MOUNT HOLYOKE COLLEGE

An Analytical Model of Neutron Star Merger R-Process Enrichment in Reticulum II

by

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Abstract

The source of rapid neutron capture process (r-process) enrichment in galaxies is a highly debated topic. The r-process is responsible for creating heavy metals such as gold, europium, and uranium in extremely neutron dense environments. While neutron star mergers (NSM) remain the only observed astronomical site of the r-process, the timescale, frequency, and retention of r-process created by NSMs are uncertain. In this work, we model an r-process enriched ultra faint dwarf galaxy known as Reticulum II. Reticulum II formed in the very early universe and its stars are fossils of early chemical evolution. Its unique r-process enrichment (72% of the stars) compared to other ultra faint dwarf galaxies can tell us whether NSMs are the sole source of r-process enrichment in the universe. We create an analytical model with star formation histories based on Simon et al. 2023 and NSM delay time distributions from current literature. Assuming fiducial values for the minimum delay time ($\alpha = -1.83$ and minimum delay time of 184 Myr), occurrence rate of neutron star binaries (1 NSM per 70,000 $M_\odot$), and current stellar mass (≈ 3300 $M_\odot$), we find that the probability of NSMs being the source of r-process enrichment of Reticulum II is statistically improbable. For our fiducial values, we get a 0.7% likelihood that NSMs are responsible for the enrichment of Ret II's stars. We conclude that an alternative source of the r-process is needed, such as collapsars.

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My roommates are not physicists or astronomers, but they all came to my Senior Symposium presentation. Irene, thank you for helping me proofread my thesis and listening to my practice. Madeline and Piper, always made me laugh about their wacky DnD shenanigans of the week no matter how stressed I was. They dragged me out to events to have fun when I needed it most. I am very grateful to have had all of you this year.

Neither physics nor astronomy is a monolith, and none of us make it to the finish line alone. There are probably a dozen more people I could list in the Physics and Astronomy Department who have shaped me and my research over the years. To everyone, thank you.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Many of the heaviest elements in the Universe, such as gold, platinum, uranium, and europium, can only be produced through the rapid neutron capture process, yet the astrophysical sites responsible for this nucleosynthesis remain an open question. In 2017, the combined detection of gravitational waves and electromagnetic radiation from the neutron star merger (NSM) GW170817 provided the first direct confirmation that NSMs are a source of rapid neutron capture (r-)process enrichment in galaxies. However, there are many concerns about whether NSMs are the only source of r-process material, especially in the early universe. In this work we analyze NSM enrichment of ultra faint dwarf galaxies (UFDs). As an early snapshot of the universe, low metallicity UFDs are the perfect site to investigate NSM r-process enrichment. They have a short and measurable time span for star formation and do not have overlapping generations of stars to cause additional noise in measurements. One highly enriched UFD known as Reticulum II (Ret II) is the perfect case study. We use an analytical model based on the star formation history Ret II to evaluate the parameters estimated for NSMs to account for the observed levels of enrichment in the galaxy.

The r-process is responsible for roughly half the abundances of all elements heavier than iron. However, the r-process requires an extremely neutron dense environment with a significant amount of energy. NSMs are one of the few astronomical sites where these conditions occur in the universe. While models of collapsars (collapsing massive stars) suggest the r-process may be possible elsewhere, NSMs are still the only observed site of the r-process. Thus, they are important to study if one wishes to understand the origins of heavy elements.

We know NSMs play a factor in r-process enrichment, but there is concern that they may not be the only source, especially in the early universe when UFDs form stars. A NSM takes time: for the binary stars to be born, live, die, and merge many millions of years later. Adding on top of that, neutron star binaries experience natal kicks that can send them flying out of star forming regions or, in the smallest of galaxies, potentially fully out of the galaxy. This can lead to additional time for the gas to mix and become absorbed in newly forming stars or even fully prevent enrichment from occurring. Collapsars, the leading theoretical source of r-process enrichment, have much shorter timescales and do not experience natal kicks which allows for short enrichment timescales. This work looks to see if collapsars or another one of these theoretical sites of the r-process is required for explaining enrichment in Ret II.

UFDs have one to two rapid bursts of star formation that can be estimated through observations, and their relatively small size means a single NSM could strongly enrich the gas in the galaxy. If a NSM occurs inside of a UFD, it is reasonable to assume all subsequently formed stars will be enriched with r-process material. This allows for a concrete method of timing star formation history and when an r-process event must have occurred in a galaxy's history. Simon et al. 2023 [32] has observed the stars of Ret II and proposes a continuous two burst model of star formation history. They found that 72% of the stars are highly r-process enriched, and this gives a good timeline for when an r-process event must occur. While studies have noted the timeline for an r-process event such as a NSM to appear, none have created a model to test r-process enrichment in galaxies.

In this work, we use the star formation history of Ret II proposed by Simon et al. 2023 [32] to estimate the probability that NSMs are the sole source of r-process enrichment. We create an analytical model to populate a galaxy with binary neutron star systems and apply a merger delay time to each star system before the r-process event enriches the galaxy. New stars forming after this point will be r-process enriched. We examine several parameters that influence the merger and r-process enrichment, including the merger delay time, the abundance of NSMs, and star formation. Because Ret II has approximately 72% of its stars r-process enriched, we investigate how a NSM might occur by 28% of star formation. If NSMs are the sole source of r-process enrichment in the universe and our current understanding of the delay time of neutron star mergers is correct, then we expect to be able to simulate a merger occurring by the time 28% of stars have formed a non-negligible amount of the time. Otherwise, our results will imply that an alternative source of the r-process is needed.

In chapter 2, we provide a detailed background on the r-process, neutron star mergers, and ultra faint dwarf galaxies. Chapter 3 focuses on defining the model parameters and characterizing both the star formation histories and NSM delay time distributions. In chapter 4, the results of the best fit and the varied star formation models are presented and discussed in relation to previous works. Finally, we summarize our conclusions and suggest future studies in chapter 5.

Chapter 2

Background

2.1 Galactic Chemical Evolution and R-process

The chemical evolution of galaxies describes origin and dispersal of all naturally occurring elements. The universe's most abundant elements were created in the Big Bang or in stellar cores, but not all elements are so readily produced. About half of the heaviest chemical elements (atomic mass number A > 69 [12, 35]) require extreme circumstances to form via the rapid neutron capture process, also known as the r-process [11]. These elements include gold, europium, and uranium among others. Because many of these elements are essential to modern life and explaining the complete chemical evolution of the Milky Way and universe, understanding the mechanisms of the r-process and where it occurs are important.

Hydrogen and helium were created during the Big Bang and remain by far the most abundant elements in both mass and number. Small traces of lithium were also synthesized before the Universe cooled beyond the threshold for further nucleosynthesis. The very first stars contained only these three elements. Elements up to iron are produced in the cores of massive stars through nuclear fusion, and when these stars die, their elements are dispersed into the surrounding gas, eventually becoming incorporated into new stars. A star like the Sun, for example, contains traces of iron, oxygen, nitrogen, and other elements because it was born after the supernovae of earlier massive stars. Different types of supernovae produce distinct chemical yields, meaning if we observe a star's chemical makeup, we can estimate what processes resulted in its composition.

To explore the formation of elements heavier than iron (A>69), we must consider neutron capture processes, in which atomic nuclei absorb free neutrons and build up to heavier masses. There are two primary variants: the slow neutron-capture process (s-process) and the rapid neutron-capture process (r-process). Both produce heavy elements, but the r-process operates on much shorter timescales, allowing nuclei to capture many neutrons before decaying. This results in distinct abundance peaks that distinguish it from elements that formed through the s-process [14]. Figure 2.1 shows which elements and isotopes form primarily through stellar burning, the s-process, and the r-process. When observing a star's spectrum, comparing the ratios of europium (Eu) to iron (Fe) helps inform astronomers which process was responsible for heavy metal enrichment [14]. Observations of many Milky Way stars and nearby galaxies have confirmed that the r-process is responsible for a significant fraction of these observed elemental abundances, making the identification of the astronomical sites of the r-process important.

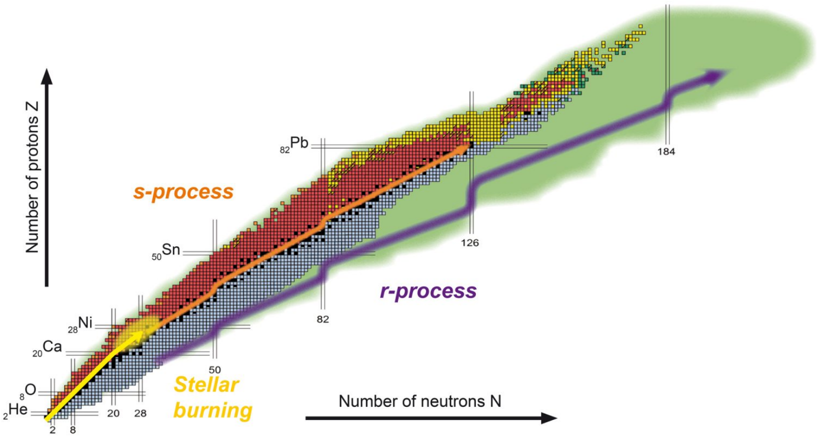

FIGURE 2.1: The astronomical origins of chemical elements. Stellar burning (yellow) accounts for lighter elements up to iron. The s-process (orange and red) accounts for lighter mass nuclei, and the r-process (purple and blue) rounds out the heaviest elements up to uranium. credit: EMMI, GSI/Different Arts

In a dense neutron environment ($\sim 10^{20}$ cm^{-3}; [15, 36, 2]), the atomic nucleus is bombarded with neutrons at a rate faster than β decay can proceed. This allows nuclei to grow to significantly larger stable masses. β decay transforms a neutron into a proton and increases the atomic number, so when β decay cannot occur quickly during the r-process, the atomic mass (number of protons and neutrons) grows without changing the atomic element. Neutron stars, composed of neutrons and some of the densest objects in the Universe, are one of the only places where the necessary neutron density occurs. Neutron stars are expanded on in subsection 2.1.1.

Depending on the neutron density, different mass atomic nuclei are produced. A core signature of the r-process is the three abundance peaks, atomic mass number A $\sim$ 82, 130, 195 [16, 23]. The strength of these peaks depends on the density of the neutron rich environment where r-process is occurring. For neutron density ρ (g cm^{-3}), $10^9 < \rho < 6 \times 10^{10}$, the r-process is minimal, producing some elements of atomic number N = 50 nuclei with $80 < A < 86$. At higher densities, N = 82 nuclei with $120 < A < 128$ for $6 \times 10^{10} < \rho < 3 \times 10^{11}$. A robust r-process with A = 195 and the typical abundances observed in the r-process can only take place in environments where the number density is at least 10^{20}cm^{-3} [2, 15, 36]. When the spectra of a star is observed, astronomers can identify r-process enrichment by measuring these three element abundance peaks. Figure 2.2 highlights these peaks for observations from our Sun.

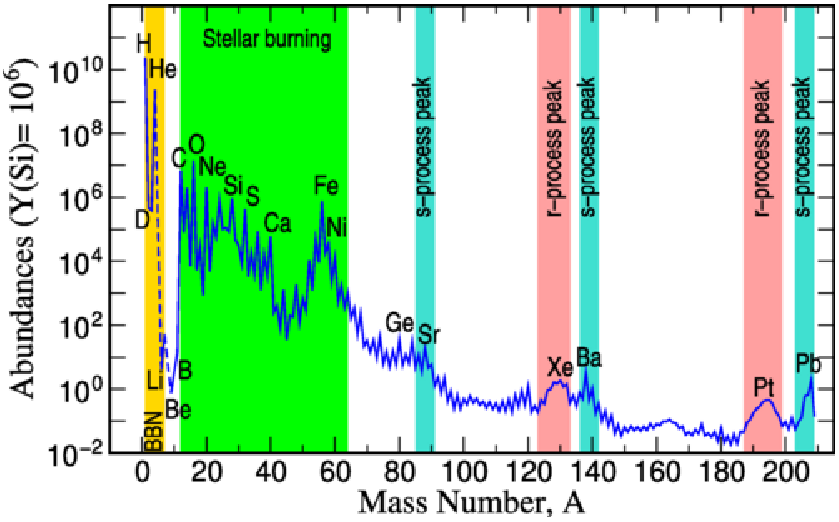

FIGURE 2.2: The r-process (red) and s-process (blue) peaks for different chemical abundances and mass fractions in the solar system. The two later r-process peaks are highlighted at 130 A and 195 A. Cowan et al. 2011 Fig 1. [14]

Observations and models confirm the r-process is responsible for the formation of many of the heaviest elements. In the next subsections we will discuss confirmed and theoretical sites of the r-process.

2.1.1 Binary Neutron Stars

Neutron stars are the remains of dead stars with masses above 1.44 $M_\odot$ and radii of about 10 km [28]. The progenitor star begins with a mass between 8 $M_\odot$ and $\sim$ 18 $M_\odot$ [3, 39], and upon death, the outer layers of the star are blown away in the supernovae leaving only the dense stellar core. Neutron stars have enough density to overcome the electron degeneracy pressure and the Chandrasekhar limit, but they do not have enough mass and density to collapse into a black hole. Only neutron degeneracy pressure prevents their total collapse, and the upper estimate for neutron star mass is 3 $M_\odot$ [7] before the neutron star becomes a black hole. Neutron degeneracy pressure prevents this collapse as neutrons do not want to occupy the same quantum state, and even more gravitational energy is required to create a black hole. This pressure is all that keeps a neutron star 'alive.' Of course neutron stars are not actually alive as they no longer undergo fusion. Because neutron stars exist in such an extreme state, the internal mechanics and our understanding of physics cannot yet explain everything that happens inside a neutron star. We can observe them, often as rapidly rotating pulsars, and model their formation, but neutron stars are elusive to astronomers.

On their own, neutron stars do not produce r-process elements, as their neutron-rich material remains gravitationally bound and is not ejected into the surrounding environment. Binary neutron stars (BNS) merging or a neutron star and a black hole merging are necessary for a neutron star to produce the r-process [2]. Binary stars are two stars bound together gravitationally in a system, and over millions of years, they come together. Once two neutron stars have gotten close enough to merge, there are a few steps to the process. First, the tidal forces begin to decompress and strip matter away from the neutron stars. Cold neutron rich material is ejected, and the r-process may occur. Next, a central mass—either a massive neutron star or a black hole—forms with a hot disk of matter around it. Finally, the energy of the merger is released into relativistic jets that are visible to us as gamma ray bursts [2]. This merging event is known as a kilonova, a smaller version of a supernova.

In 2017, NSMs were confirmed as a site of the r-process following the multi-messenger observation of GW170817 [1]. The merger was first detected by LIGO, and complementary observations of the gamma ray burst and kilonova formed a multi-messenger detection. The LIGO observations of gravitational waves confirmed the masses of the two neutron stars while the electromagnetic observations revealed signatures of r-process nucleosynthesis in the merger ejecta. In particular, the prolonged infrared emission from the kilonova indicated the presence of lanthanide-rich, radioactive r-process material, consistent with theoretical predictions [37]. GW170817 was critical in finding the first instance of an astronomical site of the r-process, and the characterization of its kilonovae has since enabled the identification of candidate kilonovae associated with other compact binary mergers.

However, the process of a neutron star binary forming and merging can take many millions of years. The progenitor stars must first die – using the relation $t \sim M^{-2.5}$ where t is the lifespan and M is the mass in solar masses, a star of $8_{\odot}$ (the minimum mass of a neutron star progenitor) will live approximately 55 million years. Many neutron star progenitors will have shorter lives and the death of the first star can transfer mass and accelerate the second's lifespan, but this can still take many years. Once the stars die and explode as supernovae, a BNS system remains as long as the supernovae did not disrupt the binary.

Once two binary stars have died and formed neutron stars, they must merge to undergo the conditions needed for the r-process to occur. Over millions of years, the two stars are pulled by gravity and spiral in until they merge in a kilonova [34, 40]. This merger delay time is expected to take at least 184 Myr [40], but this minimum time is extremely uncertain; literature values range from 10 Myr [34] to 500 Myr [33]. The delay time is a concern for ultra-faint dwarf galaxies (e.g., Ret II) which formed all their stars early in the Universe's history.

Merger delay times are not the only potential issue with NSMs being the only source of r-process enrichment. NSMs do not often occur in star forming regions either because the galaxy has been quenched (no longer forming stars) [1] or because the system traveled outside of star forming regions [24]. The supernovae that form neutron stars from their progenitors are asymmetric and can launch the system at high velocities (~ 180 km s^{-1} [27]). Natal kicks, as they are called, can eject a BNS system from their host galaxy, and in many instances, the observations of kilonovae occur outside their host galaxies [24]. Additional time beyond the merger delay needs to be considered for enrichment timescales.

When discussing the abundance and frequency of BNSs, we pull from the probability of a certain mass of star forming from a given cloud of gas. Initial mass functions characterize the probability distribution functions of star formation by stellar mass with more low-mass stars forming than high mass stars. A BNS can be estimated to occur at an abundance rate of 7×10^{-4} BNSs per stellar mass as estimated from the Kroupa initial mass function (Figure 3.2) and the ratio of core-collapse supernovae to LIGO-Virgo's NSM rate [8, 19]. This low occurrence rate matches with observations of ultra-faint dwarf galaxies as they predominantly have no r-process enrichment. Ret II is the only known UFD with a high level of r-process enrichment out of approximately 10 UFDs [18].

The exact amount of r-process metals produced by a NSM is debated, but estimates range from 10^{-4} $M_\odot$ to 0.1 $M_\odot$ [13]. Most estimates of the total ejecta mass from observations and models are between 0.01 - 0.05 $M_\odot$ [12, 25]. This aligns with observations of galaxies where a single r-process event is estimated to have occurred [18]. For a small UFD, this amount of yield per event would be enough to strongly enrich all the remaining stars.

2.1.2 Alternative Sources

While NSMs are the only confirmed source of the r-process, several other sources have been proposed. Core-collapse supernovae (CCSNe) are the most likely alternative candidate, but proposals of neutrino winds, high energy jets, and white dwarf – neutron star mergers have also be raised [12, 37, 35]. As regular CCSNe are too common and would result in an over-abundance of r-process enrichment, candidate CCSN sources are rarer subtypes, such as magneto-rotational supernovae or collapsars [8, 29, 37]. A collapsar is a rare type of CCSN where a black hole and an accretion disk form ($M_{\text{stellar}} \geq 25 M_\odot$ [21]). The r-process could occur on these accretion disks; however, observations of CCSNe thus far have yielded null results despite close observations [6, 26].

A collapsars forms from a very massive star ($M > 25$ $M_\odot$) with a very short lifetime, and as the star dies, it collapses into a black hole with jets and an accretion disk where the r-process could potentially occur. As a result, they have no additional merger delay time and occur in regions that are still forming stars, so most younger stars will become r-process enriched. In an instance where stars form rapidly and are r-process enriched, collapsars are a potential alternative to NSMs.

When comparing NSMs to these alternative sources, the yield of an r-process event is important to consider. NSMs are considered high-yield or prolific and produce a lot of the heavy elements. Some of the other proposed sites, such as white dwarf-neutron star mergers, are not expected to produce as much r-process [12, 32]. When comparing which sources may be the origin of elements, understanding which result in higher abundances is important.

2.2 Ultra Faint Dwarf Galaxies

Ultra faint dwarf galaxies (UFD) are very faint dwarf galaxies ($M_\star \sim 10^5 M_\odot$) that formed in the early universe before reionization. Reionization is the process where the stellar wind from the first stars in the universe ionized the gas clouds in their galaxies. Ionized gas clouds have more kinetic energy, so the clouds are less able to collapse and form new stars [38]. UFDs are too small and do not have enough mass or gravitational potential energy to continue star formation after reionization, so their stars are preserved from the beginning of the universe [30]. Larger galaxies such as the Milky Way have multiple generations of stars overlapping, but UFDs are important to study in regards to chemical evolution because all stars formed in a similar time span and generation.

Because of their faint nature, only recent surveys such as the Sloan Digital Sky Survey are able to detect UFDs [31]. These galaxies are satellites of the Milky Way, and many reside in the galaxy's halo. Globular clusters, despite also being low luminosity satellites of the Milky Way, are distinct from UFDs as UFDs contain a dark matter halo, a defining trait of galaxies. Some examples of UFDs include Bootes I, Canes Venatici II, and Leo IV [10]. As a whole, their stars have low metallicity and few traces of heavier metals, and these factors make them fossils of the early universe and first star formation. Metallicity is defined as the abundance of all elements heavier than helium, most notably iron. Because few supernovae have happened before the birth of the stars of these UFDs, they are very metal poor.

The largest stars of the UFDs died in the early universe after they burned through their fuel, so only the smaller stars remain for us to study. However, even these remaining stars can tell astronomers bounds of information about both the early Universe and chemical evolution.

2.2.1 Bursty Star Formation

UFDs are known for bursty star formation and often well modeled with one to two bursts new stars [9, 32]. Unlike continuous star formation, a bursty star formation is when the stars form roughly all at once before the gas is used up from a cloud. Dwarf galaxies are more prone to bursty star formation than massive galaxies due to the smaller gravitational potential. The greater kinetic energy of ionized gas can quench further star formation after a burst. UFDs, as smaller dwarfs, are more prone to bursts than moderately sized dwarf galaxies. These bursts often are separated by 10 to 100 Myr [18]. Past works have modeled UFD star formation with two bursts [10, 20, 32].

Models show that supernovae feedback in dwarf galaxies is a cause of burstyness [41], and a full hydrodynamic simulation of NSM enrichment of galaxies should incorporate supernovae and kilonavae feedback. However, for computational simplicity, we use an analytical model without a relation to feedback. Observations of varying stellar metallicities can tell us when a burst may have happened, but the model used in this paper does not account for when these bursts related to the galaxy's supernovae activity.

2.2.2 Reticulum II

Ret II is a satellite UFD of the Milky Way discovered by the Dark Energy Survey in 2014 [4], and is one of the closest to the Milky Way at a distance of 32 kpc [30]. It has a total halo mass of $\sim 5.6 \times 10^5$ $\mathrm{M}_\odot$ [30] and $\mathrm{M}_{\mathrm{stellar}} \approx 3300\mathrm{M}_\odot$ [22], and like most UFDs, its stars formed in the very beginning of the universe about 13 Gyr ago. Its stars are very metal poor ($-3 >$[Fe/H] > -2 [20, 30]) like other UFDs, which indicates that its star formation was within the first generations of star formation before reionization.

There is some evidence that 15% - 20% of the stars may have formed later [17, 32], but this has not been confirmed. For the purposes of this study, a small proportion of later star formation is not expected to impact our exploration of the NSM r-process timing.

The image of Ret II demonstrates why UFDs are difficult to detect and why only recent observations have made their discovery possible. At first glance, Ret II does

Figure 2.3: This image of Ret II from the dark energy survey shows all the stars seen by the telescope on the left and only the stars from the galaxy on the right. Credits to Dark Energy Survey/Fermilab.

not appear to look like a typical galaxy with colorful dust and spirals. In order to identify galaxy membership in Ret II, stars must be observed for several years to measure proper motion, and the estimate for number stars has grown slightly. Ret II has a slightly elongated shape, but there is not much evidence of stripping by the Milky Way's gravity. Stripping describes how a smaller galaxy is torn apart by the gravity of a larger galaxy, so if Ret II does not have evidence of stripping, the measured mass of the galaxy is what originally formed.

This dwarf galaxy is unique among UFDs for its highly r-process enriched stars. In Ret II, between 72% to 78% of stars are highly r-process enriched [18, 32], so it is an ideal UFD to investigate for r-process enrichment. The enrichment level of these stars is approximately 1000 times too high to be explained by surface accretion of r-process elements after the stars formed [18]. Additionally, all the stars with r-process elements show similar degrees of enrichment, and this indicates a singular event that uniformly impacted the galaxy [18]. Because UFDs such as Ret II are so small compared to other galaxy types, a NSM will diffuse the r-process elements throughout the galaxy on a relatively short timescale.

The metallicity differences of the stars in the galaxy can be used to estimate the timeline of star formation which provides limits on when a NSM or other r-process even must have begun by. Metallicity of elements such as iron and oxygen are different from r-process elements and have a known timescale. This means stars with spectra from Ret II can be roughly dated [18]. The details of Ret II's star formation are discussed in section 3.1.

Chapter 3

Methods

As NSMs and enrichment takes millions of years, we rely on models rather than observation to predict the likelihood of r-process enrichment from NSMs in Ret II. For this, we use a Python Notebook through the Harvard FASRC Cannon Cluster.

3.1 Star Formation History of Reticulum II

In this paper, we build an analytical model for the star formation of Ret II based on the results of Simon et al. 2023 [32]. This paper uses both a best fit model of Ret II's star formation and a model of more continuous bursts in order to estimate the probability of Ret II being enriched by a NSM. An analytical model has the advantages of being faster than simulations and being easy to adjust to fit new star formation history models.

Approximately 72% of Ret II's stars are r-process enriched, so a NSM must occur before 28% of the stars have formed to prove that NSMs are the sole astrophysical site of r-process enrichment. As a result, our model focuses more on the timing of t_{28} when 28% of star formation has finished. NSMs that happen before this time are called fast NSMs. A fast NSM produces r-process material that can enrich star forming clouds that will account for the remaining 72% of Ret II's stars. Star formation ends at ~ 5 Gyr, so we also track the number of NSMs before and after star formation has ended. The NSMs after all star formation is quenched are late NSMs.

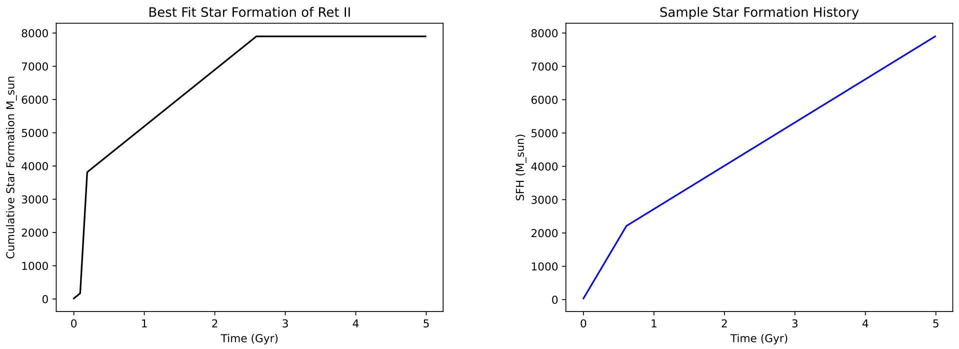

FIGURE 3.1: The best fit cumulative star formation history (left) and a varying star formation history with $t_{28} = 0.62$ Gyr (right). Based on the data of Simon et al 2023 [32].

Simon et al. 2023 [32] observed the metallicities of the stars in Ret II to estimate the bursts of star formation. While their initial model used a two burst approximation, they found that continuous bursts fit better. A continuous burst would physically represent several smaller bursts in rapid succession. The researchers estimate that Ret II finished 28% of its star formation at 500 ± 200 Myr. The best fit model consists of two overlapping bursts of star formation: 56% of star formation over 2.6 Gyr and a burst of 44% of star formation beginning 0.1 Gyr after the star of the first burst and lasting 0.1 Gyr [32].

For our model, we test both the best fit continuous model and the varying t_{28} model. Continuous bursts allow us to have higher time resolution (0.01 Gyr with continuous bursts as opposed to 0.1 Gyr with discrete bursts). We use a gaussian distribution to capture the time of 28% star formation t_{28} for the varying model.

We construct our varied star formation by first picking a random t_{28} from the time array. We then build our model so that the star formation percents between $t = 0$ and t_{28} between t_{28} and t_{end} are smooth. Star formation is not smooth and in UFDs; it is full of bursts, but the number of simulations run makes individual slope variations in the star formation rates insignificant. When tested, the results with and without a standard deviation in the star formation at each time step performed similarly over many runs.

Our model begins the time of events at the beginning of star formation in Ret II as to be independent of cosmologies. Because we are only modeling a single galaxy's evolution over a known time period, the age relative to the universe or a particular cosmology does not play a key role and has been set aside. If the estimated age of Ret II is adjusted, our results will still hold true.

3.2 Adding in NSMs

Our given rate of BNS per stellar mass requires a mass formed per unit time to resolve. As the star formation rates are in percentages, we must convert the rates into units of solar masses. The current estimated stellar mass of Ret II is $\approx$ 3300 $M_\odot$ [22]. If the majority of Ret II's stars formed in a burst 13 Gyr ago, using the relationship $t \approx M^{2.5}$, where t is the lifespan of the star and M is the stellar mass, tells us that stars more massive than $\sim$ 0.8 $M_\odot$ will have died. Based on the Kroupa Initial Mass Function and Ret II's current mass of $\sim$ 3300 $M_\odot$, we calculate that the total stellar mass of Ret II is 7900 $M_\odot$ [19, 22]. The star formation is scaled to this value.

We derive the rate of BNS systems per stellar mass based on the Kroupa initial mass function [19] and the ratio of CCSNe to NSMs. Stars greater than 8 $M_\odot$ die as CCSNe, and this accounts for about 0.34% of stars. The ratio of CCSNe to NSMs is derived in Brauer et al [8] to be 4.5×10^{-3} based on LIGO and VIRGO data. This results in an estimated rate of 1 BNS per 7×10^4 $M_\odot$.

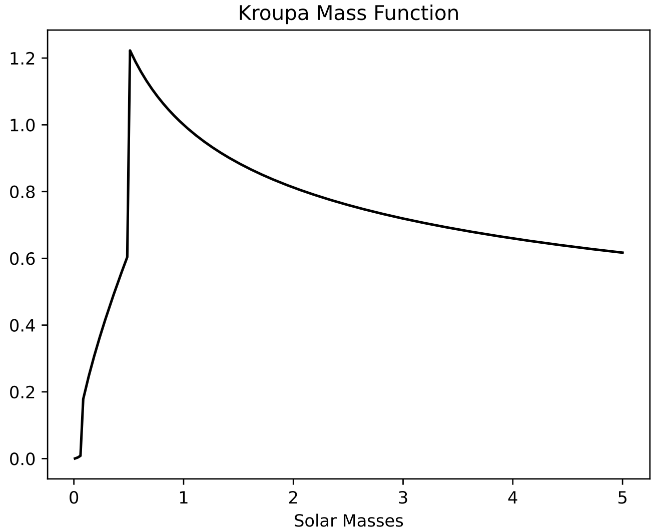

FIGURE 3.2: The Kroupa initial mass function (IMF) [19] over the range 0.5 $M_\odot$ to 5 $M_\odot$. This plots the probability density function of star formation across different masses.

3.3 Delay Time Distribution

One of the main factors differentiating NSMs as a source of r-process from their alternatives is the delay time. Other sources are quick on cosmological timescales, some only taking a few million years at most. NSMs are different because both stars must die and spiral inward before a merger event happens. Depending on the BNS system formation, this will take a variable amount of time rather than a fixed delay after the system forms. As a result, we use a delay time distribution (DTD) to model merger times.

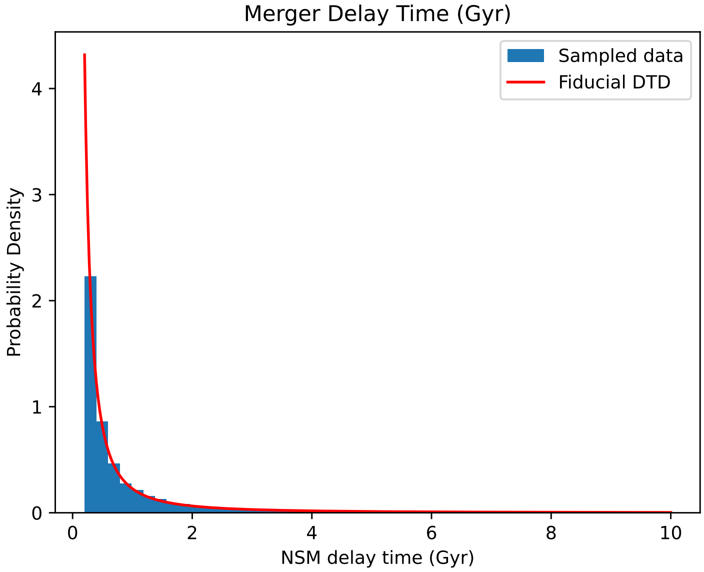

Figure 3.3: A plot of the delay time distribution (DTD) of NSM times using the fiducial values $\alpha = -1.83$ and $t_{\text{min}} = 184$ Myr. The function used is a power law distribution of the form $t^{-\alpha}$. The function is plotted in red while the samples drawn from the DTD are shown in the blue histogram.

For this work, we primarily use the DTD described by Zevin et al. 2022 [40]. The equation characterizing the DTD is $t^{-\alpha}$. With this, the power law distribution is parameterized by three variables: the power law slope α, the minimum delay time t_{min}, and the maximum delay time t_{max}. An ideal DTD extends to infinity, but a power law probability distribution requires bounds, so in this study, we fix the maximum time at 10,000 Myr. Both α and t_{min} are varied in this study.

Our fiducial value of t_{min} is 184 Myr with an α of -1.83 [40]. The plot of this distribution function is shown in Figure 3.3. Other values that were tested for t_{min} are 10, 50, 100, 200, 300, and 500 Myr. Early papers on NSM r-process enrichment

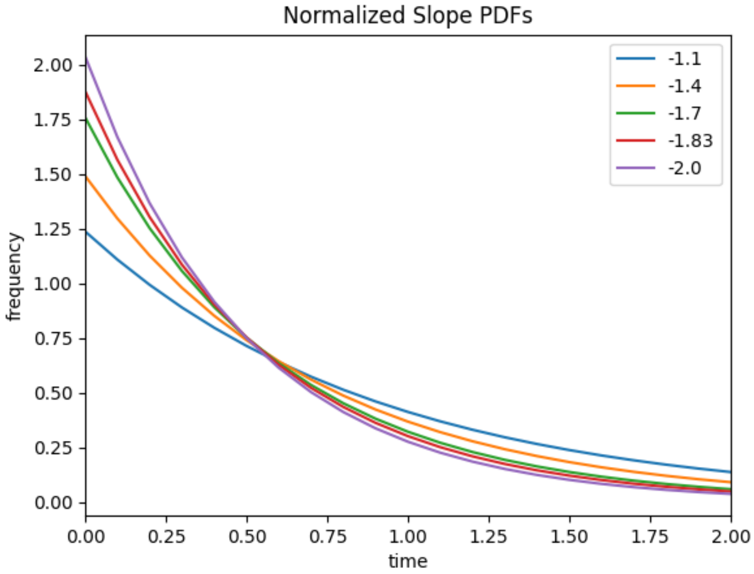

FIGURE 3.4: An example of different values of for α in a normalized power law probability distribution function and how changing the slope impacts the DTD.

favored shorter time delays, but the minimum delay time has risen in more recent years. We explore the full range of delay times proposed. The slope α ranges across -1.1, -1.4, -1.7, -1.83, and -2.0. Figure 3.4 demonstrates the values of α and how more negative values favor quicker merger delay times. We expect more negative αs and shorter delay times to produce more fast NSMs.

3.4 Putting it all together

For each test of DTD parameters, we ran the model 100,000 times to get a value of statistical significance. Because of the short range of t_{28} in the best fit star formation, not all minimum delay times were possible. We only tested values of the delay time that occurred within 150 Myr (10, 50, 100 Myr). For the varied star formation rates, we tested all values of t_{min}.

We separated NSMs that occurred before t_{28} and counted these against the number of systems that contained at least one NSM and against the total number of iterations. NSMs that would have occurred after 5 Gyr and the end of our time array were also separated. These NSMs are possible, but they would not enrich any stars. We report results on the chances that a NSM occurred by the time

28% of star formation finished for the ideal star formation rate and the varied star formation rates for all stated variations of the DTD.

Chapter 4

Results and Analysis

4.1 Chances of a NSM

With our estimated total mass of Ret II at 7900 $M_\odot$ and rate of NSMs at 1 per 7×10^4 $M_\odot$, we expected about 11% of the systems to produce at least one NSM. Our results indicated the expected values, about 10.4% of the Ret II systems had at least one NSM. Several systems experienced more than one NSM. For the purposes of this study, we cared about the timing of the NSM more than the number of NSMs, so we did not track which systems had more than one NSM or their relationship within a system. The likelihood of more than one NSM for Ret II's mass is roughly 1% and the even r-process enrichment does not indicate multiple events.

Ji et. al 2016 [18] looked at 9 other UFDs with zero r-process enrichment. This gives observational evidence that a high-yield r-process event is roughly 1/10, aligning well with the probability of a NSM in Ret II. However, additional observations of newly identified UFDs may alter this accuracy. We estimate a the probability of two NSMs or high yield r-process events in Ret II at a 1% chance [18]. We cannot observe versions of Ret II that did not have r-process enrichment, so comparing it to other UFDs is our only option. Our results for the probability of a BNS per stellar mass align with these observations. However, this does not yet cover the timing of a merger within the star formation history.

4.2 Best Fit Star Formation

In this model, the early star formation occurs very quickly as shown in Figure 3.1, making it difficult to populate a galaxy with NSM before t_{28}. The time t_{28} is 150 Myr. Given that the fiducial minimum delay time is not possible with this star formation history, our best estimate for the number of NSMs per 100,000 galaxies is 14 or 0.014% ($t_{\min} = 100$ Myr, $\alpha = -1.83$). This extremely unlikely and not statistically significant even if the enrichment is possible.

We find that NSM enrichment timescales are possible for $t_{\min} = 10$ Myr and $\alpha \leq -1.83$. This is a very short delay time and would require the neutron stars to die and merge quickly. Larger stars that become neutron stars rather than black holes can die well within 10 Myr, but they BNS system configuration would determine the full merger delay time. For other values of α and $t_{\min}$ on the best fit star formation, the values of NSMs before t_{28} were not significant as shown in Table 4.1.

$t_{\min}$ α	-1.1	-1.4	-1.7	-1.83	-2.0
10	0.416	0.679	0.911	1.058	1.159
50	0.025	0.033	0.066	0.083	0.093
100	0.006	0.001	0.009	0.014	0.013

TABLE 4.1: Results of % Fast NSM for Best Fit Star Formation in relation to all systems

The results of the best fit star formation history do not suggest that a NSM was responsible for Ret II's r-process enrichment. The timing of star formation t_{28} is too early for most assumptions of $t_{\min}$ and α to enrich the galaxy. Most recent literature suggests a longer minimum delay time of at least 100 Myr [5, 33, 40]. This is not compatible with the best fit star formation history. For the best fit model, we are forced to reject the idea that a NSM was responsible for r-process enrichment in Ret II.

4.3 Varied Star Formation Histories

We produced a star formation history based on the results of Simon et al. 2023 [32] to populate the model galaxy with BNSs and NSMs. For the varied star formation history model, we used $t_{\min} = 500 \, ^{+}_{-} \, 200$ Myr and smooth star formation rates before and after this time (see Figure 3.1b). In most cases, in order for a NSM to enrich Ret II with r-process, a later t_{28} time, an early formation of a BNS, and a short delay time were all required. In many circumstances, this was possible, but not always.

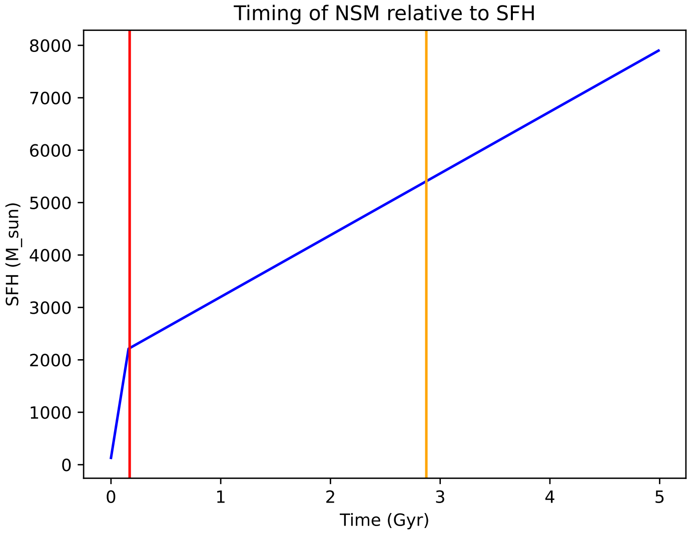

FIGURE 4.1: A sample star formation history (blue) with a late NSM (yellow vertical line). The red vertical line represents the time of 28% of star formation at $t = 170$ Myr in this example.

Figure 4.1 shows an example of when Ret II is enriched by r-process. However, in this sample circumstance, the NSM does not occur fast enough to enrich the required 72% [18] of stars with r-process. The early star formation is rapid and does not leave enough time for the BNS to merge earlier. In contrast, Figure 4.2 shows a NSM that occurs before 28% of star formation. These two example figures are a result of the same fiducial values for the DTD and represent how variation in the model can arise.

First, we will go over the results of our fiducial DTD values ($\alpha = -1.83$ and $t_{\mathrm{min}} = 184$ Myr) before summarizing our other results. For our fiducial DTD in the varying star formation history, we found 687 fast NSMs before t_{28}, a result of 0.69%. This result indicates that it is unlikely a NSM was responsible for the enrichment of Ret II. With such low rates of NSMs, we favor other theorized r-process sources as the enrichment source in Ret II. It is not impossible for a NSM to be responsible for Ret II's enrichment, but the probability is very low for the fiducial DTD.

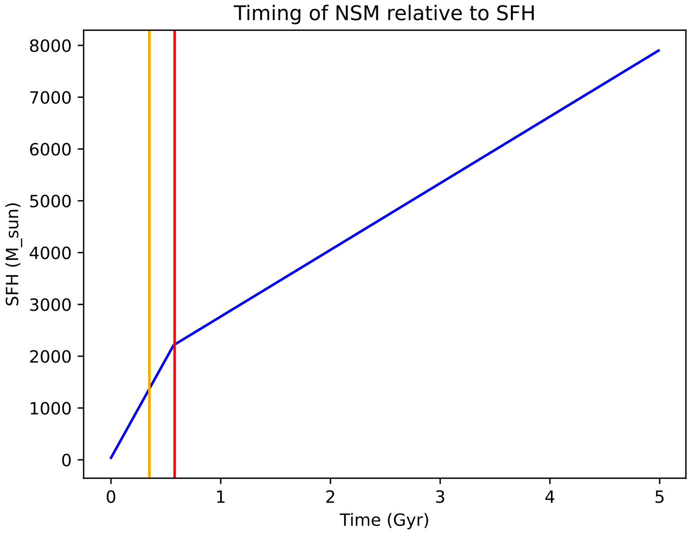

FIGURE 4.2: A sample star formation history (blue) with an early NSM (yellow vertical line, $t = 350$ Myr). The red vertical line represents the time of 28% of star formation at $t = 580$ Myr in this example.

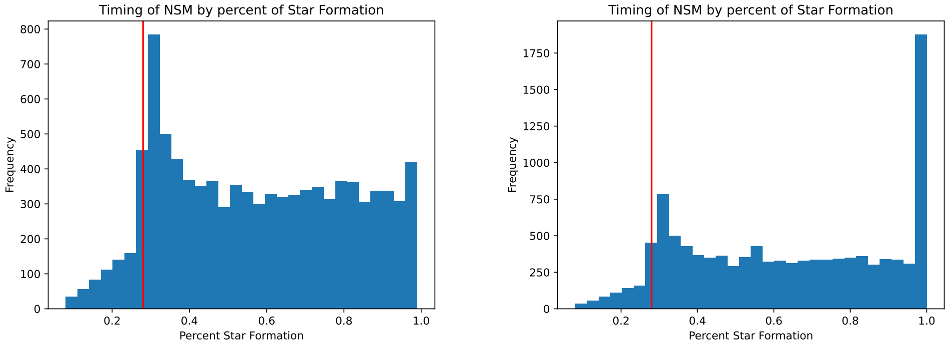

FIGURE 4.3: Histograms of the timing of NSMs based on percent of star formation for the varying t_{28} and fiducial DTD. Left: excluding late NSMs after star formation finishes; right: including late NSMs.
The x-axis shows the percentage of star formation passed when a NSM occurred. The red line represents t_{28}, and we can see that most NSMs are happening after this percent of star formation.

Figure 4.3 shows where in the star formation history for the fiducial model we expect NSMs to fall. Approximately 13.5% of NSMs occurred after all star formation had finished; these are the late NSMs. The results of these plots show how long it typically takes a NSM to form in Ret II's star formation, and very few of those points exist before the 28% marked in red. More occur slightly after the 28% mark, which could be an artifact of the slopes used in the model being more gradual after t_{28} or a sign that NSMs cannot occur fast enough. For this research, the timing before t_{28} has the most scientific value, and that is not reaching high enough significance.

$t_{\min}$ α	-1.1	-1.4	-1.7	-1.83	-2.0
10	1.471	2.112	2.396	2.505	2.708
50	0.835	1.321	1.691	1.786	1.932
100	0.579	0.871	1.134	1.21	1.428
184	0.322	0.467	0.604	0.687	0.744
200	0.257	0.422	0.568	0.618	0.636
300	0.136	0.183	0.251	0.265	0.352
500	0.023	0.027	0.042	0.052	0.05

TABLE 4.2: Results of % Fast NSM for Varying Star Formation

For other values of the DTD, we find that there is significant probability that a NSM can occur in Ret II before t_{28}. Table 4.2 shows the results for all values, and as expected, $\alpha = -2.0$ and $t_{\min} = 10$ Myr had the highest probability of producing a fast NSM at 2.7%. We were unable to get significant probabilities of a fast NSM with a minimum delay time of 184 Myr. If a BNS takes this long to merge as Zevin et al. 2022 [40] suggests, we conclude that an alternative source of the r-process enrichment in Ret II is needed. For our fiducial α, we find that there are significant probabilities for up to 100 Myr minimum delay times. Overall, the minimum delay time has a larger impact on the enrichment probability, but the effect of α should not be neglected. This is discussed in more depth in section 4.4.

Although we included a minimum delay time of 10 Myr, this is very unlikely for the age and geometry of BNSs. A minimum time of 100 - 300 Myr is the most probable [33, 40], and we find that 100 Myr delay times can enrich Ret II with DTD $\alpha < -1.7$. If NSM are the only source of r-process in the universe, we must assume they follow these parameters. However, if NSMs do not adhere to a minimum time of 100 Myr or less, we must conclude that an alternative source of the r-process is required.

4.4 Additional Considerations

This model does not consider the additional need for enriched r-process gas to reach star forming regions. Natal kicks that eject the star system from where it formed and many observed kilonovae are outside their host galaxies [24]. For a smaller UFD, there is the possibility of a BNS being completely ejected from a host galaxy where the r-process material will not return at all.

The longer it takes a BNS to merge, the farther the system has traveled from the core of the galaxy. For shorter delay times, because the system is younger, natal kick velocities will not have moved the BNS system as far from a host galaxy and star forming region. This means that less additional time for r-process enriched gas to reach forming stars is needed. Conversely, longer delay times should account for time to enrich the remaining gas in the galaxy. Nugent et al. 2025 estimates this time for r-process to return to central star forming regions to be 134^{+171}_{-83} Myr.

The high and consistent level of r-process enrichment of Ret II's stars suggests a singular event with a high yield. This is easily explained by a NSM as we have measurements of NSM kilonovae r-process yield. These observations suggest yield of 0.05 $M_\odot$ from NSM is enough to explain Ret II's r-process. If an alternative source is needed, it must produce a similar yield or r-process per event.

There have been several additional attempts to model Ret II's star formation, many with instantaneous (10-100 Myr long) bursts [17, 32]. To get the observed r-process enrichment levels of Ret II, most of these instantaneous burst models are not feasible with NSMs. The star formation in these models happens too rapidly for a NSM to occur. The two star formation models used in this work were the most likely to allow for a NSM to occur by t_{28} and provide evidence that NSMs could be the sole source of r-process enrichment. Because NSMs are unlikely to explain the level of enrichment in Ret II based on the work in this thesis, we also conclude that these alternative star formation histories will support the need for an alternative to NSMs.

Chapter 5

Conclusions

In this work, we explored the r-process enrichment timescales of Ret II from NSMs with two different star formation models and a range of DTD functions for merger delays. The DTD was characterized by a minimum delay time and a slope; our fiducial values were $\alpha = -1.83$ and $t_{\text{min}} = 184$ Myr [40]. Our star formation models included a best fit and a varied star formation based on observations of the metallicities of Ret II's stars [32]. We report the probability of a NSM being the source of Ret II's r-process enrichment based on observations that 72% of the UFD's stars are r-process enriched.

While the r-process enrichment of the galaxy Ret II is feasible with NSMs, our model suggests that alternative sources are likely necessary. With the best fit of star formation history, a merger delay time larger than 100 Myr could not enrich the galaxy more than 1% of the time, and a very short minimum time of 10 Myr and $\alpha = -1.83$ was necessary for enrichment to occur. Both the 100 Myr and the 10 Myr values for the minimum delay time are well below most expectations for the characteristics of a NSM delay.

The varied star formation model, which was characterized by having 28% of star formation at $500\ ^{+}_{-}200$ Myr, produced slightly better results. We found that a minimum time of 100 Myr and $\alpha < -1.4$ were statistically significant. This range is still below our fiducial values, however, and our ideal DTD from Zevin et al. 2022 [40] resulted in enough stars being enriched only 0.7% of the time.

There are two possible conclusions from this work. First, our understanding of NSMs may be wrong. Measuring delay times of mergers occurring over millions of years is impossible, and most models disagree on the exact values of the power law slope and minimum delay time. The precise delay time distribution is an outstanding question. Our understanding of the distribution would need to change significantly, however, to explain the enrichment of Ret II.

A second possible conclusion is that an additional astrophysical site of the r-process exists. Our current understanding of Ret II's star formation and NSMs cannot explain the level of observed r-process enrichment in the galaxy. Rather than using NSMs to explain all r-process in the universe, something else may be producing the r-process. While we do not yet have observational evidence to support collapsars, jets, or other merger events resulting in the r-process, dust and geometry of these systems could obscure some observations. For collapsars, there are many models that simulate the r-process and specific elements that would result. It may be a case of waiting for the right moment of observations. This is similar to how NSMs were theorized as a site before confirmation came in 2017.

Even under the most favorable conditions we could model, NSMs were not likely to enrich Ret II. We conclude that under the adopted Ret II star formation histories, BNS occurrence rate, and delay-time distributions, NSMs are unlikely to explain Ret II unless the delay-time distribution has a substantial very-short-delay tail. An additional source of the r-process is thus likely needed. Collapsars are currently the strongest candidate to fill this niche.

Before concluding that any specific alternative explains Ret II's r-process enrichment, observational evidence connecting them to the r-process is needed. Observational evidence of collapsars or other sites of the r-process is still necessary, and astronomers should continue to observe supernovae for signs of the r-process. Theories cannot be proven without some form of experimental or observational confirmation.

In an ideal scenario, we would expand this model to work with the star formation of another UFD with r-process enrichment, but no other known UFD has the same level of r-process enrichment. If such a UFD or globular cluster was found, testing NSMs would be important. Until then, r-process research will use Ret II as its testing grounds. Future studies could look into hydrodynamic simulations that incorporate supernovae feedback and natal kicks for a more accurate exploration of Ret II's star formation history.

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