Effects of Hyperon in Binary Neutron Star Merger

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References

- Sekiguchi, Kiuchi, Kyutoku, Shibata

- Sekiguchi, Kiuchi, Kyutoku, Shibata
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 on EOS: \( \text{Mcrit} = 1.2—1.7\text{M}_{\text{max,sph.cold.NS}} \)
      - 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

\[
M_{\text{max}}(f_s) = M_{\text{max}}(0) - 6f_s \quad \text{in solar mass unit}
\]

\[
f_s(M_{\text{max}}) < 0.17 \quad \text{for } M_{\text{max}} > 2M_{\odot} \quad (f_s: \# \text{of strange quark / baryon})
\]

\[M_{\text{max}} = 1.97 \text{ M}_\odot\]
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

- **H-EOS**: EOS with Λ hyperons

- 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)
At $T = 0$, $\Lambda$ hyperons appear at $\rho \sim$ a few $\rho_{\text{nuc}}$, and $X_{\Lambda}$ increases as density and temperature increase.

Due to the appearance of $\Lambda$ hyperons, EOS becomes softer and the maximum mass of the cold spherical NS is decreased to be $M_{\text{max,sph.cold.NS}} \sim 1.8 \, M_{\odot}$. 

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Set up of BNS

- **S-EOS (nucleonic EOS)**:
  - Equal mass BNS with individual mass of 1.35, 1.5, and 1.6 M$_\odot$
  - Referred to as S135, S15, and S16

- **H-EOS (hyperonic EOS)**:
  - Equal mass BNS with individual mass of 1.35 and 1.5 M$_\odot$
  - Referred to as H135 and H15
Nucleonic EOS
Hyper massive NS (HMNS) is formed and lives a long time characterized by neutrino cooling timescale $\sim Eth/L_\nu \sim 2-3$ sec ($L_\nu$: 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 $\sim 2-3 \text{ k}_B$ which effect increases the maximum mass by 20-30%.
Gravitational Waveforms

- inspiral
- Merger and oscillation

HMNS becomes spheroidal and GW emissivity gets small

BH formation due to angular momentum loss by GW emission
Gravitational Wave Spectra

Prominent peak associated with HMNS oscillation

Events within 20Mpc can be detected

EOS information from peak frequency (Hotokezaka+ 2012, Bauswein + 2011)
Huge neutrino luminosity of $\sim 10^{53}$ erg/s even after the BH formation

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

Events within 5Mpc can be detected by Hyper Kamiokande
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 $\Rightarrow$ 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 $\Rightarrow$ HMNS shrinks $\Rightarrow$ More Hyperons appear $\Rightarrow$ EOS becomes softer $\Rightarrow$ HMNS shrinks more $\Rightarrow$ ....

- As a result, the characteristic frequency of GW increases with time
  - Providing potential way to tell existence of hyperons (exotic particles)
Gravitational Wave Spectra

Peak is weakened and broadened reflecting the short lifetime of HMNS and the frequency shift
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

![Diagram](https://via.placeholder.com/150)
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

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![Typical Waveform](image)

- Density contour
- Log density [g/cm³]
- Amplitude
- Time [ms]
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