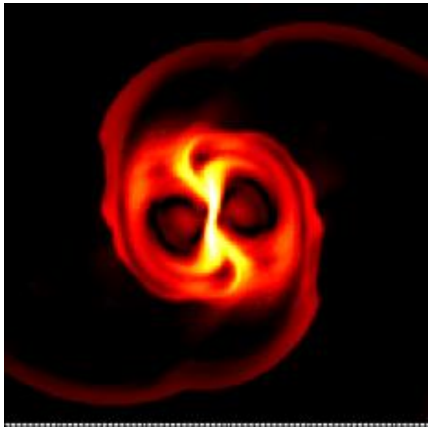
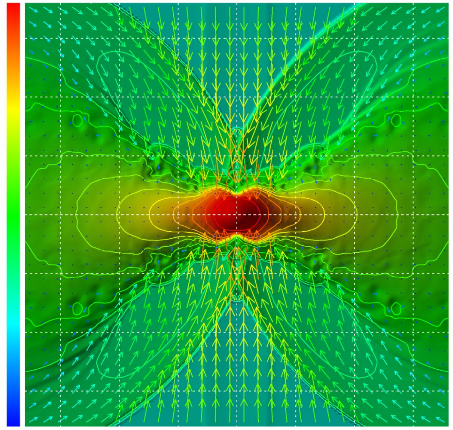
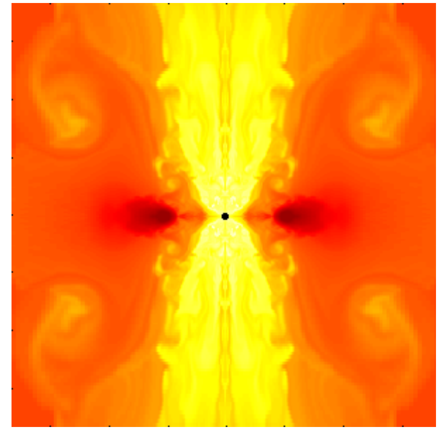
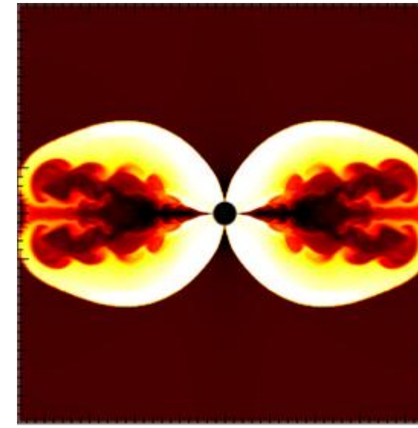





# 大質量星重力崩壊と連星中性子星合体の数値相対論シミュレーション

関口雄一郎（京都大学基礎物理学研究所）

# Summary of Studies in 2011/2012

- **Binary Neutron Star Merger**
  - Sekiguchi et al. PRL 107, 051102 (2011)
  - Sekiguchi et al. PRL 107, 211101 (2011)
- **Black-Hole-Neutron-Star Binary Merger**
  - Sekiguchi et al, in preparation
- **Collapse of Massive Stellar Core**
  - Sekiguchi & Shibata ApJ, 737, 6 (2011)
  - Sekiguchi & Shibata, in preparation
- **Collapse of PopIII Stellar Core**
  - Sekiguchi & Shibata, in preparation
- **General Relativistic Radiation Hydrodynamics (GRRHD)**
  - Sekiguchi et al. in preparation (Main Code **完成**)

# Summary of Code

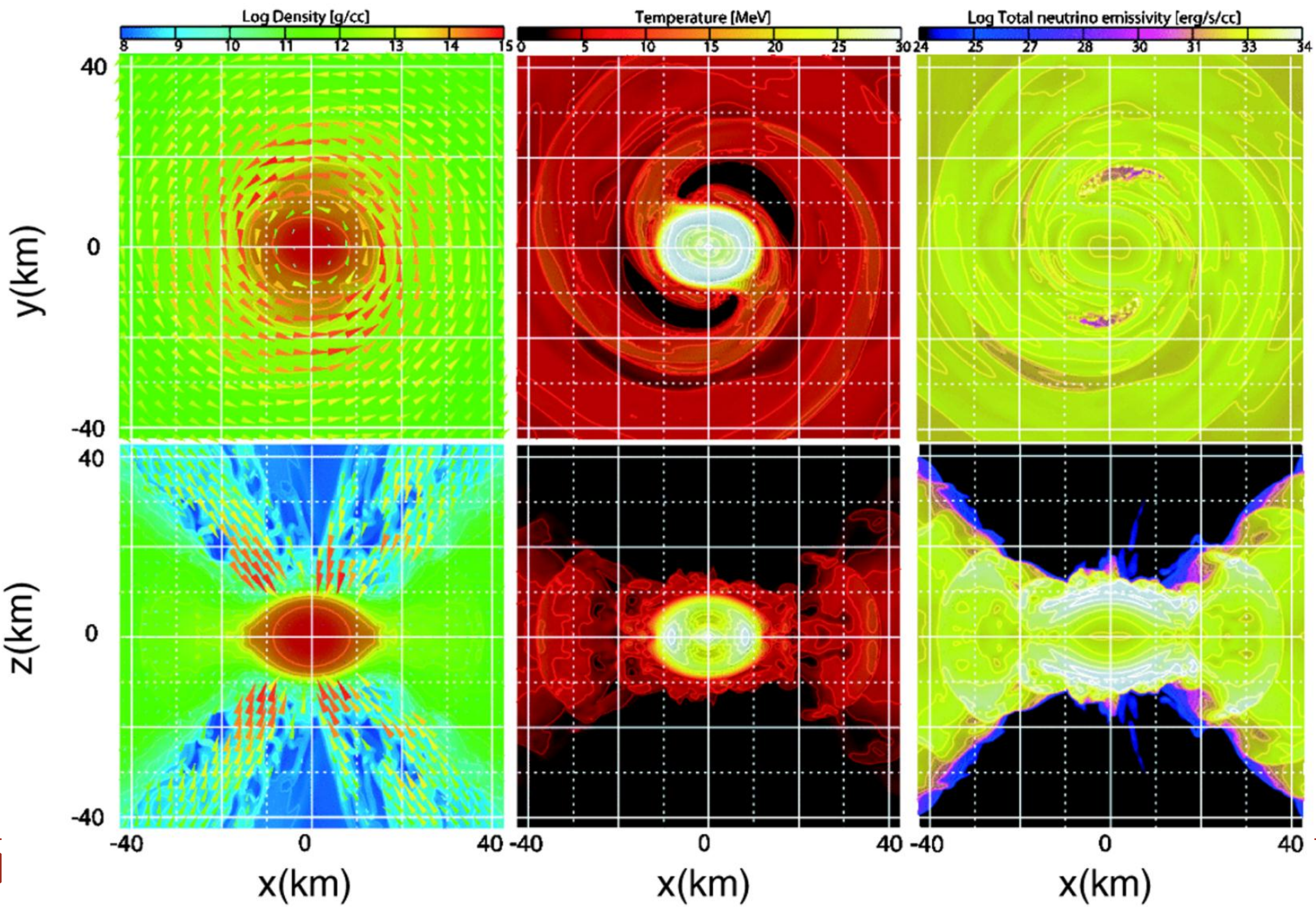
Sekiguchi (2010) Progress of Theoretical Physics **124**, 331

- 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**

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

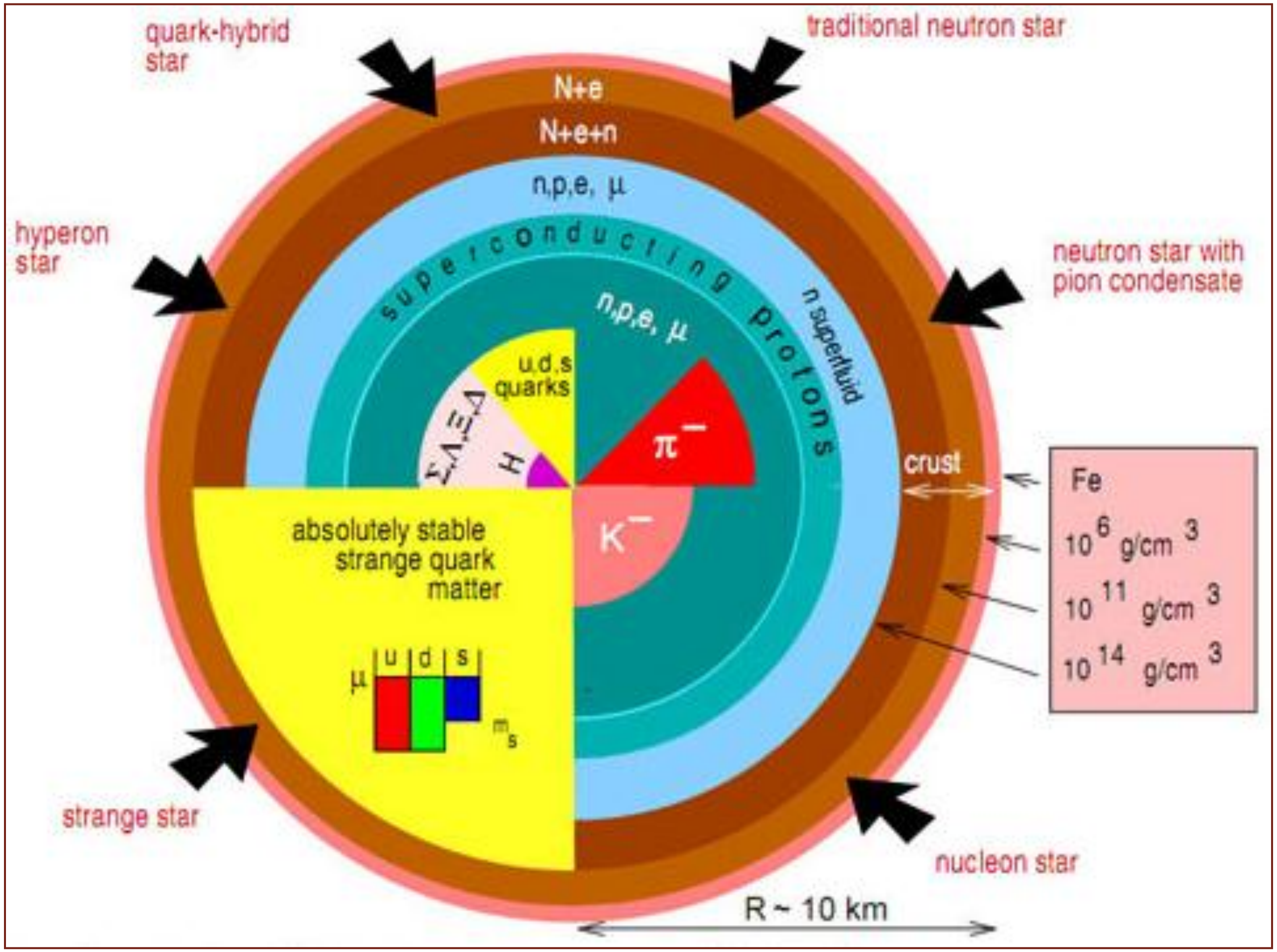
$$\frac{dYe}{dt} = -\gamma_{\rm e-cap} + \gamma_{\rm e+cap}$$
$$\frac{dY\nu_e}{dt} = \gamma_{\rm e-cap} + \gamma_{\rm pair} + \gamma_{\rm plasmon} + \gamma_{\rm Brems} - \gamma_{\nu_e \rm leak}$$
$$\frac{dY\bar{\nu}_e}{dt} = \gamma_{\rm e+cap} + \gamma_{\rm pair} + \gamma_{\rm plasmon} + \gamma_{\rm Brems} - \gamma_{\bar{\nu}_e \rm leak}$$
$$\frac{dY\nu_x}{dt} = \gamma_{\rm pair} + \gamma_{\rm plasmon} + \gamma_{\rm Brems} - \gamma_{\nu_x \rm leak}$$

# 連星中性子星合体： PRL 表紙に



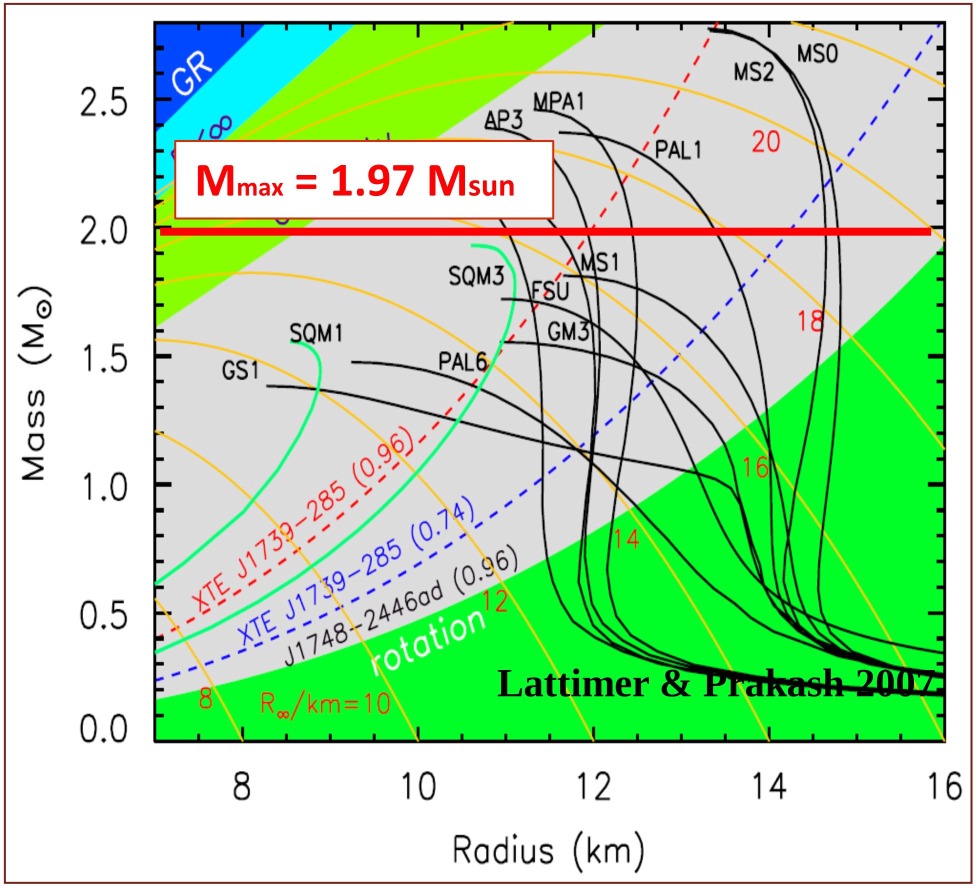
# 連星中性子星合体： Motivation

- Properties of dense matter : Still poorly understood
- There may be *exotic* phases at high densities (Pauli principle)
  - Meson cond., Quarks, **Hyperons**, …
- How to constrain state (EOS) of NS matter



# 連星中性子星合体： Motivation

- Popular method
  - Mass-Radius relation
  - Maximum mass of NS
    - Strong impact by PSR J1614-2230
    - Too soft EOS are ruled out
- However, existence of exotic phases remains unconstrained
  - Lattimer & Prakash 2011
  - Bednarek+ 2011
  - Weissenborn+ 2011




$$M_{\max}(f_S) = M_{\max}(0) - 6 f_S \quad \text{in solar mass unit}$$

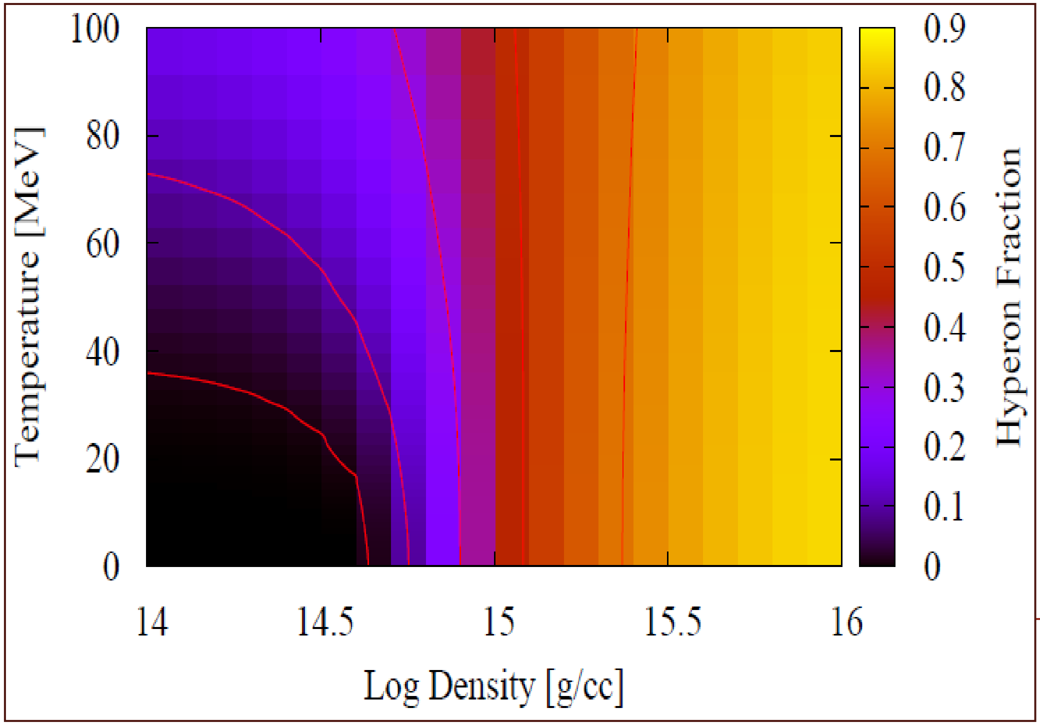
$$f_S(M_{\max}) < 0.17 \quad \text{for } M_{\max} > 2M_{\text{solar}} \quad (f_S : \#\text{of strange quark / baryon})$$

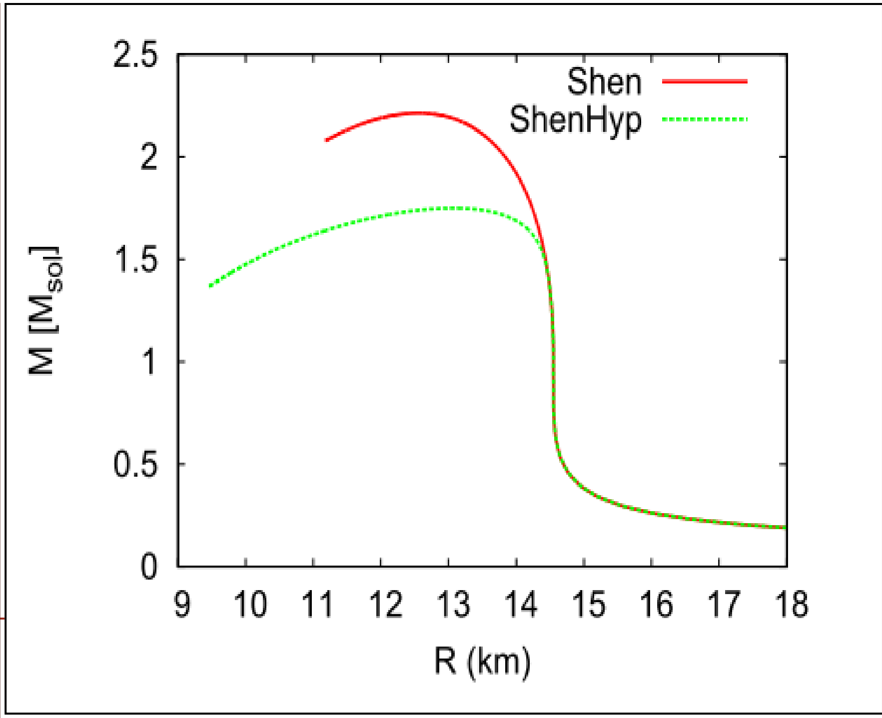
# Equation of State (EOS)

- **Key Question:**
  - **Is it possible to tell the existence of hyperons by observations of Neutrino and Gravitational-Wave (GW) signals ?**
- **S-EOS**: ‘normal’ nucleonic matter EOS
  - Shen, Toki, Oyamatsu, Sumiyoshi, NPA **637**, 435 (2011)
- **H-EOS**: EOS with Λ hyperons
  - Shen, Toki, Oyamatsu, Sumiyoshi, ApJ **197**, 20 (2011)
- We only consider contribution of **Λ hyperons** because
  - **Λ hyperons** are believed to appear first because they are lightest and feel an ***attractive potential*** (e.g. Ishizuka et al. 2008)
  - **Σ hyperons** have comparable mass but feel a ***repulsive potential*** , and will not appear at lower densities (Noumi et al. 2002)

# Equation of State (EOS)

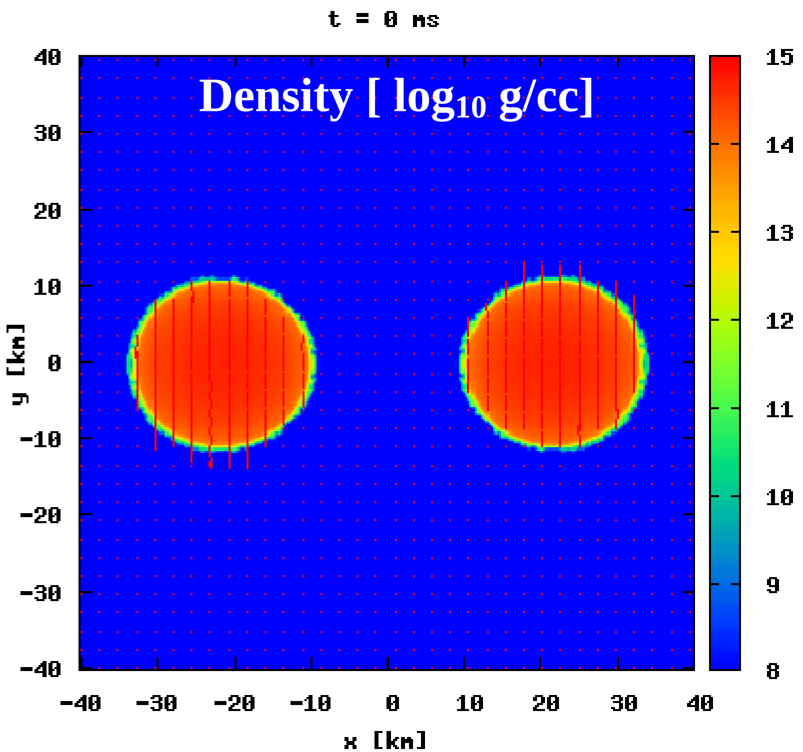
- At T = 0, Λ hyperons appear at ρ ~ a few $\rho_{nuc}$, and $X_\Lambda$ increases as density and **temperature** increase
- Due to the appearance of Λ hyperons, EOS becomes softer and the maximum mass of the cold spherical NS is decreased to be $M_{max,sph.cold.NS}$ ~ 1.8 $M_{solar}$

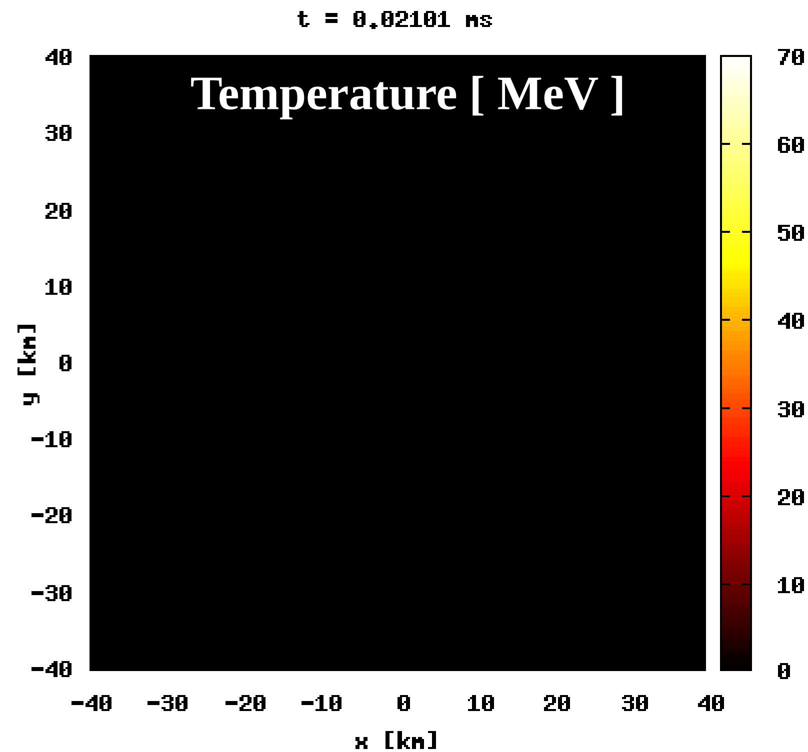


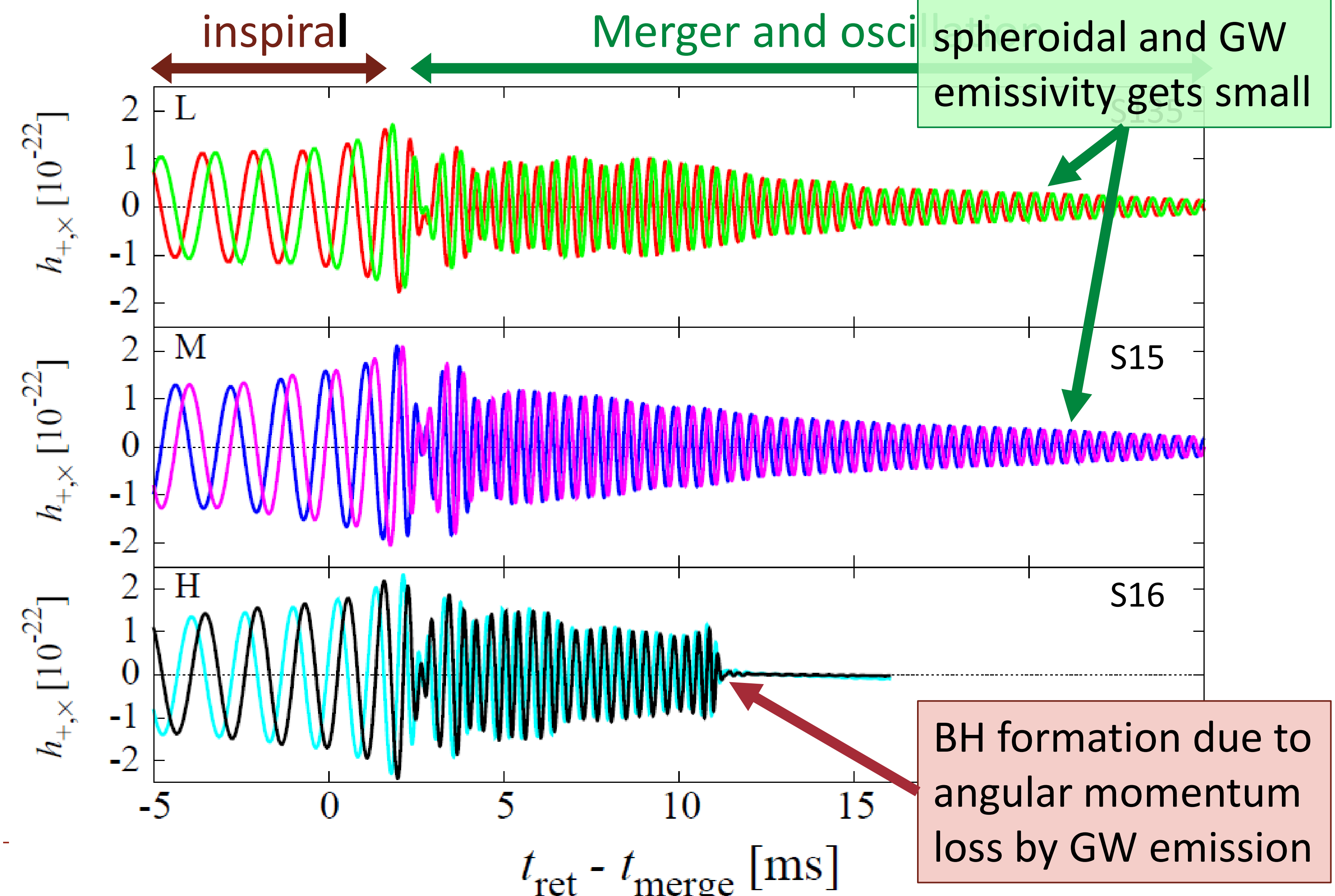
# Merger Dynamics (H135) **Hyperonic**

- Hyper massive NS (HMNS) first forms and eventually collapses to BH
  - As HMSN shrinks, density and temperature increase and consequently more hyperons appear, making EOS more softer
- After the BH formation, a massive accretion disk (~0.08 Msolar) is formed ⇒ short GRBs ?



# Gravitational Waveforms: **Nucleonic**

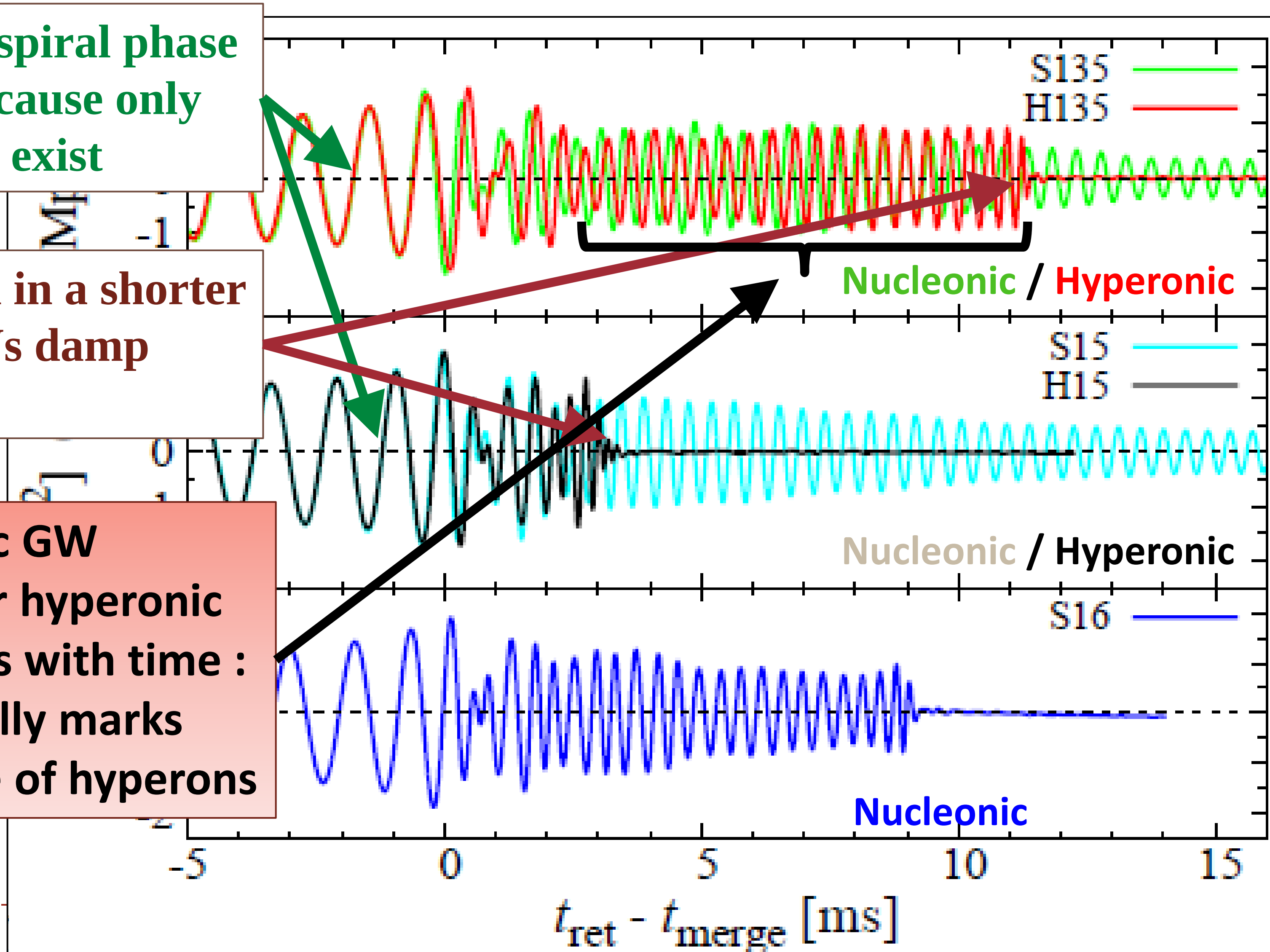


# Gravitational Waveforms : Hyperonic

GWs from inspiral phase agree well because only few hyperons exist

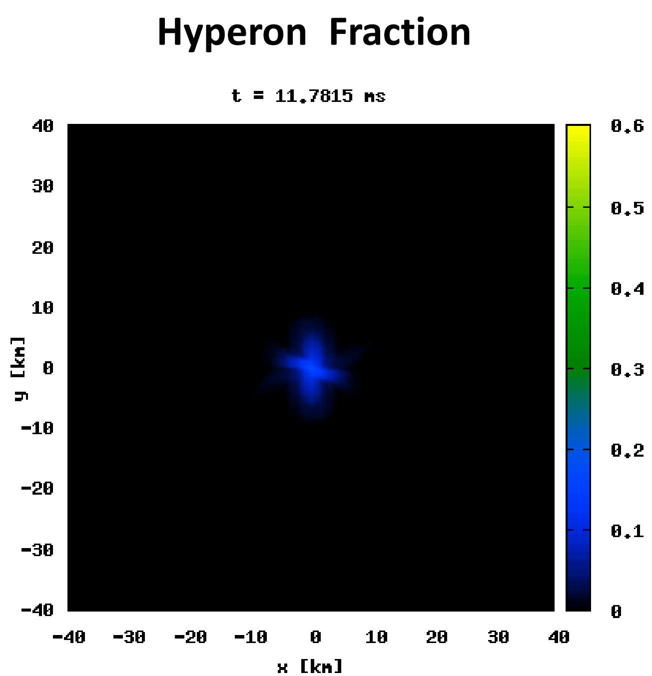
BH is formed in a shorter time and GWs damp steeply there

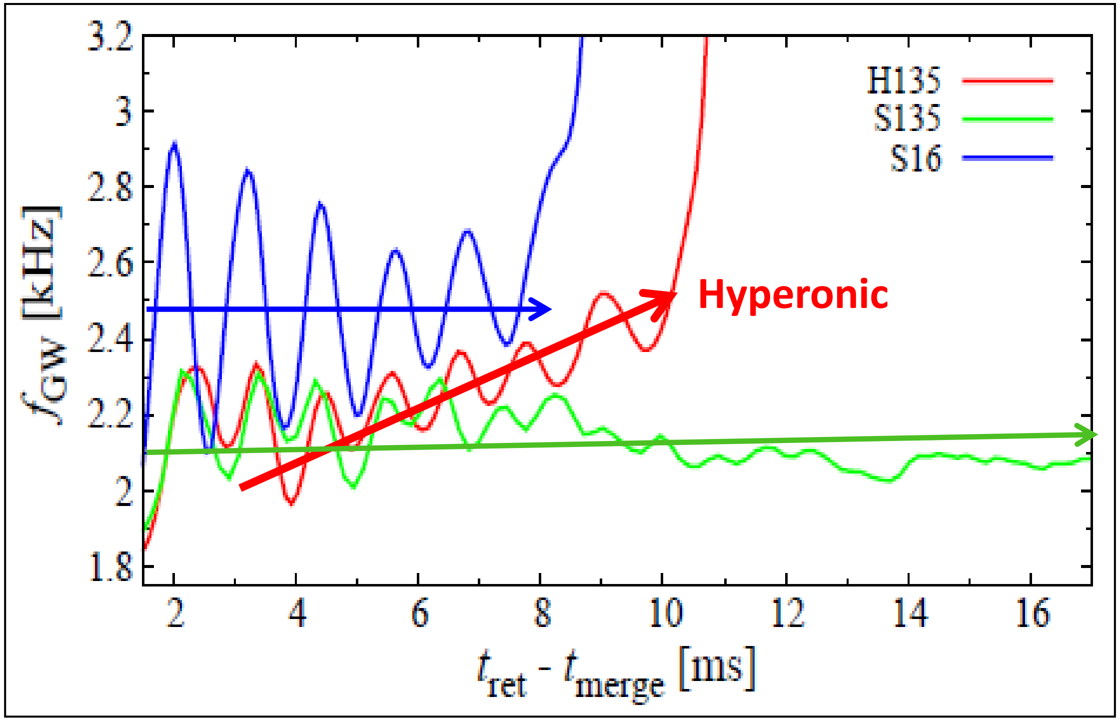
Characteristic GW frequency for hyperonic EOS increases with time : This potentially marks the existence of hyperons



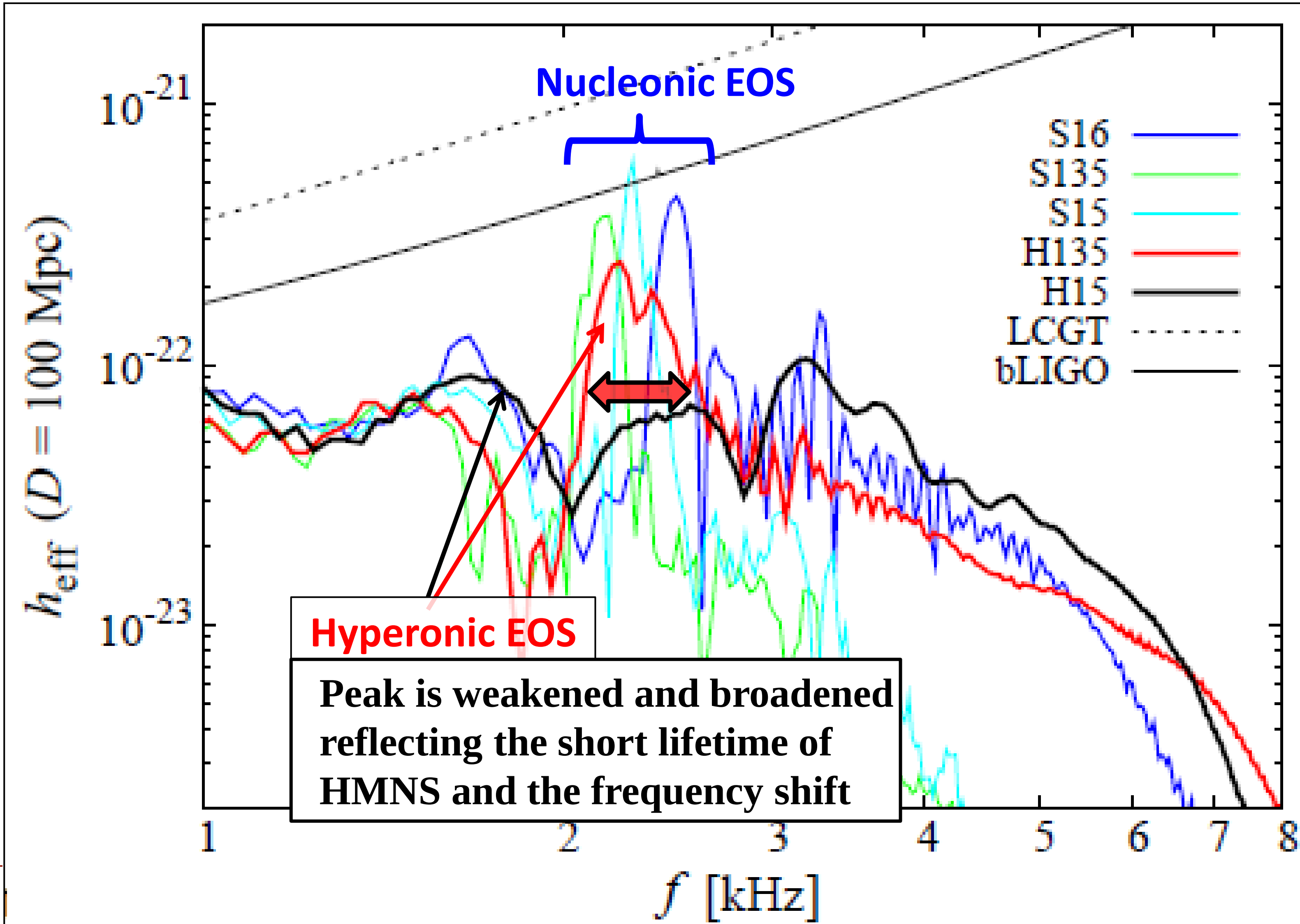
# Frequency Shift due to Hyperon

- Dynamics of HMNS formed after the merger
  - **Nucleonic** : HMNS shrinks by angular momentum loss in a long GW timescale
  - **Hyperonic** : GW emission ⇒ HMNS shrinks ⇒ More Hyperons appear ⇒ EOS becomes softer ⇒ HMNS shrinks more ⇒ ....
  - **As a result, the characteristic frequency of GW increases with time**
    - Providing potential way to tell existence of hyperons (exotic particles)



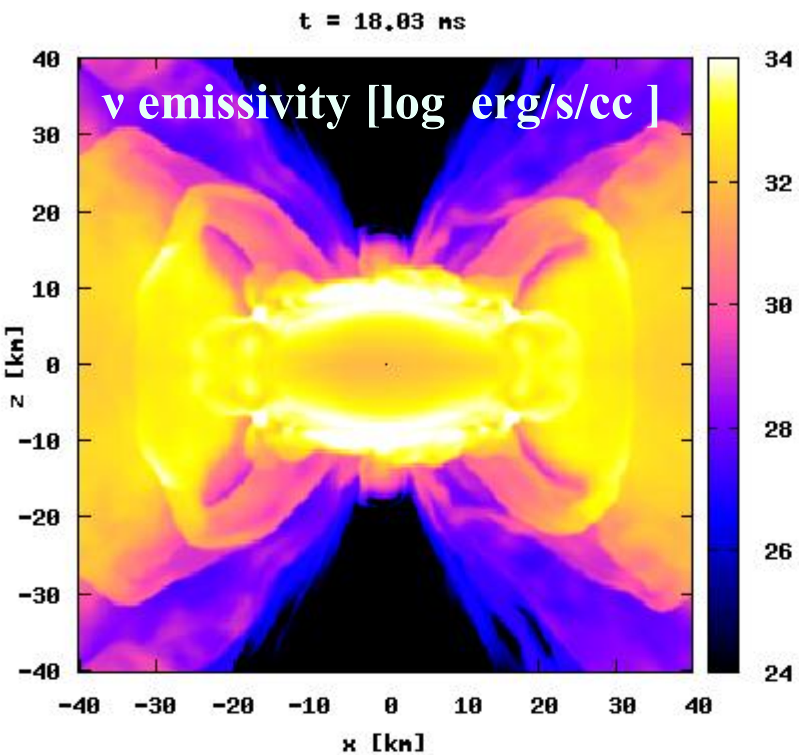



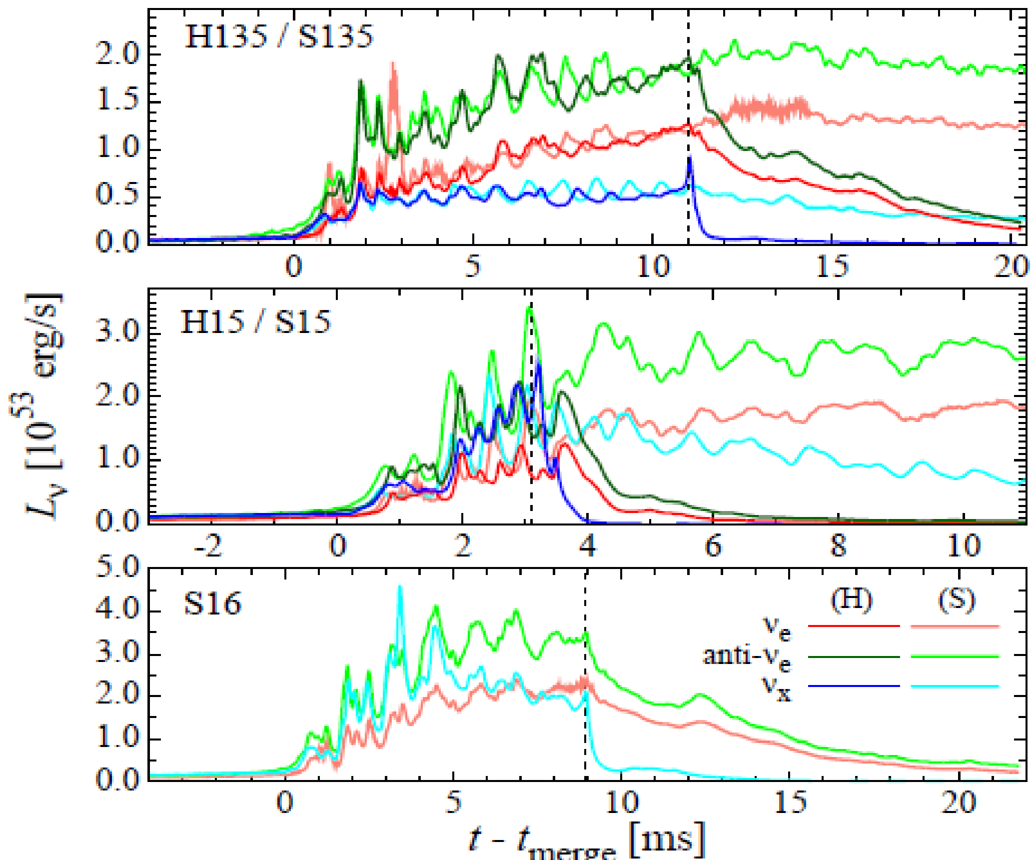
# Gravitational Wave Spectra



# Neutrino Luminosity

- There is no difference except for the duration until the BH formation
  - **Effects of hyperons are significant in the central region where neutrino diffusion time is very long, and swallowed into BH**
- Difficult to tell the existence of hyperons using the neutrino signals alone



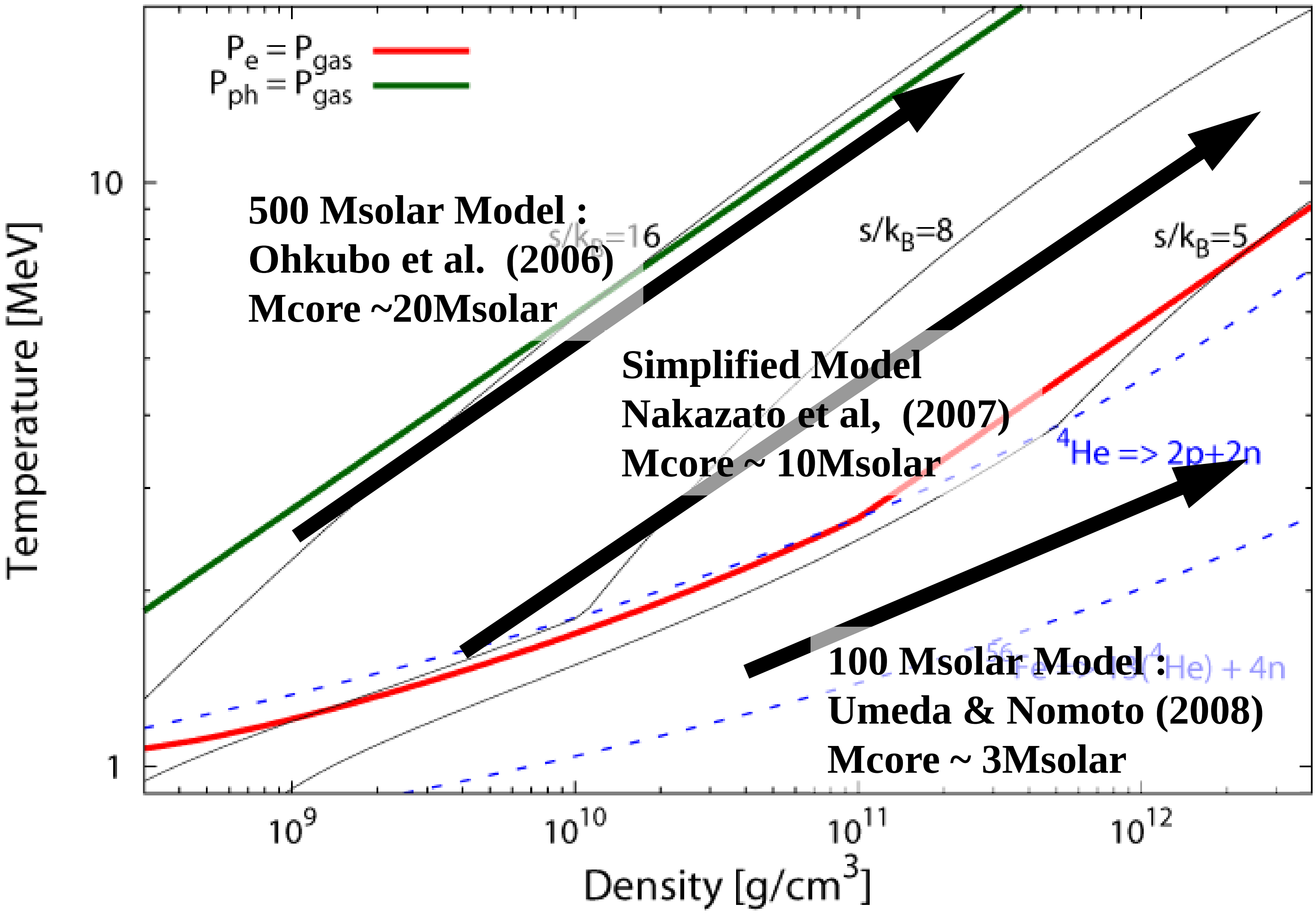
# 大質量星の重力崩壊（**BH形成**）：
# Previous full GR numerical studies

- 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, Sekiguchi & Shibata in prep.**

  **BH形成後の時空を長時間追跡**
- 3次元 **w.o. microphyics**
  - Ott et al. 2011　　　　BH 形成後の時空を多少追跡

# Three Initial Models

- **Rotational Profiles are added by hand**



# Comments on progenitor model of GRB

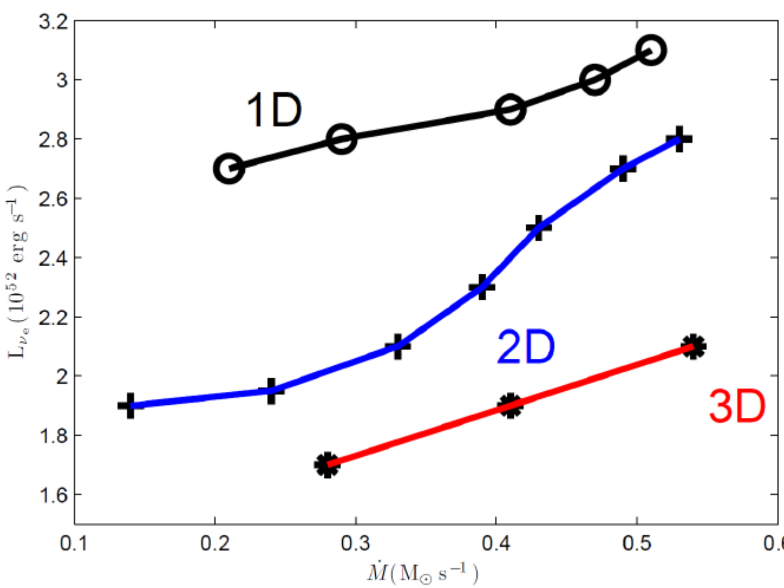
- 中心動力源：ブラックホール＋ディスク
  - 高速回転する親星コアが必要
  - ⇔ Type-Ic SN の付随: H, He を失うに伴いに回転が遅くなる
- 要：角運動量を保持しつつ外層をなくす特殊な親星モデル
  - He星合体モデル (Fryer & Heger 2005)
  - Tidal spin up モデル (van den Huevel & Yoon 2007)
  - Chemically homogeneous evolution (Woosley & Heger 2006, Yoon et al. 2006)
  - いずれのモデルも親星コアでの強いmixing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

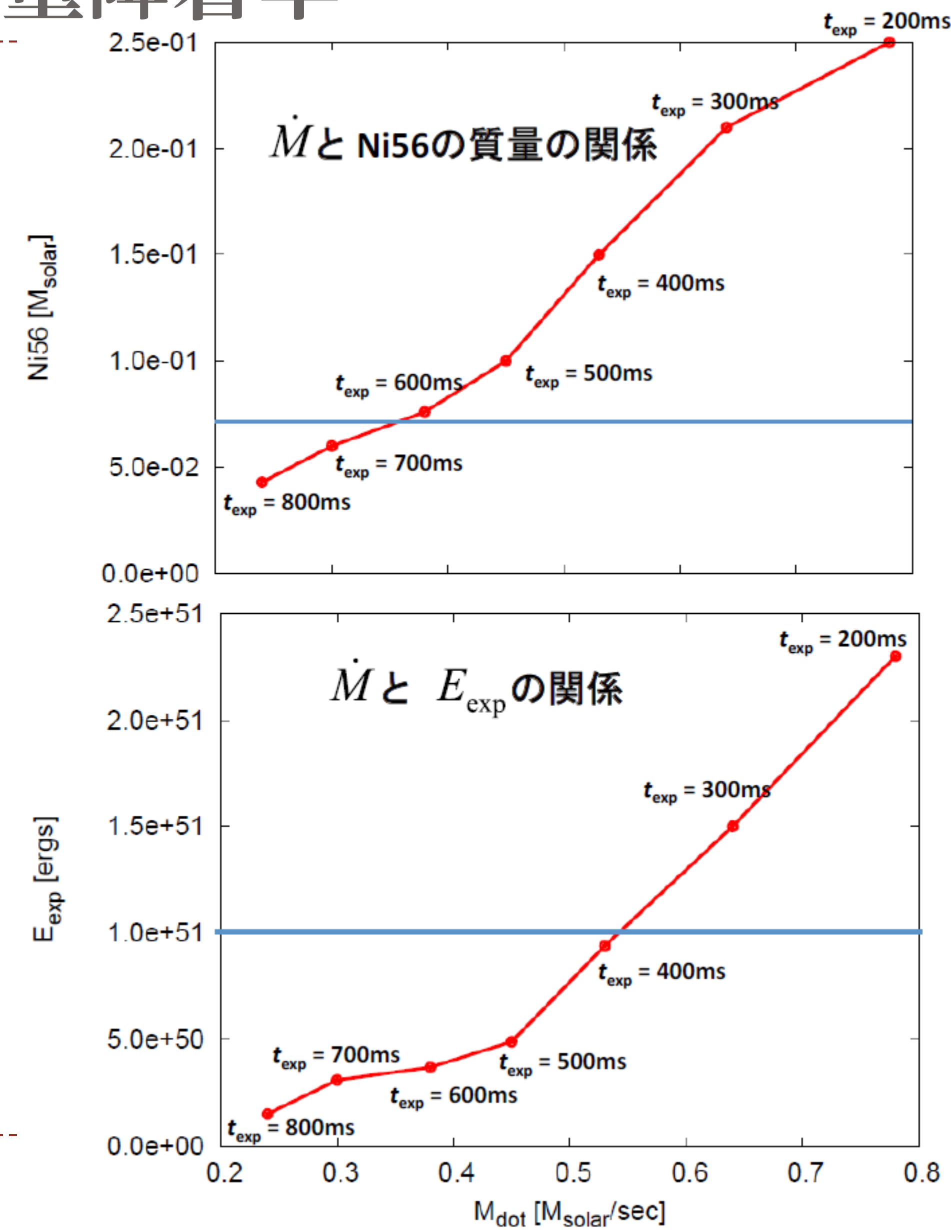
# 高速回転・高エントロピーコアの重力崩壊

- 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 0.1$M_{solar}$ 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？（by 山田さん）
- 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

# 高エントロピー・高質量降着率

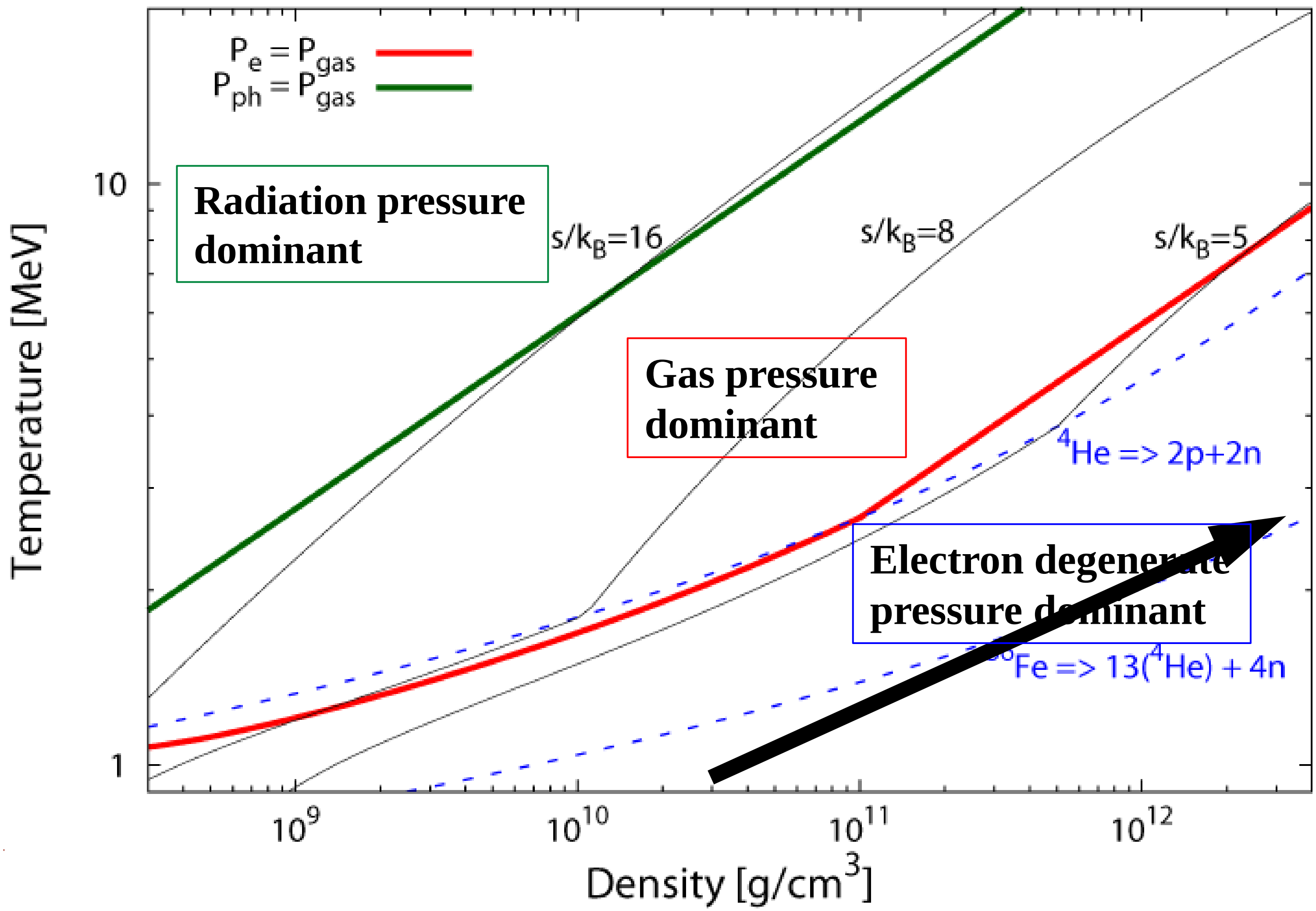
- 高質量降着率下での爆発
  - 高いニュートリノ光度
  - 大きな爆発エネルギー
  - 多量のNi56
  - Yamada-san's talk @ 超新星爆発と数値シミュレーション



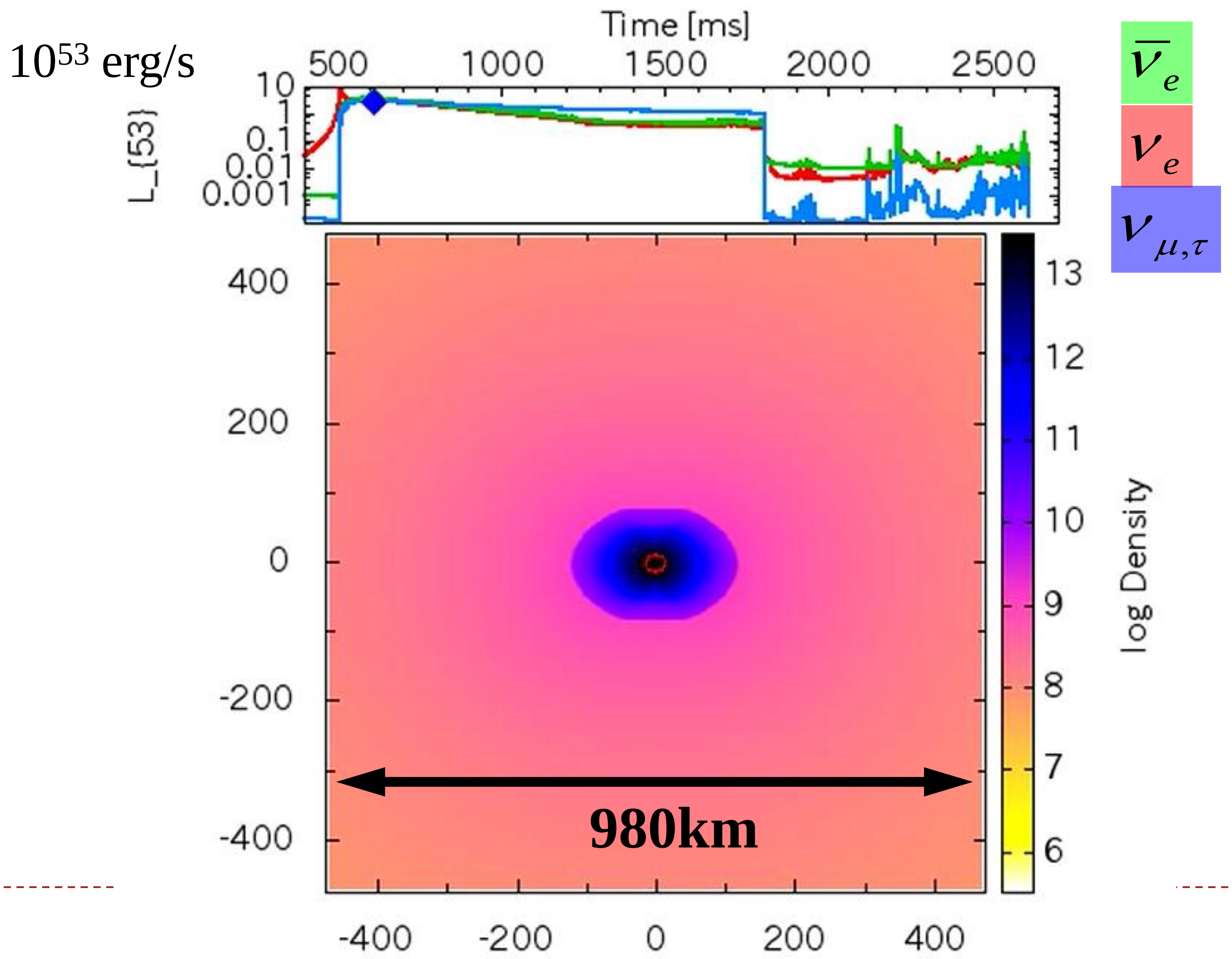
# Collapse of 100Msolar presupernova model

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



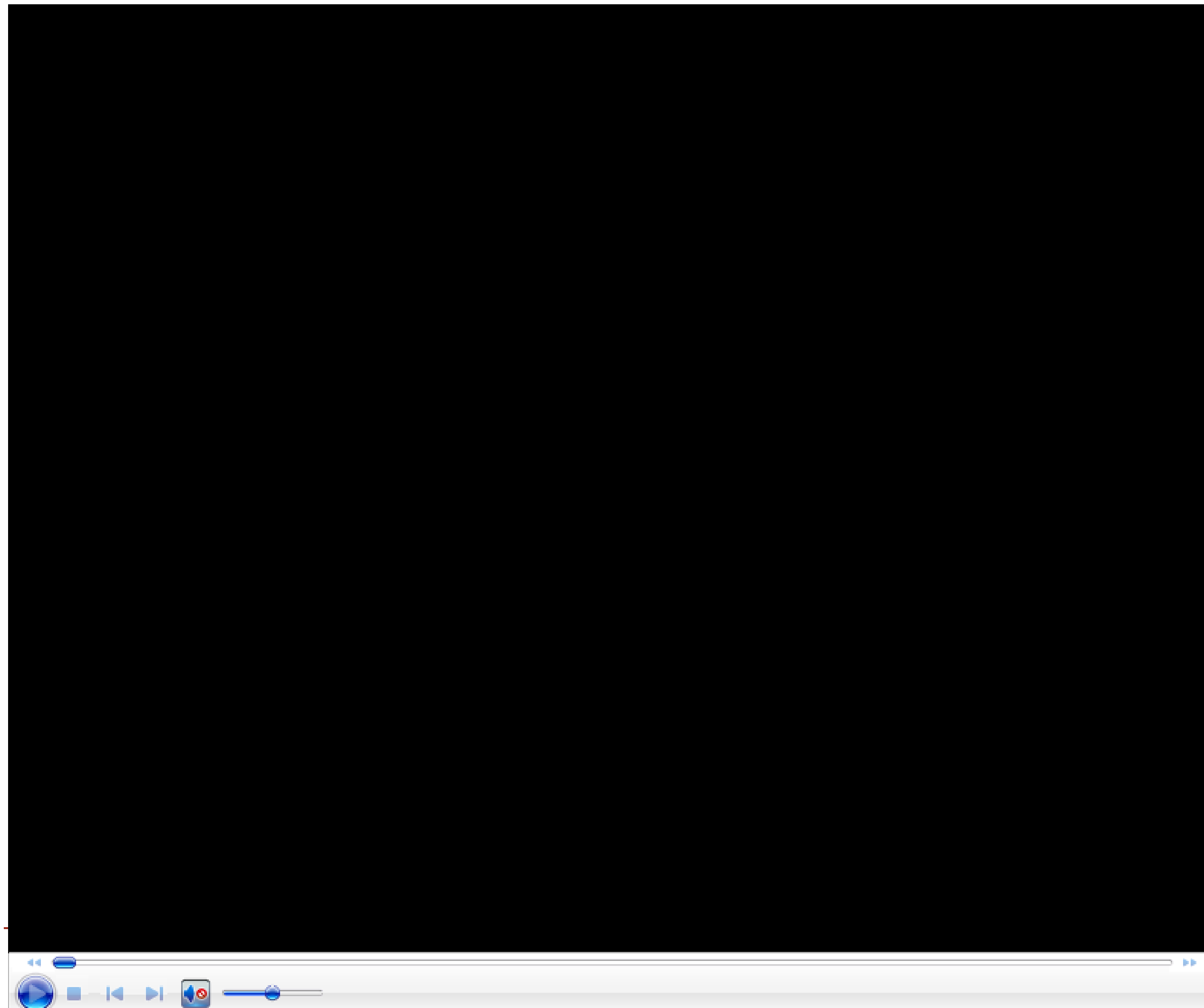
# Collapse of 100Msolar presupernova model (計算時間：1秒/a few month)

- **'Rapidly'** rotating model ($\Omega_c$=1.2 rad/s, $\Omega_{Fe}$=1.2 rad/s)



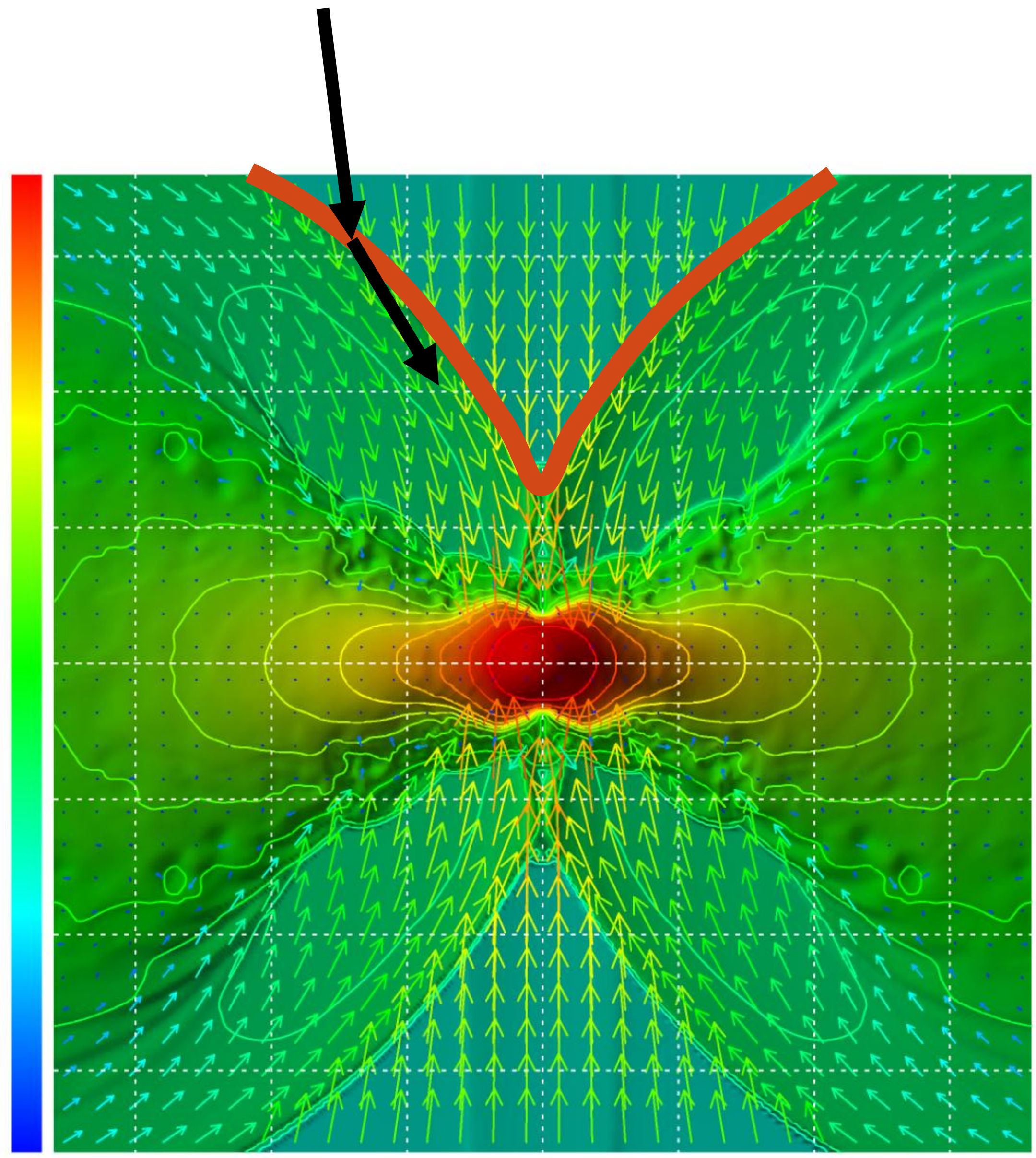
# Collapse of 100Msolar presupernova model

- **'Rapidly'** rotating model ($\Omega_c$=1.2 rad/s, $\Omega_{Fe}$=1.2 rad/s)



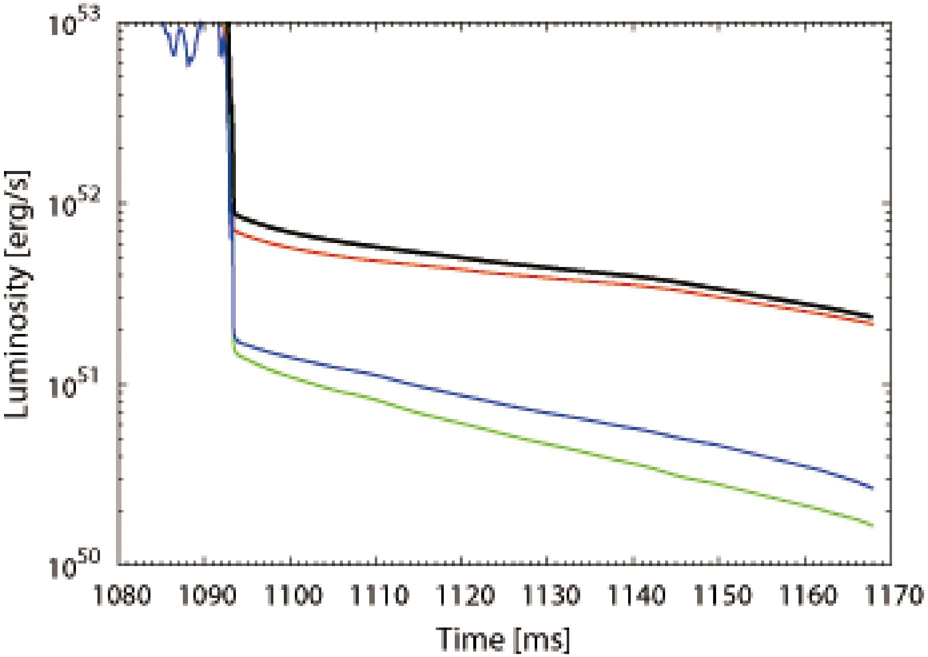
# Oblique Shock

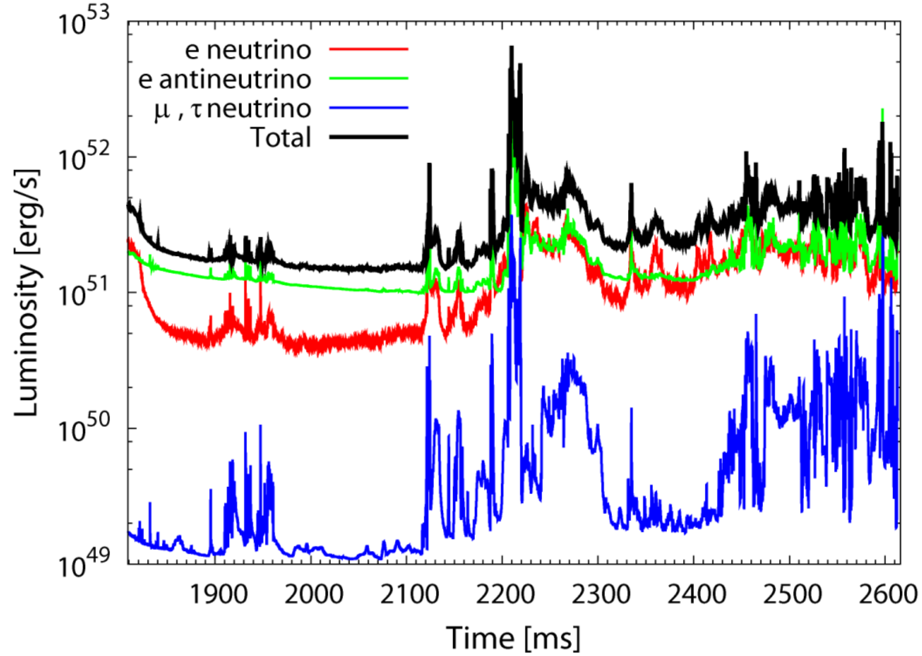
- **Rapid rotation:**
- Torus-structured shock
- Infalling materials are accumulated into the PNS due to the **oblique shock**
- Thermal energy is efficiently stored near the pole of PNS
- Ram pressure is decreasing
- ⇒Outflow



# Neutrino Luminosity (BH Phase)

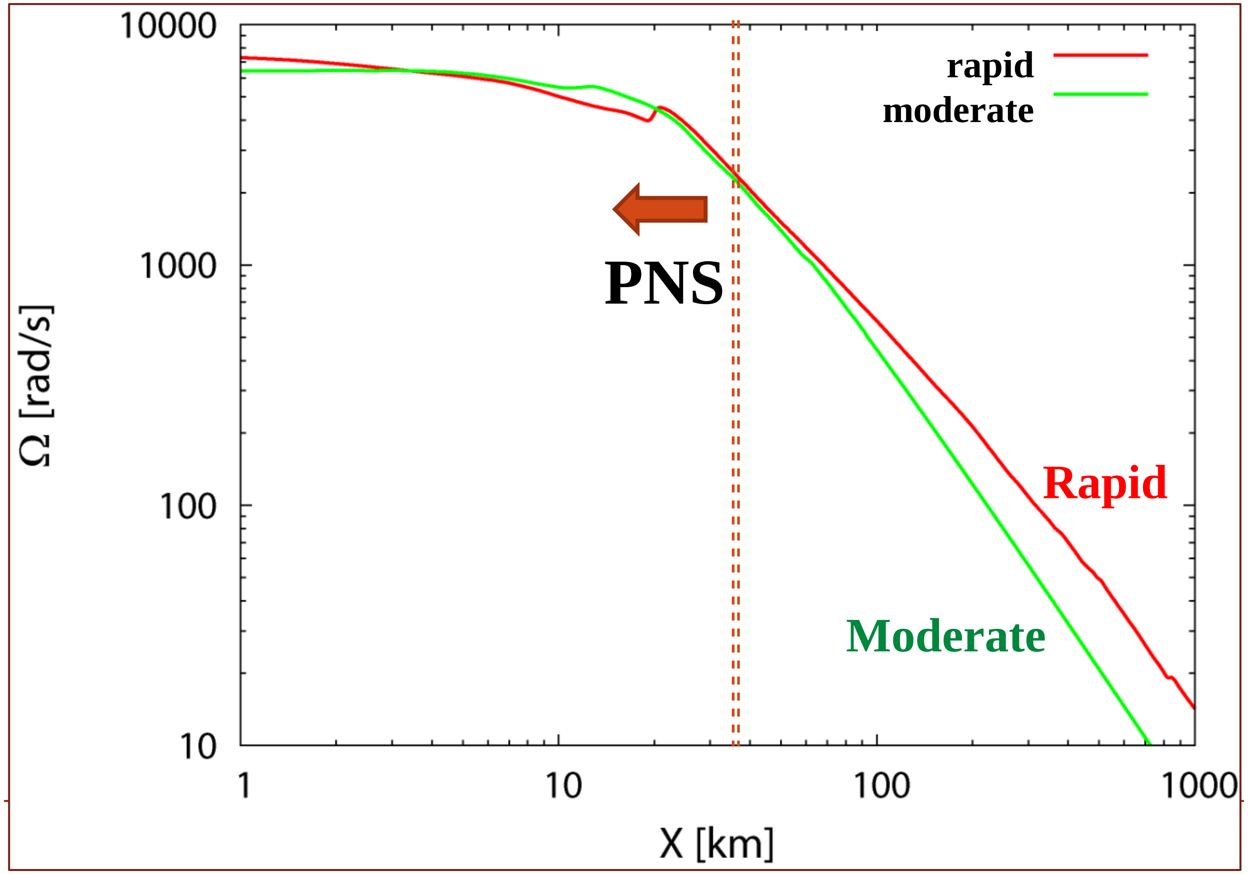
- **Moderate rotation**
  - $L_{tot} \sim 10^{51\text{-}52}$ erg/s
  - No time variability
- **Rapid rotation**
  - $L_{tot} \sim 10^{51\text{-}52}$ erg/s
  - **Violent time variability**
  - Preferable feature for GRB



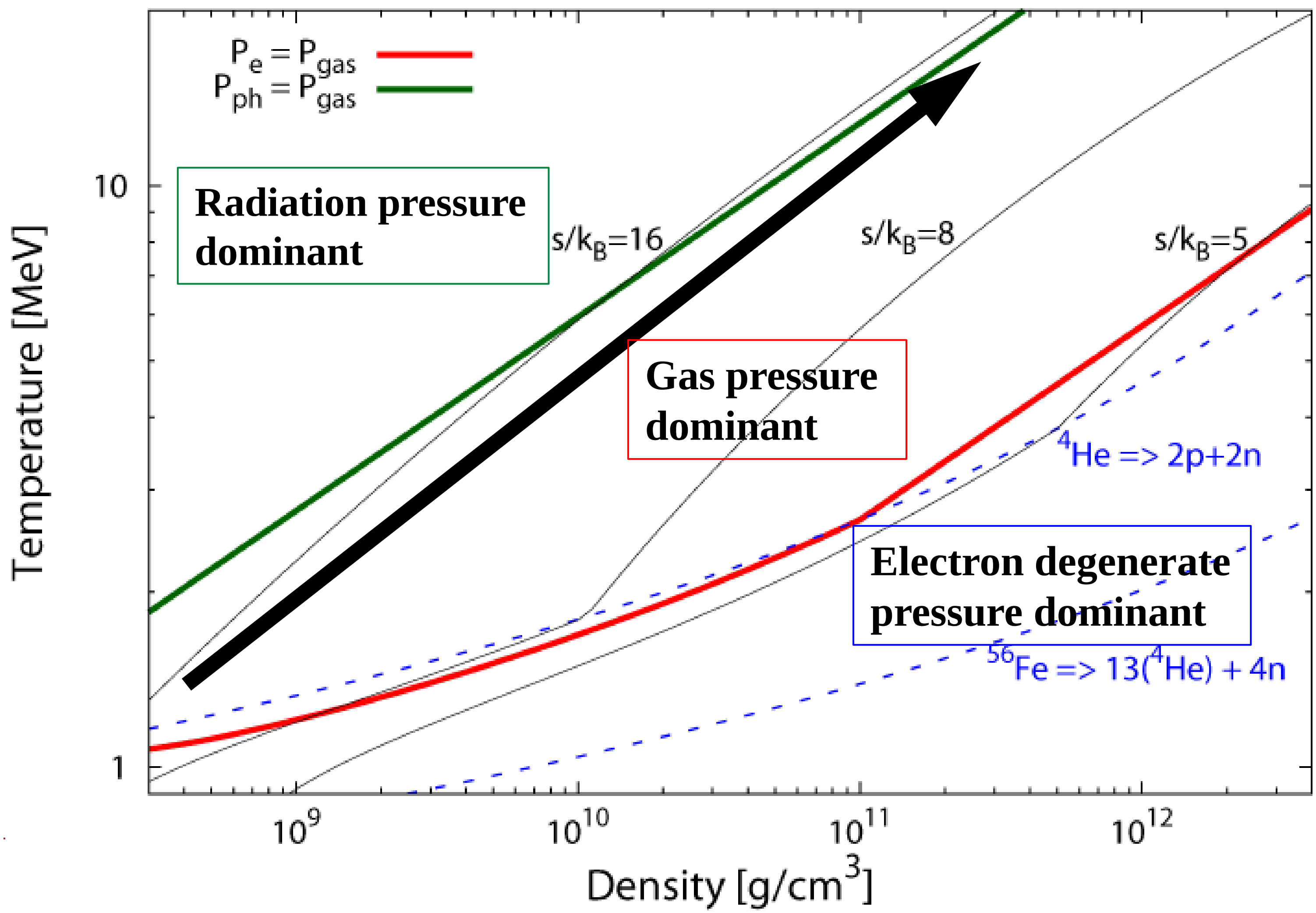
# Rotational Profile of PNS

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



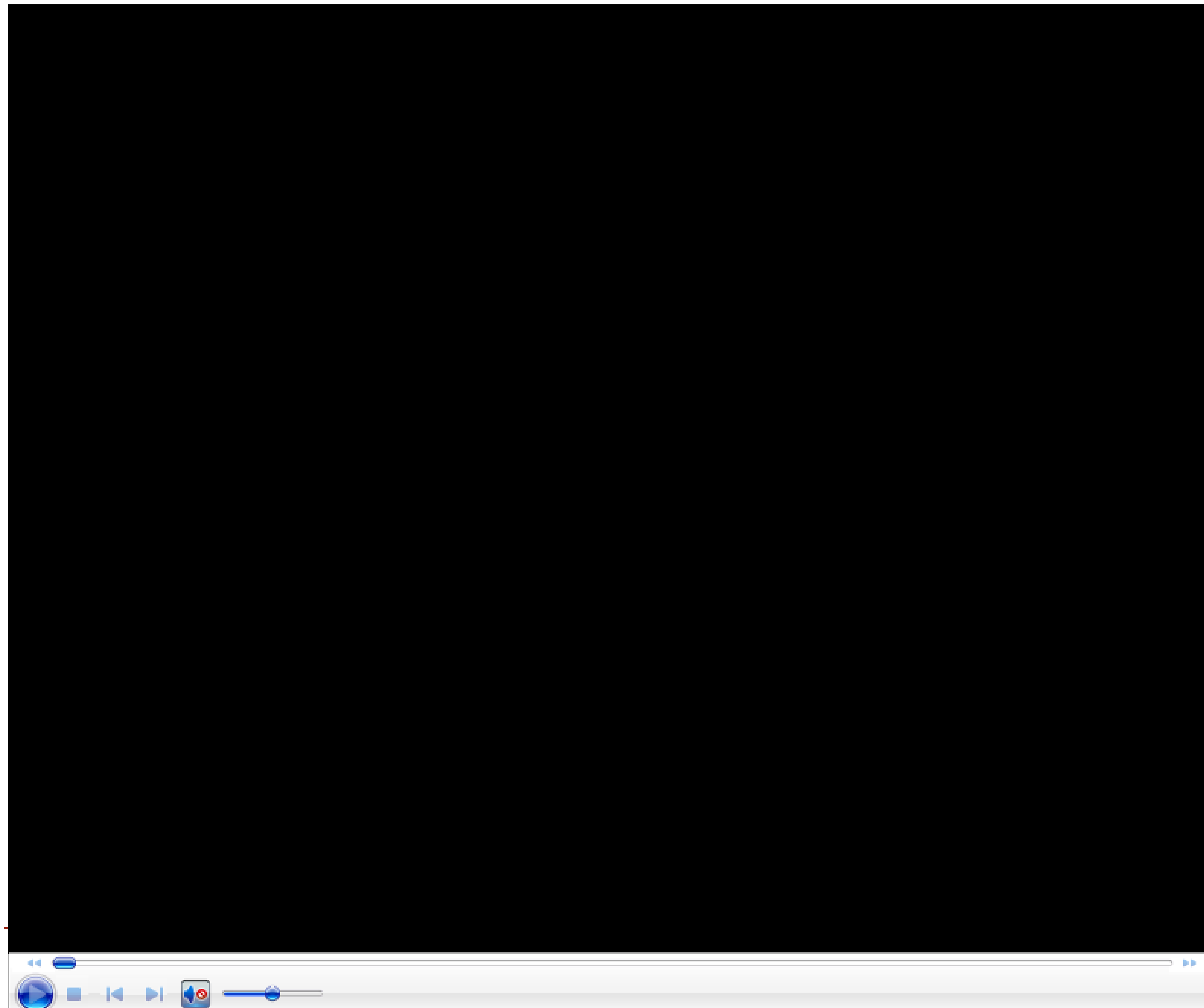
# Collapse of 500$M_{solar}$ PopIII stellar core

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

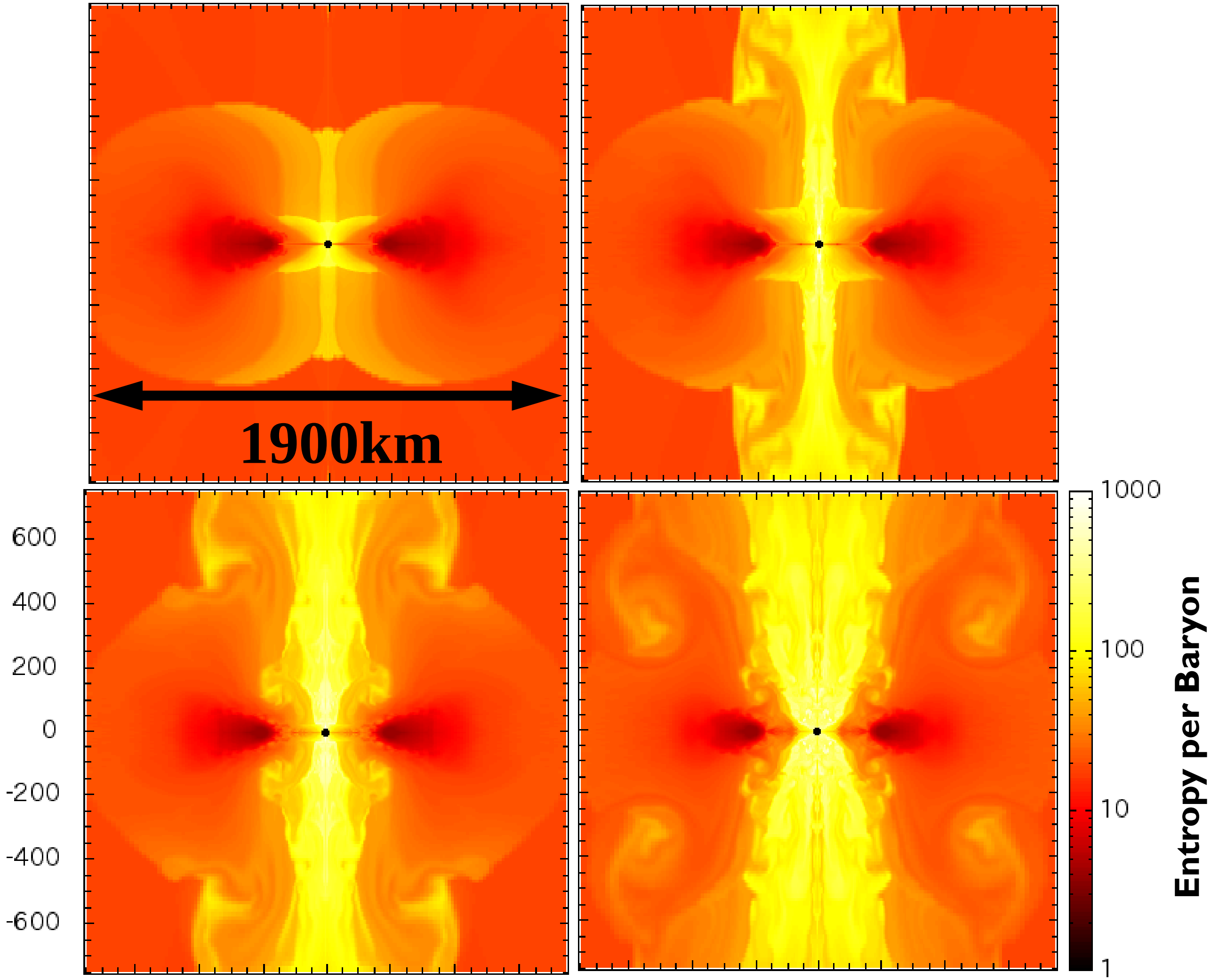


# Collapse of $500M_{solar}$ PopIII stellar core

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



# Outflow appears even when BH is formed



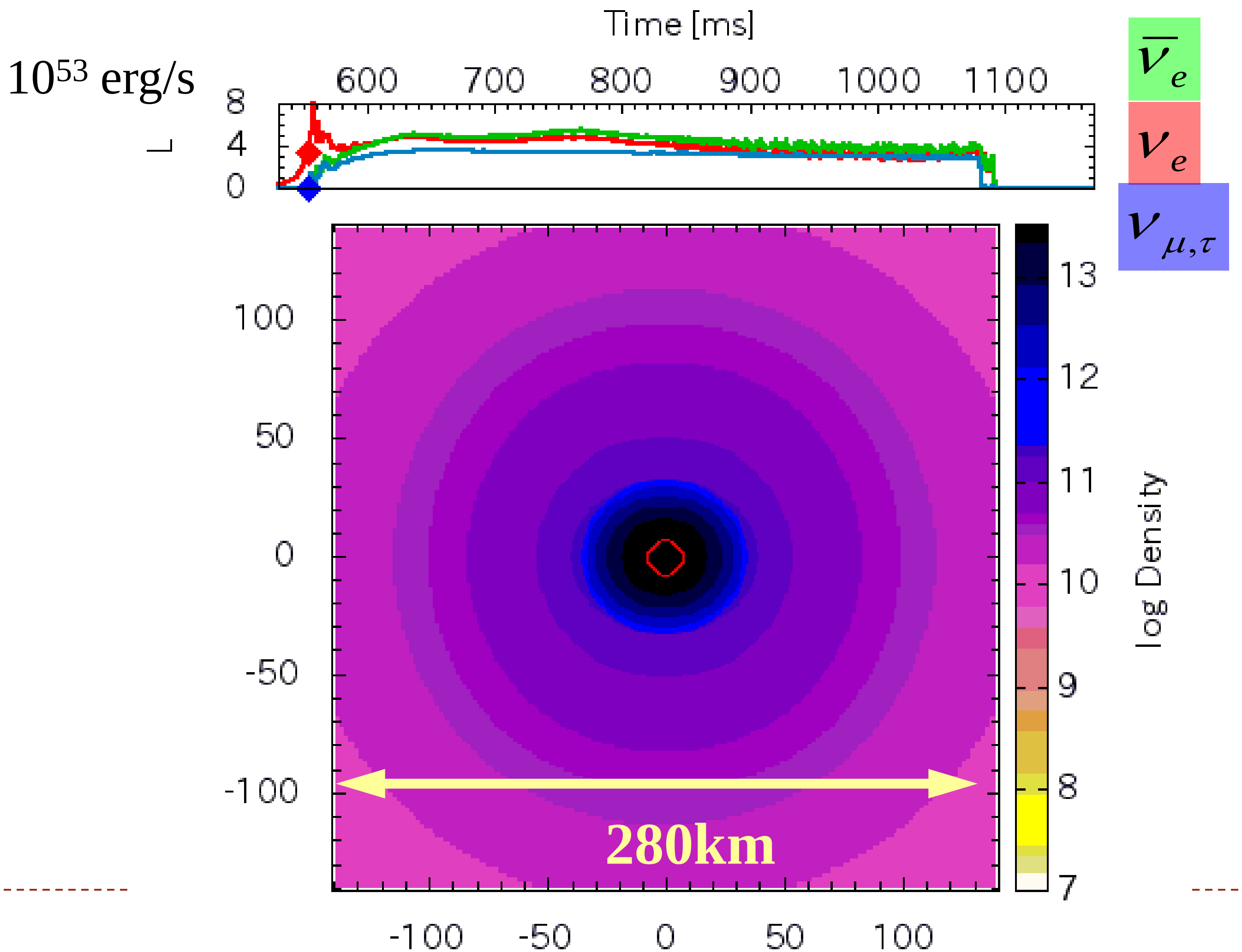

- Infalling materials are accumulated into the central region due to the oblique shock
- At a later phase BH is surrounded by shock waves
- Advection of energy into BH becomes less efficient
- Thermal energy is stored
- Outflow

# 今後の展望

- GR-Radiation-Hydrodynamics (with Fixed-Mesh-Refinement) へ
  - 定式化：Shibata et al. 2011
  - BH -Disk の GR-Rad-MHD (simplified) : (Shibata & Sekiguchi 2012)
  - Detailed microphysics ver. (Sekiguchi et al. in preparation)
- Compact Binary Merger
  - Detection Possibility of GW frequency shift (with 田越さん)
  - Quark-Hadron Phase Transition
  - r-processes (with 和南城さん)
- (3D) Collapse Simulation
  - $\nu$-対消滅率の3D-full Boltzmann 計算 ⇒ 近似的処方箋 (住吉さん)
  - BH 周りDisk の Papaloizou-Pringle不安定性 (Kiuchi et al. 2011)
  - Torus-Shaped shock の SASI は起こるか？
- MHD Simulation
  - Convection と MHD processes (e.g. MRI) の関係
    - 競合する可能性も (c.f. CDAF) / そうではないという説も
  - GR-Rad/$\nu$-MHD

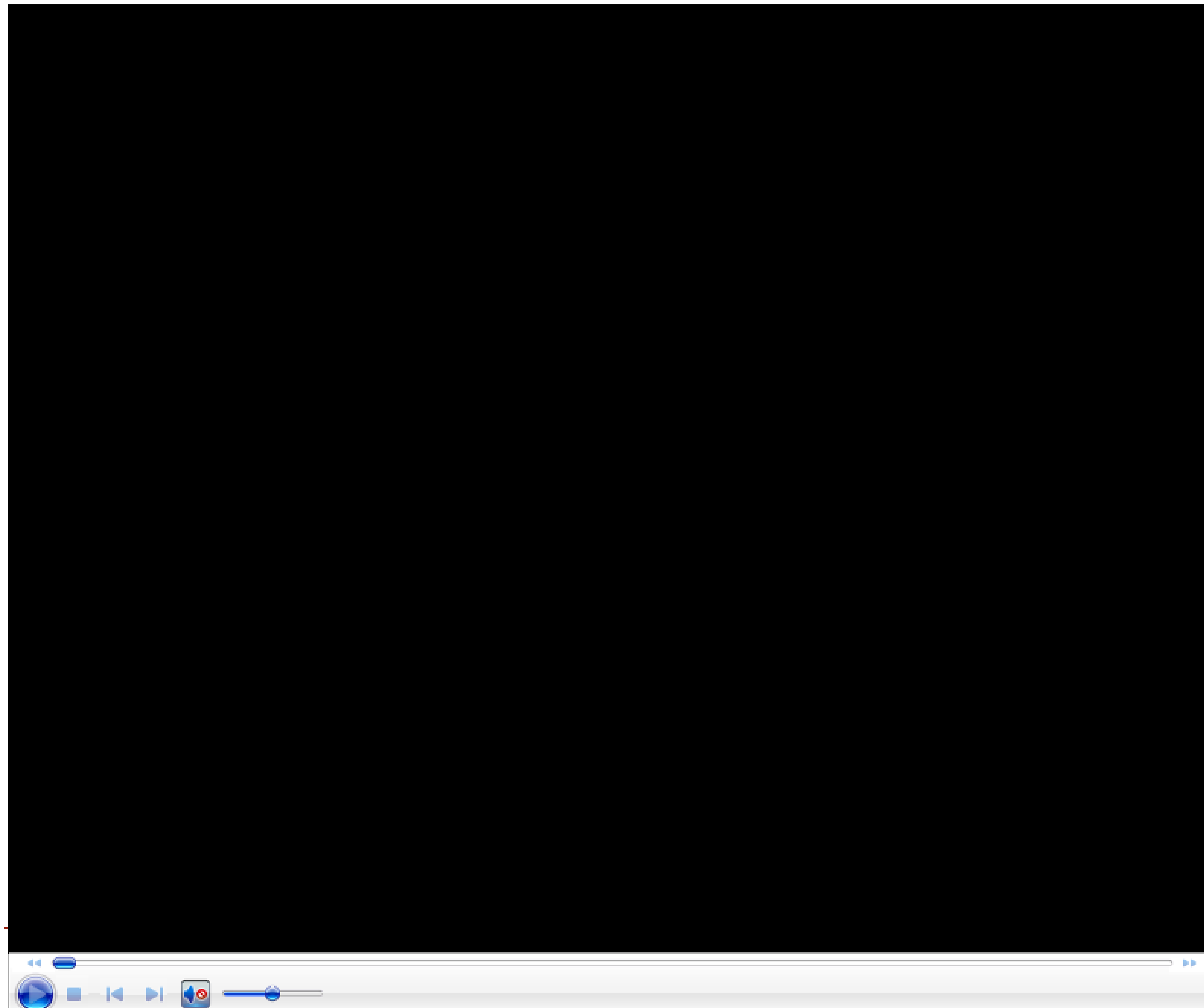
# Collapse of 100Msolar presupernova model

- **'Moderately'** rotating model ($\Omega_c$=1.2 rad/s, $\Omega_{Fe}$=0.6 rad/s)



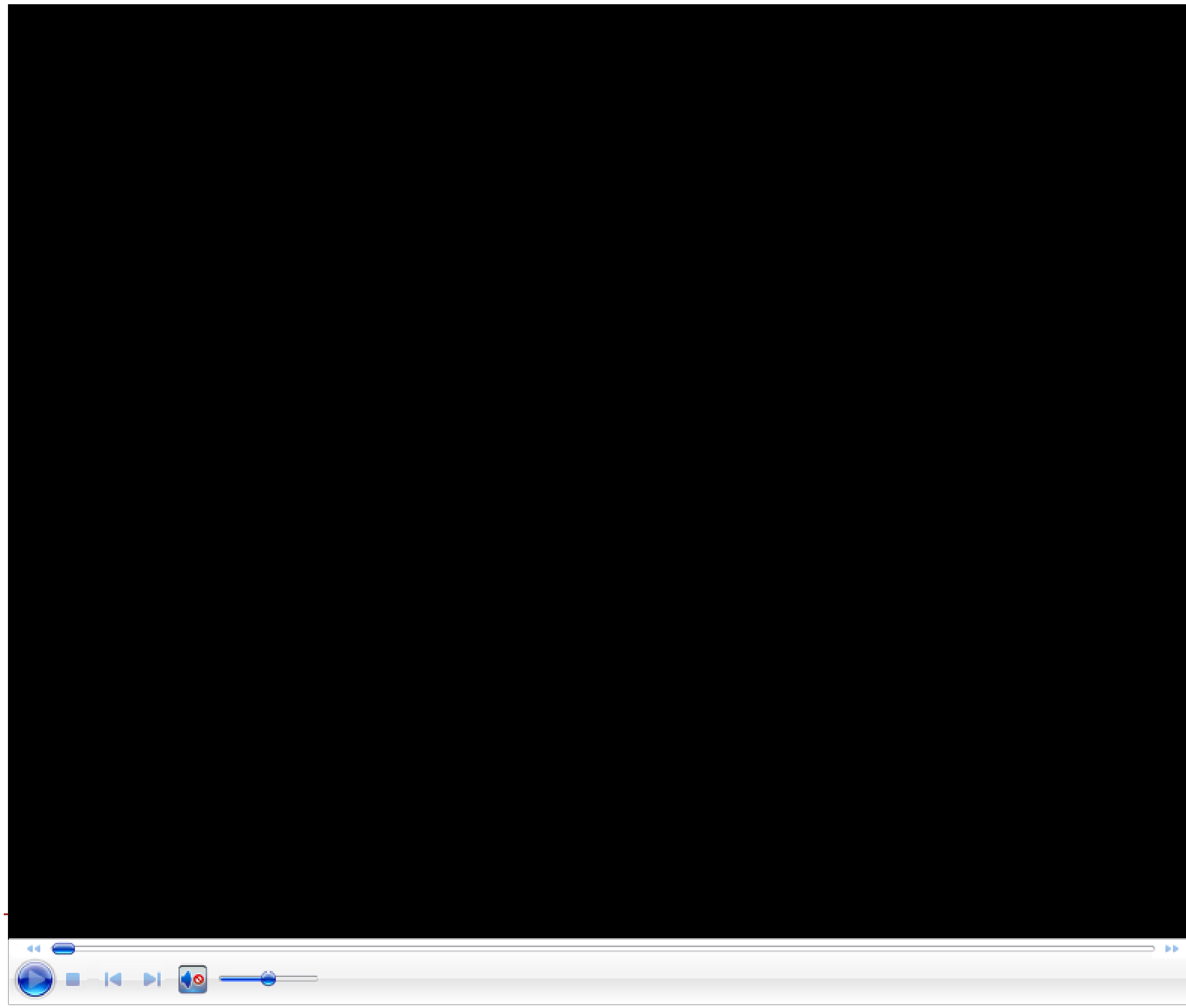
# Collapse of 100Msolar presupernova model

- **'Moderately'** rotating model ($\Omega_c$=1.2 rad/s, $\Omega_{Fe}$=0.6 rad/s)



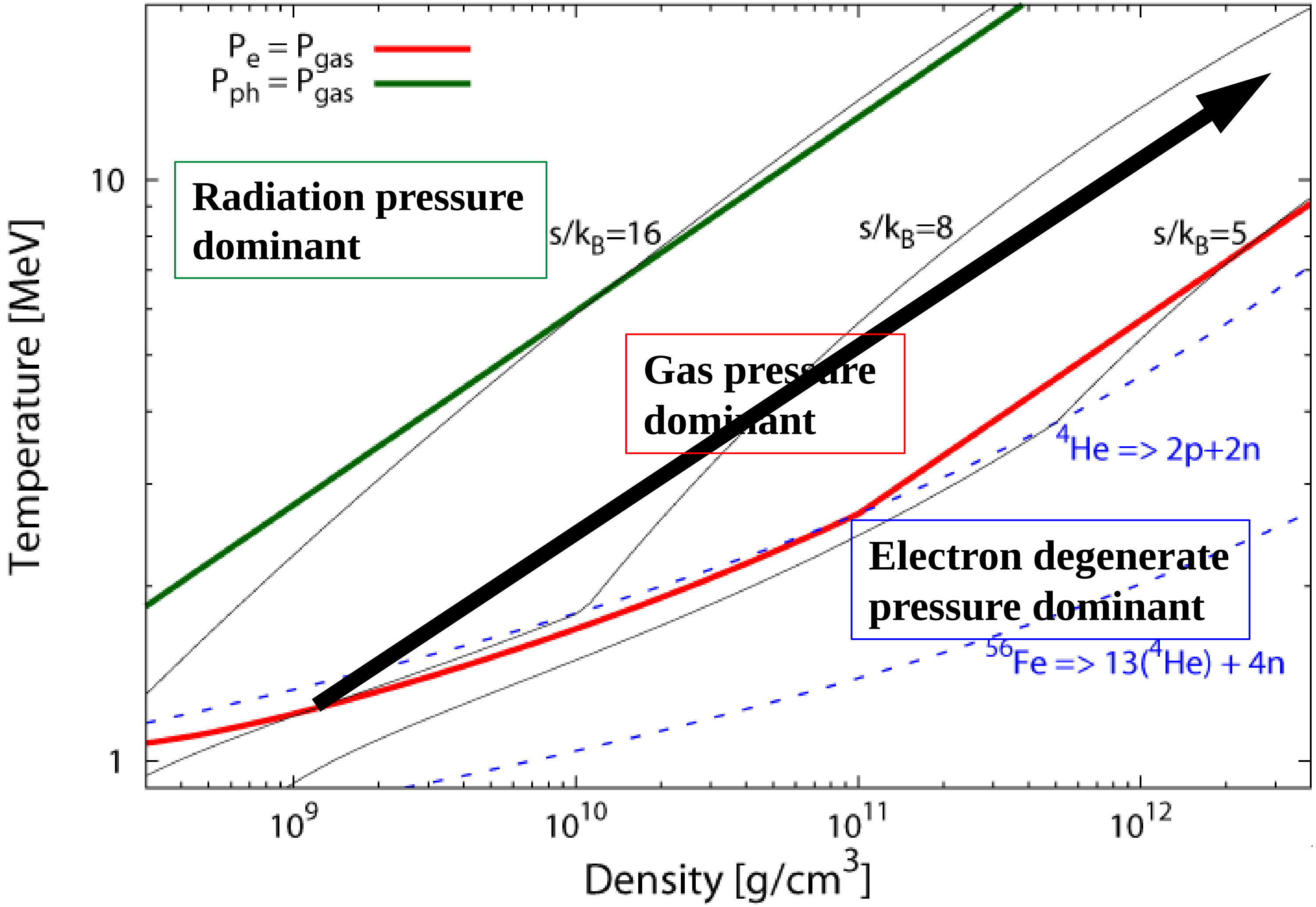
# Collapse of $500M_{solar}$ PopIII stellar core

- **Slowly rotating model** ($\Omega_c$=**0.3** rad/s)



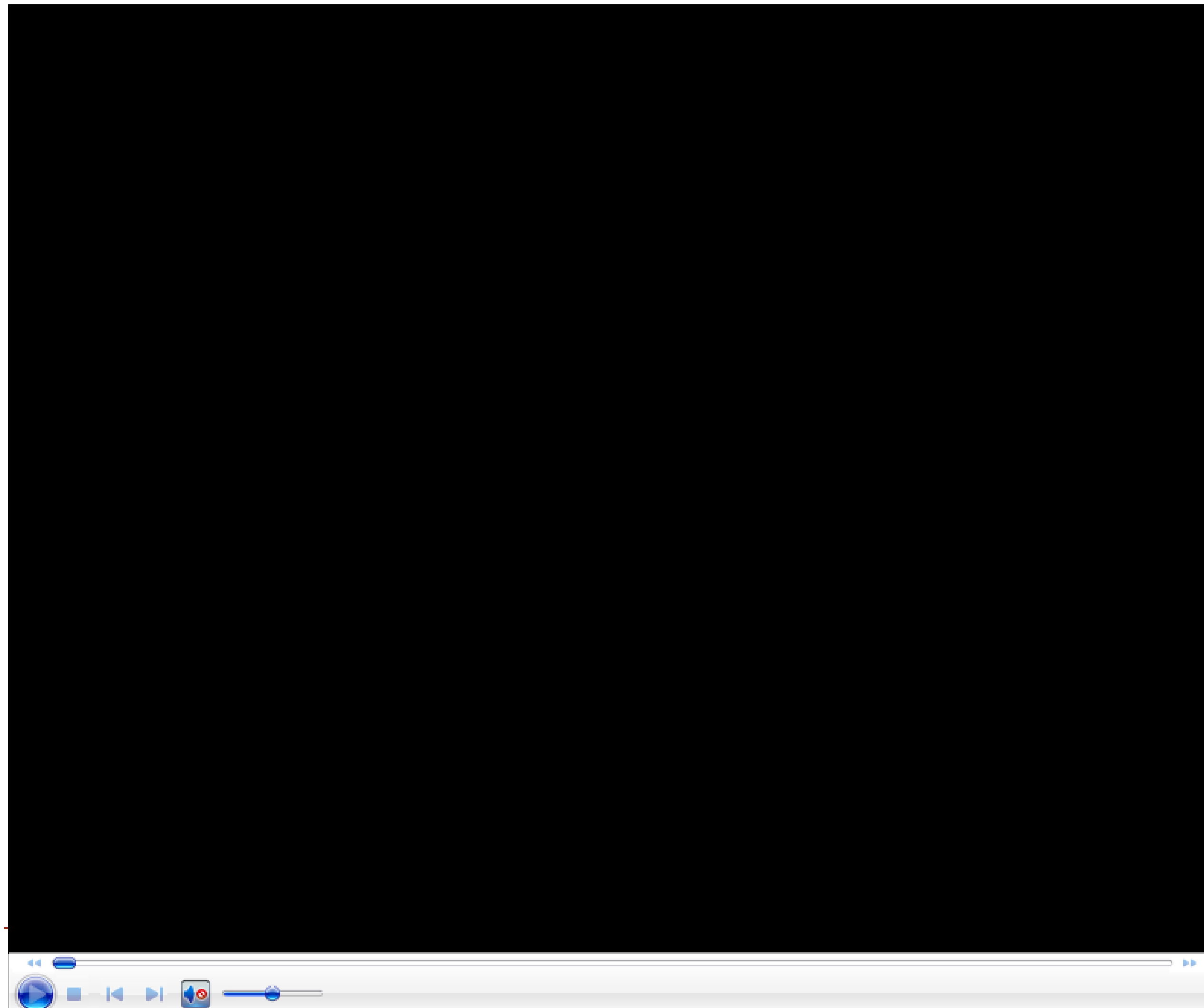
# Moderately High entropy core

- **Moderate rotation** ($\Omega_c$=**0.5** rad/s)

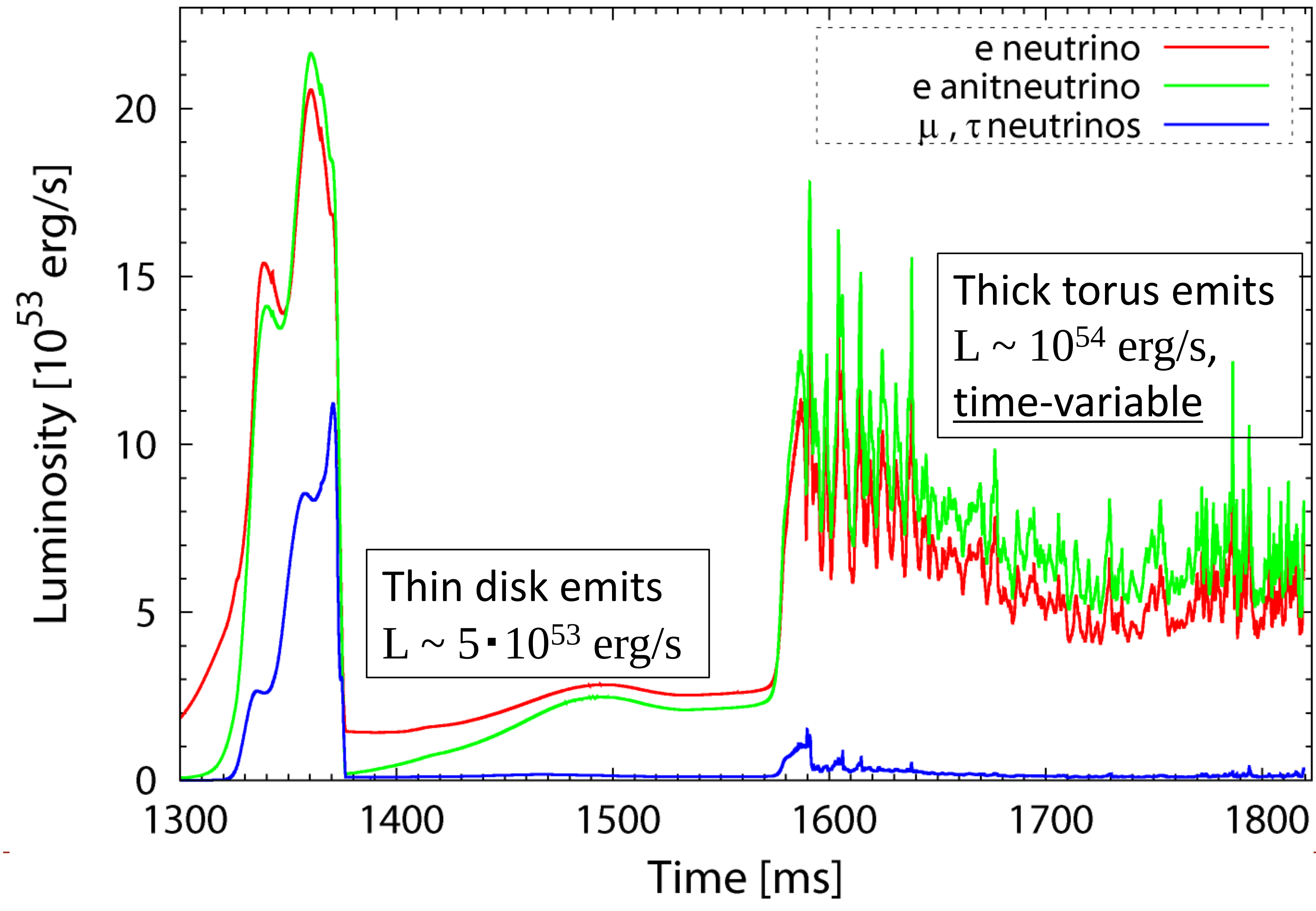


# Moderately High entropy core

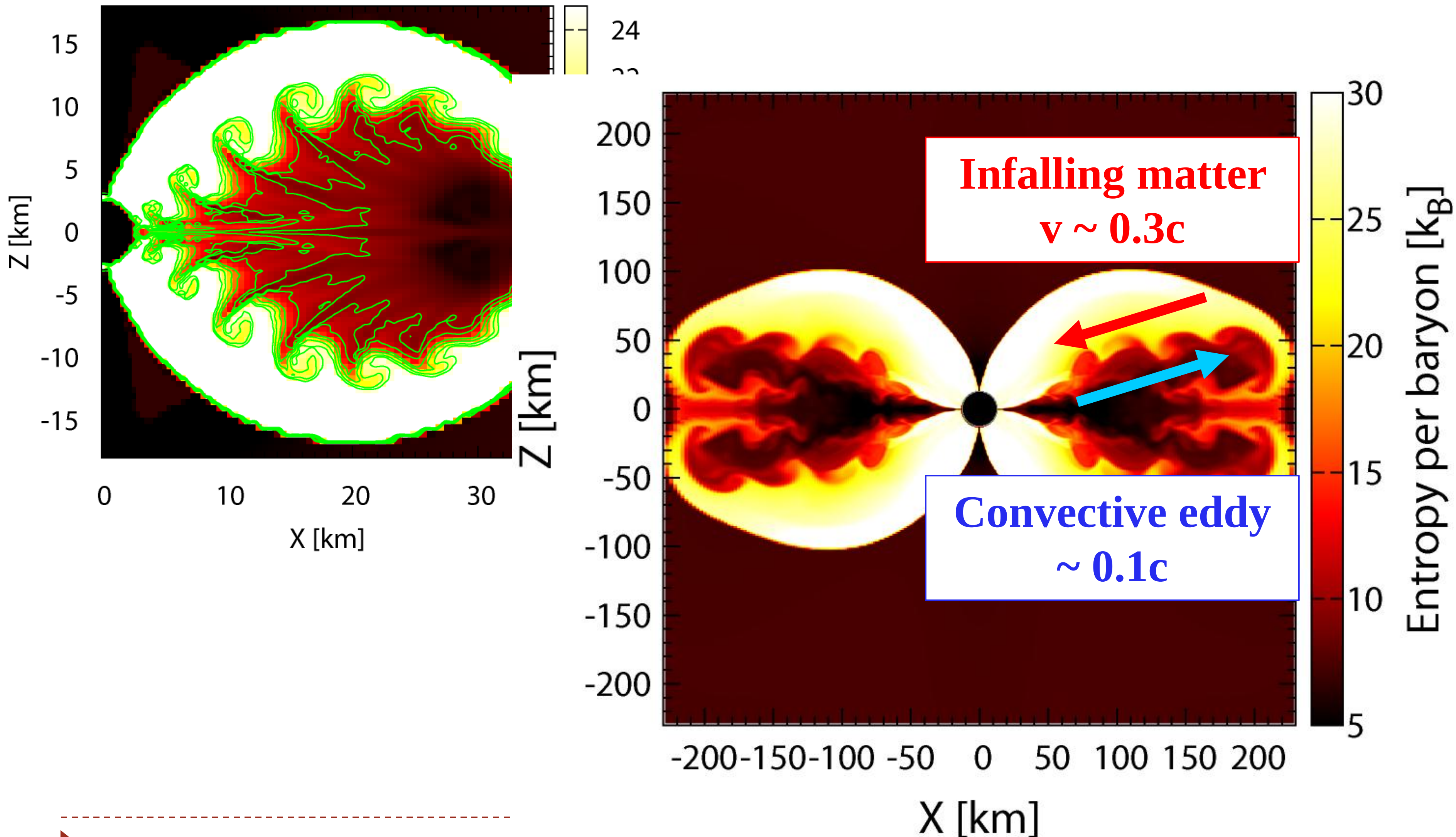
- **Moderate rotation** ($\Omega_c$=**0.5** rad/s)



# Neutrino luminosity



# KH instability



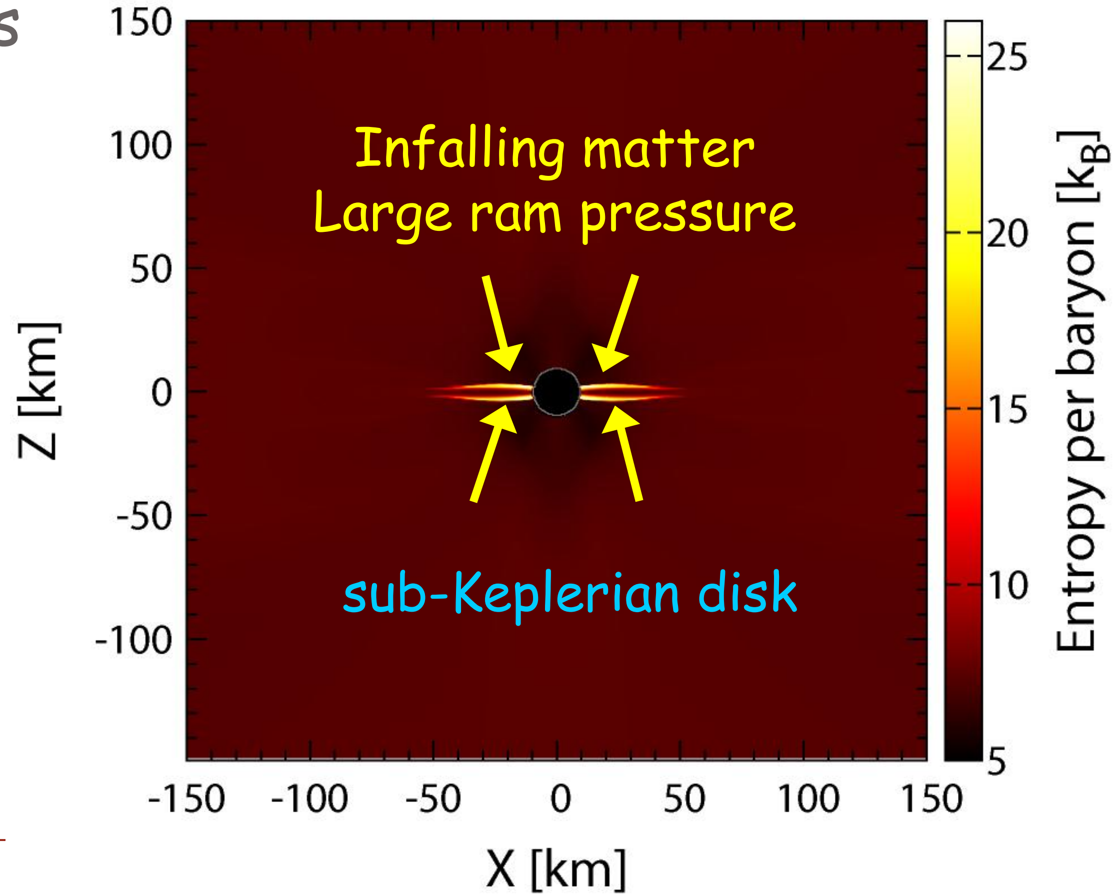
# Geometrically-thin disk phase

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

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

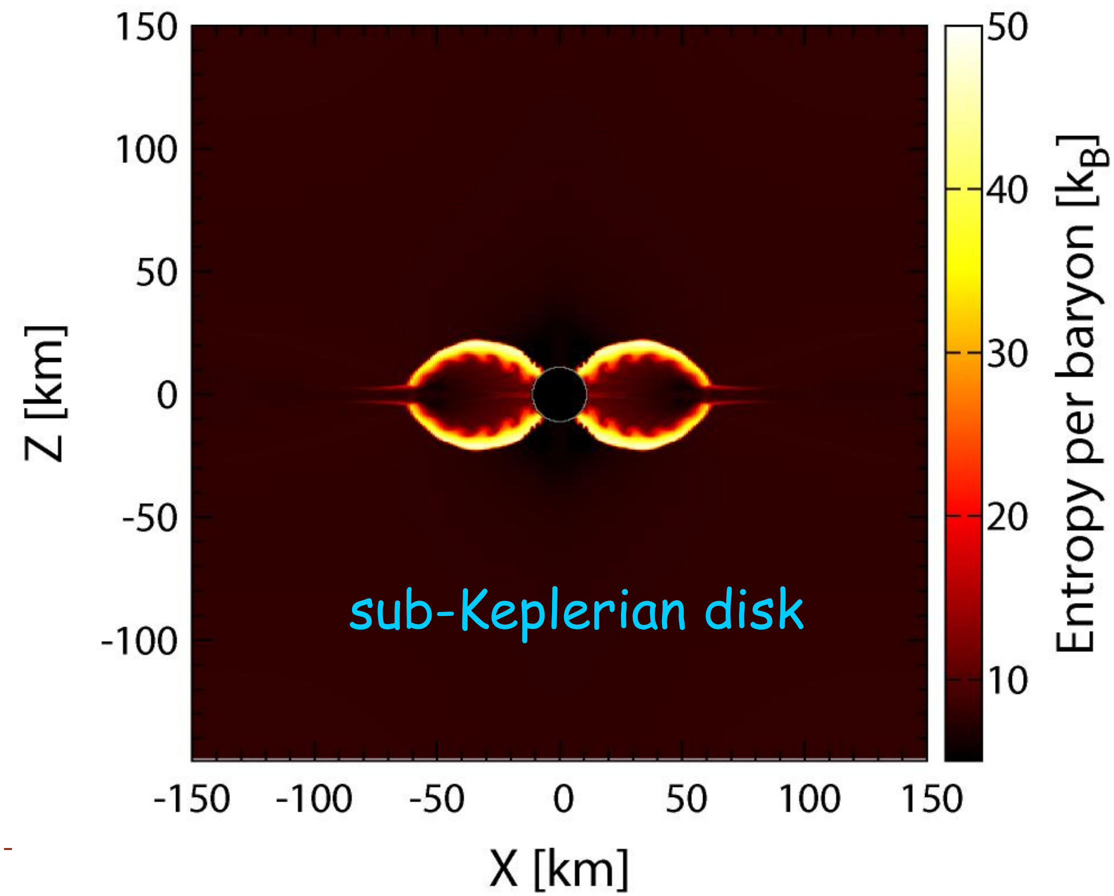
$$t_{\rm adv} \sim \frac{R}{v} \sim \frac{R}{0.1c}$$

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



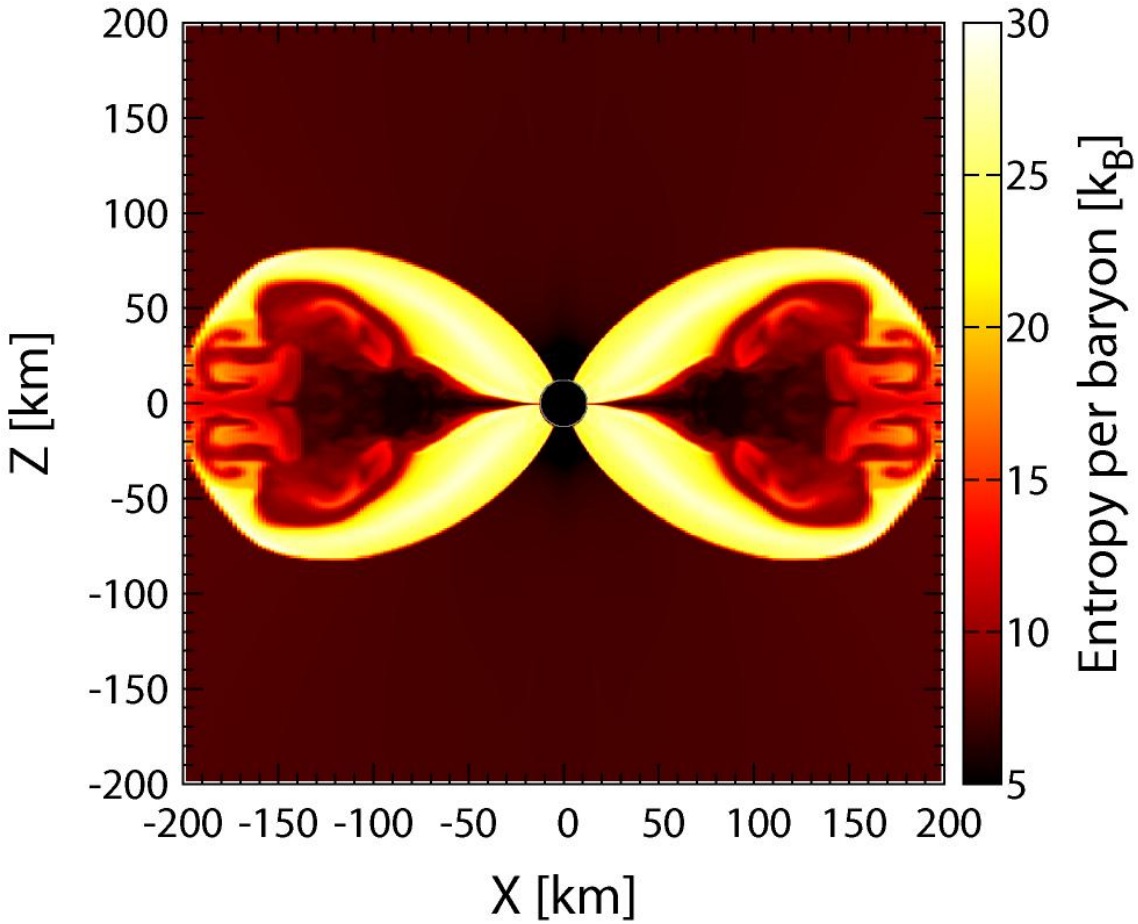
# Disk expansion

- 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



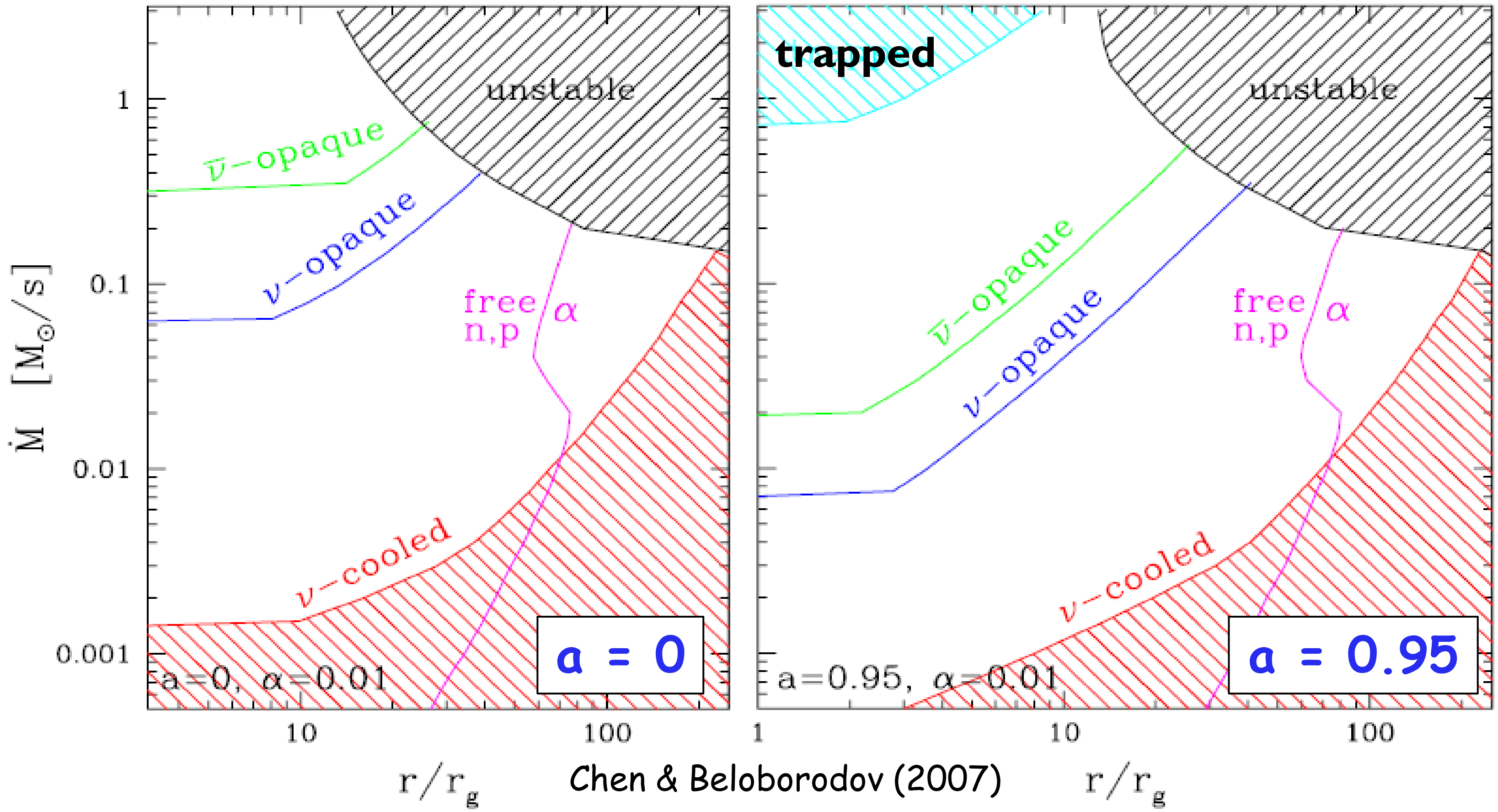
# Convective activities

- **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**