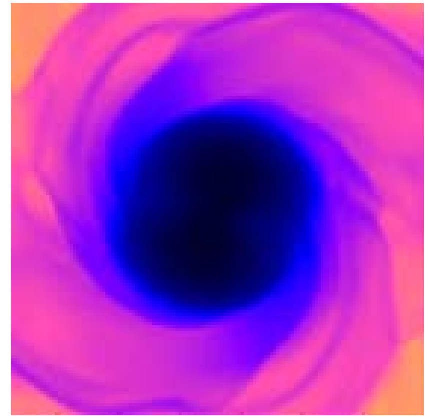
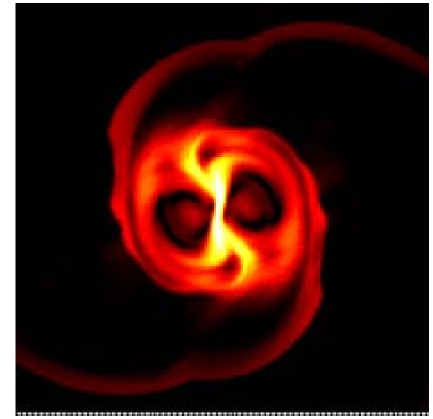




素核宇融合による計算基礎物理学の進展
－ミクロとマクロのかけ橋の構築－　　2011年12月3-5日　　合歓の郷

Effects of Hyperon in Binary Neutron Star Merger

Yuichiro Sekiguchi (YITP) with HPCI collaboration

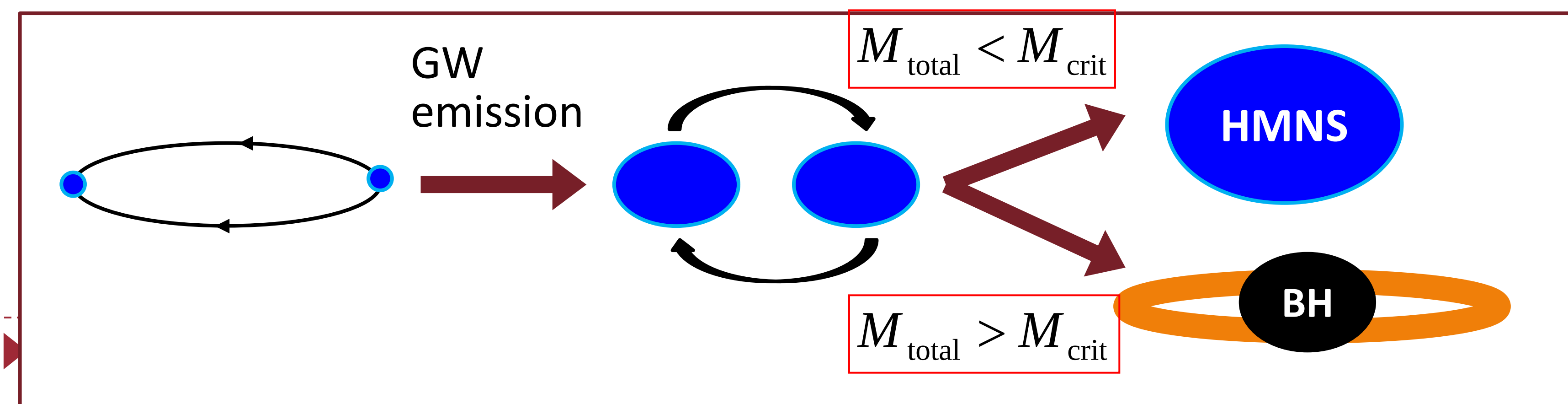
K. Kuchi, K. Kyutoku, M. Shibata, K. Hotokezaka

References

- Sekiguchi , Kiuchi, Kyutoku, Shibata
  Physical Review Letters **107**, 051102 (2011) Nucleonic EOS
- Sekiguchi , Kiuchi, Kyutoku, Shibata
  Physical Review Letters **107**, 211101 (2011) Hyperonic EOS

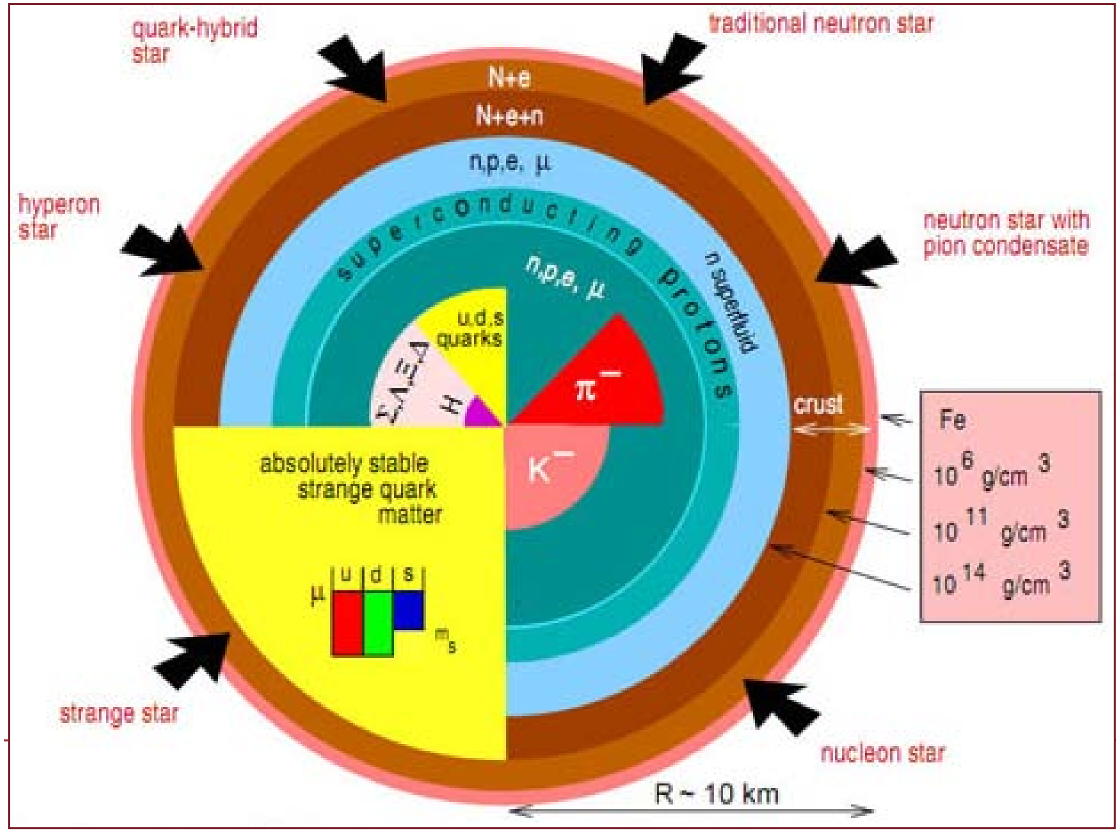
Introduction

- Coalescence of binary neutron star (BNS)
  - Promising source of GWs
  - Theoretical candidate of Short GRBs
  - **Laboratory for dense nuclear matter physics**
- Overview of BNS merger
  - Binary separation gradually shrinks due to GW emission
  - Mcrit : if the total mass is larger than this, BH will be formed
    - Mcrit depends of EOS : Mcrit = 1.2—1.7Mmax,sph.cold.NS
      - Hotokezaka et al. 2011



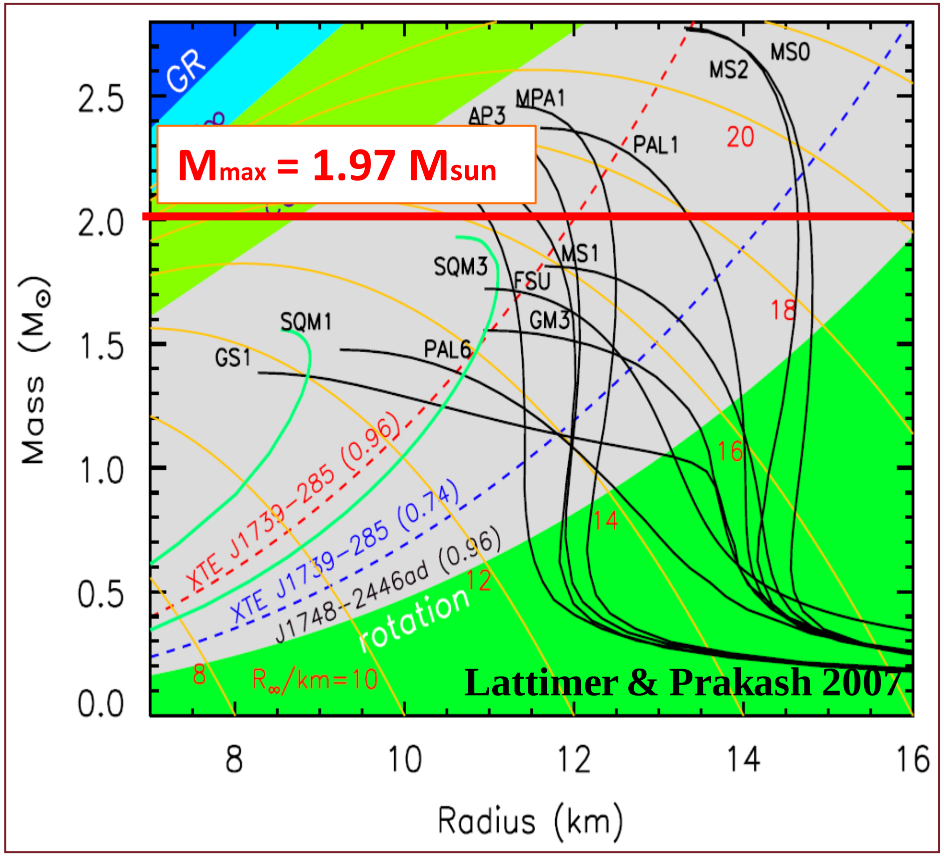
Properties of dense matter

- Still poorly understood
- There may be *exotic* phases at high densities (Pauli principle)
  - Meson cond., Quarks, **Hyperons**, …
- How to constrain equation of state (EOS) of neutron star (NS) matter
  - 12/5 talks by
  - Kyutoku (久徳)
  - Hotokezaka (仏坂)



Properties of dense matter

- 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



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

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

Numerical Studies Exploring Exotic Phases

- Stellar Core Collapse
  - Quarks (Nakazato+ 2008,2010; Sagert+ 2009; Fischer+ 2011)
  - Hyperons (Sumiyoshi+ 2009; Nakazato+ 2011)
- Binary Neutron Star (BNS) Merger
  - Not yet studied in detail
  - Parametric Study (Hotokezaka+ 2011), Bauswein+ 2011
- **This Study**
  - The first full GR simulations for BNS merger incorporating a **finite temperature hyperonic EOS**
- **Key Question:**
  - **Is it possible to tell the existence of hyperons by observations of Neutrino and Gravitational-Wave (GW) signals ?**

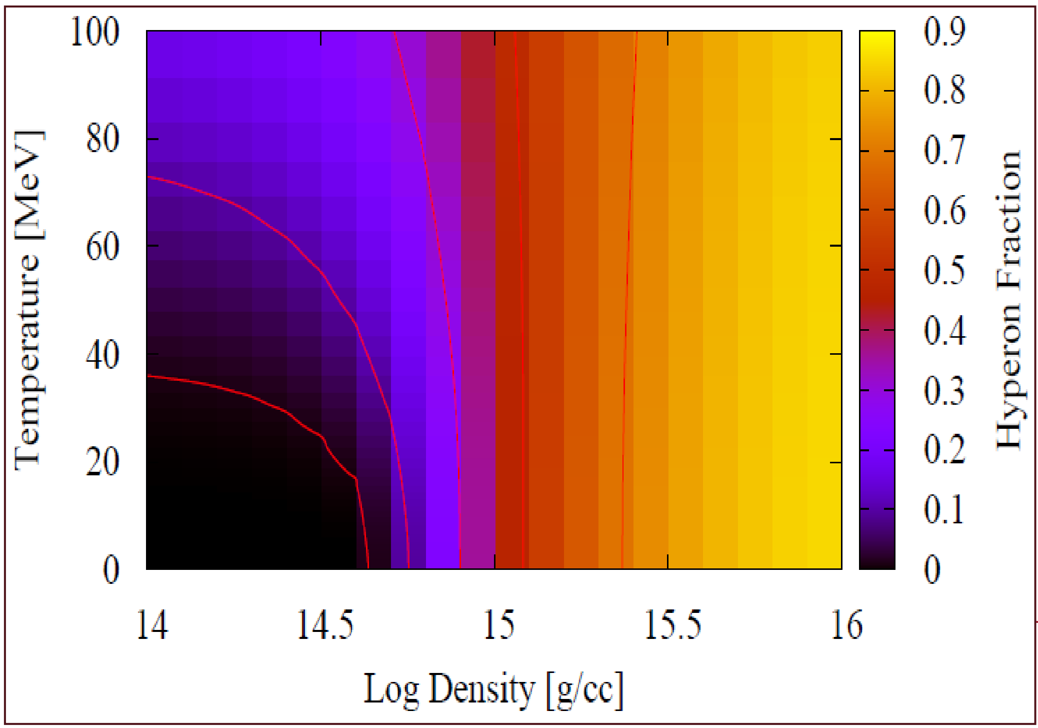
Equation of State (EOS)

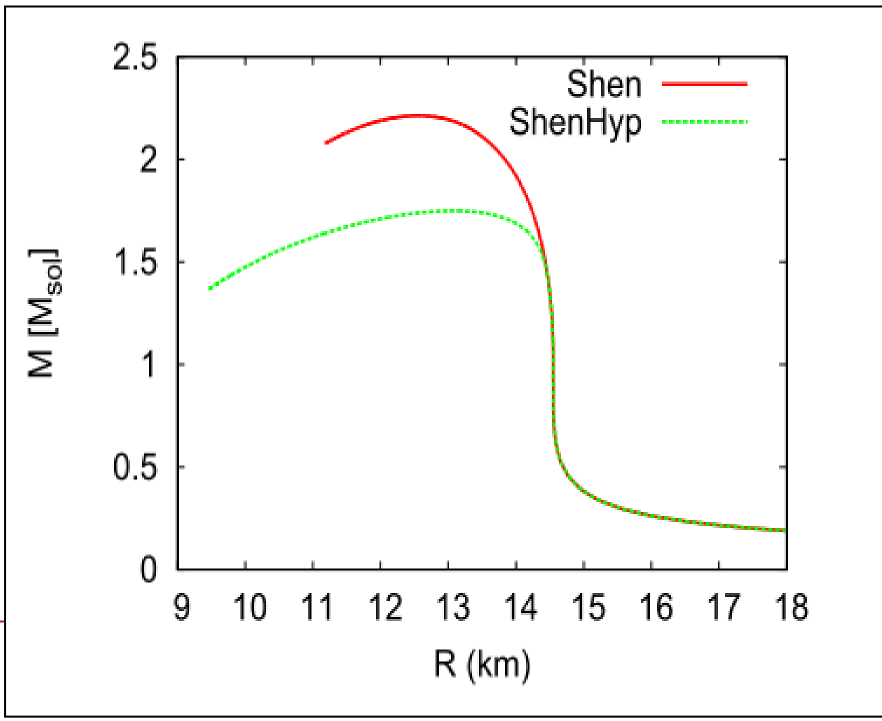
- **S-EOS**: 'normal' nucleonic matter EOS
  - Shen, Toki, Oyamatsu, Sumiyoshi, NPA **637**, 435 (1998)
- **H-EOS**: EOS with Λ hyperons
  - Shen, Toki, Oyamatsu, Sumiyoshi, ApJ **197**, 20 (2011)

- 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 $\rho \sim$ a few ρ_{nuc}, and X_Λ 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 $M_{max,sph.cold.NS} \sim 1.8\ M_{solar}$





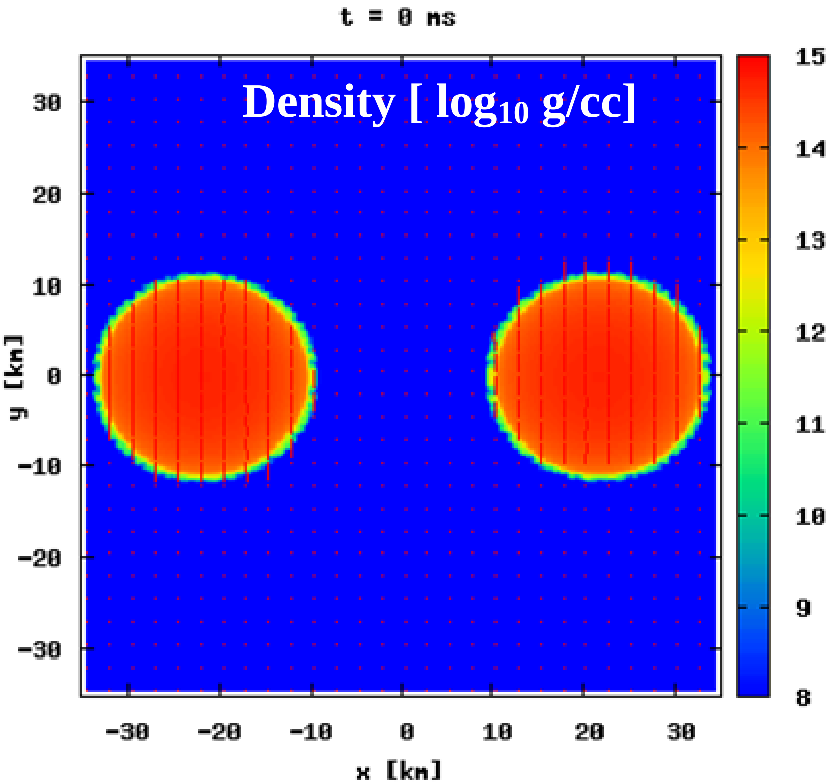
Set up of BNS

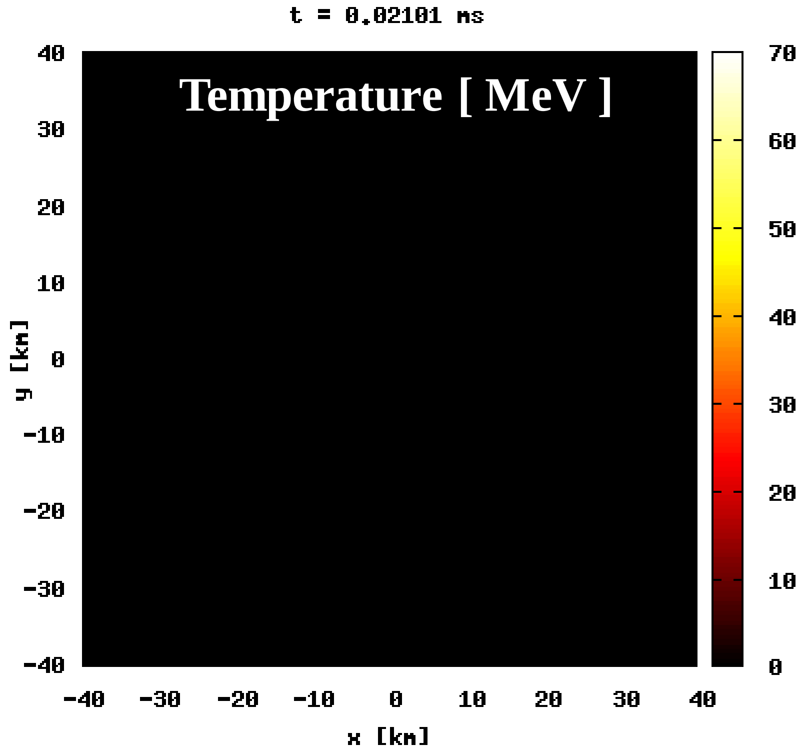
- **S-EOS (nucleonic EOS)** :
  - Equal mass BNS with individual mass of 1.35, 1.5, and 1.6 Msolar
  - Referred to as S135, S15, and S16
- **H-EOS (hyperonic EOS)** :
  - Equal mass BNS with individual mass of 1.35 and 1.5 Msolar
  - Referred to as H135 and H15

Nucleonic EOS

Merger Dynamics (S135)

- Hyper massive NS (HMNS) is formed and lives a long time characterized by neutrino cooling timescale ~ Eth/Lν ~ 2-3 sec (Lν: discuss later)
- GW emissivity declines to be low because the HMNS becomes only weakly spheroidal and relaxes to a quasi-stationary state at a later time





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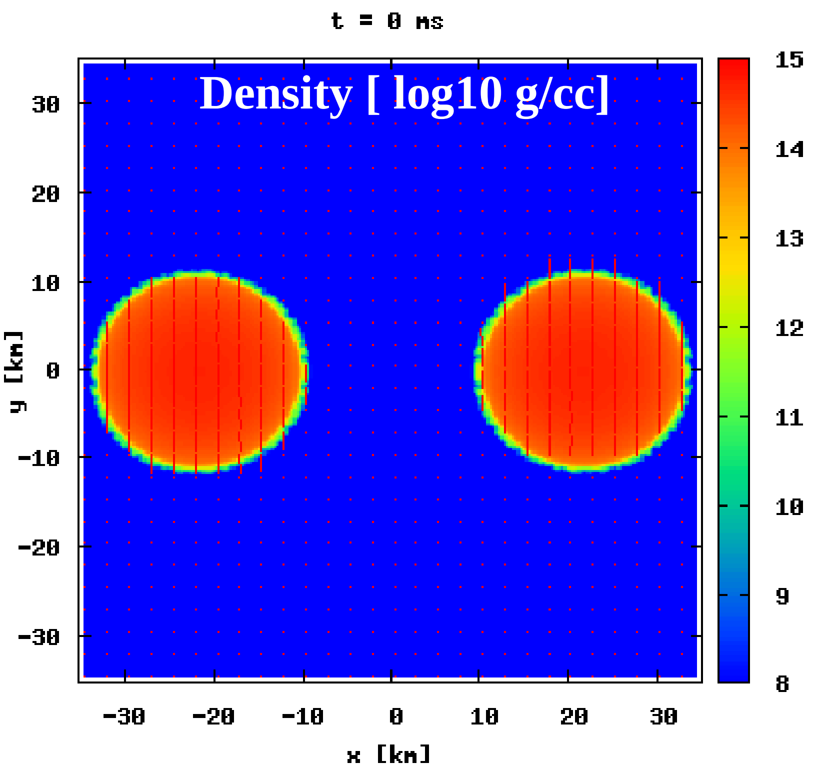
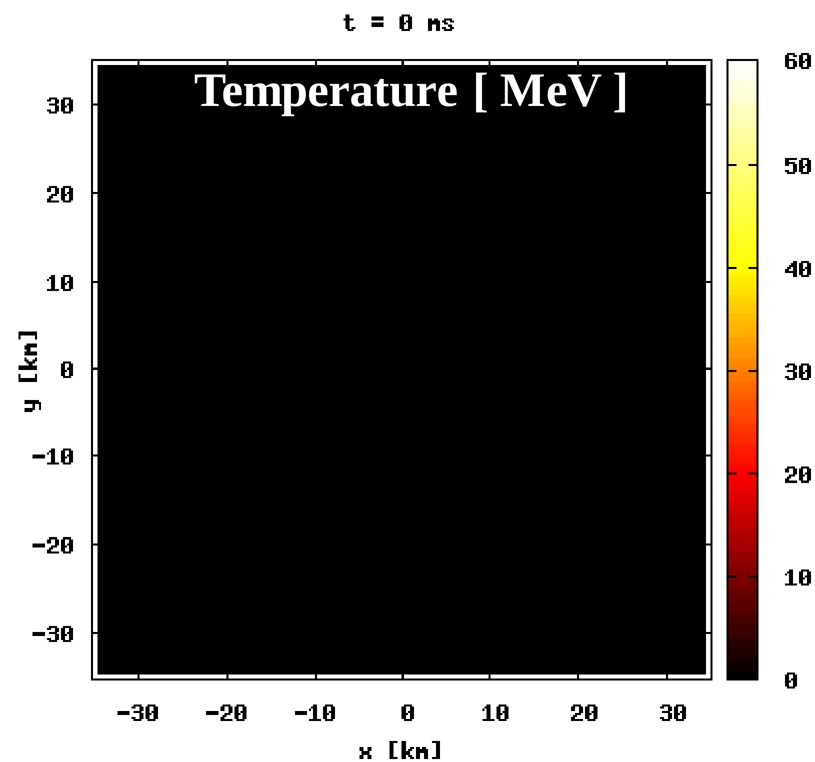
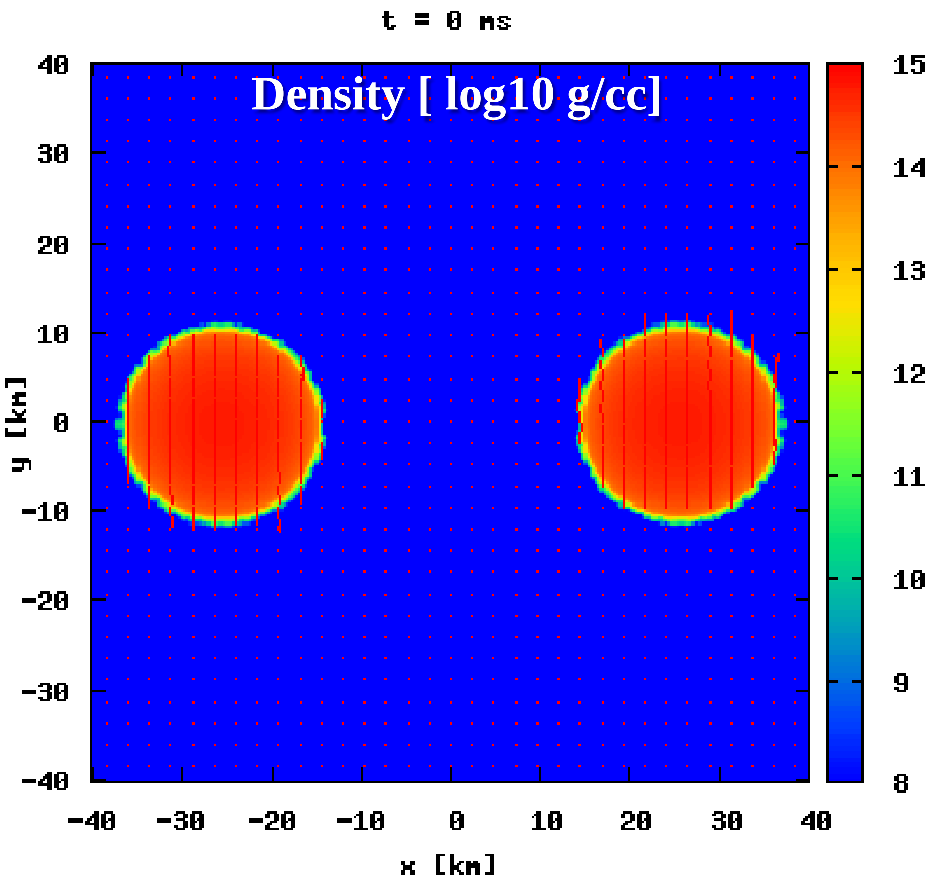
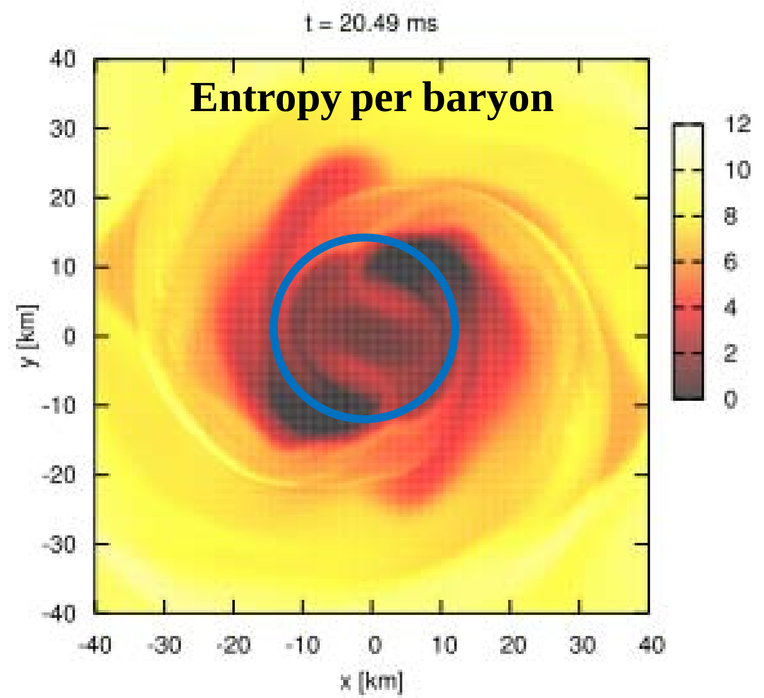




Merger Dynamics (S16)

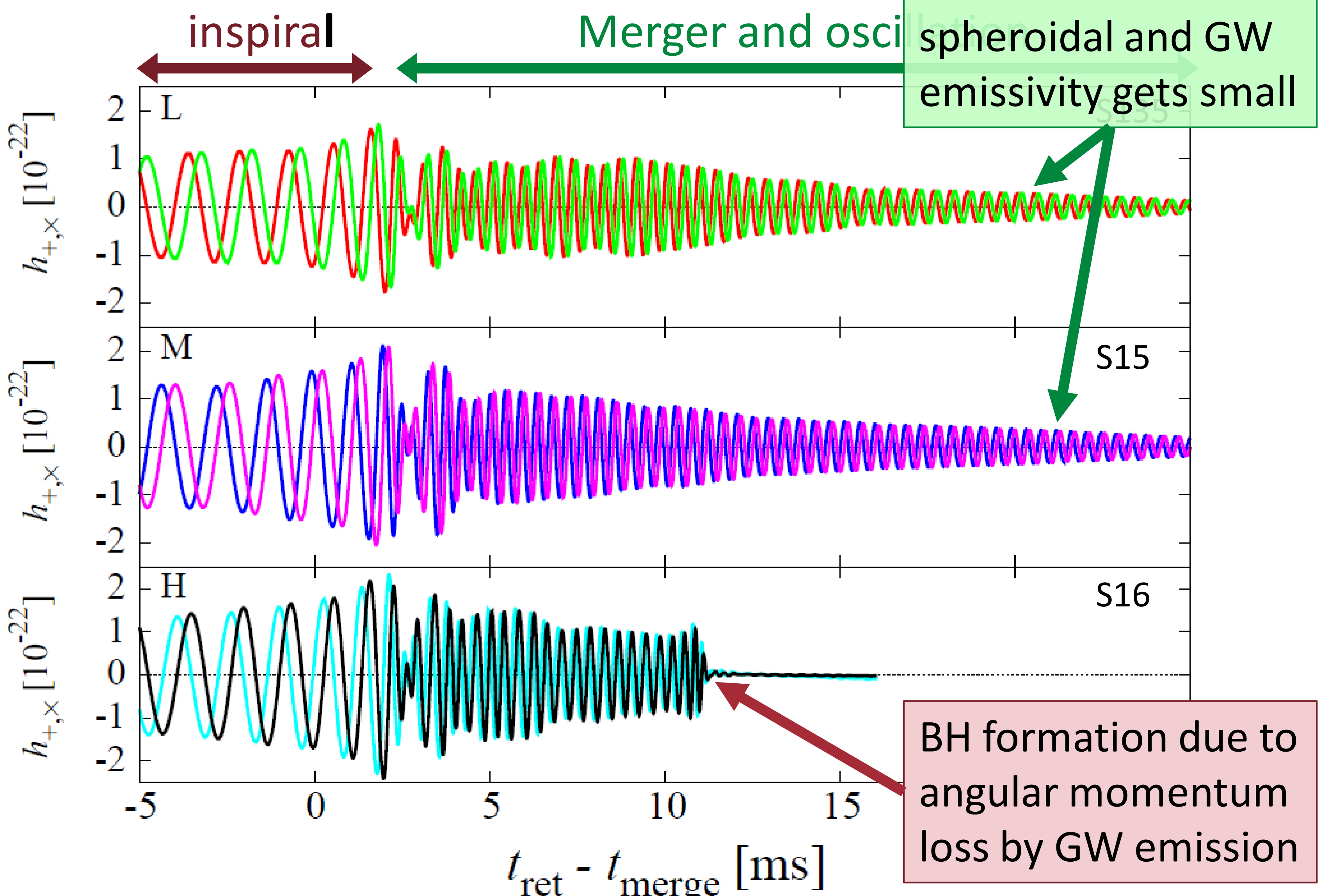
- HMNS which is supported by **thermal pressure** as well as centrifugal force is first formed and eventually collapses to a BH because the angular momentum is carried away by GW



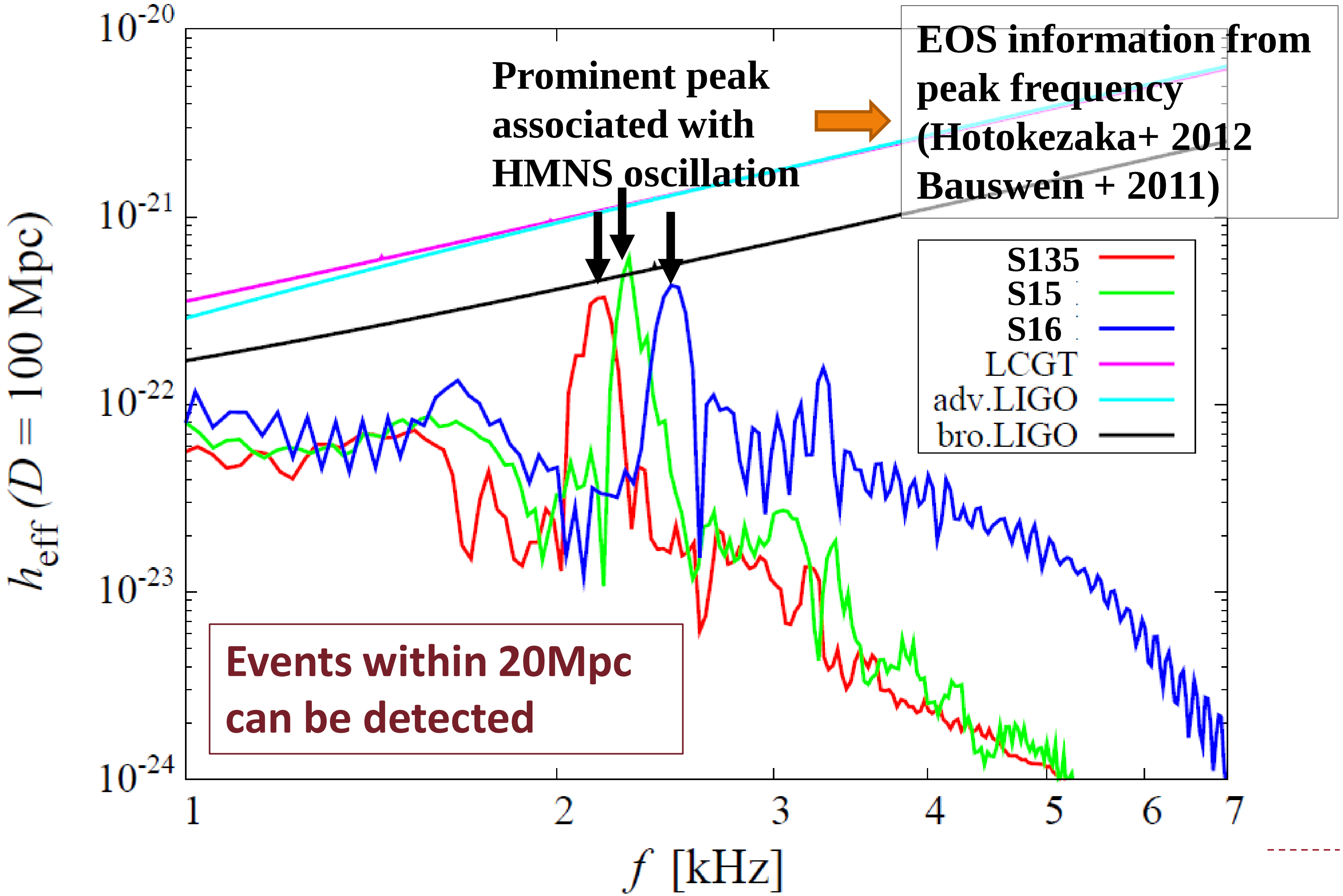


Entropy per baryon is ~ 2-3 k_B which effect increases the maximum mass by 20-30%

Gravitational Waveforms

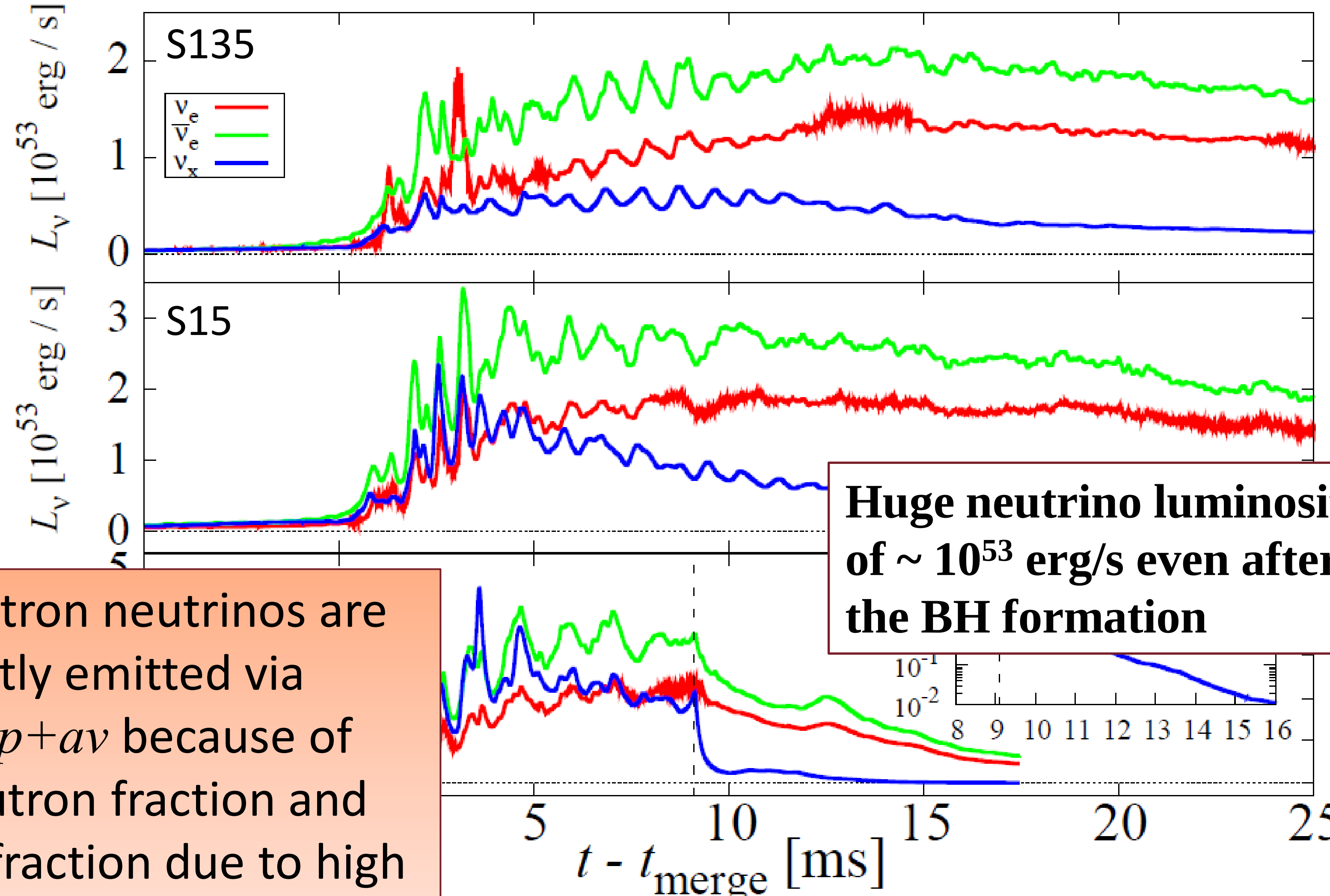


Gravitational Wave Spectra



Neutrino Luminosity

Events within 5Mpc can be detected by Hyper Kamiokande

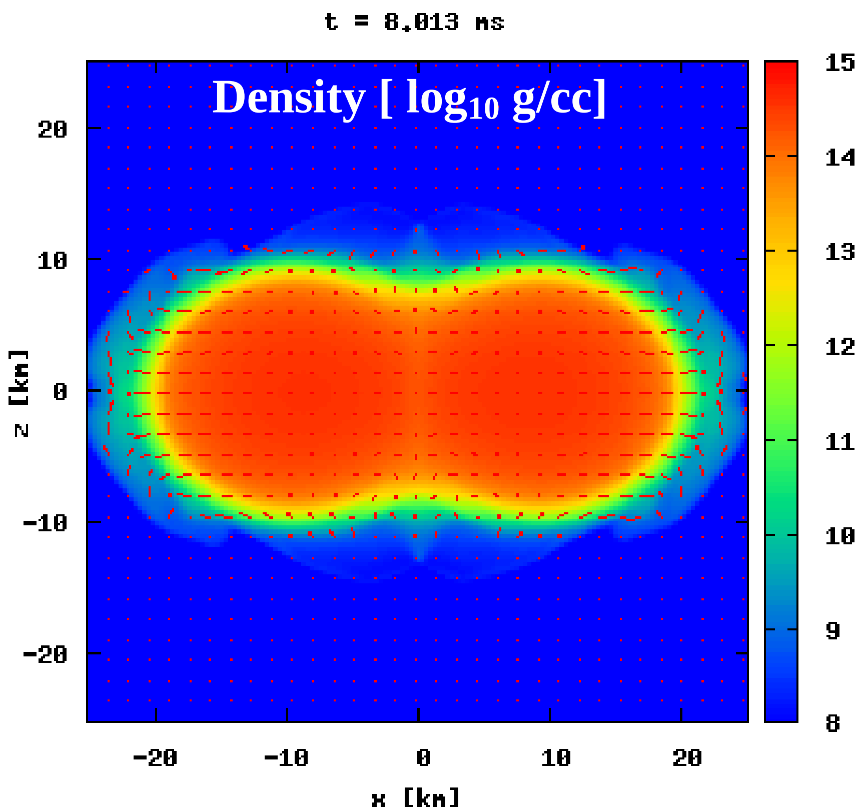


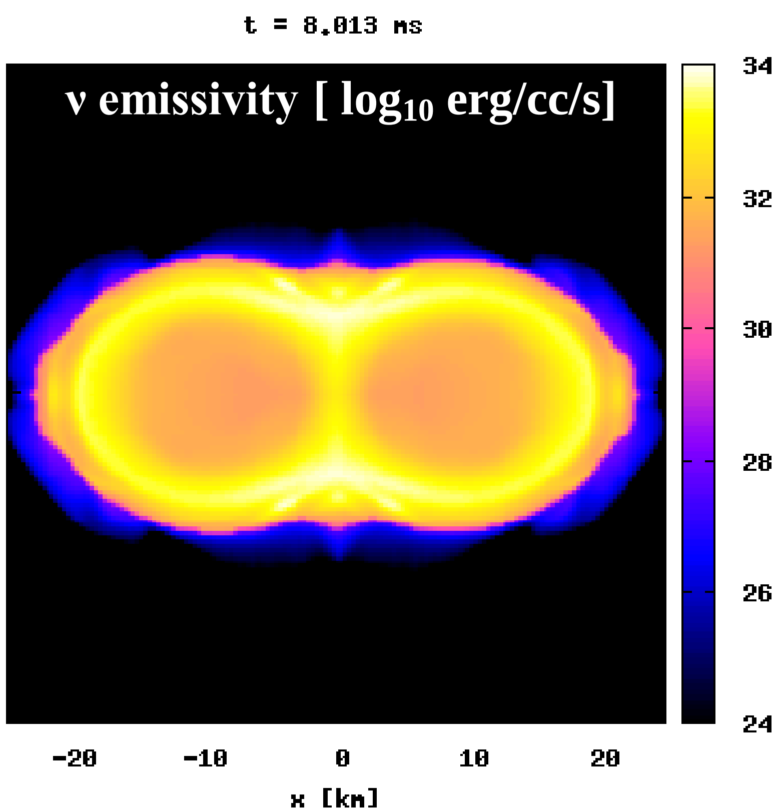
Anti-electron neutrinos are dominantly emitted via $n+e^{+} \longrightarrow p+a\nu$ because of large neutron fraction and large e^{+} fraction due to high temperature

Huge neutrino luminosity of ~ 10^{53} erg/s even after the BH formation

Neutrino is dominantly emitted from the pole-region of HMNS

- x-z plane contours of density and neutrino emissivity
- Shock waves are formed as the materials which expand hit the pole (low density) of HMNS ⇒ high emissivity

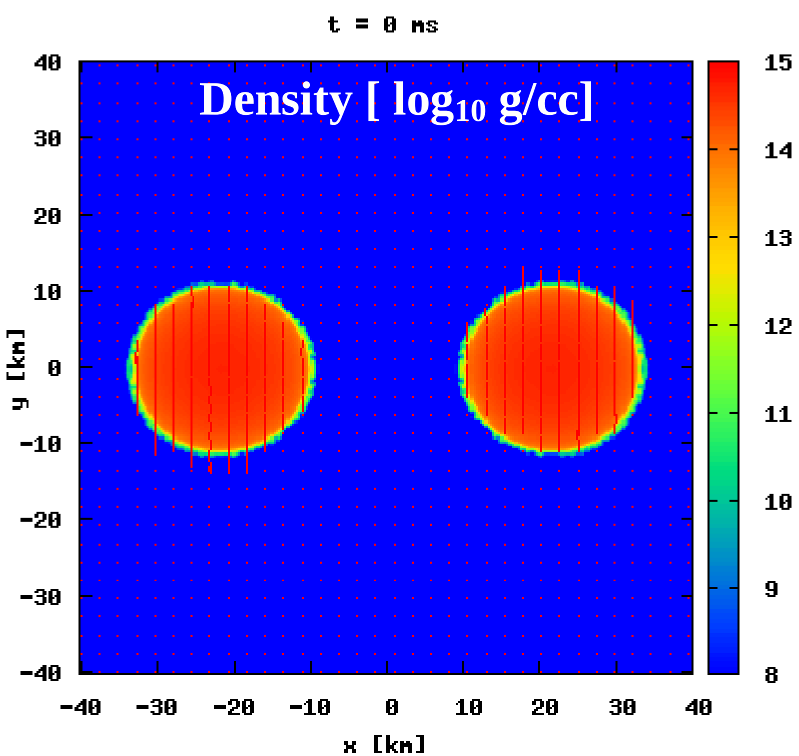


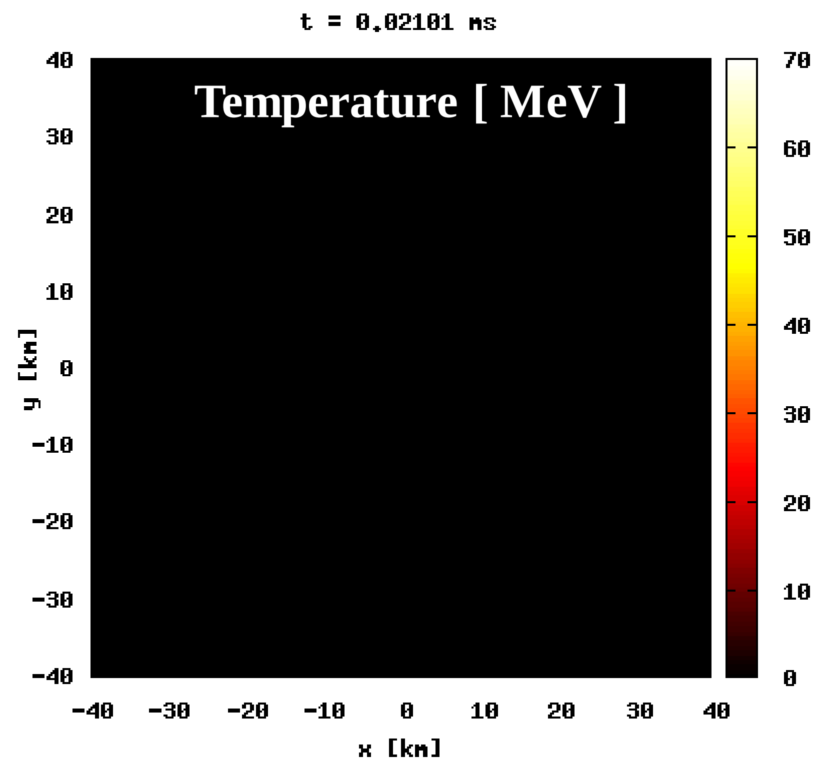


Hyperonic EOS

Merger Dynamics (H135) hyperonic EOS

- 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 ?





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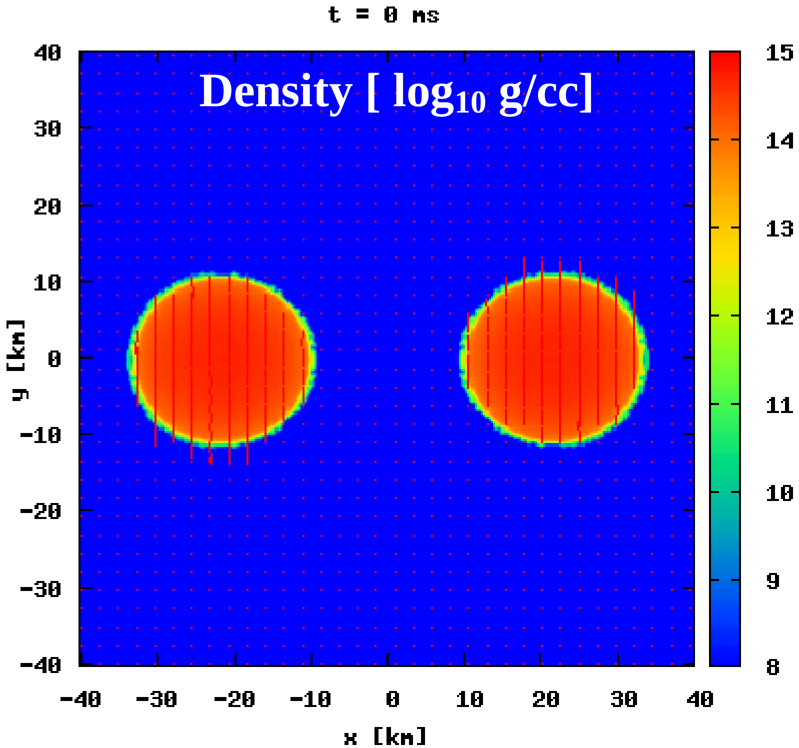
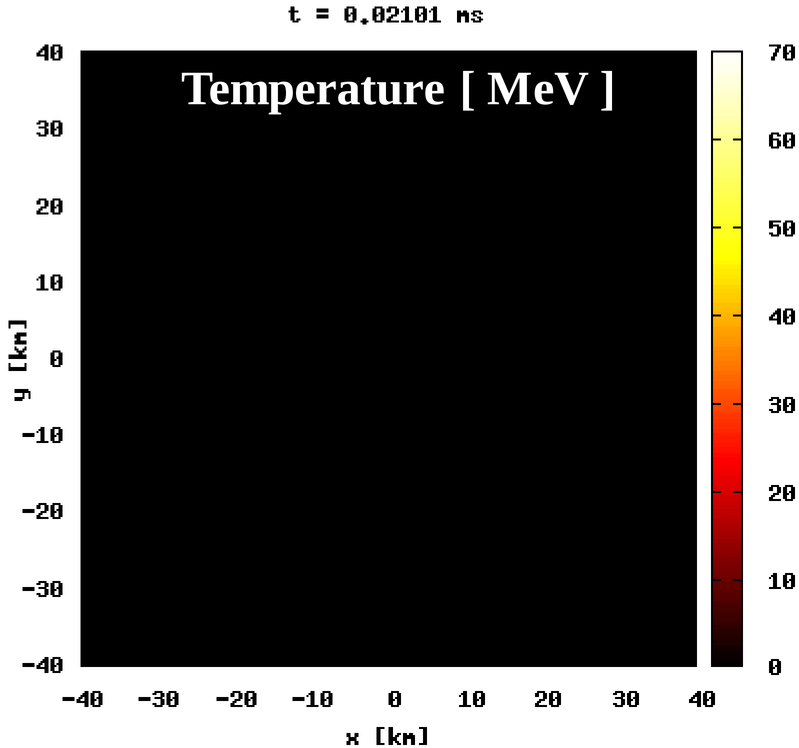


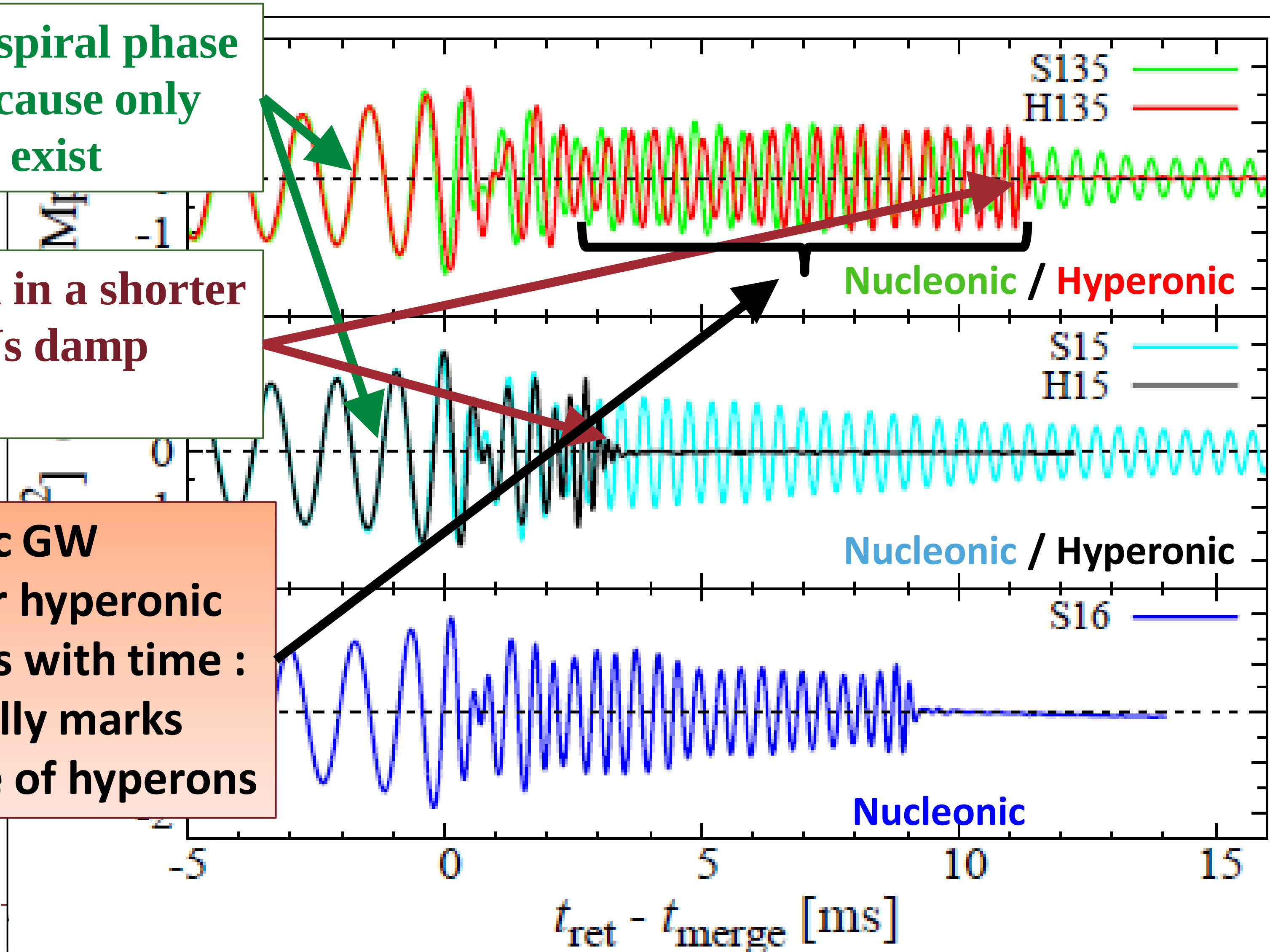


Gravitational Waveforms : Hyperonic

GWs from inspiral phase agree well because only few hyperons exist

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

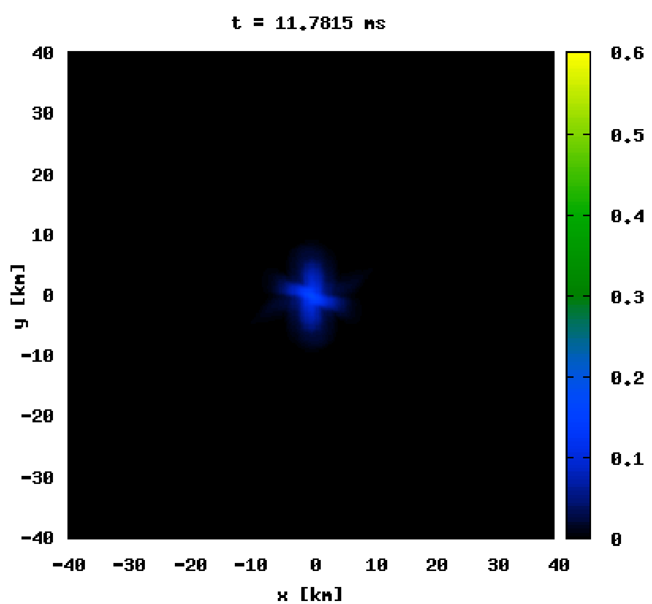
Characteristic GW frequency for hyperonic EOS increases with time : This potentially marks the existence of hyperons

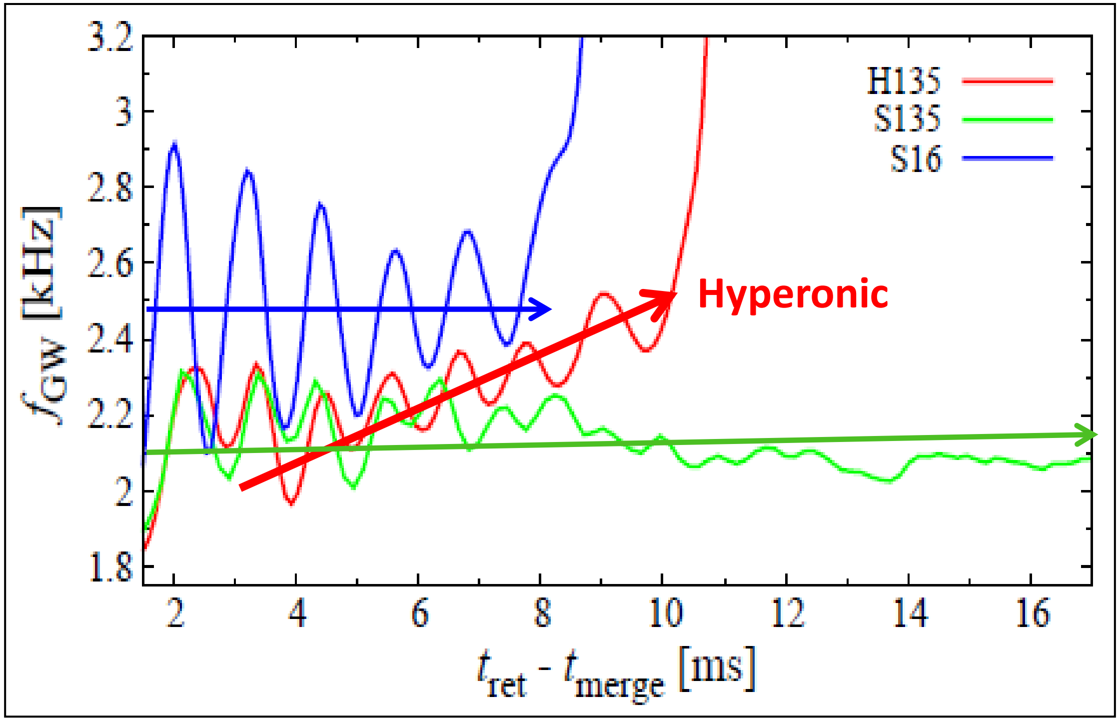


Frequency Shift due to Hyperon

- 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)

Hyperon Fraction





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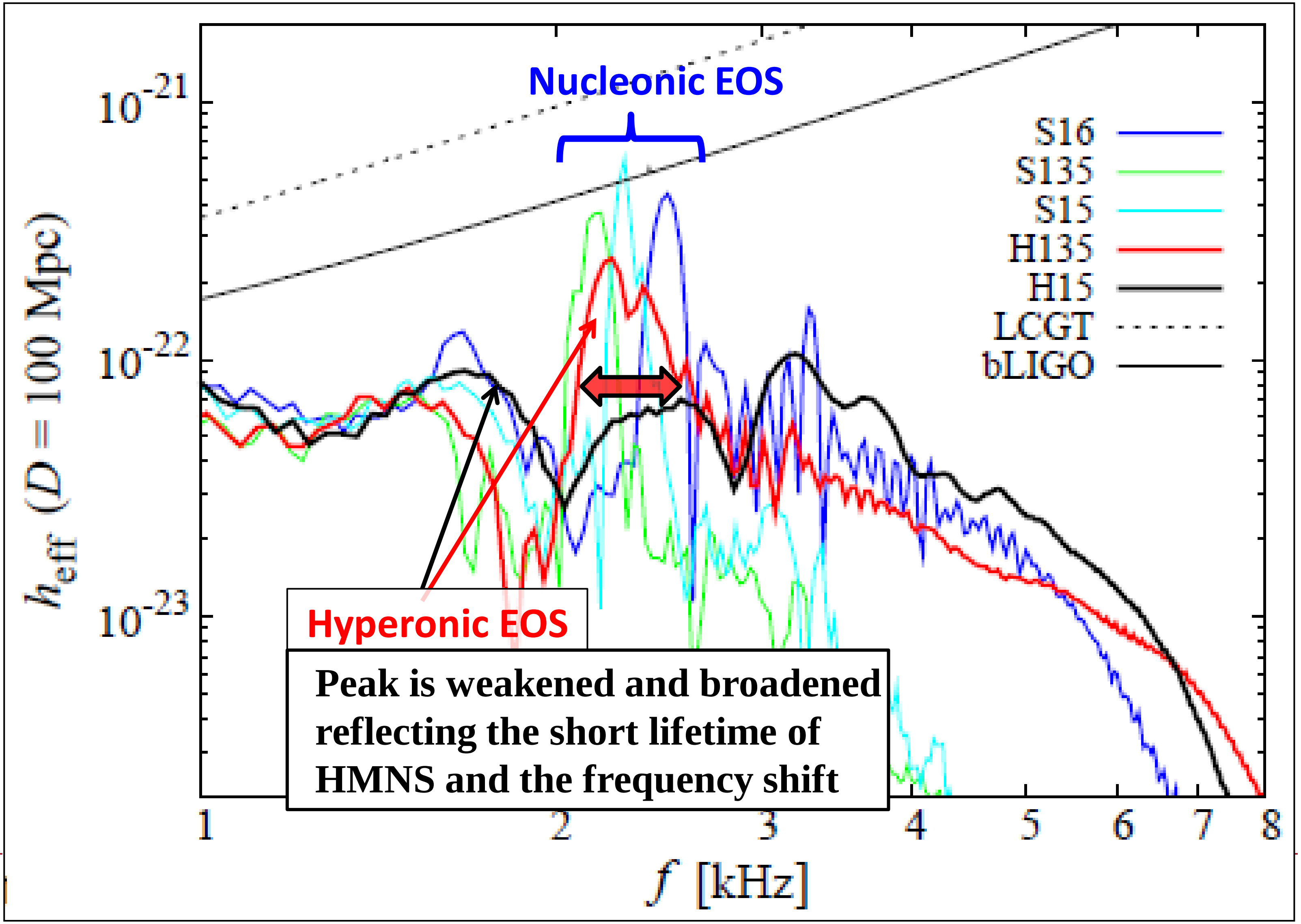
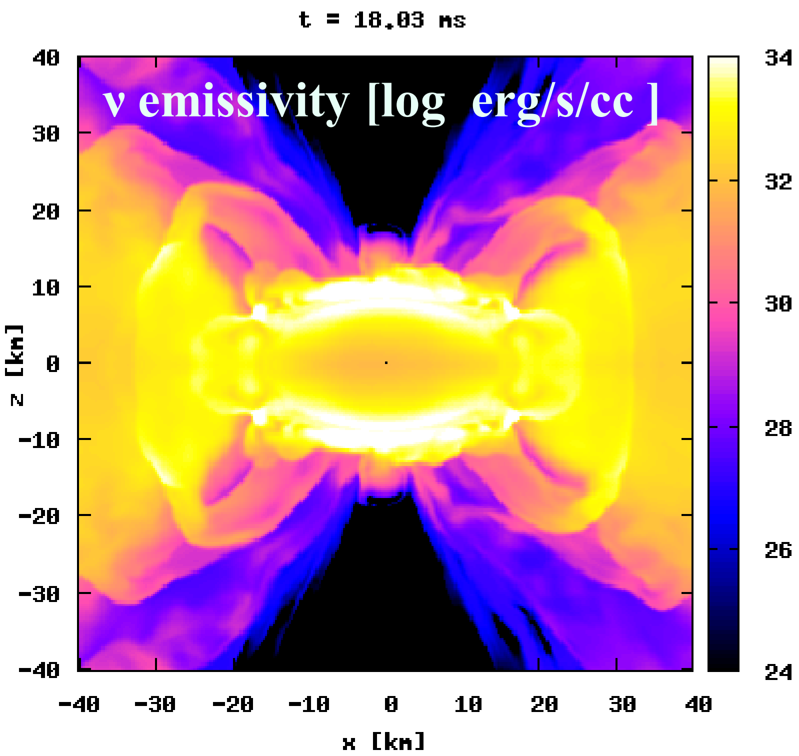
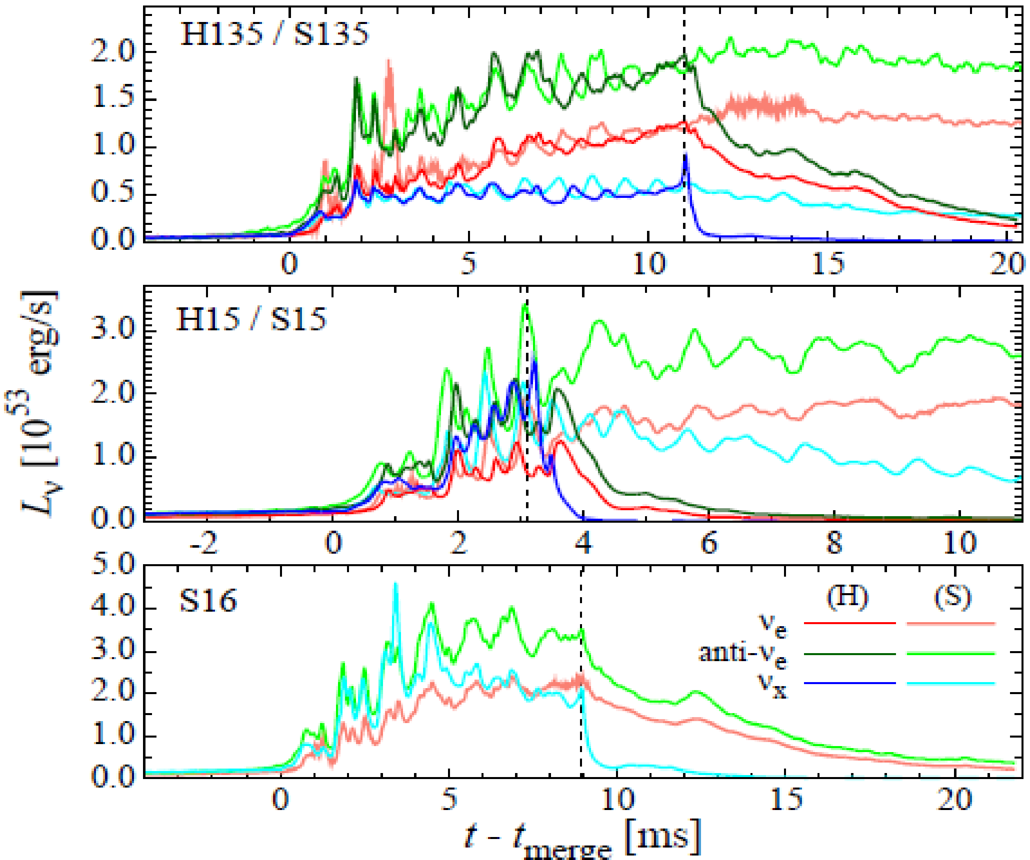


Neutrino Luminosity

- 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



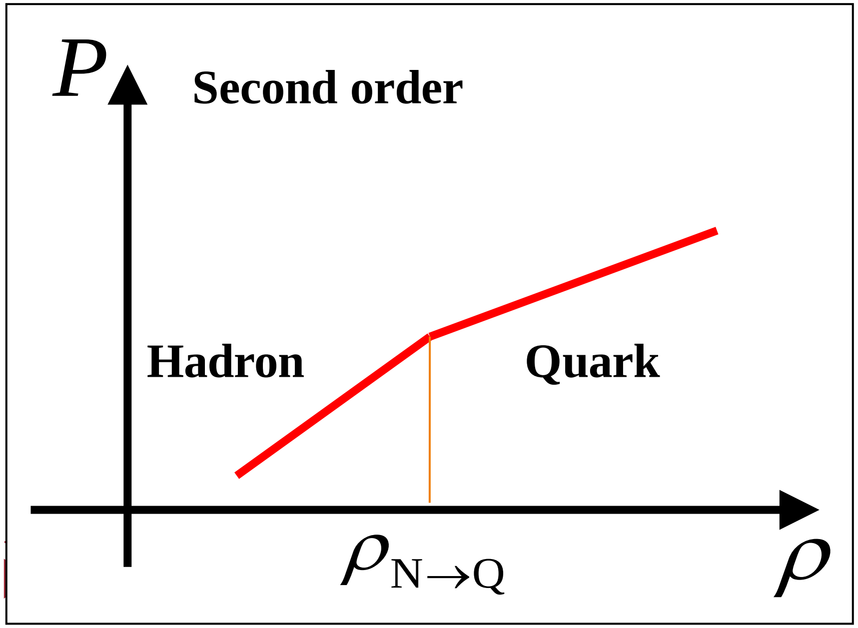


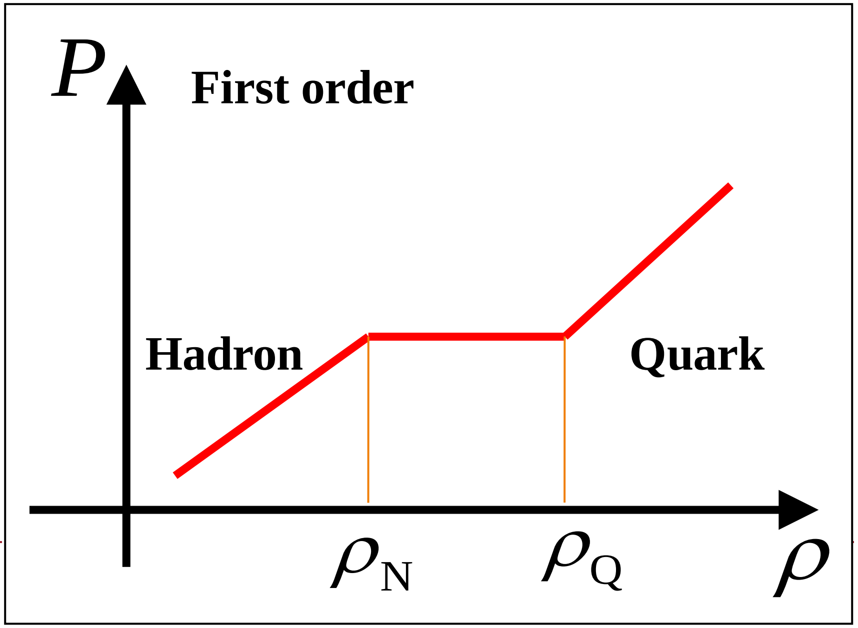
Summary

- We performed the first numerical-relativity simulations of BNS merger incorporating a finite temperature EOS with hyperons
- Existence of hyperons are imprinted in GWs
  - The characteristic GW frequency increases in time
  - **which stems from Nucleonic-to-Hyperonic Transition**
  - Providing potential way to tell existence of hyperons by GW obs.
- It is difficult to constrain EOS by neutrino signals only
  - **Effects of hyperons are significant in the central high density region which is swallowed into BH**

Future prospect

- Gravitational Waves from Hadron-to-Quark Transition
  - Second order phase transition
    - ⇒ Frequency shift (as in hyperon case)
  - First order transition
    - ⇒ **Double peaked GW spectrum is expected:**
      One associated with NS and the other with Quark star





Exploring EOS by GWs from BNS

Inspiral phase

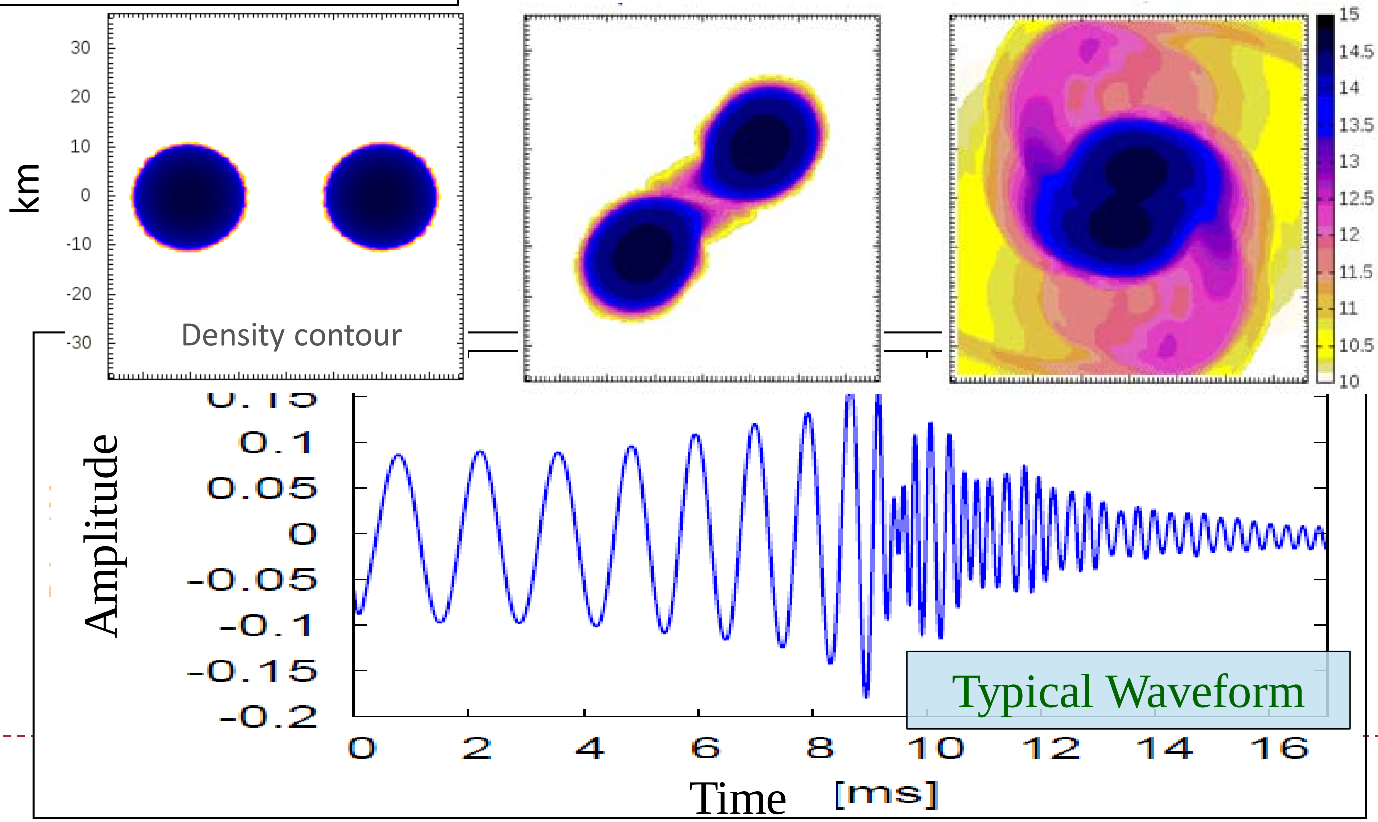
- Point particle approximation
- Information of orbits, neutron star mass etc.

Tidal deformation

- Finite size effect
- Information of equation of state

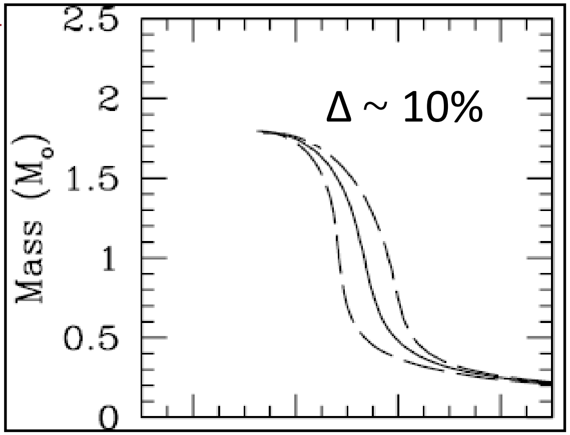
Merger and oscillation

- Maximum mass, oscillation
- Information of equation of state

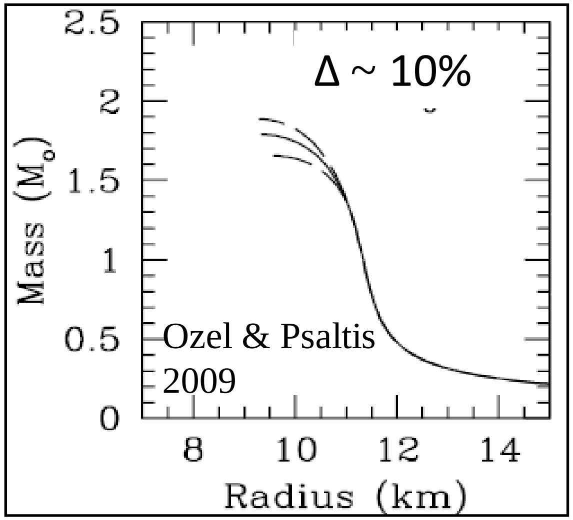


Why GWs from Binary Neutron Star Merger ?

- **One of most promising source of GWs**
  - Next generation interferometer can see ~ 350Mpc
  - Expected event rate : more than 10/yr
- **Unique window to 'see' inside dense matters**
  - Very small cross section with matter
- **Dynamical response of dense matter**
  - By contrast with static, isolated neutron star
- **Multiple information of equation of state**
  - **Tidal deformation (radius) : relatively low density**
  - Maximum mass : most high density
  - Oscillation :
- **Less uncertain parameters**
  - Inspiral waveform provides information of mass
  - Mass should be determined in isolated neutron star
- **Simple in a complementary sense**
  - Essentially quadrupole formula
  - By contrast with optical observation



Radius is sensitive to relatively low density parts



Maximum mass depends on most dense parts