Darmstadt Lecture 14 – R-Process

James Lattimer

Department of Physics & Astronomy
449 ESS Bldg.
Stony Brook University

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Darmstadt Lecture 14 – R-Process

James.Lattimer@Stonybrook.edu

The History of the r-Process

- What is the r-process?
- Abundance determinations (terrestrial, solar, meteoritic)
- Magic numbers and the nuclear shell model
- Big bang model for heavy element nucleosynthesis
- B^2FH and supernova nucleosynthesis of heavy elements
- Neutron star mergers
- *r*-process and metal-poor halo stars
- Galactic chemical evolution
- Short gamma-ray bursts and kilonova
- Live *r*-process radioactivities in the Earth's crust
- *r*-process in ultra-faint dwarf galaxies
- GW170817

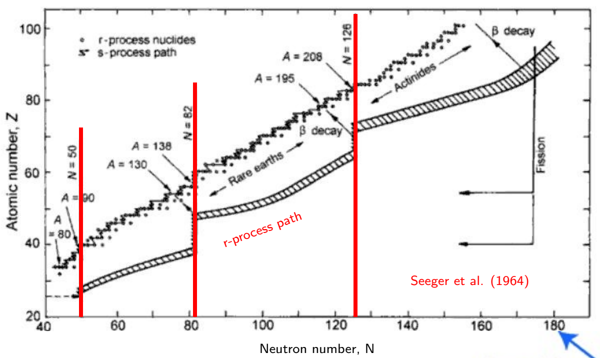
The History of the r-Process

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

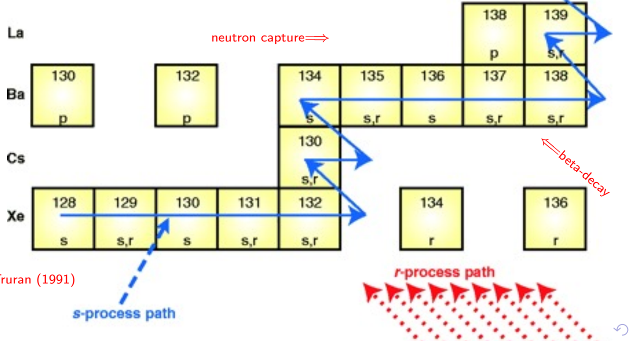
The history of the r-process involves at least 15 Nobel Laureates:

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).

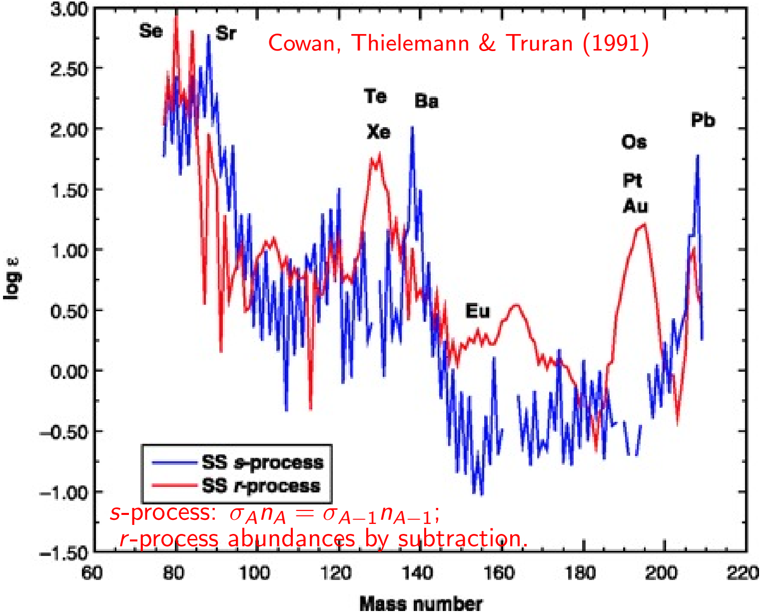
What is the r-Process?



Seeger et al. (1964)



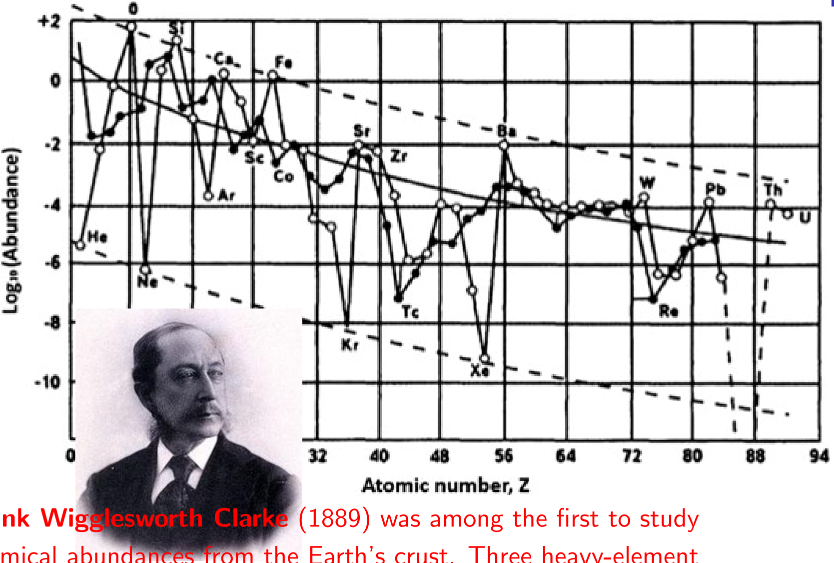
Cowan, Thielemann & Truran (1991)



Cowan, Thielemann & Truran (1991)

s-process: $\sigma_A n_A = \sigma_{A-1} n_{A-1}$;
r-process abundances by subtraction.

Clarke's Crustal Abundances



Frank Wigglesworth Clarke (1889) was among the first to study chemical abundances from the Earth's crust. Three heavy-element peaks visible. The Clarke is now a geochemical abundance unit.

Payne-Gaposchkin's Solar Abundances

Until Cecilia Payne-Gaposchkin's thesis (1925), it was widely believed that H and He were rare elements. She applied Saha's equation to stellar spectroscopy to show that H and He were the most abundant elements in the Sun and other stars. Heavier elements were found to comprise only 2% by mass, with relative abundances similar to the Earth's crust.

Unfortunately, the pre-eminent astronomer Henry Norris Russell told her that these light element abundances were wrong. She felt compelled to write "The stellar abundance deduced for these elements is improbably high, and is almost certainly not real." Russell a few years later, by a different technique, confirmed her results and credited her.

Goldschmidt's Meteoritic Abundances

Victor Goldschmidt by 1930 made the first compilation of meteoritic abundances. He combined these with solar abundances.

The meteoritic data showed twin abundance peaks associated with the larger neutron magic numbers 50, 82 and 126.

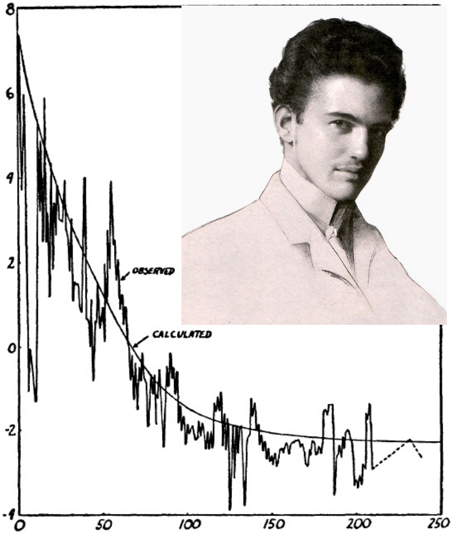


FIG. 1.

Log of relative abundance

Atomic weight

Nuclear Shell Model

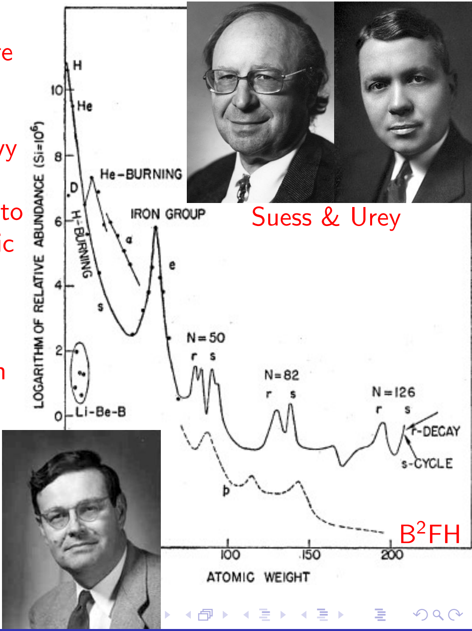
James Bartlett, Walter Elsasser, Kurt Guggenheimer, and Dmitry Ivanenko and E. Gapon, noticed in 1932-3 the enhanced stability and abundance of nuclei at special numbers, sarcastically called magic numbers by Eugene Wigner, and tried to explain them by closed nuclear shells.

Such models competed with the collective model, beginning with George Gamow's 1929 'water drop' model, which was further developed by Niels Bohr and became a standard paradigm, so much so that shell model enthusiasts ran the danger of being ostracized.

Eventually, the 1948 modern shell model (Nobel Prize in 1963) was developed by Maria Goeppert Mayer and Hans Jensen, who worked with Otto Haxel and Harold Urey. Enrico Fermi provided the important clue of spin-orbit coupling. Ironically, Wigner also received the Nobel Prize in 1963, but for unrelated discoveries.

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

- Hoyle (1946): heavy elements re- quire the explosive conditions found in core-collapse supernovae (SNII).
- Alpher, Bethe & Gamow (1948): heavy elements originate from *n*-captures in β-disequilibrium during the Big Bang to explain large abundances near N magic numbers. Alpher and Herman refined this and predicted CMB.
- Suess & Urey (1956) combined meteoritic, solar and terrestrial data in a new abundance table.
- Coryell (1956) proposed double peaks stem from slow or rapid *n*-capture; smoothness of even/odd abundances indicates universality.



Suess & Urey

B^{2}FH

Then There Was B^2FH

- Baade (1956) discovers 55 day SN I (thermonuclear explosion of white dwarf) light curve decay; Burbidge, Hoyle, Burbidge, Christy & Fowler propose light curve powered by ^{254}Cf.
  - Burbidge, Burbidge, Fowler & Hoyle (1957): The first to categorize isotopes according to *r*- and *s*-processes; proposed SN I make the *r*-process and SN II (core-collapse) make elements up to the Fe peak.
  - Cameron (1959): *r*-process elements must originate in SN II because SN I don't collapse to high density.
  - Hoyle & Fowler (1960): SN II; (1963) Supermassive stars.
  - Hoyle & Clayton (1974): Surfaces of white dwarfs.
  - Hogan & Applegate (1987): Neutrino-driven winds from compact-object accretion discs; inhomogeneous Big Bang nucleosynthesis.
  - Seeger, Fowler & Clayton (1965): Impossible to make 3 *r*-peaks in same event; assumed fixed density and temperature.
  - Cameron & Arnett (1967), Schramm (1973): *r*-process in an explosively expanding *n*-rich medium works.

The Merger Scenario

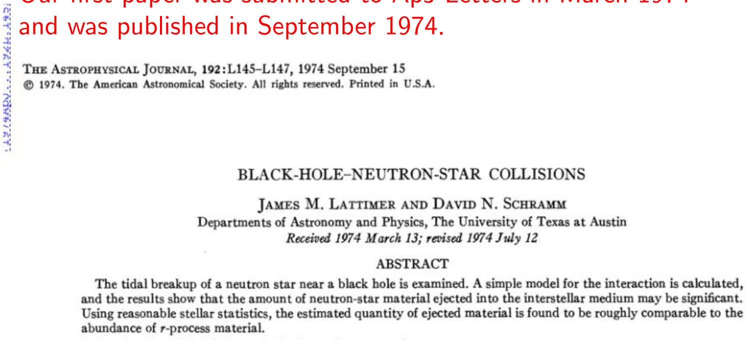
David N. Schramm (1945-1997) was no stranger to risky propositions: "Jim, investigate NS-NS mergers that will occur as a result of the gravitational radiation decay of their orbits."

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 $0.05M_\odot$) of neutron star matter are tidally ejected. Since the neutron star minimum mass is $0.1M_\odot$, it will dynamically decompress and likely form *r*-process nuclei in amounts sufficient to explain their observed abundances.

Schramm's Prescience

Our first paper was submitted to ApJ Letters in March 1974 and was published in September 1974.



1974ApJ...192L.145L

THE ASTROPHYSICAL JOURNAL, 192:L145–L147, 1974 September 15

BLACK-HOLE–NEUTRON-STAR COLLISIONS

JAMES M. LATTIMER AND DAVID N. SCHRAMM
Departments of Astronomy and Physics, The University of Texas at Austin

Received 1974 March 13; revised 1974 July 12

ABSTRACT

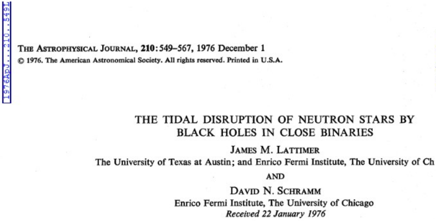
The tidal breakup of a neutron star near a black hole is examined. A simple model for the interaction is calculated, and the results show that the amount of neutron-star material ejected into the interstellar medium may be significant. Using reasonable stellar statistics, the estimated quantity of ejected 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 (Klebesadel et al.)

Decompression Gives a Natural R-Process

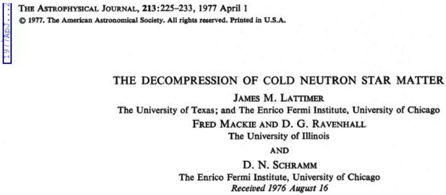


THE ASTROPHYSICAL JOURNAL, 210:549–567, 1976 December 1

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

JAMES M. LATTIMER
The University of Texas at Austin; and Enrico Fermi Institute, The University of Ch
AND
DAVID N. SCHRAMM
Enrico Fermi Institute, The University of Chicago

Received 22 January 1976

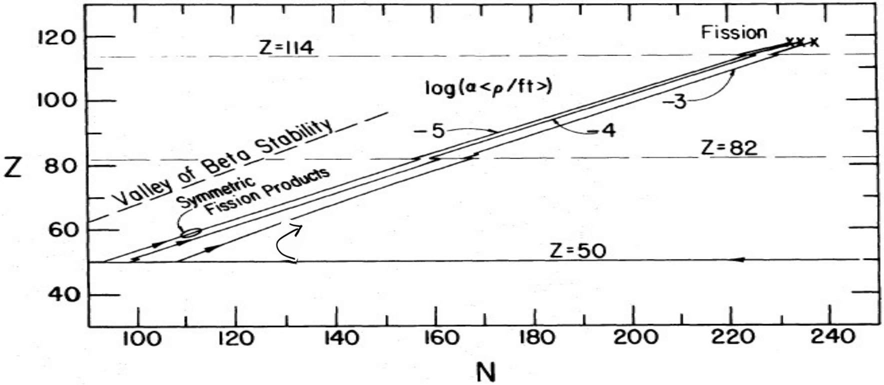


THE ASTROPHYSICAL JOURNAL, 213:225–233, 1977 April 1

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!

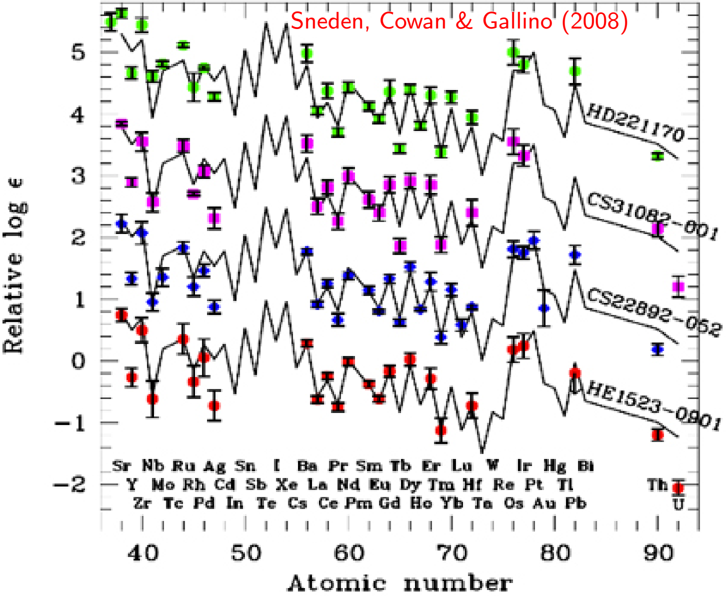
The favored site for the r-process has been supernovae. If most gravitational collapse supernovae make r-process elements, less than $10^{-5}M_\odot$ has to be made in each event.

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).

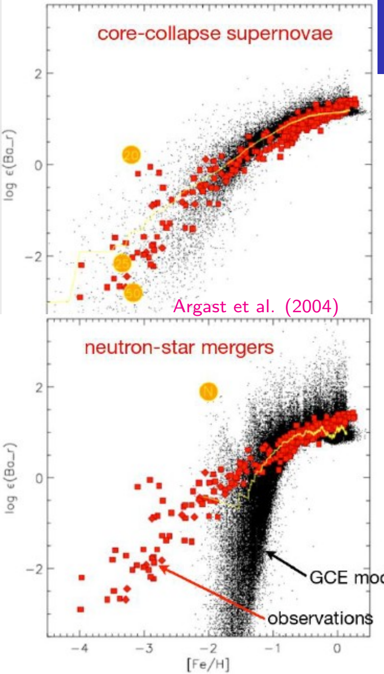
Substantial mass ejection is needed, up to $0.05M_\odot$ per merger, and enough binaries must survive two supernova explosions.

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



Chemical Evolution Problems

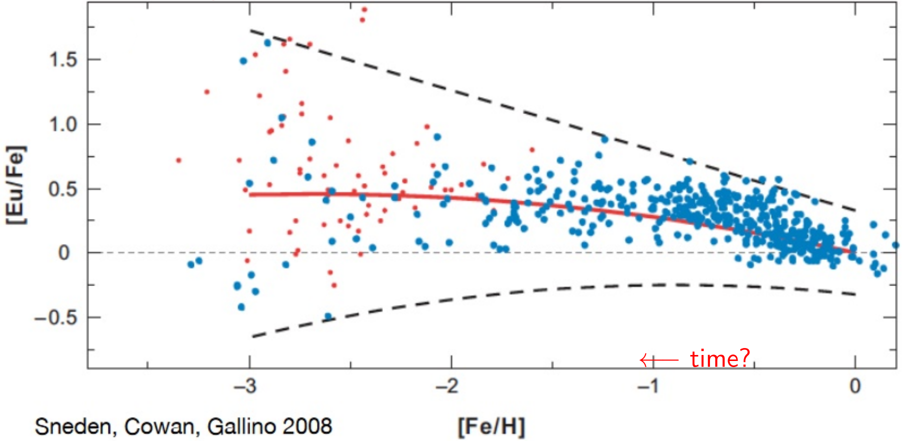
- Cowan, Thielemann & Truran (1992): event rarity plus delay between SN and merger are inconsistent with r-process abundances in metal-poor stars.
- Qian (2000) and Qian & Wasserburg (2000): energetics and mixing requirements, and meteoritic isotopic data, are unfavorable for mergers.
- See also Argast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

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.



Sneden, Cowan, Gallino 2008

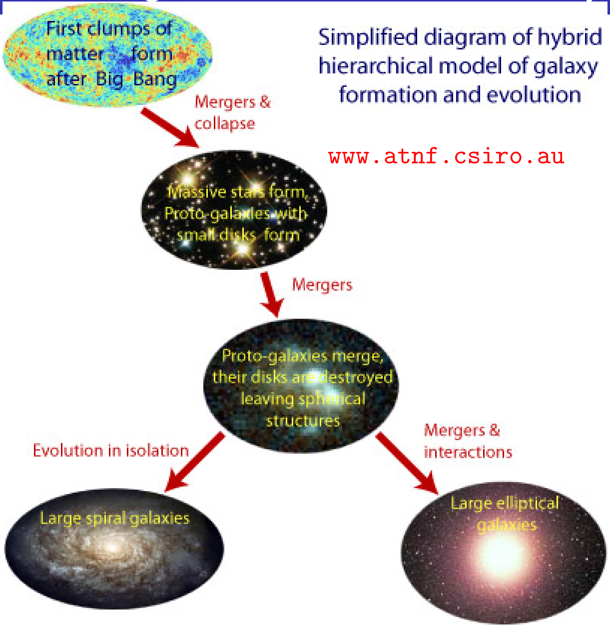
Supernova Problems

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.

A Paradigm Shift: Heirarchical Galaxy Formation



Simplified diagram of hybrid hierarchical model of galaxy formation and evolution

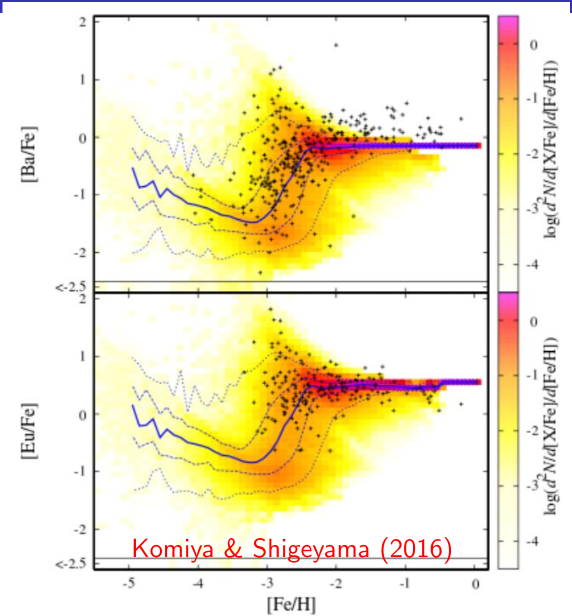
www.atnf.csiro.au

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).



Komiya & Shigeyama (2016)

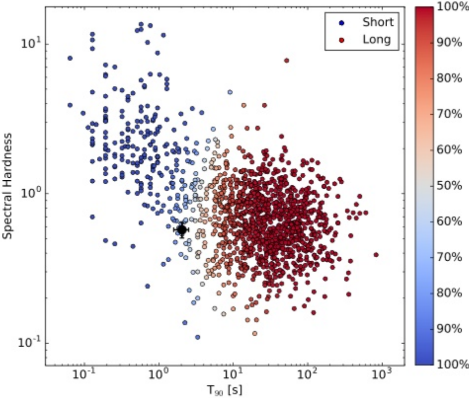
BNS Merger Work Continued (Incomplete)

- (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.

The sGRB – Merger Association

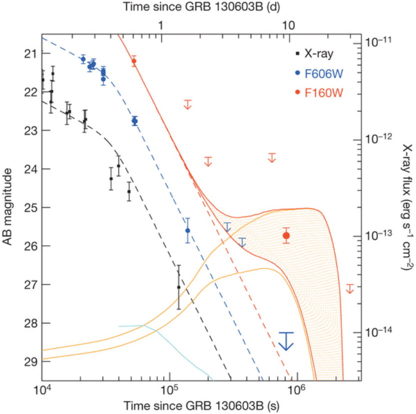
- Gehrels et al. (2005), Barthelmy et al. (2005) and Bloom et al. (2006) found observational evidence with the Swift gamma-ray telescope linking short gamma-ray bursts (sGRBs) with mergers. sGRBs are located primarily in elliptical galaxies, and far from regions of recent star formation and gravitational-collapse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

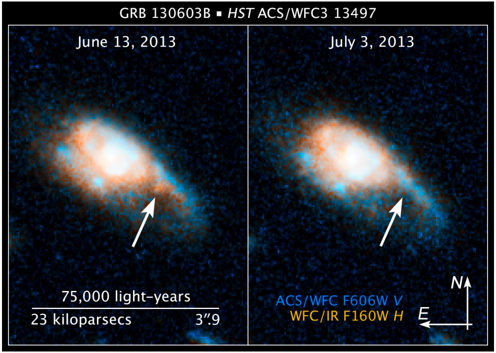


Kilonovae

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)

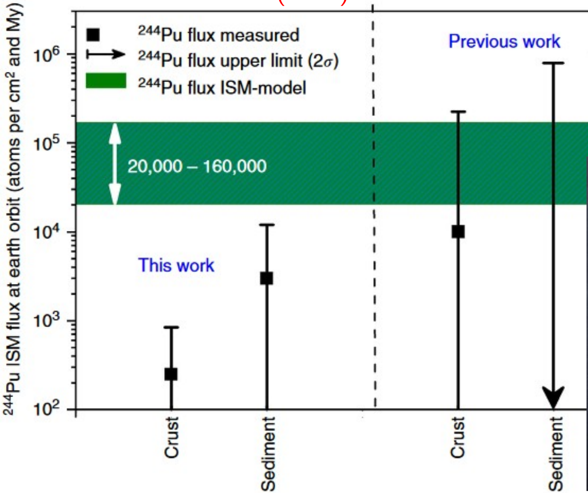


As many as 3 kilonova-like events were seen: Jin et al. (2016).

A recent development is the realization that lanthanides have high opacities (Barnes & Kasen 2013 and Tanaka & Hotokezawa 2013).

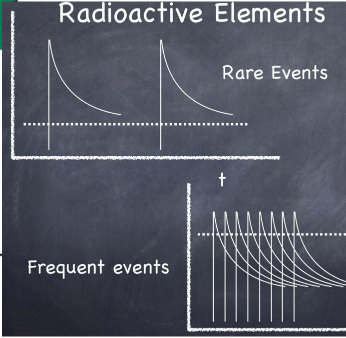
Terrestrial ^{244}Pu

Wallner et al. (2014)



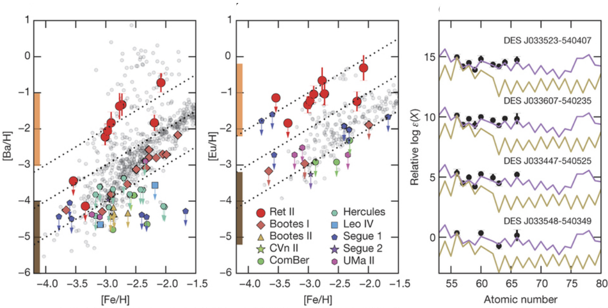
Abundance of ^{244}Pu $\sim 10 - 100$ times lower than expected from continuous (SN) creation.

From T. Piran



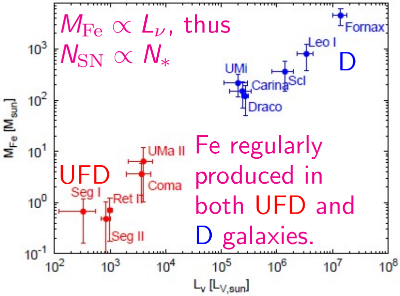
This is strong evidence in favor of the merger scenario.

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)

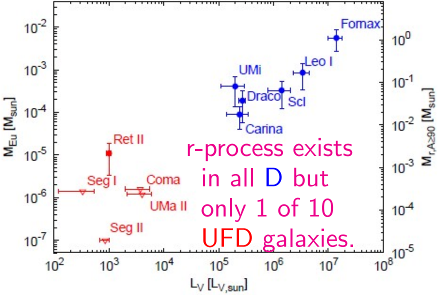


$M_{\rm Fe} \propto L_\nu$, thus $N_{\rm SN} \propto N_*$

D

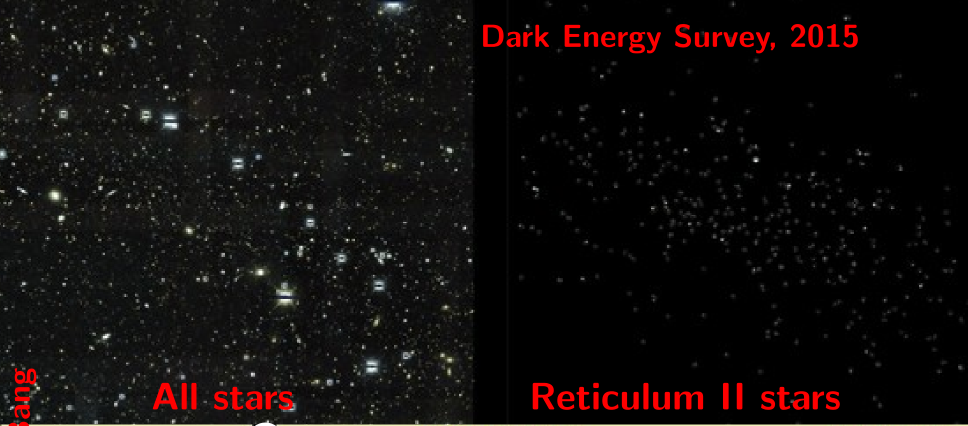
UFD

Fe regularly produced in both UFD and D galaxies.



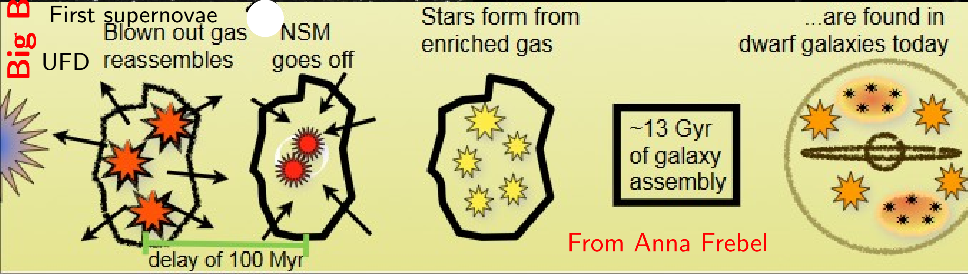
r-process exists in all D but only 1 of 10 UFD galaxies.

Dark Energy Survey, 2015



All stars

Reticulum II stars



Big Bang

First supernovae

UFD

Blown out gas reassembles

NSM goes off

delay of 100 Myr

Stars form from enriched gas

~13 Gyr of galaxy assembly

...are found in dwarf galaxies today

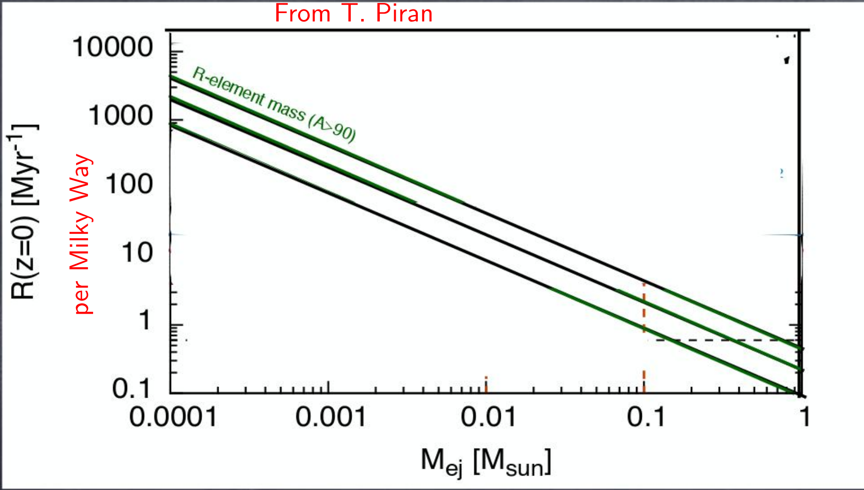
From Anna Frebel

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 $\sim$ 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).

GW170817

GW170817 carried multi-messenger astronomy to unprecedented levels. This event was observed in

- gravitational waves (Hanford, Livingston, Virgo)

Predicted signal from a neutron star merger, $M_{tot} = 2.73 M_\odot$.

- gamma rays (Fermi and Integral)

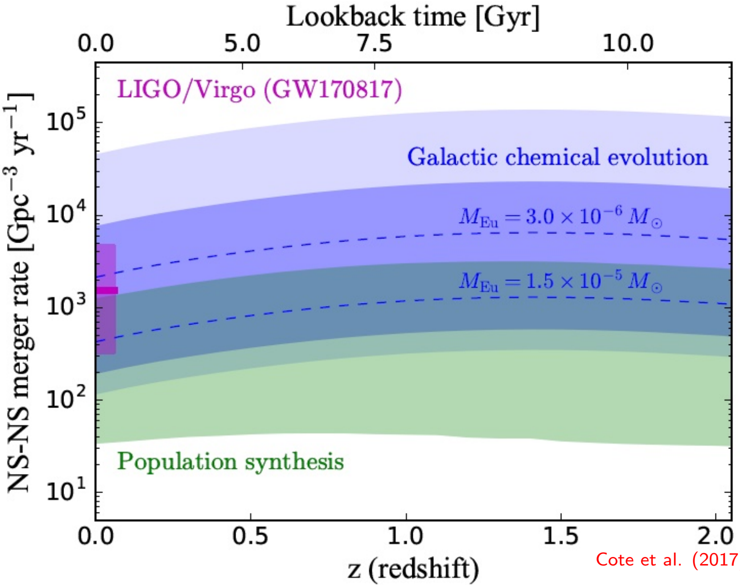
A short gamma-ray burst followed 1.7 s later. The remnant probably collapsed to a black hole. Correcting for binding, mass loss, and rotational support suggests $2.1 - 2.2 M_\odot$ is the upper limit to the neutron star maximum mass.

- UV, optical and IR (HST + more than 100 telescopes)

The predicted signal from a kilonova, powered by radioactive decay of $0.05 M_\odot$ of ejected matter forming r-process nuclei.

- X-rays (XMM, Chandra and Swift)
- mm and radio (ALMA, GMRT, VLA, others)

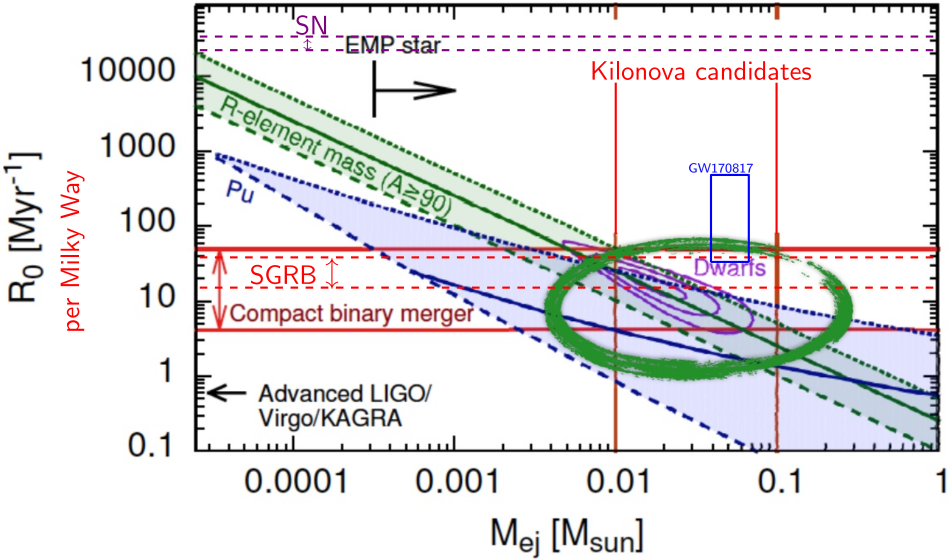
Rate Constraints from GW170817



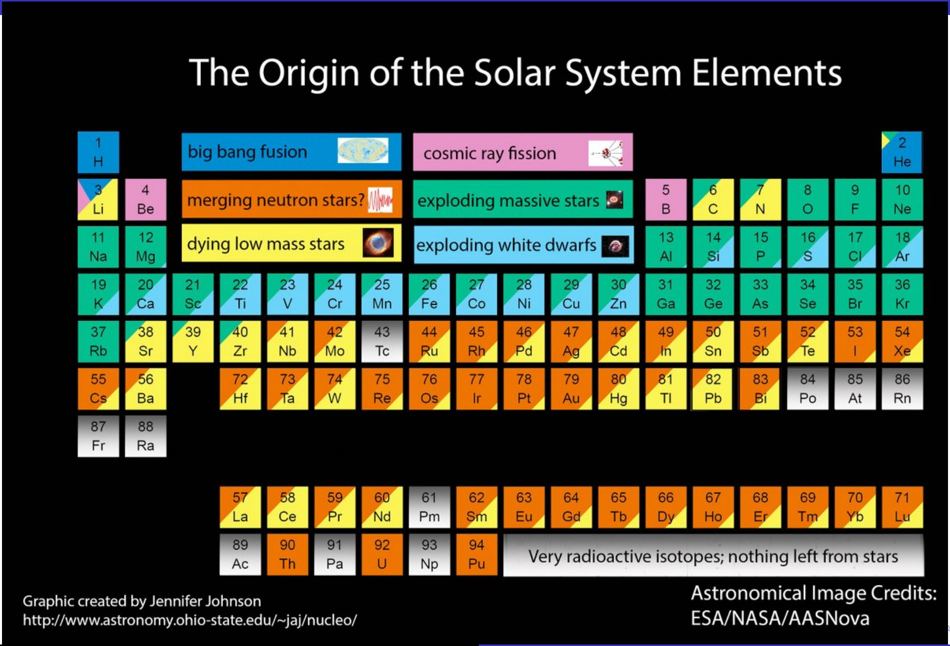
Cote et al. (2017)

Summary

From T. Piran



Is the Problem Solved?



The Origin of the Solar System Elements

big bang fusion

cosmic ray fission

merging neutron stars?

exploding massive stars

dying low mass stars

exploding white dwarfs

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	93 Np	94 Pu	Very radioactive isotopes; nothing left from stars								

Graphic created by Jennifer Johnson
http://www.astronomy.ohio-state.edu/~jaj/nucleo/

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