

# Kilonova Emissions from Neutron Star Merger Remnants: Implications for Nuclear Equation of State

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## ABSTRACT

Multi-messenger observation of binary neutron-star mergers can provide valuable information on the nuclear equation of state (EoS). Here, we investigate to which extent electromagnetic observations of the associated kilonovae allow us to place constraints on the EoS. For this, we use state-of-the-art three-dimensional general-relativistic magneto-hydrodynamics simulations and detailed nucleosynthesis modeling to connect properties of observed light curves to properties of the accretion disk, and hence, the EoS. Using our general approach, we use multi-messenger observations of GW170817/AT2017gfo to study the impact of various sources of uncertainty on inferences of the EoS. We constrain the radius of a  $1.4M_{\odot}$  neutron star to lie within  $10.19 \leq R_{1.4} \leq 13.0$  km and the maximum mass to be  $M_{\text{TOV}} \leq 3.06M_{\odot}$ .

## 1. INTRODUCTION

The nuclear equation of state (EoS) describes the pressure of dense nuclear matter as a function of density, temperature, and composition. Probing the dependence of the EoS on density and neutron-to-proton (isospin) asymmetry represents a grand challenge in nuclear physics given the difficulties associated with creating high densities and very asymmetric systems in terrestrial laboratory experiments (Danielewicz et al. 2002; Russotto et al. 2016). Neutron stars, however, explore matter at high densities and isospin asymmetry, and hence, provide an excellent astrophysical laboratory for studying the EoS (Lattimer 2012). Explosive astrophysical events involving neutron stars are particularly important as they offer an additional avenue via which to probe dense nuclear matter under extreme conditions. Great effort is being dedicated towards building statistical frameworks for EoS inference from astronomical multi-messenger observations, including binary neutron star mergers (NSM; Abbott et al. 2017a, 2018; Bauswein et al. 2017; Radice & Dai 2019; Coughlin et al. 2019; Capano et al. 2020; Dietrich et al. 2020; Miller et al. 2019c; Raaijmakers et al. 2020; Essick et al. 2021a,b; Ghosh et al. 2022; Huth et al. 2022; Pang et al. 2023; Takátsy et al. 2023). These statistical models rely on piecing together different stages of the merger, making assump-

tions at each step. For example, the nuclear EoS affects the behavior of neutron stars during the inspiral phase of a NSM (Takami et al. 2014; Abbott et al. 2018; Most et al. 2019) as well as the properties of the post-merger system. This system can generally be characterized by an accretion disk surrounding a central remnant, either a heavy neutron star ( $M \gtrsim 2M_{\odot}$ ) or a black hole (Baumgarte et al. 1999; Kiuchi et al. 2012; Bauswein et al. 2013; Lippuner et al. 2017; Metzger et al. 2018; Radice et al. 2018a; van Putten & Valle 2019; Ciolfi & Kalinani 2020; Beniamini & Lu 2021).

The ejecta from this accretion disk are a promising site for the nucleosynthesis of the heaviest elements via the rapid neutron capture process (r-process), the decays of which power an electromagnetic transient. Recent decades have seen immense efforts towards understanding the relation between the formation of the disk, its evolution, and the amount of material (especially r-process-producing material) that becomes unbound from the disk (Ruffert et al. 1997; Popham et al. 1999; Shibata et al. 2007; Surman et al. 2008; Fernández & Metzger 2013; Fernández et al. 2014; Janiuk, Agnieszka 2014; Foucart et al. 2015; Just et al. 2015; Sekiguchi et al. 2015; Siegel & Metzger 2017; Fernández et al. 2018; Miller et al. 2019b; de Haas et al. 2023; Sprouse et al. 2024; Lund et al. 2024), as well as its effectiveness

(compared to tidal and shock-driven dynamical ejecta) at robustly producing  $r$ -process material. The nuclear EoS plays a role in determining the distribution of material during and after the merger, affecting such quantities as the remnant disk mass and ejecta masses as well as the behavior of the late-time electromagnetic signal (the *kilonova*) that accompanies the merger event (Abbott et al. 2018; Coughlin et al. 2018; Malik et al. 2018; Radice et al. 2017, 2018b; Gamba et al. 2019; Krüger & Foucart 2020). In particular, the mass of the disk ejecta is a key quantity involved in interpreting the kilonova signal attributed to the disk (Korobkin et al. (2021); Holmbeck et al. (2022); Ricigliano et al. (2024)).

The NSM resulting in the combined electromagnetic and gravitational-wave observations from GW170817/At2017gfo (Abbott et al. 2017b,a; Alexander et al. 2017; Cowperthwaite et al. 2017; Villar et al. 2017, and many more) remains the most closely scrutinized multi-messenger event in recent years. While many early works have used the inspiral, increasingly more works use both electromagnetic plus gravitational wave signals to constrain the EoS (Bauswein et al. 2017; Dietrich & Ujevic 2017; Margalit & Metzger 2017; Radice et al. 2017; Pang et al. 2023).

Here, we evaluate important physical considerations and potential degeneracies involved in several common steps in the inverse problem of using electromagnetic NSM observables to infer the EoS. In Section 2, we analyze disk masses from numerical relativity (NR) simulations of NSMs published in the literature. From these, we introduce a novel fitting formula aimed at predicting the disk mass resulting from an NSM. In Section 3, we make connections between the predicted disk masses with the mass of the disk ejecta, informed by 3D general relativistic magnetohydrodynamics (3DGRMHD) simulations. In Section 4, we connect the nuclear physics involved in the nucleosynthesis occurring in these ejecta to observable properties of the kilonova light curve. In Section 6, we employ our disk mass formula to a set of chiral effective field theory ( $\chi$ EFT) informed nuclear EoSs, as described in Section 5, for binaries consistent with the inferred properties of GW170817 in order to constrain the nuclear EOS using observations of AT2017gfo. In Section 7, we discuss our results.

## 2. POST-MERGER DISK MASS

The nuclear EoS describes the properties of dense matter, which is a crucial input for understanding the behavior of neutron stars in explosive astrophysical events. It is a key input in NR simulations of NSMs as it plays a large part in determining the dynamics of the merger as well as the properties of the post-merger. The prop-

erties of the system at the end of a NR simulation determine the initial conditions for GRMHD simulations of the remnant disk. One of these properties is the disk mass. The connection between an arbitrary binary and the remnant disk mass is often made via analytic formulae, informed by NR simulations. These relate an EoS-dependent quantity with the disk.

We discuss some of the proposed methods for using these data to analytically compute a remnant disk mass in Appendix A, but here highlight that three major relations have been observed and are commonly used. Radice et al. (2018b) found a dependence of the final disk mass on the binary tidal deformability,  $\tilde{\Lambda}$ . Coughlin et al. (2019) highlighted a dependence on the threshold mass beyond which prompt collapse to a black hole occurs; Dietrich et al. (2020) refined this to include a dependence on the binary mass ratio,  $q$ . Finally, Krüger & Foucart (2020) found that the compactness of the lighter neutron star,  $C_{\text{light}}^1$ , in the binary was a good predictor of the resulting disk mass.

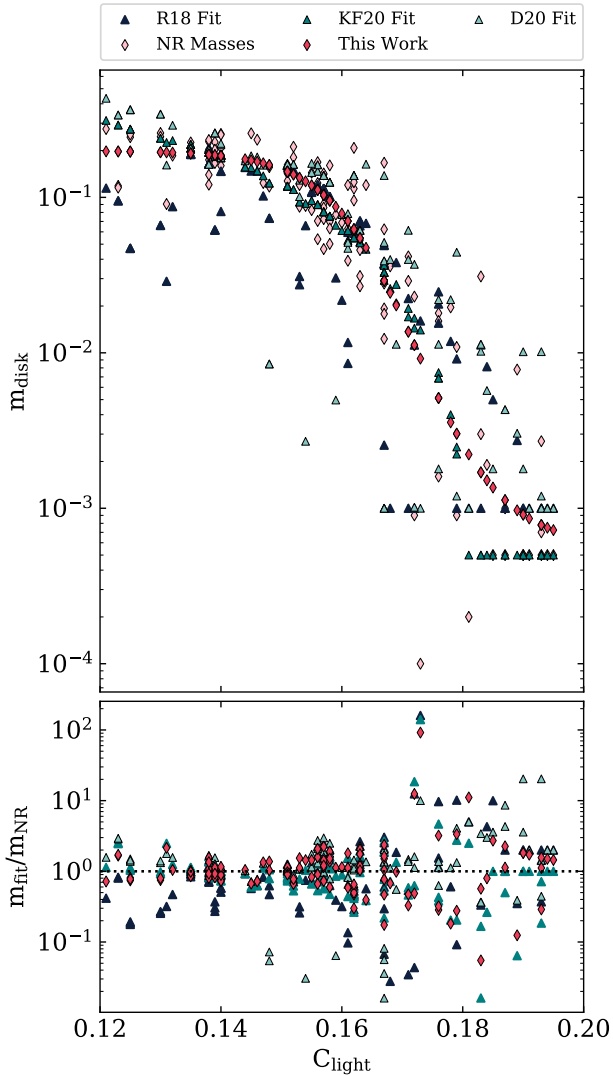
We compile disk masses from existing NR simulations, including those in Radice et al. (2018b) and Kiuchi et al. (2019), and those compiled by Camilletti et al. (2024). The compilation from Camilletti et al. (2024) includes data from Nedora et al. (2019), Perego et al. (2019), Bernuzzi et al. (2020), Endrizzi et al. (2020), Nedora et al. (2021), Cusinato et al. (2022), Perego et al. (2022), and Camilletti et al. (2022). This results in a total of 112 NR simulation data points from 11 sources; these are shown in Fig. 1. Given this larger data set, we take the opportunity to re-evaluate the aforementioned disk mass formulae. We find that the dependence on  $C_{\text{light}}$  continues to yield a reasonably good fit, albeit with a different functional form than in Krüger & Foucart (2020):

$$\log_{10}(m_{\text{disk}}) = \alpha \tanh(\beta C_{\text{light}} + \gamma) + \delta, \quad (1)$$

with best-fit parameters  $\alpha = -1.27$ ,  $\beta = 68.01$ ,  $\gamma = -11.72$ , and  $\delta = -1.98$ . We note that in determining this fit we do not consider non-EoS related dependences in the simulations, which might contribute to the spread in Fig. 1.

We show the predicted disk masses from our fit in the top panel of Figure 1 alongside those obtained from the fits of Radice et al. (2018b, R18), Krüger & Foucart (2020, KF20), and Dietrich et al. (2020, D20). The bottom panel shows the ratio of the different disk mass

<sup>1</sup> The literature often uses subscripts (1,2) followed by a designation of each to either the lightest or heaviest NS in the binary. However, due to the lack of consistent designation of the smallest/largest component in the literature, throughout this work, we use subscripts "light" and "heavy" to avoid any confusion.



**Figure 1.** *Top:* Compilation of disk masses, as a function of the smallest NS compactness,  $C_{\text{light}}$ , for the 112 NR simulation points described in the text (light pink diamonds squares). We show as triangles the results from the fitting formulae presented in R18 (dark blue), KF20 (teal), and D20 (light blue). The results from Eq. (1) are shown as dark pink diamonds. *Bottom:* Ratio between the masses obtained from the fit formulae to the NR data points.

predictions to the NR results. We find that our formulation provides a slightly better fit, with an overall RMS error of 0.041, compared to 0.067, 0.057, and 0.048 from R18, D20, and KF20, respectively. We also note that our fit has a simple functional form without an artificially imposed termination point or cutoff.

### 3. DISK TO EJECTA MASS

The mass of the ejecta from the remnant accretion disk is an open question: recent works have shown that enough  $r$ -process material can become unbound from

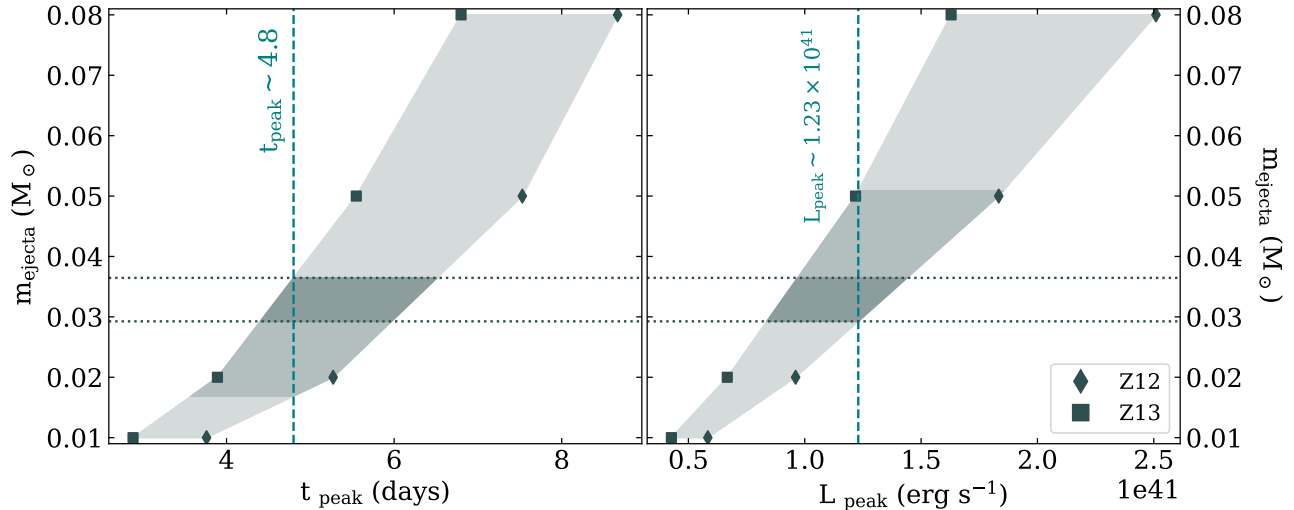
these disks to account for the entire red component of the kilonova (Siegel & Metzger 2017, 2018). Motivated in part by these results, we focus *solely* on the disk ejecta, and make the simplifying assumption that they alone are responsible for the entire red kilonova component, thus, exploring a limiting scenario of the effect of the *total* merger ejecta on the kilonova.

Proceeding under these limiting-case assumptions, for a given disk mass we need to determine the amount of material that is ejected. The most detailed evolution of material in the post-merger accretion disk is obtained via 3DGRMHD simulations, which combine the effects of magnetically-driven turbulence, radiation transport, and neutrino interactions (Gammie et al. 2003; Noble et al. 2006; Miller et al. 2019a). We discuss results from various 3DGRMHD post-NSM disk simulations and some of the differences across these different works, as well as the implications for the interpretation of their results.

Siegel & Metzger (2017, 2018) presented the earliest detailed 3DGRMHD simulation of a remnant black hole accretion disk system. An initial system consisting of a  $0.03M_{\odot}$  torus surrounding a  $3M_{\odot}$  black hole resulted in an ejecta mass of  $\sim 0.2M_{\text{disk},i}$  after 381ms, though the authors project an actual unbound mass fraction of  $\sim 40\%$  based on the black hole accretion rate. Fernández et al. (2018) presented a simulation with similar initial conditions with an initial gas-to-magnetic pressure ratio of 100 instead of 200. The major result from this work was the evolution of the disk over 9.3s and a resulting 40% of the original disk becoming unbound. The authors concluded that by the end of this extended simulation time, the mass ejection is mostly concluded, and extending the simulation time would provide minimal returns. Subsequent work by Christie et al. (2019) built on Fernández et al. (2018) by evolving one weakly magnetized disk ( $\beta = 850$ ) and one disk with a strong ( $\beta = 5$ ) toroidal seed magnetic field, both with the same initial conditions. Evolution of these two disks over  $\sim 4$ s found ejecta mass fractions of 30% and 27%, respectively.

Detailed neutrino transport was incorporated into the work presented in Miller et al. (2019b) and Sprouse et al. (2024), which evolved the same weakly magnetized ( $\beta = 100$ ),  $M_{\text{BH}} (M_{\text{disk}}) = 2.58 (0.12) M_{\odot}$  system to 127ms and 1.27s, respectively. The extended simulation time allowed for  $\sim 30\%$  of the original disk to become unbound, with an indication (based on the mass ejection rate) that more mass could become unbound had the simulation run even longer.

While these long-term simulations provide valuable insight into remnant accretion-disk mass ejection, their computational cost makes surveying different initial



**Figure 2.** Inferred peak luminosity and times from the late-time, red component assuming a two-component model to explain the GW170817 electromagnetic signal (dashed vertical lines). Shaded regions highlight variation of these quantities with respect to ejecta mass from the Z12 and Z13 models of [Zhu et al. \(2021\)](#). The second darkest shaded region shows the region through which the peak time (left) and luminosity (right) overlaps, while the darkest shaded region shows the values through which both of the inferred observed quantities overlap (also denoted by horizontal dotted lines).

conditions while maintaining high-fidelity physics prohibitive. For example, the suite of simulations from [Lund et al. \(2024\)](#) also incorporate detailed neutrino transport (as in [Miller et al. \(2019b\)](#)), but only track  $\mathcal{O}(100\text{ms})$  of evolution, albeit with different initial magnetic field strengths. Similar to [Christie et al. \(2019\)](#), these simulations indicate possible variation in the ejecta mass as well as the properties of the ejecta. One main result was the larger ejecta mass resulting from stronger initial magnetic fields, from  $< 2\%$  (for the same disk as in [Miller et al. \(2019b\)](#) and [Sprouse et al. \(2024\)](#)) to more than  $6\%$ . It is not immediately clear if this increased mass ejection over the short simulation time scale would be sustained at later times. We note that either way, differences in the time scale and geometry of mass (especially lanthanide) ejection stemming from different initial disk conditions could have more subtle impacts on the light curve. Based on the results of all these works, we proceed estimating that  $30\text{-}40\%$  of the initial disk will become unbound, and that this range is reasonable to capture uncertainties from variations in the initial conditions of the disk.

#### 4. KILONOVAE FROM DISK EJECTA

In order to relate ejecta mass to kilonova light curve observables, we now turn to the electromagnetic observations from AT2017gfo and the wealth of observations and analyses from this event for two key observables: the peak luminosity of the “red” part of the kilonova and the time at which this peak occurs. The red component describes the behavior of the light curve after  $\sim 4$

days and can be largely attributed to ejecta from the post-merger system ([Kasen et al. 2017](#); [Waxman et al. 2019](#); [Zhu et al. 2021](#)). We connect the properties of the red light curve and the disk ejecta mass following [Zhu et al. \(2021\)](#), which explored the wide variety of nuclear physics uncertainties and their effect on kilonova light curves. We use their two models to describe ground-state binding energies of atomic nuclei (based on [Dufo & Zuker \(1995\)](#) and [Kortelainen et al. \(2012\)](#)) and corresponding linear combinations of single- $Y_e$  trajectories<sup>2</sup> that were constructed to obtain a roughly solar final abundance pattern.

The purpose of comparing these two models is to gauge the uncertainties from the unknown properties of nuclei far from stability with those from changing the ejecta mass. We note that the use of these two models likely underestimates the true uncertainty from nuclear physics as these models were constructed such that the resulting abundance pattern roughly matched the solar pattern; observations of AT2017gfo only indicate the production of lanthanides, with no direct proof that a solar pattern was produced. It is important to highlight that these models, though producing very similar patterns, undergo different nuclear heating histories, which result in different light-curve evolution. For each model, light curves were computed based on the nuclear heating and using ejecta masses of  $0.01$ ,  $0.02$ ,  $0.05$ , and

<sup>2</sup> “Trajectories” refers to the time evolution of the temperature and density, which is a key ingredient for nucleosynthesis calculations.

$0.08 M_{\odot}$ , with the results shown in Figure 12(a) of the original work. For each of the masses previously listed, we show the times at which the peak bolometric luminosities occurred,  $t_{\text{peak}}$ , and the peak bolometric luminosities  $L_{\text{peak}}$  in the left and right panels of Figure 2, respectively. From the resulting bands, we are able to estimate an uncertainty in the properties of the kilonova originating from unknown nuclear physics.

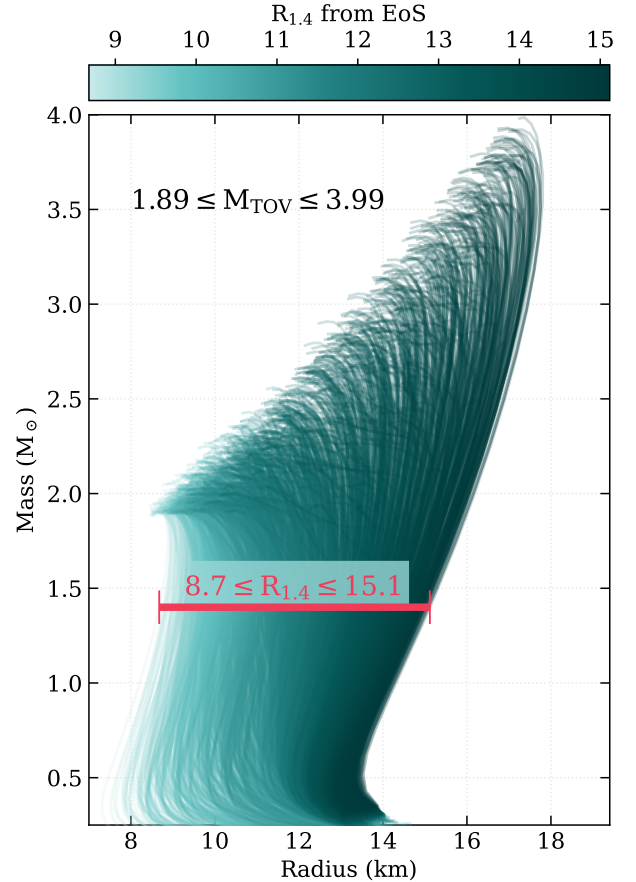
This work highlights that a single ejecta mass can result in differences of 1-2 days in  $t_{\text{peak}}$ . Similarly,  $L_{\text{peak}}$  for a given ejecta mass is subject to these same uncertainties, thus a single ejecta mass can be inferred from a variety of light curve behaviors, which themselves are influenced by the unknown properties of nuclei far from stability. Thus, if one is attributing the late-time ( $\gtrsim 1$  day) behavior of the kilonova to a disk wind, the interpretation of that late-time behavior depends to some extent on some combined assumption of both the nuclear heating history, the composition of the ejecta, and the ejecta mass itself.

We show this by selecting a luminosity of  $1.23 \times 10^{41} \text{erg s}^{-1}$  occurring at roughly 4.8 days post-merger. These are based on the two-component model shown in Fig. 13 of Waxman et al. (2018), itself based on the models of Kasen et al. (2017) with the combined data from GW170817/AT2017gfo (Cowperthwaite et al. 2017; Drout et al. 2017; Villar et al. 2017). By combining these quantities and the uncertainties in each model from Zhu et al. (2021), we infer a disk ejecta mass of  $(1.688 - 3.645) \times 10^{-2} M_{\odot}$ . Returning to our assumption that this ejecta mass corresponds to 30-40% of the original disk mass, this implies a disk mass range of  $(4.22 - 12.2) \times 10^{-2} M_{\odot}$ .

## 5. EQUATIONS OF STATE

We use the family of equations of state (EoS) presented in Capano et al. (2020). The details of the construction of this family of EoSs are included in the original publication; we include a summary of the methods used for convenience.

The construction of our EoS sample begins with microscopic quantum Monte Carlo calculations for the neutron-matter EoS based on two nuclear Hamiltonians from  $\chi$ EFT up to  $2n_{\text{sat}}$ , where  $n_{\text{sat}}$  is the nuclear saturation density. The employed interactions were fit to nucleon-nucleon scattering data, the  $\alpha$ -particle binding energy, and neutron-alpha scattering properties (Tews et al. 2018). The neutron-matter EoS was then extended to  $\beta$ -equilibrium, and a crust was added in order to obtain neutron star EoSs. The high-mass neutron star regime was accessed by computing the speed of sound,  $c_s$ , up to either  $n_{\text{sat}}$  or  $2n_{\text{sat}}$  for the microscopic cal-

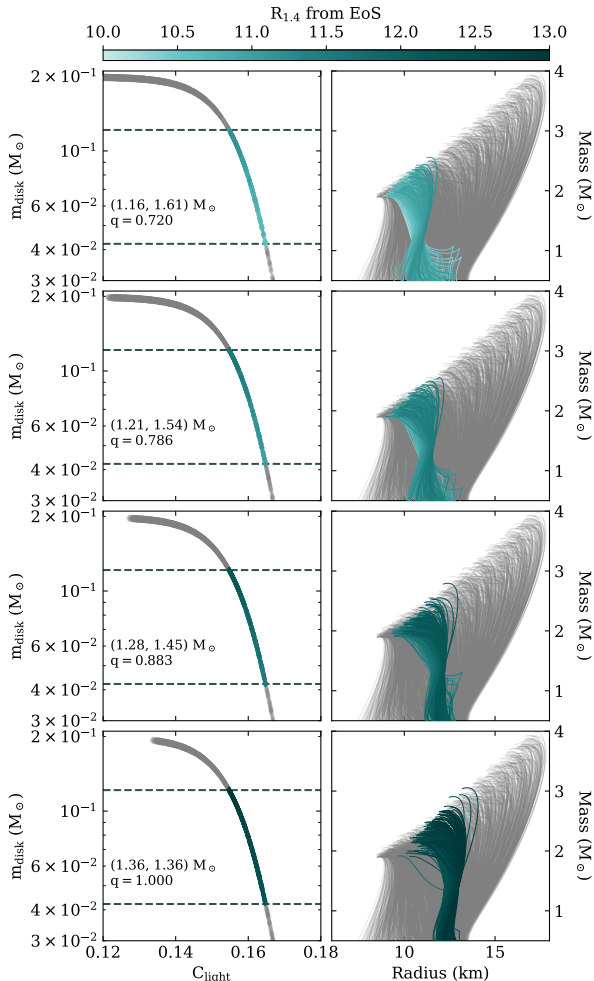


**Figure 3.** Mass radius curves for equations of state. The total sample of 2000 EoSs results in a range of  $8.7 \leq R_{1.4} \leq 15.1$  and  $1.89 \leq M_{\text{TOV}} \leq 3.99$ .

culations, then performing a six-point extension of the speed of sound calculation up to  $12n_{\text{sat}}$ , with the constraint that  $0 < c_s < c$ . This procedure is carried out for both Hamiltonians for  $\sim 10,000$  EoSs. Here, we use results up to  $n_{\text{sat}}$  and solve the Tolman-Oppenheimer-Volkoff (TOV) equations (Oppenheimer & Volkoff 1939; Tolman 1939) to obtain solutions for the neutron star mass-radius relation for each EoS, and exclude EOS with maximum masses below  $1.9 M_{\odot}$ . This initial data set is further reduced to 2000 EoSs selected such that the prior on the radius of a  $1.4 M_{\odot}$  NS ( $R_{1.4}$ ) is roughly uniform. Across the resulting EoSs, whose mass-radius curves are shown in Figure 3, the maximum TOV mass is  $3.99 M_{\odot}$ , and the radius of a  $1.4 M_{\odot}$  neutron star lies between 8.7 and 15.1 km.

## 6. KILONOVA CONSTRAINTS ON NUCLEAR EOS

The final step in this puzzle is to use our inferred ejecta and kilonova properties to interpret implications for the nuclear EoS. For this, we construct four possible binaries consistent with the literature values for the



**Figure 4.** *Left:* Disk masses as a function of lightest neutron star compactness,  $C_{\text{light}}$ , for four binaries. *Right:* Mass-radius curves for allowed EoSs. *Both columns:* For each binary, EoSs that result in disk masses between the inferred values of  $0.042 - 0.122M_{\odot}$  (indicated with dashed lines in the left column) are shown colored according to the  $1.4M_{\odot}$  radius ( $R_{1.4}$ ), as shown in the color bar. EoSs that do *not* result in masses within the aforementioned range are shown in grey for ease of comparison with Figure 3.

masses involved in GW170817. We use the constraint  $1.16 \leq m_{\text{light}} \leq 1.36$  along with the tight constraint of the chirp mass:

$$\mathcal{M} = \frac{(m_{\text{light}} \cdot m_{\text{heavy}})^{3/5}}{(m_{\text{light}} + m_{\text{heavy}})^{1/5}} = 1.186_{-0.001}^{+0.001} M_{\odot} \quad (2)$$

to obtain the mass of the larger companion. Although our disk mass formulation in Eq. (1) depends solely on the properties of the lighter neutron star, we use both masses to compare our analysis with other formulations in Appendix B.

For each binary, we compute the possible disk masses using Eq. (1) for the 2000 EoSs described in Section

5. We show the compactness values (and therefore the EoSs) that result in  $4.22 \times 10^{-2} M_{\odot} \leq m_{\text{disk}} \leq 12.2 \times 10^{-2} M_{\odot}$  in Figure 4.

One important consequence is that smaller values of  $m_{\text{light}}$  result in smaller compactness values, therefore favoring softer<sup>3</sup> EoSs. This can be seen in the right column of Figure 4, which shows the mass-radius curves of the allowed EoSs in the left column panels. Although we did not use the mass of the larger neutron star in our analysis, the aforementioned tightly constrained chirp mass for GW170817 implies that a neutron star with smaller  $m_{\text{light}}$  will have a larger companion for the same chirp mass. Thus it can be interpreted that a softer EoS is also favored for more asymmetric binaries.

Across all four sample binaries, one of the major outcomes of our analysis is a constraint on the  $1.4M_{\odot}$  radius that characterizes the EoSs with which we work. Overall, the allowed EoSs (colored in shades of blue in Figure 4) predicted values of  $10.19 \leq R_{1.4} \leq 13$  km and  $M_{\text{TOV}} \leq 3.06M_{\odot}$ . In Appendix B, we compare the resulting values of  $R_{1.4}$  and  $M_{\text{TOV}}$  when obtained using the literature fits described in Section 2.

## 7. SUMMARY AND DISCUSSION

In this work, we took a closer look at the complex interplay between the EoS, post-merger accretion disk evolution, and kilonova observations. We discussed some of the limitations and implications of different sources of uncertainty, and re-evaluated a number of existing fits from the literature that serve to predict a disk mass for a neutron-star binary from EOS properties. Our fit used results from numerical-relativity simulations, from 11 different sources, for a total of 112 data points. We find that the compactness of the lighter binary component is the best indicator of  $m_{\text{disk}}$ . We propose that the functional form of Eq. (1) performs slightly better than others, with an rms of 0.041. Our formula is limited by the availability of simulation data, which exists for more symmetric binaries. The average mass ratio of our data sample was 0.91 with 58 of 112 simulations being equal-mass binaries. We expect that the inclusion of more data points, especially those from more asymmetric binaries, will result in better fits in the future.

We then used 3DGRMHD simulations to inform the fraction of disk mass ejected after a BNS event and found a mass fraction of 30 – 40%. Using the assumption that the ejecta are entirely responsible for the red component of a KN, we then used the observation of  $L_{\text{peak}}$  and  $t_{\text{peak}}$  to estimate ejecta and disk masses. To first order, the

<sup>3</sup> Here, "soft" refers to a particular EoS predicting a smaller radius for a given mass.

incorporation of a contribution to this luminosity from the dynamical ejecta would imply that less than 100% of the peak luminosity is attributed to ejecta from the post-merger system. Given that there is no obvious link between disk mass and the *percentage* of the disk that gets ejected, this in turn implies a smaller disk mass. From Figure 4, this would push the allowed values of compactness towards higher values, therefore possibly favoring softer EoSs.

Finally, we connected these values backwards to constrain the nuclear EoS, resulting in a prediction of  $10.19 \leq R_{1.4} \leq 13$  km and  $M_{\text{TOV}} \leq 3.06M_{\odot}$ . It is apparent that the values we obtain result in error bars that are larger, but not entirely inconsistent, with other literature values. We consider, for example, the results of Bauswein et al. (2017), who make predictions regarding the  $1.6M_{\odot}$  radius guided by fairly conservative assumptions about the properties of GW170817. Their analysis was driven mostly by the constraint provided by the EoS-dependent threshold mass,  $M_{\text{thres}}$ - the same threshold mass used in the fits of Coughlin et al. (2018) and Dietrich et al. (2020). It was concluded that the minimum radius of a  $1.6M_{\odot}$  neutron star must be  $10.68^{+0.15}_{-0.04}$  km. Had we operated only under the assumption of an equal-mass binary, with each mass being  $1.36M_{\odot}$  (which is the case for the bottom row of Figure 4), the allowed EoSs from our sample result in a similar prediction of  $10.94 \leq R_{1.6}$ .

Our analysis leads to results based on simple statistics informed by a single event. It is therefore not surprising that the width of our EoS error bars be larger than, for example, the results published in Koehn et al. (2024), which are based on Bayesian statistics of a wide variety of astronomical constraints. However, even their analysis of the combined gravitational wave + kilonova + gamma-ray burst data leads to an estimate of  $R_{1.4} = 12.19^{+0.71}_{-0.63}$  km, which is in good agreement with the range of radii we obtain. It should be emphasized that the results of Koehn et al. (2024) are given in terms of 90% confidence levels; ours are meant to simply illustrate possible values given a detailed look at specific aspects of the analysis.

We highlight the importance of the underlying physics that is often overlooked in favor of fit formulae used to obtain point estimates of, for example, the remnant accretion disk mass or the ejecta mass from that disk. By propagating this uncertainty through the many degeneracies in a full inference, we hope to motivate studies aimed at probing these different physical problems. We further hope to incorporate more robust statistical methods in future work, making our approach more generally applicable to frameworks like the one described in

Pang et al. (2023). We look forward to our proposed fitting model being put to the test with new simulation data.

## 8. ACKNOWLEDGEMENTS

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## APPENDIX

## A. DISK MASS FIT FORMULAE

In this Appendix, we describe some of the proposed methods for estimating the resulting disk mass from an NSM based on fits to data from NR simulations.

A.1. *Binary Tidal Deformability*

The tidal deformability of a binary system depends on the tidal deformability of the individual binary components (from De et al. (2018)):

$$\tilde{\Lambda} = \frac{16}{13} \frac{(12q + 1)\Lambda_{\text{heavy}} + (12 + q)q^4\Lambda_{\text{light}}}{(1 + q)^5}, \text{ where} \quad (\text{A1})$$

$$q = \frac{m_{\text{light}}}{m_{\text{heavy}}} \leq 1, \text{ and} \quad (\text{A2})$$

$$\Lambda_{\text{light,heavy}} = \frac{2}{3}k_2 \left( \frac{R_{\text{light,heavy}}c^2}{Gm_{\text{light,heavy}}} \right)^5. \quad (\text{A3})$$

Radice et al. (2018b, R18) evaluated a grid of 35 numerical relativity (NR) simulations with 4 different EoSs. From the results of these calculations, they propose a best-fit formula for the disk mass that depends on the tidal deformability,  $\tilde{\Lambda}$ , of the binary:

$$\frac{M_{\text{disk}}}{M_{\odot}} = \max \left\{ 10^{-3}, \alpha + \beta \tanh \left( \frac{\tilde{\Lambda} - \gamma}{\delta} \right) \right\}, \quad (\text{A4})$$

with  $\alpha = 0.084$ ,  $\beta = 0.127$ ,  $\gamma = 567.1$ , and  $\delta = 405.14$ .

A.2. *Prompt Collapse Threshold Mass*

Coughlin et al. (2019) take the NR simulations from R18 and highlight that the lifetime of the post-merger remnant is related to the stability of said remnant, and this lifetime is strongly correlated with the resulting disk mass. Given the finding that the remnant lifetime prior to collapse is governed in large part by the ratio of the binary mass to the threshold mass (above which there is prompt collapse to a black hole). The threshold mass can be computed following Bauswein et al. (2013):

$$M_{\text{thr}} = (-jC_{1.6}^* + a)M_{\text{TOV}}, \text{ where} \quad (\text{A5})$$

$$C_{1.6}^* = \frac{GM_{\text{TOV}}}{c^2R_{1.6}}, \quad (\text{A6})$$

and best-fit parameters  $j = 3.606$  and  $a = 2.380$ .

Based on the NR simulations from Rad18 and the correlation of the binary threshold mass with the resulting disk mass, Coughlin et al. (2019) propose the following relation:

$$\log_{10} \left( \frac{M_{\text{disk}}}{M_{\odot}} \right) = \max \left\{ -3, a \left( 1 + b \tanh \frac{c - M_{\text{tot}}/M_{\text{thr}}}{d} \right) \right\}, \quad (\text{A7})$$

where  $a = -31.335$ ,  $b = -0.9760$ ,  $c = 1.0474$ , and  $d = 0.05957$ .

This relation removes dependence on the properties of the binary itself, but maintains a dependence on the tidal deformability via the compactness, and can therefore be used to characterize an EoS. However subsequent work (Dietrich et al. 2020, D20) compares results from 73 NR simulations performed by various groups resulting in a modified formulation of the resulting disk mass that incorporates a dependence on the binary mass ratio by modifying the parameters such that

$$a = a_0 + \delta a \cdot \xi \quad (\text{A8})$$

$$b = b_0 + \delta b \cdot \xi, \quad (\text{A9})$$



where the parameter  $\xi$  is given by:

$$\xi = \frac{1}{2} \tanh(\beta(\hat{q} - \hat{q}_{\text{trans}})). \quad (\text{A10})$$

Here  $\hat{q} = m_{\text{light}}/m_{\text{heavy}} \leq 1$  is the inverse binary mass ratio;  $\hat{q}_{\text{trans}}$  and  $\beta$  are free parameters. D20 report best-fit parameters  $a_0 = -1.581$ ,  $\delta a = -2.439$ ,  $b_0 = -0.538$ ,  $\delta b = -0.406$ ,  $c = 0.953$ ,  $d = 0.0417$ ,  $\beta = 3.910$ , and  $\hat{q}_{\text{trans}} = 0.900$ .

### A.3. Lightest NS Compactness

Additional efforts to continue to improve upon the results from R18 and Coughlin et al. (2019) were made by Krüger & Foucart (2020, KF20) by incorporating disk masses from an additional 22 NR simulations from Kiuchi et al. (2019) that included asymmetric binary mass ratios. These efforts resulted in a formulation dependent on the compactness parameter of the lighter of the two neutron stars,  $C_{\text{light}}$ :

$$M_{\text{disk}} = m_{\text{light}} \cdot \max\left\{5 \times 10^4, (aC_{\text{light}} + c)^d\right\}, \quad (\text{A11})$$

with best-fit parameters  $a = -8.1324$ ,  $c = 1.4820$ , and  $d = 1.7784$ .

## B. COMPARISON TO OTHER FITS

Binary	Value	Our Results	KF20	R18	D20
1.16 $M_{\odot}$ , 1.61 $M_{\odot}$	$R_{1.4}$ (km)	10.19-11.23	10.19-11.70	11.07-13.02	8.67-11.73
	$M_{\text{TOV}}$ ( $M_{\odot}$ )	1.90-2.56	1.89-2.56	1.90-2.94	1.89-2.36
1.21 $M_{\odot}$ , 1.54 $M_{\odot}$	$R_{1.4}$ (km)	10.56-11.64	10.68-12.19	11.46-12.90	10.41-12.05
	$M_{\text{TOV}}$ ( $M_{\odot}$ )	1.90-2.56	1.89-2.94	1.90-2.94	1.89-2.36
1.28 $M_{\odot}$ , 1.45 $M_{\odot}$	$R_{1.4}$ (km)	11.24-12.26	11.24-12.72	11.55-12.85	10.77-12.49
	$M_{\text{TOV}}$ ( $M_{\odot}$ )	1.89-2.80	1.89-2.94	1.90-2.94	1.90-2.43
1.36 $M_{\odot}$ , 1.36 $M_{\odot}$	$R_{1.4}$ (km)	11.70-13.00	11.70-13.38	11.70-12.82	10.77-12.54
	$M_{\text{TOV}}$ ( $M_{\odot}$ )	1.91-3.06	1.91-3.06	1.90-2.94	1.90-2.56
Overall	$R_{1.4}$	10.19-13.00	10.19-13.38	11.07-13.02	8.67-12.54
	$M_{\text{TOV}}$ ( $M_{\odot}$ )	1.89-3.06	1.89-3.06	1.90-2.94	1.89-2.56

**Table 1.** Comparison of EoS values using other fits from the literature, as described in the previous Appendix.

We include in this appendix comparison of our overall results, obtained starting from Eq. (1), to those we would have obtained had we used the methods described in Section A.

## REFERENCES

- Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017a, *Astrophysical Journal Letters*, 848, L12, doi: [10.3847/2041-8213/aa91c9](https://doi.org/10.3847/2041-8213/aa91c9)
- . 2017b, *Physical Review Letters*, 119, 30, doi: [10.1103/PhysRevLett.119.161101](https://doi.org/10.1103/PhysRevLett.119.161101)
- . 2018, *Physical Review Letters*, 121, 161101, doi: [10.1103/PhysRevLett.121.161101](https://doi.org/10.1103/PhysRevLett.121.161101)
- Alexander, K. D., Berger, E., Fong, W., et al. 2017, *The Astrophysical Journal Letters*, 848, L21, doi: [10.3847/2041-8213/aa905d](https://doi.org/10.3847/2041-8213/aa905d)
- Baumgarte, T., Shapiro, S., & Shibata, M. 1999, *Astrophysical Journal Letters*, 528, 431
- Bauswein, A., Baumgarte, T. W., & Janka, H.-T. 2013, *Phys. Rev. Lett.*, 111, 131101, doi: [10.1103/PhysRevLett.111.131101](https://doi.org/10.1103/PhysRevLett.111.131101)
- Bauswein, A., Just, O., Janka, H.-T., & Stergioulas, N. 2017, *The Astrophysical Journal Letters*, 850, L34, doi: [10.3847/2041-8213/aa9994](https://doi.org/10.3847/2041-8213/aa9994)
- Beniamini, P., & Lu, W. 2021, *The Astrophysical Journal*, 920, 109, doi: [10.3847/1538-4357/ac1678](https://doi.org/10.3847/1538-4357/ac1678)
- Bernuzzi, S., Breschi, M., Daszuta, B., et al. 2020, *Monthly Notices of the Royal Astronomical Society*, 497, 1488, doi: [10.1093/mnras/staa1860](https://doi.org/10.1093/mnras/staa1860)
- Camilletti, A., Perego, A., Guercilena, F. M., Bernuzzi, S., & Radice, D. 2024, *Phys. Rev. D*, 109, 063023, doi: [10.1103/PhysRevD.109.063023](https://doi.org/10.1103/PhysRevD.109.063023)

- Camilletti, A., Chiesa, L., Ricigliano, G., et al. 2022, *Monthly Notices of the Royal Astronomical Society*, 516, 4760, doi: [10.1093/mnras/stac2333](https://doi.org/10.1093/mnras/stac2333)
- Capano, C. D., Tews, I., Brown, S. M., et al. 2020, *Nature Astronomy*, 4, 625, doi: [10.1038/s41550-020-1014-6](https://doi.org/10.1038/s41550-020-1014-6)
- Christie, I. M., Lalakos, A., Tchekhovskoy, A., et al. 2019, *Monthly Notices of the Royal Astronomical Society*, 490, 4811, doi: [10.1093/mnras/stz2552](https://doi.org/10.1093/mnras/stz2552)
- Ciolfi, R., & Kalinani, J. V. 2020, *Astrophysical Journal*, 900, L35, doi: [10.3847/2041-8213/abb240](https://doi.org/10.3847/2041-8213/abb240)
- Coughlin, M. W., Dietrich, T., Margalit, B., & Metzger, B. D. 2019, *Monthly Notices of the Royal Astronomical Society: Letters*, 489, L91, doi: [10.1093/mnrasl/slz133](https://doi.org/10.1093/mnrasl/slz133)
- Coughlin, M. W., Dietrich, T., Doctor, Z., et al. 2018, *Monthly Notices of the Royal Astronomical Society*, 480, 3871, doi: [10.1093/mnras/sty2174](https://doi.org/10.1093/mnras/sty2174)
- Cowperthwaite, P. S., Berger, E., Villar, V. A., et al. 2017, *Astrophysical Journal Letters*, 848, L17, doi: [10.3847/2041-8213/aa8fc7](https://doi.org/10.3847/2041-8213/aa8fc7)
- Cusinato, M., Guercilena, F. M., Perego, A., et al. 2022, *The European Physical Journal A*, doi: [10.1140/epja/s10050-022-00743-5](https://doi.org/10.1140/epja/s10050-022-00743-5)
- Danielewicz, P., Lacey, R., & Lynch, W. G. 2002, *Science*, 298, 1592, doi: [10.1126/science.1078070](https://doi.org/10.1126/science.1078070)
- De, S., Finstad, D., Lattimer, J. M., et al. 2018, *Phys. Rev. Lett.*, 121, 091102, doi: [10.1103/PhysRevLett.121.091102](https://doi.org/10.1103/PhysRevLett.121.091102)
- de Haas, S., Bosch, P., Mösta, P., Curtis, S., & Schut, N. 2023, *Monthly Notices of the Royal Astronomical Society*, stad2931, doi: [10.1093/mnras/stad2931](https://doi.org/10.1093/mnras/stad2931)
- Dietrich, T., Coughlin, M. W., Pang, P. T. H., et al. 2020, *Science*, 370, 1450, doi: [10.1126/science.abb4317](https://doi.org/10.1126/science.abb4317)
- Dietrich, T., & Ujevic, M. 2017, *Classical and Quantum Gravity*, 34, 105014, doi: [10.1088/1361-6382/aa6bb0](https://doi.org/10.1088/1361-6382/aa6bb0)
- Drout, M. R., Piro, A. L., Shappee, B. J., et al. 2017, *Science*, 358, 1570
- Duffo, J., & Zuker, A. P. 1995, *Physical Review C*, 52, 23, doi: [10.1103/PhysRevC.52.R23](https://doi.org/10.1103/PhysRevC.52.R23)
- Endrizzi, A., Perego, A., Fabbri, F. M., et al. 2020, *European Physical Journal A*, 56, 15, doi: [10.1140/epja/s10050-019-00018-6](https://doi.org/10.1140/epja/s10050-019-00018-6)
- Essick, R., Landry, P., Schwenk, A., & Tews, I. 2021a, *Phys. Rev. C*, 104, 065804, doi: [10.1103/PhysRevC.104.065804](https://doi.org/10.1103/PhysRevC.104.065804)
- Essick, R., Tews, I., Landry, P., & Schwenk, A. 2021b, *Phys. Rev. Lett.*, 127, 192701, doi: [10.1103/PhysRevLett.127.192701](https://doi.org/10.1103/PhysRevLett.127.192701)
- Fernández, R., & Metzger, B. D. 2013, *Monthly Notices of the Royal Astronomical Society*, 435, 502, doi: [10.1093/mnras/stt1312](https://doi.org/10.1093/mnras/stt1312)
- Fernández, R., Kasen, D., Metzger, B. D., & Quataert, E. 2014, *Monthly Notices of the Royal Astronomical Society*, 446, 750, doi: [10.1093/mnras/stu2112](https://doi.org/10.1093/mnras/stu2112)
- Fernández, R., Tchekhovskoy, A., Quataert, E., Foucart, F., & Kasen, D. 2018, *Monthly Notices of the Royal Astronomical Society*, 482, 3373, doi: [10.1093/mnras/sty2932](https://doi.org/10.1093/mnras/sty2932)
- Foucart, F., O'Connor, E., Roberts, L., et al. 2015, *Phys. Rev. D*, 91, 124021, doi: [10.1103/PhysRevD.91.124021](https://doi.org/10.1103/PhysRevD.91.124021)
- Gamba, R., Read, J. S., & Wade, L. E. 2019, *Classical and Quantum Gravity*, 37
- Gammie, C. F., McKinney, J. C., & Toth, G. 2003, *The Astrophysical Journal*, 589, 444–457, doi: [10.1086/374594](https://doi.org/10.1086/374594)
- Ghosh, S., Pradhan, B. K., Chatterjee, D., & Schaffner-Bielich, J. 2022, *Front. Astron. Space Sci.*, 9, 864294, doi: [10.3389/fspas.2022.864294](https://doi.org/10.3389/fspas.2022.864294)
- Holmbeck, E. M., O’Shaughnessy, R., Delfavero, V., & Belczynski, K. 2022, *The Astrophysical Journal*, 926, 196, doi: [10.3847/1538-4357/ac490e](https://doi.org/10.3847/1538-4357/ac490e)
- Huth, S., et al. 2022, *Nature*, 606, 276, doi: [10.1038/s41586-022-04750-w](https://doi.org/10.1038/s41586-022-04750-w)
- Janiuk, Agnieszka. 2014, *A&A*, 568, A105, doi: [10.1051/0004-6361/201423822](https://doi.org/10.1051/0004-6361/201423822)
- Just, O., Bauswein, A., Ardevol Pulpillo, R., Goriely, S., & Janka, H. T. 2015, *Monthly Notices of the Royal Astronomical Society*, 448, 541, doi: [10.1093/mnras/stv009](https://doi.org/10.1093/mnras/stv009)
- Kasen, D., Metzger, B., Barnes, J., Quataert, E., & Ramirez-Ruiz, E. 2017, *Nature*, 551, 80, doi: [10.1038/nature24453](https://doi.org/10.1038/nature24453)
- Kiuchi, K., Kyutoku, K., Shibata, M., & Taniguchi, K. 2019, *The Astrophysical Journal Letters*, 876, L31, doi: [10.3847/2041-8213/ab1e45](https://doi.org/10.3847/2041-8213/ab1e45)
- Kiuchi, K., Sekiguchi, Y., Kyutoku, K., & Shibata, M. 2012, *Classical and Quantum Gravity*, 29, 124003, doi: [10.1088/0264-9381/29/12/124003](https://doi.org/10.1088/0264-9381/29/12/124003)
- Koehn, H., Rose, H., Pang, P. T. H., et al. 2024, An overview of existing and new nuclear and astrophysical constraints on the equation of state of neutron-rich dense matter. <https://arxiv.org/abs/2402.04172>
- Korobkin, O., Wollaeger, R. T., Fryer, C. L., et al. 2021, *The Astrophysical Journal*, 910, 116, doi: [10.3847/1538-4357/abe1b5](https://doi.org/10.3847/1538-4357/abe1b5)
- Kortelainen, M., McDonnell, J., Nazarewicz, W., et al. 2012, *Physical Review C - Nuclear Physics*, 85, doi: [10.1103/PhysRevC.85.024304](https://doi.org/10.1103/PhysRevC.85.024304)
- Krüger, C. J., & Foucart, F. 2020, *Phys. Rev. D*, 101, 103002, doi: [10.1103/PhysRevD.101.103002](https://doi.org/10.1103/PhysRevD.101.103002)

- Lattimer, J. M. 2012, *Annual Review of Nuclear and Particle Science*, 62, 485, doi: <https://doi.org/10.1146/annurev-nucl-102711-095018>
- Lippuner, J., Fernández, R., Roberts, L. F., et al. 2017, *Monthly Notices of the Royal Astronomical Society*, 472, 904, doi: [10.1093/MNRAS/STX1987](https://doi.org/10.1093/MNRAS/STX1987)
- Lund, K. A., McLaughlin, G. C., Miller, J. M., & Mumpower, M. R. 2024, *ApJ*, 964, 111, doi: [10.3847/1538-4357/ad25ef](https://doi.org/10.3847/1538-4357/ad25ef)
- Malik, T., Alam, N., Fortin, M., et al. 2018, *Physical Review C*, 98, 1, doi: [10.1103/PhysRevC.98.035804](https://doi.org/10.1103/PhysRevC.98.035804)
- Margalit, B., & Metzger, B. D. 2017, *The Astrophysical Journal Letters*, 850, L19, doi: [10.3847/2041-8213/aa991c](https://doi.org/10.3847/2041-8213/aa991c)
- Metzger, B. D., Thompson, T. A., & Quataert, E. 2018, *Astrophysical Journal*, 856, 101, doi: [10.3847/1538-4357/aab095](https://doi.org/10.3847/1538-4357/aab095)
- Miller, J. M., Ryan, B. R., & Dolence, J. C. 2019a, *The Astrophysical Journal Supplement Series*, 241, 30, doi: [10.3847/1538-4365/ab09fc](https://doi.org/10.3847/1538-4365/ab09fc)
- Miller, J. M., Ryan, B. R., Dolence, J. C., et al. 2019b, *Physical Review D*, 100, 23008, doi: [10.1103/physrevd.100.023008](https://doi.org/10.1103/physrevd.100.023008)
- Miller, M. C., Chirenti, C., & Lamb, F. K. 2019c, *The Astrophysical Journal*, 888, 12, doi: [10.3847/1538-4357/ab4ef9](https://doi.org/10.3847/1538-4357/ab4ef9)
- Most, E. R., Papenfort, L. J., Dexheimer, V., et al. 2019, *Phys. Rev. Lett.*, 122, 061101, doi: [10.1103/PhysRevLett.122.061101](https://doi.org/10.1103/PhysRevLett.122.061101)
- Nedora, V., Bernuzzi, S., Radice, D., et al. 2019, *The Astrophysical Journal Letters*, 886, L30, doi: [10.3847/2041-8213/ab5794](https://doi.org/10.3847/2041-8213/ab5794)
- . 2021, *The Astrophysical Journal*, 906, 98, doi: [10.3847/1538-4357/abc9be](https://doi.org/10.3847/1538-4357/abc9be)
- Noble, S. C., Gammie, C. F., McKinney, J. C., & Zanna, L. D. 2006, *The Astrophysical Journal*, 641, 626, doi: [10.1086/500349](https://doi.org/10.1086/500349)
- Oppenheimer, J. R., & Volkoff, G. M. 1939, *Phys. Rev.*, 55, 374, doi: [10.1103/PhysRev.55.374](https://doi.org/10.1103/PhysRev.55.374)
- Pang, P. T. H., Dietrich, T., Coughlin, M. W., et al. 2023, *Nature Communications*, 14, 8352, doi: [10.1038/s41467-023-43932-6](https://doi.org/10.1038/s41467-023-43932-6)
- Perego, A., Bernuzzi, S., & Radice, D. 2019, *European Physical Journal A*, 55, 124, doi: [10.1140/epja/i2019-12810-7](https://doi.org/10.1140/epja/i2019-12810-7)
- Perego, A., Vescovi, D., Fiore, A., et al. 2022, *The Astrophysical Journal*, 925, 22, doi: [10.3847/1538-4357/ac3751](https://doi.org/10.3847/1538-4357/ac3751)
- Popham, R., Woosley, S. E., & Fryer, C. 1999, *The Astrophysical Journal*, 518, 356, doi: [10.1086/307259](https://doi.org/10.1086/307259)
- Raaijmakers, G., Greif, S. K., Riley, T. E., et al. 2020, *The Astrophysical Journal Letters*, 893, L21, doi: [10.3847/2041-8213/ab822f](https://doi.org/10.3847/2041-8213/ab822f)
- Radice, D., & Dai, L. 2019, *Eur. Phys. J. A*, 55, 50, doi: [10.1140/epja/i2019-12716-4](https://doi.org/10.1140/epja/i2019-12716-4)
- Radice, D., Perego, A., Bernuzzi, S., & Zhang, B. 2018a, *Monthly Notices of the Royal Astronomical Society*, 481, 3670, doi: [10.1093/mnras/sty2531](https://doi.org/10.1093/mnras/sty2531)
- Radice, D., Perego, A., Hotokezaka, K., et al. 2018b, *Astrophysical Journal*, 869, 130, doi: [10.3847/1538-4357/aaf054](https://doi.org/10.3847/1538-4357/aaf054)
- Radice, D., Perego, A., Zappa, F., & Bernuzzi, S. 2017, *Astrophysical Journal Letters*, 852, L29, doi: [10.3847/2041-8213/aaa402](https://doi.org/10.3847/2041-8213/aaa402)
- Ricigliano, G., Jacobi, M., & Arcones, A. 2024, *arXiv e-prints*, arXiv:2406.03649, doi: [10.48550/arXiv.2406.03649](https://doi.org/10.48550/arXiv.2406.03649)
- Ruffert, M., Janka, H. T., Takahashi, K., & Schäfer, G. 1997, *Astronomy & Astrophysics*, 319, 122
- Russotto, P., Gannon, S., Kupny, S., et al. 2016, *Phys. Rev. C*, 94, 034608, doi: [10.1103/PhysRevC.94.034608](https://doi.org/10.1103/PhysRevC.94.034608)
- Sekiguchi, Y., Kiuchi, K., Kyutoku, K., & Shibata, M. 2015, *Physical Review D - Particles, Fields, Gravitation and Cosmology*, 91, 1, doi: [10.1103/PhysRevD.91.064059](https://doi.org/10.1103/PhysRevD.91.064059)
- Shibata, M., Sekiguchi, Y.-i., & Takahashi, R. 2007, *Progress of Theoretical Physics*, 118, 257, doi: [10.1143/PTP.118.257](https://doi.org/10.1143/PTP.118.257)
- Siegel, D. M., & Metzger, B. D. 2017, *Physical Review Letters*, 119, 1, doi: [10.1103/PhysRevLett.119.231102](https://doi.org/10.1103/PhysRevLett.119.231102)
- . 2018, *The Astrophysical Journal*, 858, 52, doi: [10.3847/1538-4357/aabaec](https://doi.org/10.3847/1538-4357/aabaec)
- Sprouse, T. M., Lund, K. A., Miller, J. M., McLaughlin, G. C., & Mumpower, M. R. 2024, *The Astrophysical Journal*, 962, 79, doi: [10.3847/1538-4357/ad1819](https://doi.org/10.3847/1538-4357/ad1819)
- Surman, R., McLaughlin, G. C., Ruffert, M., Janka, H.-T., & Hix, W. R. 2008, *The Astrophysical Journal*, 679, L117, doi: [10.1086/589507](https://doi.org/10.1086/589507)
- Takami, K., Rezzolla, L., & Baiotti, L. 2014, *Phys. Rev. Lett.*, 113, 091104, doi: [10.1103/PhysRevLett.113.091104](https://doi.org/10.1103/PhysRevLett.113.091104)
- Takátsy, J., Kovács, P., Wolf, G., & Schaffner-Bielich, J. 2023, *Phys. Rev. D*, 108, 043002, doi: [10.1103/PhysRevD.108.043002](https://doi.org/10.1103/PhysRevD.108.043002)
- Tews, I., Carlson, J., Gandolfi, S., & Reddy, S. 2018, *The Astrophysical Journal*, 860, 149, doi: [10.3847/1538-4357/aac267](https://doi.org/10.3847/1538-4357/aac267)
- Tolman, R. C. 1939, *Phys. Rev.*, 55, 364, doi: [10.1103/PhysRev.55.364](https://doi.org/10.1103/PhysRev.55.364)
- van Putten, M. H., & Valle, M. D. 2019, *Monthly Notices of the Royal Astronomical Society: Letters*, 482, L46, doi: [10.1093/mnrasl/sly166](https://doi.org/10.1093/mnrasl/sly166)

Villar, V. A., Guillochon, J., Berger, E., et al. 2017,  
Astrophysical Journal Letters, 851, L21,  
doi: [10.3847/2041-8213/aa9c84](https://doi.org/10.3847/2041-8213/aa9c84)

Waxman, E., Ofek, E. O., & Kushnir, D. 2019,  
Astrophysical Journal, 878, 93,  
doi: [10.3847/1538-4357/ab1f71](https://doi.org/10.3847/1538-4357/ab1f71)

Waxman, E., Ofek, E. O., Kushnir, D., & Gal-Yam, A.  
2018, Monthly Notices of the Royal Astronomical  
Society, 481, 3423, doi: [10.1093/mnras/sty2441](https://doi.org/10.1093/mnras/sty2441)

Zhu, Y. L., Lund, K. A., Barnes, J., et al. 2021, The  
Astrophysical Journal, 906, 94,

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