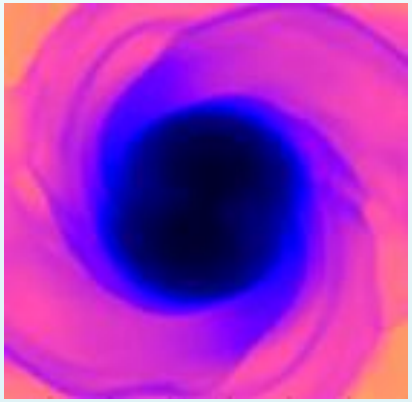

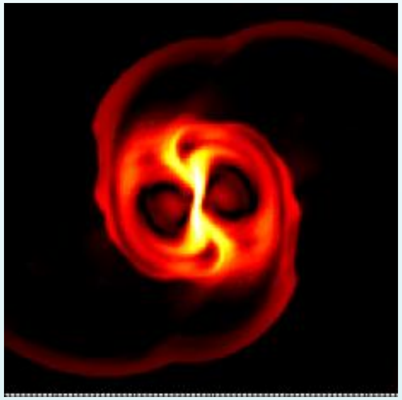

Effects of Hyperon in Binary Neutron Star Mergers

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Phys. Rev. Lett. (2011) submitted

Yukawa Institute for Theoretical Physics

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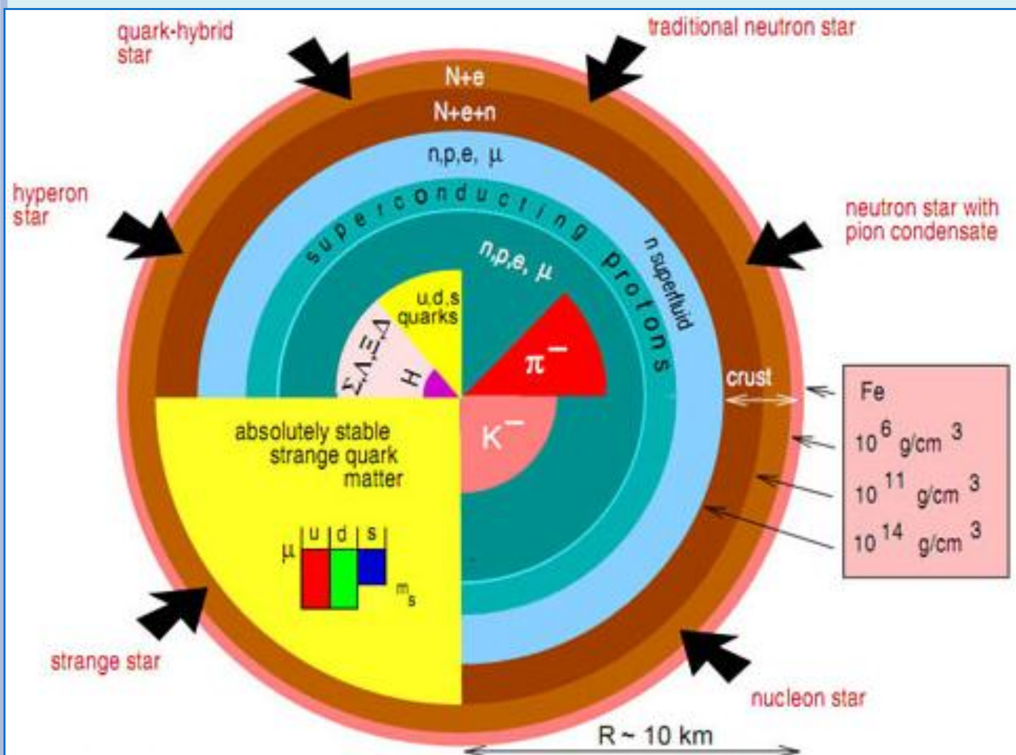
with K. Kiuchi, K. Kyutoku, & M. Shibata

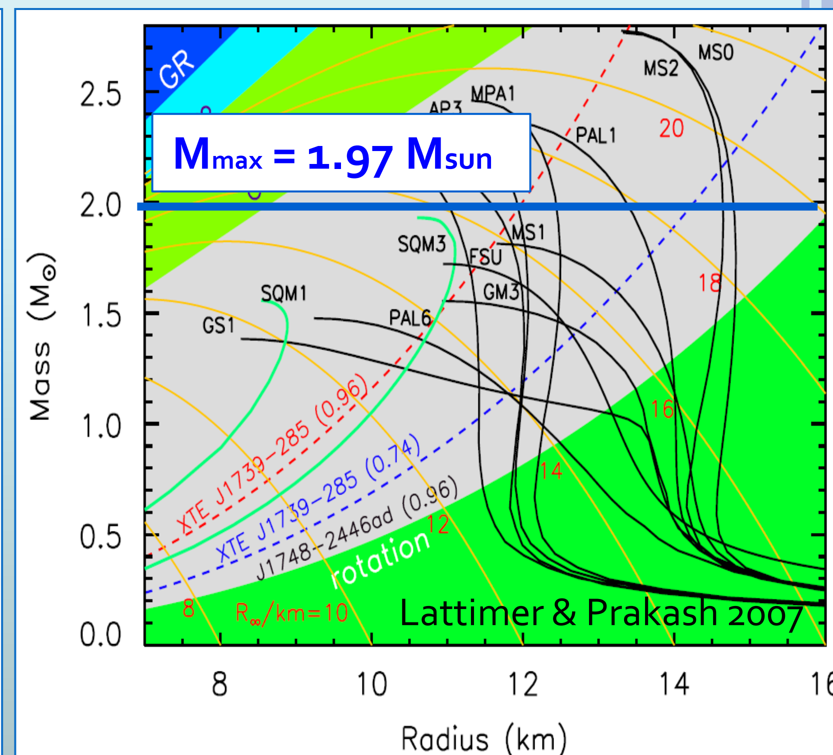
JGRG21@ Tohoku University, September 26-27, 2011

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

- Popular methods
  - Mass-Radius relation
  - Maximum mass of NS
    - Strong impact by PSR J1614-2230
- Existence of exotic phases remains unconstrained



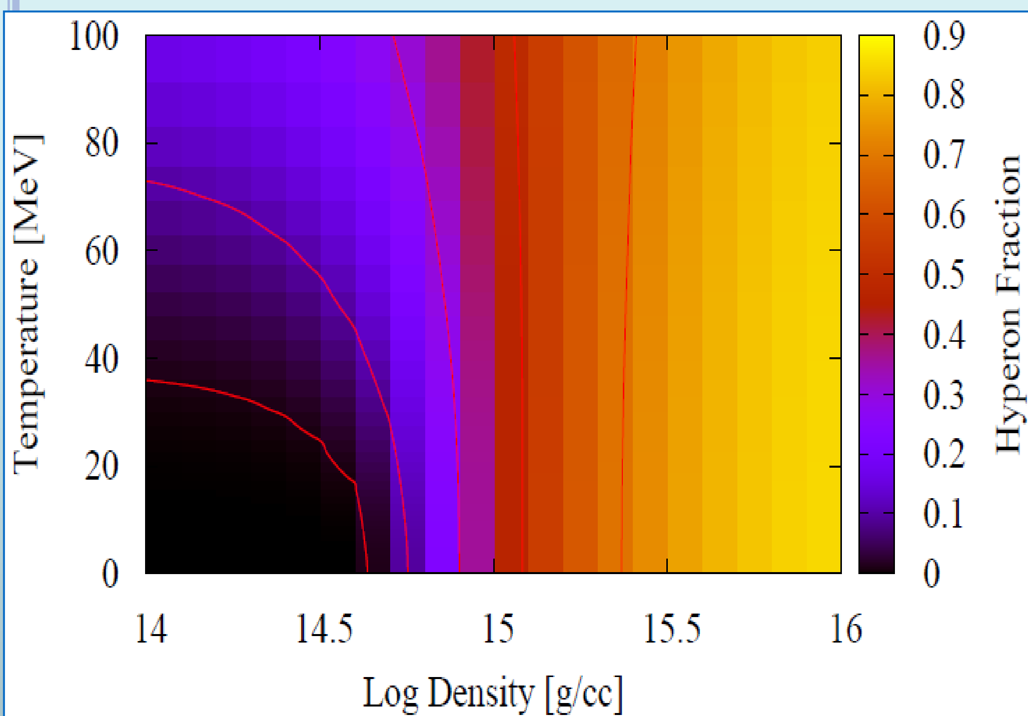


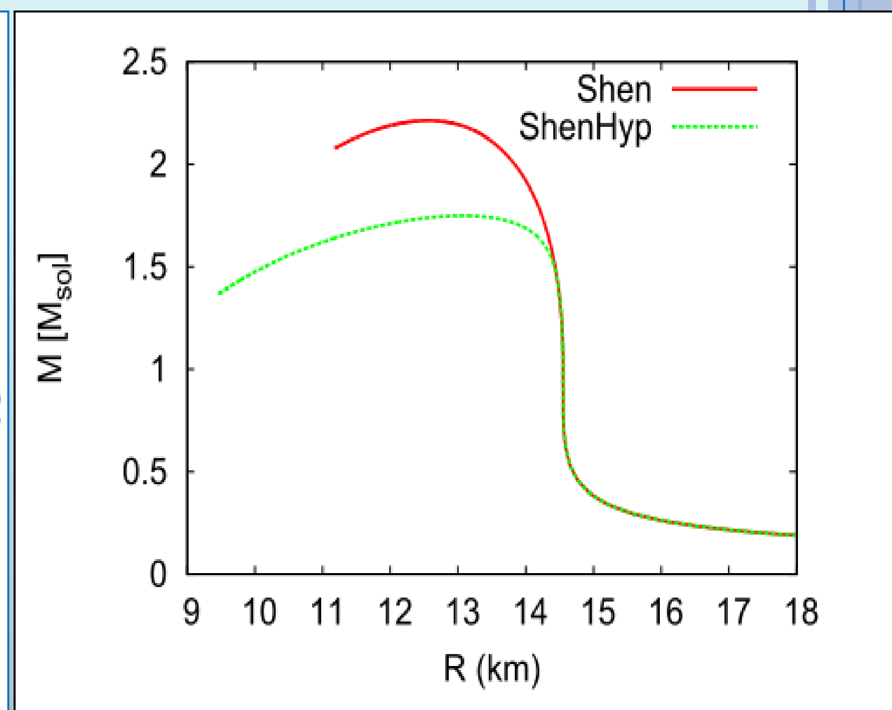
Numerical Studies Exploring Exotic Phases

- Stellar Core Collapse
  - Quarks (Nakazato+ 2008,2010; Sagert+ 2009; Fischer+ 2011)
  - Hyperons (Sumiyoshi+ 2009)
- 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 with **finite temperature EOS with Λ hyperons**
    - Λ hyperons are believed to appear first because they are lightest and feel an ***attractive potential*** (e.g. Ishizuka+ 2008)
    - Σ hyperons feel a ***repulsive potential*** and will not appear at lower densities (Noumi+ 2002)
- **Key Question:**
  - **Is it possible to tell the existence of Λ hyperons by observations of Neutrino and Gravitational-Wave (GW) signals ?**

Equations of State (EOS)

- H-EOS: EOS with Λ hyperons (Shen+ 2011: ShenHyp)
- S-EOS: 'normal' nucleonic matter EOS (Shen+ 1998)
  - Both based on the relativistic mean field theory
- 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, the maximum mass of the cold spherical NS is decreased





Basic Equations & Initial Condition

- Einstein's equations: Shibata-Nakamura (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
  - Lepton Conservations
  - Weak Interactions
    - $e^{\pm}$ captures, pair annihilation, plasmon decay, Bremsstrahlung
  - A detailed neutrino opacities
  - BH excision technique
  - High-resolution-shock-capturing scheme

$$\nabla_a T_b^a = -Q_b^{\rm (leak)}, \quad \nabla_a T_b^{a\ (\nu,{\rm stream})} = Q_b^{\rm (leak)}$$

$$\frac{d\,Ye}{dt} = -\gamma_{\rm e-\,cap} + \gamma_{\rm e+\,cap}$$

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

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

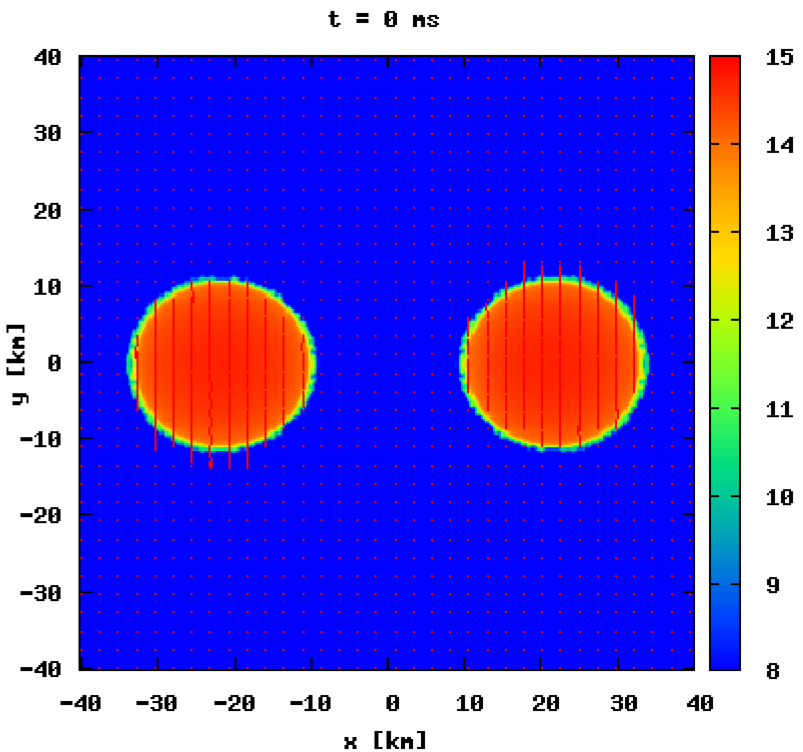
$$\frac{d\,Y\nu_{\rm x}}{dt} = \gamma_{\rm pair} + \gamma_{\rm plasmon} + \gamma_{\rm Brems} - \gamma_{\nu_{\rm x}{\rm leak}}$$

- Initial condition
  - **Equal mass BNS with individual mass of 1.35, 1.5, 1.6 Msolar**

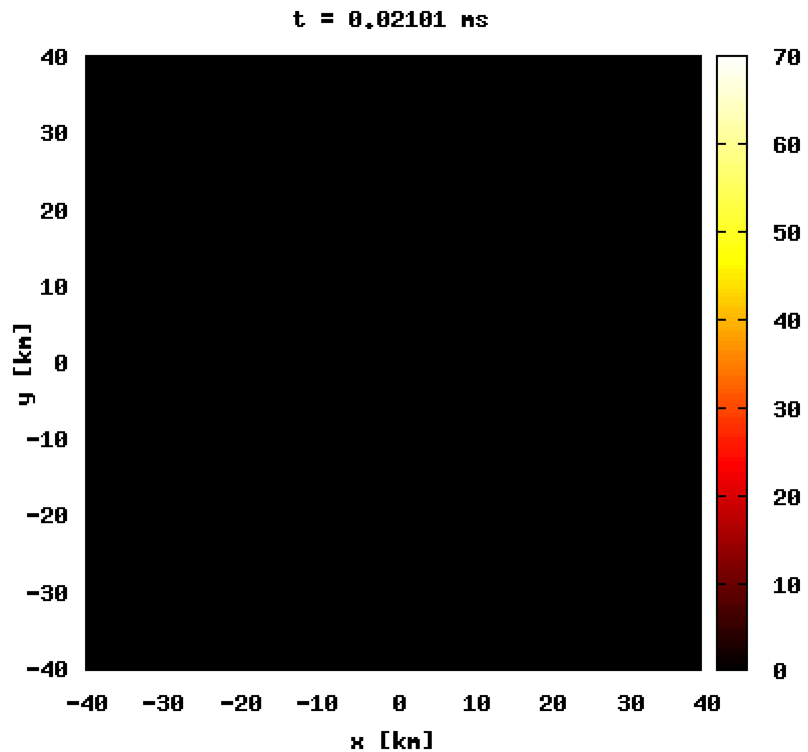
Merger Dynamics: Hyperon EOS Case

- 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 GRB ?

Density [log10 g/cc]



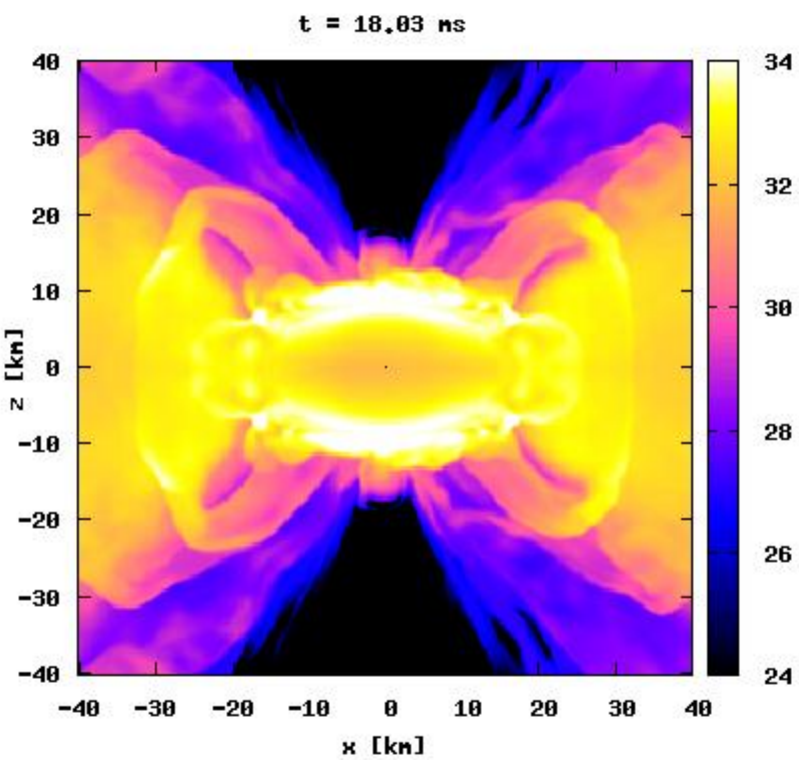
Temperature [MeV]

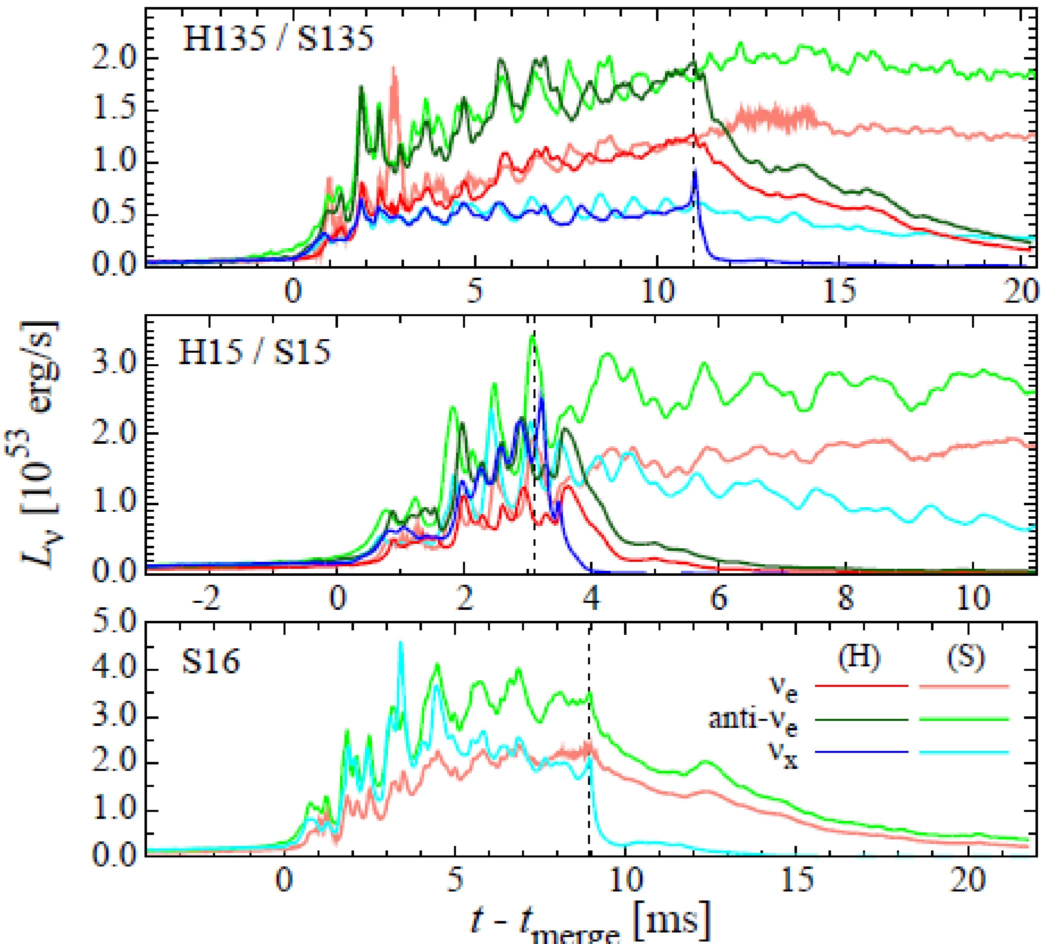


Neutrino Luminosities

- 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

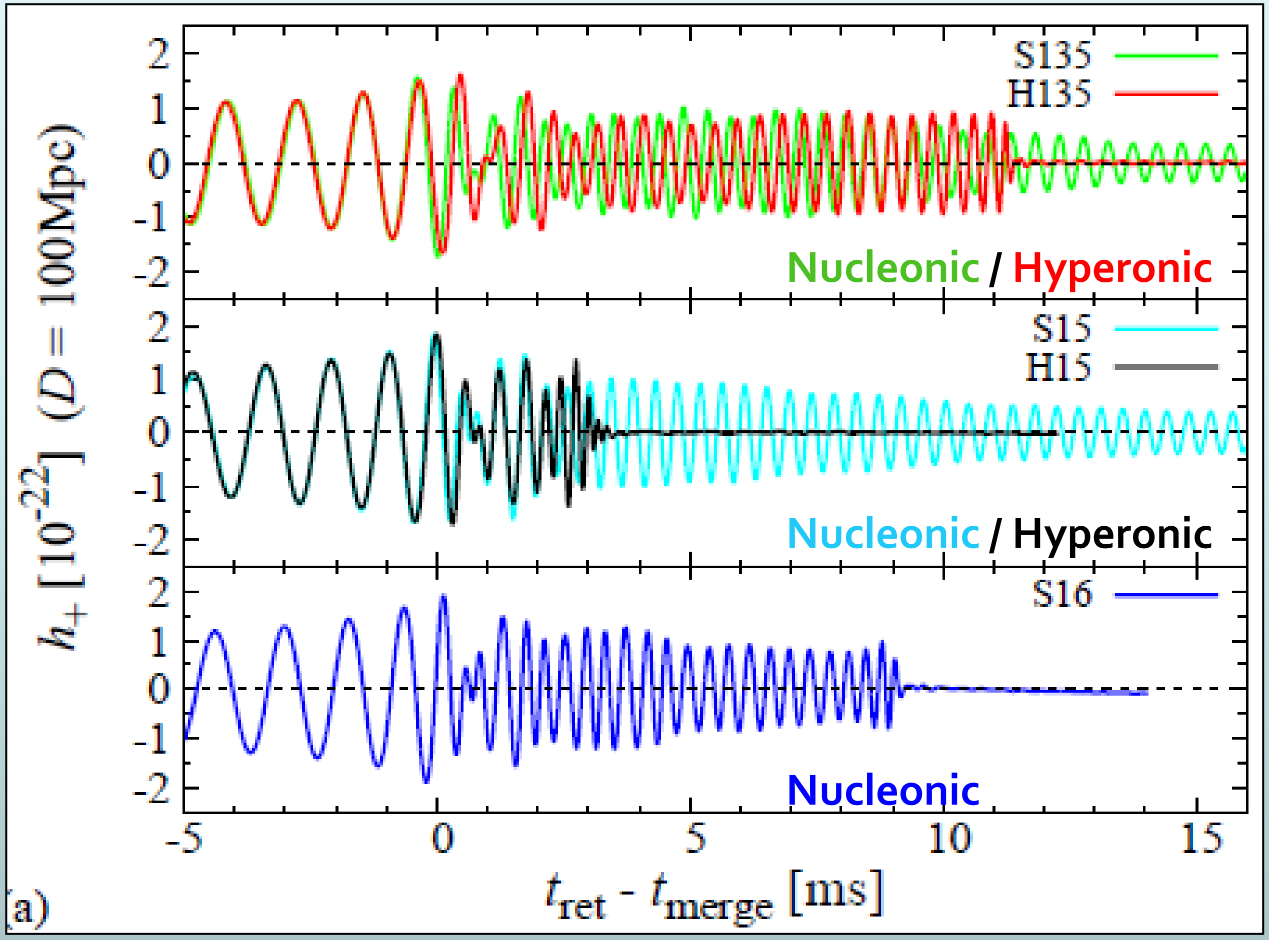
Neutrino emissivity [log erg/s/cc]





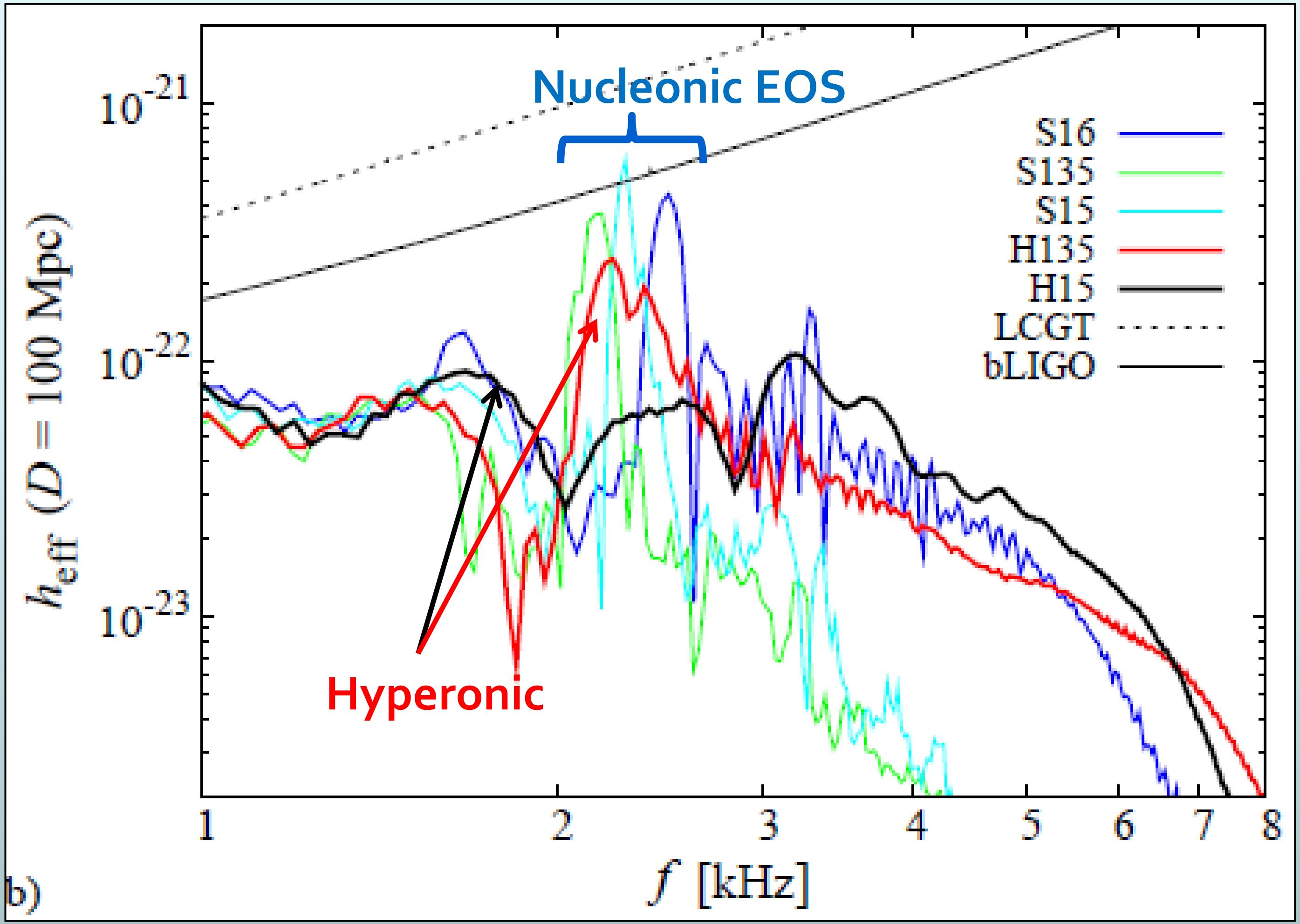
Gravitational Waveforms

- For the same mass models, GWs from inspiral phase agree well
- GWs damp steeply at BH formation
- **Characteristic GW frequency for the hyperon model increases with time** (although GWs for **H135** and **S16** look similar) ⇒ see the GW spectra



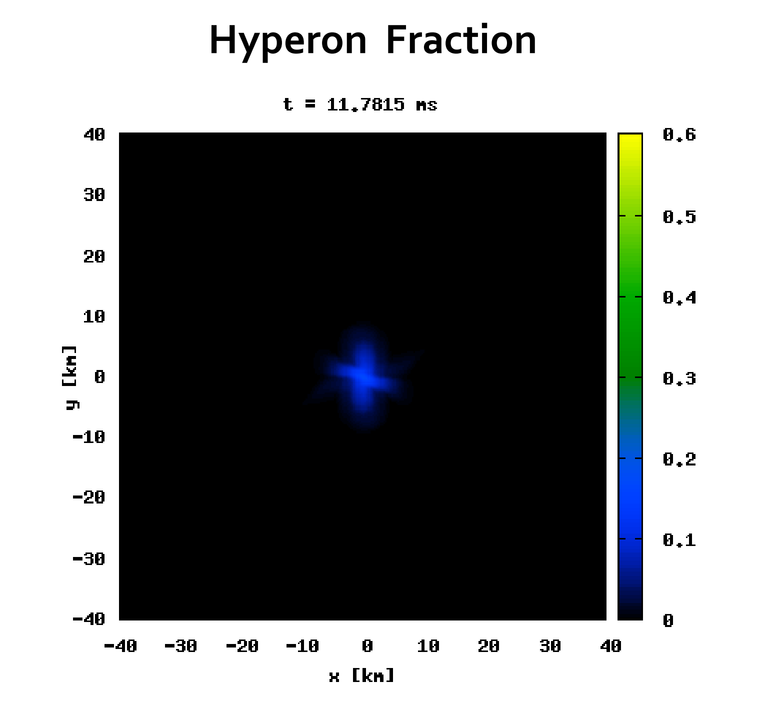
Gravitational-Wave Spectra

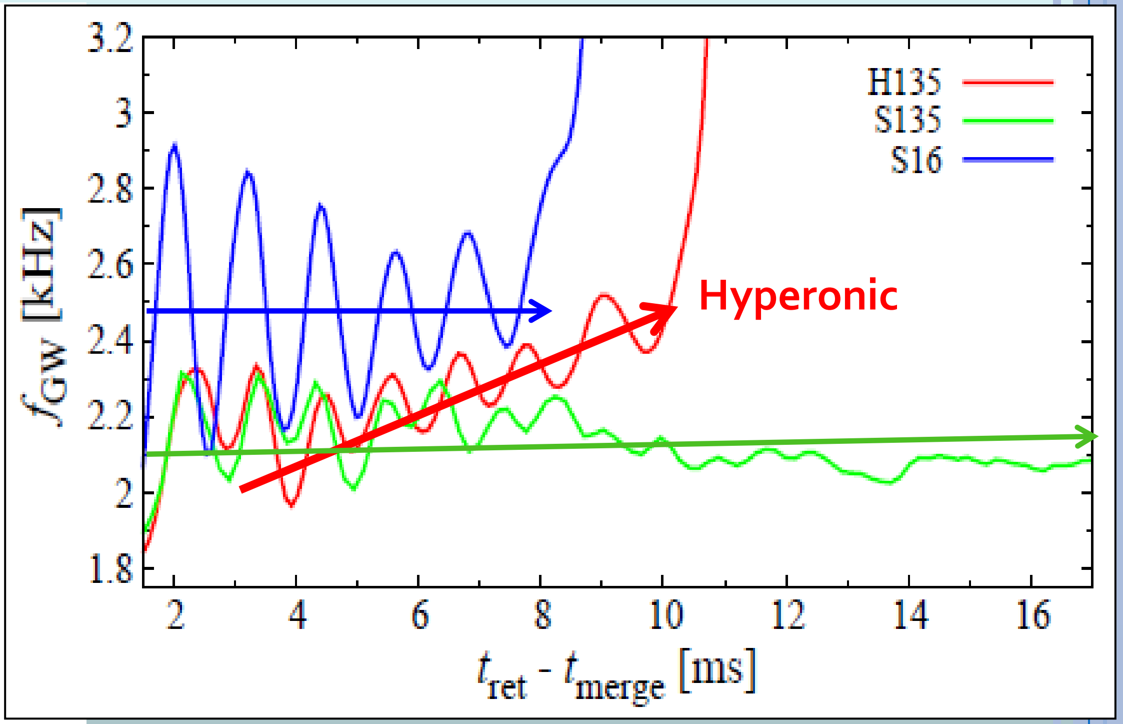
- Nucleonic models show prominent peak associated with GWs from HMNS
- **In Hyperonic models, the peak is weakened and broadened**
  - Reflecting the short lifetime of HMNS and **the frequency shift**



Frequency Shift due to Hyperon

- Dynamics of HMNS formed after the merger
  - **Nucleonic** : HMNS shrinks by angular momentum loss due to GW emission in a long 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)





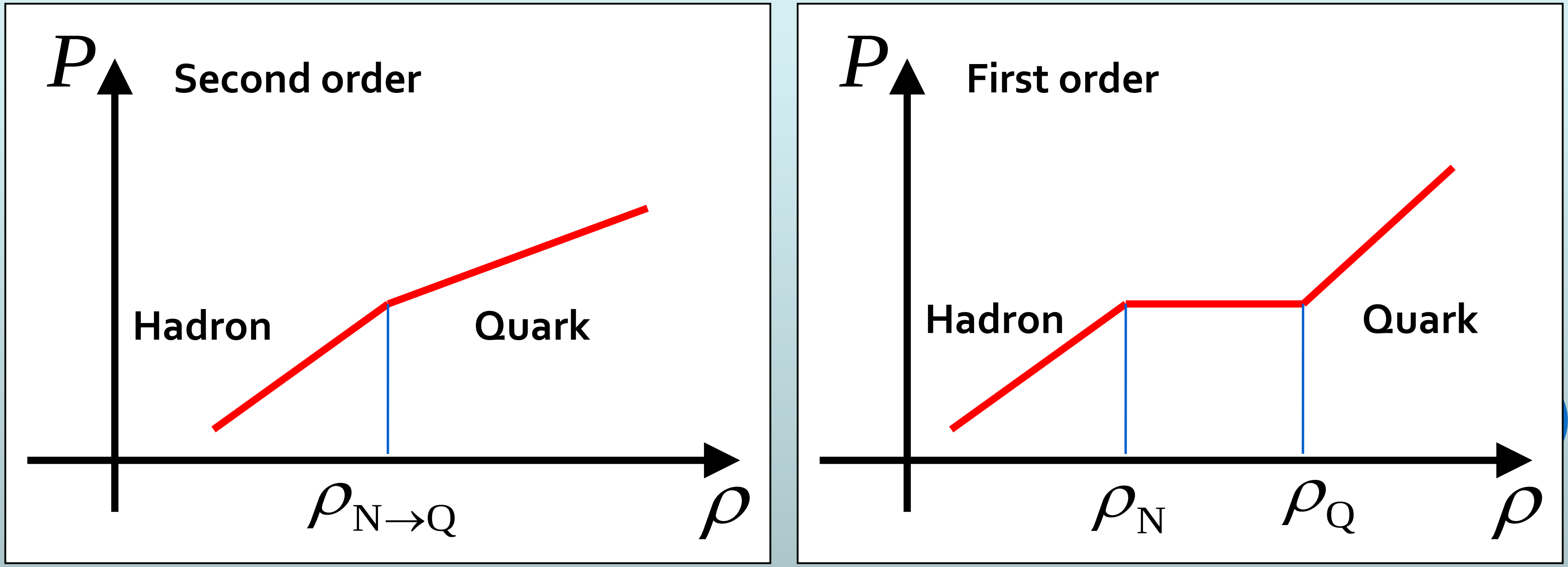
Summary

- 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**

Prospects

- Gravitational Waves from Hadron-Quark Transition
  - Second order phase transition
    - ⇒ Frequency shift (as in hyperon case)
  - First order transition
    - ⇒ <u>**Double peaked GW spectrum is expected:**</u>

      One associated with NS and the other with Quark star



Gravitational Waves from Neutron Star Merger

Inspiral phase

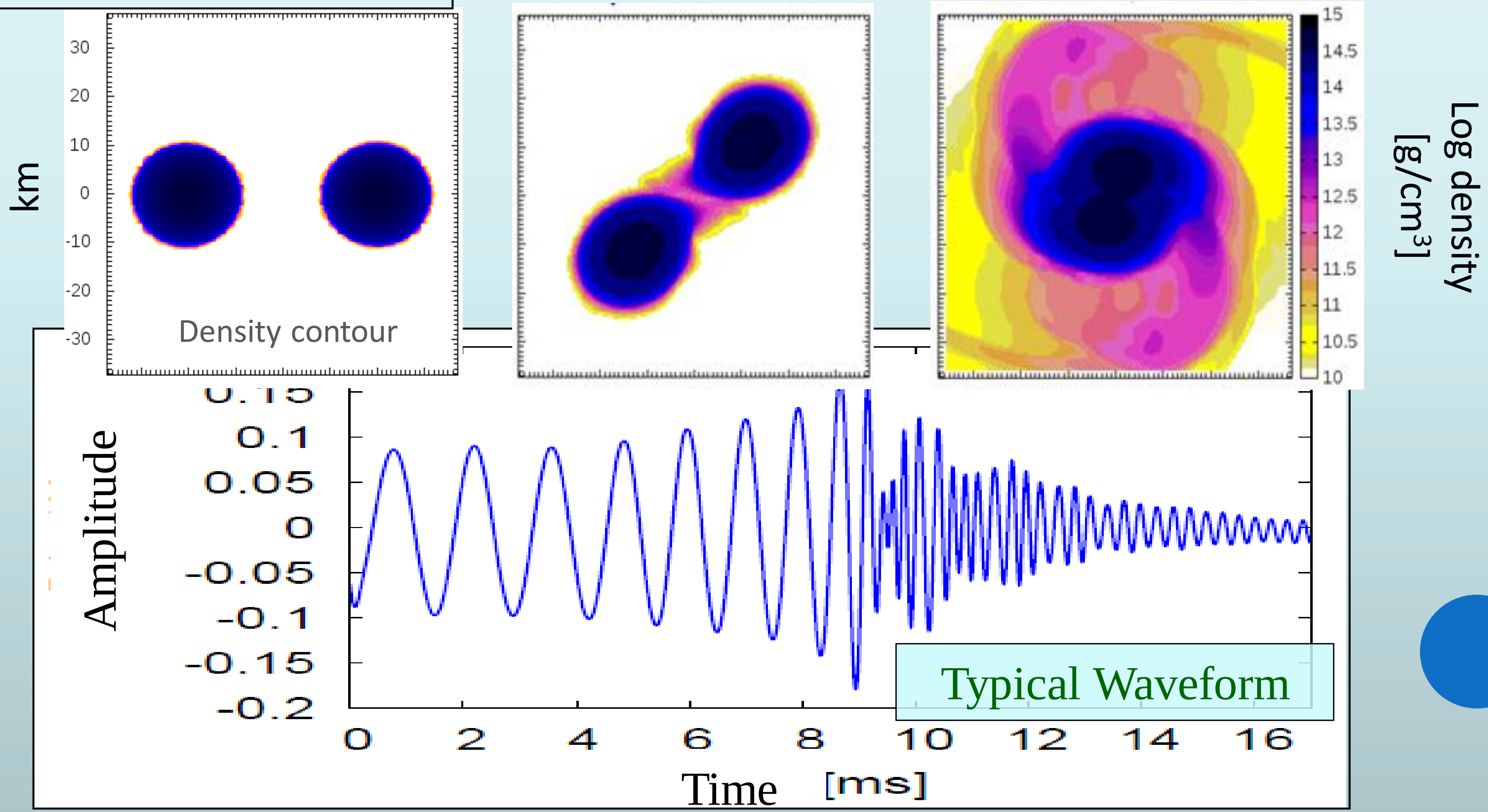
- Chirp Signals
- Information of **orbits, neutron star mass etc.**

Tidal deformation

- Finite-Size effects
- Information of radius (EOS)

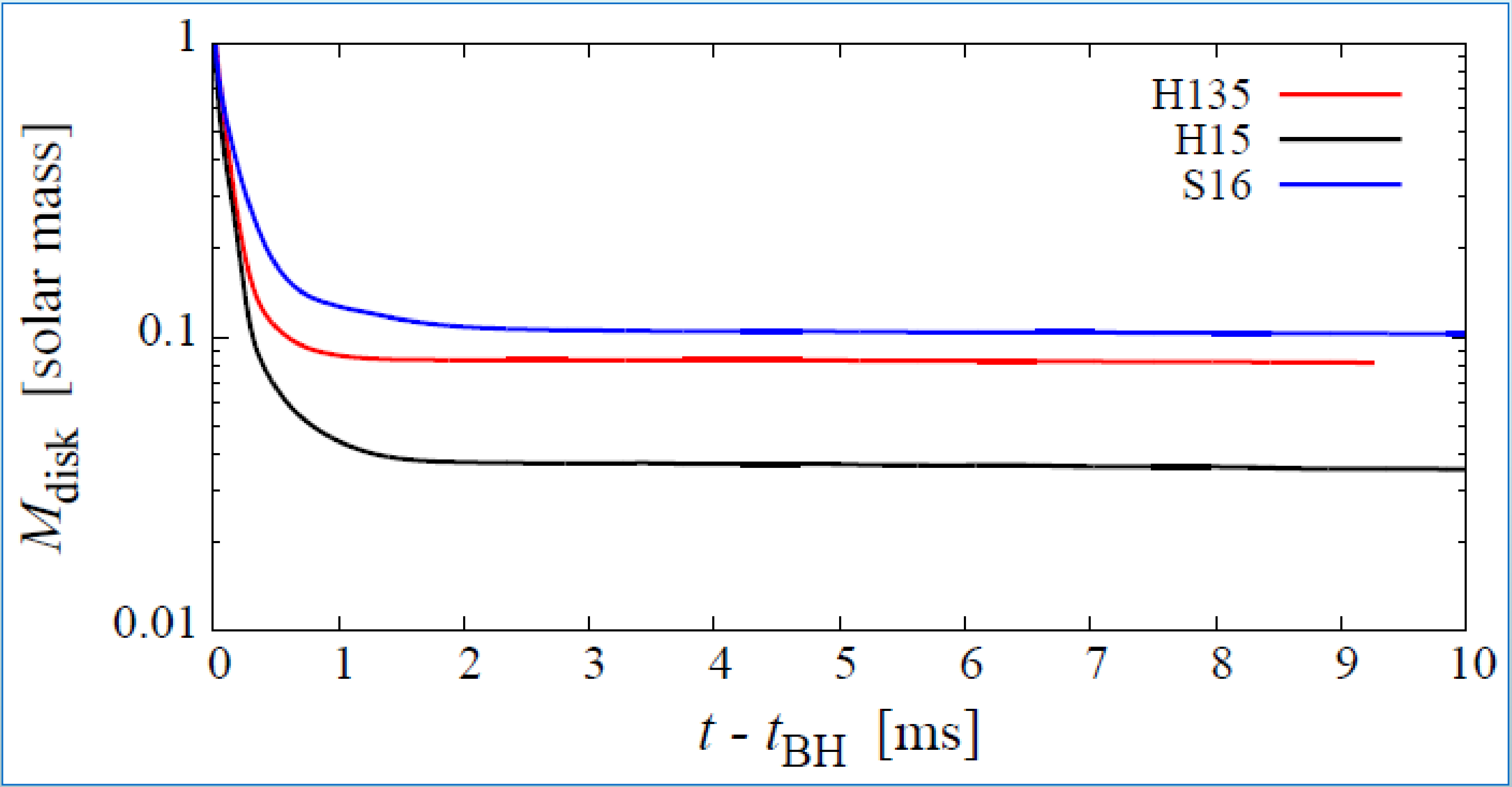
Merger and oscillation

- Maximum mass, oscillation
- Information of dense part of EOS



Disk Mass

- Disk mass is smaller for the hyperonic EOS models
  - Shorter time for angular momentum transport
  - HMNS formed after the merger is more compact



Final Fate after the Merger

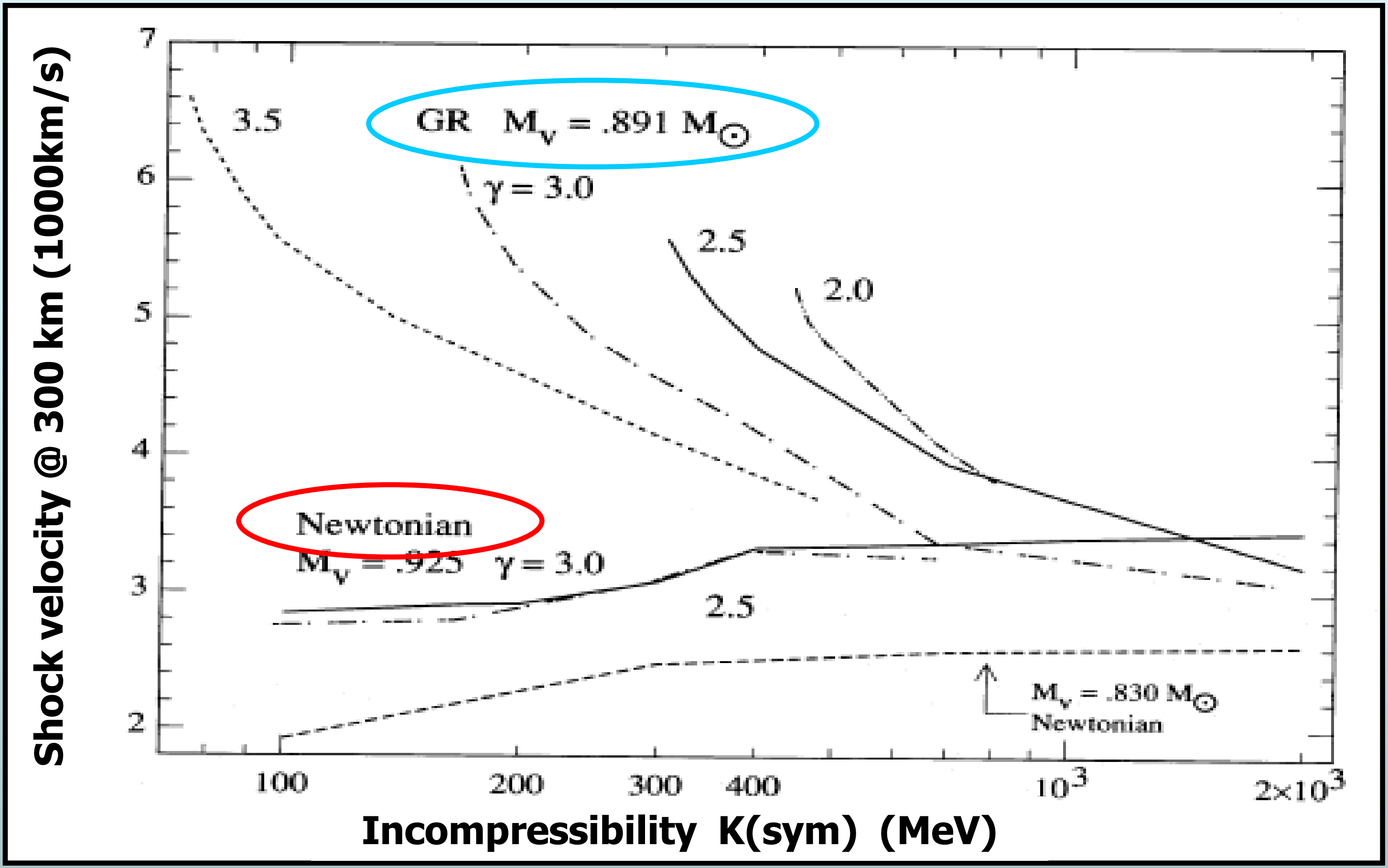
- Maximum NS mass : $M_{NS,\max} = M_{NS,\max}^{\text{cold}} + \Delta M_{\text{rot}}^{\text{rigid}} + \Delta M_{\text{rot}}^{\text{diff}} + \Delta M^{\text{th}}$
  - $M_{NS,\max}^{\text{cold}}$: maximum mass of spherical NS at T = 0, depends on EOS
    - Recent observational lower bound : 1.97 Msolar (Demorest et al. 2010)
  - $\Delta M_{\text{rot}}^{\text{rigid}}$: effects of rigid rotation $\sim O(10\%)$
  - $\Delta M_{\text{rot}}^{\text{diff}}$: effects of differential rotation typically $\sim O(10\%)$
  - ΔM^{th} : effects of finite temperature $\sim O(10\%)$
- The maximum mass can be increased by 30 — 70 % compared to the cold maximum mass

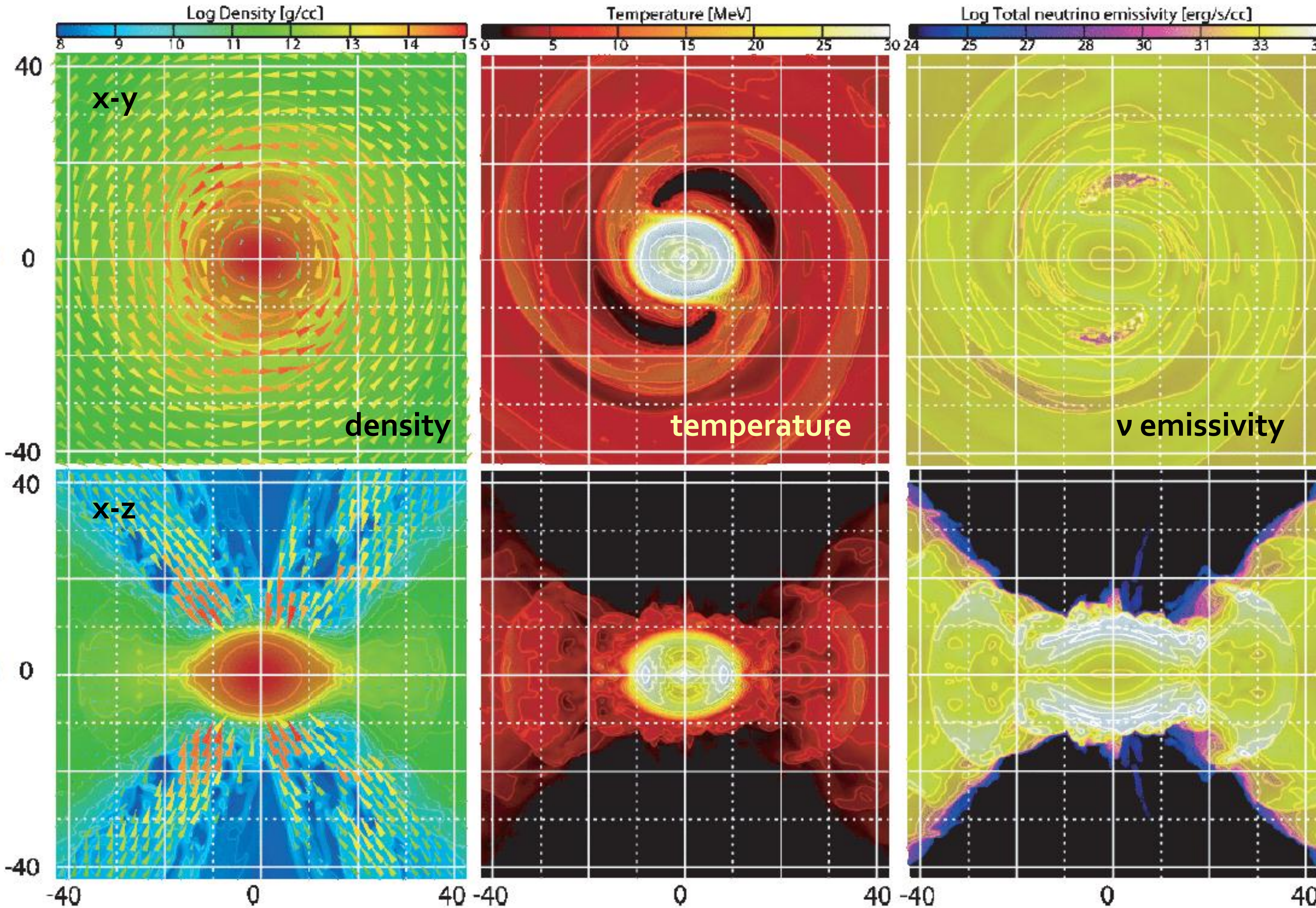
REMARK: IMPORTANCE OF GR

Van Riper (1988) ApJ 326, 235

$$P_n = K\rho_0[(\rho/\rho_0)^\gamma - 1]/9\gamma \text{ MeV fm}^{-3}$$

Kolehmainen, K., Prakash, M., Lattimer, J., and Treiner, J. 1985,




Log Density [g/cc]
8 9 10 11 12 13 14 15
Temperature [MeV]
0 5 10 15 20 25 30
Log Total neutrino emissivity [erg/s/cc]
24 25 27 28 30 31 33 34
x-y
x-z
density
temperature
ν emissivity
40
0
-40
-40 0 40