Fascinating tales of Silver and Gold

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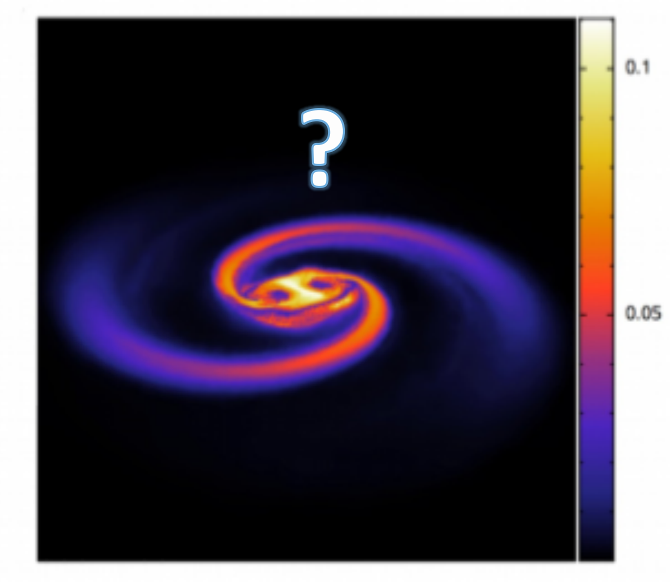
DTU Space

University of Ferrara. October 24, 2017

We think we are made of
dust from the Stars !

.. but are we also made of
dust from Neutron Stars ?



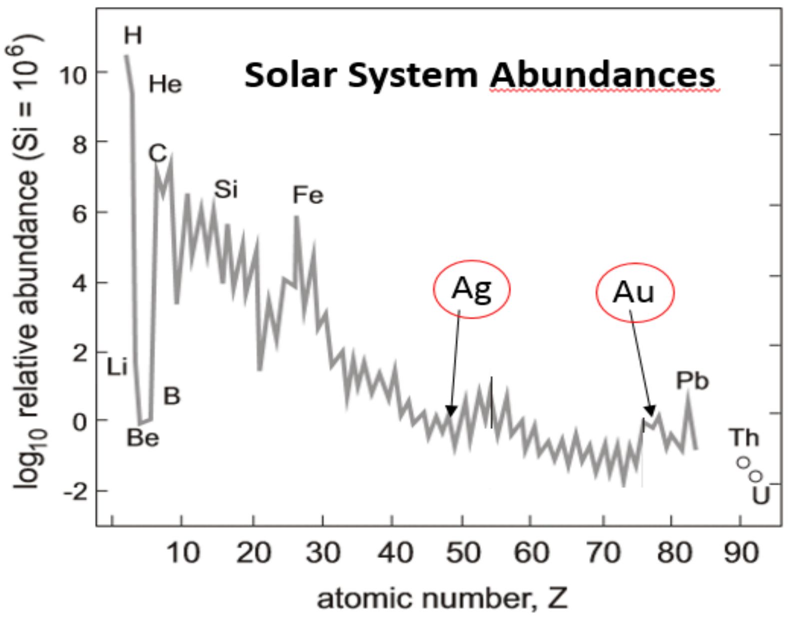
Cosmic abundances

Our knowledge of the cosmic abundances comes from many sources: terrestrial and meteoritic samples, solar & stellar spectra, cosmic rays and interstellar grains.

In the material samples we can study the details in the isotopic abundances.

But solar and stellar spectra normally only provide element abundances.

Our information on isotopic abundances is therefore limited.



Synthesis of the Elements in Stars

The classical paper: ”**B^{2}FH**”

Burbidge, Burbidge Fowler and Hoyle, 1957.

All elements up to the iron group can be synthesized by exothermic fusion processes. To form the elements beyond the iron peak we need three additional processes:

- s-process: slow neutron capture
- r-process: rapid neutron capture
- p-process: proton capture

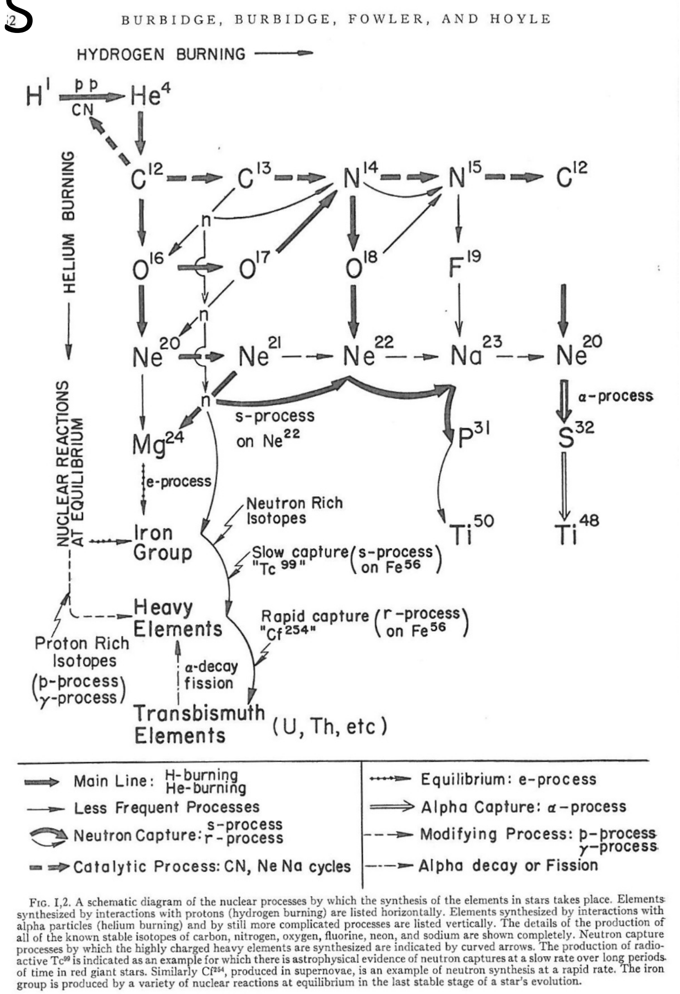

BURBIDGE, BURBIDGE, FOWLER, AND HOYLE

FIG. I,2. A schematic diagram of the nuclear processes by which the synthesis of the elements in stars takes place. Elements synthesized by interactions with protons (hydrogen burning) are listed horizontally. Elements synthesized by interactions with alpha particles (helium burning) and by still more complicated processes are listed vertically. The details of the production of all of the known stable isotopes of carbon, nitrogen, oxygen, fluorine, neon, and sodium are shown completely. Neutron capture processes by which the highly charged heavy elements are synthesized are indicated by curved arrows. The production of radioactive Tc^{99} is indicated as an example for which there is astrophysical evidence of neutron captures at a slow rate over long periods of time in red giant stars. Similarly Cf^{254}, produced in supernovae, is an example of neutron synthesis at a rapid rate. The iron group is produced by a variety of nuclear reactions at equilibrium in the last stable stage of a star's evolution.

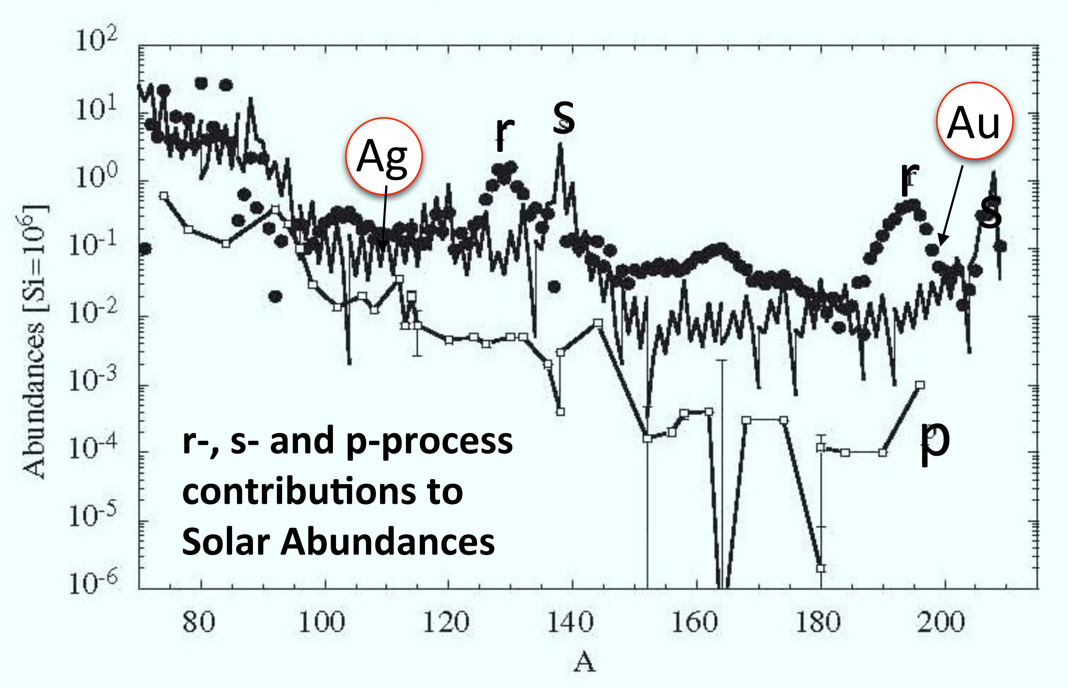
s-process sites: *AGB-stars* (*Asymptotic Giant Branch)*

Stars with masses in the range from 0.6 to 10 $M_{\odot}$ are not heavy enough to explode as supernovae. Instead, at the end of their quiet life they enter the AGB-phase where they pulsate and shed a large fraction of their mass.

Spectroscopic studies of these stars reveals a strong excess of s-process elements, and little r-process signatures.

This provides an observational handle on the s-process part of the cosmic synthesis.

We use this handle to split the Solar abundances in r- and s-process contributions.



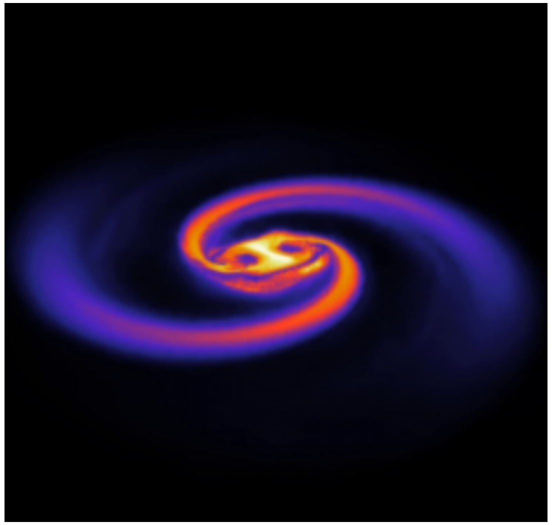
r-, s- and p-process contributions to Solar Abundances

M. Arnould, S. Goriely & K. Takahashi, (2007)

r-process sites: Exploding stars

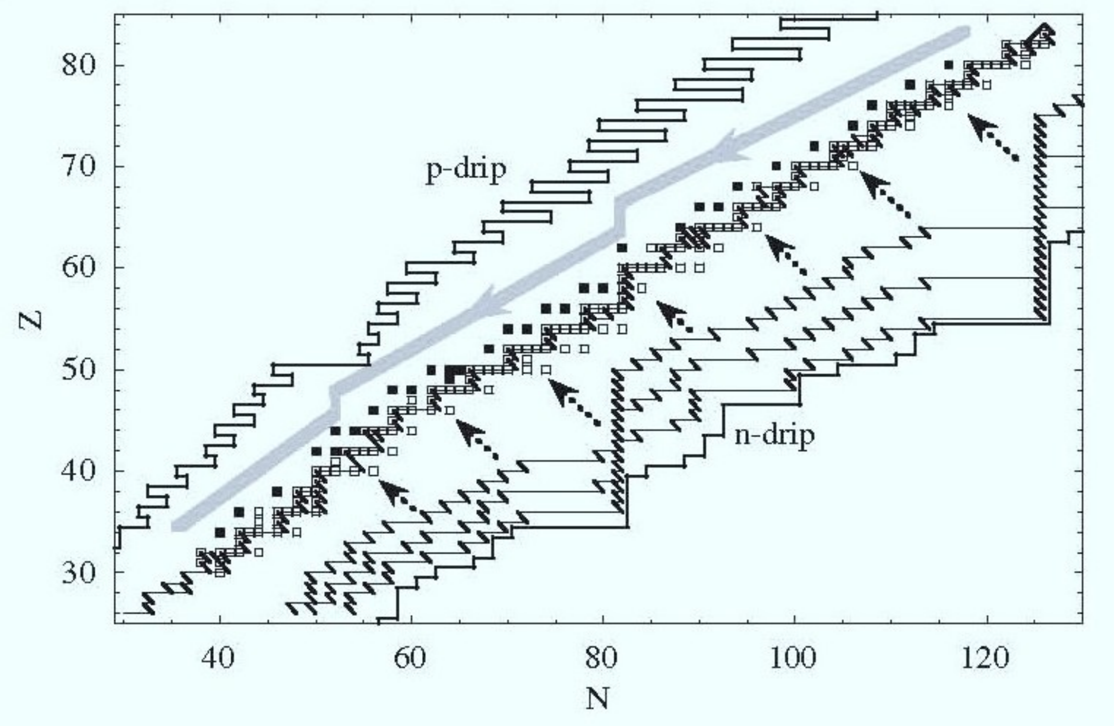
The rapid neutron capture requires a very high neutron flux, to allow the seed nuclei to capture many neutrons before they can decay via beta decay. Traditionally this process was associated with supernovae.

But also merging neutron stars have been suggested since long (Cameron (1967)).



r-process Complexity

The r-process is extremely complex to model, it depends on an enormous number of parameters, many of which cannot be measured, but must be estimated from models.



M. Arnould, S. Goriely & K. Takahashi, (2007)

r-process parameters:

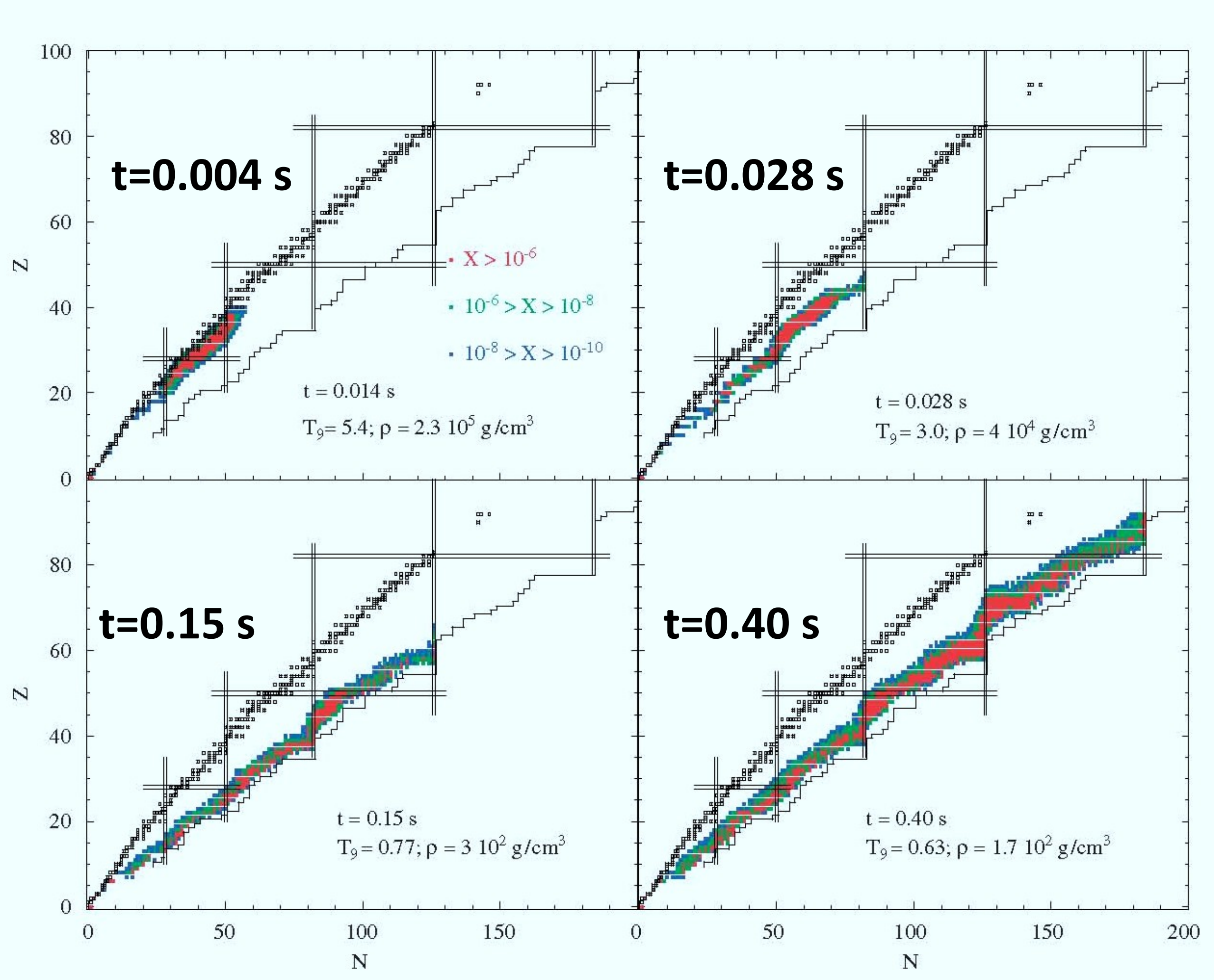
Matter Density
Temperature
Expansion timescale
Initial neutron fraction
Mean atomic mass of matter
Neutrino flux from nearby, cooling NS
Nuclear physics data such as:
    ß-decay rates
    (n,ʹY) and (ʹY,n) reaction rates
    fission rates
  for several 1000s of isotopes far from the . nuclear stability line.

……

r-process timing

Dependent on the time scale of the process the r-process may develop only part of the full path to the actinides.

For very long process times the matter may cycle many times op to the actinides, undergo fission and start neutron accretion again.



M. Arnould, S. Goriely & K. Takahashi, (2007)

Supernova complexity

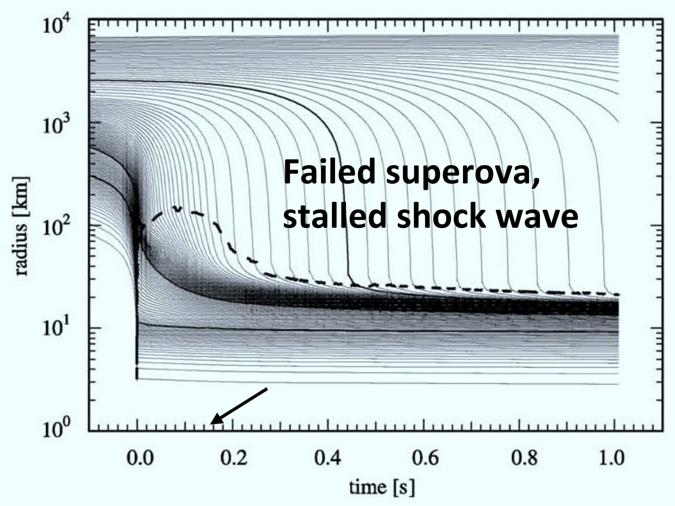
Our simulations of the r-process should be based solidly on our modelling of the supernovae.

But for 50 years, we have not been able to model successfully a supernova explosion!

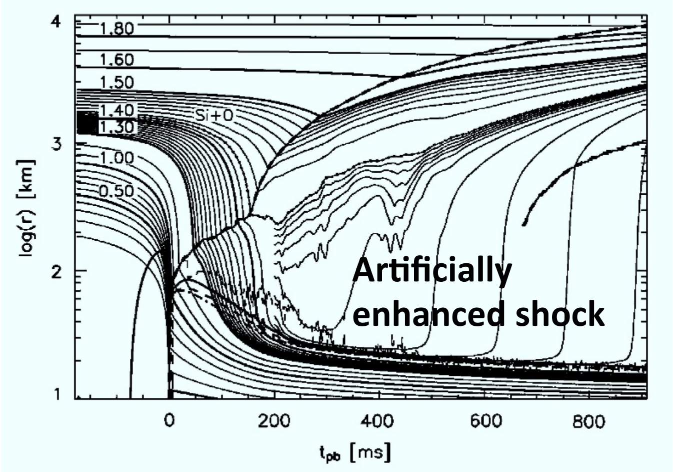
Most of the explosion energy must come from the collapse of the stellar core.

But we have not yet identified the mechanism which prevent the total collapse of the entire star into a black hole!

We miss the foundation for our r-process!



Failed superova, stalled shock wave



Artificially enhanced shock

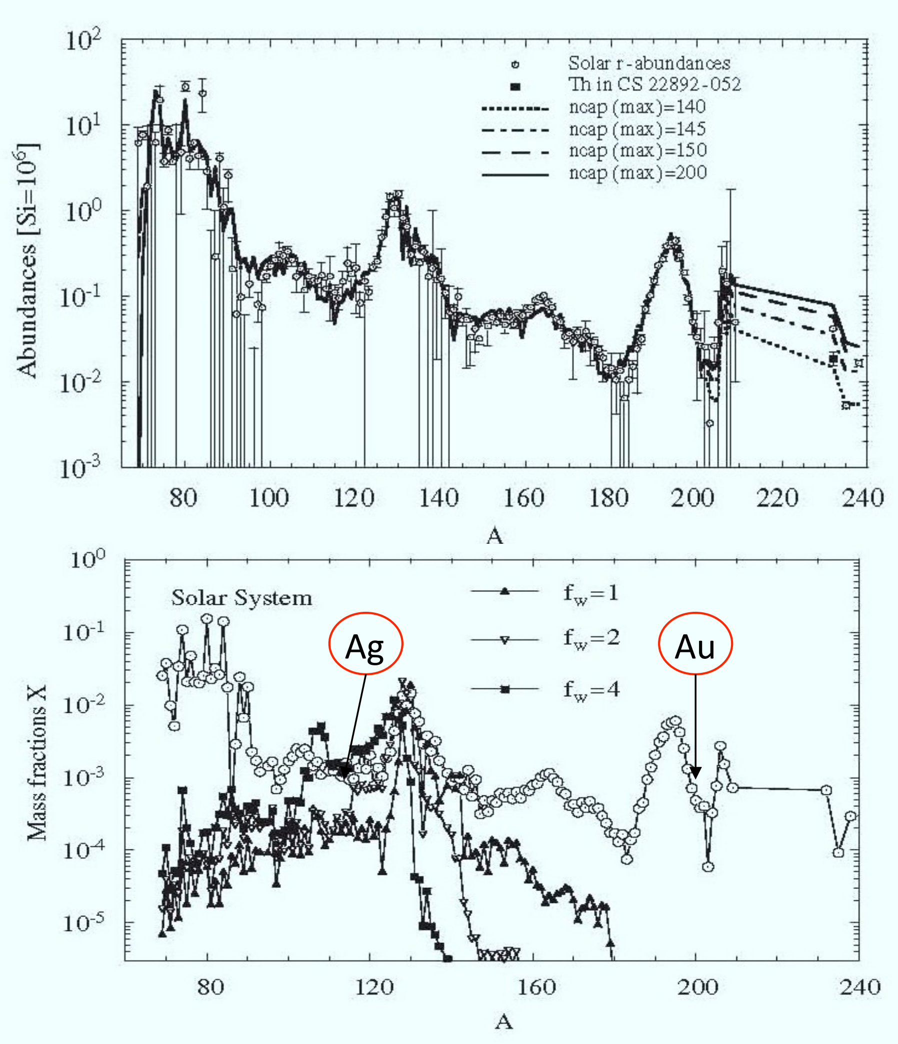
M. Arnould, S. Goriely & K. Takahashi, (2007)

Artificial ‘tuning’

By combining many r-process simulations and playing freely with the parameters it is possible to reproduce well the Solar System composition

But more ‘realistic’ supernova parameter choices apparently only populate the lower atomic mass end of the periodic table!

<u>So how do we get the gold?</u>



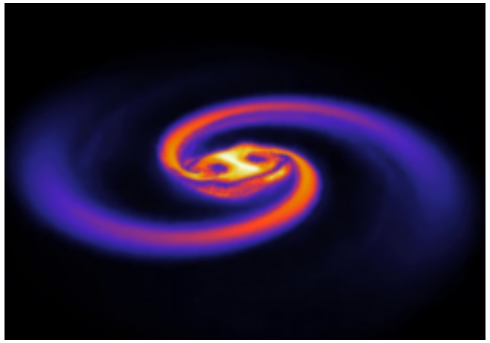
M. Arnould, S. Goriely & K. Takahashi, (2007)

An alternative r-process: Neutron star mergers

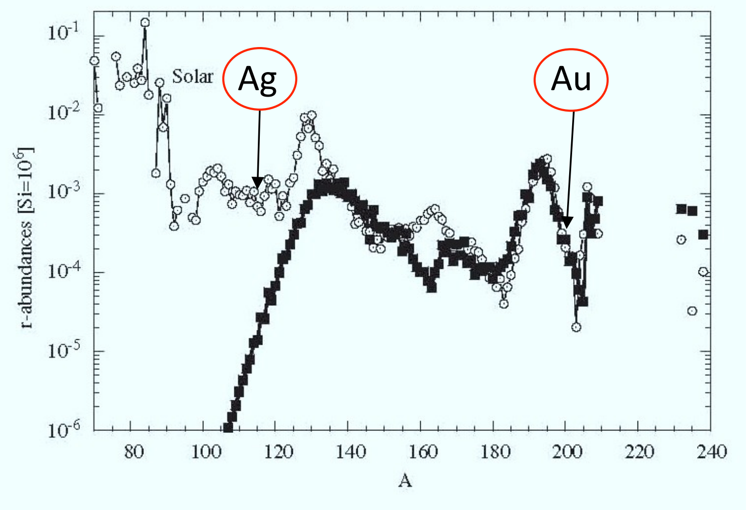
During the final merger of two neutron stars, tidal forces will tear apart the stars, and part of the neutronized matter may be ejected before the final formation of a black hole.

The ejected matter will have very high density, high temperature and an abundance of neutrons – ideal ingredients for the r-process.

Simulations indicate that the ejection of clumps of such matter may result in the formation of heavy elements, particularly those with A > 130.



U. Feindt, (2017)



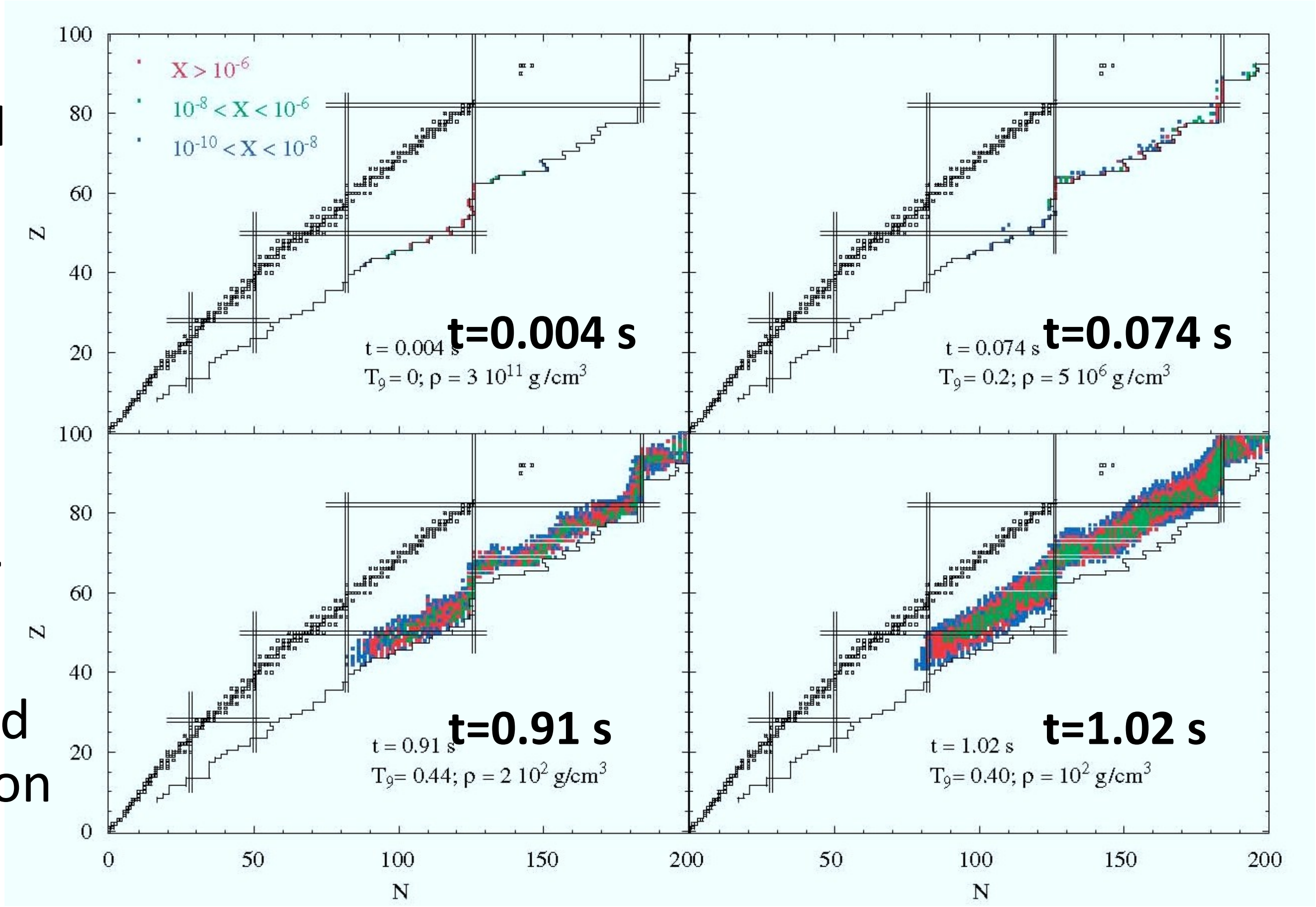
M. Arnould, S. Goriely & K. Takahashi, (2007)

NS-NS and NS-BH merger complexity

However, also the merger process depend on several unknown parameters:

- The relative spins of the two compact objects
- The magnetic fields and their orientations
- The equation of state for the neutron star matter

Thus the amount of ejected matter, and the composition is uncertain.



t=0.004 s

t=0.074 s

t=0.91 s

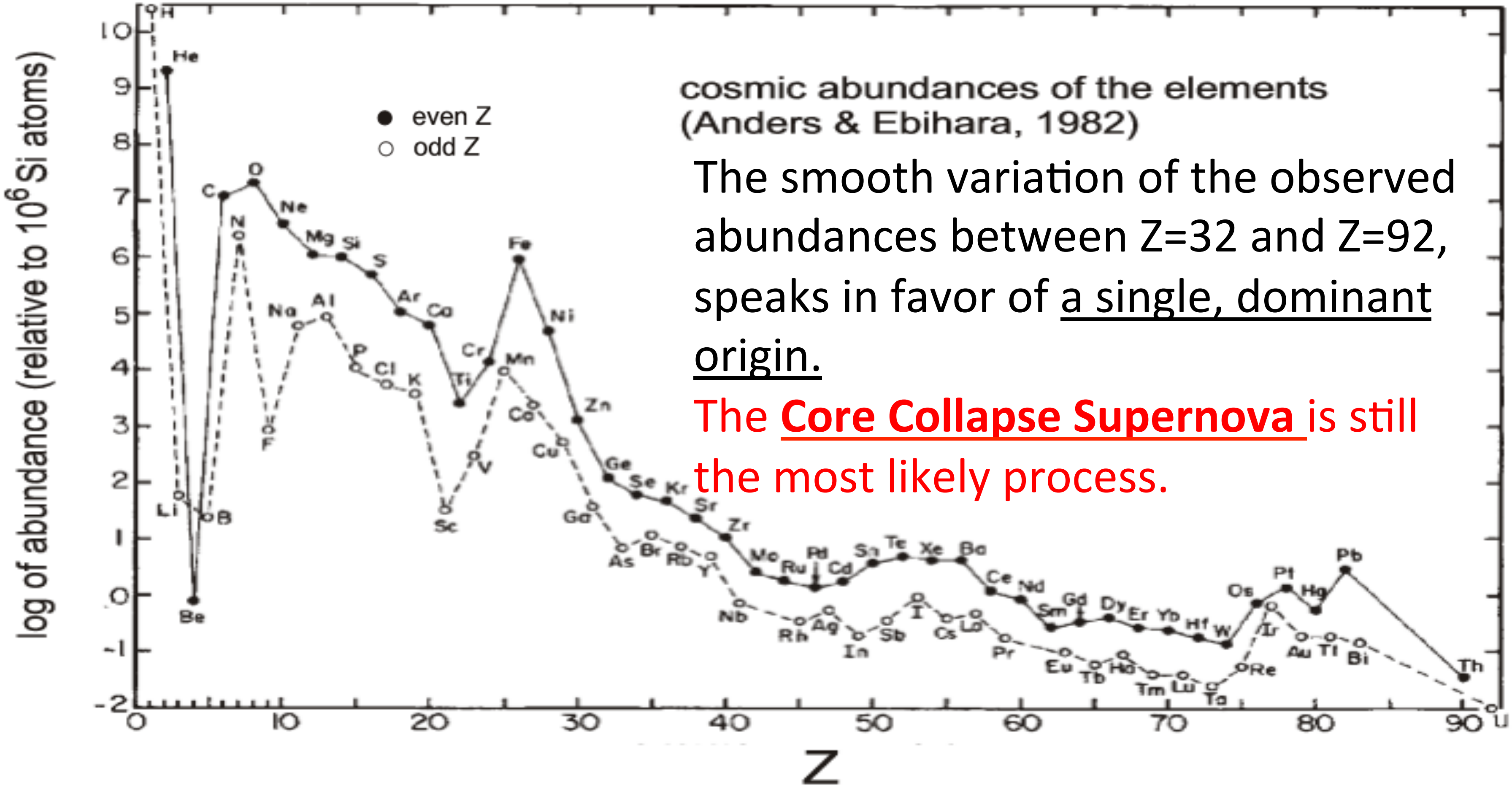
t=1.02 s

M. Arnould, S. Goriely & K. Takahashi, (2007)

Keep in mind:

The supernova explosions and the neutron star merger episodes are almost unrelated !

My conclusion – as of May this year:



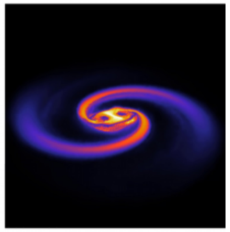
cosmic abundances of the elements (Anders & Ebihara, 1982)

The smooth variation of the observed abundances between Z=32 and Z=92, speaks in favor of a single, dominant origin.

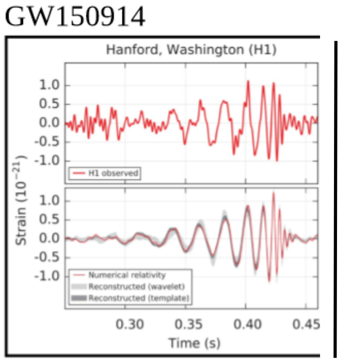
The **Core Collapse Supernova** is still the most likely process.

Gold from Neutron Stars is a fascinating tale,
- but they must be counted as minor suppliers !

My last slide from talk at the Danish astronomy meeting in May

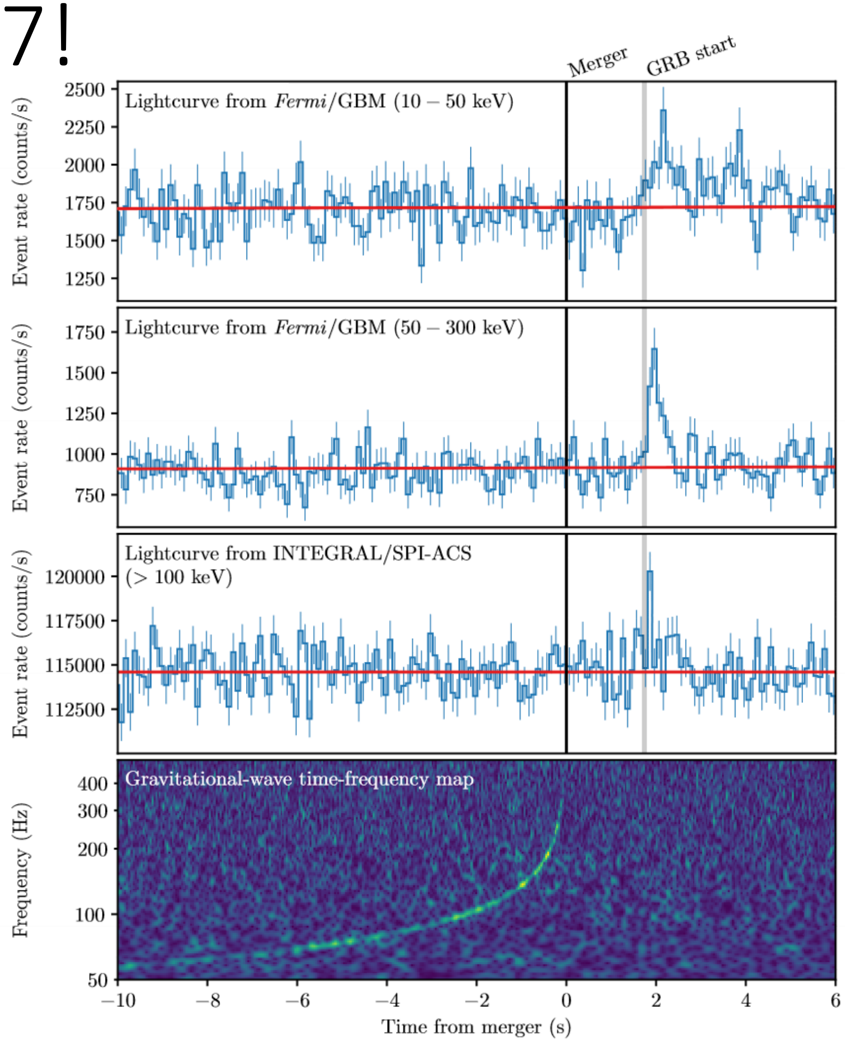


We will soon know much more here !



But today – after GW170817!

The LIGO/VIRGO detection of GW170817, the gravitational wave signal from the merger of two neutron stars – and the slightly delayed short gamma-ray burst seen by Fermi/INTEGRAL marks a new era in multimessenger astronomy.



LIGO-VIRGO, (2017)

Afterglow observations following GW170817

The afterglow of GB170817B, was searched for from observatories all over the world.

A host galaxy at a distance of 43 Mpc was soon identified.

This distance is consistent with the distance derived from the GW-signal.

THE EMERGENCE OF A KILONOVA FOLLOWING THE MERGER OF TWO NEUTRON STARS 5

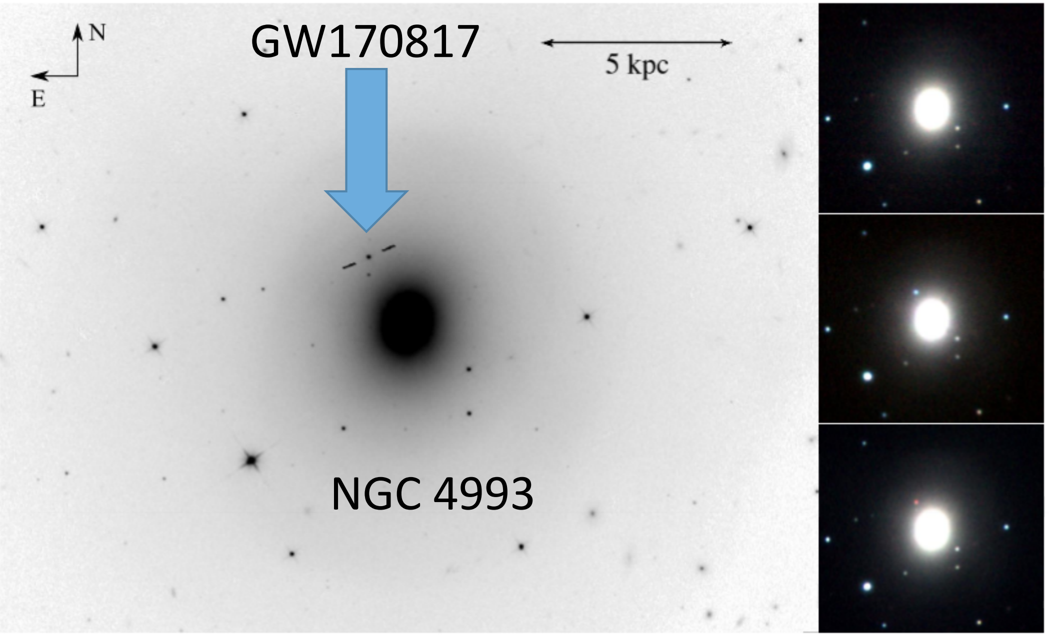


Figure 1. Main panel shows the first epoch F110W *HST*/WFC3-IR image of the field of AT2017gfo indicating its location within NGC 4993. The physical scale assuming a distance of 40 Mpc is shown. The sequence of panels on the right show VISTA imaging (RGB rendition created from Y, J, K_s images) from pre-discovery (2014; top), discovery (middle) and at 8.5 days post-merger as the transient was fading and becoming increasingly red (bottom).

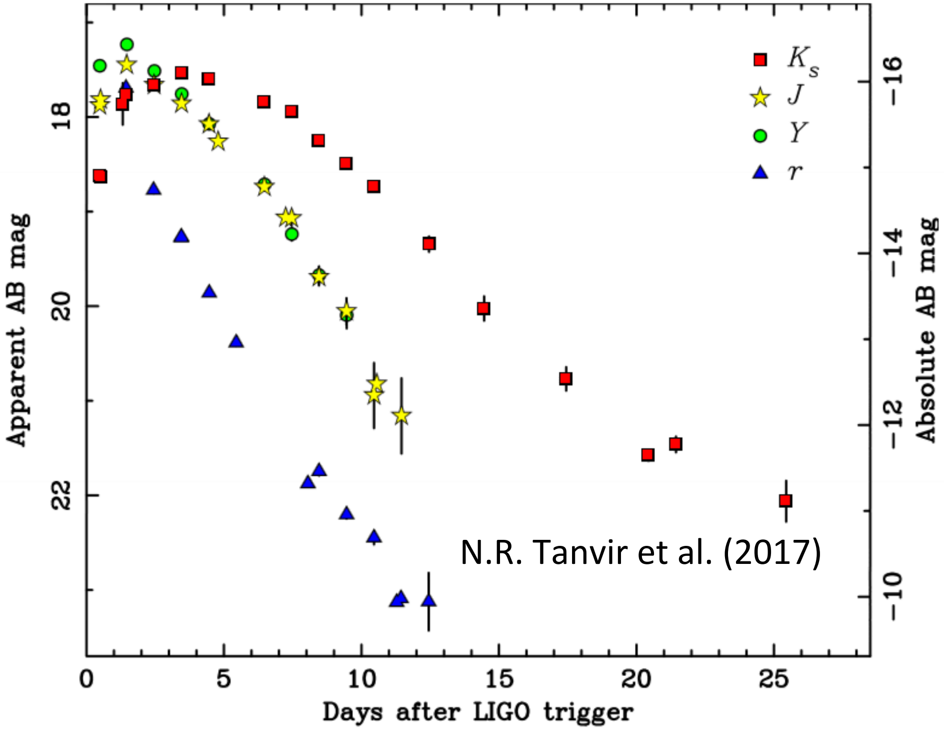
N.R. Tanvir et al. (2017)

‘Kilonova’ characteristics of afterglow

It has been predicted that short GRB’s caused by mergers of neutron stars should exhibit a characteristic ‘kilonova’ spectral signature, namely an evolution from an early blue afterglow to a late infrared stage.

<u>Indeed this behaviour was exhibited by the afterglow of GW170817.</u>

THE EMERGENCE OF A KILONOVA FOLLOWING THE MERGER OF TWO NEUTRON STARS 7



N.R. Tanvir et al. (2017)

Figure 2. The light curves of AT2017gfo in the r-, Y-, J- and K_s-bands. The absolute magnitude, assuming a distance of 40 Mpc, is shown on the right hand scale. Note that in many cases the error bars are smaller than the symbols.

r-process conclusion today

We have two viable options for the r-process site:

core-collapse supernovae or neutron star mergers.

But the smooth abundance pattern seen in the Solar system favors a single, dominant process for the full range of r-process elements.

We really dont know the origin of the r-process elements !

How can we approach the r-process enigma?

1. Get better (isotope) abundances from high resolution optical spectra of very young (low metallicity) stars. (ESO ELT)

2. Improve the synthesis models.

3. Find observational signatures of supernova and kilonova ejecta.

    a) Detailed optical spectra of supernovae and kilonovae

    b) Gamma-ray spectroscopy of kilonovae ejecta ? – Laue lenses!

Thank You

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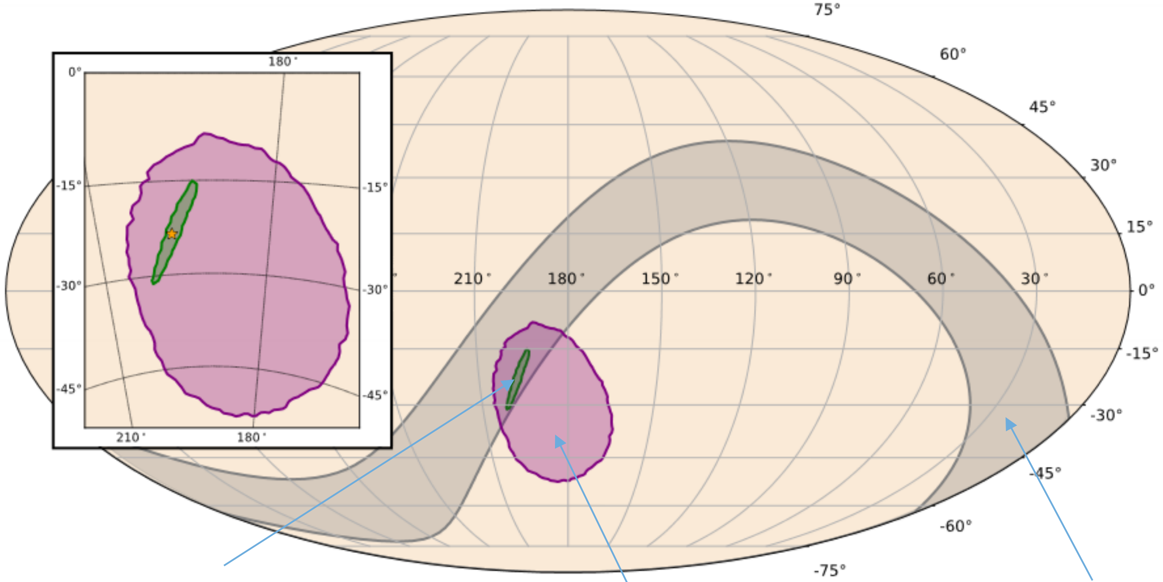
A. Goldstein et al., arXiv 1710.05446 (2017)
V. Savchenko et al., arXiv 1710.05449 (2017)
N.R. Tanvir et al., arXiv 1710.05455 (2017)
List of initial 83 papers on GW170817 from Oct 16.: https://lco.global/~iarcavi/kilonovae.html

GW-shortGRB

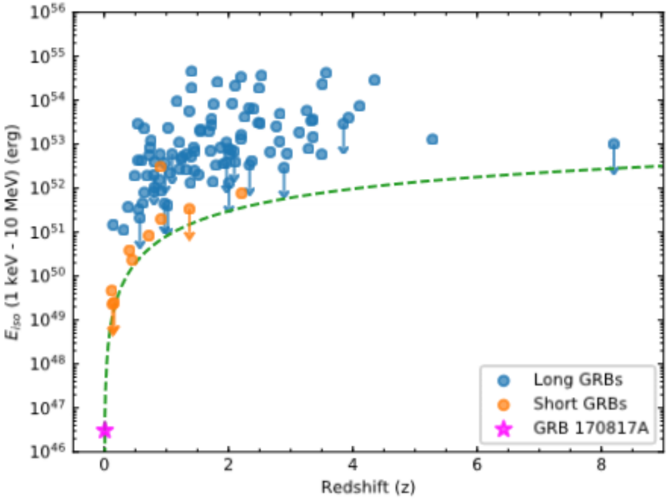


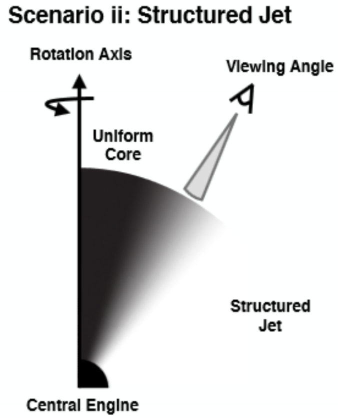
LIGO-VIRGO localization

Fermi GBM localization

GBM-INTEGRAL localization

From LIGO-VIRGO (2017)





Gamma-ray detectability of kilonovae

Radioactive decay products in NS merger ejecta 5   8 *K. Hotokezaka et al.*

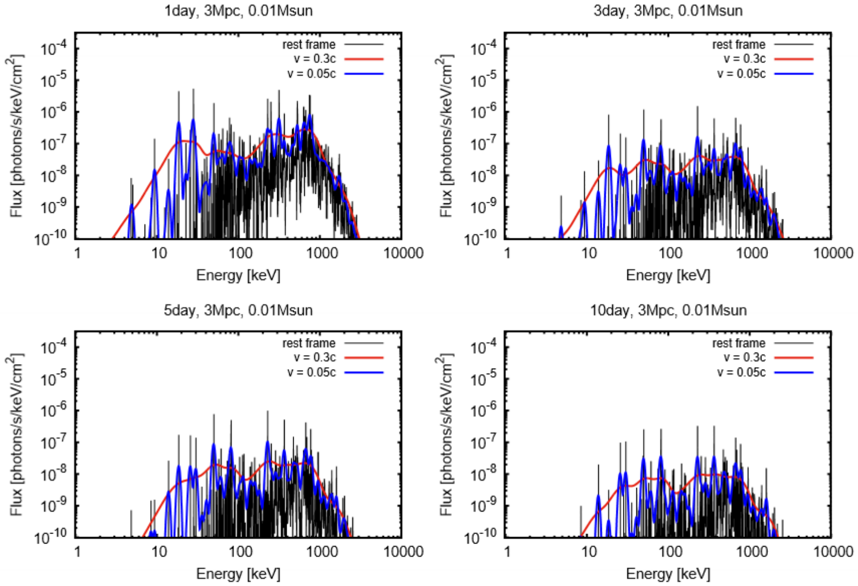


Figure 2. Spectrum of γ-rays at 1, 3, 5 and 10 days after merger for NSM-solar. Black lines depict the γ-ray spectrum produced by nuclei at rest. The red (blue) curve shows the spectrum with the Doppler broadening with an expansion velocity of 0.3c (0.05c). The normalization is determined with the mass of ejected r-process elements of 0.01$M_\odot$ and the observed distance of 3 Mpc. Here we do not take any absorption and scattering processes into account.

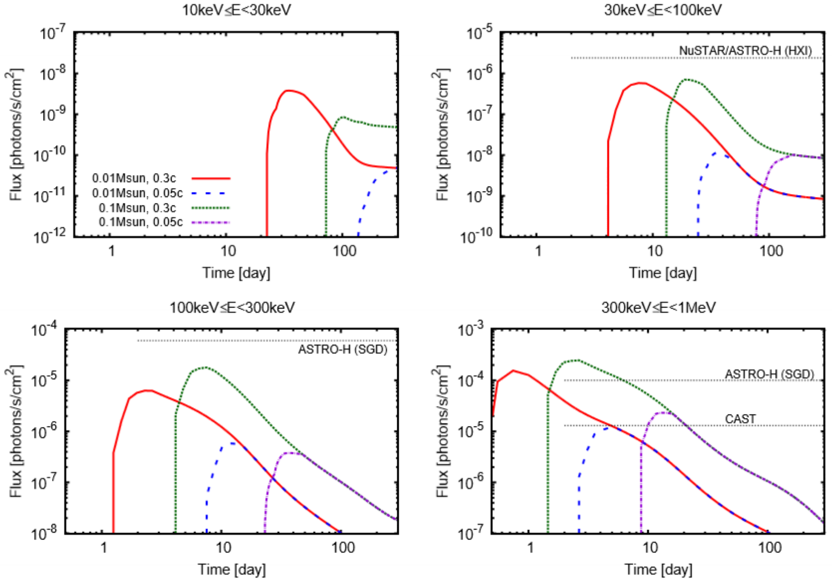


Figure 5. Light curves of nuclear γ-rays for NSM-solar in the ranges of 10 keV $\leqslant E_\gamma <$ 30 keV (top left), 30 keV $\leqslant E_\gamma <$ 100 keV (top right), 100 keV $\leqslant E_\gamma <$ 300 keV (bottom left), and 300 keV $\leqslant E_\gamma <$ 1 MeV (bottom right) at a distance of 3 Mpc. Here we show the four different ejecta models: ($M_{\rm ej}$, v) = (0.01 M$_\odot$, 0.3c), (0.01$M_\odot$, 0.05c), (0.1$M_\odot$, 0.3c), and (0.1$M_\odot$, 0.05c). Also shown are the sensitivity with exposure at 100 ks of current and future X-ray missions: *NuSTAR* (Harrison et al. 2013), *ASTRO-H* (Takahashi et al. 2012), and *CAST* (Nakazawa et al. 2014).

From Hotokezaka et al. (2015)

Europeum abundance scatter

Large scatter in [Eu/Fe] implies Eu-synthesis through infrequent events, whereas Fe is synthesized more gradually in many events

From Sneden et al (2008)

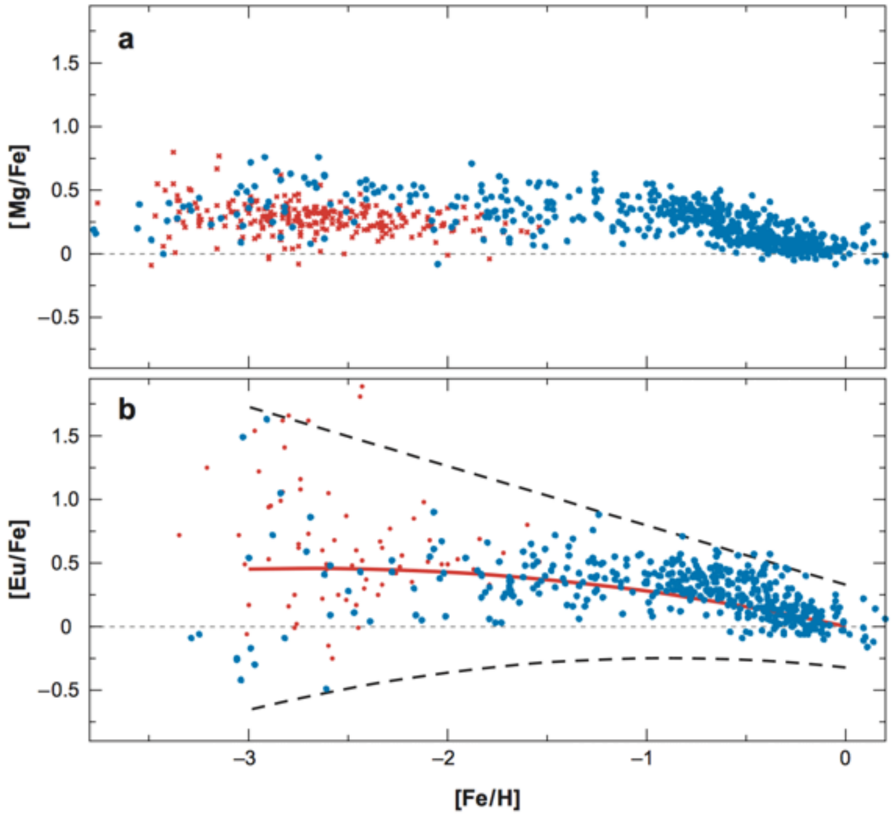


Figure 14

[Mg/Fe] and [Eu/Fe] abundances as a function of [Fe/H] metallicity for halo and disk stars. For this figure the data have been taken only from large-sample surveys: Fulbright (2000); Reddy et al. (2003); Cayrel et al. (2004); Cohen et al. (2004); Simmerer et al. (2004); Barklem et al. (2005, red points); Reddy, Lambert & Allende Prieto (2006); François et al. (2007). In both panels the dotted lines represent the Solar abundance ratios. In panel *b*, the solid red line is a least-square fit to the Eu data, and the two dashed black lines indicate the approximate extent of the Eu/Fe data (similar to Cowan & Thielemann 2004).

N-capture synthesis

The color scale indicates the predicted lifetime against beta-decay.

From Sneden (2007)

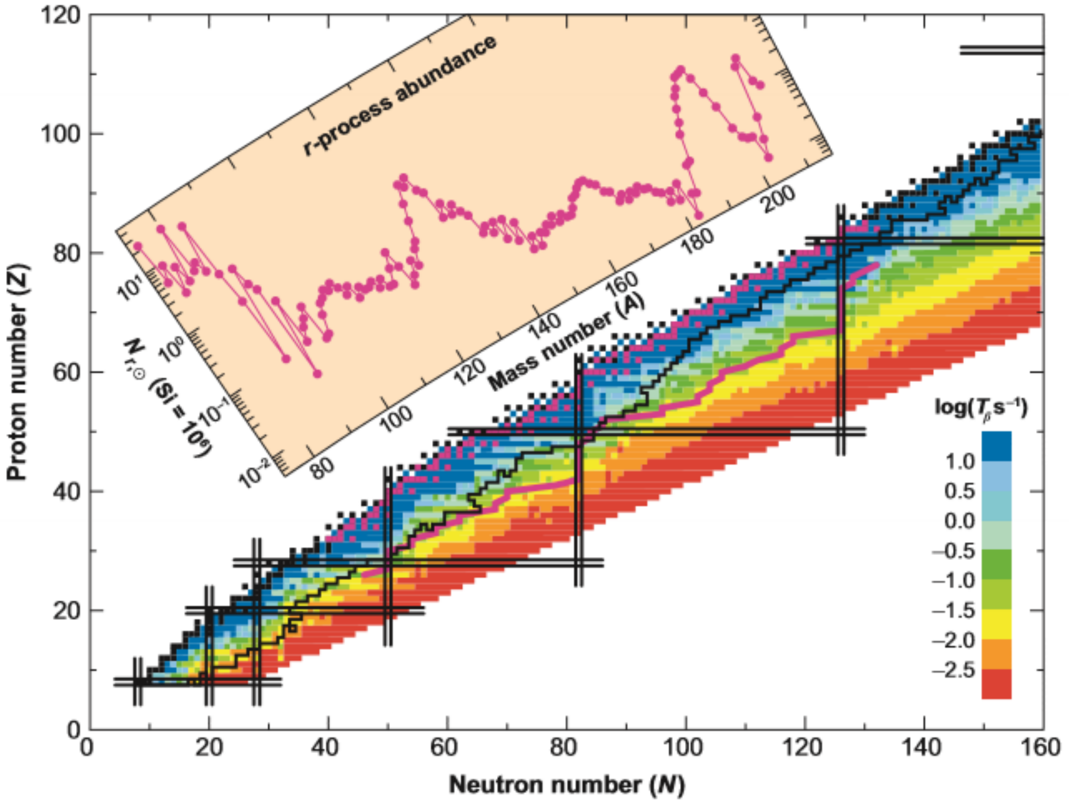


Figure 1

Chart of the nuclides showing proton number versus neutron number after Möller, Nix & Kratz (1997). Black boxes indicate stable nuclei and define the so-called valley of β-stability. Vertical and horizontal lines indicate closed proton or neutron shells. The magenta line indicates the so called *r*-process path, with the magenta boxes indicating where there are final stable *r*-process isotopes. Color shading denotes the timescales for β decay for nuclei and the jagged black line denotes the limits of experimentally determined nuclear data at the time of their article.