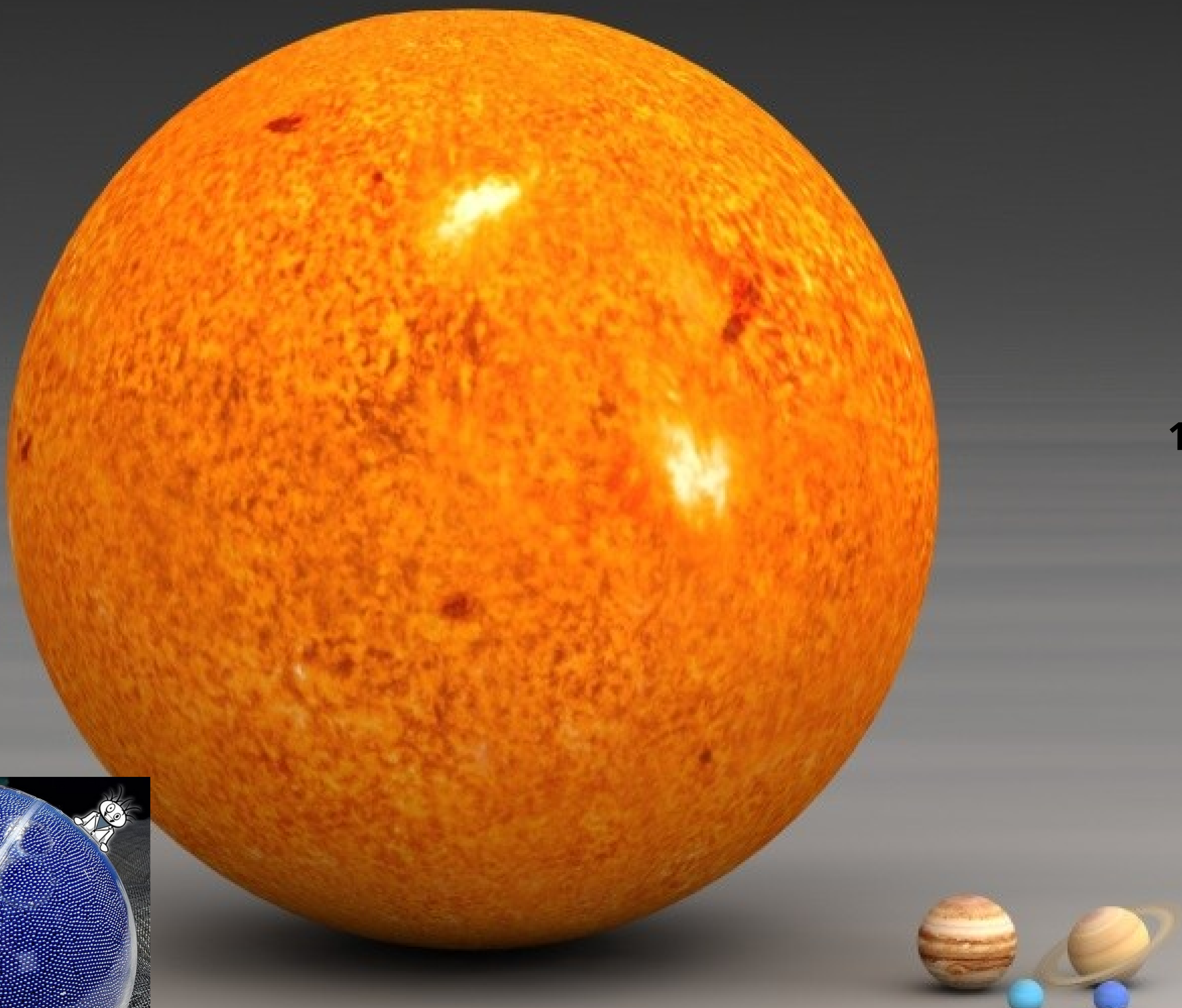
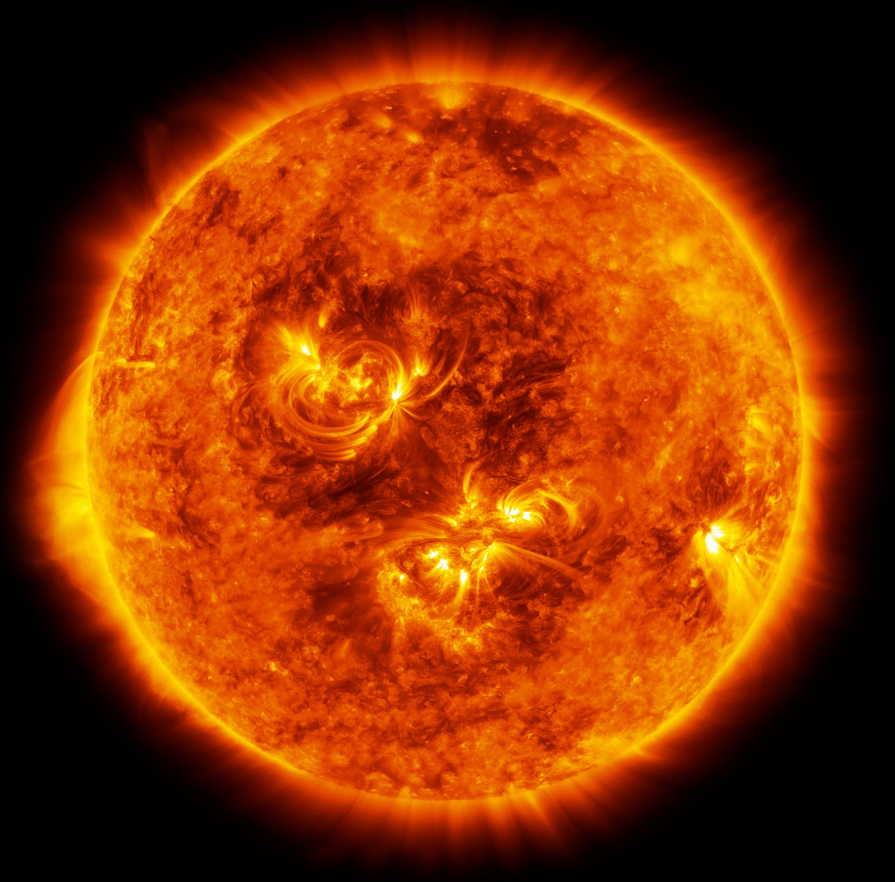
# Sun and Stellar Evolution


1,391,000 km


DANGER
NINJAS
Physics
1,300,000
EARTHS?!



The **Sun's mass** is approximately **333,000 times** the mass of the Earth.

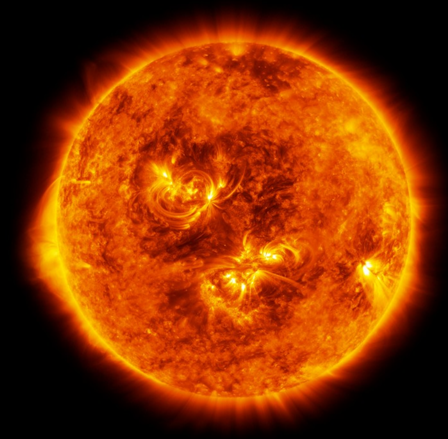
1989000000000000000000000000000kg

# Sun-Composition

**The Abundance of Elements in the Sun**

| Element | Percentage by Number of Atoms | Percentage By Mass |
|---|---|---|
| Hydrogen | 92.0 | 73.4 |
| Helium | 7.8 | 25.0 |
| Carbon | 0.02 | 0.20 |
| Nitrogen | 0.008 | 0.09 |
| Oxygen | 0.06 | 0.80 |
| Neon | 0.01 | 0.16 |
| Magnesium | 0.003 | 0.06 |
| Silicon | 0.004 | 0.09 |
| Sulfur | 0.002 | 0.05 |
| Iron | 0.003 | 0.14 |

# Sun-Composition



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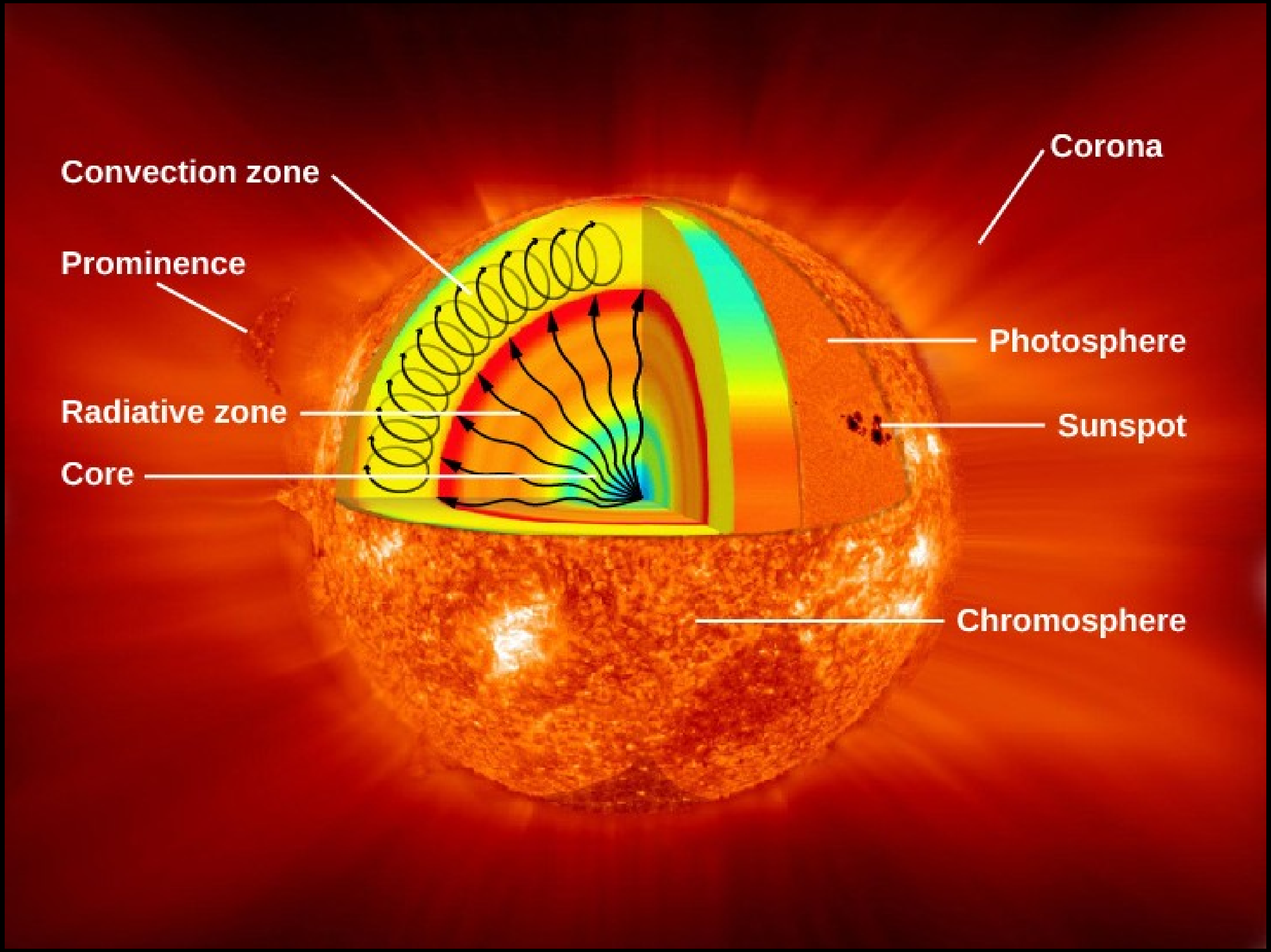
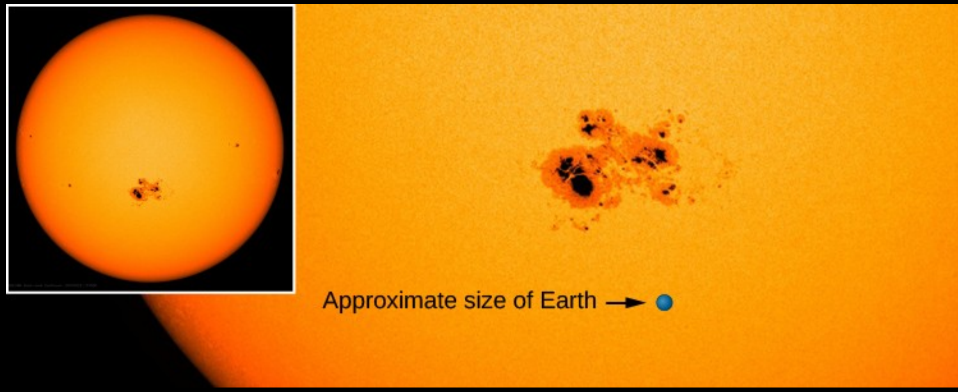
- Early belief: Sun and stars share Earth's composition.
- Cecilia Payne’s work revealed the Sun’s composition is dominated by hydrogen and helium.
- Sun and stars’ composition reflects the broader universe, unlike Earth's heavier elements.
- Most elements exist as atoms with a few molecules, all in gaseous form.
- Extreme Heat: No liquids or solids can exist due to the Sun’s intense heat.
- Many atoms are ionized, losing one or more electrons.
- The Sun’s environment is electrically charged, unlike Earth’s neutral atmosphere. This state is known as plasma.

# Sun-Structure



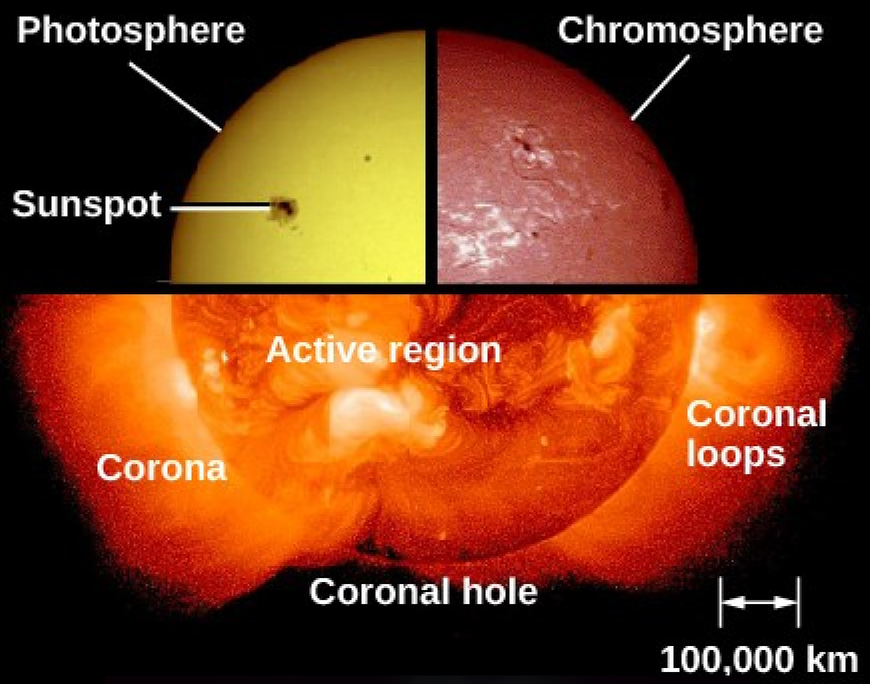
# Solar Photosphere

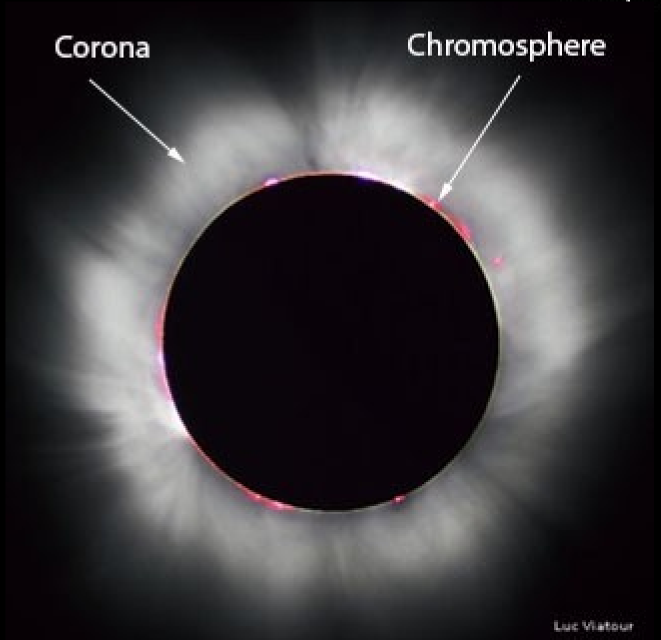
- The photosphere is the layer where the Sun becomes opaque and marks the boundary past which we cannot see
- Energy that emerges from the photosphere was originally generated deep inside the Sun
- This energy is in the form of photons, which make their way slowly toward the solar surface.
- Outside the Sun, we can observe only those photons that are emitted into the solar photosphere, where the density of atoms is sufficiently low and the photons can finally escape from the Sun without colliding with another atom or ion.
- Temperature 4000-6500K



# Chromosphere

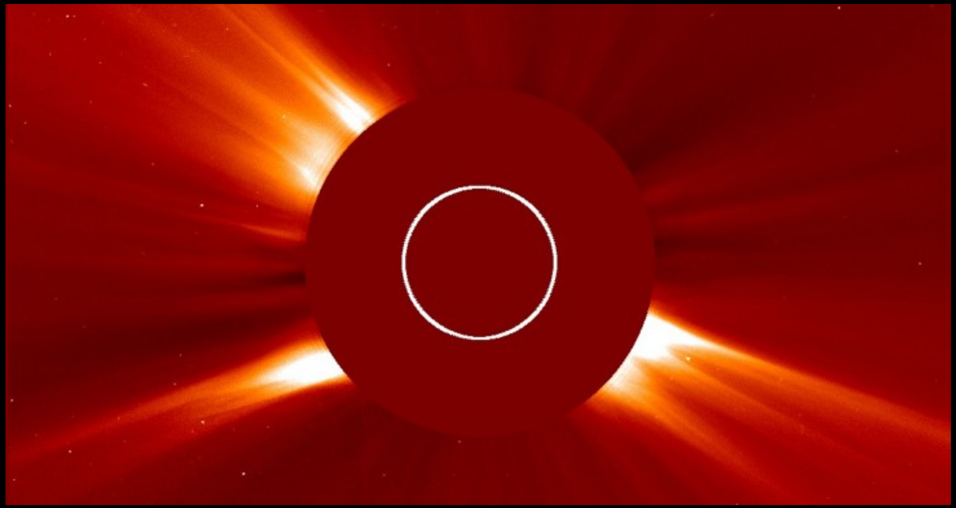
- The region of the Sun’s atmosphere that lies immediately above the photosphere is called the chromosphere.
- Until this century, the chromosphere was visible only when the photosphere was concealed by the Moon during a total solar eclipse
- Chromosphere is about 2000 to 3000 kilometers thick, and its spectrum consists of bright emission lines.
- The reddish color of the chromosphere—the bright red line caused by hydrogen
- In 1868, observations of the chromospheric spectrum revealed a yellow emission line that did not correspond to any previously known element on Earth.
- Scientists quickly realized they had found a new element and named it helium
- The temperature of the chromosphere is about 10,000 K.



# Corona

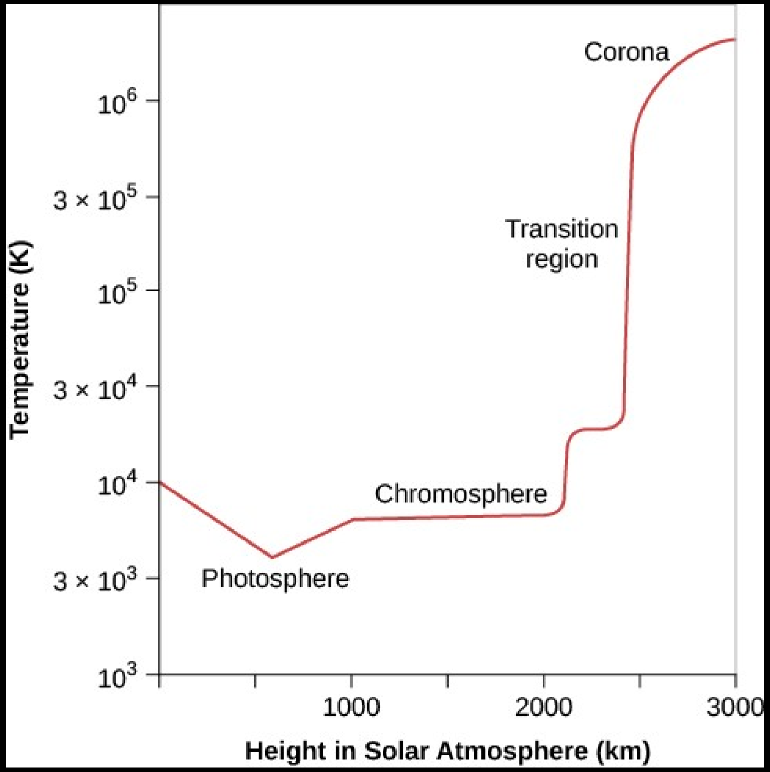
- The outermost part of the Sun's atmosphere is called the corona
- Corona was first observed during total eclipses
- The corona extends millions of kilometers above the photosphere and emits about half as much light as the full moon.
- The reason we don't see this light until an eclipse occurs is the overpowering brilliance of the photosphere.
- Temperature : 3 million Kelvin

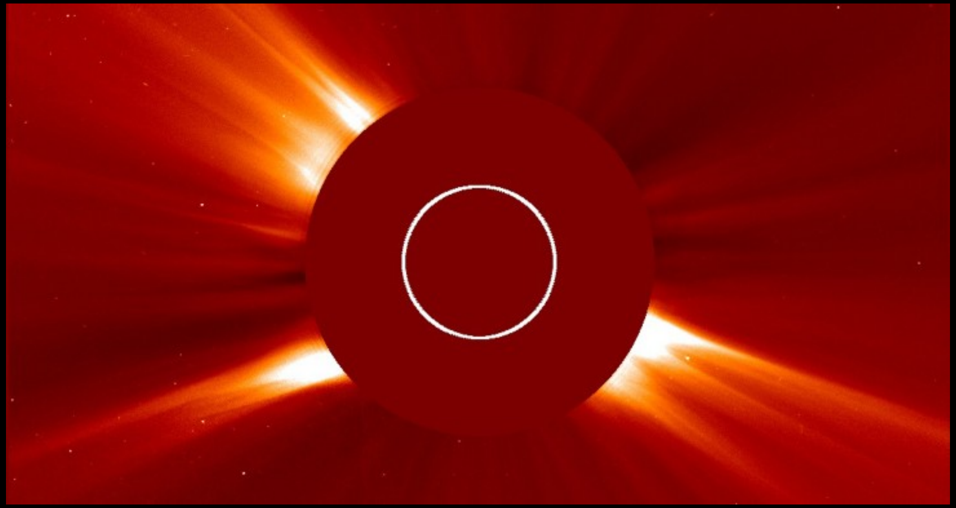


# Corona

- **Magnetic Heating (Magnetic Reconnection)** -The Sun’s magnetic field lines tangle, twist, and reconnect, releasing vast amounts of energy. These reconnection events transfer energy to the corona, heating it significantly.
- **Nanoflares:** Tiny, frequent bursts of magnetic energy (smaller versions of solar flares) occur constantly in the corona. Though individually small, their cumulative effect can generate significant heating.
- **Thermal Conduction Suppression:** Unlike typical heat conduction, the highly ionized plasma in the corona prevents efficient transfer of heat back to the cooler layers. This helps maintain the high temperatures in the corona.

*Despite these theories, the exact mechanism behind coronal heating remains an active area of research in solar physics.*



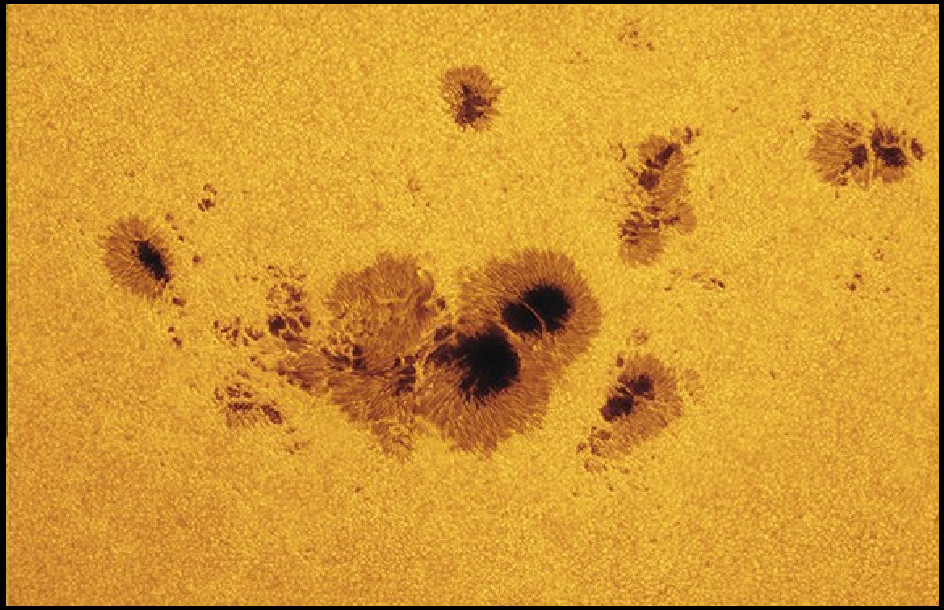



# Solar Wind

- Sun’s atmosphere produces a stream of charged particles (mainly protons and electrons) - solar wind.
- These particles flow outward from the Sun into the solar system at a speed of about 400 kilometers per second. Although the solar wind material is very, very rarified, the Sun has an enormous surface area. Astronomers estimate that the Sun is losing about 1–2 million tons of material each second through this wind.
- *At the surface of Earth, we are protected to some degree from the solar wind by our atmosphere and Earth’s magnetic field*
- *However, the magnetic field lines come into Earth at the north and south magnetic poles.*
- *Here, charged particles accelerated by the solar wind can follow the field down into our atmosphere. As the particles strike molecules of air, they cause them to glow, called the auroras, or the northern and southern lights*

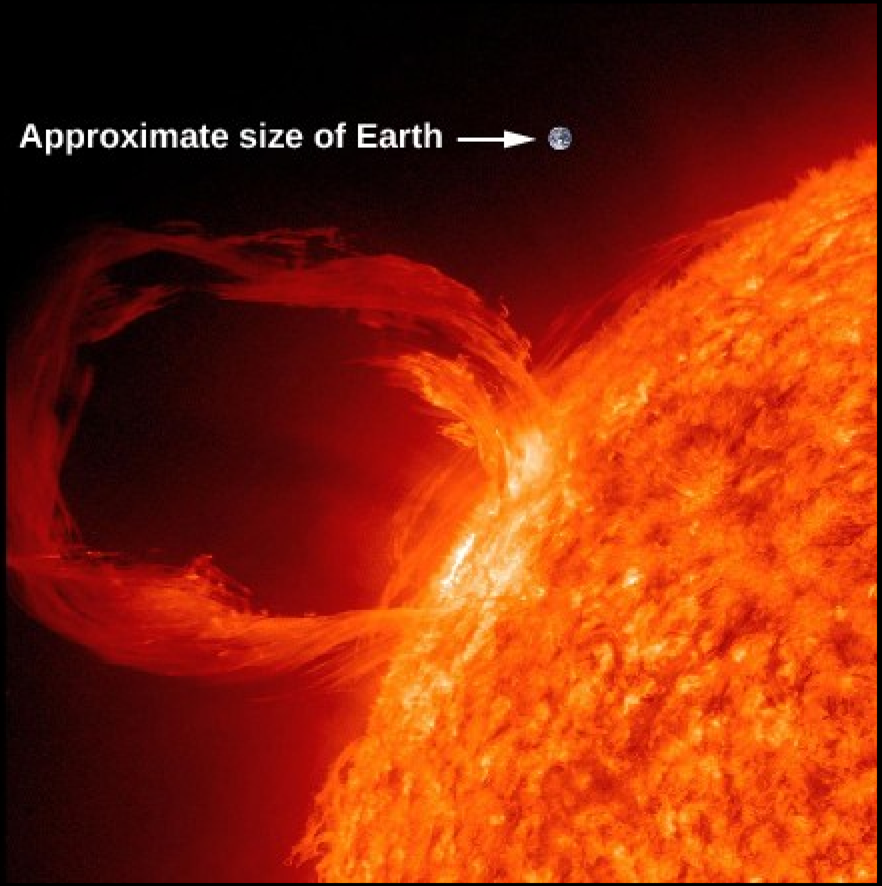
# Sunspots

- Sunspots are large, dark features seen on the surface of the Sun caused by increased magnetic activity.
- They look darker because the spots are typically at a temperature of about 3800 K, whereas the bright regions that surround them are at about 5800 K
- *Lifetimes range from a few hours to a few months.*
- *Consists of two parts: an inner darker core, the umbra, and a surrounding less dark region, the penumbra.*
- *By recording the apparent motions of the sunspots as the turning Sun carried them across its disk  Galileo, in 1612, demonstrated that the Sun rotates on its axis with a rotation period of approximately 1 month.*
- *Speed of rotation of the Sun varies according to latitude.*
- *The rotation period is about 25 days at the equator, 28 days at latitude 40°, and 36 days at latitude 80°. We call this behavior differential rotation.*



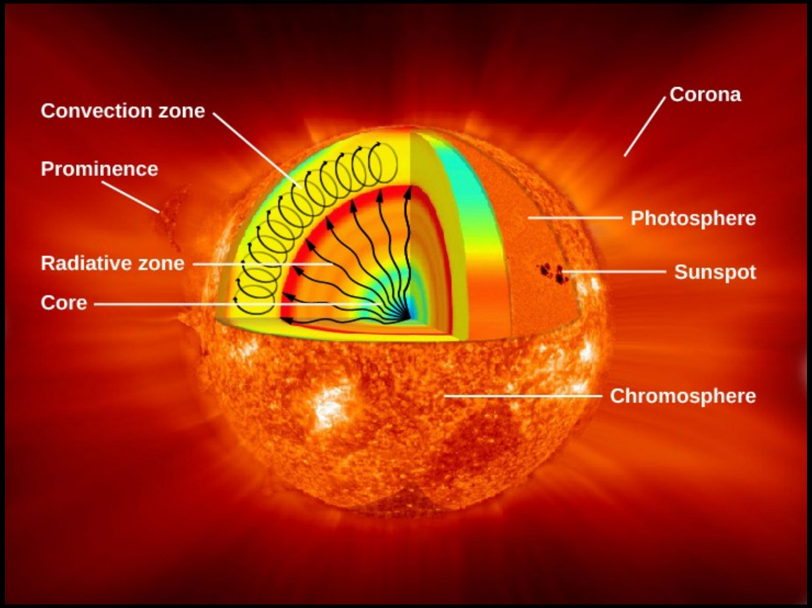
# Prominences

- Prominence, sometimes referred to as a filament, is a large plasma and magnetic field structure extending outward from the Sun's surface,] often in a loop shape.
- Prominences are anchored to the Sun's surface in the much brighter photosphere, and extend outwards into the solar corona.
- While the corona consists of extremely hot plasma, prominences contain much cooler plasma, similar in composition to that of the chromosphere.
- Eclipse observers often see prominences as red features rising above the eclipsed Sun and reaching high into the corona.
- The relatively rare eruptive prominences appear to send matter upward into the corona at high speeds, and the most active surge prominences may move as fast as 1300 kilometers per second
- Some eruptive prominences have reached heights of more than 1 million kilometers above the photosphere.



# Heat Transfer in a Star

- **Conduction**, atoms or molecules pass on their energy by colliding with others nearby. For example, when the handle of a metal spoon heats up as you stir a cup of hot coffee.
- **Convection**, currents of warm material rise, carrying their energy with them to cooler layers. A good example is hot air rising from a fireplace.
- **Radiation**, energetic photons move away from hot material and are absorbed by some material to which they convey some or all of their energy.  You can feel this when you put your hand close to the coils of an electric heater, allowing infrared photons to heat up your hand.

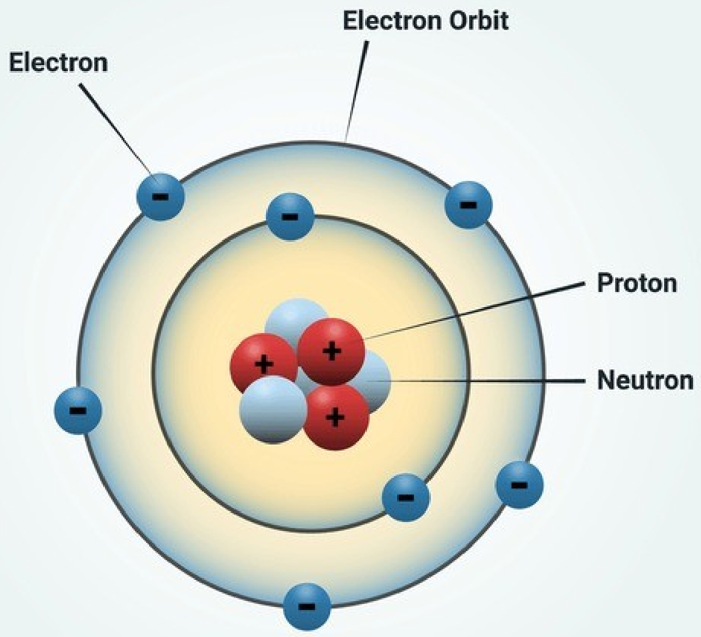



*In stars, which are much more transparent, radiation and convection are important, whereas conduction can usually be ignored.*

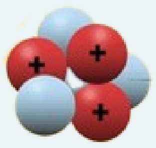
$$E = mc^2$$

# Into the World of Atoms

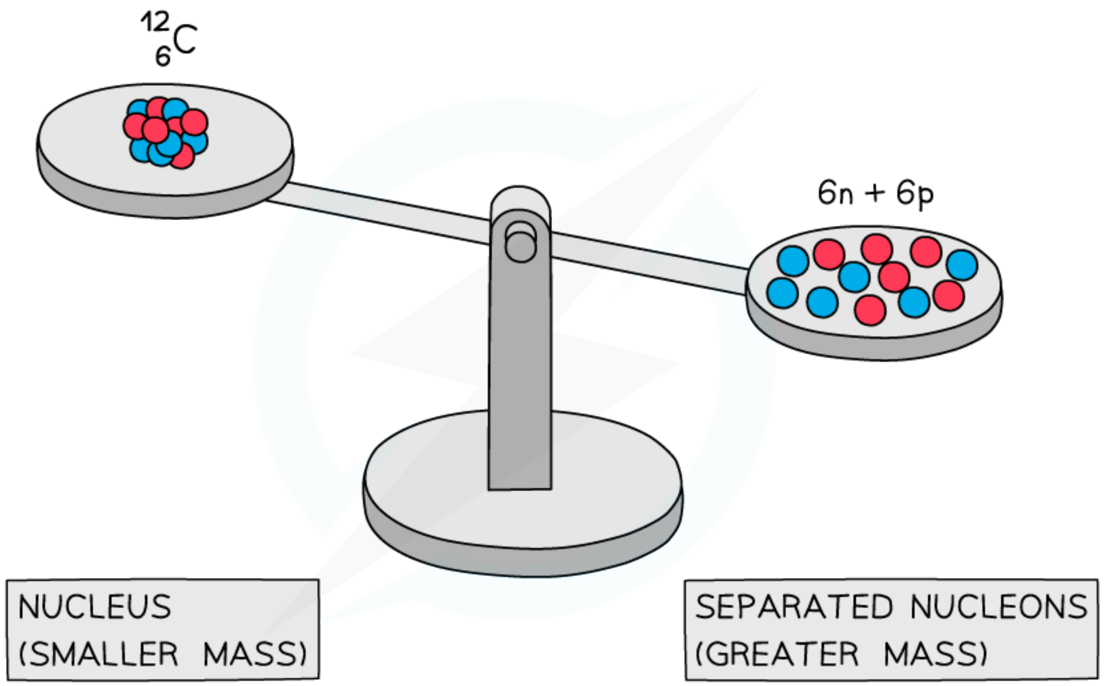
[Video Link]




Atom



Nucleus



$^{12}_{6}C$
6n + 6p
NUCLEUS
(SMALLER MASS)
SEPARATED NUCLEONS
(GREATER MASS)

Hydrogen Nucleus

P 1.007825 u

+

P 1.007825 u

+

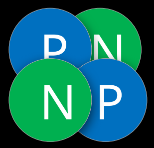
P 1.007825 u

+

P 1.007825 u

**4.0313 u**

=




He

**4.002603u**

4.031300 u -
4.002603 u

**0.0287 u**

Hydrogen Nucleus

P 1.007825 u

+

P 1.007825 u

+

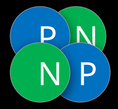
P 1.007825 u

+

P 1.007825 u

**4.0313 u**

=




He

**4.002603u**

4.031300 u -
4.002603 u

**0.0287 u**

1u = 1.66 x $10^{-27}$kg

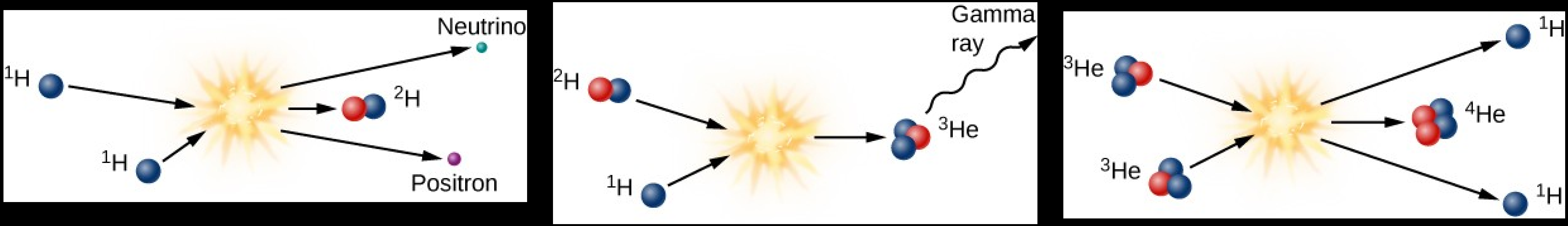
$$\Delta m = 0.0287\,\text{u} \times 1.66054 \times 10^{-27}\,\text{kg/u}$$

$$\Delta m \approx 4.76 \times 10^{-29}\,\text{kg}$$

Using $E = \Delta mc^2$:

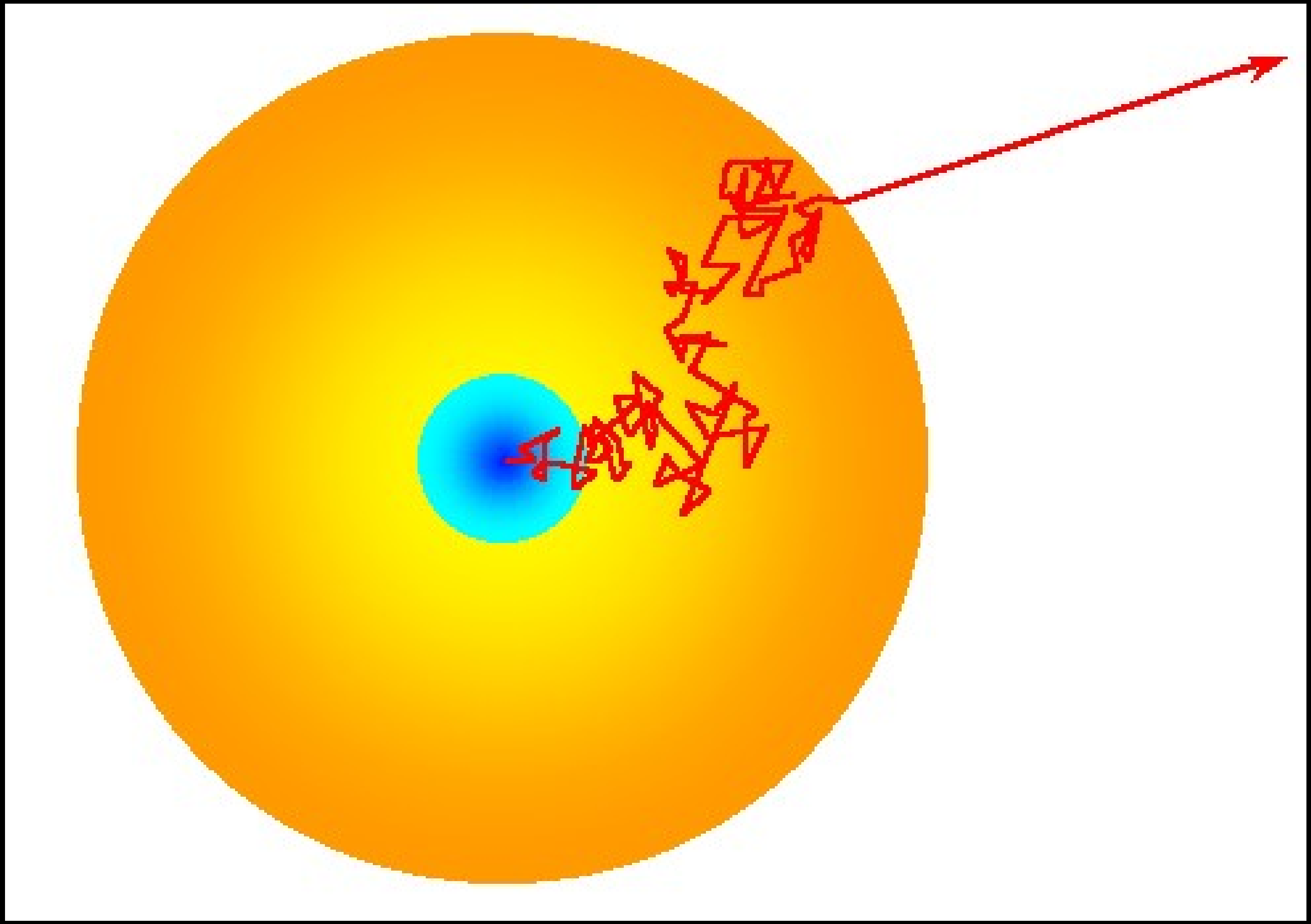
$$E = (4.76 \times 10^{-29}\,\text{kg}) \times (3 \times 10^8\,\text{m/s})^2$$

$$E \approx \underline{4.28 \times 10^{-12}\,\text{joules}}$$




$$^{1}\mathrm{H} + {}^{1}\mathrm{H} \longrightarrow {}^{2}\mathrm{H} + \mathrm{e}^{+} + v$$
$$^{2}\mathrm{H} + {}^{1}\mathrm{H} \longrightarrow {}^{3}\mathrm{He} + \gamma$$
$$^{3}\mathrm{He} + {}^{3}\mathrm{He} \longrightarrow {}^{4}\mathrm{He} + {}^{1}\mathrm{H} + {}^{1}\mathrm{H}$$

# Journey of a Photon from Core



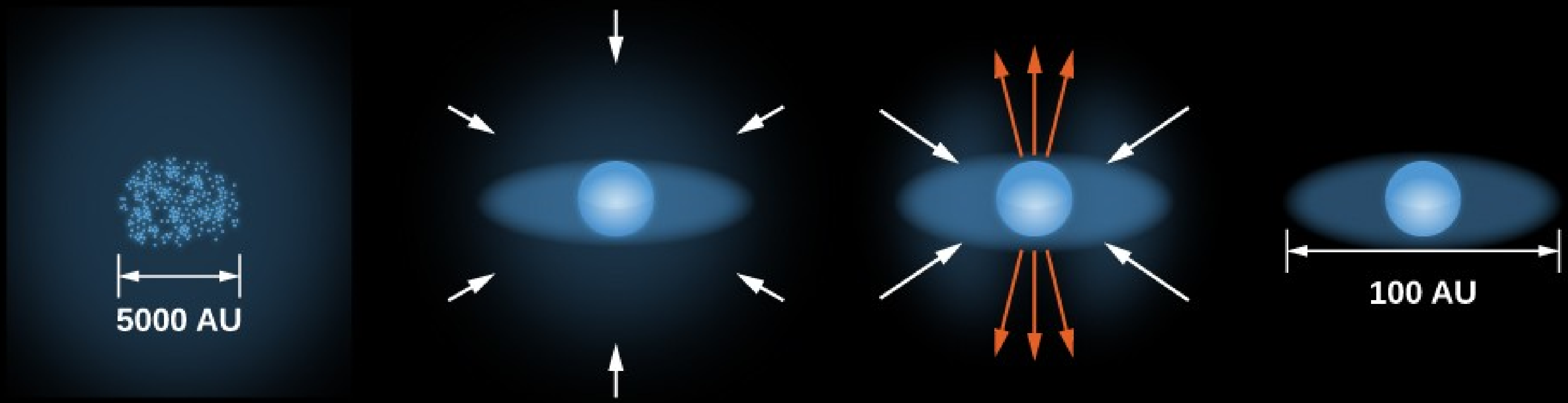
# Stellar Evolution

Credit: ESO/M. Kornmesser

# Molecular Clouds: Stellar Nurseries

- Masses of molecular clouds range from a thousand times the mass of the Sun to about 3 million solar masses.
- Molecular clouds have a complex filamentary structure, similar to cirrus clouds in Earth’s atmosphere, but much less dense.
- The molecular cloud filaments can be up to 1000 light-years long.
- cold, dense regions with typical masses of 50 to 500 times the mass of the Sun- clumps. Within even denser, smaller regions called cores-embryos of stars.
- Air – $10^{25}$ Partcles / m3
- Nebula $10^{5}$ Partcles/$m^{3}$

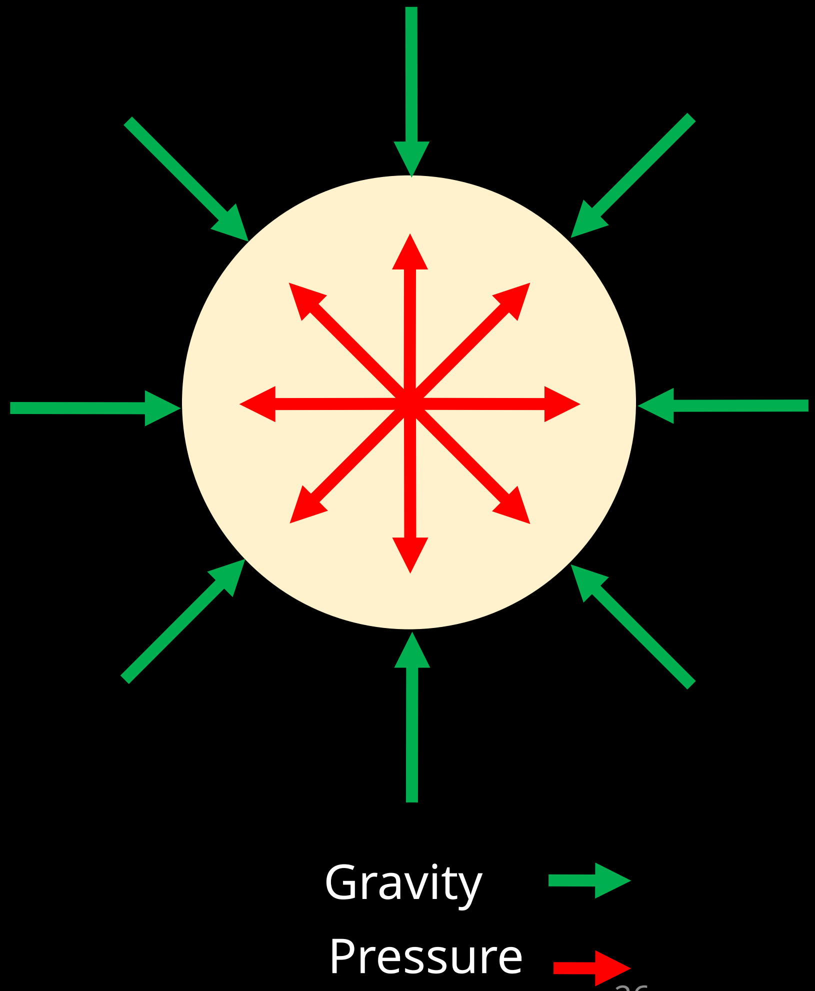
# Birth of a proto-Star




| Stage | Key Events | Outcome |
|---|---|---|
| 1. Nebula | Cold gas and dust | Gravitational collapse begins |
| 2. Collapse | Gravity pulls particles inward | Dense core forms |
| 3. Core Formation | Central core heats up | Accretion disk forms |
| 4. Disk Formation | Rotation accelerates | Accretion continues |
| 5. Heating | Temperature rises | Infrared radiation emitted |
| 6. Protostar Stage | No fusion yet, core heats | Protostar glows |

# Birth of Star

- Energy Source: Initially, gravitational contraction supplies energy as the protostar collapses.
- As the protostar contracts, gravitational potential energy is converted into heat, raising the core temperature.
- Problem: Protons (hydrogen nuclei) are positively charged, so they repel each other due to the Coulomb force.
- Coulomb Barrier: For fusion to occur, protons must overcome the electrostatic repulsion.
- Quantum mechanics allows particles to "tunnel" through the barrier
- At around 10 million K, the protons' kinetic energy and quantum tunnelling enable fusion despite the Coulomb barrier.
- **Hydrostatic Equilibrium** is achieved when the outward radiation pressure from fusion balances the inward gravitational pull.



# Mass Criteria

- **Jeans Mass**
  - The minimum mass required for a gas cloud to collapse under its own gravity and form a protostar.
  - If a cloud’s mass is less than the Jeans mass, it will not collapse; instead, it will disperse due to thermal pressure.

- **Hydrogen Burning Limit**
  - The minimum mass a protostar needs to sustain hydrogen fusion in its core.
  - Value : $\approx 0.08\,M_{\odot} \approx 80\,M_{\text{Jupiter}}$
  - Above this limit: The object becomes a main-sequence star.
  - Below this limit: The object becomes a brown dwarf, which cannot sustain continuous hydrogen fusion.

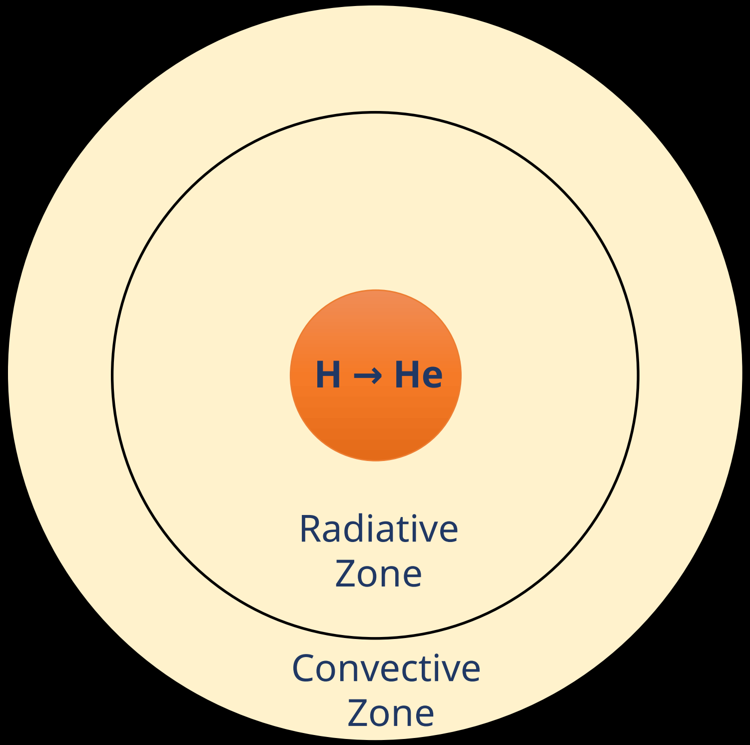
- **Eddington Limit**
  - The maximum mass a star can have before radiation pressure overcomes gravitational pull, causing the star to lose mass.
  - Value: Generally estimated at ~100 to 150 solar masses.
  - Stars exceeding this mass limit become unstable due to intense radiation pressure and may lose mass rapidly or explode as supernovae.

# Main-Sequence Stars

1. Core:
   - Site of hydrogen fusion.
   - Temperature: ~10 million to 40 million K
   - Very high, with ionized hydrogen and helium.

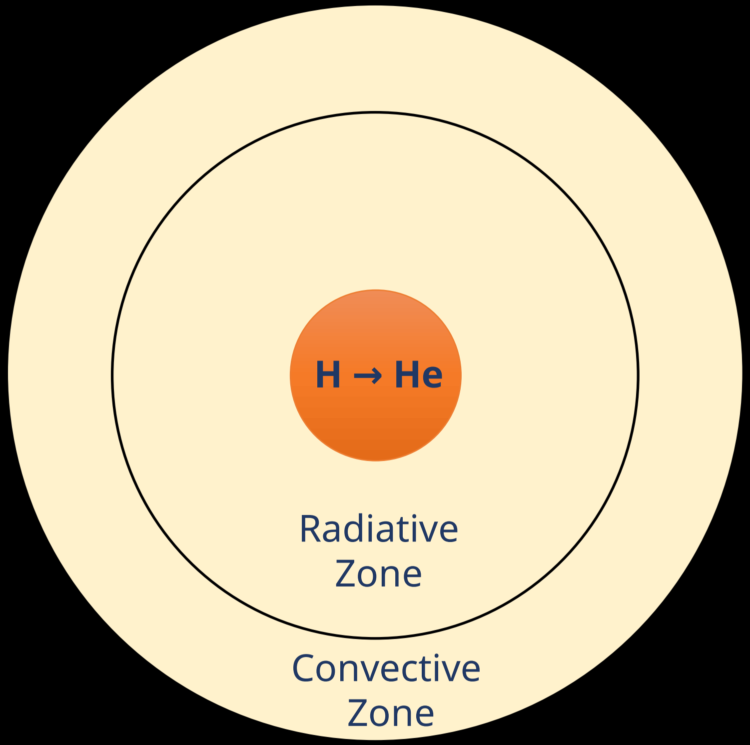
2. Radiative Zone:
   - Energy is transported outward by radiation.
   - Photons are absorbed and re-emitted multiple times, taking thousands to millions of years to reach the surface.

3. Convective Zone:
   1. Energy is transported by convection currents More prominent in low-mass stars like the Sun.



# Main-Sequence Stars

| **Mass** $M_s$ | **Surface Temperature (K)** | **Lifetime on Main Sequence (years)** |
|---:|---:|---|
| 40 | 54,000 | 1 million |
| 16 | 29,200 | 10 million |
| 3.3 | 9600 | 500 million |
| 1.7 | 7350 | 2.7 billion |
| 1.1 | 6050 | 9 billion |
| 0.8 | 5240 | 14 billion |
| 0.4 | 3750 | 200 billion |



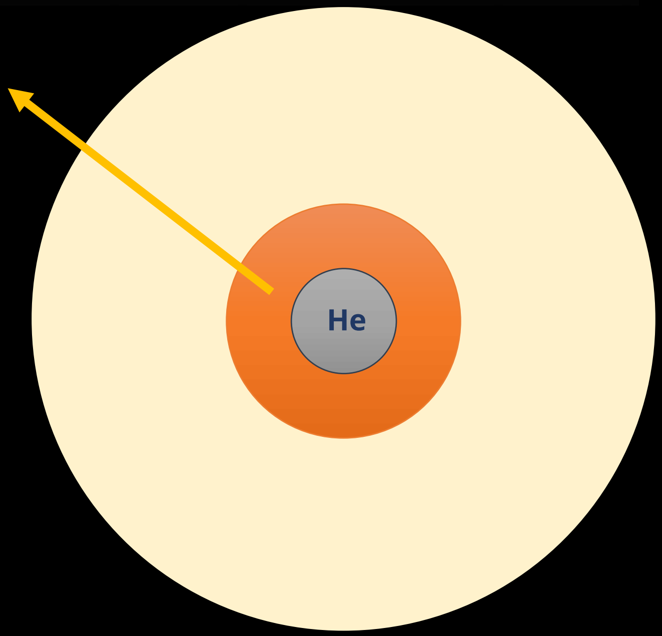
# From Main-Sequence Star to Red Giant

Hydrogen Depletion in the Core

- Core Contraction: As hydrogen is depleted in the core, fusion slows, and the core starts to collapse under gravity.

- Helium Core Formation: Core consists mostly of inert helium, unable to fuse (helium fusion requires ~100 million K).

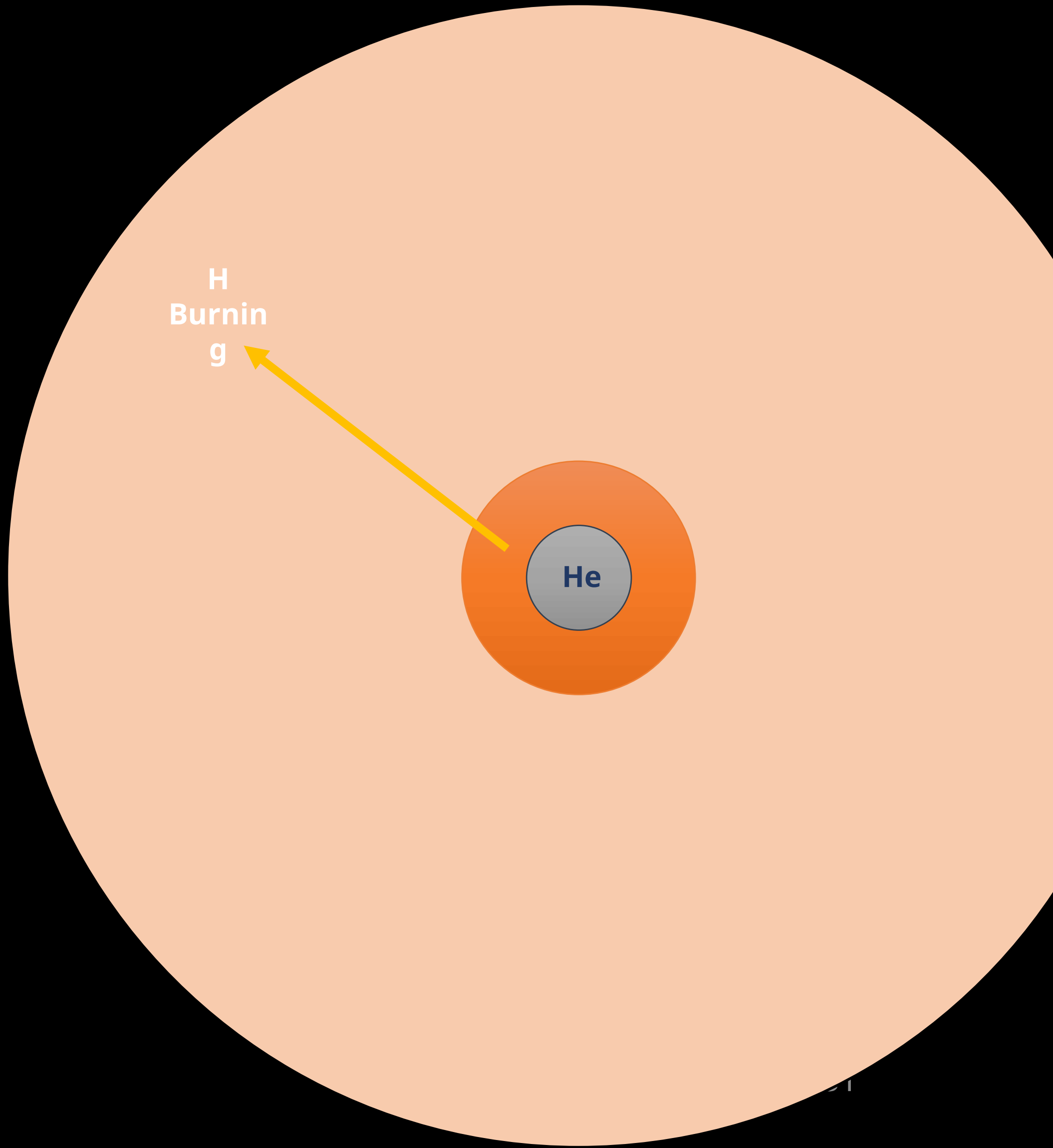
- Hydrogen Shell Burning: Hydrogen fusion continues in a shell surrounding the helium core, causing the core to heat up further.

# From Main-Sequence Star to Red Giant

Core Contraction and Shell Expansion

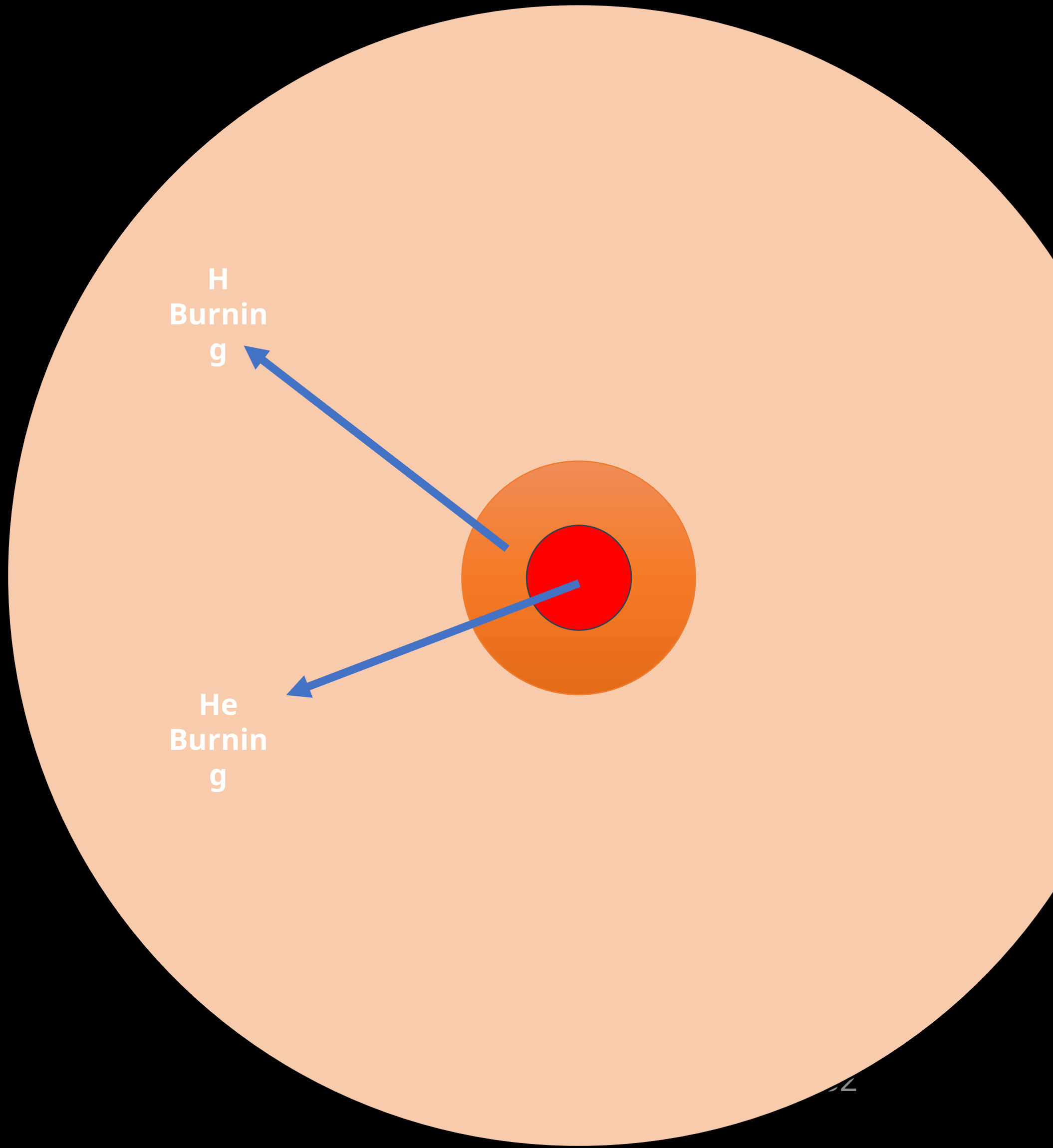
- Energy Increase: As the core contracts, gravitational potential energy is converted into thermal energy, heating the core and shell.
- Outer Layers Expand: The increased energy from the hydrogen shell burning causes the star's outer layers to expand significantly.
- Surface Cooling: As the star's radius increases, its surface temperature decreases, making the star appear cooler and redder.



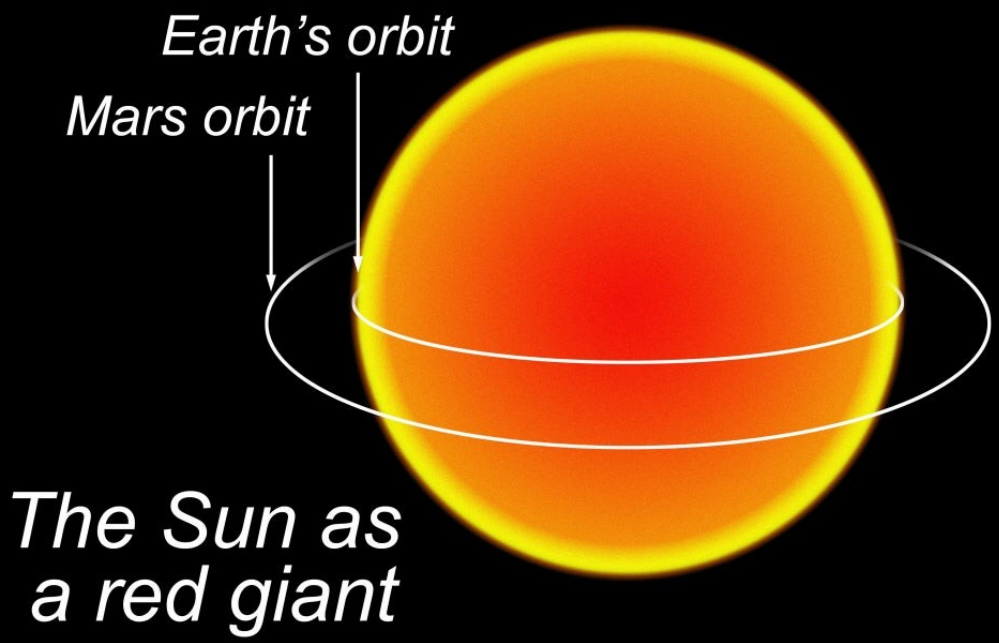
# From Main-Sequence Star to Red Giant

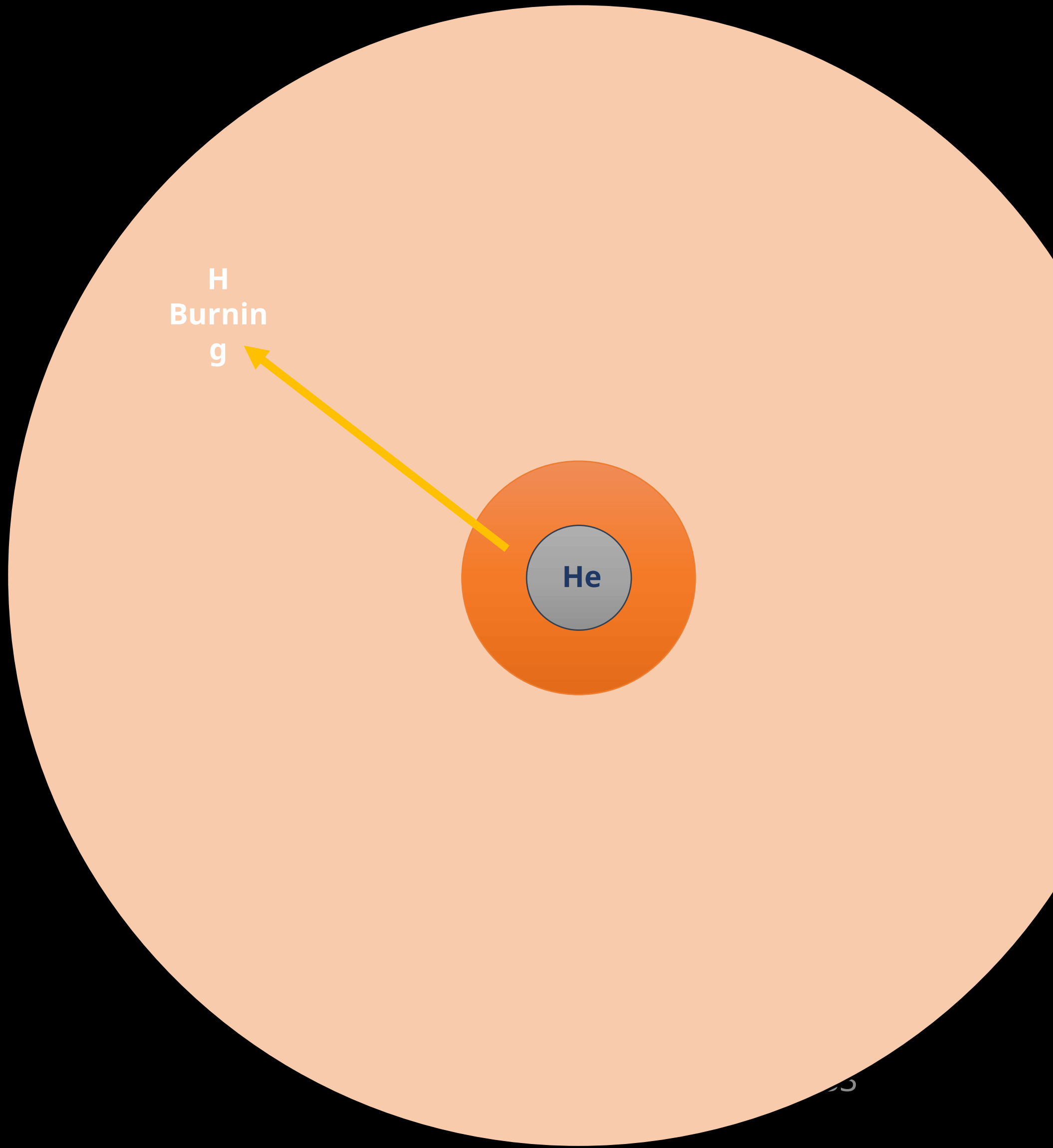
Helium Flash (for Low- and Medium-Mass Stars)

- In stars like the Sun:
  - Core Ignition: When the core temperature reaches ~100 million K, helium fusion begins in a sudden, explosive event called the helium flash.
  - Helium Fusion: Helium nuclei fuse to form carbon and oxygen via the triple-alpha process
- High-mass stars smoothly ignite helium fusion without a helium flash.



# From Main-Sequence Star to Red Giant

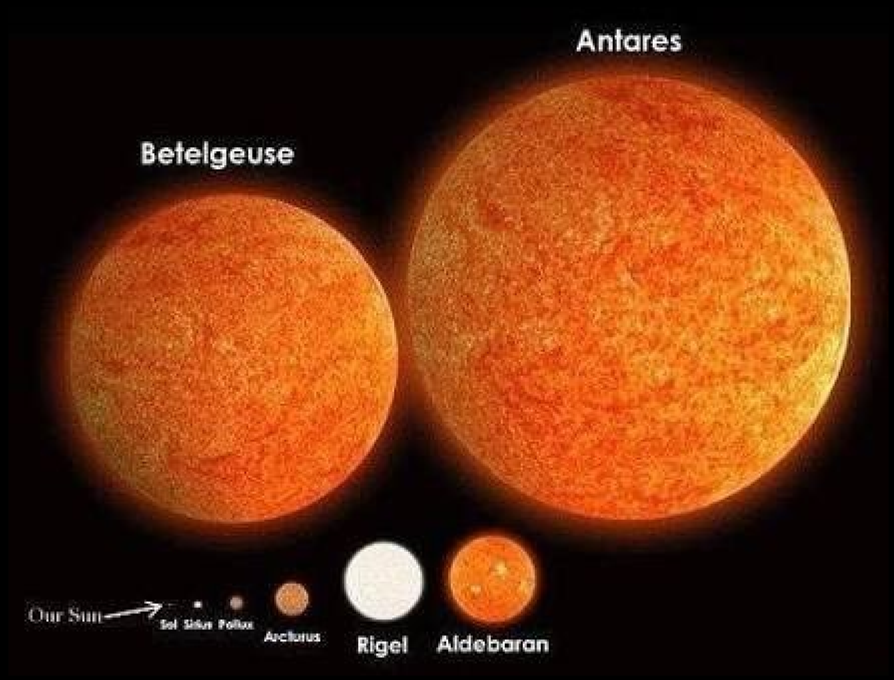


# From Main-Sequence Star to Red Giant

Red Giant Characteristics

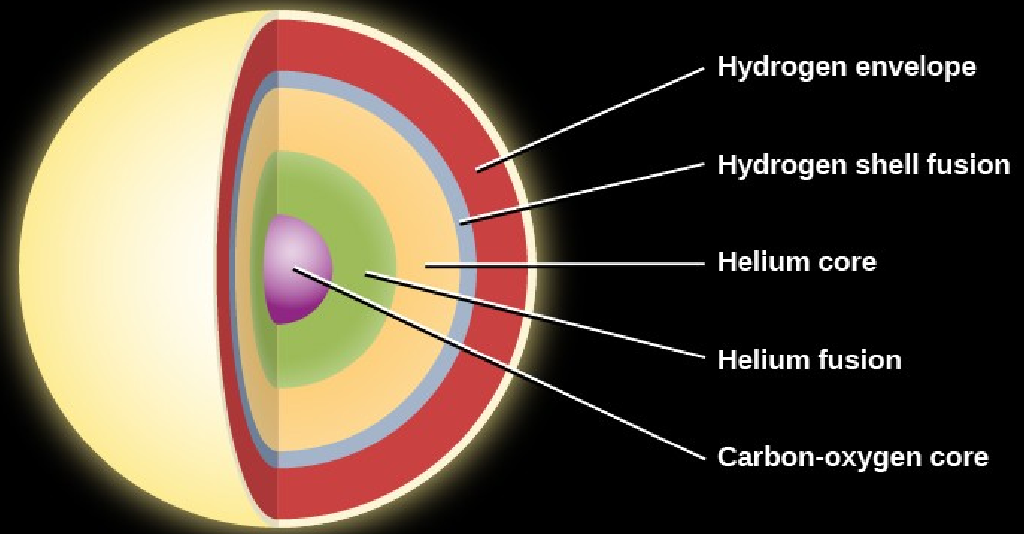
- Increased Luminosity
  - Despite cooling, the star becomes much more luminous due to its enormous size.
- Radius Expansion
  - The star can expand to tens or hundreds of times its original radius.
- Surface Temperature Drop
  - The surface temperature decreases, leading to a reddish appearance.



# Evolution of a Low-Mass Star (M < 8 Solar Masses)

Asymptotic Giant Branch (AGB)

- Helium Exhaustion in the Core
    - Helium in the core is depleted, leaving a core made mostly of carbon and oxygen.
- Double Shell Burning:
    - Helium Shell Burning: Helium fusion occurs in a shell around the core.
    - Hydrogen Shell Burning: Hydrogen fusion continues in an outer shell.
- Pulsations and Mass Loss: The star undergoes thermal pulses, and powerful stellar winds drive away its outer layers, enriching the interstellar medium with heavier elements.



# Evolution of a Low-Mass Star (M < 8 Solar Masses)

| Stage | Time in This Stage (years) | Surface Temperature (K) | Luminosity ($L_{sun}$) | Diameter (Sun = 1) |
|---|---|---|---|---|
| **Main sequence** | 11 billion | 6000 | 1 | 1 |
| **Becomes red giant** | 1.3 billion | 3100 at minimum | 2300 at maximum | 165 |
| **Helium fusion** | 100 million | 4800 | 50 | 10 |
| **Giant again** | 20 million | 3100 | 5200 | 180 |

# Evolution of a Low-Mass Star (M < 8 Solar Masses)

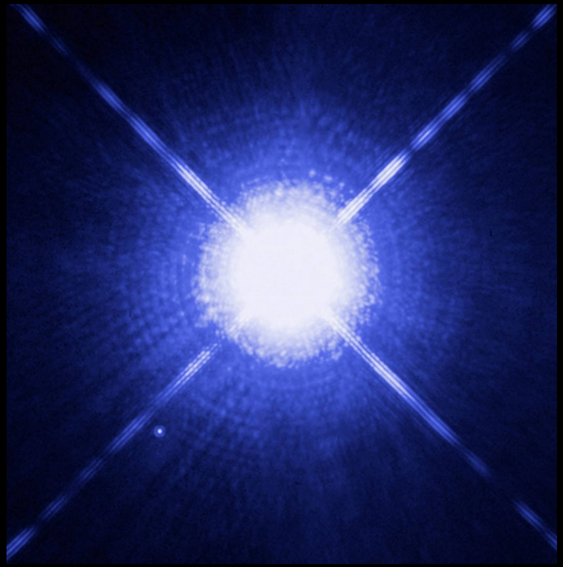
Planetary Nebula Formation

- Ejection of Outer Layers: The outer layers are expelled due to strong stellar winds, forming a planetary nebula.
- Core Exposure: The hot, dense core is exposed at the center of the nebula.
- Illumination: Ultraviolet radiation from the core ionizes the surrounding gas, causing the nebula to glow.

# Evolution of a Low-Mass Star (M < 8 Solar Masses)

White Dwarf Formation

- Core Cooling and Collapse: The remaining core, composed of carbon and oxygen, collapses into a white dwarf.
- Degenerate Matter: The core is supported by electron degeneracy pressure, not fusion.
- Mass Limit: If the mass is below the **Chandrasekhar limit** (~1.4 solar masses), it becomes a stable white dwarf.
- Temperature and Size: Extremely hot initially (up to 100,000 K), but small (about the size of Earth).
- No Fusion: The white dwarf slowly cools and fades over billions of years.
- After trillions of years, the white dwarf will cool to become a black dwarf

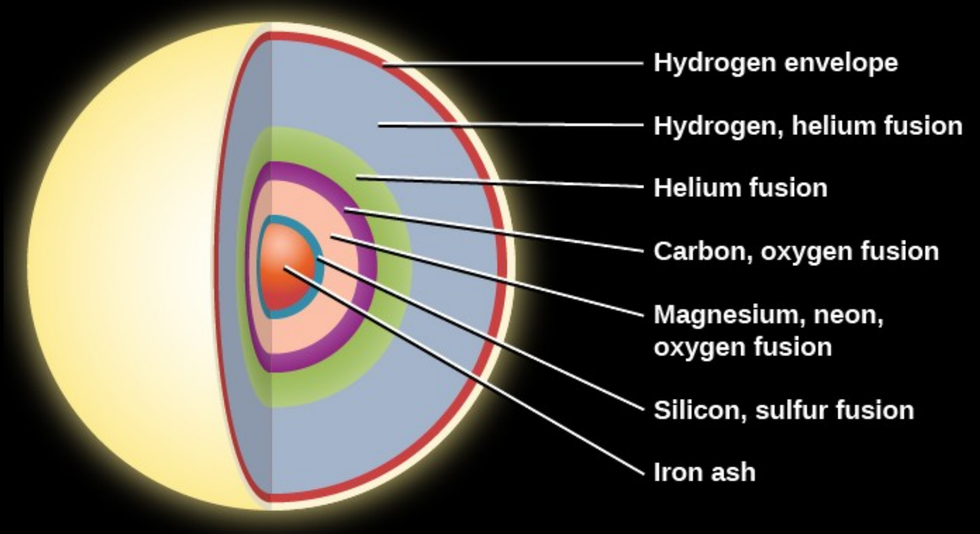


A teaspoon of white dwarf star = 9000kg

# Evolution of High-Mass Stars (M > 8 Solar Masses)

Helium Fusion and the Supergiant Phase

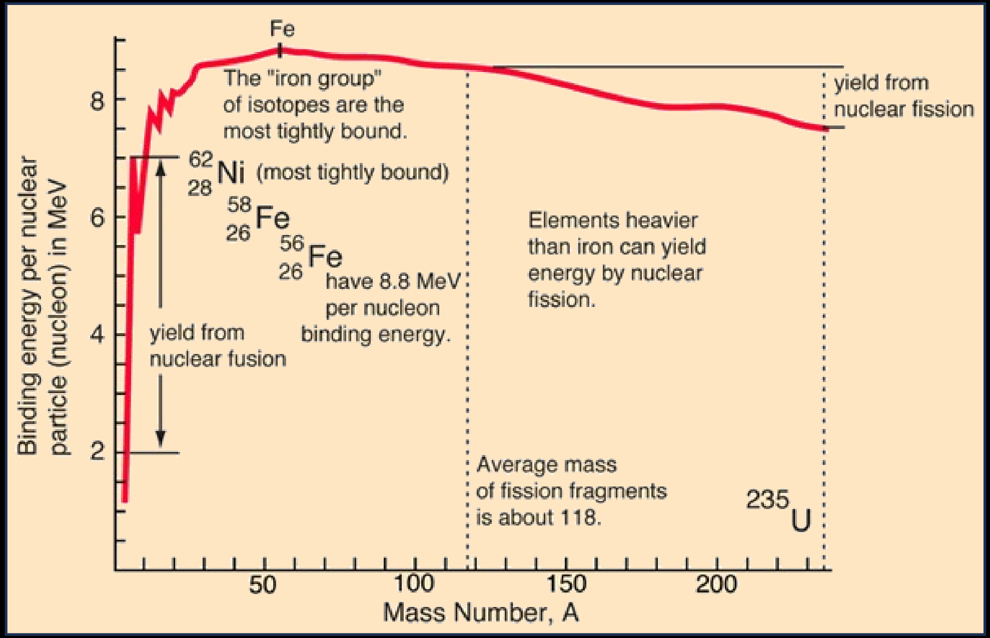
- After helium fusion begins, the high-mass star progresses into the supergiant phase.
  - Helium Core Fusion: In the supergiant phase, helium is fused into heavier elements like carbon and oxygen.
  - Multi-shell Fusion: As helium is depleted, the core contracts further, and the star starts to fuse heavier elements, such as carbon, neon, oxygen, and silicon, in multiple shells surrounding the core.
- Layered Fusion
  - Each element requires progressively higher temperatures for fusion, so the star creates successive "shells" of fusion.
- The inner core may be fusing iron and nickel toward the end.



# Evolution of High-Mass Stars (M > 8 Solar Masses)

Iron Core Formation and the End of Fusion

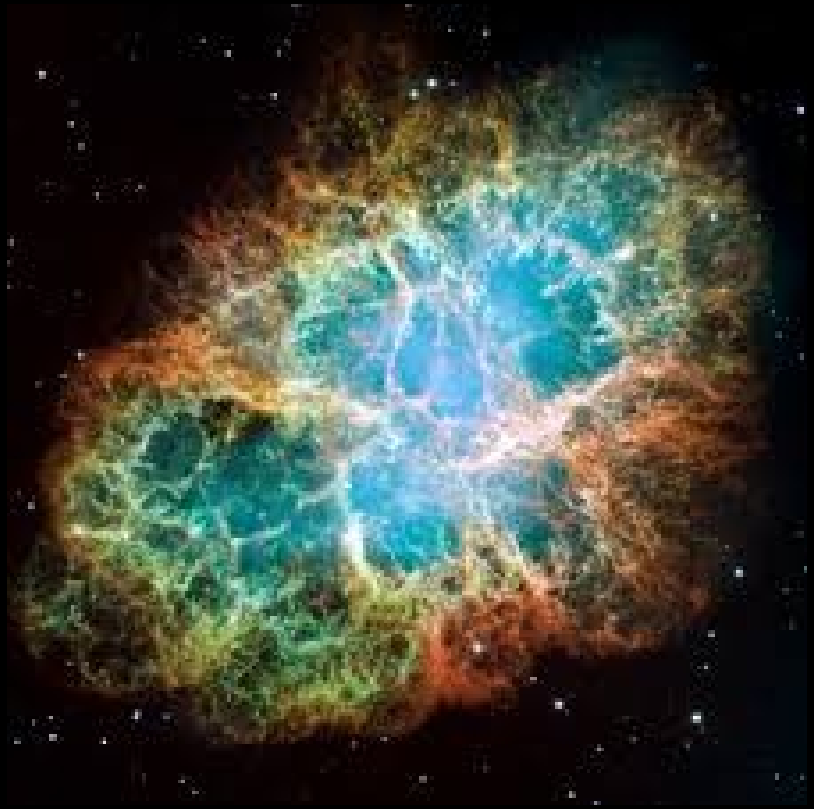
- As fusion continues, the core accumulates heavier elements, eventually forming an iron core.
- Iron cannot be fused into heavier elements with the release of energy
- Fusion Stops : Star can no longer sustain fusion to counterbalance gravity.
- Core Collapse: Without the outward pressure from fusion, gravity causes the iron core to collapse inward, increasing its density and temperature dramatically.



# Evolution of High-Mass Stars (M > 8 Solar Masses)

Supernova Explosion

- Iron core reaches a mass > Chandrasekhar limit (1.4 solar mass), core collapses violently.
- This triggers a supernova explosion, which is one of the most energetic events in the universe.
- Core Collapse: The core’s collapse causes the outer layers to be ejected at high velocities.
- Shock Wave: The collapse sends out a shockwave that blasts the outer layers into space, creating the spectacular light and energy output of a Type II Supernova.
- Heavy Element Synthesis: The intense energy of the supernova can fuse even heavier elements beyond iron

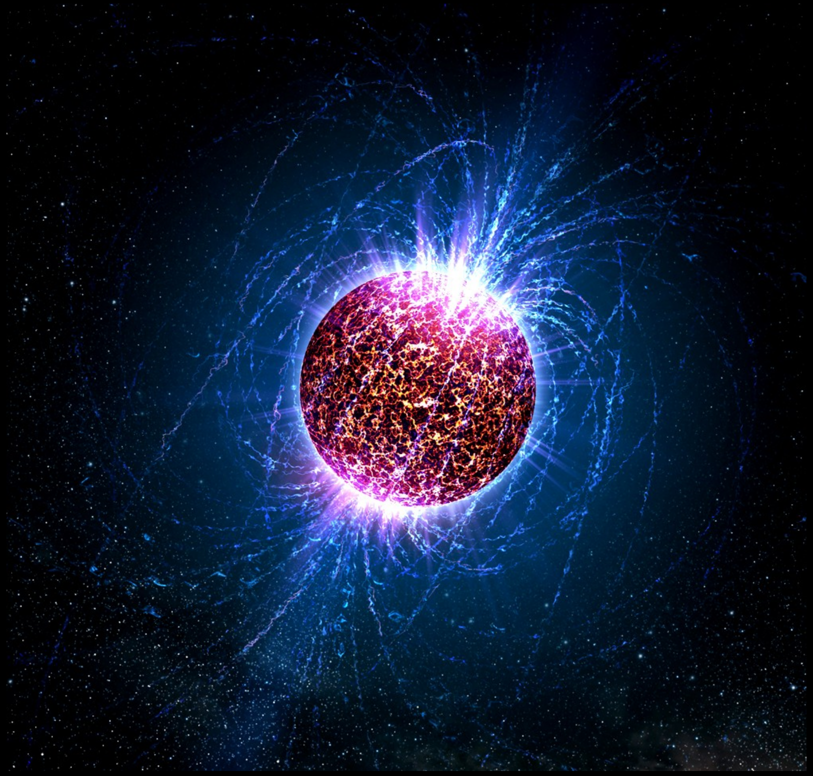


# Supernova

- Energy released is approximately $10^{44}$ joules. $10^9$ times the total energy output of the Sun over its entire 10-billion-year lifetime.
- Supernova can outshine an entire galaxy for a brief period, becoming as bright as $10^9$ Suns.
- Temperature in the core of the exploding star can reach up to 10 billion Kelvin. Sun's core temperature is around 15 million Kelvin
- Supernova: The material ejected from a supernova can travel at speeds of up to 10,000 to 30,000 km/s. Solar wind  about 400 to 800 km/s

# Evolution of High-Mass Stars (M > 8 Solar Masses)

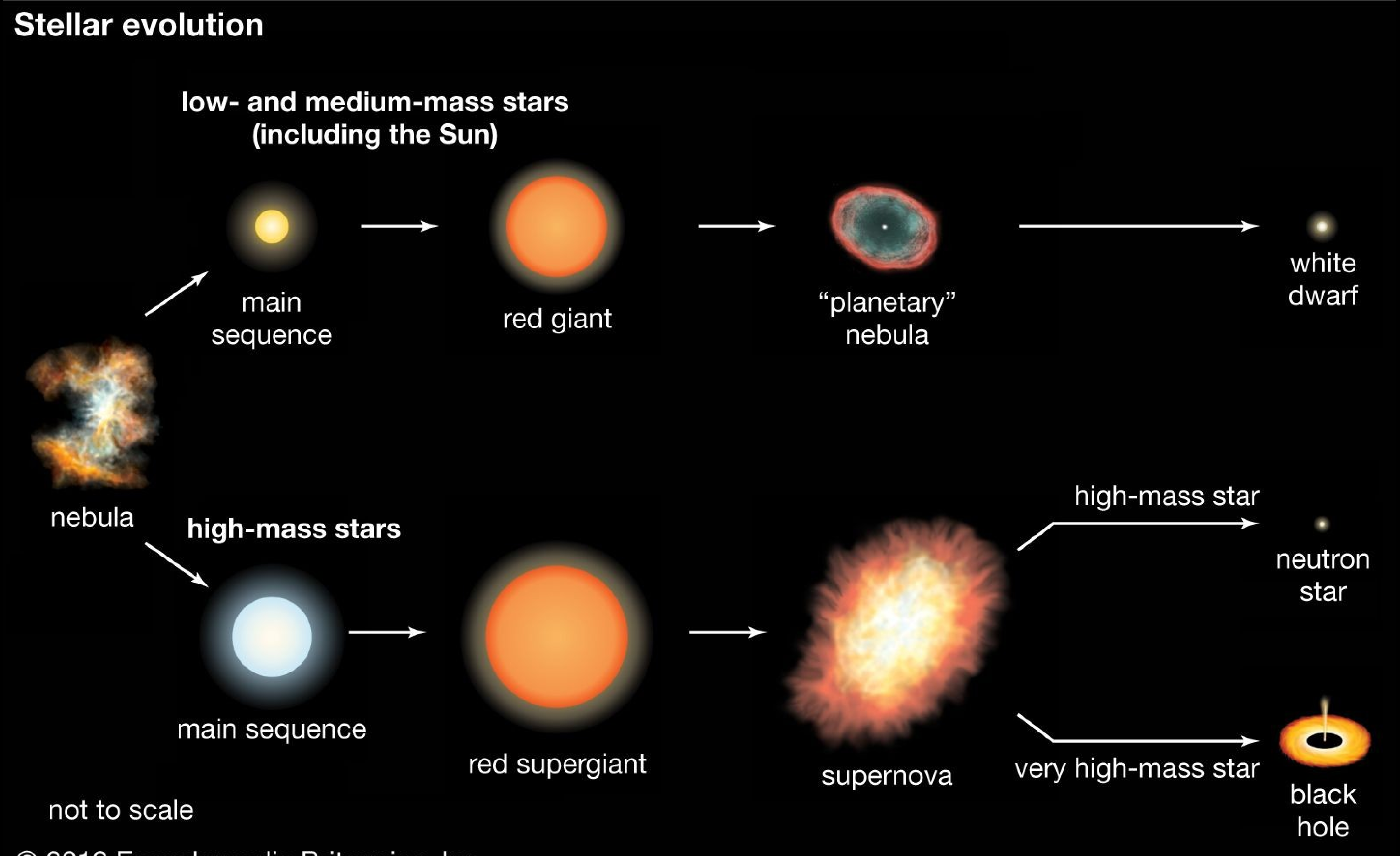
- Neutron Star
  - If the remaining core is between 1.4 and about 3 solar masses, the pressure from neutrons halts further collapse, and a neutron star is formed.
  - Neutron stars are incredibly small (~10–20 km in radius)
  - A neutron star's density is such that a teaspoon of its matter would weigh billions of tons.
  - Neutron stars often have extremely strong magnetic fields and can emit beams of radiation, sometimes observed as pulsars.



# Evolution of High-Mass Stars (M > 8 Solar Masses)

Black Hole

- If the core mass exceeds approximately 3 solar masses, **Tolman–Oppenheimer–Volkoff Limit**, not even neutron degeneracy pressure can support the core against gravitational collapse.
- The core continues to collapse into a black hole, where gravity is so strong that not even light can escape.
- Event Horizon: The boundary around a black hole beyond which nothing can escape is called the event horizon.
- Singularity: At the center of a black hole, all mass is compressed into an infinitely small point, known as the singularity.


Stellar evolution
low- and medium-mass stars
(including the Sun)
main
sequence
red giant
"planetary"
nebula
white
dwarf
nebula
high-mass stars
main sequence
red supergiant
supernova
high-mass star
neutron
star
very high-mass star
black
hole
not to scale

# Evolution of a Low-Mass Star (M < 8 Solar Masses)

| Phase | Core Composition | Energy Source | Outcome |
|---|---|---|---|
| Main Sequence | Hydrogen | Hydrogen fusion | Stable star |
| Red Giant | Helium (inert) | Hydrogen shell burning | Expands and cools |
| Horizontal Branch | Helium | Helium core fusion | Stable, smaller |
| Asymptotic Giant Branch | Carbon, Oxygen | Hydrogen & helium shell fusion | Pulsations, mass loss |
| Planetary Nebula | Carbon, Oxygen | No fusion (core remnant) | Expelled outer layers |
| White Dwarf | Carbon, Oxygen | No fusion, degenerate core | Slowly cools and fades |

# Evolution of High-Mass Stars (M > 8 Solar Masses)

| Phase | Core Composition | Fusion Process | Outcome |
|---|---|---|---|
| **Main Sequence** | Hydrogen | Hydrogen fusion | Stable, large star |
| **Red Supergiant** | Helium, Carbon, Oxygen | Helium, Carbon fusion | Expands and cools |
| **Supergiant** | Carbon, Oxygen, Silicon | Fusion of heavier elements | Expands further, multiple fusion shells |
| **Iron Core** | Iron | No fusion (no energy release) | Core collapse begins |
| **Supernova Explosion** | Iron, Heavy Elements | No fusion (core collapse) | Shockwave blasts outer layers |
| **Neutron Star or Black Hole** | Neutron-rich or Singularity | No fusion (degeneracy pressure) | Neutron star or black hole |

Thank You

Time for Questions....