Gravitational waves and neutrino emissions from the merger of binary neutron stars

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Introduction

Coalescence of binary neutron stars

✓Promising source of GWs ⇒ Verification of GR

✓Theoretical candidate of Short-Gamma-Ray Burst

✓High-end laboratory for Nuclear theory

Mass-Radius relation for Neutron Star ⇒ True nuclear theory

GW detectors

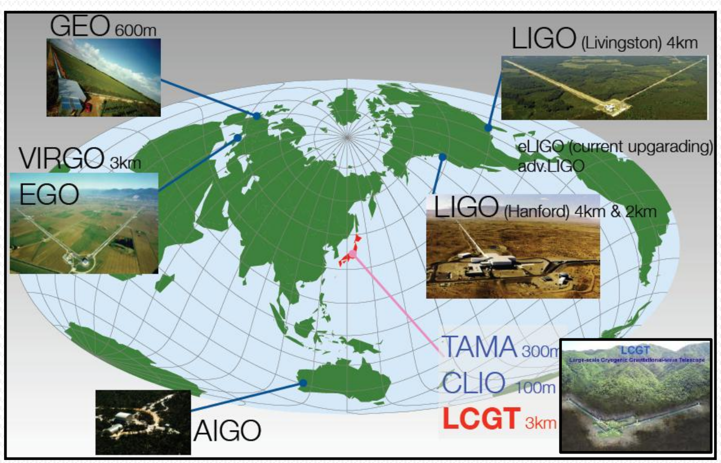
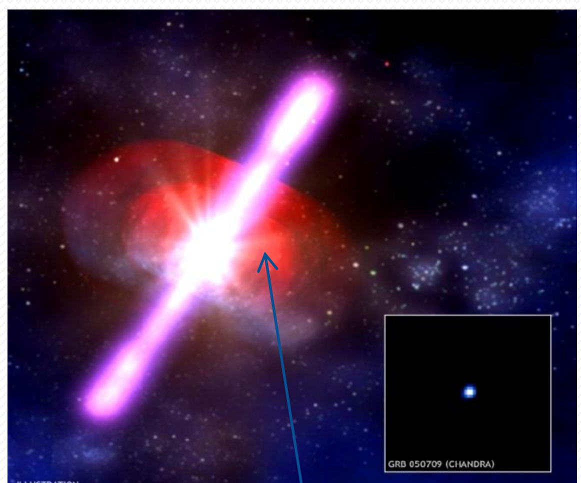
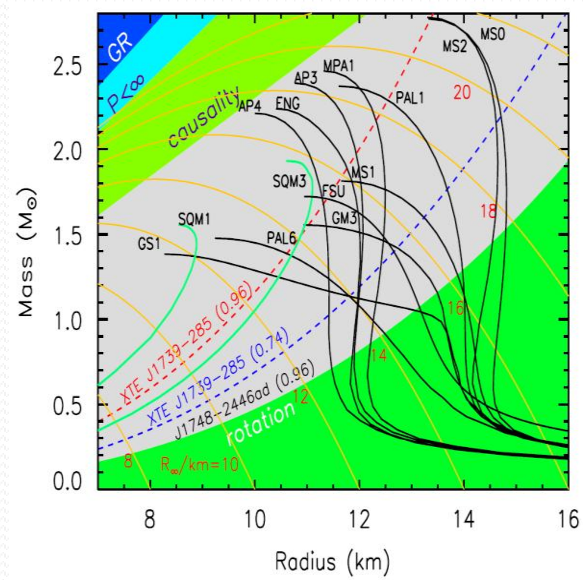


Image of GRB



Black hole + disk?

Mass-Radius

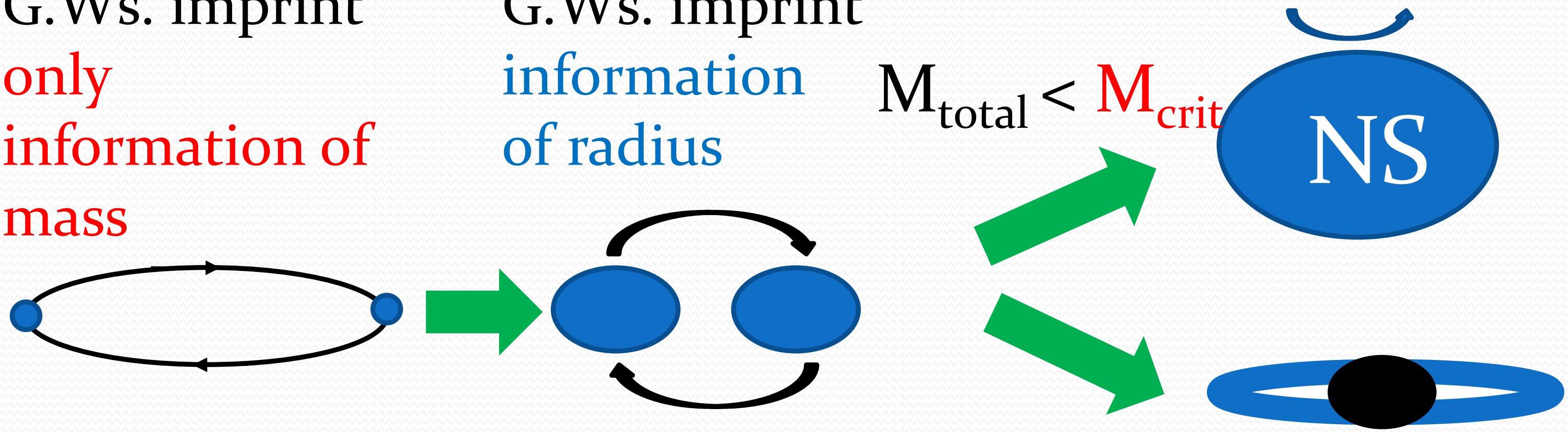


Overview of binary neutron star merger

Rapidly rotating massive NS

G.Ws. imprint only information of mass

G.Ws. imprint information of radius



BH and torus

✓ M_{crit} depends on the Equation of State, i.e. M_{crit} = 1.2-1.7 M_{max} (Hotokezaka+11)

✓ Final massive NS or torus around BH are extremely hot, T ~O(10) MeV ⇒Neutrino cooling plays an important role

<u>So far, the microphysics is neglected in NR simulations, except for the special case (Oechslin-Janka 07).</u>

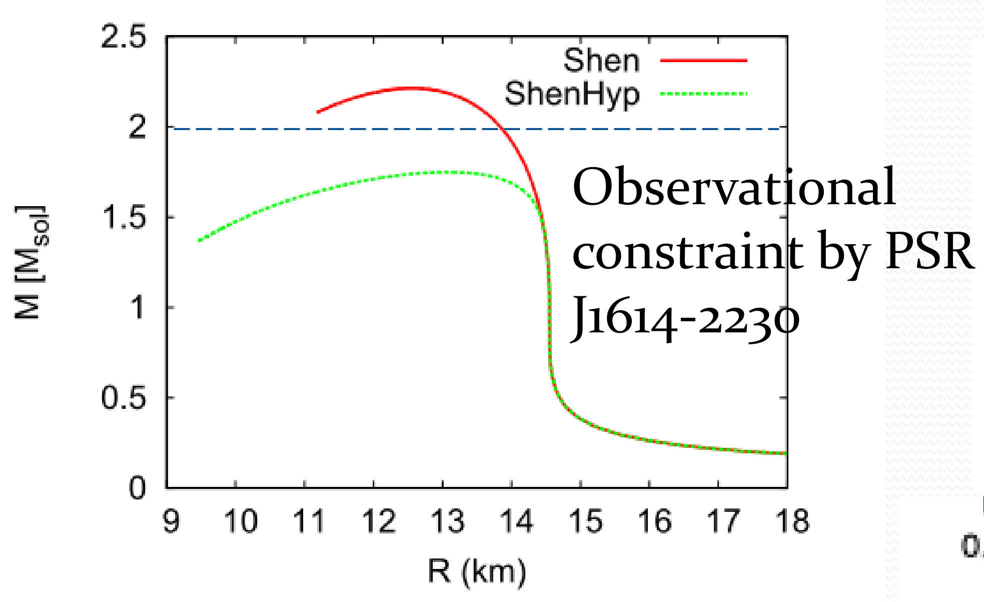
Set up of binary neutron star

○ Shen EOS based on RMF theory (Shen+,98) ⇒ M_{crit} = 2.8-2.9 $M_\odot$

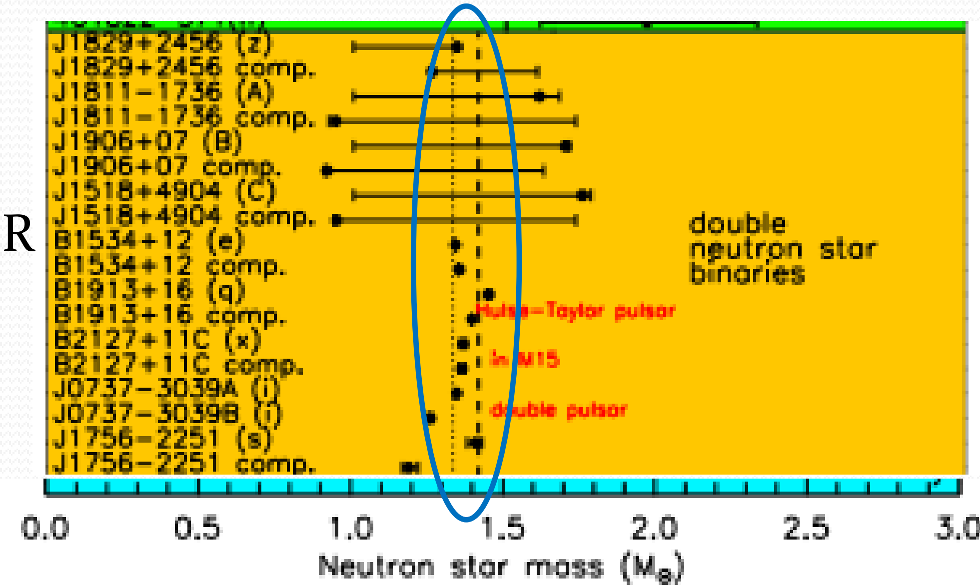
○ Equal mass model with 1.35, 1.5, 1.6 $M_\odot$, i.e., M_{tot}=2.7, 3, 3.2 $M_\odot$

⇒ Light model : Hyper massive NS, Normal model : marginal, Heavy model : BH

Mass-Radius



Observed BNSs (Lattimer & Paraksh 06)



Basic equations

$G_{\mu\nu} = 8\pi T_{\mu\nu} \Rightarrow$ BSSN formulation (Shibata-Nakamura, 95, Baumgarte-Shapiro, 99)

$\nabla_\mu(\sqrt{-g}\rho u^\mu) = 0$

$\nabla_\mu(T^{\mu\nu}_{\text{(fluid)}}) = -Q^\nu \Rightarrow$ HRSC scheme (LLF)

$\nabla_\mu(T^{\mu\nu}_{\text{(rad)}}) = +Q^\nu$: Radiation field

$\frac{d}{dt}Y_{e,\nu_e,\bar{\nu}_e,\cdots} = \gamma_{e,\nu_e,\bar{\nu}_e,\cdots}$: Electron fraction etc.

$Q^\mu \& \gamma_{e,\nu_e,\bar{\nu}_e,\cdots} \Rightarrow$ GR leakage scheme (Sekiguchi 10)

Reaction : $e^- + p \to n + \nu_e,\ e^+ + n \to p + \bar{\nu}_e,\ \cdots$

<u>Numerics</u>

Non-uniform grid structure with $\Delta x_{\text{uni}} = 300\text{m}, \quad L \approx 500\text{km}$

4th-order Runge-kutta shceme

Einstein equations : 4th-order accuracy in space

Hydrodynamics : 3rd-order accuracy in space

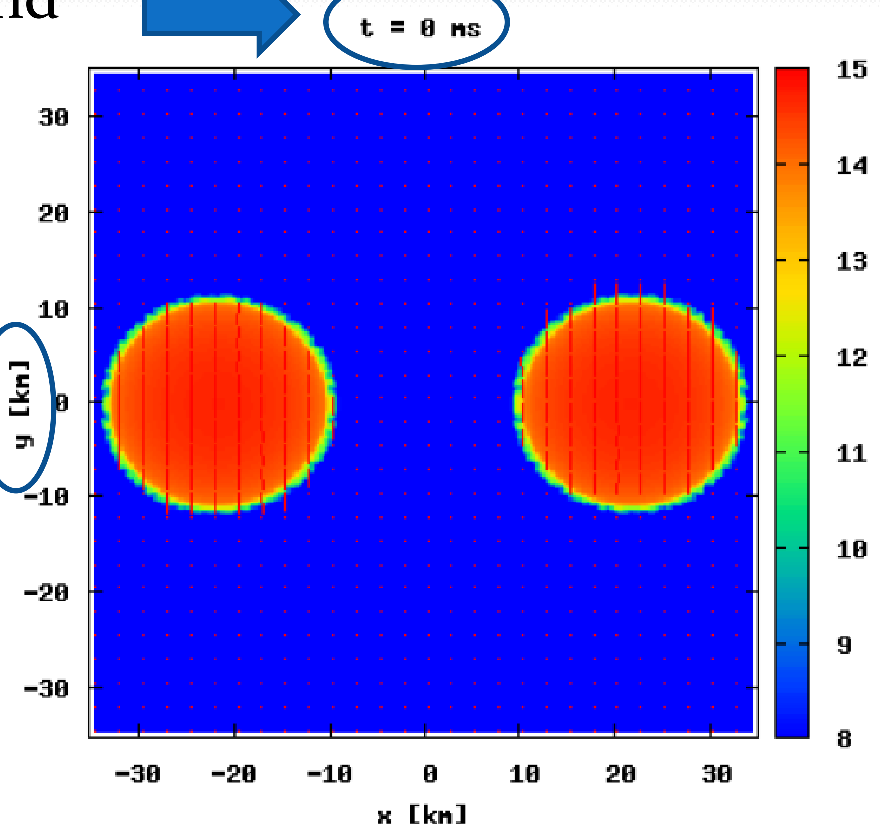
Result

Density color contour on x-y plane = orbital plane

In units of millisecond

In units of kilometer

$\mathrm{Log}_{10}(\rho\ [g/cc])$

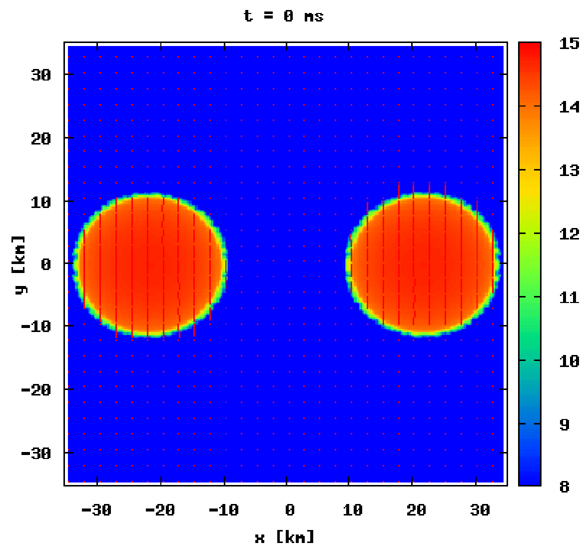


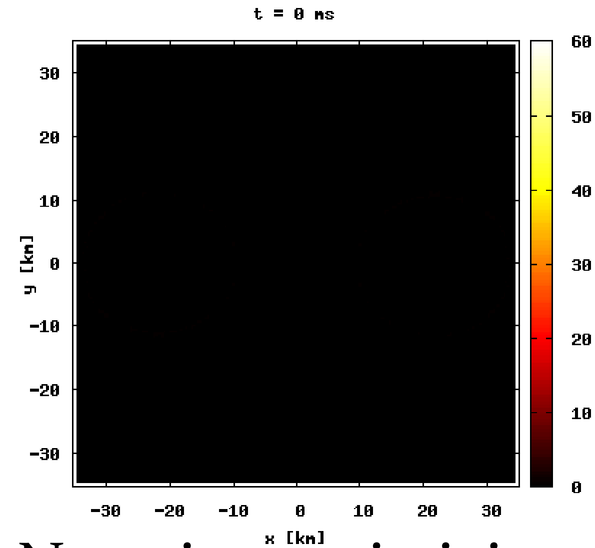
Light model (2.7 $M_{\odot}$)

Density

Temperature

x-y plane

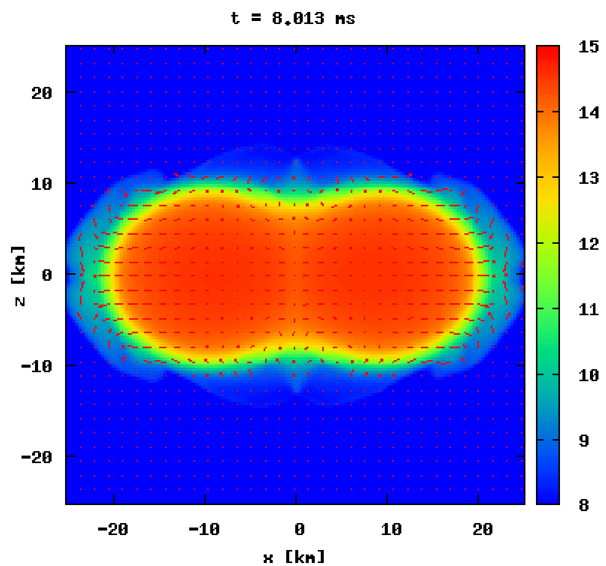


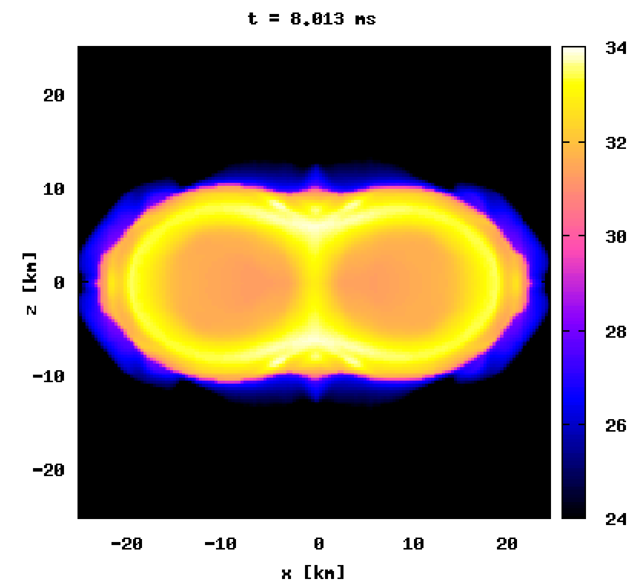


MeV

Neutrino emissivity

x-z plane





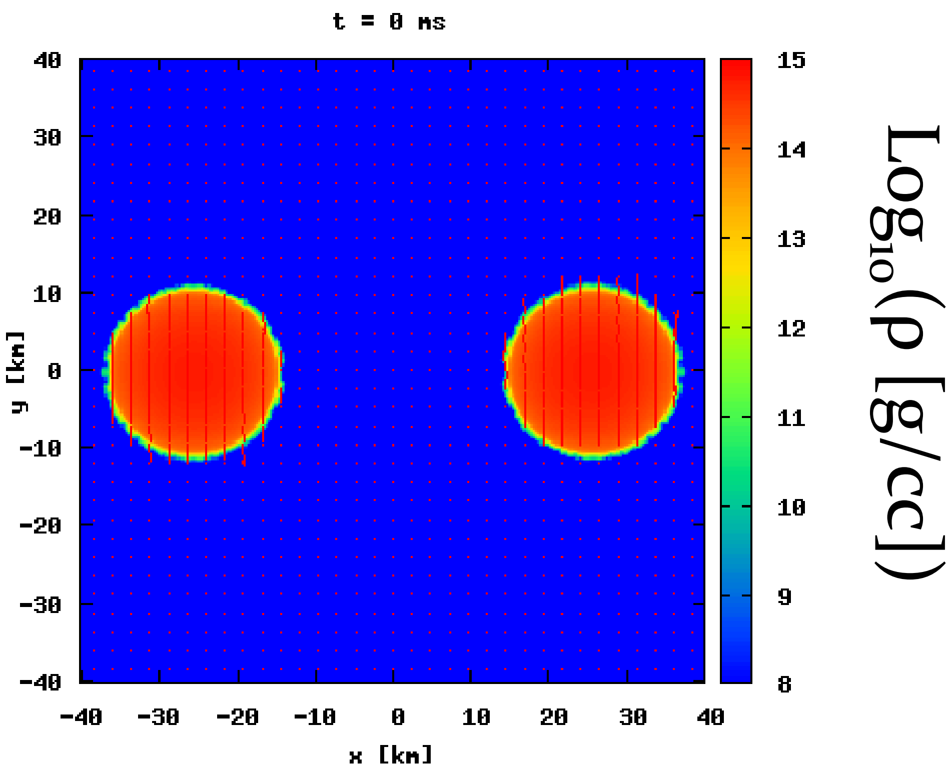
$\mathrm{Log}_{10}(\mathrm{erg/s/cc})$

Dependence of total mass on merger process

○ M_{crit} = 2.8-2.9 $M_\odot$ for Shen EOS

⇒ M_{tot}=3.2 $M_\odot$ model is expected to collapse to a BH directly.

Heavy model (3.2 $M_\odot$)



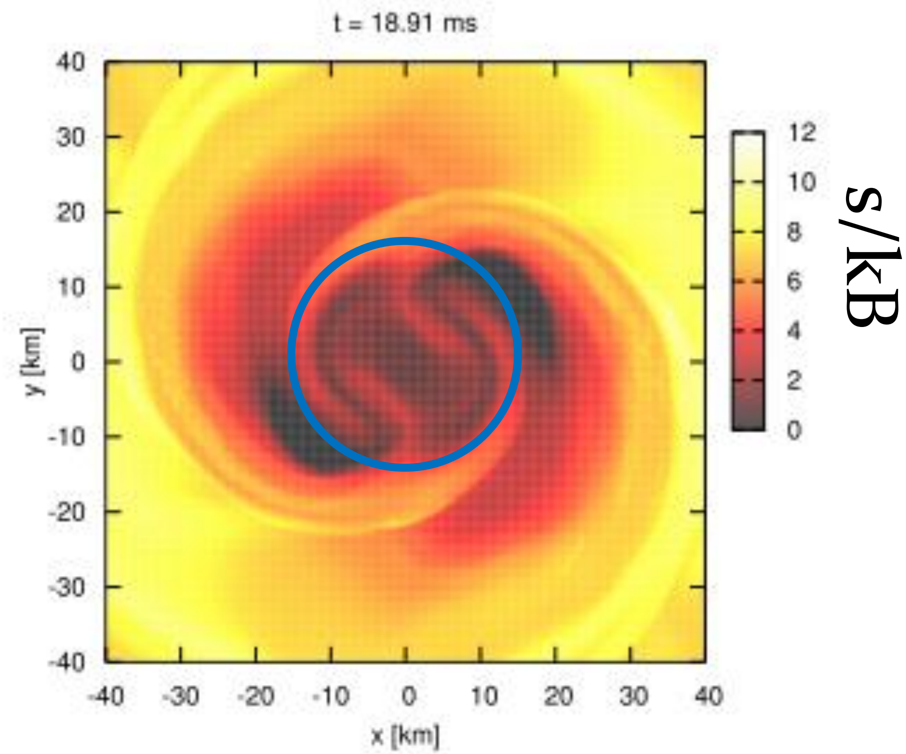
Hyper massive neutron star (HMNS) is transiently produced

⇒ Black hole

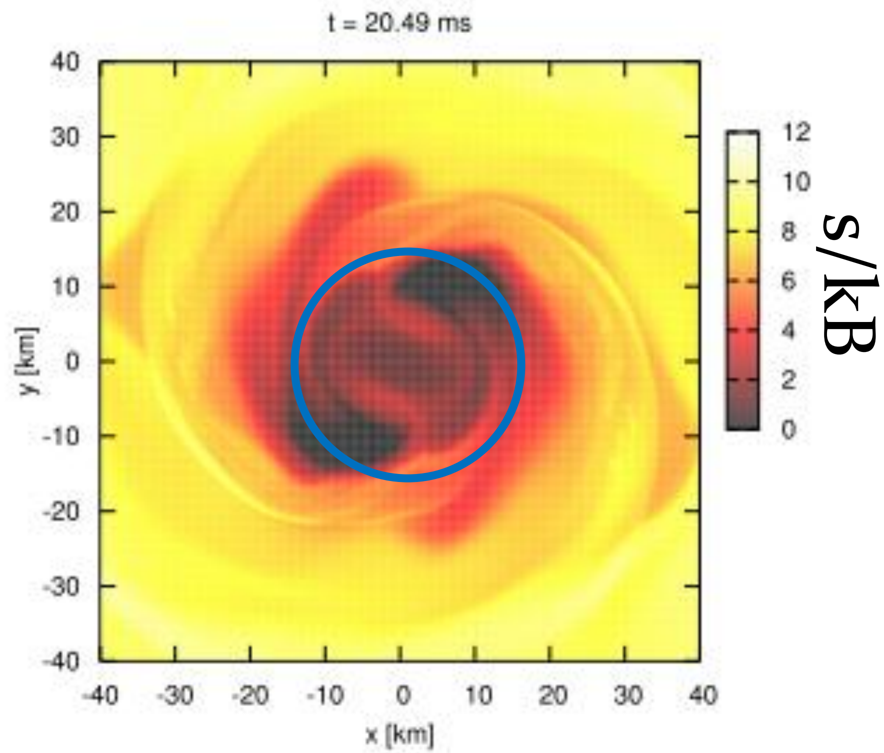
Finite temperature effect

Entropy / baryon on x-y plane

just after the contact



2 ms after the contact



Finite temperature as well as rapid rotation bottoms up M_{crit}

$\Rightarrow$ Maximum mass of an equilibrium configuration of differentially rotating star with non-zero T EOS (Galeazzi+ 11)

Gravitational Waveforms

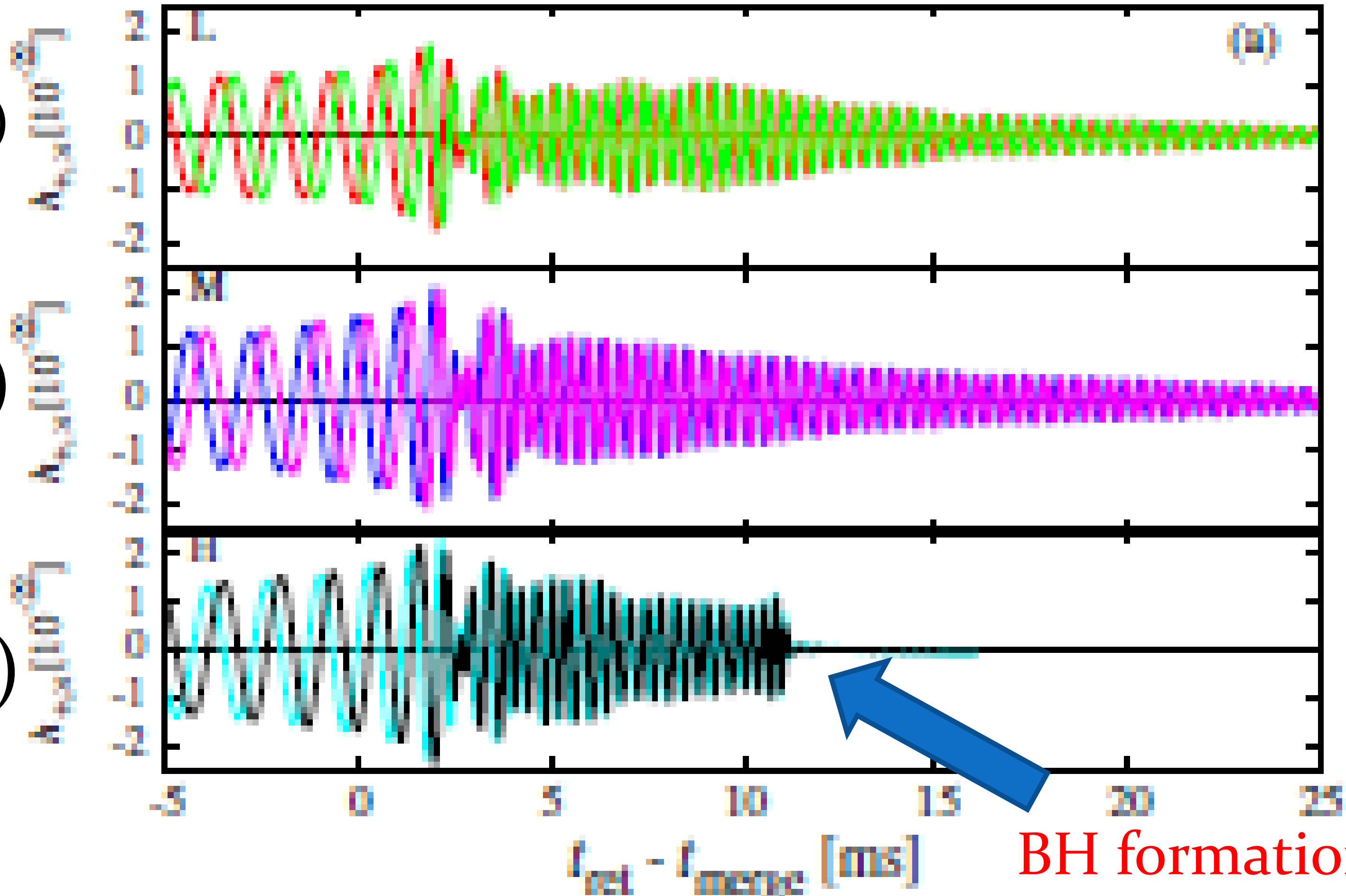
NSs orbit around each other

Massive NS oscillates

Light (2.7 $M_\odot$)

Normal(3 $M_\odot$)

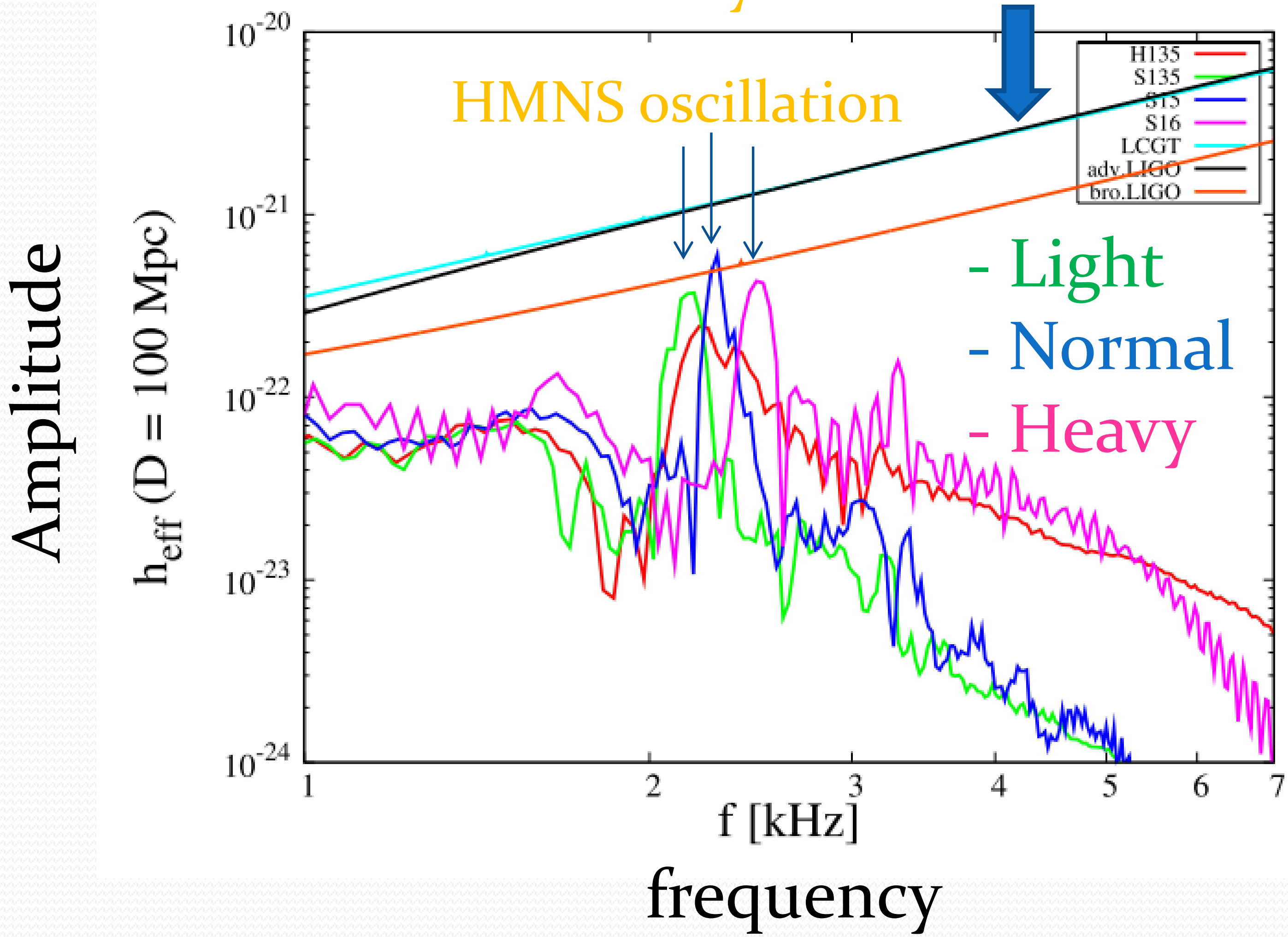
Heavy(3.2 $M_\odot$)



BH formation

Gravitational Wave Spectrum

Sensitivity curves for LCGT and LIGO

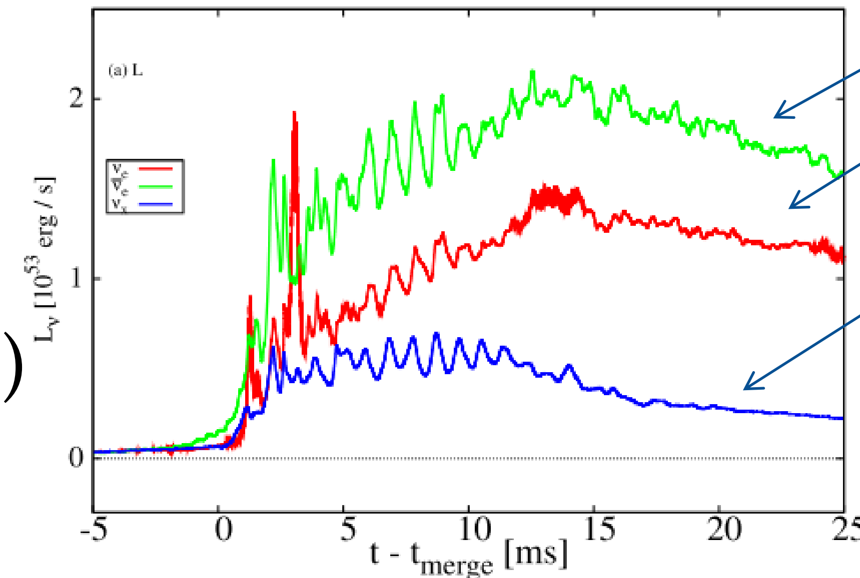


GWs could be detected if the merger happens within 20 Mpc.

Constraining EOS from HMNS peak frequency (Stergioulas+ 11)

Neutrino Luminosity

Light ($\underline{2.7}\ M_\odot$)



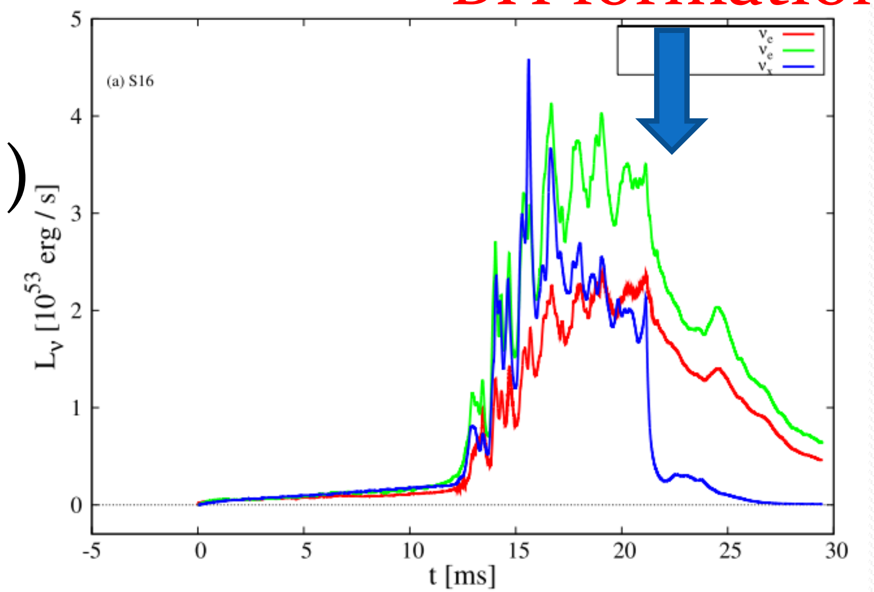
Anti electron neutrino

Electron neutrino

μ, τ neutrino

Heavy ($3\underline{.2}\ M_\odot$)

BH formation



○ Huge luminosity ~ 10^{53} erg/s even after BH formation

○ Neutrino cooling timescale ~ 2-3 second

○ Could be detected if it happened within 5 Mpc for Hyper Kamiokande

Hierarchy of Neutrino Luminosity

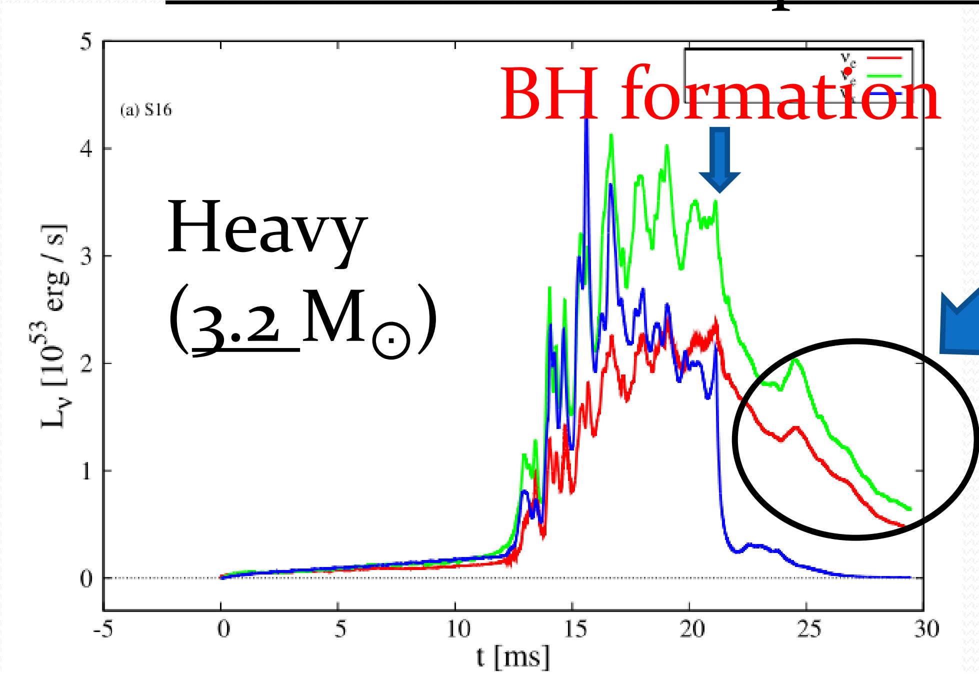
Hierarchy is $\bar{\nu}_e,\ \nu_e,\ \nu_{\mu,\tau}$

High temperature in HMNS $\Rightarrow$ e^- & e^+ by thermal photon, in particular the HMNS envelope

○ $n + e^+ \Rightarrow p + \bar{\nu}_e$

△ $p + e^- \Rightarrow n + \nu_e$

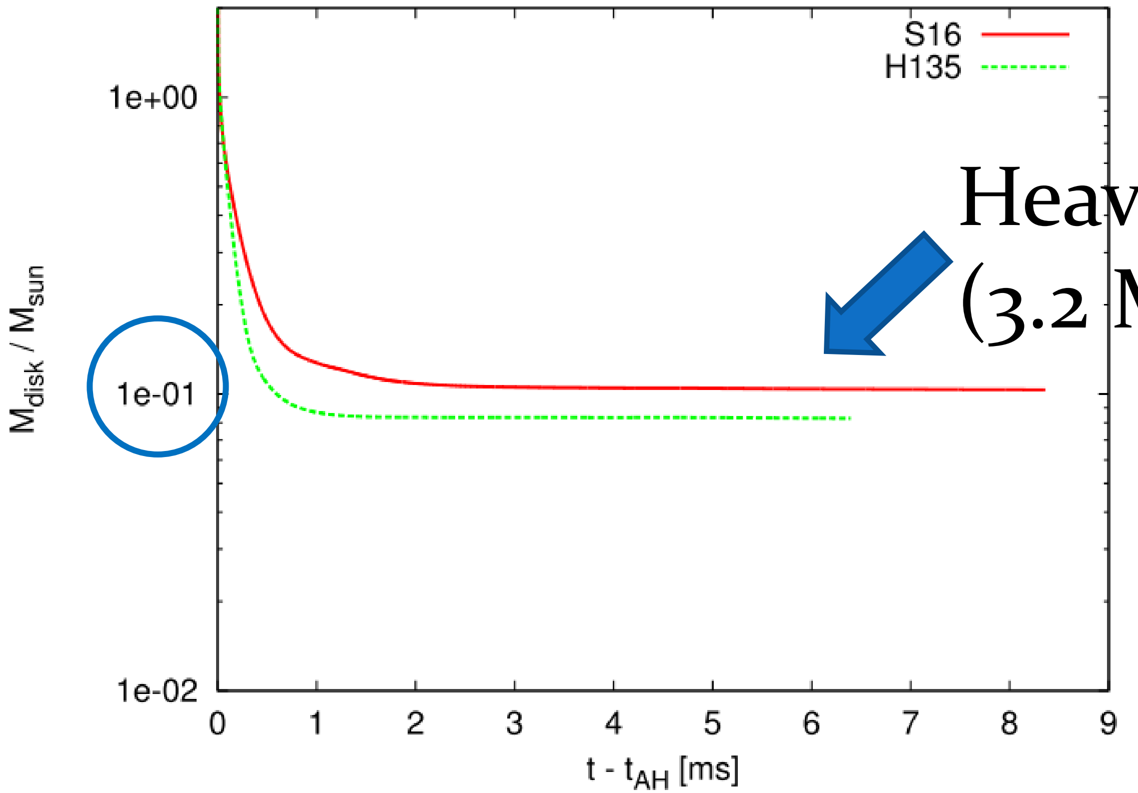
because <u>neutron fraction > proton fraction</u>



Hot and dense accretion disk

Central engine of Short Gamma-Ray burst

Accretion disk mass $\gtrsim 0.01\ M_\odot$ to be a central engine
(Setiawan+ 04)



Heavy model
($3.2\ M_\odot$)

Potential candidate of SGRB central engine

Summary

○ Binary neutron star merger Numerical Relativity simulations with microphysical process for the first time
○ GWs could be detected if it happened within 20 Mpc
○ Neutrino could be detected if it happened within 5 Mpc ⇒ Multi messenger astronomy
○ Possible candidate of SGRB central engine

Thank you for your attention.