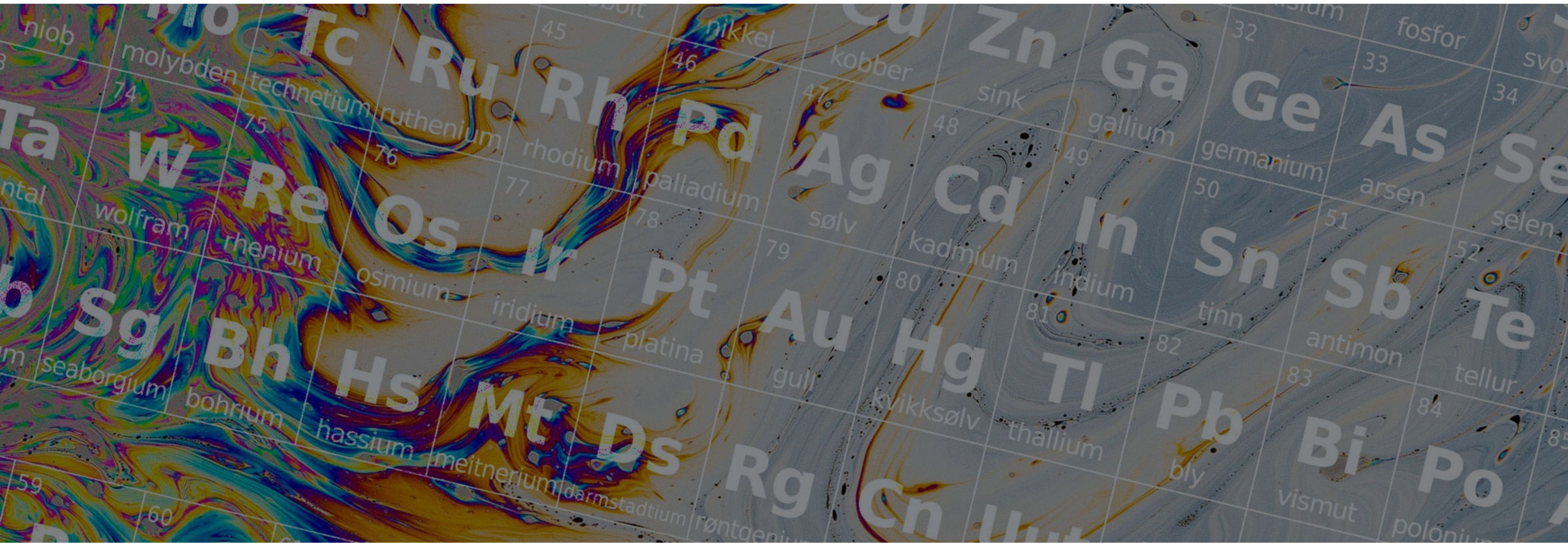
THE ORIGIN OF THE **ELEMENTS**



STEPHEN M. WILKINS
READER IN ASTRONOMY
PUBLIC ENGAGEMENT FELLOW
DIRECTOR OF OUTREACH AND PUBLIC ENGAGEMENT

UNIVERSITY OF SUSSEX

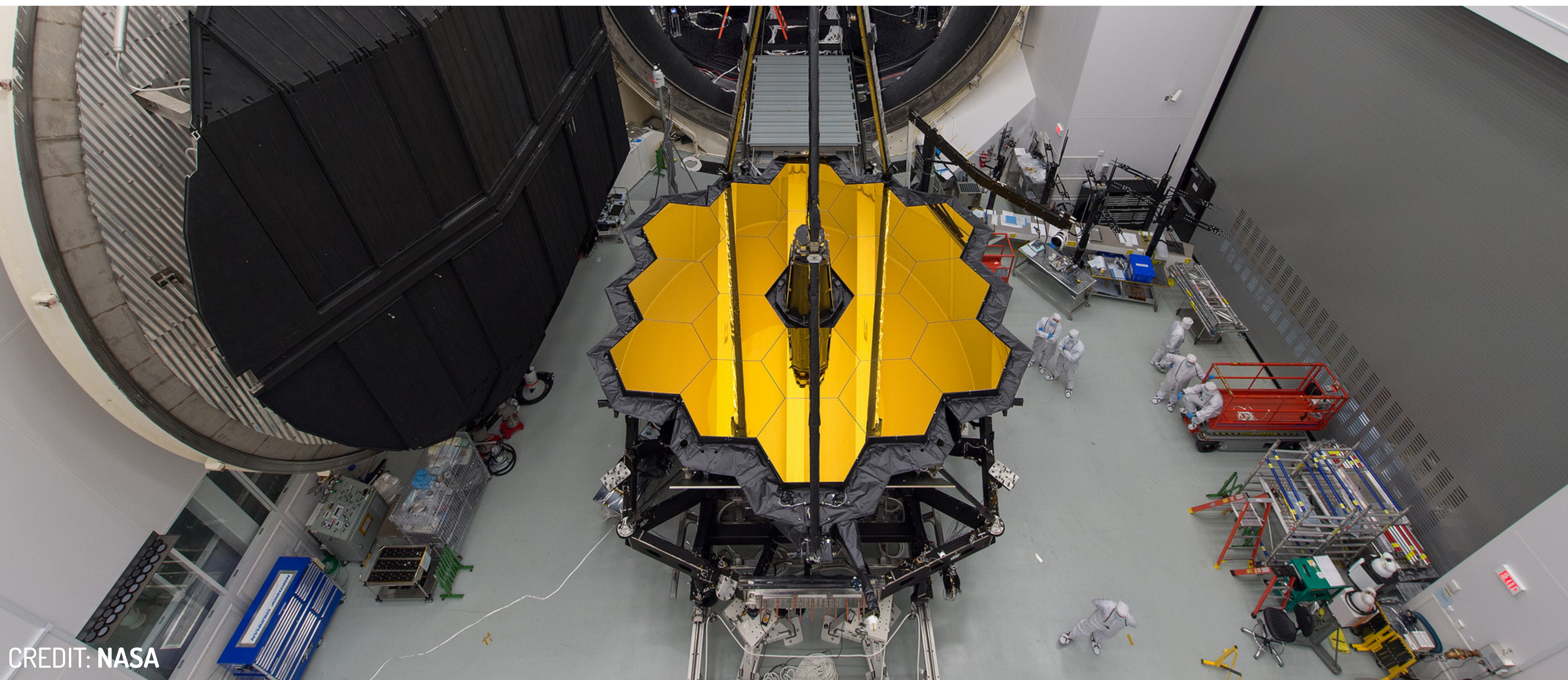
ABOUT ME

- Born in **Leeds, Yorkshire**.
- Undergraduate student in **Physics and Astronomy at the University of Durham**.
- Doctorate (PhD) in **Astronomy at the University of Cambridge**.
- Post-doctoral researcher at the **University of Oxford** (3.5 years).
- Lecturer, then Senior Lecturer, the Reader in Physics and Astronomy at the **University of Sussex**. Currently also Director of Outreach and Public Engagement and STFC Public Engagement Fellow.

ABOUT ME

My research focusses on the first stars and galaxies to form in the Universe. The early Universe is accessible due to the finite speed of light; when we look out into the Universe we are **looking back in time**.

Much of my current work is in preparation for the **Webb Telescope** – the flagship astronomical observatory of NASA/ESA/CSA due to launch in 2021.



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ABOUT THIS TALK

2019 is the 150th anniversary of the **Periodic Table**. The formulation of the Periodic Table was an important milestone in understanding the properties of the elements and ultimately atoms themselves.

In this talk:

- I will give a brief overview of the structure of atoms and how atoms can be **re-arranged** to form new elements.

- I will describe the observed abundances of the elements in the **Solar System**, the **Earth's crust**, and the **human body**.

- I will then describe the various astrophysical processes responsible for producing the elements.

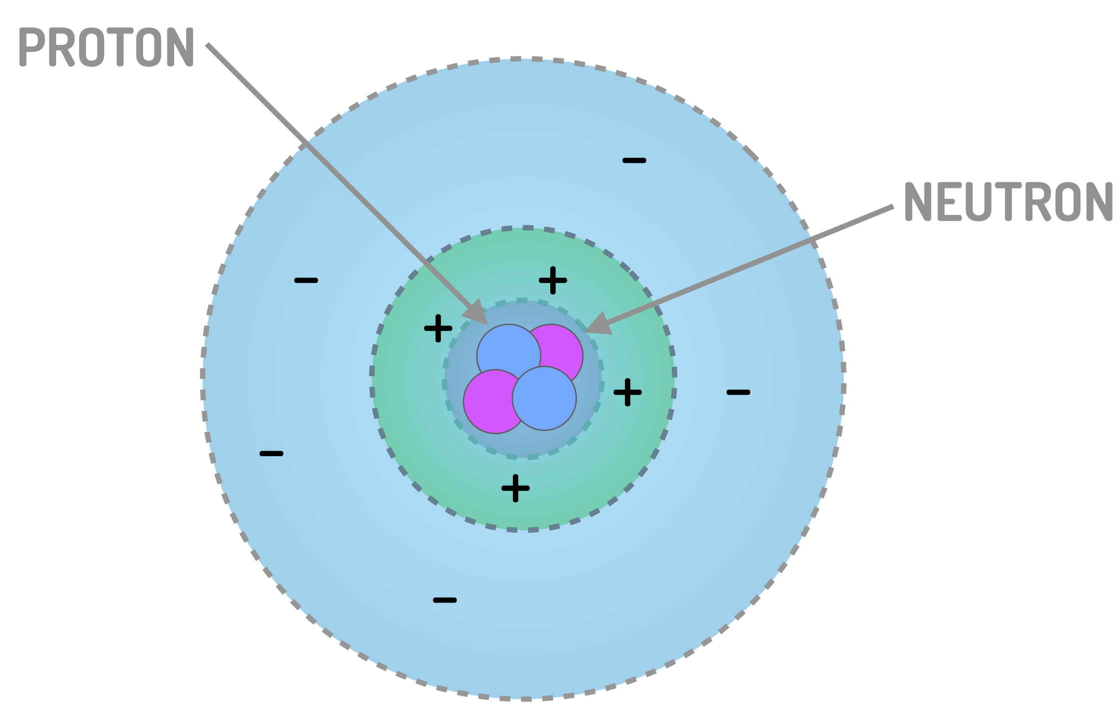
ATOMS

I'll now talk about atoms and how they can be **re-arranged**.

ATOMS

Every atom is composed of a **nucleus**, containing one or more **protons**, and a similar number of **neutrons**. Collectively these are called **nucleons** and they contain more than 99.94% of the atom's mass.

Atoms also have one or more **electrons** bound to the nucleus.



ATOMS: ELEMENTS AND ISOTOPES

Any two atoms with **identical number of protons** in their nuclei belong to the same **chemical element**.

Atoms with the same number of protons but different amounts of neutrons are called **isotopes**.

The common isotopes of hydrogen and helium are:

Isotopes have **similar chemical** and molecular properties but, crucially, different masses and stabilities.

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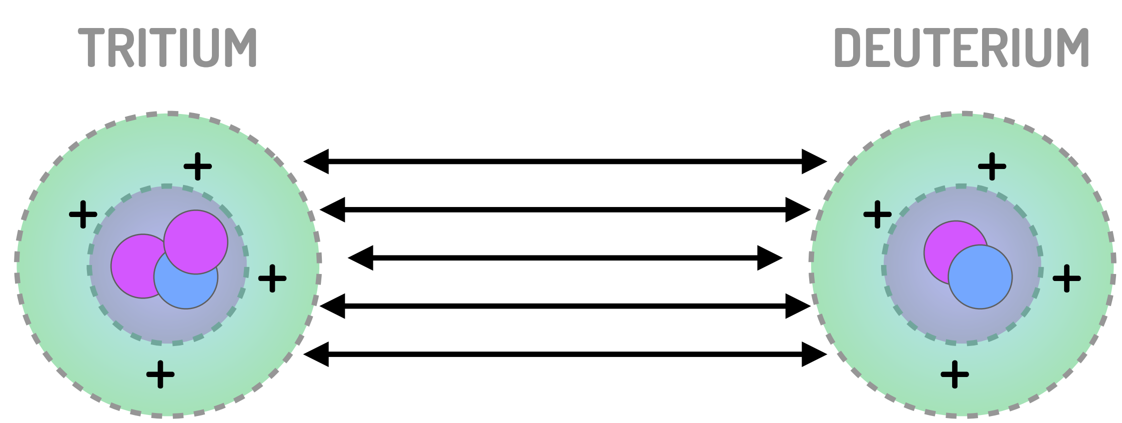
ATOMS: RE-ARRANGING ATOMS

Atoms can be **re-arranged** through several processes.

ATOMS: RE-ARRANGING ATOMS: FUSION

Nuclear **fusion** is the reaction where two nuclei are combined to form a heavier nuclei, often also producing energy.

To fuse atomic nuclei must have sufficient energy to overcome the **repulsive electrostatic force** between the two nuclei. This requires high temperatures.



Fusion of tritium and deuterium to form Helium-4 and a free proton (and energy)

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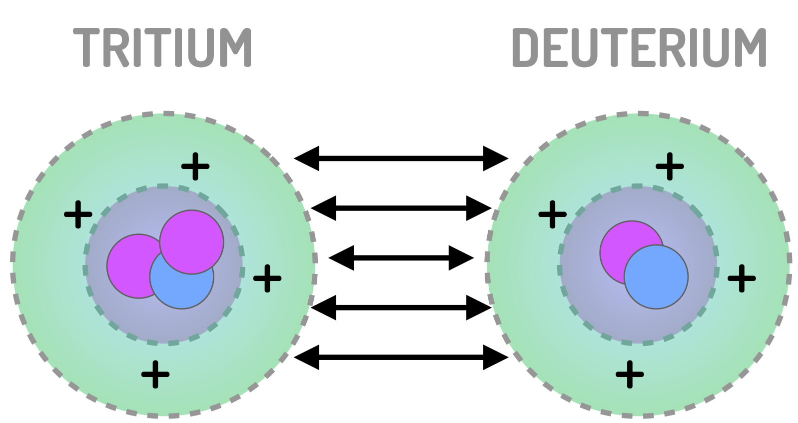

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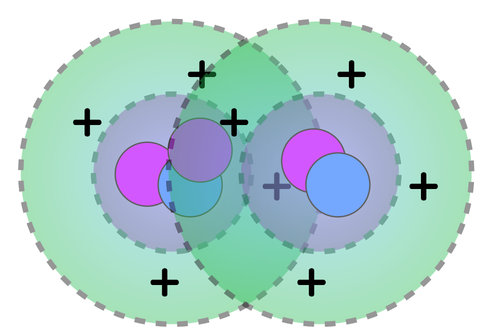

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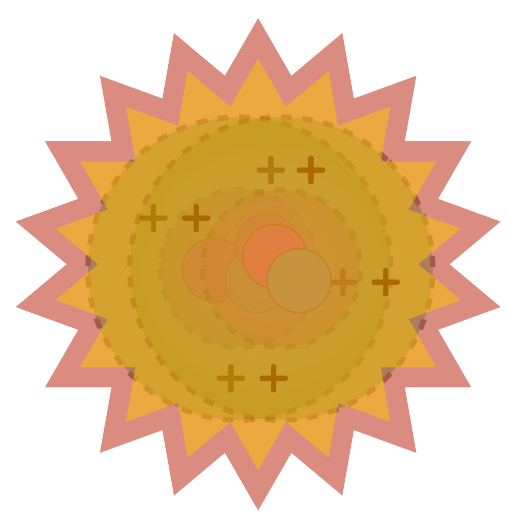

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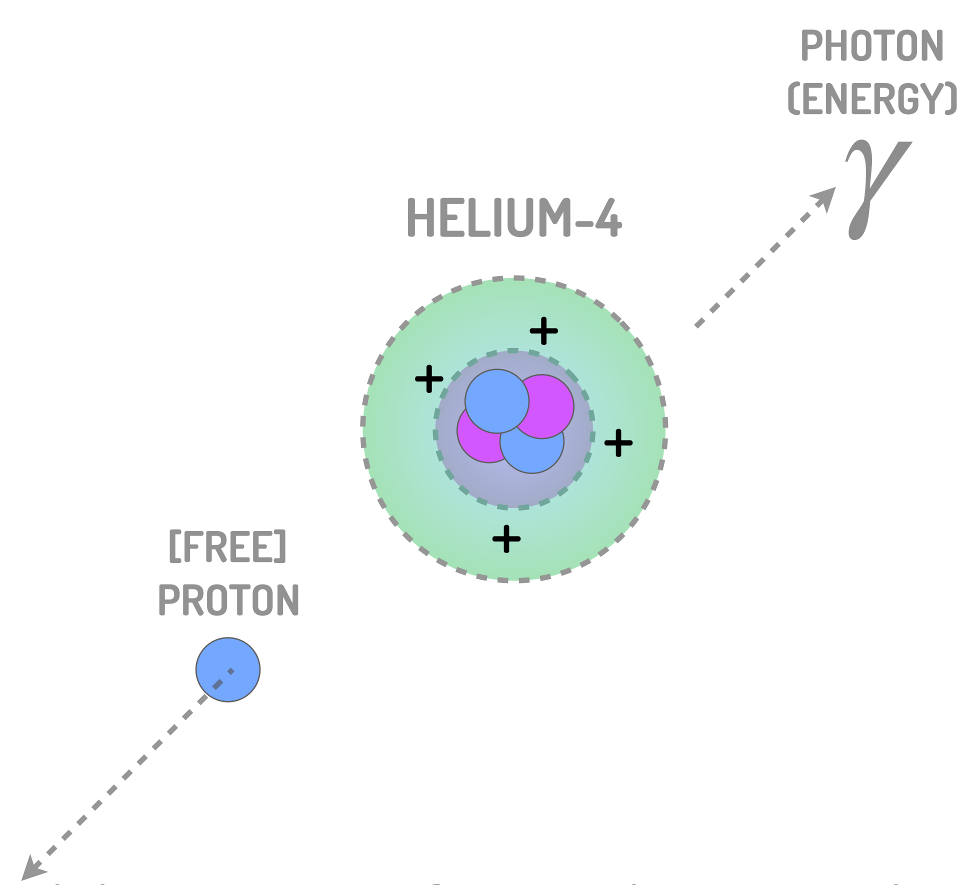
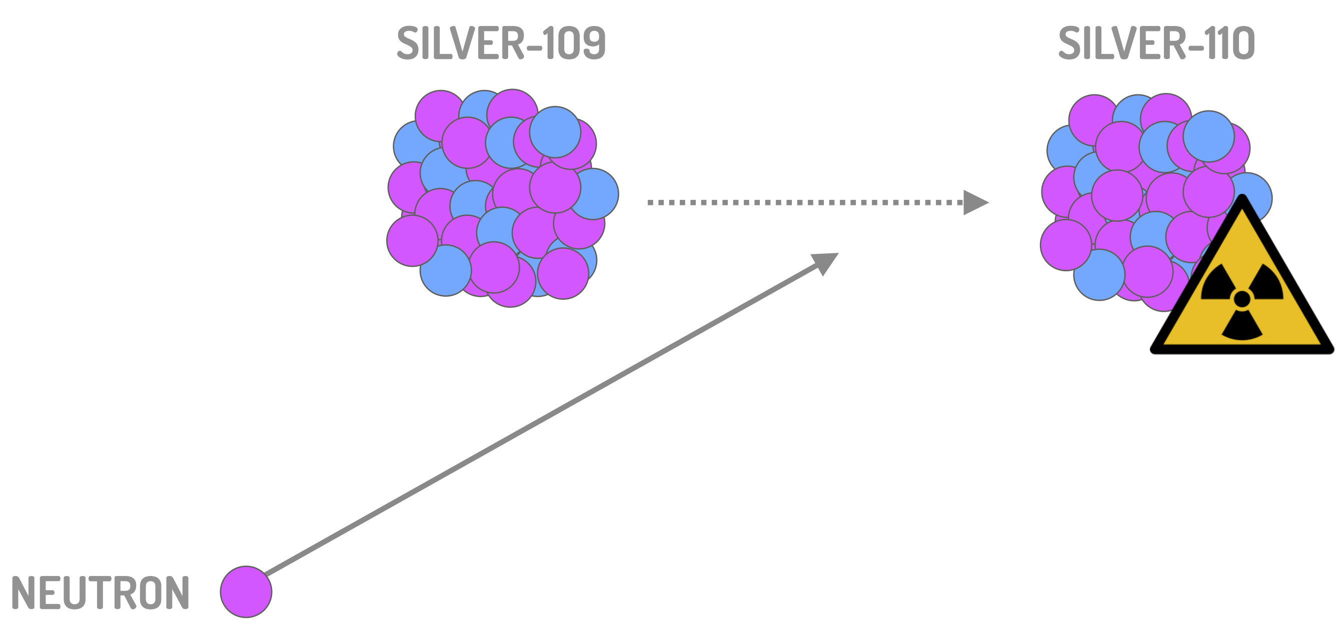


Fusion of tritium and deuterium to form Helium-4 and a free proton (and energy)

ATOMS: RE-ARRANGING ATOMS: NEUTRON CAPTURE

Nuclei can also **capture neutrons**.

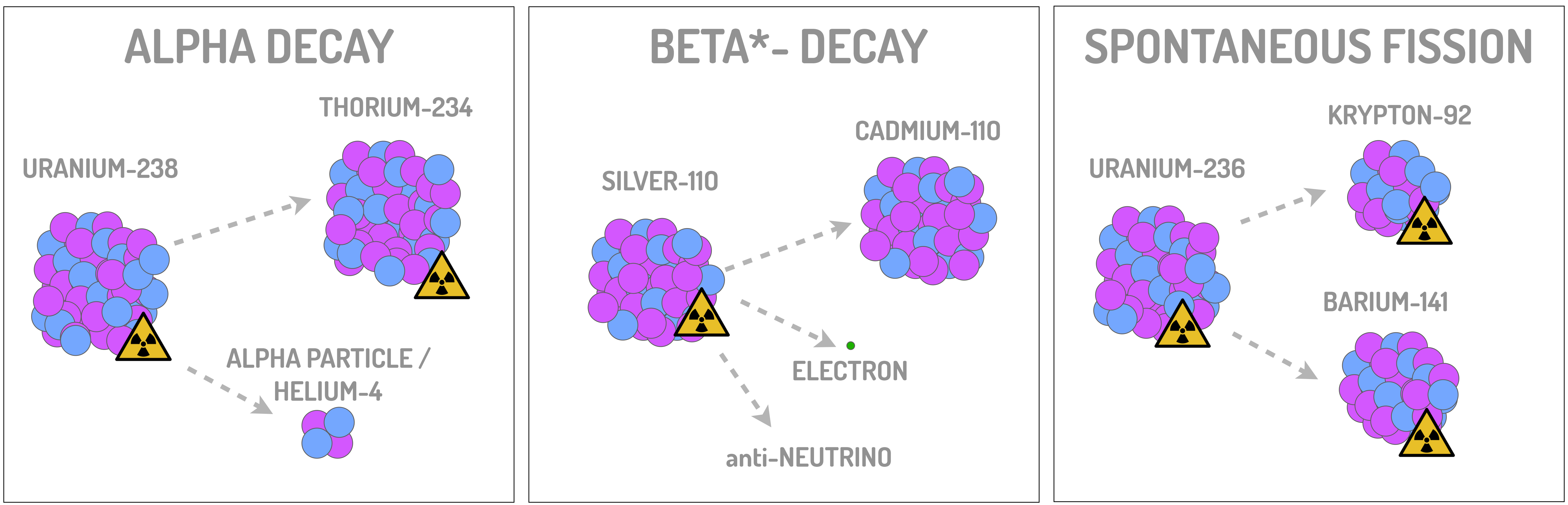
This is important in nuclear reactors but, as we'll see, it is also crucial to explain much of the periodic table.



ATOMS: RE-ARRANGING ATOMS: DECAY

Atoms can also disintegrate, or **decay**.

There are several types of decay, though the most prominent are **alpha-decay**, **beta-decay**, and **spontaneous fission**:



*beta decay itself comes in several flavours.

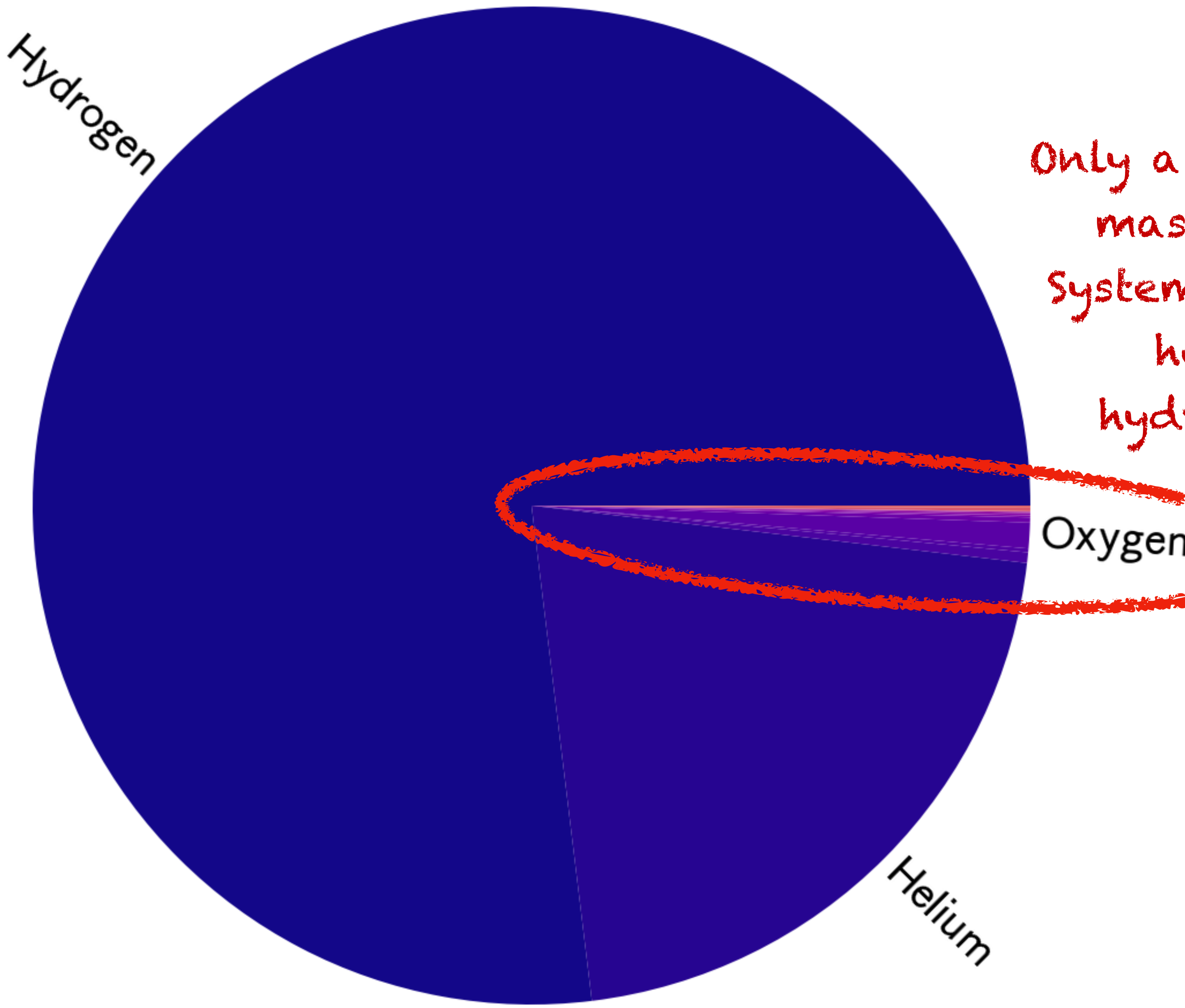
ABUNDANCES

I’ll now talk about the abundance of each element in the **Universe**, the **Earth’s crust**, and in **human bodies**.

ABUNDANCES: ~~THE UNIVERSE~~

actually, the Solar System

Difficult to do for the Universe, as it depends "when" you look



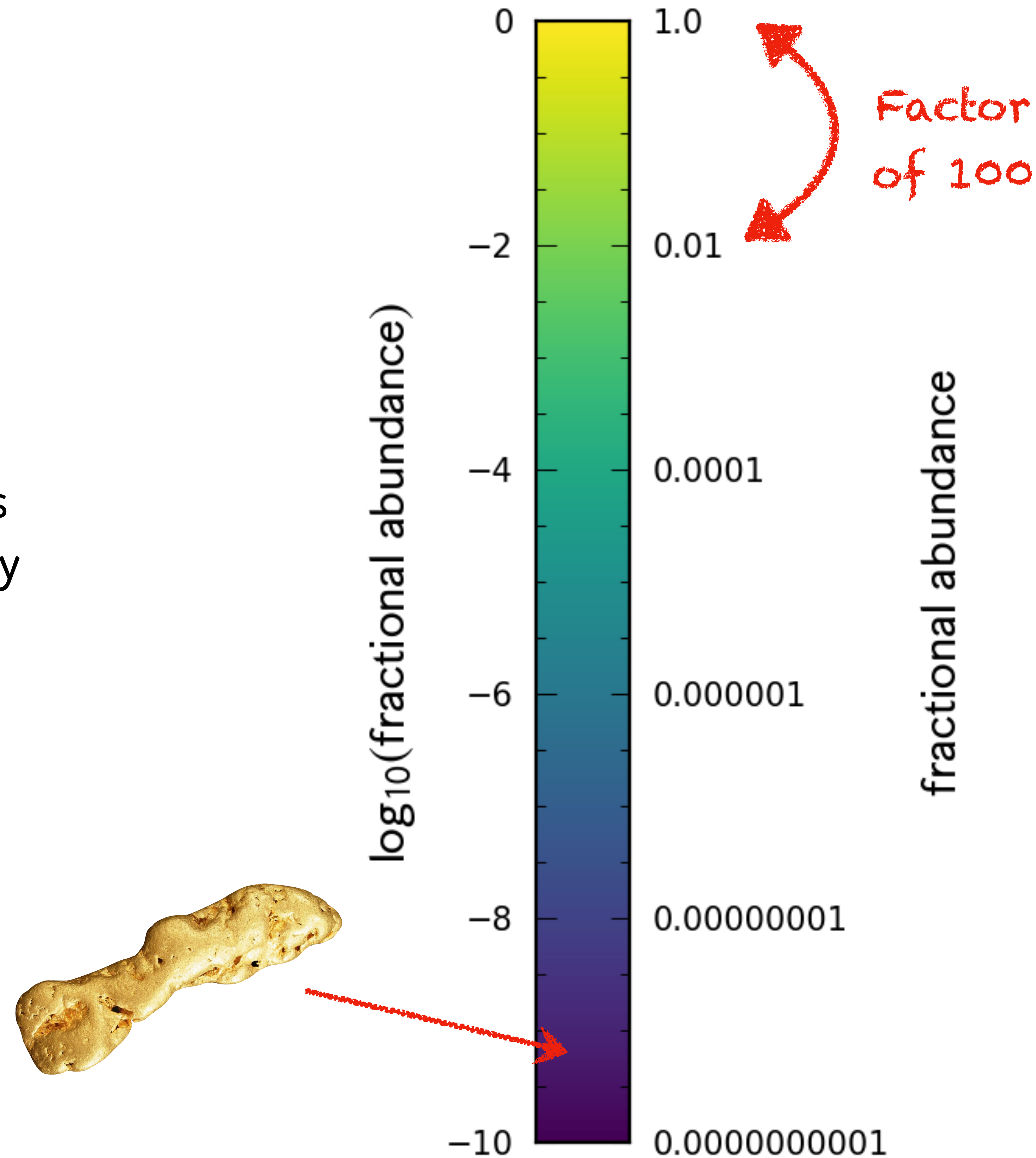
Only a couple % of the mass in the Solar System is in elements heavier than hydrogen/helium

Each element/segment is colour coded by its **mass**.

ABUNDANCES: ~~THE UNIVERSE~~

actually, the Solar System

I'm going to denote **abundance by colour on a logarithmic scale**. This allows us to compare large and very small abundances.



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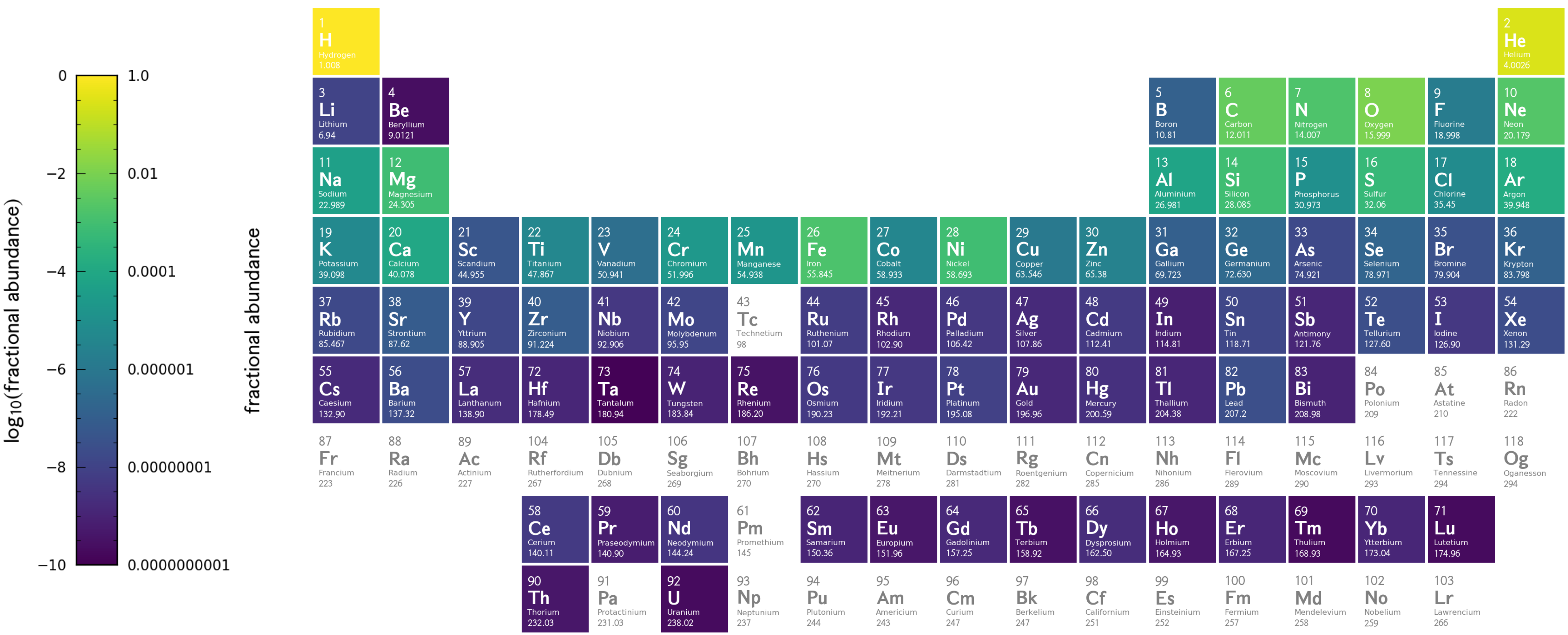
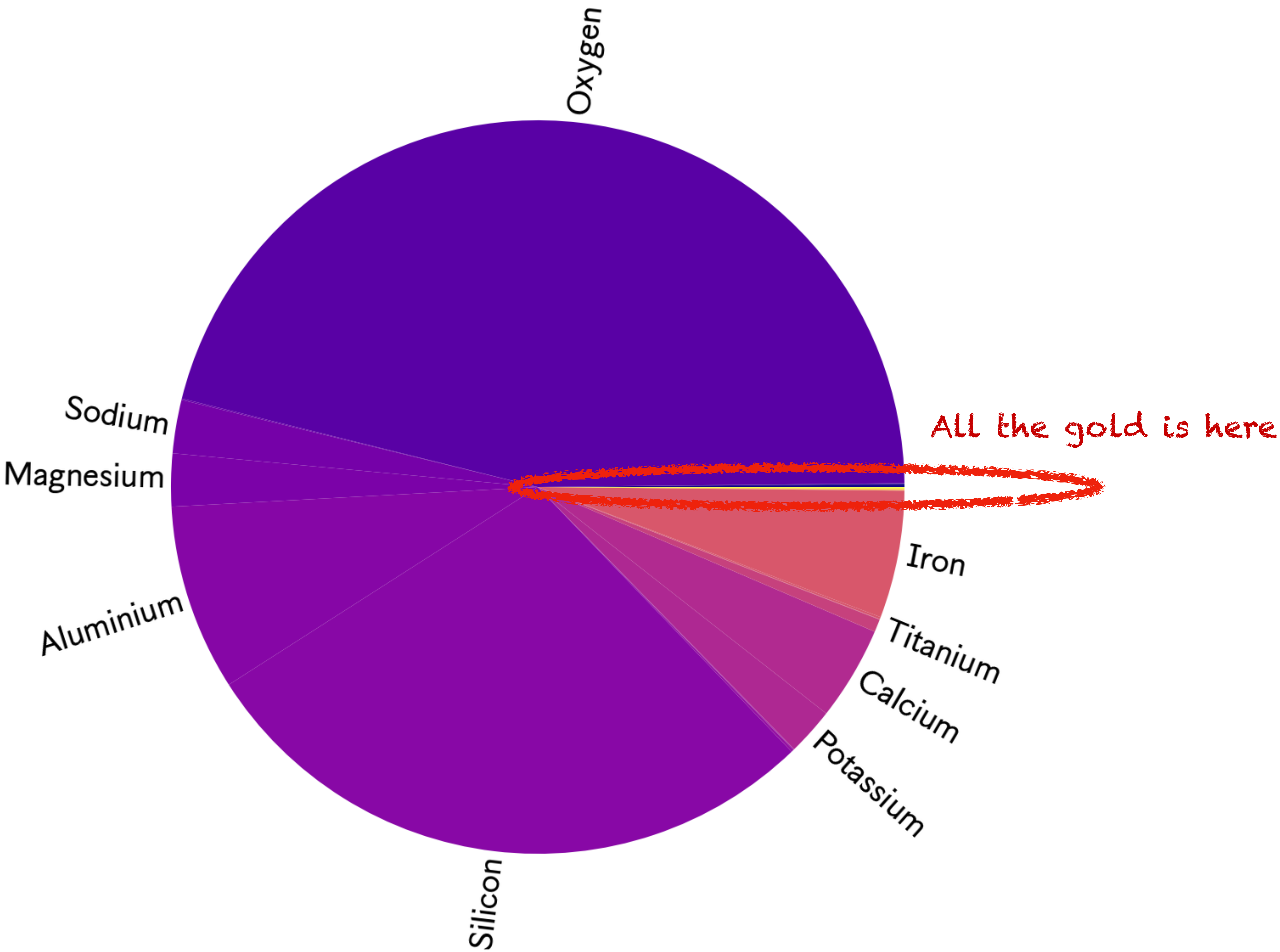
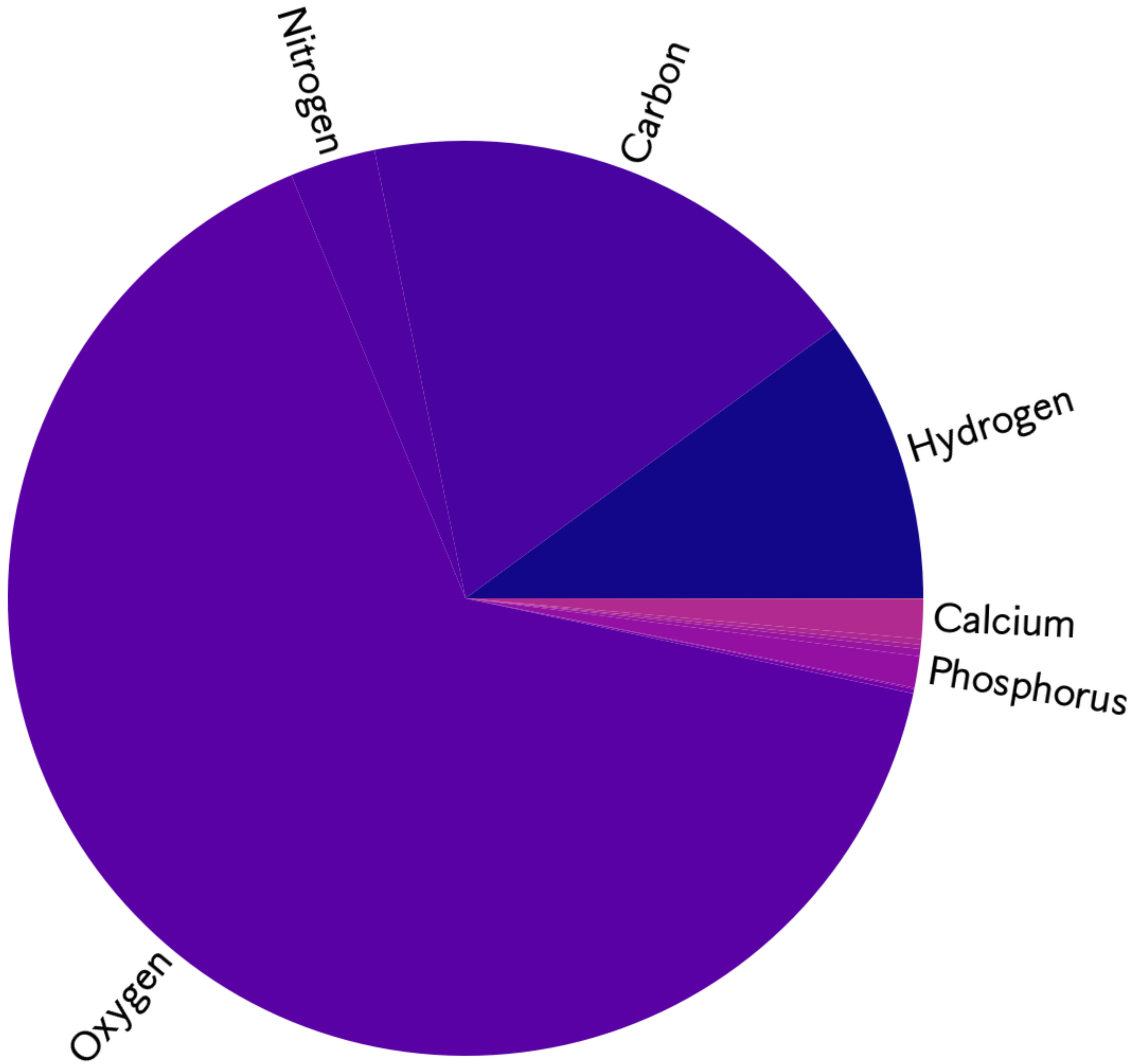


ABUNDANCES: THE EARTH'S CRUST



ABUNDANCES: THE EARTH'S CRUST

ABUNDANCES: HUMANS



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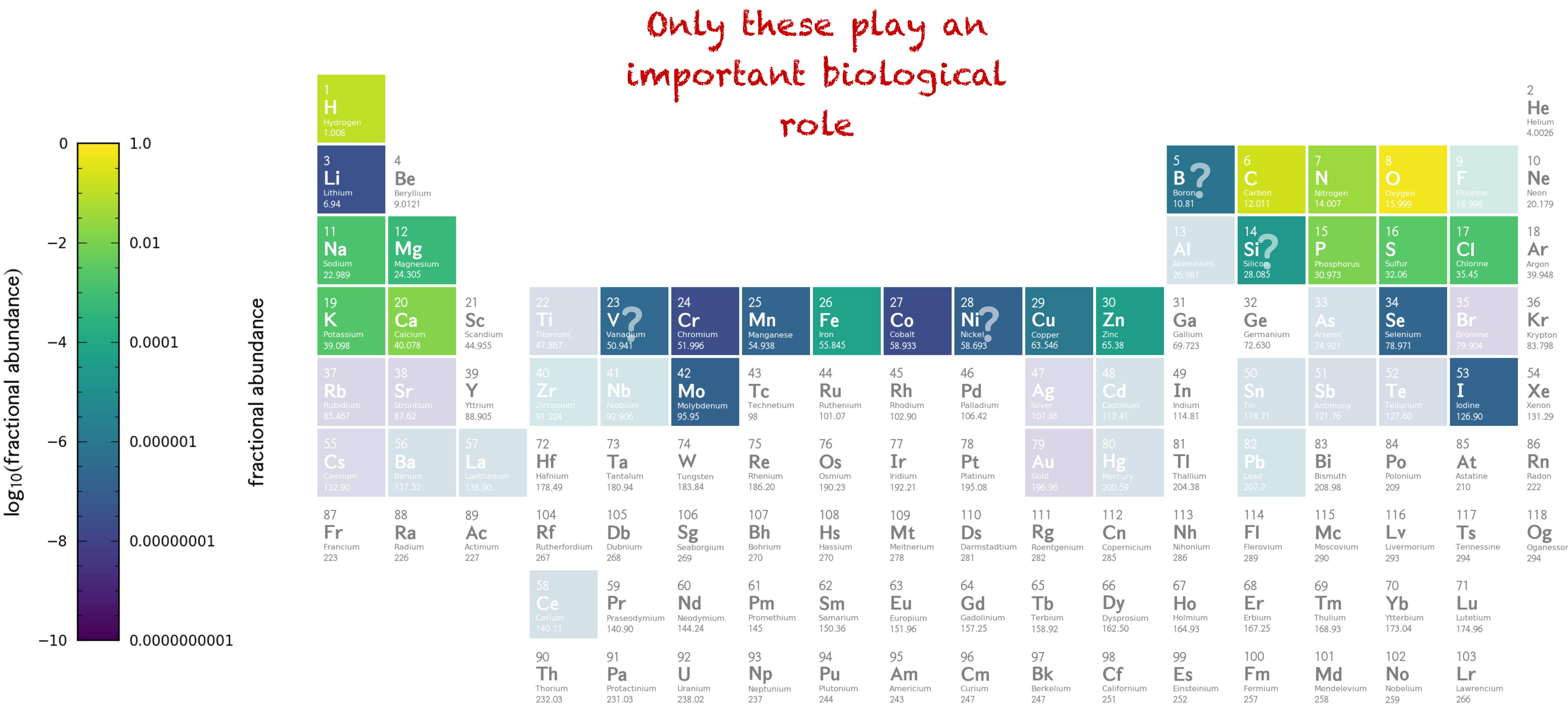
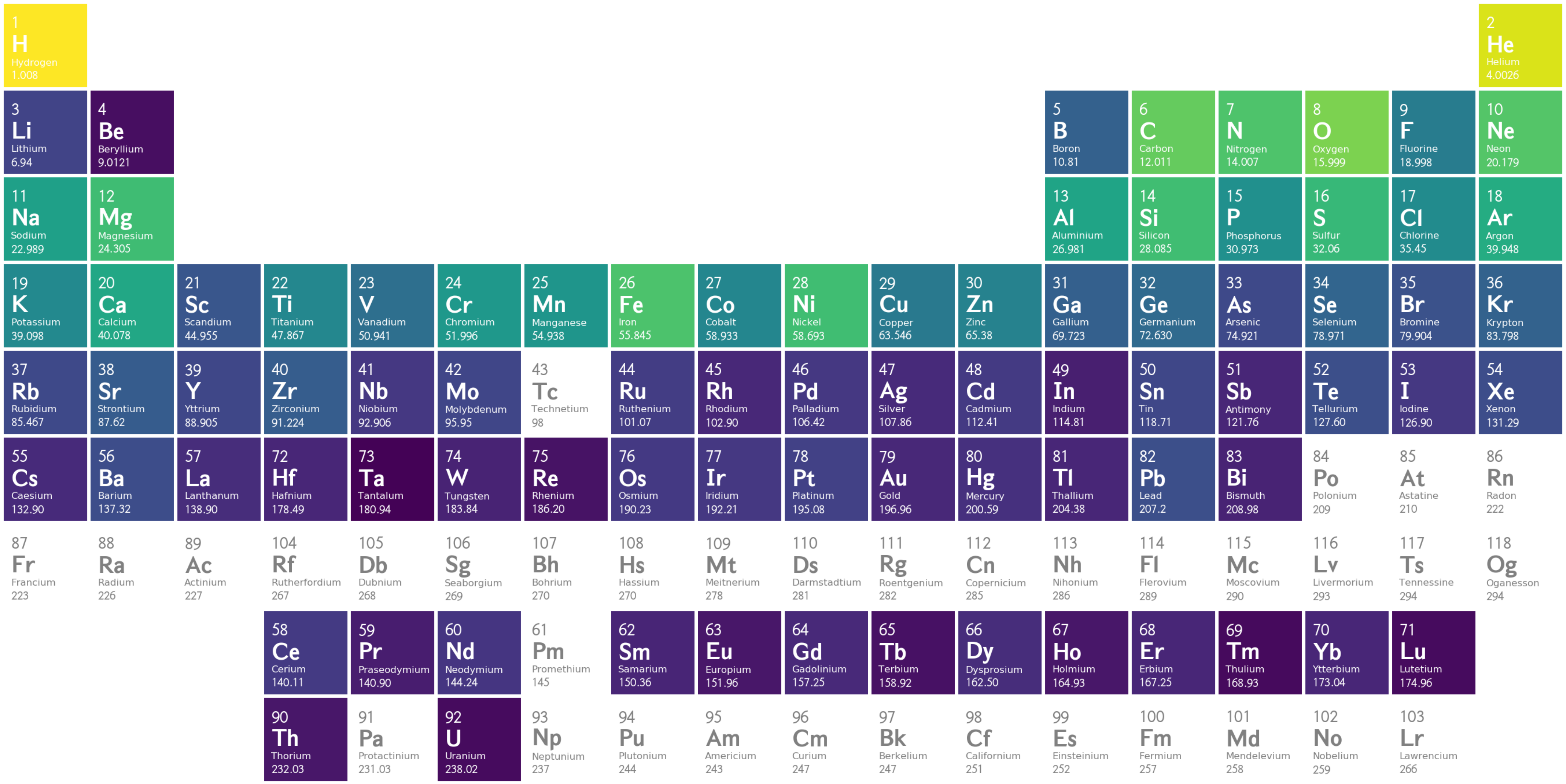


ORIGINS

I'll now talk about the astrophysical processes responsible for the formation of the elements.

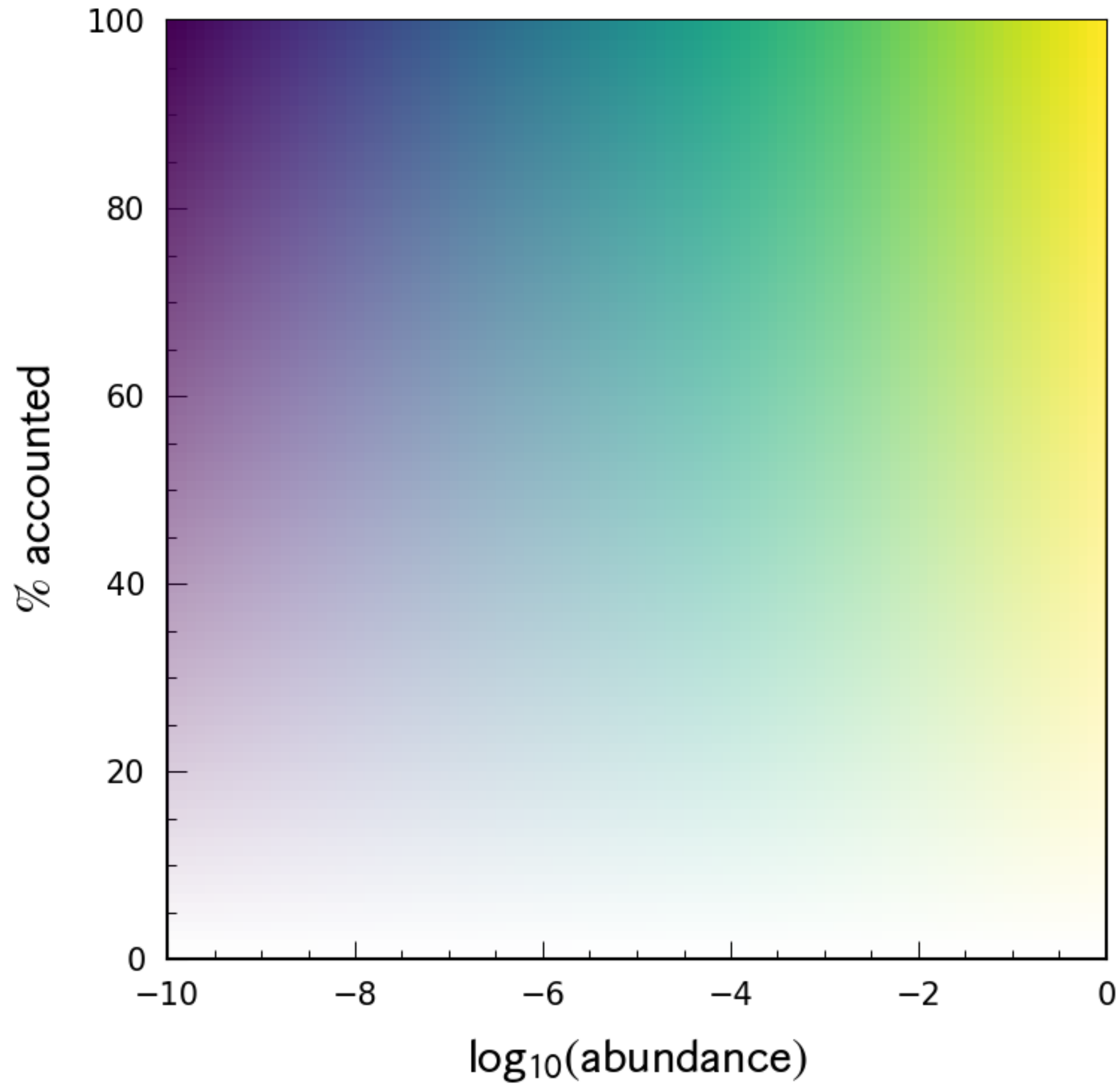
ORIGINS



The periodic table colour coded by elemental abundance in the Solar System.

ABUNDANCES AND ACCOUNTED FRACTION

As well as using colour for abundance I'm going to use **opacity to denote the fraction we've accounted for so far**.



ORIGINS: BIG BANG NUCLEOSYNTHESIS

In the **first ~10 seconds** of the Universe's history it was **so hot** that atomic nuclei could not form without almost immediately being broken apart.

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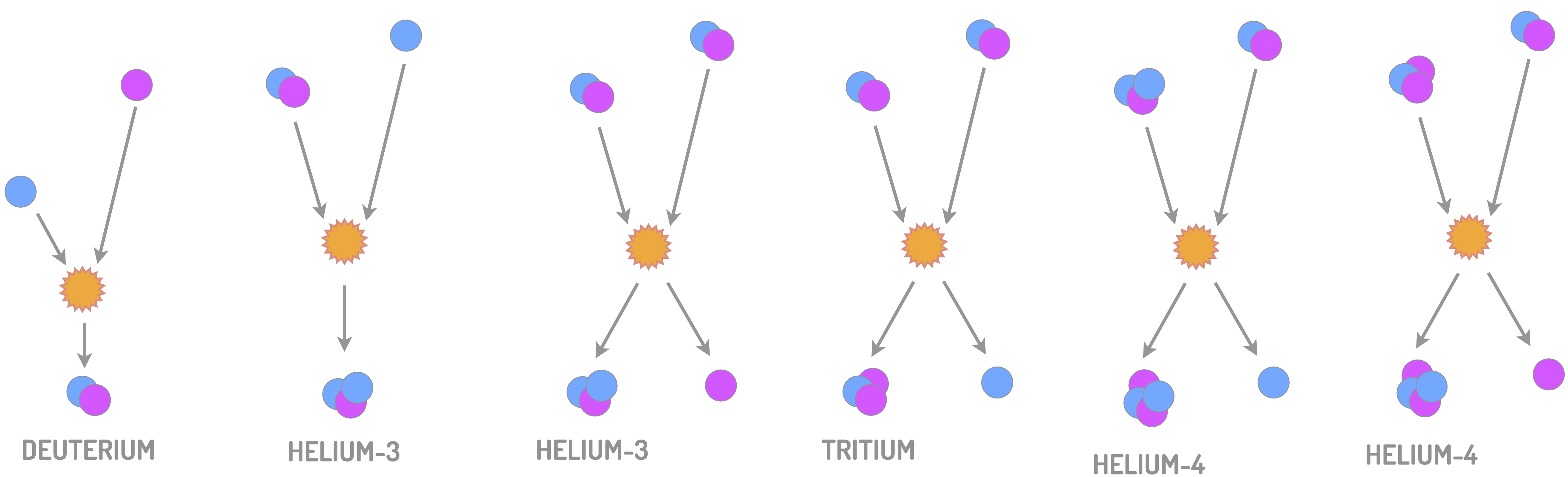
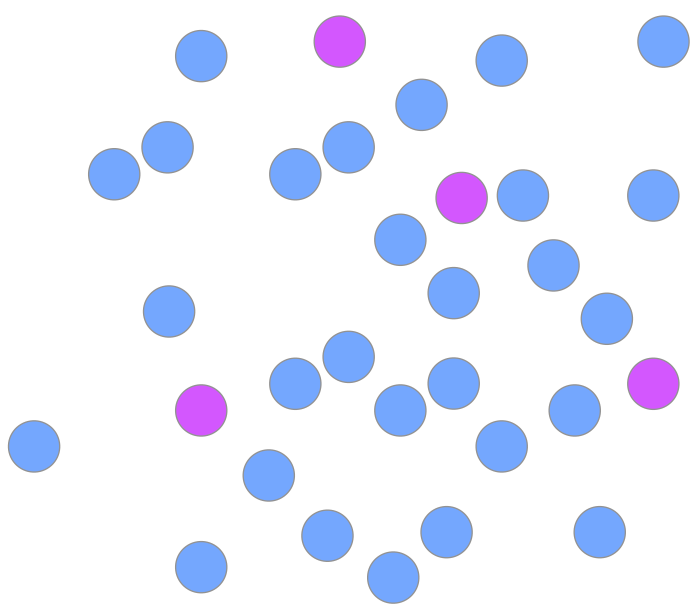
As the Universe expanded it **cooled**. Eventually nuclei could form without being immediately broken apart.



ORIGINS: BIG BANG NUCLEOSYNTHESIS

Over the next 20 minutes almost all of the neutrons present in the Universe are locked into **helium-4**.

Because there were fewer neutrons than protons present not all of the protons went to form helium-4, instead they remain as hydrogen-1.



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ORIGINS: BIG BANG NUCLEOSYNTHESIS

BBN accounts for virtually all the H and He in the Universe, and a bit of Li

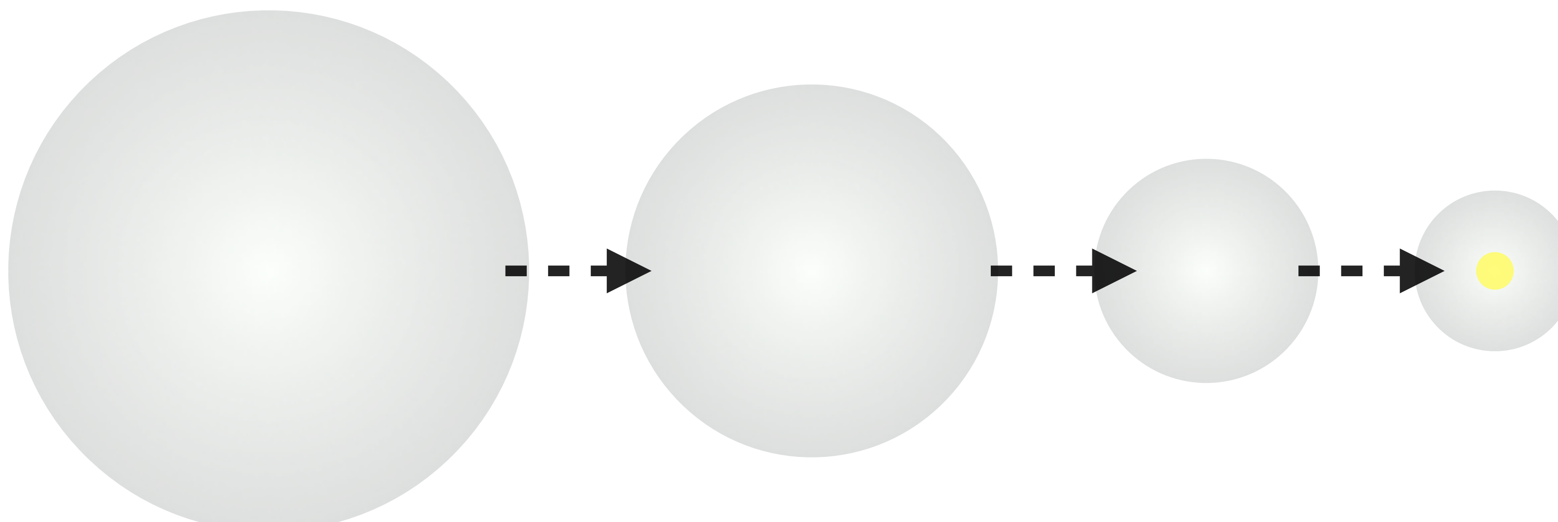
1 H Hydrogen 1.008																	2 He Helium 4.0026
3 Li Lithium 6.94	4 Be Beryllium 9.0121											5 B Boron 10.81	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.179
11 Na Sodium 22.989	12 Mg Magnesium 24.305											13 Al Aluminium 26.981	14 Si Silicon 28.085	15 P Phosphorus 30.973	16 S Sulfur 32.06	17 Cl Chlorine 35.45	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.955	22 Ti Titanium 47.867	23 V Vanadium 50.941	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.630	33 As Arsenic 74.921	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 83.798
37 Rb Rubidium 85.467	38 Sr Strontium 87.62	39 Y Yttrium 88.905	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90	46 Pd Palladium 106.42	47 Ag Silver 107.86	48 Cd Cadmium 112.41	49 In Indium 114.81	50 Sn Tin 118.71	51 Sb Antimony 121.76	52 Te Tellurium 127.60	53 I Iodine 126.90	54 Xe Xenon 131.29
55 Cs Caesium 132.90	56 Ba Barium 137.32	57 La Lanthanum 138.90	72 Hf Hafnium 178.49	73 Ta Tantalum 180.94	74 W Tungsten 183.84	75 Re Rhenium 186.20	76 Os Osmium 190.23	77 Ir Iridium 192.21	78 Pt Platinum 195.08	79 Au Gold 196.96	80 Hg Mercury 200.59	81 Tl Thallium 204.38	82 Pb Lead 207.2	83 Bi Bismuth 208.98	84 Po Polonium 209	85 At Astatine 210	86 Rn Radon 222
87 Fr Francium 223	88 Ra Radium 226	89 Ac Actinium 227	104 Rf Rutherfordium 267	105 Db Dubnium 268	106 Sg Seaborgium 269	107 Bh Bohrium 270	108 Hs Hassium 270	109 Mt Meitnerium 278	110 Ds Darmstadtium 281	111 Rg Roentgenium 282	112 Cn Copernicium 285	113 Nh Nihonium 286	114 Fl Flerovium 289	115 Mc Moscovium 290	116 Lv Livermorium 293	117 Ts Tennessine 294	118 Og Oganesson 294
			58 Ce Cerium 140.11	59 Pr Praseodymium 140.90	60 Nd Neodymium 144.24	61 Pm Promethium 145	62 Sm Samarium 150.36	63 Eu Europium 151.96	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93	68 Er Erbium 167.25	69 Tm Thulium 168.93	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.96	
			90 Th Thorium 232.03	91 Pa Protactinium 231.03	92 U Uranium 238.02	93 Np Neptunium 237	94 Pu Plutonium 244	95 Am Americium 243	96 Cm Curium 247	97 Bk Berkelium 247	98 Cf Californium 251	99 Es Einsteinium 252	100 Fm Fermium 257	101 Md Mendelevium 258	102 No Nobelium 259	103 Lr Lawrencium 266	

ORIGINS: STAR FORMATION

CREDIT: **NASA**

ORIGINS: STAR FORMATION

Long story short...



Clouds of gas collapse to form objects in the cores of which nuclear fusion is able to occur.

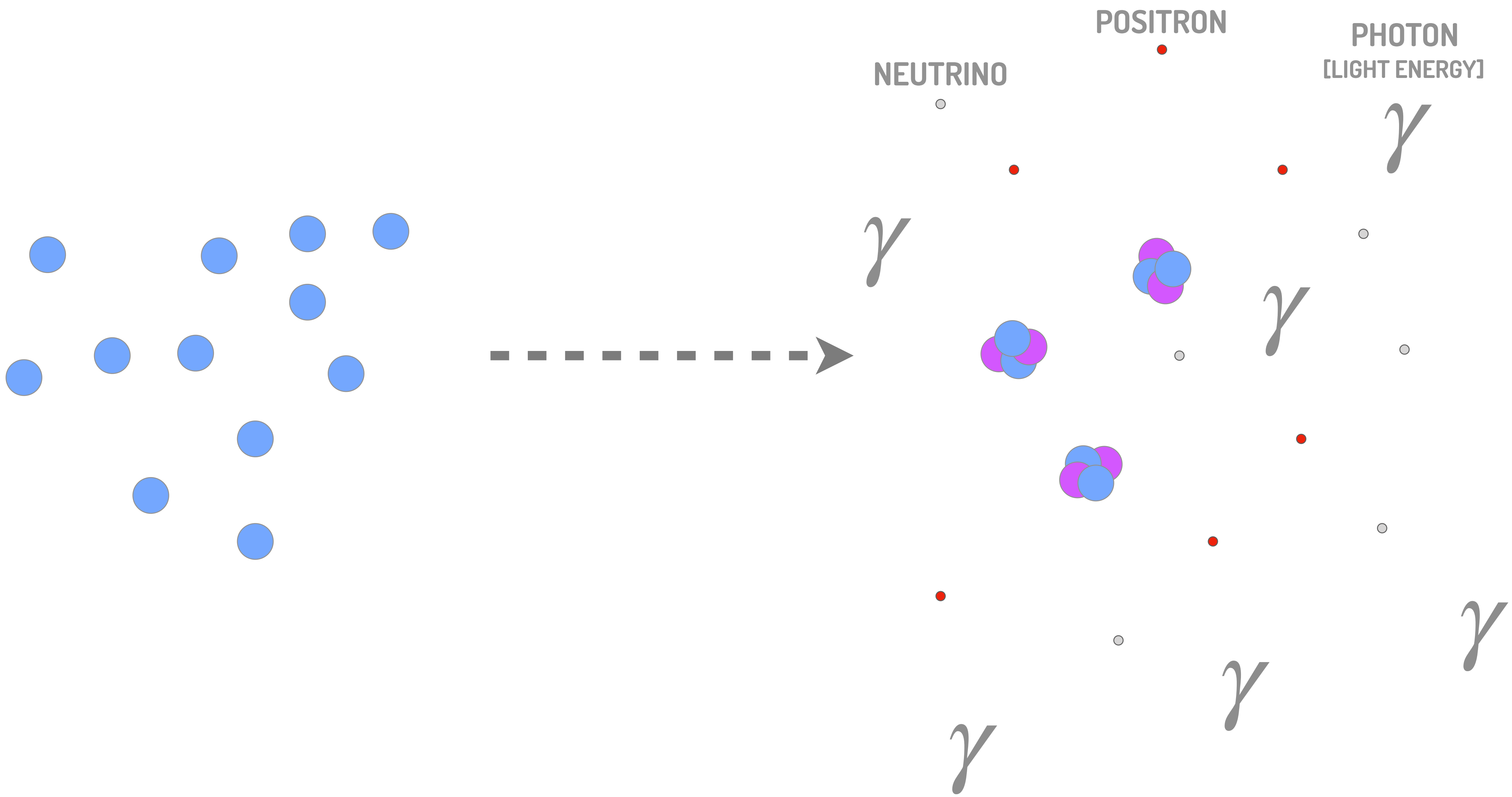
This produces a source of energy which halts subsequent collapse of the object and thus producing **a star**.

ORIGINS: STAR FORMATION

CREDIT: **ESO**

ORIGINS: STELLAR NUCLEOSYNTHESIS

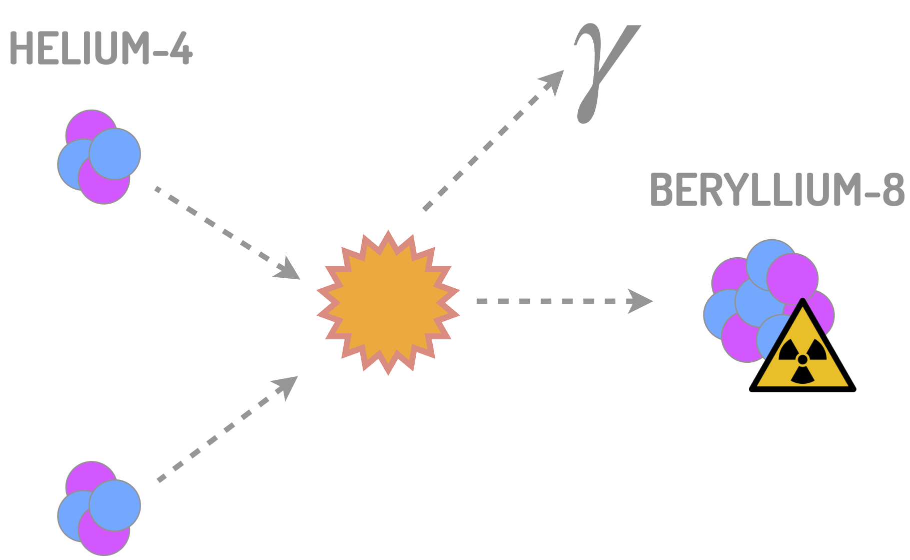
For most of star's lifetime it fuses hydrogen to produce helium (and energy).



ORIGINS: STELLAR NUCLEOSYNTHESIS

For most of star's lifetime it fuses hydrogen to produce helium (and energy).

Eventually the star runs out of core hydrogen. Fusing helium is tricky for two reasons: helium is <u>hard to fuse</u> and the initial fusion product is **<u>unstable</u>**.



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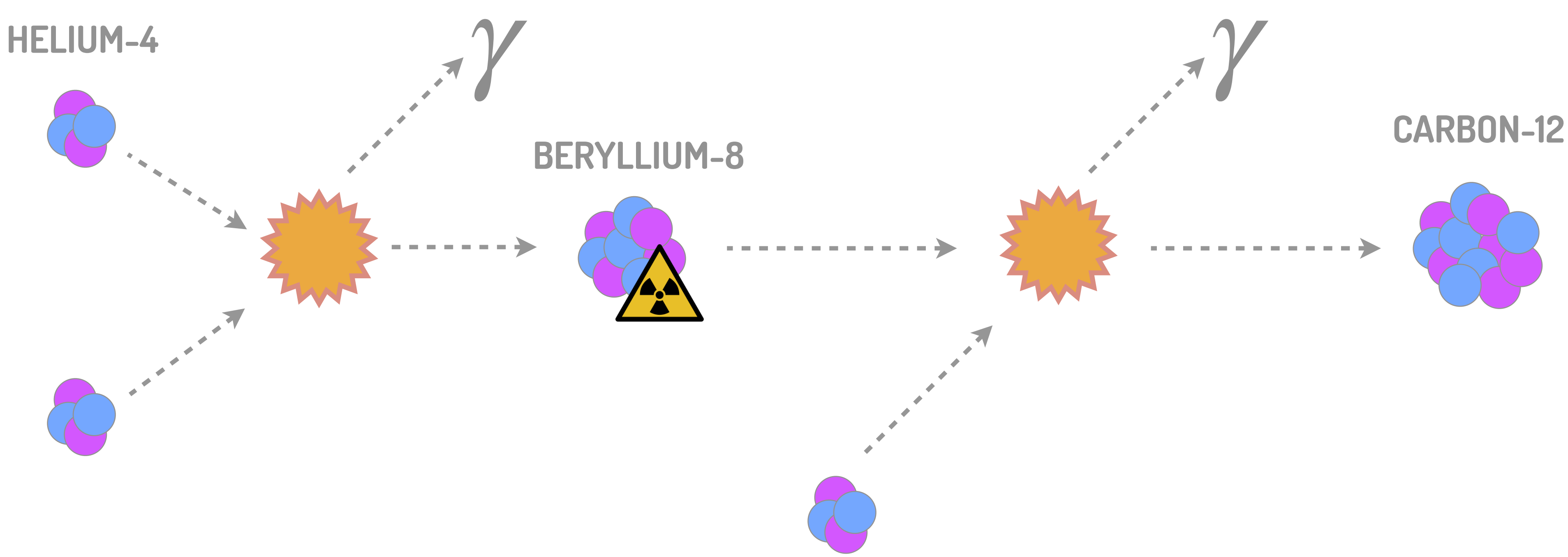
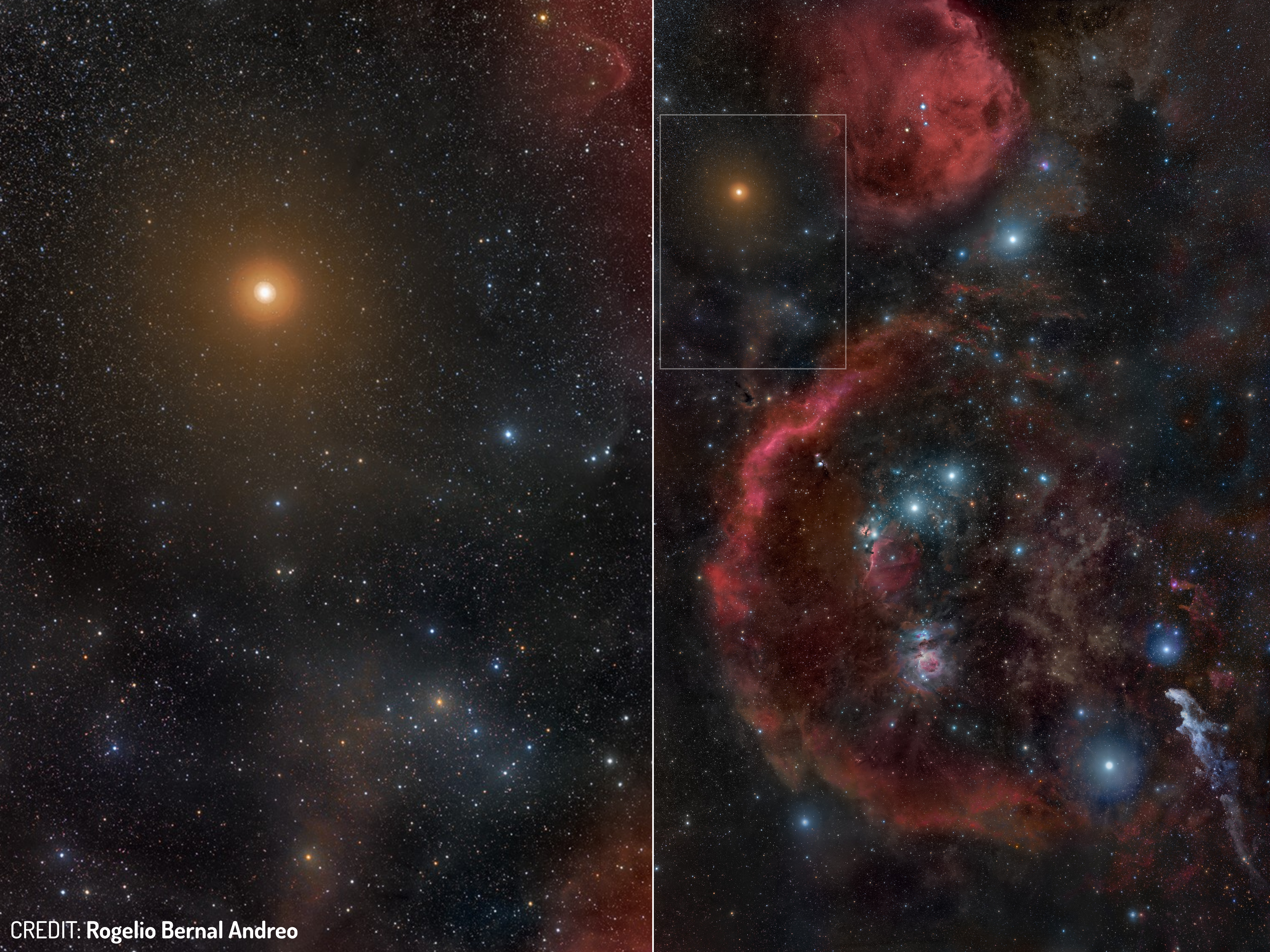
Eventually the star runs out of core hydrogen. Fusing helium is tricky for two reasons: helium is hard to fuse and the initial fusion product is **unstable**.

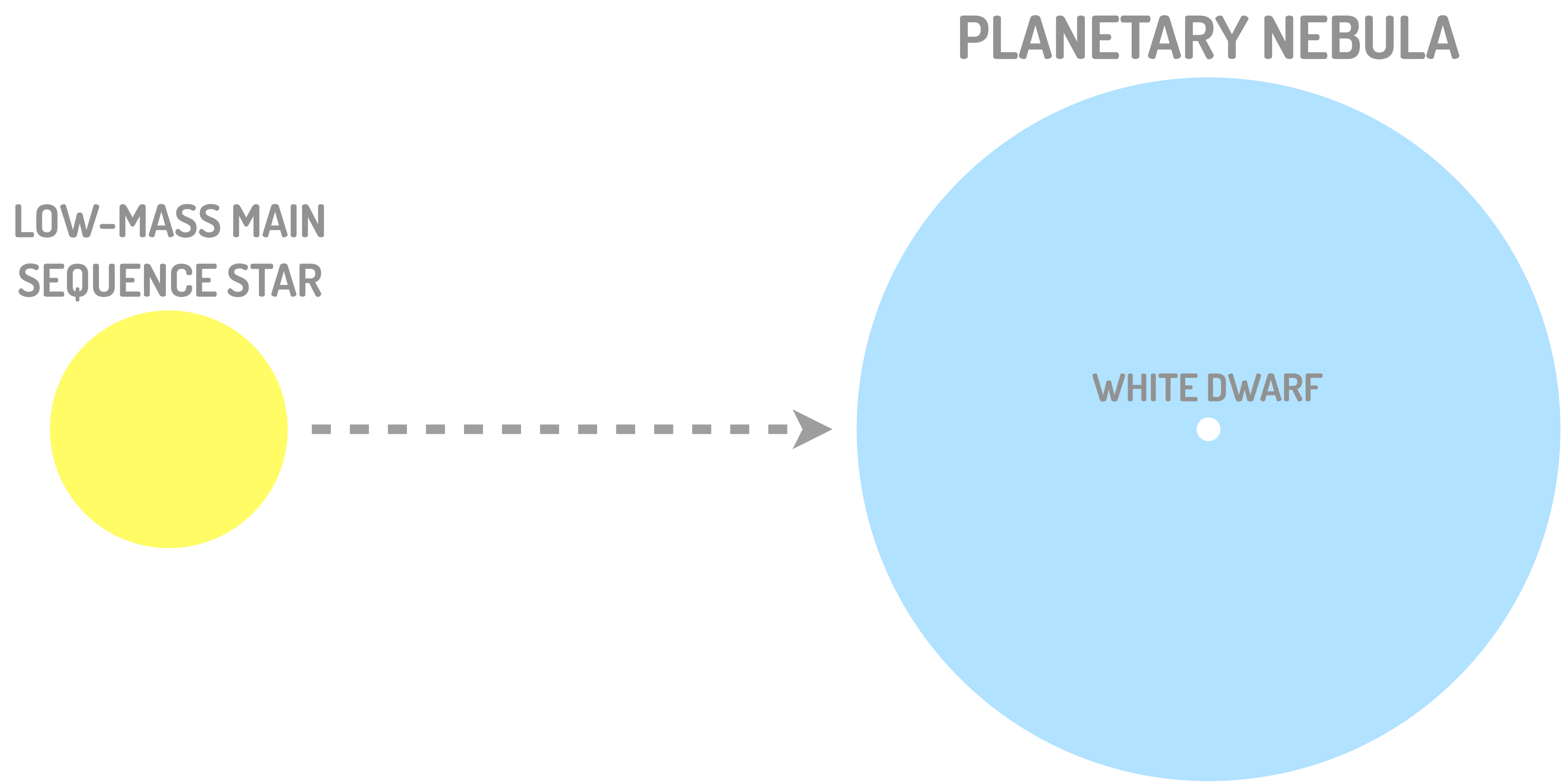
However, some stars are able quickly fuse three helium-4 nuclei via the **triple-alpha process** producing **carbon-12**.



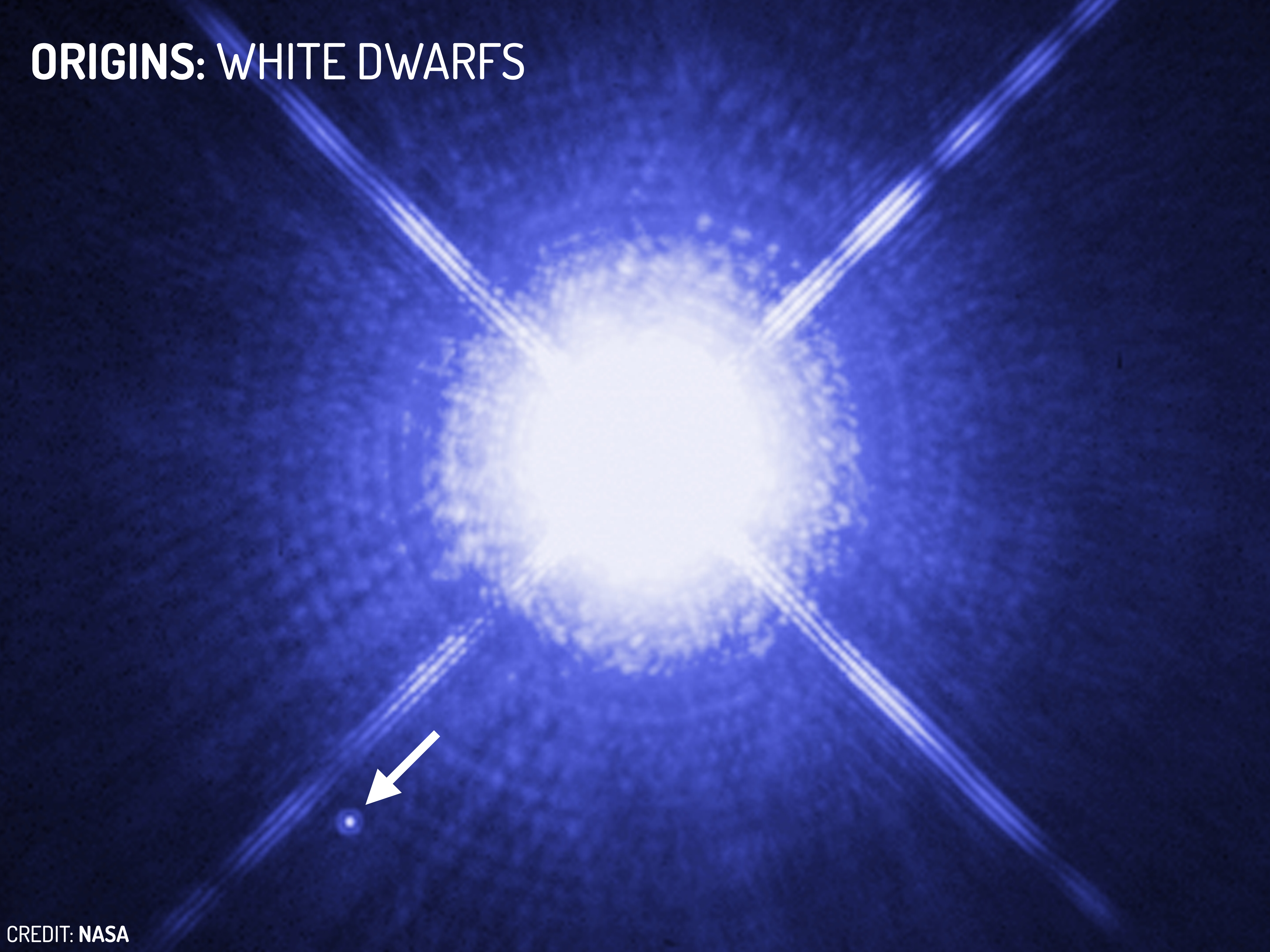

CREDIT: Rogelio Bernal Andreo

ORIGINS: LOW-MASS STARS

Low-mass stars never fuse beyond carbon & nitrogen. Instead their core collapses to form an inert lump of material, a **white dwarf** with the remaining material expelled to form an envelope of material called a **planetary nebula**.

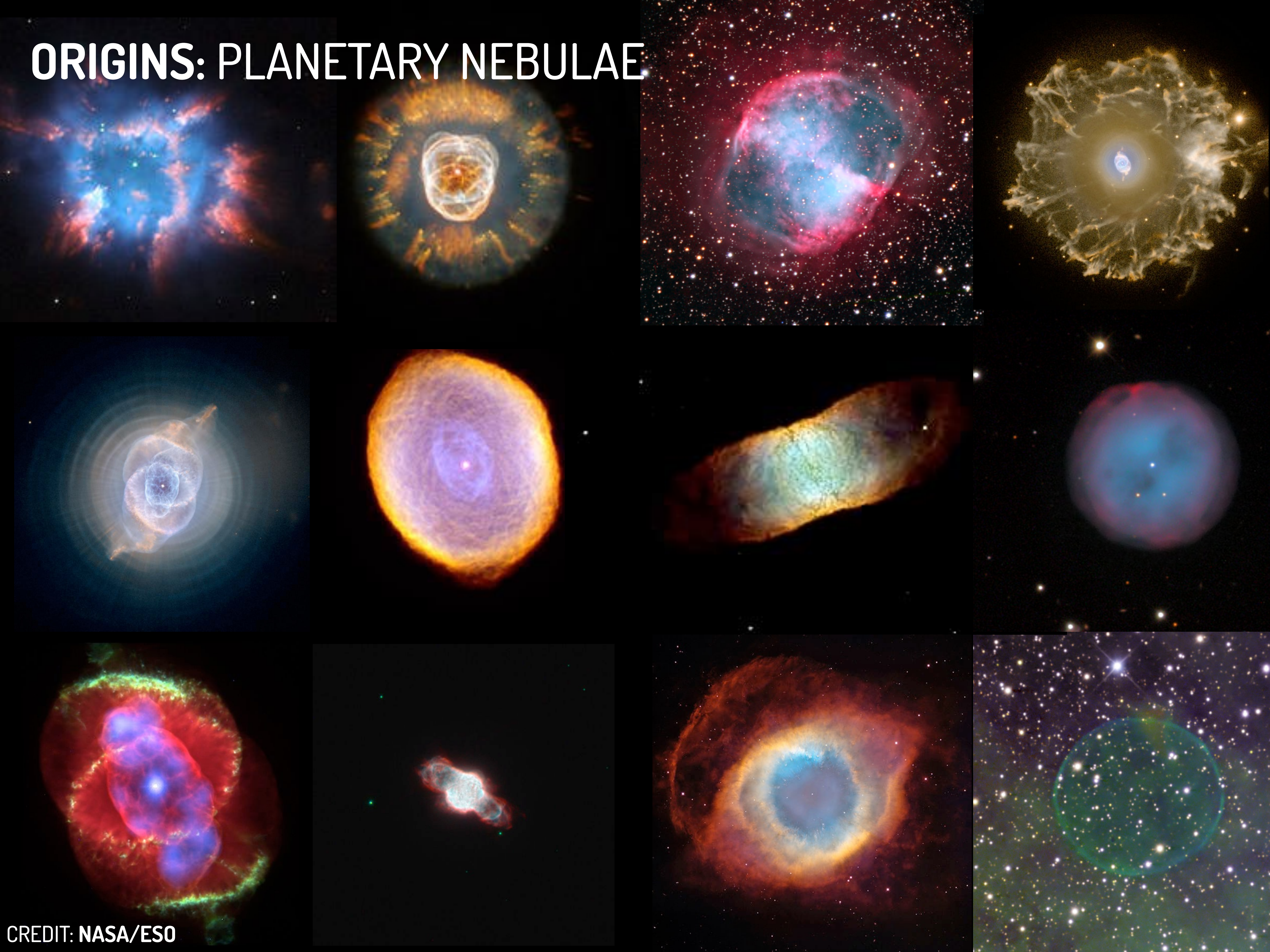


ORIGINS: WHITE DWARFS



CREDIT: **NASA**

ORIGINS: PLANETARY NEBULAE



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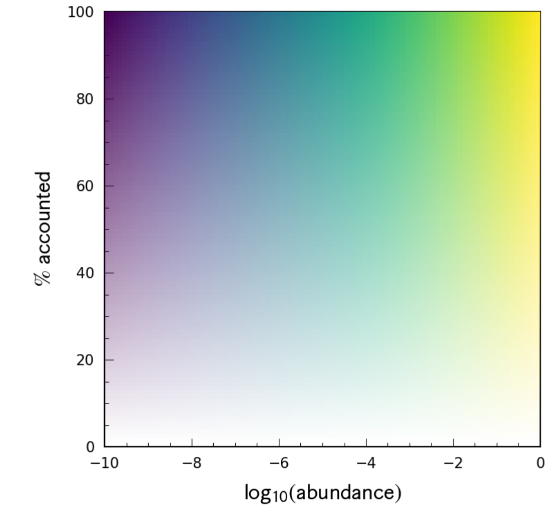
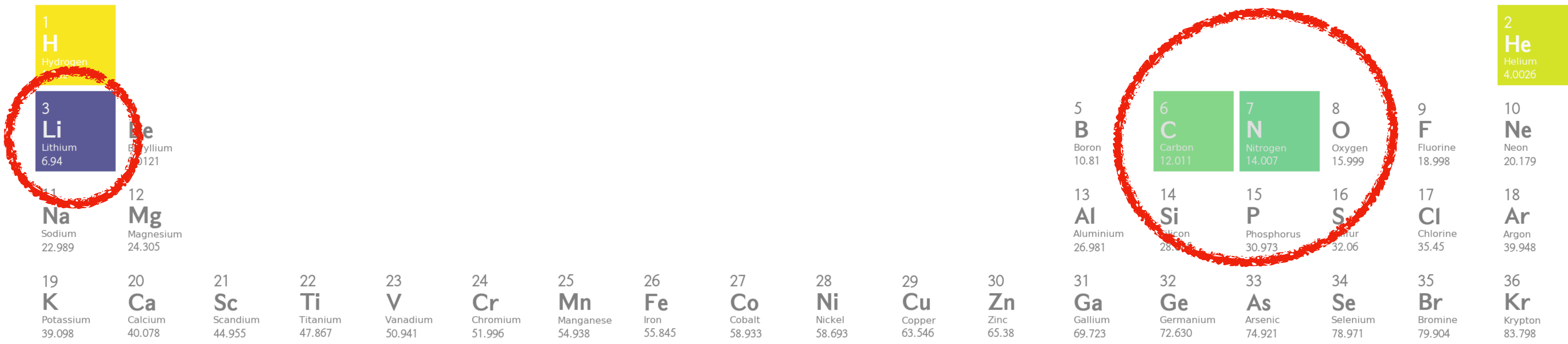
ORIGINS: LOW-MASS STARS





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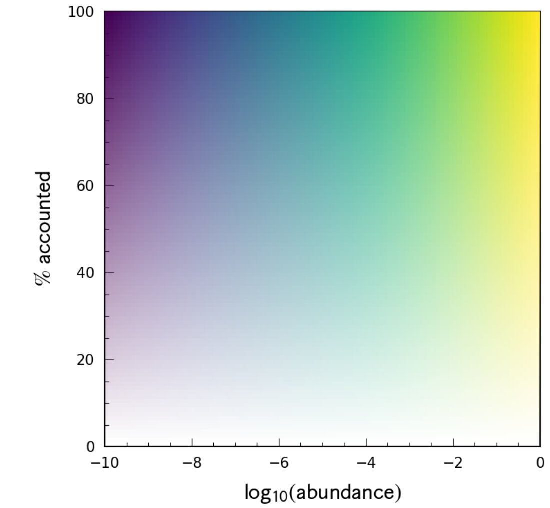

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As it turns out low-mass stars can also produce some heavy elements, but they need to be "seeded" first. More in a minute.

ORIGINS: EXPLODING HIGH-MASS STARS

In the cores of more massive stars nuclear fusion can progress **beyond pure helium fusion**. They do this by fusing the result of the previous reaction with a helium-4 nucleus. This is the **alpha process/ladder**.

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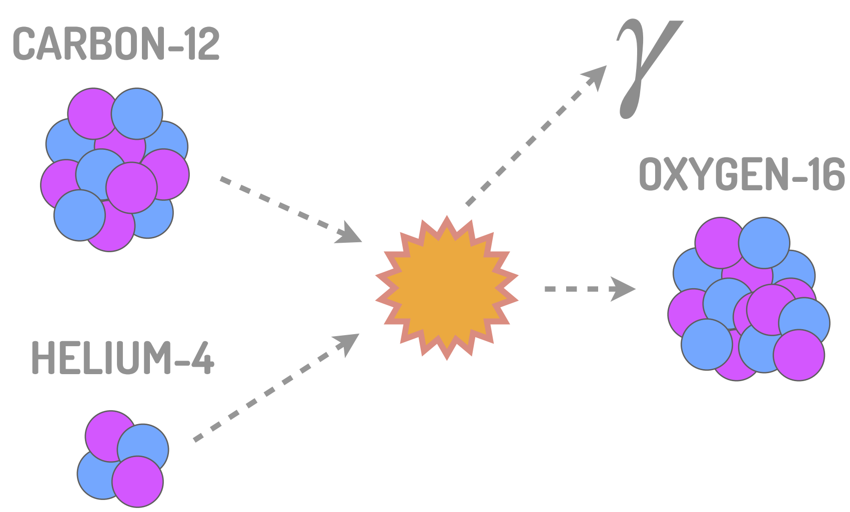

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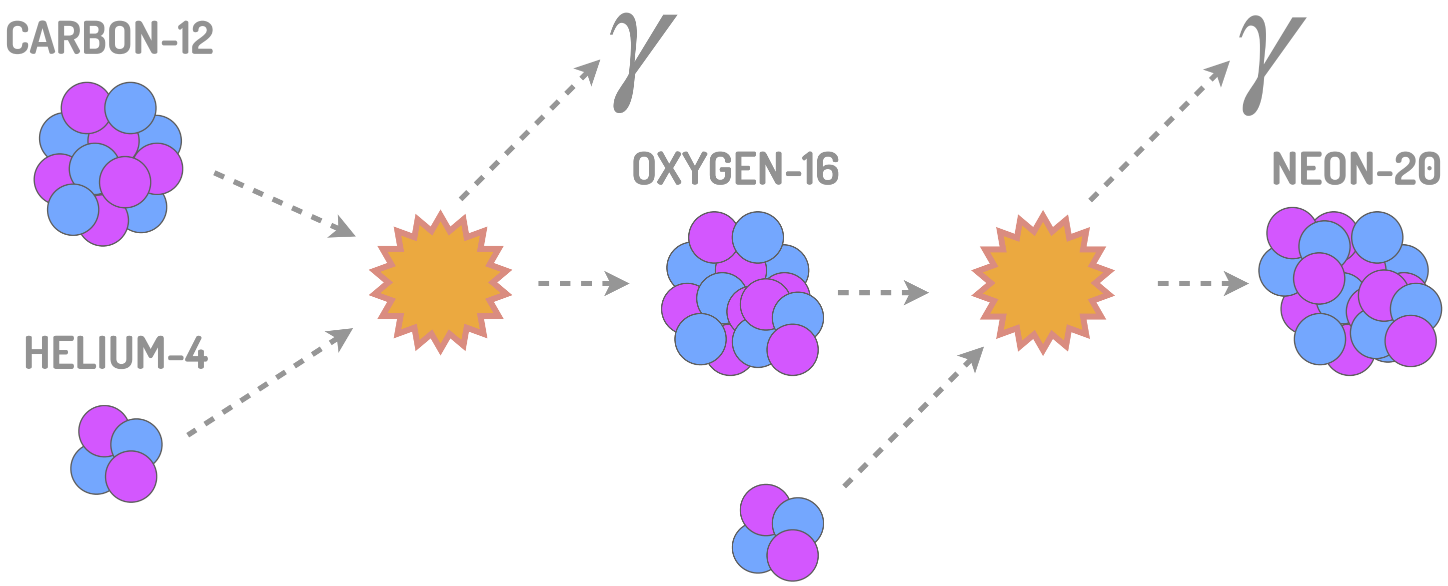

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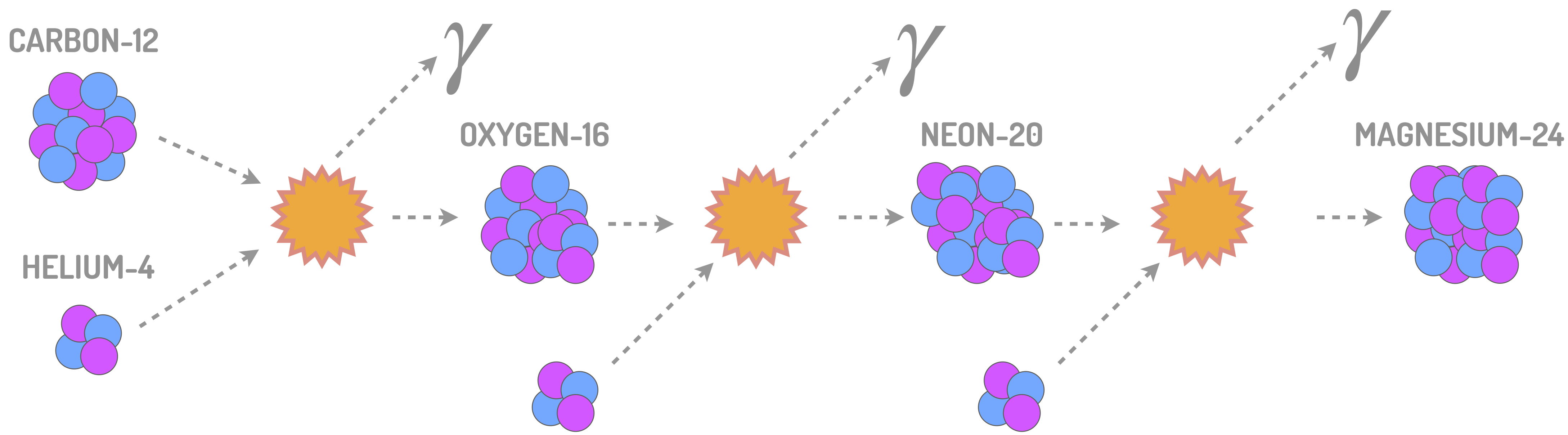

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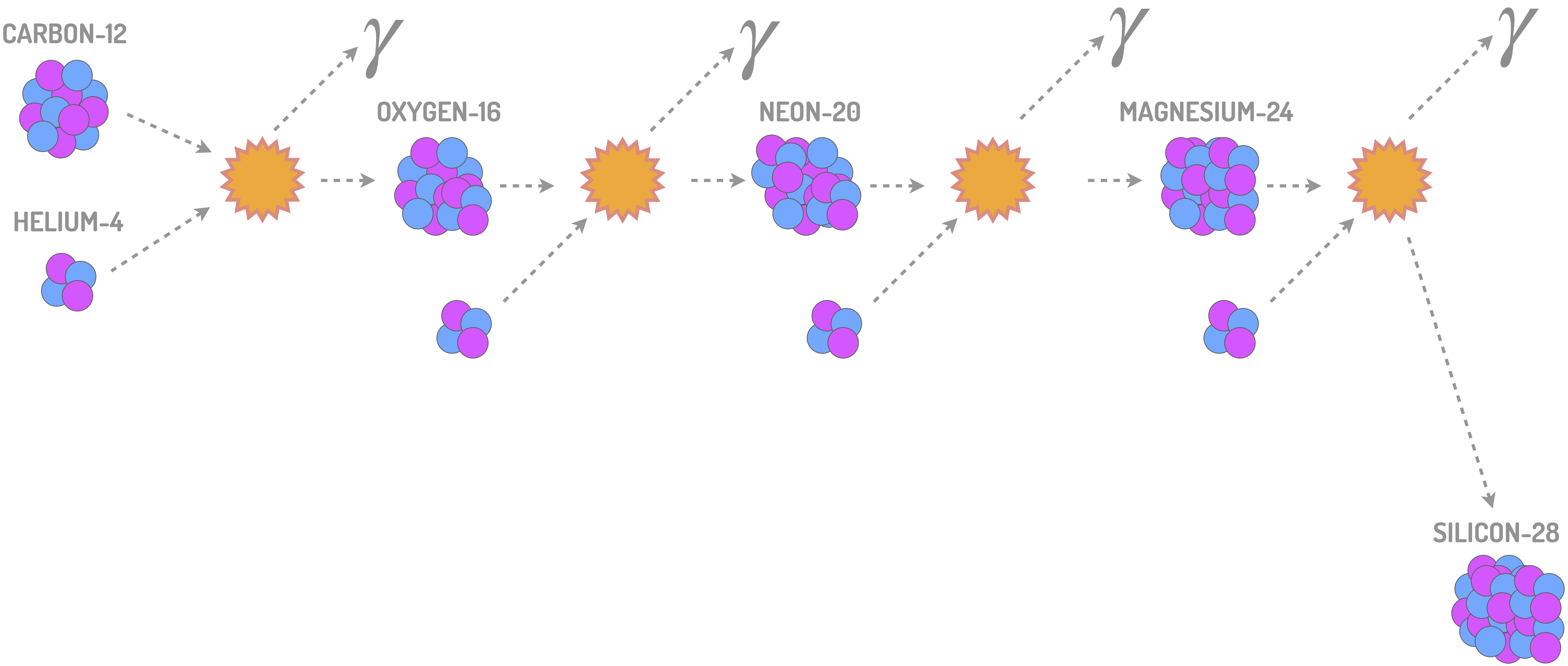

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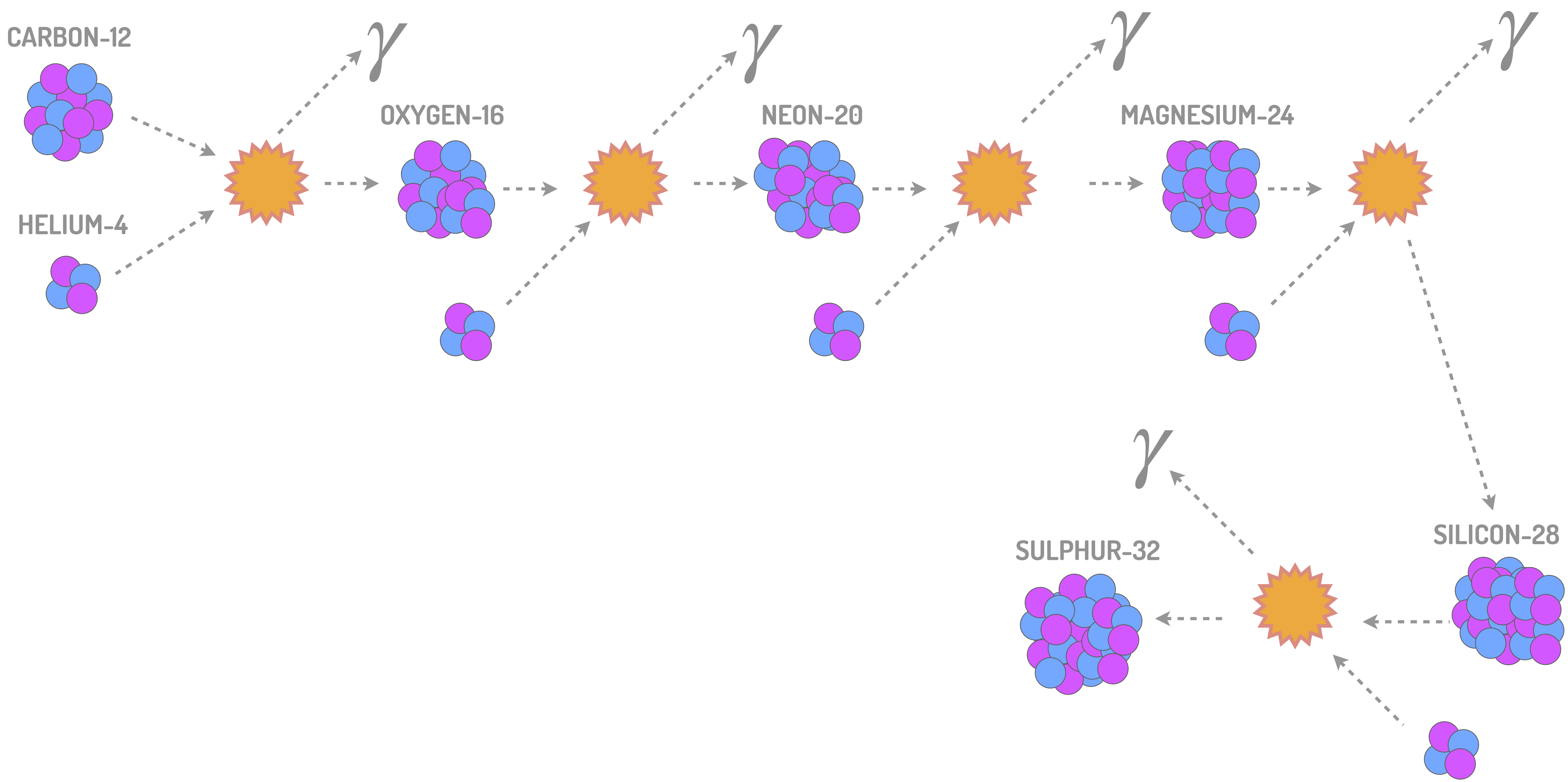

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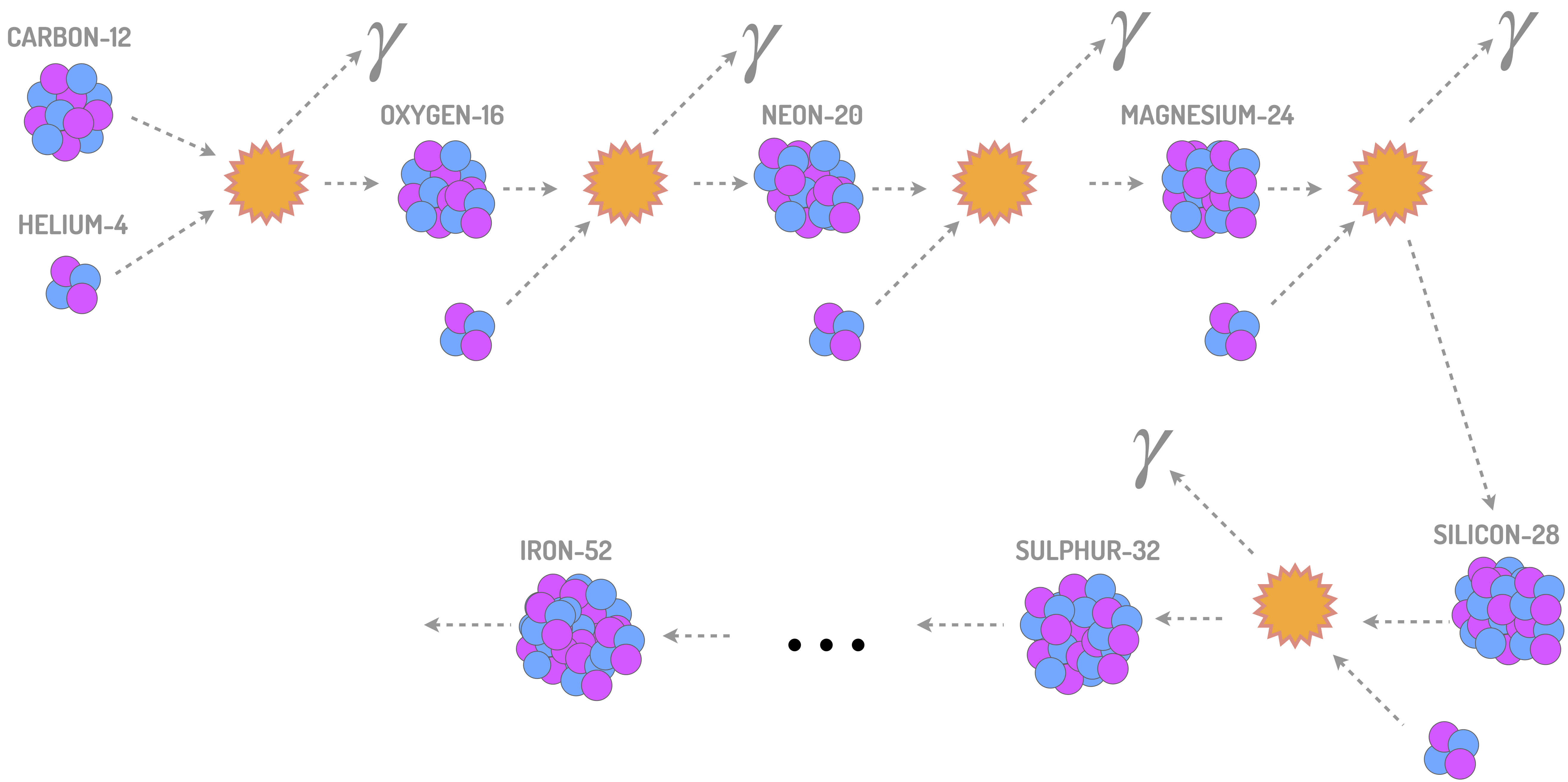
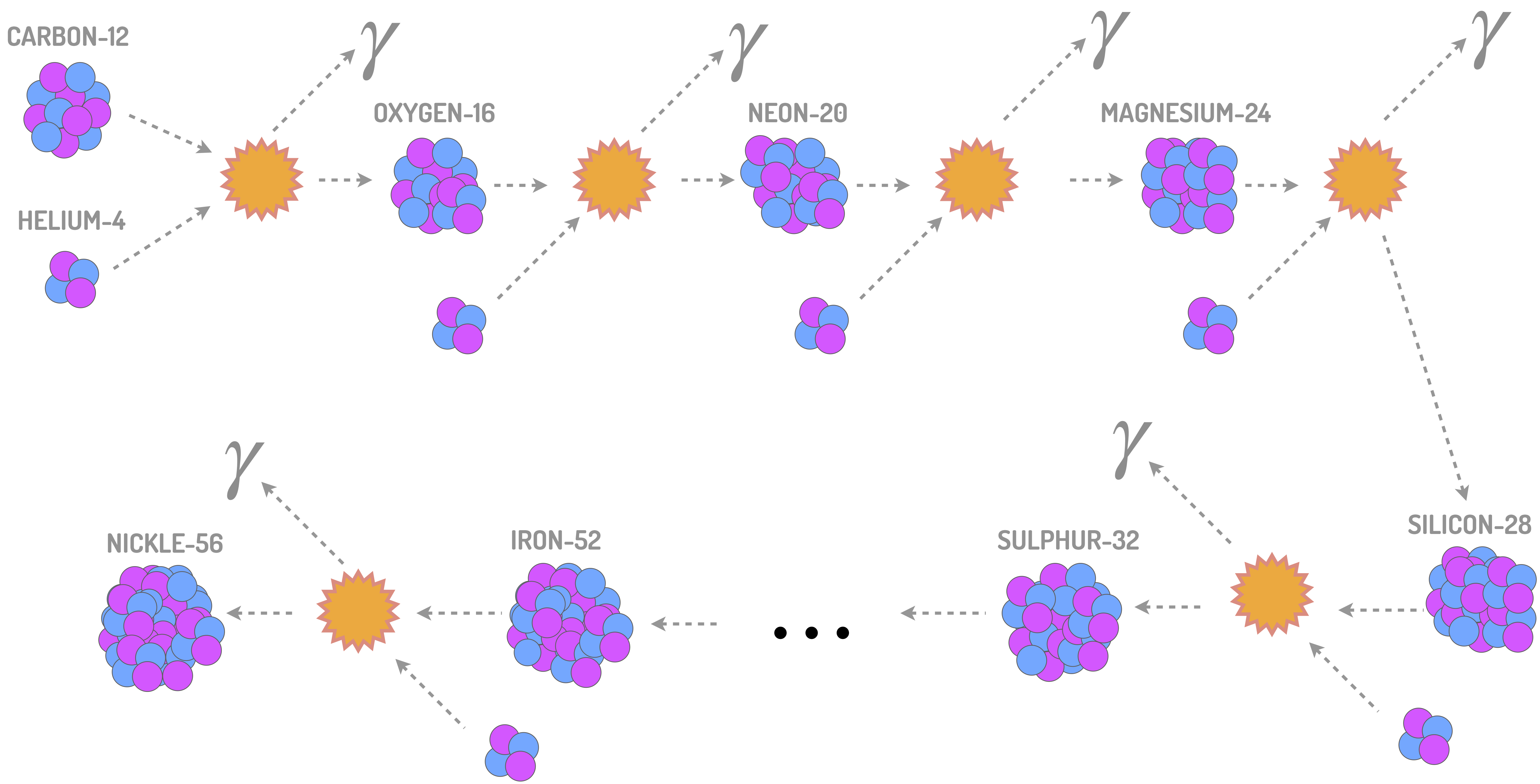


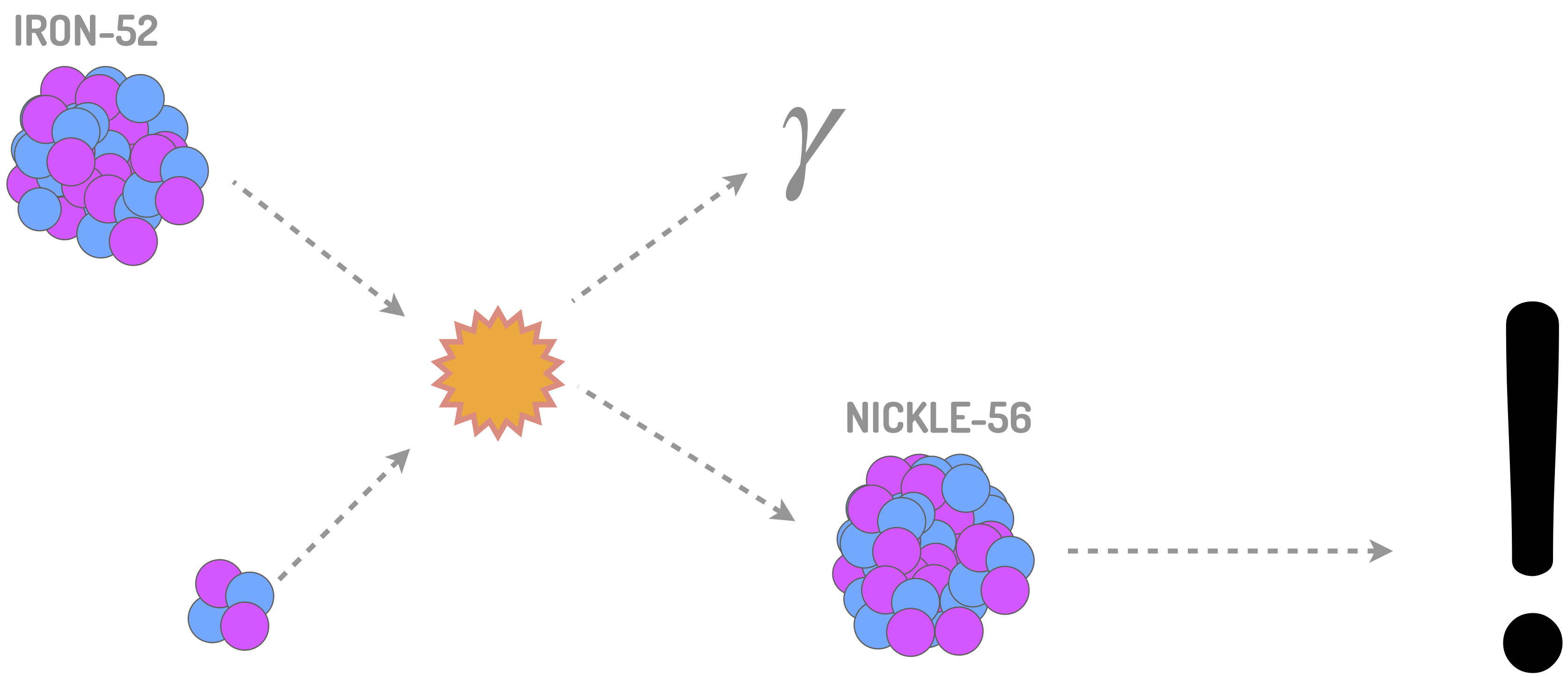
ORIGINS: EXPLODING HIGH-MASS STARS

In the cores of more massive stars nuclear fusion can progress **beyond pure helium fusion**. They do this by fusing the result of the previous reaction with a helium-4 nucleus. This is the **alpha process/ladder**.



ORIGINS: CORE COLLAPSE SUPERNOVAE

This process produces energy up to Nickel. Beyond Nickel the process requires more energy than is produced – it's **endothermic**.



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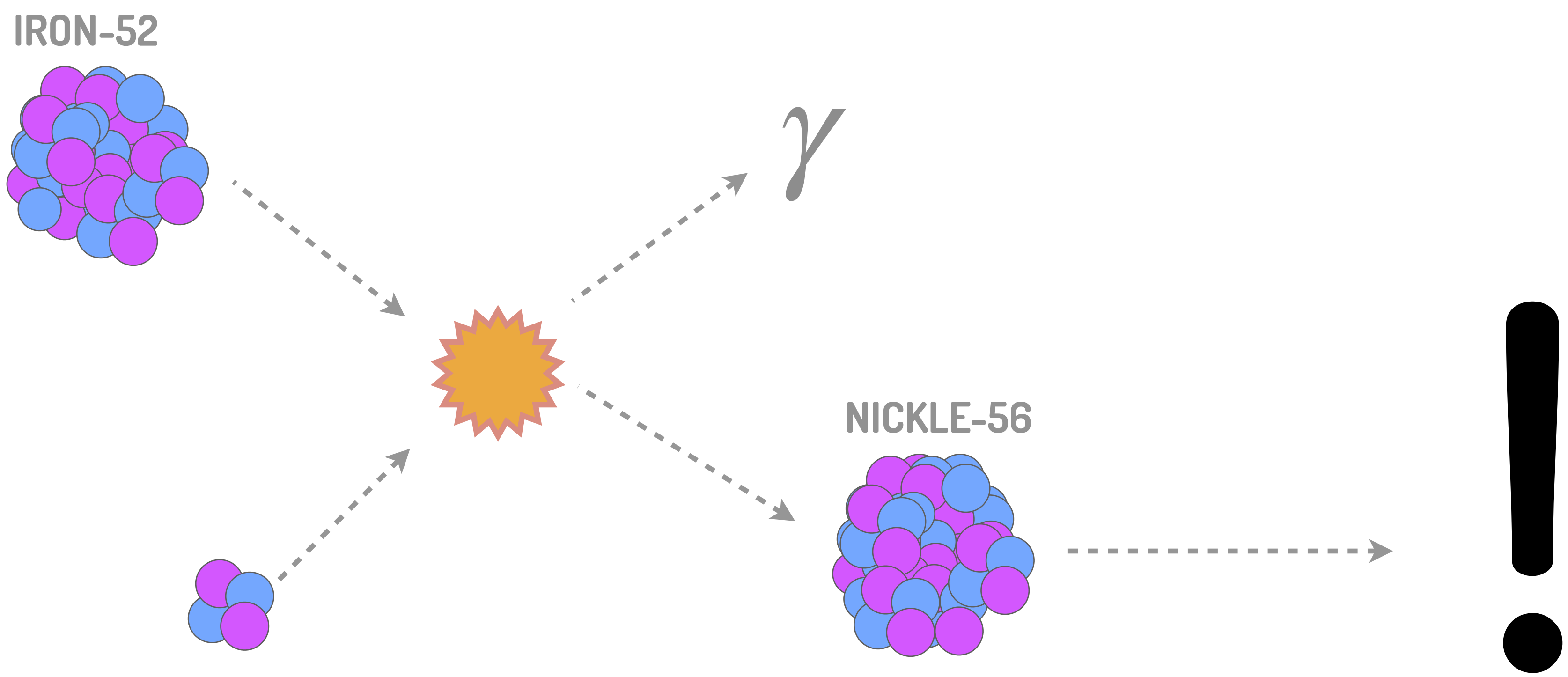
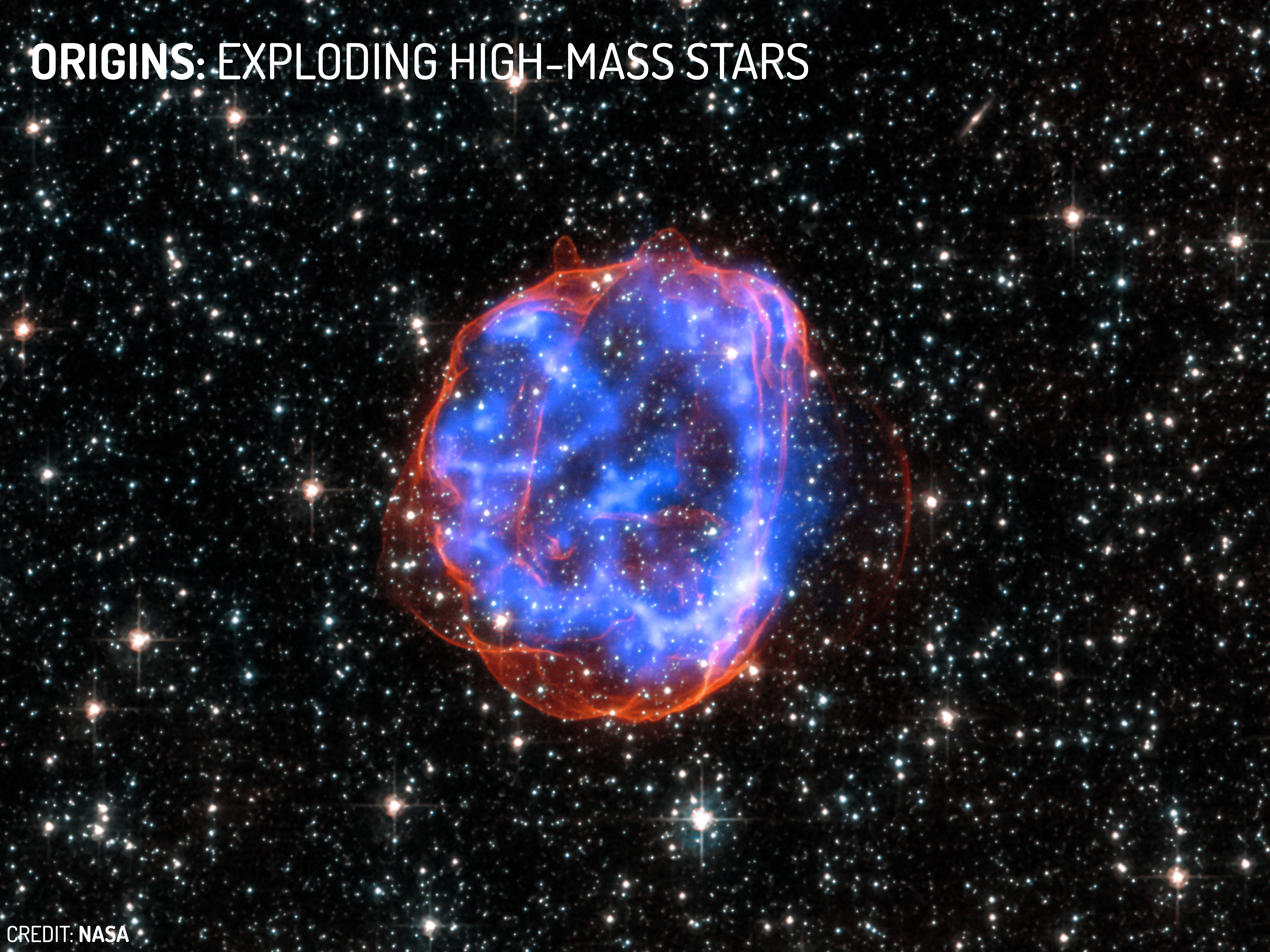


This saps the core of energy causing it collapse under its own gravity producing an explosion called **a core collapse supernova**.

These supernovae disperse the fusion products into space.

ORIGINS: EXPLODING HIGH-MASS STARS



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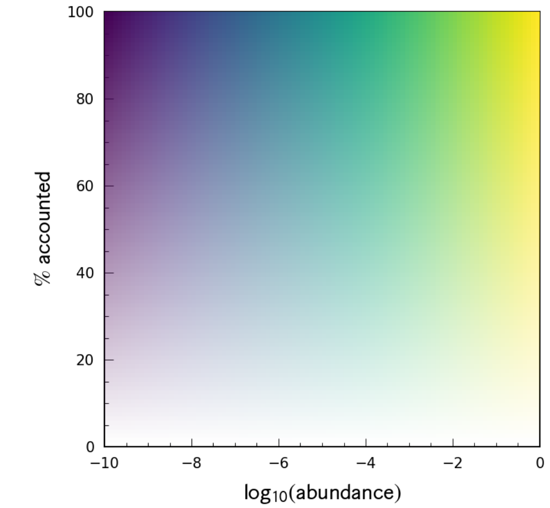
ORIGINS: EXPLODING HIGH-MASS STARS

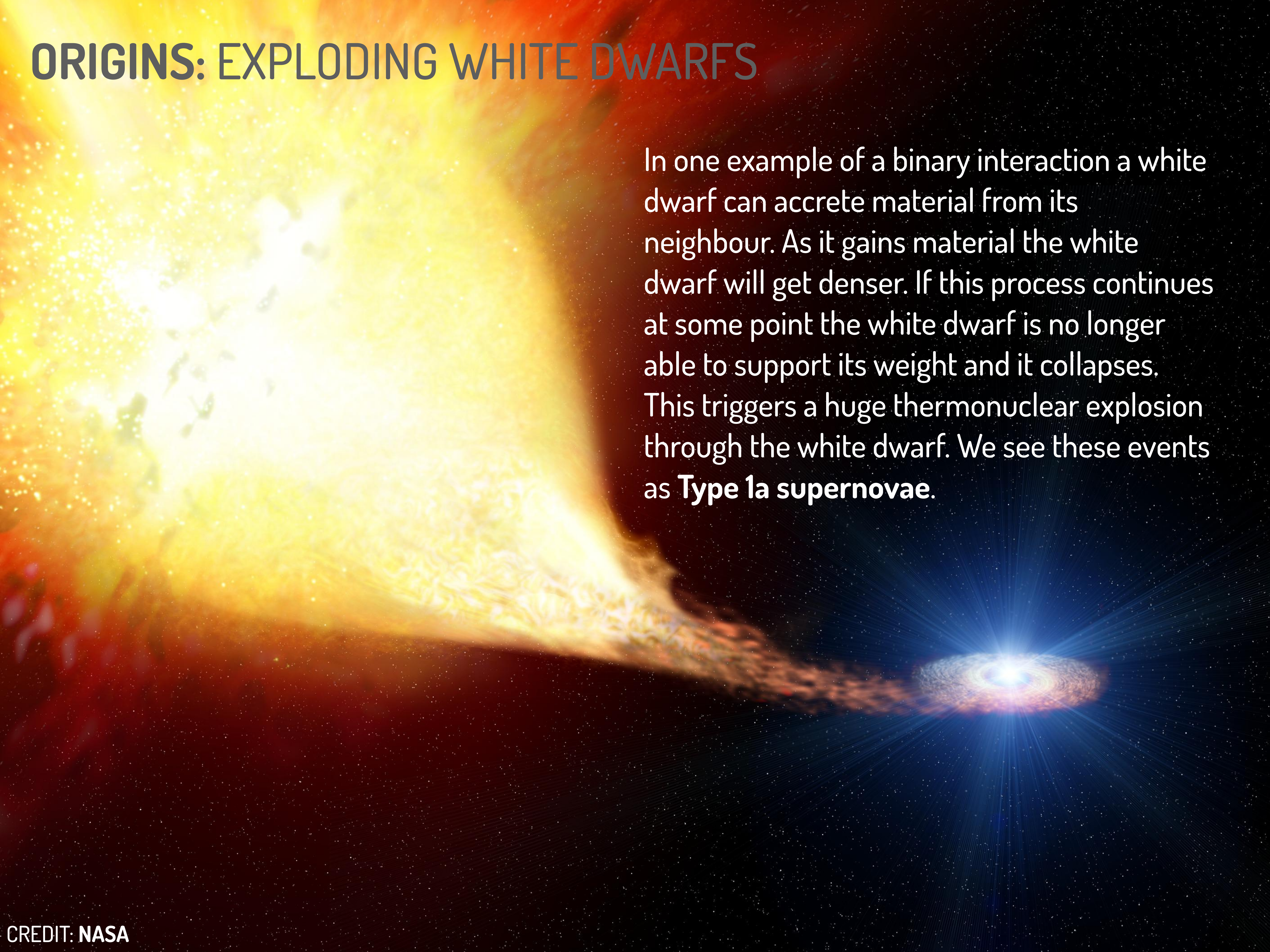


+EXPLODING HIGH MASS STARS

ORIGINS: EXPLODING WHITE DWARFS

Most stars exist in binary star systems. In some cases the two stars are close enough that the stars **can interact**.

ORIGINS: EXPLODING WHITE DWARFS



In one example of a binary interaction a white dwarf can accrete material from its neighbour. As it gains material the white dwarf will get denser. If this process continues at some point the white dwarf is no longer able to support its weight and it collapses. This triggers a huge thermonuclear explosion through the white dwarf. We see these events as **Type 1a supernovae**.

CREDIT: **NASA**

ORIGINS: EXPLODING WHITE DWARFS

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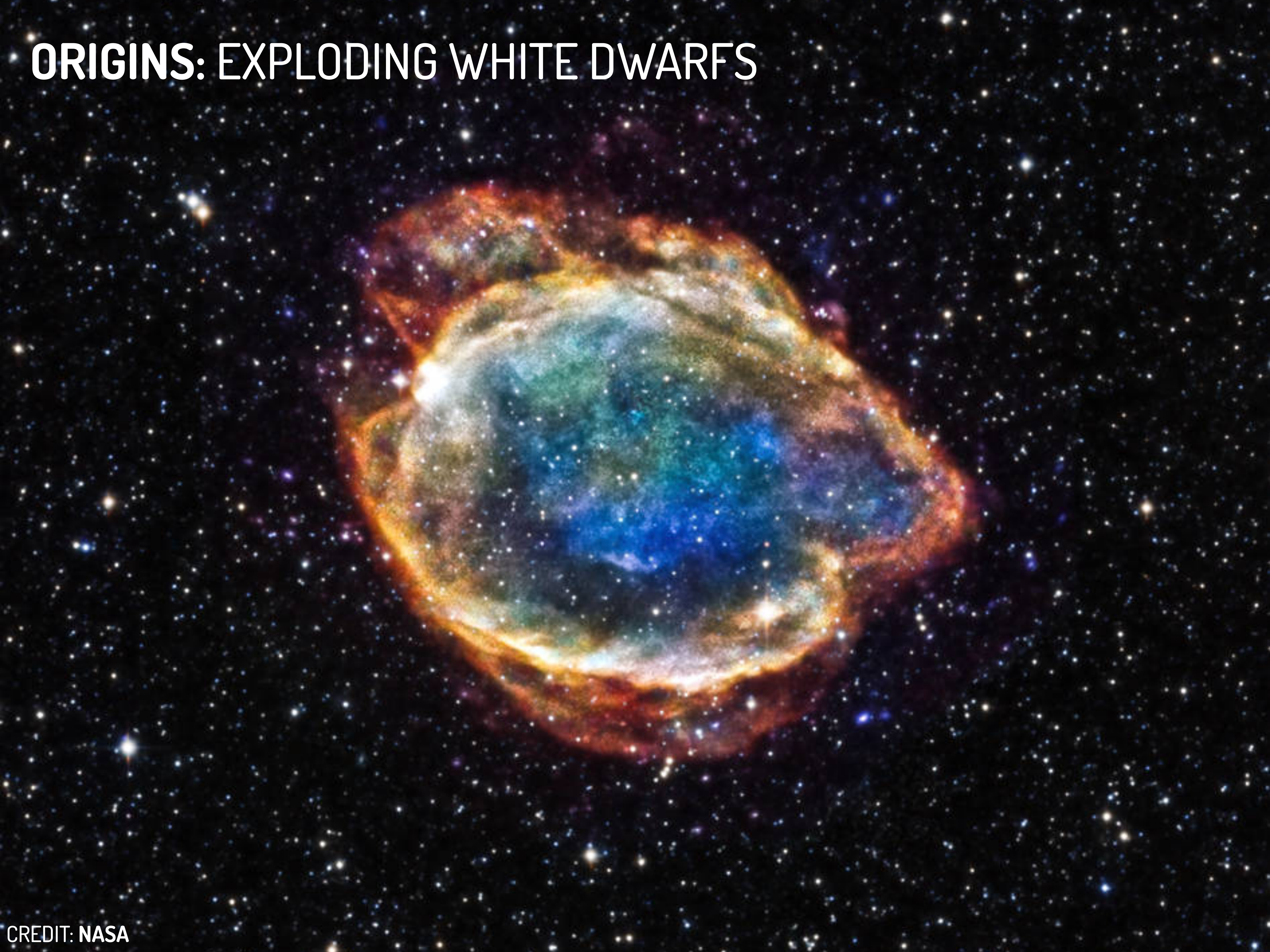
ORIGINS: EXPLODING WHITE DWARFS



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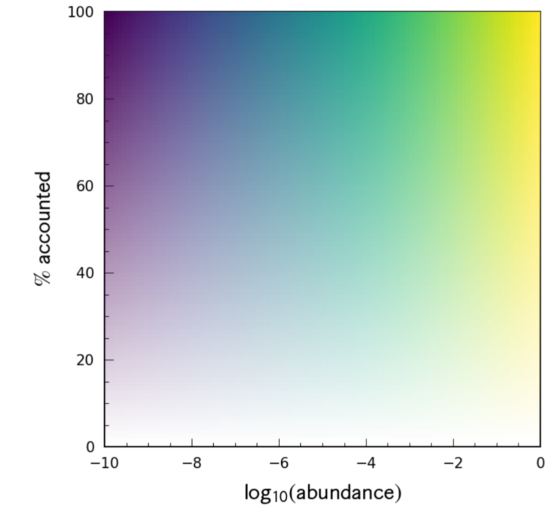
ORIGINS: EXPLODING WHITE DWARFS



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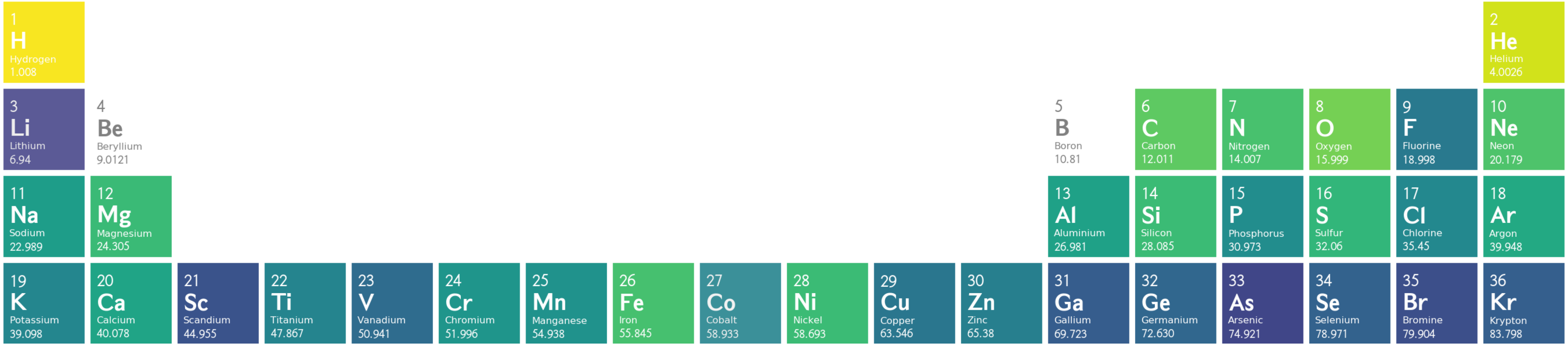
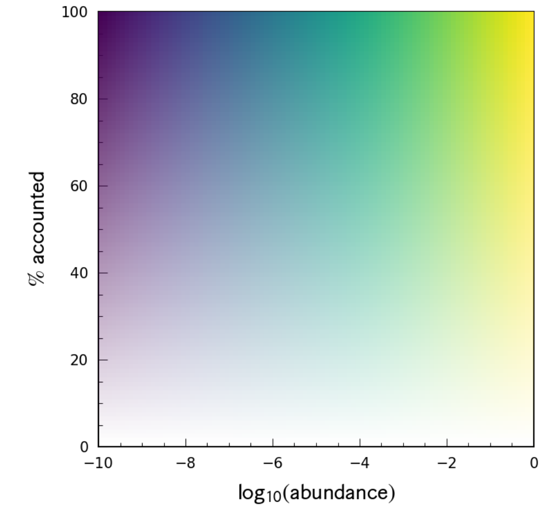
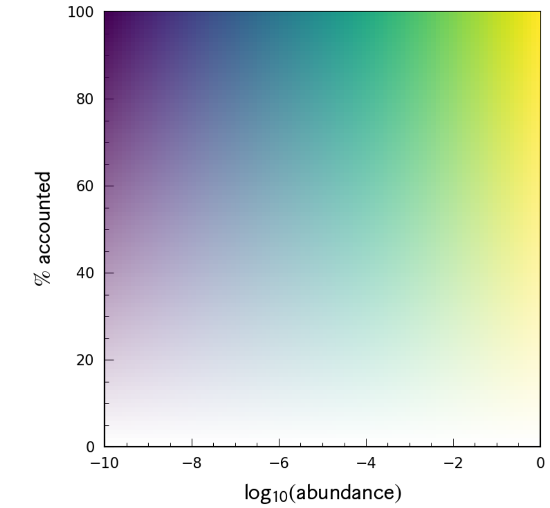


ORIGINS: EXPLODING WHITE DWARFS



-EXPLODING WHITE DWARFS

ORIGINS: EXPLODING WHITE DWARFS



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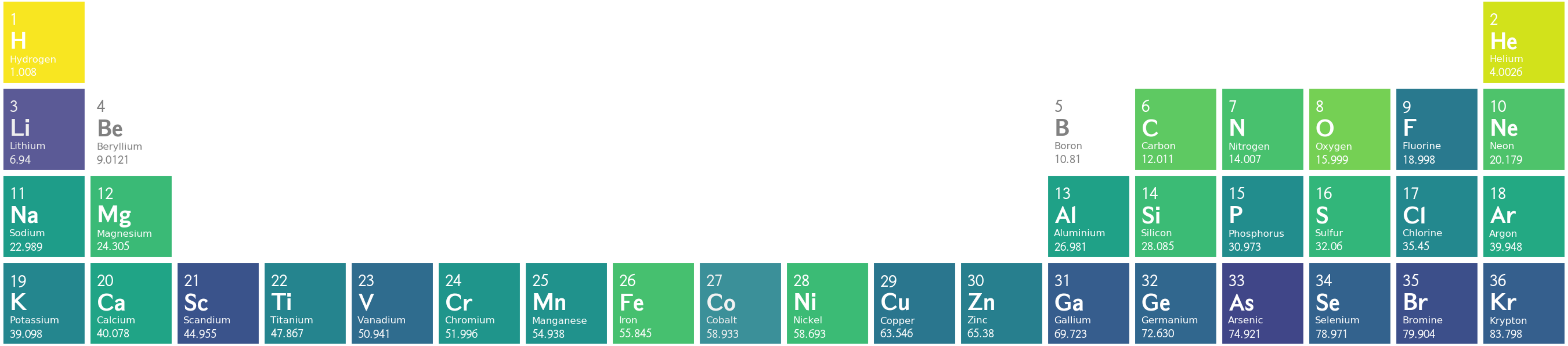

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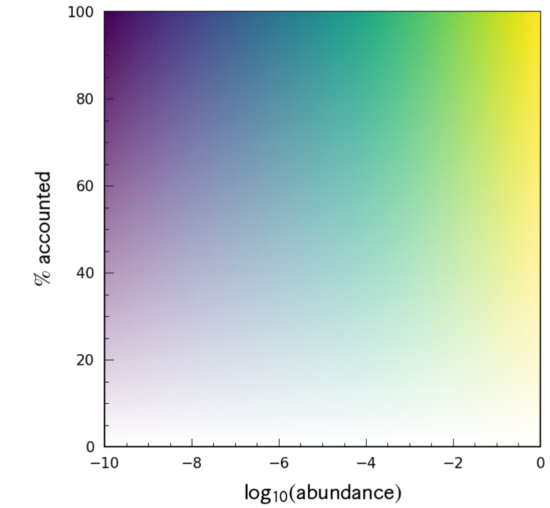

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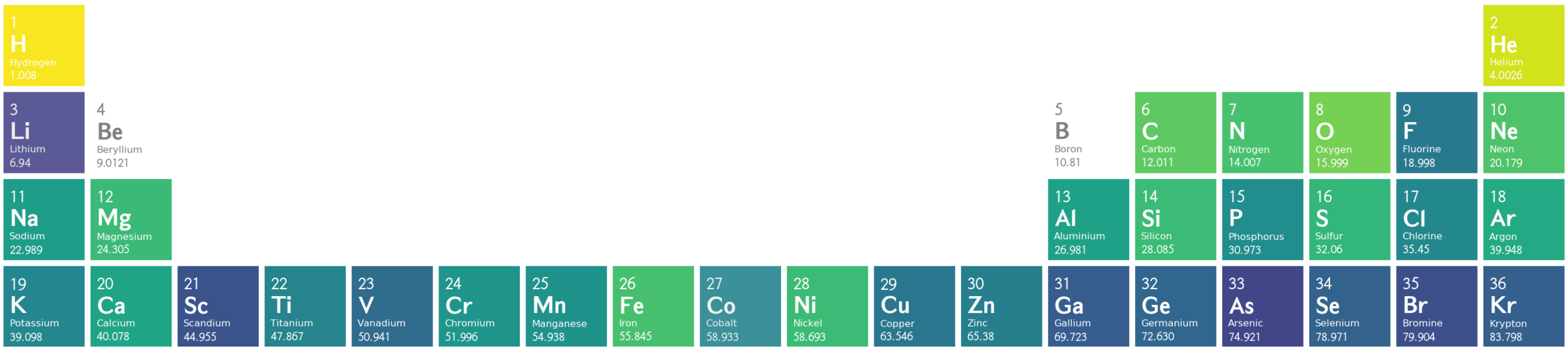

ORIGINS: NEUTRON CAPTURE

Many of the nuclear reactions described so far produce **large number of neutrons**. These can be **absorbed** by nuclei to make successively heavier atoms.

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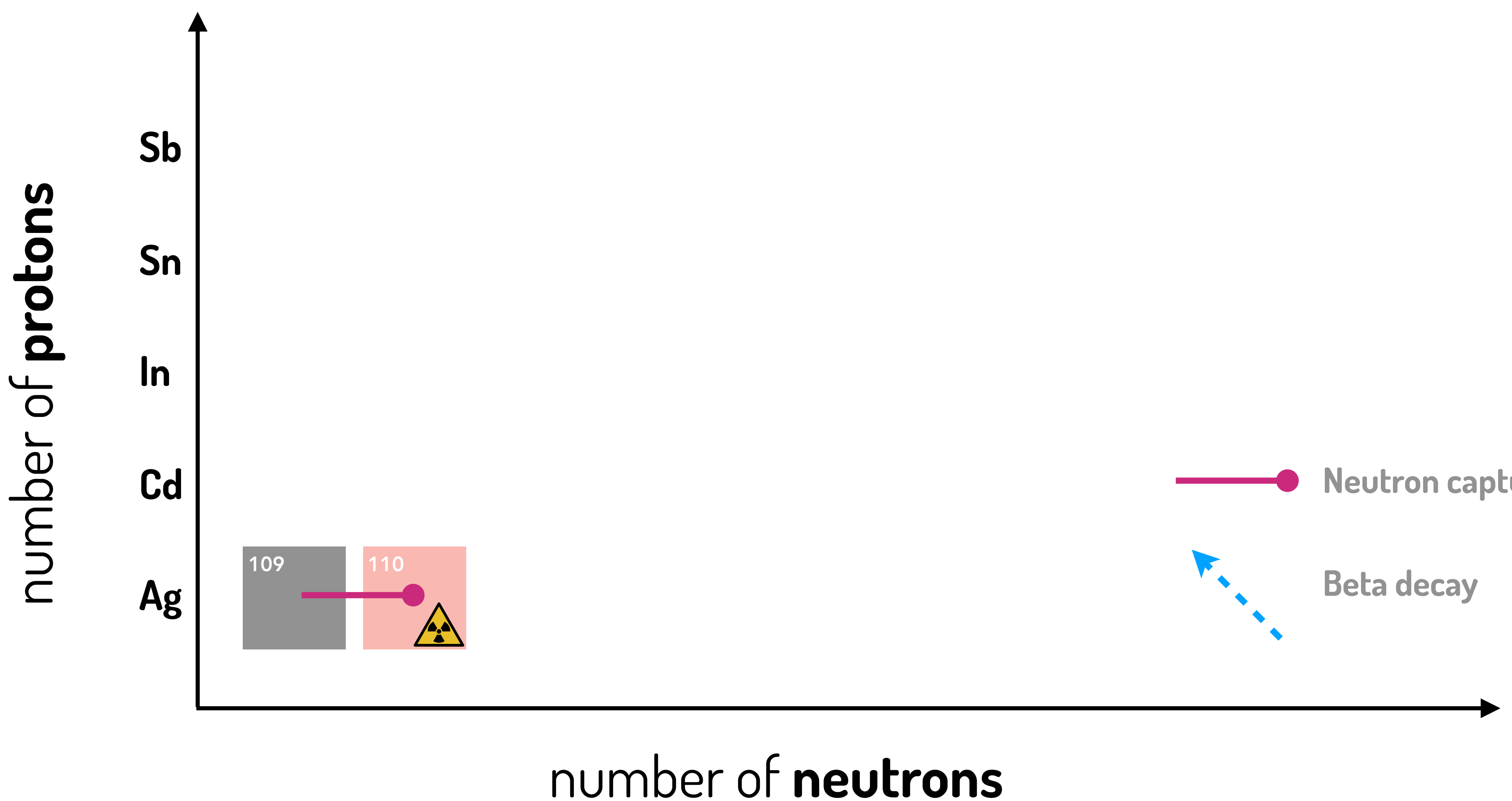
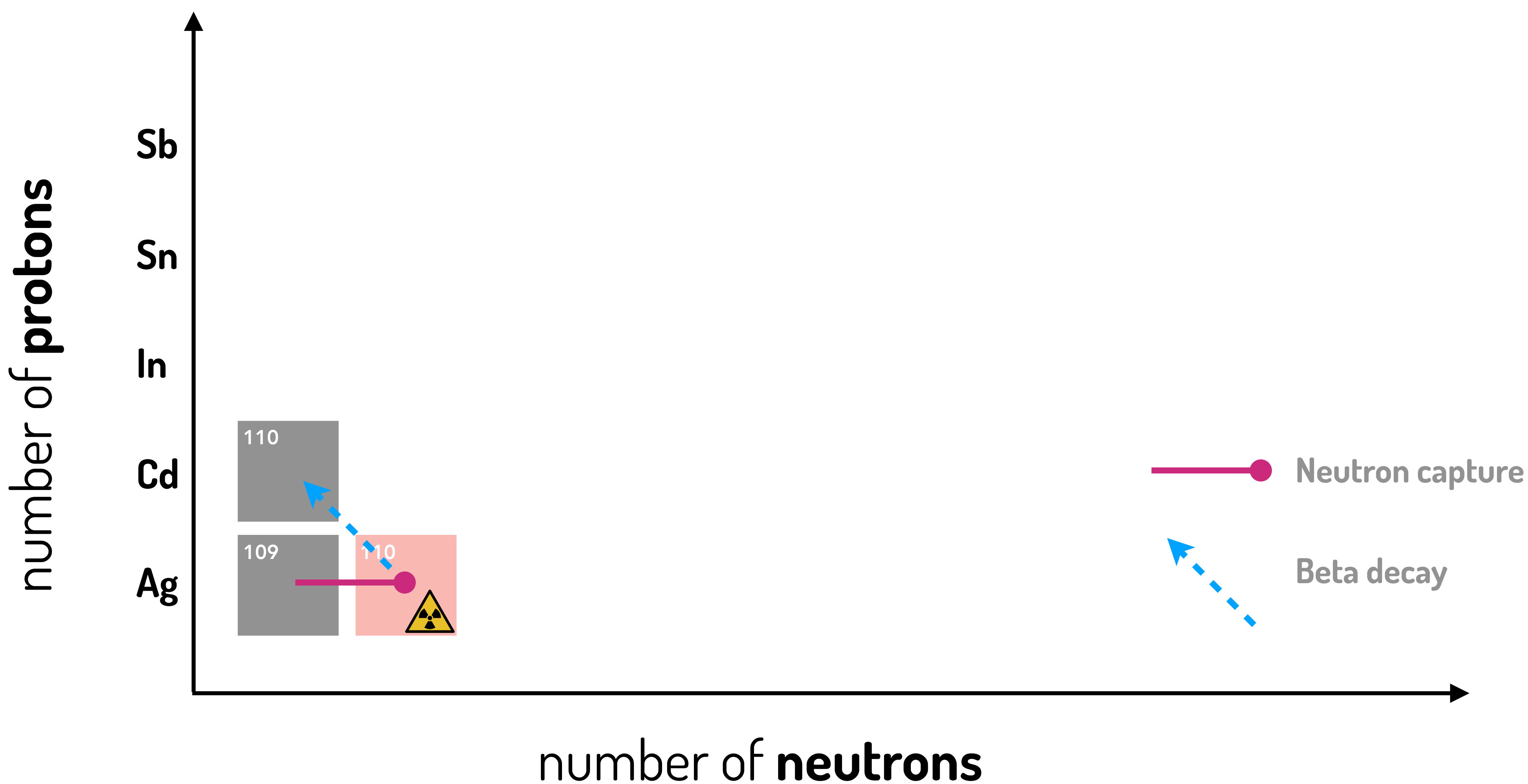


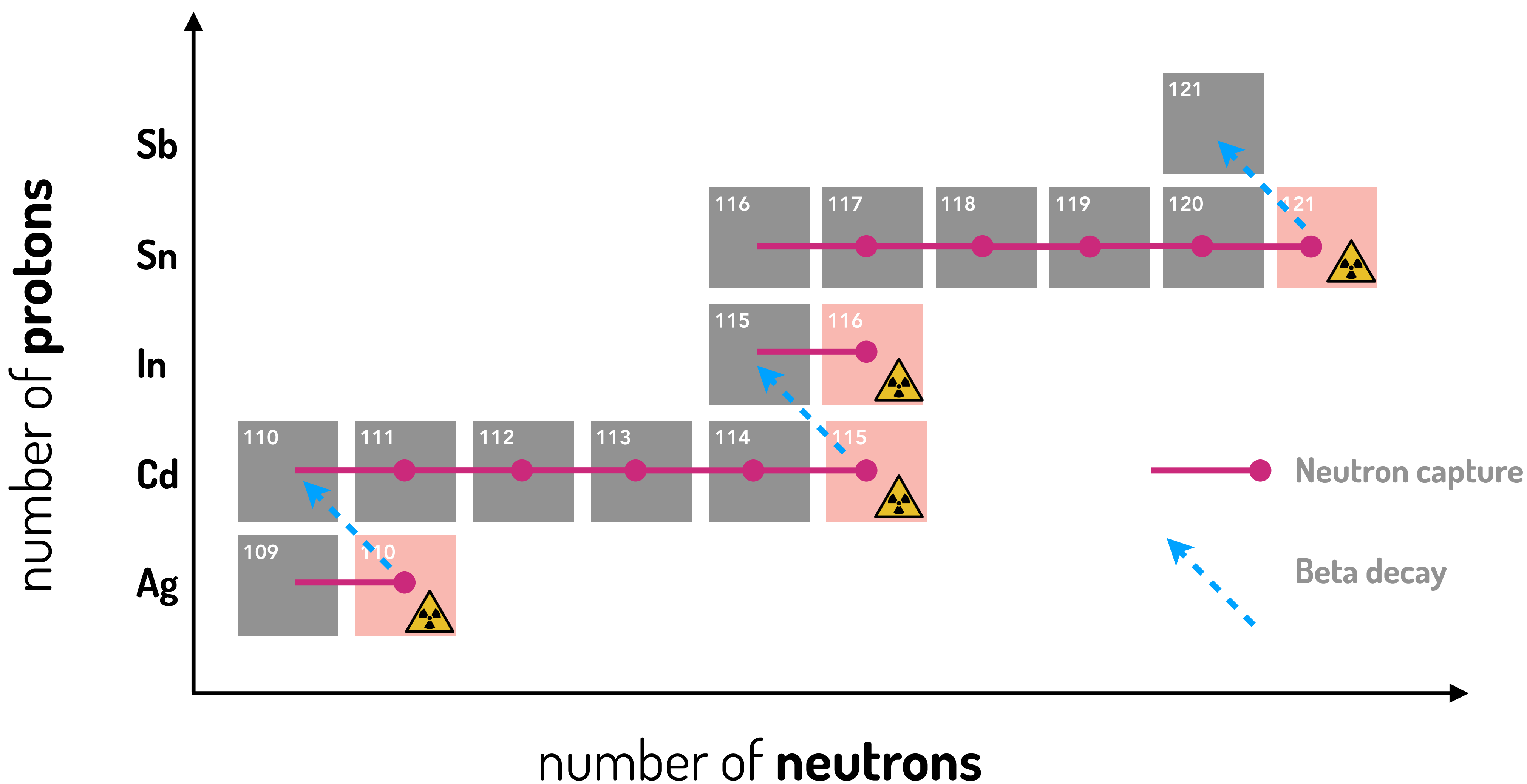
ORIGINS: NEUTRON CAPTURE

If the resulting nuclei is **unstable**, it can decay via **beta decay**. A neutron is effectively turned into a proton.

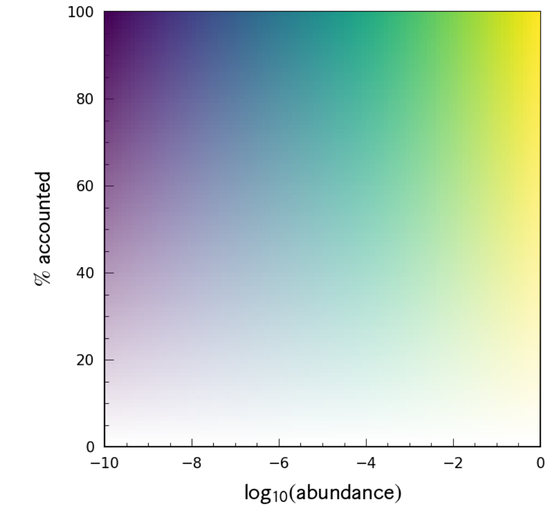


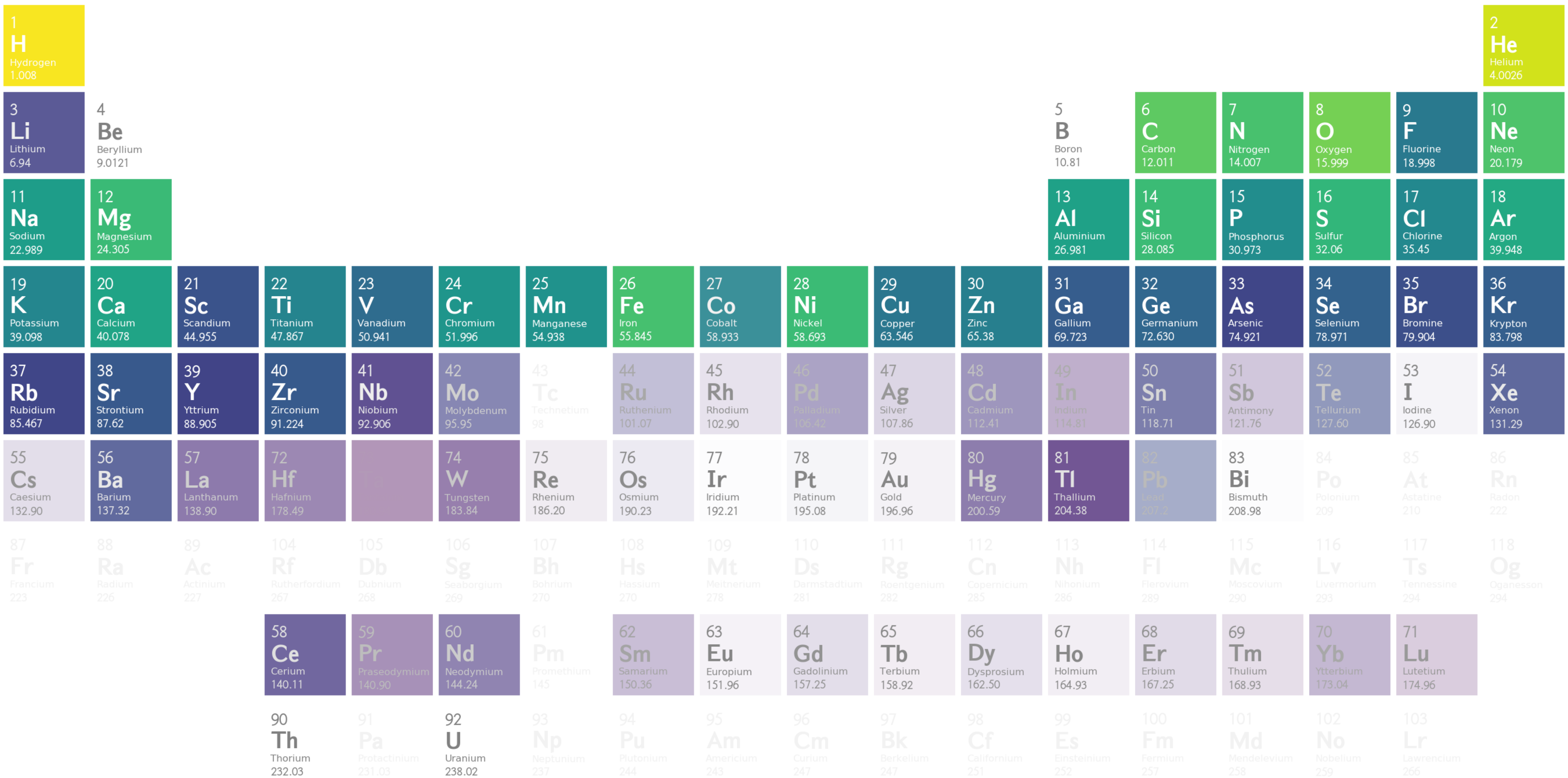
ORIGINS: NEUTRON CAPTURE

This process can continue creating heavier and heavier nuclei.



ORIGINS: SO FAR





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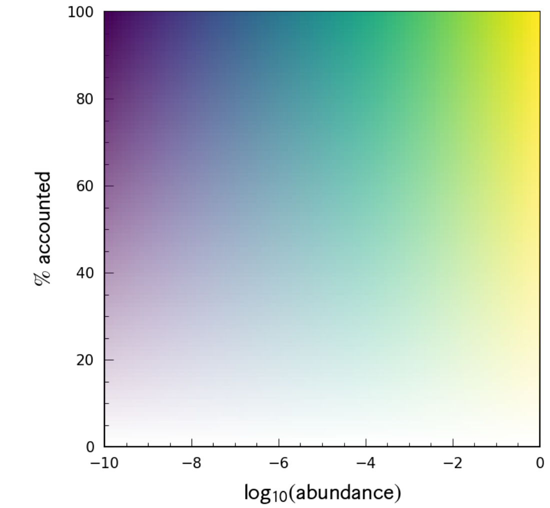
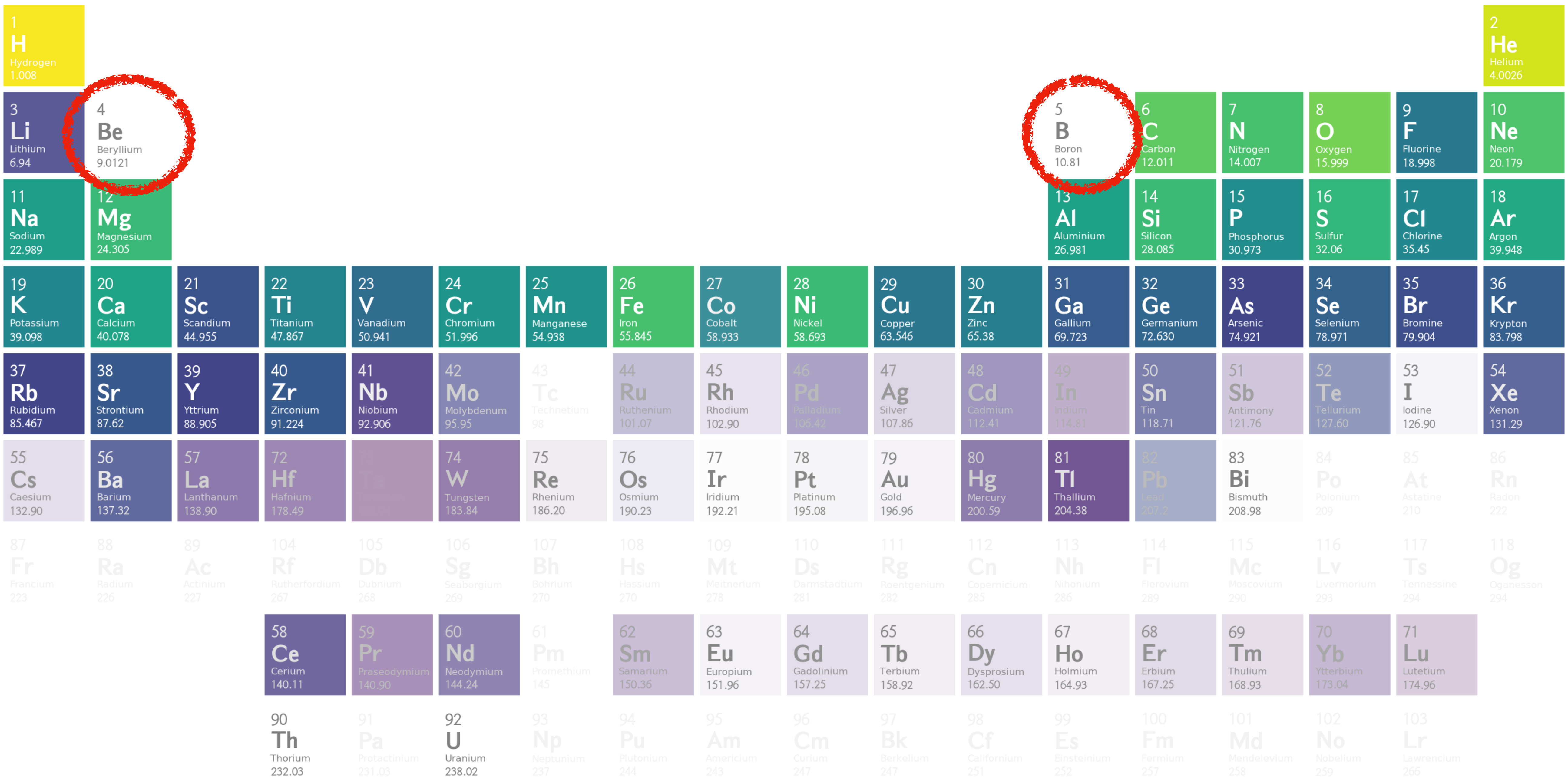
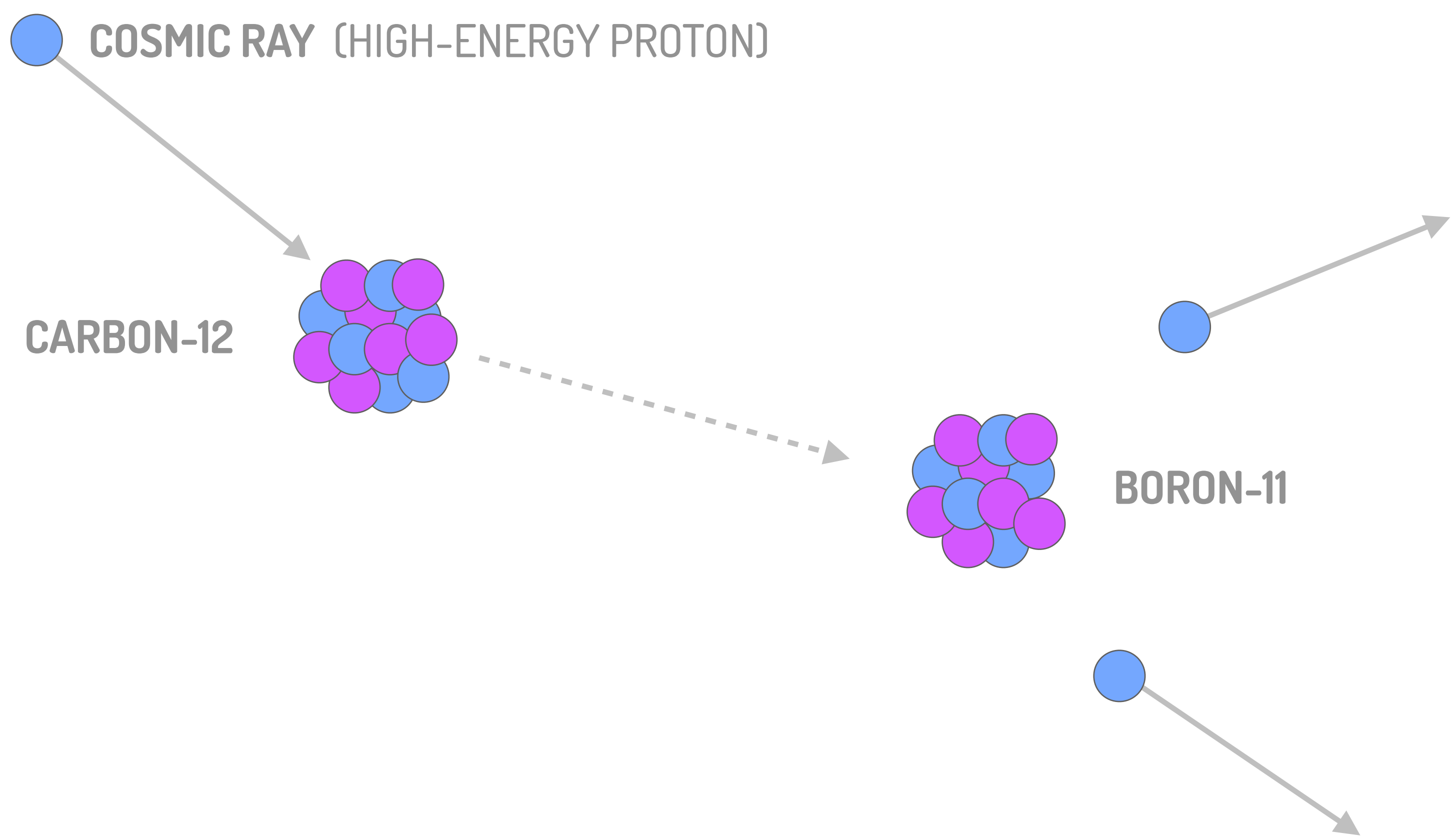




ORIGINS: COSMIC RAY SPALLATION



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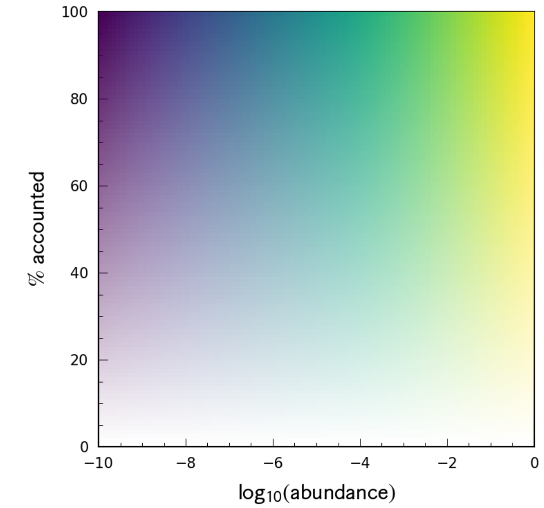
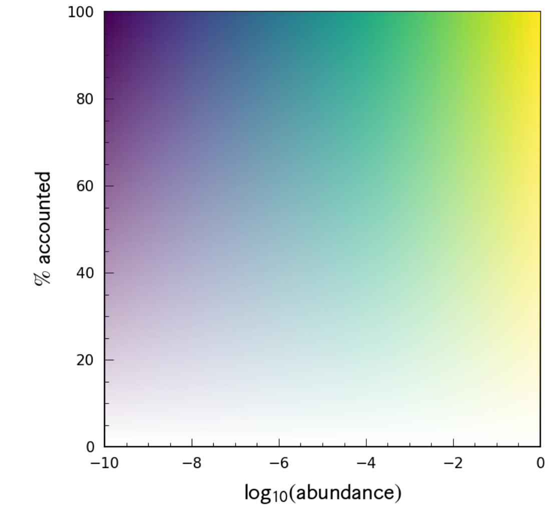


+COSMIC RAY SPALLATION

1 H Hydrogen 1.008																	2 He Helium 4.0026
3 Li Lithium 6.94	4 Be Beryllium 9.0121											5 B Boron 10.81	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.179
11 Na Sodium 22.989	12 Mg Magnesium 24.305											13 Al Aluminium 26.981	14 Si Silicon 28.085	15 P Phosphorus 30.973	16 S Sulfur 32.06	17 Cl Chlorine 35.45	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.955	22 Ti Titanium 47.867	23 V Vanadium 50.941	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.630	33 As Arsenic 74.921	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 83.798
37 Rb Rubidium 85.467	38 Sr Strontium 87.62	39 Y Yttrium 88.905	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90	46 Pd Palladium 106.42	47 Ag Silver 107.86	48 Cd Cadmium 112.41	49 In Indium 114.81	50 Sn Tin 118.71	51 Sb Antimony 121.76	52 Te Tellurium 127.60	53 I Iodine 126.90	54 Xe Xenon 131.29
55 Cs Caesium 132.90	56 Ba Barium 137.32	57 La Lanthanum 138.90	72 Hf Hafnium 178.49	Ta	74 W Tungsten 183.84	75 Re Rhenium 186.20	76 Os Osmium 190.23	77 Ir Iridium 192.21	78 Pt Platinum 195.08	79 Au Gold 196.96	80 Hg Mercury 200.59	81 Tl Thallium 204.38	82 Pb Lead 207.2	83 Bi Bismuth 208.98	84 Po Polonium 209	85 At Astatine 210	86 Rn Radon 222
87 Fr Francium 223	88 Ra Radium 226	89 Ac Actinium 227	104 Rf Rutherfordium 267	105 Db Dubnium 268	106 Sg Seaborgium 269	107 Bh Bohrium 270	108 Hs Hassium 270	109 Mt Meitnerium 278	110 Ds Darmstadtium 281	111 Rg Roentgenium 282	112 Cn Copernicium 285	113 Nh Nihonium 286	114 Fl Flerovium 289	115 Mc Moscovium 290	116 Lv Livermorium 293	117 Ts Tennessine 294	118 Og Oganesson 294
			58 Ce Cerium 140.11	59 Pr Praseodymium 140.90	60 Nd Neodymium 144.24	61 Pm Promethium 145	62 Sm Samarium 150.36	63 Eu Europium 151.96	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93	68 Er Erbium 167.25	69 Tm Thulium 168.93	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.96	
			90 Th Thorium 232.03	91 Pa Protactinium 231.03	92 U Uranium 238.02	93 Np Neptunium 237	94 Pu Plutonium 244	95 Am Americium 243	96 Cm Curium 247	97 Bk Berkelium 247	98 Cf Californium 251	99 Es Einsteinium 252	100 Fm Fermium 257	101 Md Mendelevium 258	102 No Nobelium 259	103 Lr Lawrencium 266	

ORIGINS: COSMIC RAY SPALLATION



+COSMIC RAY SPALLATION


ORIGINS: NEUTRON STAR MERGERS
CREDIT: **NASA**

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Occasionally these pairs of neutron stars can in-spiral and eventually **collide**.

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These release huge amounts of neutrons allowing heavy elements to be assembled through **neutron capture and subsequent decays.**

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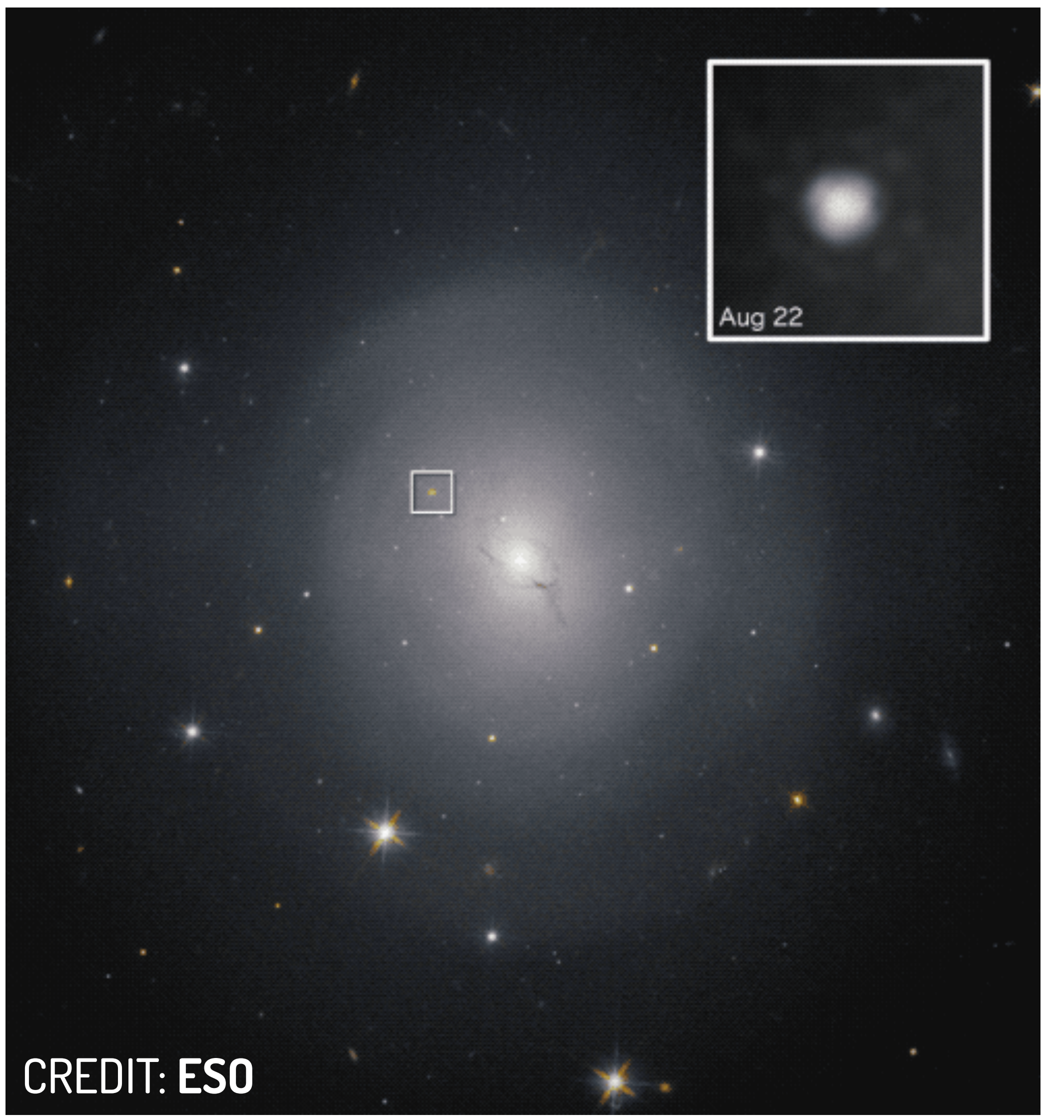
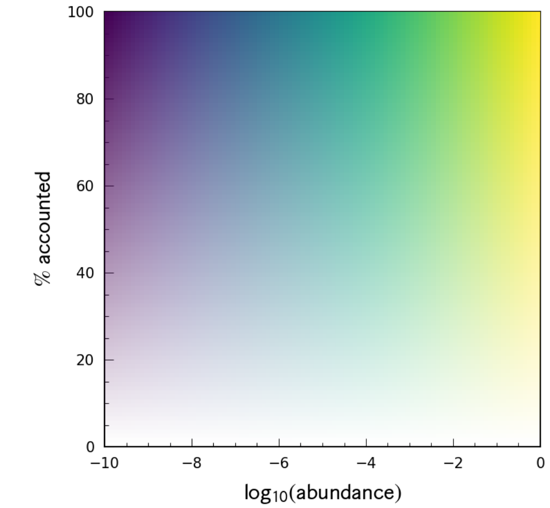


While previously hypothesised this was only confirmed recently.

The first neutron star collision was detected in 2017 by the **LIGO/Virgo gravitational wave observatory**. The light from this explosion was later detected by gamma ray and visible light observatories.

ORIGINS: NEUTRON STAR MERGERS



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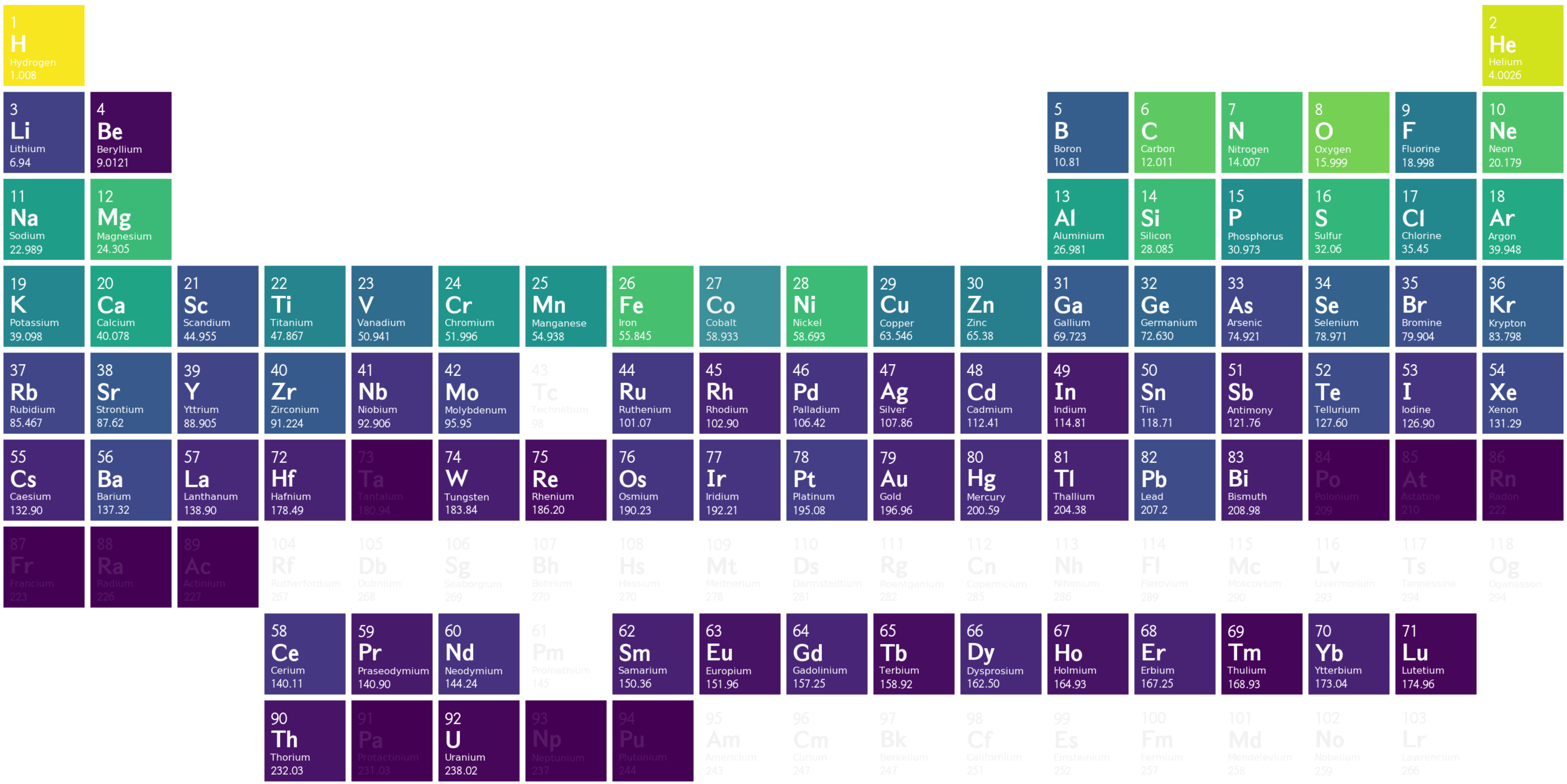
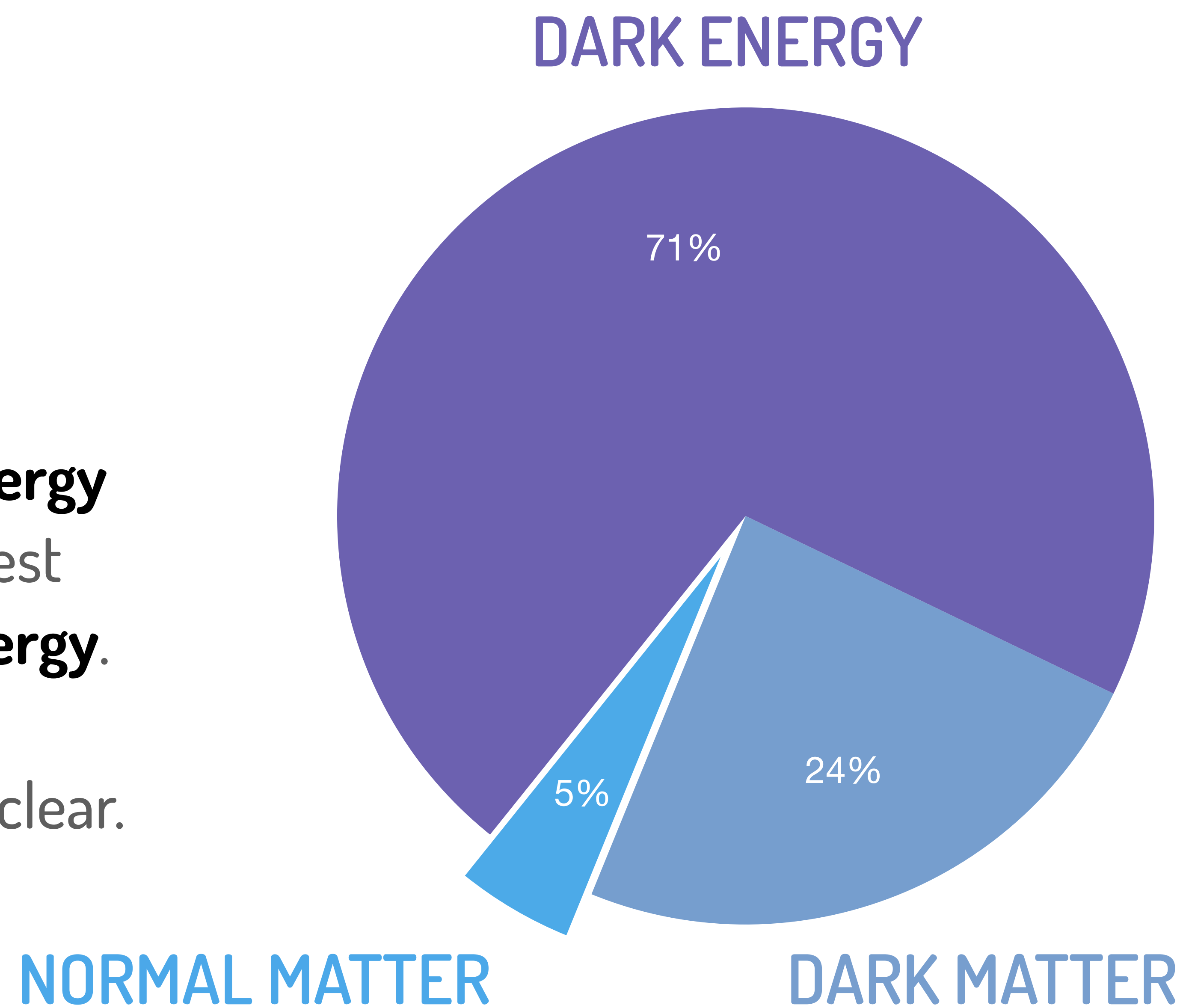


ANYTHING ELSE?

It's worth noting that Astronomers currently believe that the entire contents of the periodic table only make up a small fraction of the **energy content** of the Universe with the rest being in **dark matter** and **dark energy**.

Exactly what these are remains unclear.



THE END

- The atoms that make up your body were mostly produced during the **death throes of massive stars** billions of years ago.

- The precious metal in your jewellery was mostly created when **two neutron stars collided***.

- We still don't have a good idea about ~95% of the Universe.

* Arguably this is more impressive than being forged in the fires of Mount Doom.

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Webb Telescope

COMING **2021***

*maybe