The History of the R-Process

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GW170817

This was a unique event in astronomy, maybe the most important observation since SN 1987A.

SN 1987A was the first ‘multi-messenger’ observation in which observations of a nearby supernova were accompanied by neutrino detections in at least two neutrino observatories.

GW170817 carried this to unprecedented levels. This event was observed in

- gravitational waves (GW)
- gamma rays (Fermi and Integral)
- X-rays (Swift, XMM and Chandra)
- UV, optical and IR (HST + more than 100 telescopes)
- mm and radio (ALMA, GMRT, VLA, others)

In all, about 3500 astronomers observed this event.

There are only 10,000 astronomers worldwide.

The History of the R-Process

- Accurate determination of isotopic abundances
- Realization that heavy elements were synthesized by neutron-capture processes involving dramatically different neutron fluxes, i.e., the s-process and the r-process.
- Determination of the thermodynamical and dynamical conditions necessary for r-process nucleosynthesis
- Identification of possible sites for the r-process: the Big Bang, supernovae, and compact object mergers.
- Vigorous experimental and theoretical efforts to determine the properties of neutron-rich nuclides.
- Decades of simulations
- Realization of the importance of neutrino-matter interactions.

The History, Continued

- Identification of r-process elements in metal-poor stars.
- Changing theoretical ideas concerning galactic chemical evolution.
- Non-association of SGRBs with supernovae and their default association with compact object mergers.
- Development of the kilonova hypothesis as the photon signature of a merger: multimessenger astronomy.
- Some SGRB afterglows suspected to be kilonovae.
- Terrestrial ^{244}Pu, an unstable r-process nucleus, discovered.
- Identification of r-process enriched stars in a small minority of ultra-faint dwarf galaxies.
- GW170817.

Why is GW170817 Important?

- The GW signal is what is expected from a binary neutron star (BNS) merger.
- The GW signal was followed within 1.7 seconds by a short gamma-ray burst (SGRB) from the same location.
- The optical and infrared radiation observed from 11 hours to two weeks afterwards indicated that a few percent of the total mass was ejected at velocities up to c/3, which then created very heavy elements.
- The X-rays were delayed by two weeks, indicating that we observed this gamma-ray burst off-axis.
- The radio emission comes from the interaction of the blast wave with the surrounding interstellar medium.

Triumph for Astrophysics Theory and Computation

Mergers of neutron stars and many of the subsequent observations had been predicted to occur.

- BNS and black hole-NS (BHNS) mergers were suspected, but never confirmed, to be the source of SGRBs.
- BNS mergers had been predicted to eject $0.01 - 0.1 M_\odot$ of NS matter at higher than escape velocities, $v \gtrsim c/10$.
- The subsequent decompression of the neutron star matter was expected to synthesize extremely neutron-rich nuclei.
- These highly-radioactive nuclei decay to form the stable r-process nuclei (half the nuclides heavier than iron).
- γ-rays from β-decays and fission were predicted to power an optical/IR kilonova .
- Only high-opacity lanthanides in the ejecta can seemingly account for the duration of the observed light curve.

Evidently, very heavy radioactive elements are being synthesized in this event.

Why is this important?

The origin of the heavy elements has been one of Nuclear Physics outstanding questions.

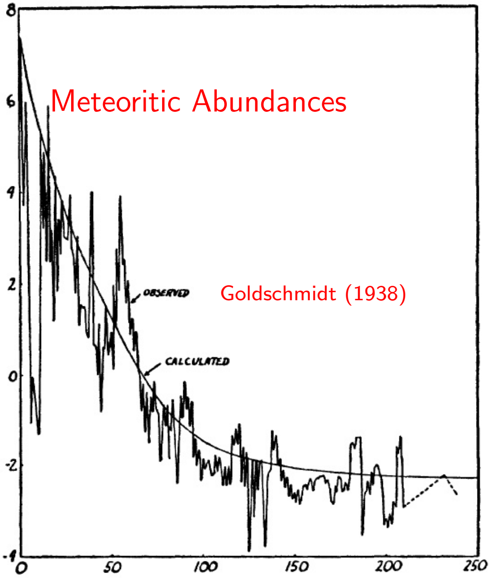
We now consider the history of this question.

Abundances of Nuclides

Earliest abundances from the Earth's crust (Clark 1889) and meteorites (Goldschmidt 1938) were largely ignored, being too early.

The nuclear shell model was developed in 1949 by Wigner, Mayer and Jensen, and the significance of the magic numbers was realized.

When N or Z equal 2, 8, 20, 28, 50, 82 or 126 nucleon shells are closed and nuclei are particularly stable.



Meteoritic Abundances

Goldschmidt (1938)

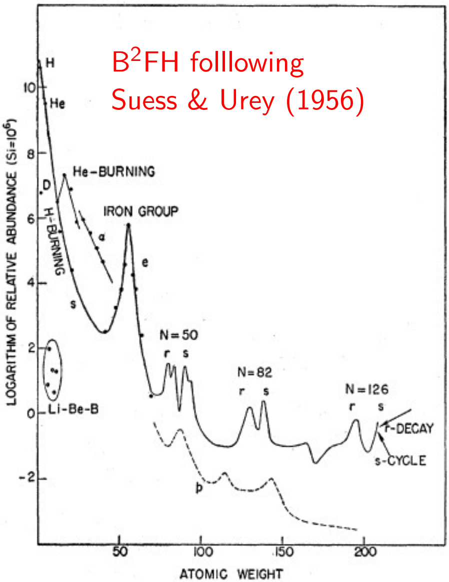
FIG. 1.

Log of relative abundance

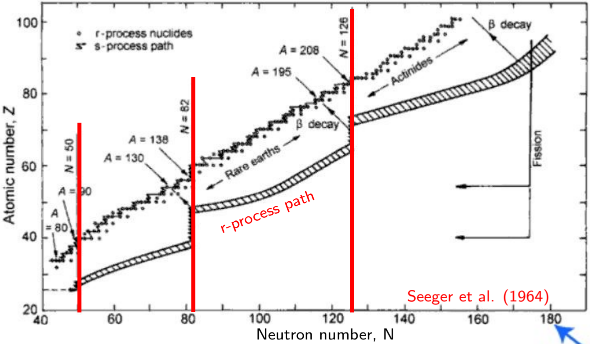
Atomic weight

In the beginning, before B^{2}FH . . .

- Hoyle (1946): heavy elements require the explosive conditions found in the core collapse of stars.
- Alpher, Bethe & Gamow (1948): heavy elements originate from *n* captures in β-disequilibrium to explain large abundances near *n* magic numbers. Occurs during the Big Bang. Later work with Herman further refined this idea.
- Suess & Urey (1956) compiled abundances revealing two peaks near each *N* magic number.
- Coryell (1956): two peaks stem from slow or rapid *n*-capture; the continuity of the abundance pattern indicates universality.

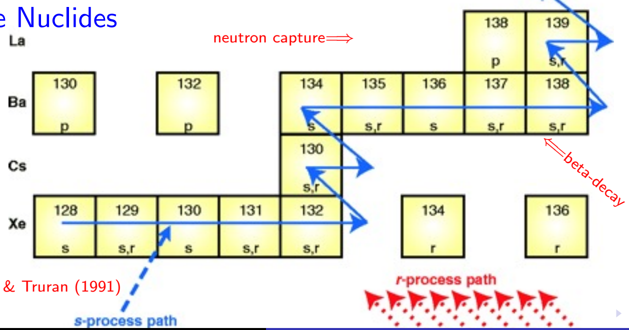


B^{2}FH folllowing Suess & Urey (1956)

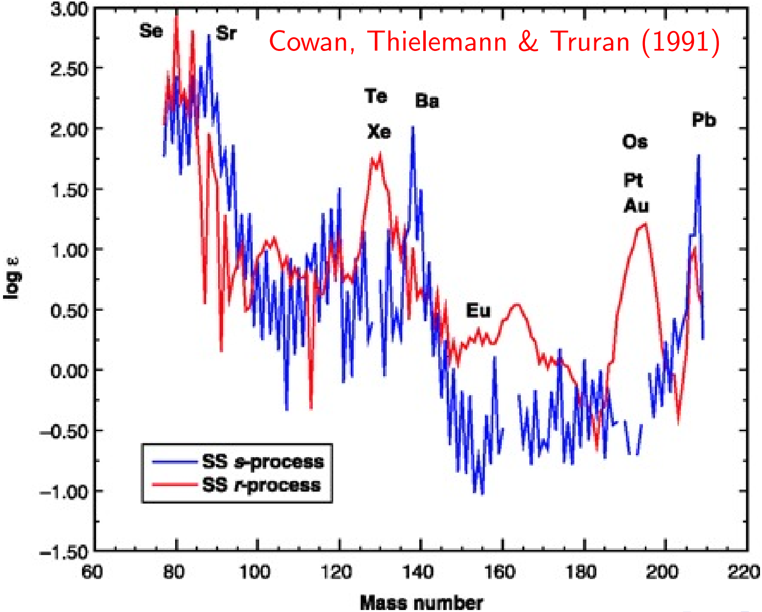


Seeger et al. (1964)

Chart of the Nuclides



Cowan, Thielemann & Truran (1991)



Cowan, Thielemann & Truran (1991)

Then There Was B^2FH

- Burbridge, Hoyle, Burbridge, Christy & Fowler (1956): SN I light curves due to ^{254}Cf decay, 55 d timescale discovered by Baade et al. (1956). Also makes elements heavier than Fe.
- Burbridge, Burbridge, Fowler & Hoyle (1957): The first to categorize isotopes according to *r*- and *s*-processes. SN I makes *r*-process; SN II makes Fe.
- Cameron (1959): *r*-process elements must originate in SN II (massive progenitor) because SN I (light progenitor) cores can't collapse to high density.
- Hoyle & Fowler (1963): Supermassive stars ($M > 10^4 M_\odot$) make *r*-process.
- Focus shifted to site-independent aspects and the importance of nuclear data.
- Seeger, Fowler & Clayton (1965): *r*-process operates in $\gamma - n$ equilibrium; not possible to make all 3 *r*-peaks in same event.
- Schramm (1973): If the *r*-process occurs in a dynamically expanding *n*-rich medium, possible to create all 3 peaks.

The Merger Scenario

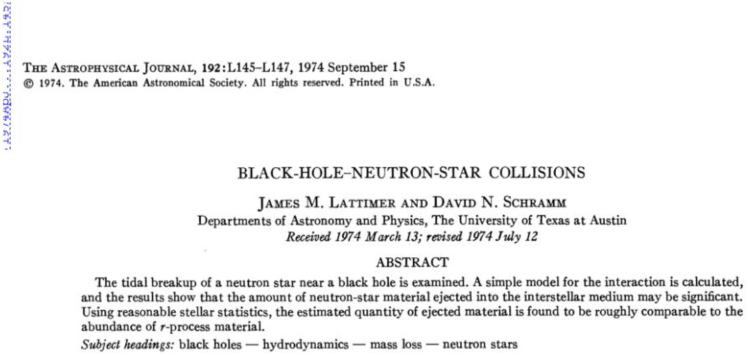
David N. Schramm (1945-1997), no stranger to risky propositions: "Jim, investigate NS-NS mergers that will occur from the orbital decay due to gravitational radiation."

I changed the project to BH-NS mergers to allow a BH background and a NS perturbation.

Conclusions: about $0.05M_{\odot}$ of neutron star matter is ejected which, upon decompression, wil likely form *r*-process nuclei; the mass of the ejecta times the merger rate could explain the observed abundances of r-process nuclei.

Schramm's Prescience

Our first paper was submitted for publication in March 1974 and was published in September 1974.



The Astrophysical Journal, 192:L145–L147, 1974 September 15

BLACK-HOLE–NEUTRON-STAR COLLISIONS

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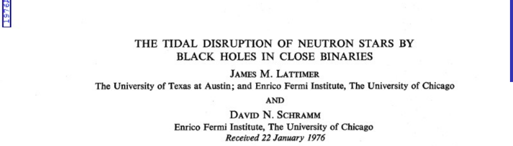
ABSTRACT

The tidal breakup of a neutron star near a black hole is examined. A simple model for the interaction is calculated, and the results show that the amount of neutron-star material ejected into the interstellar medium may be significant. Using reasonable stellar statistics, the estimated quantity of ejected material is found to be roughly comparable to the abundance of *r*-process material.

Subject headings: black holes — hydrodynamics — mass loss — neutron stars

The pulsar B1913+16 was discovered by Hulse & Taylor in July 1974. It was realized to be the first binary neutron star system in September 1974. Their paper was submitted to ApJ in October 1974 and published in January 1975.

Follow-Up Studies



THE TIDAL DISRUPTION OF NEUTRON STARS BY
BLACK HOLES IN CLOSE BINARIES

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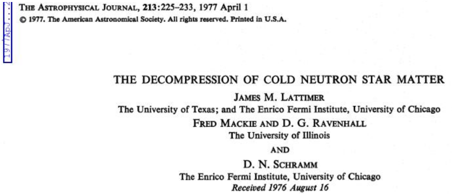
Received 22 January 1976



The Astrophysical Journal, **213**:225–233, 1977 April 1

THE DECOMPRESSION OF COLD NEUTRON STAR MATTER

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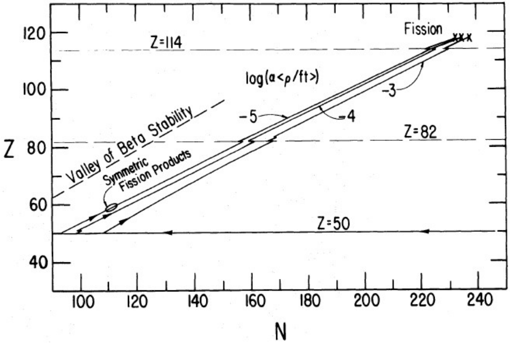
Received 1976 August 16



Almost Nobody Believed This Scenario

The favored site for r-process nucleosynthesis has long been supernovae.

Whatever makes the r-process, it's universal: metal-poor stars have the same relative r-process abundances.

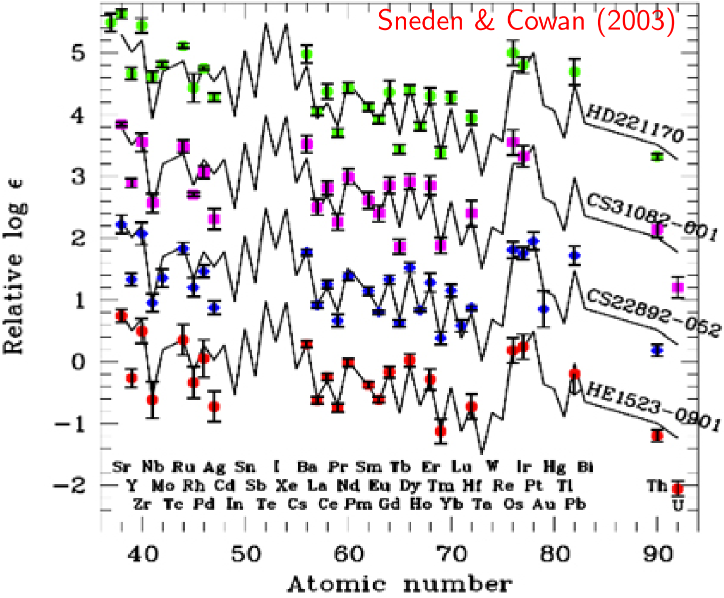
If most gravitational collapse supernovae make r-process elements, less than $10^{-5} M_{\odot}$ has to be made in each.

Observations of metal-poor stars, which are presumably the oldest stars, show that they generally also have r-process elements.

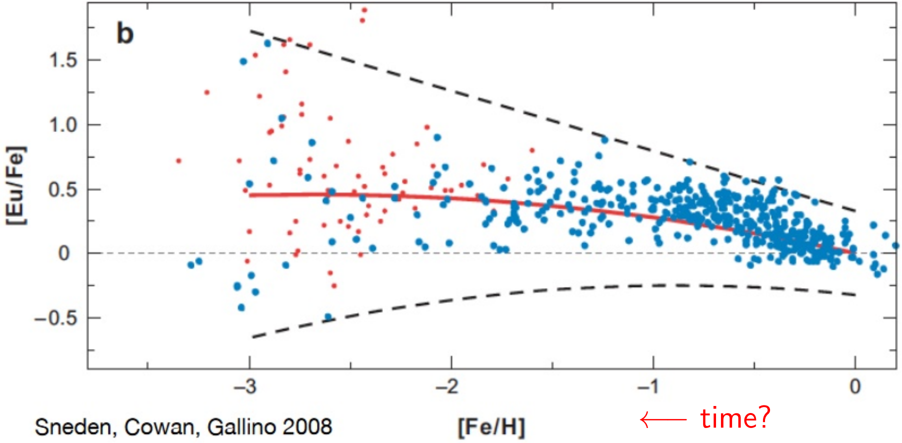
This seems difficult to reconcile with the apparently long delay between supernovae, which make neutron stars, and the final merger (10-100 Myrs?).

Nevertheless, the large scatter in r-process abundances seems to favor a rare, high-yield event.

R-Process Abundances in Metal-Poor Stars



R-Process Scatter Decreases With Metallicity

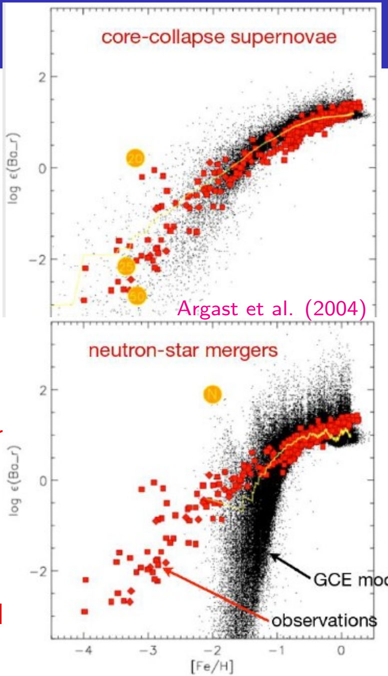


Sneden, Cowan, Gallino 2008

⟵ time?

Chemical Evolution Problems

- Cowan, Thielemann & Truran (1992): event rarity plus delay between SN and merger are inconsistent with r-process abundances in metal-poor stars (but overestimated delays).
- Qian (2000) and Qian & Wasserburg (2000) used energetics and mixing to argue against mergers as the dominant r-process source.
- See also Argast et al. (2004), De Donder & Vanbeveren (2004), Wanajo & Janka (2012), Komiya et al. (2014), Matteucci et al. (2014), Mennekens & Vanbeveren (2014), Tsujimoto & Shigeyama (2014), Cescutti et al. (2015), van de Voort et al (2015) and Wehmeyer et al. (2015).



Argast et al. (2004)

Other Proposed Sites

- Supernova shocks (Colgate 1971)
- Novae (Hoyle & Clayton 1974)
- An $n-$process in nova or SN shocks (Blake & Schramm 1976)
- MHD instabilities in SNe (LeBlanc & Wilson 1970; Schramm & Barkat 1972; Meier et al. 1976)
- Shock-processed He SN zones (Molnar 1971; Hillebrandt & Thielemann 1977; Truran, Cowan & Cameron 1978)
- High entropy neutrino-driven winds (Woosley 1994; Takahashi, Wiiti & Janka 1994), but difficulties from $\nu-$matter interactions (Meyer 1995)

Supernova Problems

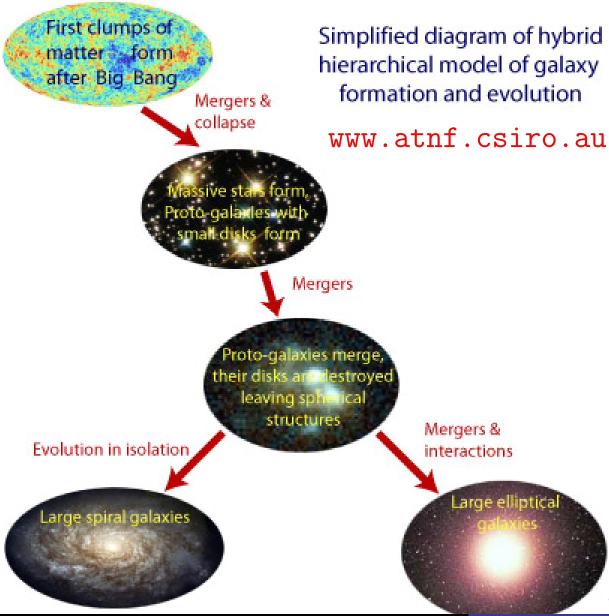
Supernovae simulations have consistently had severe difficulties producing suffiiciently *n*-rich ejecta. It is necessary to produce a high n/seed nucleus ratio, which implies high temperatues and/or low electron fractions.

The scenario under most active investigation is nucleosynthesis in a neutrino-driven wind following core-collapse.

But it seems difficult to achieve high-enough temperatures to produce n-rich conditions. Neutrinos tend to convert neutrons back to protons.

An alternate possibility is a rapidly rotating supernova progenitor with strong magnetic fields. These are rare, so would require the synthesis of a lot of r-process nuclei compared to the case in which all supernovae contributed. It might be possible to create $0.005 M_\odot$ per event.

Heirarchical Galaxy Formation



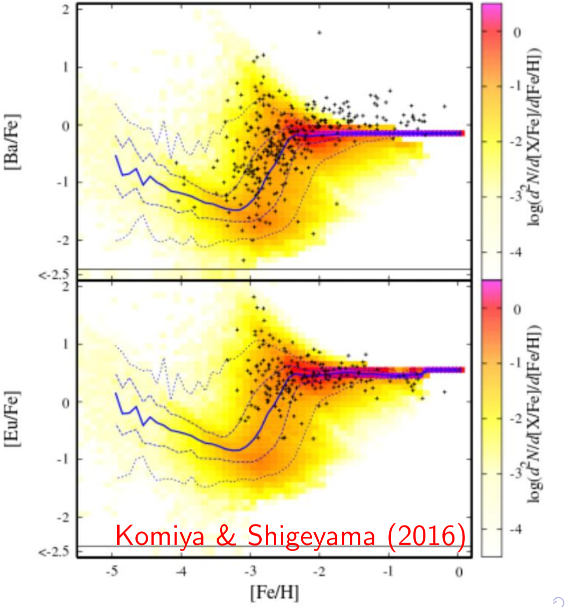
`www.atnf.csiro.au`

Prantzos (2006) showed the unique relation between time and metallicity [Fe/H] is destroyed.

The observed early appearance of r-elements and their large abundance dispersions in metal-poor stars can be explained even if delay times are large.

Chemical Evolution, Revised

Simulations with heirarchical galaxy evolution don't require ultra-short merger delay times to match observations: Isimaru, Wanajo & Prantzos (2015), Shen et al. (2015) and Komiya & Shigeyama (2016).



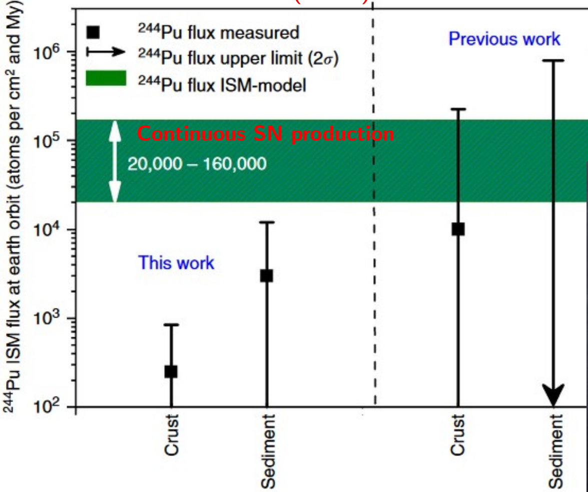
Komiya & Shigeyama (2016)

The sGRB – Merger Association

- Gehrels et al. (2005), Barthelmy et al. (2005) and Bloom et al. (2006) found observational evidence with Swift linking sGRBs with mergers: locations in elliptical galaxies and no associated supernovae.
- Many more examples are now known.

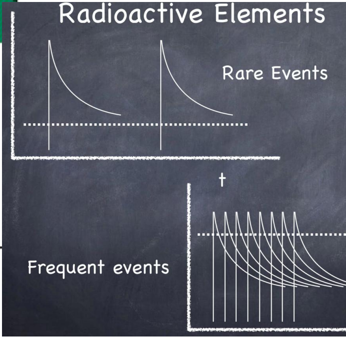
Terrestrial ^{244}Pu

Wallner et al. (2014)



Abundance of ^{244}Pu $\sim 10 - 100$ times lower than expected from continuous, and, therefore, frequent (SN) creation.

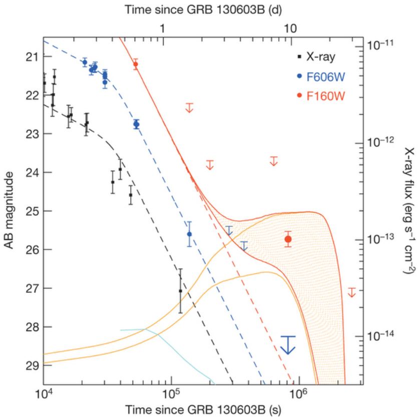
From T. Piran

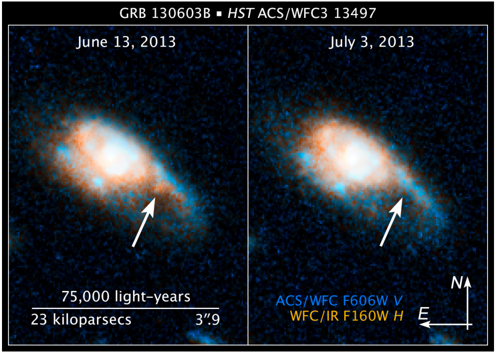


Kilonovae

Li & Paczynski: GRB afterglows from the heated *r*-process ejecta appear as optical or infrared emission days to weeks after event.

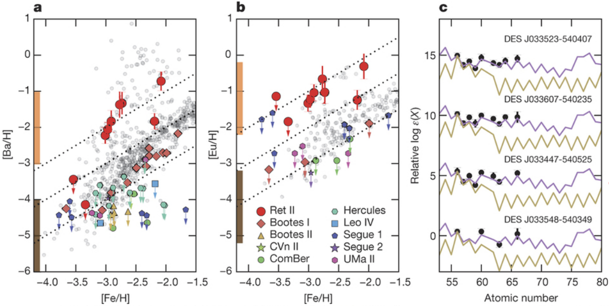
Tanvir et al. (2013)





As many as 3 kilonova-like events were seen: Jin et al. (2016). Recent development is realization that lanthanides have high opacity Barnes & Kasen (2013) and Tanaka & Hotokezawa (2013).

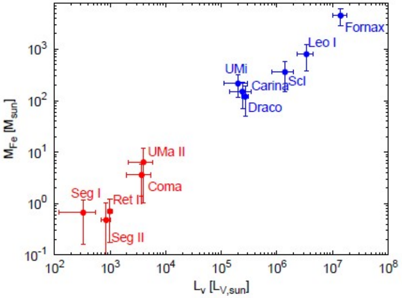
R-Process Abundances in Ultrafaint Dwarf Galaxies

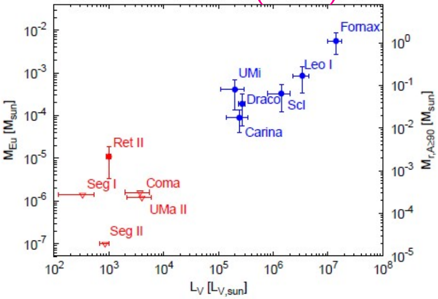


Ji et al. (2016) found 1 of 10 UFD galaxies had detectable *r*-process. Implies a rare, hi-yield event; $N_{\rm SN} \sim 10^3 N_{\rm NSM}$.

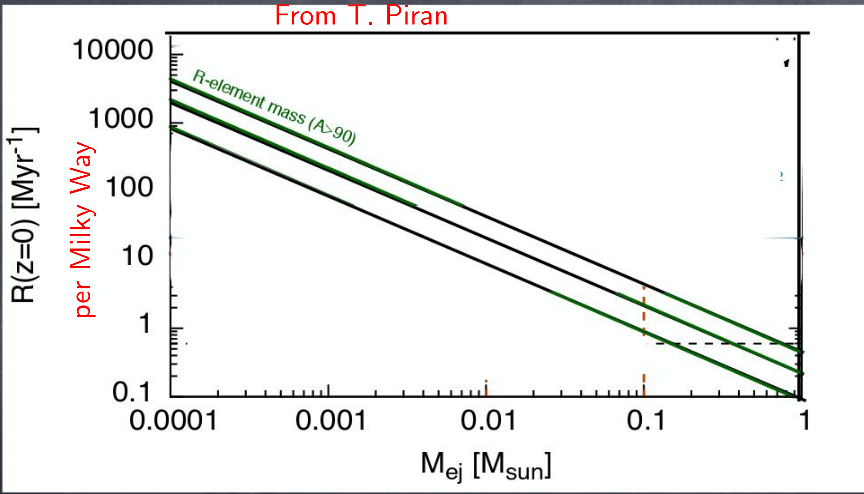
$M_{\rm Fe} \propto L_\nu \to N_{\rm SN} \propto N_*$

Beniamini, Hotokezawa & Piran (2017)



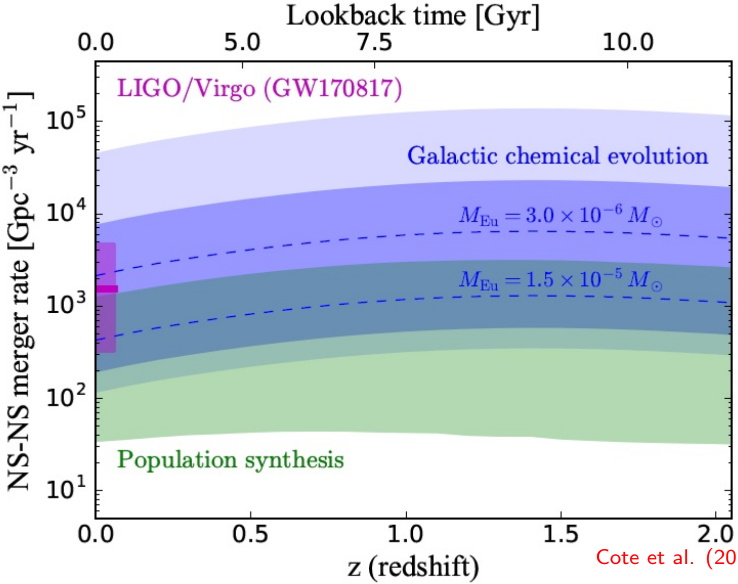


R-Process



lines of R-mass: Current event rate is lower than the average one by a factor of 5 (lower line), 3 (middle line).

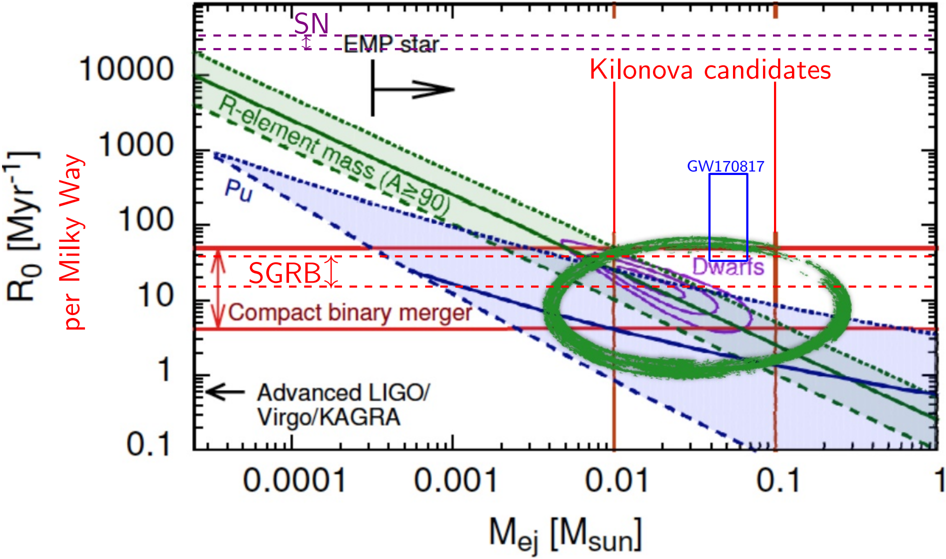
Rate Constraints from GW170817



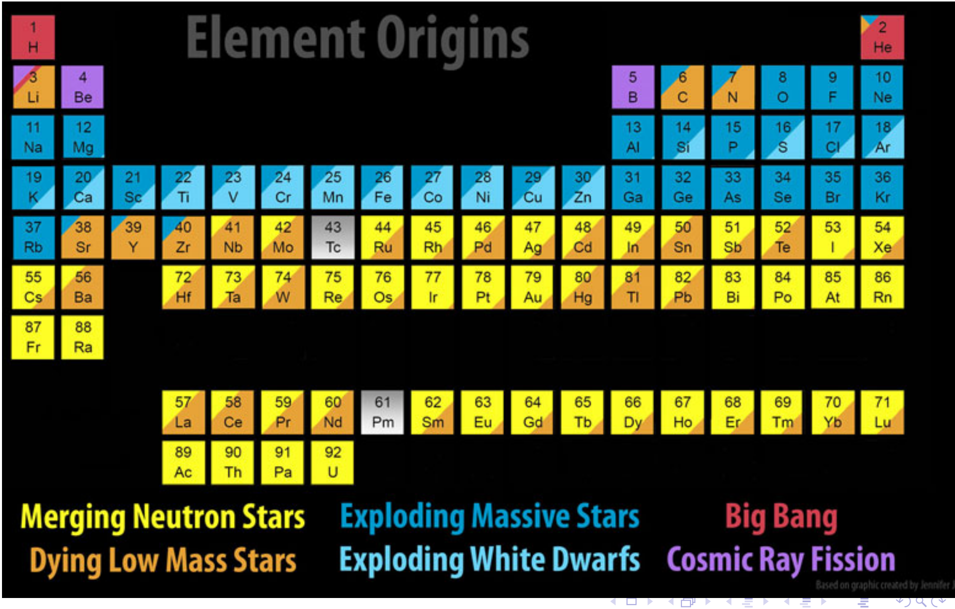
Cote et al. (2017)

Summary

From T. Piran



Problem Solved?



1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																
			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
			89 Ac	90 Th	91 Pa	92 U											

Based on graphic created by Jennifer J

Summary

- GW170817: first detection of a neutron star merger.
- Confirmed that short gamma-ray bursts are associated with mergers and not with supernovae.
- Optical and infrared observations confirmed the predicted ejection of $0.04-0.07M_\odot$ of r-process heavy elements at $v/c=0.1-0.4$
- Observed light curves indicate ejection of both first-r-process-peak (blue) ejecta with lower opacities and full r-process (red) ejecta with high opacities dominated by lanthanides.
- The LIGO-estimated merger rate coupled with the inferred ejected mass is more than sufficient to explain observed r-process abundances in meteorites and stars.
- This observation seems to have solved the long-standing mystery surrounding the origin of the r-process elements.