Constraint on the maximum mass of neutron stars using GW170817 event

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We revisit the constraint on the maximum mass of cold spherical neutron stars coming from the observational results of GW170817. We develop a new framework for the analysis by employing both energy and angular momentum conservation laws as well as solid results of latest numerical-relativity simulations and of neutron stars in equilibrium. The new analysis shows that the maximum mass of cold spherical neutron stars can be only weakly constrained as $M_{\text{max}} \lesssim 2.3M_\odot$. Our present result illustrates that the merger remnant neutron star at the onset of collapse to a black hole is not necessarily rapidly rotating and shows that we have to take into account the angular momentum conservation law to impose the constraint on the maximum mass of neutron stars.

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I. INTRODUCTION

The first direct detection of gravitational waves from the coalescence of binary neutron stars (GW170817)1 was accompanied with a wide variety of the observations of electromagnetic counterparts 2–5. These observations give us new constraints for the properties of neutron stars. Gravitational-wave observation for the late inspiral phase of the binary neutron stars constrains the binary tidal deformability in the range of $100 \lesssim \tilde{\Lambda} \lesssim 800$ 1, 2. This suggests that the radius of the 1.4$M_\odot$ neutron star would be in the range between $\sim 10.5$ km and $\sim 13.5$ km.

Electromagnetic observations, in particular a possible observation of a gamma-ray burst 5, and ultraviolet-optical-infrared observation 2, 6, are also used for constraining the maximum mass of neutron stars. If we assume that the gamma-ray burst was driven from a remnant black hole surrounded by a torus, the black hole might have to be formed in a short timescale after the merger. In this hypothesis, Ref. 5 suggests that the maximum mass of neutron stars would be fairly small central value of $\approx 2.17M_\odot$. Reference 6 suggests that the maximum mass of neutron stars would be $2.16\sim 2.28M_\odot$, supposing that the merger remnant neutron star has the same mass as that of the inspiraling binary neutron star and is a rapidly rotating state (note that the actual mass of the remnant neutron star should be smaller: see Sec. II). The optical and infrared counterparts also suggest that the remnant massive neutron star would survive at least for several hundreds ms 2–4, while the absence of an extremely bright emission in the ultraviolet and optical bands at $\lesssim 1$ d suggests that the remnant formed after the merger would collapse to a black hole within a timescale of $\sim 100$ s after the merger 7, 8, 9. This speculation could also give a constraint on the maximum mass of neutron stars, and Refs 7, 9 suggest a fairly small value of the maximum mass as $\lesssim 2.2M_\odot$. However, these constraints are imposed in the assumption that the merger remnant neutron star is rapidly rotating at the onset of collapse; the constraint is imposed without taking into account details of angular momentum dissipation process in the post-merger stage self-consistently.

In this paper, we revisit the constraint on the maximum mass of cold spherical neutron stars imposed by the observational results of GW170817. The analysis is done taking into account the evolution process in the post-merger phase of binary neutron stars, by carefully analyzing both energy and angular momentum conservation laws and by employing solid results of latest numerical-relativity simulations and of rotating neutron stars in equilibrium. In particular, we show that it is essential to take into account the angular momentum conservation for this kind of analysis. We then find that the maximum mass of cold spherical neutron stars could be as large as $\sim 2.3M_\odot$: that is, the upper bound may be by $\sim 0.1M_\odot$ larger than in our previous analysis 10. We thus conclude that a simplified analysis and an inappropriate assumption lead to an inaccurate constraint on the maximum mass.

The paper is organized as follows. In Sec. II, we describe assumptions imposed in our present analysis and resulting basic equations. In Sec. III, we derive the constraint on the maximum mass of cold spherical neutron stars. Section IV is devoted to a summary. Throughout this paper, $G$ and $c$ denote the gravitational constant and speed of light, respectively.

II. ASSUMPTIONS AND BASIC EQUATIONS

In this paper, we postulate or assume the following interpretation for the observational results of neutron-star merger event GW170817. First, we postulate that a remnant neutron star was formed after the merger and survived temporarily as a quasi-steady strong neutrino emitter. This is supported by the observations of electromagnetic (ultraviolet-optical-infrared) counterparts for the merger event 6, because the neutrino irradiation from the remnant neutron stars would play an important role.
for reducing the neutron richness and lanthanide fraction of the ejecta (e.g., Refs. [6, 11, 12]). Second, we postulate that the remnant neutron star collapsed to a black hole within the dissipation timescale of its kinetic energy via electromagnetic radiation like the magnetic dipole radiation (i.e., within ~ 100 sec). This is because after the merger of binary neutron stars, magnetic fields are likely to be significantly amplified in the remnant neutron star [14] and in the presence of a strong energy injection comparable to the rest-mass energy of the ejecta by the electromagnetic radiation associated with large kinetic energy of the remnant, the ultra-violate-optical-infrared counterparts for GW170817 would be much brighter than the observational results [9, 10]. However, it should be noted that if the rotational kinetic energy of the remnant neutron star is dissipated by gravitational radiation and/or carried away by mass ejection in a short timescale (e.g., ~ 10 s), we may accept the formation of a stable neutron star, although this possibility is not very likely (see Sec. III D for a discussion). Third, we assume that the remnant neutron star at the onset of collapse was rigidly rotating. This could be a reasonable assumption for the case that the remnant neutron star was long-lived, because the degree of the differential rotation is likely to be reduced sufficiently via long-term angular momentum transport process (e.g., Ref. [13]). Thus, we suppose that the collapse of the remnant neutron star should occur at a turning point (a marginally stable state) along an equilibrium sequence of rigidly rotating supramassive neutron stars [16, 17] (see Fig. 1 for turning points). Fourth, we postulate that an appreciable fraction of the baryon of mass \( \gtrsim 0.05 M_\odot \) was located outside the black hole at its formation because the ultraviolet-optical-infrared observations for the GW170817 event indicate that the ejecta mass was likely to be \( \gtrsim 0.03 M_\odot \) [6]. Finally, in this paper, we assume that neutron stars are described by simple nuclear matter equations of state (see Appendix A) and do not suppose other exotic possibilities like quark stars, twin stars, and hybrid stars (e.g., Ref. [18]). We also postulate that general relativity is a high-precision theory for neutron stars and binary neutron star mergers.

The quantities which are referred to in this paper are as follows; the baryon rest mass and gravitational mass at the formation of the binary neutron stars, \( M_* \) and \( M_\nu \), respectively; the torus mass around the remnant neutron star and ejecta mass at the formation of a black hole, \( M_{\text{out}} \) and \( M_{\text{eje}} \), respectively; the total energy radiated by gravitational waves throughout the inspiral to post-merger phases, \( E_{\text{GW}} \); total energy radiated by neutrinos throughout the merger to post-merger phases, \( E_{\nu} \); and the maximum mass for cold spherical neutron stars, \( M_{\text{max}} \). Here, we know that \( M = 2.74^{+0.04}_{-0.01} M_\odot \) with the 90% credible level [11, 12]. In \( M_{\text{out}} \), we include mass of an atmosphere surrounding the central object. \( E_{\text{GW}} \) can be divided into two parts: One is that emitted in the inspiral phase, \( E_{\text{GW},i} \), and the other is that in the merger and post-merger phases, \( E_{\text{GW},p} \). The subject of this paper is to constrain the value of \( M_{\text{max}} \) by using the relations satisfied among these quantities.

The first relation employed is the energy conservation law together with the rest-mass conservation law, which gives

\[
M_{sf} := M_* - M_{\text{out}} - M_{\text{eje}} = f_{\text{MS}} M_f, \tag{2.1}
\]

where

\[
M_f := M - E_{\text{GW}} c^2 - E_{\nu} c^2 - M_{\text{out}} - M_{\text{eje}}, \tag{2.2}
\]

and \( M_{sf} \) and \( M_f \) denote the rest mass and gravitational mass at the onset of collapse of the remnant neutron star, respectively. In Eq. (2.2), we assumed that the thermal, kinetic, and gravitational binding energy of the matter outside the remnant neutron star is much smaller than (at most ~ 10% of) its rest-mass energy. This could affect the values of \( M_f, M_{\text{out}}, \) and \( M_{\text{eje}} \) only by \( \sim 0.01 M_\odot \). We ignore the dissipation by electromagnetic radiation like the magnetic dipole radiation because in a short timescale of \( \lesssim 10 \text{ s} \) which we consider here, the effect is likely to be negligible.

In Eq. (2.1), we denoted the ratio of the baryon rest mass to the gravitational mass for the remnant neutron star at the onset of collapse by \( f_{\text{MS}} := M_{sf}/M_f \). For cold spherical neutron stars at a marginally stable state to collapse, the ratio of the baryon rest mass to the gravitational mass is \( \approx 1.19 \pm 0.05 \) (see Appendix A). For rigidly rotating neutron stars near the marginally stable state, this value is smaller by a factor of up to \( \sim 0.02 \),

![FIG. 1. Several important curves for rigidly rotating neutron stars in the plane of the gravitational mass (M) as a function of the central density (\( \rho_c \)). In this example, we employ EOS-6 (see Sec. III) as the neutron-star equation of state. The lower and upper solid curves show the sequences of non-rotating neutron stars (labeled by \( J = 0 \)) and rigidly rotating neutron stars at mass shedding limits. The dashed curve shows the sequence of neutron stars that are marginally stable to gravitational collapse (the sequence of the turning points); the neutron stars in the lower-density side of this dashed curve are stable, otherwise they are unstable. The filled circles denote the predicted points at the onset of collapse for GW170817 in this model equation of state with \( M_{\text{out}} + M_{\text{eje}} = 0.484, 0.096, \) and 0.150\( M_\odot \) (from higher to lower mass: see Sec. III).](image-url)
and thus, it depends only weakly on angular momentum (cf. Fig. 2 of Sec. III).

We also denote the ratio of $M_*$ to $M$ as $f_0 := M_*/M$. Since the ratio of the baryon rest mass to the gravitational mass is $\sim 1.08-1.14$ for realistic neutron stars with mass 1.2–1.6$M_\odot$, $f_0$ should be also $\approx 1.11 \pm 0.03$ (see Appendix A).

For larger radii of neutron stars, $f_0$ and $f_{MS}$ are in general smaller. It should be cautioned that the values of $f_0$ and $f_{MS}$ depend on the equation of state and their deviation is not negligible for imposing the constraint to $M_{max}$ within an error of 0.1$M_\odot$. Thus, in the analysis for constraining $M_{max}$, we must not use particular values for them.

By eliminating $M_*$ from Eqs. (2.1) and (2.2), we finally obtain

$$M \left(1 - \frac{f_0}{f_{MS}}\right) = E_GW e^{-2} + E_\nu c^{-2} + (M_{out} + M_{eje}) \left(1 - \frac{1}{f_{MS}}\right).$$

(2.3)

From Eqs. (2.2) and (2.3), we also obtain the gravitational mass at the onset of collapse as

$$M_f = \frac{f_0}{f_{MS}} M - \frac{M_{out} + M_{eje}}{f_{MS}}.$$

(2.4)

As we show in Appendix A, for cold spherical neutron stars of a variety of equations of state with the constraint that the tidal deformability of 1.35$M_\odot$ neutron stars, $\Lambda_{1.35}$, is smaller than 1000, the value of $f_0/f_{MS}$ is approximately $0.920 \pm 0.025$. For this range, the left-hand side of Eq. (2.3) is found to be in a wide range as

$$M \left(1 - \frac{f_0}{f_{MS}}\right) = 0.219^{+0.073}_{-0.069} M_\odot.$$

(2.5)

and also,

$$M_f = 2.521^{+0.106}_{-0.077} M_\odot - \frac{M_{out} + M_{eje}}{f_{MS}}.$$

(2.6)

We note that $f_{MS}$ depends only weakly on the angular momentum, as we find in Sec. IIII Equations (2.9) and (2.10) clearly illustrate that the dissipated energy and the gravitational mass at the onset of collapse have uncertain of approximately $\pm 0.1M_\odot$ because the equation of state is not well constrained. As we show in Appendix A, the values of $f_0/f_{MS}$ are correlated with $M_{max}^{-1}$. Thus, smaller values of $M_{max}$ lead to larger values of $M_f$ and to smaller energy dissipated from the system (see Sec. III).

The electromagnetic (ultraviolet-optical-infrared) counterpart observations for GW170817 show that the ejecta mass would be approximately $M_{eje} \approx 0.03-0.05M_\odot$ (e.g., Ref. 4). This value is also supported by numerical simulations for a neutron star surrounded by a torus (14, 15, 21). Numerical simulations (e.g., Refs. 10, 13, 21) also indicate that the mass of the torus around the remnant neutron star would be $\sim 0.1-0.2M_\odot$ for its early stage, and reduce to $\sim 0.02-0.05M_\odot$ for its late stage $\tau \geq 1s$ due to the mass ejection and mass accretion onto the remnant neutron star. Thus, $M_{out}$ depends on the lifetime, $\tau$, of the remnant neutron star. Also, at the formation of a black hole, it is decreased by $\lesssim 50\%$ because a substantial fraction of the torus matter in the vicinity of the central object is swallowed by the black hole at its formation. Thus, we suppose $0.02M_\odot \leq M_{out} \leq 0.10M_\odot$ at the collapse of the remnant neutron star in the following. For $M_{out} = 0.06 \pm 0.04M_\odot$, $(M_{out} + M_{eje})/f_{MS}$ is approximately $(0.083 \pm 0.042)M_\odot$ and $(M_{out} + M_{eje})(1 - 1/f_{MS})$ is $(0.016 \pm 0.008)M_\odot$, which is much smaller than the value of Eq. (2.4). Using this result, we approximately obtain

$$M_f = 2.44^{+0.15}_{-0.12} M_\odot,$$

(2.7)

and

$$(E_GW + E_\nu) c^{-2} = (1 - \frac{f_0}{f_{MS}}) - \frac{(M_{out} + M_{eje}) f_{MS}}{f_{MS}} = (0.20 \pm 0.08) M_\odot.$$
velocity is approximately written as (see also Table I)
\[ \Omega_K \approx \sqrt{GM_{\text{MNS}}/R_{\text{MNS}}^3} \approx 1.01 \times 10^4 \text{rad/s} \left( \frac{M_{\text{MNS}}}{2.6M_\odot} \right)^{1/2} \left( \frac{R_{\text{MNS}}}{15 \text{ km}} \right)^{-3/2}. \] (2.10)

As we find in the following, one of the key parameters for determining the angular momentum at the onset of collapse of the remnant neutron star is \( E_{\text{GW},p} \). While \( E_{\text{GW},p} \) could be \( \sim 0.125M_\odot c^2 \) if most of the rotational kinetic energy is dissipated by gravitational radiation, the post-merger evolution process is highly uncertain. If an efficient angular momentum transport works in the remnant neutron star and the degree of its non-axisymmetric deformation is reduced quickly, \( E_{\text{GW},p} \) would be of order \( 0.01M_\odot c^2 \) \cite{23}. These facts together with Eq. (2.3) suggest that an appreciable amount of energy of \( \sim 0.1M_\odot c^2 \approx 2 \times 10^{53} \text{erg} \) would be dissipated by the emission of neutrinos until the onset of collapse to a black hole, unless the remnant neutron star radiates gravitational waves of energy comparable to \( \sim 100 \text{ms} \), e.g., within the 0.1 ms error, we could obtain the value of \( E_{\text{GW},p} \) to satisfy Eq. (2.8) (see Sec. III for more specific examples).

Since the remnant neutron star is rotating, the gravitational mass at the onset of collapse has to be larger than the maximum mass, \( M_{\text{max}} \), for cold spherical neutron stars by a factor of \( f_r = M_f/M_{\text{max}} > 1 \). Here, the value of \( f_r \) is determined at a turning point along an equilibrium sequence of rigidly rotating neutron stars. If we could obtain the value of \( f_r \) together with \( M_f \), we can determine the value of \( M_{\text{max}} \). For the change of \( f_r \) by 0.1, \( M_{\text{max}} \) could be changed by \( \approx 0.2M_\odot \). Thus, for constraining \( M_{\text{max}} \), e.g., within the 0.1 ms error, we have to determine the value of \( f_r \) within an error of \( \sim 0.05 \). For the maximally rotating neutron star along the turning point sequence, the value of \( f_r \) is known to be \( \sim 1.2 \) \cite{13,23} (see also Fig. 2 of Sec. III). Since it has been used for guessing the maximum mass of cold spherical neutron stars \cite{23,11}. However, the remnant neutron star is not always rotating in such a high rotation speed as shown in Sec. III In setting \( f_r \approx 1.2 \), one would assume a particular angular momentum of the remnant neutron star neglecting the angular momentum conservation. In addition, the maximum value of \( f_r \) depends on the equation of state (see Fig. 2 of Sec. III). It should be cautioned again that in the analysis for constraining the value of \( M_{\text{max}} \), we must not a priori employ a particular value for \( f_r \).

For inferring the angular momentum of the remnant neutron star at the onset of collapse, we have to seriously analyze the dissipation of angular momentum in the post-merger phase. Let \( J_0 \) and \( J_f \) be the angular momentum at the onset of merger and at the onset of collapse of the remnant neutron star to a black hole, respectively. Then, we obtain
\[ J_f = J_0 - J_{\text{GW},p} - J_{\nu} - J_{\text{out}} - J_{\text{ej}}, \] (2.11)
where \( J_{\text{GW},p}, J_{\nu}, J_{\text{out}}, \) and \( J_{\text{ej}} \) are the angular momentum carried away (after the merger) by gravitational radiation, by neutrinos, angular momentum of the torus surrounding the remnant black hole at its formation, and angular momentum of ejecta (at the black-hole formation). In the following, we give or determine these quantities based on the results of numerical-relativity simulations. We also note that by angular momentum transport processes from the remnant neutron star to the surrounding matter, the angular momentum of torus and ejecta in general increases with time in the post-merger phase.

Since gravitational waves emitted in the post-merger phase are dominated by a fundamental mode of its frequency \( f = 2 - 4 \text{kHz} \), \cite{28,29}, \( J_{\text{GW},p} \) is approximately written as
\[ J_{\text{GW},p} \approx \frac{E_{\text{GW},p}}{\pi f} \approx 9.5 \times 10^{48} \text{erg s} \left( \frac{E_{\text{GW},p}}{0.05 M_\odot c^2} \right) \left( \frac{f}{3.0 \text{kHz}} \right)^{-1}. \] (2.12)
Our latest numerical-relativity simulation confirms that this relation is satisfied within 1% accuracy \cite{30}. Here, for the binaries of total mass \( \approx 2.7M_\odot \), \( f \approx 3.6, 3.1, \) and 2.5 kHz for \( R_{t_{150}} \approx 11, 12, \) and 13.5 km \cite{28,29} with \( R_M \) the radius of a spherical neutron star of its gravitational mass \( M \) (in units of \( M_\odot \)). Thus, for \( R_{t_{150}} \approx R_{t_{150}} \lesssim 13.5 \text{km} \) (this constraint was given from the observational result of the tidal deformability of GW170817 \cite{1,2}), \( f \gtrsim 2.5 \text{kHz} \). In this paper, we infer the value of \( f \) by using the relation of Eq. (3) of Ref. 22.

Since the angular momentum of neutrinos are dissipated due to the fact that the emitter (remnant neutron star) is rotating, \( J_{\nu} \) is written approximately by \( J_{\nu} \approx (2/3)c^{-2}R_{\text{MNS}}^2\Omega E_{\nu} \) \cite{31}, and thus,
\[ J_{\nu} \approx 3.0 \times 10^{48} \text{erg s} \left( \frac{E_{\nu}}{0.1M_\odot c^2} \right) \left( \frac{R_{\text{MNS}}}{15 \text{ km}} \right)^2 \times \left( \frac{\Omega}{10^4 \text{rad/s}} \right)^{-1}. \] (2.13)
We note that the value of \( J_{\nu} \) described here agrees with the results of a numerical-relativity simulation within a factor of 2 \cite{21}. Equation (2.13), in comparison with Eq. (2.12), illustrates that this is a non-negligible but minor effect for dissipating the angular momentum (thus, the error would be also a minor effect).

\( J_{\text{out}} \) is associated with the typical radius of the torus surrounding the remnant neutron star (at the onset of

\[ J_f = J_0 - J_{\text{GW},p} - J_{\nu} - J_{\text{out}} - J_{\text{ej}}. \] (2.11)
collapse). Denoting it by $R_{\text{out}}$, it is approximated by $J_{\text{out}} \approx M_{\text{out}} \sqrt{G M_{\text{MS}} R_{\text{out}}}$, and thus,

$$J_{\text{out}} \approx 5.8 \times 10^{48} \text{ erg s} \left( \frac{M_{\text{out}}}{0.05 M_{\odot}} \right) \left( \frac{R_{\text{out}}}{100 \text{ km}} \right)^{1/2} \times \left( \frac{M_{\text{MS}}}{2.6 M_{\odot}} \right)^{1/2}.$$  \hfill (2.14)

Here $R_{\text{out}}$ would be fairly small ~50 km in the early evolution stage of the accretion torus. However, during its long-term viscous evolution as well as angular momentum transport from the remnant neutron star, the typical radius increases to be $\gtrsim 100 \text{ km}$ for $\tau \gtrsim 300 \text{ ms}$ \cite{12} which shows $R_{\text{out}} \approx 40 + 100(\tau/1 \text{ s})^{1/2} \text{ km}$ for $\tau \lesssim 1.5 \text{ s}$ and for a longer term, $R_{\text{out}}$ approaches $\sim 200 \text{ km}$.

Jeje is associated with the location at which the mass ejection occurs. Denoting the typical location by $R_{\text{eje}}$, it is approximated by $J_{\text{eje}} \approx M_{\text{eje}} \sqrt{G M_{\text{MS}} R_{\text{eje}}}$, and thus,

$$J_{\text{eje}} \approx 6.9 \times 10^{48} \text{ erg s} \left( \frac{M_{\text{eje}}}{0.05 M_{\odot}} \right) \left( \frac{R_{\text{eje}}}{140 \text{ km}} \right)^{1/2} \times \left( \frac{M_{\text{MS}}}{2.6 M_{\odot}} \right)^{1/2}.$$  \hfill (2.15)

For long-lived remnant neutron stars which we consider in this paper, mass ejection mainly occurs through the long-term viscous process in the post-merger stage from an accretion torus \cite{13, 19, 20} with mass $\sim 0.05 M_{\odot}$, while for dynamical mass ejection that occurs at merger, the matter would be ejected at $R_{\text{eje}} \sim 30 \text{ km}$ with mass $\lesssim 0.01 M_{\odot}$. (Note that in $M_{\text{eje}}$ both contributions are included.) Thus, for $J_{\text{eje}}$, only the post-merger mass ejection could contribute dominantly to the angular momentum loss. Since this mass ejection is driven from the torus, we simply set $R_{\text{out}} = R_{\text{eje}}$ in this paper; that is, we employ a relation as $J_{\text{out}} + J_{\text{eje}} = (M_{\text{out}} + M_{\text{eje}}) \sqrt{G M_{\text{MS}} R_{\text{out}}}$. Here, we may overestimate $J_{\text{eje}}$ because the dynamical ejecta would have smaller angular momentum than the post-merger one. However, since the mass of the dynamical ejecta would be much smaller than the post-merger ejecta, the degree of the overestimation would be minor.

We note that the error for the estimate in $J_{\text{out}} + J_{\text{eje}}$ associated with the uncertainty in $R_{\text{out}}$ would be of order 10%. This error will be reflected in $M_{\text{out}} + M_{\text{eje}}$, for determining it (see Sec. III). However, its error size does not affect our final conclusion.

Thus, besides $J_0$, the quantities in the right-hand side of Eq. (2.11) is related to $E_{\text{GW}}$, $E_{\nu}$, $M_{\text{out}}$, and $M_{\text{eje}}$ with $f$, $\Omega$, $M_{\text{MS}}$, and $R_{\text{out}}$, as given parameters.

In addition, there is important role in Sec. III. We note that the error for the estimate in $J_{\text{out}} + J_{\text{eje}}$ associated with the uncertainty in $R_{\text{out}}$ would be of order 10%. This error will be reflected in $M_{\text{out}} + M_{\text{eje}}$, for determining it (see Sec. III). However, its error size does not affect our final conclusion.

### III. ANALYSIS BASED ON NUMERICAL MODELING OF NEUTRON STARS AND BINARY NEUTRON STAR MERGERS

#### A. Preparation

In the analysis of Sec. III we have several unknown parameters: $f_0$, $f_{\text{MS}}$, $E_{\text{GW},i}$, $E_{\text{GW},p}$, $E_{\nu}$, $f$, $\Omega$, $M_{\text{MS}}$, $M_{\text{out}}$, $M_{\text{eje}}$, $R_{\text{MS}}$, $R_{\text{out}}$, and $J_0$. Among them, $f_0$, $f_{\text{MS}}$, $\Omega$, $M_{\text{MS}}$, and $R_{\text{MS}}$ for a given equation of state are calculated (at least with good approximation) by constructing equilibrium states of non-rotating and rotating neutron stars. Also, $E_{\text{GW},i}$, $f$, $M_{\text{out}}$, $M_{\text{eje}}$, and $R_{\text{out}}$ are approximately obtained with the help of numerical-relativity simulations as already mentioned in Sec. III. $J_0$ is also obtained accurately with the help of numerical relativity. The dependence of $J_0$ on total binary mass $M_0$, symmetric mass ratio (hereafter referred to as $\eta$), and $R_{1.35}$ is determined by the results by numerical relativity simulations \cite{30} as

$$J_0 \approx Gc^{-1} \left[ a_1 + a_2 \delta\eta + a_3 R_{1.35}^4 (1 + a_4 \delta\eta) \right],$$  \hfill (3.1)

where $R_{1.35}$ denotes $R_{1.35}$ in units of 10 km, $\delta\eta = \eta - 1/4(\leq 0)$, $a_1 \approx 3.32$, $a_2 \approx 31$, $a_3 \approx 0.137$, and $a_4 \approx 27$. We note that $J_0$ increases with the increase of $R_{1.35}$ and with the decrease of $\eta$ because the merger occurs at a more distant orbit for larger stellar radii and for more asymmetric binaries.

Equation (3.1) shows that $J_0$ is in the range between $\approx 5.8 \times 10^{49} \text{ erg s}$ and $\approx 6.3 \times 10^{49} \text{ erg s}$ for neutron stars with $R_{1.35} = 10.5-14 \text{ km}$, total mass $M_0 \approx 2.74M_{\odot}$, and $\eta = 0.244-0.250$ (i.e., mass ratio 0.73–1.00). The value of $J_0$ is by $\sim 1 \times 10^{49} \text{ erg s}$ larger than the maximum angular momentum of rigidly rotating neutron stars (see Fig. 2) and $2\pi/\Omega \approx \Omega \approx \Omega_K$ (see Eq. (2.6)), and this fact suggests that the remnant neutron star would initially have a differentially rotating state with the maximum angular velocity slightly larger than $\Omega_K$, as has been found in many numerical-relativity simulations since Ref. \cite{32}.

In contrast to $J_0$ and $E_{\text{GW},i}$, $E_{\text{GW},p}$ and $E_{\nu}$ are not determined into a narrow range although $E_{\text{GW},p} + E_{\nu}$ is constrained by Eq. (2.8) for given values of $f_0/f_{\text{MS}}$. This becomes a condition that determines a particular state of the remnant neutron star at the onset of collapse for a given equation of state. This equation plays an important role in Sec. III.
TABLE I. Selected piecewise polytropic equations of state and important quantities for spherical neutron stars. The units of the mass and radius are $M_\odot$ and kilometer, and that of $p$ is dyn/cm$^2$. $f_{\text{MS}}$ is the ratio of the baryon rest mass to $M_{\text{max}}$ for the maximum mass neutron star. $f_0$ shown here is $M_f/M$ for binaries of mass $1.35M_\odot$ and $1.40M_\odot$. $f$ denotes the dominant frequency of post-merger gravitational waves predicted approximately by the formula in Ref. [28].

| Model | $\Gamma_2$ | $\Gamma_3$ | $\log_{10} P$ | $M_{\text{max}}$ | $f_{\text{MS}}$ | $R_{1.65}$ | $R_{1.35}$ | $\Lambda_{1.35}$ | $f_0$ | $f$ (kHz) |
|-------|------------|------------|----------------|------------------|------------------|------------|------------|----------------|------|----------|
| EOS-1 | 3.15       | 2.81       | 34.350         | 2.075            | 1.200            | 11.27      | 11.30      | 366.6         | 1.113| 3.45     |
| EOS-2 | 2.60       | 2.84       | 34.550         | 2.106            | 1.172            | 12.67      | 12.94      | 746.0          | 1.092| 2.71     |
| EOS-3 | 3.45       | 2.70       | 34.300         | 2.133            | 1.208            | 11.17      | 11.12      | 348.2          | 1.117| 3.50     |
| EOS-4 | 3.80       | 2.80       | 34.200         | 2.147            | 1.221            | 10.91      | 10.80      | 302.8          | 1.122| 3.62     |
| EOS-5 | 2.70       | 2.78       | 34.575         | 2.176            | 1.177            | 12.88      | 13.06      | 821.9          | 1.092| 2.65     |
| EOS-6 | 3.00       | 2.80       | 34.500         | 2.212            | 1.196            | 12.21      | 12.25      | 599.0          | 1.102| 3.01     |
| EOS-7 | 3.15       | 2.81       | 34.475         | 2.246            | 1.204            | 12.06      | 12.04      | 555.7          | 1.105| 3.08     |
| EOS-8 | 3.65       | 2.78       | 34.325         | 2.252            | 1.222            | 11.39      | 11.27      | 395.2          | 1.116| 3.40     |
| EOS-9 | 3.05       | 2.80       | 34.550         | 2.306            | 1.200            | 12.57      | 12.56      | 720.7          | 1.099| 2.74     |
| EOS-10| 2.85       | 2.85       | 34.625         | 2.328            | 1.189            | 13.24      | 13.29      | 967.6          | 1.092| 2.55     |
| EOS-11| 3.80       | 2.50       | 34.375         | 2.353            | 1.229            | 11.66      | 11.50      | 459.7          | 1.113| 3.27     |
| EOS-12| 3.25       | 2.78       | 34.575         | 2.433            | 1.212            | 12.68      | 12.60      | 757.8          | 1.100| 2.70     |

$E_{\text{GW}}$, and $(M_{\text{out}} + M_{\text{ej}})/f_{\text{MS}}$ fairly well. We note that $E_{\nu}$ is associated with the lifetime of the remnant neutron star of GW170817, $\tau$, as $E_{\nu} \approx L_{\nu} \tau$. Here, the neutrino luminosity is $L_{\nu} \gtrsim 10^{53}$ erg/s [27]. but $\tau$ is not very clear. Thus, we consider $E_{\text{GW}}$ and $E_{\nu}$ as values to be determined in the present analysis.

In the following, we constrain the value of $M_{\text{max}}$ by analysing rigidly rotating neutron stars at marginally stable states (at turning points) for several equations of state. For computing rigidly rotating neutron stars in equilibrium, we employ a piecewise polytropic equation of state, for which the details are described in Appendix A. The selected equations of state used in this section are listed in Table I. We selected many equations of state rather randomly for each range of $M_{\text{max}}$. For the analysis, we only employ the equations of state with which 2$M_\odot$ neutron stars are reproduced, $\Lambda_{1.35} \leq 1000$, and the sound speed is always smaller than the speed of light for stable neutron stars. We ignore the thermal effect of the remnant neutron star for constructing equilibrium rotating neutron stars because it is a minor contribution to the neutron-star properties if we consider its age to be of order 0.1–1 s [35].

Figure 2 displays several key quantities as functions of the angular momentum, $J$, along the sequences of the marginally stable neutron stars (cf. the dashed curve of Fig. 1). Here, the neutron stars with $J = 0$ denote the marginally stable state for the spherical neutron stars of mass $M_{\text{max}}$, and at $J = J_{\text{max}}$, the neutron stars are at the mass-shedding limit; the angular velocity at the equatorial surface is equal to the Keplerian one. Table I also lists several quantities of rigidly rotating neutron star at a turning point and mass shedding limit.

Figure 3 displays the relation between $f_0/f_{\text{MS}}$ and $M_{\text{max}}$ for marginally-stable rigidly-rotating neutron stars with several piecewise polytropic equations of state. Here, $f_0$ is calculated for binaries of mass $1.35M_\odot$, $1.40M_\odot$ and $(1.20M_\odot, 1.55M_\odot)$, but the values for two cases are different only by 0.2–0.3% (see Fig. 5), and thus, the difference in $f_0$ is not very important in the following. The uncertainty in Fig. 3 reflects the variation of $f_{\text{MS}}$ for the different angular momentum of the marginally stable rotating neutron stars: As found from Fig. 2, $f_0/f_{\text{MS}}$ is smallest for $J = 0$ and largest for $J = J_{\text{max}}$. The tilted lines show the relation of Eq. (2.17) for $f_r = 1.20 - 0.02 \times i$ up to 1.00 (from left to right) with $(M_{\text{out}} + M_{\text{ej}})/f_{\text{MS}} = 0.04M_\odot$ and 0.08$M_\odot$, while $M$ is fixed to be 2.74$M_\odot$. We note that for a given value of $M_{\text{max}}$, the value of $f_0/f_{\text{MS}}$ is in general larger for the larger values of $\Lambda_{1.35}$, and hence, the upper bound is determined by the constraint for $\Lambda_{1.35}$ (see Appendix A).

For rigidly rotating neutron stars, the upper limit of $f_r$ is approximately 1.2 as found from Fig. 2 (see also Table I). Thus, the left region of the line of $f_r = 1.2$ in Fig. 3 is prohibited in our model. That is, for the equations of state with small values of $M_{\text{max}} = 2.0 - 2.1M_\odot$, the remnant neutron star cannot achieve the rigidly rotating state at the onset of collapse (we show the examples in Sec. III). For such equations of state, the remnant neutron star would collapse before the rigidly rotating state is achieved, i.e., its lifetime is shorter than the angular momentum transport timescale in the remnant neutron star. It is natural to consider that the lifetime of the remnant neutron star with such equations of state is fairly short $\ll 1$. s.

For the right region of the line of $f_r = 1$, on the other hand, the collapse cannot occur, because the mass of the remnant neutron star is smaller than $M_{\text{max}}$. Thus, for such equations of state, a stable neutron star should be the final outcome. As mentioned in the first paragraph of Sec. I if such a stable remnant is formed in GW170817 and has large rotational kinetic energy $\gtrsim 10^{52}$ erg, an energy injection to ejecta through electromagnetic radiation like the magnetic dipole radiation would occur and
be inconsistent with the observational results for the elec-
tromagnetic counterparts of GW170817 [9, 10]. However,
if the rotational kinetic energy is dissipated or removed in
a short timescale ($\lesssim 100$ s), e.g., by gravitational radia-
tion and neutrino emission, we may accept the formation
of a stable neutron star [35].

Figure 3 shows an important fact as follows: If the
maximum mass of spherical neutron stars in nature is
relatively small $\lesssim 2.1M_\odot$, the collapse would occur for
the remnant neutron star in a rapidly rotating state with
$f_r \approx 1.2$. On the other hand, if the maximum mass of
spherical neutron stars is relatively large $\gtrsim 2.3M_\odot$, the
collapse would not occur for rapidly rotating remnant
neutron star but for $f_r \lesssim 1.05$. Then the next issue is
whether we can find a self-consistent solution for such
collapses, because $f_r$ is determined by the angular mo-
mentum dissipation process in the post-merger stage. In
the following, we show several realistic scenarios for this
process in some of equations of state that we select.

**FIG. 2.** Gravitational mass, $M$, ratio of $M$ to $M_{\text{max}}$ ($f_r$), ratio of baryon rest mass to the gravitational mass, $f_{\text{MS}}$, and rotational kinetic energy $T = J\Omega/2$ as functions of $J$ for rigidly rotating neutron stars along the marginally stable sequence (i.e., along the turning point sequence) with selected equations of state (see Table I). Note that $M$ at $J = 0$ is $M_{\text{max}}$.

**B. Method**

For each equation of state, we try to find a solution
that satisfies the conservation relations of energy and an-
gular momentum self-consistently. We will have a brief
summary of our model by analyzing the degree of free-
doms of all unknown variables here. There are in total
14 variables in the conservation law of rest mass, energy
and angular momentum (cf. Eq. (2.1), (2.2) and (2.11)).
Nevertheless, $M$ is determined by observation and $M_{\ast}$
is related to $M$ by factor $f_0$ which could be determined
once a model equation of state is assumed. Similarly,
according to the marginally stable solution results,
$M_{\ast}$ and $J_{\ast}$ are fixed once $M_{\ast}$ is fixed and an equation of
state is given. Hence, there is only one degree of free-
dom among $M_{\ast}$, $M_{\ast}$ and $J_{\ast}$. $J_0$ is given by Eq. (3.1).
There are 8 other variables left: $E_\nu$ and $J_\nu$ are related by
Eq. (2.13), $E_{\text{GW},p}$ and $J_{\text{GW},p}$ are related by Eq. (2.12),
$M_{\text{ej}} + M_{\text{out}}$ and $J_{\text{ej}} + J_{\text{out}}$ are related by Eq. (2.13)
and (2.14). As a consequence, there are only 3 degrees of
freedom in the remaining 8 variables. In total, there are
4 degrees of freedom and we have 3 equations (laws of
conservation). Once we have input one parameter, such
FIG. 3. Relation between \( f_0 \) and \( M_{\text{max}} \) for marginally-stable rigidly-rotating neutron stars with several equations of state listed in Table I. The lower and upper ends of each uncertainty range correspond to \( J = 0 \) and \( J = J_{\text{max}} \), respectively. The numbers attached in each data denote the model equations of state. The tilted lines show the relation of Eq. (2.17) for \( f_r = 1.20, 1.18, 1.16, \cdots, 1.04, 1.02, \) and 1.00 (from left to right) with \((M_{\text{out}} + M_{\text{eje}})/f_{\text{MS}} = 0.04M_\odot \) (left panel) and 0.08\( M_\odot \) (right panel) and with \( M = 2.74M_\odot \). The thick lines are for \( f_r = 1.20, 1.10, \) and 1.00.

TABLE II. Key quantities for rigidly rotating neutron stars at the maximum mass along the marginally stable sequences for selected equations of state listed in Table I: \( M_{\text{MS, R}} \): gravitational mass, \( M_{\text{MS, R}} \): baryon rest mass, \( J_{\text{MS, R}} \): angular momentum, \( \Omega_{\text{MS, R}} \): angular velocity, \( T_{\text{MS, R}} \): rotational kinetic energy, and \( R_{\text{MS, R}} \): circumferential radius at the equatorial surface.

| Model | \( M_{\text{MS, R}} \) (\( M_\odot \)) | \( M_{\text{MS, R}}/M_{\odot} \) | \( M_{\text{MS, R}}/M_{\text{max}} \) | \( J_{\text{MS, R}} \) (\( 10^{52} \text{erg s} \)) | \( \Omega_{\text{MS, R}} \) (\( 10^{5} \text{rad/s} \)) | \( T_{\text{MS, R}} \) (\( 10^{53} \text{erg} \)) | \( R_{\text{MS, R}} \) (\( \text{km} \)) |
|-------|-------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| EOS-1 | 2.497 | 1.185 | 1.203 | 3.875 | 1.160 | 2.247 | 13.04 |
| EOS-2 | 2.474 | 1.161 | 1.175 | 3.567 | 1.055 | 1.880 | 13.74 |
| EOS-3 | 2.570 | 1.193 | 1.216 | 4.183 | 1.155 | 2.415 | 13.15 |
| EOS-4 | 2.631 | 1.203 | 1.225 | 4.492 | 1.192 | 2.677 | 13.11 |
| EOS-5 | 2.574 | 1.167 | 1.183 | 3.919 | 1.028 | 2.014 | 14.19 |
| EOS-6 | 2.649 | 1.182 | 1.198 | 4.315 | 1.077 | 2.323 | 13.87 |
| EOS-7 | 2.707 | 1.188 | 1.205 | 4.580 | 1.090 | 2.496 | 13.93 |
| EOS-8 | 2.757 | 1.203 | 1.224 | 4.932 | 1.143 | 2.819 | 13.73 |
| EOS-9 | 2.770 | 1.185 | 1.208 | 4.756 | 1.049 | 2.494 | 14.33 |
| EOS-10 | 2.774 | 1.176 | 1.191 | 4.668 | 1.007 | 2.349 | 14.79 |
| EOS-11 | 2.907 | 1.209 | 1.234 | 5.548 | 1.099 | 3.049 | 14.26 |
| EOS-12 | 2.945 | 1.195 | 1.210 | 5.504 | 1.039 | 2.858 | 14.77 |

as \( M_{\text{eje}} + M_{\text{out}} \), and a model equation of state is given, all the other quantities related to the properties of the star at the moment of collapse, the total energy of neutrino emission and gravitational wave in the post-merger phase could be solved (cf. Table III). With this analysis we can tell whether the assumed equation of state model is consistent with the observation, for instance, the obtained values of \( E_{\nu} \) and \( E_{\text{GW, p}} \) have to be positive and within a plausible range.

In this analysis, we employ \( M_f \), \( R_{\text{MS}} \) (circumferential radius), and \( \Omega_{\text{MS}} \) (angular velocity) for rigidly rotating neutron stars at turning points as \( M_{\text{MNS}}, R_{\text{MNS}}, \) and \( \Omega_{\text{MNS}} \), respectively. \( J_{\text{MS}} \) is also found from a solution of rigidly rotating neutron stars at turning points. \( f_0 \) is calculated from the solutions of spherical neutron stars of mass 1.35-1.40\( M_\odot \) or 1.20-1.50\( M_\odot \). \( E_{\text{GW, i}} \) is set to be \((0.40 \pm 0.005)M_\odot c^2 \). \( J_0 \) is determined by Eq. (3.1) for a given value of \( R_{1.35} \) and \( \eta \). Here the variation in \( \eta \) by ±0.003 systematically changes the values of \( E_{\text{GW, p}} \) and \( E_{\nu} \) only by at most ±0.007\( M_\odot \) and +0.007\( M_\odot \). Hence, we only show the results with \( \eta = 0.247 \). Since the dependence of \( J_{\text{out}} + J_{\text{eje}} \) on \( R_{\text{out}} \) is not very strong (compared with the dependence on \( M_{\text{out}} + M_{\text{eje}} \)), we fix \( R_{\text{out}} \) to be 140 km. On the other hand, \( M_{\text{out}} + M_{\text{eje}} \) has a strong effect on the solution. Thus, we vary it in a wide range (e.g., see Fig. 4).

With these preparations, Eq. (2.17) can be considered as a relation between \( f_r \) and \( f_{\text{MS}} \). Here, in Eq. (2.17), \( M \) is given (2.74\( M_\odot \), \( f_0 \) is determined for a given equation of state and each mass of binary, and \( M_{\text{out}} + M_{\text{eje}} \) is an input parameter. An equilibrium sequence of rigidly rotating neutron stars along the turning points for a given equation of state also gives another monotonic relation between these two variables as found in Fig. 2. Thus,
we first determine \( f_r \) and \( f_{\text{MS}} \) by solving a simultaneous equation composed of two independent relations and specify a model for the rigidly rotating neutron star at a turning point. (We note that for some equations of state, e.g., EOS-12, the solution does not exist.)

We can then immediately determine, if the solution exists. (Again we note that for some equations of state, a physical solution does not exist: see below.)

We can subsequently determine \( E_{\text{GW,p}} + E_\nu \) and \( J_{\text{GW,p}} + J_\nu \) from Eqs. (2.2) and (2.11). For Eq. (2.11), we employ \( J_0, M_{\text{MS}} (= M_f), R_{\text{out}}, R_{\text{MS}} (= R_f), \Omega (= \Omega_{\text{MS}}) \) for each equation of state. Then these two relations, \( E_{\text{GW,p}} + E_\nu = \text{const} \) and \( J_{\text{GW,p}} + J_\nu = \text{const} \), constitute a simultaneous equation for \( E_{\text{GW,p}} \) and \( E_\nu \), because we have already given the values of \( R_{\text{MS}}, \Omega, \) and \( f \), which are necessary to relate \( J_{\text{GW,p}} \) and \( J_f \) to \( E_{\text{GW,p}} \) and \( E_\nu \), respectively. Thus, these two quantities are immediately determined, if the solution exists. (Again we note that for some equations of state, a physical solution does not exist: see below.)

### C. Results

Table III shows the solutions that self-consistently satisfy the conservation relations of energy and angular momentum for each equation of state with the selected values of \( M_{\text{out}} + M_{\text{ej}} \): 0.048 \( M_\odot \), 0.096 \( M_\odot \), and 0.150 \( M_\odot \).

The reason for this is that (i) for large values of \( M_{\text{out}} + M_{\text{ej}} \), the predicted final mass of the remnant neutron star, \( M_f \), becomes smaller than \( M_{\text{max}} \), and hence, no solution with \( f_r \geq 1 \) is present and (ii) for \( M_{\text{out}} + M_{\text{ej}} \lesssim 0.057 M_\odot \), the value of \( f_r \) is determined but physical (positive) values for the set of \( (E_{\text{GW,p}}, E_\nu) \) are not found. If this type of equation of state with \( M_{\text{max}} \gtrsim 2.4 M_\odot \) would be the real one, the final outcome should be a stable neutron star in the GW170817 event. However, this is not likely as we discuss in Sec. III D.

For EOS-1 and 2 for which \( M_{\text{max}} \) is rather small, \( \lesssim 2.1 M_\odot \), we often fail to find a solution. The reason for this is that Eq. (2.17) can be satisfied only for a high value of \( f_r \sim 1.2 \), and thus, for small values of \( M_{\text{out}} + M_{\text{ej}} \).
For EOS-1, the solution for $f$ lower bounds (thick curves) as well as the central value (thin curve) for neutron star.

The angular momentum transport timescale of the remnant $\gg 1$ GW170817 event. If so, the value of $r$ for the collapse to a black hole could occur in a stage that fact does not imply that these equations of state with and the bottom-right panel of Fig. 4. However, this table III shows that for EOS-3–7 for which $M_{\text{max}} = 2.10-2.25M_\odot$, we find solutions with plausible values of $E_{\text{GW,p}}$ and $E_v$ as $0.03M_\odot c^2 \lesssim E_{\text{GW,p}} \lesssim 0.11M_\odot c^2$ and $0.03M_\odot c^2 \lesssim E_v \lesssim 0.10M_\odot c^2$ for plausible values of $M_{\text{out}} + M_{\text{ej}}$. Also, as Fig. 4 illustrates for EOS-3 and 6, reasonable solutions exist for a wide range of $M_{\text{out}} + M_{\text{ej}}$ for this class of the equations of state. Here, the value of $E_v$ indicates that the predicted lifetime of the remnant neutron star in these equations of state is of order 0.1 s to 1 s, which is also quite reasonable. Thus, we conclude that we do not have any reason to exclude equations of state with $2.10M_\odot \lesssim M_{\text{max}} \lesssim 2.25M_\odot$. It should be emphasized that for these cases, the value of $f_r$ is not always close to $\approx 1.2$ but in a wide range between 1.07 and 1.20 (see the bottom-right panel of Fig. 4). Thus, $f_r \approx 1.2$ does not always hold for many candidate equations of state.

For EOS-9 and 10 for which $M_{\text{max}} \approx 2.30M_\odot-2.33M_\odot$, we can also find solutions. However, for these cases, a highly efficient energy dissipation by gravitational radiation with $E_{\text{GW,p}} \gtrsim 0.11M_\odot$ is necessary in particular for small values of $M_{\text{out}} + M_{\text{ej}}$ (see the bottom-left panel of Fig. 4). As found from Table 4, the maximum rotational kinetic energy of the rigidly rotating neutron stars is $T_{\text{MS,R}} \approx 2.5 \times 10^{50}$ erg $\approx 0.125M_\odot c^2$. This implies

\[ \text{Fig. 4. Top-left, top-right, and bottom-left panels display $E_{\text{GW,p}}$ and $E_v$ as functions of $M_{\text{out}} + M_{\text{ej}}$ for EOS-3, 6, and 9, respectively, and for the 1.35-1.40} \ M_\odot \text{case. Associated with the uncertainties in $J_0$ and $E_{\text{GW,1}}$, an uncertainty exists in $E_{\text{GW,p}}$ and $E_v$. The three curves for each plot in the the top-left, top-right, and bottom-left panels denote the upper and lower bounds (thick curves) as well as the central value (thin curve) for $E_{\text{GW,p}}$ and $E_v$. The horizontal dot-dot line shows $E_{\text{GW,p}} = 0.125M_\odot c^2$ (plausible upper limit of $E_{\text{GW,p}}$). Bottom-right panel shows $f_r$ as a function of $M_{\text{out}} + M_{\text{ej}}$ for EOS-1, 3, 6, 9, and 11. For EOS-1, the solution for $f_r$ does not exist for small value of $M_{\text{out}} + M_{\text{ej}}$. For EOS-11, $E_v$ becomes negative for $M_{\text{out}} + M_{\text{ej}} \lesssim 0.02M_\odot$ and $\geq 0.127M_\odot$, and thus, we do not plot the solution for these ranges.} \]
that the energy dissipated by gravitational radiation has to be comparable to the rotational kinetic energy of the remnant neutron star. To know if this class of equations of state is really viable, we have to perform a numerical-relativity simulation to check whether such efficient gravitational radiation is possible or not. However, this is beyond the scope of this paper and is left for our future study. The bottom-right panel of Fig. [I] illustrates that for this class of equations of state, the value of $f_r$ has to be small ($\lesssim 1.1$). That is, an efficient angular momentum dissipation is supposed.

For EOS-8 of $M_{\text{max}} \approx 2.25 M_\odot$, we also find solutions with high values of $E_{\text{GW},p}$. However, for this case, with high values of $M_{\text{out}} + M_{\text{ej}}$, the required value of $E_{\text{GW},p}$ can be reduced. Also, the maximum rotational kinetic energy of the rigidly rotating neutron stars for this equation of state is relatively high, $T_{\text{MS},R} \approx 2.8 \times 10^{53}$ erg $\approx 0.14 M_\odot c^2$. Thus, the restriction for this equation of state is not as strong as for EOS-9 and 10.

For EOS-11 for which $M_{\text{max}} \approx 2.35 M_\odot$, the required energy dissipated by gravitational radiation, $E_{\text{GW},p}$, far exceeds 0.125 $M_\odot c^2$ that is a plausible maximum value [22]. Moreover, for this case, $E_{\text{GW},p}$ required exceeds the maximum rotational kinetic energy of the rigidly rotating neutron stars, $T_{\text{MS},R}$. The reason why the required value of $E_{\text{GW},p}$ is very large is that for this case the value of $f_r$ is quite small, $\lesssim 1.05$, and thus, a large fraction of the angular momentum dissipation, $\sim 4 \times 10^{49}$ erg s, is necessary to reach a marginally stable state. However, for such significant angular momentum dissipation, unrealistically large dissipation by gravitational radiation is necessary. Therefore it is reasonable to exclude these equations of state.

To conclude, it is easy to find model equations of state with $M_{\text{max}} \lesssim 2.25 M_\odot$ that satisfy the conservation laws of energy and angular momentum self-consistently. Also it is not impossible to find model equations of state with $M_{\text{max}} \lesssim 2.3 M_\odot$ that satisfy the required laws. For these cases, $f_r$ is not always $\lesssim 1.2$. By contrast, it would not be easy to find an equation of state with $M_{\text{max}} \geq 2.35 M_\odot$ that satisfy the required laws.

### D. Stable neutron star star formation: not likely

For $M_{\text{max}} \gtrsim 2.4 M_\odot$, a stable neutron star could be the final outcome (e.g., EOS-12) as already mentioned above. For this case to be viable, its angular momentum (and rotational kinetic energy) has to be sufficiently small, since the observational results for the electromagnetic counterparts of GW170817 do not show the evidence for the energy injection to ejecta from strong electromagnetic radiation like the magnetic dipole radiation associated with the rotational kinetic energy of the remnant neutron star [2]. If we require that the resulting rotational kinetic energy of the stable neutron star at its age of $\sim 100$ s is smaller than $10^{52}$ erg (i.e., by one order of magnitude smaller than the rest-mass energy of ejecta of mass $\sim 0.05 M_\odot$), we need $J_f \lesssim 0.5 \times 10^{49}$ erg s (see Fig. 2). Because $J_0 \approx 6.0 \times 10^{49}$ erg s for stiff equations of state like EOS-12, we obtain a constraint as

$$J_{\text{GW},p} + J_\nu + J_{\text{out}} + J_{\text{ej}} \gtrsim 5.5 \times 10^{49} \text{ erg s} \approx 0.9 J_0.$$  

(3.2)

Thus, it is necessary for the remnant neutron star to relax to a fairly slow rotation state close to a spherical star.

Figure [I] shows $J_\nu/f_{\text{MS}} \gtrsim 0.90$ ($f_{\text{MS}} \lesssim 1.2$) for spherical neutron stars of $M_{\text{max}} \approx 2.4 M_\odot$. Then we also obtain the following conditions from Eq. (2.3) and $E_{\text{GW},i} = (0.040 \pm 0.005) M_\odot$:

$$E_{\text{GW},p} + E_\nu c^2 + (M_{\text{out}} + M_{\text{ej}}) \left( 1 - \frac{1}{f_{\text{MS}}} \right) \leq (0.234 \pm 0.005) M_\odot.$$  

(3.3)

Here, we supposed that the remnant neutron star would be located along a stable branch near the marginally stable sequence, and hence, we employed the equations derived in Sec. [I].

In the hypothesis of this subsection, the remnant is long-lived and it is natural to suppose that $E_\nu \lesssim 0.1 M_\odot c^2 \approx 2 \times 10^{53}$ erg or more [21]. Note that it is often mentioned that the total energy dissipated by the neutrino emission from a protoneutron star formed in each supernova would be $\sim (2-3) \times 10^{53}$ erg (e.g., Ref. [36]). Here, the value is larger for larger mass of the protoneutron stars. The remnant neutron star of binary neutron star mergers is more massive and hotter than the protoneutron star, and hence, it is natural to consider $E_\nu \gtrsim 3 \times 10^{53}$ erg. In the following, we conservatively assume that $E_\nu = 3 \times 10^{53}$ erg $\approx 0.15 M_\odot c^2$. For this case, we can estimate as $J_\nu \sim 0.5 \times 10^{49}$ erg s using Eq. (2.14).

We also suppose $M_{\text{out}} \ll M_{\text{ej}}$ for $f \gtrsim 100$ s in the following because the torus matter would accrete onto the neutron star or be ejected from the system by viscous angular momentum transport and/or propeller effect [27].

Equation (3.3) with $M_{\text{out}} = 0$ gives a constraint as

$$E_{\text{GW},p} + E_\nu c^2 + M_{\text{ej}} (1 - 1/f_{\text{MS}}) \leq 0.24 M_\odot.$$  

(3.4)

Now we consider two extreme cases (assume $f_{\text{MS}} = 1.2$): $E_{\text{GW},p} = 0.085 M_\odot c^2$ and $M_{\text{ej}} = 0.03 M_\odot$ (minimum ejecta mass required for the GW170817 event), and $E_{\text{GW},p} = 0.055 M_\odot$ and $M_{\text{ej}} = 0.15 M_\odot$. Here, for the GW170817 event, the value of $M_{\text{ej}}$ would be smaller than 0.15 $M_\odot$.

For $E_{\text{GW},p} = 0.085 M_\odot c^2$ and $f = 2.5$ kHz (which would be the possible lowest value), $J_{\text{GW},p} \approx 1.9 \times 10^{49}$ erg s. For $M_{\text{ej}} = 0.03 M_\odot$, the ejection of the angular momentum would be $\approx 0.5 \times 10^{49}$ erg s for $R_{\text{ej}} \approx 200$ km (cf. Eq. (2.13)). Since $J_0 \approx 0.5 \times 10^{49}$ erg s, the constraint of Eq. (3.2) cannot be satisfied in this model at all.
For $M_{\text{ej}} = 0.15 M_\odot$, the ejection of the angular momentum would be $\approx 2.5 \times 10^{49}$ erg s for $R_{\text{ej}} \approx 200$ km (e.g., Eq. (2.15)). With $E_{GW,p} = 0.055 M_\odot c^2$ and $f = 2.5$ Hz, $J_{GW,p} \approx 1.3 \times 10^{49}$ erg s. For $J_r = 0.5 \times 10^{49}$ erg s, it is found that the constraint of Eq. (3.2) cannot be also satisfied in this model.

As found from the above analysis, for a larger value of $M_{\text{ej}}$, $J_{GW,p} + J_r + J_{\text{ej}}$ increases. However, for the GW170817 event, $M_{\text{ej}}$ is not very likely to be larger than 0.15$ M_\odot$. If $f$ is smaller than 2.5 Hz, $J_{GW,p}$ would be larger. However, a number of numerical-relativity simulations have shown $f \gtrsim 2$ kHz \cite{28,29,38}; $J_{GW,p}$ could be increased only by 20%. Thus, we conclude that it is quite difficult to find a mechanism of the angular momentum dissipation by $\approx 0.9 J_0$ in a short timescale of $\sim 100$ s.

Since the values of $E_r$, $R_{\text{ej}}$, $M_{\text{ej}}$, and $f$ have uncertainty, it is possible to make up the possibility of forming a stable neutron star. In particular, in case that $E_r$ could be much smaller than $3 \times 10^{53}$ erg, the angular momentum of the remnant neutron star could be smaller than 0.15$ J_0$, e.g., by setting $E_{GW,p} = 0.125 M_\odot c^2$, $E_r = 0.09 M_\odot c^2$, and $M_{\text{ej}} = 0.15 M_\odot$ with $f = 2.5$ kHz and $R_{\text{ej}} = 200$ km. However, we need a (unphysical) fine tuning, and hence, such a possibility would not be very likely.

**IV. SUMMARY**

We study the constraint on the maximum mass of cold spherical neutron stars coming from the observational results of GW170817 more strictly than our previous study. We develop a framework which employs not only energy conservation law but also angular momentum conservation one, as well as solid results of latest numerical-relativity simulations and of neutron stars in equilibrium.

In this framework, we postulate that a massive neutron star was formed as a remnant after the merger in the GW170817 event, and the collapse occurred after the remnant neutron star relaxes to a rigidly rotating state. Thus, we construct several rigidly rotating neutron stars in equilibrium as models of the remnant neutron stars at the onset of collapse. In the analysis, we first give plausible values for $M_{\text{out}} + M_{\text{ej}}$ taking into account the observational results of electromagnetic counterparts of GW170817. Then, the energy conservation law gives a relation between the maximum mass, $M_{\text{max}}$, and angular momentum of the remnant neutron star at the onset of collapse. This relation indicates that for smaller values of $M_{\text{max}}$, the collapse occurs at higher angular momentum (i.e., at larger values of $f_r$; cf. Fig. 6). We also find that the correlation between $M_{\text{max}}$ and $M_f$: the gravitational mass at the onset of collapse. Thus, for smaller values of $M_{\text{max}}$, $M_f$ has to be larger, i.e., less energy and angular momentum have to be dissipated prior to the onset of collapse.

We find that the energy conservation laws can be satisfied for a wide range of equations of state with various values of $f_r = 1.0$--1.2. Also, it is found that the combination of energy and angular momentum conservation laws gives plausible values of $E_{GW,p}$ and $E_r$ for the equations of state in which $M_{\text{max}}$ is between $\sim 2.1 M_\odot$ and $\sim 2.3 M_\odot$. In particular, the cases of the $M_{\text{max}} \lesssim 2.5 M_\odot$ result in quite plausible values of $E_{GW,p}$ and $E_r$. For $M_{\text{max}} = 2.30 - 2.35 M_\odot$, it is still possible to find solutions although for such a case, we need to require large energy dissipation by gravitational radiation, $E_{GW,p} \gtrsim 0.11 M_\odot c^2$. It is also found that if the value of $M_{\text{max}}$ is not very high, i.e., $M_{\text{max}} \lesssim 2.1 M_\odot$, the collapse is likely to occur before the velocity profile of the remnant neutron star relaxes to a rigidly rotating state. Thus, we infer that if $M_{\text{max}} \lesssim 2.1 M_\odot$, the remnant neutron star collapses to a black hole in the timescale of angular momentum transport inside it.

The previous analysis often assumes $f_r \approx 1.2$ \cite{38}, i.e., the collapse occurs at a rapidly rotating stage of the remnant neutron star. As Fig. 6 shows, this assumption together with the energy conservation law would automatically lead to an inaccurate conclusion that the value of $M_{\text{max}}$ is small, $\lesssim 2.1 M_\odot$ (i.e., the conclusion is derived from the assumption). The lesson obtained from our present analysis is that inappropriate assumptions could lead to an inaccurate constraint on the maximum mass.

The framework of our analysis for the maximum mass of neutron stars developed in this paper will be applied for future events, in which the remnant after the mergers is a massive neutron star that eventually collapses to a black hole, by simply replacing the values of $M$ and $M_{\text{out}} + M_{\text{ej}}$. This analysis will be in particular interesting if post-merger gravitational waves are observed in future. For this case, $E_{GW,p}$ and $J_{GW,p}$ will be constrained, and then, the constraint for the equation of state and the value of $M_{\text{max}}$ will be better imposed. Furthermore, it will be also feasible to infer how much energy is carried away by neutrinos.

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Appendix A: Model equations of state

To model the neutron-star equation of state with a small number of parameters, we employ a piecewise polytrope introduced by Read et al. [33]. It is a phenomenologically parameterized equation of state of the form

\[ P(\rho) = \kappa_i \rho F_i \]

for \( \rho_{i-1} \leq \rho < \rho_i \) (1 \( \leq i \leq n \)), \( (A1) \)

where \( n \) is the number of the pieces used to parameterize an equation of state, \( \rho_i \) is the rest-mass density at the boundary of two neighboring \( i \)th and \((i + 1)\)th pieces, \( \kappa_i \) is the polytropic constant for the \( i \)th piece, and \( \Gamma_i \) is the adiabatic index for the \( i \)th piece. Here, \( \rho_0 = 0 \), and other parameters \((\rho_i, \kappa_i, \Gamma_i)\) are freely chosen. Requiring the continuity of the pressure at each value of \( \rho_i \), \( 2n \) free parameters, \((\kappa_i, \Gamma_i)\), determine the equation of state completely. The specific internal energy, \( \varepsilon \), is determined by the first law of thermodynamics and continuity of each variable at \( \rho_i \).

In this paper we employ the case of \( n = 3 \) and fix \( \rho_2 = 10^{14.7} \text{g/cm}^3 \) and \( \rho_3 = \infty \). The lowest-density piece models the crust equation of state and the other two do the core equation of state. Following Ref. [33], the equation of state for the crust region is fixed by \( \Gamma_1 = 1.35692395 \) and \( \kappa_1 c^2 = 3.99873692 \times 10^{-8} \text{g/cm}^3 \text{cm/s}^2 \). The equation of state for the core region is determined by two adiabatic indices, \( \Gamma_3 \) and \( \Gamma_4 \), and the pressure, \( p \), at a fiducial density \( \rho_f = 10^{14.7} \text{g/cm}^3 \). Here, \( p \) is closely related to the radius and tidal deformability of neutron stars [10]. For \( \Gamma_2 \), we employ a wide range of values between 2.10–5.00, \( \Gamma_3 \) is chosen to be small values in a narrow range between 2.00–2.91 because for the large values, the sound speed exceeds the speed of light even for stable neutron stars while for the small values, the maximum mass for given equations of state cannot exceed 2\( M_\odot \) [35]. The value of \( \log_{10} p \) is varied between 33.8 and 34.8. Here, for large values of \( \Gamma_2 \), only small values of \( p \) is accepted (e.g., for \( \Gamma_2 = 4.0 \) and 5.0, \( p \lesssim 10^{34.35} \text{dyn/cm}^2 \) and \( p \lesssim 10^{35.18} \text{dyn/cm}^2 \), respectively). If this condition is not satisfied, the sound velocity exceeds the speed of light near \( \rho \sim 10^{15} \text{g/cm}^3 \). With the given values of \( \Gamma_2 \), \( \Gamma_3 \), and \( p, \kappa_2, \kappa_3, \) and \( \rho_1 \) are determined as \( \kappa_2 = p \rho_f \Gamma_2 \), \( \kappa_3 = \kappa_2 \rho_2 \Gamma_3 - \Gamma_2 \), and \( \rho_1 = (\kappa_1/\kappa_2)^{1/(\Gamma_2 - \Gamma_1)} \).

We analyzed the values of \( f_0 \) and \( f_{\text{MS}} \) for spherical neutron stars with the piecewise polytropes. Figure 9 displays a result. In this figure, we plot the data in the piecewise polytropes with which 2\( M_\odot \) neutron stars are reproduced and dimensionless tidal deformability of 1.35\( M_\odot \) neutron stars satisfies \( \Lambda_{1.35} < 1000 \) taking into account the results of GW170817 [1]. It is found that \( f_0 \) and \( f_{\text{MS}} \) are in a wide range approximately between 1.08 and 1.14 and between 1.14 and 1.24, respectively. Because \( f_0 \) and \( f_{\text{MS}} \) are weakly correlated, \( f_0/\text{fMS} \) is not distributed as widely as \( f_{\text{MS}} \), but it is still in a fairly wide range as 0.895–0.945. This value depends weakly on each mass of binaries: For 1.20–1.55\( M_\odot \) binaries, the values of \( f_0/\text{fMS} \) is 0.2–0.5% larger than that for 1.35–1.40\( M_\odot \) binaries for a given equation of state.

One interesting and key fact for the context of the present paper is that \( f_{0}/f_{\text{MS}} \) is correlated with \( M_{\text{max}} \); for larger value of \( f_0/\text{fMS} \), the maximum mass of neutron stars is smaller. The reason for this is that for the equations of state with smaller maximum mass, the neutron star at the maximum mass is less compact and thus has smaller value of \( f_{\text{MS}} \). This fact implies that for smaller maximum mass, the mass of the remnant neutron-star mass at the onset of collapse, \( M_f = M_{f0}/f_{\text{MS}} - (M_{\text{sat}} + M_{\text{He}})/f_{\text{MS}} \), is larger (see Eq. (2.3)), and hence, the merger remnant is more subject to gravitational collapse. We note that the upper boundary of \( f_0/\text{fMS} \) for a give value of \( M_{\text{max}} \) is determined by the condition of \( \Lambda_{1.35} < 1000 \).

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FIG. 5. Left panel: $f_0$ for the case of $1.20-1.55M_\odot$ and $1.35-1.40M_\odot$ binary neutron stars and $f_{\text{MS}}$ for spherical maximum-mass stars as a function of the maximum mass for a variety of equations of state. Right panel: The same as the left panel but for $f_0/f_{\text{MS}}$. We plot the data with equations of state by which $2M_\odot$ neutron stars are reproduced and dimensionless tidal deformability of $1.35M_\odot$ star, $\Lambda_{1.35}$, is smaller than 1000.

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