

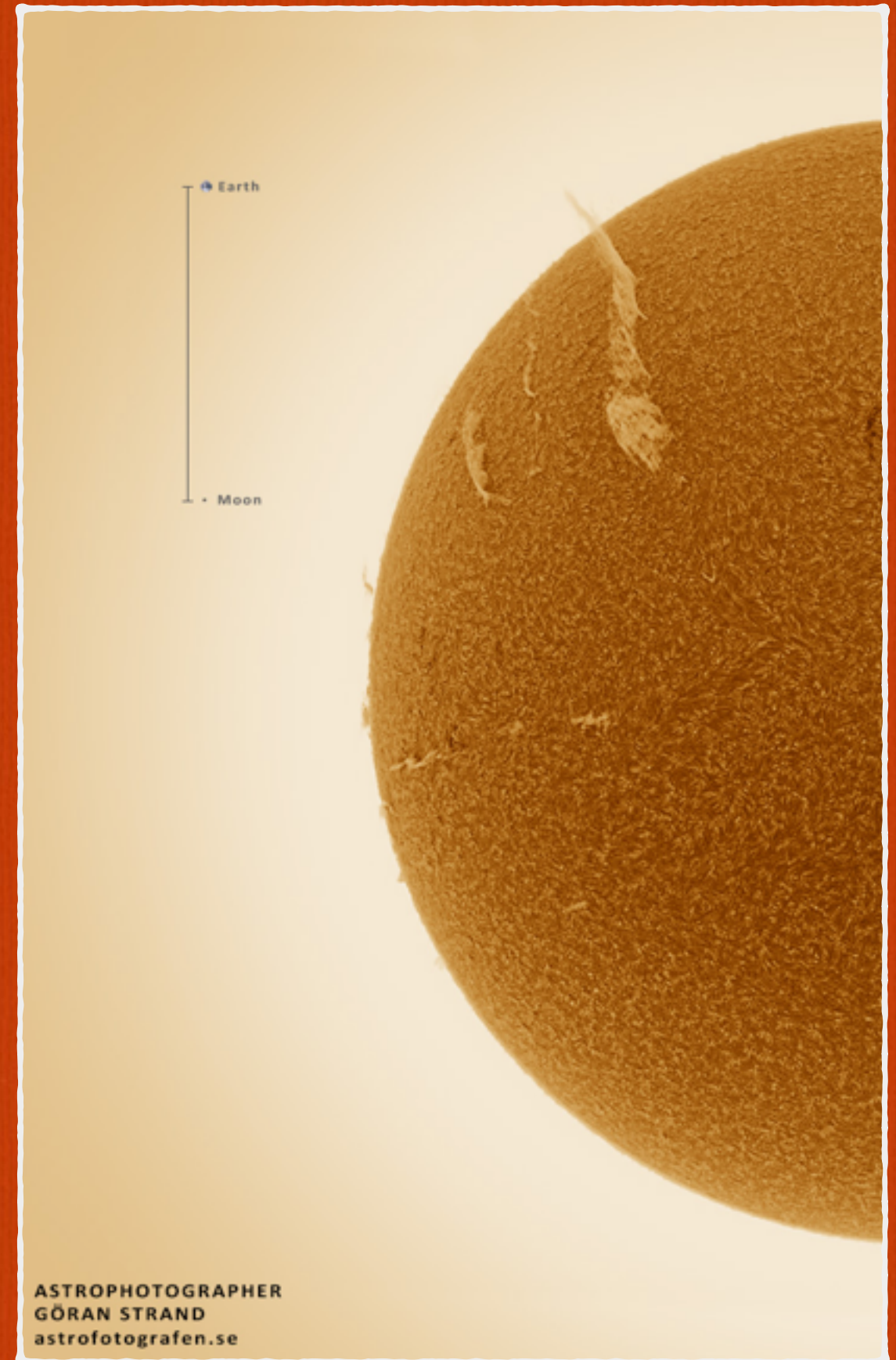
Stellar Fusion & Nucleosynthesis

Learning Targets

- ☐ I can use a model based on evidence to illustrate the life span of the Sun and the role of nuclear fusion in the Sun's core to release energy in the form of radiation.
(NGSS HS-ESS1-1)
- ☐ I can communicate scientific ideas about the way stars, over their life cycle, produce elements.
(NGSS HS-ESS1-3)

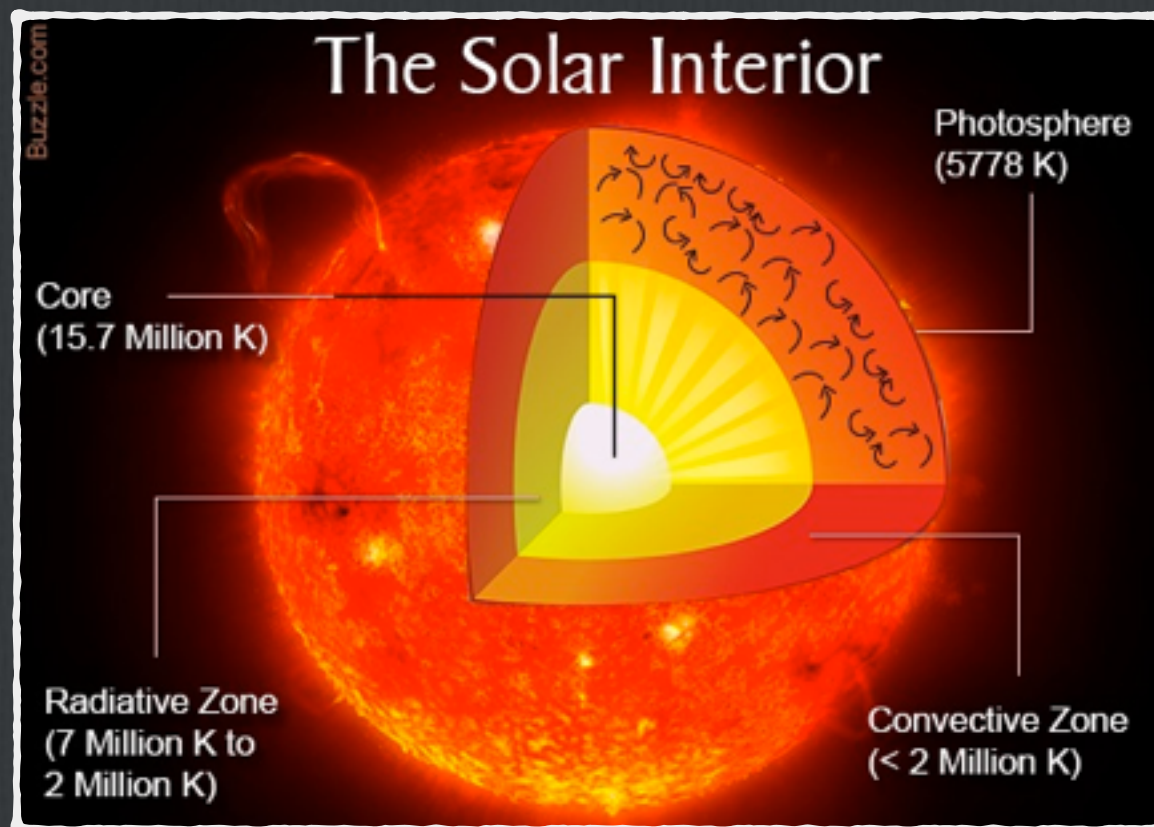
Nuclear Fusion

Fusion is process by which atomic nuclei are combined. This is the process stars employ to convert mass to energy.



ASTROPHOTOGRAPHER
GÖRAN STRAND
astrofotografen.se

Nuclear Fusion...not so easy

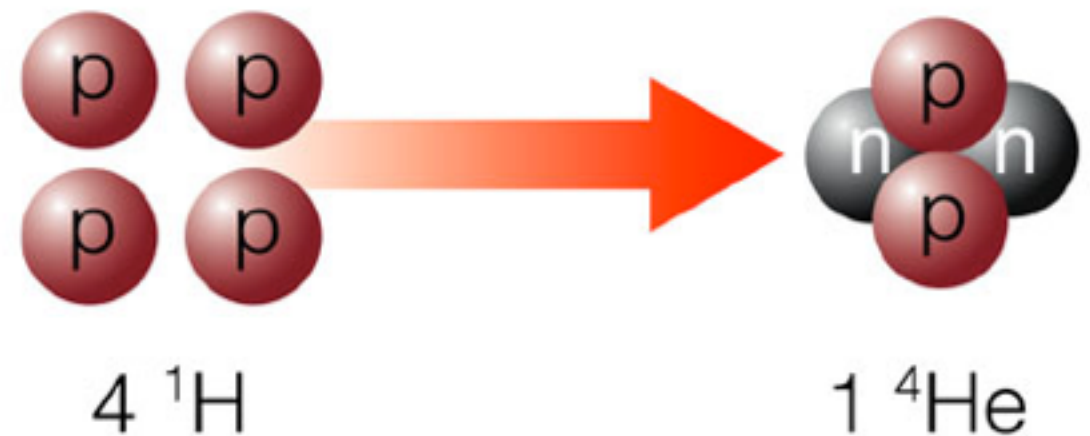


- ☐ Because fusion involves positive nuclei getting close enough to combine, it's a difficult process to get going because the nuclei electrically repel.
- ☐ Fusion therefore requires high temperatures (speeds) and pressures
- ☐ The requirements are hard to obtain on Earth, but stars have those in abundance!

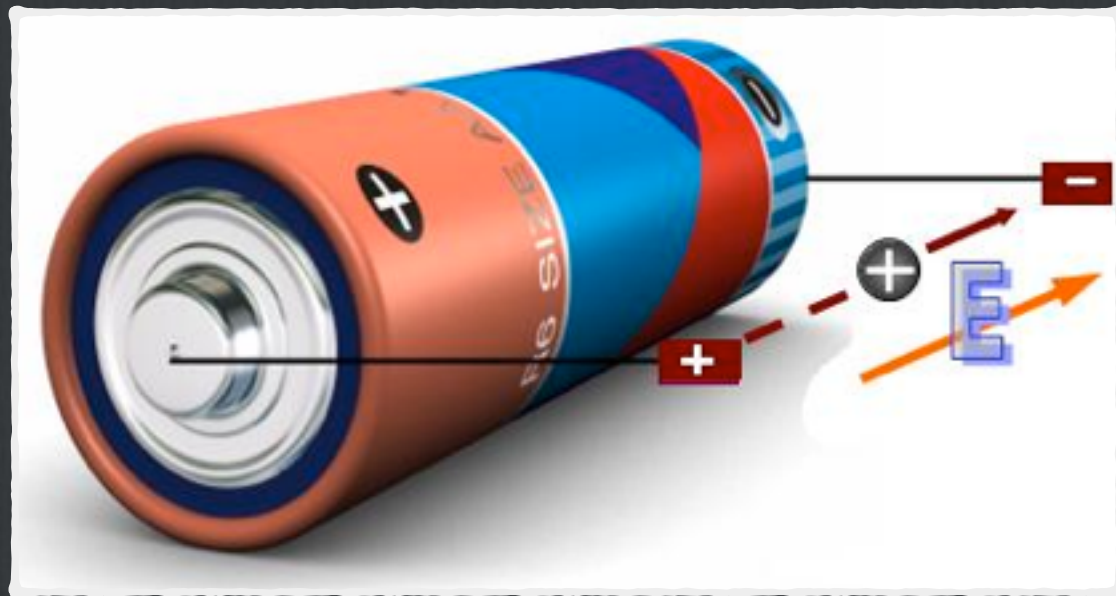
<http://www.buzzle.com/images/astronomy/sun/solar-interior.jpg>

Hydrogen to Helium

- Since 91% of the universe is hydrogen, most stars spend their lives fusing hydrogen into helium.
- As it turns out, the mass of the helium produced is slightly less than the mass of the hydrogen that fuses to make it...the missing mass is converted to energy via $E=mc^2$



Energy Units



- ☐ The SI unit of measurement for energy is the Joule (J).
- ☐ A smaller unit of energy called the electron-Volt (eV) is often used in nuclear science.
- ☐ $1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$
- ☐ Sometimes you'll see energies written in MeV or million electron-Volts.

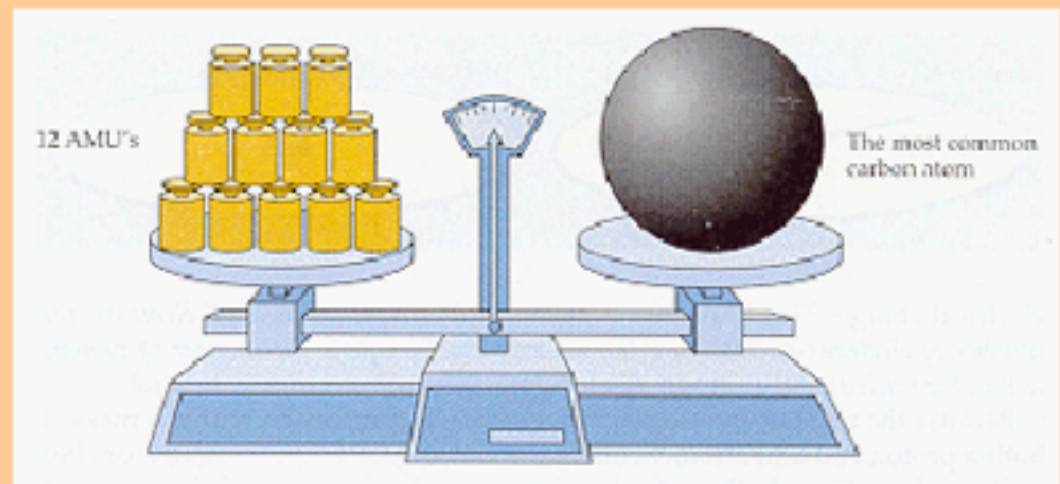
Mass Units

Nuclear scientists also use mass units called atomic mass units (amu or u for short).

1 u = 1/12 the mass of a Carbon-12 atom

$$1 \text{ u} = 1.660\,539 \times 10^{-27} \text{ kg}$$

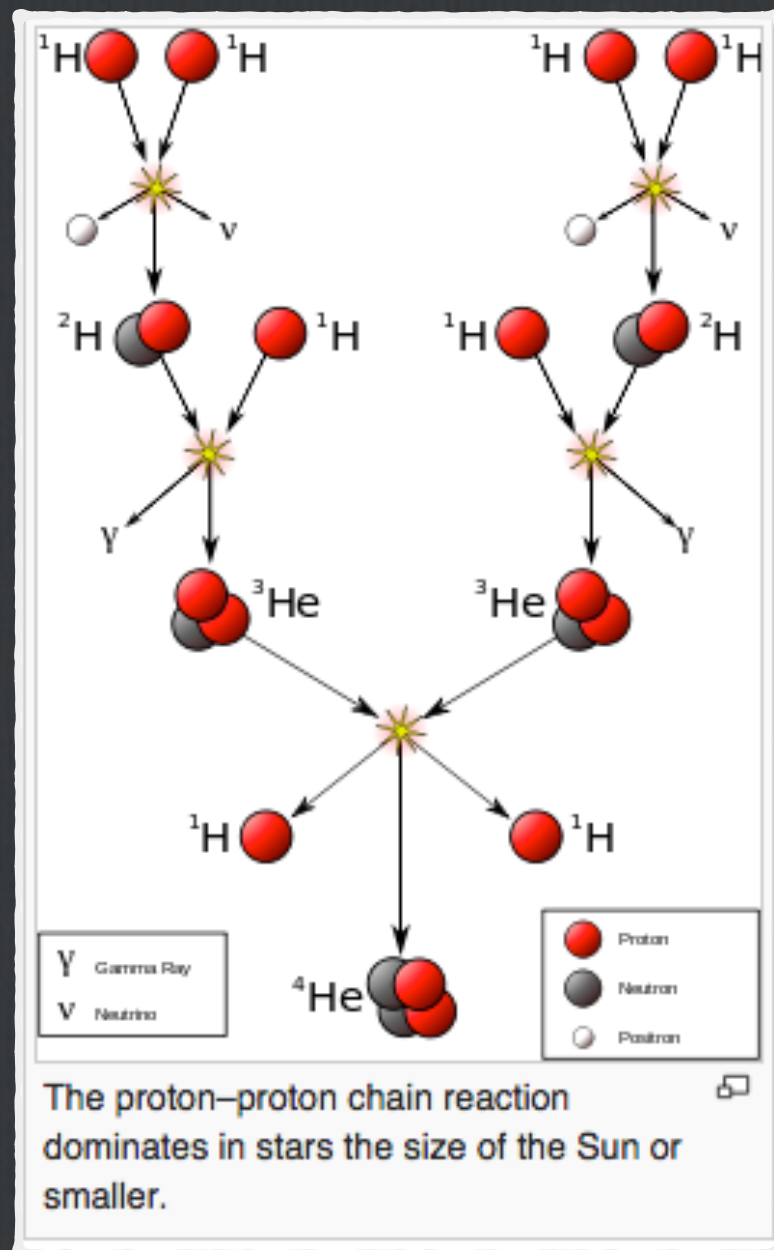
The Atomic Mass Unit, amu



The atomic mass unit, or amu, is 1/12 of the mass of the most common *isotope* of carbon.

Example 1: Using $E=mc^2$, convert the mass of an electron ($9.109\,383 \times 10^{-31}$ kg) into its energy equivalent in Joules and electron-Volts and MeV.

Fusion in stars like the Sun



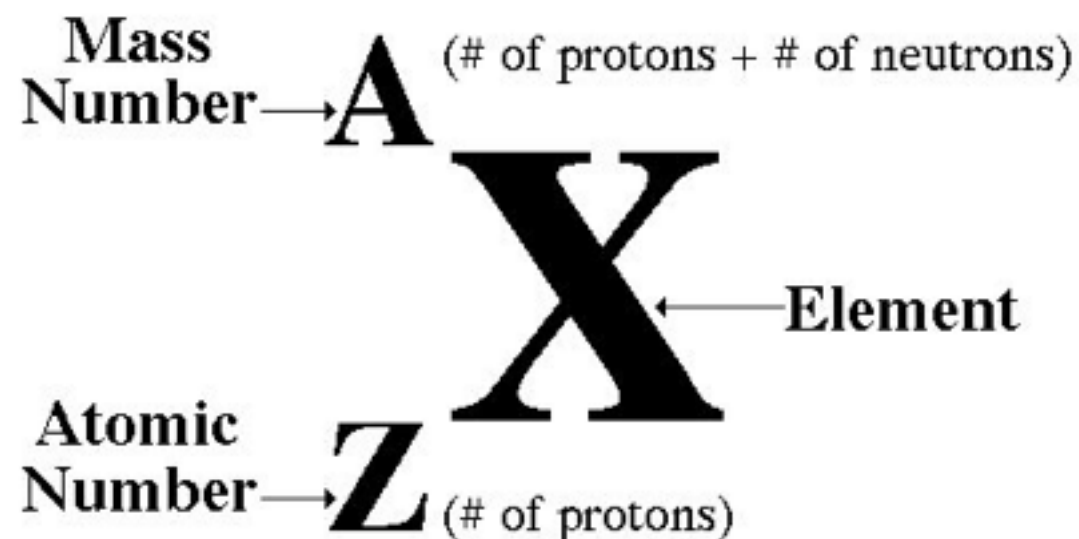
- ☐ If it's hard to get two hydrogen nuclei (protons) to fuse because of electric repulsion, you can imagine how difficult it is to get four of them to fuse!
- ☐ Low mass stars like our Sun, end of using a series of reactions called the proton-proton chain (p-p chain) to fuse 4 hydrogen into 1 helium.

Symbols in Nuclear Reactions

Make note of the small changes to symbols
in nuclear reactions

- We call the top number on the left the “nucleon number.”
- We use the bottom number on the left for “electric charge.”
- The symbol X can now be used for things that aren’t elements like neutrons, electrons, etc.

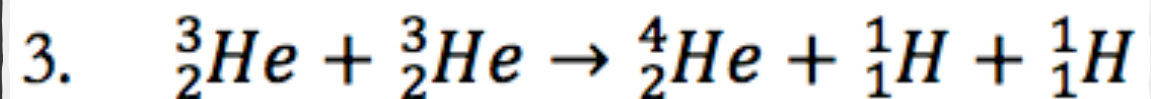
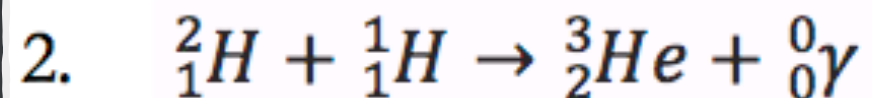
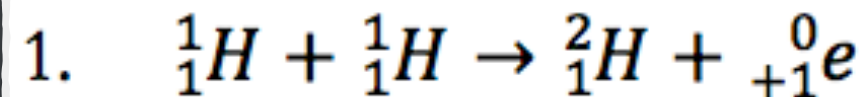
Isotope Symbols



Some Common Nuclear Equation Symbols and Masses

Atomic Number (z)	Element	Symbol	Mass (u)
0	(<u>electron</u>)	${}_{-1}^0e$	0.000 549
0	(<u>positron</u>)	${}_{+1}^0e$	0.000 549
0	(<u>neutron</u>)	${}_0^1n$	1.008 665
1	Hydrogen-1	${}_1^1H$	1.007 825
1	Hydrogen-2, Deuterium	${}_1^2H$	2.014 102
1	Hydrogen-3, Tritium	${}_1^3H$	3.016 049
2	Helium-3	${}_2^3He$	3.016 029
2	Helium-4	${}_2^4He$	4.002 603

p-p chain



- ☐ The first reaction involves two hydrogen nuclei fusing to make a deuterium nucleus and a positron.
- ☐ The second reaction involves a deuterium fusing with ordinary hydrogen to make helium-3 and a gamma photon.
- ☐ The third reaction fuses two helium-3 to make helium-4 and two protons.

u to MeV

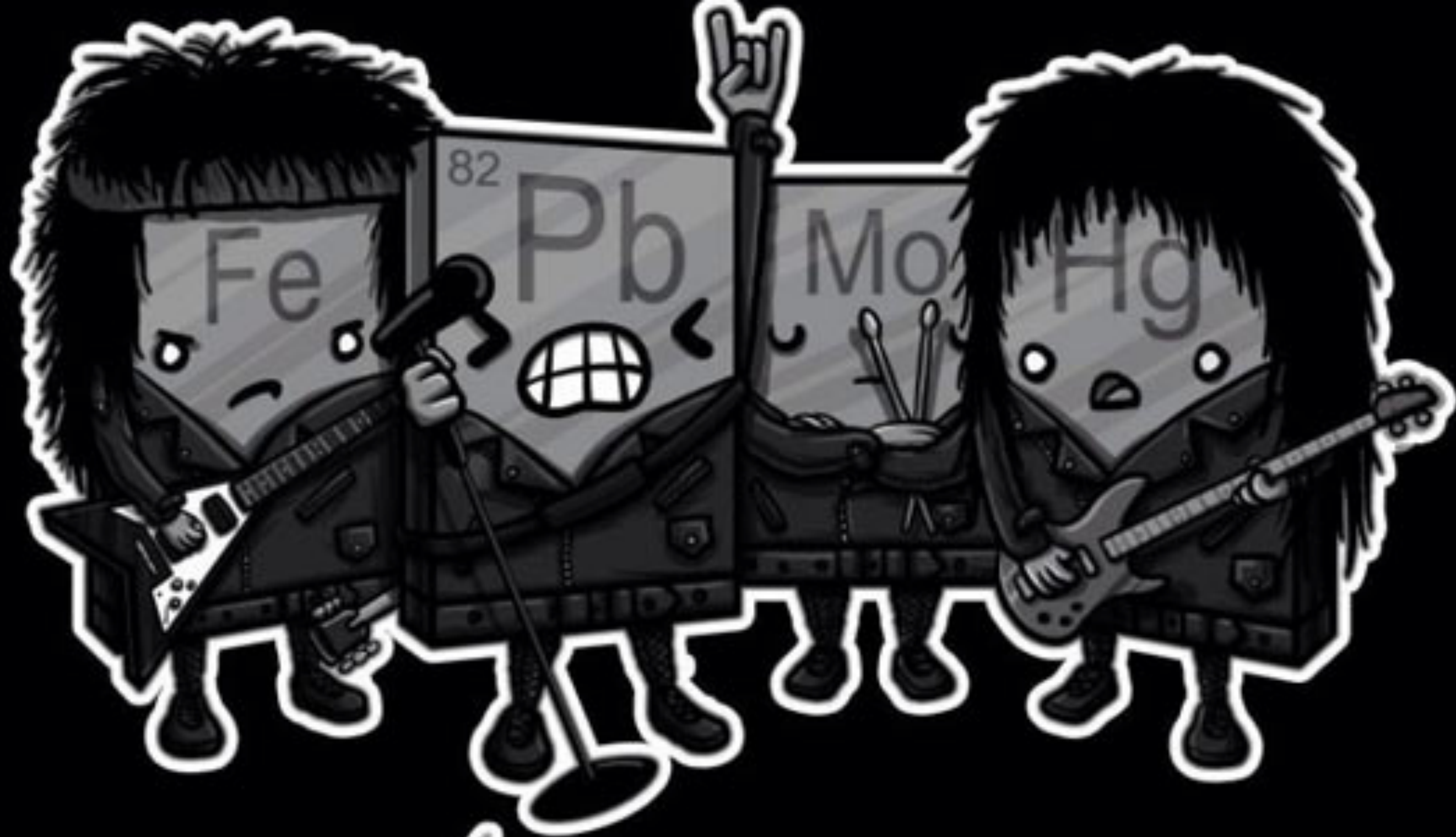
1 u = 931.5 MeV



Example 2: Using the information in the mass table and the first reaction equation, determine the amount of mass lost in the reaction in u and then convert to MeV.

**“In theory, theory and practice
are the same. In practice, they
are not.”**

–Albert Einstein



HEAVY METALS

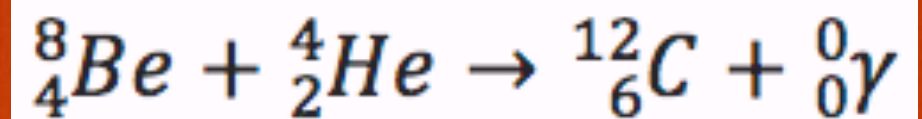
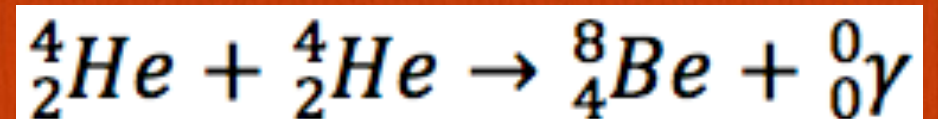
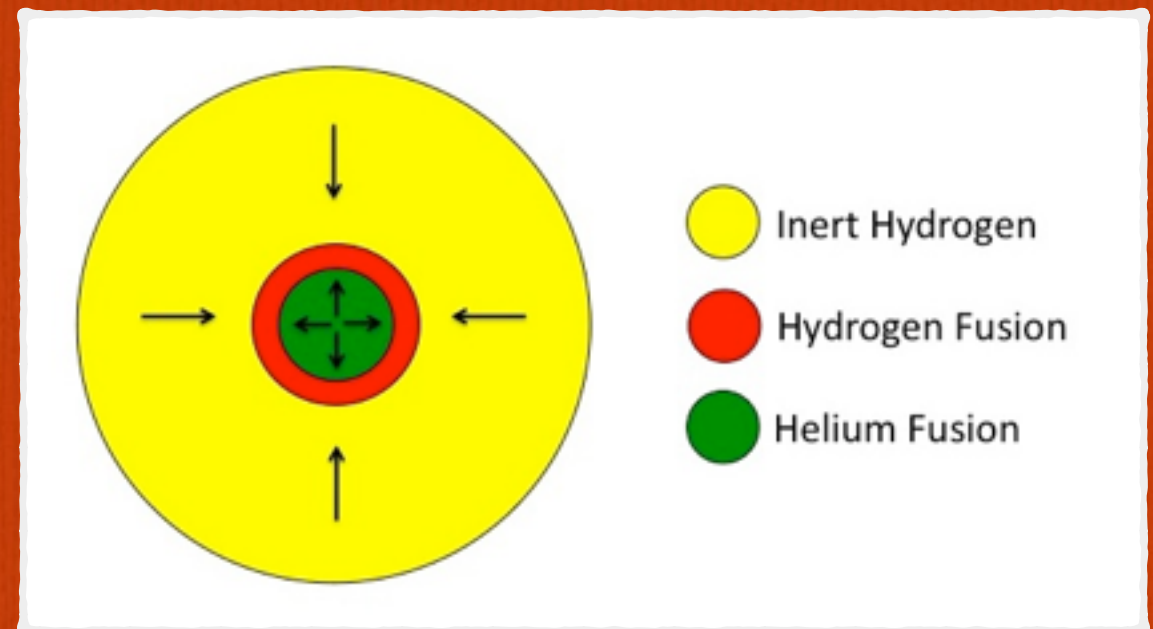
What about the heavier elements?...first equilibrium.



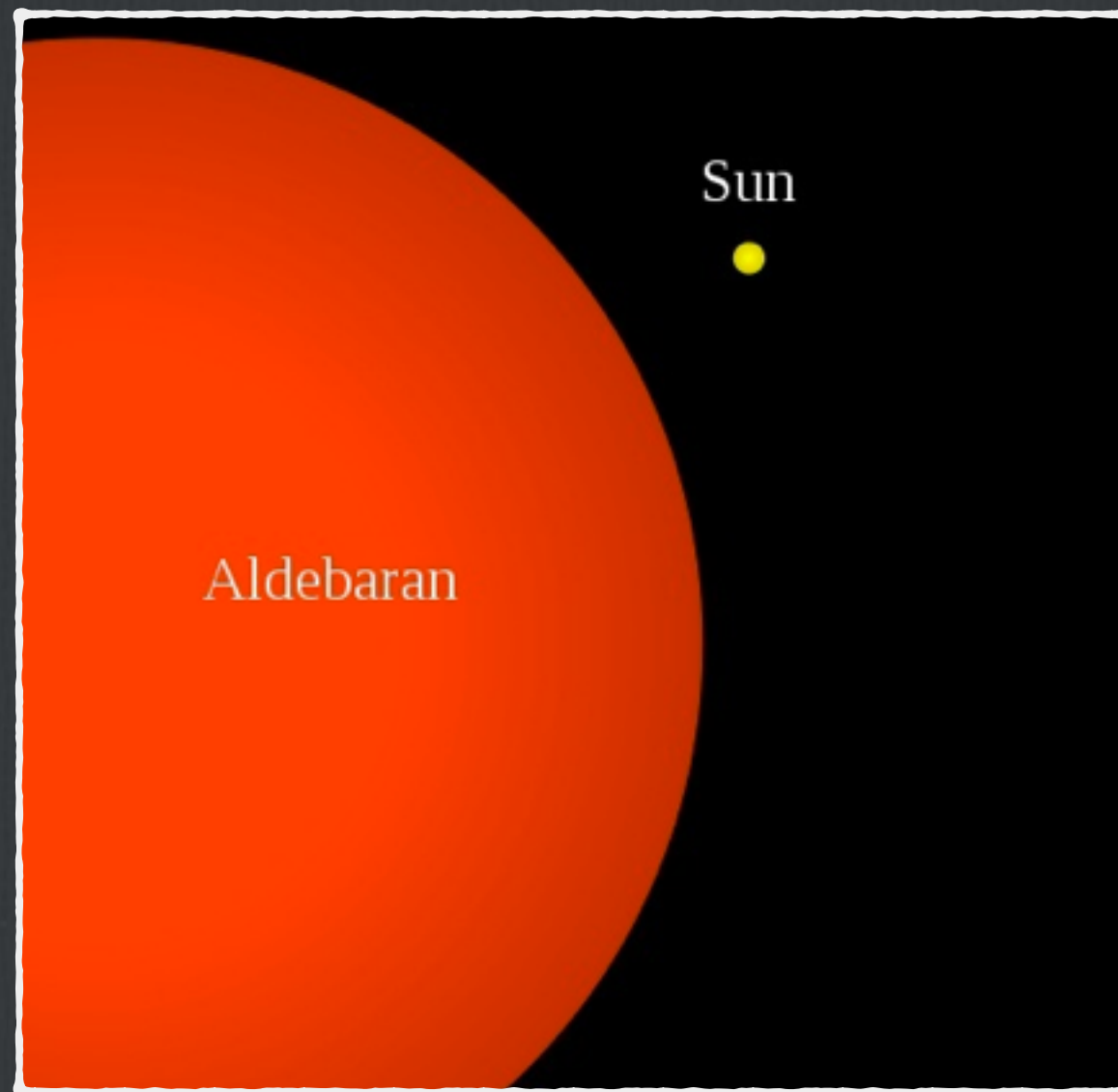
- ☐ Stars spend most of their lives fusing hydrogen into helium—with pressure from fusion reactions keeping gravity from collapsing the star into a smaller object.
- ☐ What do you think happens when the star runs out of hydrogen in the core?

Core Contraction

- As stars run out of hydrogen to fuse in the core, the core contracts and heats up.
- If the star's mass is large enough, this extra heat (higher velocity particles) allows nuclei with more positive charge to begin fusing.
- The Sun for example will begin fusing helium into beryllium and carbon.



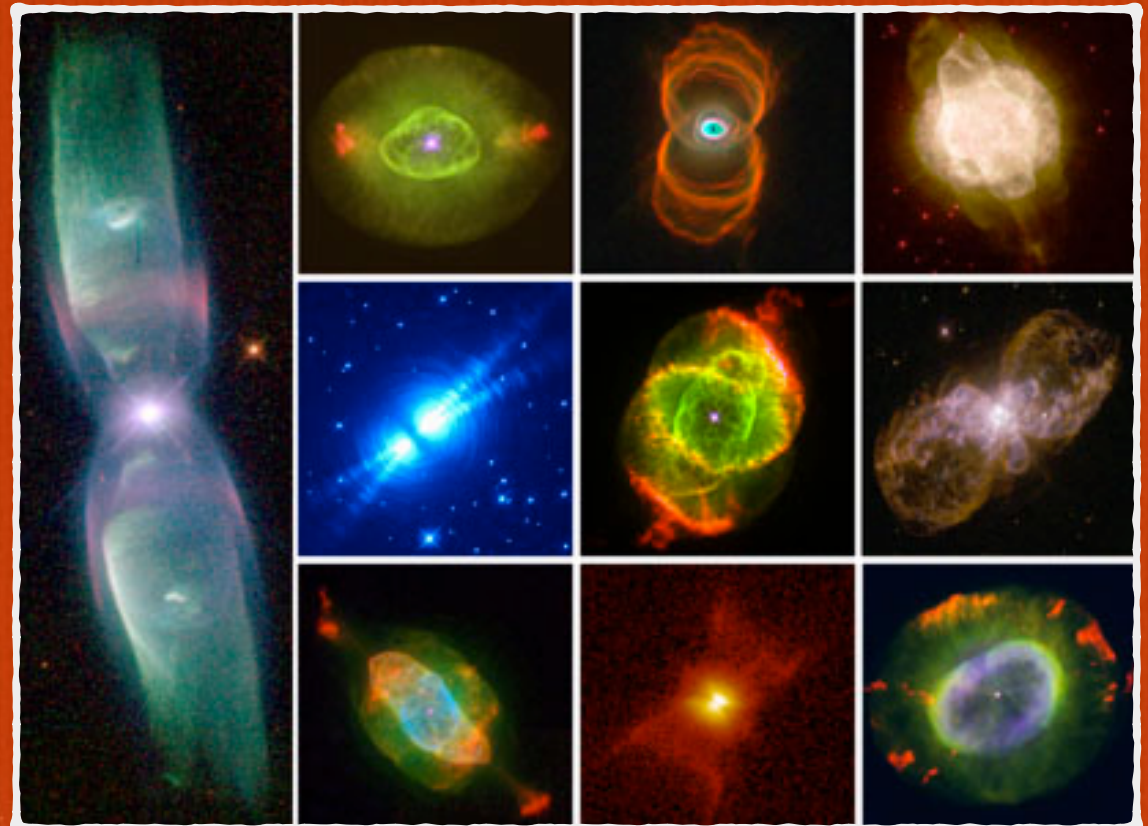
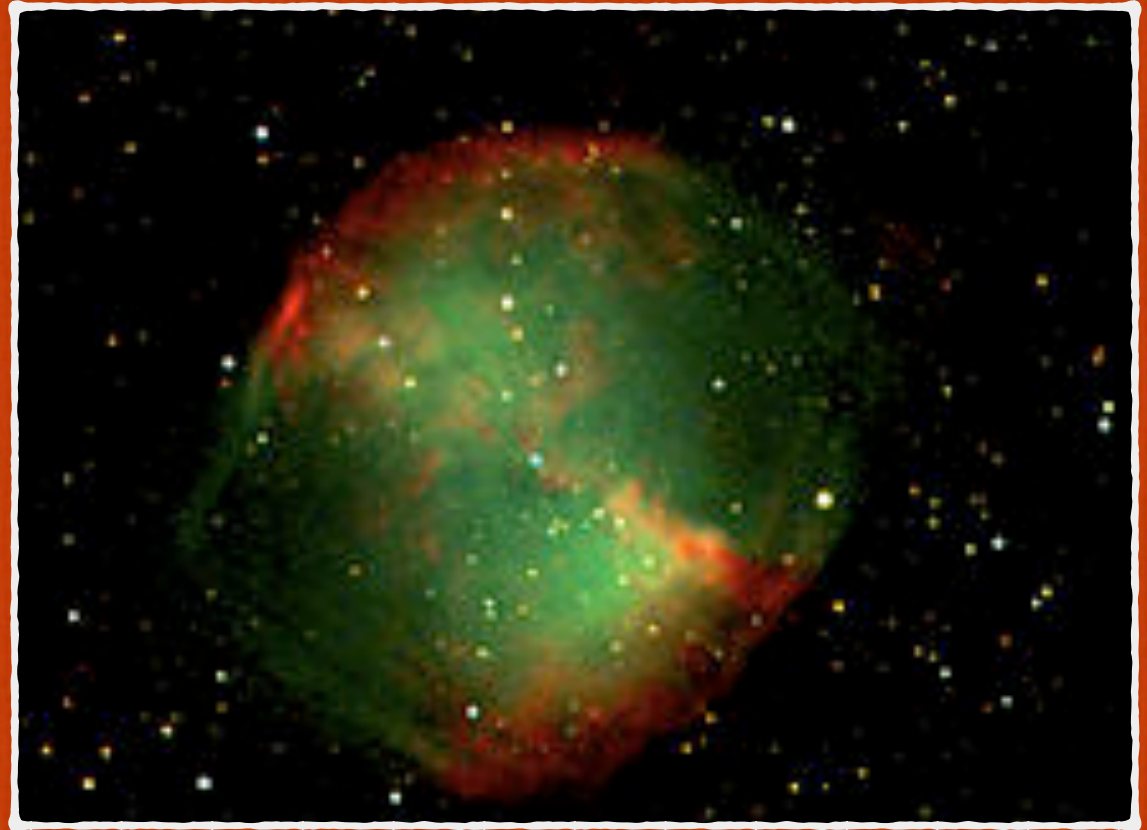
The End of the Sun



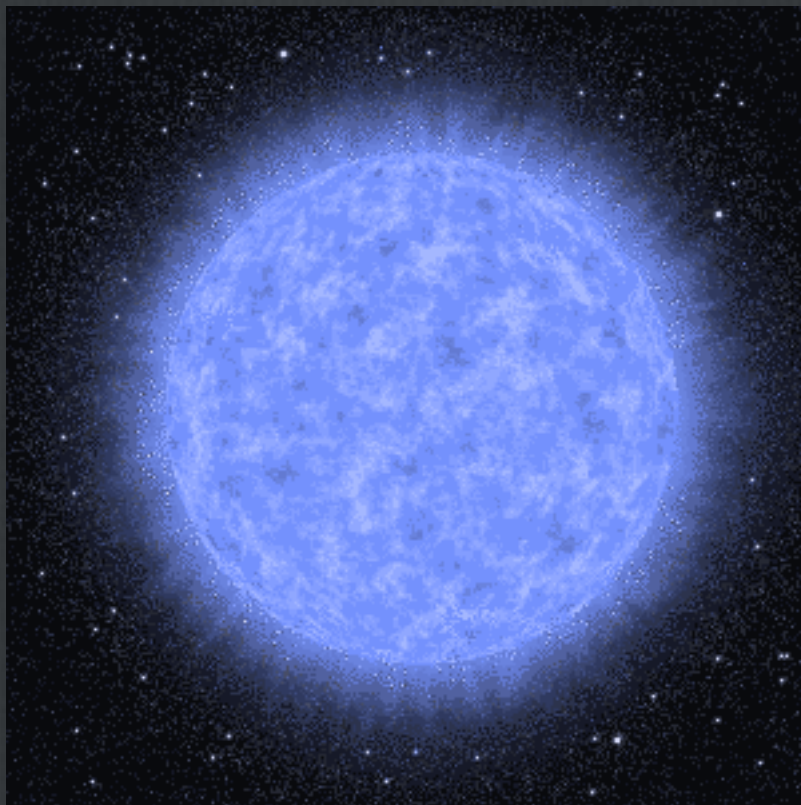
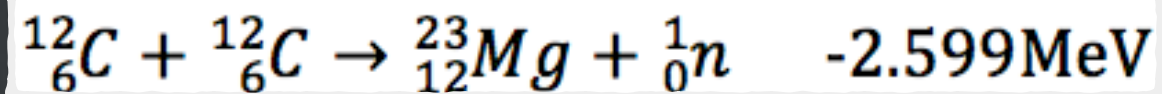
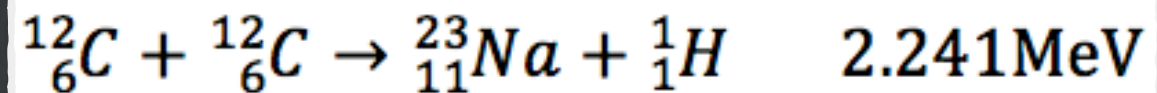
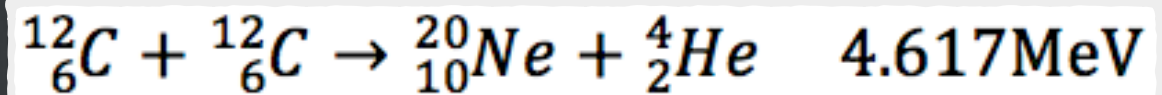
- ☐ For stars around the mass of the Sun and a smaller, even when they run out of helium and the core contracts again, there won't be enough heat to start fusing carbon into other elements—the electric repulsion is too large.
- ☐ But, the Sun will grow into a Red Giant (like Aldebaran in Taurus) during the helium fusion—ending Earth.

Planetary Nebulae form as medium mass stars throw off their outer layers and the core contracts to become a slowly cooling White Dwarf star.

This is the likely fate of the Sun, but the nebulae can be “out of this world” beautiful!



Massive Stars



- Massive stars (>8 solar masses), can continue to fuse even heavier elements since the extra gravity allows the core to continue to contract and increase temperature.
- After they run out of helium in the core, there's enough heat to begin carbon fusion.

There's a limit

Even massive stars have fusion limits.

- As it turns out, fusing some elements is impossible without adding energy. (unlike Mr. Fusion from Back to the Future).
- What did you notice about the last carbon fusion reaction?



Binding Energy



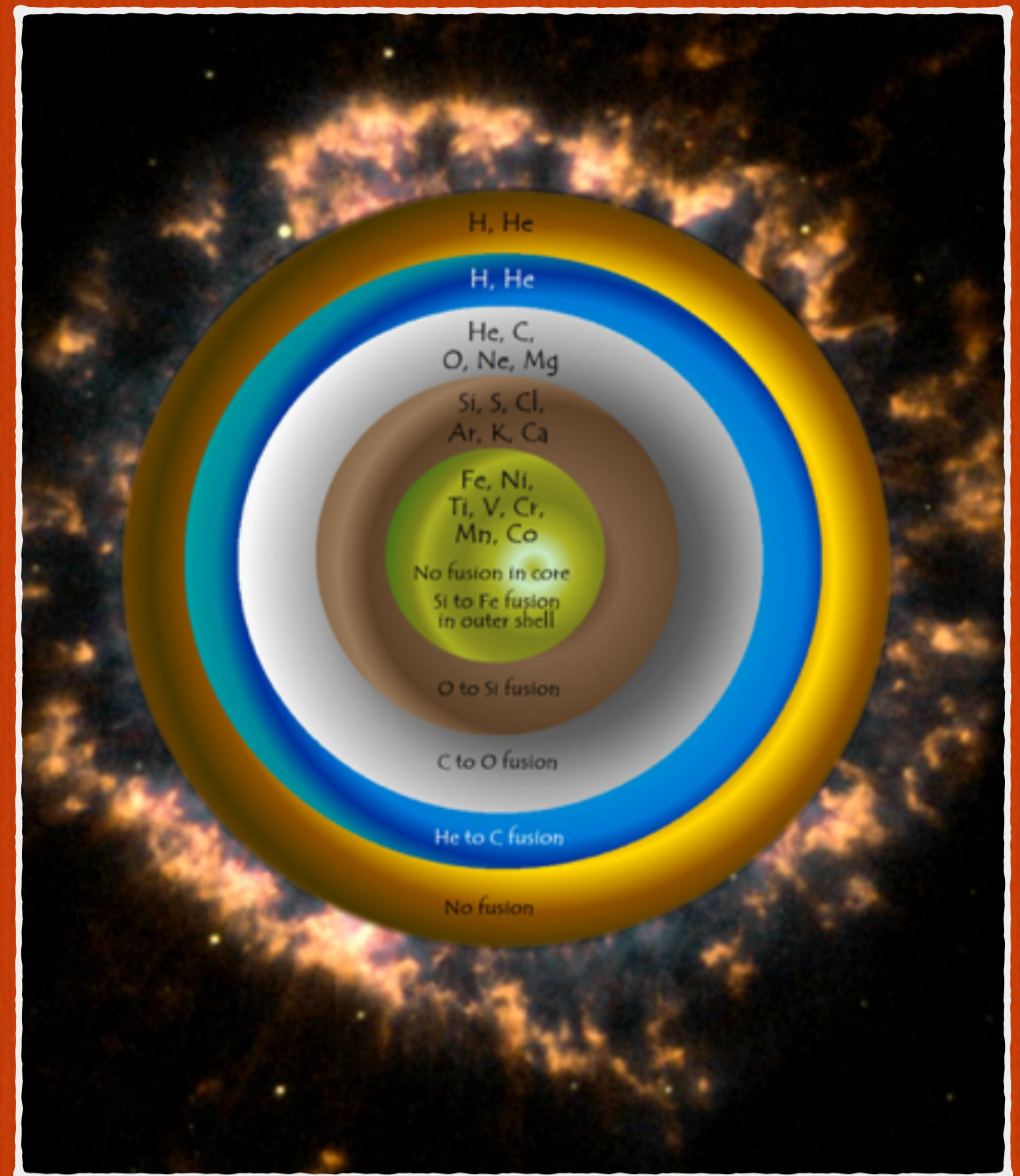
- ☐ To discover that elemental limit, we need to know some more nuclear science.
- ☐ The mass of an atomic nucleus is less than the mass of its constituent protons & neutrons. This mass difference is called “binding energy.”
- ☐ It's as if the nucleons have to pay dues to join various clubs—they do so in mass. It's the cost of keeping those nucleons bound.

Let's try and discover the elemental limit for stellar fusion by investigating binding energy in more detail. See the Binding Energy Background and Binding Energy Practice handouts.

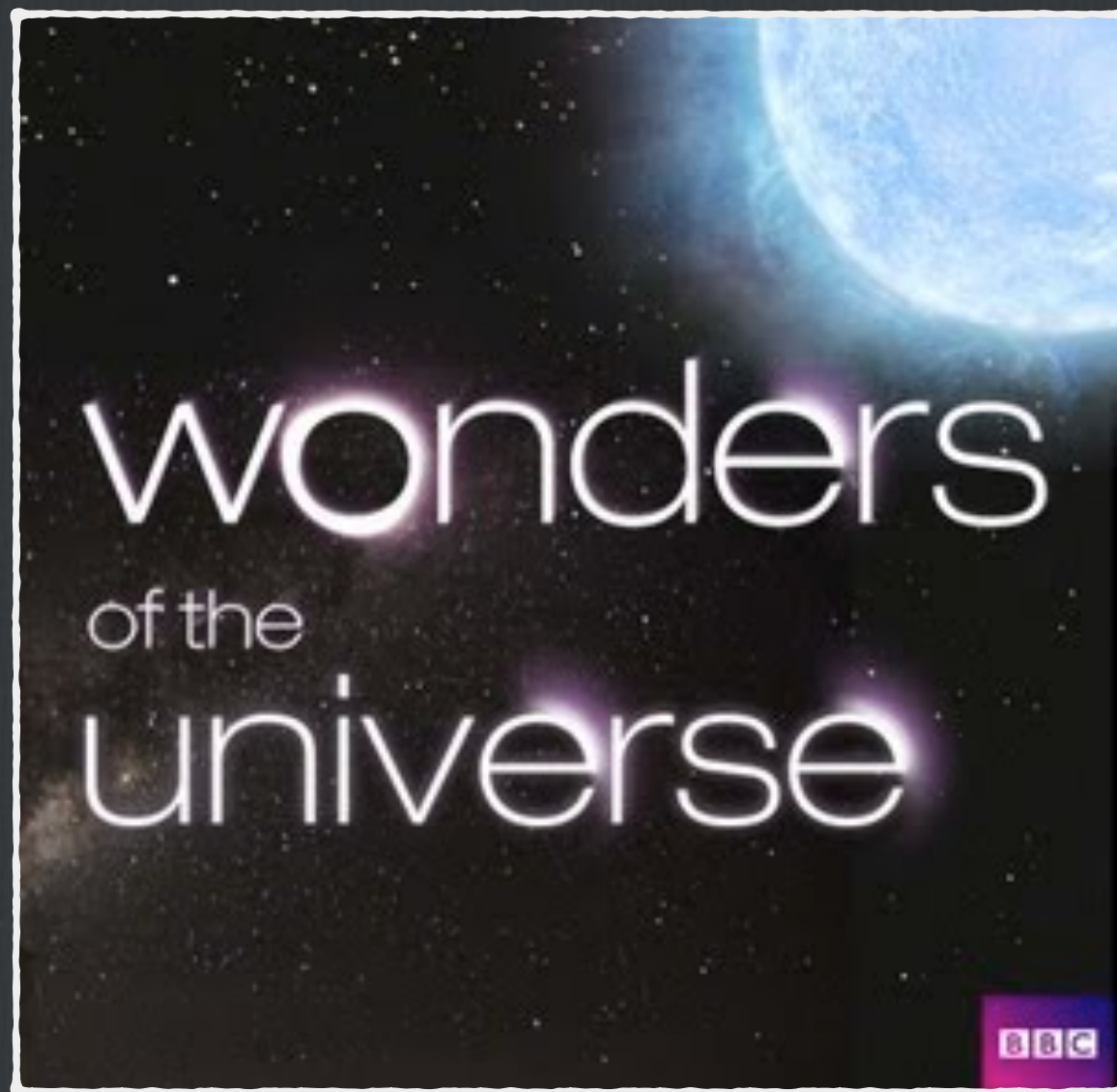
Once a Massive star reaches that final element...

...Iron, nuclear fusion reactions no longer release energy and the star dies within a matter of seconds.

The core collapses and the outer layers fall in and rebound off the collapsed core forming the most powerful explosion in the universe—a supernova.



Nuclear Synthesis Recap



- ☐ Wonders of the Universe, Star Death and Synthesis of the Elements (~6 min)
- ☐ <https://www.youtube.com/watch?v=DEw6X2Bhly8>

Supernova

- Supernova (Type II) occur soon after a massive star begins to fuse iron in its core.
- They can briefly outshine an entire galaxy of stars and release as much energy as the Sun does over its entire lifetime!
- The Crab Nebula on the right is made of the ejected matter of a supernova first reported by Chinese astronomers in 1054 C.E.





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Gold

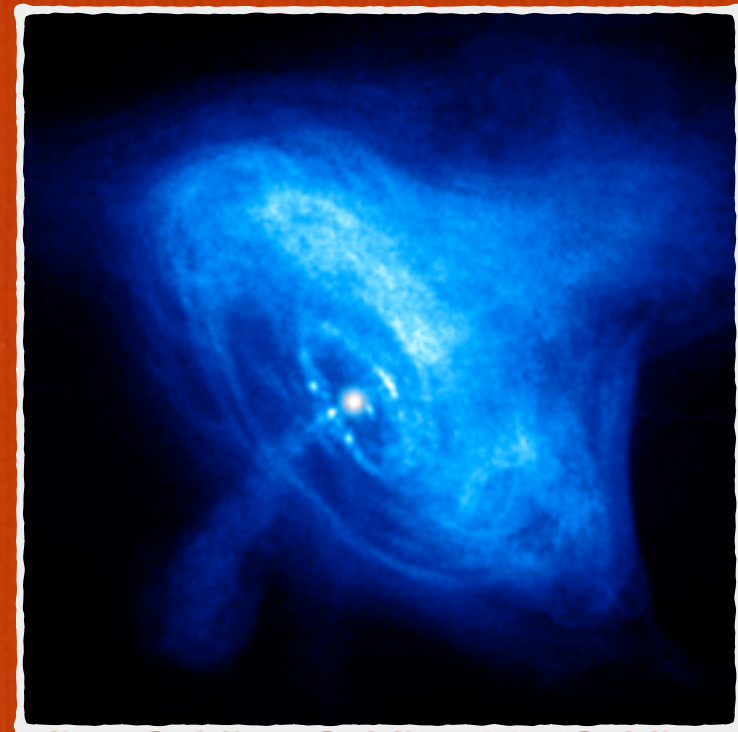
(& Cu, Zn, Sn, Ag, Pb, U, etc.)



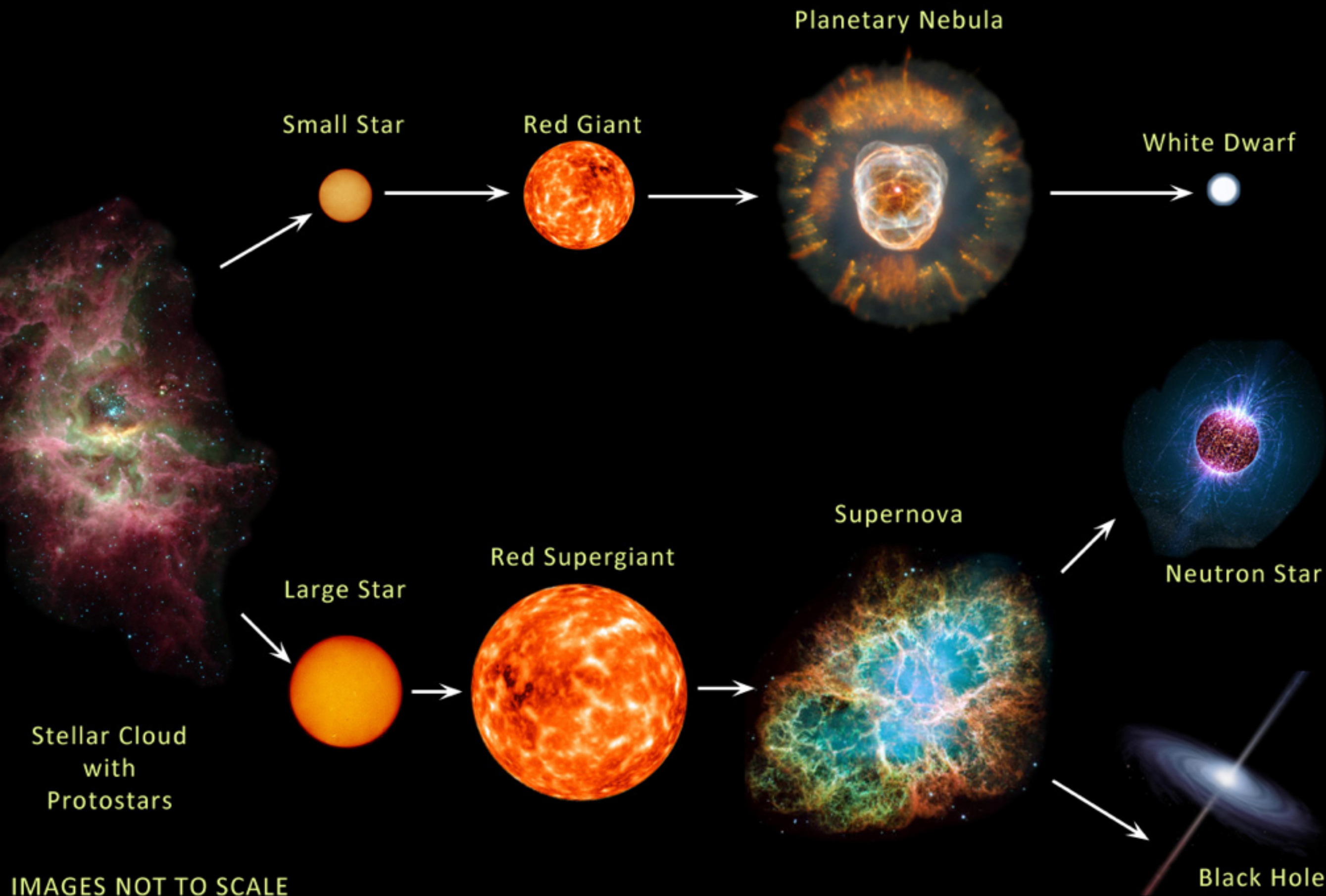
- ☐ The enormous energy released in supernova allow for elements heavier than iron to be formed.
- ☐ Gold is a great example. The video below is about 3.5min
- ☐ https://www.youtube.com/watch?v=yC7p_Bey5lU
- ☐ Or check out “Why We Are All Made of “Star Stuff.”
<https://www.youtube.com/watch?t=22&v=2bm479V8qPs>

What remains?

- After a supernova has spread much of the star's former mass out into space, the collapsed core remains as one of a few interesting objects:
- Neutron Star—all the core's mass compacted into neutrons about 10 miles across
- Black Hole—all the core's mass is mathematically predicted to be at a single point!



EVOLUTION OF STARS





The Most Astounding Fact

Neil deGrasse Tyson

<https://www.youtube.com/watch?v=9D05ej8u-gU>

“The nitrogen in our DNA, the calcium in our teeth, the iron in our blood, the carbon in our apple pies—were all made in the interiors of collapsing stars. We are all made of star stuff.”

—Carl Sagan