History of the r-Process

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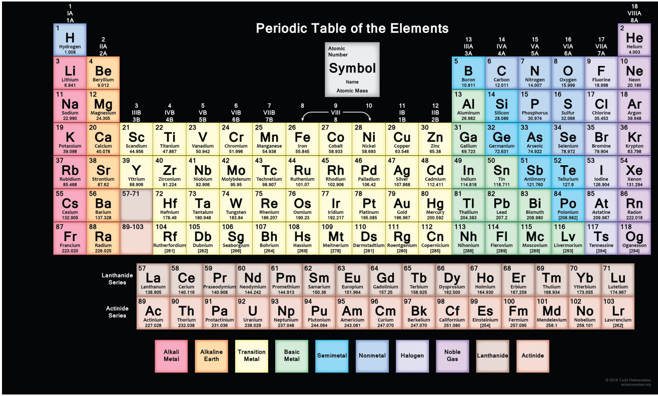
Elements In The Universe

H - Li were mostly made in the Big Bang.

Cosmic rays make Li - B by fission.

Heavier elements up to Rb are mostly made in stars and stellar explosions.



Half of the heaviest elements, from Sr to Bi, called *s*-process, are made in red giants and expelled in stellar winds.

The source of the other half of the heaviest elements, from Sr to Pu, called *r*-process, has long been a mystery.

GW170817

GW170817, the first observed merger of two neutron stars, may have solved this mystery. This event was a **multi-messenger event** observed in

- gravitational waves (LIGO Hanford and Livingston, VIRGO Pisa);
- gamma rays (Fermi and Integral) from a gamma-ray burst detected 1.7 seconds later;
- UV, optical and IR (HST + more than 100 other observatories) after several hours from a kilonova;
- X-rays (XMM, Chandra and Swift) after about two weeks;
- millimeter and radio waves (ALMA, GMRT, VLA, among others) after about two weeks.

In all, about 3500 astronomers observed this event.

There are fewer than 10,000 astronomers worldwide.

Multi-Messenger Astronomy

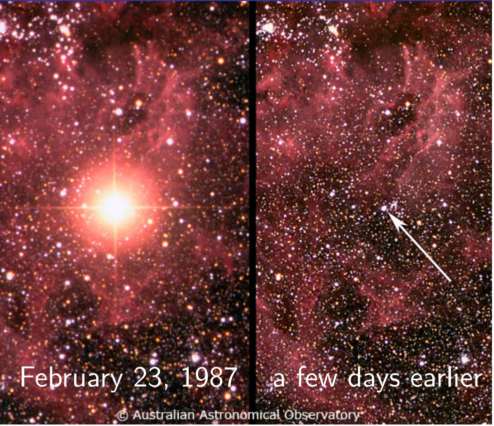
GW170817 was a unique event in astronomy, the most important since the supernova SN 1987A.

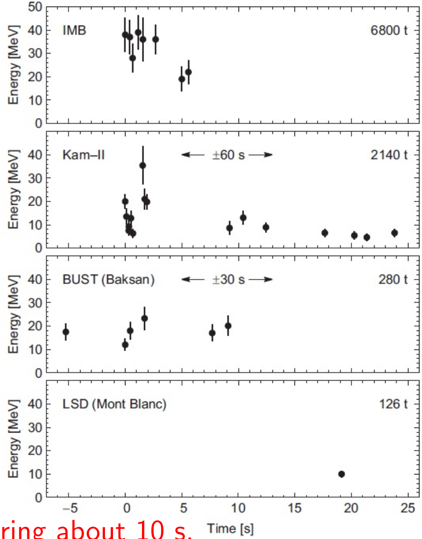
But the first 'multi-messenger observation', combining near-simultaneous electromagnetic and neutrino observations from the same source, was the late 1960's detection of solar neutrinos by Ray Davis (Brookhaven National Lab).

BNL

SN 1987A became the first 'multi-messenger event', combining electromagnetic observations of a 51-kpc distant supernova with non-electromagnetic neutrino detections by the IMB, Kamiokande and Baksan neutrino observatories.

SN 1987A





About 20 neutrinos were observed during about 10 s.
The estimated total ν energy was about $3 \cdot 10^{53}$ erg, the predicted gravitational binding energy of a $1.4 M_\odot$, 12 km-radius neutron star.
Their duration was much longer than their free escape time (40μs), showing that νs were trapped in the dense proto-neutron star core.

Neutron Stars

Neutron stars, first conceived in 1932, became reality when Jocelyn Bell discovered pulsars (1964)

A neutron star has an average density a few times larger than atomic nuclei, about $1.4 M_\odot$ in a 25-km diameter sphere, or a density 10^{15} times that of water.

A pulsar is a rapidly rotating, highly magnetized neutron star. Rotational frequencies up to 700 Hz and magnetic fields up to 10^{15} G are observed. Beams originate from electron-positron pairs formed at the magnetic poles which are tilted from the rotational axis. A pulsar is like a beacon, observed in radio and/or $\gamma-$rays.

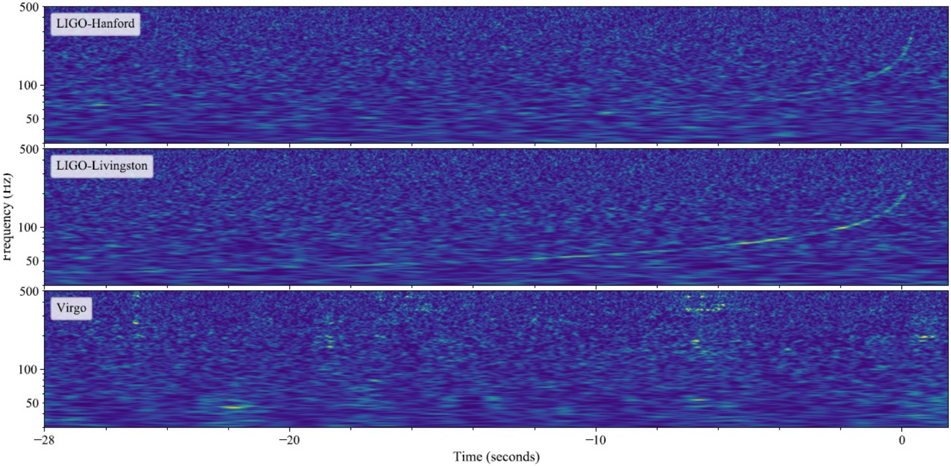
The exterior is a crust of neutron-rich nuclei, n and e^-; the interior is a liquid with $n/p \sim 20$, e^- and μ^-. The center may be a liquid of quarks and/or hyperons, perhaps in a mixed phase with nucleons.

Over 3400 of the billions of neutron stars in the Galaxy have been discovered. They are formed as remnants of supernovae.

GW170817: What Was Observed and Inferred?

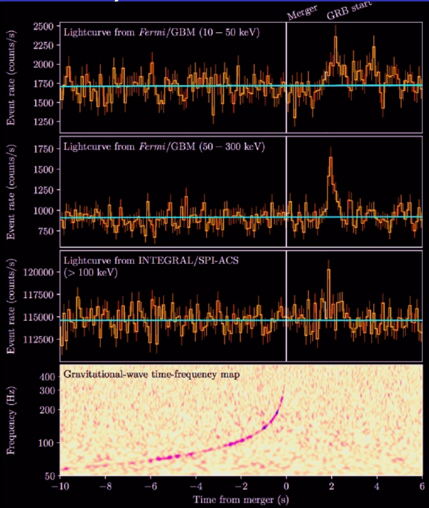
- The GW signal matches what was expected from the merger of a binary consisting of two $1.4 M_\odot$ neutron stars.
- We already know of at least 16 binary neutron stars (pulsars).
- The GW signal is consistent with objects having tidal effects, indicating radii of 10–13 km.
- The GW signal shows the source was 40 ± 10 Mpc distant.
- The GW signal was followed within 1.7 seconds by a weak short gamma-ray burst (sGRB) from the same location, suggesting a black hole formed within about 0.1 second.
- Electromagnetic radiation lasting weeks indicated that $\simeq 0.05 - 0.1 M_\odot$ was ejected at velocities up to c/3, and that the remnant had quickly collapsed into a black hole.
- The inferred high opacity of the ejected matter can be explained by the synthesis of lanthanide and actinide elements, which may solve the mystery of where those elements originate in nature.

The GW Event of Aug. 17, 2017



Abbott et al. (2017)

The Appearance of a Short Gamma-Ray Burst (sGRB)

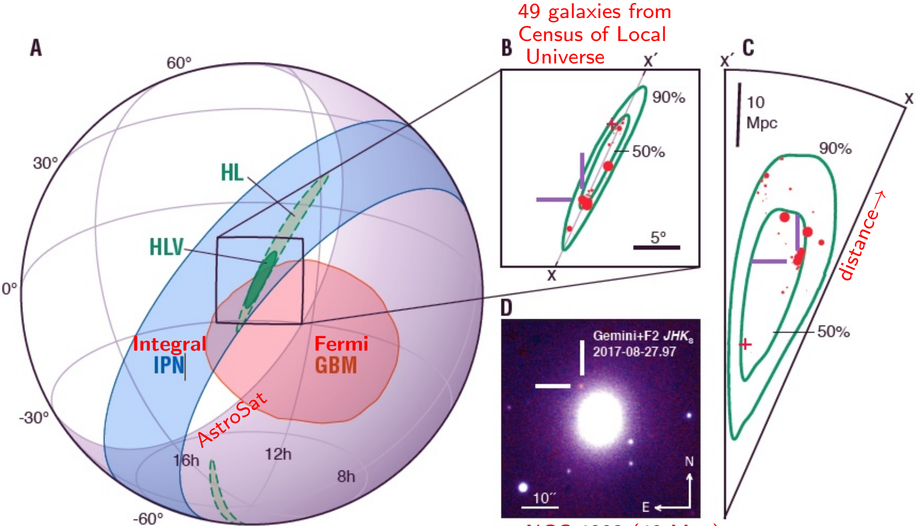


- The probability of a chance temporal and spatial association of GW170817 and GRB170817A is 5.0 x 10^{-8}
- We can confirm binary neutron stars as the progenitors of short, hard gamma-ray bursts
- The time delay between the end of the gravitational-wave signal and the start of the gamma-ray burst is 1.74 (+/- 0.05) s

Abbott,..., DAB et al. (LSC, Virgo, Fermi, Integral) ApJ **848** L13 (2017)

This observation also confirms that gravitational waves travel exactly at the speed of light: at most they lose 510,000 km after

The Discovery of the Host Galaxy NGC 4993



NGC 4993 (40 Mpc)

Kasliwal et al. (2017)

Triumph for Astrophysics Theory and Computation

It had long been predicted that mergers involving neutron stars

- could eject $0.01M_{\odot} - 0.1M_{\odot}$ of neutron star matter at higher than escape velocities, i.e., $v \gtrsim c/10$;
- would involve the violent decompression of tidally- and shock-ejected neutron-rich matter capable of synthesizing extremely neutron-rich nuclei in a classical r-process;
- would result in radioactive decays ultimately forming r-process heavy nuclei and gamma-rays which, thermalized, power the observed optical/IR kilonova; and
- are the most likely source of sGRBs.

The observed kilonova luminosity and decay time can only be accounted for by the ejection of $0.05 - 0.1M_{\odot}$ high-opacity matter: r-process lanthanide and actinide elements.

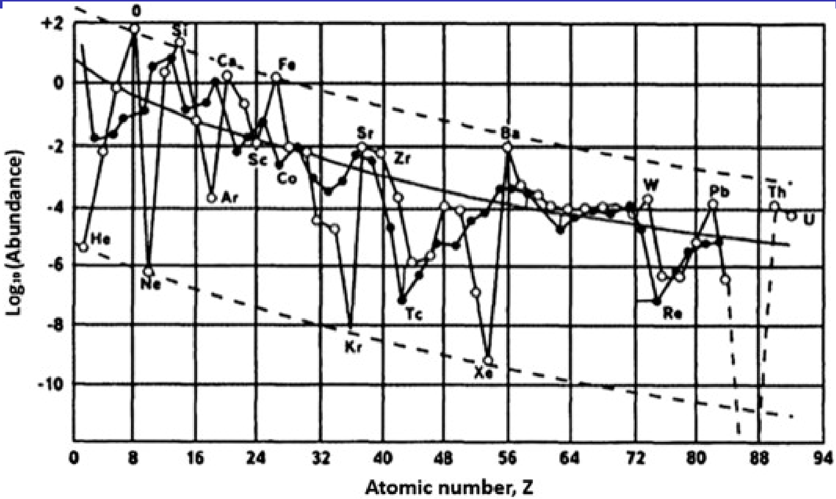
The History of the r-Process

The origin of the heavy elements has been one of the major unsolved problems in physics.

The history behind the r-process has involved at least 15 Nobel Laureates:

Albert Einstein (1915),
Harold Urey (1934),
Enrico Fermi (1938),
Maria Geoppert Mayer and Hans Jensen (1963),
Richard Feynman (1965),
Hans Bethe (1967),
Martin Ryle and Anthony Hewish (1974),
William Fowler(1983),
Russell Hulse and Joseph Taylor (1993),
Rainer Weiss, Barry Barish and Kip Thorne (2017).

Abundances of the Elements



Frank Wigglesworth Clarke (1889) was among the first to study chemical abundances from the Earth's crust. No clear patterns emerged, but the clarke is now a geochemical abundance unit.

Abundance of the Nuclides

Goldschmidt's 1938 compilation of meteoritic abundances was a key observable, and likely inspired Maria Goeppert-Mayer.

Abundance peaks coincide with large neutron magic numbers, a clue in the development of the nuclear shell model by Goeppert-Mayer and Jensen in 1948 (Wigner coined the term 'magic numbers' as sarcasm).

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

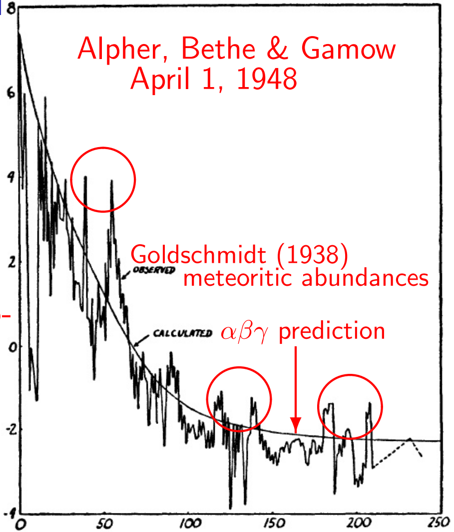


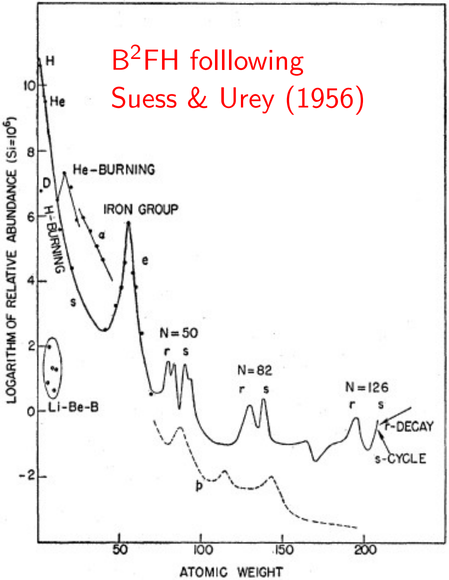
FIG. 1.

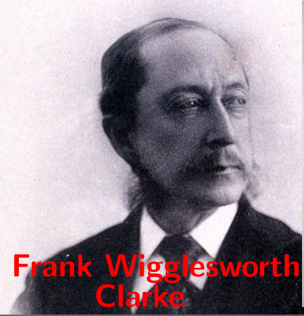
Log of relative abundance

Atomic weight

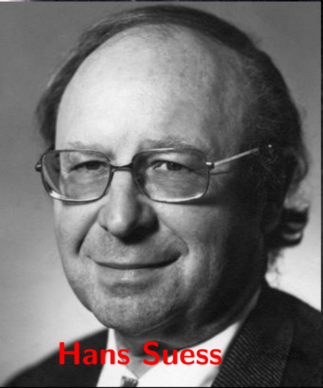
The Origin Of The Heavy Elements

- Hoyle (1946): heavy elements require explosive conditions found in core-collapse of massive stars.
- Alpher, Bethe & Gamow (1948, April 1), Herman: *n*-captures during the Big Bang. However, cannot explain double abundance peaks, also fails because no stable nuclei with $A = 5, 8$ exist. But did correctly predict CMB!
- Suess & Urey (1956): compiled new abundances combining meteoritic, solar and terrestrial data.
- Coryell (1956): double peaks stem from slow and rapid neutron capture; smoothness of even/odd abundances indicates universality.



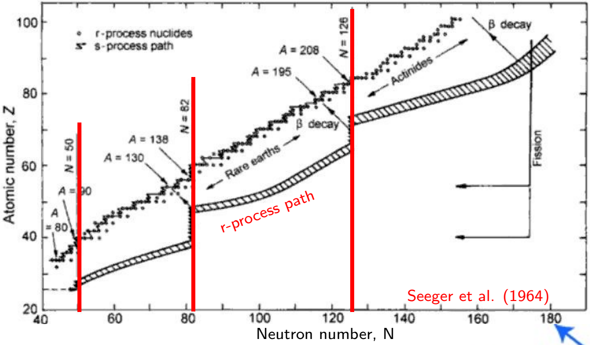

Frank Wigglesworth
Clarke

Victor Goldschmidt

Maria
Goeppert-Mayer

Hans Suess

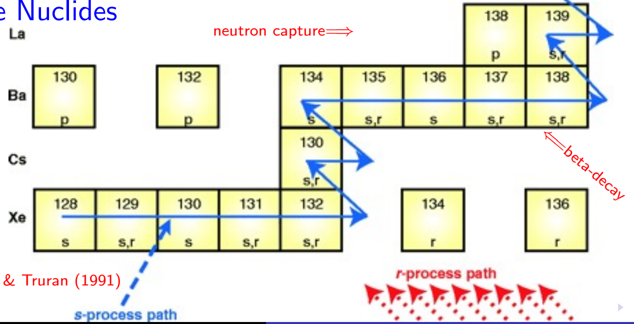
Harold Urey

Charles Coryell

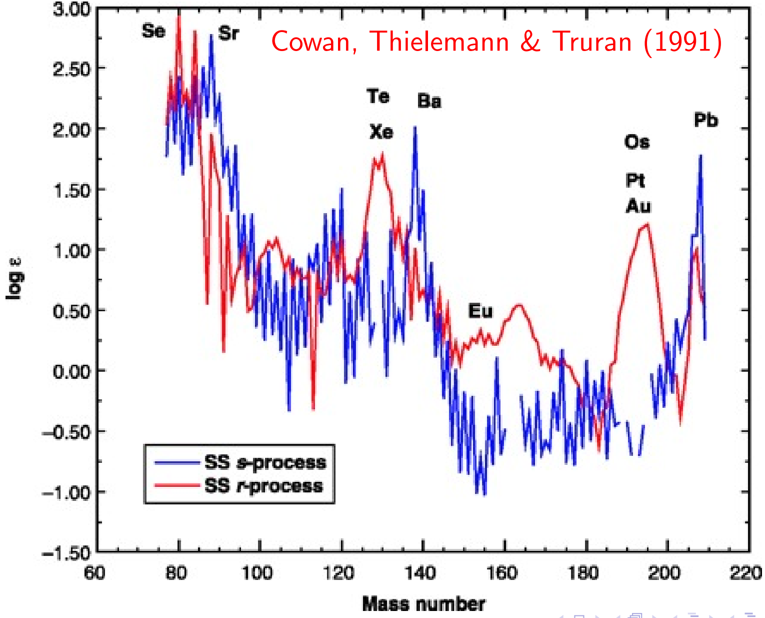


Seeger et al. (1964)

Chart of the Nuclides

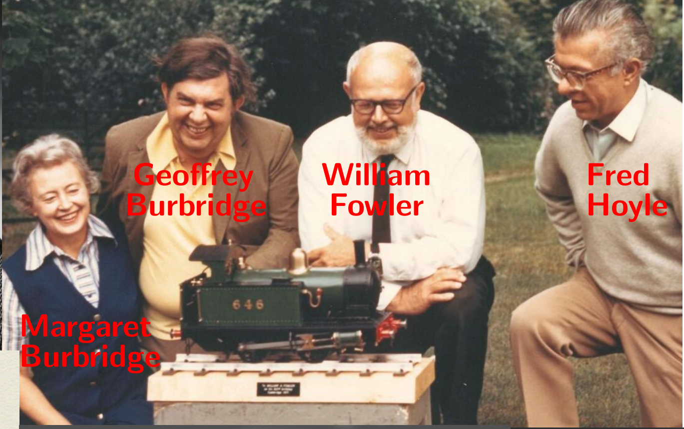


Cowan, Thielemann & Truran (1991)

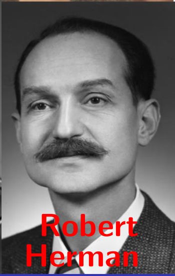

Cowan, Thielemann & Truran (1991)
Se
Sr
Te
Xe
Ba
Eu
Os
Pt
Au
Pb
SS s-process
SS r-process
log ε
Mass number
3.00
2.50
2.00
1.50
1.00
0.50
0.00
−0.50
−1.00
−1.50
60
80
100
120
140
160
180
200
220

Then There Was B^2FH

- Baade (1943, 45): SNe I have 55 ± 5 d exponential decays
- Burbridge, Hoyle, Burbridge, Christy & Fowler (1956): SN I light curve due to ^{254}Cf; formation of $Z > 26$ elements.
- Burbridge, Burbridge, Fowler & Hoyle (1957): The first to categorize isotopes according to *r*- or *s*-processes. They proposed SNe I make the *r*-process and SNe II make Fe.
- Cameron (1959): *r*-process must originate in massive progenitor core-collapses (SNe II) because light progenitor white dwarfs (SNe I) don't collapse to high density.
- Hoyle & Fowler (1963): Supermassive stars ($M > 10^4 M_\odot$) make *r*-process.
- Formation controversies caused a shift of focus 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, it's possible to create all 3 peaks.


Walter Baade

Geoffrey Burbridge
William Fowler
Fred Hoyle
Margaret Burbridge

Alastair Cameron

Ralph Alpher
Hans Bethe
George Gamow

Robert Herman

The Merger Scenario

David N. Schramm (1945-1997) was no stranger to risky propositions: "Jim, investigate NS-NS mergers that will occur as a result of the gravitational radiation decay of their orbits."

I changed the topic to BH-NS mergers so as to model a NS as perturbing a BH background, although tidal effects in BNS mergers are larger. If some BH-NS eject mass, then BNS certainly do (Roche limit $= 2.5R$.)

Conclusions: significant ($\sim 0.05 M_\odot$) neutron star matter is tidally ejected, dynamically decompresses, and forms r-process nuclei in amounts sufficient to explain observed abundances.

Schramm's Prescience

Our first paper was submitted to ApJ Letters 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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Received 1974 March 13; revised 1974 July 12

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 not discovered by Hulse & Taylor until July 1974. It was only realized to be a BNS in September 1974 (the first known). Their paper was submitted to ApJ Letters in October 1974 and published in January 1975.

Gamma-ray bursts first detected by Vela 4a,b satellite July 2, 1967, but only disclosed on June 1, 1973 (Kleberson et al.)

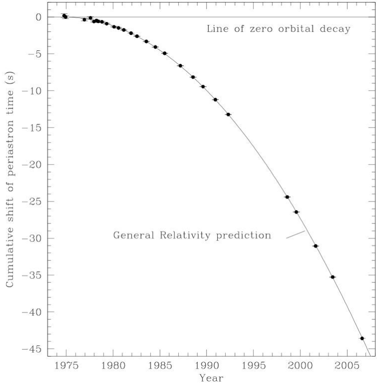
Gravitational Waves and Compact Object Mergers

In a small fraction of massive star binaries, one or even two supernovae occur without disrupting the binary.

Surviving a SN ($\sim 1\%$) results in enormous orbital shrinkage. BNS or BH-NS binaries are necessarily extremely compact, allowing gravitational waves to cause measureable orbital decay.

This was observationally confirmed by 1979 for B1913+16, for which Hulse & Taylor obtained a Nobel Prize.

After millions or billions of years, components will approach to the point of tidal disruption, which occurs before contact, and then merge while ejecting mass.



Decompression Gives a Natural R-Process

THE ASTROPHYSICAL JOURNAL, 210:549–567, 1976 December 1

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

JAMES M. LATTIMER
The University of Texas at Austin; and Enrico Fermi Institute, The University of Ch
AND
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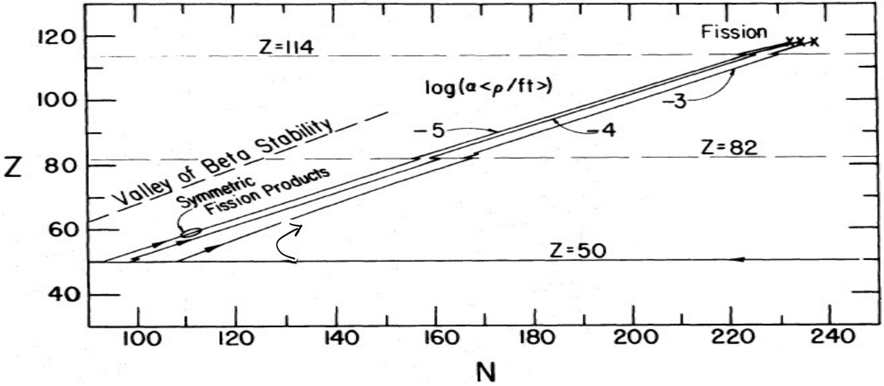
Received 22 January 1976

THE ASTROPHYSICAL JOURNAL, 213:225–233, 1977 April 1

THE DECOMPRESSION OF COLD NEUTRON STAR MATTER

JAMES M. LATTIMER
The University of Texas; and The Enrico Fermi Institute, University of Chicago
FRED MACKIE AND D. G. RAVENHALL
The University of Illinois
AND
D. N. SCHRAMM
The Enrico Fermi Institute, University of Chicago
Received 1976 August 16



But Almost Nobody Believed This Scenario!

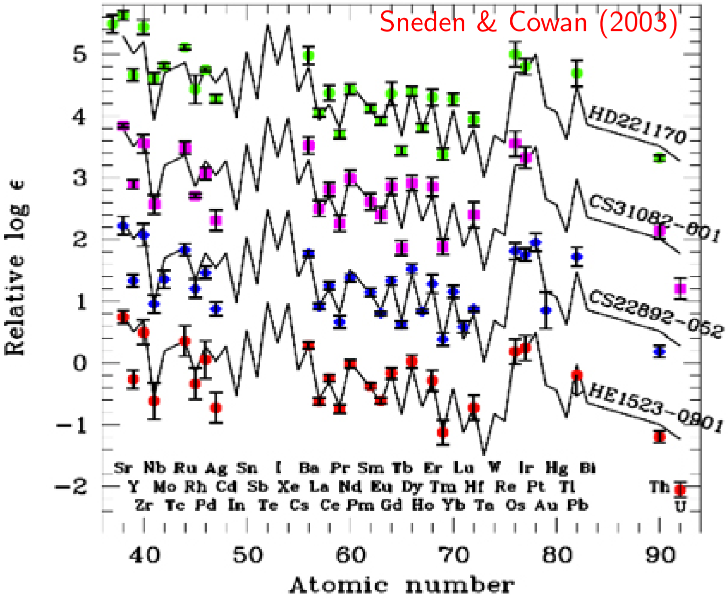
The favored site for the r-process has been supernovae. If most gravitational collapse supernovae make r-process elements, less than $10^{-5}M_\odot$ has to be made in each event.

Observations of metal-poor, and presumably the oldest, stars show that they generally contain r-process elements in the same relative proportions as in the solar system. Wherever the r-process is made, it's source hasn't changed with time.

The early onset of the r-process seemed difficult to reconcile with the apparently long delay between supernovae, which make metals and the neutron stars, and the eventual merger (gravitational wave inspiral times of 10-100 Myrs or longer).

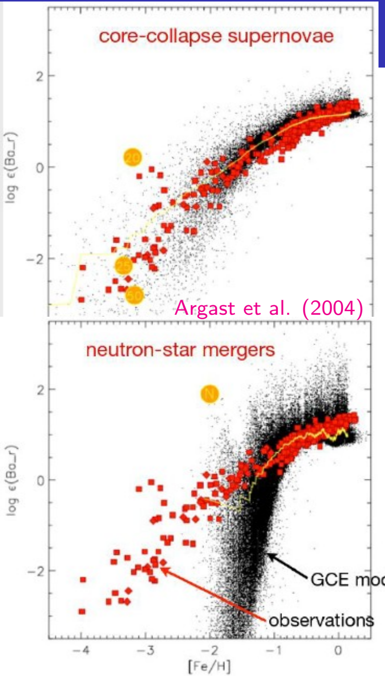
Substantial mass ejection is needed, up to $0.05M_\odot$ per merger, and enough binaries must survive two supernova explosions.

R-Process in Metal-Poor Stars: Same as in Sun



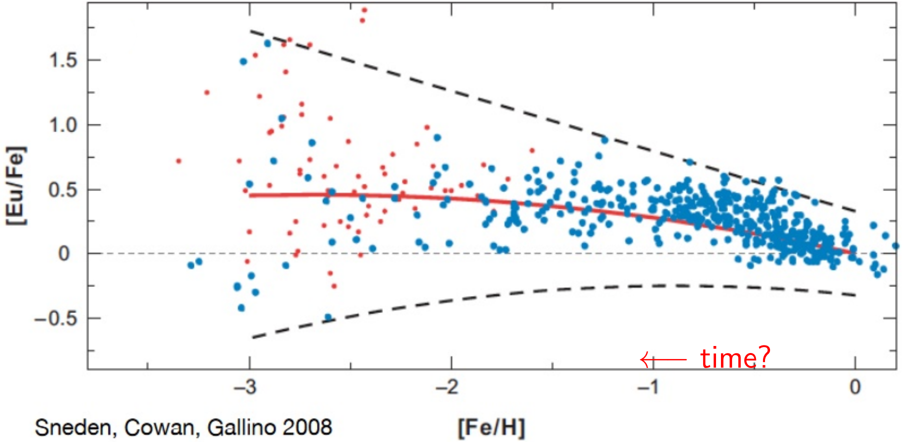
Chemical Evolution Problems

- Cowan, Thielemann & Truran (1992): event rarity plus delay between SN and merger are inconsistent with r-process abundances in metal-poor stars (but they overestimated merger delays).
- Qian (2000) and Qian & Wasserburg (2000): energetics and mixing requirements are unfavorable for mergers (but they overestimated mixing volumes).
- 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).



R-Process Abundance Scatter and Metallicity

One advantage of the merger scenario is that the observed scatter in r-process abundances increases towards small metallicities, which seems to favor rare, high-yield events.



Supernova Problems

A second advantage of mergers has been that supernovae simulations consistently fail to produce sufficiently n-rich or hot-enough ejecta to synthesize the r-process.

The supernova scenario under the 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, and neutrinos tend to convert neutrons back to protons.

An alternate scenario is a rapidly rotating supernova progenitor with strong magnetic fields that could eject n-rich matter. But these are rare, and require the synthesis of a lot of r-process nuclei in each event, which seems unlikely.

Improved Theoretical Simulations

Beginning in the mid 1990's, tremendous advances in theoretical merger simulations have occurred (Ruffert, Janka, Takahashi & Schaeffer 1996, Rosswog, Thielemann, Davies, Benz & Piran 1998, Lee & Kluzniak 1999, Freiburghaus, Rosswog & Thielemann 1999, Oechslin, Rosswog & Thielemann 2001).

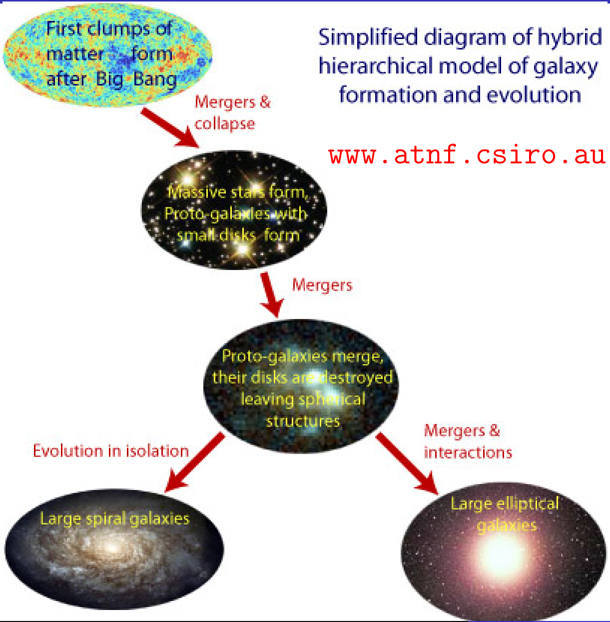
Improved simulations confirm the basic conclusions of the first primitive models.

But these simulations have also shown additional ejecta pathways other than tidal, each with different n/p ratios. More ejecta with a range of n/p ratios could improve fits to observed abundances.

Newer simulations necessarily take into account the role of neutrinos and flavor mixing, and show that their roles are important for the ejection and final nucleosynthesis products.

Vastly improved predictions for optical afteglows (kilonovae) now exist, which were totally lacking in the first simulations.

A Paradigm Shift: Heirarchical Galaxy Formation



www.atnf.csiro.au

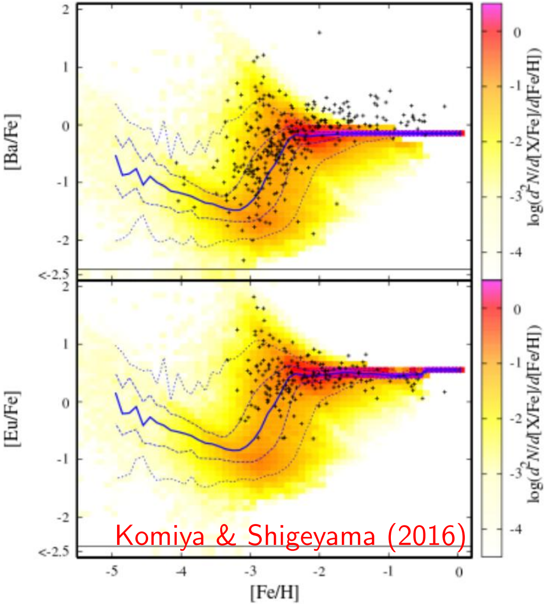
Prantzos (2006) showed the unique relation between time and metallicity [Fe/H] is destroyed if the Milky Way formed from small units.

The observed early appearance in metal-poor stars of r-elements with large [r/Fe] abundance dispersions can be explained even with large time delays.

Galactic Chemical Evolution, Revised

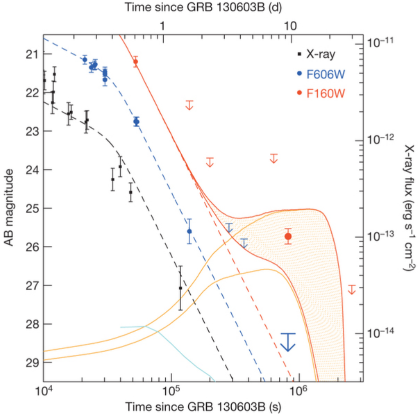
Simulations with heirarchical galaxy evolution don't require ultra-short merger delay times to match observations: Isimaru, Wanajo & Prantzos (2015), Shen et al. (2015) and Komiya & Shigeyama (2016).

Heirarchical galaxy formation breaks the [Fe/H] - time relation.

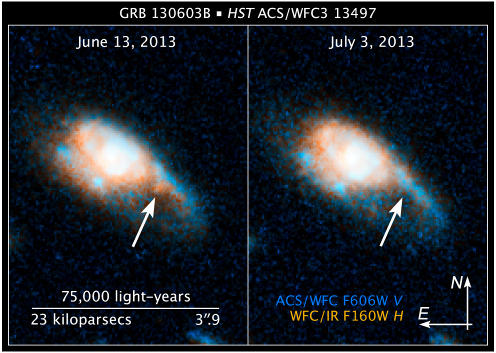


Kilonovae and Gamma-Ray Bursts

Li & Paczynski: GRB afterglows are produced from the heated r-process ejecta by β-decay γ rays, downscattered to appear as optical emission days after event.



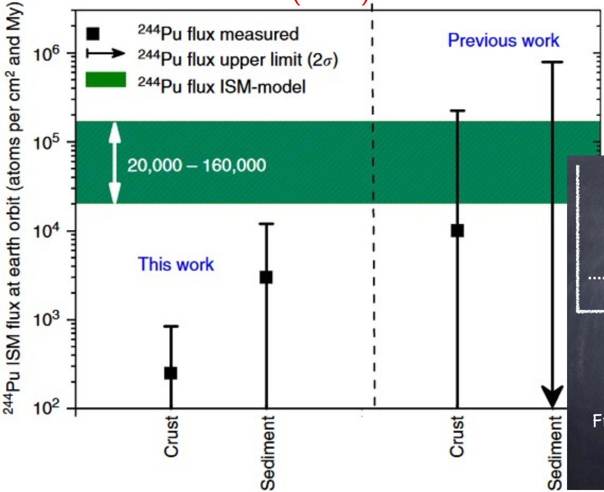
Tanvir et al. (2013)



As many as 3 kilonova-like events were seen: Jin et al. (2016).
A major development was the realization that lanthanides have high opacities (Barnes & Kasen 2013 and Tanaka & Hotokezawa 2013).

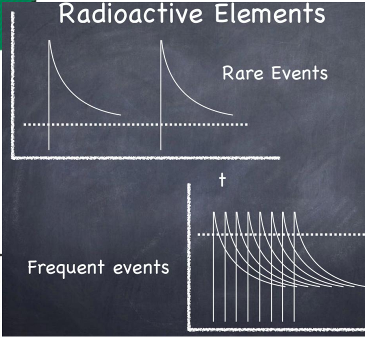
Terrestrial ^{244}Pu

Wallner et al. (2014)



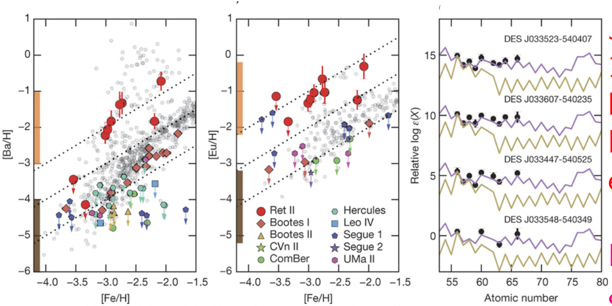
Abundance of ^{244}Pu is 10 − 100 times less than expected from **models assuming continuous (SN) creation (band).**

From T. Piran



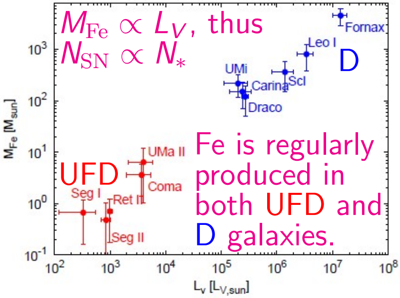
This is strong evidence in favor of a high-yield, rare scenario.

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; $N_{\rm SN} \sim 10^3 N_{\rm NSM}$.

Beniamini, Hotokezawa & Piran (2017)

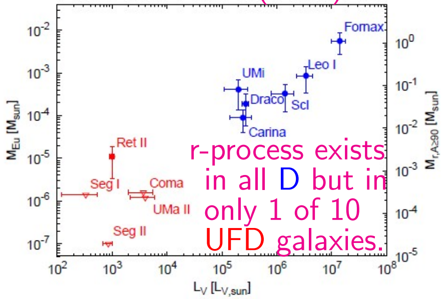


$M_{\rm Fe} \propto L_V$, thus $N_{\rm SN} \propto N_*$

D

UFD

Fe is regularly produced in both UFD and D galaxies.



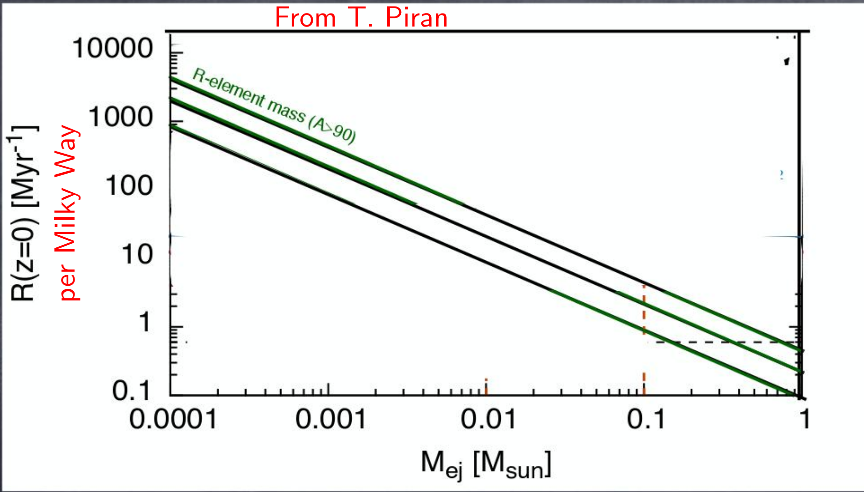
r-process exists in all D but in only 1 of 10 UFD galaxies.

Conclusions From UFD Galaxy Observations

r-process elements in UFD galaxies (2 so far, including Tucana III [Hansen et al. (2017)]) cannot be explained by supernovae.

- The *r*-process mass ($0.01 - 0.1 M_\odot$) in these two UFD galaxies is consistent with a single merger, would otherwise have to be made in $\sim$ 2000 supernovae.
- The energy of thousands of supernovae would have blown these UFD galaxies apart.
- UFD galaxies have Fe in proportion to their masses the same as in dwarf galaxies, indicating a fixed supernovae rate. Why would supernovae in most UFD galaxies fail to make the *r*-process, but those in two others succeed?
- The initial burst of supernovae making the observed Fe would have halted star formation for more than 100 Myrs, long enough for a merger to have made the observed *r*-process elements contained in the next-generaion stars.

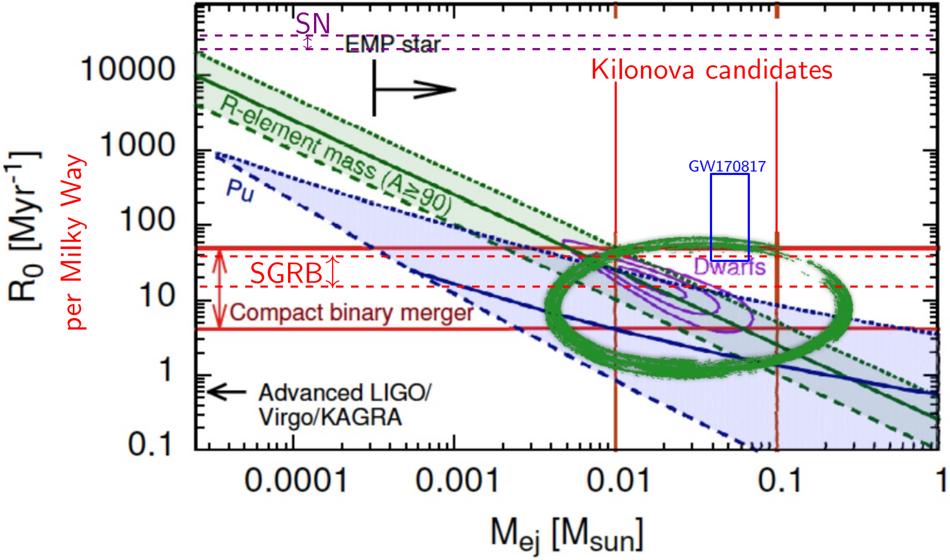
R-Process



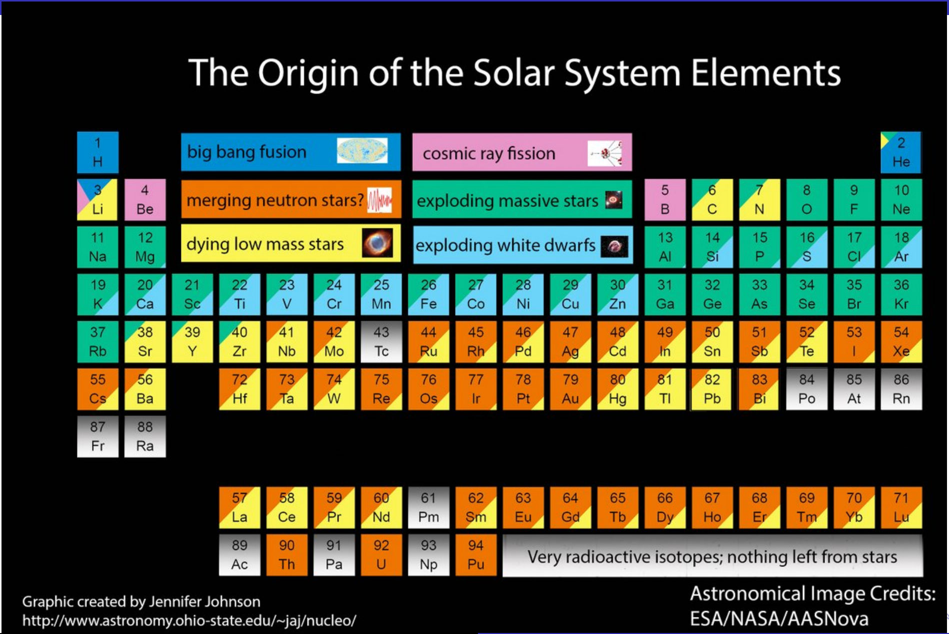
lines of R-mass: Current event rate is lower than the average one by a factor of 5 (lower line), 3 (middle line).

Summary

From T. Piran



Is the Problem Solved?



Outlook

- Future gravitational-wave and gamma-ray burst observations will determine the average BNS and BHNS merger rates.
- Will kilonovae/ejected mass be observable from enough of these events to explain the measured solar system and galactic r-process abundances?
- Will individual elements be identified from spectra, and reliable abundance patterns be determined? Preliminary studies indicate identification of Sr, Y, Zr ($Z = 38 - 40$), but incomplete line information for heavy nuclei is crucial.
- Will kilonovae be observed from gamma-ray bursts connected with rare supernovae, confirming additional r-process sources?