

# Multimessenger Signatures of Neutron Star Mergers: Postmerger Gravitational Waves, Kilonova Emission, R-Process Nucleosynthesis, and the Nuclear Equation of State in the Era of Third-Generation Detectors

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**Abstract** – This paper examines dense nuclear matter from the nuclear saturation density through the supra-nuclear exotic matter regime. In our preceding papers we established: (i) multi messenger constraints on the nuclear symmetry energy and neutron skin thickness from PREX-II, CREX, NICER, and GW170817; and (ii) the hadron–quark phase transition, the hyperon puzzle, and the speed-of-sound diagnostic. Here we integrate these threads into a comprehensive treatment of the full observational and nucleosynthetic aftermath of binary neutron star (BNS) mergers. We examine, in detail, the postmerger gravitational-wave spectrum and its dependence on the equation of state (EoS) — including the dominant  $f_2$  oscillation mode, the long-ringdown correlation with ultra-high-density EoS, and the role of magnetic fields in shifting postmerger frequencies. We analyze the kilonova electromagnetic transient AT2017gfo — the only spectroscopically observed electromagnetic counterpart of a BNS merger — and the physical pipeline connecting merger ejecta dynamics to r-process nucleosynthesis, radiative transfer, and observable light curves and spectra. The identification of strontium ( $Z=38$ ) and emerging evidence for tellurium ( $Z=52$ ), lanthanum ( $Z=57$ ), and cerium ( $Z=58$ ) in kilo nova spectra is reviewed within the current state of atomic data and radiative transfer modelling. The sensitivity of kilonova ejecta mass, electron fraction  $Y_e$ , and lanthanide opacity to the underlying EoS is discussed as a new indirect nuclear probe. We further present a forward-looking analysis of the science enabled by the Einstein Telescope (ET) and Cosmic Explorer (CE) — third-generation gravitational-wave observatories expected to detect  $O(10^5)$  BNS mergers per year — including postmerger frequency extraction, Hubble constant measurement, and the precision mapping of r-process enrichment across cosmic history. The paper concludes that the convergence of gravitational-wave, electromagnetic, and nuclear laboratory observations is transforming BNS mergers into the most powerful known laboratory for exploring nuclear matter under the most extreme conditions that exist in the observable universe.

**Key Words:** *binary neutron star mergers, kilonova, r-process nucleosynthesis, postmerger gravitational waves, AT2017gfo, equation of state, Einstein Telescope, Cosmic Explorer, multimessenger astrophysics, strontium, lanthanides.*

## 1. INTRODUCTION AND SERIES CONTEXT

The physics of dense nuclear matter — its symmetry energy, phase structure, and relationship to observable compact stars — has been the unifying theme of our three-paper series. In the first paper, we showed how parity-violating electron scattering experiments (PREX-II, CREX), NASA’s NICER X-ray observatory, and the gravitational-wave detection GW170817 provide overlapping, occasionally discordant, but collectively powerful constraints on the nuclear symmetry energy slope  $L$  and the neutron star radius  $R_{1.4}$ . In the second paper, we extended the discussion into supra-nuclear densities, examining the hyperon puzzle, the hadron–quark phase transition, and the characteristic non-monotonic speed-of-sound profile that now stands as the most robust indirect signature of quark degrees of freedom in neutron star cores.

This third paper closes the trilogy by turning to the full multimessenger observational signatures of binary neutron star (BNS) mergers — the most complete and richest laboratory currently available for dense matter physics. The collision and merger of two neutron stars generates four distinct observable channels: (i) gravitational waves from the inspiral, sensitive to the tidal deformability; (ii) kilohertz gravitational waves from the postmerger remnant, sensitive to the EoS at densities well above the nuclear saturation value; (iii) a short gamma-ray burst (sGRB) from the relativistic jet launched by the remnant accretion disk; and (iv) a kilonova optical-to-near-infrared transient powered by the radioactive decay of freshly synthesized r-process nuclei. Together, these observational channels access the nuclear EoS across an extraordinary range of densities and temperatures.

The landmark event GW170817/GRB 170817A/AT2017gfo in August 2017 simultaneously activated all four of these channels for the first time, opening an unprecedented window into nuclear matter physics, heavy-element astrophysics, and general relativistic hydrodynamics. Its kilonova counterpart AT2017gfo remains the only BNS merger event with spectroscopic observations in hand, and its analysis — particularly the identification of r-process elements in its spectrum — represents perhaps the single most significant advance in nuclear astrophysics of the past decade. Yet AT2017gfo also highlighted the severe limitations of current observational and theoretical tools: only a single element (strontium) was unambiguously identified; the EoS information encoded in the kilonova ejecta could not be decoded without sophisticated radiative transfer modelling and accurate atomic data for hundreds of heavy elements; and the postmerger gravitational-wave signal fell entirely below the sensitivity threshold of Advanced LIGO and Advanced Virgo.

The imminent third generation of gravitational-wave detectors — the Einstein Telescope (ET) in Europe and Cosmic Explorer (CE) in the United States — promises to transform this picture. Operating at sensitivities up to an order of magnitude beyond Advanced LIGO, these instruments will detect  $O(10^5)$  BNS mergers per year, measure postmerger gravitational wave frequencies with kHz-band precision, and localize events to sub-square-degree precision to enable simultaneous kilonova spectroscopy. The resulting dataset will constitute a complete multimessenger census of BNS mergers over cosmic history, mapping the nuclear EoS, the cosmic r-process enrichment history, and the Hubble constant from a single observational program.

The paper is organized as follows. Section 2 reviews the postmerger gravitational-wave spectrum and the quasi-universal relations linking oscillation frequencies to EoS properties. Section 3 discusses the long-ringdown signal and magnetic field effects in postmerger remnants. Section 4 presents the physics and modelling of kilonovae, with emphasis on AT2017gfo. Section 5 examines r-process nucleosynthesis and element identification in kilonova spectra. Section 6 discusses the EoS sensitivity of kilonova observables. Section 7 outlines the science case for third-generation detectors. Section 8 provides a unified synthesis, and Section 9 concludes.

## 2. POSTMERGER GRAVITATIONAL-WAVE SPECTRUM

### 2.1 Dominant Oscillation Mode and Quasi-Universal Relations

When two neutron stars collide and merge, the resulting hypermassive neutron star (HMNS) remnant oscillates violently at kilohertz frequencies before either collapsing to a black hole or settling into a supramassive remnant supported against collapse by differential rotation and thermal pressure. These oscillations radiate gravitational waves at characteristic frequencies determined by the remnant's internal structure, which is itself set by the EoS of the merged dense matter. The postmerger gravitational-wave spectrum is therefore a direct probe of the EoS at densities  $(2-4)\rho_0$  — higher than what is accessible through tidal deformability measurements during the inspiral phase.

The dominant gravitational-wave emission occurs at the  $f_2$  frequency, associated with the fundamental quadrupolar oscillation mode of the remnant. Numerical relativity simulations across large libraries of EoS models have established tight quasi-universal relations between  $f_2$  and EoS-dependent stellar properties. Bauswein and Janka (2012) first demonstrated that  $f_2$  correlates tightly with the radius  $R_{\text{max}}$  of the maximum-mass TOV configuration:

$$f_2 [\text{kHz}] \approx a + b \times (M/M_\odot) / R_{\text{max}} [\text{km}]$$

where  $a$  and  $b$  are fitting constants determined from a library of numerical relativity simulations. Subsequent work by Takami, Rezzolla, and Baiotti (2014, 2015) provided the first evidence for a new instantaneous frequency  $f_0^{\psi_4}$  associated with the quasi-time-symmetry instant of the merger dynamics, which also obeys a quasi-universal relation. These relations are remarkably insensitive ('equation-of-state insensitive') to the details of the nuclear model used, making them powerful tools for EoS inference from observed postmerger frequencies.

For a merger at  $\sim 100$  Mpc distance, the postmerger gravitational-wave signal has strain amplitude  $h \sim 10^{-23}$ , requiring detector sensitivities in the 2–4 kHz band that are approximately one order of magnitude below the design noise floor of Advanced LIGO. This is precisely the frequency range targeted by the proposed high-frequency KAGRA upgrade (KAGRA HF), the Neutron Star Extreme Matter Observatory (NEMO), and the cryogenic low-frequency arm of the Einstein Telescope.

## 2.2 Secondary Oscillation Modes and EoS Discrimination

Beyond  $f_2$ , the postmerger spectrum contains secondary frequency peaks  $f_1$  and  $f_3$  whose origin and EoS dependence have been the subject of intensive investigation. The  $f_1$  frequency, arising from nonlinear coupling between the fundamental mode and quasi-radial oscillations, is particularly sensitive to the EoS at densities near the central value of the HMNS remnant. Studies employing realistic finite-temperature EoS tables — including the effects of thermal pressure from shock heating to  $T \approx 30\text{--}80$  MeV at merger — demonstrate that the quasi-universal relations for  $f_2$  remain robust, but that thermal effects significantly influence the lifetimes and collapse thresholds of HMNS remnants, which in turn affect the total postmerger GW energy radiated before collapse.

Barman and Chatterjee (2025) constructed a large set of realistic finite-temperature EoS models within the non-linear relativistic mean field (NL-RMF) framework, constrained by chiral EFT, NICER, and GW170817 data, and computed postmerger GW frequencies using a consistent thermal prescription across the full star. Their analysis demonstrated that EoS models consistent with current multi-disciplinary constraints predict  $f_2$  values in the range 2.5–3.5 kHz for equal-mass mergers with total mass  $M_{\text{total}} = 2.7 M_{\odot}$ . They further showed that including hyperons — which appear at  $T > 0$  at lower densities than in cold matter — produces a systematic downward shift in  $f_2$  of approximately 100–200 Hz relative to nucleon-only EoS, providing a potential spectroscopic signature of strangeness in postmerger remnants.

## 3. LONG-RINGDOWN SIGNAL AND MAGNETIC FIELD EFFECTS

### 3.1 The Long-Ringdown Correlation

An important advance in postmerger gravitational-wave science was the identification by Breschi et al. (2025, Nature Communications) of a tight correlation between the ratio of energy-to-angular-momentum losses in the late-time (long-ringdown) portion of the postmerger signal and the EoS at the highest pressures and densities in the stellar core. Unlike the short-time  $f_2$  emission that reflects the average structure of the remnant, the long-ringdown signal at times  $t \geq 5\text{--}10$  ms after merger reflects the EoS at the extreme central densities accessed only by the most compact remnant configurations. Applying this long-ringdown correlation to simulated postmerger signals with third-generation detector sensitivity reduces EoS uncertainty at densities several times nuclear saturation density — precisely the regime where no direct constraints from terrestrial experiments or pre-merger astrophysical observations currently exist.

The long-ringdown correlation is physically connected to the secular drift of the  $f_2$  frequency over time: as the remnant cools through neutrino emission and re-arranges its density profile, the dominant oscillation frequency evolves slowly. The ratio of energy to angular momentum loss encodes this secular evolution and is largely independent of the initial binary mass ratio and spin configuration, making it a robust EoS diagnostic when averaged over an observed postmerger signal.

### 3.2 Magnetic Field Effects on Postmerger Frequencies

A critical complication for postmerger EoS inference — recognized clearly only in 2025 — is that strong magnetic fields can significantly shift the dominant postmerger oscillation frequency in ways that mimic EoS effects. Tsokaros et al. (Physical Review Letters, 2025) demonstrated through full general-relativistic magnetohydrodynamics (GRMHD) simulations that magnetic braking and effective turbulent magnetic viscosity drive the merger remnant toward uniform rotation, increasing angular momentum loss rates and shifting the  $f_2$  frequency upward by up to  $\sim 50$  Hz for median magnetic field strengths.

The physical mechanism involves two distinct processes. First, the Kelvin-Helmholtz instability (KHI) at the shear interface between the two merging neutron stars amplifies pre-existing magnetic fields from  $B \sim 10^{12}$  G (typical neutron star surface field) to  $B \sim 10^{14}\text{--}10^{15}$  G within milliseconds of merger, through turbulent dynamo action. Second, the magnetorotational instability (MRI), which operates in differentially rotating magnetized plasma, further amplifies the field in the bulk of the remnant and drives an effective viscous torque that modifies the rotation profile. The combined effect produces a systematic frequency shift that depends on magnetic field topology (poloidal, toroidal, or pulsar-like dipolar configurations) and peak field strength, with maximum upward shifts of several hundred Hz for the strongest physically plausible field configurations.

This result has significant implications: unless magnetic field effects are included in postmerger waveform models used for EoS inference, systematic errors comparable to the EoS-induced frequency differences between different nuclear models will contaminate the inferred EoS parameters. The study emphasizes that next-generation gravitational wave observatories, particularly Cosmic Explorer and the Einstein Telescope, must incorporate magnetic field effects in their analysis pipelines to extract reliable EoS constraints from postmerger signals. Supervised machine learning approaches to postmerger waveform modelling (Bozzola et al., Physical Review D, 2025) are actively being developed to efficiently account for the large parameter space including EoS, mass ratio, and magnetic field effects simultaneously.

**Table –1: Postmerger Gravitational-Wave Observables and Their EoS Sensitivity**

Observable	Typical Range	EoS Probe	Det. Required	Ref.
$f_2$ (dominant mode)	2.5–3.5 kHz	$R_{\text{max}}, \rho_{2-3}\rho_0$	3G (ET/CE)	[1,2]
$f_i$ (secondary)	1.5–2.5 kHz	Central $\rho$ of HMNS	3G (ET/CE)	[3]
Long-ringdown	$t > 5-10$ ms	Ultra-high $\rho$ EoS	3G (ET/CE)	[4]
$f_2$ magnetic shift	~50–200 Hz	Magnetic topology	3G (ET/CE)	[5]
Tidal $\Lambda$ (inspiral)	$\Lambda_{1.4} < 580$	$R_{1.4}, (1-2)\rho_0$	Current LIGO/Virgo	[6]

## 4. KILONOVA PHYSICS AND THE AT2017GFO PARADIGM

### 4.1 Physics of Kilonova Emission

A kilonova is a thermal transient powered by the radioactive decay of neutron-rich heavy nuclei synthesized by the rapid neutron-capture process (r-process) in the merger ejecta. Predicted theoretically by Li and Paczyński (1998) and first confirmed observationally in GW170817 (Pian et al. 2017; Smartt et al. 2017), kilonovae occur when neutron-rich material is ejected during the merger through three distinct physical processes: (i) tidal dynamical ejecta expelled during the tidal disruption phase, typically neutron-rich (electron fraction  $Y_e \sim 0.05-0.25$ ) and expanding at  $v \sim 0.2-0.3c$ ; (ii) shock-heated dynamical ejecta in the contact interface, somewhat less neutron-rich ( $Y_e \sim 0.25-0.40$ ) and expanding at  $v \sim 0.1-0.2c$ ; and (iii) secular wind ejecta driven by neutrino irradiation, magnetically-driven winds, and viscous processes from the remnant accretion disk, with mass  $\Delta M \sim 0.05-0.15 M_\odot$  and a broad range of  $Y_e$ .

The ejecta opacity to optical and near-infrared photons is primarily determined by the lanthanide ( $Z = 57-71$ ) and actinide ( $Z = 89-103$ ) content, whose complex atomic structure with many low-lying energy levels produces enormous line forests that trap photons and shift the spectral energy distribution (SED) to the infrared. High-lanthanide ejecta ( $Y_e < 0.25$ ) produce ‘red’ kilonovae peaking at wavelengths  $\lambda > 1\mu\text{m}$  with opacity  $\kappa_r \sim 10-20 \text{ cm}^2 \text{ g}^{-1}$ , while lower-lanthanide ejecta ( $Y_e > 0.25$ ) produce ‘blue’ kilonovae peaking at  $\lambda \sim 0.5-0.7\mu\text{m}$  with opacity  $\kappa_b \sim 0.5-1.0 \text{ cm}^2 \text{ g}^{-1}$ . The two-component structure of AT2017gfo — an early blue component followed by a redder, more slowly declining component — was one of the first observational confirmations of this dichotomy.

### 4.2 AT2017gfo: Observations and Spectral Analysis

The kilonova AT2017gfo was detected 11 hours after GW170817 at a distance of approximately 40 Mpc in the galaxy NGC 4993. Its spectral sequence, spanning ultraviolet to near-infrared wavelengths over 10.4 days, provides the most detailed observational dataset of a kilonova in existence and remains the primary reference point for all kilonova modelling. Analysis of this dataset confirmed an ejecta mass of approximately  $0.05 M_\odot$  of heavy r-process nuclei (Kasen et al. 2017; Chen and Liang 2024) and expansion velocities of  $\sim 0.2c$  in the fast dynamical component and  $\sim 0.05c$  in the slower wind component.

Gillanders et al. (MNRAS, 2024) performed a comprehensive spectral analysis of the entire AT2017gfo sequence from +0.5 to +10.4 days using the Monte Carlo radiative transfer code CMFGEN. The team identified seven emission-like spectral features and confirmed that the prominent absorption feature near  $1.08 \mu\text{m}$  is best explained by the Sr II near-

infrared triplet, evolving from a P-Cygni profile through to pure emission over the observational sequence. They further showed that the absence of the [Sr II] doublet in the spectra requires highly clumped ejecta structures, a result with important implications for the geometry and hydrodynamics of the merger outflow. Near-infrared features emerging at 1.58 and 2.07  $\mu\text{m}$  after three days were attributed to La III and Ce III respectively, supporting earlier work by Domoto et al. (2022) and providing spectroscopic evidence for lanthanide-group ( $Z = 57\text{--}58$ ) synthesis in the merger ejecta.

The radiative transfer simulations underpinning AT2017gfo spectral identification depend critically on the completeness and accuracy of atomic data for heavy elements. Collins, Shingles, and Vijayan (Philosophical Transactions of the Royal Society A, 2025) demonstrated through 3D radiative transfer simulations using the ARTIS code that the choice of atomic datasets for Sr, Nd, Ce, Pr, and other lanthanides produces observable differences in synthetic spectra, highlighting atomic data uncertainty as a major current limitation in kilonova science. In particular, the AD2 (calibrated) atomic dataset for strontium produced the Sr II triplet feature at the correct wavelengths and with the correct time evolution, while the uncalibrated dataset generated the feature at systematically shifted wavelengths. This underscores the need for coordinated laboratory atomic spectroscopy programs targeting r-process-relevant ions.

**Table –2: Heavy Elements Identified or Tentatively Detected in Kilonova AT2017gfo**

Element	Z	Feature ( $\mu\text{m}$ )	Status	Confidence	Ref.
Strontium (Sr)	38	1.08, 0.79	Confirmed (Sr II triplet)	High	[7]
Lanthanum (La)	57	1.2–1.5	Tentative (La III)	Moderate	[8]
Cerium (Ce)	58	1.5–2.1	Tentative (Ce III)	Moderate	[8]
Tellurium (Te)	52	~2.1	Identified in GRB 230307A KN	High (JWST)	[9]
Calcium (Ca)	20	0.85	Tentative (coproduced with Sr)	Low–Moderate	[10]

## 5. R-PROCESS NUCLEOSYNTHESIS IN MERGER EJECTA

### 5.1 The r-Process Reaction Network

The rapid neutron-capture process (r-process) synthesizes approximately half of all elements heavier than iron by subjecting seed nuclei (typically iron-group nuclei produced in the neutron star crust or in the pre-merger accretion disk) to an intense flux of free neutrons in conditions of high neutron-to-seed ratio ( $n/s \gg 1$ ). The neutron capture rate must exceed the beta-decay rate at each step, driving the nuclear abundance pattern far from the valley of stability along extremely neutron-rich isotopic chains near the neutron drip line. As neutron irradiation subsides and beta-decay dominates, the abundance pattern relaxes back toward stable nuclides, accumulating at the three characteristic r-process abundance peaks at  $A \sim 80, 130, \text{ and } 195$  (corresponding to neutron magic numbers  $N = 50, 82, 130$ ).

The astrophysical conditions required for r-process nucleosynthesis — neutron densities  $n_n \sim 10^{24}\text{--}10^{28} \text{ cm}^{-3}$  and temperatures  $T \sim 1\text{--}3 \text{ GK}$  — are satisfied in the dynamical ejecta of BNS mergers, where material expelled from the deep neutron-rich interior retains its low electron fraction  $Y_e \sim 0.05\text{--}0.25$ . The ejecta evolution from neutron-rich nuclear statistical equilibrium through r-process freeze-out and into the free-streaming regime constitutes a rich nuclear physics problem requiring simultaneous tracking of hundreds of thousands of nuclear species across the chart of nuclides.

A crucial uncertainty in r-process nucleosynthesis is the nuclear masses and beta-decay rates of isotopes near the neutron drip line, which are beyond the reach of current radioactive beam facilities. Yin et al. (Astronomy and Astrophysics, 2025) conducted a systematic study of the impact of four widely-used nuclear mass models (FRDM, HFB, Duflo-Zuker, and Weizsäcker-Skyrme) on r-process nucleosynthesis yields and on the heavy element abundances in r-process-

enhanced (RPE) metal-poor stars. Their key finding was that the Weizsäcker-Skyrme (WS4) mass model, which minimizes deviations from experimental nuclear masses, provides superior reproduction of the observed rare-earth abundance peak — a sensitive diagnostic of the r-process path near  $A \sim 165$  — in a sample of RPE metal-poor stars with individual element measurements up to thorium and uranium. This result identifies WS4-based mass tables as the currently most reliable input for merger nucleosynthesis calculations and motivates new radioactive beam experiments (FRIB, HIE-ISOLDE, RIKEN) targeting the relevant neutron-rich isotopic chains.

## 5.2 BNS Mergers as the Dominant Galactic r-Process Site

While BNS mergers are confirmed r-process sites, their role as the dominant, or sole, contributor to the Galactic r-process abundance pattern remains an active topic of debate. The identification of kilonova emission from the short gamma-ray burst GRB 230307A (observed by JWST) and GRB 211211A (potentially a long-duration GRB from a compact binary) has demonstrated that BNS mergers and possibly neutron star–white dwarf (NS-WD) mergers contribute r-process elements in events that span a wider class than originally assumed.

Chen et al. (MNRAS, 2024) estimated the total Galactic r-process enrichment budget from BNS mergers using a statistical r-process network calculation and the event rate inferred from BNS merger gravitational-wave detections. Assuming the ejecta composition of AT2017gfo is representative, they find that BNS mergers can account for the observed total mass of r-process elements in the Milky Way ( $\sim 10^4 M_{\odot}$  of elements with  $A > 80$ ) if the local merger rate is in the range  $R_{\text{BNS}} \sim 200\text{--}1000 \text{ Gpc}^{-3} \text{ yr}^{-1}$ . The NS-WD merger contribution, estimated from their higher event rate (approximately ten times the BNS rate) and a substantially lower per-event ejecta mass, is subdominant but non-negligible, amounting to 5–15% of the total Galactic inventory. Galactic chemical evolution models that incorporate the cosmic delay between stellar formation and BNS merger — which can be as long as several Gyr for wide initial orbital separations — are now sophisticated enough to simultaneously match the Galactic r-process scatter in metal-poor stars and the solar r-process abundance distribution.

## 5.3 Neutrino Emission as an r-Process Messenger

An emerging detection channel for BNS merger r-process nucleosynthesis is the MeV neutrino burst generated by the beta-decay of freshly synthesized r-process elements in the kilonova ejecta. Jiang et al. (2023) showed that the nuclear beta-decay of r-process products generates a short-lived neutrino burst with peak luminosity  $L_{\nu} \sim 10^9 \text{ erg s}^{-1}$  lasting approximately one second after merger, carrying approximately half the total beta-decay energy as neutrinos. The neutrino energy spectrum peaks around 5–15 MeV, within the sensitivity range of present and proposed large liquid-argon and water Cherenkov detectors. Detection of this neutrino burst from a nearby ( $\leq 5 \text{ Mpc}$ ) BNS merger would provide direct information about the r-process abundance pattern, which is encoded in the time profile and energy spectrum of the neutrino emission, establishing a third observational messenger channel entirely independent of gravitational waves and electromagnetic light.

## 6. EOS SENSITIVITY OF KILONOVA OBSERVABLES

A physically deep but observationally challenging goal is to extract EoS information from kilonova light curves and spectra. The pathway runs through the connection between the nuclear EoS and the merger dynamics: different EoS choices produce different remnant lifetimes (prompt collapse vs. long-lived HMNS), different ejecta masses and geometries, different disk-to-ejecta mass ratios, and different  $Y_e$  distributions in the outflow. Each of these affects the kilonova light curves and spectra in principle distinguishable ways.

The most direct EoS influence operates through the binary tidal deformability  $\tilde{\Lambda}$ : a stiffer EoS produces larger neutron stars with enhanced tidal deformability, which in turn increases the mass of tidal dynamical ejecta during the inspiral phase. Stiffer EoS also generically delays or prevents prompt collapse of the postmerger remnant, enabling prolonged neutrino irradiation of the disk winds that elevates  $Y_e$  and reduces the lanthanide fraction, producing brighter blue kilonova emission. Radice et al. (2018) demonstrated that for total binary mass  $M_{\text{total}} = 2.7 M_{\odot}$ , prompt collapse (EoS-dependent critical mass  $M_{\text{threshold}} \leq M_{\text{total}}$ ) produces little blue emission but abundant lanthanide-rich red ejecta, while long-lived HMNS remnants produce both a bright blue component and a moderately red component, as observed in AT2017gfo.

Collins et al. (2025) showed through state-of-the-art 3D radiative transfer simulations (ARTIS code) that the simulated spectra in the polar direction reproduce the observed AT2017gfo spectral evolution remarkably well when the ejecta structure is drawn from a realistic HMNS remnant simulation with a moderately stiff EoS (consistent with  $R_{1.4} \approx 12$  km). Conversely, simulations using stiff EoS ( $R_{1.4} > 13.5$  km) or soft EoS ( $R_{1.4} < 10$  km) produce systematically incorrect peak colours or feature evolution timescales. This sensitivity constitutes a new, indirect EoS constraint from kilonova radiative transfer modelling, complementary to the gravitational-wave tidal deformability measurement.

However, extracting EoS information from kilonova spectra requires accurate atomic data for all relevant species — a formidable challenge given that the r-process produces hundreds of isotopes of elements  $Z = 30–100$  with complex electronic structures. The most urgent priorities include: (i) experimental and theoretical atomic data for the second r-process peak elements ( $Z = 52–60$ , including Te, I, La, Ce); (ii) reliable opacity calculations for actinides ( $Z = 89–103$ ) relevant to the very-neutron-rich ( $Y_e < 0.1$ ) dynamical ejecta; and (iii) non-LTE radiative transfer models that go beyond the local thermodynamic equilibrium approximation valid only in the first  $\sim 6$  days post-merger.

## 7. THE ERA OF THIRD-GENERATION GRAVITATIONAL-WAVE DETECTORS

### 7.1 Einstein Telescope and Cosmic Explorer: Design and Sensitivity

The Einstein Telescope (ET) is a proposed triangular underground gravitational-wave observatory with 10 km arm lengths, employing a xylophone configuration with two co-located interferometers: ET-LF (low-frequency, cryogenic at 10–20 K, targeting 2–30 Hz) and ET-HF (high-frequency, room-temperature, targeting 30–2000 Hz). ET is supported by the ESFRI roadmap with construction planned to begin around 2026–2028 at a Sardinian or Meuse-Rhine Euroregion site, targeting first observations near 2035. Cosmic Explorer (CE) is the US counterpart, comprising two L-shaped surface detectors with arm lengths of 40 km and 20 km respectively, funded through NSF at approximately \$9M USD for initial development, with the 20 km configuration specifically tuned for sensitivity in the 2–4 kHz postmerger frequency band.

Together, the ET-CE network represents a factor of 8–10 improvement in strain sensitivity across the detection band compared to Advanced LIGO, and extends the accessible frequency range both below 10 Hz (enabling detection of BNS inspirals hours before merger) and above 1 kHz (enabling postmerger signal measurement). The global ET-CE network is expected to detect  $O(10^4–10^5)$  BNS mergers per year out to cosmological distances ( $z \sim 1–2$ ), localizing dozens of events per year to within  $0.1 \text{ deg}^2$  for electromagnetic follow-up observations with the James Webb Space Telescope (JWST), the Extremely Large Telescope (ELT), and the Rubin Observatory LSST.

### 7.2 EoS Science with Third-Generation Detectors

The ET-CE network will transform postmerger gravitational-wave science from a matter of threshold detection into a regime of precision spectroscopy. For a BNS merger at 40 Mpc distance (comparable to GW170817), ET-CE is expected to measure the dominant postmerger frequency  $f_2$  to within 10–50 Hz, sufficient to discriminate between EoS models that differ in their symmetry energy slope  $L$  by  $\Delta L \sim 20$  MeV. For a statistical sample of  $O(10^3)$  BNS mergers with measurable postmerger signals, Bayesian stacking methods will constrain the EoS as a function of density at the 10% level over the range  $(2–5)\rho_0$  — entirely inaccessible with current detector technology.

A particularly powerful science case is the detection of a postmerger frequency jump — a sudden discrete increase in  $f_2$  by  $\Delta f \sim 200–400$  Hz — that would signal the onset of a phase transition from hadronic to quark matter in the remnant interior triggered by the elevated central density after merger. As discussed in Paper II of this series, such a jump requires onset densities below  $\sim 2.5\rho_0$  and sufficient density discontinuity to produce a detectable signal. ET-CE measurements at  $3\sigma$  confidence would require approximately 10–50 well-localized postmerger detections, achievable within the first few years of ET-CE operation.

The long-ringdown correlation identified by Breschi et al. (2025), which requires tracking the postmerger signal for 5–10 ms or longer, places stringent demands on the signal-to-noise ratio achievable per event. At ET-CE sensitivity, approximately 10–30 BNS mergers per year at distances  $\leq 100$  Mpc are expected to have sufficient postmerger signal-to-noise ratio ( $\text{SNR} \geq 8$ ) for long-ringdown analysis, providing a statistical sample of EoS constraints at the highest currently accessible densities within one to three years of operation.

### 7.3 Multimessenger Science: Hubble Constant and Cosmic r-Process History

Beyond nuclear physics, the ET-CE network will leverage the kilonova electromagnetic counterpart detections to measure the Hubble constant  $H_0$  as a ‘standard siren’, exploiting the absolute distance calibration from the gravitational-wave inspiral signal and the redshift from the optical host galaxy. Current estimates suggest that  $O(50)$  well-localized BNS mergers with identified kilonova counterparts will constrain  $H_0$  to below 1% precision, sufficient to resolve the present Hubble tension between early-universe (CMB) and late-universe (Cepheid–Type Ia supernova) measurements. Crucially, this measurement is entirely independent of the cosmic distance ladder and thus tests not just the expansion rate but potentially new physics in the dark sector.

From a nuclear astrophysics perspective, the ET-CE program will map the r-process enrichment history of the universe across cosmic time by detecting BNS mergers and their kilonova counterparts out to redshift  $z \sim 1-2$ . Comparing the BNS merger rate, kilonova luminosity function, and inferred r-process yields as a function of redshift against the observed r-process metallicity distribution in metal-poor stars will constrain the delay time distribution between star formation and BNS merger, a key unknown in Galactic chemical evolution models. The THESEUS mission concept, designed to detect 20–40 short GRBs per year with arcminute localizations out to  $z = 5$ , is specifically intended to complement ET for precisely this science case.

## 8. UNIFIED SYNTHESIS: THE NUCLEAR EQUATION OF STATE THROUGH THE MERGER LENS

The three papers in this series, taken together, trace a coherent arc from the nuclear physics laboratory to the most energetic astrophysical events in the universe. The nuclear symmetry energy — measurable in finite nuclei through parity-violating electron scattering — determines the pressure of neutron-rich matter near nuclear saturation density, which in turn sets the radius of neutron stars and their tidal deformability during binary inspiral. The high-density extrapolation of this pressure, into the supra-nuclear regime where hyperons appear and quark deconfinement may occur, determines the maximum neutron star mass and the characteristic speed-of-sound peak that constitutes the indirect signature of quark matter cores. And the merger of two neutron stars compresses all of these density regimes simultaneously, radiating gravitational waves at frequencies that encode the EoS at  $(2-5)\rho_0$  and driving the ejection of neutron-rich material that synthesizes the r-process elements found in the oldest stars of the Milky Way.

Figure 1 (schematic) illustrates the complete observational and theoretical pipeline: from nuclear structure experiments (PREX-II, CREX, J-PARC hypernuclear measurements) through neutron star structure observations (NICER, X-ray timing) through binary inspiral gravitational waves (GW170817 tidal deformability) through postmerger gravitational waves (ET/CE future) and through kilonova spectroscopy (JWST, ELT). Each arrow in this pipeline represents both an observational constraint and a theoretical extrapolation, with uncertainties that accumulate from the nuclear force model through the many-body calculation to the macroscopic stellar observable. The reduction of these accumulated uncertainties requires simultaneous progress on all fronts.

The PREX-CREX tension identified in Paper I — which cannot be resolved by any current nuclear energy density functional — propagates uncertainties into the neutron star radius predictions that are detectable even at the level of postmerger gravitational-wave frequencies: a difference of  $\Delta L \sim 60$  MeV between PREX-II and CREX-preferred models translates to a  $\Delta R_{1.4} \sim 1-2$  km and  $\Delta f_2 \sim 100-200$  Hz, potentially measurable with ET-CE for nearby events. Resolving the PREX-CREX tension is therefore not merely a nuclear structure issue but a prerequisite for accurate EoS inference from next-generation postmerger observations.

The kilonova r-process element identification program, still in its infancy with only AT2017gfo observed spectroscopically, will expand dramatically with ET-CE localization of dozens of nearby events per year to within  $0.1$  deg<sup>2</sup>. JWST spectroscopy of nearby kilonova counterparts will extend element identification beyond strontium and the first-generation lanthanides to the actinide region (thorium, uranium), providing direct constraints on the r-process neutron flux and freeze-out neutron density — quantities that depend sensitively on the  $Y_e$  distribution of the merger ejecta, which is itself EoS-dependent. The emerging program of coordinated nuclear mass measurements at FRIB, HIE-ISOLDE, and RIKEN for the key neutron-rich isotopes along the r-process path will progressively sharpen these interpretive tools.

## 9. CONCLUSIONS

This paper has presented a comprehensive review of the multimessenger signatures of binary neutron star mergers, integrating postmerger gravitational-wave physics, kilonova emission, and r-process nucleosynthesis within the broader program of nuclear EoS determination initiated in our preceding two papers. The principal conclusions are as follows:

1. The postmerger gravitational-wave spectrum, dominated by the  $f_2$  oscillation mode of the hypermassive remnant at 2.5–3.5 kHz, encodes the EoS at  $(2\text{--}4)\rho_0$  through quasi-universal relations. Secondary modes and the long-ringdown signal extend EoS sensitivity to even higher densities. These signals are beyond current LIGO/Virgo sensitivity and require third-generation detectors.
2. Strong magnetic fields ( $B \sim 10^{14}\text{--}10^{15}$  G), amplified during merger by the Kelvin-Helmholtz and magnetorotational instabilities, can shift the dominant postmerger frequency by up to  $\sim 200$  Hz, masking or mimicking EoS effects. Accurate postmerger EoS inference with ET/CE requires incorporating magnetic field models in waveform analysis pipelines.
3. AT2017gfo remains the sole spectroscopically observed kilonova, with strontium ( $Z=38$ ) firmly identified and lanthanum/cerium ( $Z=57\text{--}58$ ) tentatively detected. Tellurium ( $Z=52$ ) was identified by JWST in a kilonova associated with GRB 230307A, representing the heaviest confirmed r-process element detection in a kilonova spectrum.
4. Kilonova light curves and spectra carry indirect EoS information through the EoS's influence on ejecta mass, geometry, and electron fraction  $Y_e$ . Radiative transfer simulations with realistic 3D ejecta structures and calibrated atomic data reproduce AT2017gfo spectral evolution for moderately stiff EoS models ( $R_{1.4} \approx 12$  km), providing a new EoS constraint independent of gravitational-wave measurements.
5. The Einstein Telescope and Cosmic Explorer, expected to detect  $O(10^5)$  BNS mergers per year from 2035 onward, will enable precision postmerger spectroscopy, phase-transition detection through postmerger frequency jumps, sub-1% Hubble constant measurement, and cosmic r-process enrichment history reconstruction across  $z = 0\text{--}2$ .
6. A convergent program combining next-generation gravitational-wave detectors, JWST and ELT kilonova spectroscopy, J-PARC and FRIB nuclear data, and NICER X-ray timing will, within 10–15 years, map the nuclear EoS as a continuous function of density from  $0.5\rho_0$  to  $5\rho_0$  at the level of precision currently achieved only for symmetric nuclear matter at saturation.

This three-paper series has traced the problem of dense nuclear matter from its most precisely measurable properties near saturation — the symmetry energy and neutron skin thickness — through the unknown exotic-matter regime of neutron star cores, and finally to the rich observational aftermath of binary neutron star mergers, where the EoS is written in gravitational waves, visible light, and the heavy elements woven into the chemistry of the galaxy. The field stands at a genuinely transformative juncture, and the coming decade of multimessenger nuclear astrophysics will determine whether we can finally read the nuclear force in the stars.

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## BIOGRAPHY

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