OPEN ACCESS



Where Has All the *R*-process Gone? Timescales for Gamma-Ray Burst Kilonovae to Enrich Their Host Galaxies

Anya E. Nugent^{1,2}, Alexander P. Ji^{3,4}, Wen-fai Fong², Hilay Shah⁵, and Freeke van de Voort⁶

¹ Center for Astrophysics | Harvard & Smithsonian, 60 Garden Street, Cambridge, MA 02138, USA; anya.nugent@cfa.harvard.edu

² Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA) and Department of Physics and Astronomy, Northwestern University, Evanston, IL

60208, USA

³Department of Astronomy & Astrophysics, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637, USA

^{*} Kavli Institute for Cosmological Physics, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637, USA

Research School of Astronomy and Astrophysics, Australian National University, Canberra, ACT 2611, Australia

⁶ Cardiff Hub for Astrophysics Research and Technology, School of Physics & Astronomy, Cardiff University, Queen's Buildings, Cardiff, CF24 3AA, UK Received 2024 September 30; revised 2025 February 10; accepted 2025 February 26; published 2025 March 26

Received 2024 September 50, revised 2025 February 10, accepted 2025 February 20, published 2025 March 20

Abstract

Neutron star (NS) mergers are currently the only observed source of *r*-process production in the Universe. Yet, it is unclear how much *r*-process mass from these mergers is incorporated into star-forming gas to enrich stars. This is crucial to consider as all other *r*-process mass estimates in the Universe beyond Earth are based on stellar *r*-process abundances. Here, we explore the extent to which merger location and host-galaxy properties affect the incorporation of *r*-process elements into star-forming gas, and quantify an "enrichment" timescale to account for this process. To put this timescale in context, we analyze a population of 12 gamma-ray bursts (GRBs) with probable associations to *r*-process kilonovae (GRB-KNe) and 74 short GRBs without claimed KNe, including new nonparametric star formation histories for the GRB-KN hosts. We find the enrichment timescales for this sample are between \approx 7 Myr and 1.6 Gyr, suggesting that environmental enrichment is delayed from NS merger occurrence. Moreover, we find a correlation between the amount of environmental enrichment from a single event and increasing host specific star formation rate (sSFR), and little correlation with stellar mass and GRB galactocentric offset. Environments with low sSFRs (<10^{-10.5} yr⁻¹), which comprise 18% of short-GRB hosts and the host of GW170817, will have little to no capacity for stellar enrichment. Our results indicate that not all *r*-process from NS mergers is incorporated into newly forming stars, and instead some remains "lost" to the circumgalactic medium or intergalactic medium. Future studies should consider these losses to understand the total contribution from NS mergers to the Universe's *r*-process budget.

Unified Astronomy Thesaurus concepts: Gamma-ray bursts (629); Galaxies (573); Early-type galaxies (429); R-process (1324); Neutron stars (1108)

1. Introduction

The astrophysical birthsites of heavy r-process elements (A > 130) have long been debated. There are several proposed channels of *r*-process, including neutron star (NS) mergers (D. Eichler et al. 1989; E. Berger 2014; P. Beniamini et al. 2016; K. Kawaguchi et al. 2016; K. Hotokezaka et al. 2018) and rare types of core-collapse supernovae (CCSNe; Y. Z. Qian 2000; D. Argast et al. 2004; T. Tsujimoto et al. 2015; G. Halevi & P. Mösta 2018; D. M. Siegel et al. 2019; Á. Skúladóttir et al. 2019; K. Brauer et al. 2021). While NS mergers are subject to a wide range of progenitor formation timescales (delay times) and host environments (K. Belczynski et al. 2010; M. Dominik et al. 2012; R. O'Shaughnessy et al. 2017), collapse of massive stars (collapsars) and CCSNe are almost exclusively connected to short delay times and star-forming host galaxies (K. M. Svensson et al. 2010; D. A. Perley et al. 2013; S. D. Vergani et al. 2015; F. Y. Wang & Z. G. Dai 2014; P. K. Blanchard et al. 2017; Y. Niino et al. 2017; S. Schulze et al. 2021; K. Taggart & D. A. Perley 2021). Given this diversity in progenitor timescales and environments, the channel(s) through which r-process material is synthesized has substantial impact on the chemical

Original content from this work may be used under the terms of the Creative Commons Attribution 4.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI. enrichment of the Universe, as well as how our solar system achieved its *r*-process mass and abundance pattern.

Despite relevant observations of a handful of CCSNe and collapsars to determine if they produce any r-process, there are no clear signs of r-process element production in these events thus far (P. K. Blanchard et al. 2024; S. Anand et al. 2024; J. C. Rastinejad et al. 2024). On the other hand, we have direct evidence of r-process production in NS mergers, with the coincident detection of an r-process kilonova (KN) with a binary NS merger, the gravitational-wave (GW) event GW170817 (B. P. Abbott et al. 2017a, 2017b; R. Chornock et al. 2017; D. Kasen et al. 2017; C. McCully et al. 2017; E. Pian et al. 2017; B. J. Shappee et al. 2017; N. R. Tanvir et al. 2017). Because of the coincidence of GW170817 to the short gamma-ray burst (GRB) 170817A (B. P. Abbott et al. 2017a; A. Goldstein et al. 2017; V. Savchenko et al. 2017), it is also now confirmed that at least some short GRBs are connected to the local population of GW-NS mergers and contribute to *r*-process enrichment. Additionally, a number of short GRBs have been followed by photometric near-IR excesses, presumed to be KNe (E. Berger et al. 2013; N. R. Tanvir et al. 2013; Z.-P. Jin et al. 2015, 2016, 2020; B. Yang et al. 2015; W. Fong et al. 2016, 2021; M. M. Kasliwal et al. 2017; B. P. Gompertz et al. 2018; E. Troja et al. 2018; G. P. Lamb et al. 2019; A. Rossi et al. 2020; B. O'Connor et al. 2021; J. C. Rastinejad et al. 2021).

Observations of *r*-process elements across a wide variety of environments have further supported a NS merger production pathway. The stochastic r-process abundance pattern observed in Galactic metal-poor stars (D. Eichler et al. 1989; A. McWilliam et al. 1995; B. Côté et al. 2018) and lowmetallicity Local Group dwarf galaxies (M. D. Shetrone et al. 2001; K. A. Venn et al. 2012; A. P. Ji et al. 2016; T. Matsuno et al. 2021; M. Molero et al. 2021; H. Reggiani et al. 2021; R. P. Naidu et al. 2022; G. Limberg et al. 2024) suggests that r-process events are much rarer than normal CCSNe. Indeed, the r-process event rate and mass yield estimates from inferred stellar r-process abundances are well matched to those derived for GW170817 and short GRBs (A. P. Ji et al. 2016; K. Hotokezaka et al. 2018; P. Macias & E. Ramirez-Ruiz 2018; A. Rouco Escorial et al. 2023). This implies that NS mergers may be responsible for the majority of r-process elements in the Universe.

To complicate the picture, three long GRBs, GRBs 060614 (Z.-P. Jin et al. 2015; B. Yang et al. 2015; B. P. Gompertz et al. 2018; A. Rossi et al. 2020; J. C. Rastinejad et al. 2021), 211211A (J. C. Rastinejad et al. 2022; E. Troja et al. 2022; J. Yang et al. 2022), and 230307A (J. H. Gillanders et al. 2023; A. J. Levan et al. 2024; Y.-H. Yang et al. 2024), which typically derive from collapsars, had photometric excesses consistent with KNe. The potential association of these events to KNe not only implies they have merger (as opposed to collapsar) progenitors, but also that long GRBs can also contribute to the Universe's r-process budget. Taken at face value, the addition of this long-GRB r-process channel may suggest that the total mass yield of r-process material from NS mergers exceeds the mass observed within Galactic metal-poor stars and Local Group dwarfs (M.-H. Chen et al. 2024). This dilemma only becomes more serious if rare types of CCSNe also contribute appreciably to the *r*-process budget.

Given that r-process studies of Galactic metal-poor stars and Local Group dwarf galaxies focus on the r-process enrichment of stars, it is imperative to consider how r-process material from various production channels is incorporated into starforming gas to understand their potential contribution in these environments. The delay between r-process events and the redistribution of the metals into star-forming gas, or the "enrichment timescale," may be comparable to progenitor delay times. Indeed, if this enrichment timescale is comparatively very long, the *r*-process mass may not be able to enrich star-forming gas and would remain in the circumgalactic medium (CGM) or intergalactic medium (IGM). This would result in "losses" when we compare the r-process material produced to that which makes it into stars. For NS mergers, their older stellar populations and natal kicks could result in substantial losses. For instance, GW170817 occurred in an old, massive host with little ongoing star formation (P. K. Blanchard et al. 2017; A. J. Levan et al. 2017; A. Palmese et al. 2017; C. D. Kilpatrick et al. 2022), and, thus, likely a small amount of star-forming gas left to enrich at the time of merger. Beyond GW170817, $\approx 15\%$ of short GRBs are associated with transitioning and quiescent host galaxies that have low ongoing star formation rates (SFRs) of $\approx 0.14 M_{\odot} \text{ yr}^{-1}$ (A. E. Nugent et al. 2022; M. Jeong & M. Im 2024). Furthermore, NS mergers in general occur on more delayed timescales than, for example, collapsar events following a star-forming burst within their hosts (E. Nakar et al. 2006; E. Berger et al. 2007; S. Jeong & C.-H. Lee 2010;

J.-M. Hao & Y.-F. Yuan 2013; D. Wanderman & T. Piran 2015; T. M. Tauris et al. 2017; N. Anand et al. 2018; J. J. Andrews & I. Mandel 2019; M. Zevin et al. 2022). It therefore remains unclear what fraction of NS mergers are capable of enriching star-forming gas before the next possible star-forming period within their hosts.

In addition, NSs can experience significant natal kicks at their formation, translating to large systemic velocities, as observed by the Galactic binary NS population (T. M. Tauris et al. 2017; A. Vigna-Gómez et al. 2018; J. J. Andrews & A. Zezas 2019). Coupled with the long expected delay times of NS mergers, NS systems can easily migrate and merge well outside of their host galaxies (M. Zevin et al. 2020; S. Mandhai et al. 2022; N. Gaspari et al. 2024). This is backed by observations of the short GRB population, which have large galactocentric offsets of \approx 5.6–7.7 kpc (R. P. Church et al. 2011; W. Fong & E. Berger 2013; R. L. Tunnicliffe et al. 2014; W.-f. Fong et al. 2022; B. O'Connor et al. 2022). Subsequently, offsets may also play an important role in contributing to a prolonged *r*-process enrichment timescale.

Here, we assess how significant *r*-process losses are from a population of 12 GRBs with claimed KNe (GRB-KNe). We model the GRB-KN host-galaxy stellar masses and star formation histories (SFHs), and use their galactocentric offsets to constrain the enrichment timescale and the fraction of stellar mass capable of enrichment from these events. We additionally compare these results to those determined for the literature sample of short GRBs without claimed KNe. In Section 2, we discuss our GRB sample. In Section 3, we describe the stellar population modeling methods used to determine host-galaxy stellar masses and SFHs, and present our results on these and the hosts' halo properties. We describe our method for quantifying the *r*-process enrichment timescale in Section 4. We discuss major implications from these findings in Section 5. Finally, we list our conclusions in Section 6.

Unless otherwise stated, all observations are reported in the AB magnitude system and have been corrected for Galactic extinction in the direction of the GRB (J. A. Cardelli et al. 1989; E. F. Schlafly & D. P. Finkbeiner 2011). We employ a standard WMAP9 cosmology of $H_0 = 69.6 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.286$, and $\Omega_{vac} = 0.714$ (G. Hinshaw et al. 2013; C. L. Bennett et al. 2014).

2. Sample

2.1. GRB-KN Sample

Our main sample consists of 12 GRBs with probable KNe, confident host-galaxy associations, and confirmed spectroscopic redshifts from their hosts. We focus on the sample with claimed KNe as it is reasonable to assume they produced r-process material. We begin with eight short GRBs that have claimed KNe, extensively discussed in the literature: GRBs 050709 (Z.-P. Jin et al. 2016; B. P. Gompertz et al. 2018; A. Rossi et al. 2020; J. C. Rastinejad et al. 2021), 050724 (A. Rossi et al. 2020; J. C. Rastinejad et al. 2021), 070714B (A. Rossi et al. 2020; J. C. Rastinejad et al. 2021), 070809 (Z.-P. Jin et al. 2020; A. Rossi et al. 2020; J. C. Rastinejad et al. 2021), 130603B (E. Berger et al. 2013; N. R. Tanvir et al. 2013; B. P. Gompertz et al. 2018; A. Rossi et al. 2020; J. C. Rastinejad et al. 2021), 150101B (W. Fong et al. 2016; E. Troja et al. 2018; A. Rossi et al. 2020; J. C. Rastinejad et al. 2021), 160821B (M. M. Kasliwal et al. 2017; G. P. Lamb et al. 2019; A. Rossi et al. 2020; J. C. Rastinejad et al. 2021), and 200522A (W. Fong et al. 2021; B. O'Connor et al. 2021; J. C. Rastinejad et al. 2021). We further include GW170817/GRB 170817A, a known NS merger with spectroscopic evidence for a KN (AT 2017gfo; R. Chornock et al. 2017; D. Kasen et al. 2017; C. McCully et al. 2017; E. Pian et al. 2017; B. J. Shappee et al. 2017; N. R. Tanvir et al. 2017) that produced $\approx 0.05-0.08 M_{\odot}$ of *r*-process material (V. A. Villar et al. 2017; K. Hotokezaka et al. 2018; S. Rosswog et al. 2018).

Finally, we include three long GRBs that were followed by possible KNe: GRBs 060614 (Z.-P. Jin et al. 2015; B. Yang et al. 2015; B. P. Gompertz et al. 2018; A. Rossi et al. 2020; J. C. Rastinejad et al. 2021), 211211A (J. C. Rastinejad et al. 2022; E. Troja et al. 2022; J. Yang et al. 2022), and the recently detected 230307A (J. H. Gillanders et al. 2023; A. J. Levan et al. 2024; Y.-H. Yang et al. 2024). Relative to traditional Type Ic supernovae (SNe) following collapsars, all three GRBs had near-IR photometric excesses that peaked at earlier times, were less luminous, and faded more rapidly, suggesting these were not typical long-GRB events. The lightcurves of the excesses for GRBs 211211A and 230307A also faded at rates similar to that of AT 2017gfo (J. C. Rastinejad et al. 2022; A. J. Levan et al. 2024). These characteristics suggest that the observed excesses were KNe, and therefore that these events were merger-driven rather than deriving from collapsars. In addition, spectroscopic follow-up of the counterpart observed for GRB 230307A revealed detection of an emission feature at $\sim 2.15 \,\mu\text{m}$. This was claimed to be Te III at z = 0.065(J. H. Gillanders et al. 2023; A. J. Levan et al. 2024), although the identification is not definitive. A broad emission feature was observed for AT 2017gfo at a similar (but not exact) restframe wavelength, also proposed to be Te III (K. Hotokezaka et al. 2023). If the identification is correct, this spectroscopically validates that the GRB 230307A derived from an NS merger and that the excess was an r-process KN.

We obtained host associations for the short GRBs and long GRBs 060614 and 211211A in W.-f. Fong et al. (2022). GW170817 is associated with host galaxy NGC 4993 (P. K. Blanchard et al. 2017; A. J. Levan et al. 2017; A. Palmese et al. 2017; C. D. Kilpatrick et al. 2022). A. J. Levan et al. (2024) claimed the host of GRB 230307A is a galaxy at z = 0.065, ≈ 40 kpc offset from the transient, given the tentative Te III detection at the same redshift and a low probability of chance coincidence of $P_{cc} = 0.09$. Using the classification scheme from W.-f. Fong et al. (2022), 10 of these events have "Gold" standard host associations ($P_{cc} < 0.02$), and two (GRBs 160821B and 230307A) have "Silver" standard host associations ($0.02 < P_{cc} < 0.09$); thus, this sample all has fairly robust host associations.

We collect host-galaxy optical and IR photometry for this sample from J. Hjorth et al. (2005), S. Covino et al. (2006), J. Gorosabel et al. (2006), A. Gal-Yam et al. (2006), P. Morrissey et al. (2007), J. F. Graham et al. (2009), W. Fong et al. (2010, 2016, 2021), C. N. Leibler & E. Berger (2010), W. Fong & E. Berger (2013), A. de Ugarte Postigo et al. (2014), S. Alam et al. (2015), P. K. Blanchard et al. (2017), W.-f. Fong et al. (2022), and J. C. Rastinejad et al. (2022), as displayed in Table A1 from W.-f. Fong et al. (2022). For the host of GRB 230307A, we find near-UV host photometry from the Galaxy Evolution Explorer survey (P. Morrissey et al. 2007), *ugriz* optical photometry from the Sloan Digital Sky Survey (R. Ahumada et al. 2020), and mid-IR photometry from the Wide-field Infrared Survey Explorer (E. L. Wright et al. 2010). We correct all photometry for Galactic extinction in the direction of each GRB, using the E. F. Schlafly & D. P. Finkbeiner (2011) dust maps. We furthermore collect the reduced, extinction-corrected host spectra on the Broadband Repository for Investigating Gamma-ray burst Host Traits (or BRIGHT),⁷ which are available for all host galaxies except for those of GRB 070809, GW170817, and GRB 230307A.

In Table 1, we provide the redshift and host association confidence level for this sample. We note that this GRB sample has a lower median redshift ($z \approx 0.1615$) than that reported for the full short-GRB sample ($z \approx 0.64$) in W.-f. Fong et al. (2022), A. E. Nugent et al. (2022), and B. O'Connor et al. (2022). This is an expected observational bias, given that KNe become much more difficult to detect with increasing redshift. As the distance of the KN to the host galaxy will also inform the *r*-process enrichment timescale (see Section 4), we further provide the projected galactocentric offsets for this sample. We find that the GRB-KN sample has a median projected physical offset of ≈ 6.6 kpc, within the median and 68% confidence interval for the full sample of short GRBs ($\approx 7.7^{+20.9}_{-6.1}$ kpc; W.-f. Fong et al. 2022).

2.2. Short-GRB Sample

Given that most of the general short GRB population also likely derives from NS mergers, it is probable that the majority of events also produce some r-process materials even if their KNe are not detectable. As previously mentioned, KNe are difficult to detect beyond z = 0.3 with ground-based detectors (J. C. Rastinejad et al. 2021), and the majority of short GRBs are observed over this redshift limit. Thus, under the premise that short GRBs will also produce *r*-process, we include the short GRB samples from W.-f. Fong et al. (2022) to increase our population size. This sample contains an additional 74 short GRBs with confident host associations and offsets. Host-galaxy properties (including stellar mass, SFR, and either photometric or spectroscopic redshifts) are available for 59 hosts in A. E. Nugent et al. (2022), and stellar mass and spectroscopic or photometric redshift estimates for another 11 hosts are described in A. E. Nugent et al. (2024).

3. Host-galaxy and Halo Properties

3.1. Stellar Population Modeling and Properties

The *r*-process enrichment timescale will be heavily influenced by host-galaxy properties, such as stellar mass (see Section 4). We further seek to understand if host-galaxy properties affect the capacity for an environment to be enriched from a single NS merger event. To determine the host-galaxy stellar masses and SFHs, we use the stellar population inference code Prospector (J. Leja et al. 2019; B. D. Johnson et al. 2021). We jointly fit the photometry and spectroscopy (when available) for each host galaxy and employ the nested sampling fitting routine dynesty (J. S. Speagle 2020) to produce posterior distributions for the stellar population properties of interest. Internally, Prospector utilizes the MIST models (B. Paxton et al. 2018) and MILES spectral libraries (J. Falcón-Barroso et al. 2011) through Flexible Stellar Population Synthesis (FSPS) and

⁷ http://bright.ciera.northwestern.edu

 Table 1

 GRB, Host, and Halo Properties

GRB	Sample	Ζ	Projected Offset (kpc)	$\log (M_*/M_{\odot})$	$\frac{\text{SFR}}{(M_{\odot} \text{ yr}^{-1})}$	$\log_{(M/M_{\odot})h}$	r _{vir} (kpc)	V _{vir} (km s ⁻¹)	log(T _{vir}) (K)
050709	Gold	0.161	3.76	$9.07\substack{+0.05\\-0.09}$	$0.11_{-0.02}^{+0.03}$	11.31	152.83	75.6	5.31
050724	Gold	0.257	2.74	$11.12\substack{+0.02\\-0.01}$	$0.2\substack{+0.02\\-0.02}$	13.28	697.86	345.21	6.63
060614	Gold	0.125	0.7	$7.77_{-0.09}^{+0.11}$	$0.07\substack{+0.02\\-0.02}$	10.66	93.46	46.23	4.88
070714	Gold	0.925	12.33	$9.70\substack{+0.07\\-0.09}$	$1.89\substack{+0.89\\-0.62}$	11.68	203.40	100.62	5.55
070809	Gold	0.473	34.11	$10.9_{-0.07}^{+0.14}$	$9.75^{+12.89}_{-8.55}$	12.97	546.21	270.20	6.41
130603B	Gold	0.357	5.4	$9.66^{+0.15}_{-0.12}$	$18.27\substack{+4.6\\-4.89}$	11.59	189.48	93.73	5.50
150101B	Gold	0.134	11.31	$11.31_{-0.02}^{+0.02}$	$1.84_{-0.45}^{+0.57}$	13.60	887.92	439.23	6.84
160821B	Silver	0.162	15.74	$9.44\substack{+0.03\\-0.04}$	$0.01\substack{+0.0\\-0.0}$	11.48	175.07	86.60	5.43
170817	Gold	0.0097	2.125	$10.80\substack{+0.04\\-0.07}$	$0.01\substack{+0.02\\-0.01}$	12.51	384.54	190.35	6.11
200522A	Gold	0.554	0.93	$9.50_{-0.03}^{+0.04}$	$11.75^{+1.59}_{-1.84}$	11.53	181.54	89.81	5.46
211211A	Gold	0.076	7.92	$8.91\substack{+0.06\\-0.06}$	$0.35_{-0.04}^{+0.04}$	11.21	142.14	70.31	5.25
230307A	Silver	0.065	38.9	$9.66\substack{+0.09\\-0.08}$	$0.09\substack{+0.09\\-0.06}$	11.60	190.7	94.34	5.50

Note. Given are the sample (confidence of host association), spectroscopic redshifts, projected galactocentric offsets, stellar masses, present-day SFRs, halo masses, virial radii, virial velocities, and virial temperatures for our GRB sample. For stellar masses and SFRs, we report the median and 68% confidence interval, as determined in our Prospector fits.

python-FSPS (C. Conroy et al. 2009; C. Conroy & J. E. Gunn 2010) to produce model spectral energy distributions. For all Prospector fits, we utilize the P. Kroupa & T. Jerabkova (2021) initial mass function, the M. Kriek & C. Conroy (2013) dust attenuation model, which determines an offset from the D. Calzetti et al. (2000) attenuation curve and the ratio of light attenuated from old to young stellar populations, and the A. Gallazzi et al. (2005) mass-metallicity relation to probe realistic stellar mass and stellar metallicity combinations. Although all redshifts are spectroscopically confirmed, we allow redshift to be a free parameter in our fits with a tight (± 0.01) prior range around the host redshift to mitigate any uncertainty in the redshift that may arise from varying data reduction methods. In addition, we include the B. T. Draine & A. Li (2007) IR dust emission model and sample the polycyclic aromatic hydrocarbon mass fraction (q_{PAH}) , given that five GRB hosts in this sample have mid-IR photometry. For the hosts with a spectrum, we model their spectral continua with a 12th-order Chebyshev polynomial, apply a spectral smoothing model to normalize the spectra to their respective photometry, and determine a gas-phase metallicity based on their spectral line strengths. For the hosts with only photometry, we assume a solar gas-phase metallicity. We further adopt a nebular marginalization template to marginalize over the observed emission lines. We also employ a spectral noise inflation model to ensure that the spectra are not overweighted in the fit in comparison to the photometry, and a pixel outlier model to marginalize over noise in the spectra.

Finally, we incorporate the nonparametric continuity SFH in Prospector. This contrasts with previous work that has modeled short GRB hosts with parametric delayed- τ SFHs (e.g., A. E. Nugent et al. 2022, which modeled 69 short GRB hosts). A nonparametric SFH is advantageous for this study as we are capable of modeling recent bursts of star formation, and can therefore place firmer constraints on the fraction of newly forming stars that are capable of being enriched with *r*-process elements from our sample. This SFH is constructed by assuming a constant SFR within an age bin. We use eight age bins: the first two range from 0 to 30 Myr and 30 to 100 Myr, and the final six are log-spaced from 100 Myr to the age of the Universe at each host's redshift.

In Table 1, we report the median and 68% confidence interval for the stellar mass (M_*) and present-day SFR (average SFR from 0 to 100 Myr) for each GRB host. We note that in nearly all cases the stellar masses from the nonparametric SFH Prospector fits are consistent within the error bars or higher by $\approx 0.1-0.5$ dex than those reported in A. E. Nugent et al. (2022) and A. J. Levan et al. (2024), which both employed parametric delayed- τ SFH Prospector fits. This is a wellknown discrepancy between nonparametric and parametric SFH models (J. Leja et al. 2019). The majority of SFRs also differ slightly from those in A. E. Nugent et al. (2022) and A. J. Levan et al. (2024), although with no systematic offset to higher or lower values. This change is also due to the nonparametric versus parametric model choice. In Figure 1, we present the SFHs for each host. This sample appears to have a diversity in SFH shapes, with four having rising SFH, two with constant SFHs, five with falling, and one with a burst of star formation. For our full sample, the stellar mass median and 68% confidence interval is $\log(M_*/M_{\odot}) = 9.64^{+1.45}_{-0.69}$, while the SFR = $0.42^{+8.96}_{-0.38}M_{\odot}$ yr⁻¹. The large confidence intervals reflect the diversity in host-galaxy properties for this sample. Both properties are consistent with those of the entire short-GRB host population (A. E. Nugent et al. 2022), suggesting the GRB-KN sample should be fairly representative of the observed NS merger population.

3.2. Halo Properties

Since many short GRBs are observed to be far offset from their host-galaxy centers, within their hosts' CGM (W.-f. Fong et al. 2022; B. O'Connor et al. 2022), the *r*-process transport will be affected by their hosts' dark matter halos (see Section 4). Thus, we define several halo properties. We calculate halo masses (M_h) using the redshift-dependent M_*-M_h relation defined by UniverseMachine (P. Behroozi et al. 2019), using the M_* median value for each GRB host determined in our Prospector fits. We use Equation (2) in J. Stern et al. (2019) to find the virial radius $r_{\rm vir}$ of each host



Figure 1. The Prospector-derived star formation histories (SFHs) of the 12 GRB-KN host galaxies in our sample. This sample has a diverse array of SFHs and recent star formation bursts, hinting that some events might be more capable of enriching their environmental star-forming gas with *r*-process elements than others.

(in kiloparsecs), which is given by

$$r_{\rm vir} = 260 \,\mathrm{kpc} \times \left(\frac{M_h}{10^{12} M_\odot}\right)^{1/3}.$$
 (1)

We define the virial velocity $V_{\rm vir}$ as

$$V_{\rm vir} = \sqrt{GM_h/r_{\rm vir}}, \qquad (2)$$

and the virial temperature $T_{\rm vir}$ as

$$T_{\rm vir} = \frac{\mu m_p V_{\rm vir}^2}{2k_{\rm B}} \,\mathrm{K},\tag{3}$$

where $\mu = 0.59$ is the molecular mass for fully ionized primordial gas, and m_p is the mass of a proton. We list the M_h , $r_{\rm vir}$, $V_{\rm vir}$, and $T_{\rm vir}$ for each host galaxy in Table 1.

4. *R*-process Enrichment Timescale

To determine the total *r*-process enrichment timescale for each event, we consider two separate scenarios that can transport metals from the halo into the host interstellar medium (ISM): freefall/cooling and diffusion. We show a schematic of these transport mechanisms in Figure 2. In the following subsections, we describe each of these scenarios and their impact on the *r*-process enrichment timescale.



Figure 2. The two scenarios we use to model the transport of *r*-process metals from the offset of the KNe (yellow stars) in our sample to the host-galaxy center. In Scenario 1, we assume that the thermal pressure from hot halo gas can support the metals against gravitational freefall if the gas is hot enough, and the timescale to transport the *r*-process will be the maximum of the freefall ($t_{\rm frf}$) and cooling ($t_{\rm cool}$) timescales. In Scenario 2, the metals are transported with turbulent diffusion mechanisms within the halo gas, and the fallback timescale is the diffusion timescale ($t_{\rm diff}$). The *r*-process enrichment timescale will be the faster of Scenario 1 or 2. As shown in Section 4, diffusion is more efficient at transporting the metals at small KN offsets, whereas freefall is more efficient at larger KN offsets, and cooling is only relevant for events highly offset from large halos.

4.1. Scenario 1: Freefall and Cooling

In Scenario 1, we consider freefall and cooling. As the galaxy exerts a gravitational force on the *r*-process metals, thermal pressure from surrounding hot gas can keep the metals in a quasi-static equilibrium (e.g., J. Stern et al. 2019). If the cooling timescale t_{cool} is shorter than the timescale of gravitational freefall $t_{\rm ff}$, suggesting the halo gas is not hot enough to support the metals against gravitational freefall, the timescale for r-process metals to be transported to the center of the galaxy will be roughly $t_{\rm ff}$ (M. J. Rees & J. P. Ostriker 1977; J. Silk 1977; S. D. M. White & M. J. Rees 1978; J. Stern et al. 2019, 2020; C.-A. Faucher-Giguère & S. P. Oh 2023). Otherwise, the halo gas around the metals will need to cool, and the transport timescale will be $\approx t_{cool}$. We quantify the freefall timescale as $t_{\rm ff} = \sqrt{2} r_{\rm KN}/v_c$ (e.g., J. Stern et al. 2020). Here, $r_{\rm KN}$ is the deprojected KN galactocentric offset,⁸ and v_c represents the circular velocity at $r_{\rm KN}$, assuming a J. F. Navarro et al. (1996) density profile with concentration c from C. A. Correa et al. (2015), which correlates c with z and M_h . Given the broad range of redshifts of the short-GRB sample $(0 \le z \le 2.6; W.-f.$ Fong et al. 2022; A. E. Nugent et al. 2022), we determine c only at the median short-GRB redshift

(z = 0.64). We note that this assumption will add minimal uncertainty to our analysis.

Following the methods in J. Stern et al. (2020), we characterize t_{cool} as a function of v_c , the gas density ρ_{gas} and hydrogen gas density $n_{\rm H}$ surrounding the *r*-process metals at their initial location, and the R. P. C. Wiersma et al. (2009) cooling function $\Lambda_{\rm T}$, which is dependent on $T_{\rm vir}$ and the halo gas metallicity.⁹ Assuming $\rho_{\rm gas} = 2.25 \,\mu m_p n_{\rm H}$ for a completely ionized gas of primordial composition, we find that

$$t_{\rm cool} = \frac{\rho_{\rm gas} v_c^2}{n_{\rm H}^2 \Lambda_T(T_{\rm vir}, Z)} \approx \frac{5.06 \mu^2 m_p^2 v_c^2}{\rho_{\rm gas} \Lambda_T(T_{\rm vir}, Z)}.$$
 (4)

For simplicity, we assume that the gas metallicity is solar and that ρ_{gas} follows an isothermal gas density profile, given by

$$\rho_{\rm gas} = \frac{f_{\rm CGM} f_b M_h}{4\pi c r_s^2} \times \left(\frac{r_{\rm KN}}{r_s}\right)^{-2},\tag{5}$$

where $r_s = R_{\rm vir}/c$ is the scale radius, $f_b = \Omega_b/\Omega_M$ is the baryon fraction, and $f_{\rm CGM}$ is the fraction of baryons in the CGM. As described in J. Stern et al. (2020), the true $f_{\rm CGM}$ will depend on feedback and is related to the fraction of baryons that are kept in the halo versus the IGM. We adopt $f_{\rm CGM} = 0.25$, based on median $f_{\rm CGM}$ values determined for halos within the range $11 < \log(M_h/M_{\odot}) < 14$ from EAGLE simulations performed in B. D. Oppenheimer et al. (2020). This $f_{\rm CGM}$ selection only affects the events that occur highly offset ($\gtrsim 30$ kpc) from galaxies with larger halos ($\gtrsim 10^{12.5} M_{\odot}$), which is a small fraction of our observed GRB population.

We note that advection is another possible mechanism for metal transport (e.g., B. Amend et al. 2022), which we expect to occur on a similar timescale as the freefall or cooling timescales.

4.2. Scenario 2: Diffusion

In Scenario 2, we consider metal transport in turbulent gas, which we will model as a diffusion process (e.g., B. G. Elmegreen & J. Scalo 2004; J. Scalo & B. G. Elmegreen 2004). Turbulent diffusion is driven by physical processes like gas accretion, SN feedback, galactic winds, tidal disruption of satellite galaxies, and galaxy mergers, as well as other characteristics of the halo gas that might force diffusive transport (B. G. Elmegreen & J. Scalo 2004; M. E. Putman et al. 2012). Diffusion has often been used to model *r*-process transport in galaxies, and generally helps explain observed *r*-process abundances and scatter (S. Shen et al. 2015; F. van de Voort et al. 2015, 2020, 2022; G. Montes et al. 2016; P. Beniamini & K. Hotokezaka 2020; Y. Tarumi et al. 2020; A. P. Ji et al. 2023; A. N. Kolborg et al. 2023).

Here, we estimate the diffusion timescale using recent cosmological zoom-in simulations by H. Shah et al. (2025, in preparation) of Milky Way–mass $10^{12} M_{\odot}$ halos from the Simulating the Universe with Refined Galaxy Environments (or SURGE) project (F. van de Voort et al. 2021; F. van de Voort et al. 2025, in preparation) based on the Auriga galaxy formation model (R. J. J. Grand et al. 2017). In brief, H. Shah et al. (2025, in preparation) study diffusive metal transport by injecting tracer dyes (passive scalars) into the CGM and

⁸ Given that it is impossible to determine the *z*-direction of the KN, we assume the event lies at the median of an isotropic distribution of angles (30°). Thus, to calculate the median deprojected offsets, we simply multiply the observed projected offsets in Table 1 by $\cos(30^\circ)$, or $\sqrt{3}/2$.

⁹ We note that this metallicity is different from the gas-phase metallicity determined in our Prospector fits.

 Table 2

 Enrichment Timescales for GRB-KNe and GRB Populations

					$\% M_*$
GRB	Freefall	Cooling	Diffusion	Enrichment	Enriched
	(Gyr)	(Gyr)	(Gyr)	(Gyr)	
050709	0.094	3.0e-4	0.241	Freefall	9%-12%
050724	0.043	1.6e-4	0.158	Freefall	<1%
060614	0.043	3.4e-6	0.028	Diffusion	44%-57%
070714	0.173	8.5e-3	1.169	Freefall	54%-71%
070809	0.198	0.209	4.53	Cooling	4%-45%
130603B	0.105	8.8e-3	0.39	Freefall	85%-90%
150101B	0.067	3.0e-3	0.589	Freefall	1%
160821B	0.226	1.4e-2	1.618	Freefall	<1%
170817	0.047	7.6e-5	0.114	Freefall	<1%
200522A	0.041	5.3e-6	0.037	Diffusion	91%-93%
211211A	0.157	2.2e-2	0.649	Freefall	17%-20%
230307A	0.449	0.129	5.396	Freefall	1%
GRB-KNe				$0.100\substack{+0.114\\-0.058}$	15%
All GRBs				$0.134\substack{+0.171 \\ -0.083}$	59%

Note. The freefall, cooling, diffusion, and *r*-process enrichment timescales for our GRB-KN sample. The enrichment timescale is taken as the minimum of the diffusion timescale with the maximum of the freefall and cooling timescales. We further present ranges (from uncertainties on the host SFR) of the percent of stellar mass enriched from the single GRB event after the *r*-process enrichment timescale to z = 0 (p_{enrich}). Finally, we show the median and 68% confidence interval of the enrichment timescale for the GRB-KN and entire GRB sample studied in this work, as well as the median p_{enrich} for these samples.

quantifying the distance spread *S*, which encompasses the 68th percentile of the tracer dye. In these simulations, the rate of dye spread is approximately linear in time and can be modeled as

$$\frac{dS}{dt} = K * \sigma_{\text{vel}} [\text{km s}^{-1}]^b, \qquad (6)$$

where K = 0.55/(0.2 Gyr) and b = 0.473. The diffusion rate depends on the gas velocity dispersion profile, which follows the radial dependence

$$\sigma_{\text{vel}}(r)[\text{km s}^{-1}] = A * r[\text{kpc}]^{-B}, \tag{7}$$

where σ_{vel} is evaluated at 1 kpc scales, A = 155, and B = 0.7. The numerical coefficients for these relations are derived by averaging properties of three simulations with halo masses $10^{11} M_{\odot}$, $10^{12} M_{\odot}$, and $10^{13} M_{\odot}$. We did not find clear evidence for a halo mass dependence in these simulations, so for now we assume the metal diffusion rate is constant with halo mass, though an additional study is clearly warranted. The dependence of the diffusion timescale on $r_{\rm KN}$ can be found by solving

$$\int_0^{2r_{\rm KN}} \frac{dS}{K * \sigma_{\rm vel} (r_{\rm KN} - S/2)^b} = \int_0^{t_{\rm diff}} dt \tag{8}$$

which assumes that diffusion is effective if *S* surpasses $2r_{KN}$. Solving for t_{diff} gives the final result:

$$t_{\rm diff}[\rm Gyr] = 0.05 * r_{\rm KN}[\rm kpc]^{1.331}.$$
 (9)

4.3. Timescale Results

We present the freefall, cooling (Scenario 1), and diffusion (Scenario 2) timescales for the GRB-KN sample in Table 2. We assume that the *r*-process enrichment timescale will be the

more efficient process (or minimum timescale) between the two scenarios quantified in Figure 2; thus, the enrichment timescale is min(t_{diff} , max(t_{ff} , t_{cool})). In Figure 3, we compare the freefall, cooling, and diffusion timescales in r_{KN} versus halo mass. For the GRB-KN sample, we find that freefall timescales range from \approx 40 to 450 Myr, cooling timescales range from \approx 0.003 to 130 Myr, and diffusion timescales range from \approx 30 Myr to 5 Gyr. When including the short-GRB populations from A. E. Nugent et al. (2022) and A. E. Nugent et al. (2024), we find a wider range of all three timescales: $t_{\text{ff}} \approx$ 20–600 Myr, $t_{\text{cool}} \approx$ 700 yr–1.6 Gyr, and $t_{\text{diff}} \approx$ 7 Myr–13 Gyr. Generally, $t_{\text{ff}} > t_{\text{cool}}$, except at very large offsets from large halos, which suggests that cooling is not typically a rate-limiting step in transporting the *r*-process.

As we seek to understand how quickly an environment can be enriched with *r*-process from NS mergers, we compare these timescales to possible minimum NS merger delay times. From stellar population synthesis simulations of the Galactic binary neutron star (BNS) population, it has been estimated that the minimum delay time is ≈ 10 Myr (K. Belczynski et al. 2002; M. Dominik et al. 2012; A. Vigna-Gómez et al. 2018; P. Beniamini & T. Piran 2019). A larger minimum delay time of ≈ 200 Myr has been determined from the observations of the short-GRB host population (M. Zevin et al. 2022), with a typical delay time of \approx 3–7 Gyr (E. Nakar et al. 2006; E. Berger et al. 2007; S. Jeong & C.-H. Lee 2010; J.-M. Hao & Y.-F. Yuan 2013; D. Wanderman & T. Piran 2015; N. Anand et al. 2018), and Galactic BNS systems (T. M. Tauris et al. 2017; J. J. Andrews & I. Mandel 2019). Given that the majority of freefall and diffusion timescales for the full GRB-KN and short-GRB populations are >100 Myr, this indicates that the enrichment timescale is about or more than the minimum NS merger delay time. Thus, these findings hint that the enrichment timescale is nontrivial in comparison to delay times, and that environments are not immediately enriched following an event.

In Figure 4 and Table 2, we show the *r*-process enrichment timescales in the $r_{\rm KN}$ -halo mass parameter space along with those determined for the GRB-KN and short-GRB samples. As expected, we find that at small deprojected offsets (≤ 1 kpc) and smaller halo masses ($M_h \leq 10^{11.55} M_{\odot}$), diffusion is more efficient at transporting the metals. Only two of the GRB-KNe in our sample are within the region where diffusion is more efficient: GRBs 060614 and 200522A, which have the smallest projected offsets in this sample. We further find that five of the short GRBs in A. E. Nugent et al. (2024), which all occurred within central locations of dwarf galaxy hosts ($M_{\star} < 10^9 M_{\odot}$), also fall within this region. The majority of both the GRB-KN (nine events) and the short-GRB (62 events) samples fall within the region where gravitational freefall is the most efficient process. For events in hosts with high halo masses $(M_h \gtrsim 10^{13} \ \dot{M}_{\odot})$ and that have large deprojected offsets (25 kpc), which includes one GRB-KN (GRB 070809) and three short GRBs, their r-process falls back into the host on the cooling timescale.

For our GRB-KN sample, we find a range of enrichment timescales, from ≈ 28 to 449 Myr, with a median and 68% confidence interval of 100^{+114}_{-58} Myr. For the full short-GRB host sample (excluding the GRB-KN sample), we find a larger range of enrichment timescales (≈ 7 Myr–1.6 Gyr) and a higher median (138^{+177}_{-78} Myr). When combining samples, we find a median and 68% confidence interval of 134^{+171}_{-83} Myr for the enrichment timescale. We further notice that the enrichment timescales exceed 1 Gyr when the GRB is highly offset from



Figure 3. Grids in KN deprojected offset (in kiloparsecs) vs. halo mass $(\log(M_h/M_{\odot}))$ space for the three timescales considered in this work: freefall (left), cooling (middle), and diffusion (right). All timescales are in gigayears. Our GRB-KN sample (Table 1) is shown by the stars, and the short-GRB sample in A. E. Nugent et al. (2022) and A. E. Nugent et al. (2024) is shown by the black circles. The black contour lines represent where 10 Myr and 200 Myr fall for each of the two timescales. The majority of the freefall and diffusion timescales for the KN and short-GRB samples are >10 Myr, while the cooling timescales are generally much shorter.



Figure 4. The same as Figure 3, but for the *r*-process enrichment timescale, which is the minimum of the cooling or diffusion timescale. We find that both the sample of KNe and sample of short GRBs have significant enrichment timescales, on order of a ≈ 100 Myr, compared to the minimum expected delay time for NS mergers ($\approx 10-200$ Myr).

its host galaxy (\gtrsim 20–30 kpc in deprojected space for $M_h < 10^{11} M_{\odot}$ and \gtrsim 45 kpc for $M_h < 10^{12} M_{\odot}$). This only accounts for two short GRBs.

In related work, B. Amend et al. (2022) argued that the enrichment timescale should be substantially longer than the freefall timescale, and thus the results found here. They showed that Rayleigh–Taylor instabilities will cause the *r*-process ejecta to mix in the halo gas clouds and Kelvin–Helmholtz instabilities will fragment the clouds and force the ejecta to completely mix in the halo gas. The authors speculate that the *r*-process will return to star-forming regions in the host through diffusion and advection, and estimate $\gtrsim 1$ Gyr enrichment timescales for Milky Way–like halos. They assume the diffusion timescales are driven by diffusion coefficients

 $D \approx 1 \,\mathrm{kpc}^2 \,\mathrm{Gyr}^{-1}$, where $t_{\mathrm{diff}} = r_{\mathrm{KN}}^2/D$, typically used to describe diffusion in the galactic disk rather than the halo (B. G. Elmegreen & J. Scalo 2004; P. Beniamini & K. Hotokezaka 2020), and that the advection timescale is $\sim M_{\mathrm{halo}}/\mathrm{SFR}$, predicted for hot-mode accretion. Our results suggest that the diffusion timescales should be much shorter than their estimates, and given the relatively small radii where KNe occur, we suggest that the advection timescales should be much shorter than their enclosed by t_{ff} and t_{cool} . However, this disagreement in enrichment timescales emphasizes the importance of a more detailed simulation study in the future.

In summary, our results highlight that environmental enrichment is significantly delayed from the merger and that host properties and merger location dictate the length of the enrichment timescale.

5. Discussion

5.1. Enriched Stellar Mass

Our next goal is to understand what host and NS merger properties dictate whether a NS merger actually enriches starforming gas, or if the *r*-process is lost to the CGM or IGM. This, in turn, will help us determine whether the inferred *r*process masses in, for example, Galactic metal-poor stars and Local Group dwarf galaxies are directly comparable to the *r*process masses produced from mergers. Thus, we perform a simple exercise to determine the percentage of the stellar mass of each host galaxy that is enriched by the observed GRB-KN event, projected forward in time (hereafter, p_{enrich}). We define p_{enrich} as

$$p_{\text{enrich}} = \frac{M_{*,\text{enrich}}}{M_{*,0} + M_{*,\text{enrich}}},$$
(10)

where $M_{*,0}$ is the stellar mass formed in the host before enrichment (z_{enrich}), and $M_{*,enrich}$ represents the stellar mass formed after z_{enrich} to a future point in time. We assume that all stellar mass formed after z_{enrich} will procure some *r*-process materials, and thus $M_{*,enrich}$ is the "enriched" stellar mass. We show an illustration of p_{enrich} in Figure 5. Note that p_{enrich} characterizes the enrichment from a *single* KN event, and fully describing *r*-process chemical evolution in galaxies requires



Figure 5. An illustration of p_{enrich} and how it is affected by the host's SFH. In the "high" p_{enrich} example, a substantial fraction of stellar mass is produced after z_{enrich} in the host compared to the amount of stellar mass formed before z_{enrich} . In the "low" p_{enrich} example, the amount of stellar mass produced after z_{enrich} is small in comparison to the amount formed before.

accounting for other effects like the yield and rate of NS mergers over time, which are highly unconstrained both observationally and theoretically. It is estimated, for instance, that a typical Milky Way–sized galaxy has an *r*-process event rate of ~tens Myr^{-1} , translating to tens of thousands per billion years of events per Gyr (K. Hotokezaka et al. 2018; A. Rouco Escorial et al. 2023).

To determine p_{enrich} , we choose two lengths of time for a common comparison point within our sample: from z_{enrich} to z = 0, and 5 Gyr following z_{enrich} . We assume that the hosts have a constant SFR between z_{GRB} to these future points, and calculate the amount of mass formed in the host over this time period. We note that this a reasonable assumption as it mandates that the hosts will have decreasing specific SFR $(sSFR = SFR/M_* \text{ in yr}^{-1})$ with growing stellar mass. A more sophisticated SFH extrapolation would require simulations, which goes beyond the scope of this work. For the star-forming hosts in the sample, this extrapolation further also appears to keep the galaxies on the star-forming main sequence (J. S. Speagle et al. 2014; K. E. Whitaker et al. 2014; J. Leja et al. 2022), a well-known galaxy correlation between a galaxy's sSFR and stellar mass. We use the stellar mass-tomass formed fraction, obtained from Prospector, to convert the mass formed into stellar mass and calculate $M_{*,0}$ and $M_{*,\text{enrich}}$, projected to z=0 and 5 Gyr after enrichment, for each host.

We ignore any effects of galactic outflows or winds, as well as the fact that some *r*-process may be ejected in the opposite direction of star-forming gas given the isotropic nature of KNe, that may prevent some of this stellar mass from being enriched. We use the 68% confidence interval on their host SFRs (Table 1) to determine ranges of p_{enrich} of each host at z = 0 and 5 Gyr past enrichment. We also perform a similar calculation for the rest of the short GRB sample in A. E. Nugent et al. (2022) without detected KNe, using their reported stellar mass and SFR medians. With this analysis, we determine if the observed GRB population can be responsible for the stellar enrichment in their observed host galaxies.

In Figure 6, we show cumulative distribution functions (CDFs) of p_{enrich} for the GRB-KN and full GRB samples for



Figure 6. CDFs of the percentage of stellar mass of the host galaxy that is enriched by the observed GRB-KN sample (p_{enrich}) at z = 0 (solid blue) and by the full GRB-KN and short GRB sample (solid gray). We show the same for p_{enrich} 5 Gyr after enrichment (dashed lines). We find that the median $p_{enrich} = 13\%$ for the GRB-KN sample, suggesting that the majority of their *r*-process will be lost to the CGM or IGM. The median p_{enrich} for the full sample is 59%. Given that there is a significant fraction of hosts that have $\lesssim 50\%$ enrichment, this suggests that not all environments are capable of being strongly enriched from a single event.

both of the timescales between z_{GRB} to z = 0 and 5 Gyr after z_{enrich} . We first focus on p_{enrich} determined for z_{GRB} to z = 0. We find that five of the GRB-KN hosts in our sample have $p_{\text{enrich}} \leq 1\%$, suggesting very little capacity for enrichment from a single *r*-process event, while three GRB-KN hosts have high $p_{\text{enrich}} \gtrsim 50\%$. Including the A. E. Nugent et al. (2022) short GRB population, we find that 13% of the population has $p_{\text{enrich}} \lesssim 1\%$ and 59% of the population has high $p_{\text{enrich}} \gtrsim 50\%$. A key result is, therefore, that not all NS merger environments



Figure 7. Left: the host-galaxy stellar mass (at z_{GRB}) vs. physical projected offset for our GRB-KN sample (stars) and the A. E. Nugent et al. (2022) short GRB sample (circles). The color indicates the percent of stellar mass enriched with *r*-process (p_{enrich}) from each event at z = 0, and the black dashed line denotes the Milky Way properties (T. C. Licquia & J. A. Newman 2015). Middle: the same figure, but for the specific SFR (SFR/ M_*) vs. physical projected offset. Right: the redshift vs. p_{enrich} at z = 0. While there does not appear to be a trend between p_{enrich} and host stellar mass, GRB offset, or redshift (at $0.3 \leq z \leq 1$), we do find that p_{enrich} increases with sSFR. Importantly, this emphasizes that NS mergers occurring in environments with little ongoing star formation will have no impact on their *r*-process enrichment. From this, we can infer that not all NS mergers are contributing to stellar *r*-process enrichment.

have the capacity to be significantly enriched with r-process material, despite the existence of an r-process source. This is especially true if the environment has already formed the majority of stellar mass before a merger event, thereby leaving a small fraction of newly formed stellar mass for the NS merger to enrich (see Figure 5). Thus, we infer that a substantial fraction of r-process mass from NS mergers will be lost to the CGM or IGM, unlikely ever to be reincorporated in stars, implying that r-process "losses" are indeed significant. Similar results were found in F. van de Voort et al. (2022), where stellar r-process abundances were measured from simulated NS mergers with and without natal kicks. When including natal kicks in their simulations, they found NS mergers are more likely to occur with larger galactocentric offsets, and stellar rprocess abundances in the host are decreased by $\approx 50\%$ than when not including kicks. This suggests a substantial amount of r-process is not being reincorporated into stars. We find that when we evolve all host galaxies for 5 Gyr beyond z_{enrich} , p_{enrich} changes only minimally, with an average change of 5% for each GRB host. This implies that the length of time given to enrich star-forming gas has a small effect on the overall p_{enrich} from a single event.

We reiterate that our method for determining p_{enrich} is simple and likely unsuitable for several specific cases. For instance, given that SFRs are generally higher at higher redshifts, an extrapolation of constant SFR to z = 0 is unlikely to be realistic. Moreover, this method ignores any instances of possible future bursts of star formation after z_{GRB} . However, we emphasize that regardless of how p_{enrich} is determined, it remains clear that some galaxies will not have the capacity to be enriched from mergers similar to the sample studied in this work, assuming that they do not have a future burst of star formation that would increase their capacity for enrichment.

5.2. Trends with Host Properties and Offset

To understand if there are specific factors that dictate how highly enriched an environment is from a single NS merger event, we compare p_{enrich} (determined at z = 0) to different host and GRB properties. Naively, we might expect that a highly offset event would have the majority of *r*-process lost to the CGM and IGM, resulting in a low p_{enrich} . On the contrary, a higher-mass galaxy with a larger population of stars to enrich might receive more enrichment from a single NS merger.

In Figure 7, we show a median p_{enrich} in comparison to the projected physical offset and host stellar mass for each GRB-KN and A. E. Nugent et al. (2022) short GRB sample. We find little correlation between p_{enrich} and either of these properties, suggesting that the proximity to the host and its stellar mass has little or no effect on the host's capacity for enrichment. This is notable given that both properties strongly affect the enrichment timescale (Section 4). We do, however, observe that GRB hosts with $\log(M_*/M_{\odot}) \approx 9.5$ have a higher degree of enrichment. This is likely explained by the fact that galaxies around this stellar mass have higher sSFRs, and are still building up their stellar mass.

Indeed, we see a much stronger trend between the sSFR at z_{GRB} and p_{enrich} , as shown in Figure 7. Given the stronger dependence on sSFR rather than stellar mass or offset, this suggests that the enrichment timescale will only be a small perturbation in the host SFH. When considering all GRB-KNe and short GRBs with sSFR > 10^{-10} yr⁻¹ (70% of the population), all p_{enrich} are >19%, with median $p_{\text{enrich}} = 79\%$. In contrast, the maximum p_{enrich} for GRBs in hosts with low sSFR < 10^{-10} yr⁻¹ is 27% with median $p_{\text{enrich}} = 2\%$. For very low values below sSFR < $10^{-10.5}$ yr⁻¹ (18% of the population), the maximum $p_{\text{enrich}} = 5\%$, implying that environments with little to no ongoing star formation (and that have likely already built up the majority of their stellar mass) will not procure r-process material in newly forming stars. Interestingly, we also find that the Milky Way lies within this sSFR regime (T. C. Licquia & J. A. Newman 2015), with sSFR $\approx 10^{-10.6}$ yr⁻¹, implying that current or future Galactic NS mergers will have a minimal effect on the overall enrichment of the Milky Way. This is because the Milky Way has already formed most of its stars (C. Sneden et al. 2008), so future NS mergers will impact a very low fraction of all Milky Way stars.

Overall, our results indicate that there are specific circumstances that allow a NS merger environment to be more enriched with *r*-process. Specifically, the amount of active star formation in the host will heavily influence the fraction of stellar mass enriched. This is intuitive, given that a galaxy needs ongoing star formation in order to be enriched by subsequent *r*-process events. For instance, the long-delay-time NS merger GW170817, which occurred in an old, quiescent host galaxy, will have negligible effect on the *r*-process composition of the stars in its host. Future exploration using more complex simulations of galaxies and NS mergers is needed to better constrain the true rate of NS mergers that do indeed contribute *r*-process to their environments.

5.3. Redshift Effects

We further test if p_{enrich} (determined at z = 0) depends on the GRB redshift. It would be natural to assume, for instance, that the degree of enrichment might increase with GRB redshift as the *r*-process has more time to enrich newly forming stars. In Figure 7, we show p_{enrich} versus redshift. We find that at $0.3 \leq z \leq 1.0$ (60% of the full GRB sample), there is a large scatter in the values of p_{enrich} and no obvious trend between p_{enrich} and z_{GRB} . We verify this observed trend with a linear regression test, which indicates no linear correlation of p_{enrich} within this redshift range. This indicates that the majority of the observed NS merger population will not have p_{enrich} affected by redshift.

While there is no trend between p_{enrich} and z_{GRB} at $0.3 < z_{\text{GRB}} < 1$, we do find that at $z_{\text{GRB}} > 1$ all hosts have high enrichment from a single event ($p_{\text{enrich}} > 76\%$), while at z < 0.3 the majority of hosts have minimal enrichment ($p_{\text{enrich}} < 51\%$). Indeed, when including all GRBs, a linear regression test leads to a positive linear correlation between z and p_{enrich} .

A natural subsequent question might be whether the majority of observed r-process in stars derives from high-redshift events. There are a couple of competing factors that make it difficult to answer this. For one, at higher redshifts the sSFR of an average galaxy is higher, which would lead to more stars forming and a higher capacity for enrichment. However, the rates of NS mergers at higher redshifts are also lower than at lower redshifts, which is backed by the short GRB luminosity distribution (D. Wanderman & T. Piran 2015; A. Lien et al. 2016) and estimates on the NS merger delay-time distribution (K. Belczynski et al. 2002; E. Nakar et al. 2006; E. Berger et al. 2007; S. Jeong & C.-H. Lee 2010; M. Dominik et al. 2012; J.-M. Hao & Y.-F. Yuan 2013; D. Wanderman & T. Piran 2015; T. M. Tauris et al. 2017; N. Anand et al. 2018; A. Vigna-Gómez et al. 2018; J. J. Andrews & I. Mandel 2019; P. Beniamini & T. Piran 2019; M. Zevin et al. 2022). Moreover, from both observational studies of tidally disrupted dwarfs in the Milky Way (e.g., R. P. Naidu et al. 2022; X. Ou et al. 2024) and simulation-based studies on Milky Way analogs (e.g., S. Shen et al. 2015; F. van de Voort et al. 2015, 2020), it is apparent that delayed r-process sources throughout galaxies' star formation period are needed to explain their stars' chemical enrichment. Thus, it is unlikely that highredshift GRBs alone could be responsible for the bulk of observed r-process in stars.

5.4. R-process Enrichment at Low Metallicity

Finally, we speculate on the *r*-process events that were responsible for the enrichment observed in Galactic metal-poor stars and low-metallicity Local Group dwarf galaxies. Enrichment at low metallicity prefers *r*-process from short merging delay times, which has been invoked many times (e.g., D. Argast et al. 2004; B. Wehmeyer et al. 2015). If NS mergers are capable of merging as quickly as the minimum delay time predicted by

theoretical work (≈ 10 Myr; K. Belczynski et al. 2002; M. Dominik et al. 2012; A. Vigna-Gómez et al. 2018; P. Beniamini & T. Piran 2019), then enrichment at low metallicity is almost certainly created by NS mergers. However, if the delay time is longer, as predicted by observations of short GRBs and Galactic NS systems (≈ 200 Myr; E. Nakar et al. 2006; E. Berger et al. 2007; S. Jeong & C.-H. Lee 2010; J.-M. Hao & Y.-F. Yuan 2013; D. Wanderman & T. Piran 2015; T. M. Tauris et al. 2017; N. Anand et al. 2018; A. Vigna-Gómez et al. 2018; J. J. Andrews & I. Mandel 2019; M. Zevin et al. 2022), then NS mergers are unlikely to be a viable r-process source at low metallicity. Moreover, our work highlights that there is an additional timescale that needs to be incorporated when determining how quickly an environment is enriched after an r-process event: the enrichment timescale. Given that the enrichment timescale we find is not trivial (≈134 Myr), it becomes even more difficult for NS mergers to contribute at early times in low-metallicity dwarf galaxies. Additionally, we show in Figure 4 that the enrichment timescales can be quite long for small, dwarf-galaxy-sized halos ($\leq 10^{11} M_{\odot}$), even at moderate NS merger offsets.

If collapsars and rare types of CCSNe were discovered to also produce r-process, this would be a more natural explanation for metal-poor stellar enrichment. Indeed, their delay times are much faster than NS mergers, ≈ 10 Myr, and they are typically found embedded in star-forming regions within their hosts (P. L. Kelly et al. 2008; J. L. Prieto et al. 2008; P. K. Blanchard et al. 2016). Many works have also suggested that a faster r-process channel like CCSNe is required to explain observed r-process abundances (S. Shen et al. 2015; F. van de Voort et al. 2015; Y. Komiya & T. Shigeyama 2016; K. Hotokezaka et al. 2018; B. Côté et al. 2019; P. Simonetti et al. 2019; Á. Skúladóttir & S. Salvadori 2020). However, there is still skepticism from both observations and theory that any class of CCSNe produces *r*-process; thus, this may not be a valid explanation for enrichment at low metallicity. Furthermore, r-process material from CCSNe may be subject to other processes that prevent enrichment (like SN winds) given their proximity to star-forming regions, or, contrarily, may lead to environments that are too well enriched and thus not representative of the observed scatter in r-process abundances at low metallicity.

While we find that it would be unlikely for NS mergers to be responsible for enrichment in low-metallicity environments, we caution the reader against assuming that it is *impossible*. The delay-time distribution of NS mergers is still unconstrained, especially at low metallicity. Thus, it is still ambiguous if NS systems can merge on more rapid timescales. Additionally, while uncommon within our sample, we do find that nine GRBs (all with small physical deprojected offsets of <1.5 kpc) have enrichment timescales <50 Myr. Were these GRBs to also have similarly fast delay times, this may represent a population that could be capable of enriching low-metallicity environments. An observational study of 11 short GRBs occurring in central locations within dwarf galaxy hosts (A. E. Nugent et al. 2024) has further hinted that NS mergers may indeed be the source of r-process enrichment within low-mass galaxies. Thus, it is difficult to interpret at this time if another r-process channel is required to explain enrichment of all environments.

We finally note that the source of *r*-process enrichment at all metallicities remains an open, unanswered question. Several

works have shown, using assumptions on the NS merger delaytime distribution, that a more prompt channel than NS mergers, like collapsars, is also needed to explain the r-process abundance pattern of higher-metallicity Milky Way disk stars (e.g., B. Côté et al. 2019; D. M. Siegel et al. 2019). Given that we find the enrichment timescale is not trivial in comparison to the delay time, we suggest that it should be included in future chemical evolution simulations to better probe the dominant source of *r*-process in stars at the full metallicity range.

6. Conclusion

In this paper, we quantify the timescale for r-process from observed GRB-KNe and short GRBs to be transported back into their host and mix with the ISM. We further consider the impact of a single event on the stellar r-process enrichment of their host environments. We find that the typical r-process enrichment timescale is 134^{+171}_{-83} Myr. In comparison to minimum NS merger delay times of $\approx 10-200$ Myr, the enrichment timescale is significant, implying that there is an additional, substantial delay following the merger to when the environment can be enhanced by *r*-process. We find that only $\approx 60\%$ of the observed GRB-KN and short GRB population will contribute significant r-process enrichment to the stellar mass of their host galaxy. The capacity of environmental rprocess enrichment from a single event most strongly correlates with the amount of active star formation in the hosts, as hosts with little to no ongoing star formation have a low fraction of stellar mass enriched by a single event (including that of GW170817). This implies that a significant fraction of rprocess mass from NS mergers either is not incorporated into a large fraction of stellar mass within their hosts or is lost to the CGM and IGM.

Given our findings, it is useful to consider whether there is any possibility of detecting r-process lines in the IGM or CGM to observationally quantify the amount of "lost" r-process mass. Unfortunately, we suspect that it is highly unlikely that rprocess signatures can be detected outside of stars or stellar remnants. The high atomic mass of *r*-process elements implies that the material will be split into fewer atoms of each element and across many different isotopes. Moreover, r-process masses from single events tend to be quite small, suggesting that it will be extremely difficult to detect spectral emission or absorption features. Thus, future studies on r-process event rates should focus on the fraction of material making it back into star-forming gas and consider the impact of losses for any relevant observational comparison.

Acknowledgments

We thank the anonymous referee for comments and suggestions. We thank Claude-André Faucher-Giguère, Alexa Gordon, and Michael Zevin for helpful discussions and commentary. The Fong Group at Northwestern acknowledges support by the National Science Foundation under grants AST-1909358, AST-2206494, AST-2308182, and CAREER grant No. AST-2047919. A.P.J. acknowledges support by the National Science Foundation under grants AST-2206264 and AST-2307599. W.F. gratefully acknowledges support by the David and Lucile Packard Foundation, the Alfred P. Sloan Foundation, and the Research Corporation for Science Advancement through Cottrell Scholar Award 28284. F.v.d.V.

is supported by a Royal Society University Research Fellowship (URFR1191703).

This research was supported in part through the computational resources and staff contributions provided for the Ouest high-performance computing facility at Northwestern University, which is jointly supported by the Office of the Provost, the Office for Research, and Northwestern University Information Technology.

Software: Prospector (B. D. Johnson et al. 2021), Python-fsps (C. Conroy et al. 2009; C. Conroy & J. E. Gunn 2010), Dynesty (J. S. Speagle 2020), Astropy (J.-M. Hao & Y.-F. Yuan 2013).

ORCID iDs

Anya E. Nugent () https://orcid.org/0000-0002-2028-9329 Alexander P. Ji ⁽¹⁾ https://orcid.org/0000-0002-4863-8842 Wen-fai Fong https://orcid.org/0000-0002-7374-935X Hilay Shah (1) https://orcid.org/0000-0002-9136-6731 Freeke van de Voort https://orcid.org/0000-0002-6301-638X

References

- Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017a, ApJL, 848, L13
- Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017b, ApJL, 848, L12
- Ahumada, R., Prieto, C. A., Almeida, A., et al. 2020, ApJS, 249, 3
- Alam, S., Albareti, F. D., Allende Prieto, C., et al. 2015, ApJS, 219, 12
- Amend, B., Zrake, J., & Hartmann, D. H. 2022, ApJ, 939, 59
- Anand, N., Shahid, M., & Resmi, L. 2018, MNRAS, 481, 4332
- Anand, S., Barnes, J., Yang, S., et al. 2024, ApJ, 962, 68
- Andrews, J. J., & Mandel, I. 2019, ApJL, 880, L8
- Andrews, J. J., & Zezas, A. 2019, MNRAS, 486, 3213
- Argast, D., Samland, M., Thielemann, F. K., & Qian, Y. Z. 2004, A&A, 416, 997
- Behroozi, P., Wechsler, R. H., Hearin, A. P., & Conroy, C. 2019, MNRAS, 488, 3143
- Belczynski, K., Dominik, M., Bulik, T., et al. 2010, ApJL, 715, L138
- Belczynski, K., Kalogera, V., & Bulik, T. 2002, ApJ, 572, 407
- Beniamini, P., & Hotokezaka, K. 2020, MNRAS, 496, 1891
- Beniamini, P., Hotokezaka, K., & Piran, T. 2016, ApJ, 832, 149
- Beniamini, P., & Piran, T. 2019, MNRAS, 487, 4847
- Bennett, C. L., Larson, D., Weiland, J. L., & Hinshaw, G. 2014, ApJ, 794, 135 Berger, E. 2014, ARA&A, 52, 43
- Berger, E., Fong, W., & Chornock, R. 2013, ApJL, 774, L23
- Berger, E., Fox, D. B., Price, P. A., et al. 2007, ApJ, 664, 1000
- Blanchard, P. K., Berger, E., Fong, W., et al. 2017, ApJL, 848, L22
- Blanchard, P. K., Berger, E., & Fong, W.-f. 2016, ApJ, 817, 144
- Blanchard, P. K., Villar, V. A., Chornock, R., et al. 2024, NatAs, 8, 774
- Brauer, K., Ji, A. P., Drout, M. R., & Frebel, A. 2021, ApJ, 915, 81
- Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, ApJ, 533, 682
- Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
- Chen, M.-H., Li, L.-X., Chen, Q.-H., Hu, R.-C., & Liang, E.-W. 2024, MNRAS, 529, 1154
- Chornock, R., Berger, E., Kasen, D., et al. 2017, ApJL, 848, L19
- Church, R. P., Levan, A. J., Davies, M. B., & Tanvir, N. 2011, MNRAS, 413, 2004
- Conroy, C., & Gunn, J. E. 2010, ApJ, 712, 833
- Conroy, C., Gunn, J. E., & White, M. 2009, ApJ, 699, 486
- Correa, C. A., Wyithe, J. S. B., Schaye, J., & Duffy, A. R. 2015, MNRAS, 452, 1217
- Côté, B., Eichler, M., Arcones, A., et al. 2019, ApJ, 875, 106
- Côté, B., Fryer, C. L., Belczynski, K., et al. 2018, ApJ, 855, 99
- Covino, S., Malesani, D., Israel, G. L., et al. 2006, A&A, 447, L5 de Ugarte Postigo, A., Thöne, C. C., Rowlinson, A., et al. 2014, A&A, 563, A62
- Dominik, M., Belczynski, K., Fryer, C., et al. 2012, ApJ, 759, 52
- Draine, B. T., & Li, A. 2007, ApJ, 657, 810
- Eichler, D., Livio, M., Piran, T., & Schramm, D. N. 1989, Natur, 340, 126
- Elmegreen, B. G., & Scalo, J. 2004, ARA&A, 42, 211
- Falcón-Barroso, J., Sánchez-Blázquez, P., Vazdekis, A., et al. 2011, A&A, 532, A95

- Faucher-Giguère, C.-A., & Oh, S. P. 2023, ARA&A, 61, 131
- Fong, W., & Berger, E. 2013, ApJ, 776, 18
- Fong, W., Berger, E., & Fox, D. B. 2010, ApJ, 708, 9
- Fong, W., Laskar, T., Rastinejad, J., et al. 2021, ApJ, 906, 127
- Fong, W., Margutti, R., Chornock, R., et al. 2016, ApJ, 833, 151
- Fong, W.-f., Nugent, A. E., Dong, Y., et al. 2022, ApJ, 940, 56
- Gal-Yam, A., Fox, D. B., Price, P. A., et al. 2006, Natur, 444, 1053
- Gallazzi, A., Charlot, S., Brinchmann, J., White, S. D. M., & Tremonti, C. A. 2005, MNRAS, 362, 41
- Gaspari, N., Levan, A. J., Chrimes, A. A., & Nelemans, G. 2024, MNRAS, 527, 1101
- Gillanders, J. H., Troja, E., Fryer, C. L., et al. 2023, arXiv:2308.00633
- Goldstein, A., Veres, P., Burns, E., et al. 2017, ApJL, 848, L14
- Gompertz, B. P., Levan, A. J., Tanvir, N. R., et al. 2018, ApJ, 860, 62
- Gorosabel, J., Castro-Tirado, A. J., Guziy, S., et al. 2006, A&A, 450, 87
- Graham, J. F., Fruchter, A. S., Levan, A. J., et al. 2009, ApJ, 698, 1620
- Grand, R. J. J., Gómez, F. A., Marinacci, F., et al. 2017, MNRAS, 467, 179
- Halevi, G., & Mösta, P. 2018, MNRAS, 477, 2366
- Hao, J.-M., & Yuan, Y.-F. 2013, A&A, 558, A22
- Hinshaw, G., Larson, D., Komatsu, E., et al. 2013, ApJS, 208, 19
- Hjorth, J., Watson, D., Fynbo, J. P. U., et al. 2005, Natur, 437, 859
- Hotokezaka, K., Beniamini, P., & Piran, T. 2018, IJMPD, 27, 1842005
- Hotokezaka, K., Tanaka, M., Kato, D., & Gaigalas, G. 2023, MNRAS, 526. L155
- Jeong, M., & Im, M. 2024, ApJ, 974, 114
- Jeong, S., & Lee, C.-H. 2010, JKPS, 56, 1619
- Ji, A. P., Frebel, A., Chiti, A., & Simon, J. D. 2016, Natur, 531, 610
- Ji, A. P., Simon, J. D., Roederer, I. U., et al. 2023, AJ, 165, 100
- Jin, Z.-P., Covino, S., Liao, N.-H., et al. 2020, NatAs, 4, 77
- Jin, Z.-P., Hotokezaka, K., Li, X., et al. 2016, NatCo, 7, 12898
- Jin, Z.-P., Li, X., Cano, Z., et al. 2015, ApJL, 811, L22
- Johnson, B. D., Leja, J., Conroy, C., & Speagle, J. S. 2021, ApJS, 254, 22
- Kasen, D., Metzger, B., Barnes, J., Quataert, E., & Ramirez-Ruiz, E. 2017, latur, 551, 80
- Kasliwal, M. M., Korobkin, O., Lau, R. M., Wollaeger, R., & Fryer, C. L. 2017, ApJL, 843, L34
- Kawaguchi, K., Kyutoku, K., Shibata, M., & Tanaka, M. 2016, ApJ, 825, 52
- Kelly, P. L., Kirshner, R. P., & Pahre, M. 2008, ApJ, 687, 1201
- Kilpatrick, C. D., Fong, W.-f., Blanchard, P. K., et al. 2022, ApJ, 926, 49
- Kolborg, A. N., Ramirez-Ruiz, E., Martizzi, D., Macias, P., & Soares-Furtado, M. 2023, ApJ, 949, 100
- Komiya, Y., & Shigeyama, T. 2016, ApJ, 830, 76 Kriek, M., & Conroy, C. 2013, ApJL, 775, L16
- Kroupa, P., & Jerabkova, T. 2021, arXiv:2112.10788
- Lamb, G. P., Tanvir, N. R., Levan, A. J., et al. 2019, ApJ, 883, 48
- Leibler, C. N., & Berger, E. 2010, ApJ, 725, 1202
- Leja, J., Johnson, B. D., Conroy, C., et al. 2019, ApJ, 877, 140
- Leja, J., Speagle, J. S., Ting, Y.-S., et al. 2022, ApJ, 936, 165
- Levan, A. J., Gompertz, B. P., Salafia, O. S., et al. 2024, Natur, 626, 737
- Levan, A. J., Lyman, J. D., Tanvir, N. R., et al. 2017, ApJL, 848, L28
- Licquia, T. C., & Newman, J. A. 2015, ApJ, 806, 96
- Lien, A., Sakamoto, T., Barthelmy, S. D., et al. 2016, arXiv:1606.01956
- Limberg, G., Ji, A. P., Naidu, R. P., et al. 2024, MNRAS, 530, 2512
- Macias, P., & Ramirez-Ruiz, E. 2018, ApJ, 860, 89
- Mandhai, S., Lamb, G. P., Tanvir, N. R., et al. 2022, MNRAS, 514, 2716
- Matsuno, T., Hirai, Y., Tarumi, Y., et al. 2021, A&A, 650, A110
- McCully, C., Hiramatsu, D., Howell, D. A., et al. 2017, ApJL, 848, L32
- McWilliam, A., Preston, G. W., Sneden, C., & Searle, L. 1995, AJ, 109, 2757
- Molero, M., Romano, D., Reichert, M., et al. 2021, MNRAS, 505, 2913
- Montes, G., Ramirez-Ruiz, E., Naiman, J., Shen, S., & Lee, W. H. 2016, ApJ, 830, 12
- Morrissey, P., Conrow, T., Barlow, T. A., et al. 2007, ApJS, 173, 682
- Naidu, R. P., Ji, A. P., Conroy, C., et al. 2022, ApJL, 926, L36
- Nakar, E., Gal-Yam, A., & Fox, D. B. 2006, ApJ, 650, 281
- Navarro, J. F., Frenk, C. S., & White, S. D. M. 1996, ApJ, 462, 563 Niino, Y., Aoki, K., Hashimoto, T., et al. 2017, PASJ, 69, 27
- Nugent, A. E., Fong, W.-f., Castrejon, C., et al. 2024, ApJ, 962, 5
- Nugent, A. E., Fong, W.-F., Dong, Y., et al. 2022, ApJ, 940, 57
- O'Connor, B., Troja, E., Dichiara, S., et al. 2021, MNRAS, 502, 1279
- O'Connor, B., Troja, E., Dichiara, S., et al. 2022, MNRAS, 515, 4890
- Oppenheimer, B. D., Davies, J. J., Crain, R. A., et al. 2020, MNRAS, 491, 2939
- O'Shaughnessy, R., Bellovary, J. M., Brooks, A., et al. 2017, MNRAS, 464, 2831
- Ou, X., Ji, A. P., Frebel, A., Naidu, R. P., & Limberg, G. 2024, ApJ, 974, 232

Palmese, A., Hartley, W., Tarsitano, F., et al. 2017, ApJL, 849, L34

Nugent et al.

- Paxton, B., Schwab, J., Bauer, E. B., et al. 2018, ApJS, 234, 34
- Perley, D. A., Levan, A. J., Tanvir, N. R., et al. 2013, ApJ, 778, 128
- Pian, E., D'Avanzo, P., Benetti, S., et al. 2017, Natur, 551, 67
- Prieto, J. L., Stanek, K. Z., & Beacom, J. F. 2008, ApJ, 673, 999
- Putman, M. E., Peek, J. E. G., & Joung, M. R. 2012, ARA&A, 50, 491 Qian, Y. Z. 2000, ApJL, 534, L67
- Rastinejad, J. C., Fong, W., Kilpatrick, C. D., et al. 2021, ApJ, 916, 89
- Rastinejad, J. C., Fong, W., Levan, A. J., et al. 2024, ApJ, 968, 14
- Rastinejad, J. C., Gompertz, B. P., Levan, A. J., et al. 2022, Natur, 612, 223
- Rees, M. J., & Ostriker, J. P. 1977, MNRAS, 179, 541
- Reggiani, H., Schlaufman, K. C., Casey, A. R., Simon, J. D., & Ji, A. P. 2021, AJ, 162, 229
- Rossi, A., Stratta, G., Maiorano, E., et al. 2020, MNRAS, 493, 3379
- Rosswog, S., Sollerman, J., Feindt, U., et al. 2018, A&A, 615, A132
- Rouco Escorial, A., Fong, W., Berger, E., et al. 2023, ApJ, 959, 13
- Savchenko, V., Ferrigno, C., Kuulkers, E., et al. 2017, ApJL, 848, L15
- Scalo, J., & Elmegreen, B. G. 2004, ARA&A, 42, 275 Schlafly, E. F., & Finkbeiner, D. P. 2011, ApJ, 737, 103
- Schulze, S., Yaron, O., Sollerman, J., et al. 2021, ApJS, 255, 29
- Shappee, B. J., Simon, J. D., Drout, M. R., et al. 2017, Sci, 358, 1574
- Shen, S., Cooke, R. J., Ramirez-Ruiz, E., et al. 2015, ApJ, 807, 115
- Shetrone, M. D., Côté, P., & Sargent, W. L. W. 2001, ApJ, 548, 592
- Siegel, D. M., Barnes, J., & Metzger, B. D. 2019, Natur, 569, 241
- Silk, J. 1977, ApJ, 211, 638

848, L27

512, 5258

481, 4009

13

- Simonetti, P., Matteucci, F., Greggio, L., & Cescutti, G. 2019, MNRAS, 486, 2896
- Skúladóttir, Á., Hansen, C. J., Salvadori, S., & Choplin, A. 2019, A&A, 631, A171
- Skúladóttir, Á., & Salvadori, S. 2020, A&A, 634, L2
- Sneden, C., Cowan, J. J., & Gallino, R. 2008, ARA&A, 46, 241 Speagle, J. S. 2020, MNRAS, 493, 3132
- Speagle, J. S., Steinhardt, C. L., Capak, P. L., & Silverman, J. D. 2014, ApJS, 214, 15
- Stern, J., Fielding, D., Faucher-Giguére, C.-A., & Quataert, E. 2019, MNRAS, 488, 2549
- Stern, J., Fielding, D., Faucher-Giguére, C.-A., & Quataert, E. 2020, MNRAS, 492, 6042
- Svensson, K. M., Levan, A. J., Tanvir, N. R., Fruchter, A. S., & Strolger, L. G. 2010, MNRAS, 405, 57

Tanvir, N. R., Levan, A. J., González-Fernández, C., et al. 2017, ApJL,

Tsujimoto, T., Ishigaki, M. N., Shigeyama, T., & Aoki, W. 2015, PASJ, 67, L3

Tunnicliffe, R. L., Levan, A. J., Tanvir, N. R., et al. 2014, MNRAS, 437, 1495 van de Voort, F., Bieri, R., Pakmor, R., et al. 2021, MNRAS, 501, 4888

van de Voort, F., Pakmor, R., Bieri, R., & Grand, R. J. J. 2022, MNRAS,

van de Voort, F., Pakmor, R., Grand, R. J. J., et al. 2020, MNRAS, 494, 4867

van de Voort, F., Quataert, E., Hopkins, P. F., Kereš, D., &

Vigna-Gómez, A., Neijssel, C. J., Stevenson, S., et al. 2018, MNRAS,

Wehmeyer, B., Pignatari, M., & Thielemann, F. K. 2015, MNRAS, 452, 1970

Wiersma, R. P. C., Schaye, J., Theuns, T., Dalla Vecchia, C., & Tornatore, L.

Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, AJ, 140, 1868

Venn, K. A., Shetrone, M. D., Irwin, M. J., et al. 2012, ApJ, 751, 102

Vergani, S. D., Salvaterra, R., Japelj, J., et al. 2015, A&A, 581, A102

Villar, V. A., Guillochon, J., Berger, E., et al. 2017, ApJL, 851, L21

Whitaker, K. E., Franx, M., Leja, J., et al. 2014, ApJ, 795, 104

Yang, Y.-H., Troja, E., O'Connor, B., et al. 2024, Natur, 626, 742

Zevin, M., Kelley, L. Z., Nugent, A., et al. 2020, ApJ, 904, 190 Zevin, M., Nugent, A. E., Adhikari, S., et al. 2022, ApJL, 940, L18

Tanvir, N. R., Levan, A. J., Fruchter, A. S., et al. 2013, Natur, 500, 547

Tauris, T. M., Kramer, M., Freire, P. C. C., et al. 2017, ApJ, 846, 170 Troja, E., Fryer, C. L., O'Connor, B., et al. 2022, Natur, 612, 228

Tarumi, Y., Yoshida, N., & Inoue, S. 2020, MNRAS, 494, 120

Taggart, K., & Perley, D. A. 2021, MNRAS, 503, 3931

Troja, E., Ryan, G., Piro, L., et al. 2018, NatCo, 9, 4089

Faucher-Giguère, C.-A 2015, MNRAS, 447, 140

Wanderman, D., & Piran, T. 2015, MNRAS, 448, 3026

White, S. D. M., & Rees, M. J. 1978, MNRAS, 183, 341

Yang, B., Jin, Z.-P., Li, X., et al. 2015, NatCo, 6, 7323 Yang, J., Ai, S., Zhang, B.-B., et al. 2022, Natur, 612, 232

Wang, F. Y., & Dai, Z. G. 2014, ApJS, 213, 15

2009, MNRAS, 399, 574