# Kilonova Emission from Neutron Star Mergers with Different Equations of State postprint

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## Full Text

## Preamble

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### Kilonova Emission from Neutron Star Mergers with Different Equations of State

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## Abstract

A kilonova is an optical-infrared transient powered by the radioactive decay of heavy nuclei from a binary neutron star merger. Its observational characteristics depend on the mass and nuclide composition of merger ejecta, which are sensitive to the equation of state (EoS) of neutron stars. We use astrophysical conditions derived from different EoSs as nucleosynthesis inputs to explore the impact of various EoSs on r-process nucleosynthesis and kilonova emission. Our results show that both the abundance patterns of merger ejecta and kilonova light curves are strongly dependent on the neutron star EoS. For a given binary neutron star mass, mergers with softer EoSs tend to generate larger amounts of ejected material and produce brighter kilonova peak luminosities. This relationship between neutron star EoS and peak luminosity provides a probe for constraining EoS properties through multi-messenger observations of neutron star mergers.

**Key words:** nuclear reactions, nucleosynthesis, abundances — equation of state — stars: neutron

## 1. Introduction

Kilonovae are optical-infrared transients powered by radioactive decay of heavy r-process nuclei produced in neutron star mergers (Li & Paczyński 1998; Metzger et al. 2010; Korobkin et al. 2012; Barnes & Kasen 2013; Kasen et al. 2013; Barnes et al. 2016; Metzger 2019). The first direct detection of a binary neutron star merger by LIGO/Virgo, GW170817, was followed by a gamma-ray burst (GRB 170817A; Goldstein et al. 2017) and a kilonova (AT2017gfo; Abbott et al. 2017b; Arcavi et al. 2017; Coulter et al. 2017; Cowperthwaite et al. 2017; Drout et al. 2017; Evans et al. 2017; Kasen et al. 2017; Kasliwal et al. 2017; Pian et al. 2017; Shappee et al. 2017; Smartt et al. 2017). The kilonova's features agreed well with r-process models, suggesting synthesis of 0.05M of heavy r-process nuclei in the ejecta. Watson et al. (2019) identified strontium ($Z = 38$) in the merger ejecta through spectral analysis. These observations confirm that binary neutron star mergers are primary sources of heavy r-process nuclei (Kasen et al. 2017; Hotokezaka et al. 2018; Chen et al. 2024a).

Estimating ejecta mass from kilonova observations involves significant systematic uncertainties from astrophysical conditions (Shibata & Hotokezaka 2019; Radice et al. 2020) and nuclear physics inputs (Mumpower et al. 2016; Cowan et al. 2021). Uncertainties in nuclear masses, $\beta$-decay half-lives, neutron capture rates, and fission distributions can cause order-of-magnitude variations in inferred ejecta mass (Zhu et al. 2021). Additionally, neutron star merger simulations must account for extreme gravitational and magnetic fields, as well as unprecedented densities and temperatures.

The amount and properties of ejected material are highly sensitive to binary parameters and the neutron star equation of state (EoS) (Radice et al. 2018). The EoS determines the maximum allowed mass for neutron stars (Özel & Freire 2016), which affects the merger remnant's fate—whether it collapses to a black hole or remains as a massive or stable neutron star. A surviving neutron star remnant can eject additional mass via disk winds and neutrino emission, altering the electron fraction. Furthermore, the EoS affects ejecta mass through its influence on neutron star radii: stiffer EoSs produce larger radii for a given mass, leading to more pronounced tidal effects, earlier mergers at lower velocities, and less efficient shock heating, thereby reducing mass ejection.

Zhao et al. (2023) investigated the EoS-luminosity relationship using a semi-analytical model without detailed r-process simulations, neglecting EoS effects on nucleosynthesis, nuclear heating rates, and radiative transfer. In this paper, we explore how EoS impacts merger ejecta composition and kilonova light curves through detailed r-process simulations for binary neutron star mergers, using numerical relativity simulations as astrophysical inputs and modeling kilonova radiation from radioactive decay of heavy nuclei.

## 2. Methods

### 2.1. r-Process Nucleosynthesis

We use the improved SkyNet nuclear reaction network (Lippuner & Roberts 2015, 2017) to obtain detailed heavy r-process nuclei compositions. Nuclear physics data and reaction rates follow our previous work (Chen et al. 2023, 2024b, 2025). Radioactive decay energy data for heavy r-process nuclei come from the Evaluated Nuclear Data File library (ENDF/B-VIII.0; Brown et al. 2018). Astrophysical inputs for different EoSs are taken from numerical relativity simulations by Radice et al. (2018).

Following Chen & Liang (2024), the total r-process heating rate is given by

$$\dot{q}_{\mathrm{tot}}(t) = f(t)\,\dot{q}(t)$$

where $f(t)$ is the thermalization efficiency and $\dot{q}(t)$ is the radioactive energy generation rate. The radioactive decay energy released by heavy r-process nuclei in merger ejecta can be written as

$$\dot{q}(t) = \sum_i \lambda_i E_i Y_i(t) N_A$$

where $\lambda_i$ is the nuclear reaction rate of the $i$th nucleus, $E_i$ is the radioactive decay energy, $Y_i(t)$ is the elemental abundance, and $N_A$ is Avogadro's number. The thermalization efficiency follows the analytic formula from Barnes et al. (2016):

$$f(t) = 0.36\left[\exp(-t_{\mathrm{day}}) + \frac{2}{\pi}\frac{1-\exp(-t_{\mathrm{day}})}{1+2t_{\mathrm{day}}}\right]$$

where $t_{\mathrm{day}}$ is the time in days after merger.

For the electron fraction $Y_e$, we adopt the analytical formula fitted by Nedora et al. (2022):

$$Y_e = b_0 + b_1\tilde{\Lambda} + b_2 q + b_3\tilde{\Lambda}q + b_4\tilde{\Lambda}^2 + b_5 q^2$$

where $q$ is the mass ratio of binary neutron stars, $\tilde{\Lambda}$ is the reduced tidal deformability parameter (Nedora et al. 2022), and $b_0$ to $b_5$ are fitting coefficients. We use the best-fit parameters from Nedora et al. (2022). The opacity $\kappa$ as a function of $Y_e$ follows Tanaka et al. (2020), derived from systematic analysis of heavy element compositions.

### 2.2. Kilonova Model

Our kilonova model follows Chen & Liang (2024). We divide the ejected material into $n$ layers with density profile

$$\rho_n(t) = \frac{m_n}{4\pi R_n(t)^3/3}$$

where $v_n$ is the expansion velocity of the $n$th layer. The thermal energy evolves according to

$$\dot{E}_n(t) = -P_n\frac{dV_n}{dt} - L_n(t) + \dot{q}_{\mathrm{tot}}(t)m_n$$

where $R_n$ is the radius, $m_n$ is the mass, $E_n$ is the internal energy, and $L_n$ is the radiation luminosity of the $n$th layer. The thermal luminosity is given by

$$L_n(t) = \frac{E_n(t)}{t_{\mathrm{lc,n}} + t_{\mathrm{d,n}}}$$

where $t_{\mathrm{lc,n}} = R_n(t)/c$ is the light-crossing time and $t_{\mathrm{d,n}} = \tau_n R_n(t)/c$ is the photon diffusion timescale, with $\tau_n$ being the optical depth. The total kilonova luminosity from all layers is

$$L_{\mathrm{bol}}(t) = \sum_n L_n(t)$$

## 3. Results

[Figure 1: see original paper] shows abundance patterns from r-process nucleosynthesis simulations for binary neutron star mergers using different EoSs (BHBlp, DD2, LS220, SFHo) from Radice et al. (2018). The patterns differ significantly, particularly for atomic mass numbers $A \gtrsim 200$ and $A \lesssim 120$, indicating that neutron star EoS substantially influences r-process nucleosynthesis and potentially affects kilonova light curves.

[Figure 2: see original paper] presents kilonova light curves in JWST NIRCam bands F200W and F444W for a symmetric 1.35+1.35M binary. The characteristic radii for a 1.35M non-rotating neutron star are 11.92 km (SFHo), 12.64 km (LS220), and 13.21 km (BHBlp and DD2). Generally, EoSs with smaller $R_{1.35}$ are "softer" and those with larger $R_{1.35}$ are "stiffer." Softer EoSs produce brighter kilonova light curves with higher peak luminosities. In F200W, the peak luminosity for the softest EoS (SFHo) exceeds that for the stiffest (DD2) by a factor of 2.4, while in F444W the factor is 3.7.

To further investigate the EoS-peak luminosity relation, we performed r-process simulations using 40 distinct EoSs from Bauswein et al. (2013). [Figure 3: see original paper] shows the relationship between electron fraction $Y_e$ and characteristic radius $R_{1.35}$, with softer and stiffer EoSs tending to produce smaller $Y_e$ values. [Figure 4: see original paper] displays the peak luminosity versus $R_{1.35}$ for a symmetric 1.35+1.35M binary. As $R_{1.35}$ decreases, ejecta mass increases significantly, producing brighter peak luminosities. The softest EoS yields a peak flux 3.13 times higher than the stiffest. This occurs because softer EoSs have smaller $R_{1.35}$, reducing the tidal disruption radius, enhancing shock heating efficiency, amplifying oscillation kinetic energy, and generating more ejecta.

We also investigated ejecta from binaries with different masses using analytical fits from Radice et al. (2018). [Figure 5: see original paper] shows ejecta mass as a function of binary component masses for SFHo, LS220, DD2, and BHBlp. In symmetric binaries, larger component masses produce more ejecta, and softer EoSs (SFHo, LS220) generate greater ejecta masses than stiffer ones (BHBlp, DD2), consistent with Kasen et al. (2013) and Tanaka & Hotokezaka (2013). [Figure 6: see original paper] shows the corresponding peak luminosities, which increase with binary mass. Notably, for a given binary system, softer EoSs produce brighter kilonovae, demonstrating that kilonova emission directly probes neutron star EoS.

## 4. Conclusions and Discussions

We explored how neutron star EoS affects r-process nucleosynthesis and kilonova emission in binary neutron star mergers. Detailed r-process simulations reveal that different EoSs produce distinct abundance patterns, particularly for $A \gtrsim 200$ and $A \lesssim 120$ ([Figure 1: see original paper]), suggesting EoS significantly influences r-process nucleosynthesis and kilonova light curves.

Using detailed compositions from r-process simulations, we calculated kilonova light curves powered by radioactive decay of heavy nuclei ([Figure 2: see original paper]). Peak luminosities from soft EoSs exceed those from stiff EoSs. To further investigate this relationship, we performed r-process simulations using 40 distinct EoSs from numerical relativity. Kilonova emission directly correlates with neutron star EoS: softer EoSs produce brighter light curves and higher peak luminosities ([Figure 4: see original paper]). This can be attributed to softer EoSs having smaller characteristic radii $R_{1.35}$, which reduces tidal disruption radius, enhances shock heating efficiency, amplifies oscillation kinetic energy, and generates more ejecta. These results are consistent with previous studies (Bauswein et al. 2013; Hotokezaka et al. 2013; Sekiguchi et al. 2016; Radice et al. 2018; Rosswog & Korobkin 2024).

We further investigated ejecta from binaries with different masses ([Figure 5: see original paper] and [Figure 6: see original paper]). Softer EoSs (SFHo, LS220) tend to generate more merger ejecta and produce brighter kilonova emission than BHBlp and DD2, suggesting kilonova emission provides a direct probe for constraining neutron star EoS.

We note that our astrophysical conditions from numerical relativity simulations typically produce ejecta masses about one order of magnitude lower than those inferred from observed kilonova light curves (Siegel 2019). This discrepancy may arise from uncertainties in nuclear physics inputs, as properties of heavy r-process nuclei remain unmeasured (Barnes et al. 2021; Zhu et al. 2021; Chen et al. 2025). Zhu et al. (2021) show nuclear physics uncertainties can cause order-of-magnitude variations in kilonova luminosity. However, these uncertainties do not affect our main conclusions, as nuclear properties are intrinsic characteristics that influence all kilonovae.

Multi-messenger observations of GW170817/GRB 170817A/AT2017gfo provide a solid case for studying neutron star EoS. The peak luminosity of AT2017gfo appears brighter than our calculated results (at 40 Mpc), suggesting the observed light curves support a soft EoS (i.e., smaller characteristic radius for a given neutron star mass). This is consistent with tidal deformability analyses from GW170817 suggesting neutron star radii must be 13 km (Abbott et al. 2018; De et al. 2018; Raithel et al. 2018). Note that we adopted a spherically symmetric model, which may affect peak luminosity (Zhu et al. 2020; Korobkin et al. 2021). However, recent analysis shows AT2017gfo's merger ejecta is highly spherical with uniform heavy element distribution (Sneppen et al. 2023).

To effectively utilize the direct relationship between kilonova peak luminosity and neutron star EoS for studying dense nuclear matter, the masses of both neutron stars must be specified. Neutron star masses are typically determined from gravitational wave observations by LIGO/Virgo. Given the success of joint GW170817 and AT2017gfo detection, multi-messenger analysis has great potential for probing neutron star EoS. However, degeneracies among multiple parameters introduce uncertainty in neutron star masses from gravitational wave signals. As LIGO/Virgo sensitivity improves, constraints on neutron star masses will be greatly enhanced. The ongoing O4 run is expected to detect neutron star mergers within 200 Mpc and may detect 10 merger events. Additionally, JWST is a powerful infrared instrument for observing kilonovae, offering comprehensive coverage from early to late phases (Chen & Liang 2024).

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