KILONOVAE: CREATION OF ELEMENTS

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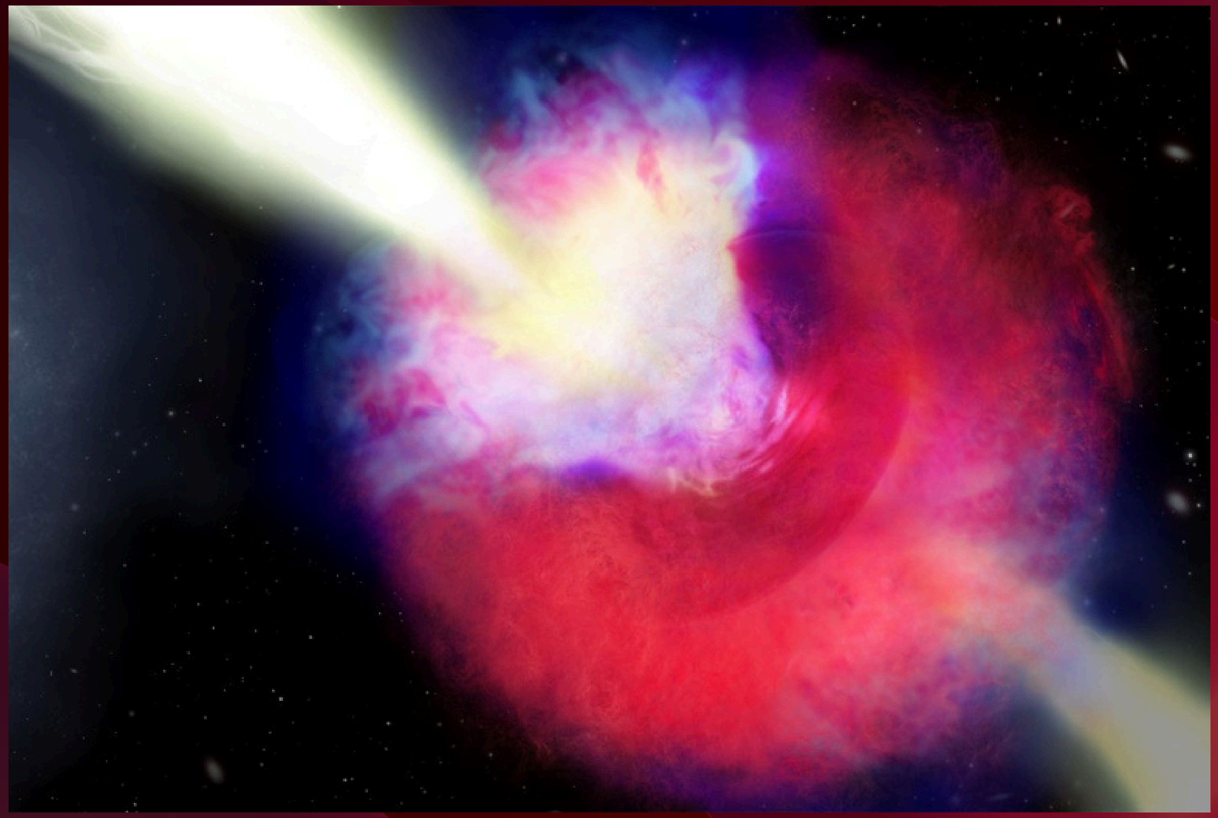
KILONOVAE: MERGER OF TWO NEUTRON STARS OR BLACKHOLES INTO ONE

when A massive star collapses to a supernova explosion, it can form a neutron star or a black hole depending on the mass. They are incredibly dense, with a mass greater than that of our Sun packed into a sphere just a few kilometers wide.

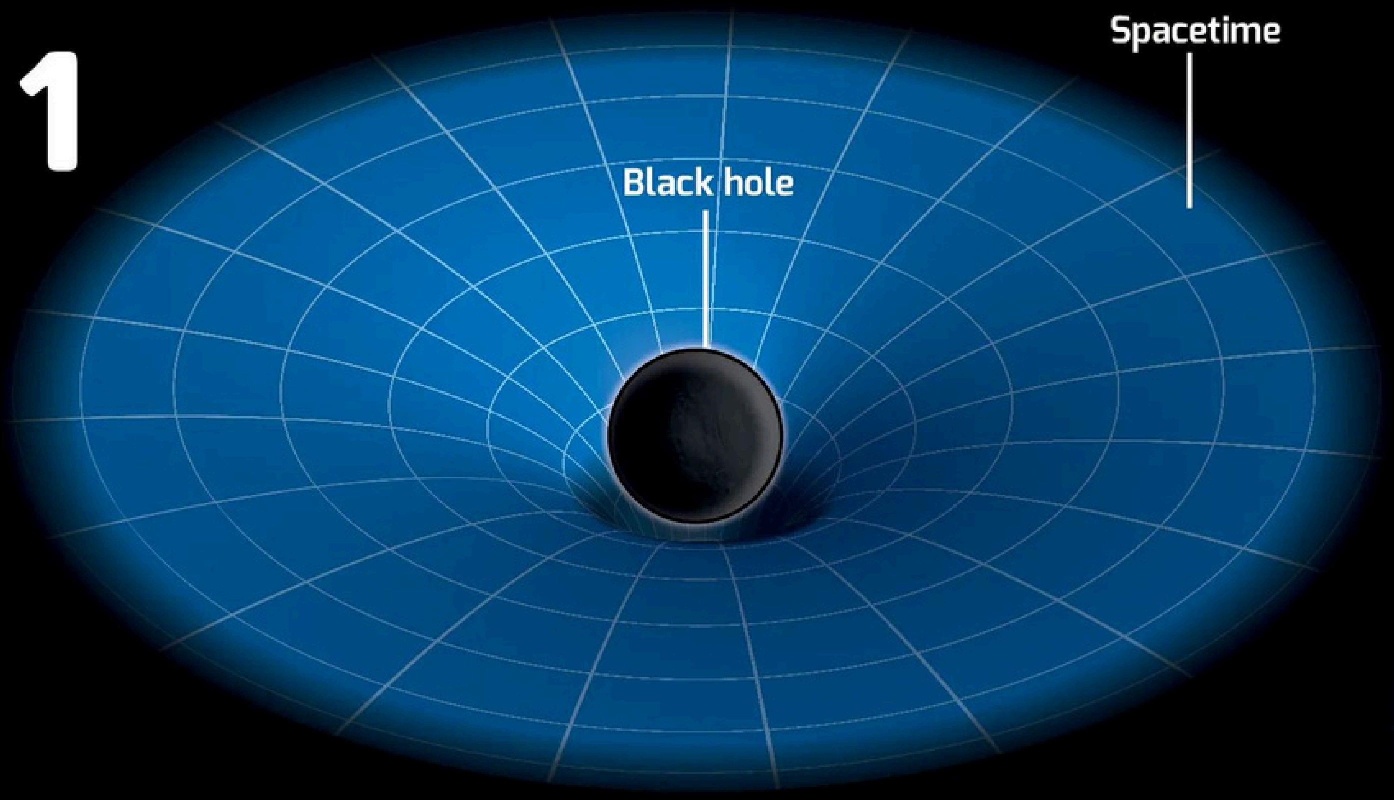


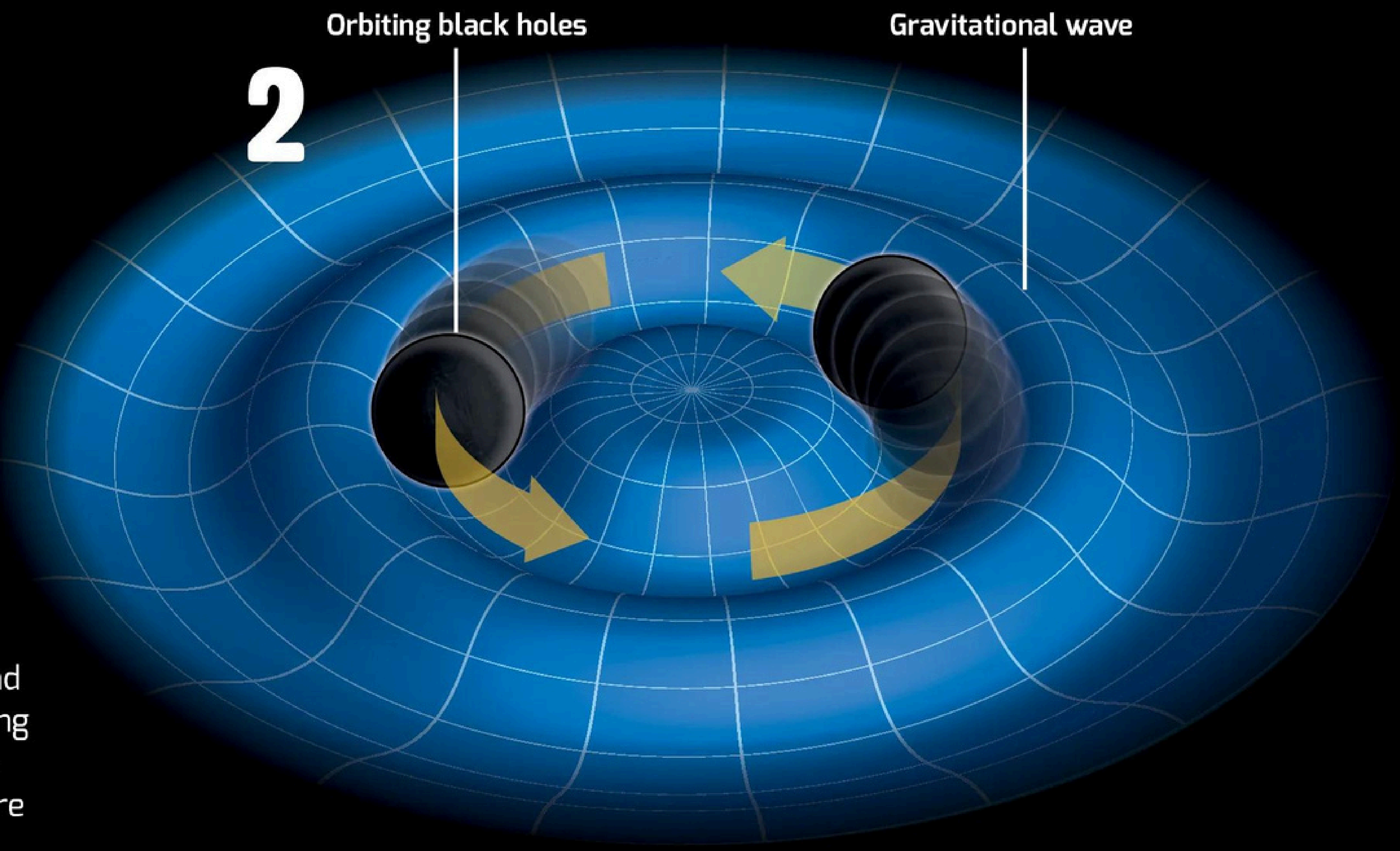
METHODOLOGIES: i) merger of neutron stars or blackholes

WHAT ARE GRAVITATIONAL WAVES?

Just as waves in a pond are created by disturbances in the water, gravitational waves are created by disturbances in the fabric of spacetime.

Lots of things can create gravitational waves, but most are too weak to us to measure. Luckily, because black holes distort spacetime so much, they can create waves that we can detect here on Earth.





1. A black hole by itself makes a deep dent in the fabric of spacetime, but it doesn't throw out any gravitational waves.

2. Here are two black holes orbiting each other (binary system). As they orbit, they whiz around each other so quickly that, instead of just making a dent in spacetime, they plough up waves (like when you stir soup with your finger) – these are gravitational waves.

But it takes energy to create gravitational waves and, with each orbit, the pair lose energy, which is carried away by the gravitational waves. As they lose energy, their orbits will begin to shrink. Eventually, it will shrink so much that the black holes will crash together.

SOURCE: SCIENCE AND TECHNOLOGY FACILITIES COUNCIL (STFC)

METHODOLOGIES: ii) simulation of merger of two blackholes, LIGO for detection of gravitational waves

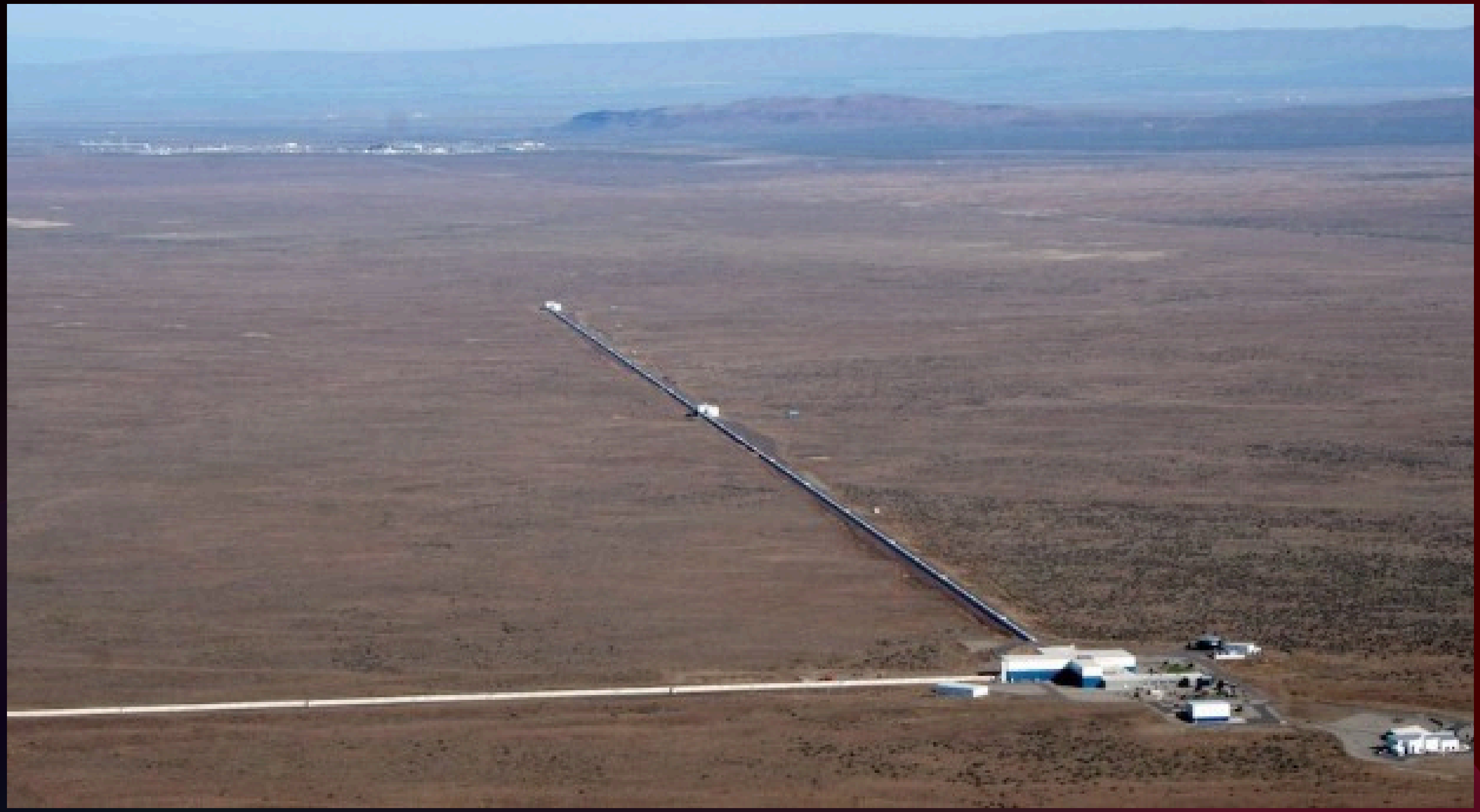
KILONOVA AND IT'S SIGNIFICANCE: GRAVITATIONAL WAVES AND CREATION OF HEAVY ELEMENTS

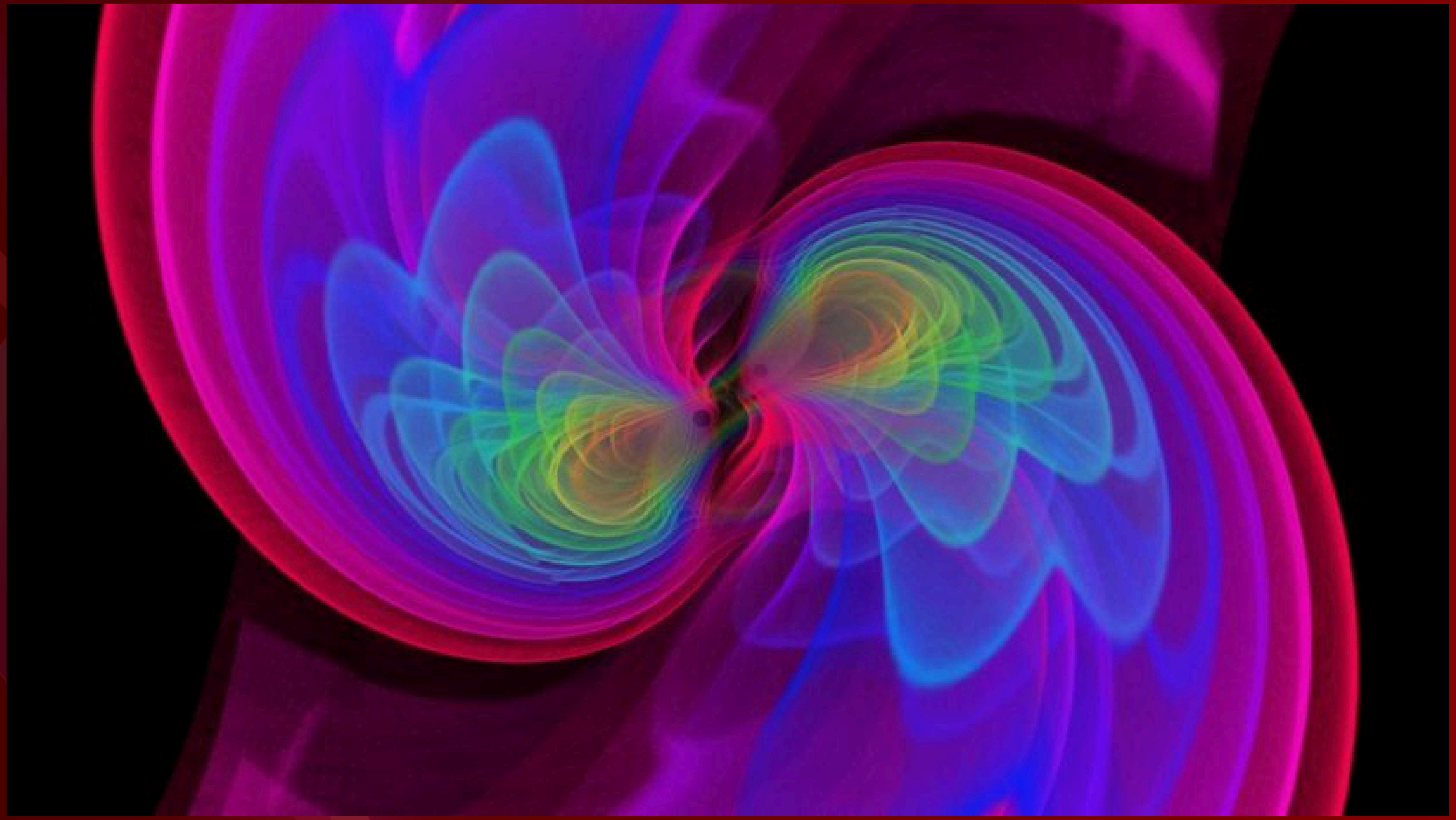
Kilonova is the event when two neutron stars or a neutron star and a black hole collide and merge into one neutron star or black hole, they also expel a few percent of their mass. The kilonovae are the astrophysical phenomena we observe of these extremely rapid, radioactive explosions of matter. This matter is very special because it is very rich in neutrons and starts immediately to form very heavy elements. The ejected matter that forms the kilonovae is the origin of half of the elements in the periodic table heavier than iron. By observing kilonovas, we can detect the origin site of the elements and measure how they are formed.

gravitational waves were predicted but couldnt be detected until 2015

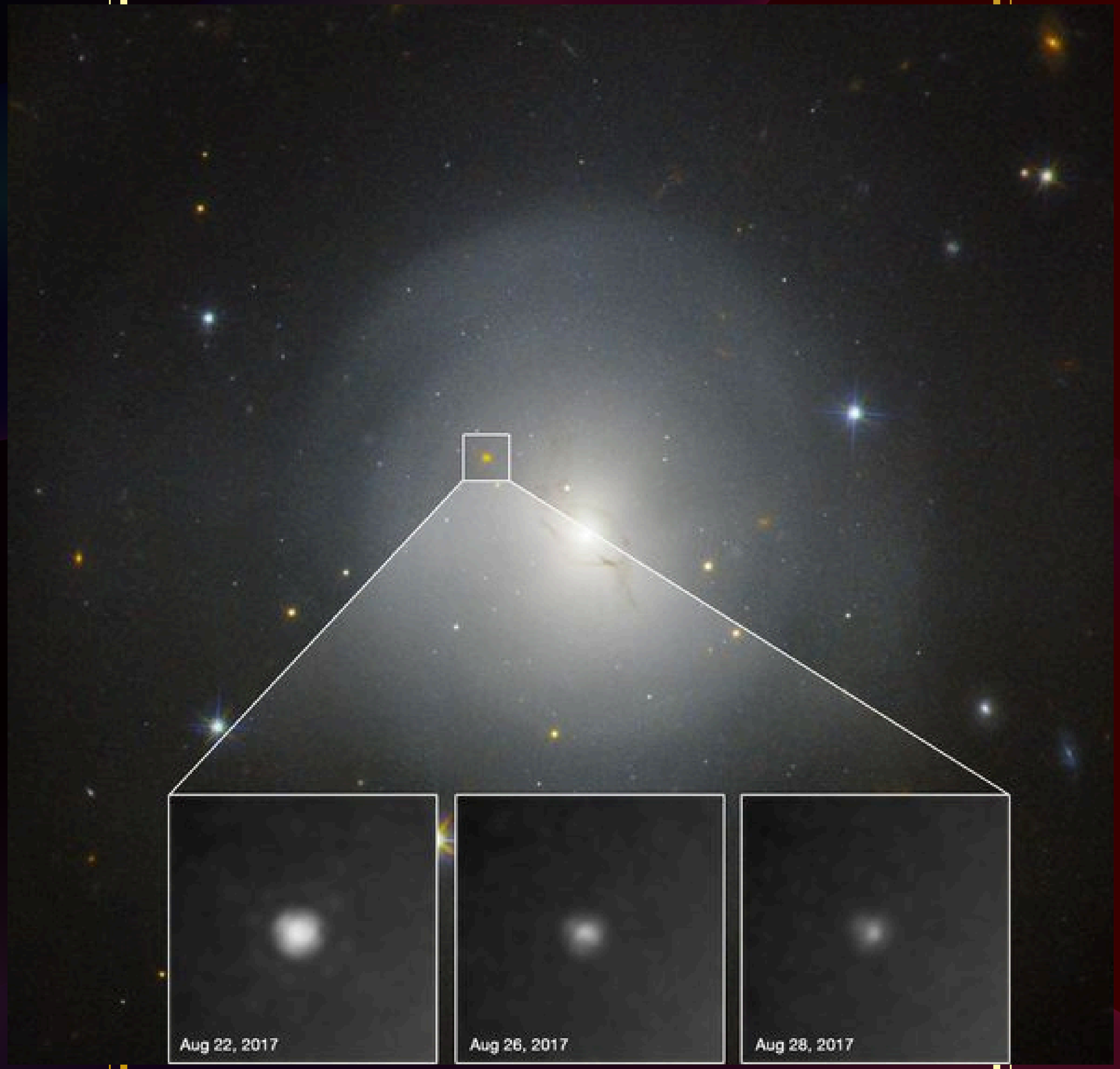
the model that predicted gravitational waves created at kilonova is the ligo set up (picture on the left)

it was designed to detect gravitational waves in the 1960s, ligo uses laser spectroscopy for detection (in 2017 scientists detected creation of heavy elements in kilonova)





METHODOLOGIES: ii) merger of two blackholes, LIGO for detection of gravitational waves



DETECTION OF KILONOVAE

Mergers between neutron stars and collisions between black holes and neutron stars are responsible for a range of emissions across the electromagnetic spectrum, such as fast radio bursts, short gamma-ray bursts and an X-ray glow. These can be used to locate the violent event that created them, which astronomers use to hunt kilonovas or their afterglow. Early suspected kilonova detections in 2009 and 2013 were associated with short gamma-ray bursts. Gravitational waves can also be useful in tracking down kilonovas. When spiraling neutron stars finally collide and merge, this creates a sudden blast of gravitational waves that can be detected when they finally reach Earth.

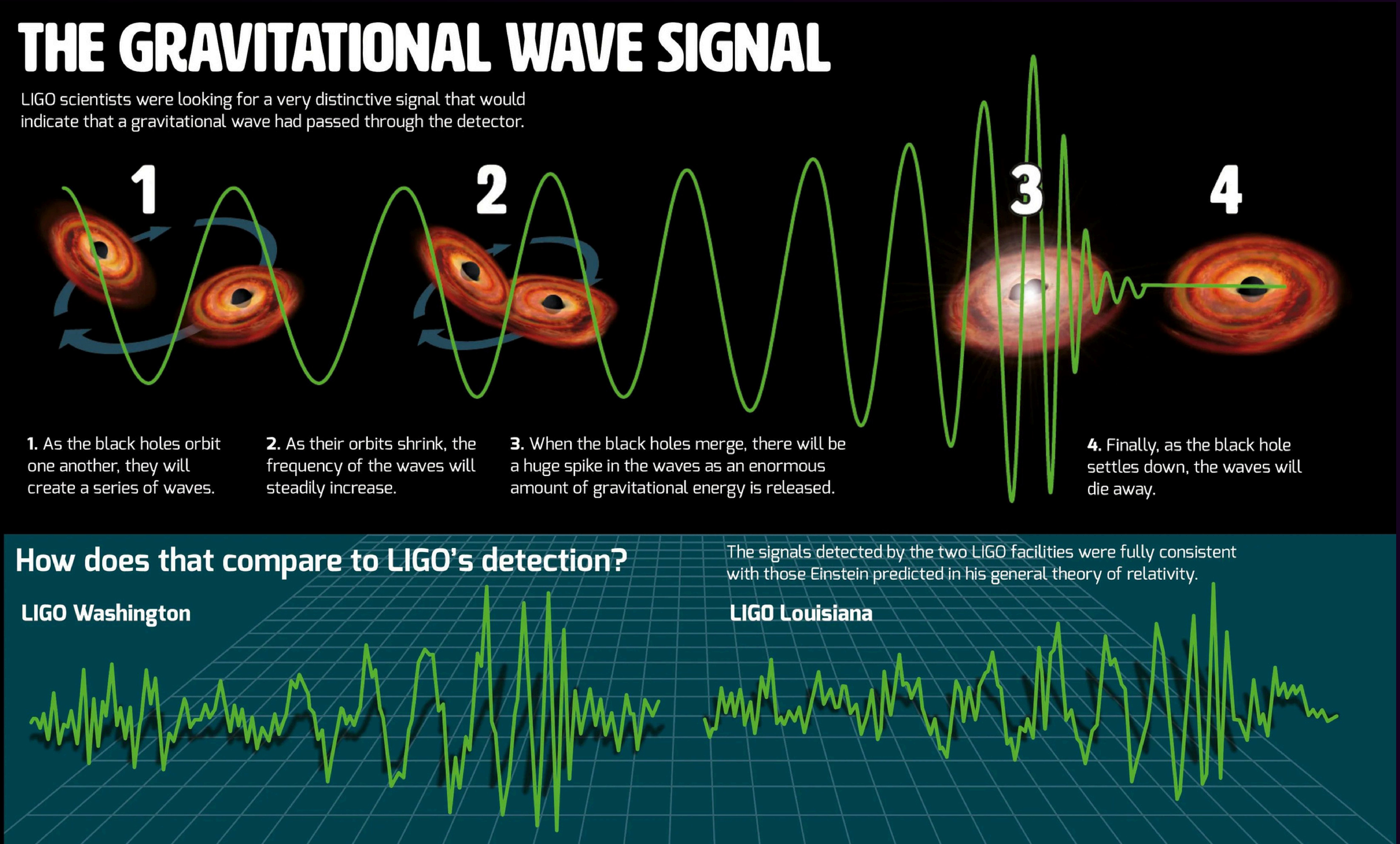
in August 2017, LIGO and its fellow gravitational wave detector Virgo detected gravitational waves from a merger of neutron stars located 130 million light-years from Earth. Within 12 hours, the source of the gravitational wave signal was found.

In 2022, a team of astronomers spotted what could be a kilonova afterglow that occurred around 3.5 years after the collision and merger of the two neutron stars that created the gravitational wave signal GW170817. This was the result of an X-ray jet from the merger expanding and slowing but leaving behind an X-ray glow with constant brightness.
In early 2023, astronomers saw, for the first time, what they think is a system that is destined to birth a kilonova. The kilonova progenitor system CPD-29 2176 is located 11,400 light-years away and contains two tight, binary objects: a neutron star created in an ultrastripped supernova, and a Be star that the neutron star is stripping of its outer layers and that will eventually become a neutron star via the same process.

in February 2023, scientists found that the kilonova blast associated with GW170817 appears to take on a perfectly spherical shape.

This finding contrasts with all previous models, which suggested that two colliding neutron stars orbiting each other 100 times a second should create an explosion in the shape of a flattened disk. This means kilonovas may be hiding some hitherto undiscovered physics.

METHODOLOGIES: ii) merger of two blackholes, LIGO for detection of gravitational waves

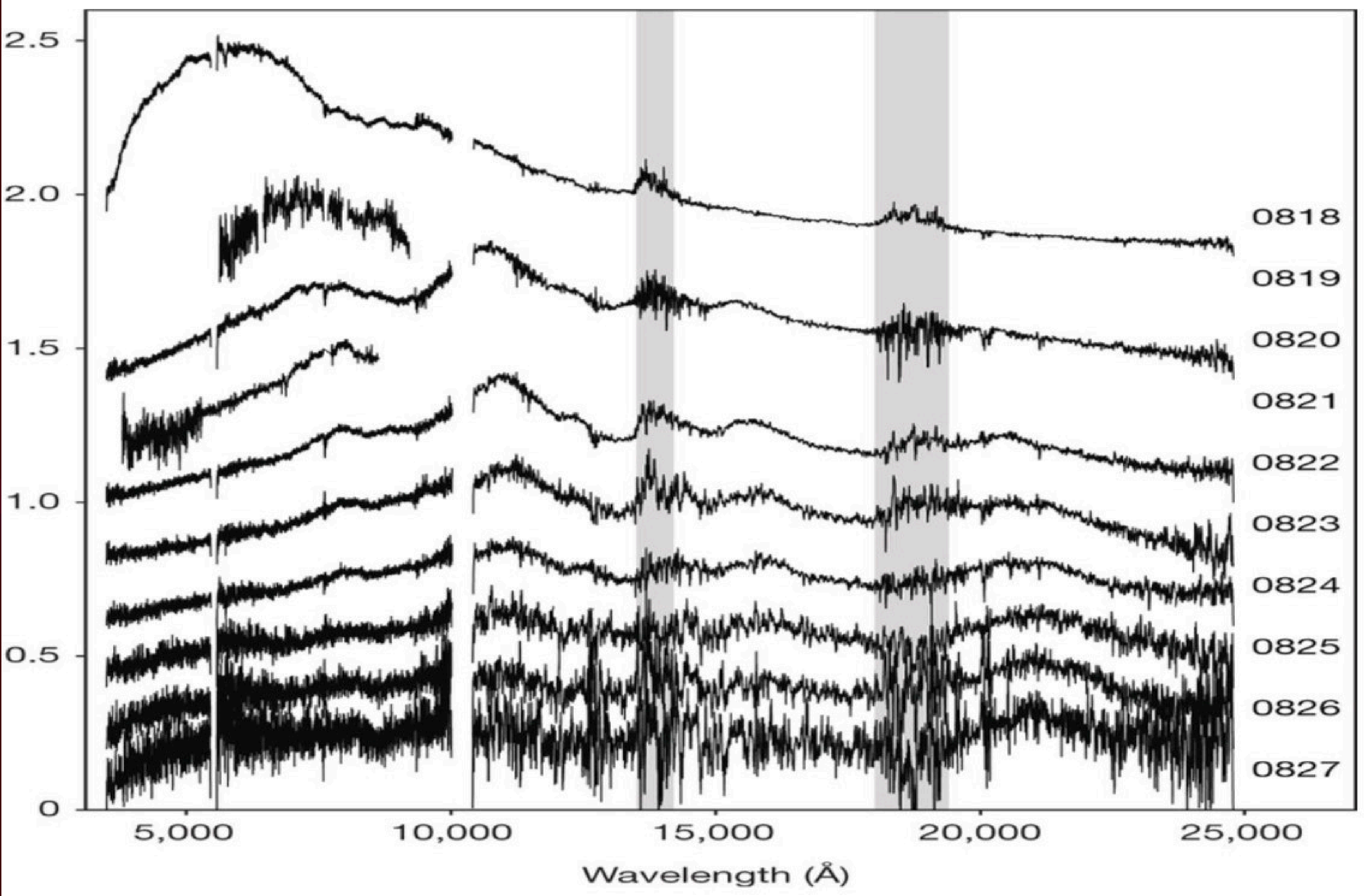


METHODOLOGIES: iii) spectra of electromagnetic waves from merger of neutron stars

MERGER OF NEUTRON STARS - KILONOVA 2017: SPECTRUM OF HEAVY ELEMENTS

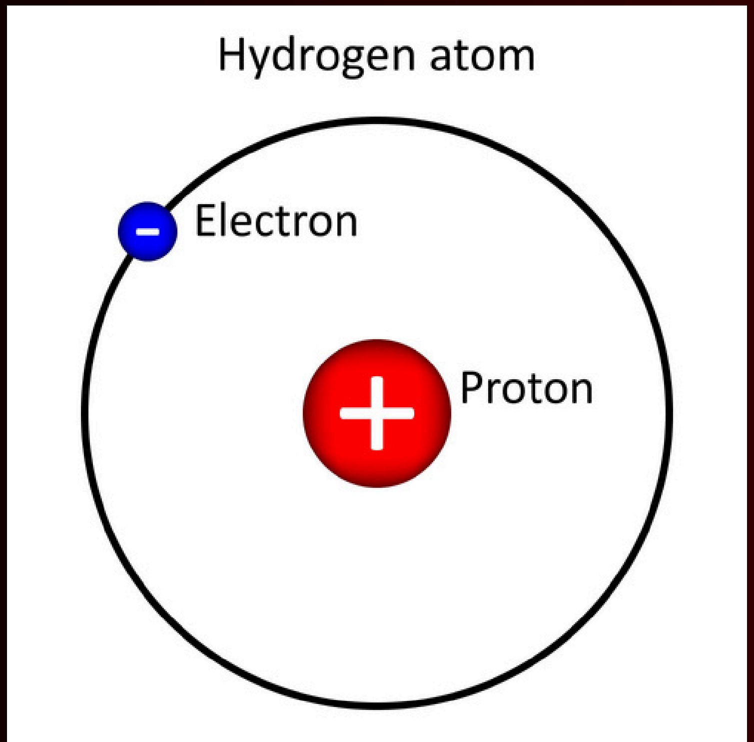
Time variation of kilonova spectra from August 18 (top curve) to 27 (lowest curve) in 2017 shows the peak emission in O (5000˚A) shifting to NIR 2.5 μm match lanthanide (Z=57-71) (Pain et al 2017)

opacity of plasma causes the radiation to become weaker from the optical broad feature to infrared
when radiation comes out of the spectrum away from the center loses less energy by plasma and when its closer to the center it loses more energy and radiation becomes weaker example optical infrared

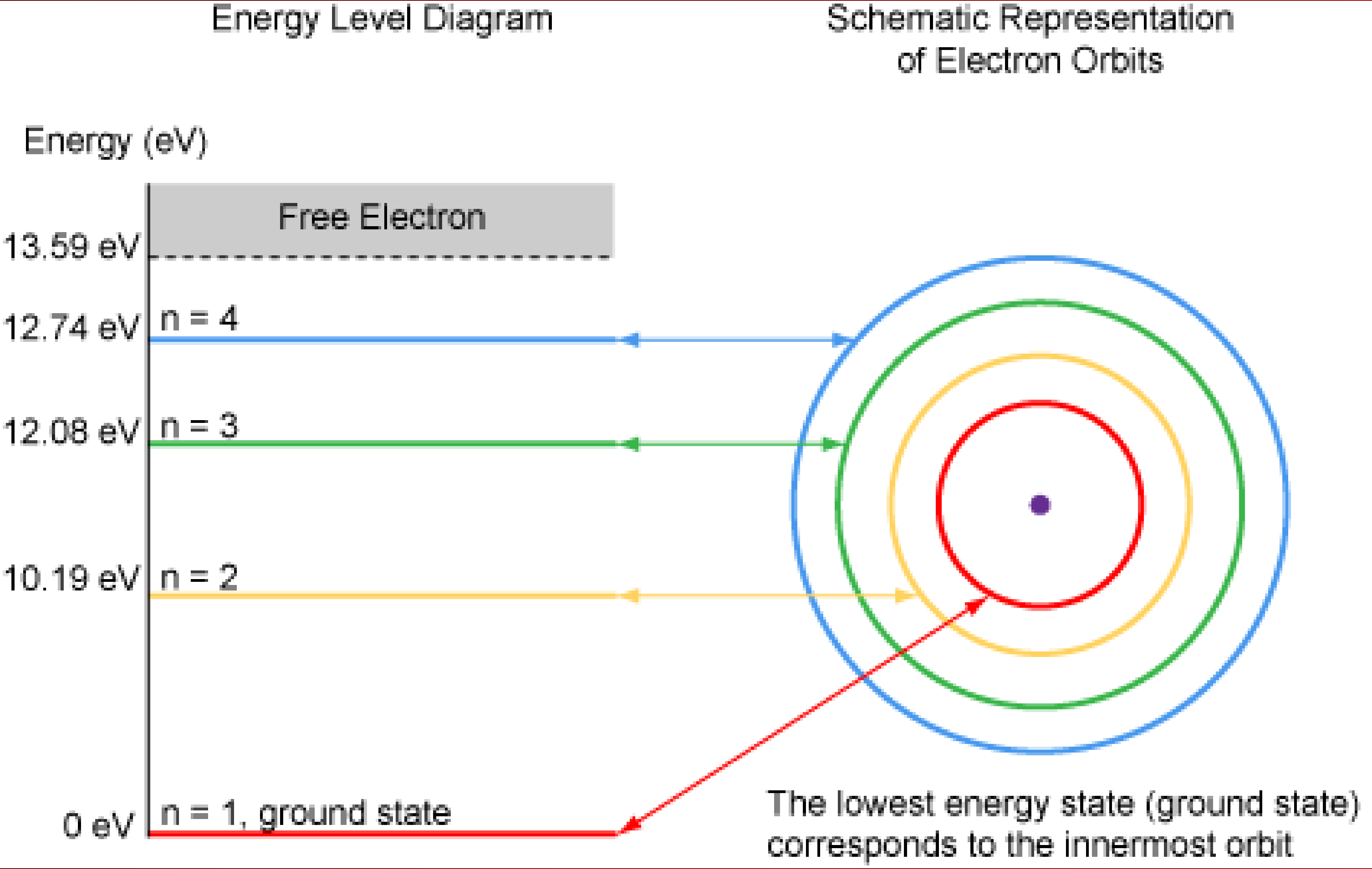


QUANTUM PICTURE OF AN ATOM

Hydrogen Atom: Energy Levels and Photon Emission



- Hydrogen has one proton and one electron.
- When excited, electrons move to higher energy levels.
- Photons are emitted when electrons return to lower levels.



1) Calculating Number of Photon Types

- **Total photon types** emitted from transitions up to level ***n*** is:

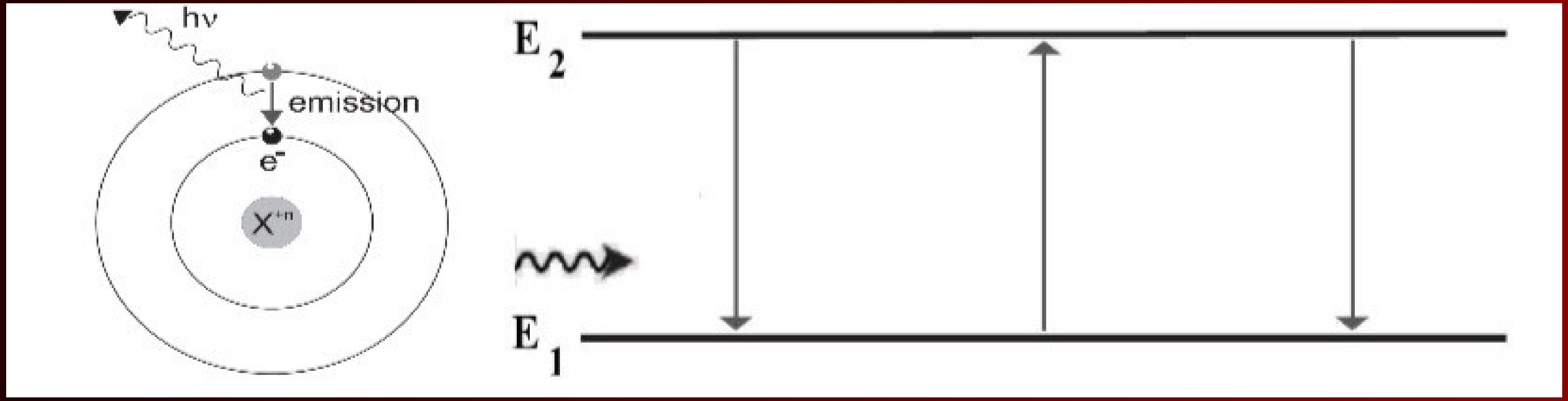
n(n-1)/2

e.g. n=5: 5(5−1)/2=10

Each orbital corresponds to a quantum energy level as given below:

$$\text{Quantum enegy level} : \mathrm{E_n} = \mathcal{R}_{\mathrm{H}} \frac{\mathrm{Z}^2}{\mathrm{n}^2}$$

RADIATIVE ATOMIC TRANSITION



Atomic radiative transition: when an electron goes from one quantum energy level E1 to quantum energy level E2 or comes down from E2 to E1.

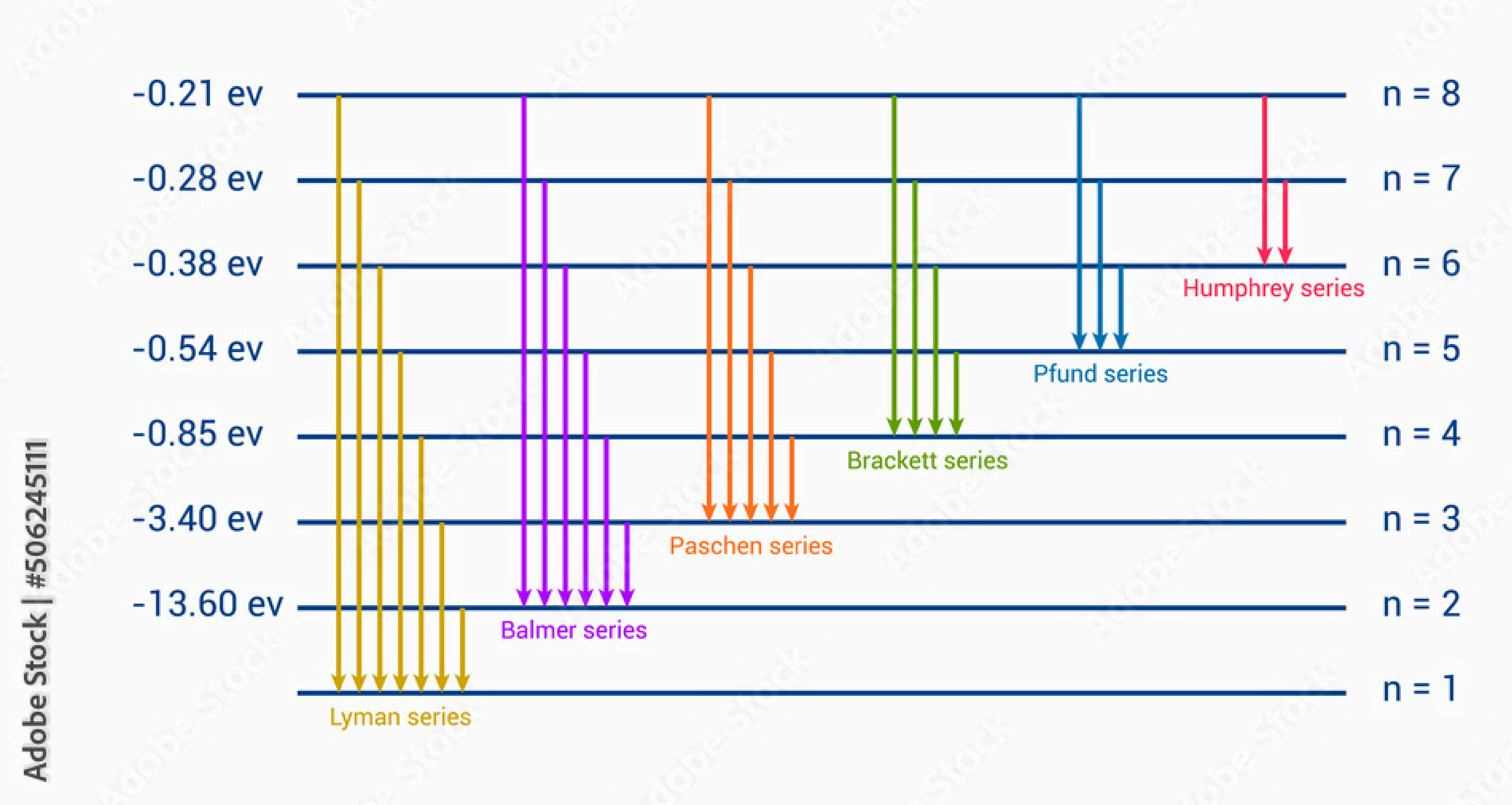
2) Rydberg Formula for Photon Energy

- **Rydberg formula** for photon wavelength:

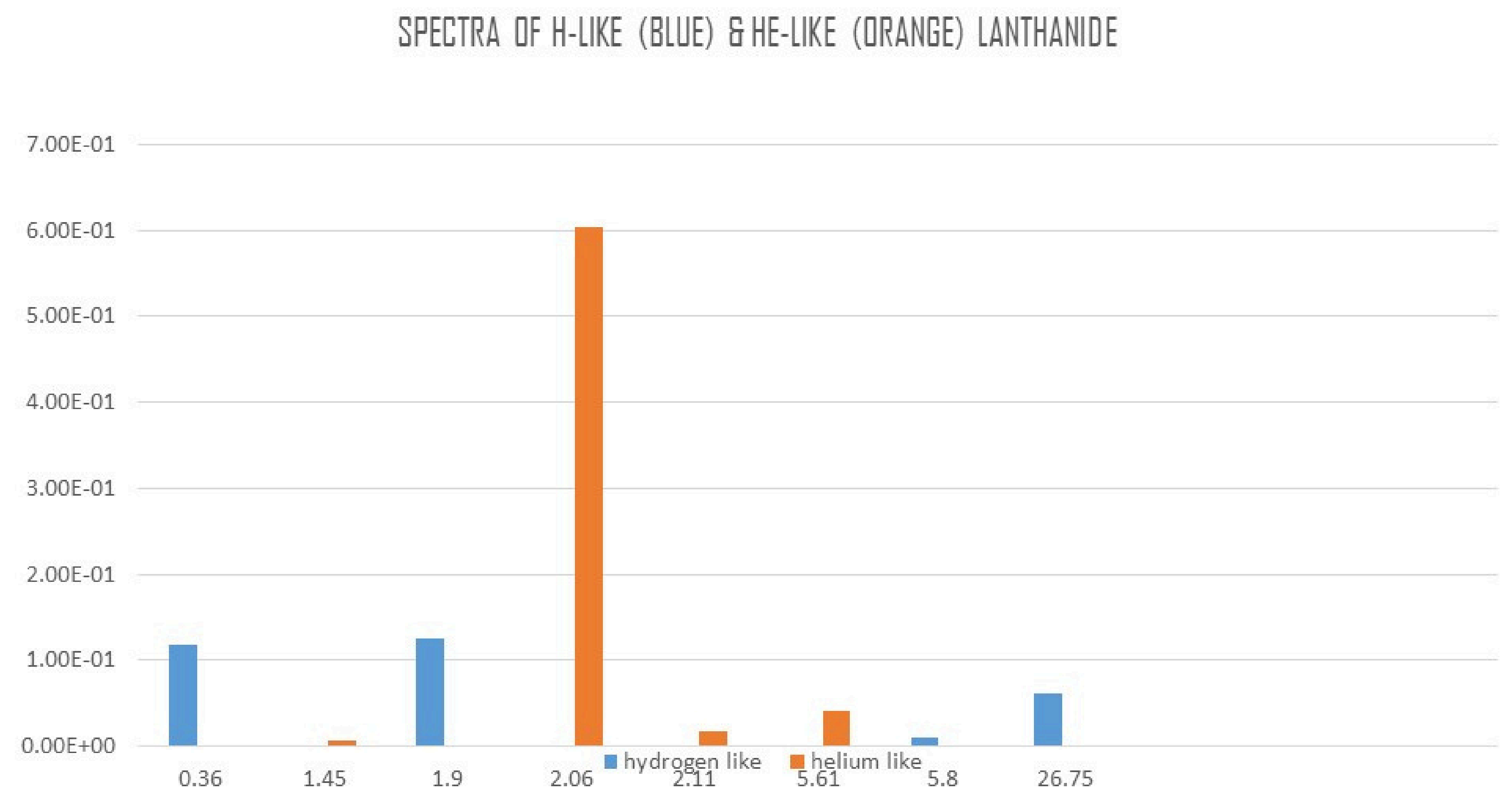
$$\Delta E_{n,n'} = \frac{1}{\lambda} = \mathcal{R}_H \left[\frac{1}{n^2} - \frac{1}{n'^2} \right] \quad (n' > n)$$

The energy of the photon, ΔEn,n', emitted due to transition between the two levels, n (lower) and n' (upper).

λ is the wavelength of the photon and RH = 1/912 / Å is the Rydberg constant.



Quantum mechanics of atoms and spectroscopy



I carried out research on spectra formed by lanthanides (shown on the left)
a spectral line is formed when an atomic electron jumps to an upper energy level or drops down to a lower energy level

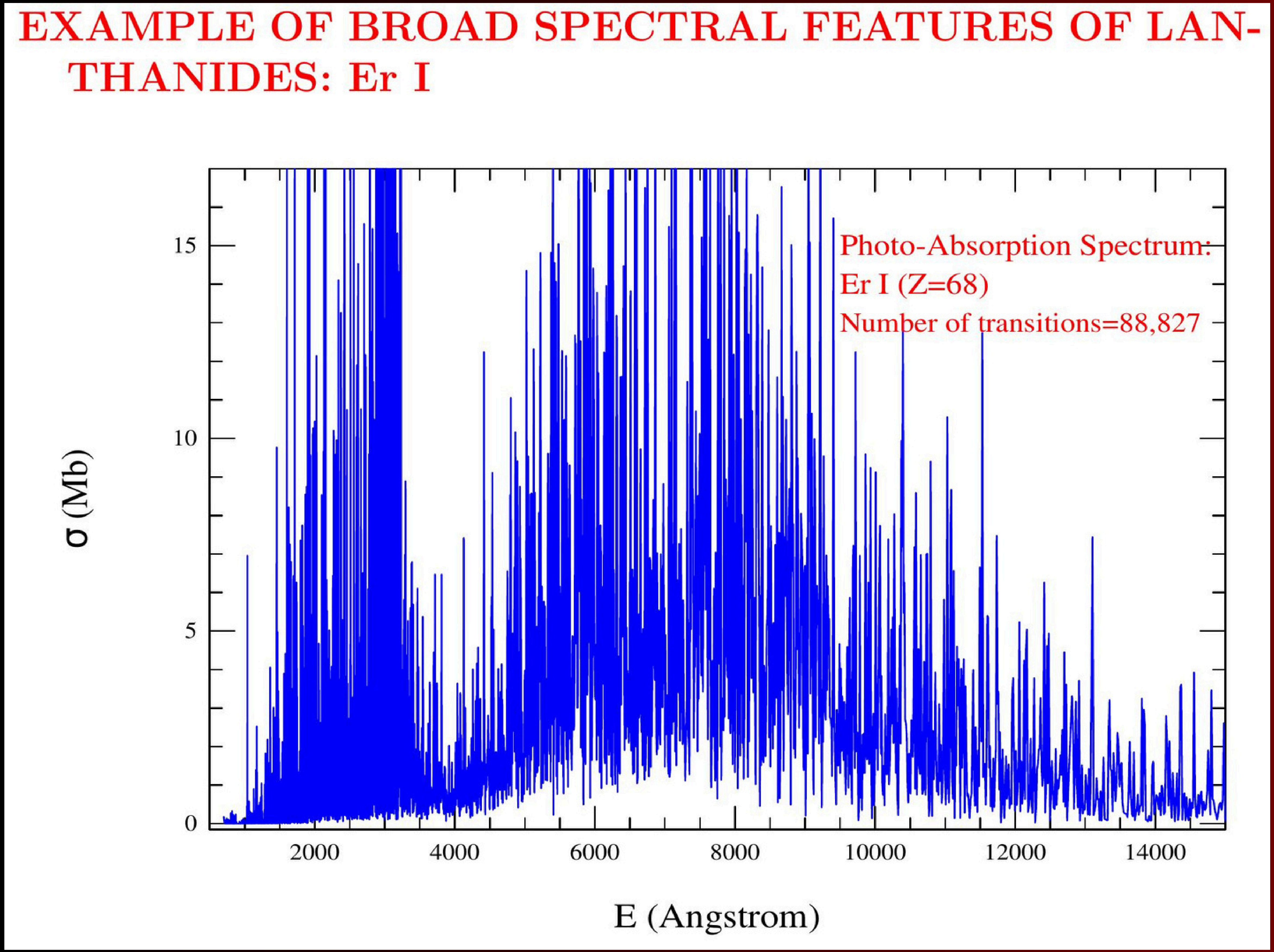
an absorption line is formed when it goes to an upper level by absorption of a photon and an emission line forms when it emits a photon by going down to a lower level

the figure on the side shows the spectra of a H-like (blue) & He-like (orange) lanthanide
H-like and He-like lanthanides are one. electron and two electrons atomic systems.
The atomic number of lanthanide lanthunum is 57, that is, it has 57 protons and at neutral staate it has 57 electrons

even though there are many quantum energy levels, infinite in total, not all transitions form strong spectral lines because the heights of spectral lines in the figure

the strong tranisitions are known as allowed transitions but there are many transitions that are called forbiden because of their weak transition probability

METHODOLOGIES: iii) spectroscopy of atomic lines - A Lanthanide Spectrum



Number of spectralines in this figure is 88,827 making the broad features. the second broad feature is similar to what kilonova produced.

This is how the spectrum was identified with lanthanides.

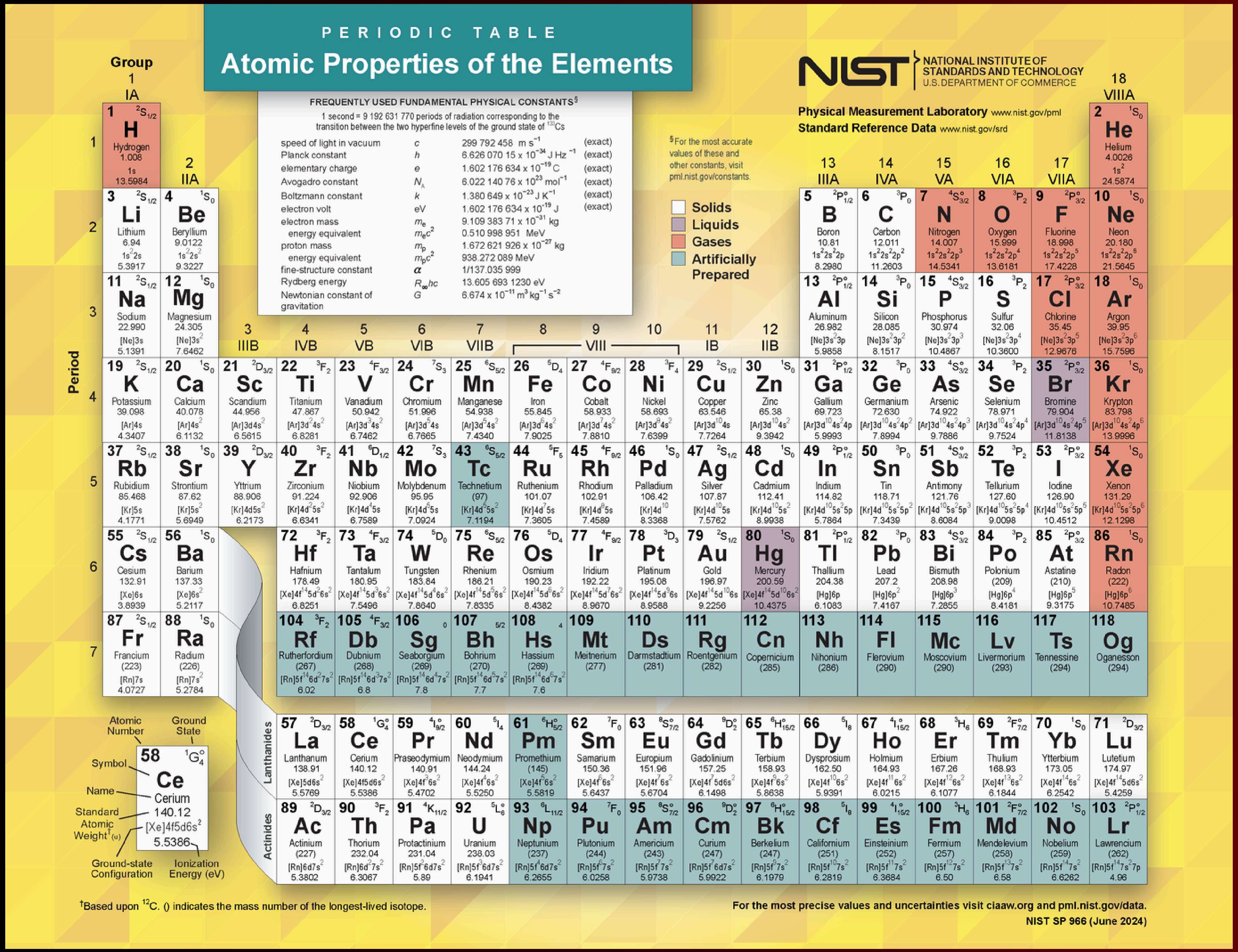
If we average the spectral lines using the Gaussian distribution formula, given below, the spectra will look similar to the kilonovae spectrum shown previously.

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} .$$

The parameter μ is the mean or expectation of the distribution (and also its median and mode), while the parameter σ2 is the variance. The standard deviation of the distribution is σ (sigma).

REF: (NAHAR 2024)

METHODOLOGIES: iv) creation of elements - nuclear fusion and neutron capture



Lanthanides are a group of 15 chemical elements in the periodic table, spanning atomic numbers 57 (lanthanum) to 71 (lutetium). They are often referred to as rare earth elements and have unique properties that make them valuable in various applications.

H AND HE FORMATION

Immediately after the Big Bang, the universe was extremely hot and dense, preventing the formation of elements.

Within a fraction of a second after the Big Bang, neutrinos, quarks, and electrons emerged. Protons and neutrons followed shortly after, with hydrogen nuclei forming within about 3 minutes in a period known as nucleosynthesis.

Around 20 minutes after the Big Bang, nucleosynthesis ceased, halting further nucleus formation. However, electrons couldn't remain in orbit around atomic nuclei due to the intense heat and radiation prevailing in the universe. Neutral atoms that did manage to form were quickly disrupted by energetic radiation.

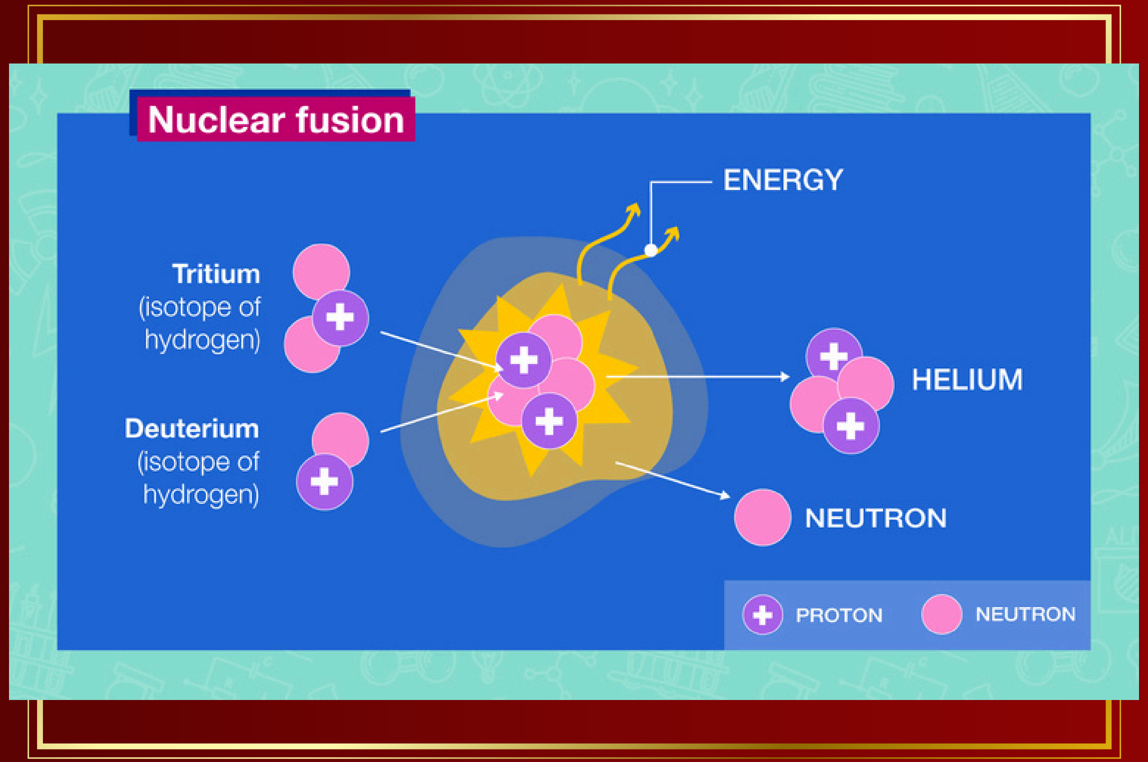
After approximately 380,000 years, the universe had expanded and cooled sufficiently for electrons to orbit atomic nuclei without being easily dislodged by radiation. This phase marked recombination, allowing for the stable formation of neutral hydrogen and helium as electrons could now bind to nuclei without being readily scattered by stray radiation.
thesis

- this periodic table shows all 118 elements that we know of (created in stars)
- in general elements from He to Fe are created through nuclear fusion in the core of the star
- the rest of the elements are created through neutron capture

METHODOLOGIES: iv) creation of elements - nuclear fusion and neutron capture

Nuclear fusion is the process by which two light atomic nuclei combine to form a single heavier one while releasing massive amounts of energy.

Fusion reactions take place in a state of matter called plasma — a hot, charged gas made of positive ions and free-moving electrons with unique properties distinct from solids, liquids or gases.



- Fusion: Primarily responsible for creating lighter elements (e.g., hydrogen fusing into helium) in stars. As stars evolve, they can fuse elements up to iron through successive fusion processes.
- Neutron Capture: Focuses on producing heavier elements. The s-process gradually builds heavier isotopes in stars like red giants, while the r-process produces the heaviest elements (e.g., gold, uranium) during explosive events like neutron star mergers or supernovae.

The relationship between nuclear fusion and neutron capture is fundamental to cosmic nucleosynthesis. While fusion builds the initial light elements and powers stars, neutron capture transforms these lighter elements into the heavier ones essential for the diversity of matter in the universe. Together, they illustrate the complex processes that govern element formation in the cosmos.

METHODOLOGIES: iv) creation of elements - neutron capture

PROCESSES OF NUCLEOSYNTHESIS/ NEUTRON CAPTURES IN STARS

Neutron Capture: under extreme pressure and temperatures , such as supernova explosion, a neutron joins another nucleus which is followed by beta decay (electron ejection) forming new elements.

s-process

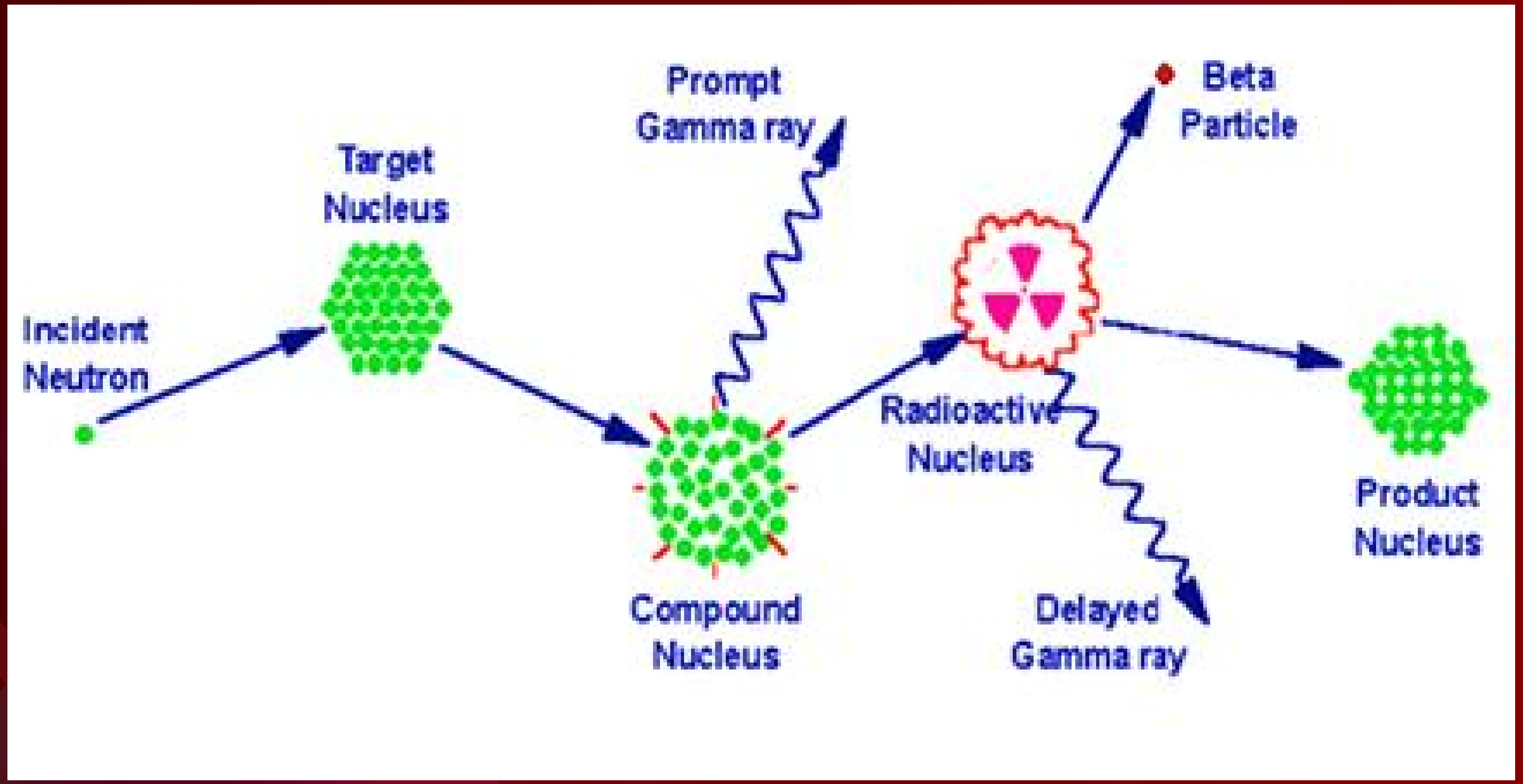
A series of nuclear reactions (nucleosynthesis) that occur in stars, particularly AGB stars (older red giants). Approximately half the atomic nuclei heavier than iron are created through s-process.

r-process

Successive neutron captures that is rapid for a beta (electron) decay. It happens in environments with higher fluxes of free neutrons, typically beginning with nuclei in the abundance peak centered on 56Fe.

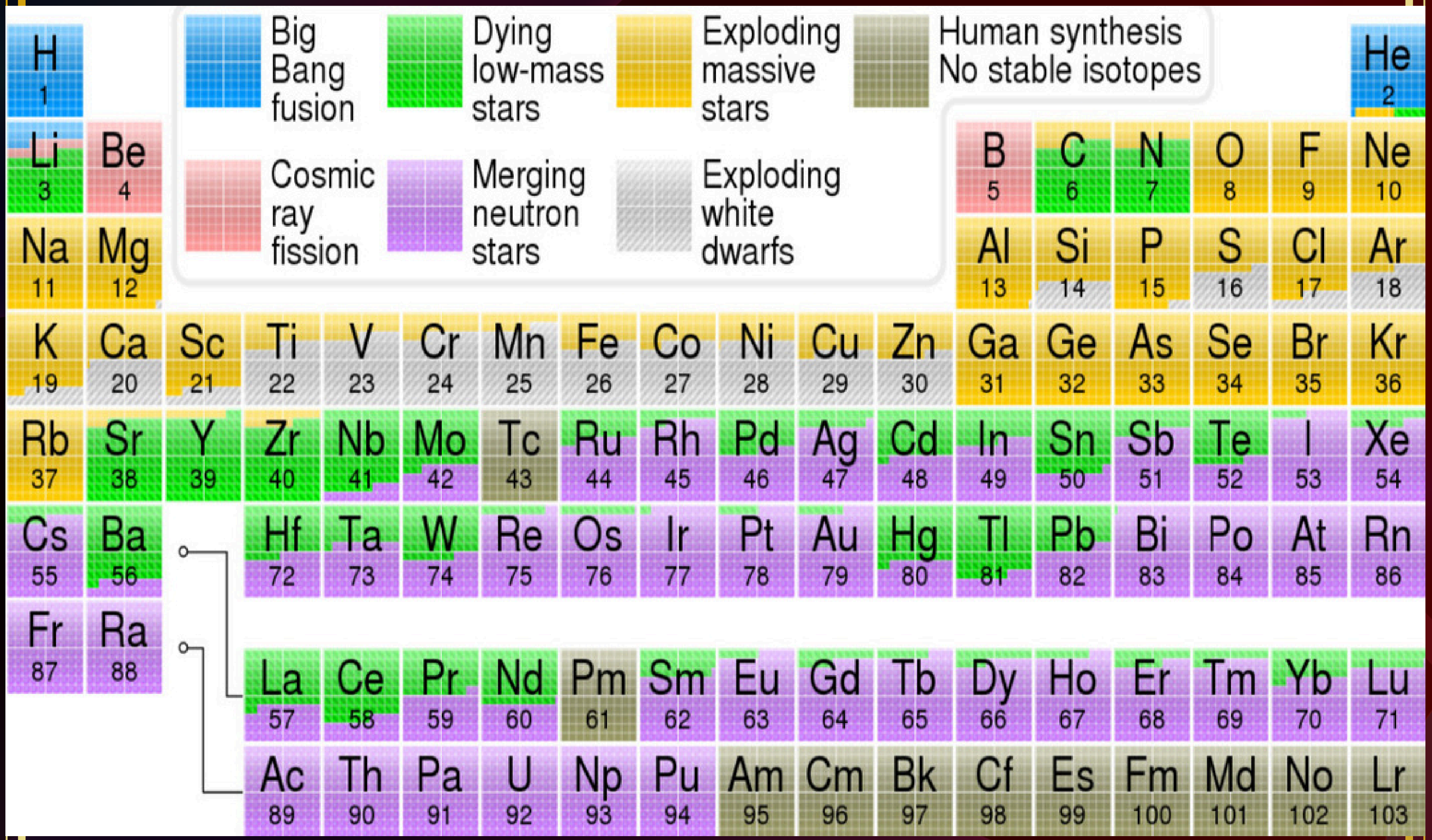
p-process

Proton capture process in astrophysical origin of the elements The nuclides are called p-nuclei and their origin is still not completely understood.



RESULTS AND FINDINGS: SIX WAYS OF ELEMENT CREATION

PERIODIC TABLE: WITH ORIGIN OF ELEMENTS (JOHNSON 2019)



this is a special periodic table that demonstrates the six main causes of each elements production using small squares that we can differentiate through colors
research is still ongoing to make this table more accurate

1) **Big Bang Fusion:** The formation of light elements (hydrogen, helium, lithium) during the first few minutes after the Big Bang, when temperatures and densities were extremely high

2) **Dying Low-Mass Stars**: Stars like our Sun end their life by shedding their outer layers, creating planetary nebulae, while their cores shrink into white dwarfs, primarily composed of carbon and oxygen.

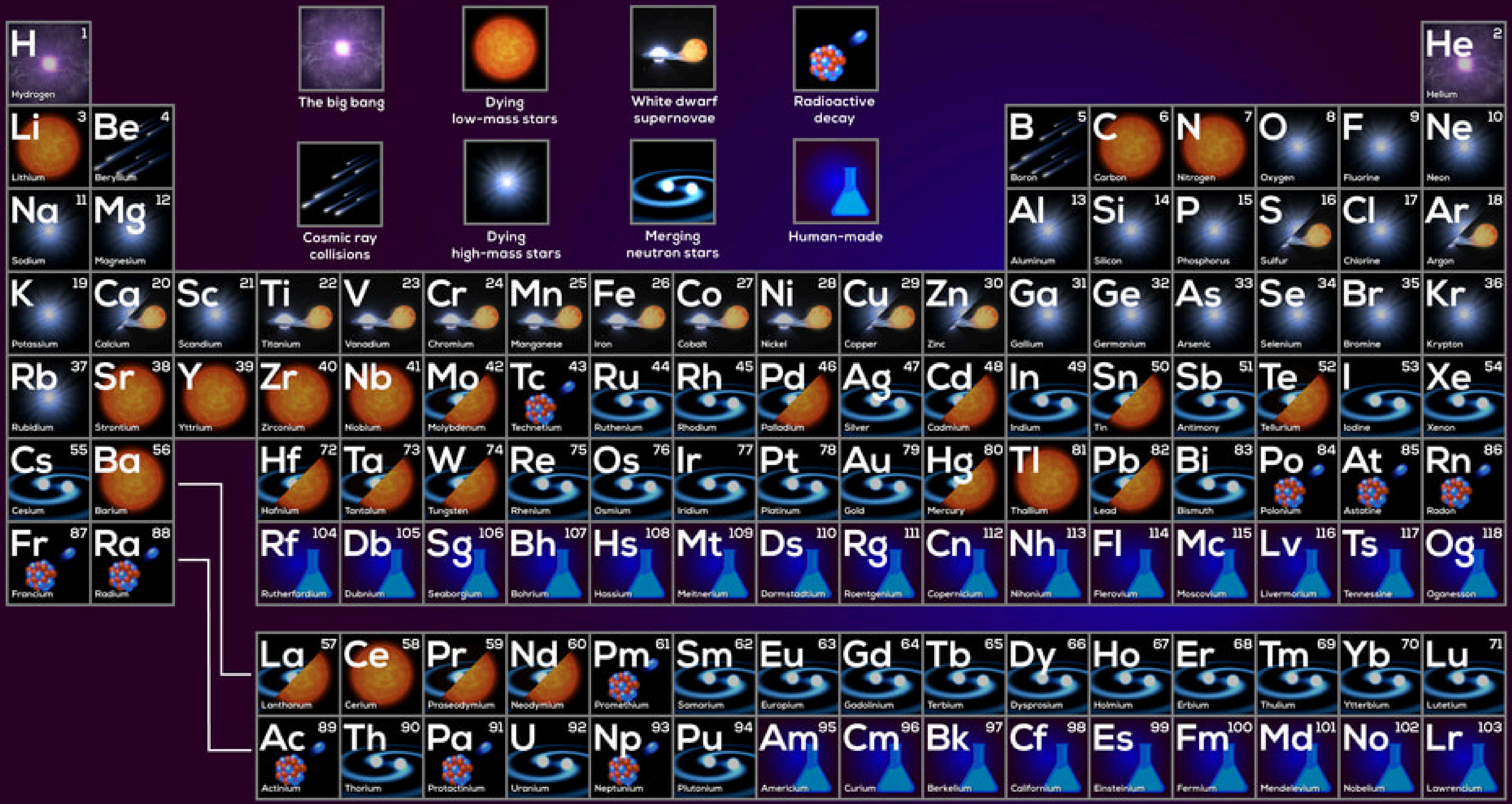
3) **Exploding Massive Stars**: Massive stars (over 8 solar masses) undergo supernova explosions at the end of their life cycle, creating heavy elements (like iron) and dispersing them into space.

4) **Exploding White Dwarfs**: When a white dwarf in a binary system accumulates enough material from its companion, it can undergo a thermonuclear explosion (Type Ia supernova), producing elements like nickel and iron.

5) **Merging Neutron Stars**: When two neutron stars collide, they create heavy elements (such as gold and platinum) through rapid neutron capture (r-process) and release gravitational waves.

6) **Cosmic Ray Fission**: High-energy cosmic rays interact with atomic nuclei in space, causing fission reactions that can lead to the creation of new isotopes and elements.

ORIGINS OF THE ELEMENTS



This periodic table depicts the primary source on Earth for each element. In cases where two sources contribute fairly equally, both appear.

CONCLUSION

In summary, we have explored the incredible mechanisms that shape the universe as we know it. We started by examining kilonovae, the explosive events that occur when two neutron stars or blackholes merge, producing heavy elements and releasing an immense amount of energy.

We then connected these stellar events to the groundbreaking work of LIGO, whose first detection of gravitational waves gave us direct evidence of these mergers. following up we came up with the electromagnetic spectrum This detection marked a new era in astrophysics, allowing us to observe the universe through a completely new lens.

2017 kilonova showed a broad emission feature similar to those of lanthanides. We examined the broad spectral features of lanthanides and found matching of spectra of lanthanides and other elements with the kilonova emission bump . This indicates creation of heavy elements during kilonovae.

As we investigate the origin of elements in the periodic table, we find six different cosmic processes responsible for them - The Big Bang Fusion, Dying Low-Mass Stars, Exploding Massive Stars, Exploding White Dwarfs, Merging Neutron Stars and Cosmic Ray Fission.

As we continue to refine our understanding of these cosmic processes, we open new windows into the origins of matter and the dynamic forces that govern the universe—reminding us that the story of creation is still unfolding, one discovery at a time.

(THESIS) THE DIFFERENCE?

supernovae

Supernovae are stellar explosions so energetic they can briefly outshine an entire galaxy, radiating as much energy in a short amount of time as an ordinary star like the Sun is expected to emit over its 10 billion-year life span. Supernovae are dynamic events that occur on time scales of hours to months.

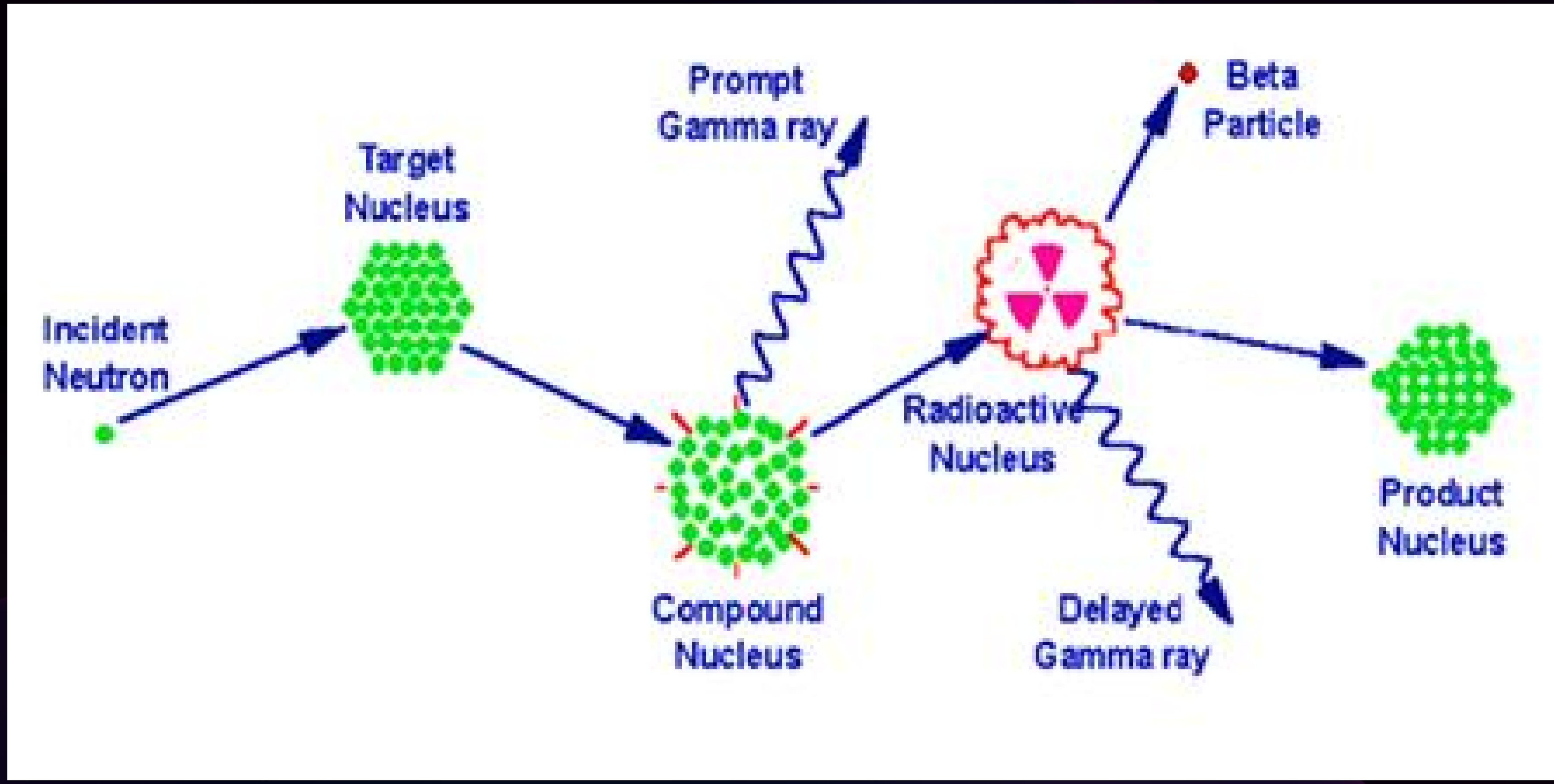
kilonovae

the radiation flashes of neutron star mergers were predicted to be between 1% and 10% as bright as those from typical supernovas. a kilonova is less powerful than a supernova, it is still 1,000 times more powerful than a standard nova.

nova

Classical novae are due to the runaway nuclear burning of hydrogen-rich material slowly accreted on to a white dwarf from its binary companion.

THE R-PROCESS: NEUTRON CAPTURE AND ELEMENT FORMATION IN KILONOVAE

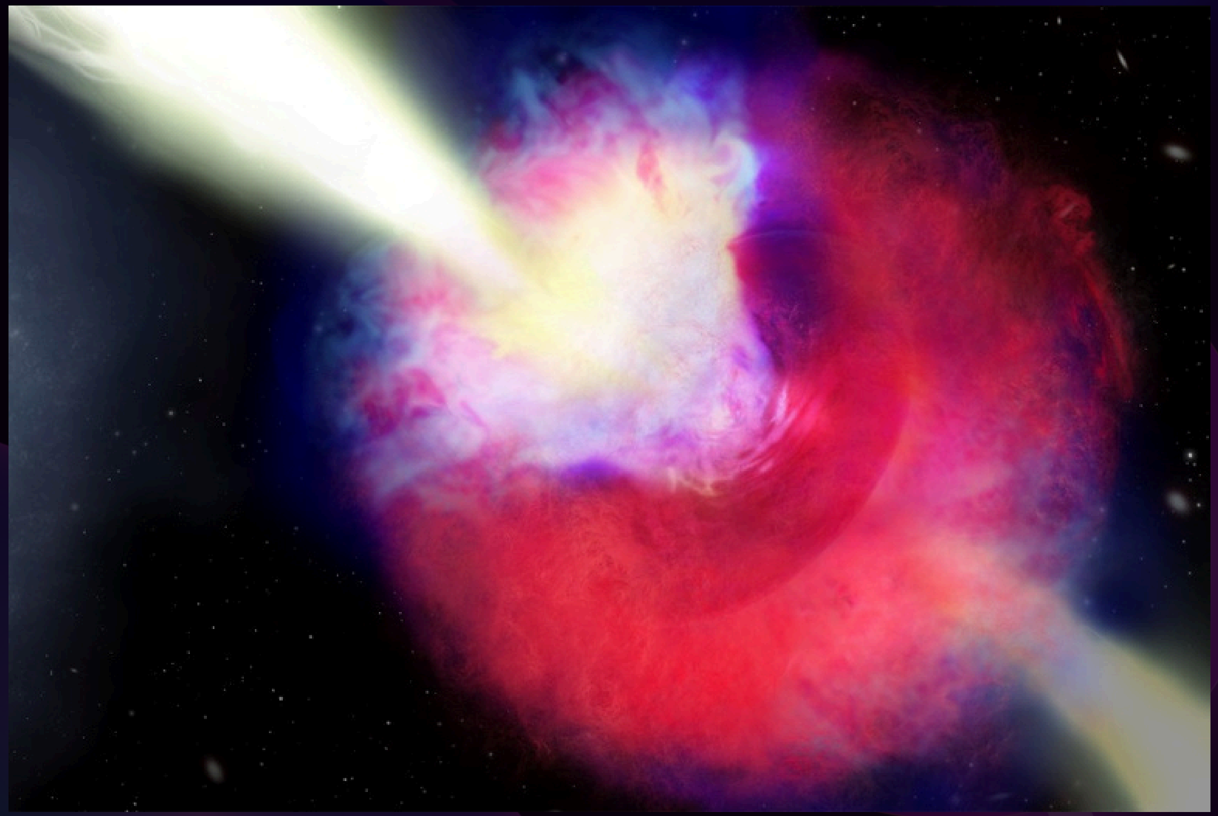


Scientists have long understood that the nuclear fusion processes that power stars forge the elements, beginning with the nucleosynthesis of helium from hydrogen, the universe's lightest element. Scientists thought these elements could be created via the rapid neutron-capture process, or "-r-process," but for this to proceed stably, it would require an environment absolutely flooded with free neutrons. Because neutron stars are made almost entirely of a dense soup of neutrons, during collisions, they eject around a gram of neutrons per cubic centimeter into their surroundings. This creates a neutron-rich environment around the merger in which the r-process can proceed. The r-process begins when the seed nuclei of iron are bombarded with these free neutrons, soaking them up. Stable atoms of iron, such as the isotope iron-56, have 26 protons and 30 neutrons. The excess of neutrons granted to iron by neutron capture makes the iron atoms unstable and radioactive due to a huge imbalance between protons and neutrons. This results in some of the atoms undergoing beta decay, with neutrons transforming into protons via the emission of electrons and other particles like the antimatter equivalent of neutrinos–antineutrinos. An element is defined by the number of protons in its nucleus, so this process transforms iron into heavier elements, like gold, in what is almost a form of cosmic alchemy. It is the radiation from the decay of the radioactive elements created during the r-process that makes the material ejected from the neutron stars glow , and it's this light that's called a kilonova.

(thesis)

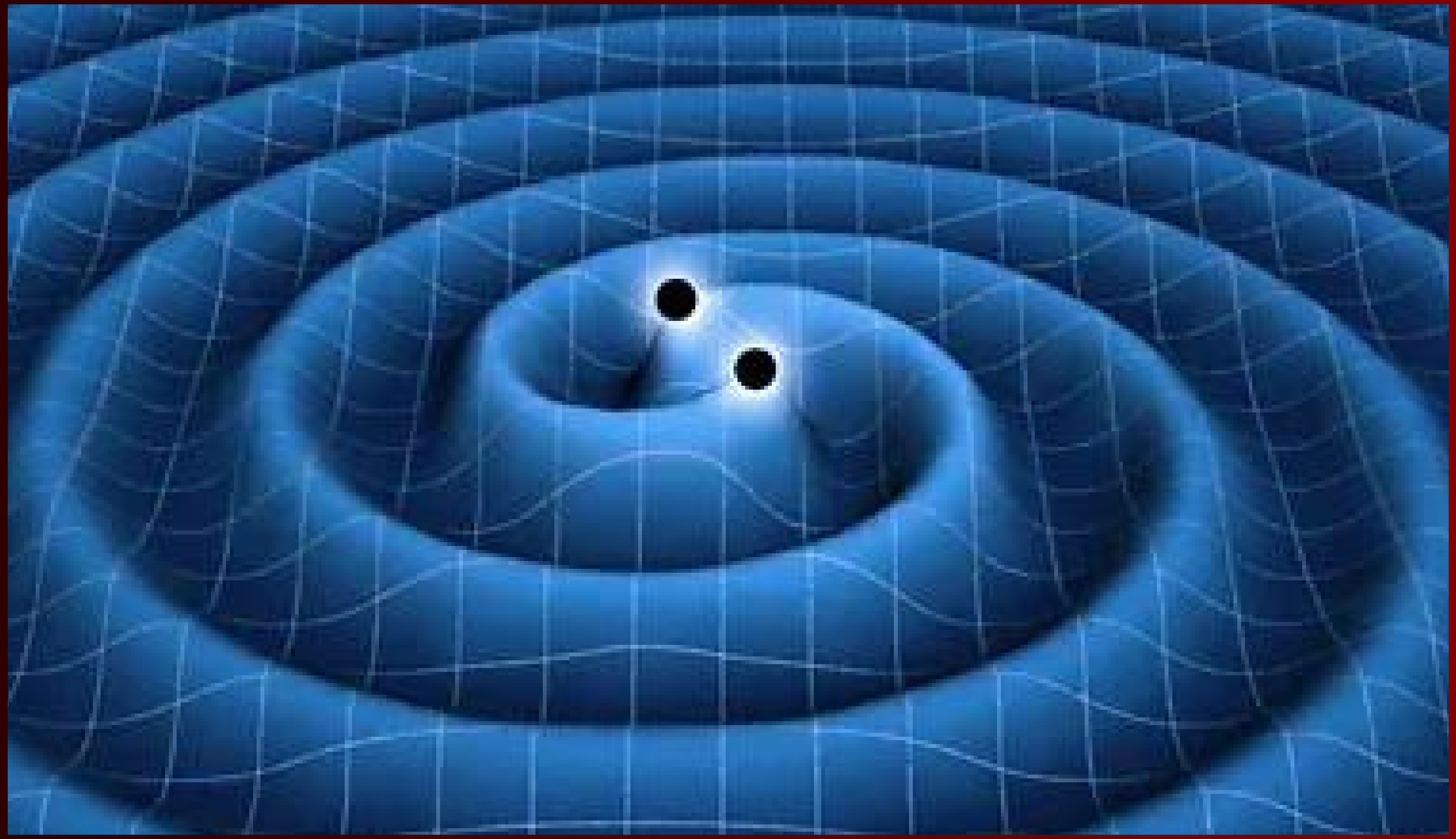
KILONOVAE: MERGER OF TWO NEUTRON STARS OR BLACKHOLES INTO ONE

Neutron stars are one of the universe's most intriguing cosmic objects. (thesis) when A massive star collapses to a supernova explosion, it can form a neutron star or a black hole depending on the mass. They are incredibly dense, with a mass greater than that of our Sun packed into a sphere just a few kilometers wide.



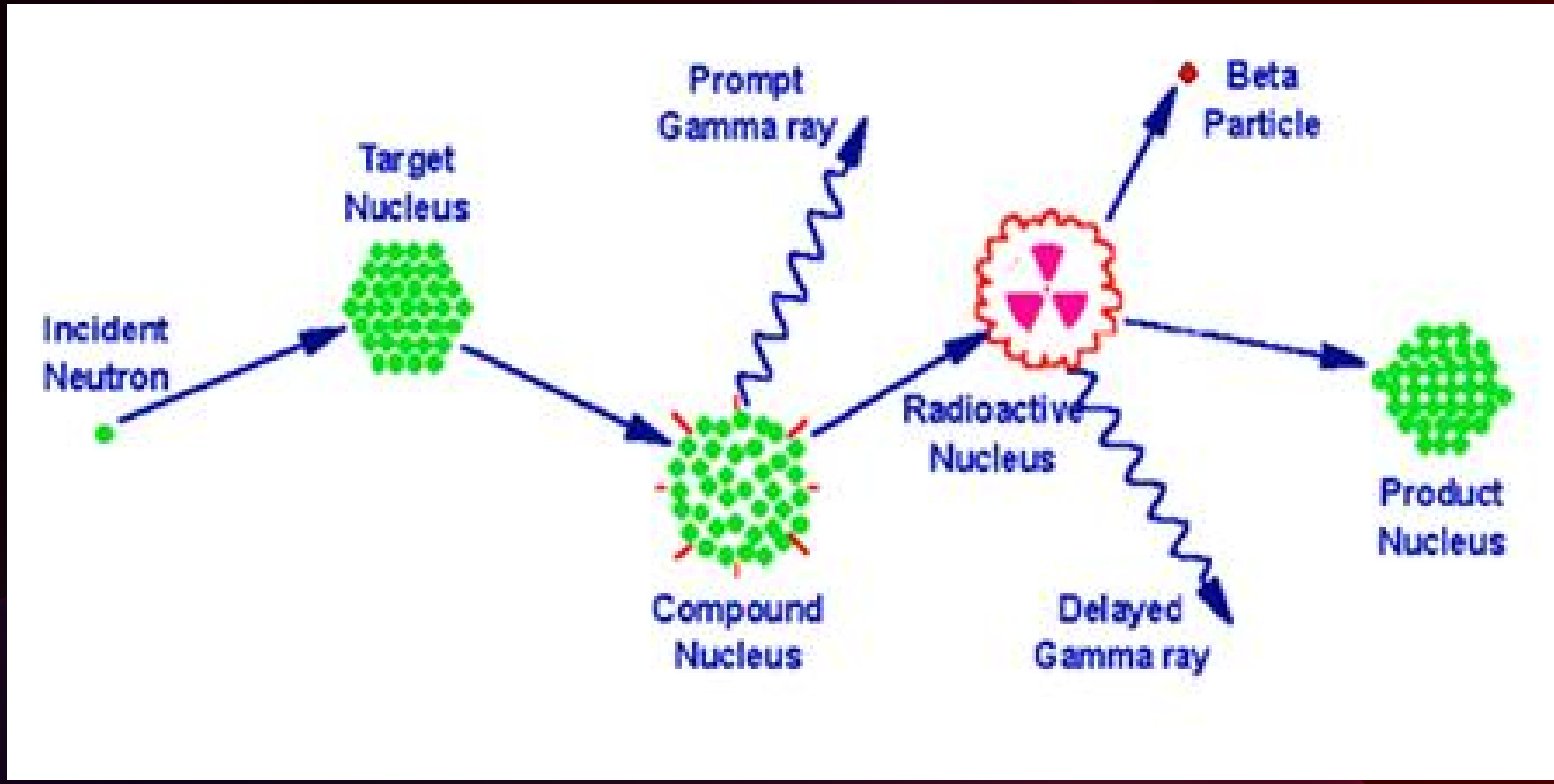
WHAT ARE GRAVITATIONAL WAVES?

Gravitational waves are disturbances in the fabric of spacetime that manifest when mass undergoes acceleration. Greater mass or faster acceleration results in more powerful gravitational waves.



Gravitational waves can be produced by all gravitational systems, but they are typically very faint. Einstein himself doubted the feasibility of detecting these waves due to their weakness. Hence, scientists focus on observing events that generate the most powerful gravitational waves in the universe, such as the merging of compact binaries like black holes or neutron stars, supernova explosions, rapidly rotating neutron stars like pulsars, or the residual gravitational wave background from the Big Bang.

THE R-PROCESS: NEUTRON CAPTURE AND ELEMENT FORMATION IN KILONOVAE



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