Gravitational waves and neutrinos from **L**GRBs

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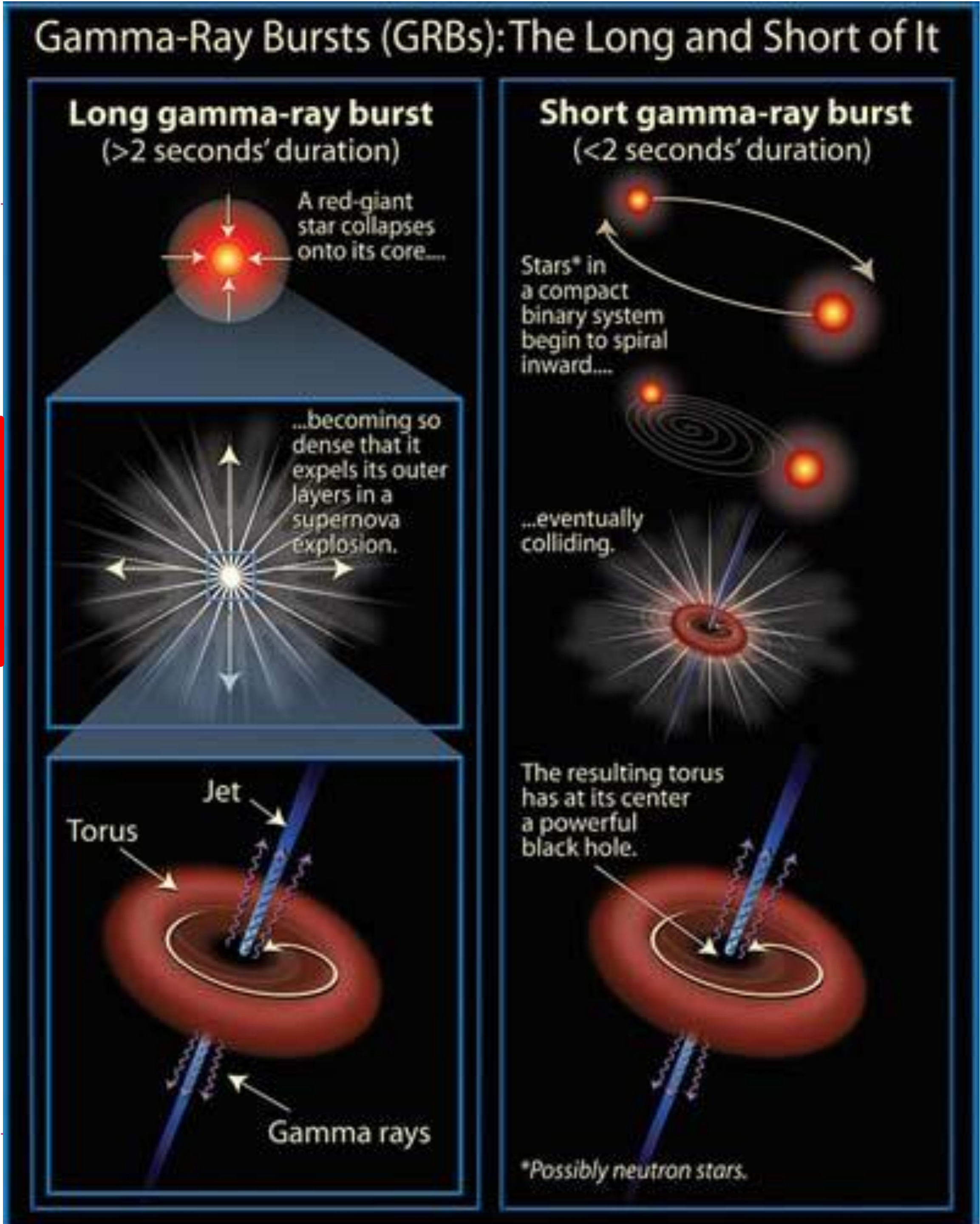
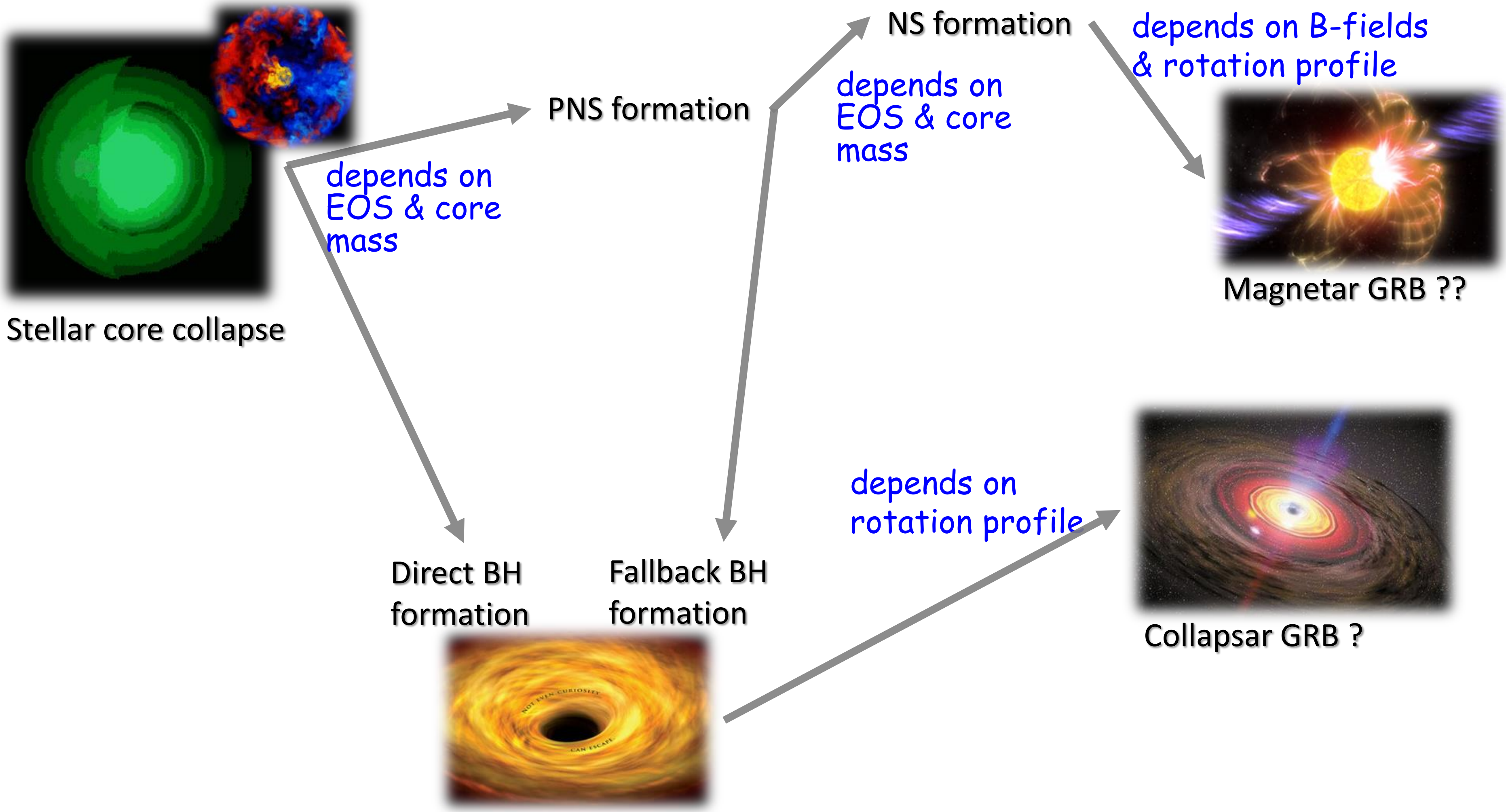
Collaboration with Masaru Shibata (YITP)

GRB engine

- **BH + accretion disk / magnetar formed by**
  - LGRB : Stellar core collapse
  - Hypernova association
    - Talks by Della Valle, Mazzali …
  - SGRB : NS-NS/BH merger
  - Timescale argument
    - Talks by Rosswog, Metzger, Shibata ….



Dynamics of stellar core collapse



Stellar core collapse

PNS formation

depends on
EOS & core
mass

NS formation

depends on
EOS & core
mass

depends on B-fields
& rotation profile

Magnetar GRB ??

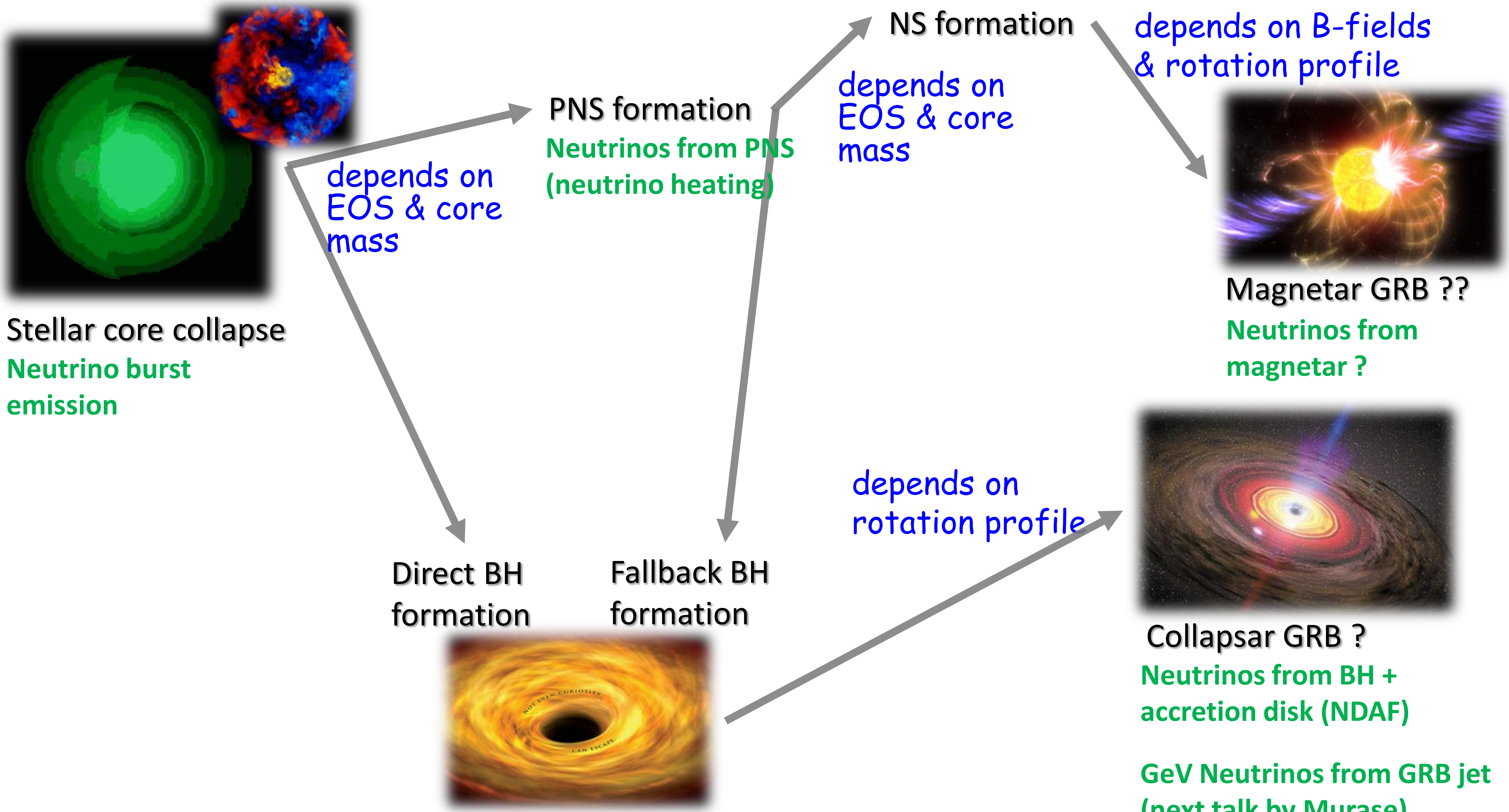
Direct BH
formation

Fallback BH
formation

depends on
rotation profile

Collapsar GRB ?

Dynamics of stellar core collapse



Stellar core collapse

Neutrino burst emission

depends on EOS & core mass

PNS formation

Neutrinos from PNS (neutrino heating)

depends on EOS & core mass

NS formation

depends on B-fields & rotation profile

Magnetar GRB ??

Neutrinos from magnetar ?

Direct BH formation

Fallback BH formation

depends on rotation profile

Collapsar GRB ?

Neutrinos from BH + accretion disk (NDAF)

GeV Neutrinos from GRB jet (next talk by Murase)

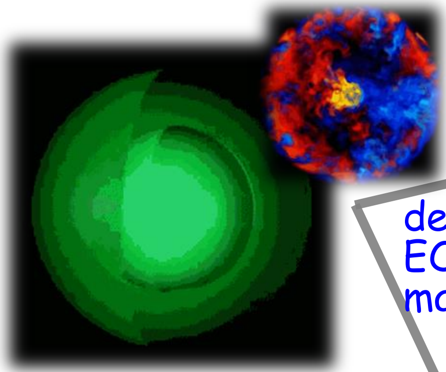
Gravitational waves

- GW Luminosity : quadrupole formula

$$L_{GW} = \frac{G}{5c^5}\left\langle \dddot{I}_{\alpha\beta}\dddot{I}^{\alpha\beta}\right\rangle \sim \frac{c^5}{G}\ \varepsilon^2 \left(\frac{GM}{c^2 R}\right)^2 \left(\frac{v}{c}\right)^6$$

- To be a strong emitter of GWs
  - Higher degree of asymmetry : $\varepsilon \sim (I_{xx} - I_{yy})/I_{zz}$
  - General relativistic (compact)
    - Black hole (BH) : $GM/Rc^2 \sim 1$
    - Neutron star (NS) : $GM/Rc^2 \sim 0.1$
    - BH accretion disk : $GM/Rc^2 \sim 0.01$—0.1 (for $R_{\mathrm{Disk}} \sim R_{\mathrm{ISCO}}$)
  - Special relativistic (v~c)
- How about in LGRBs

GW sources in stellar core collapse



Stellar core collapse

GW from rotational core bounce

Zwerger & Muller (1997)
Dimmelmeier et al (2002)
Shibata & YS (2003)
Ott et al. (2011)

GW from convection/SASI

YS et al. (2013)
Cerda-Duran et al. (2013)
Muller et al. (2004)

depends on EOS & core mass

PNS formation

GW from non-axisym. Instabilities

Rampp et al. (1998)
Shibata & Sekiguchi (2005)
Kobayashi & Meszaros (2003)

GW from PNS g-modes

Ott et al. (2006)

Anisotropic neutrino emission

Muller et al. (2004)

depends on EOS & core mass

NS formation

depends on B-fields & rotation profile

Magnetar GRB ??

GW from GRB jet

Direct BH formation

Fallback BH formation

GW from BH quasi-normal modes

depends on rotation profile

Collapsar GRB ?

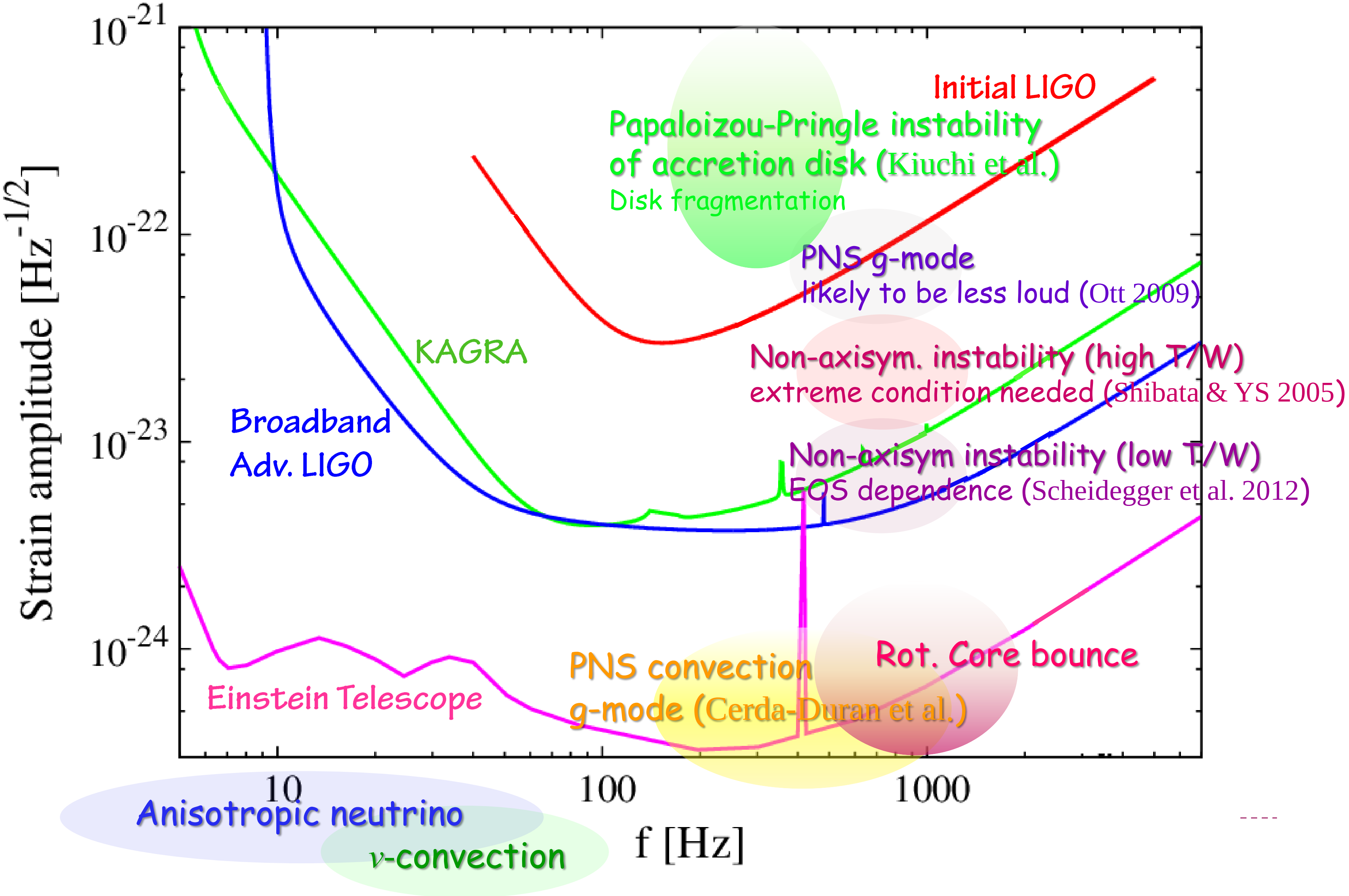
GW from BH+Disk system

Papaloizou-Pringle instability (Kiuchi et al. 2011**)**

Disk fragmentation (Piro & Pfahl 2007**)**

Disk precession (Romero et al. 2010**)**

GW from collapsar optimal @ 20Mpc



Papaloizou-Pringle instability of accretion disk (Kiuchi et al.)
Disk fragmentation

PNS g-mode
likely to be less loud (Ott 2009)

Non-axisym. instability (high T/W)
extreme condition needed (Shibata & YS 2005)

Non-axisym instability (low T/W)
EOS dependence (Scheidegger et al. 2012)

PNS convection
g-mode (Cerda-Duran et al.)

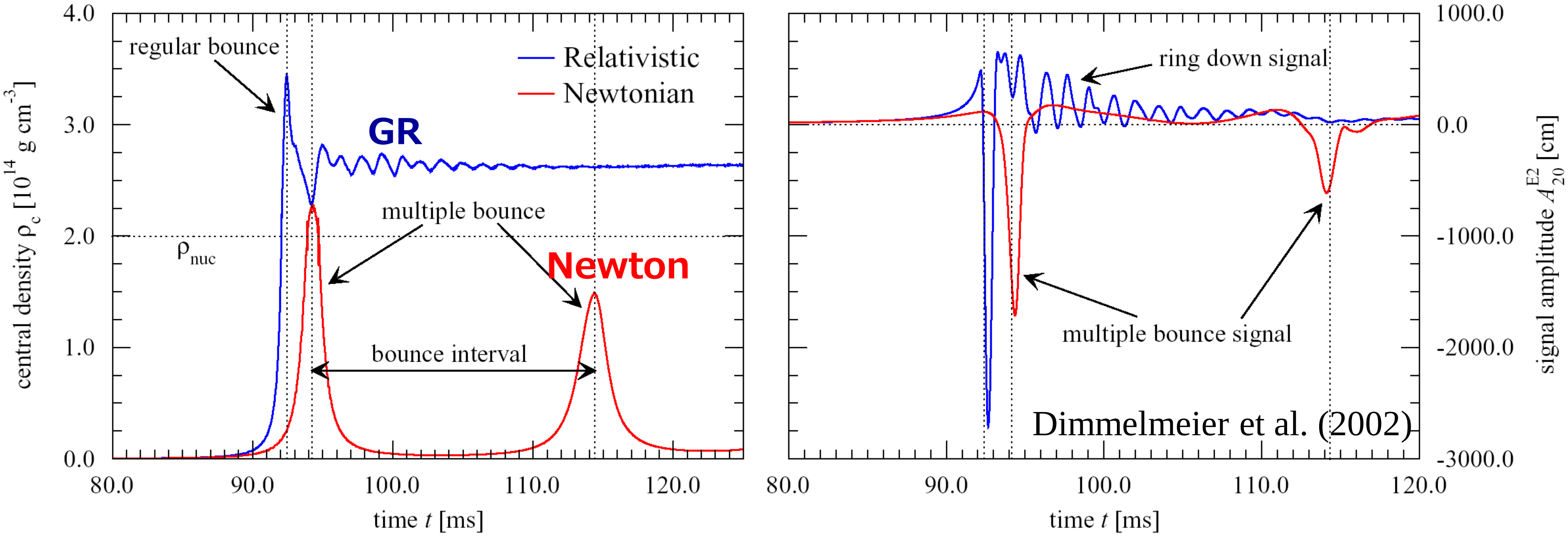
Rot. Core bounce

Anisotropic neutrino

ν-convection

Need for more studies

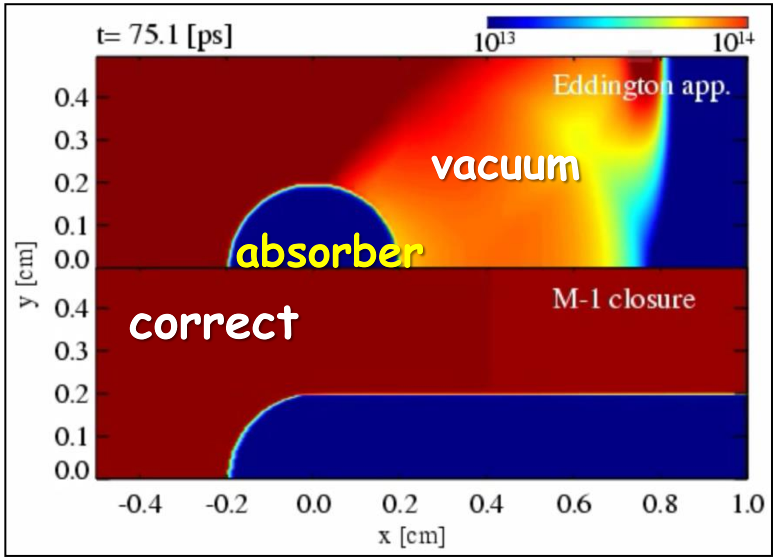
- Previous studies are based on ordinary supernova simulations
  - But see Ott+. (2011); Sekiguchi+. (2011;2013); Cerda-Duran+. (2013)
- Important physics is included incompletely
  - (Pseudo-) Newtonian simulations with detailed microphysics
  - Full GR simulations with simplified microphysics
    - But see Sekiguchi (2010); Kuroda+ (2012); Muller+ (2012) Cerda-Duran+ (2013)



Dimmelmeier et al. (2002)

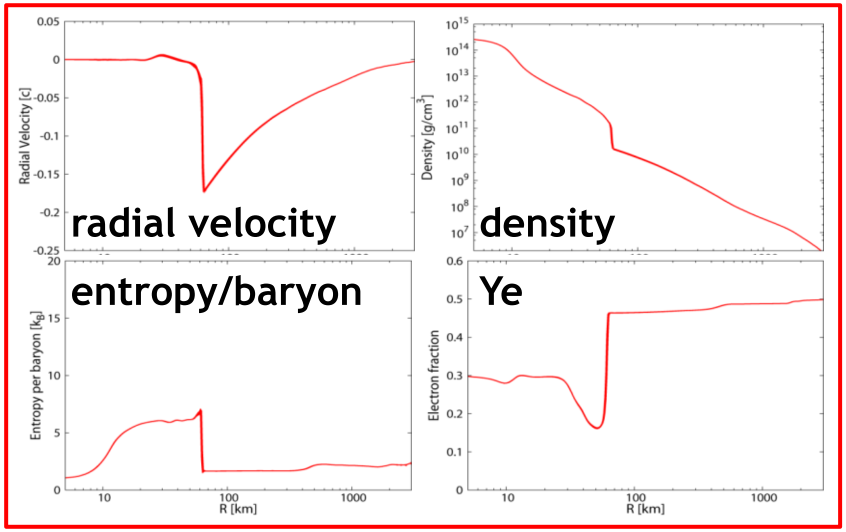
Full GR Radiation-Hydrodynamics

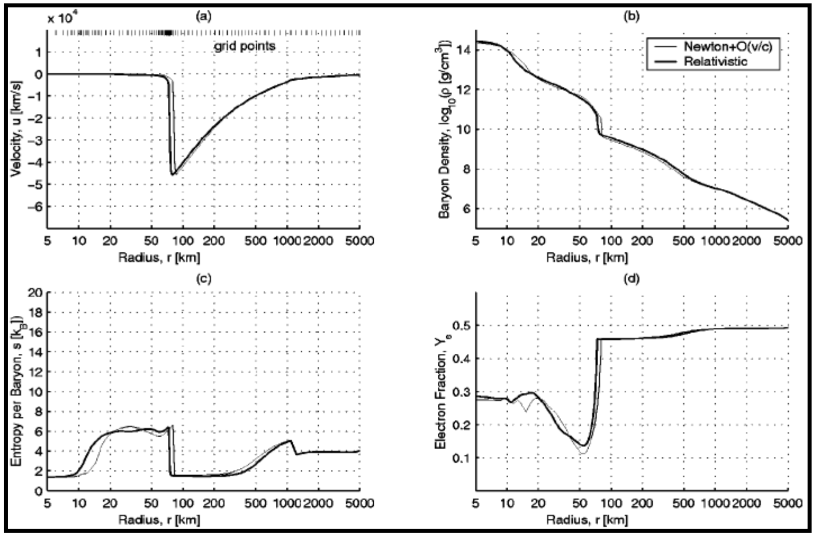
- **Einstein's equations:** Puncture-BSSN/Z4c formalism
- **GR radiation-hydrodynamics** (*Sekiguchi 2010; Sekiguchi + in prep*.)
  - **EOS** : any tabulated EOS with 3D smooth extended connection to Timmes EOS
  - **Advection terms** : Truncated (two) **Moment scheme** (*Shibata et al. 2011*)
    - Fully covariant and relativistic
    - gray or multi-energy but advection in energy is not included
    - M-1 closure
  - **Source terms** : two options
    - Implicit treatment : Bruenn's prescription
    - Explicit treatment : trapped/streaming ν's
      - ☐ e-captures: thermal unblocking/weak magnetism; NSE rate
      - ☐ Iso-energy scattering : recoil, Coulomb, finite size
      - ☐ e±annihilation, plasmon decay, bremsstrahlung
      - ☐ diffusion rate (Rosswog & Liebendoerfer 2004)
      - ☐ two (beta- and non-beta) EOS method
  - **Lepton conservation equations**

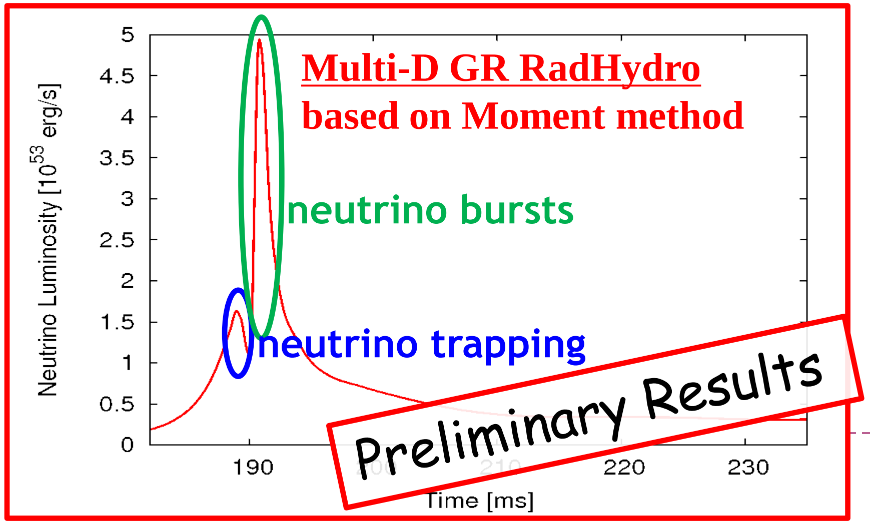


Code verification by 1D stellar collapse

- Our implicit scheme qualitatively (or semi-quantitatively) reproduce results in 1D GR Boltzmann simulations !





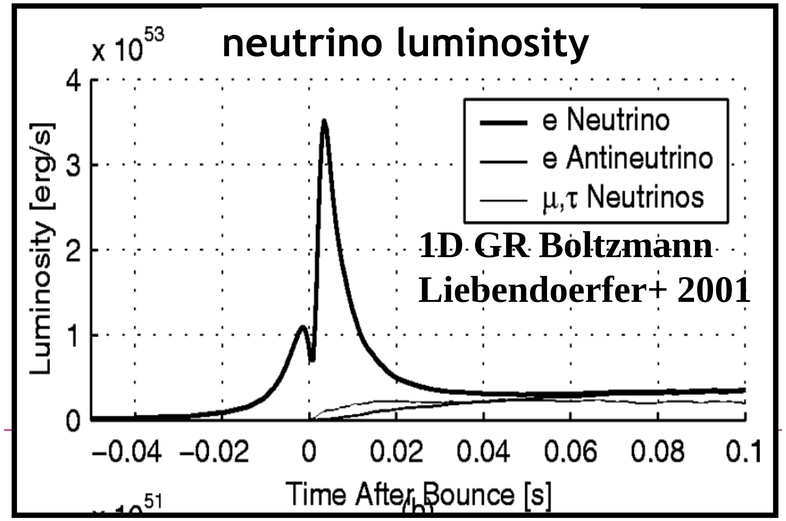


Multi-D GR RadHydro based on Moment method

neutrino bursts

neutrino trapping

Preliminary Results

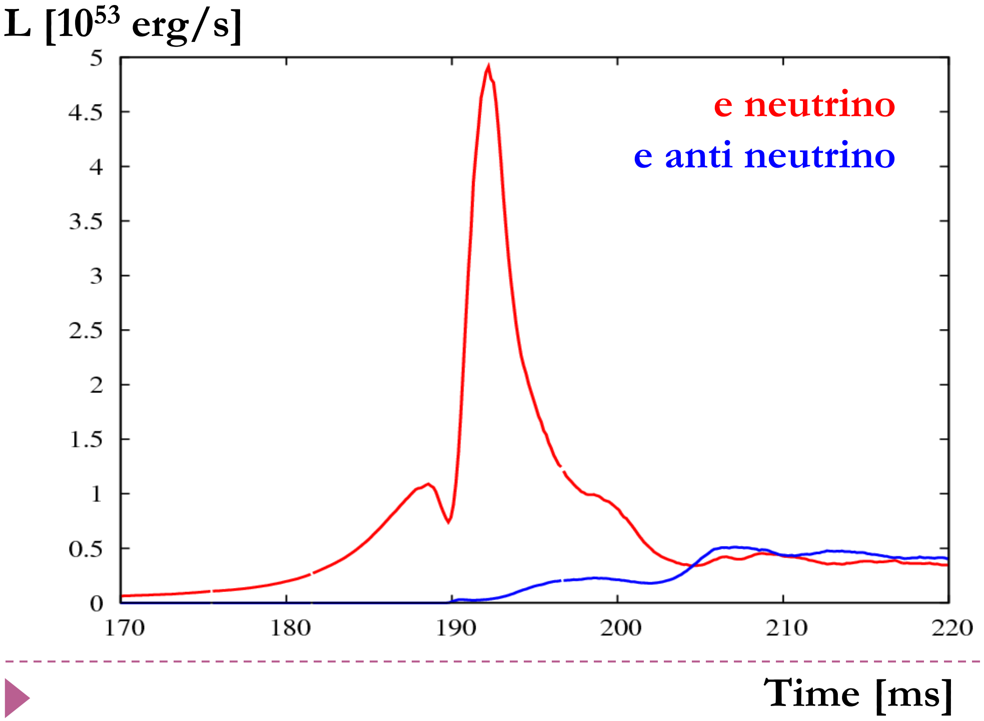


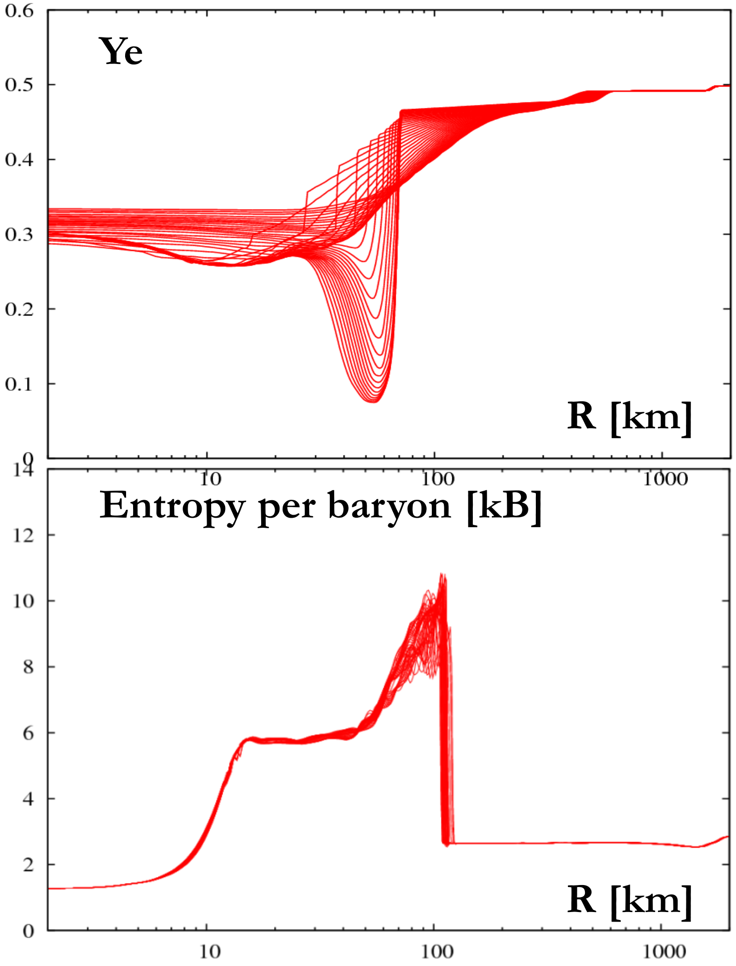
neutrino luminosity

1D GR Boltzmann Liebendoerfer+ 2001

Approx. Explicit treatment works well

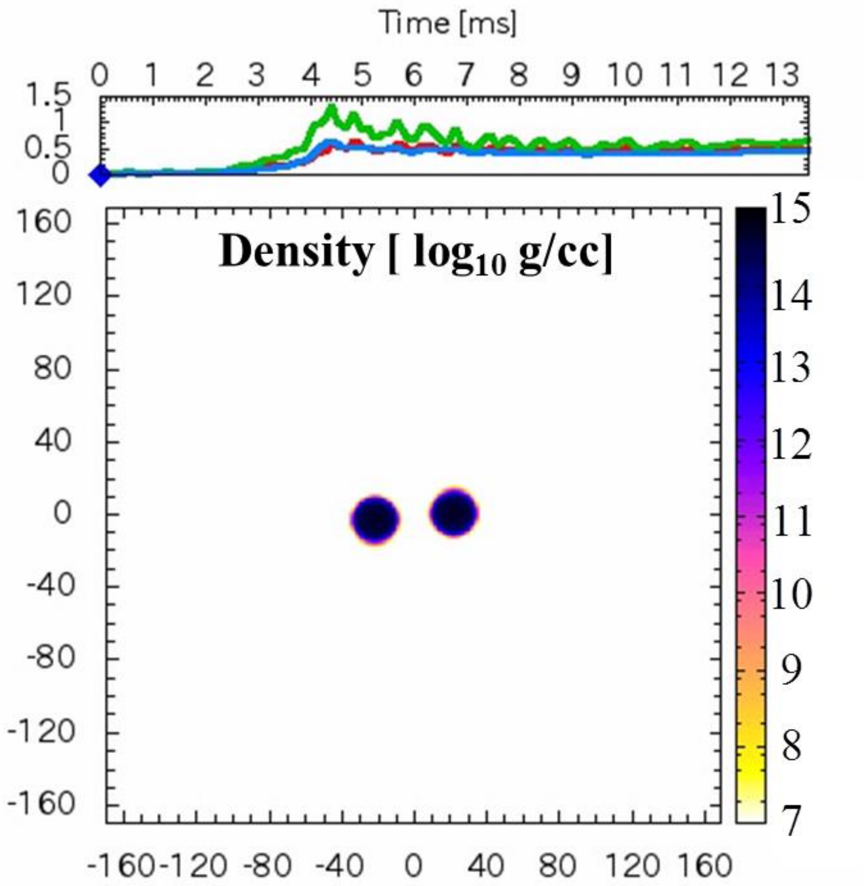
- Reasonable agreements with full transfer
  - Lv calculated from neutrino flux (not from source term !)
    - Do not use Liebendorfer's simplified prescription
- Heating effects can be included

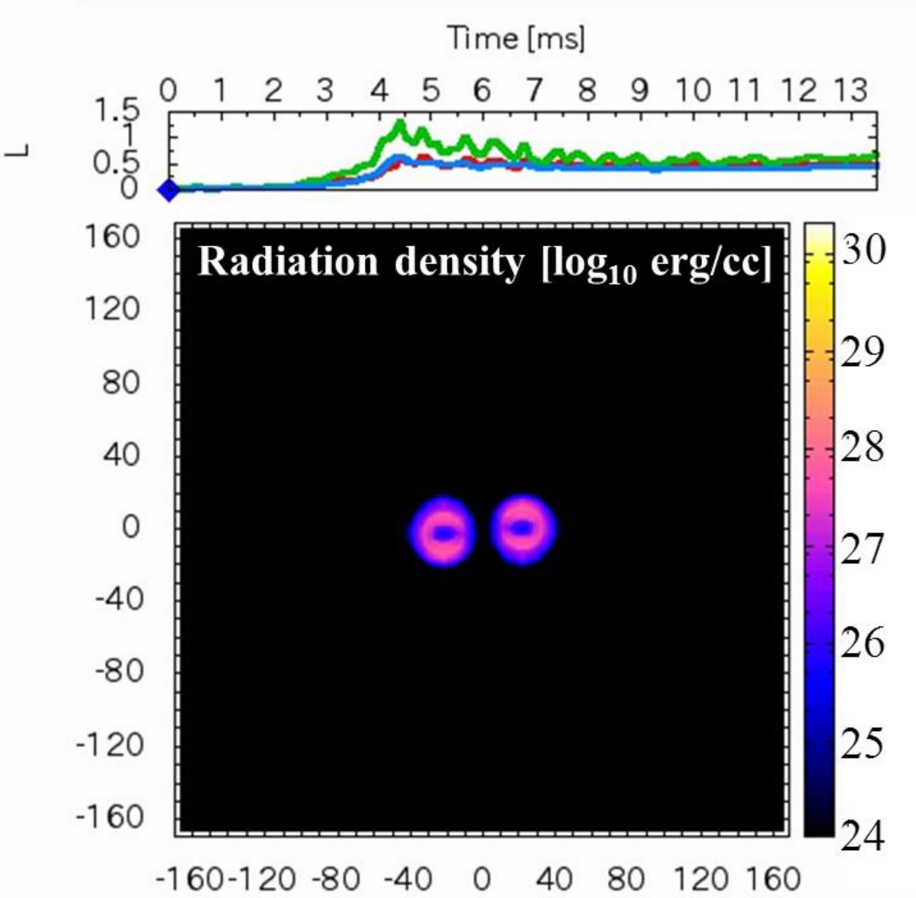




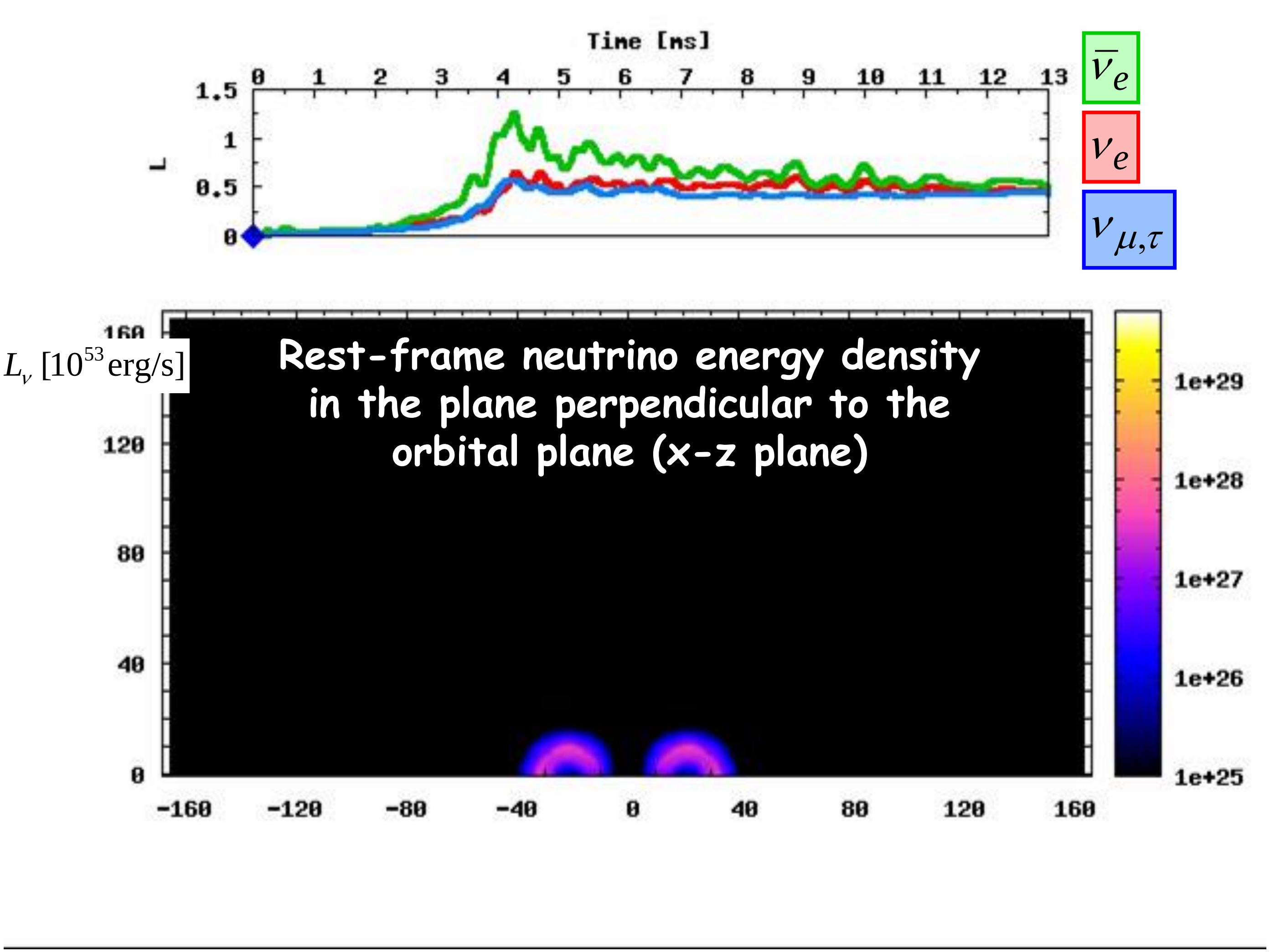
Application to BNS merger

- Approximate solution by Thorne’s Moment scheme with a closure relation
- Partial implicit treatment with an iterative time evolution / Explicit treatment
- Talk by Wanajo





Application to BNS merger



$\bar{\nu}_e$

ν_e

$\nu_{\mu,\tau}$

L_ν [10^{53} erg/s]

Rest-frame neutrino energy density in the plane perpendicular to the orbital plane (x-z plane)

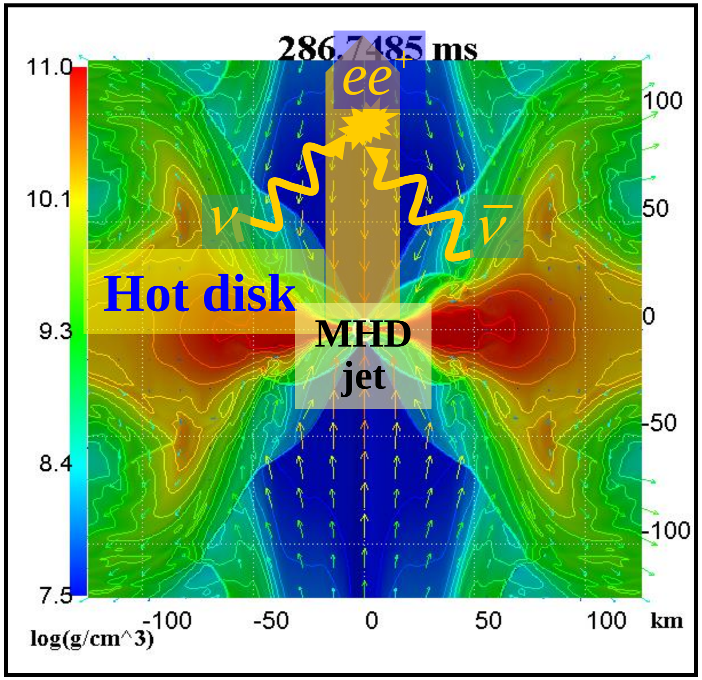
Full GR simulation of collapsar

- Based on old version of code (Sekiguchi 2010)
  - Simple Eddington closure instead of M-1 closure
  - Approximate explicit treatments for source terms
  - Heating effects are not included

- Sekiguchi & Shibata (2011)
- Sekiguchi et al. (2013)

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
      (might be more severe due to strong B fields)



Sekiguchi & Shibata 2007

- **Association of Type-Ic SNe**
  - Progenitor must have been ‘lost’ H and 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 ?**

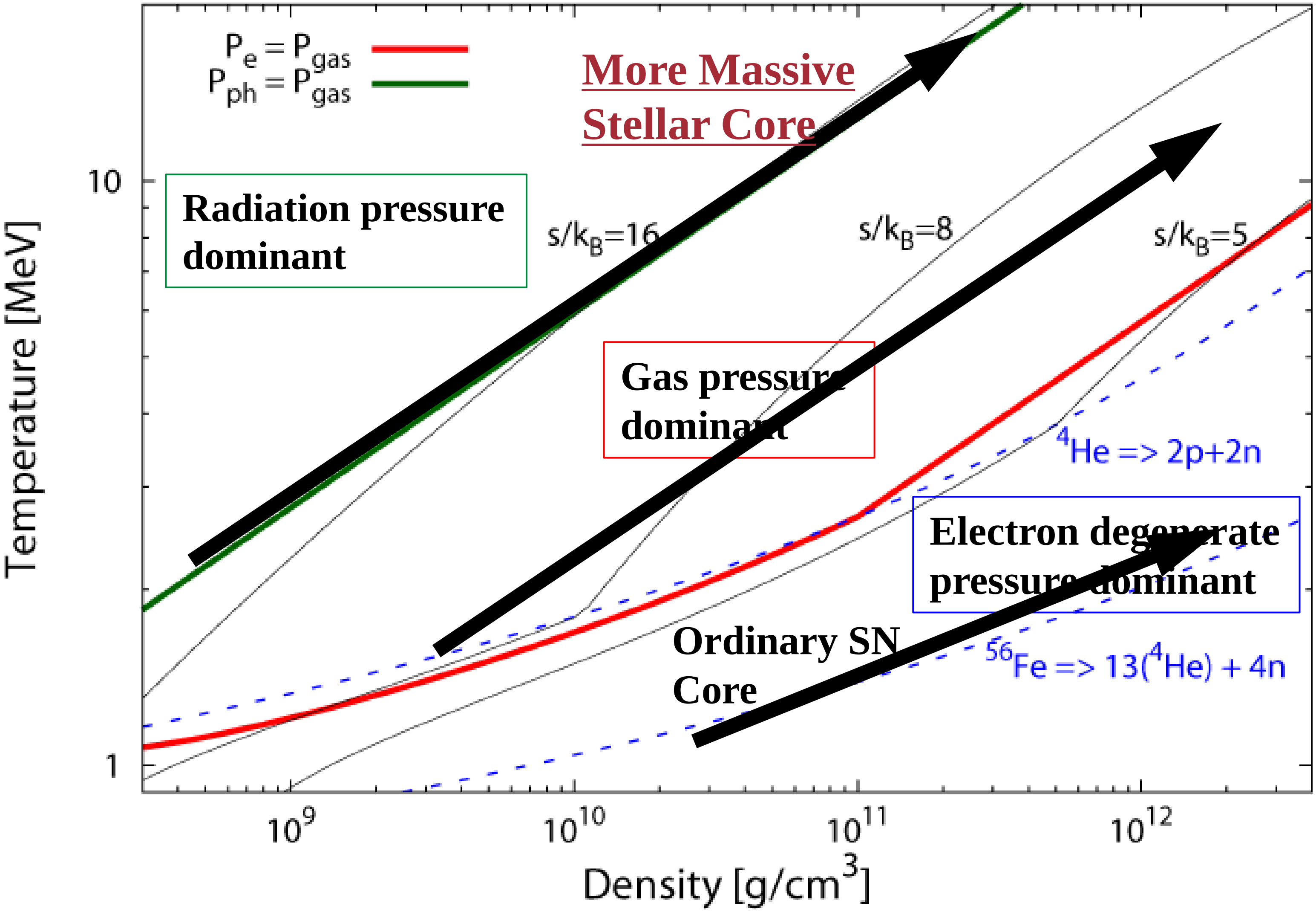
Dilemma in LGRB progenitor model

- **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 a 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 Rotation : Disk formation / amplification of B-fields
  - Evolution pass in density-temperature plane could be different from ordinary SN

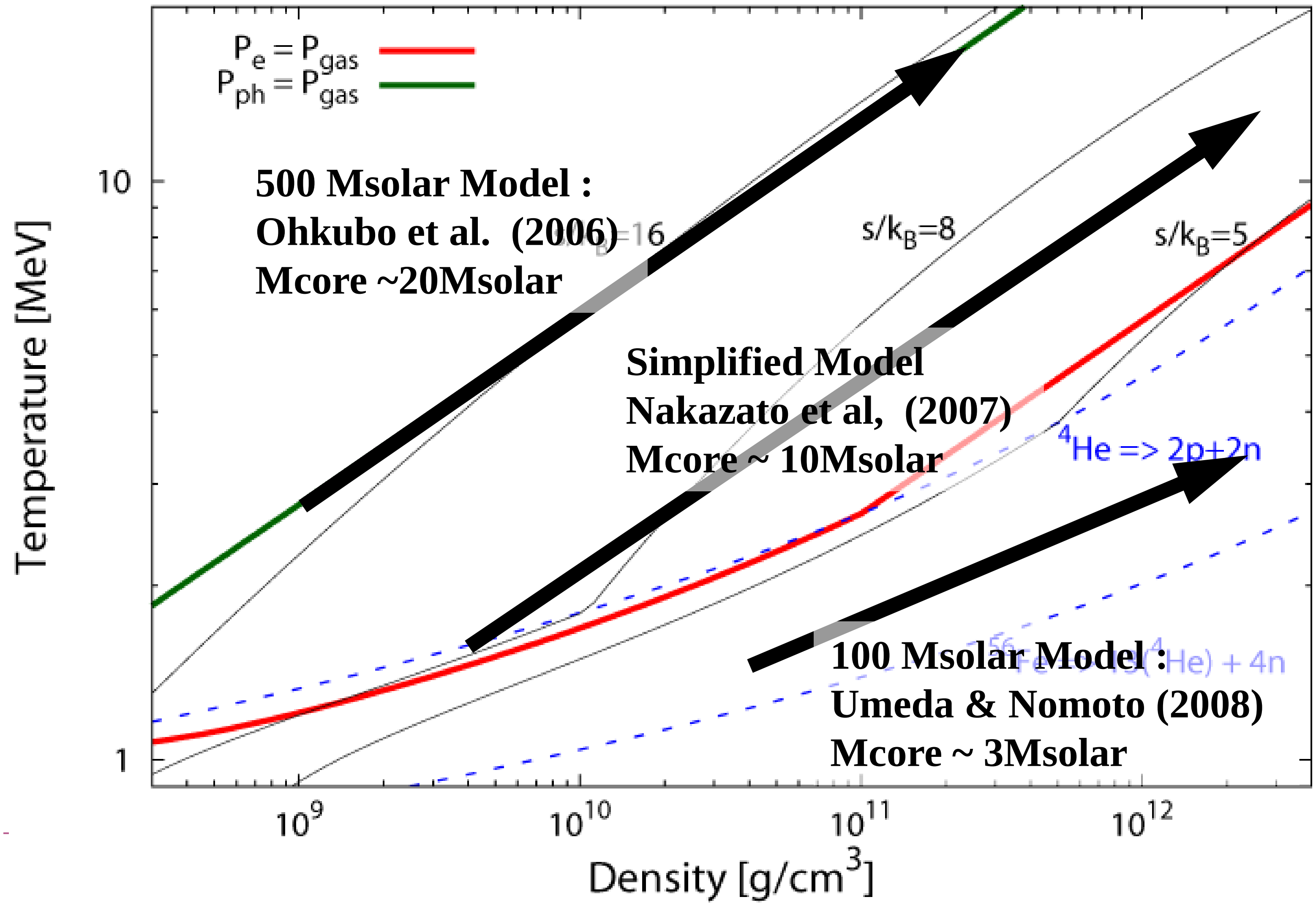
Three Initial Models

- Evolution path is characterized by central entropy (mass)



Three Initial Models

- Rotational Profiles are added by hand



500 Msolar Model :
Ohkubo et al. (2006)
Mcore ~20Msolar

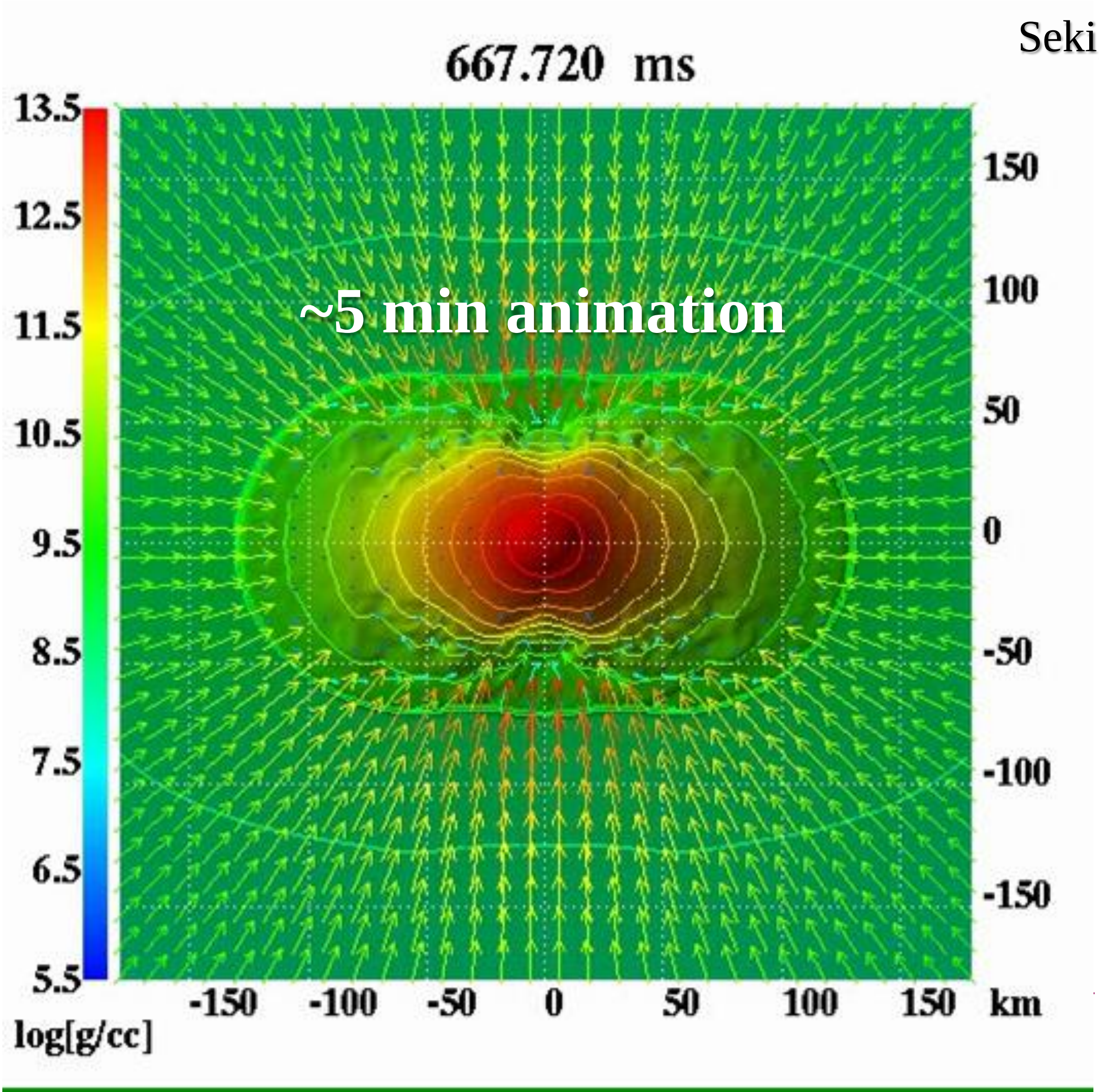
Simplified Model
Nakazato et al, (2007)
Mcore ~ 10Msolar

100 Msolar Model :
Umeda & Nomoto (2008)
Mcore ~ 3Msolar

Collapse of 100Msolar presupernova model:

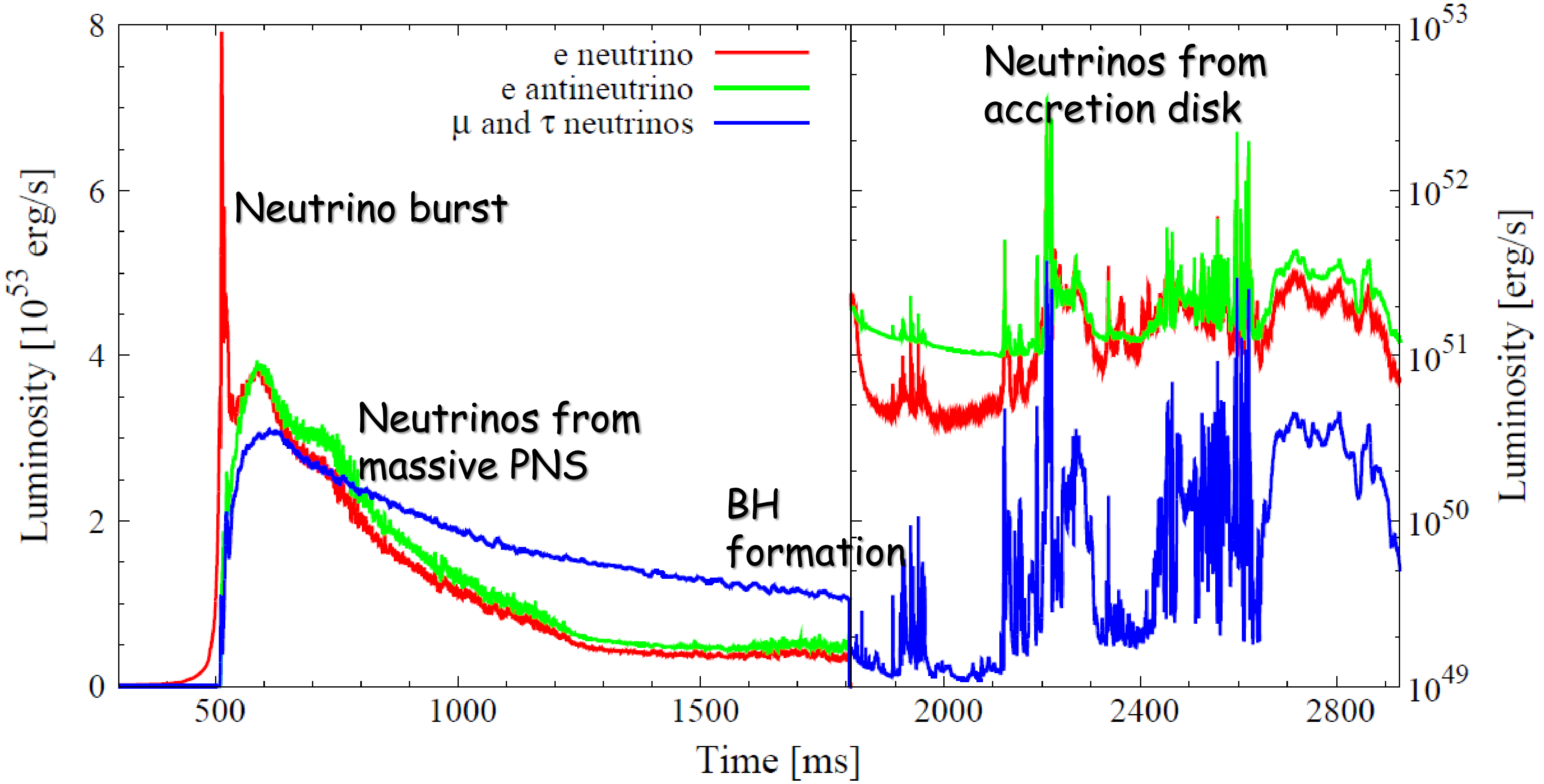
Umeda & Nomoto (2008) + rigid rotation Ω = 1.2 rad/s

Sekiguchi et al. (2013)



~5 min animation

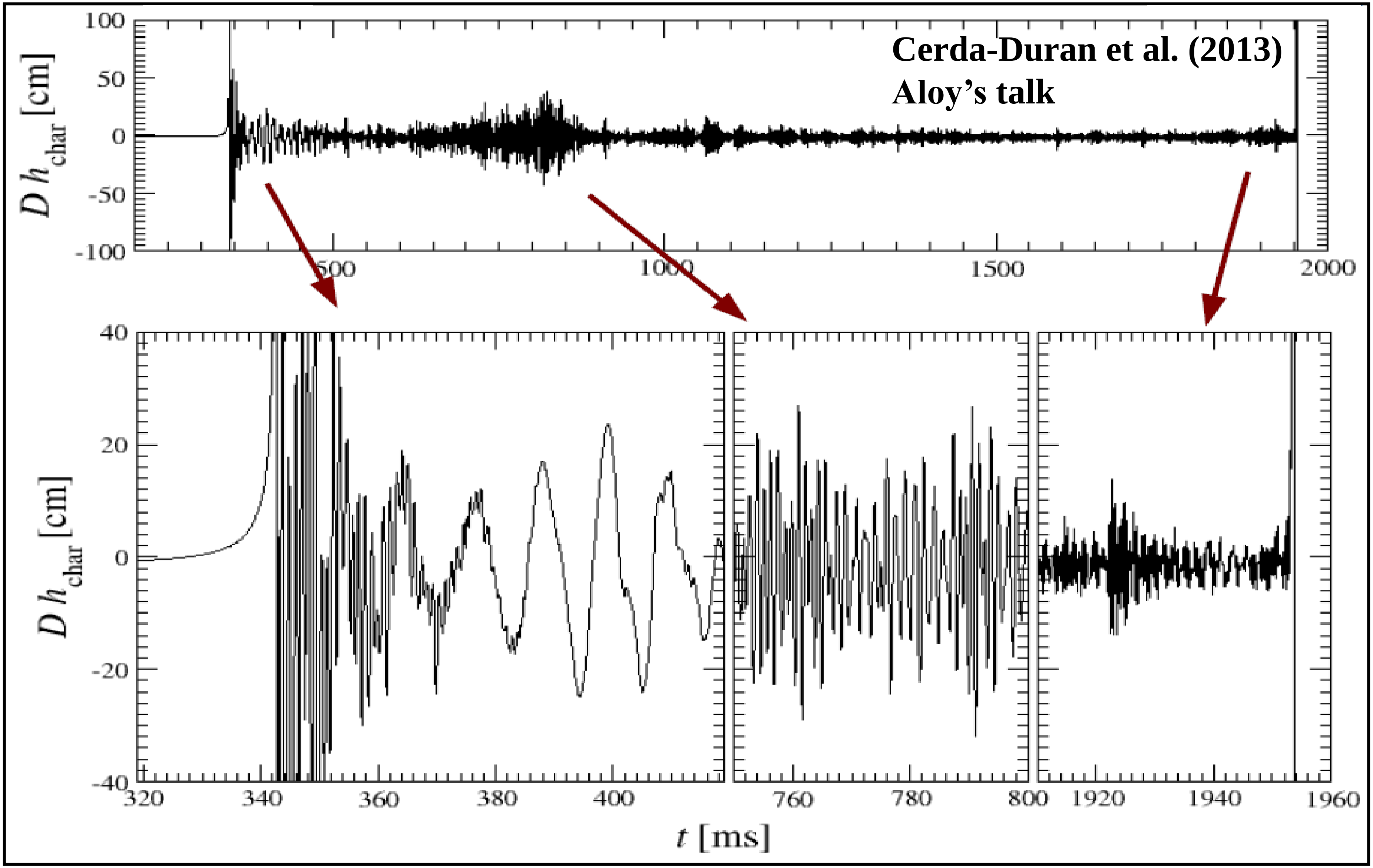
Neutrino luminosity



Sekiguchi et al. (2013)

Ott et al. (2011)
Sekiguchi et al. (2013)
Cerda-Duran et al. (2013)

GWs from collapsar



Cerda-Duran et al. (2013)
Aloy's talk

Ott et al. (2011)
Sekiguchi et al. (2013)
Cerda-Duran et al. (2013)

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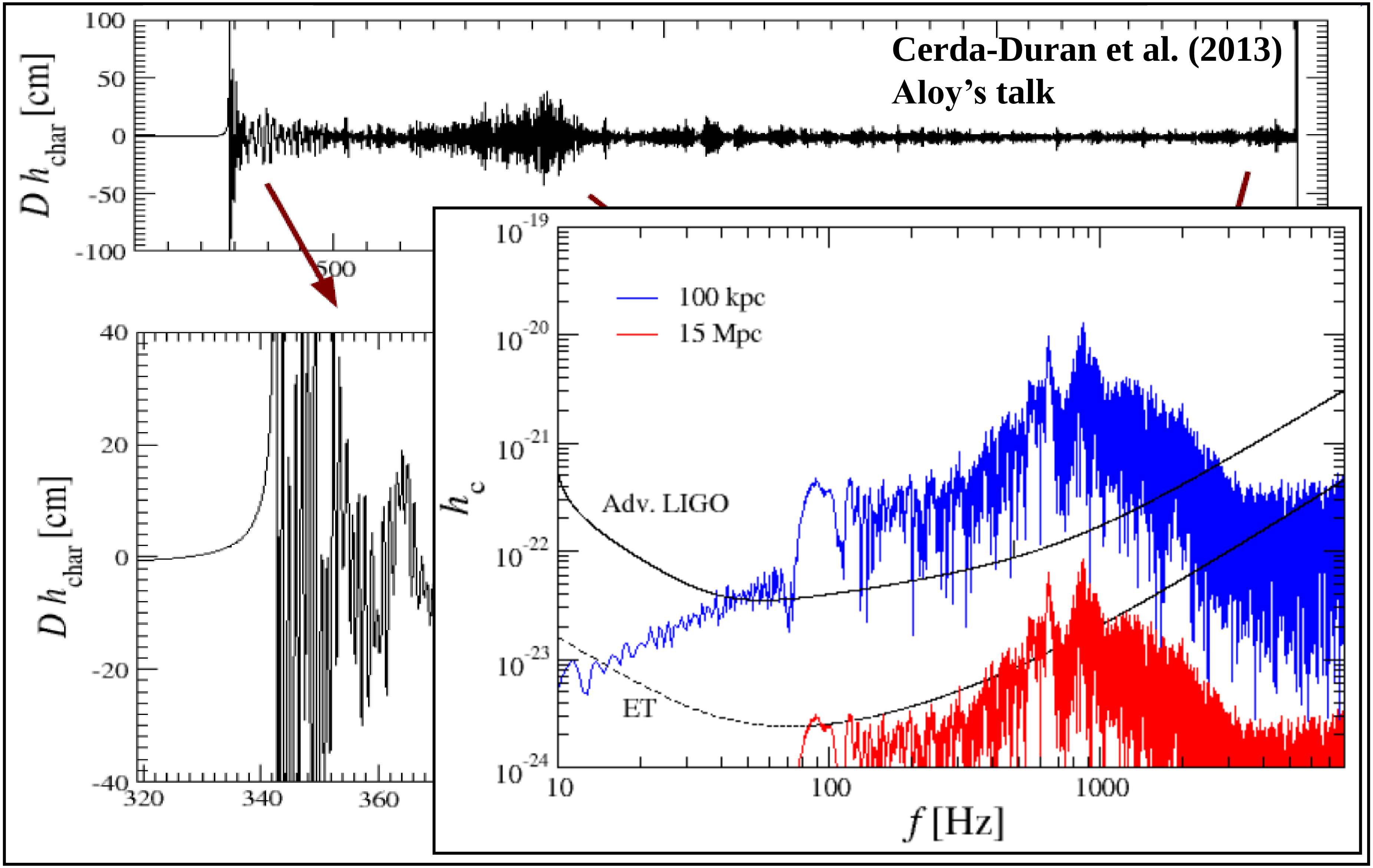
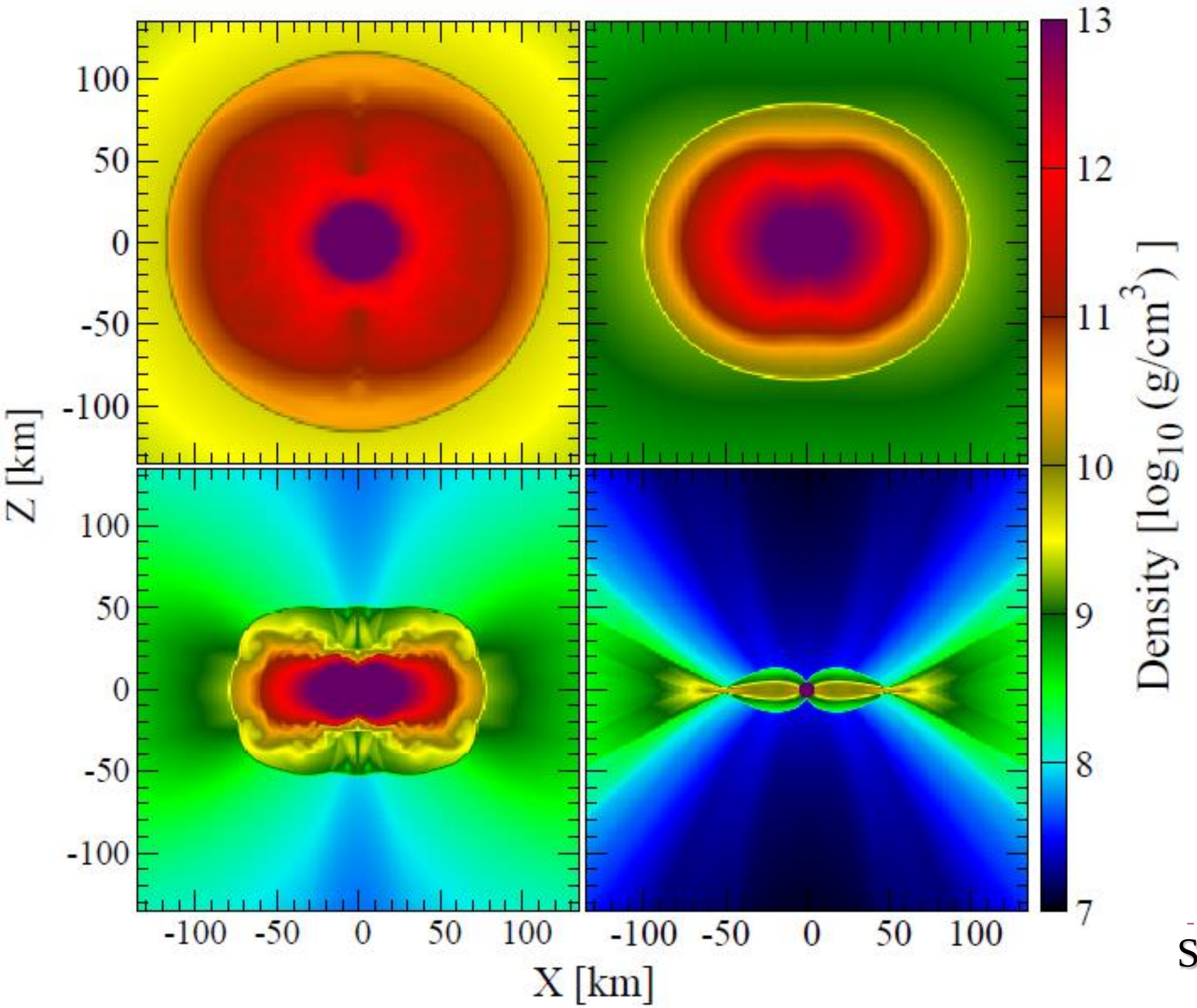


Cerda-Duran et al. (2013)
Aloy's talk

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



Sekiguchi et al. (2013)

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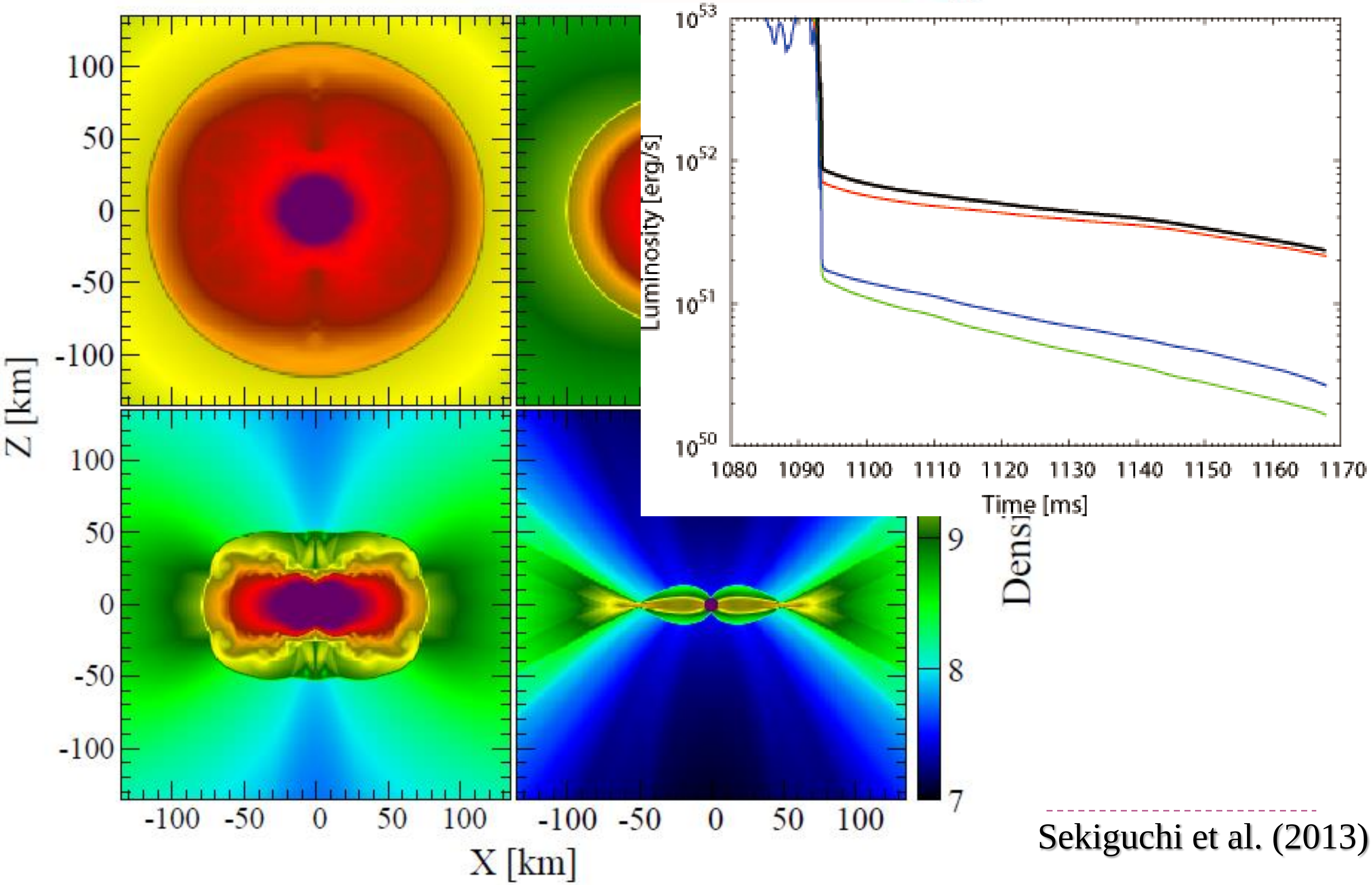
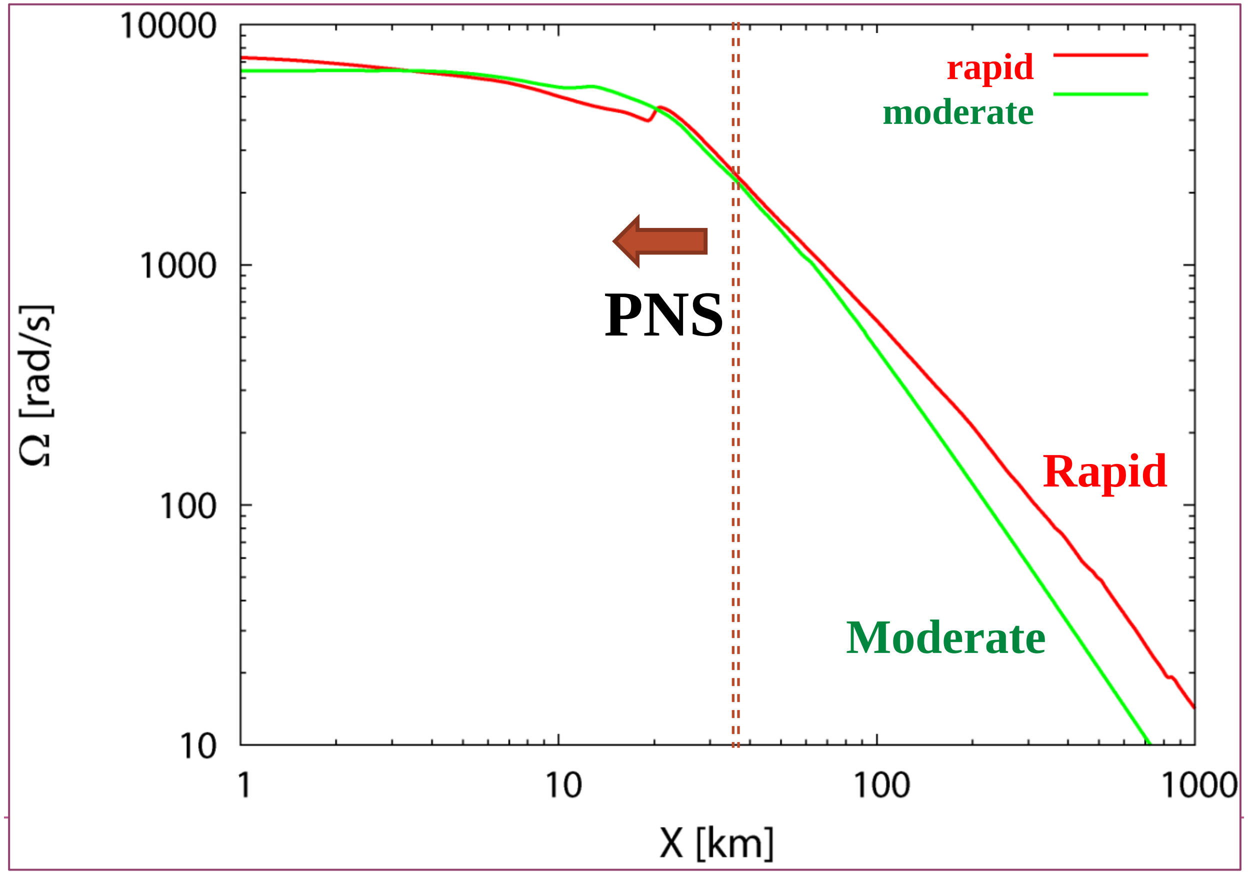


Sekiguchi et al. (2013)

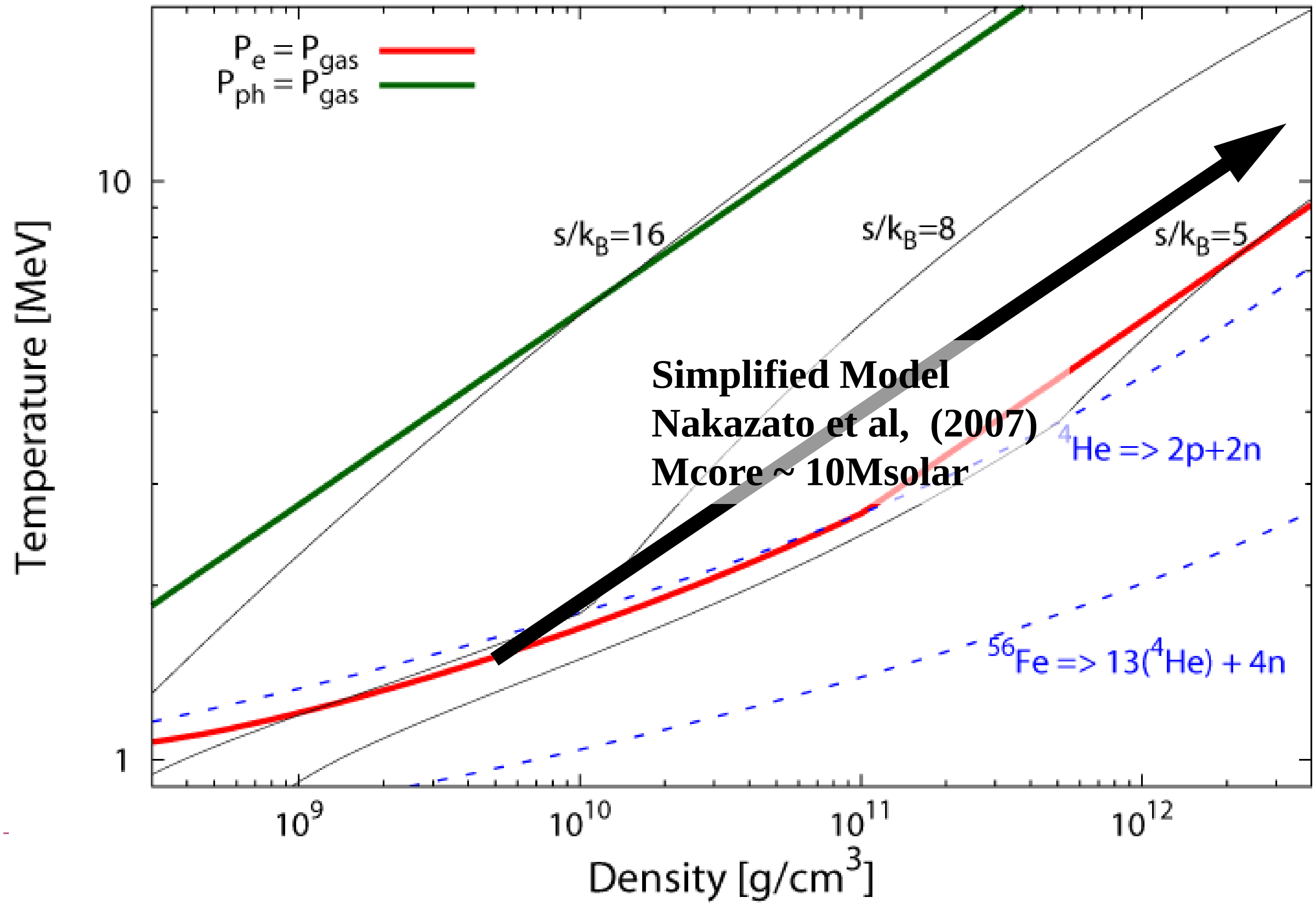
Comparison of Rotational Profile

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



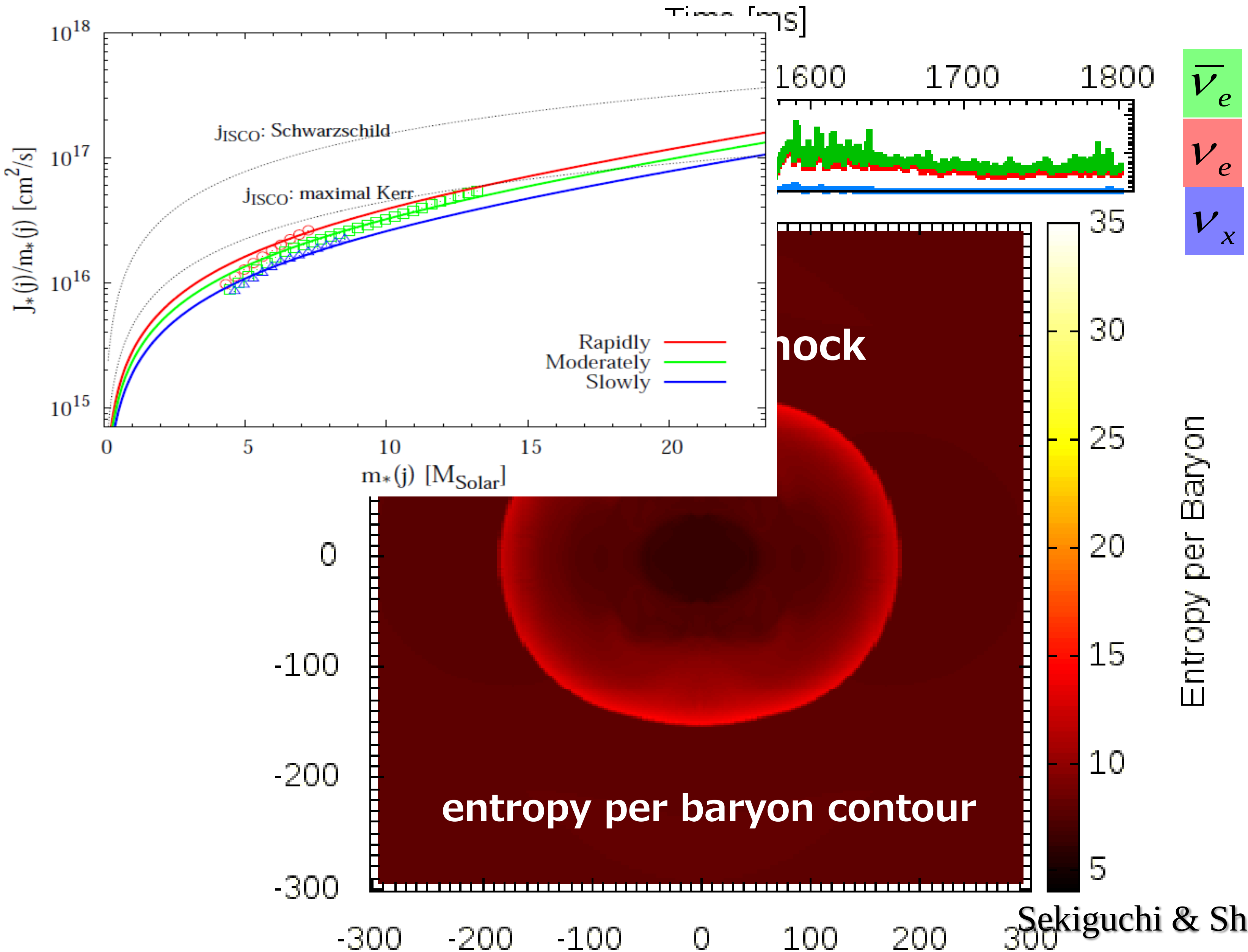
A higher entropy core

- Rotational Profiles are added by hand



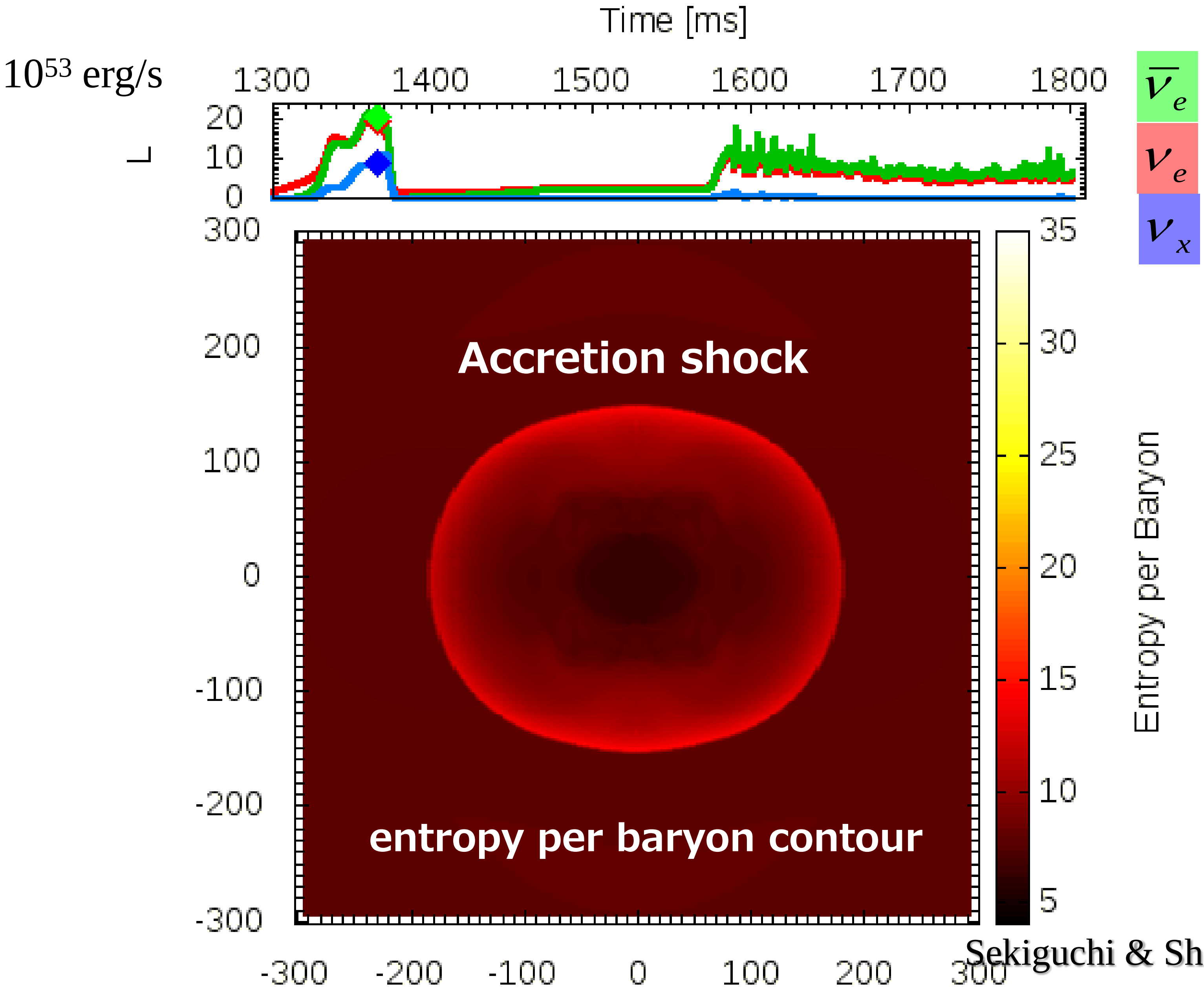
Simplified Model
Nakazato et al, (2007)
Mcore ~ 10Msolar

GRB without SNe ? : Collapse of Higher entropy core



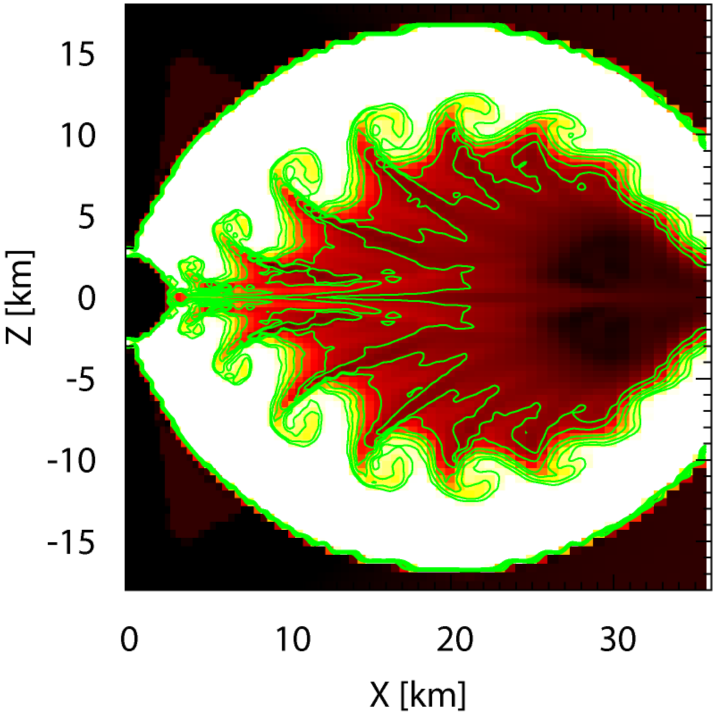
Sekiguchi & Shibata (2011)

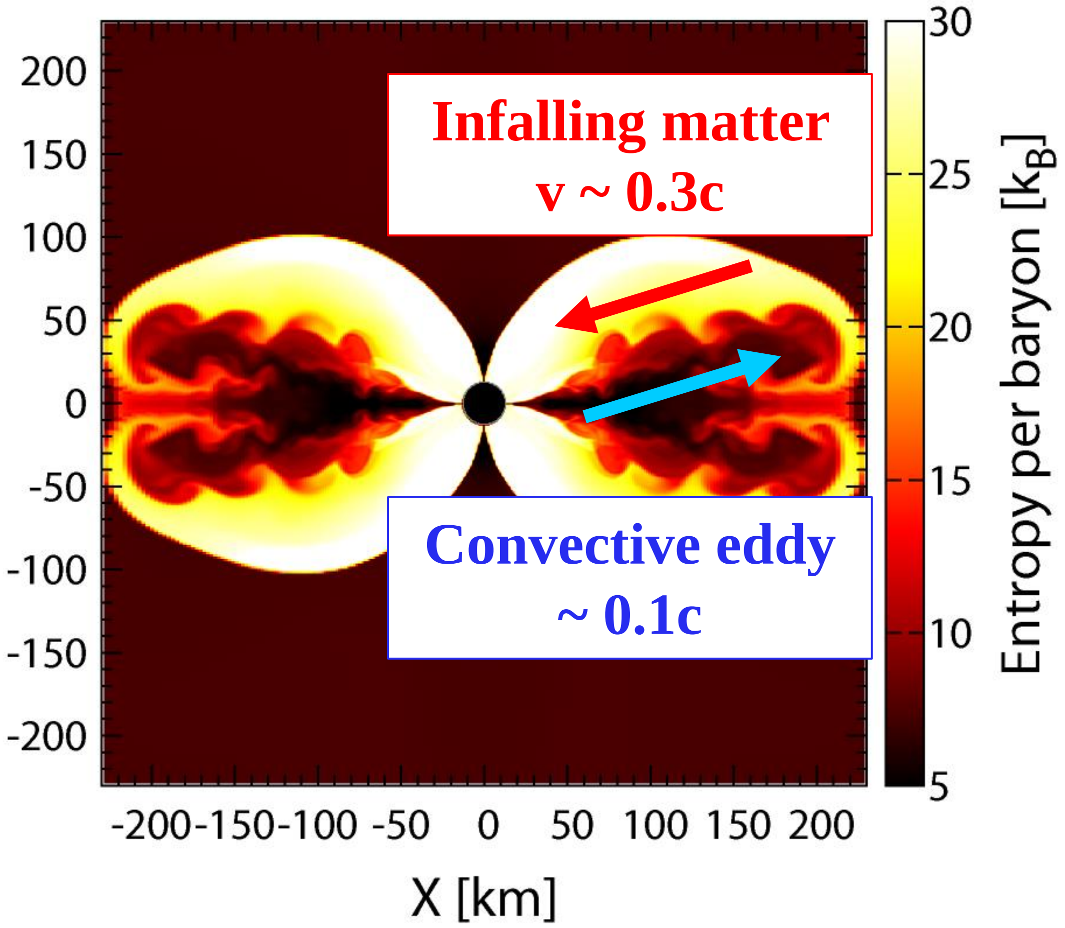
GRB without SNe ? : Collapse of Higher entropy core



Sekiguchi & Shibata (2011)

Kelvin-Helmholtz instability

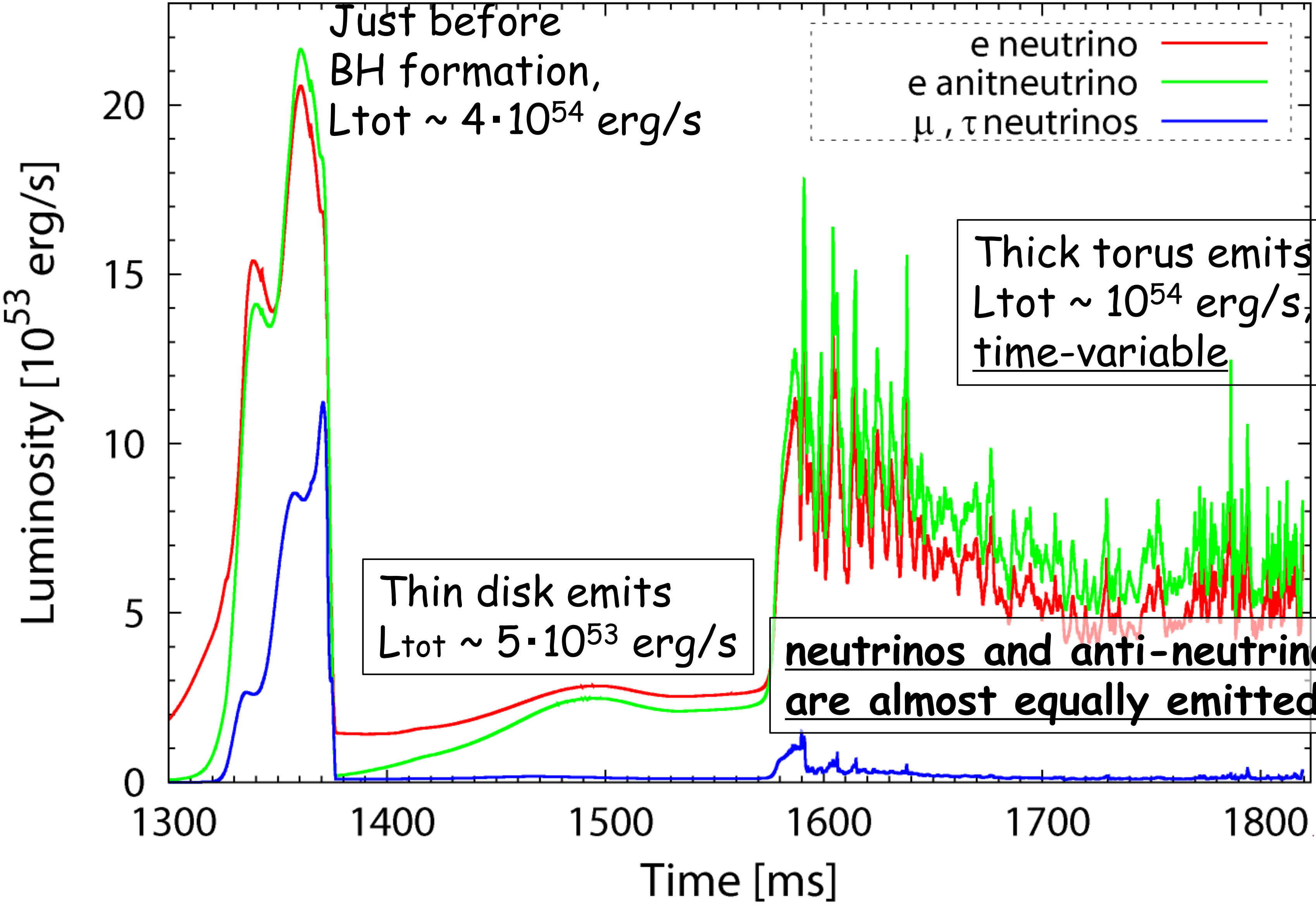




Infalling matter
v ~ 0.3c

Convective eddy
~ 0.1c

Neutrino luminosity



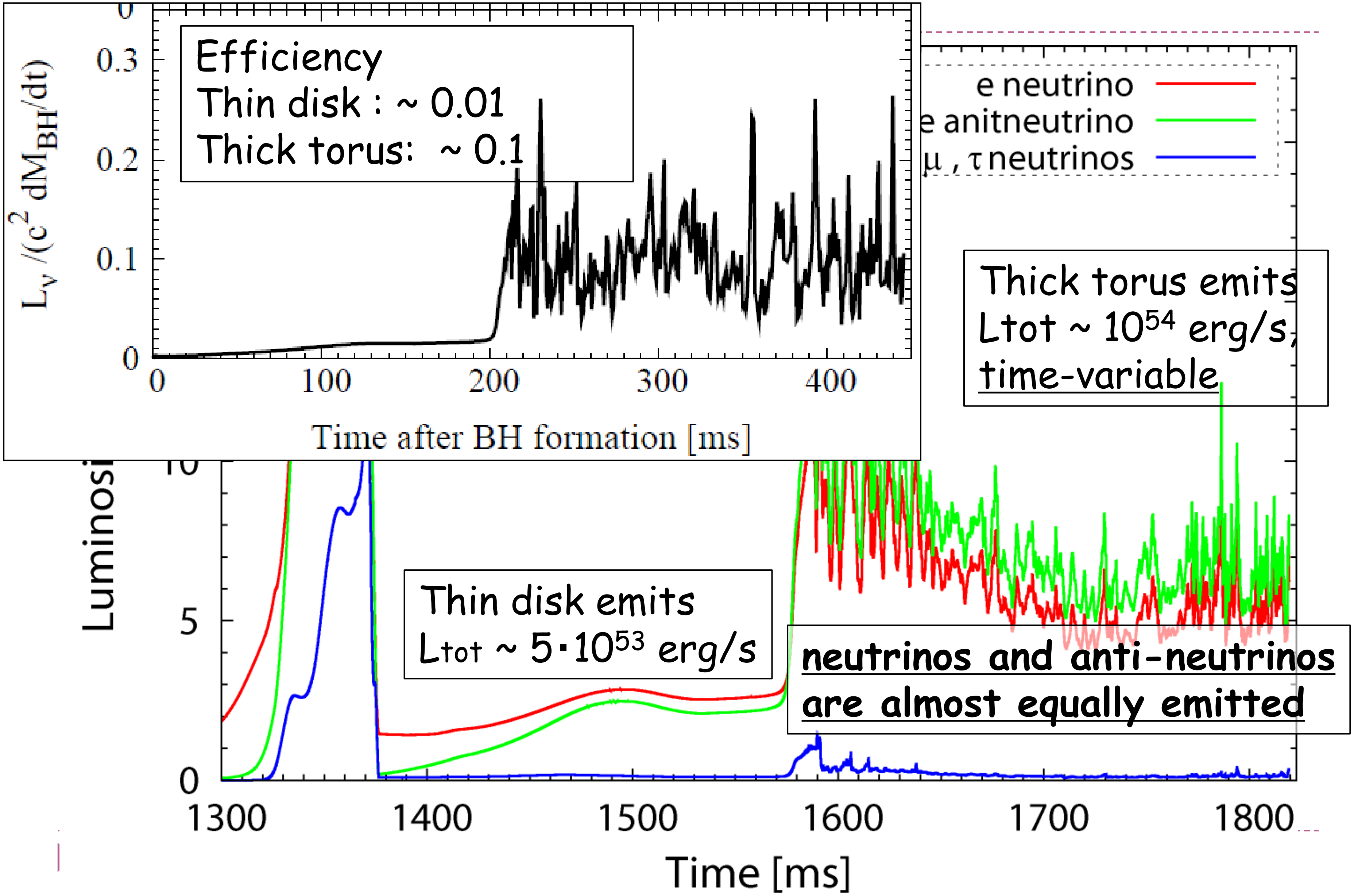
Just before BH formation, Ltot ~ $4\cdot10^{54}$ erg/s

Thick torus emits Ltot ~ 10^{54} erg/s, time-variable

Thin disk emits $L_{tot} \sim 5\cdot10^{53}$ erg/s

neutrinos and anti-neutrinos are almost equally emitted

Neutrino luminosity



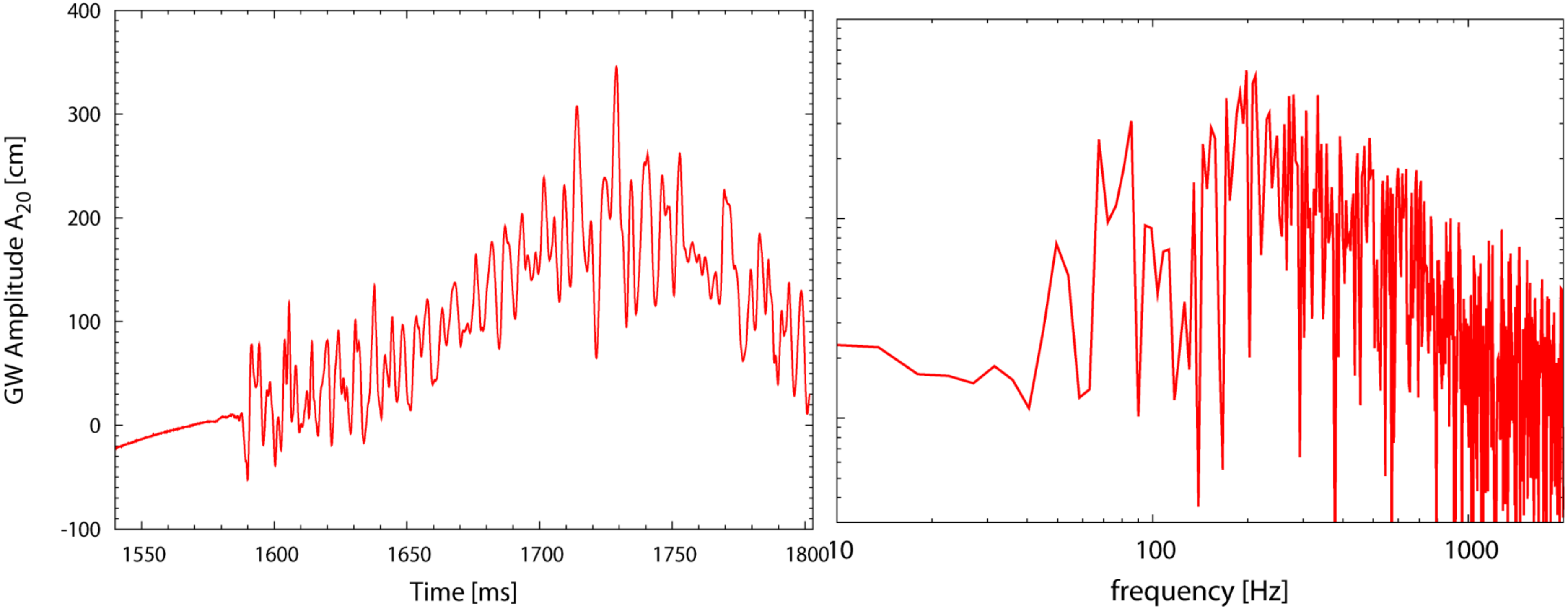
Efficiency
Thin disk : ~ 0.01
Thick torus: ~ 0.1

Thick torus emits
Ltot ~ 10^{54} erg/s,
<u>time-variable</u>

Thin disk emits
Ltot ~ 5・10^{53} erg/s

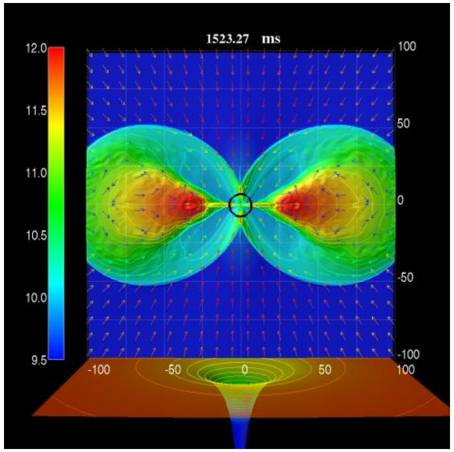
<u>neutrinos and anti-neutrinos are almost equally emitted</u>

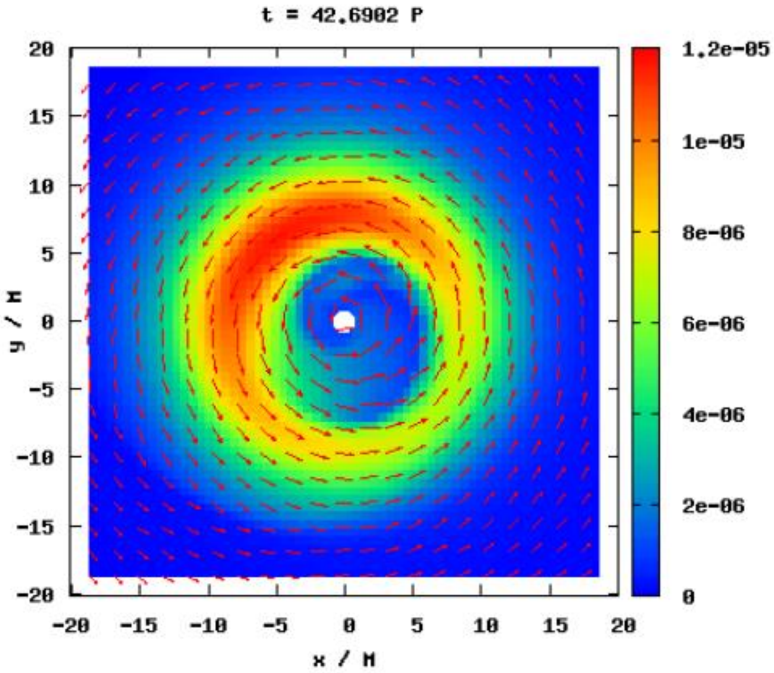
GW from disk convection

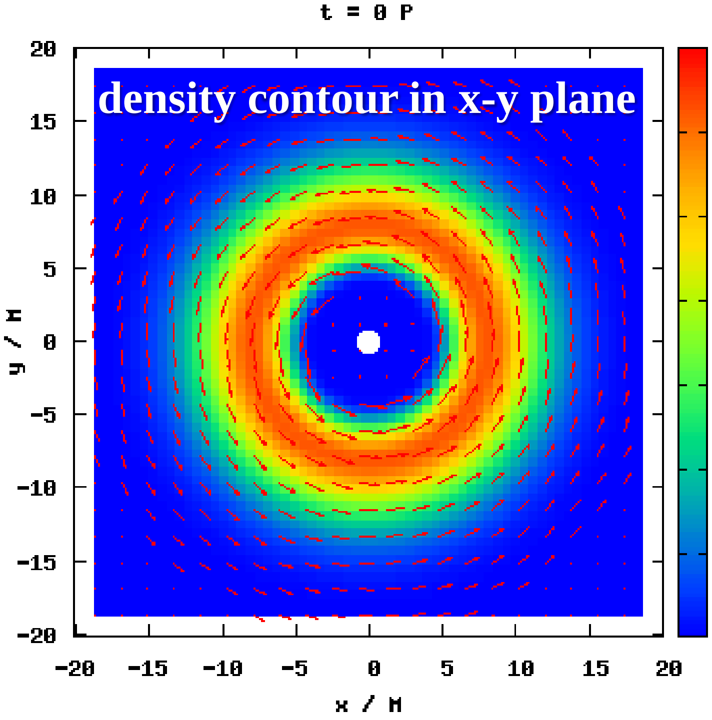


GW from Papaloizou-Pringle instability

- BH + massive disk formation in collapsar
- Subject to Papaloizou-Pringle instability
  - Mode amplification between disk edge and corotation point
    - 3D Full GR simulations by Kiuchi et al. (2011)
  - GWs from D ~ 100Mpc could be detected







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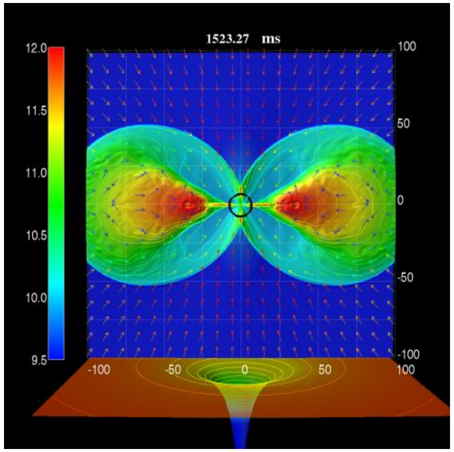
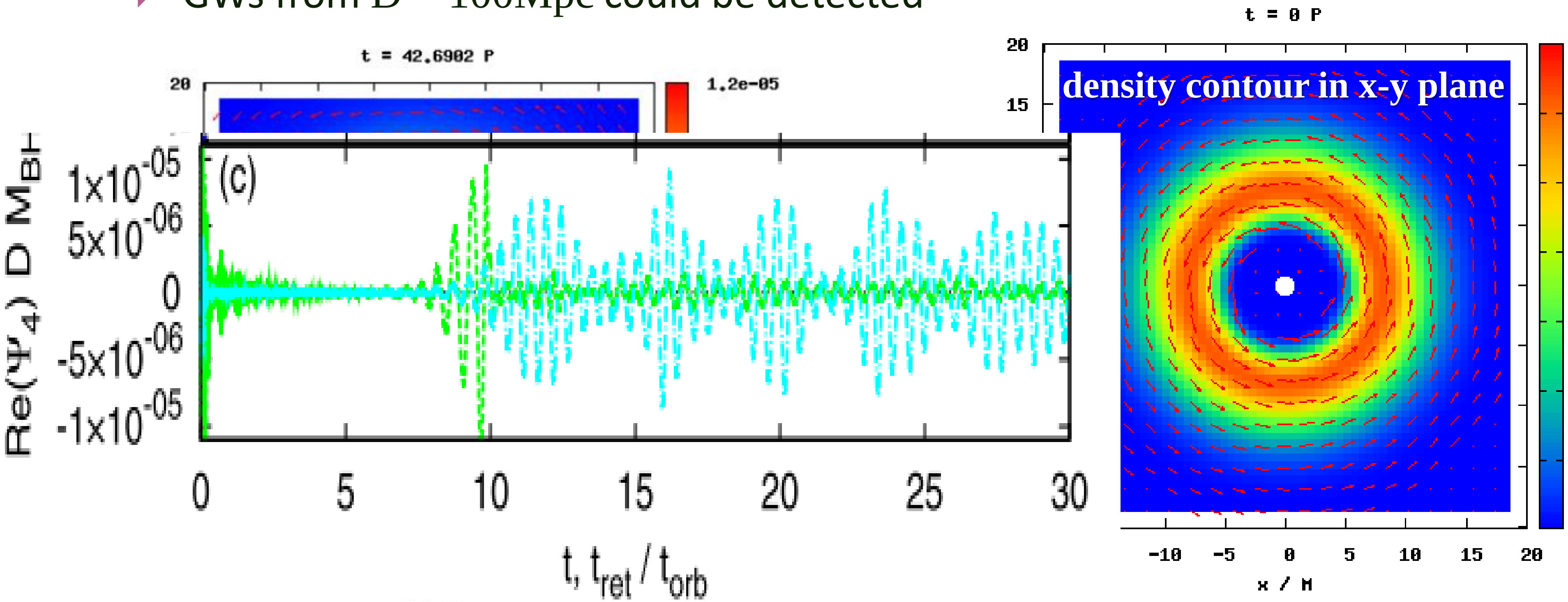
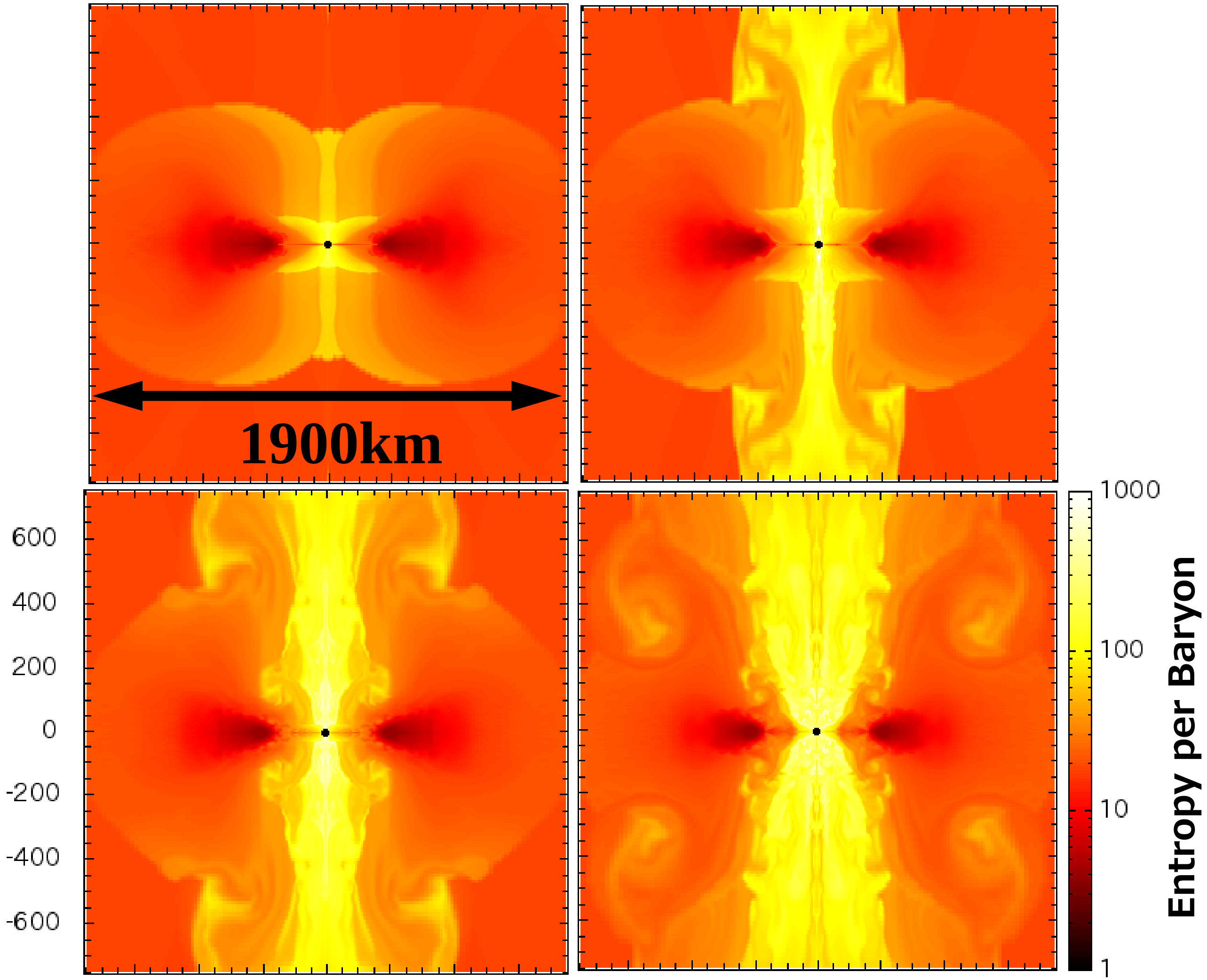




500Msolar-PopIII (Ohkubo et al. 2006) core collapse: Outflow appears even when BH is formed directly



- 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

Neutrino pair annihilation

- $$(\mathrm{eff})_{\nu\bar{\nu}} \equiv \frac{\dot{E}_{\nu\bar{\nu}}}{L_{\nu,\,\mathrm{tot}}} \sim 0.01 \left(\frac{\dot{M}}{M_\odot\,\mathrm{s}^{-1}}\right)^{5/4} \left(\frac{M_{\mathrm{BH}}}{10\,M_\odot}\right)^{-3/2}$$

Zalamea & Beloborodov (2010)

- **$L_{\mathrm{pair}} \sim 10^{49\text{-}50}$ erg/s** for Umeda & Nomoto (2008) model
- **$L_{\mathrm{pair}} \sim 10^{52\text{-}53}$ erg/s** for higher entropy model
- Strong dependence : dot(M)^(9/4) ⇒ early phase

BZ powered Jet

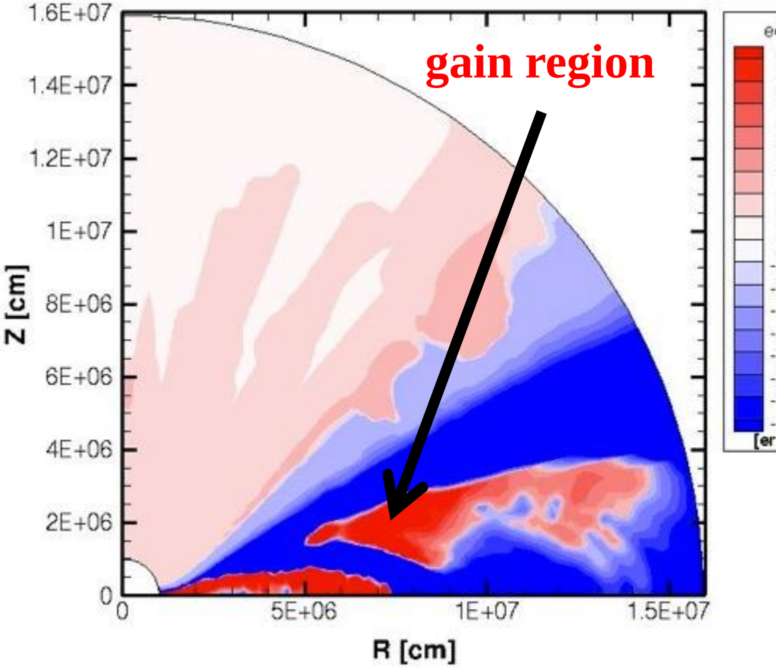
- $$\dot{E}_{\mathrm{BZ}} \sim 10^{52} f_{\Omega_H}\, q_{\mathrm{BH}}^2 \left(\frac{\dot{M}}{M_\odot\,\mathrm{s}^{-1}}\right) \mathrm{erg/s},$$

McKinney (2005)

  - fΩ = 3 (a=0.8), 10 (a=0.9), 80 (a=1.0)
  - ~ 10 % can be used for GRB Jet (McKinney 2005)
- **$L_{\mathrm{BZ}} \sim 10^{50\text{-}51}$ erg/s** for higher entropy model
- **$L_{\mathrm{BZ}} \sim 10^{51\text{-}52}$ erg/s** for higher entropy model
- Weaker dependence : dot(M)^(1) ⇒ later phase

How to make SN component

- Ingredients (ν-sphere + standing shock) are same, topology is different
  - 1. There are 'gain regions'.
  - 2. SASI (Standing Accretion Shock Instability) will set in.
    - Simulations relaxing equatorial symmetry should be done
- Consequences of higher entropy
  - Smaller amount of heavy elements
    - Less severe photo-dissociation loss
    - Fe：$\sim 10^{52}$ erg per $1M_{solar}$
  - Larger ram pressure
    - Larger energy explosion if succeeded
- How important convection is ?
  - Milosavljevic+ 2011



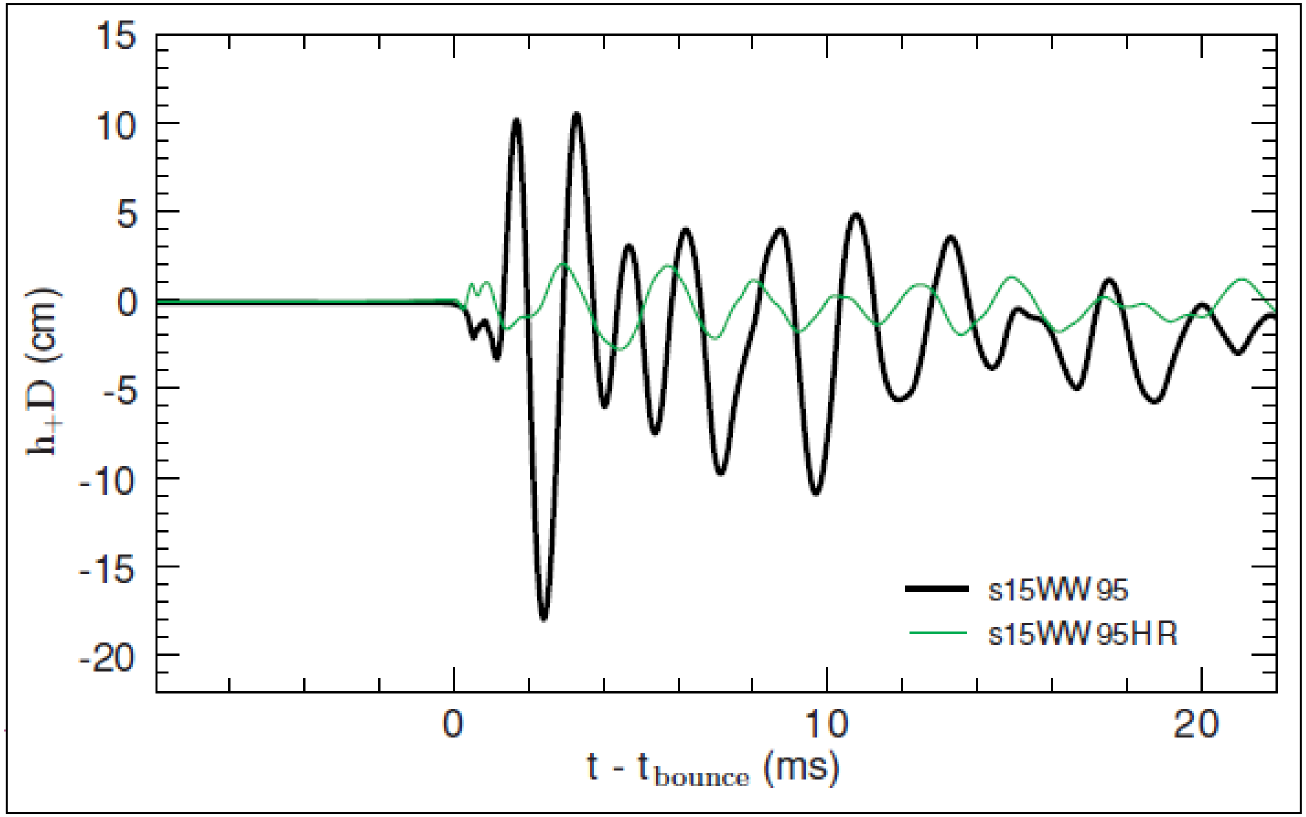
Summary

- The first full GR simulations, incorporating microphysics, of stellar core collapse are performed, adopting high entropy models
- PNS phase in collapsar is good source for GWs and neutrinos
  - Aloy's talk
- BH formation process is quite dynamical, accompanying oblique shock, convection, KH instability, outflows, and so on
  - The dynamics is sensitive to the rotational profile which is poorly known
- Massive accretion disk around BH is also dynamical
  - Time variability in mass accretion rate and neutrino luminosity
  - Could be a strong GW emitter
- The resulting system has preferable features for LGRBs

appendix

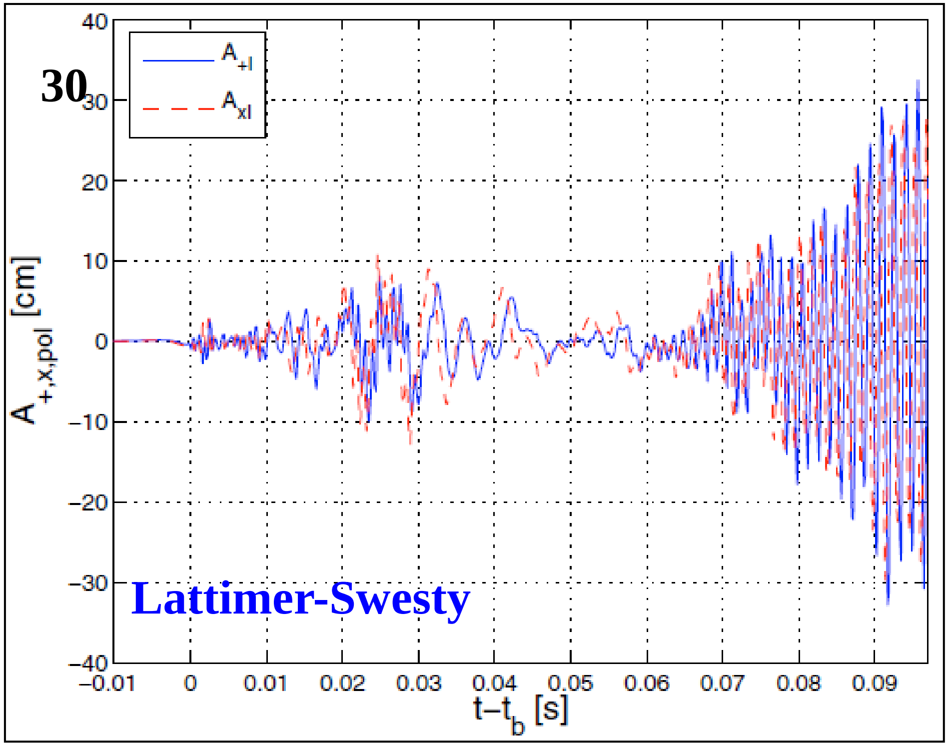
GWs from PNS g-mode

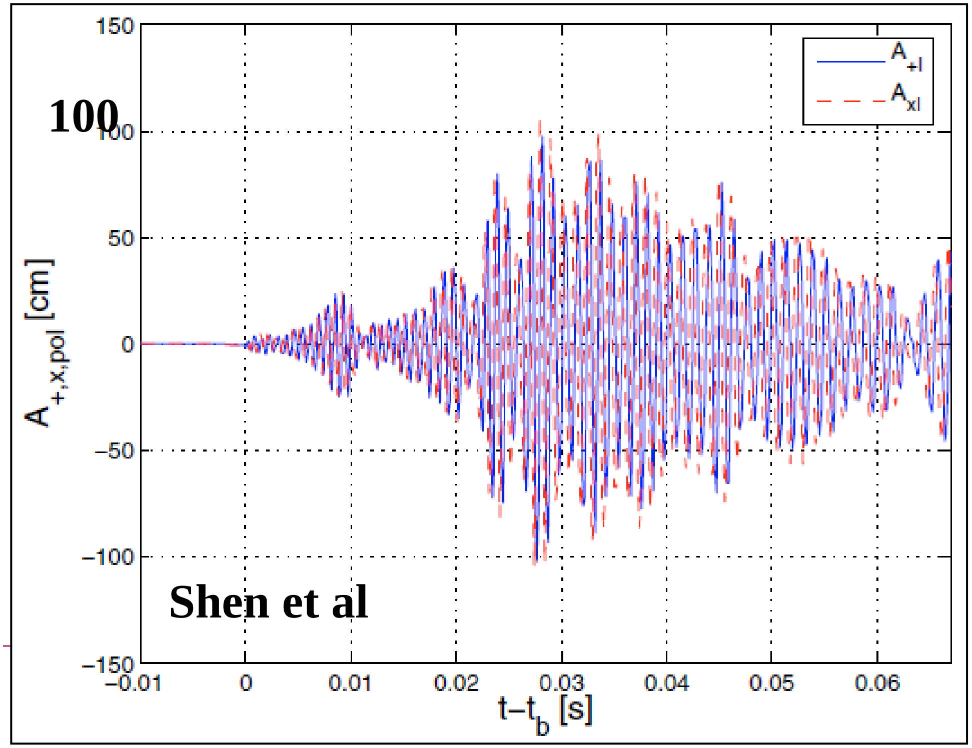
- PNS g-mode (Burrows et al. (2006); Ott et al. (2006)):
  - Can not reproduce in other groups / or very weak
- Ott (2009) : g-mode amplitude strongly depends on grid resolution and grid setting (they use a special grid)



GWs from non-axisymmetric deformation

- Strong EOS dependence (Scheidegger et al. A&A 514, A51 2010)
  - 3D Newtonian MHD simulation without deleptonisation
- **Lattimer-Swesty** vs **Shen** (T/W@bounce ~ 9%)
  - **Amplitude: $\mathbf{h_{Shen}}$** is 3-10 times larger than $\mathbf{h_{LS}}$





Basic equations for (ν-)radiation field

- Boltzmann (3+3+1 dim) equation for the distribution function
  - Computationally not feasible to solve it directly
  - Some approximate treatment is necessary

$$p^a \frac{\partial f}{\partial x^a} + \frac{dp^a}{d\tau}\frac{\partial f}{\partial p^a} = (-p^a u_a) S[x^a, p^a, f]$$

- **Truncated moment formalism** (Thorne 1981; Shibata et al. 2011)
  - Truncation at 2nd order,
  - gray (for simplicity)

$$T_{ab} = \int f(p^c, x^c)\, p_a p_b dV_p = E n_a n_b + F_a n_b + F_b n_a + P_{ab}$$

$$\nabla_b T^{ab} = S^a$$

  - Energy and flux conservation equations for radiation field
    - **Closure relation : $P_{ij}=P_{ij}(E,F_k)$**
      - **essential for properties of radiation fields**
    - **Stiff source terms** (characterized by weak interaction)
      - **numerically cumbersome to treat**

$$\partial_t E + \partial_j(\alpha F_\nu^j - \beta^j E) = \boxed{S_E}$$

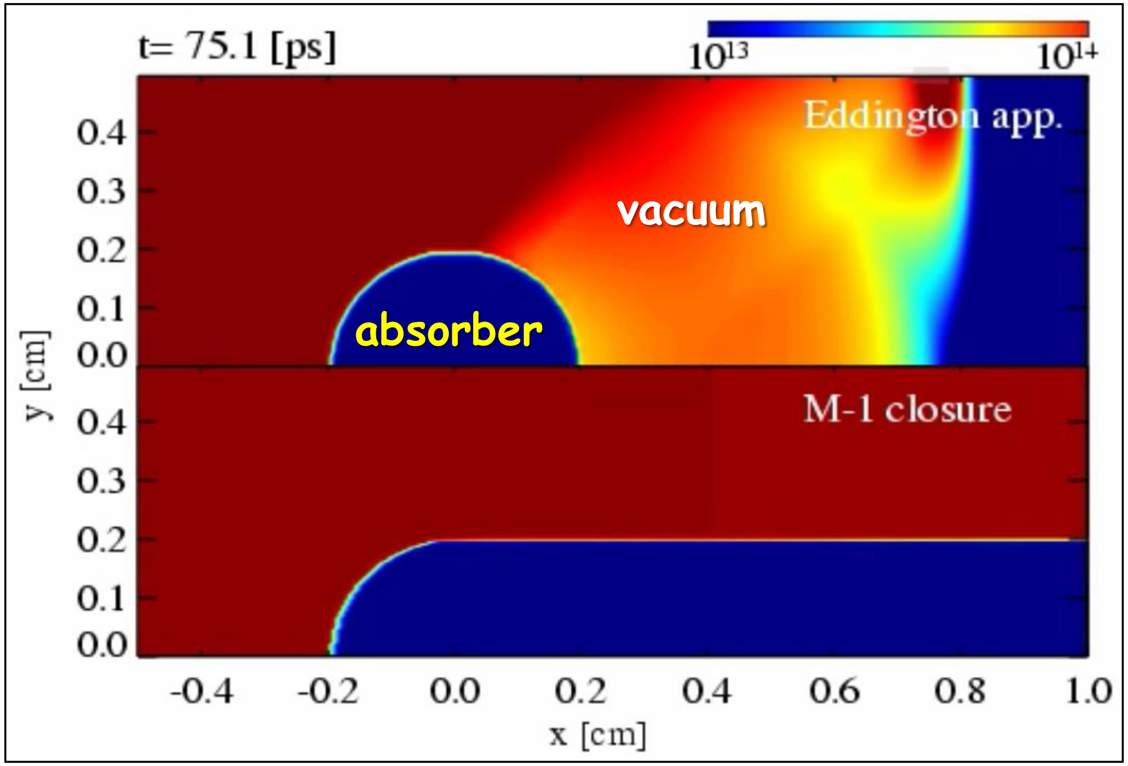
$$\partial_t F_i + \partial_j(\alpha \boxed{P_i^j} - \beta^j F_i) = \boxed{S_F}$$

Closure relation: M-1 closure

- $$P^{ij} = \frac{3\chi-1}{2} P^{ij}_{\rm thin} + \frac{3(1-\chi)}{2} P^{ij}_{\rm thick}$$
- exact in optically thin and thick limits
- can solve the so-called 'shadow test'

$$\chi = \frac{3+4f^2}{5+2\sqrt{4-3f^2}} \qquad f^2 = \frac{F_{0a}F_0^{\ a}}{E_0}$$

$$P^{ab}_{0,\rm thick} = \frac{1}{3}E_0(g^{ab}+u^a u^b) \qquad P^{ab}_{0,\rm thin} = E_0 \frac{F_0^{\ a} F_0^{\ b}}{|F_0|^2}$$



Takahashi, Ohsuga, YS, Inoue, & Tomida (2013)

Approx. Explicit treatment

- A problematic issue
  - ***Local***, weak timescale is too short in dense regions

$$\boxed{t_{\text{weak}} \sim Y_e / \dot{Y}_e \;<<\; t_{\text{dyn}}}$$

- ***Leak-out timescale*** with which neutrinos leak away from the system is ***much longer***

$$\boxed{t_{\text{weak}} << t_{\text{leak}} (\sim R/c) \sim t_{\text{dyn}}}$$

- Rewrite the system of equation using this

$$\boxed{\begin{aligned} \nabla^a T^{\text{Fluid}}_{ab} &= -Q^{(\text{weak})}_b \\ \nabla^a T^{\;\nu}_{ab} &= Q^{(\text{weak})}_b \end{aligned}} \;\Rightarrow\; \boxed{\begin{aligned} \nabla^a T^{\text{Fluid}}_{ab} &= -Q^{(\text{leak})}_b \\ \nabla^a T^{\;\nu}_{ab} &= Q^{(\text{leak})}_b \end{aligned}}$$

- We can also include the neutrino heating in this framework

$$\boxed{S^a_{(\nu\text{-heating})} = \kappa_{(\nu)} \left[(J^{\beta\text{-eq}} - J) u^a - H^a \right]}$$

Approx. Explicit treatment

- **Step 1.** Neutrinos are divided into ‘trapped’ and ‘streaming’ parts

$$\boxed{T^{(\nu)}_{ab} = T^{(\nu,\mathrm{trap})}_{ab} + T^{(\nu,\mathrm{stream})}_{ab}}$$

$$\begin{array}{|l|}\hline \nabla_a \left(T_b^{a\,(\nu,\,\mathrm{trap})} + T_b^{a\,(\nu,\,\mathrm{stream})}\right) = Q_b^{(\mathrm{weak})} \\ \nabla_a T_b^{a\,(\nu,\,\mathrm{trap})} = Q_b^{(\mathrm{weak})} - Q_b^{(\mathrm{leak})} \\ \boxed{\nabla_a T_b^{a\,(\nu,\,\mathrm{stream})} = Q_b^{(\mathrm{leak})}} \\ \hline \end{array}$$

  - Trapped : interact sufficiently frequently with matter
  - Streaming : phenomenological flow of freely streaming neutrinos (characterized by **leakage timescale**)

- **Step2.** Trapped-ν is combined with fluid part: $\boxed{T_{ab} = T^{(\mathrm{fluid})}_{ab} + T^{(\nu,\mathrm{trap})}_{ab}}$

$$\begin{array}{|l|}\hline \nabla_a T_b^{a\,(\mathrm{fluid})} = -Q_b^{(\mathrm{weak})} \\ \nabla_a T_b^{a\,(\nu,\,\mathrm{trap})} = Q_b^{(\mathrm{weak})} - Q_b^{(\mathrm{leak})} \\ \hline \end{array} \Longrightarrow \boxed{\nabla_a T_b^{a} = -Q_b^{(\mathrm{leak})}}$$

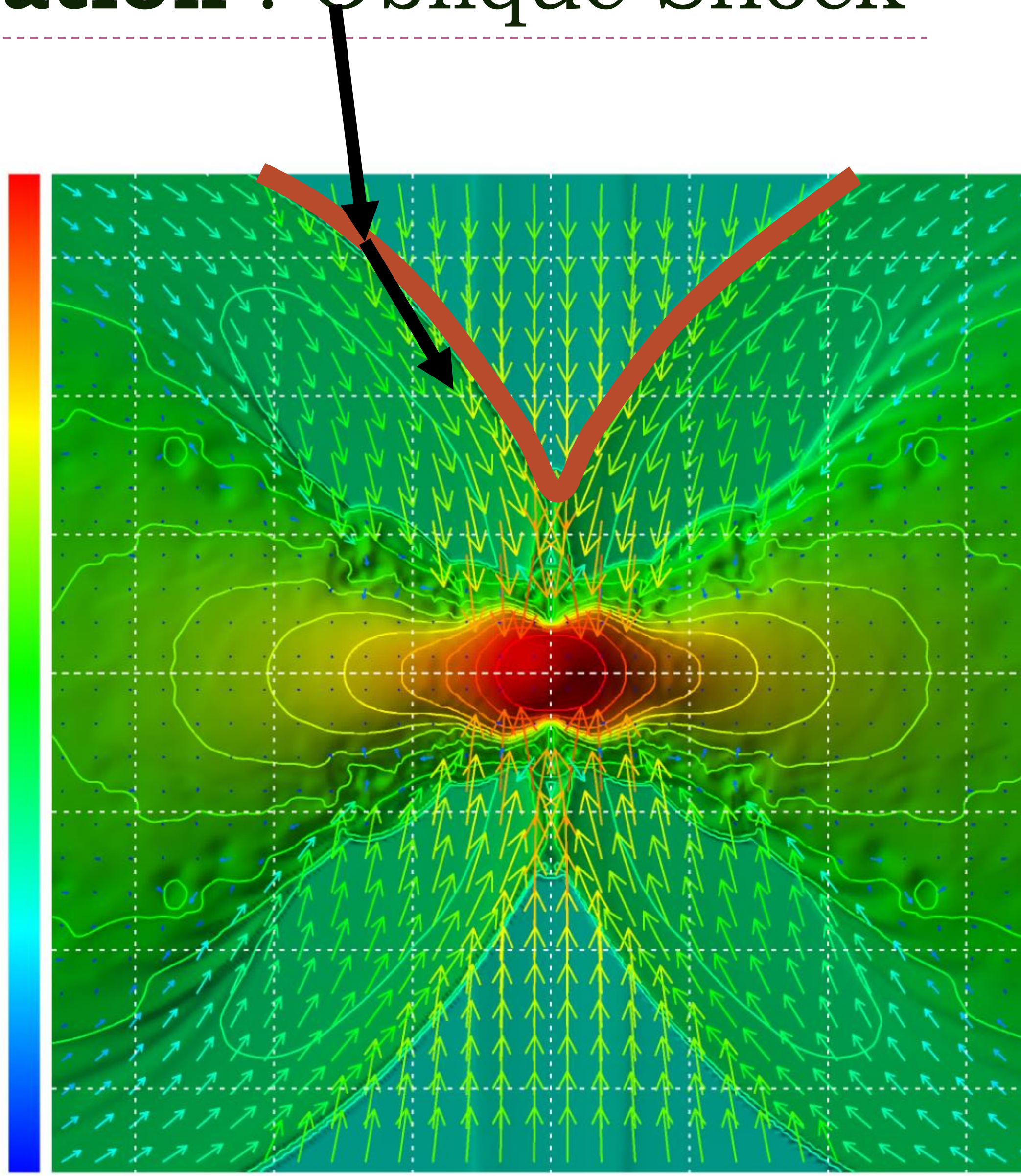
  - Solve this equation using truncated (two) momentum formalism

- **Summary.** The equations to be solved is characterized by $t_{,\mathrm{leak}}$

See Sekiguchi et al. (2013) for further details

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 near 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| & |Qν| (dense disk)**
  - **Additional 'cooling' sources required**

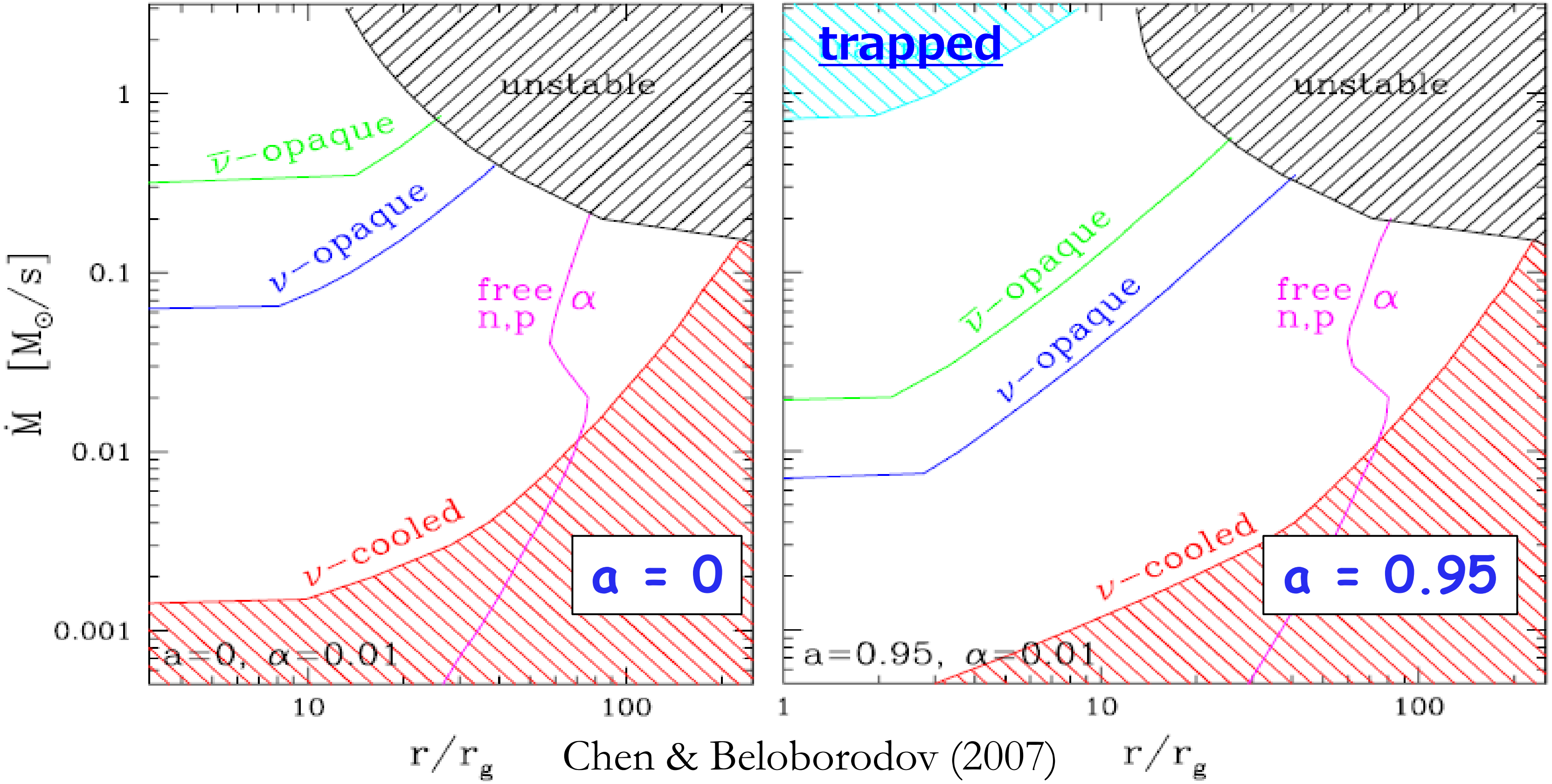
$$\dot{Q}^{+}_{\mathrm{acc}} = \dot{Q}^{-}_{\mathrm{adv}} + \dot{Q}^{-}_{\nu}$$

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

  - **Strong dependence of Qν (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**

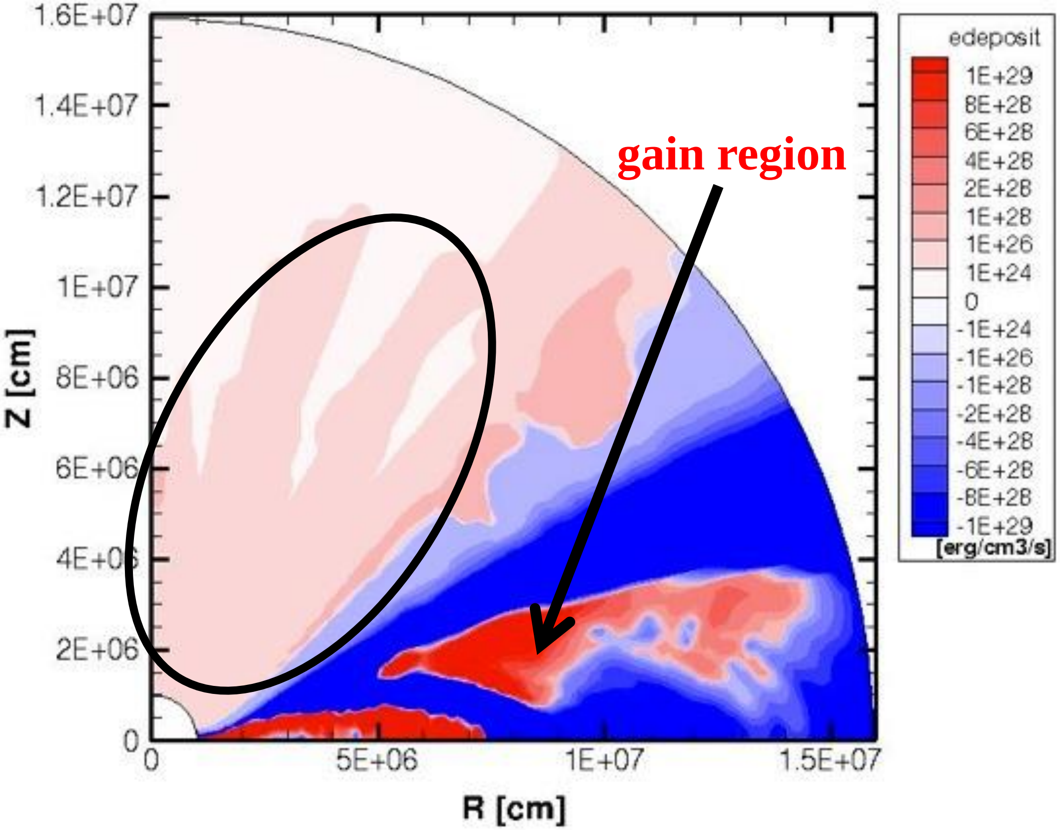


Chen & Beloborodov (2007)

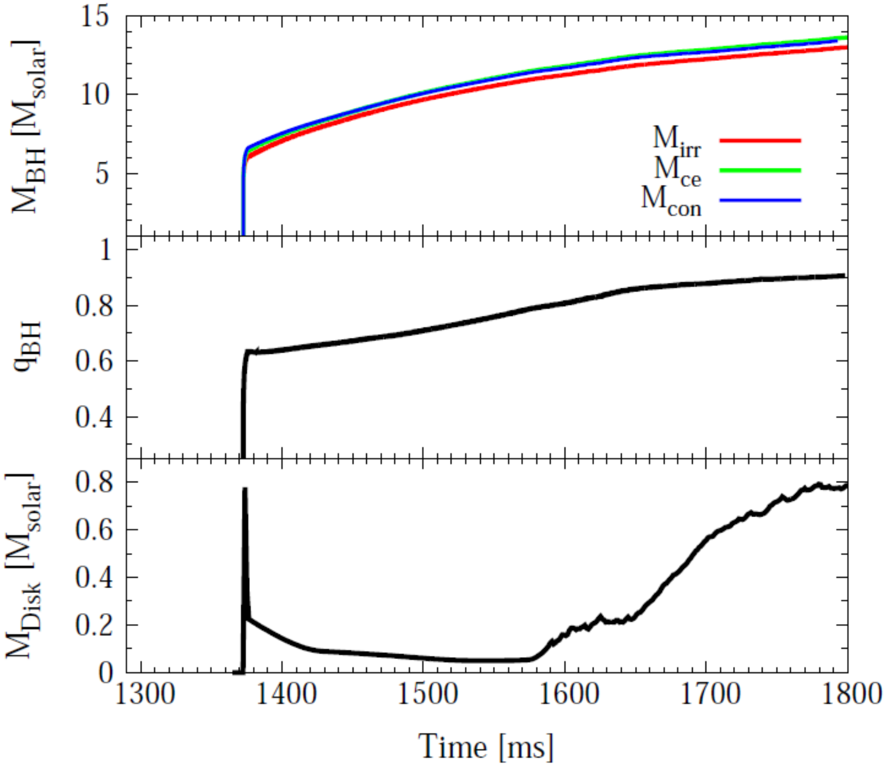
Similarities to ordinary SN

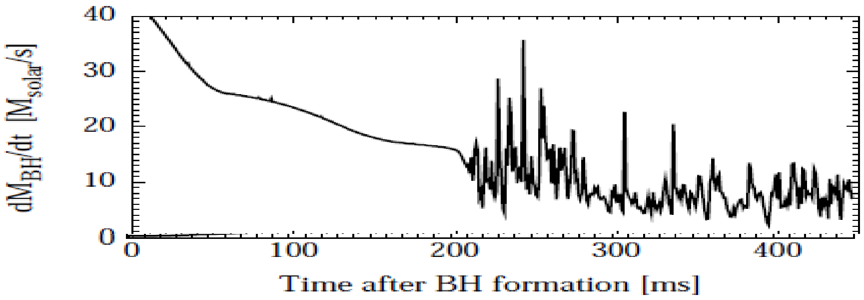
- Same components: ‘stalled’ shock + neutrino sphere/torus
  - **SASI-like activities are likely to occur**
  - **The gain (neutrino-heated) regions do exist**
  - Only topology is different

- **Smaller amount of heavy nuclei due to high entropy ⇒ more energetic SNe ?**
  - Dissociation of 0.1 Msolar Fe costs ~ 10^{51} erg



Property of the BH and the accretion disk





- BH mass : 6.5 M_{solar} → 14 M_{solar}
- BH spin : 0.6 → 0.9
- Disk mass :
  - thin disk phase ~ 0.1 M_{solar}
    - Rapid advection into BH
  - Thick torus phase ~ 0.8 M_{solar}
    - High angular momentum
- Mass accretion rate into BH
  - Thin disk phase ~ 20-40 M_{solar}/s
  - Convective torus ~ 5-10 M_{solar}/s rapid time variability