*How the Sun Works* Unit

# Week 4 – Where does the sun’s energy come from?

WATERFORD ASTRONOMY

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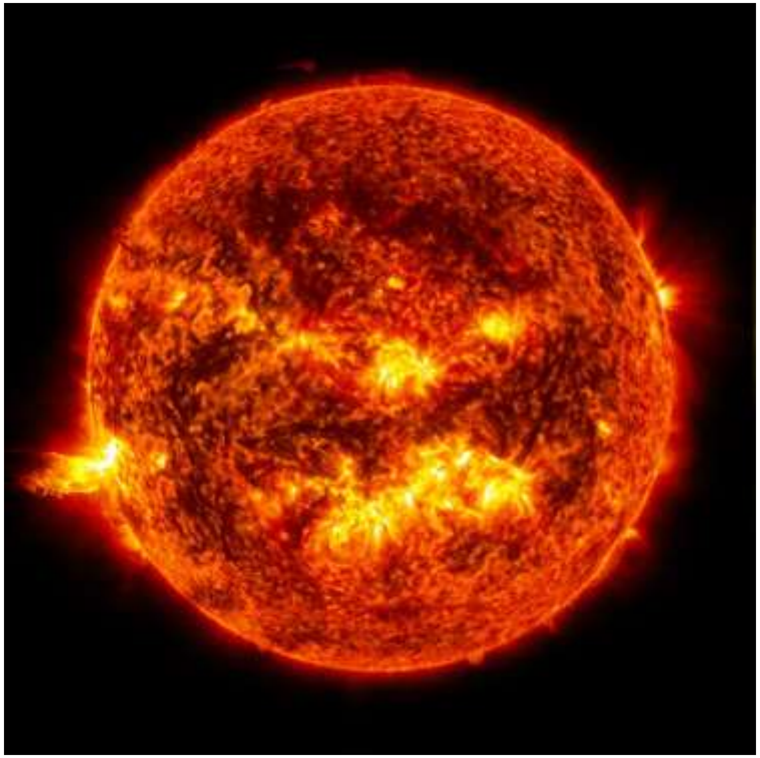
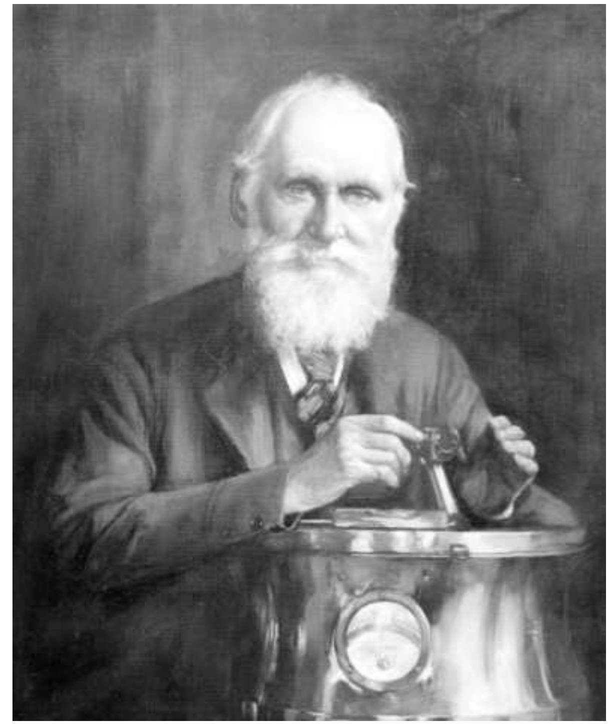
# Sun Unit – W3 Driving Question

- **This week's driving question:** Where does the sun's energy come from?



# Week 2 Recap

- **We now know that the sun is primarily composed of hydrogen and helium.**
  - We also know the size, distance, and temperature of the sun.
  - We now have the info we need to answer our original question – *How can the Sun burn continuously for more than a few tens of millions of years at most without exhausting its fuel?*



*Lord Kelvin is still waiting for an explanation…*

# The Big Ideas

- **If you know the mass and surface temperature of the sun, you can determine the temperature inside the sun.**
  - This determination is based on the relationship between pressure and temperature in gases.
  - If you know the temperature inside the star and its atomic composition, you can begin to determine how the sun is able to ‘burn’ continuously for billions of years.

# Gas Laws

- **When you heat a gas, the pressure increases**.
  - Hotter temps increase the speed at which particles move.
  - This increase the rate and force at which particles collide, generating more heat.
  - Similarly, if you increase pressure, a gas heats up as particles collide more frequently.

**The relationship between pressure and temp can be summarized as P = knT.**

- P = pressure of the gas [dynes/cm2]
- n = number density [atoms/cm3]
- T = temperature [degrees Kelvin]
- k = Boltzmann's constant
  - *Boltzmann's constant (k) refers to how much energy a typical atom has at any temp.*

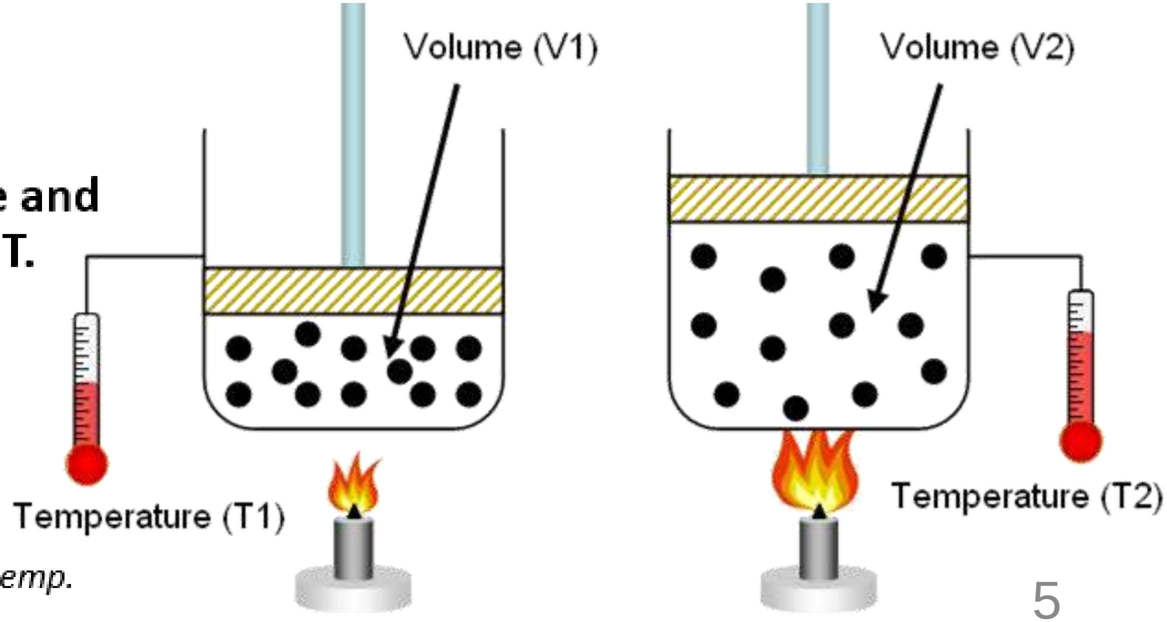
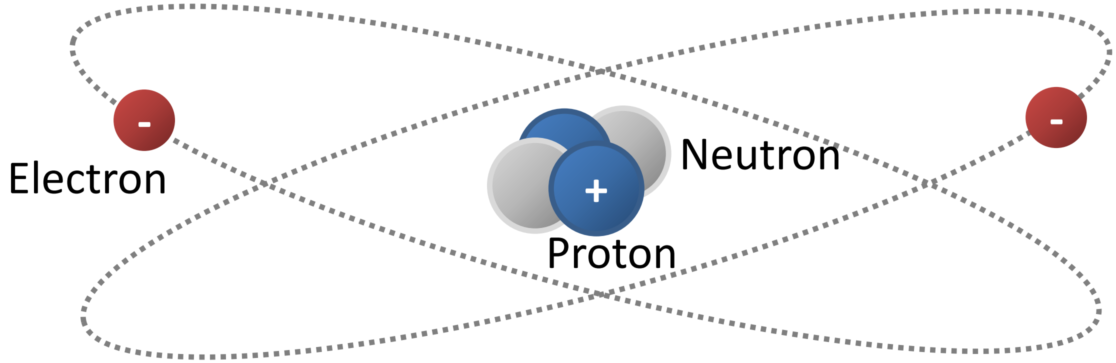



*Image Source: https://www.chem.fsu.edu/chemlab/chm1045/gas_laws.html*

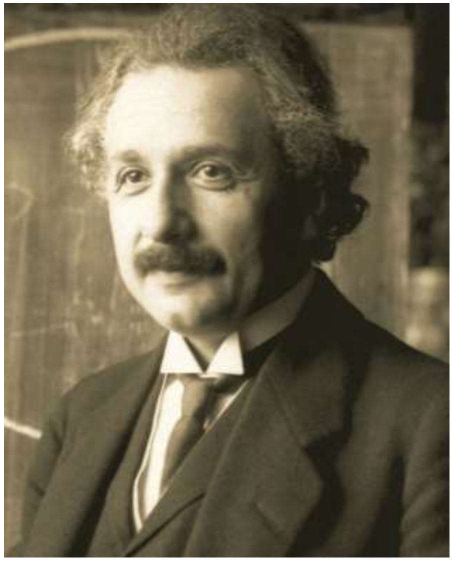
# Subatomic Components




- **Reminder: atoms consist of three components: electrons, protons, and neutrons.**
  - Electrons are negatively charged, orbiting the nucleus of the atom.
  - The nucleus consists of positively charged protons and uncharged neutrons.
  - The number of protons determines the type of element (*e.g., hydrogen atoms have one proton; helium atoms have two protons*).

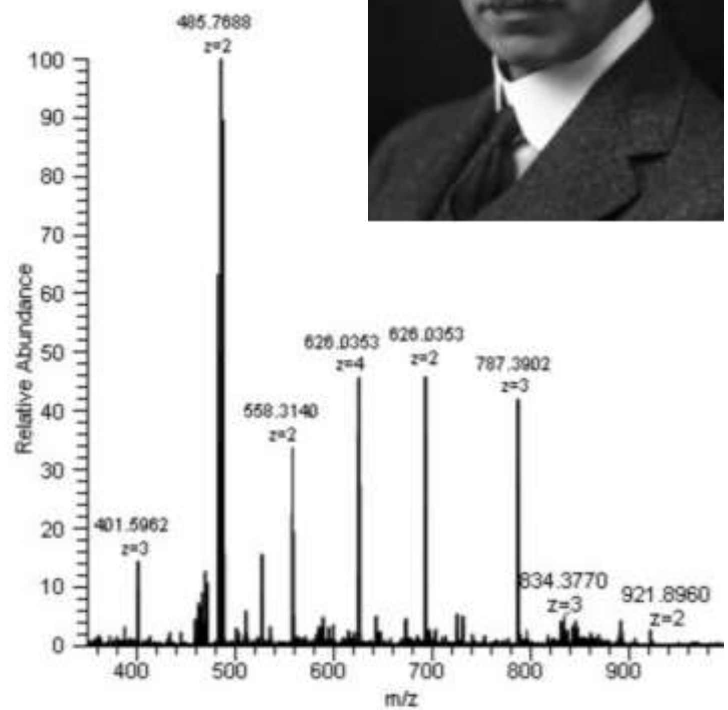
# Origins of Understanding

- **Our understanding of the function of the sun emerged in part from Einstein's most famous work in 1905 - $\underline{E = mc^2}$.**
  - This equation indicates that the amount of energy in a substance is equal to its mass (m) multiplied by the speed of light squared.
  - This alludes to the notion that energy and matter are interchangeable.
- **In other words, matter and energy are different forms of the same thing.**
  - Because the speed of light is an enormous number (300,000 km/sec or 186,000 miles/sec), even tiny amounts of matter contain large quantities of energy.
- **Why the speed of light?**
  - If something is converted into pure energy, it would have to be moving at the speed of light, as all electromagnetic radiation travels at a constant speed.



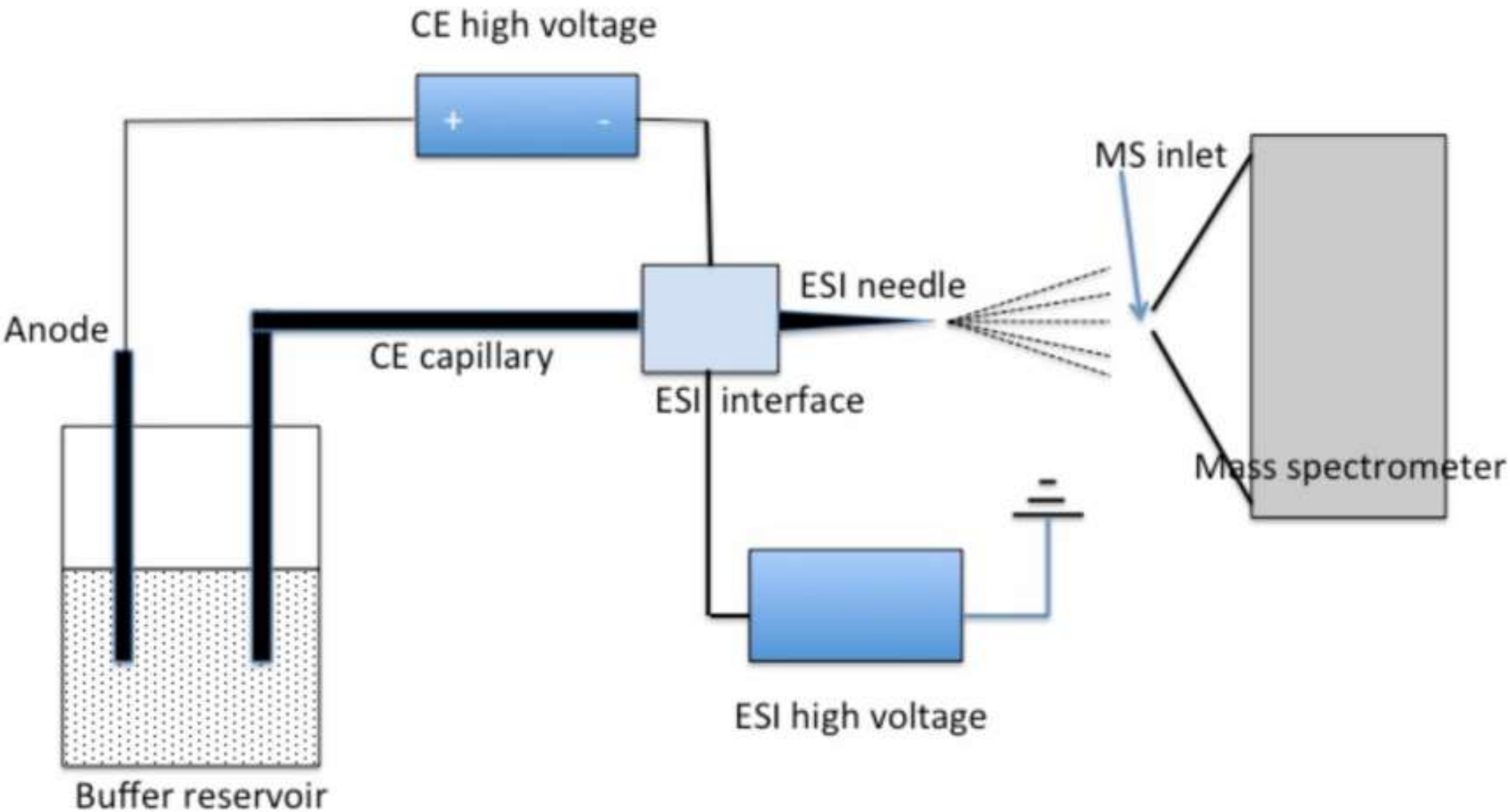
# Origins of Understanding

- **In the 1920s, F. W. Aston developed a method for calculating the exact molecular weight of elements.**
  - Aston's work led to the development of <u>mass spectrometry</u>.
  - This analytical tool converts substances into gases.
- **The individual components are then separated by relative electrical charge using electromagnetic fields**.
  - The gases are then passed through a tiny needle according to their mass-to-charge (m/z) ratios.




Example of a mass spectrum

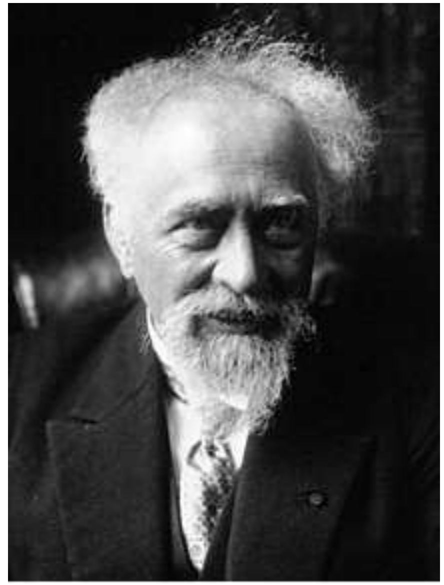
# Mass Spectrometer




By converting a substance into an ionized gas and separating it by its mass-to-charge (m/z) ratio, researchers can determine the mass at the atomic and subatomic level.

# Origins of Understanding

- **In conducting his work, Aston inadvertently determined that four hydrogen nuclei were heavier than a helium nucleus.**
  - Around the same time, Jean Perrin independently suggested that that the fusion of hydrogen into helium was the energy source of the Sun and other stars.
- **Perrin's ideas provided a potential explanation for the 'missing mass' observed by Aston.**
  - I.e., some of the mass of hydrogen atoms might be converted into energy if fused.



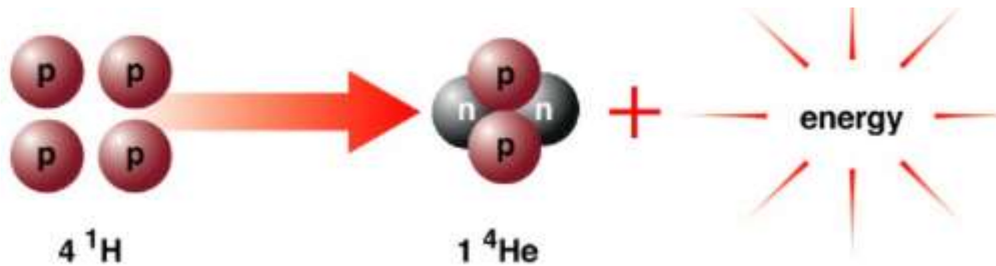



*Image Source: https://www.physicsoftheuniverse.com/how-does-the-sun-shine.html?scrlybrkr=b3fbf18e*

# Eddington's Realizations

- **Arthur Eddington first recognized the implications of the collective findings of Einstein, Aston, and Perrin.**
  - Einstein proposed that matter could be converted into energy (*which Eddington confirmed by measuring the 'bending' of light during an eclipse due to gravity*).
  - Perrin proposed that hydrogen fusion into helium powered the sun.
  - Aston observed that fused hydrogen (i.e., helium) was lighter than the hydrogen atoms by themselves.
- **Eddington provided the first evidence-based argument that the "vast reservoir of energy" in the sun was "subatomic energy which, it is known, exists abundantly in all matter…"**

# Gas Laws

- **In most cases, the nuclei of atoms cannot interact.**
  - This is due to the <u>Coulomb barrier</u> – two positively charged nuclei will repel each other.
  - Large amounts of energy (in the forms of heat and motion) are needed to overcome this barrier and allow the nuclei to interact.
- **Under extremely high temps and pressure, electrons are stripped from their atoms.**
  - Under these conditions (which exist within all stars), protons can merge or fuse (hence the term, <u>nuclear fusion</u>).

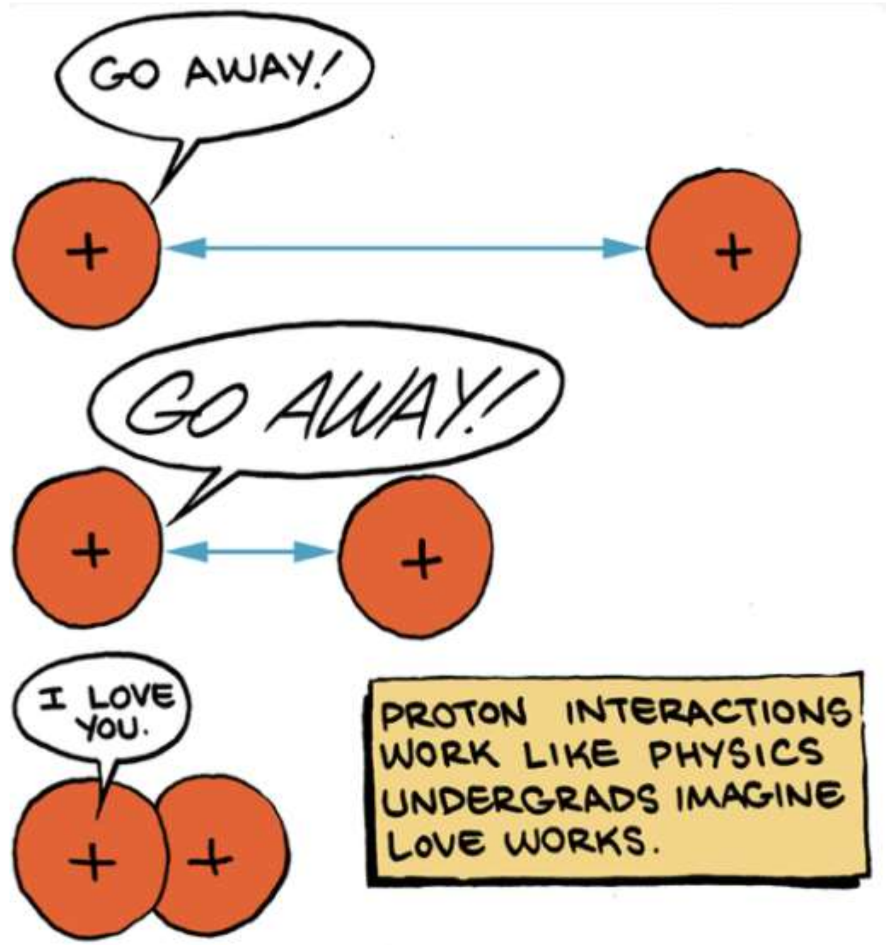



*Image Source: https://www.physicsforums.com/threads/what-is-an-electrostatic-coulomb-barrier-how-is-it-created.921720/*

# Hydrogen Fusion

- **We now know that the sun's energy output is primarily due to the fusion of hydrogen into helium.**
  - Specifically, four hydrogen protons are fused to form a helium nucleus in a process called proton-proton chain.
  - In this process, 0.7% of the mass of hydrogen is converted into heat energy and neutrinos (an uncharged particle that mostly does not interact with matter).

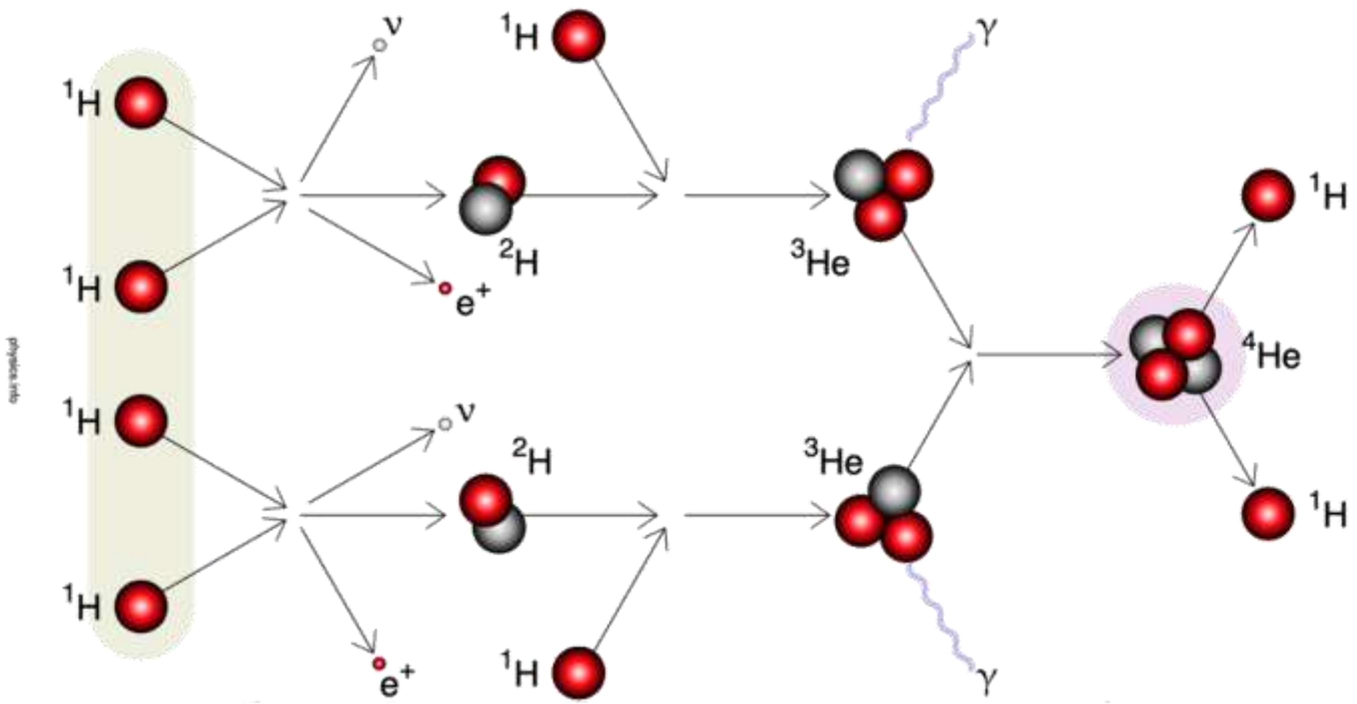
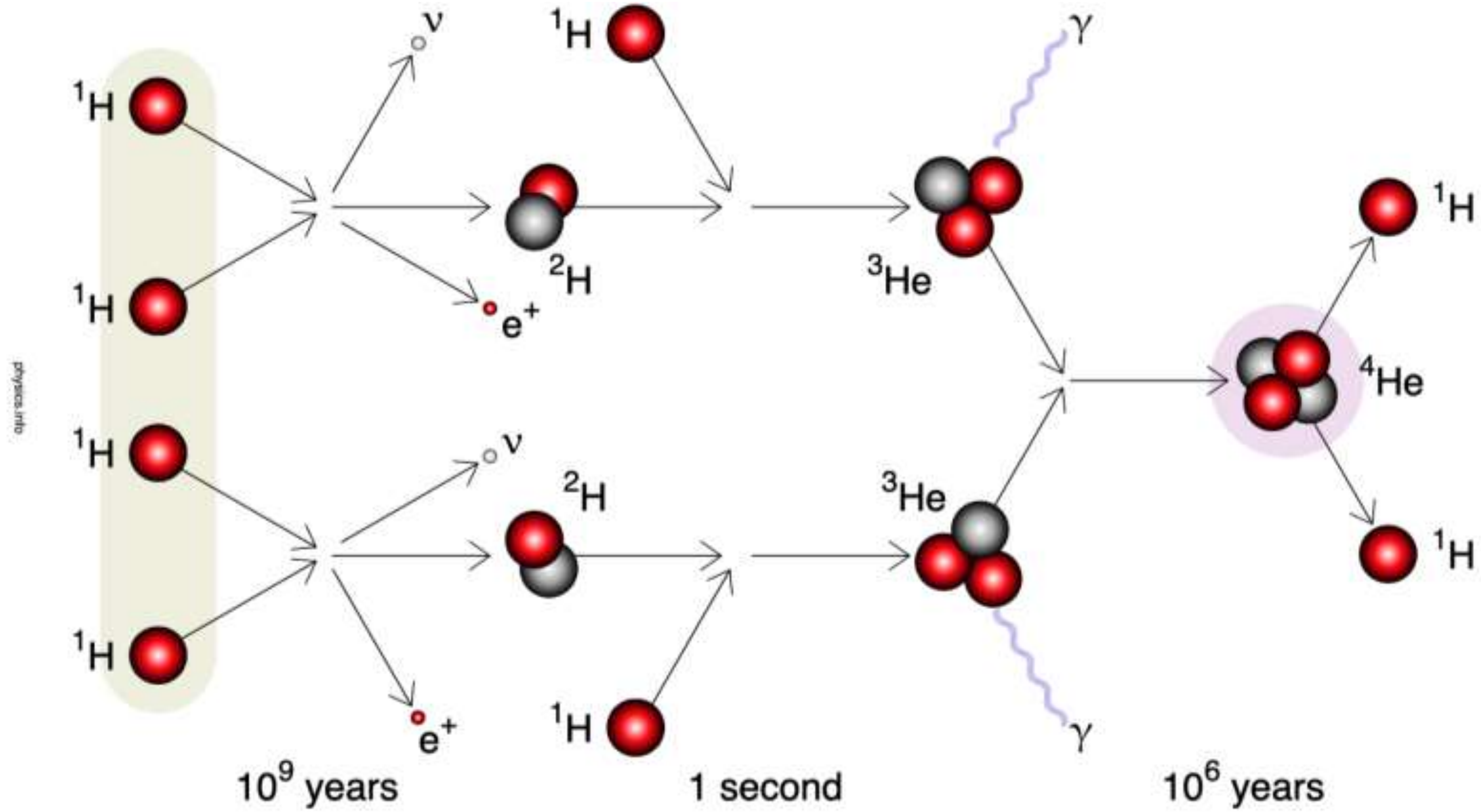



*Image Source: https://physics.info/fusion/*

# Proton-Proton Chain




1. Two hydrogen protons ($^1H$) fuse, making deuterium ($^2H$, a proton & neutron). Because a proton becomes a neutron, a positive electron (or positron, $e^+$) and a neutrino are ejected.

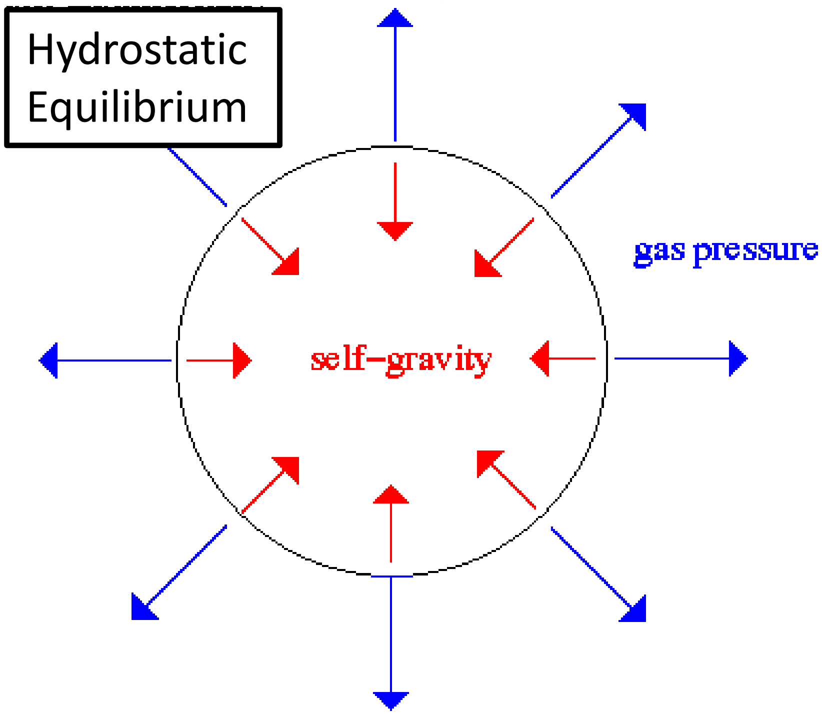
2. The deuterium ($^2H$) captures another $^1H$ proton to form Helium-3 ($^3He$). Radiation is emitted as gamma rays ($\gamma$).

3. Two Helium 3 ($^3He$) fuse to form one helium-4 ($^4He$) nucleus. They eject two hydrogen protons ($^1H$).

*Image Source: https://physics.info/fusion/*

# Gas Laws

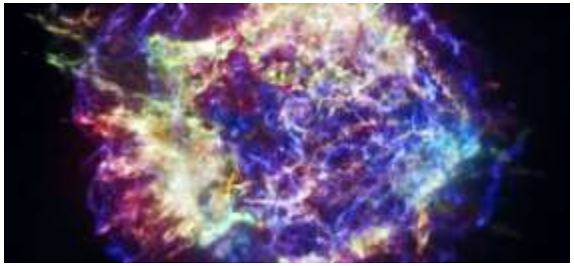
- **A key principle that determines the structure and life of stars is <u>hydrostatic equilibrium</u>**
  - In other words, the outward pressure of radiation from nuclear fusion must balance gravity`s inward pressure.
  - At every position in a star, the pressure of the gas must be just enough to support the ``weight'' of the star above it.
  - If this is not the case, the star would expand or contract and eventually become unstable.




*Source: http://ircamera.as.arizona.edu/NatSci102/NatSci102/text/hydrostat.htm*

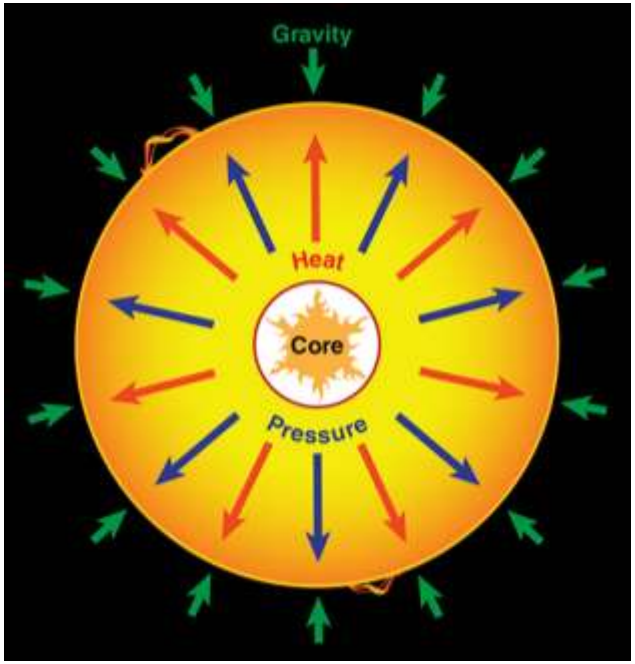
# Eddington's 3 Outcomes

- **Eddington determined there are only 3 possible outcomes for a ball of gas like a star:**
  - 1) If too small to create the conditions needed for fusion, it becomes a cool ball of gas (e.g., the gas planets).
    - This is any planet under $10^{32}$ g of gas.
  - 2) If it is the right size to balance outward and inward pressures, it becomes a star.
    - This is any planet between $10^{32}$ and $10^{35}$ g of gas.
  - 3) If it is too big, it will eventually explode due to excess outward pressure from radiation.
    - This is any planet above $10^{35}$ g of gas



# Thermal Regulation

- **Nuclear reactions produce outward pressure, counteracting the forces of gravity and its effects on pressure/temp.**
  - If a star shrinks, it will get hotter, making it expand and cool, causing it to shrink.
  - If a star expands, it will cool, and gravitational pressure will make it contract.
- **While nuclear reactions are what make a star hot, they also keep a star from getting *too* hot.**
  - Without these outward pressures, the star would contract, raising the temperature due to the relationship between temperature & pressure.




*Source: https://iopscience.iop.org/book/978-1-64327-422-5/chapter/bk978-1-64327-422-5ch5*

# Revisions to W3 Driving Question

- **Can we now improve our answers to our driving questions?**
- *Where does the sun's energy come from?*