Astrofisica Nucleare e Subnucleare

Nuclear Astrophysics -- 4

Heavy element nucleosynthesis: the r process

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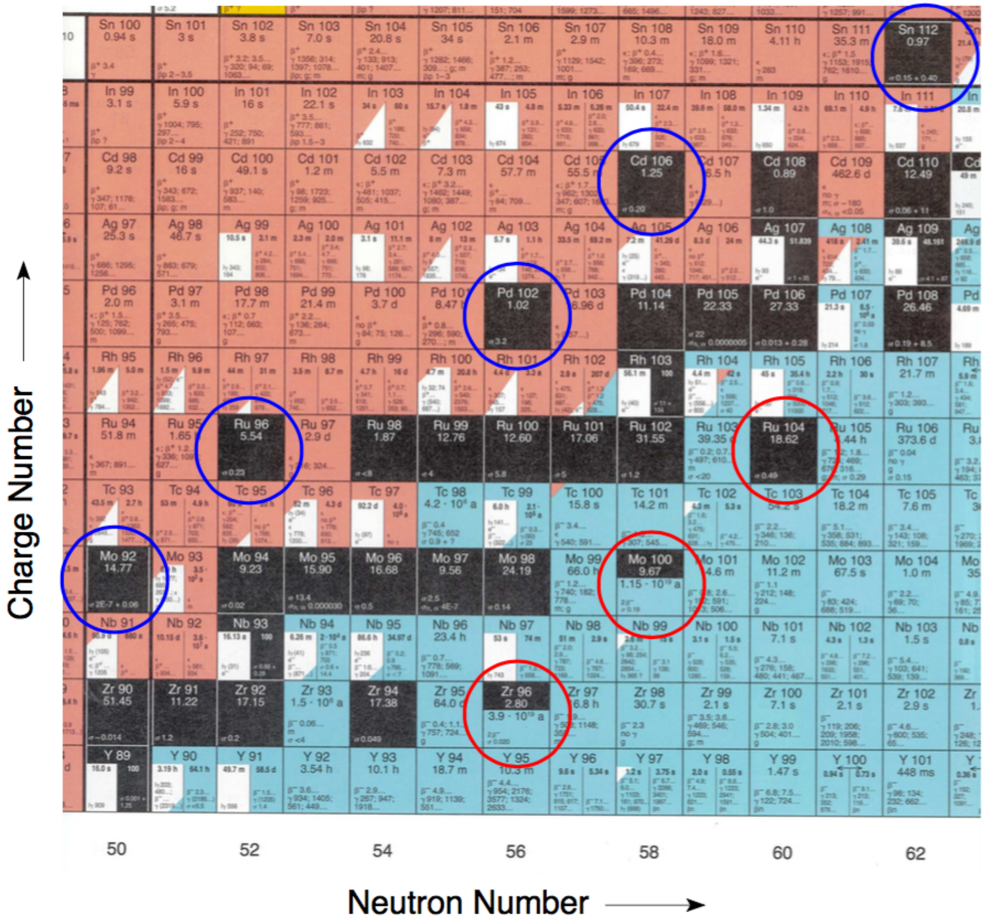
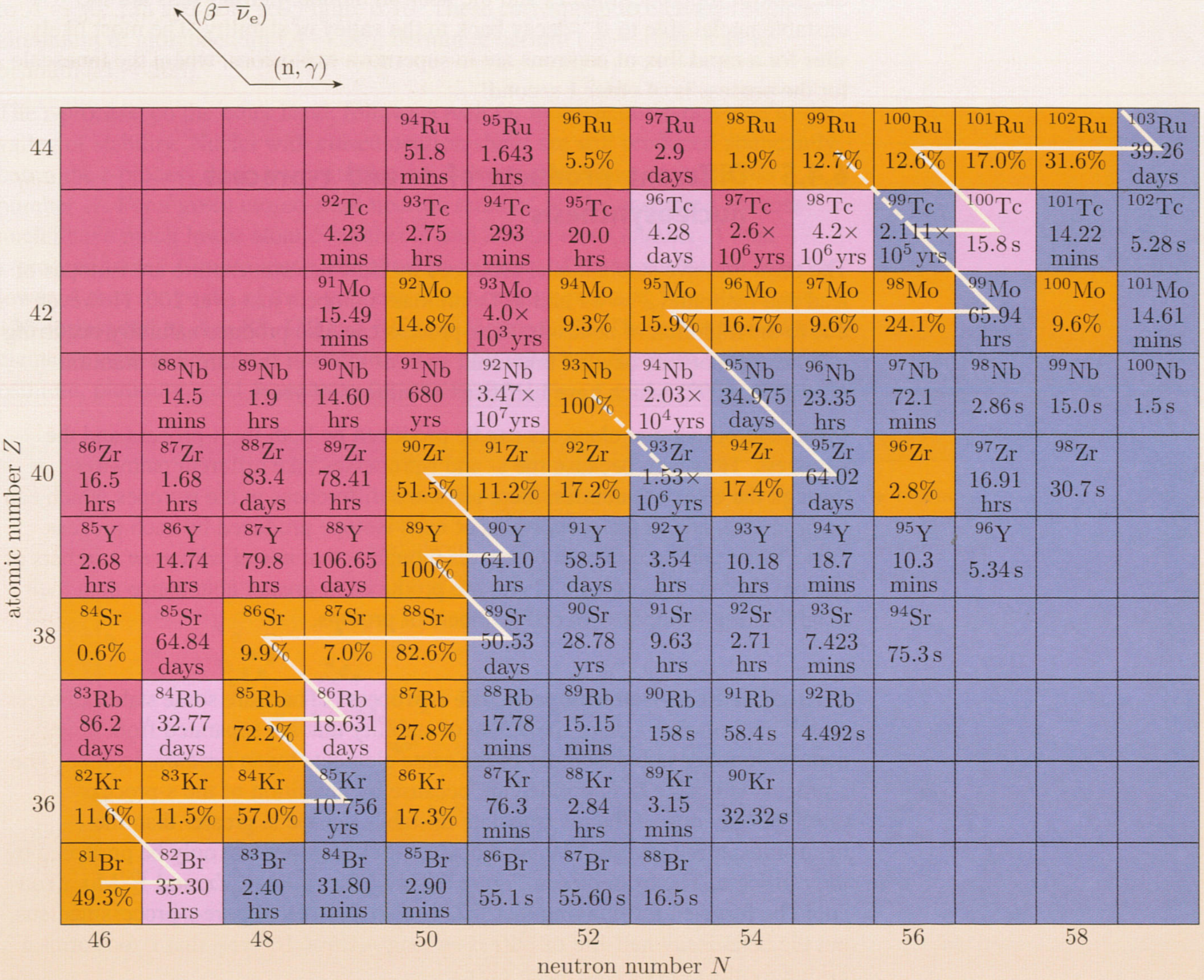
Nucleosynthesis beyond iron

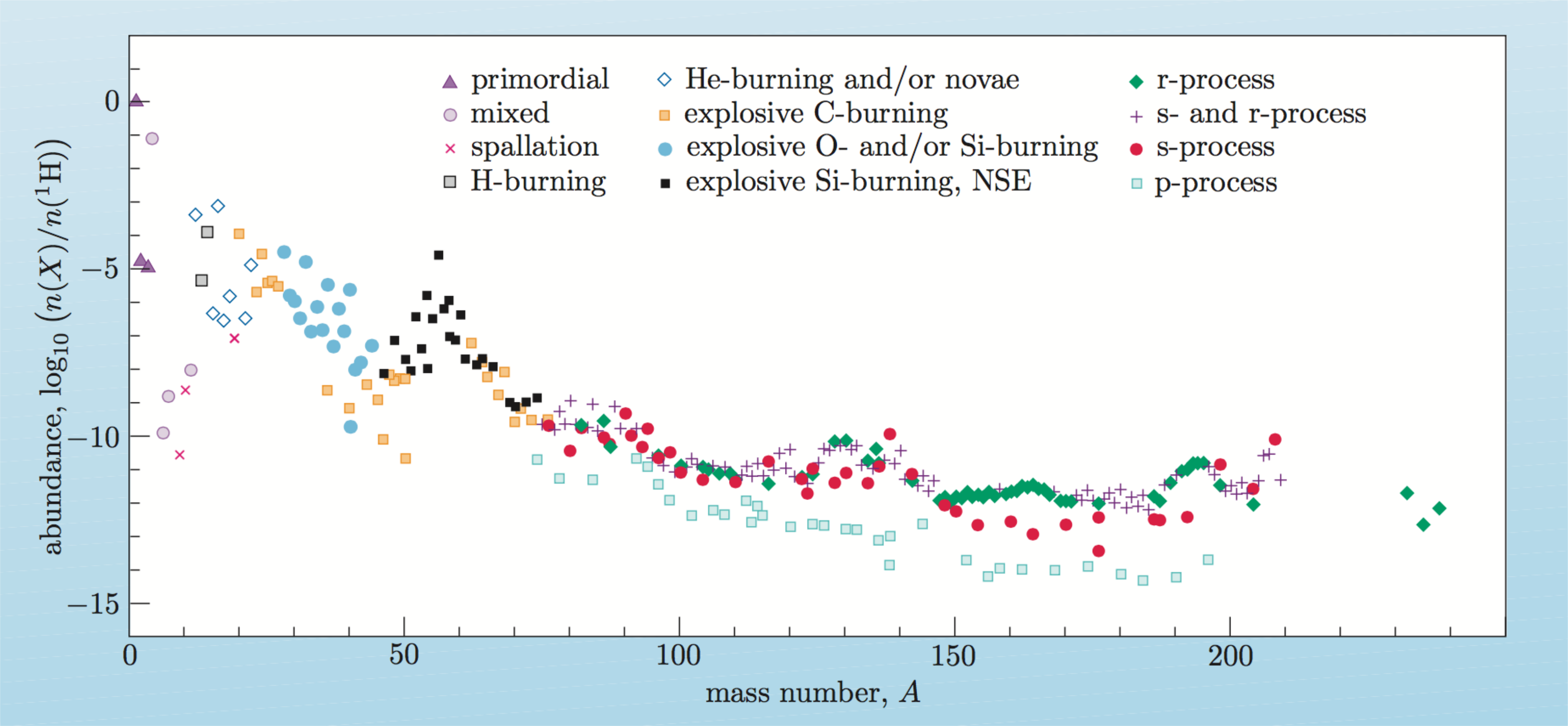


The stable nuclei beyond iron can be classified in three categories depending of their origin:

- s-process
- r-process
- p-process (γ-process)

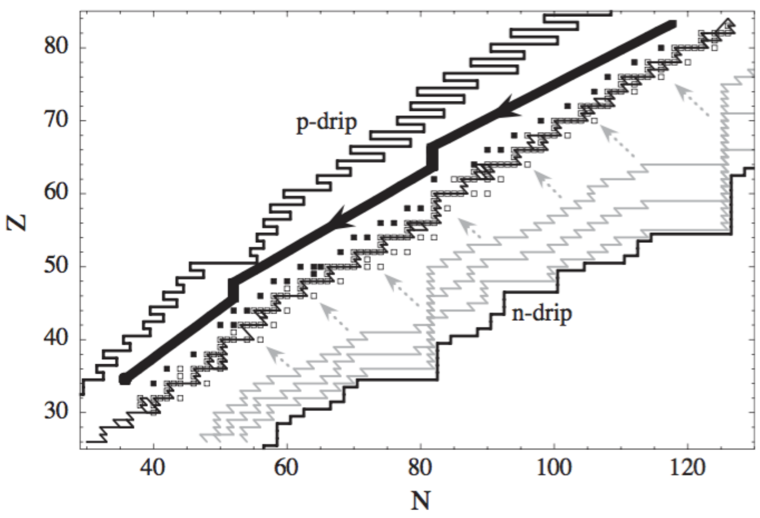


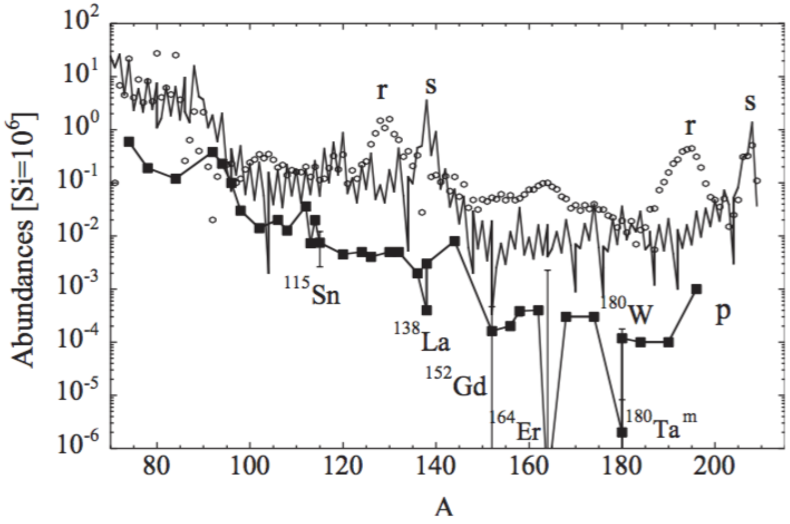
Z \ N	46	47	48	49	50	51	52	53	54	55	56	57	58	59
44					^{94}Ru 51.8 mins	^{95}Ru 1.643 hrs	^{96}Ru 5.5%	^{97}Ru 2.9 days	^{98}Ru 1.9%	^{99}Ru 12.7%	^{100}Ru 12.6%	^{101}Ru 17.0%	^{102}Ru 31.6%	^{103}Ru 39.26 days
43				^{92}Tc 4.23 mins	^{93}Tc 2.75 hrs	^{94}Tc 293 mins	^{95}Tc 20.0 hrs	^{96}Tc 4.28 days	^{97}Tc 2.6×10^6 yrs	^{98}Tc 4.2×10^6 yrs	^{99}Tc 2.111×10^5 yrs	^{100}Tc 15.8 s	^{101}Tc 14.22 mins	^{102}Tc 5.28 s
42				^{91}Mo 15.49 mins	^{92}Mo 14.8%	^{93}Mo 4.0×10^3 yrs	^{94}Mo 9.3%	^{95}Mo 15.9%	^{96}Mo 16.7%	^{97}Mo 9.6%	^{98}Mo 24.1%	^{99}Mo 65.94 hrs	^{100}Mo 9.6%	^{101}Mo 14.61 mins
41		^{88}Nb 14.5 mins	^{89}Nb 1.9 hrs	^{90}Nb 14.60 hrs	^{91}Nb 680 yrs	^{92}Nb 3.47×10^7 yrs	^{93}Nb 100%	^{94}Nb 2.03×10^4 yrs	^{95}Nb 34.975 days	^{96}Nb 23.35 hrs	^{97}Nb 72.1 mins	^{98}Nb 2.86 s	^{99}Nb 15.0 s	^{100}Nb 1.5 s
40	^{86}Zr 16.5 hrs	^{87}Zr 1.68 hrs	^{88}Zr 83.4 days	^{89}Zr 78.41 hrs	^{90}Zr 51.5%	^{91}Zr 11.2%	^{92}Zr 17.2%	^{93}Zr 1.53×10^6 yrs	^{94}Zr 17.4%	^{95}Zr 64.02 days	^{96}Zr 2.8%	^{97}Zr 16.91 hrs	^{98}Zr 30.7 s	
39	^{85}Y 2.68 hrs	^{86}Y 14.74 hrs	^{87}Y 79.8 hrs	^{88}Y 106.65 days	^{89}Y 100%	^{90}Y 64.10 hrs	^{91}Y 58.51 days	^{92}Y 3.54 hrs	^{93}Y 10.18 hrs	^{94}Y 18.7 mins	^{95}Y 10.3 mins	^{96}Y 5.34 s		
38	^{84}Sr 0.6%	^{85}Sr 64.84 days	^{86}Sr 9.9%	^{87}Sr 7.0%	^{88}Sr 82.6%	^{89}Sr 50.53 days	^{90}Sr 28.78 yrs	^{91}Sr 9.63 hrs	^{92}Sr 2.71 hrs	^{93}Sr 7.423 mins	^{94}Sr 75.3 s			
37	^{83}Rb 86.2 days	^{84}Rb 32.77 days	^{85}Rb 72.2%	^{86}Rb 18.631 days	^{87}Rb 27.8%	^{88}Rb 17.78 mins	^{89}Rb 15.15 mins	^{90}Rb 158 s	^{91}Rb 58.4 s	^{92}Rb 4.492 s				
36	^{82}Kr 11.6%	^{83}Kr 11.5%	^{84}Kr 57.0%	^{85}Kr 10.756 yrs	^{86}Kr 17.3%	^{87}Kr 76.3 mins	^{88}Kr 2.84 hrs	^{89}Kr 3.15 mins	^{90}Kr 32.32 s					
35	^{81}Br 49.3%	^{82}Br 35.30 hrs	^{83}Br 2.40 hrs	^{84}Br 31.80 mins	^{85}Br 2.90 mins	^{86}Br 55.1 s	^{87}Br 55.60 s	^{88}Br 16.5 s						


▲ primordial
○ mixed
× spallation
☐ H-burning
◇ He-burning and/or novae
☐ explosive C-burning
● explosive O- and/or Si-burning
■ explosive Si-burning, NSE
◆ r-process
+ s- and r-process
● s-process
☐ p-process
abundance, $\log_{10}(n(X)/n(^1H))$
0
−5
−10
−15
0
50
100
150
200
mass number, A

Nucleosynthesis beyond iron

Three processes contribute to the nucleosynthesis beyond iron: s-process, r-process and p-process (γ-process).

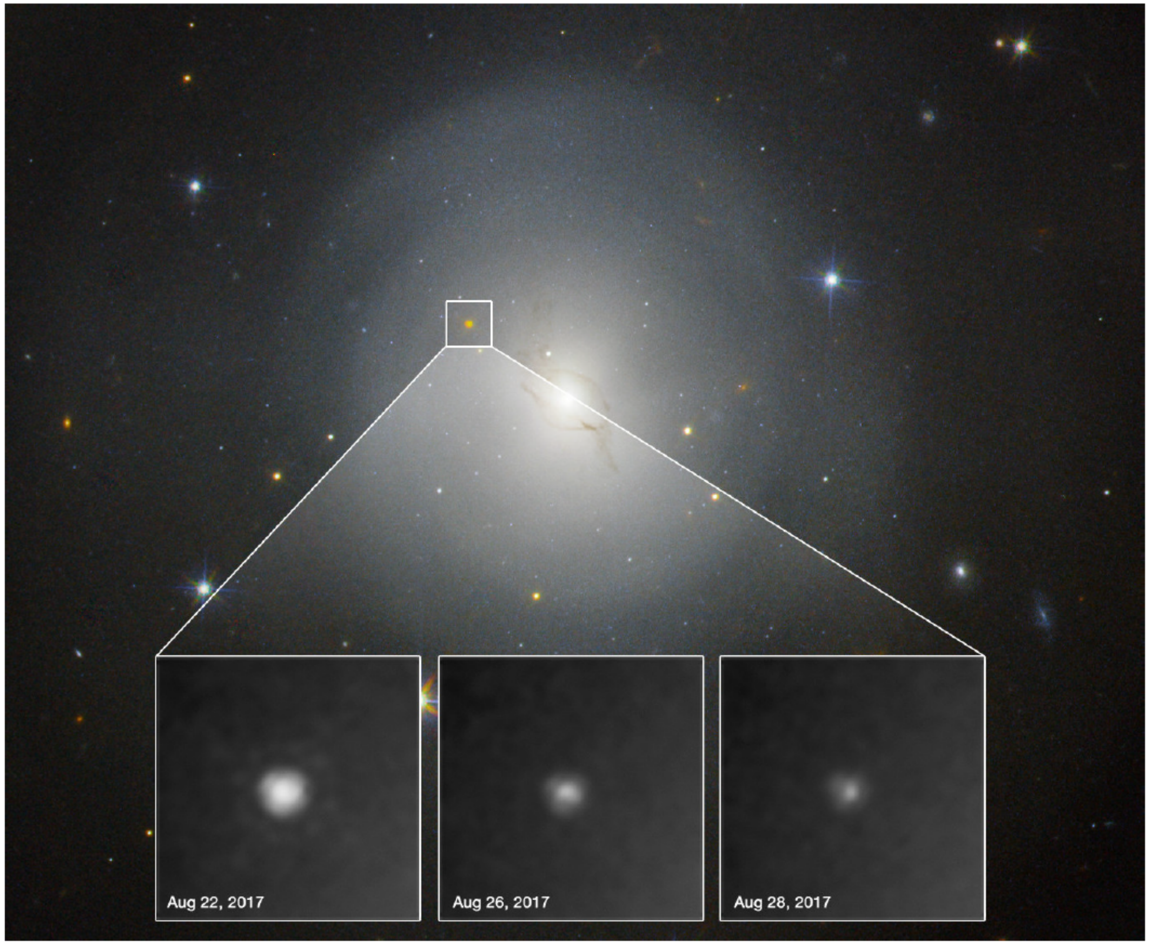




- s-process: relatively low neutron densities, $n_n = 10^{10-12}\ \mathrm{cm}^{-3}$, $\tau_n > \tau_\beta$
- r-process: large neutron densities, $n_n > 10^{20}\ \mathrm{cm}^{-3}$, $\tau_n < \tau_\beta$.
- p-process: photodissociation of s-process material.

Kilonova/Macronova luminosity

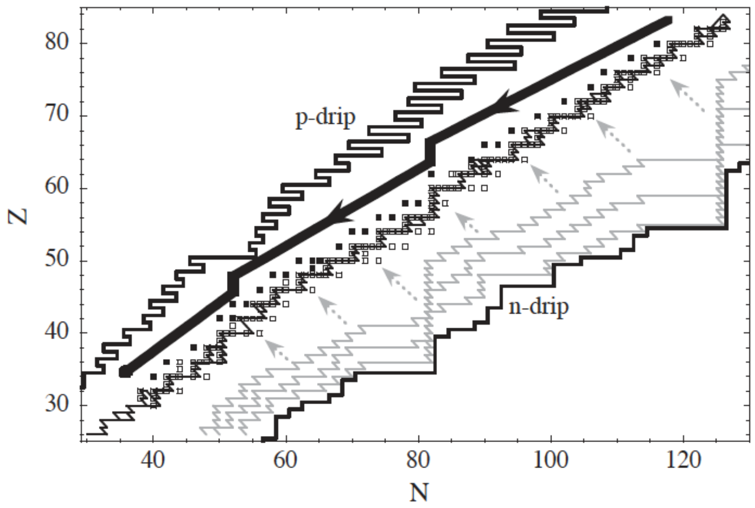
First direct signal from “in situ” r process operation.

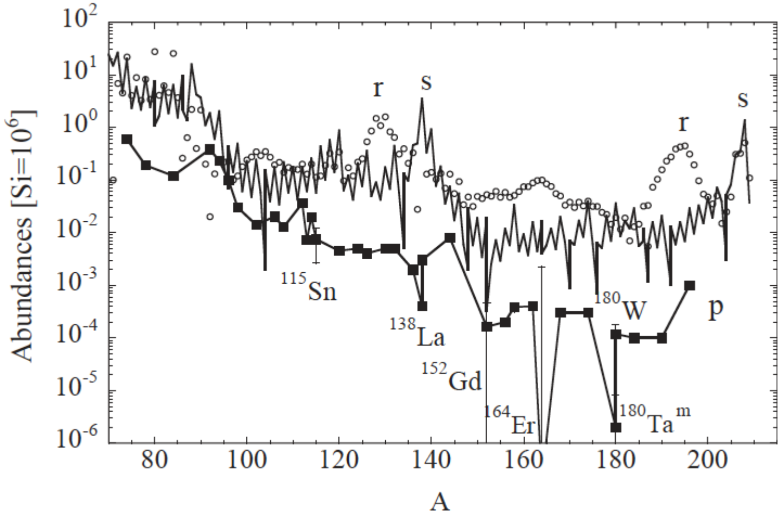


Credit: NASA & ESA. N. Tanvir (U. Leicester), A. Levan (U. Warwick), and A. Fruchter and O. Fox (STScI)

Nucleosynthesis beyond iron

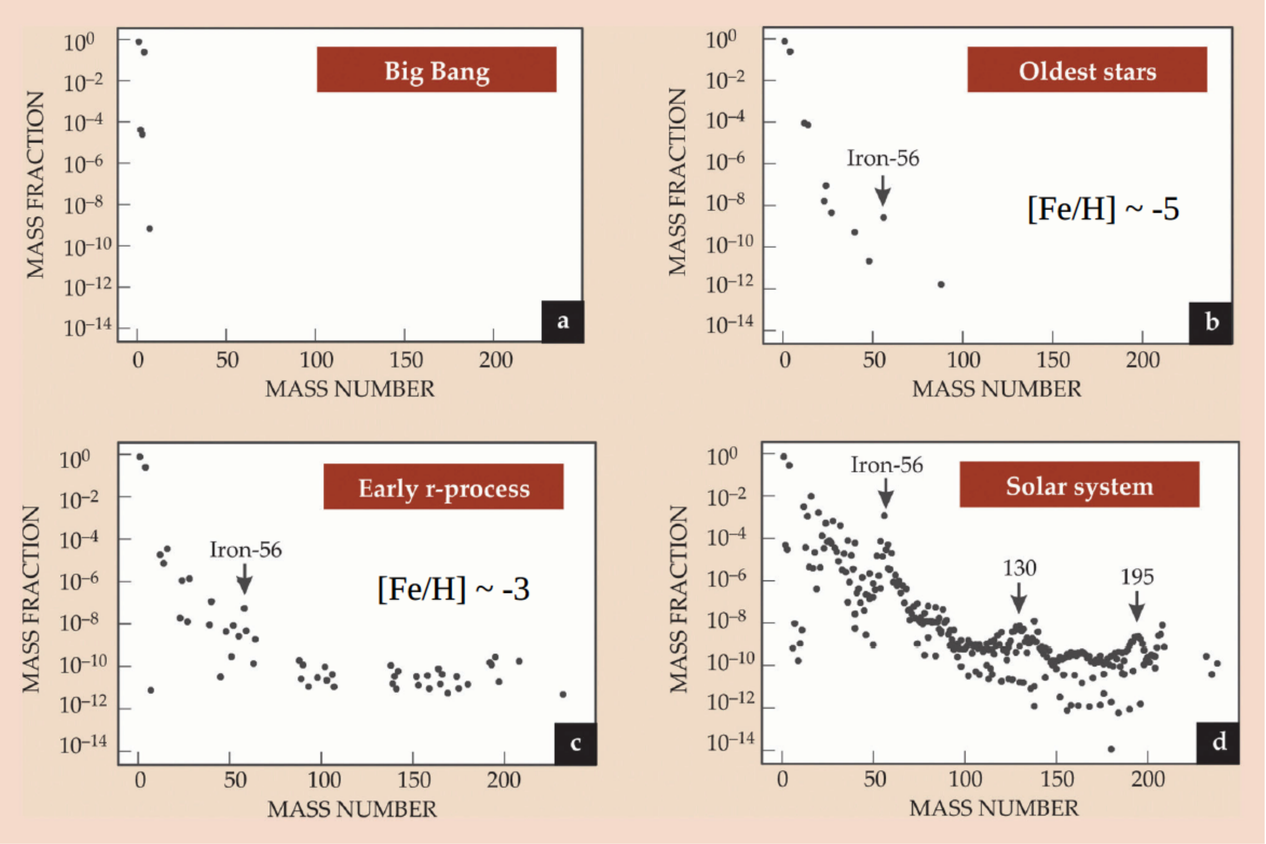
Three processes contribute to the nucleosynthesis beyond iron: s process, r process and p process (γ-process).





- s process: low neutron densities, $n_n = 10^{10-12}\ \mathrm{cm}^{-3}$, $\tau_n > \tau_\beta$ (site: intermediate mass stars)
- r process: large neutron densities, $n_n > 10^{20}\ \mathrm{cm}^{-3}$, $\tau_n \ll \tau_\beta$ (unknown astrophysical site)
- The r-process abundance is obtained by subtracting the calculated s-process abundance from the observed solar abundance of heavy elements, $N_r = N_\odot - N_s$. Very different odd-even staggering in s and r abundances.
- Can we validate the above assumptions?

Time evolution: metalicity



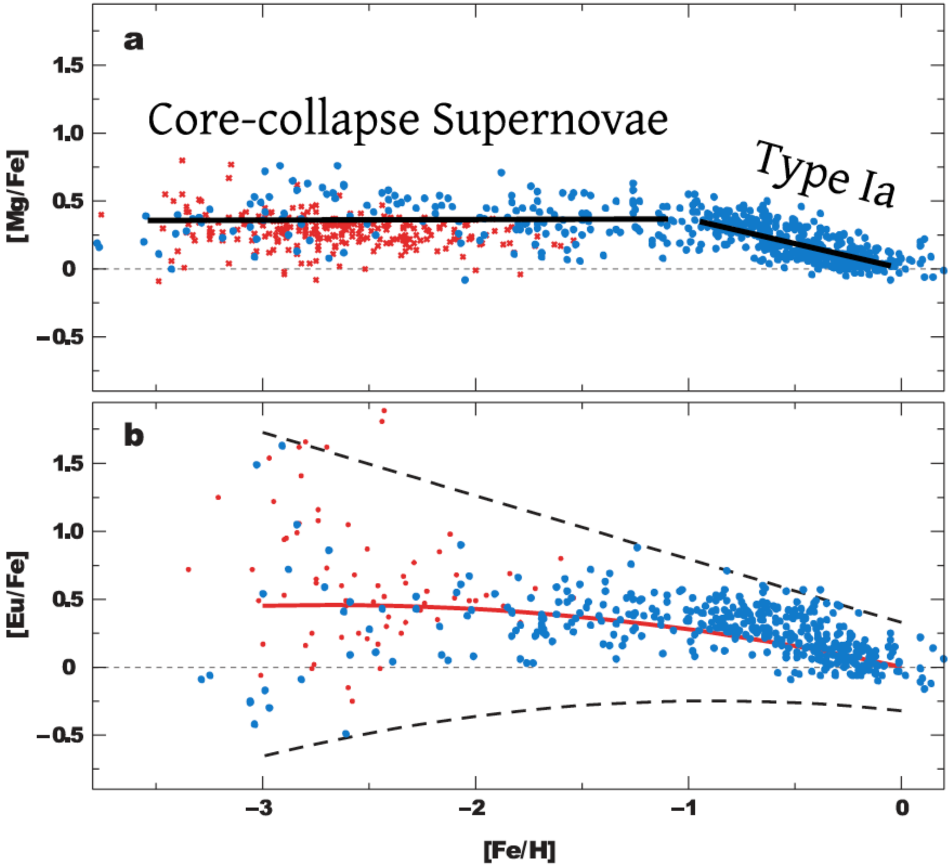
Astronomers use the metalicity:

$$[\mathrm{Fe}/\mathrm{H}] = \log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_{*} - \log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_{\odot}$$

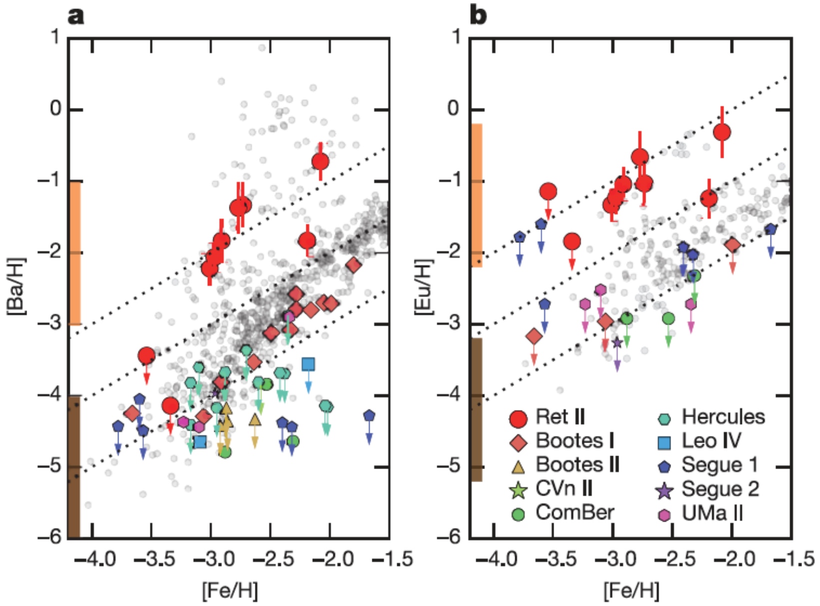
as a proxy for age.

Implications from observations

Individual stars, Milky Way Halo
Sneden, Cowan & Gallino, 2008



Ji et al 2016 found that only 1 of 10 ultrafaint dwarf galaxies is enriched in r-process elements

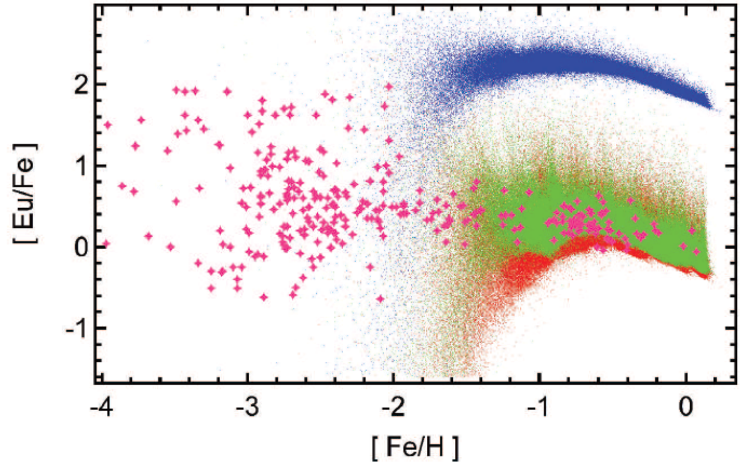


R process related to rare high yield events not correlated with Iron enrichment

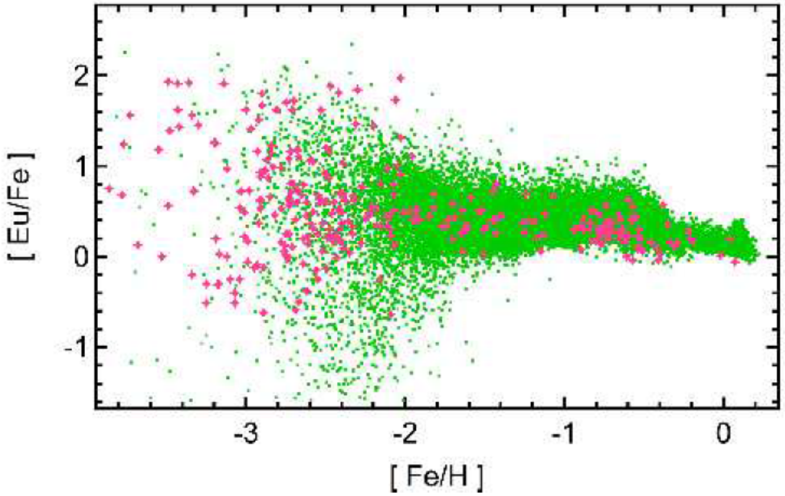
Similar results obtained by ^{60}Fe and ^{244}Pu observations in deep sea sediments (Wallner et al, 2015; Hotokezaka et al, 2015)

Introduction: Summary

- The r process is a primary process operating in a site that produces both neutrons and seeds. Large neutron densities imply a site with extreme conditions of temperature and/or density.
- There is strong evidence that the bulk of r-process content in the Galaxy originates from a high yield/low frequency events.
- Neutron star mergers may account for most of the r-process material in the galaxy. However, due to the coalescent delay time they may not contribute efficiently at low metalicities. Magneto-rotational supernova may contribute at low metalicities.



- Red dots: 10^8 yr coalescence time
- Green dots: 10^6 yr coalescence time
- Blue dots: larger merger probability.



- Including MHD-jet supernovae

Wehmeyer, B., M. Pignatari, and F.-K. Thielemann , Mon. Not. Roy. Astron. Soc. 452, 1970 (2015)

R-process sites

- Any r-process site should be able to produce both the “seed” nuclei where neutrons are captured and the neutrons that drive the r-process. The main parameter describing the feasibility of a site to produce r-process nuclei is the neutron-to-seed ratio: n_n/n_{seed}.
- If the seed nuclei have mass number A_{seed} and we have n_n/n_{seed} neutrons per seed, the final mass number of the nuclei produced will be $A = A_{\text{seed}} + n_n/n_{\text{seed}}$.
- For example, taking $A_{\text{seed}} = 90$ we need $n_n/n_{\text{seed}} = 100$ if we want to produce the 3rd r-process peak ($A \sim 195$) and $n_n/n_{\text{seed}} = 150$ to produce U and Th.

R-process sites

In an astrophysical site there are only two possible ways to achieve large neutron-to-seeds:

1. Let us consider high temperature neutron-rich matter with high entropy that it is ejected at high velocities. As the material expands α particles will be formed. However, the build up of heavy nuclei by 3-body reactions becomes very unefficient by two reasons: 1) Too many photons per nucleon due to the high entropy, 2) Too litle time to produce heavy nuclei due to the fast expansion. It means that we will have an α-rich freeze out with a few heavy nuclei produced and many neutrons left ($Y_\alpha \approx Y_e/2$, $Y_n \approx 1 - 2Y_e$). This is commonly denoted as “high entropy” r-process
2. Let us consider matter very high density matter with low entropies. Due to the high densities electrons have large fermi energies and will drive the composition very neutron rich. At some point the neutron drip line is reached and nuclei start to “drip” neutrons. This is the situation in the crust of neutron stars where densities are 10^{12-13} g cm^{-3} and $Y_e \sim 0.05$: $Y_n = 1 - \langle A \rangle Y_e / \langle Z \rangle$, $Y_s = Y_e / \langle Z \rangle$; $Y_n / Y_s = \langle Z \rangle / Y_e - \langle A \rangle$; $Y_n / Y_s \sim 500 - 2000$. This is commonly denoted as “low entropy” r-process.

r-process nucleosynthesis relevant parameters

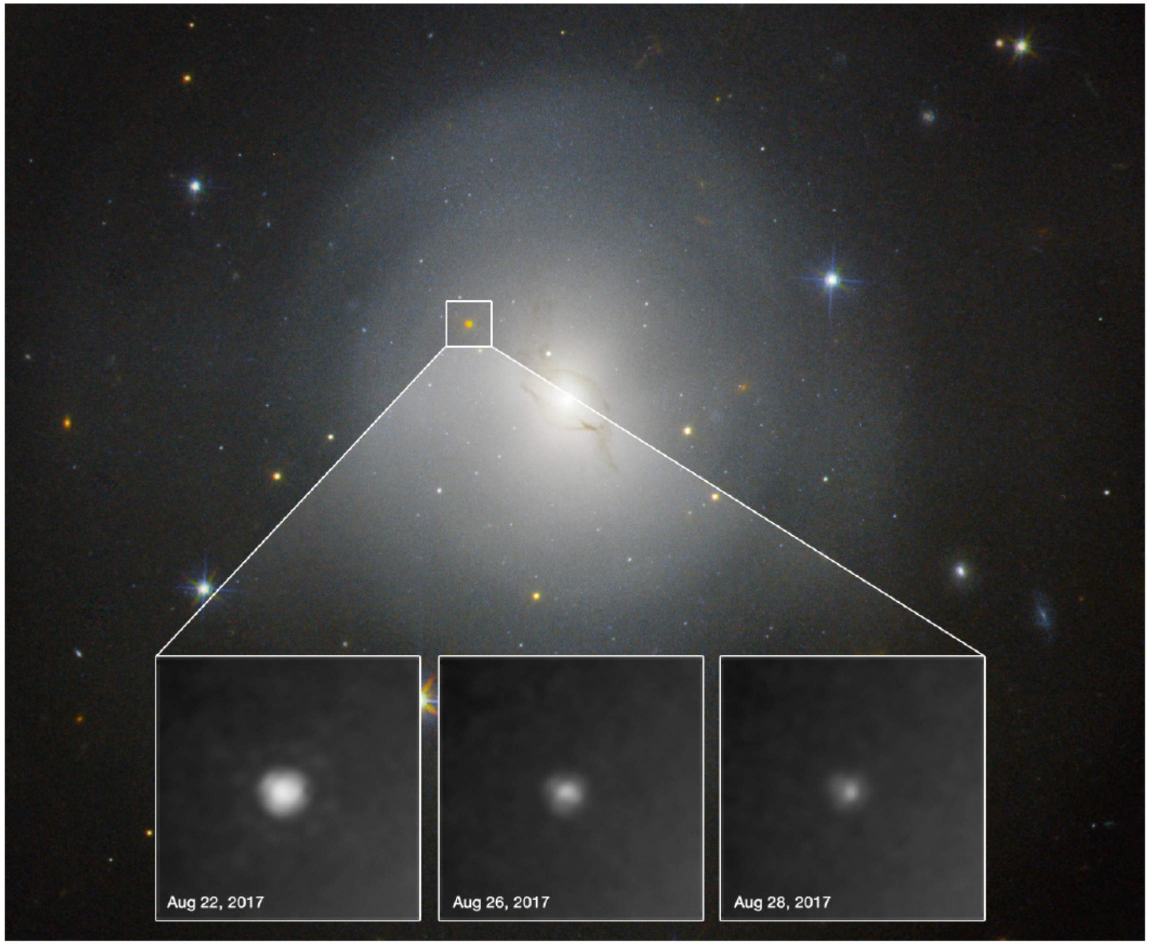
Independently of the astrophysical site the nucleosynthesis is sensitive to a few parameters that determine the neutron-to-seed ratio and the heavier elements that can be produced:

$$A_f = A_i + n_s, \quad n_s = n_n/n_{\text{seed}} \sim s^3/(Y_e^3 \tau_{\text{dyn}})$$

Y_e	The lower the value of Y_e more neutrons are available and the larger n_s
entropy	Large entropy $s \sim T^3/\rho$, means low density and high temperature (large amount of photons). Both are detrimental to the build up of seeds by 3-body reactions.
expansiton time scale	The faster the matter expands, smaller τ_{dyn}, the less time one has to build up seeds

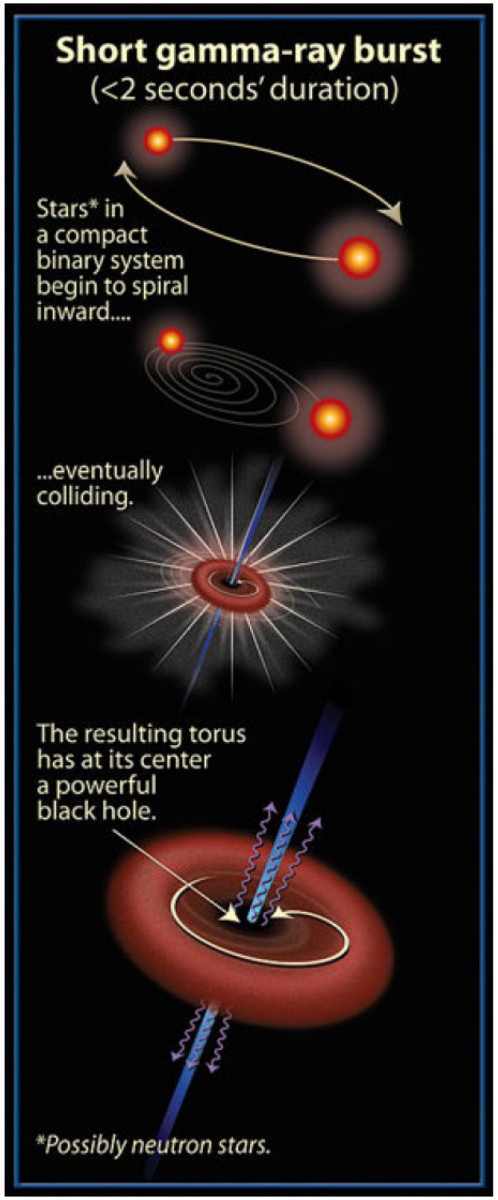
Kilonova/Macronova luminosity

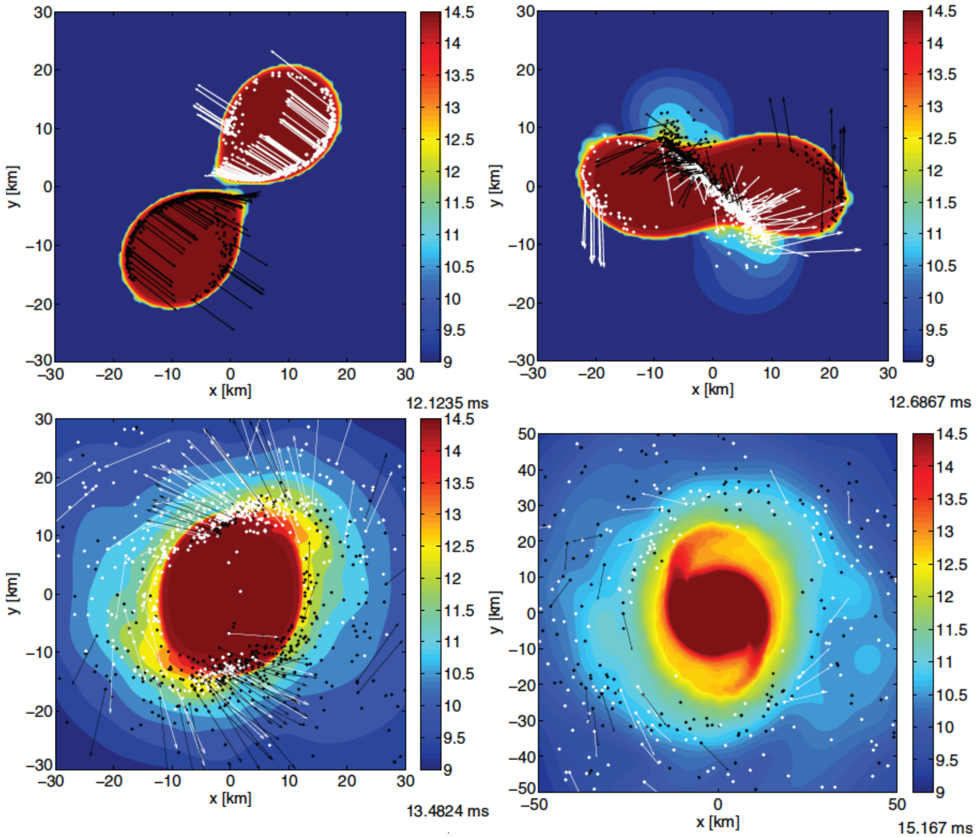
First direct signal from “in situ” r process operation.



Credit: NASA & ESA. N. Tanvir (U. Leicester), A. Levan (U. Warwick), and A. Fruchter and O. Fox (STScI)

Neutron star mergers: Short gamma-ray bursts and r-process



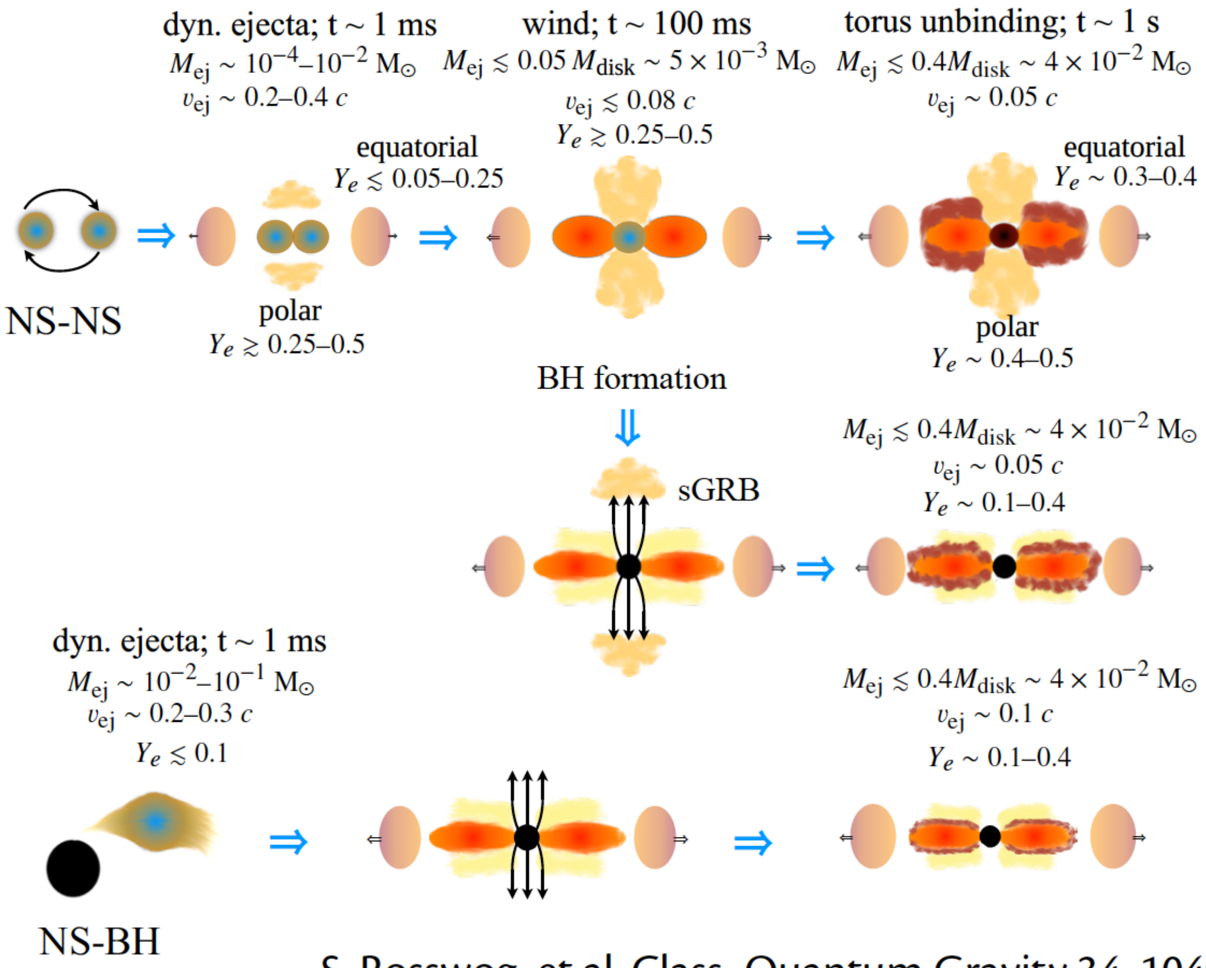


Basuswein, Goriely, Janka, ApJ 773, 78 (2013)

- Mergers are associated with short-gamma ray bursts.
- They are also promising sources of gravitational waves.
- Observational signatures of the r-process?

Merger channels and ejection mechanism

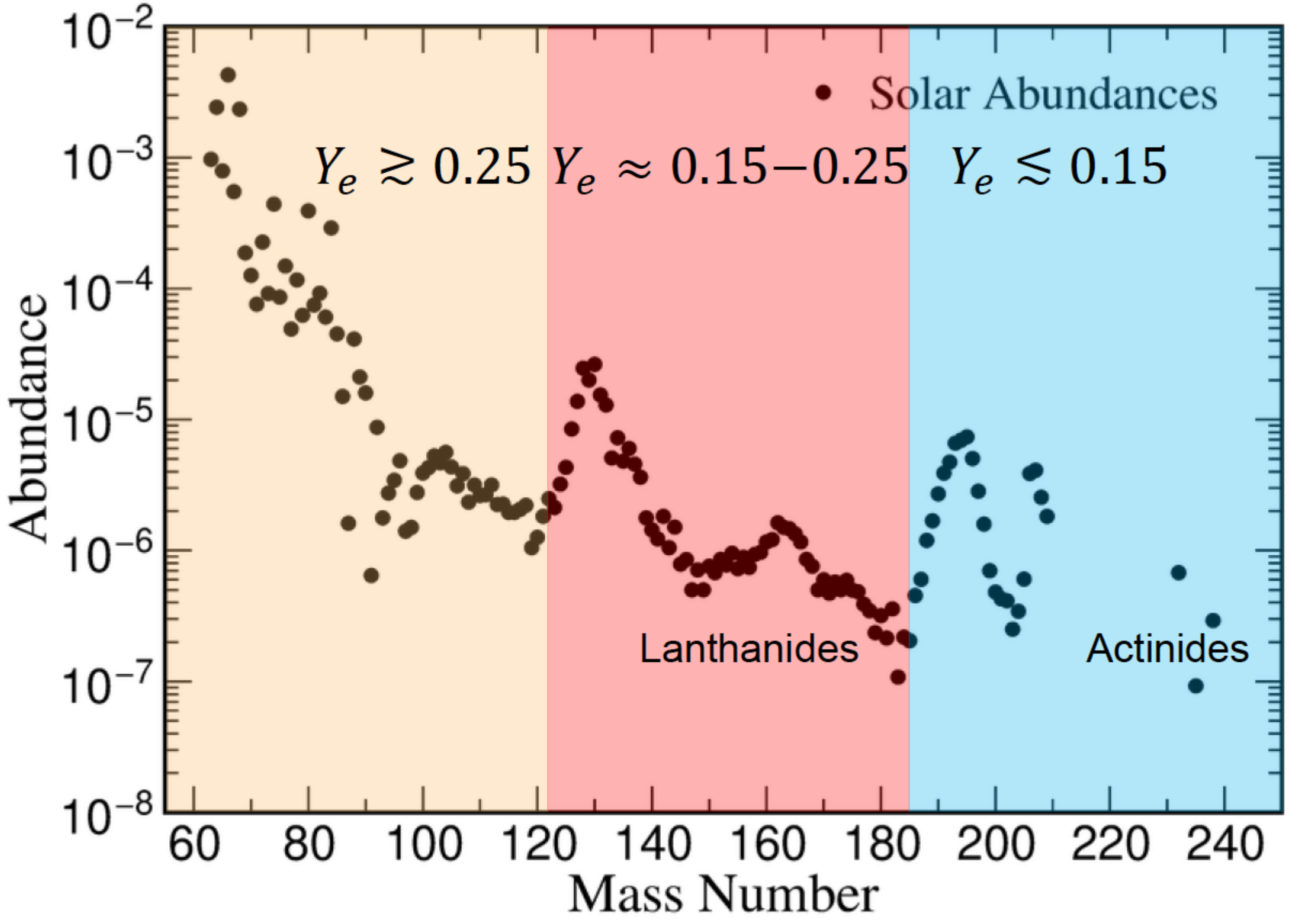
In mergers we deal with a variety of initial configurations (netron-star neutron-star vs neutron-star black-hole) with additional variations in the mass-ratio. The evolution after the merger also allows for further variations.



S. Rosswog, et al, Class. Quantum Gravity 34, 104001 (2017).

Dependence nucleosynthesis on Y_e

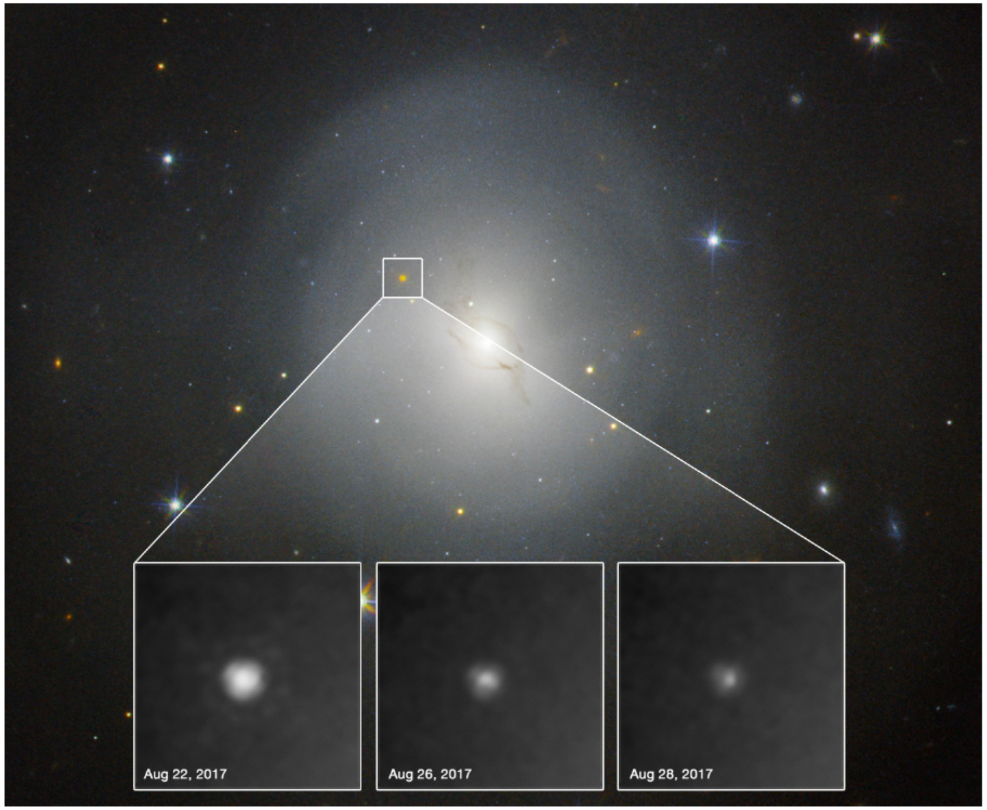
Nucleosynthesis depends on neutron richness of ejecta



The relevant nuclear physics depends on the particular conditions.

AT 2017 gfo: electromagnetic signature from r process

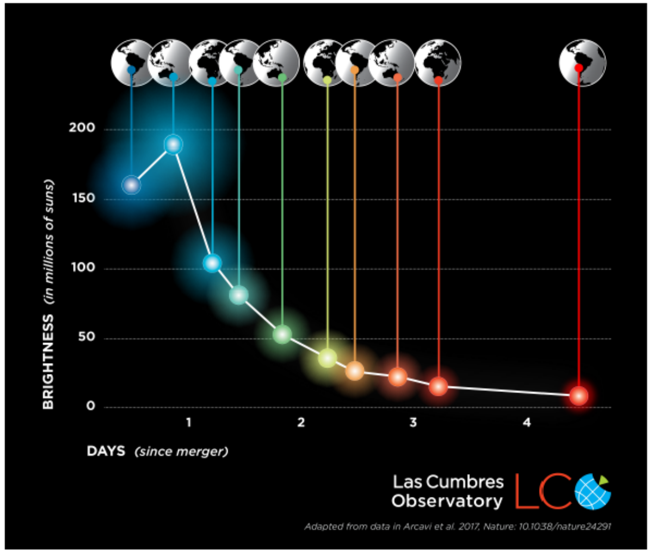
In-situ signature of r process nucleosynthesis



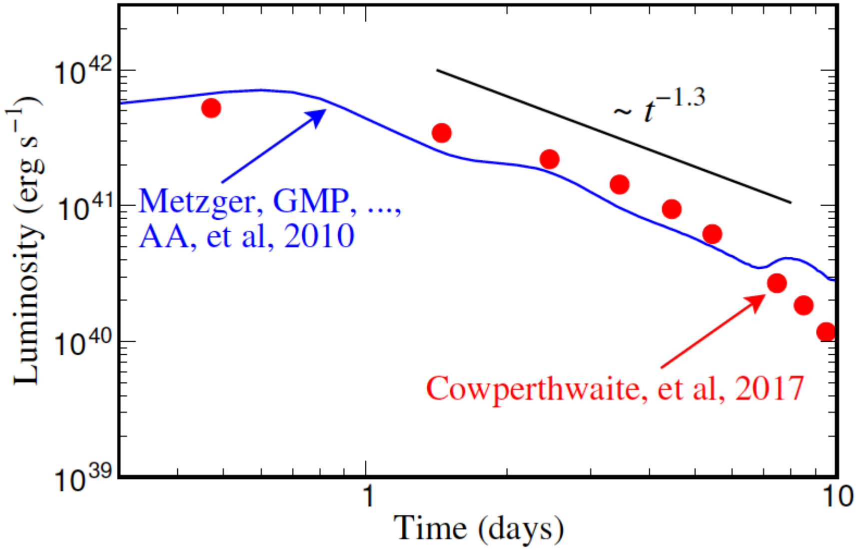
NASA and ESA. N. Tanvir (U. Leicester), A. Levan (U. Warwick), and A. Fruchter and O. Fox (STScI)

- Novel fastly evolving transitent
- Signature of statistical decay of fresly synthesized r process nuclei

AT 2017 gfo: interpretation



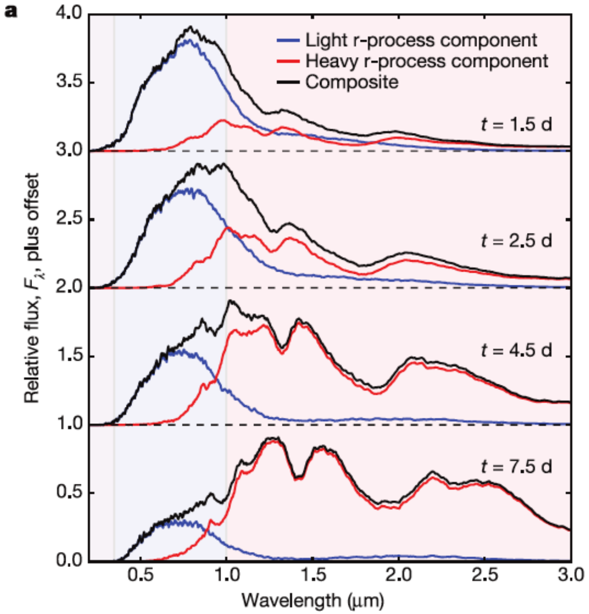
Adapted from data in Arcavi et al. 2017, Nature: 10.1038/nature24291



- Time evolution determined by the radioactive decay of r-process nuclei
- Two components:
  - blue dominated by light elements ($Z < 50$)
  - Red due to presence of Lanthanides ($Z = 57$–71) and/or Actinides ($Z = 89$–103)
- Likely source of heavy elements including Gold, Platinum and Uranium

Two components model

Kasen et al, Nature 551, 80 (2017)

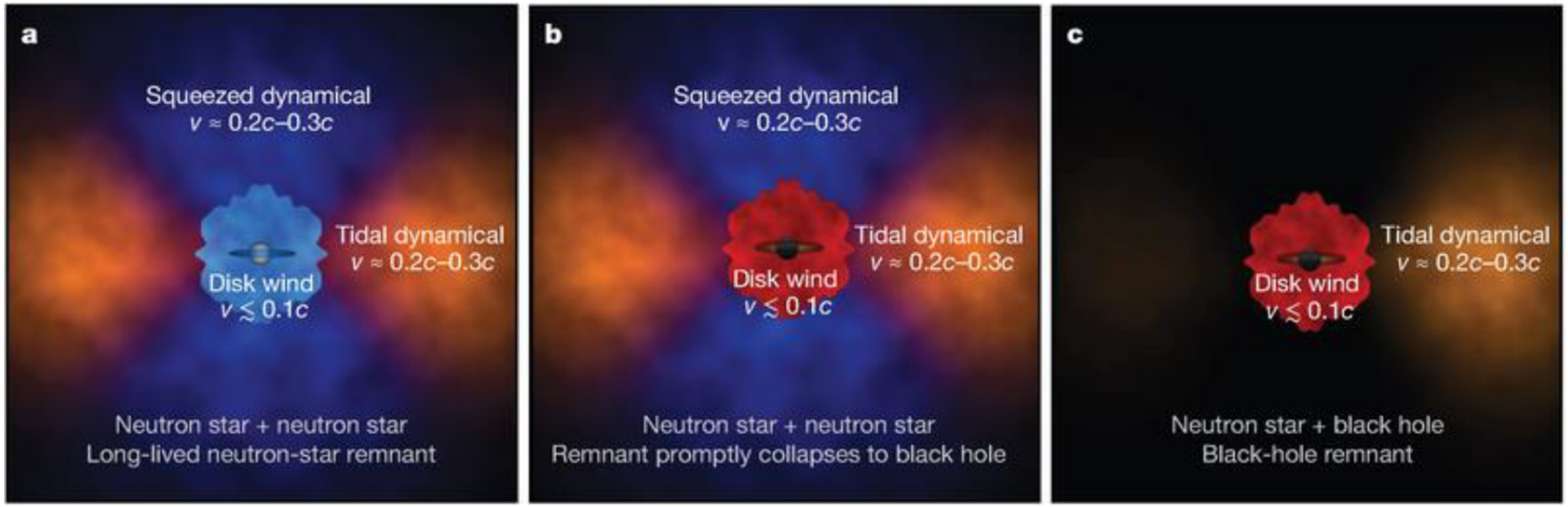


- Blue component from polar ejecta subject to strong neutrino fluxes (light r process)

$$M = 0.025\, M_\odot, v = 0.3c, X_\mathrm{lan} = 10^{-4}$$

- Red component disk ejecta after NS collapse to a black hole (includes both light and heavy r process)

$$M = 0.04\, M_\odot, v = 0.15c, X_\mathrm{lan} = 10^{-1.5}$$



Summary

- Heavy elements are observed at very early times in Galactic history. Produced by a primary process that creates both neutrons and seeds.
- Neutron star mergers are likely the site where the "main r process" takes place.
- Radioactive decay of r-process ejecta produces an electromagnetic transient observed for the first time after GW170817.
- Observations of Blue and Red kilonova components show that both light ($A \lesssim 120$) and heavy ($A \gtrsim 120$) elements are produced. No direct evidence of individual elements.
    - How can we determine composition?
    - What were the heavier elements produced in the merger?
    - How does the nucleosynthesis depends on merging system?
    - What is the contribution of mergers to light r process elements?

Bibliography:

Cowan, *et al.*, *Making the Heaviest Elements in the Universe: A Review of the Rapid Neutron Capture Process*, arXiv:1901.01410 [astro-ph.HE]