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Where has all the r-process gone? Timescales for GRB-Kilonovae to Enrich their Host Galaxies

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Introduction

- Neutron Star (NS) mergers are the only observed evidence of r-process production in the Universe. (r-process : one of the origins of heavier elements than Fe)
- They explore the extent to which **NS merger location** and **host galaxy properties affect the incorporation of r-process elements into star-formation gas**
- They **quantify an "enrichment" timescale** to account for this process.
  - "enrichment" timescale : the delay between r-process events and the redistribution of the metals into star-forming gas

Sample

- 12 Gamma Ray Bursts (GRB) with probable kilonovae (KNe)
  - Confident host galaxy associations
  - Confirmed spectroscopic redshifts from their hosts
- 74 short GRBs without claimed KNe

- to determine M_* and SFRs, Code *Prospector* was used.
- The redshift dependent relation defined M_*-M_h by UniverseMachine was used

Table 1. GRB, Host, and Halo Properties

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

$$r_{\rm vir} = 260\ \mathrm{kpc} \times \left(\frac{M_h}{10^{12} M_\odot}\right)^{1/3}. \qquad V_{\rm vir} = \sqrt{GM_h/r_{\rm vir}}, \qquad T_{\rm vir} = \frac{\mu m_p V_{\rm vir}^2}{2k_B}\ \mathrm{K},$$

Two scenarios of transportation of r-process metal

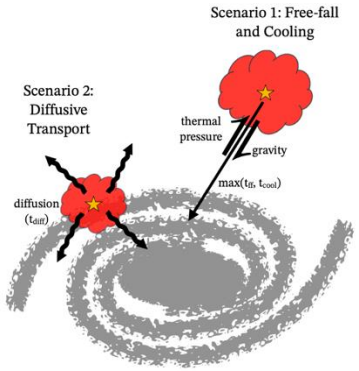
- how to quantify the enrichment timescale

1.free-fall & cooling scenario

- gravity vs thermal pressure
- $t_{cool} < t_{ff}$ → halo gas is not enough to support the r-process metals against gravitational free-fall.
- enrichment timescale = max (t_{ff}, t_{cool})

2.Diffusion scenario

- r-process metal transport in turbulent gas
- Using cosmological zoom-in simulations by Shah et al.(2024)
- enrichment timescale = t_{diff}



Results

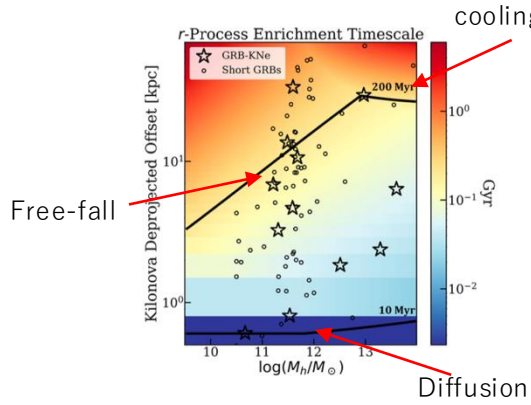
- The enrichment timescale : min(t_{diff}, max(t_{ff}, t_{cool}))
  - GRB-KNe : 28-449Myr , median 100^{+114}_{-58} Myr.
  - Full short GRBs : 7Myr-1.6Gyr, median 138^{+177}_{-78} Myr
- Environment enrichment is significantly delayed form the merger
- Host properties and merger location dictate the length of the enrichment timescale

Offset and halo mass are very large

offset is < 1kpc

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

Table 2. Enrichment Timescales for GRB-KNe and GRB Populations



Disuccsion&Conclusion

- p_{enrich}: the percentage of enriched host stellar mass within KN host sample (M_{enrich}/M^*) , projected forward in time, assuming hosts have constant SFR after z_{GRB}
  - Between $z = z_{GRB}$ and $z = 0$
  - following 5Gyr after z_{enrich}
- 5 GRB-KN hosts have very little capacity for enrichment $p_{enrich} < 1\%$, 3 GRB-KN hosts have high $p_{enrich} > 50\%$
  - Not all NS mergers environments have the capacity to be significantly enriched with r-process material.
  - a substantial fraction of r-process mass from NS mergers will be lost to the CGM or IGM.
- p_{enrich} is <u>little affected by host stellar mass or physical offset</u> and more influenced by <u>sSFR.</u>