The Origin of Heavy Elements in the Universe in the Context of Neutron Stars merger

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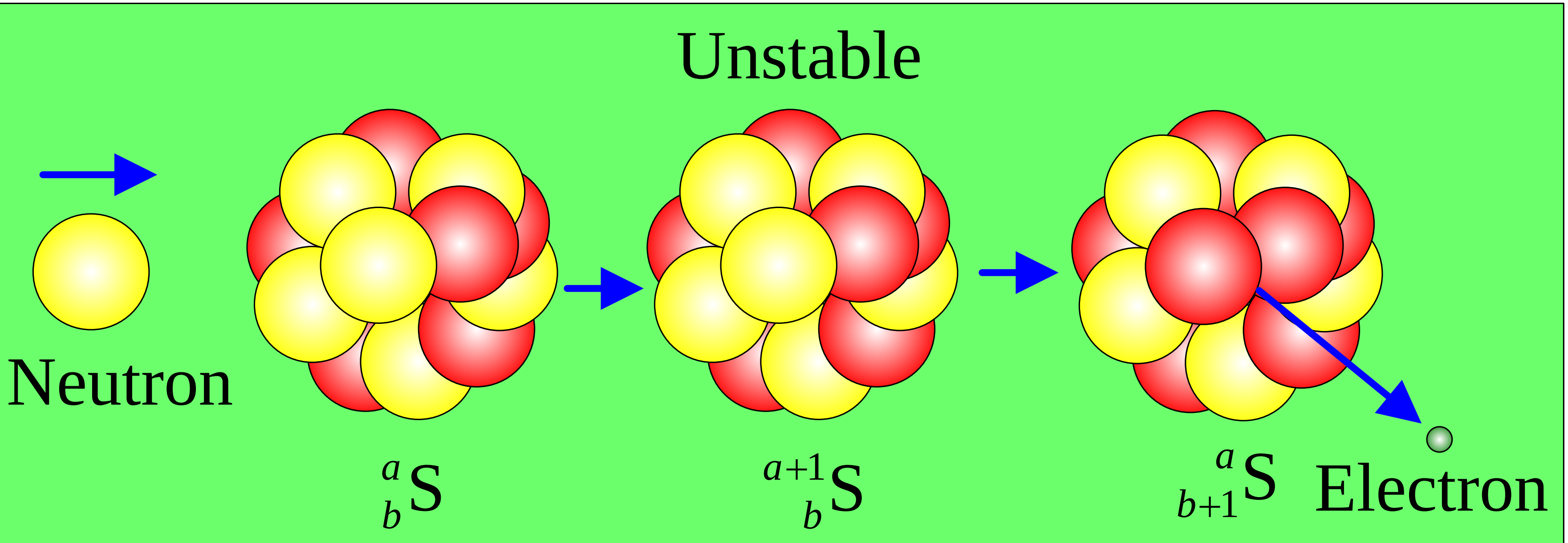
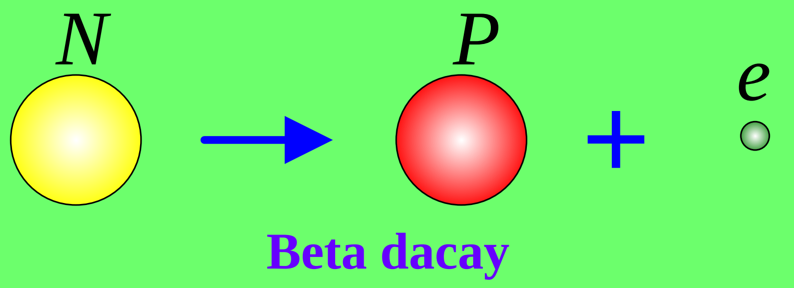


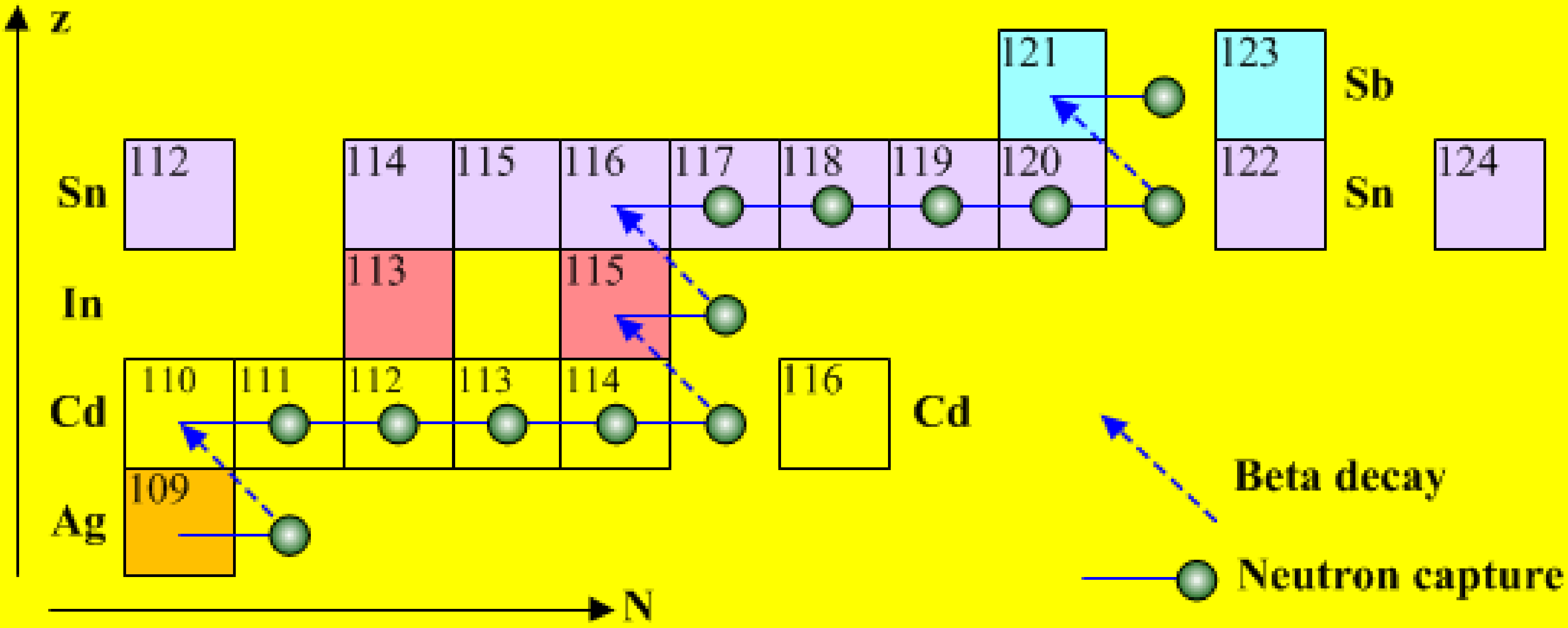
Principle of beta decay



S - process

$$^{13}_{6}\mathrm{C} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{16}_{8}\mathrm{O} + n$$

$$^{22}_{10}\mathrm{Ne} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{25}_{12}\mathrm{Mg} + n$$

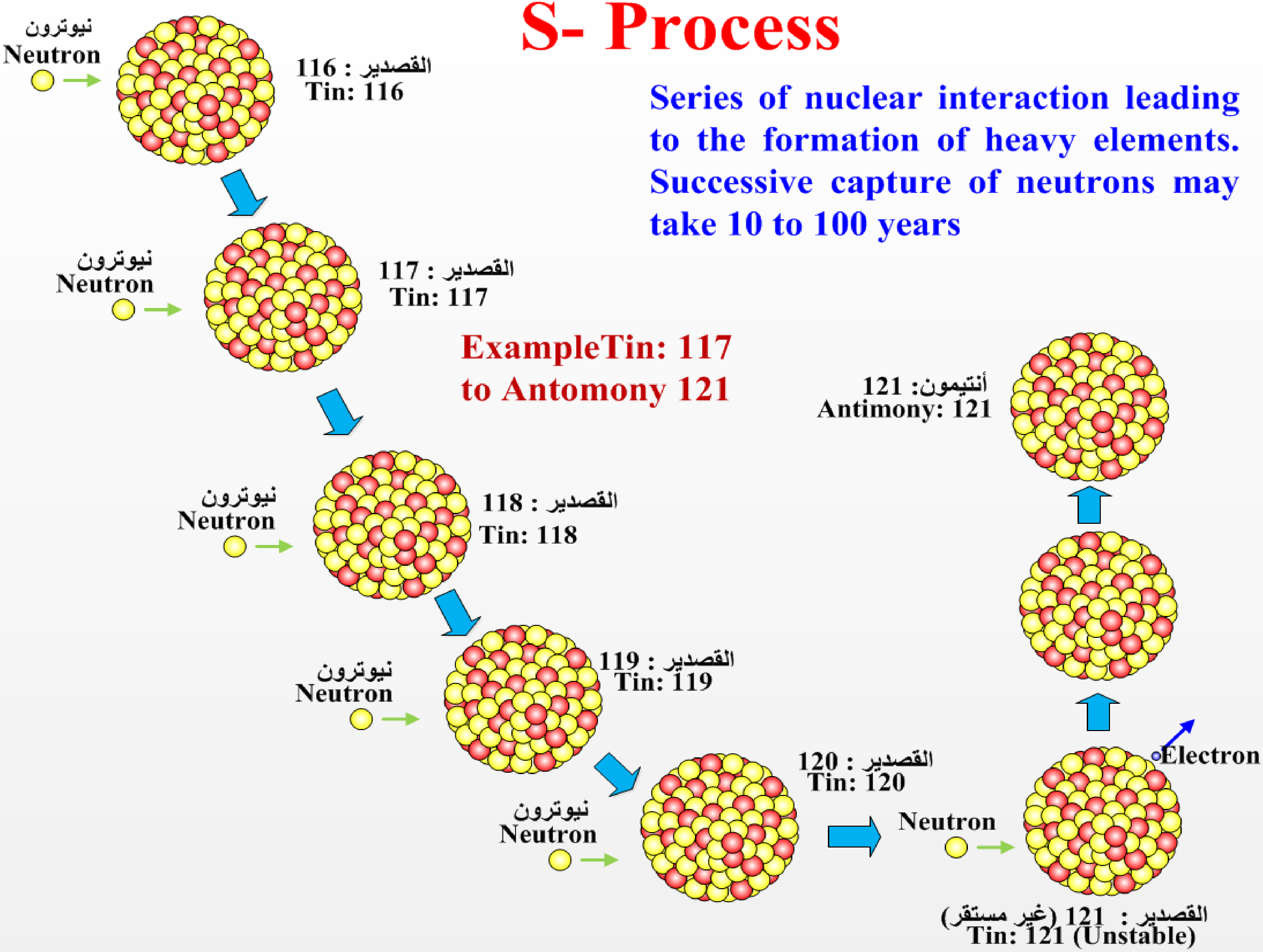


The s-process acting in the range from Ag to Sb

S- Process

Series of nuclear interaction leading to the formation of heavy elements. Successive capture of neutrons may take 10 to 100 years

ExampleTin: 117 to Antomony 121



Termination of the s-process cycle

The s-process terminates in Bi and Po

$$^{209}_{83}\mathrm{Bi} + n \rightarrow {}^{210}_{83}\mathrm{Bi} + \gamma$$

$$^{210}_{83}\mathrm{Bi} \rightarrow {}^{210}_{84}\mathrm{Po} + \mathrm{e}' + \overline{\nu_e}$$

$$^{210}_{84}\mathrm{Po} \rightarrow {}^{206}_{82}\mathrm{Pb} + {}^{4}_{2}\mathrm{He}$$

Bi is almost stable whereas Po decays into Pb with a lifetime of 138 days

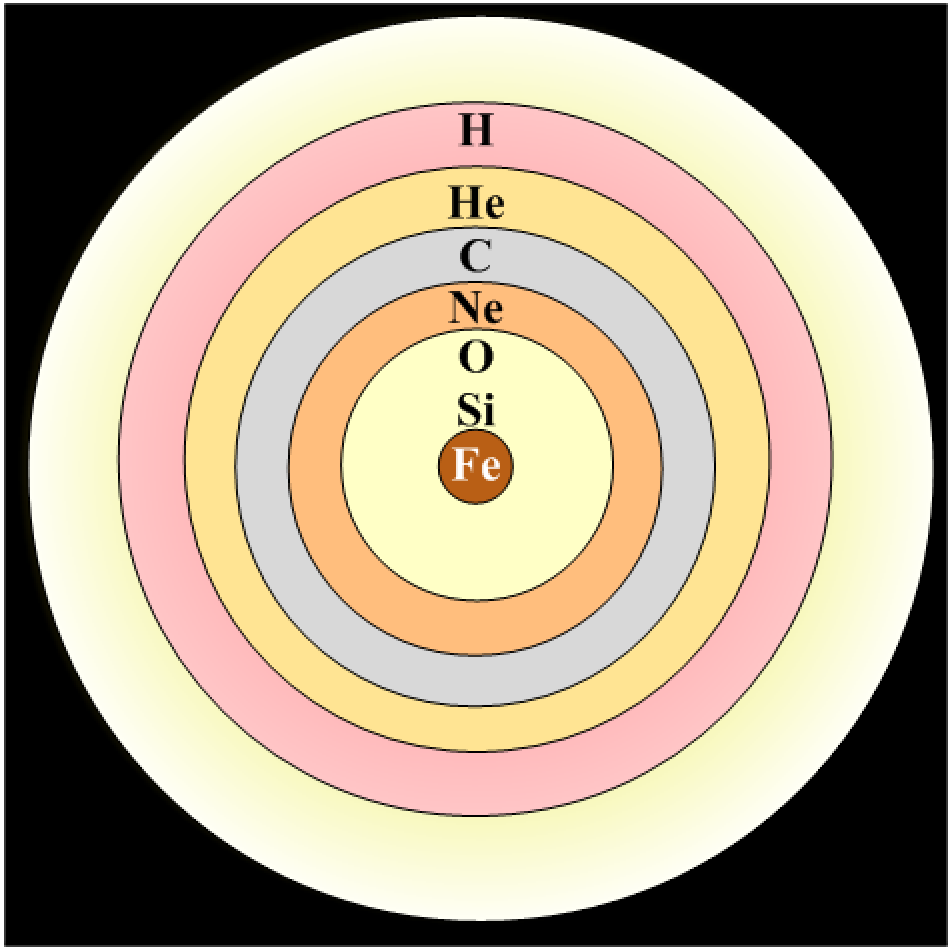
$$^{206}_{82}\mathrm{Pb} + 3n \rightarrow {}^{209}_{82}\mathrm{Pb}$$

$$^{209}_{82}\mathrm{Pb} \rightarrow {}^{209}_{83}\mathrm{Bi} + \mathrm{e}' + \overline{\nu_\mathrm{e}}$$

Net result

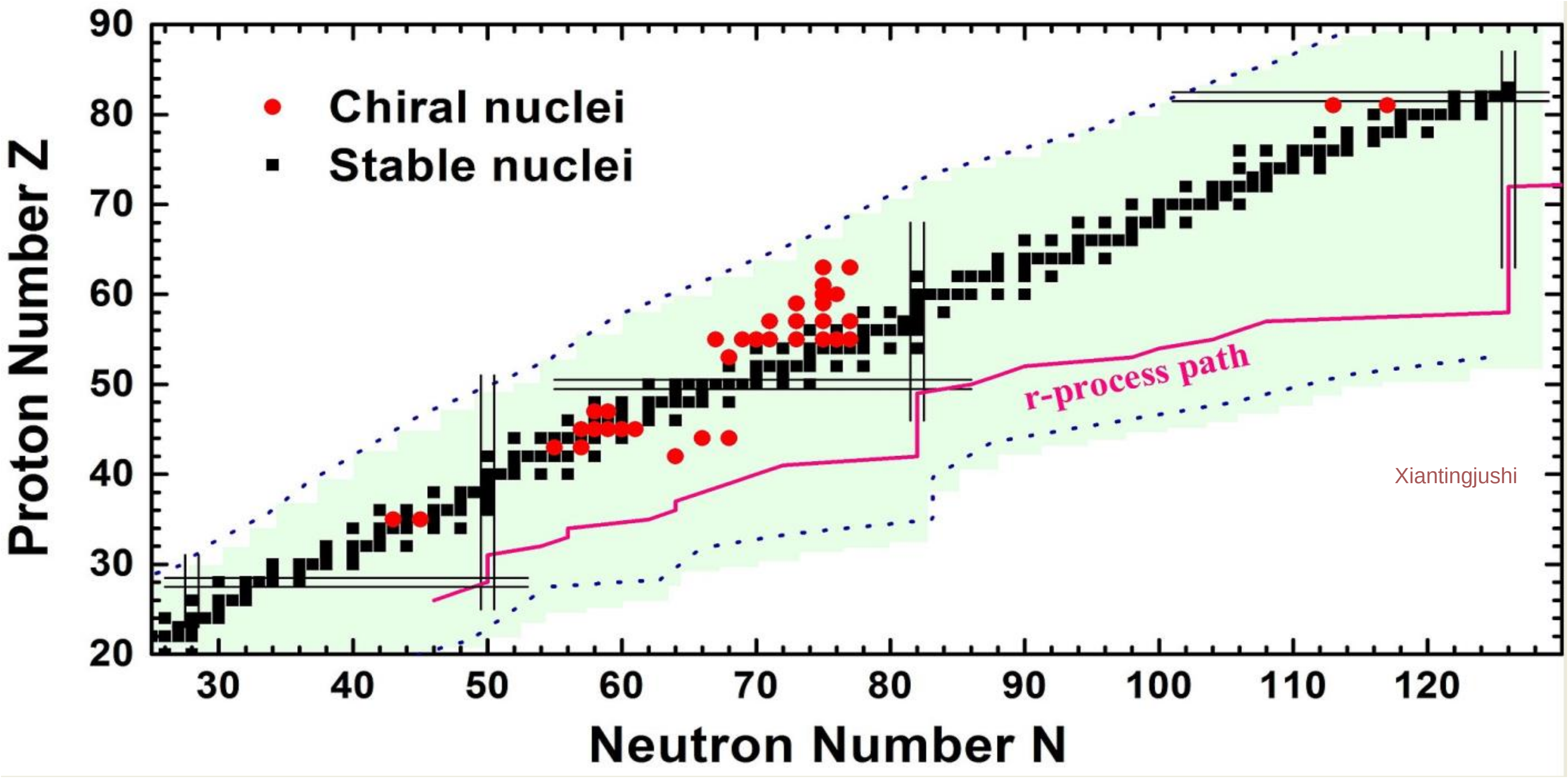
$$4\mathrm{n} \rightarrow {}^{4}_{2}\mathrm{He} + 2\mathrm{e}' + 2\overline{\nu_\mathrm{e}} + \gamma$$

TYPE II SUPERNOVA



Layers are produced because of the lack of thermal convection

r - process



Schematic illustrating the r-process as it occurs in supernovae or neutron star collisions.[1] Neutrons are rapidly absorbed faster than the resulting nuclei can beta-decay; this allows the r-process to produce very neutron-rich nuclei follow the neutron drip line. There are waiting points located at magic numbers N = 50, 82, 126, where beta-decay is favored due to low neutron-capture cross sections resulting from the closed shells. The cycle then repeats until the next waiting point, creating yet heavier nuclei of elements up to the actinides; the natural abundance of these elements results entirely from the r-process. In the superheavy mass region (A = 270), neutron-induced fission or spontaneous fission are expected to become dominant and end the r-process.

R- Process

Iron core collapse: 5-6 x 10^9 K

$^{56}\mathrm{Fe} + \gamma \longrightarrow {}^{57}\mathrm{Fe}$

$^{57}\mathrm{Fe} + \mathrm{n} \longrightarrow {}^{58}\mathrm{Fe}$

$^{58}\mathrm{Fe} + \mathrm{n} \longrightarrow {}^{59}\mathrm{Fe}$

$^{59}\mathrm{Fe} + \mathrm{n} \longrightarrow {}^{60}\mathrm{Fe}$

$^{60}\mathrm{Fe} + \mathrm{n} \longrightarrow {}^{61}\mathrm{Fe}$

R- Process

Iron core collapse:T = 5-6 x 10^9 K

$^{56}Fe + \gamma \longrightarrow {}^{57}Fe$

$^{57}Fe + n \longrightarrow {}^{58}Fe$

$^{58}Fe + n \longrightarrow {}^{59}Fe$

$^{59}Fe + n \longrightarrow {}^{60}Fe$

$^{60}Fe + n \longrightarrow {}^{61}Fe$

- ^{61}Fe is stable for only 6 min> If no neutron ia captured during this time, then the following interaction takes place by the s – process:

$$^{61}Fe \rightarrow {}^{61}Co + e' + n$$

Binary Neutron Stars Merger

- Afterglow of Merging NS → Multicomponent Spectral Energy Distribution: Optical → NIR
- Afterglow is characterized by:

- Rapid fading of the UV and blue optical band

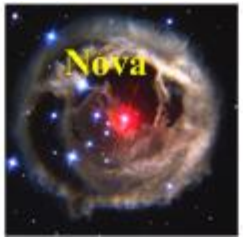
- Reddening of the optical/NIR colors.

Kilonova (optical/NIR): Isotropic thermal transient powered by radiative decay of rapid neutron capture elements synthesized in the merger ejecta.

Example of NS Merger

- GRB170817 NS Event: Heating from r – process nuclei requires at least TWO components consistent with lanthanide- poor and lanthanide-rich opacities.
- Each component arises from different region of the ejecta.
- We distinguish TWO types of Kilo nova:
- RED kilo nova: Characterized by low velocity and originates from ejecta tidal tails in the equatorial plane of the binary.
- BLUE Kilo nova: Characterized by high velocity and originates from shock-heated polar region created when NS collide.

Kilonova



- **Kilonova is characterized by:**
- **Luminosity; Time Scale; Spectral Peak**
- **Optical Kilonova**
- **Ejecta rich with Fe group or light r-process nuclei**

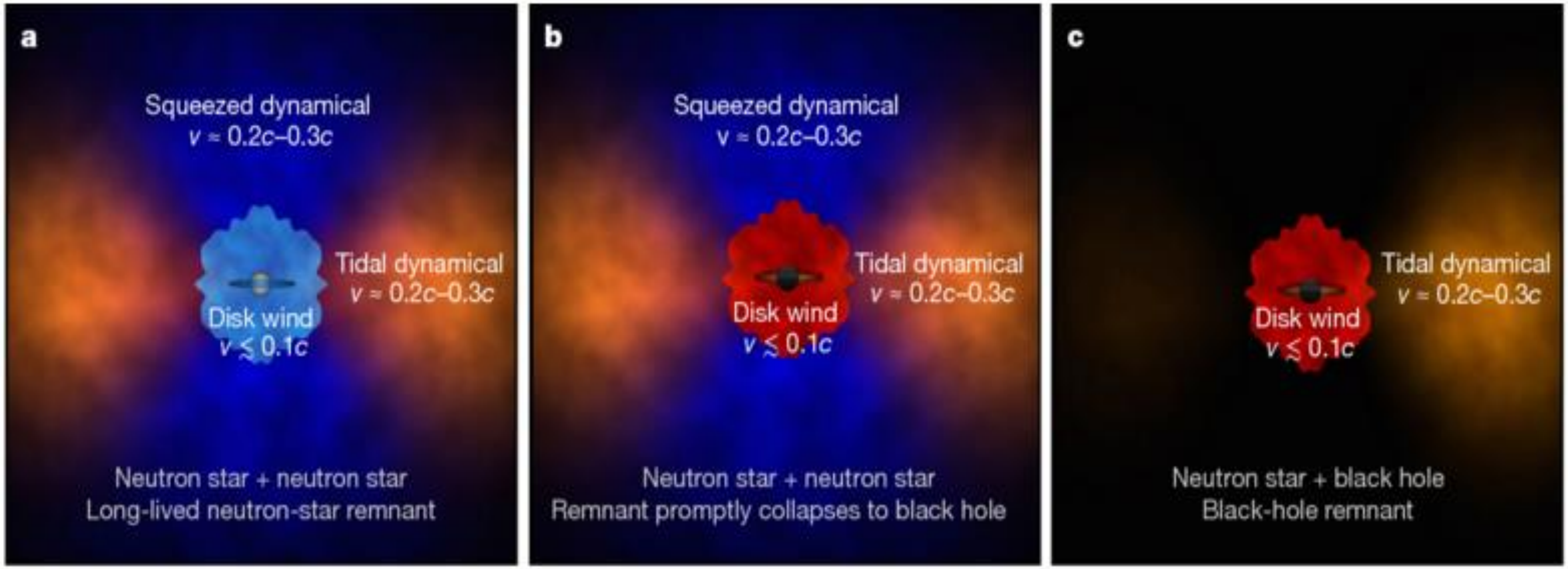
$(A \leq 140): L_p \approx 10^{41} - 10^{42}$ erg/sec, Time Scale : $t_p \approx 1$day,

Spectral peak : Optical Wavelength

- **Red Kilonova**
- **Ejecta rich with heavier lanthanide elements**

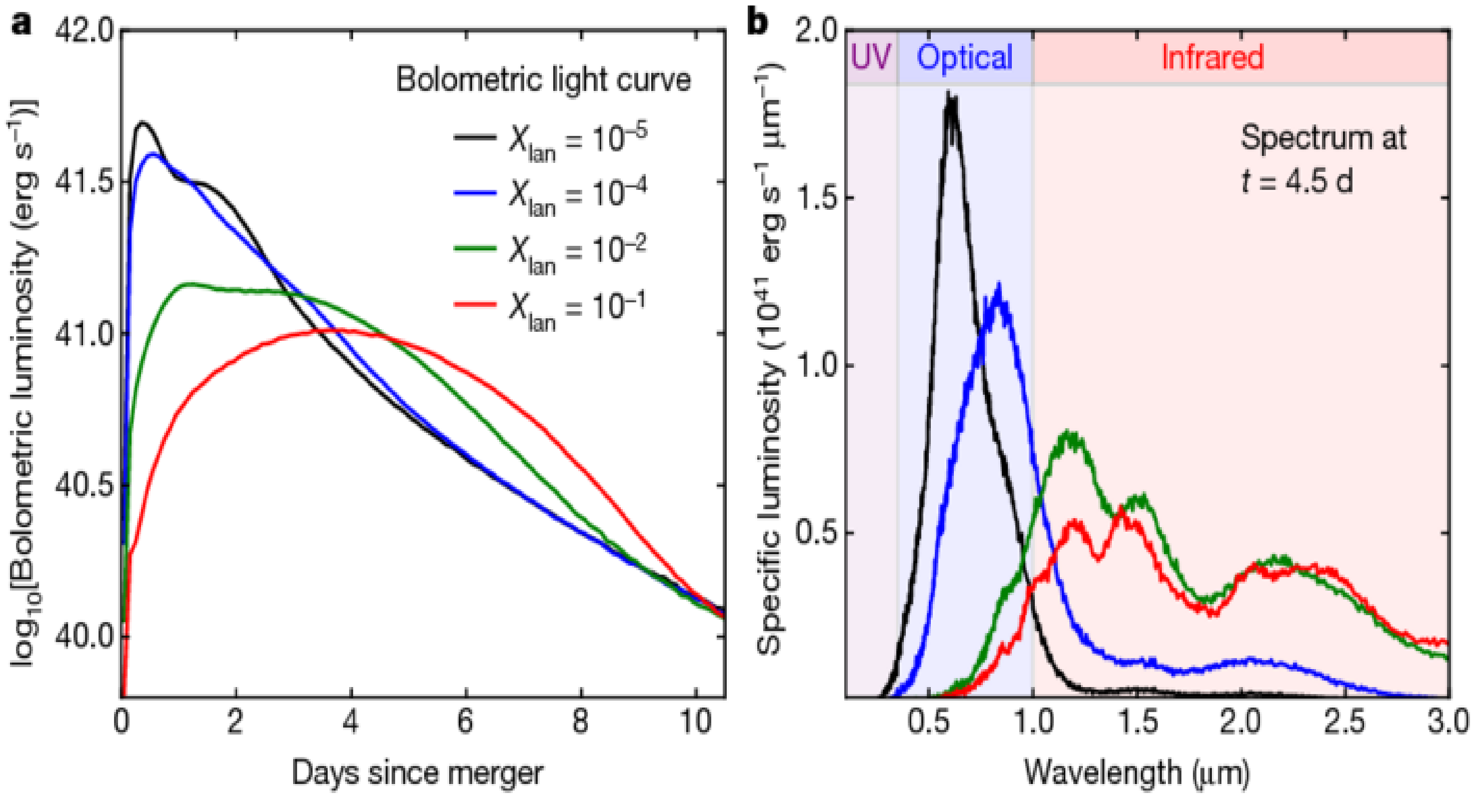
$(A \geq 140): L_p \approx 10^{40} - 10^{41}$ erg/sec, Time Scale : $t_p \approx 1\,week$,

Spectral peak : NIR Wavelength



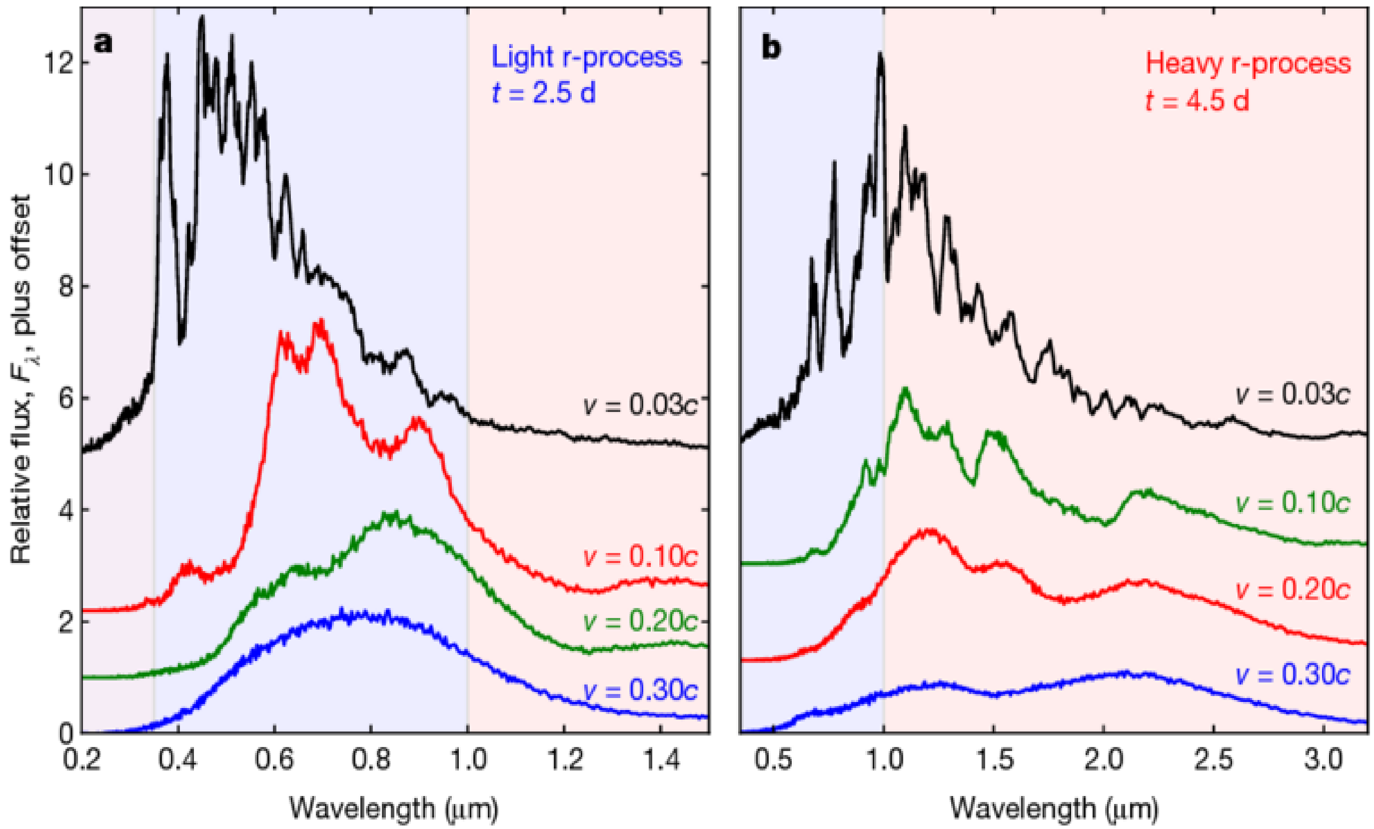
: 1 | **Schematic illustration of the components of matter ejected** contribute, and are sensitive to the fate of the central merger remnan

Figure 1 | Schematic illustration of the components of matter ejected from neutron-star mergers. Red colours denote regions of heavy r-process elements, which radiate red/infrared light. Blue colours denote regions of light r-process elements which radiate blue/optical light. During the merger, tidal forces peel off tails of matter, forming a torus of heavy r-process ejecta in the plane of the binary. Material squeezed into the polar regions during the stellar collision can form a cone of light r-process material. Roughly spherical winds from a remnant accretion disk can also



lonovae demonstrating the observable signatures diffusion times and longer-duration bolometric light

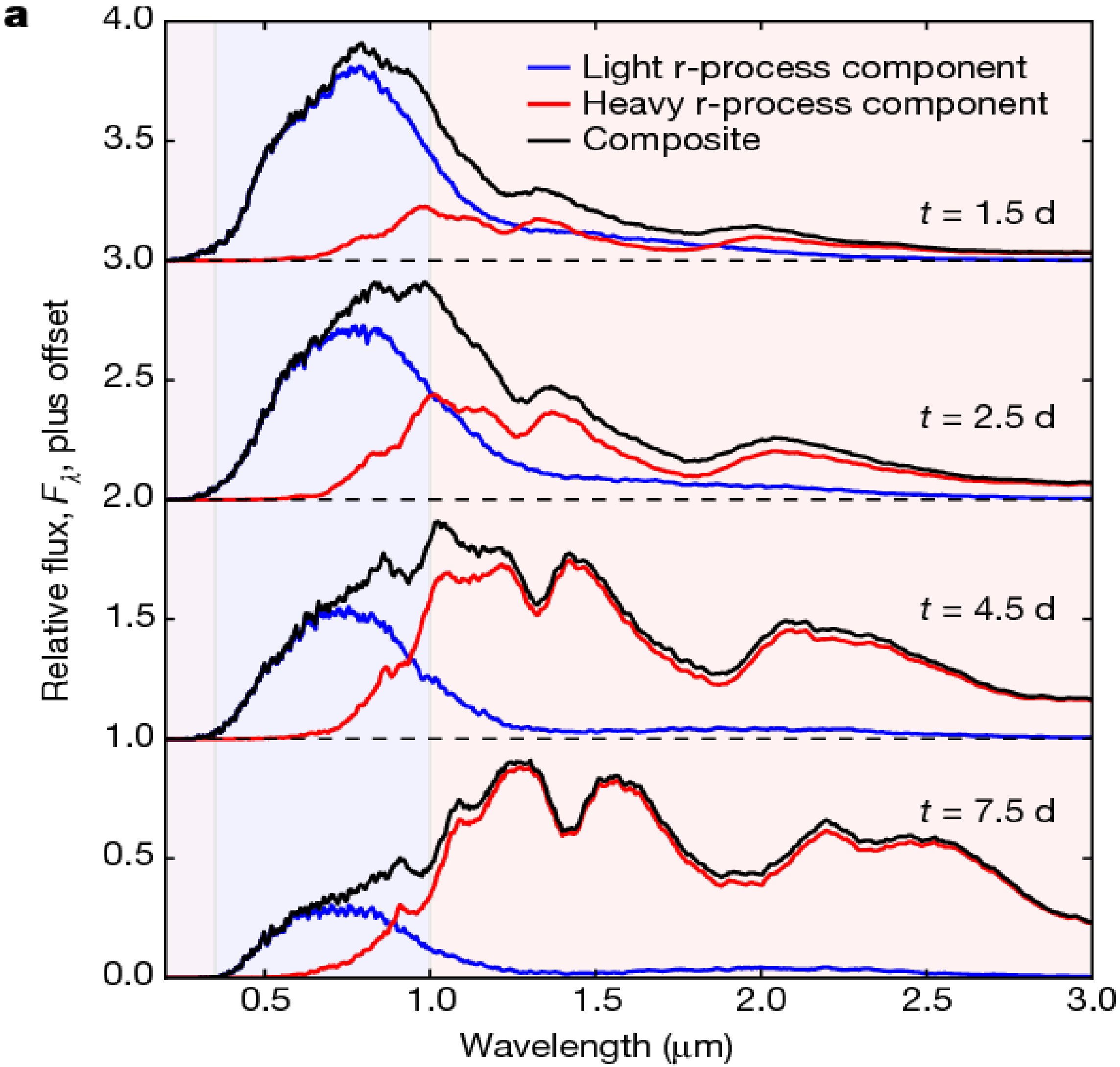
Figure 2 | Models of kilonovae demonstrating the observable signatures of r-process abundances. All models have an ejecta mass M = 0.05M and velocity vk = 0.2c, but different mass fractions of lanthanides Xlan. a, Model bolometric light curves. If the ejecta is composed primarily of heavier r-process material (Xlan ≥ 10−2) the opacity is higher, resulting in a longer



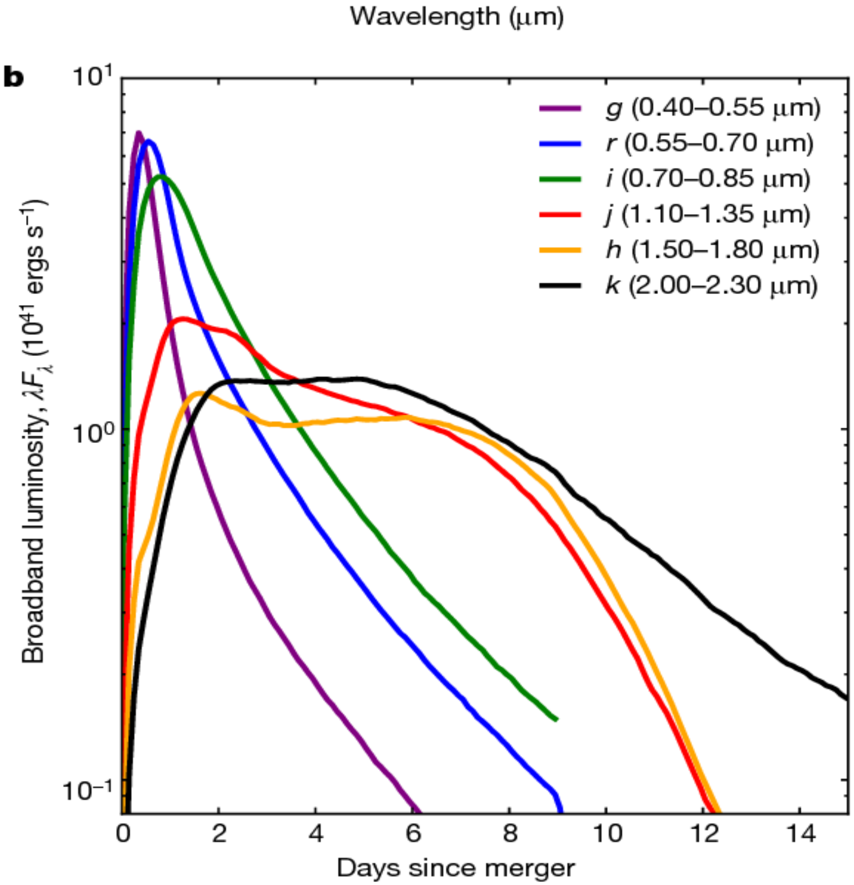
ilonovae demonstrating the spectral diagnostics

The optical spectra of AT 2017gfo were featureless, i

Figure 3 | Models of kilonovae demonstrating the spectral diagnostics of the ejecta velocity. The models all have ejecta mass M = 0.03M. a, Spectra of models composed of light r-process material (Xlan = 10−4) observed 1.5 days after the merger. Modest ejecta velocities (vk = 0.03c, typical of supernovae) produce conspicuous absorption spectral features. At higher velocities (vk = 0.1c–0.2c) the features are broadened and blended, while for vk = 0.3c the spectra are essentially featureless.

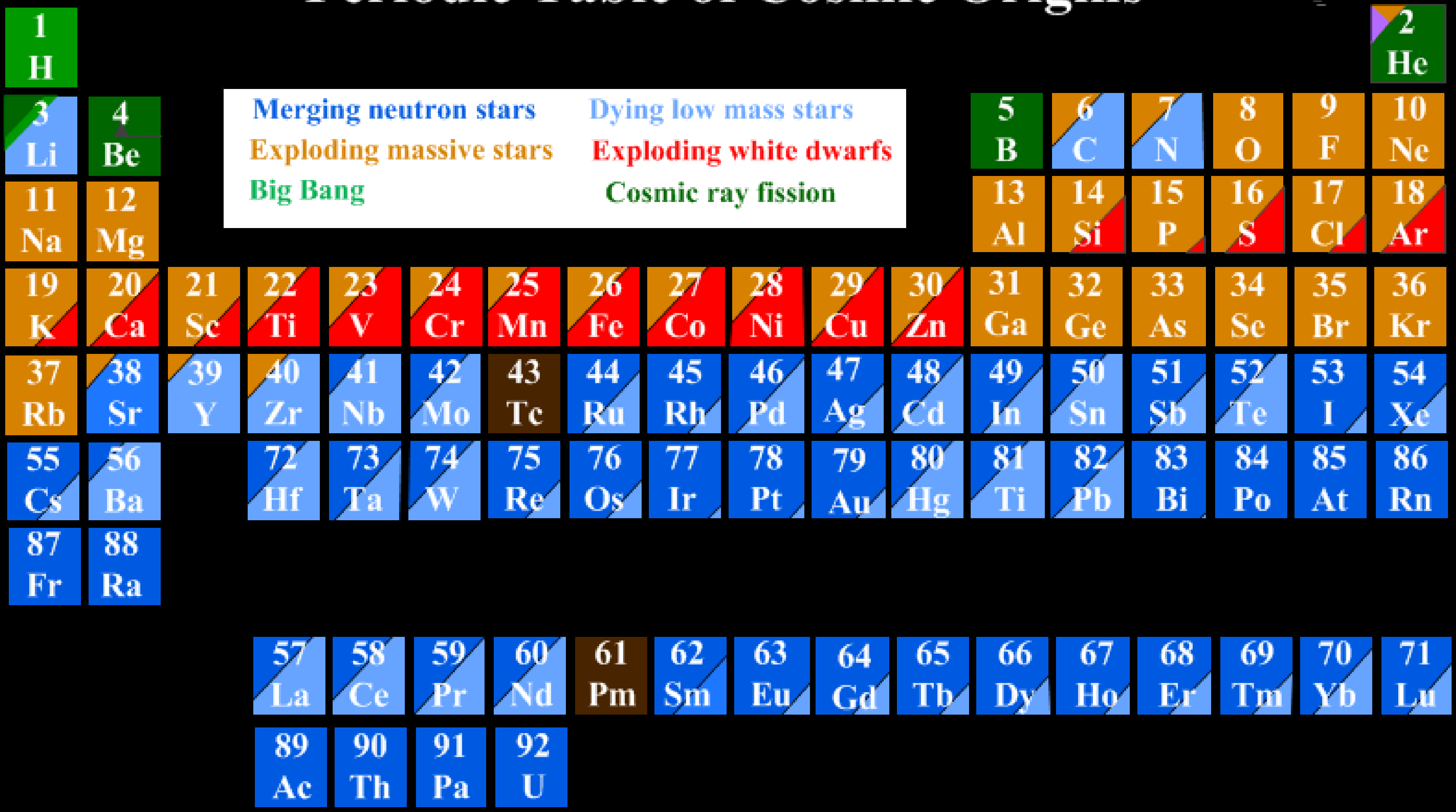

a
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Relative flux, F_λ, plus offset
Light r-process component
Heavy r-process component
Composite
t = 1.5 d
t = 2.5 d
t = 4.5 d
t = 7.5 d
0.5
1.0
1.5
2.0
2.5
3.0
Wavelength (μm)

A unified kilonova model explaining the optical/ linfrared



A unified kilonova model explaining the optical/infrared counterpart of GW170817. The model is the superposition of the emission from two spatially distinct ejecta components: a 'blue' kilonova (light r-process ejecta with M = 0.025M, vk = 0.3c and Xlan = 10−4) plus a 'red' kilonova (heavy r-process ejecta with M = 0.04M, vk = 0.15c and Xlan = 10−1.5). a, Optical–infrared spectral time series, where the black line is the sum of the light r-process (blue line) and heavy r-process (red line) contributions. b, Composite broadband light curves. The light r-process component produces the rapidly evolving optical emission while the heavy r-process component produces the extended infrared emission. The composite model predicts a distinctive colour evolution, spectral continuum shape and infrared spectral peaks, all of which resemble the properties of AT 2017gfo.

Periodic Table of Cosmic Origins



Merging neutron stars
Dying low mass stars
Exploding massive stars
Exploding white dwarfs
Big Bang
Cosmic ray fission

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 Ti	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											

Cosmic origin of Elements in the Solar System

Many of the heaviest elements are coming from Neutron Stars Merger

CONCLUSION

- **Neutron Stars *Merger* is the main source of heavy elements in the Universe**