ASTR 1P02

Brock University
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Lecture 11:
How stars shine

We will learn about…

- Mass, energy, and how they are related.
- Subatomic particles and fundamental interactions.
- How stars produce light using nuclear fusion.

Stars in the Milky Way galaxy
Credits: NASA/JPL-Caltech/S. Stolovy (Spitzer Science Center/Caltech)

Mass and energy

- First, let us learn about mass, energy, and the relation between them according to relativity.
- WARNING: There are a lot of misconceptions about what we are going to learn in this section! Even the textbook doesn't get it right. So pay attention...

Mass and energy

- We first learned about mass in lecture 6 of ASTR 1P01.
- Mass, denoted by m, intuitively measures "how much matter" is in an object. But that's not a precise definition.
- Mass is related to force F and acceleration a by Newton's 2^{nd} law:
$$F = ma$$
- In words: force is the product of mass and acceleration.

Mass and energy

- We can divide by m:

$$F = ma \quad \Longrightarrow \quad a = \frac{F}{m}$$

- Note that F is in the numerator while m is in the denominator.
- This means that for the same force F, if m gets larger, then a gets smaller.
- So the more mass the object has, the less acceleration it will get from the same amount of force.
- Therefore, we can define mass as resistance to acceleration.

Mass and energy

- Mass is also related to gravity by Newton's law of universal gravitation:

$$F = G\frac{m_1 m_2}{r^2}$$

  - m_1 is the mass of the first object.
  - m_2 is the mass of the second object.
  - F is the force of gravity between the objects.
  - r is the distance between the objects.
  - G is a constant of proportionality called the gravitational constant. Its value doesn’t matter, it’s just used to convert units.
- In words: “the force of gravity is proportional to the product of the masses of the two objects divided by the distance squared”.

Mass and energy

- So mass has two different meanings:
  1. Resistance to acceleration by any force (inertial mass).
  2. Strength of the gravitational force (gravitational mass).
- It turns out that the inertial mass and gravitational mass of an object are always the same, so we just call it “mass”.
- This didn’t have to be the case! We can imagine a universe where the inertial and gravitational masses of an object are not the same.
- The principle guaranteeing the equivalence of the two types of mass is called the equivalence principle.
- It is a crucial ingredient of general relativity, which we will learn about later.

Mass and energy

- Energy is usually denoted by E.
- You can think of energy as a “currency”, like money.
- Different things have different values in this currency, and you can exchange two things if they have the same value.
- If I have 1 table worth $100, I can trade it for 5 chairs worth $20.
- So I exchanged something worth $100 with something else also worth $100.
- No money was created or lost in the process. We can say the total amount of money was conserved.

Mass and energy

- Energy works in a similar way.
- An object’s motion (speed) contributes to its kinetic energy.
- An object’s height in a gravitational field contributes to its gravitational potential energy.
- When the object falls, its height decreases. So its gravitational potential energy decreases too.
- This energy is conserved, so it must go somewhere. In this case, it gets converted into kinetic energy, so the object’s speed increases.
- That explains why an object accelerates as it falls.

Simulation

- I will show a simulation of a skater going up and down a track, changing speed due to exchanging potential and kinetic energy.
- The simulation can be found at this URL:

https://phet.colorado.edu/sims/html/energy-skate-park/latest/energy-skate-park_en.html

Mass and energy

- There’s no such thing as “pure energy”.
- Energy is just a “currency” used to convert something (e.g. height) to something else (e.g. speed).
- Imagine a world where you cannot have money. You can know how much money something is worth, but you can’t sell it and get “pure money” back, you can only trade two things worth the same amount of money. That’s how energy works.
- When an object is falling, the concept of energy gives us a precise formula for how much height is “worth” (potential energy) compared to how much speed is “worth” (kinetic energy).

Mass and energy

- Food energy is another example. The number of calories in the food indicates how much energy it is “worth”.
- Our bodies convert food energy to other types of energy:
  - Thermal energy, to maintain body temperature.
  - Kinetic energy, to move the muscles.
  - And so on.
- Energy is the “currency” that tells us how much of one thing (food) can be converted to another thing (e.g. heat or motion).

Mass and energy

- According to Einstein’s theory of relativity, mass is also “worth” energy. This is described by his most famous equation:
$$E = mc^2$$
- m is the mass of the object.
- E is the energy that this mass is “worth”, also called rest energy.
- $c \approx 3 \times 10^8$ m/s is the speed of light.
  - This doesn’t mean this equation has anything to do with light!
  - The speed of light is really just a conversion factor, like an exchange rate.
  - 1 USD = 1.3 CAD, and similarly, 1 unit of mass = c^2 units of energy.

Mass and energy

- Remember: energy isn't a "thing" by itself. There is no such thing as "pure energy".
- The equation $E = mc^2$ simply means that mass can be converted to other things.
- The concept of rest energy tells us how much mass we need in order to get a certain amount of the other things.

Mass and energy

- A common misconception goes as follows:
  - Mass is a measure of the quantity of matter.
  - Therefore $E = mc^2$ means that "matter can be converted into energy".
- This is not entirely accurate.
- This misconception is very common, even among physicists and other scientists.
  - It also appears in section 16.2 of the course textbook.

Mass and energy

- Energy cannot exist on its own – there is no “pure energy”.
- Therefore, the statement “matter can be converted into energy” is wrong.
- Just like we can’t “convert speed into energy”, we also can’t “convert matter into energy”.
- $E = mc^2$ means we can convert mass into something else, like speed.
- Kinetic energy is how much the speed is “worth” in this conversion. Rest energy (mc^2) is how much the mass is “worth”.

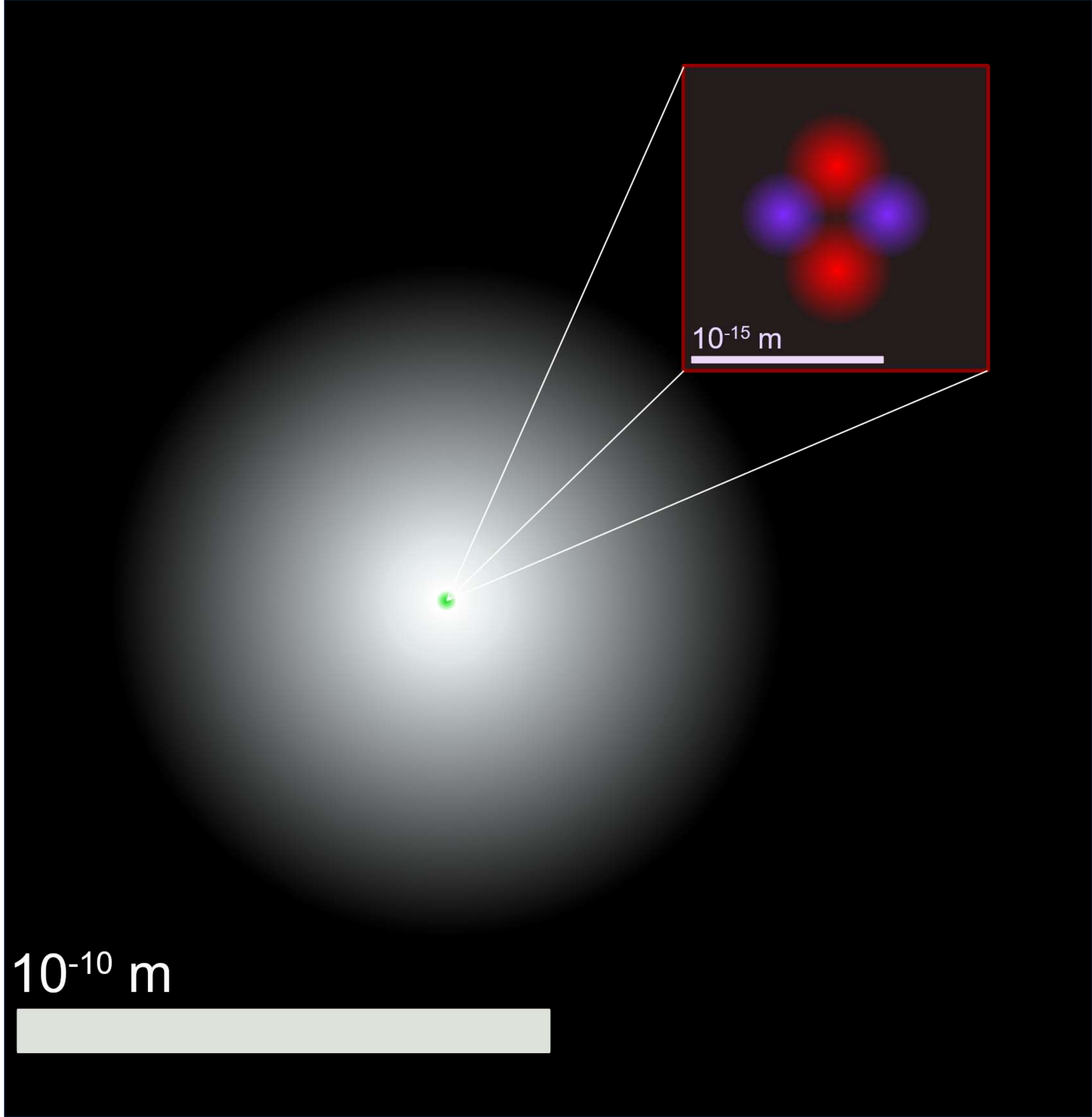
Mass and energy

- Another thing wrong with this misconception is that it confuses mass with matter.
- Mass intuitively measures “how much matter” is in an object, but that’s not a precise definition, just intuition.
- Mass is a property of matter, not the matter itself.
- As we will see, in the process that happens inside stars, the matter doesn’t exactly disappear. It just becomes a different kind of matter, with less mass but more speed.

Atoms and particles

- So it’s more precise to say that stars convert mass into speed, not matter into energy.
- But even that isn’t entirely accurate, since other things are also created in this process, not just speed (or kinetic energy).
- To better understand how this works, we need to review atoms and subatomic particles.
- We learned a bit about this topic back in lecture 1 of ASTR 1P01. Now we will learn about it in more depth.

- Most things we can see or detect, like stars, planets, and humans, are made of atoms.
- Every atom is composed of a nucleus, surrounded by a cloud of electrons.
- The nucleus itself is made of protons and neutrons, each of which is around 100,000 times smaller than an atom.



A Helium Atom
Credits: Modification of work by Yzmo (Wikipedia)

Atoms and particles

- Size of an atom: 10^{-10} m = 0.000 000 000 1 m
  - If you don't remember powers of 10, please review lecture 1!
- Size of a nucleus: 10^{-15} m = 0.000 000 000 000 001 m
- Size of a proton or neutron: just a bit smaller than the nucleus.

- This illustration of an atom you may have seen before is wrong!
- The electrons don't orbit the nucleus, they're "probability clouds".
- I'll explain what this means later, when we learn about quantum mechanics.

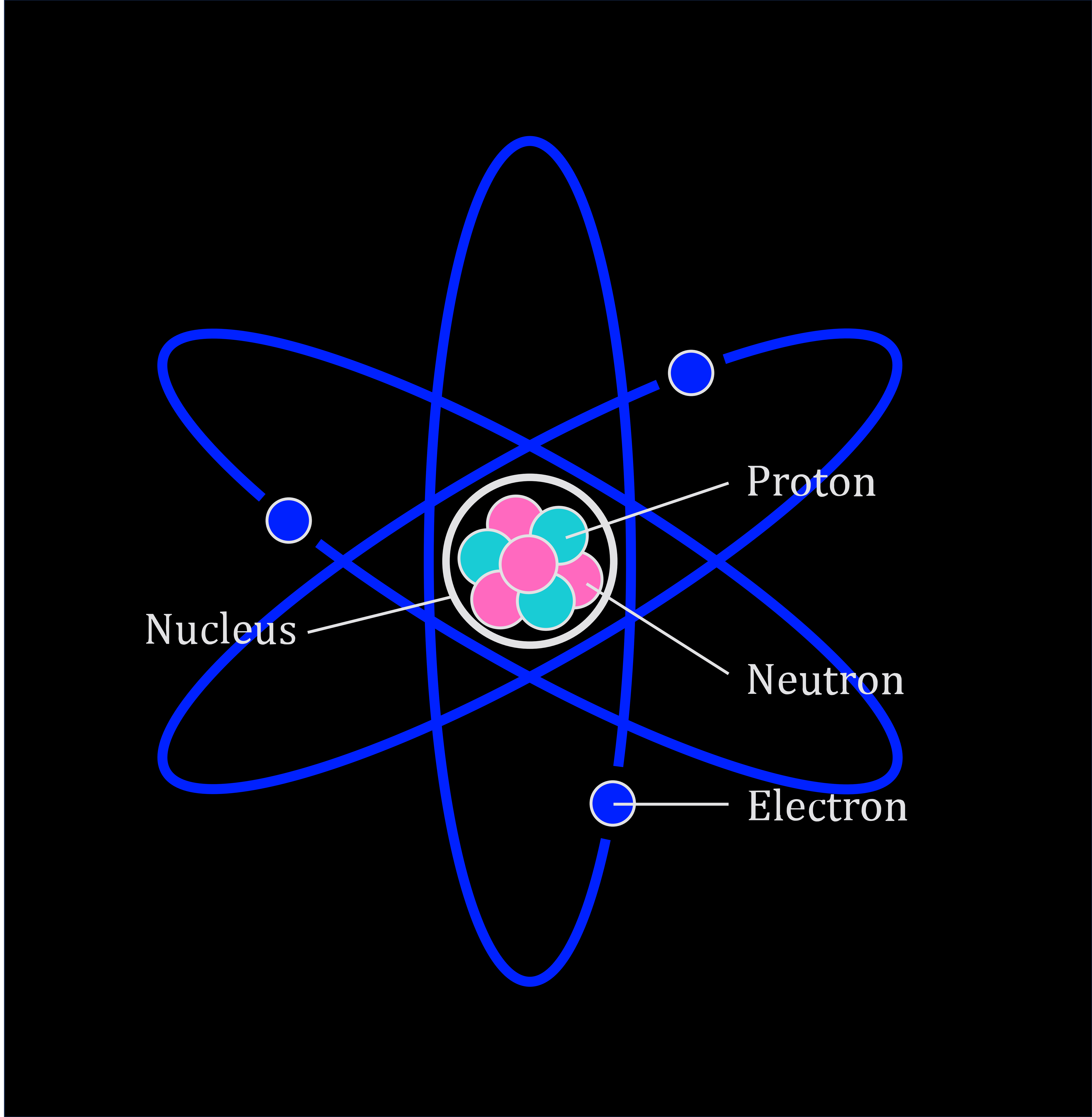


Diagram of an Idealized Lithium Atom
Credits: Modification of work by AG Caesar (Wikipedia)

Atoms and particles

- There are 118 different types of atoms that we know of, which are also called chemical elements.
- All atomic matter in the universe is made of different combinations of these 118 elements.
- The number of protons, known as the atomic number, determines the type of the chemical element.
- Hydrogen has 1 proton, helium has 2 protons, and so on.

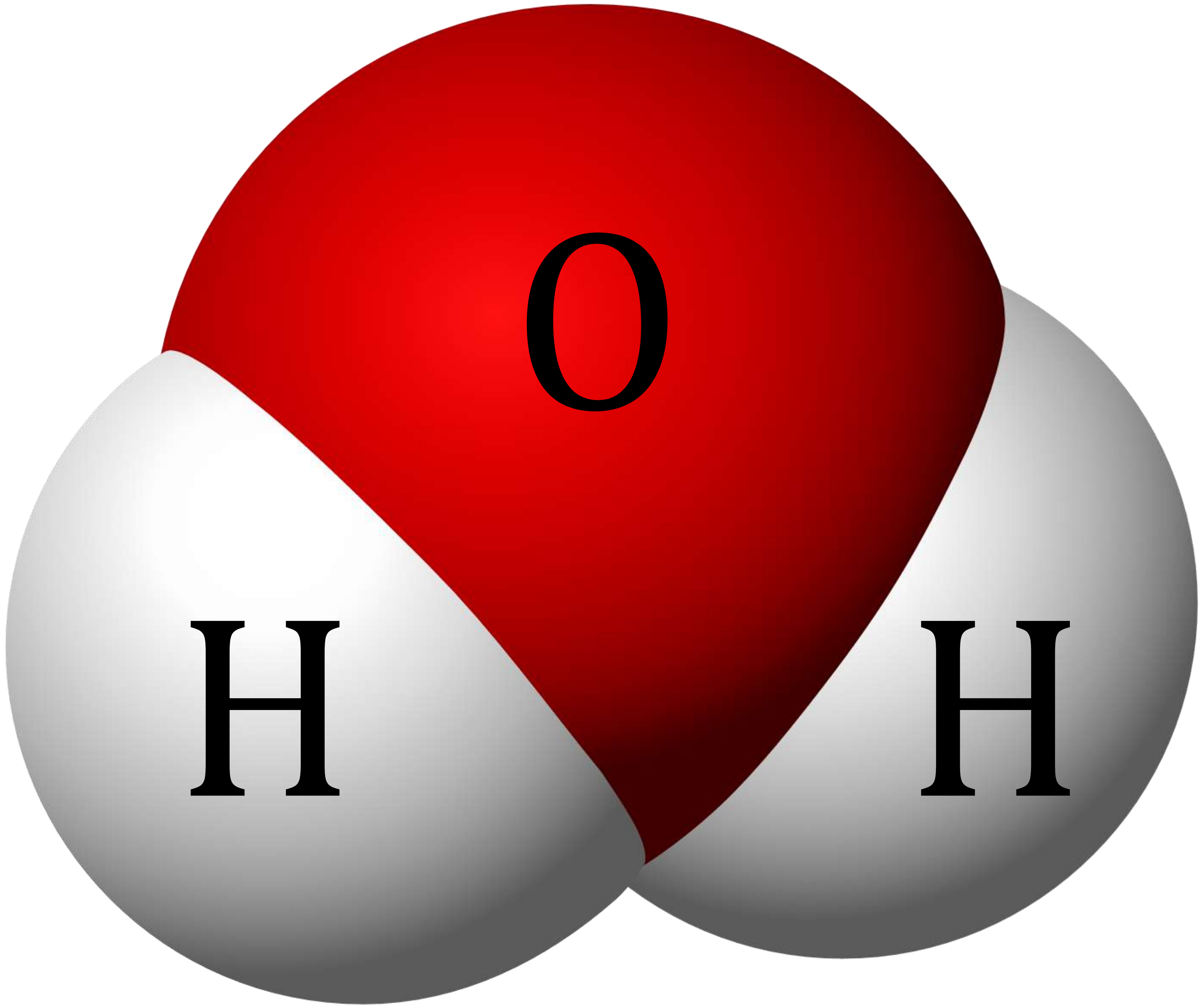
The Periodic Table of Elements

Credits: Modification of work by Robert Campion

Atoms and particles

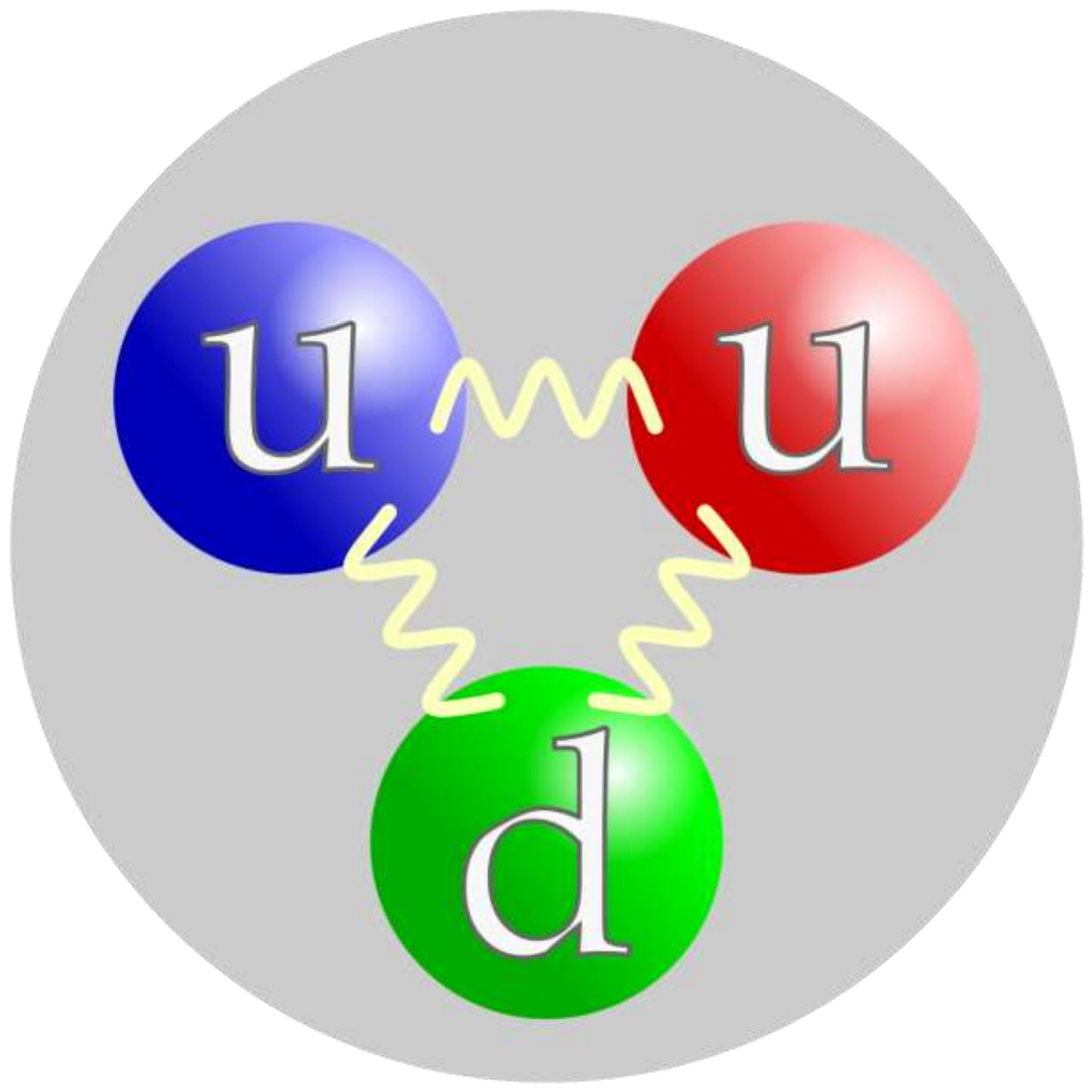
- Hydrogen (1 proton) is the most common element. It makes up 74% of atomic matter.
- Helium (2 protons) makes up 24% of atomic matter.
- The other 116 elements make up the remaining 2%!

- Some matter is made of molecules, which are groups of two or more atoms bonded together.
- For example, water is made of water molecules, which consist of 2 hydrogen atoms and 1 oxygen atom.

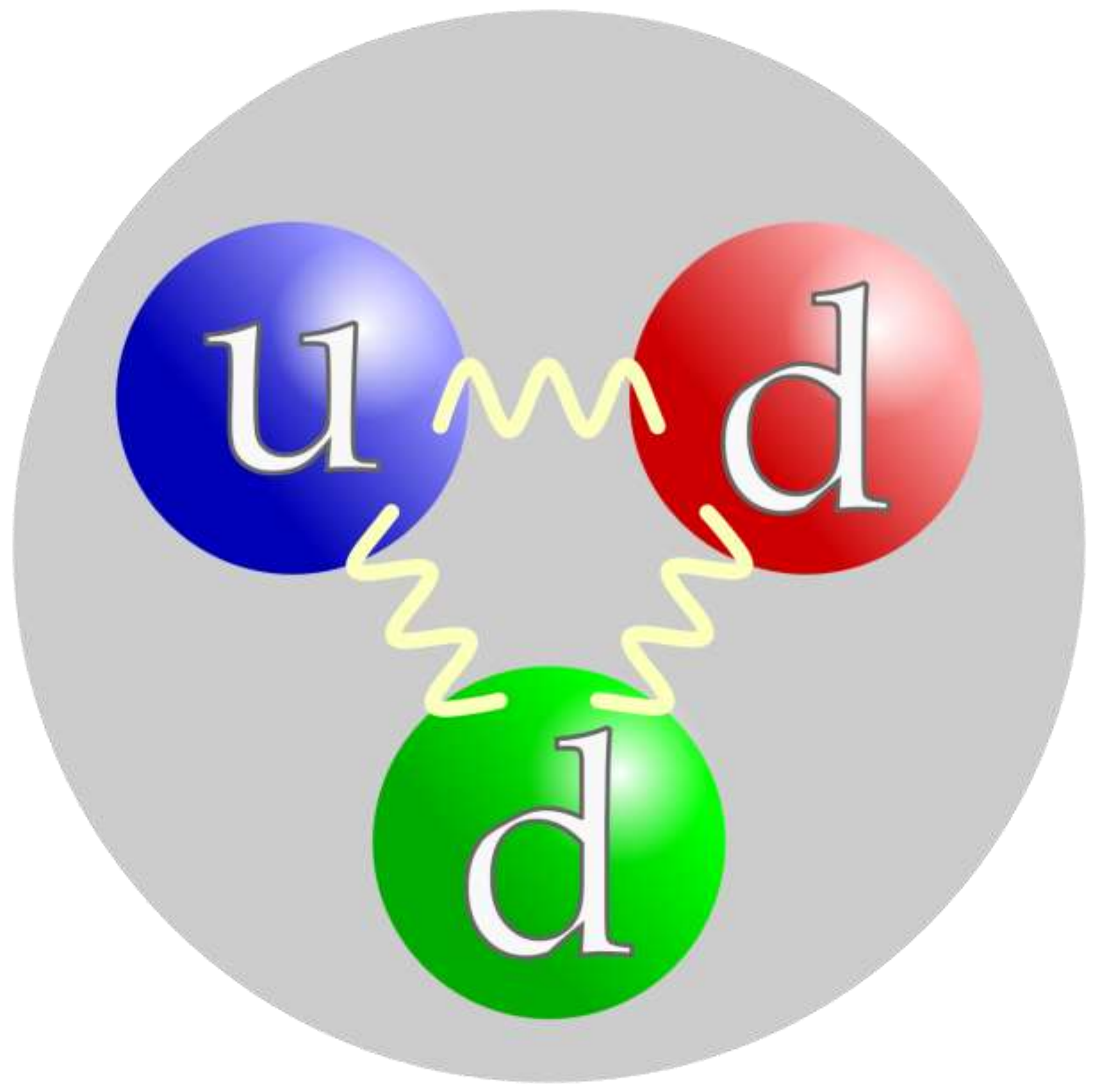


A Water Molecule
Credits: Modification of work by Dbc334 and Jynto (Wikipedia)

- The protons and neutrons in the nucleus are made of particles called up and down quarks.
- These are examples of subatomic particles: particles that compose atoms. Electrons are also subatomic particles.



Proton:
2 up quarks
1 down quark



Neutron:
1 up quark
2 down quarks

Atoms and particles

- So all atomic matter in the universe is actually made of just 3 kinds of particles: electrons, up quarks, and down quarks.
- As far as we know, electrons and quarks are not made of any smaller particles, which is why we call them elementary particles.
- Another common elementary particle you may have heard about is the photon: the particle of light and electromagnetic radiation.

Atoms and particles

- The Standard Model of Particle Physics is the model that describes all known elementary particles and their fundamental interactions.
- These interactions are also known as “forces”. They are mediated by elementary particles called force carriers.
- Basically, the particles interact by “sending” a force carrier from one particle to another.

Atoms and particles

- The Standard Model describes 3 fundamental interactions.
- The electromagnetic interaction, responsible for the familiar electric and magnetic forces (and other things), is mediated by photons.
- The strong interaction, responsible for gluing together the quarks inside protons and neutrons and the protons and neutrons inside nuclei, is mediated by gluons.
- The weak interaction, responsible for nuclear reactions (which we will learn about soon), is mediated by W and Z bosons.

Atoms and particles

- Gravity is also a fundamental interaction, but it is not described by the Standard Model.
- Instead, gravity is described by general relativity, a different theory that follows different rules from the Standard Model.
- It would be nice to combine these two theories into one theory that describes all of the particles and interactions, including gravity.
- Unfortunately, we don’t know yet how to do that. Thousands of physicists are currently working on different aspects of this problem, but it might take decades or centuries before it is solved.
  - I also worked on some aspects of this problem, in my MSc and PhD theses.

The 4 fundamental interactions
Credits: Mark Garlick/Science Photo Library/Getty Images Plus; adapted by L. Steenblik Hwang

Atoms and particles

- In particle physics, we measure energy in electron volts (eV).

$$1\ \text{eV} \approx 1.6 \times 10^{-19}\ \text{J (joule, a unit of energy).}$$

- From $E = mc^2$, the mass corresponding to energy E is $m = E/c^2$.
- So we can measure mass in units of eV/c^2:

$$1\ \text{eV}/c^2 \approx 1.8 \times 10^{-36}\ \text{kg}$$

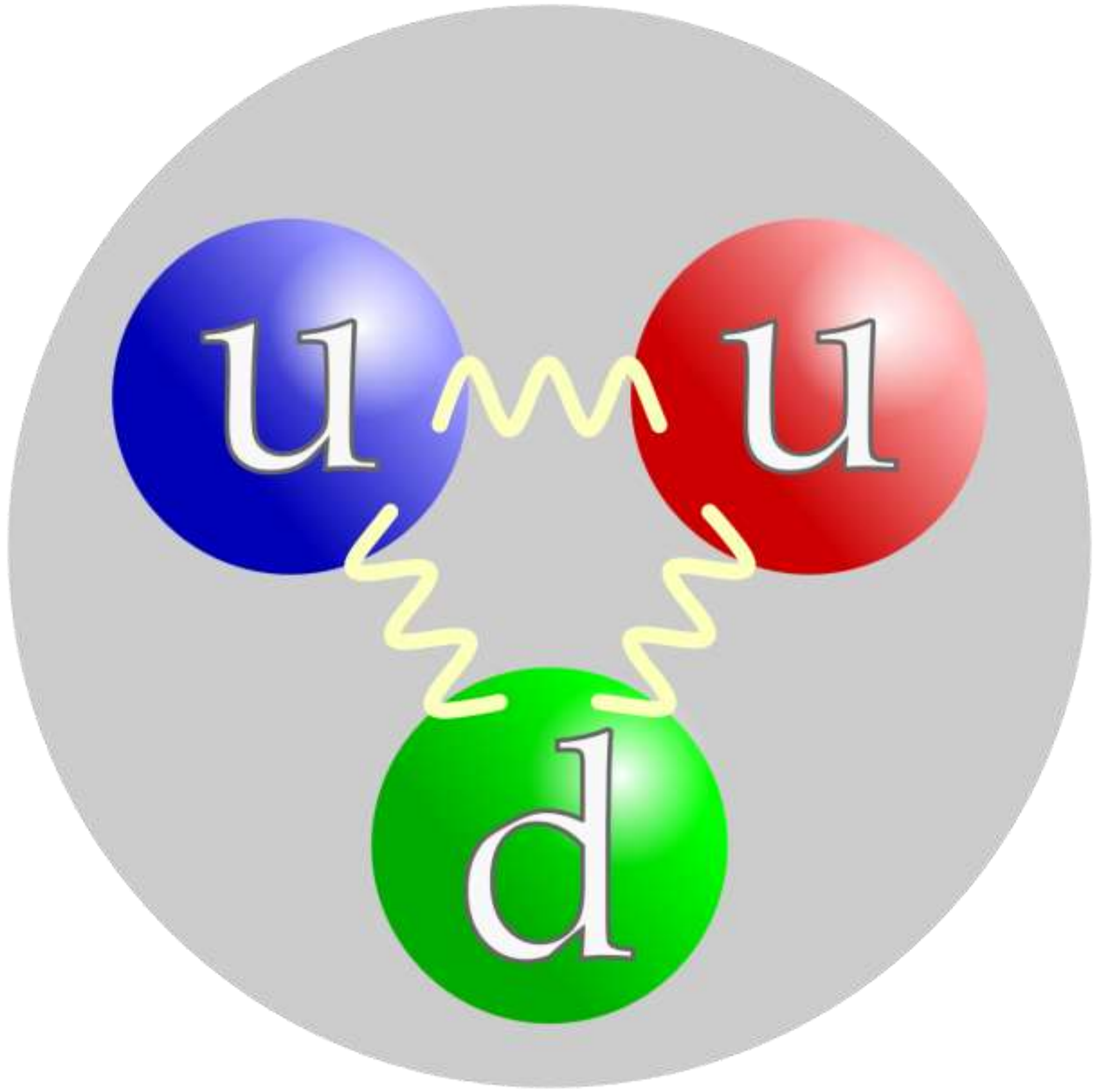
$$\text{where } c \approx 3.0 \times 10^8\ \text{m/s.}$$

- It is also convenient to use metric prefixes:
  - MeV = mega (1 million) eV
  - GeV = giga (1 billion) eV

Atoms and particles

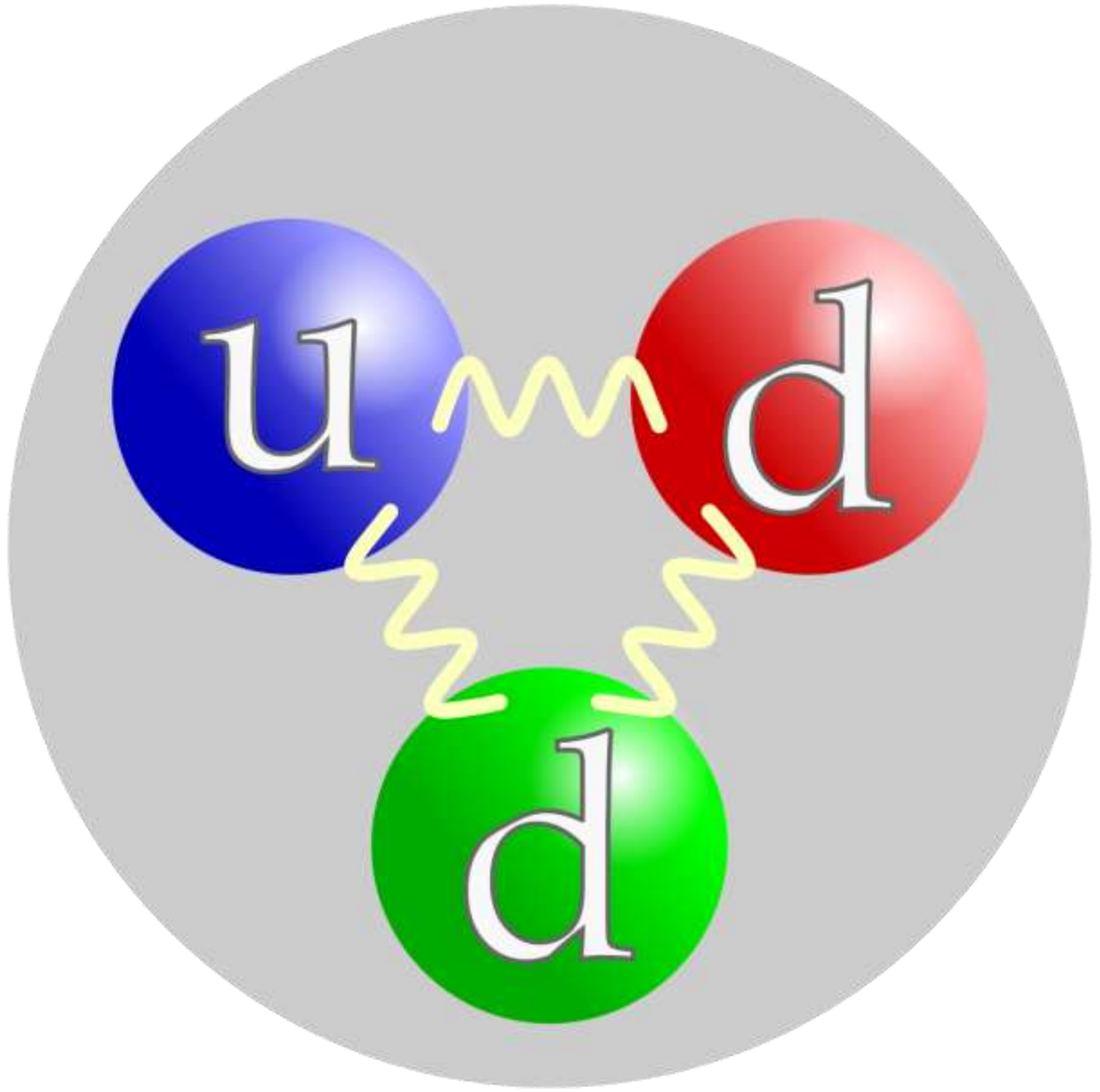
- We measure the electric charge of particles in units of elementary charge, often expressed as pure numbers.
- The charge of a single proton in these units is $+1$.
- The charge of a single electron is -1.
- Quarks actually have fractional charge:
  - Up quarks have charge $+2/3$.
  - Down quarks have charge $-1/3$.
- Photons, gluons, and Z bosons have no charge; they are neutral.

- In a proton, the charges of the 3 quarks add up to exactly 1.
- In a neutron, the charges of the 3 quarks exactly cancel.



Proton:
2 up quarks (charge +2/3)
1 down quark (charge −1/3)

$$2 \times \frac{2}{3} - 1 \times \frac{1}{3} = 1$$



Neutron:
1 up quark (charge +2/3)
2 down quarks (charge −1/3)

$$1 \times \frac{2}{3} - 2 \times \frac{1}{3} = 0$$

Video

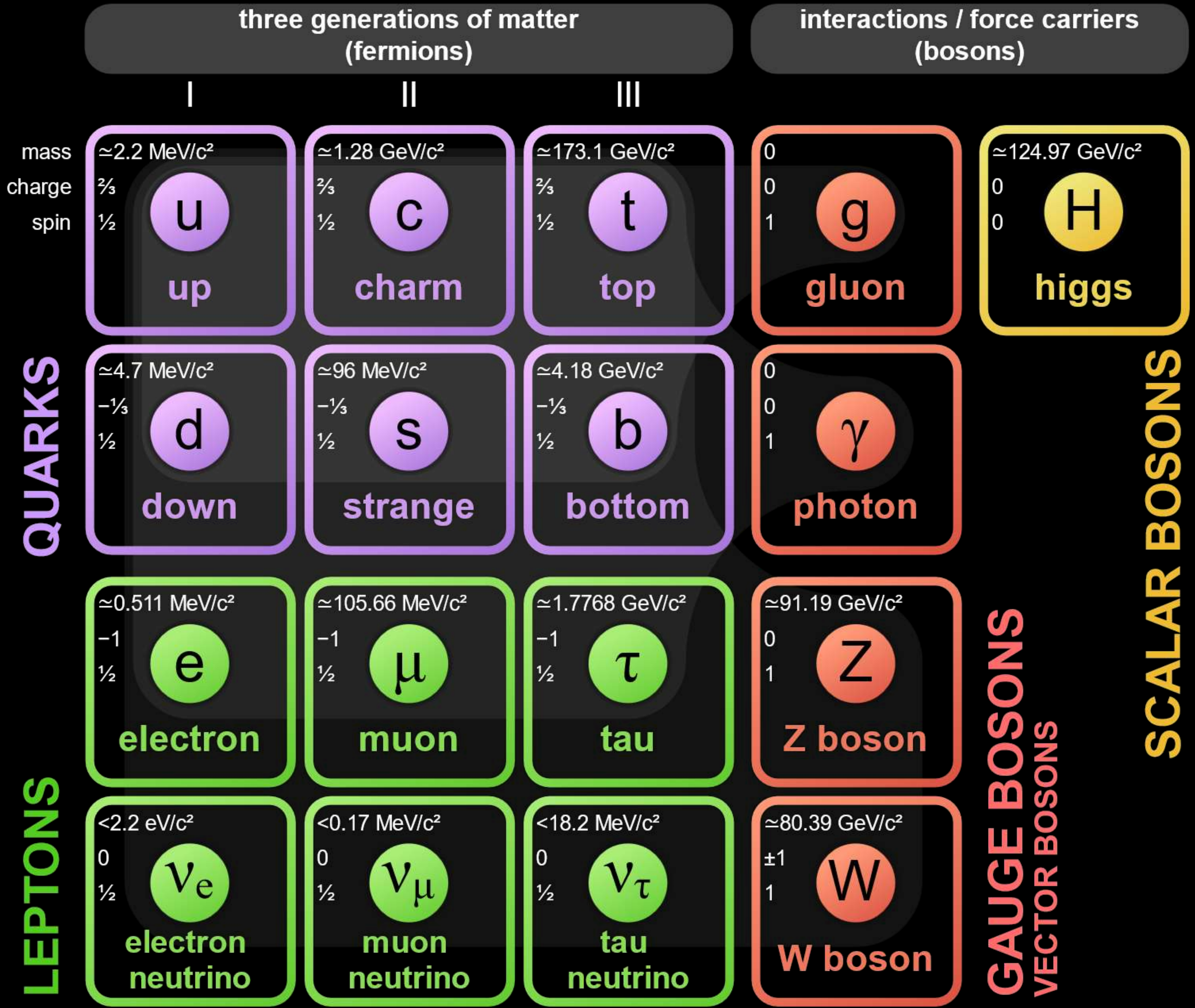
- Neutrinos are electrically neutral particles with a very small mass, created in nuclear reactions.
  - Warning: do not confuse neutrinos with neutrons!
- This video, the first episode of the series “Even Bananas” by Fermilab, explains the history of neutrinos.
- It also mentions some other concepts, like radioactive decay, which we will talk about in a bit.
- The video can be found at this URL:

https://youtu.be/bGGrdeZuFWo

Atoms and particles

- Electrons, neutrinos, and quarks are called matter particles.
- There are actually 3 generations of each of the matter particles. The particles we listed so far are just the 1st generation.
    - The first generation of neutrinos are called electron neutrinos.
- The 2 higher generations consist of similar but more massive particles.
- They are unstable and decay almost immediately into other particles, so they don't make up normal matter.
- The table in the next slide lists all 3 generations of matter, as well as the force carriers.

Standard Model of Elementary Particles



The particles of the Standard Model
Credits: Modification of work by Cush (Wikipedia)

Atoms and particles

- Particles have another very important property: spin.
- Remember from lecture 6 of ASTR 1P01:
  - Momentum is the “total movement” of all the atoms in an object.
  - Angular momentum is the “total rotation” of an object around an axis.
- Basically, spin is angular momentum due to the particle “spinning” around its own axis (like the spin of a planet).
  - This is an oversimplification, but the precise definition is very complicated.
  - Physics students will learn all the details in my 4^{th}-year course PHYS 4P51: Quantum Mechanics.

Atoms and particles

- Spin can be integer (0, 1, 2, ...) or half-integer (1/2, 3/2, 5/2, ...)
- Particles that have integer spin are called bosons.
  - Force carriers (photons, gluons, W and Z bosons) have spin 1. Therefore, they are bosons.
- Particles that have half-integer spin are called fermions.
  - Matter particles (electrons, quarks, neutrinos) have spin 1/2. Therefore, they are fermions.

Atoms and particles

- The Higgs boson is the only known particle with spin 0.
- It is not a force carrier (spin 1) nor a matter particle (spin 1/2).
- Instead, it is responsible for giving mass to some elementary particles, including quarks, electrons, and W & Z bosons.
  - The Higgs boson does not give mass to composite particles like protons, neutrons, or atoms. That is a common misconception.
- The Higgs boson is the most recent particle to be discovered, in 2012, using the Large Hadron Collider (LHC) at CERN.
- It was theorized in 1964, but only in 2012 we had sufficiently advanced technology to detect it.

Atoms and particles

- CERN is the European Organization for Nuclear Research (in French: *Conseil Européen pour la Recherche Nucléaire*), established in 1954.
- It is located near Geneva, on the France-Switzerland border, and operated by 23 member states (all European, except for Israel).
- CERN is the largest particle physics laboratory in the world, employing and hosting thousands of scientists.
- In addition, it's also the birthplace of the World Wide Web (meaning the concept of websites and web browsers).

Atoms and particles

- The Large Hadron Collider (LHC) is located at CERN.
- Large: It is a tunnel of 27 km in circumference.
- Hadron: All composite subatomic particles that are made of two or more quarks are called “hadrons”.
  - This includes protons, neutrons, and other particles I haven’t mentioned.
- Collider: The LHC accelerates protons to give them very high kinetic energy, and then collides them together.

Atoms and particles

- In this collision, some of the kinetic energy of the protons is converted to rest energy (mass).
- So very massive particles, like the Higgs boson, can be created and studied.
- Imagine two cars crashing into each other, but in the collision, 2 trucks, 5 motorcycles, and 9 skateboards appear out of nowhere!
- This is our first example of converting between mass and speed.

Video

- I will show a short animation of a collision in the LHC.
- The animation is available at this URL:

https://youtu.be/imOpF9bP0wc

Atoms and particles

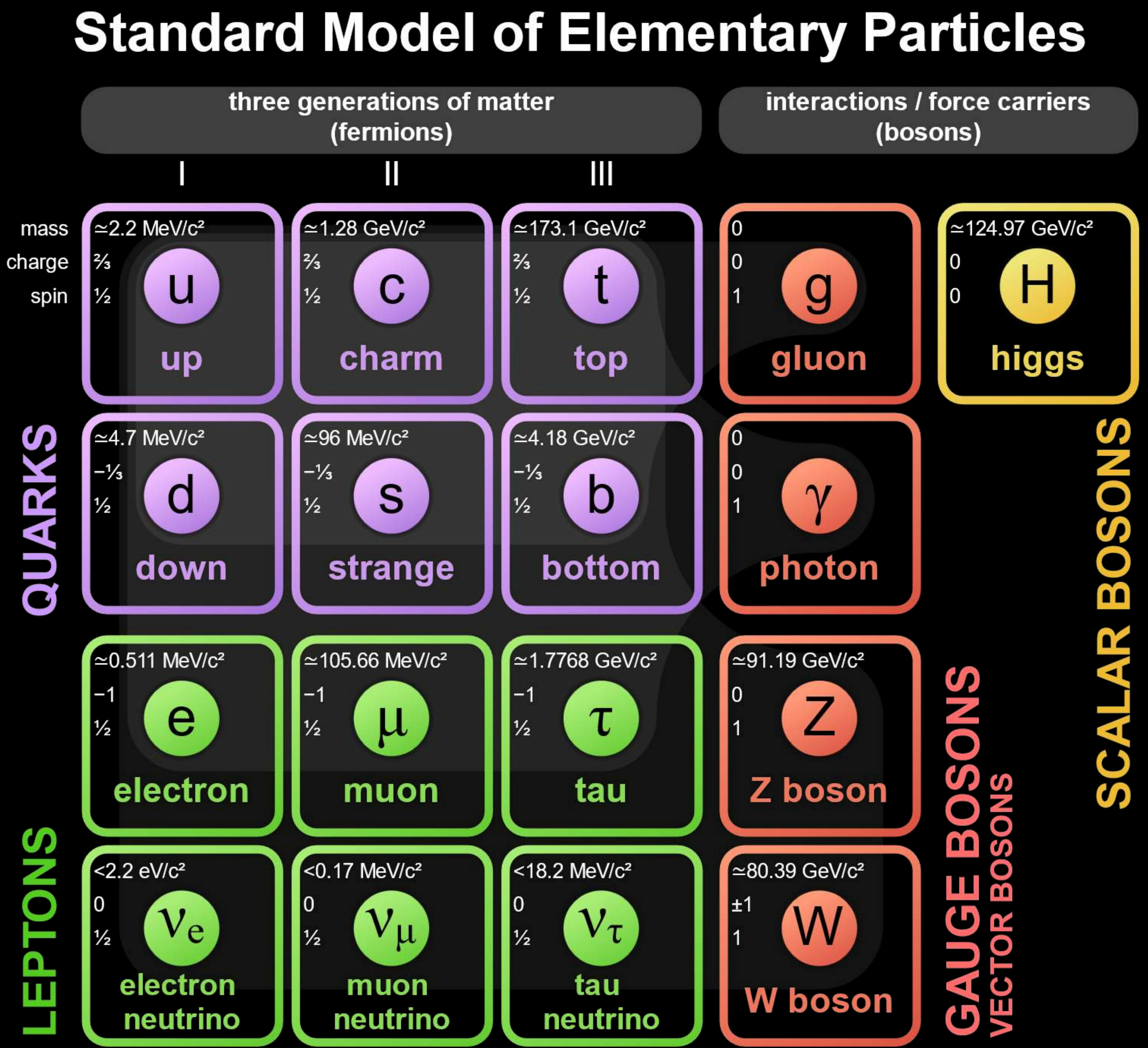
- I was an undergraduate summer student at CERN in 2012, when the Higgs boson discovery was announced.
- The goal of my summer research project was to improve the accuracy of the Higgs boson measurements.
- This was after it was already detected, so I can't take credit for the discovery...

Prof. Barak Shoshany in 2012, as an undergraduate summer student at CERN near Geneva, Switzerland.

Prof. Barak Shoshany in 2012, as an undergraduate summer student at CERN near Geneva, Switzerland.

Atoms and particles

- To summarize, subatomic particles can be either:
  - Elementary particles, not made of any smaller particles (as far as we know), for example quarks and electrons.
  - Composite particles, made of smaller particles, for example protons and neutrons (made of quarks).
- In the next slide I will summarize what we learned about all the elementary particles of the Standard Model.



The particles of the Standard Model
Credits: Modification of work by Cush (Wikipedia)

Antimatter

- For every particle, there is a corresponding antiparticle, which is the same in all aspects, but has the opposite charge.
- For example:
  - The electron has charge -1. Its antiparticle is the positron, with charge $+1$.
  - The proton has charge $+1$. Its antiparticle is the antiproton, with charge -1.
  - The photon has charge 0. Its antiparticle is itself.
- Antimatter is matter composed of antiparticles.

Antimatter

- Most things, including us and everything around us, are made of “ordinary” matter: electrons, protons, and so on.
- Antimatter is very rare. It can be generated in some natural processes, or in particle accelerators like the LHC, but only in microscopic quantities.
- Even when antimatter is generated, it doesn’t survive long.
- The reason is that when a particle and its antiparticle collide, they annihilate and are converted to other particles.
- There are matter particles everywhere, so it doesn’t take long before such a collision happens.

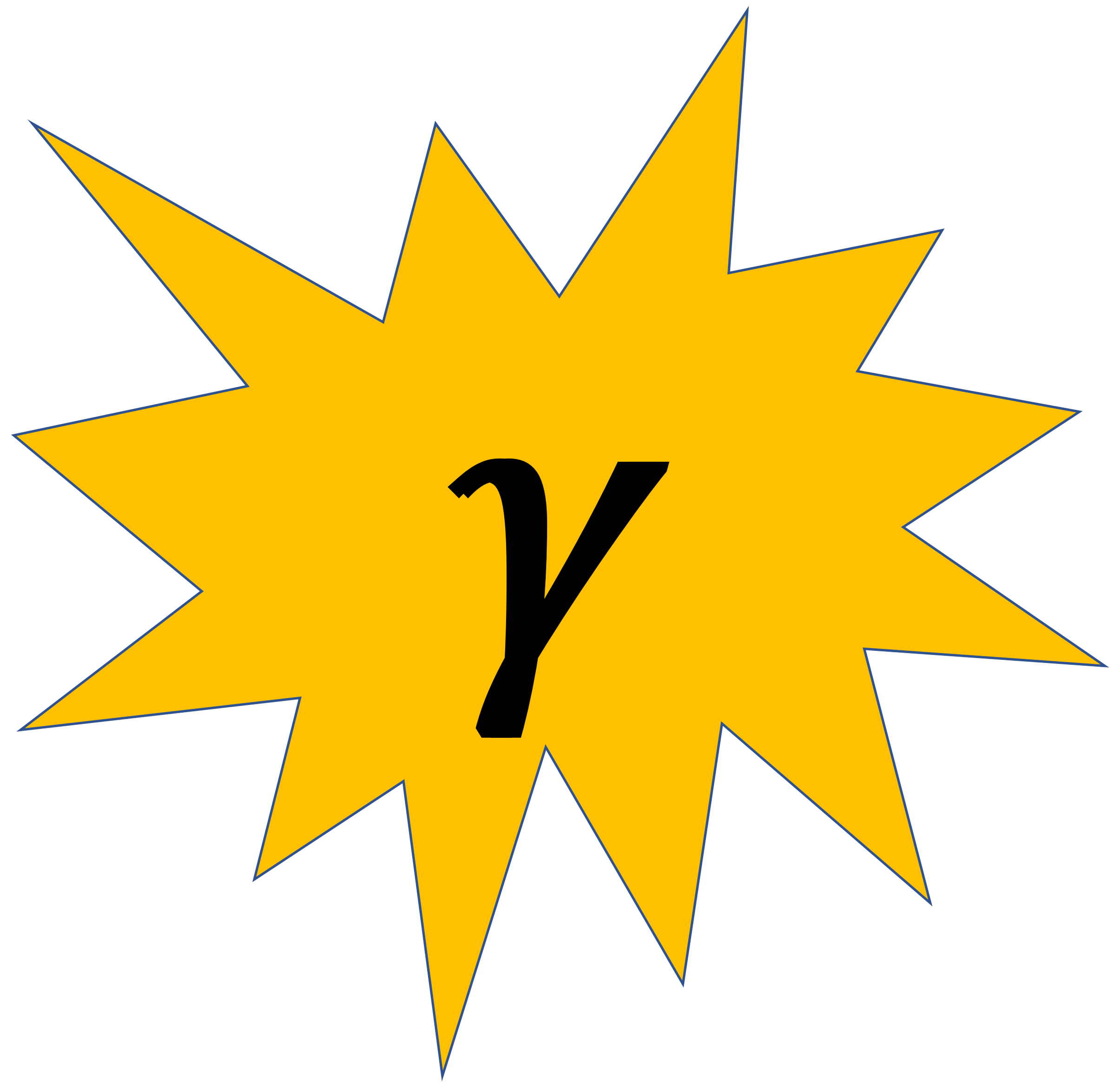
Antimatter

- For example, an electron and a positron can collide, annihilate, and produce two photons.
- In equation form, we can represent this as:

$$e^- + e^+ \rightarrow \gamma + \gamma$$

  - e^- is an electron (negative charge)
  - e^+ is a positron (positive charge, antiparticle of the electron)
  - γ is a photon (denoted by the Greek letter gamma)

Animation of electron-positron annihilation



e^- e^+

Antimatter

- An electron has a mass of ~ 0.5 MeV and charge of -1.
  - We often write just MeV instead of MeV$/c^2$ for brevity.
- A positron has the same mass, but its charge is $+1$.
- So the total mass before the collision is ~ 1 MeV. The total charge is 0 because the charges cancel.
- Now the collision happens:

$$e^- + e^+ \rightarrow \gamma + \gamma$$

- The photons have no mass and no charge.
- Charge is conserved: 0 before, 0 after. What about mass?

Antimatter

- We see that mass is not conserved.
- A total of ~ 1 MeV of mass has "disappeared".
- Due to $E = mc^2$, this mass is equivalent to ~ 1 MeV of rest energy.
- This energy becomes the kinetic energy of the photons.
  - But wait! Photons are light, so they always move at the speed of light, no matter what. What role does kinetic energy have?
  - It turns out that photons oscillate, and the kinetic energy determines how fast they oscillate – that is, the frequency (and wavelength) of the light. We will learn more about that later.
- This is our second example of converting between mass and speed.

Nuclear fusion

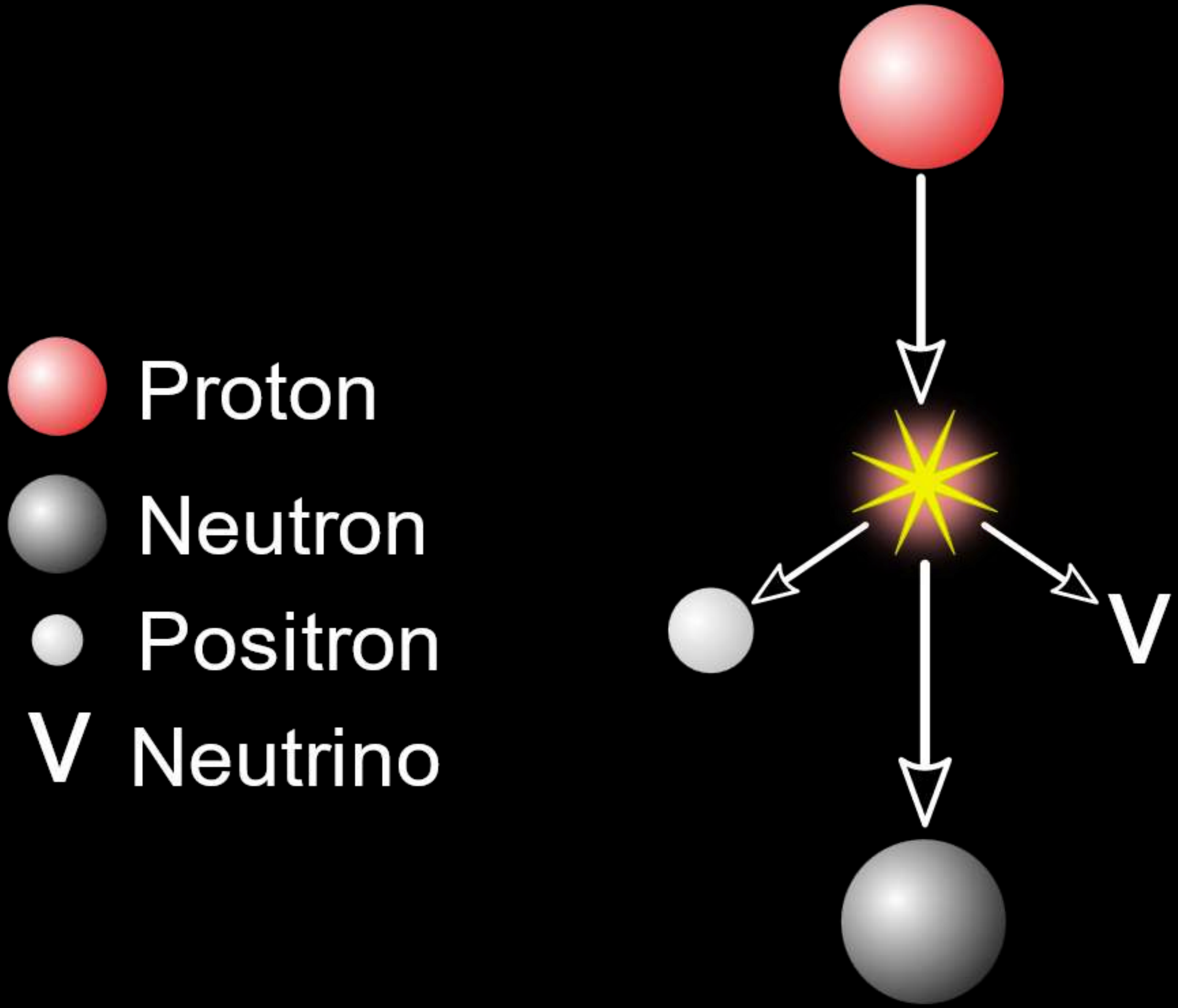
- Stars produce light using the same basic idea: converting mass into speed.
- However, the process is not the same as proton-proton collisions or matter-antimatter annihilation. Instead, it involves atomic nuclei.
- This process is called nuclear fusion, and involves converting hydrogen (1 proton) into helium (2 protons).
- In stars with up to 1.3 times the mass of the Sun, nuclear fusion occurs mostly via the proton-proton chain (a.k.a. the p-p chain).
  - This includes the Sun itself.
- In more massive stars, it occurs mostly via the CNO cycle.

Nuclear fusion

- In step 1 of the proton-proton chain, two protons collide.
- One of the protons undergoes positron emission, a.k.a. β^+ (beta plus) decay. The proton becomes a neutron and emits a positron and an electron neutrino:

$$p \rightarrow n + e^+ + \nu_e$$

  - p is the proton (charge $+1$)
  - n is the neutron (neutral)
  - e^+ is the positron (charge $+1$)
  - ν_e is the electron neutrino (neutral); ν is the Greek letter nu.
  - Note that total charge is conserved: it's $+1$ before and after the decay.



β^+ **decay**

Credits: Modification of work by Sarang (Wikipedia)

Nuclear fusion

- Isotopes are atoms that have the same number of protons (so the same atomic number) but a different number of neutrons.
- The isotopes of hydrogen (1 proton) are:
  - Hydrogen-1 or ^{1}H or protium: 0 neutrons. Very common (99.98%). Stable.
  - Hydrogen-2 or ^{2}H or deuterium: 1 neutron. Less common (0.002%). Stable.
  - Hydrogen-3 or ^{3}H or tritium: 2 neutrons. Extremely rare. Unstable; decays into helium-3 (^{3}He) with a half-life of ~12 years.
    - Half-life is the time required for half of the atoms in a radioactive substance to decay. We learned about it in lecture 8 of ASTR 1P01.
- There are also heavier isotopes with 3 or more neutrons. However, they decay after a fraction of a second, so are not found in nature.

Isotopes of hydrogen
Credits: BruceBlaus (Wikipedia)

Nuclear fusion

- Going back to the proton-proton chain, the first proton decays:

$$p \rightarrow n + e^{+} + \nu_e$$

- Let's add back the second proton:

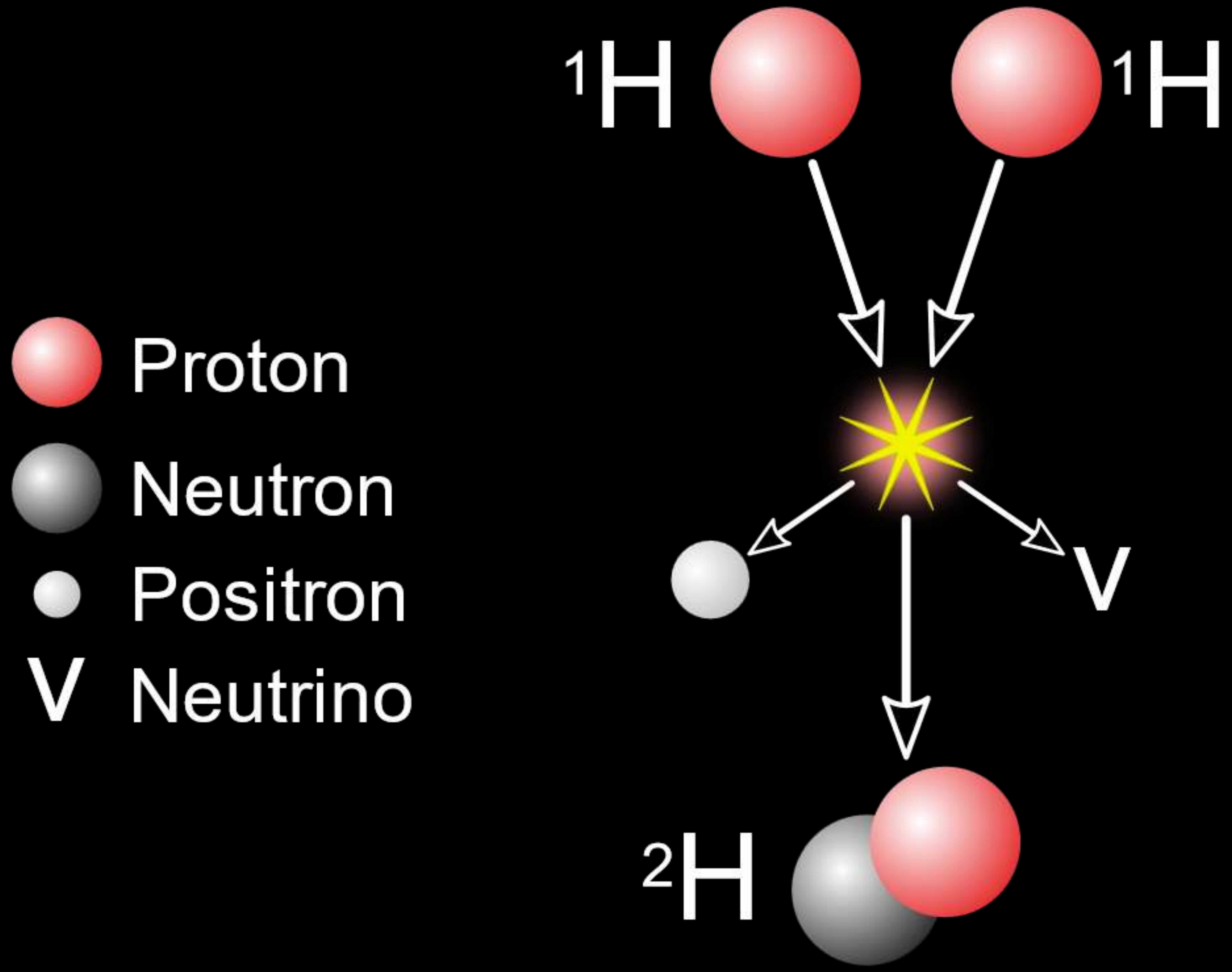
$$p + p \rightarrow p + n + e^{+} + \nu_e$$

- The second proton combines with the neutron to form a deuterium nucleus $^{2}\mathrm{H}$:

$$p + p \rightarrow 2\mathrm{H} + e^{+} + \nu_e$$

- We can write $^{1}\mathrm{H}$ for the protons, since they're just protium nuclei:

$$^{1}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow {}^{2}\mathrm{H} + e^{+} + \nu_e$$



Proton-proton chain step 1
Credits: Modification of work by Sarang (Wikipedia)

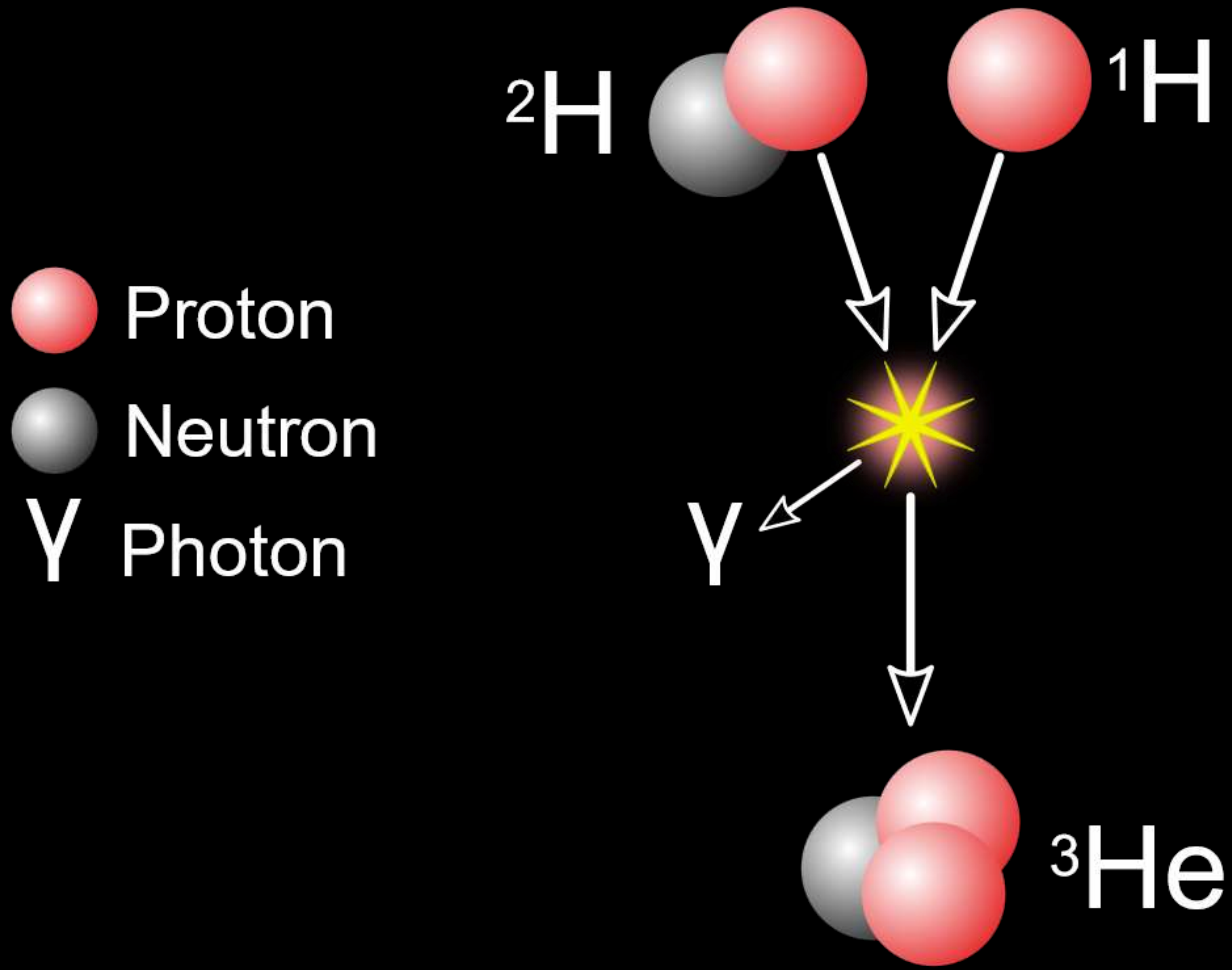
Nuclear fusion

- Step 1 is mediated by the weak interaction.
  - Remember that this is one of the 4 fundamental interactions: electromagnetic, strong, weak, and gravity.
  - The weak interaction is responsible for nuclear reactions.
- Each proton in the core of the Sun waits a few billion years (on average) before it manages to successfully fuse with another proton!

Nuclear fusion

- Helium (He) has 2 protons. Its stable isotopes are:
  - Helium-3 or ^{3}He: 1 neutron. Very rare.
  - Helium-4 or ^{4}He: 2 neutrons. Very common (99.99986%).
- In step 2 of the proton-proton chain, the ^{2}H from step 1 collides with a ^{1}H (proton) to form ^{3}He and a photon:

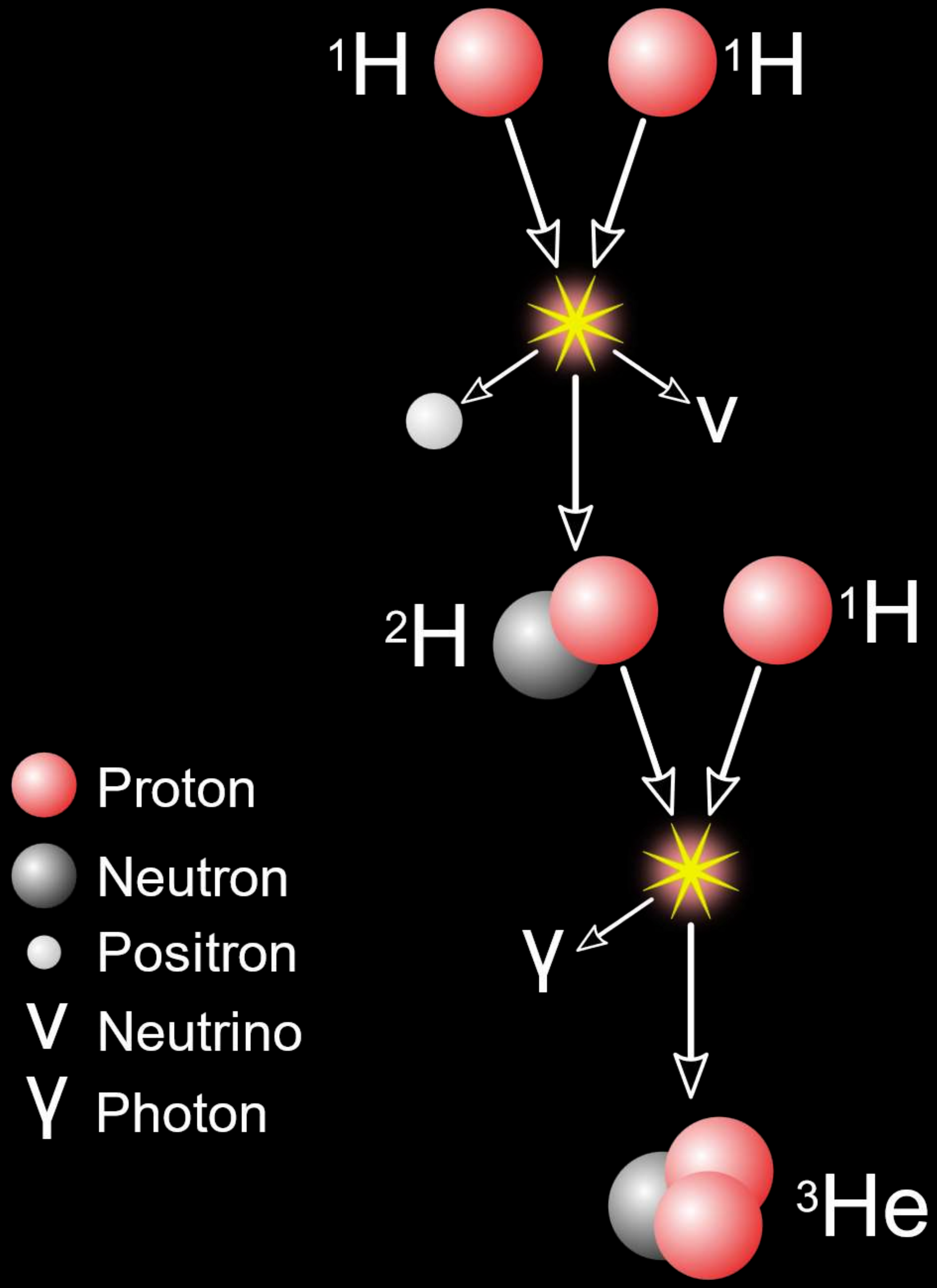
$$^2\mathrm{H} + {}^1\mathrm{H} \rightarrow {}^3\mathrm{He} + \gamma$$



Proton-proton chain step 2
Credits: Modification of work by Sarang (Wikipedia)

Nuclear fusion

- Step 2 is mediated by the strong interaction.
- Therefore, it is much faster (since the interaction is stronger).
- In the core of the Sun, each ^2H nucleus created in step 1 only exists for a few seconds before it is converted into ^3He in step 2.



Proton-proton chain steps 1+2 combined

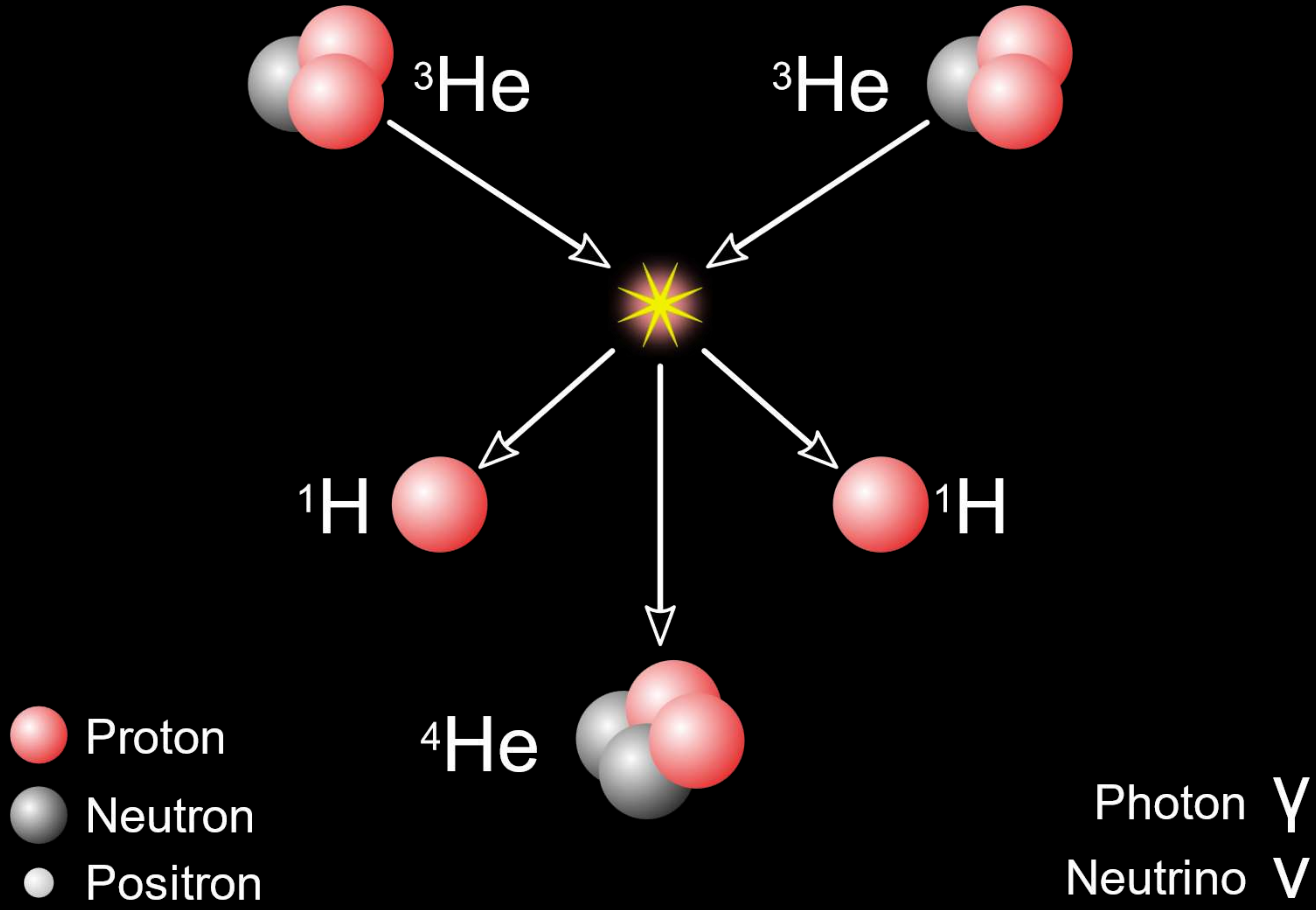
Credits: Modification of work by Sarang (Wikipedia)

Nuclear fusion

- In step 3 of the proton-proton chain, two ^{3}He, produced in step 2, collide to form ^{4}He and two protons:

$$^3\text{He} + {}^3\text{He} \rightarrow {}^4\text{He} + {}^1\text{H} + {}^1\text{H}$$

- In the Sun, it takes each ^{3}He a few hundred years to convert to ^{4}He.
- This is the most common way (~83%) for step 3 to occur, called branch I, but there are at least 3 other less common branches which we won't talk about here.

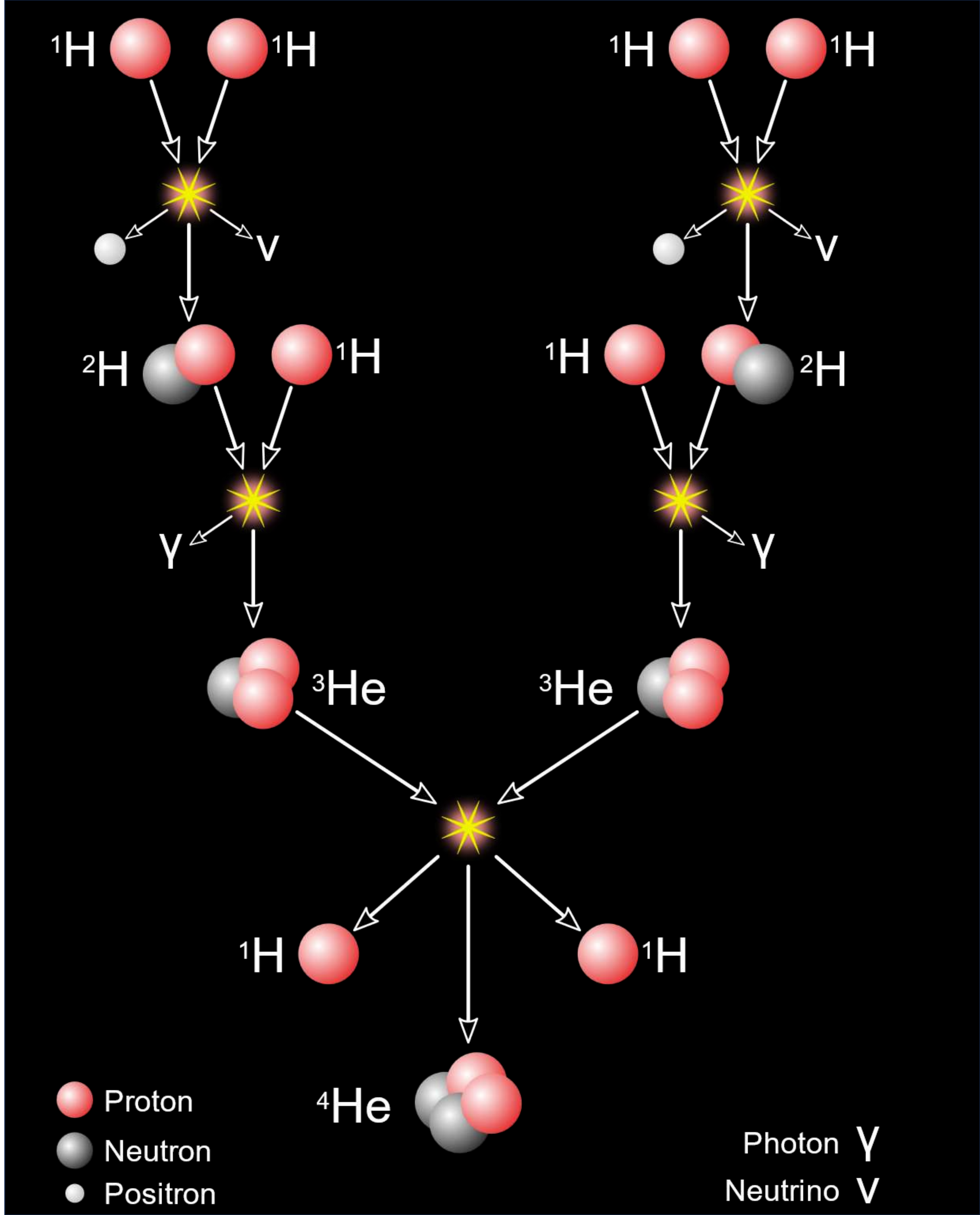


Proton-proton chain step 3 (branch I)
Credits: Modification of work by Sarang (Wikipedia)

Combining all the steps together:
$$6\ {}^1\text{H} \rightarrow {}^4\text{He} + 2\ {}^1\text{H} + 2\nu_e + 2e^+ + 2\gamma$$

Since there are 2 protons on each side, we can "subtract" them:
$$4\ {}^1\text{H} \rightarrow {}^4\text{He} + 2\nu_e + 2e^+ + 2\gamma$$

In this process we "fused together" 4 hydrogen nuclei (protons) to create one helium nucleus (plus other stuff).



The full proton-proton chain (branch I)
Credits: Modification of work by Sarang (Wikipedia)

Nuclear fusion

- Remember that antimatter quickly annihilates with matter.
- A positron (e^+) is antimatter, so it annihilates with an electron (e^-) to produce 2 photons (γ) like we discussed earlier:

$$e^+ + e^- \rightarrow 2\gamma$$

- This happens twice since we have 2 positrons. So

$$4\ {}^{1}\text{H} \rightarrow {}^{4}\text{He} + 2\nu_e + 2e^+ + 2\gamma$$

becomes

$$4\ {}^{1}\text{H} + 2\text{e}^- \rightarrow {}^{4}\text{He} + 2\nu_e + 6\gamma$$

Nuclear fusion

$$4\ {}^{1}\mathrm{H} + 2\mathrm{e}^{-} \rightarrow {}^{4}\mathrm{He} + 2\nu_e + 6\gamma$$

- The mass of a proton is $\sim$938.3 MeV.
- So the total mass of the original 4 protons is $\sim$3,753 MeV.
- The mass of the resulting ^{4}He nucleus is $\sim$3,728 MeV.
- There is a difference of $\sim$25 MeV (0.7% of the original mass)!
- The rest energy of this lost mass is converted to kinetic energy of the neutrinos and photons.

Nuclear fusion

- So in conclusion, this is how stars like the Sun generate light:
  - They fuse hydrogen to helium.
  - In the process, photons of light are emitted.
  - The helium has a smaller mass than the hydrogen.
  - The mass difference gets converted to the kinetic energy of the photons.
- When the photons from the Sun reach Earth, their kinetic energy is converted into heat and makes life and many other things possible!
  - Neutrinos are also emitted, so they “steal” some of that kinetic energy for themselves. Since neutrinos just pass through everything without affecting it in any way, that energy is effectively lost.

Nuclear fusion

- As mentioned before, the proton-proton chain is dominant in stars with up to 1.3 times the mass of the Sun, including the Sun itself.
- In more massive stars, nuclear fusion occurs mostly via the CNO (carbon-nitrogen-oxygen) cycle.
- The CNO cycle is a bit more complicated, so we won’t cover it here. But it basically does the same thing: 4 hydrogen nuclei are fused into a helium nucleus, and neutrinos and photons are released in the process.

Nuclear fusion

- The are $\sim 10^{57}$ protons in the Sun.
- Every second, the Sun fuses $\sim 10^{38}$ protons ($\sim$600 million tons of hydrogen) into helium nuclei.
- In this process, $\sim$4 million tons ($\sim$0.7%) of rest energy from the mass difference is converted to kinetic energy of released photons.
- Using $E = mc^2$, this is equivalent to $\sim 10^{26}$ W of energy.
- This is 10 million times Canada's yearly energy consumption, every second!

Conclusions

- In this lecture, we learned many advanced concepts from relativity, particle physics, and nuclear physics.
- We saw how different subatomic particles and interactions contribute to the nuclear fusion process that allows stars to generate their light.

- <u>Reading:</u> OpenStax Astronomy, chapter 16.
- <u>Exercises:</u> Practice questions are available in the textbook and on the course website.