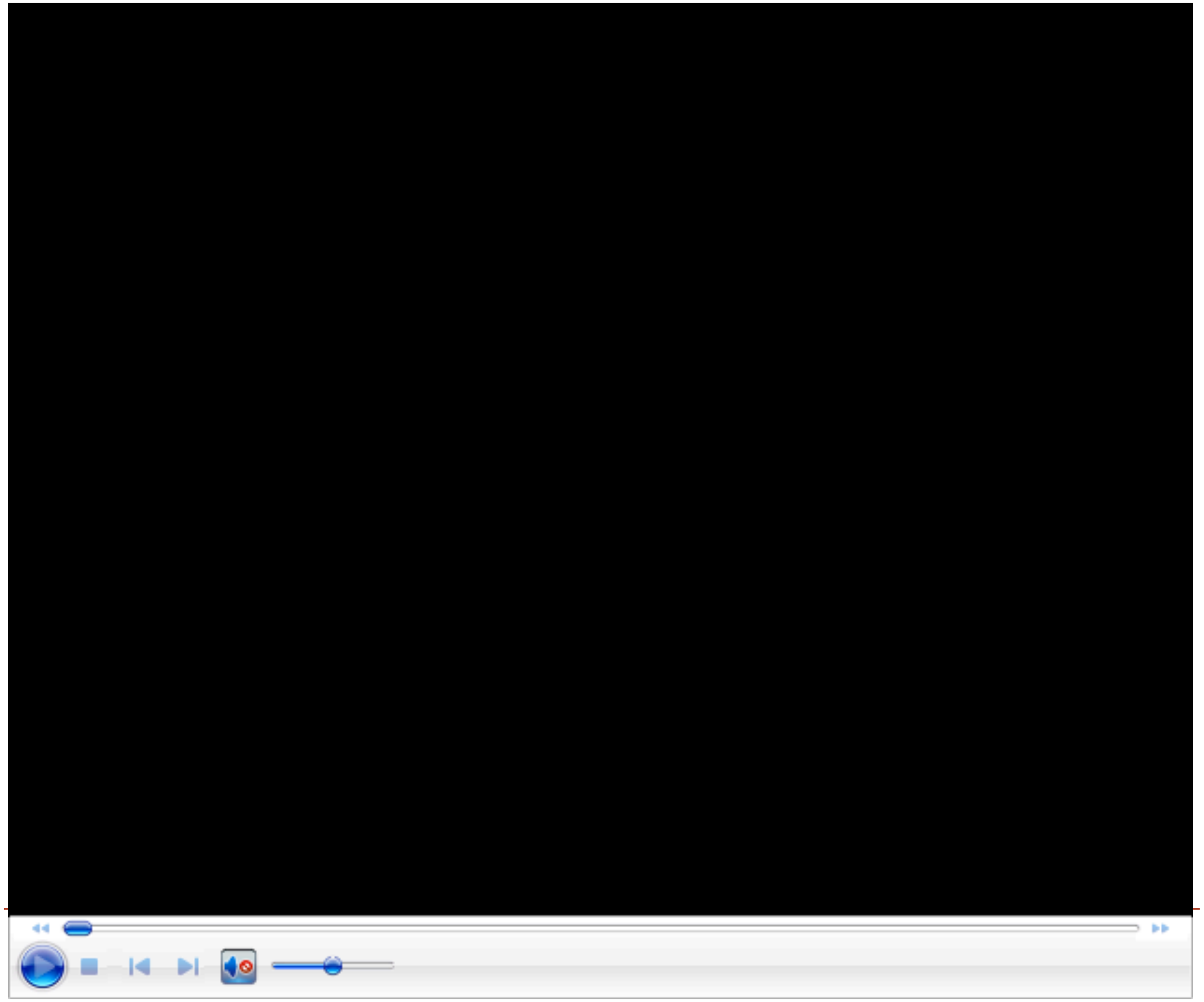
今後の展望

- より"現実的な"初期条件/回転プロファイルの採用



Collapse of 500M_{solar} PopIII stellar core

- **Slowly rotating model** (Ω_c=**0.3** rad/s)



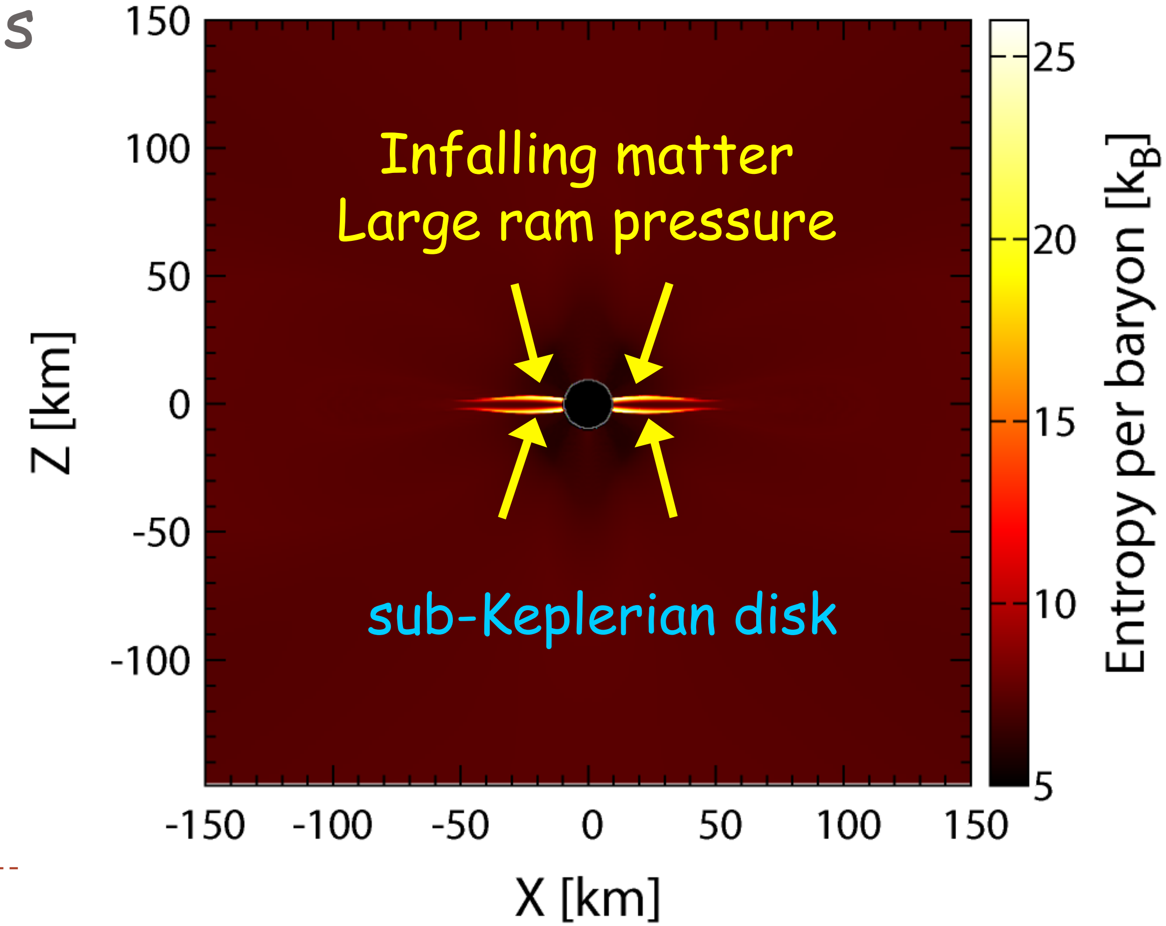
Geometrically-thin disk phase

- Heating source : Shocks at the surface of disk
- Cooling source : neutrinos, advection
  - Advection vs neutrinos

$$t_{\rm diff} \sim \frac{H\tau_\nu}{c} \sim \frac{H}{0.1\,c}$$

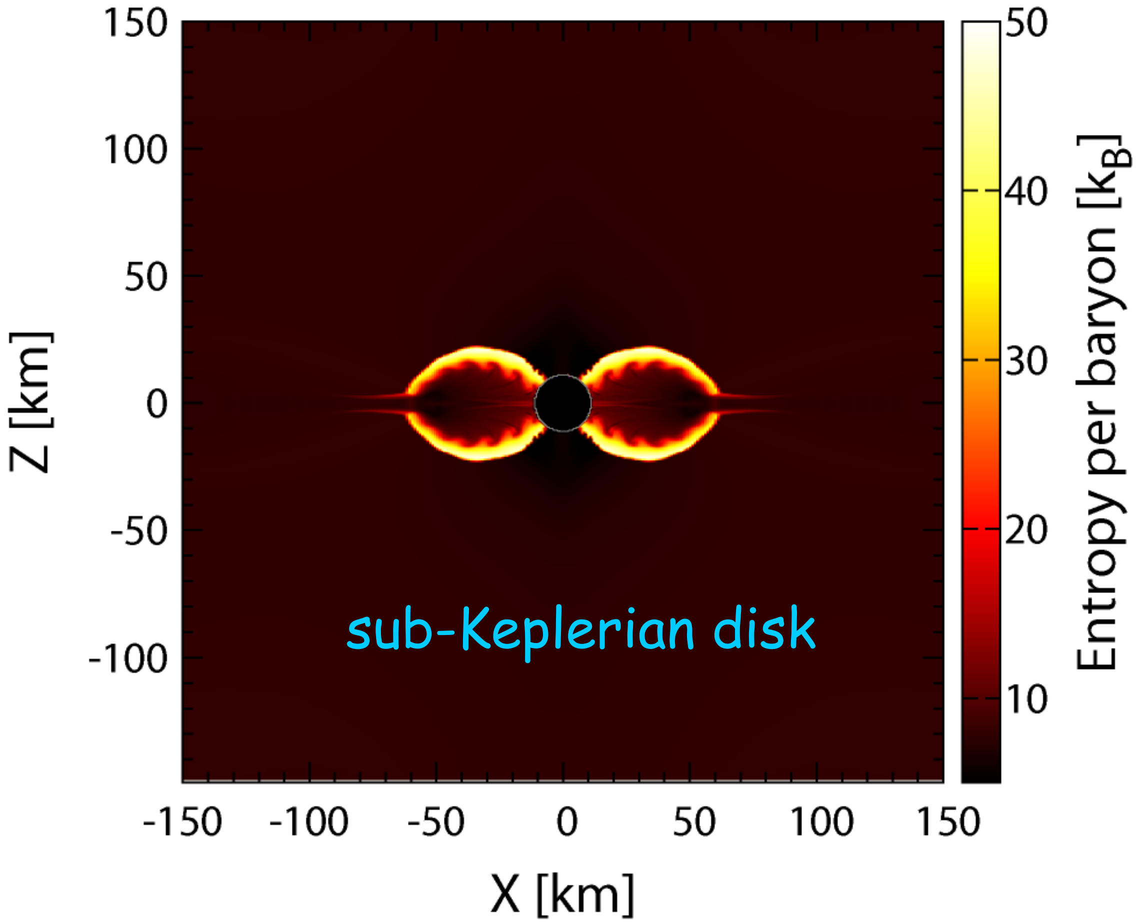
$$t_{\rm adv} \sim \frac{R}{v} \sim \frac{R}{0.1\,c}$$

  - R >> H ⇒ $t_{\rm diff} \ll t_{\rm adv}$



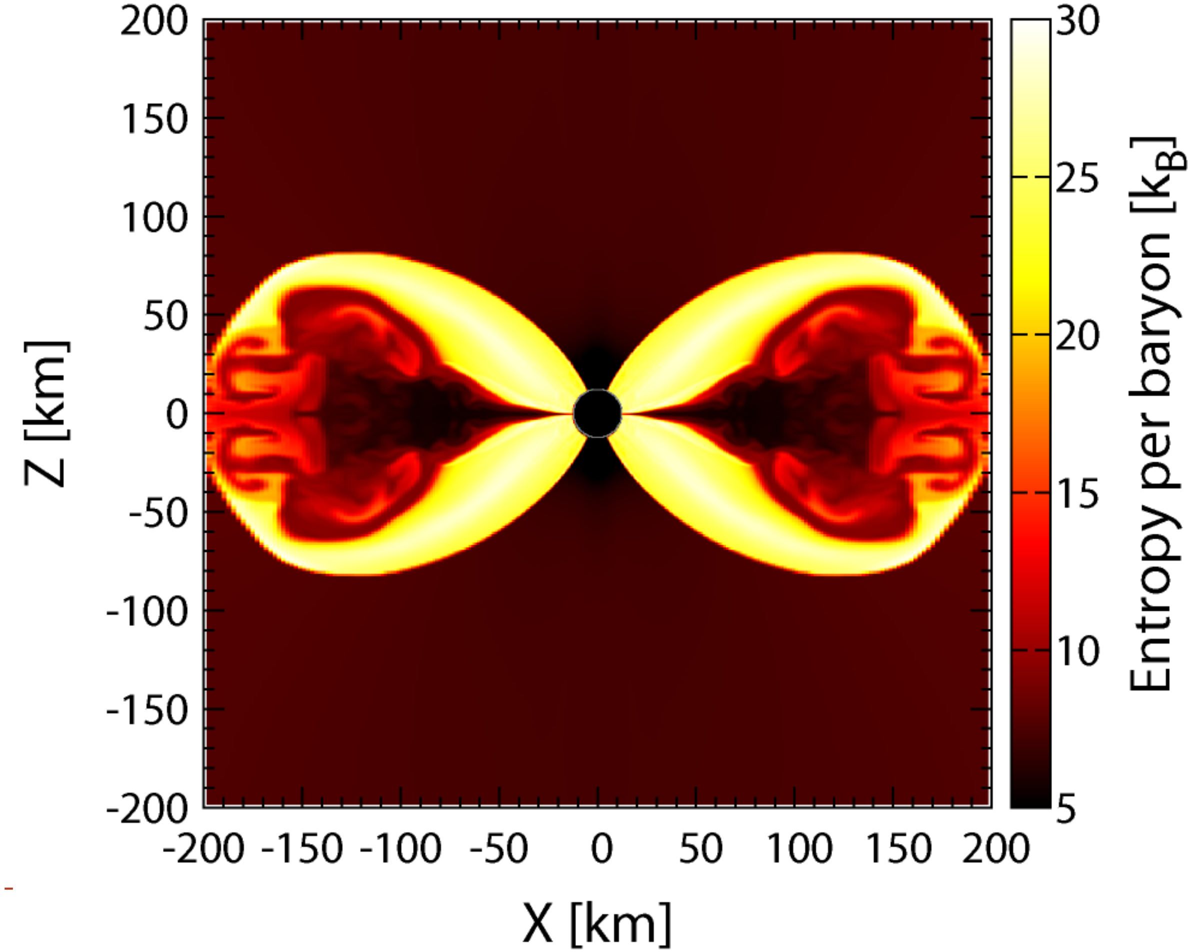
Disk expansion

- As a result of subsequent accretion of high-angular-momentum matter…
  - Density ↑
  - optical depth ↑
  - thermal energy ↑
  - H increases
- When $t_{diff} = t_{adv}$, neutrinos are 'trapped'
- Ram pressure ↓
- Disk expand to be geometrically-thick torus



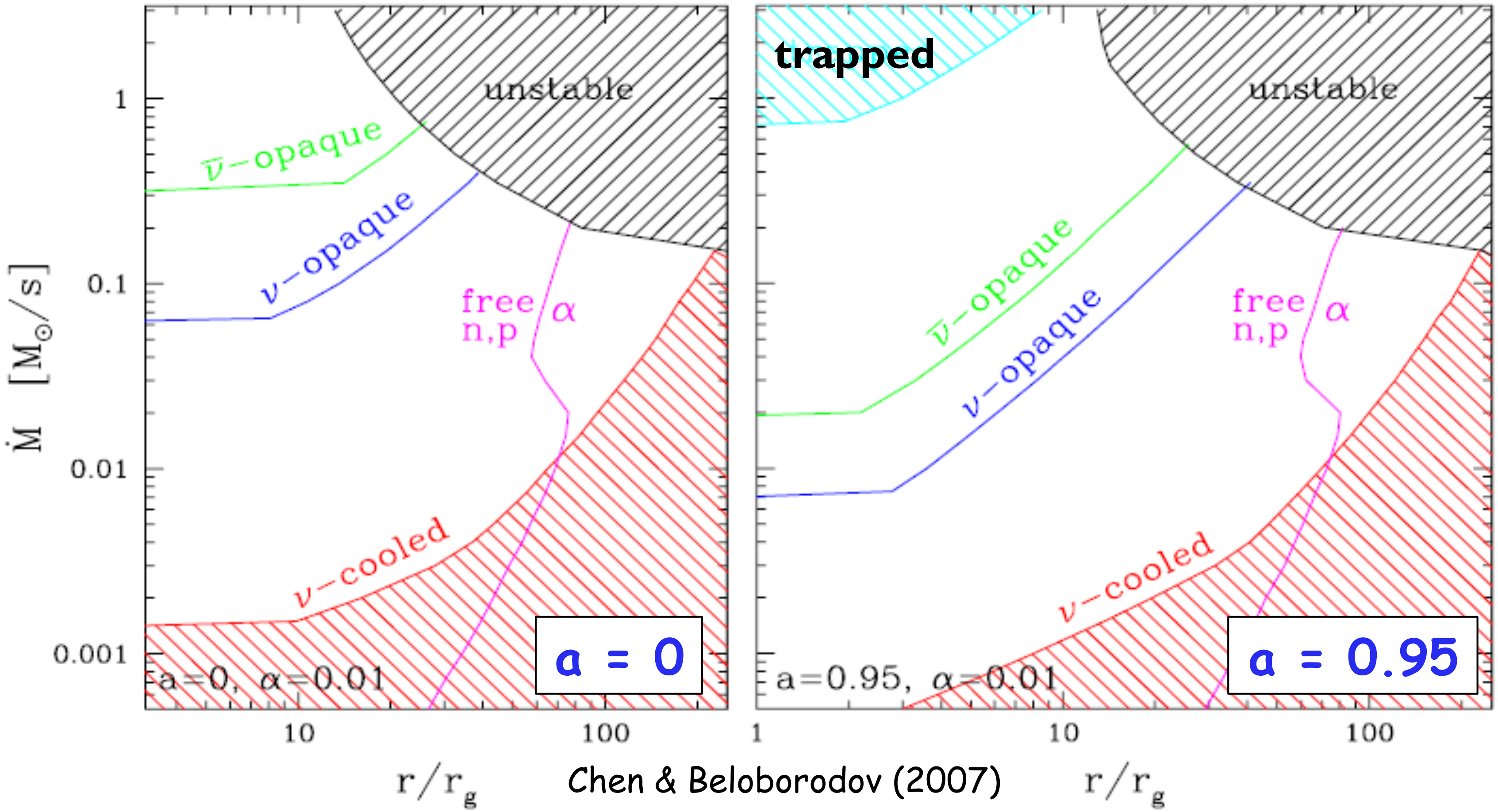
Convective activities

- **Accretion disk in collapsar is convectively unstable !**
- Point: the disk is, effectively, "heated from below"
- In inner region…
  - Shock heating is stronger
  - Neutrino cooling is less efficient
- Negative entropy gradient
- SN component ?
  - Convective luminosity is sufficient (Milosavljevic et al.2010)



Importance of BH spin

- Efficiency of exchange of gravitational binding energy : ~ 0.01 (a=0) ⇒ ~ 0.4 (a=1)
- Disk properties : **no neutrino trapping for a=0**
  - Efficient cooling ⇒ no/very-weak negative entropy gradient
  - No convective activities, no time variability



Chen & Beloborodov (2007)

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**