The History of the R-Process

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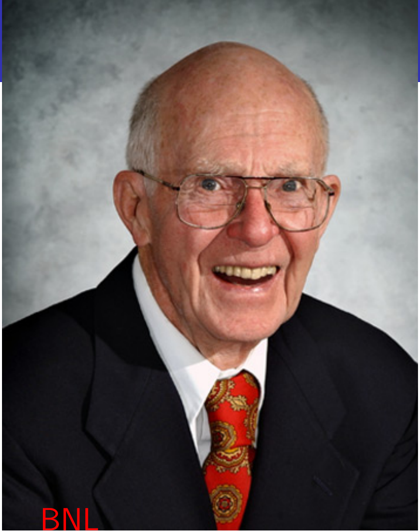
Multi-Messenger Astronomy

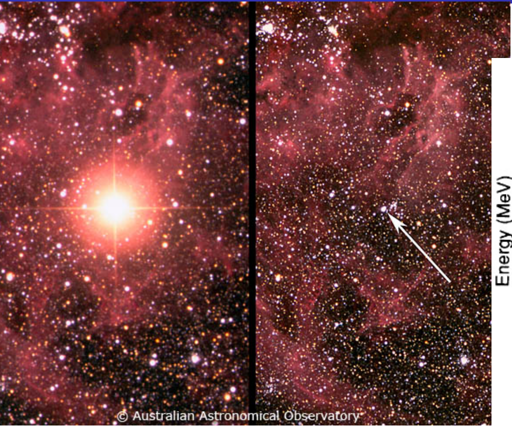
GW170817 was a unique event in astronomy, maybe the most important observation since SN 1987A.

But the first 'multi-messenger' observation, combiining electromagnetic and neutrino information from the same source, was the detection of solar neutrinos (Ray Davis, BNL).

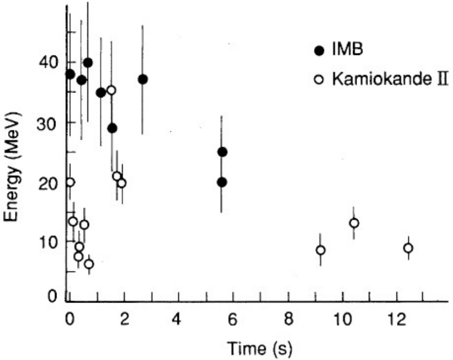

BNL

Subsequently, SN 1987A became the first multi-messenger 'event', combining electromagnetic observations of a nearby supernova with neutrino detections by at least two neutrino observatories.

SN 1987A



February 23, 1987



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

GW170817

GW170817 carried this to even further levels. This event was observed in

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

GW170817: What Was Observed and Inferred?

- The GW signal is what is expected from a binary neutron star (BNS) merger with a total mass $\simeq 2.75 M_\odot$.
- The GW signal has evidence for tidal effects, indicating 9.1 km $< R_{1.4} <$ 13.2 km.
- The GW signal was followed within 1.7 seconds by a weak short gamma-ray burst (sGRB) from the same location.
- Electromagnetic radiation observed from 11 hours to two weeks afterwards indicates that $\simeq 0.05 M_\odot$ was ejected at velocities up to c/3, which then created very heavy elements.
- The combination of large mass ejection and a sGRB implies a black hole formed after a delay, but still in less than a second.
- The remnant, corrected for gravitational binding, mass loss, and rotational support, was $\sim 2.2 M_\odot$, which therefore could represent an upper limit to the neutron star maximum mass.

Triumph for Astrophysics Theory and Computation

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

- BNS mergers have been suspected, but never confirmed, to be the source of sGRBs.
- BNS and black hole-neutron star (BHNS) mergers had been predicted to eject $0.01M_\odot - 0.1M_\odot$ of neutron star matter at higher than escape velocities, i.e., $v \gtrsim c/10$.
- The subsequent decompression of the neutron star matter was predicted to synthesize extremely neutron-rich nuclei.
- These highly-radioactive nuclei decay to form stable r-process nuclei (half of nuclides heavier than iron).
- Gamma-rays from radioactive decays were predicted to power an optical/IR kilonova lasting longer than a week.
- Only high-opacity lanthanide elements can account for the observed light curve.

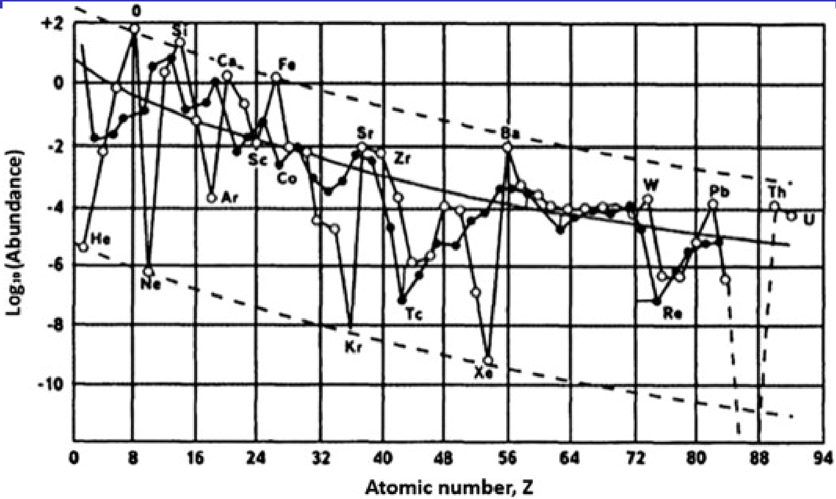
The History of the r-Process

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

The history of the r-process has involved at least 14 Nobel Laureates:

Albert Einstein (1915), Harold Urey (1934), 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.

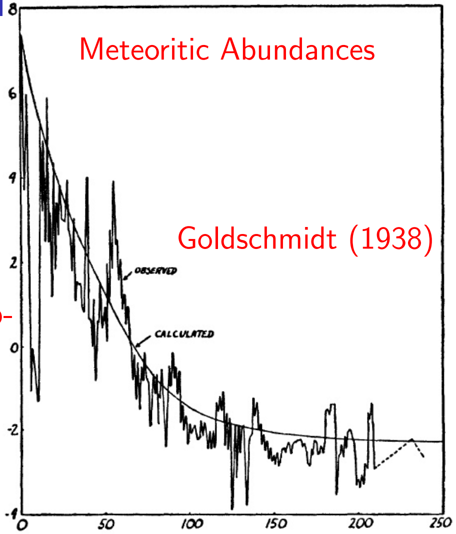


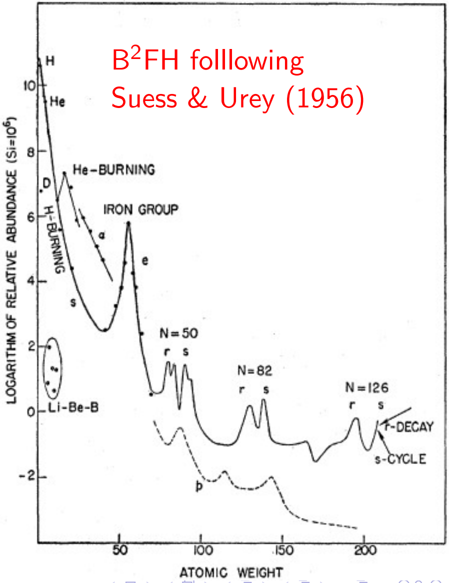
FIG. 1.

Log of relative abundance

Atomic weight

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 new abundances combining meteoritic, solar and terrestrial data.
- Coryell (1956) proposed double peaks stem from slow or rapid $n-$capture; smoothness of even/odd abundances indicates universality.



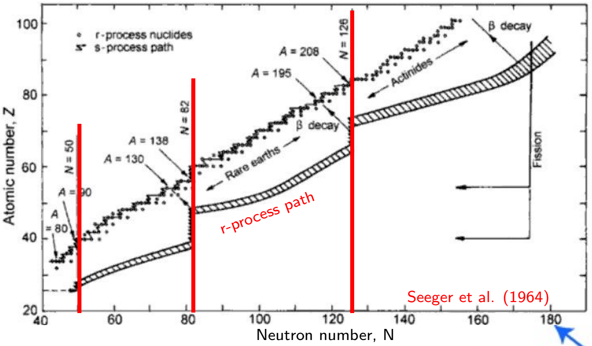
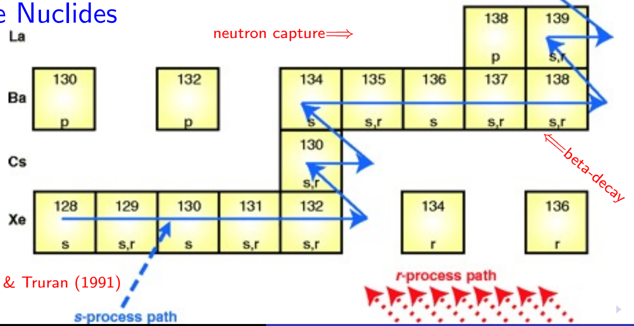
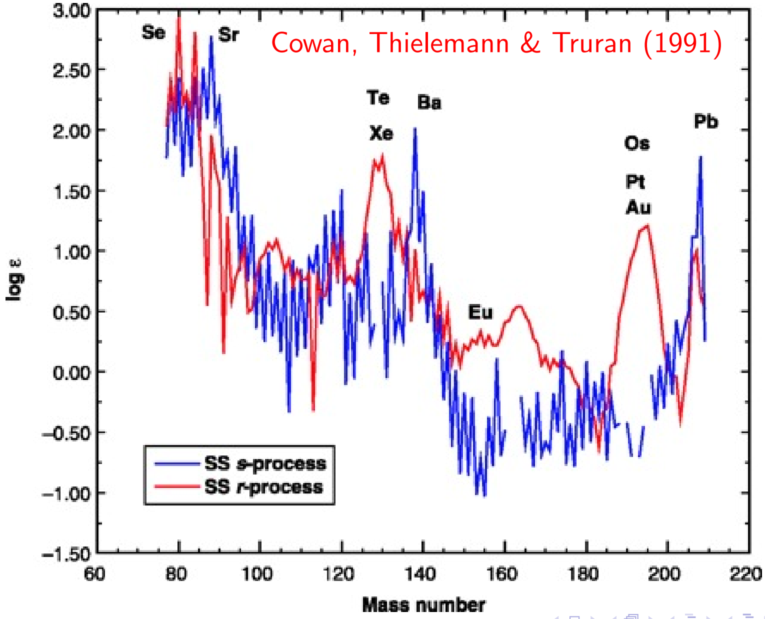


Chart of the Nuclides



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

- 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. They proposed SNe I make the *r*-process and SNe II make Fe.
- Cameron (1959): *r*-process elements must originate in SNe II (massive progenitor core-collapse) because SNe I (light progenitor white dwarf) don'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, it's possible to create all 3 peaks.

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 project to BH-NS mergers to allow a NS perturbation to a BH background, although tidal effects in NS-NS mergers are larger.

Conclusions: significant amounts (about $0.05 M_{\odot}$) of neutron star matter are tidally ejected, dynamically decompress, and likely form r-process nuclei in amounts sufficient to explain observed r-process 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 discovered by Hulse & Taylor in July 1974. It was realized to be the first binary neutron star system in September 1974. This paper was submitted to ApJ Letters in October 1974 and published in January 1975.

Gamma-ray bursts announced June 1, 1973 (Kleberson et al.)

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

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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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The University of Illinois
AND
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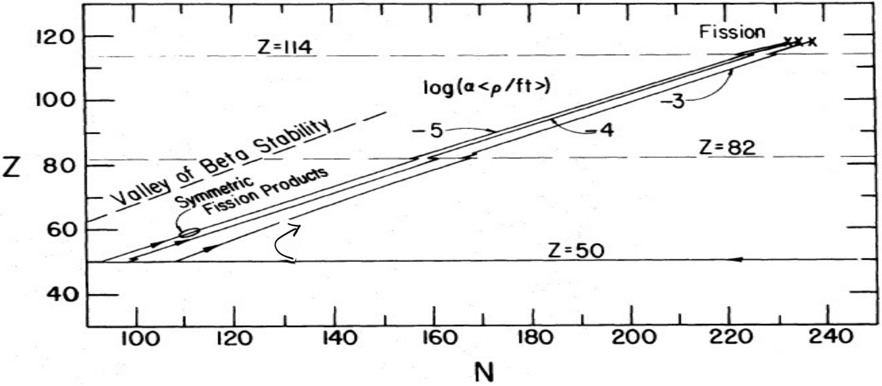
Received 1976 August 16



But Almost Nobody Believed This Scenario!

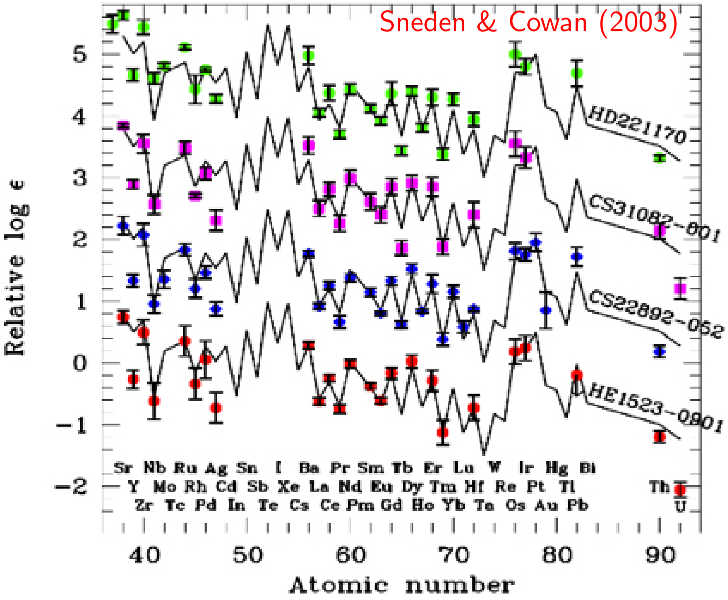
The favored site for the r-process has been supernovae. If most gravitational collapse supernovae make r-process elements, less than $10^{-5}M_\odot$ has to be made in each event.

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).

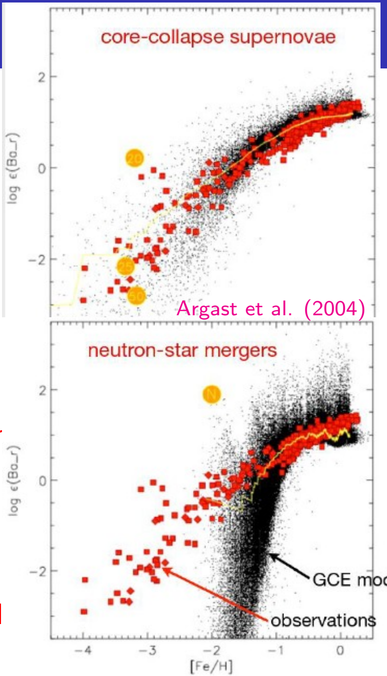
Substantial mass ejection is needed, up to $0.05M_\odot$ per merger, and enough binaries must survive two supernova explosions.

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



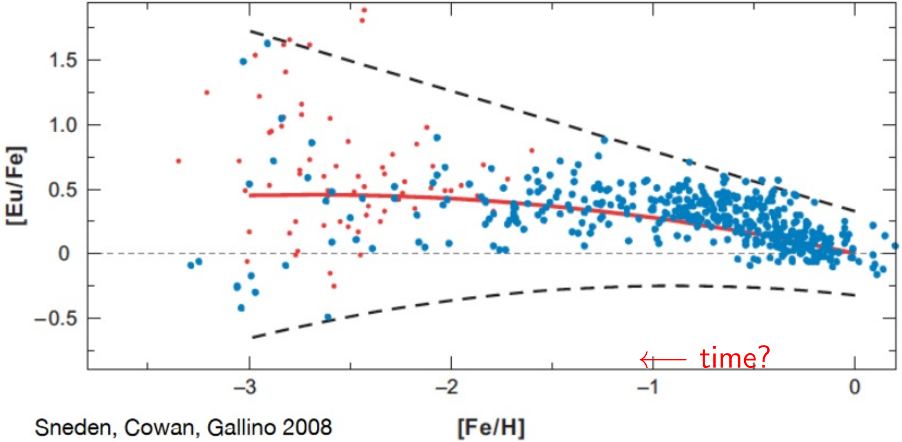
Chemical Evolution Problems

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

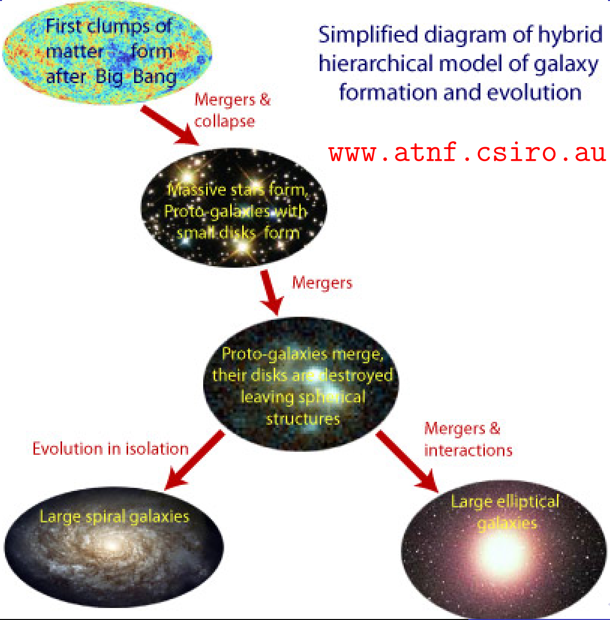
The supernova scenario under the most-active investigation is nucleosynthesis in a neutrino-driven wind following core-collapse. But it seems difficult to achieve high-enough temperatures to produce n-rich conditions, and neutrinos tend to convert neutrons back to protons.

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.

BNS Merger Work Continued (Incomplete)

- (1982) Symbalisty, Meyers & Schramm extend to BNS
- (1989) Eichler, Livio, Piran & Schramm suggested connection to GRBs
- (1998) Li & Paczynski suggested post-merger radioactive decays power optical transients following GRBs.
- (1999) Freiburghaus, Rosswog & Thielemann confirmed ejection of matter following merges using 'real' hydrodynamics and that decompression makes the r-process using detailed network calculations.
- (2003) Shibata, Taniguchi & Uryu GR BNS simulations.
- (2010) Metzger et al. showed observable optical transients would accompany mergers and sGRBs.
- (2013) Barnes, Kasen, Tanaka & Hotokezawa: high opacity lanthanides shift optical transients to infrared.

A Paradigm Shift: Heirarchical Galaxy Formation

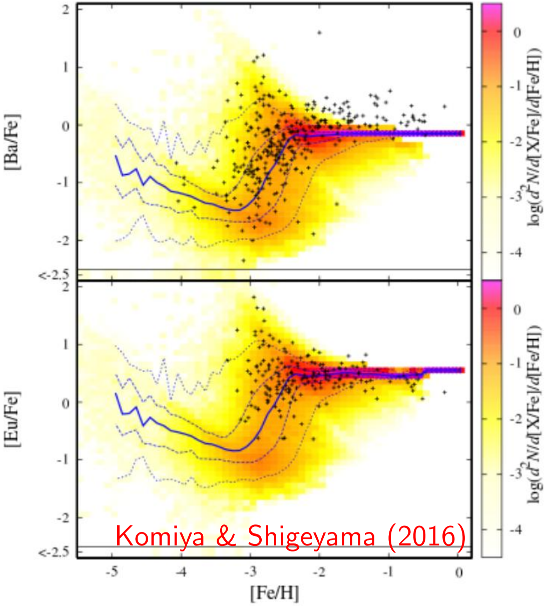


Prantzos (2006) showed the unique relation between time and metallicity [Fe/H] is destroyed if the Milky Way formed from small units.

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).

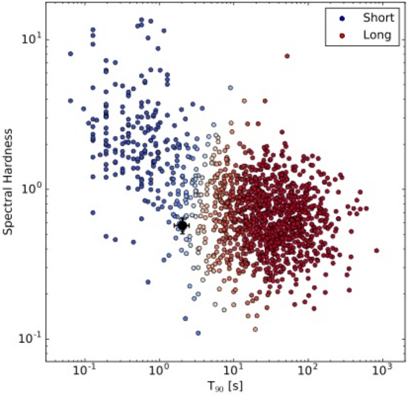


The sGRB – Merger Association

- Gehrels et al. (2005), Barthelmy et al. (2005) and Bloom et al. (2006) found observational evidence with the Swift gamma-ray telescope linking short gamma-ray bursts (sGRBs) with mergers. sGRBs are located primarily in elliptical galaxies, and far from regions of recent star formation and gravitational-collapse supernovae.

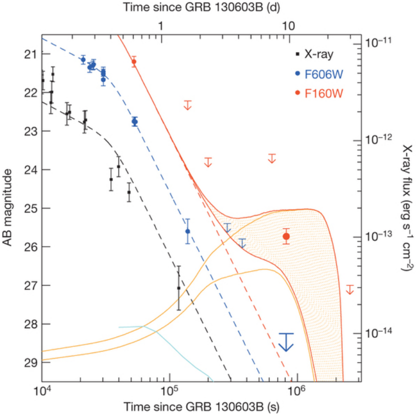
- No sGRB has been associated with a supernova, unlike long gamma-ray bursts, of which many are associated with particularly powerful supernovae.

- The connection with mergers has become more robust with the observation of infrared afterglows from some sGRBs.

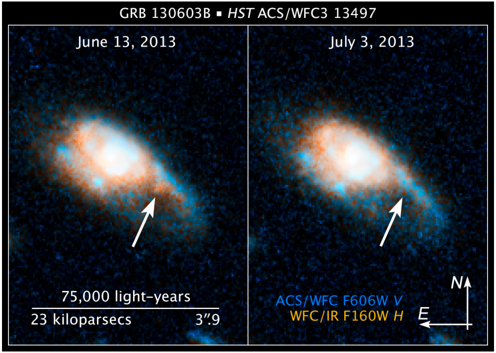


Kilonovae

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



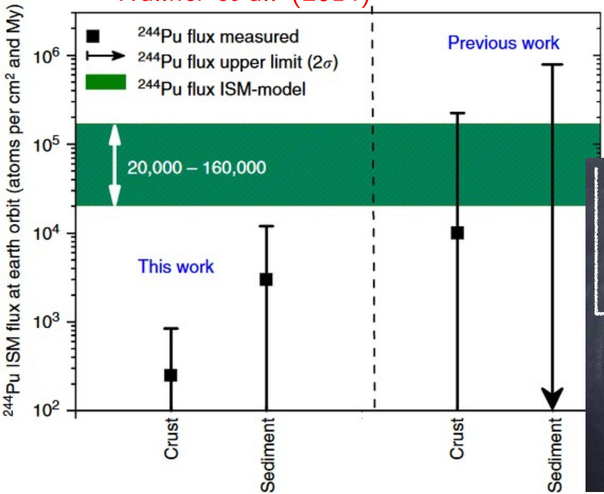
Tanvir et al. (2013)



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

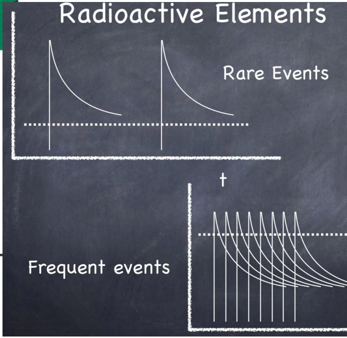
Terrestrial ^{244}Pu

Wallner et al. (2014)



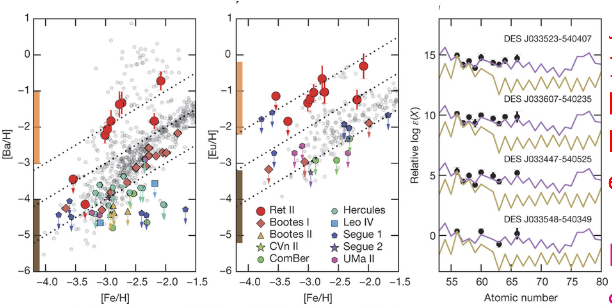
Abundance of ^{244}Pu $\sim 10 - 100$ times lower than expected from continuous (SN) creation.

From T. Piran



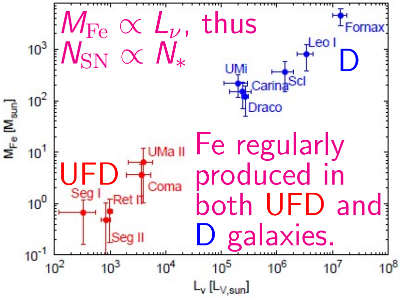
This is strong evidence in favor of the merger scenario.

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)

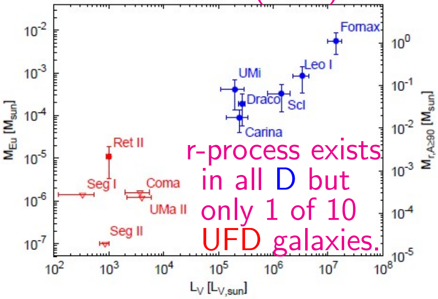


$M_{\rm Fe} \propto L_\nu$, thus $N_{\rm SN} \propto N_*$

D

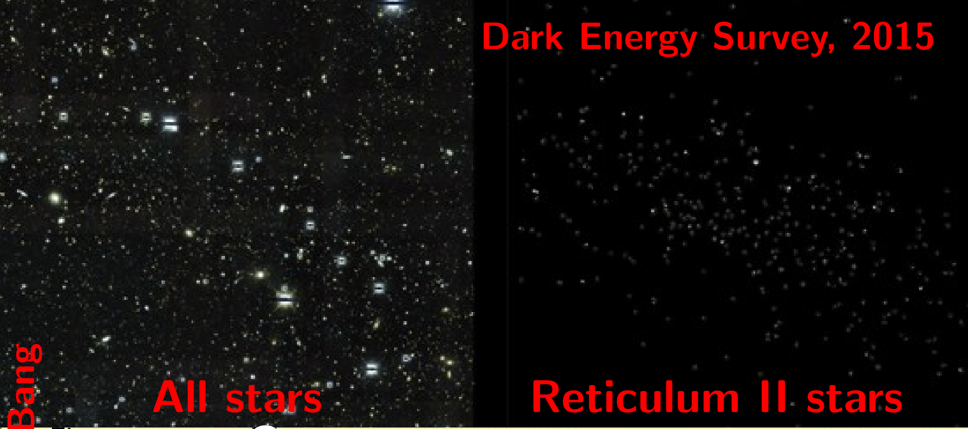
UFD

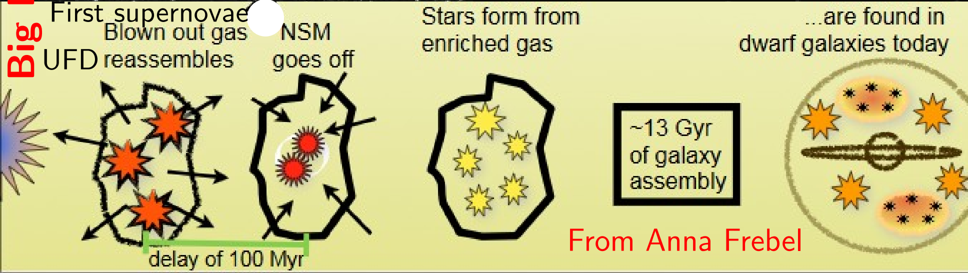
Fe regularly produced in both UFD and D galaxies.



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

Dark Energy Survey, 2015





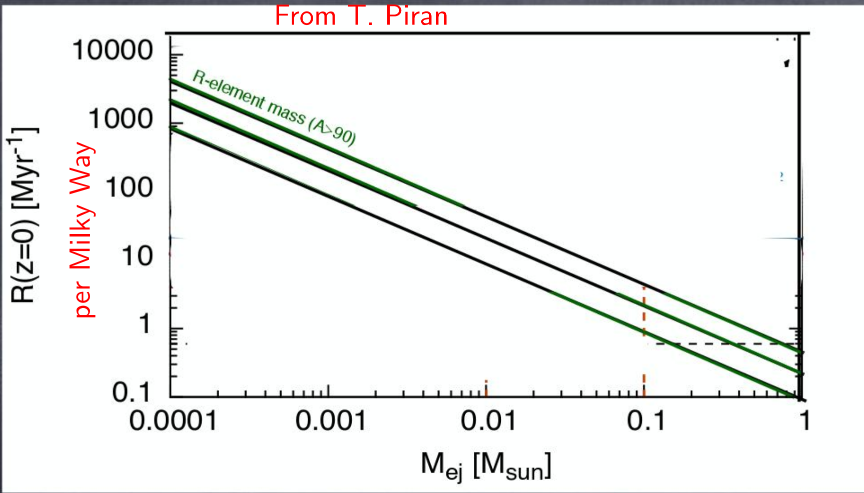
From Anna Frebel

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.

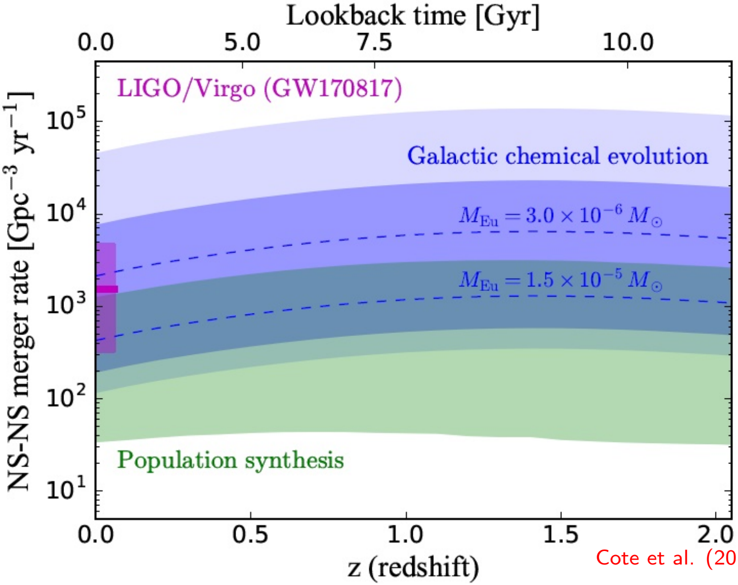
- The r-process mass $(0.01 - 0.1 M_\odot)$ in these two UFD galaxies is consistent with a single merger, would otherwise have to be made in ~ 2000 supernovae.
- The energy of thousands of supernovae would have blown these UFD galaxies apart.
- UFD galaxies have Fe in proportion to their masses the same 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).

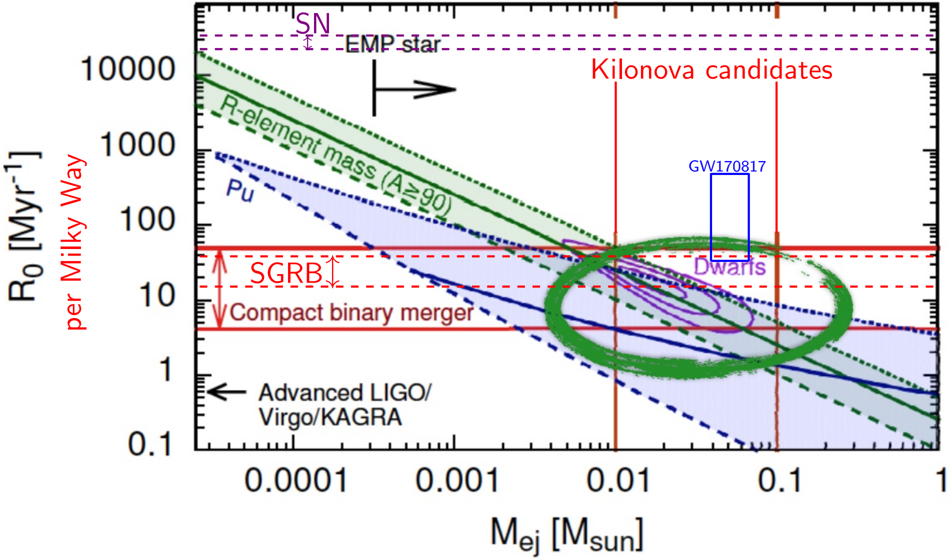
Rate Constraints from GW170817



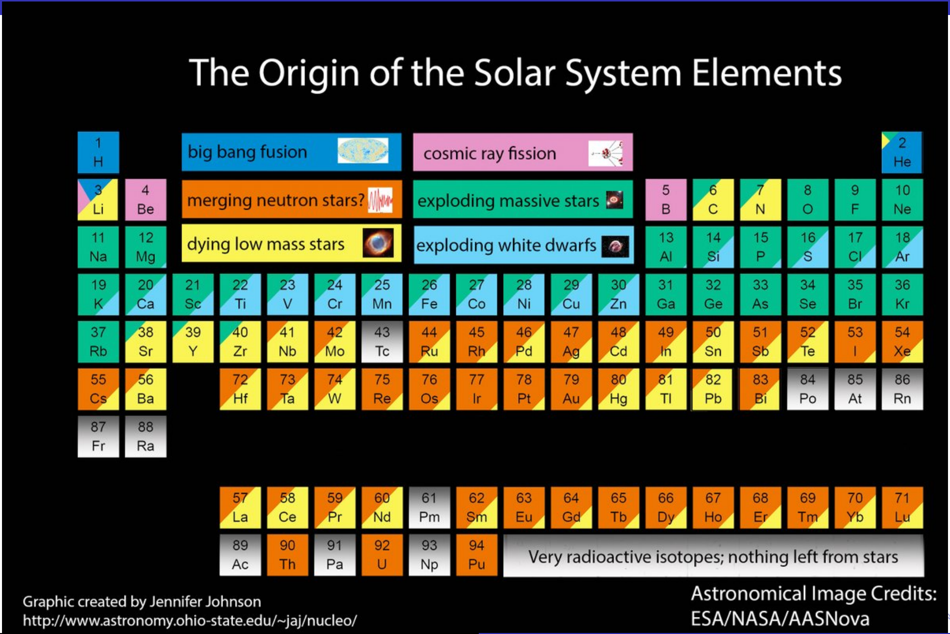
Cote et al. (2017)

Summary

From T. Piran



Is the Problem Solved?



Outlook

- Future gravitational-wave observations will determine the average binary neutron star merger rate.
- Will ejected mass be observable from enough of these events to explain the measured solar system and galactic r-process abundances?
- Will we observe black hole-neutron star mergers, and will they also lead to mass ejection and r-process nucleosynthesis?