The Sun's Source of Energy

Chapter 16

The Source of the Sun's Energy

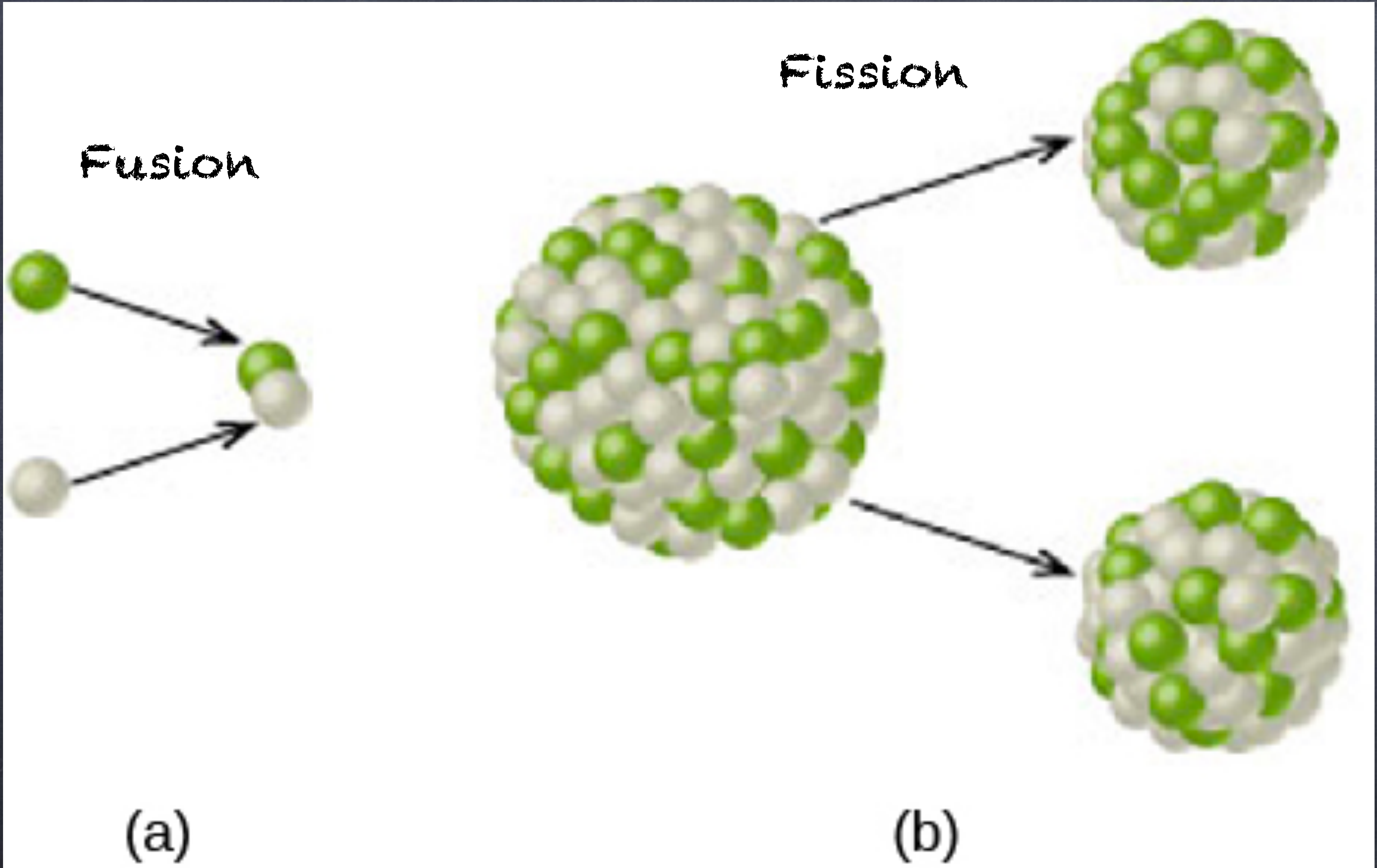
- The source of the sun's energy was a mystery for a long time. One can calculate that if the sun was made of something like wood or coal and its energy came from burning this fuel it would only shine for a few thousand years.
- Much more energy is available to the sun from gravitational contraction. If the sun shrinks in size it compresses making it hotter. The energy available from gravity would allow the sun to shine for 100 million years.
- However, the Earth is 4.5 billion years old, so another form of energy was needed.

Relativity and Energy

- Einstein's discovery of special relativity explained where this energy could be coming from. He found that
- energy = mass × (speed of light)^2
- This is a tremendous amount of energy, the conversion of 4 million tons of matter every second equals the energy output of the sun.

Nuclear Energy

- The source of the sun's energy is nuclear energy, the energy that gets released when the nucleus of an atom changes. There are two types of changes:
  - Fusion - this is when two smaller atomic nuclei combine into a larger nucleus emitting radiation. This is the energy source of stars.
  - Fission - when a large atomic nucleus splits into two smaller nuclei. This is the type of energy we use in nuclear plants on Earth.


Fusion
Fission
(a)
(b)

Fusion

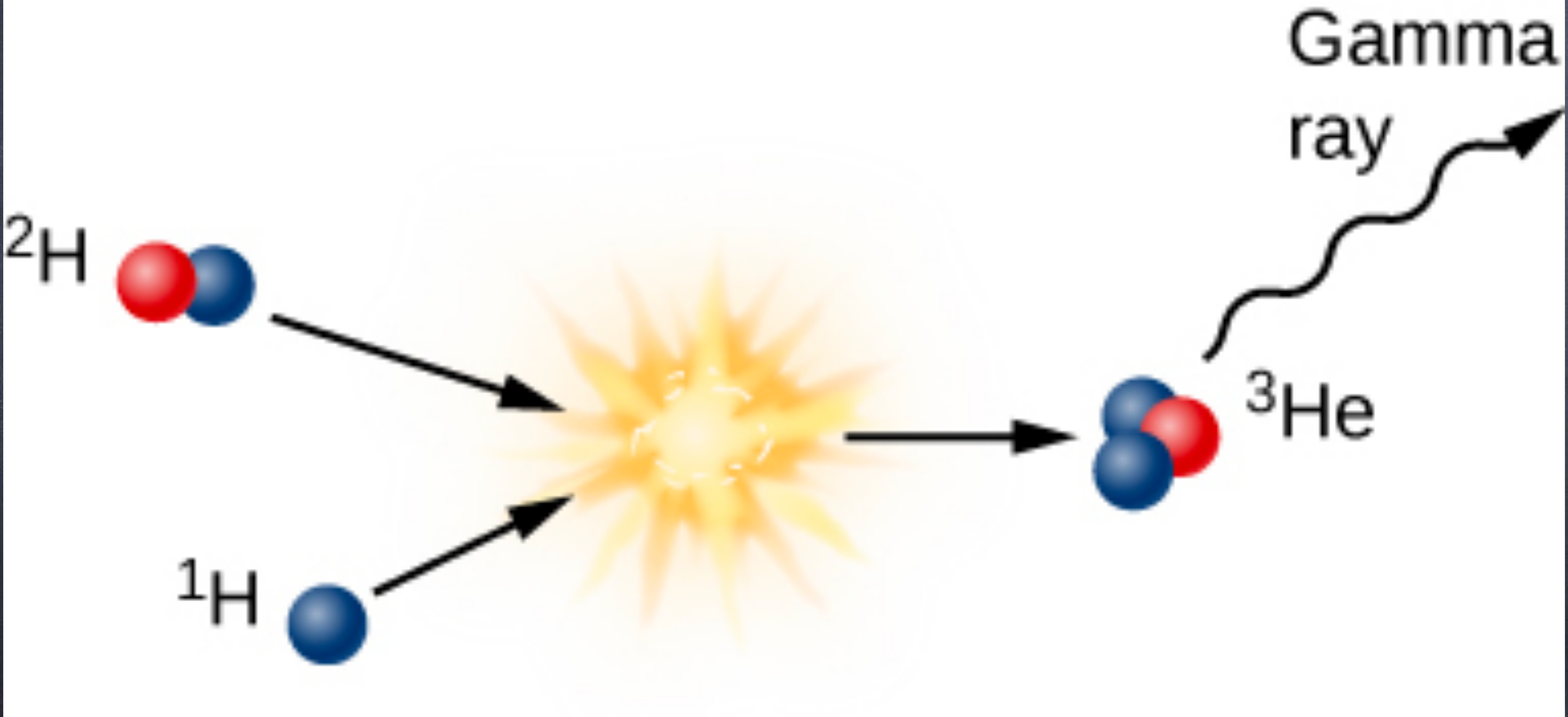
- If fusion produces so much energy why dont we use it instead of hydrocarbons on Earth.
- The positive electric charges of the nuclei repel so it is very hard to get nuclei close together to fuse. They need to be moving at 1000km/s which is a temperature of 12 million K for fusion to occur.
- We can get atoms to fuse on Earth, but it takes so much energy to get it to happen that currently it doesnt produce net energy. However, scientist are working on it since if successful the impact would be tremendous.

The proton-proton chain

- The main process of nuclear fusion in the sun is known as the proton-proton chain. In total 6 protons are converted into 1 helium-4 nucleus and 2 protons, plus 2 positrons, 2 neutrinos and radiation.
- Even in the sun this process is extremely rare. The average proton in the sun will take 14 billion years to fuse with another proton when it is having 100 million collisions per second.

The nuclear processes in the sun start with one hydrogen atom fusing with another hydrogen atom. This results in an atom of heavy hydrogen, a positron and a neutrino.
A positron is an anti-matter electron and a neutrino is a subatomic particle that has no charge, almost no mass and hardly interacts with anything. Most neutrinos will escape the sun in 2 seconds.

The the deuterium (hydrogen-2) combines with a normal hydrogen to form helium-3 and radiation. But we aren't done yet. On average deuterium is converted to helium-3 in 6 seconds.



Finally, two helium-3 nuclei must combine to form stable helium-4 and two additional protons. This is much slower taking a million years on average. The mass difference between 1 protons and helium-4 is 0.71% of an initial hydrogen atom.

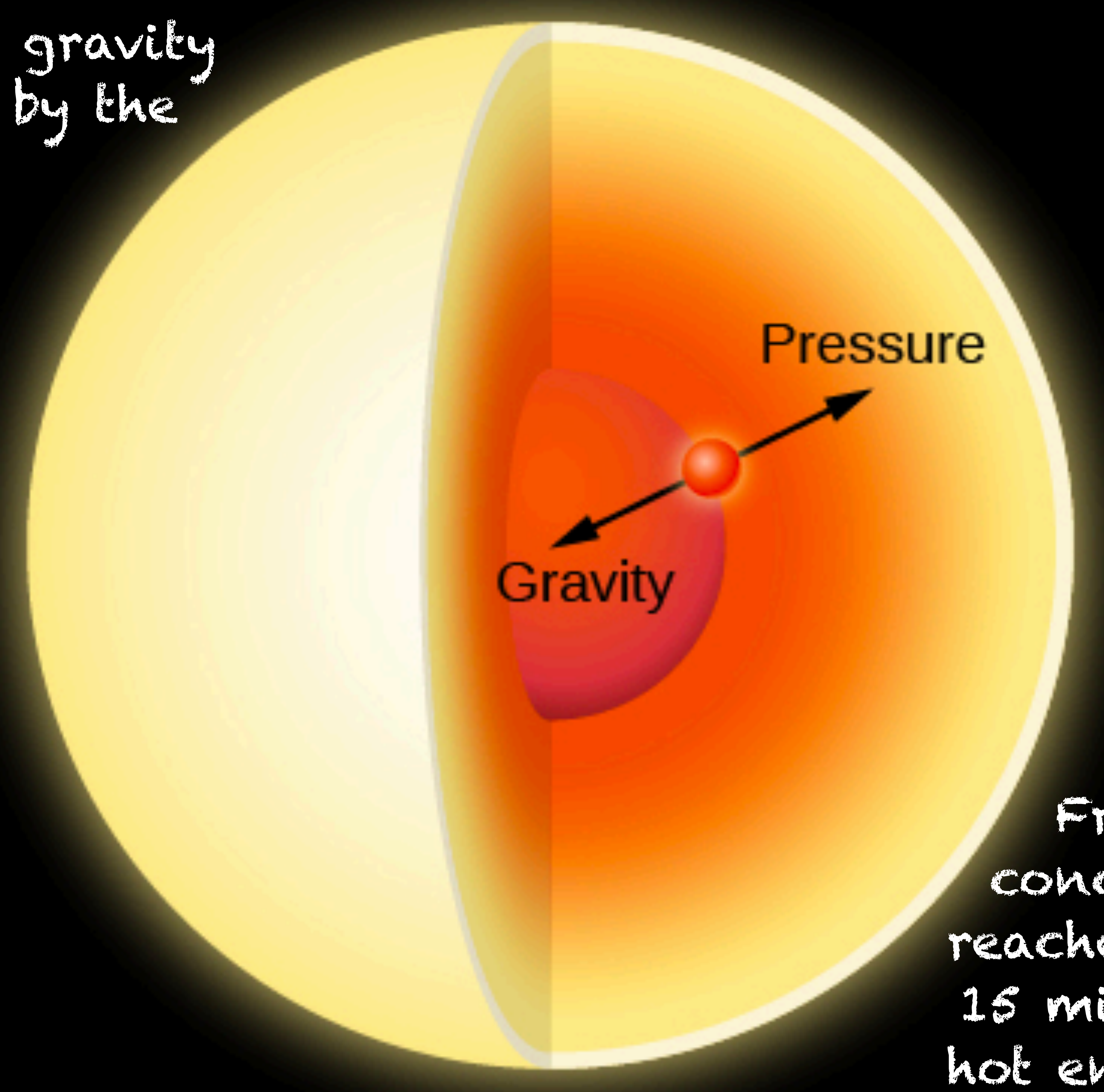
The sun's energy needs

- So if 1kg of hydrogen is converted to helium-4 0.0071kg is converted to energy. From Einstein's equation that gives us 6.4×10^{14} J, which is enough energy to power a typical US household for 17,000 years.
- To produce the sun's luminosity of 4×10^{26} W, requires the conversion of 600 million tons of hydrogen every second.
- As big as this number is, the sun is enormous and can do this for billions of years.

The solar interior

- We can not see inside the sun with electromagnetic radiation. So we have to use physics to guess as to its structure.
- Hydrostatic equilibrium - we know the sun is stable, has been unchanged for millions of years, this means the gravity that wants it to contract must be balanced by the pressure inside.
- Not getting colder - we know the sun is not losing energy, so the energy that comes out must be created in the core and transport its way to the surface.

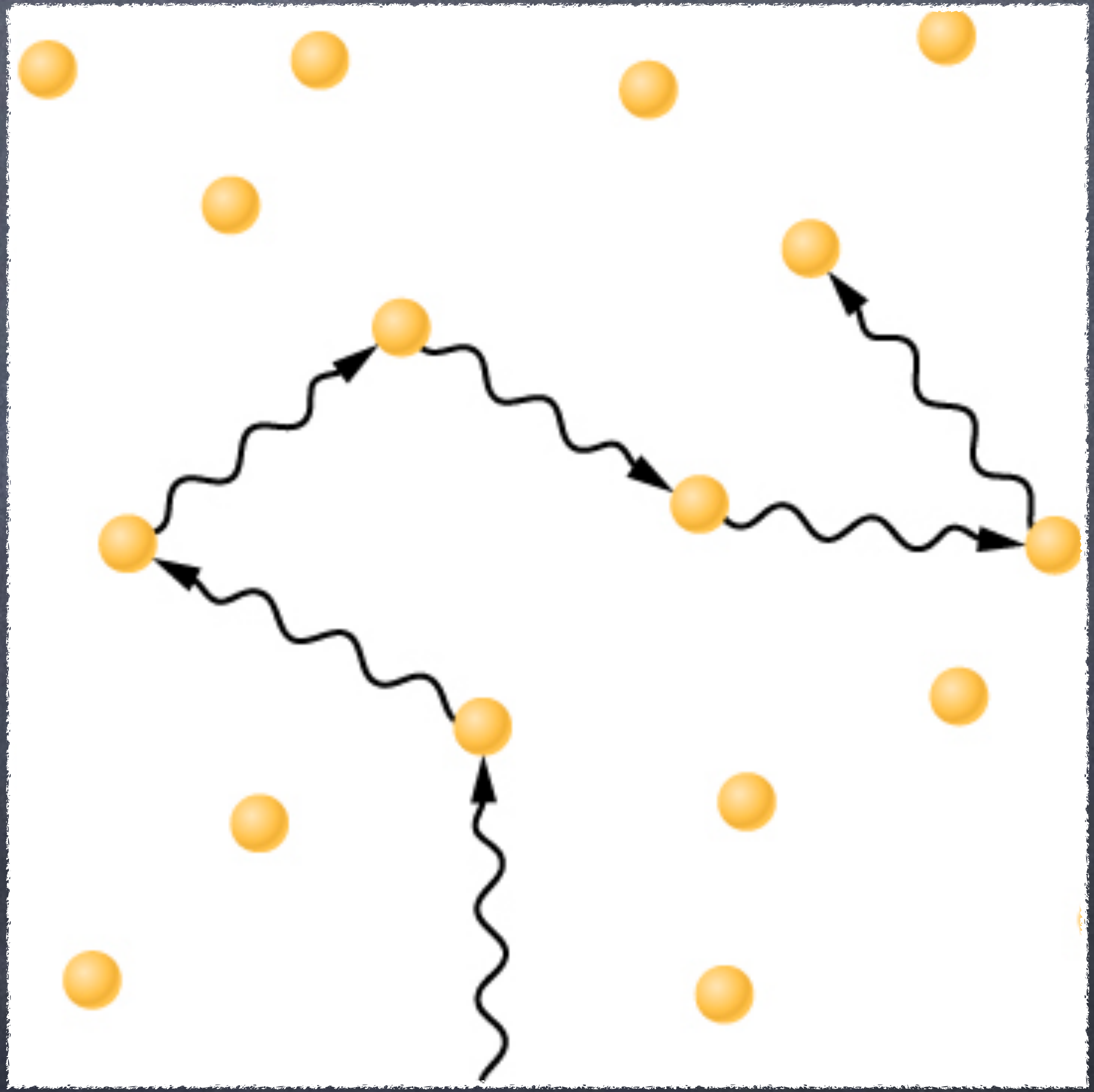
The sun is stable, which means the force of gravity must be balanced by the pressure.



From this we can conclude that the sun reaches a temperature of 15 million K in its core, hot enough for fusion to occur.

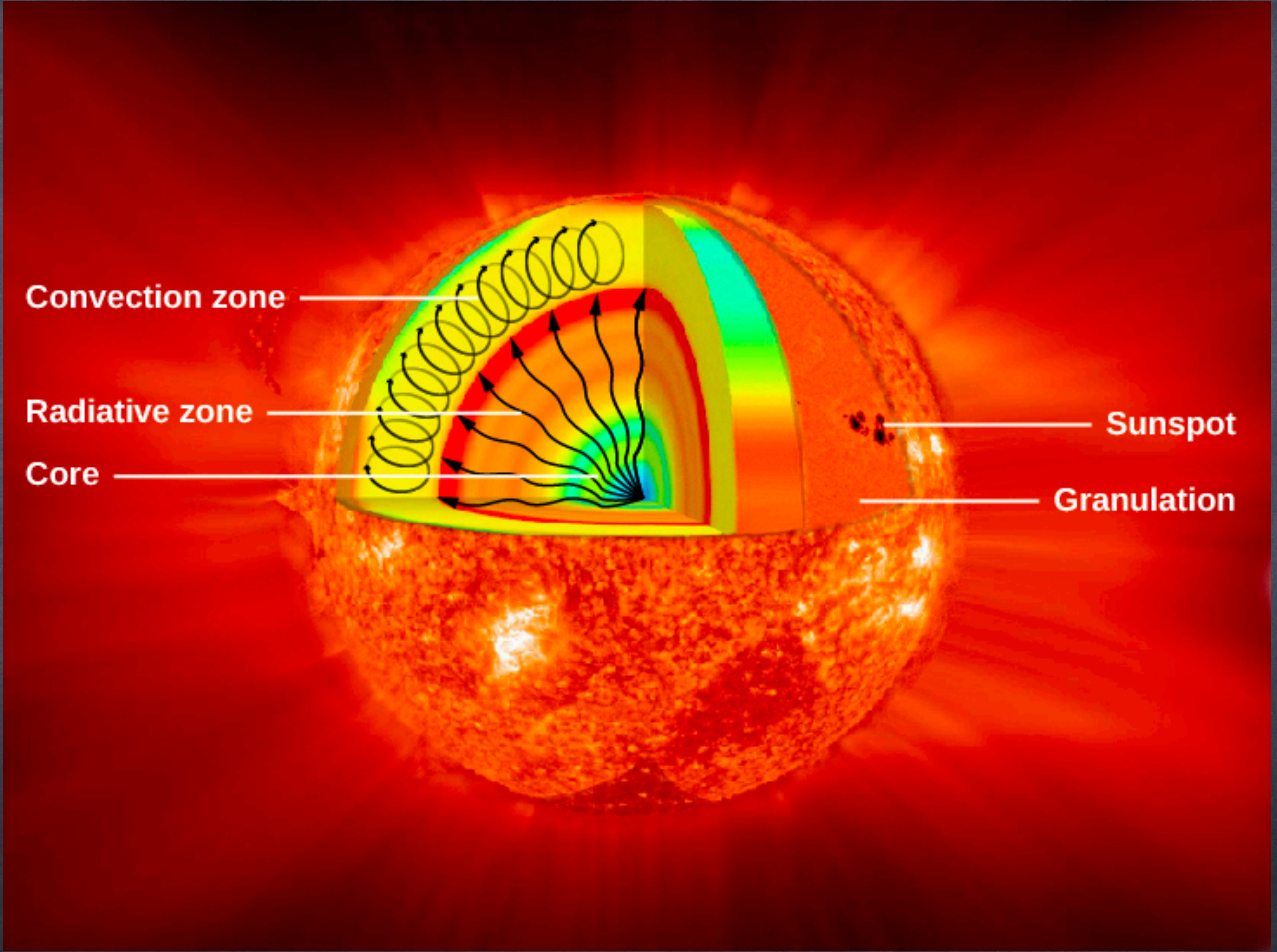
Radiative Zone

- Based on density we can calculate from the pressure that light would not be able to travel far.
- Typically a photon only travels 1cm before being absorbed by an atom.
- Photons take 10^5 - 10^6 years to make it to the photosphere.
- In this region energy is transported by radiation.



photons take a long time to exit the sun, neutrinos zip right out

When the density gets low enough energy can be transported by gas. This is convection where hot material rises and cool material sinks.



The density drops pretty quickly from the core. The energy is all produced in the core and transported out. The core has a higher fraction of helium as hydrogen is fused.

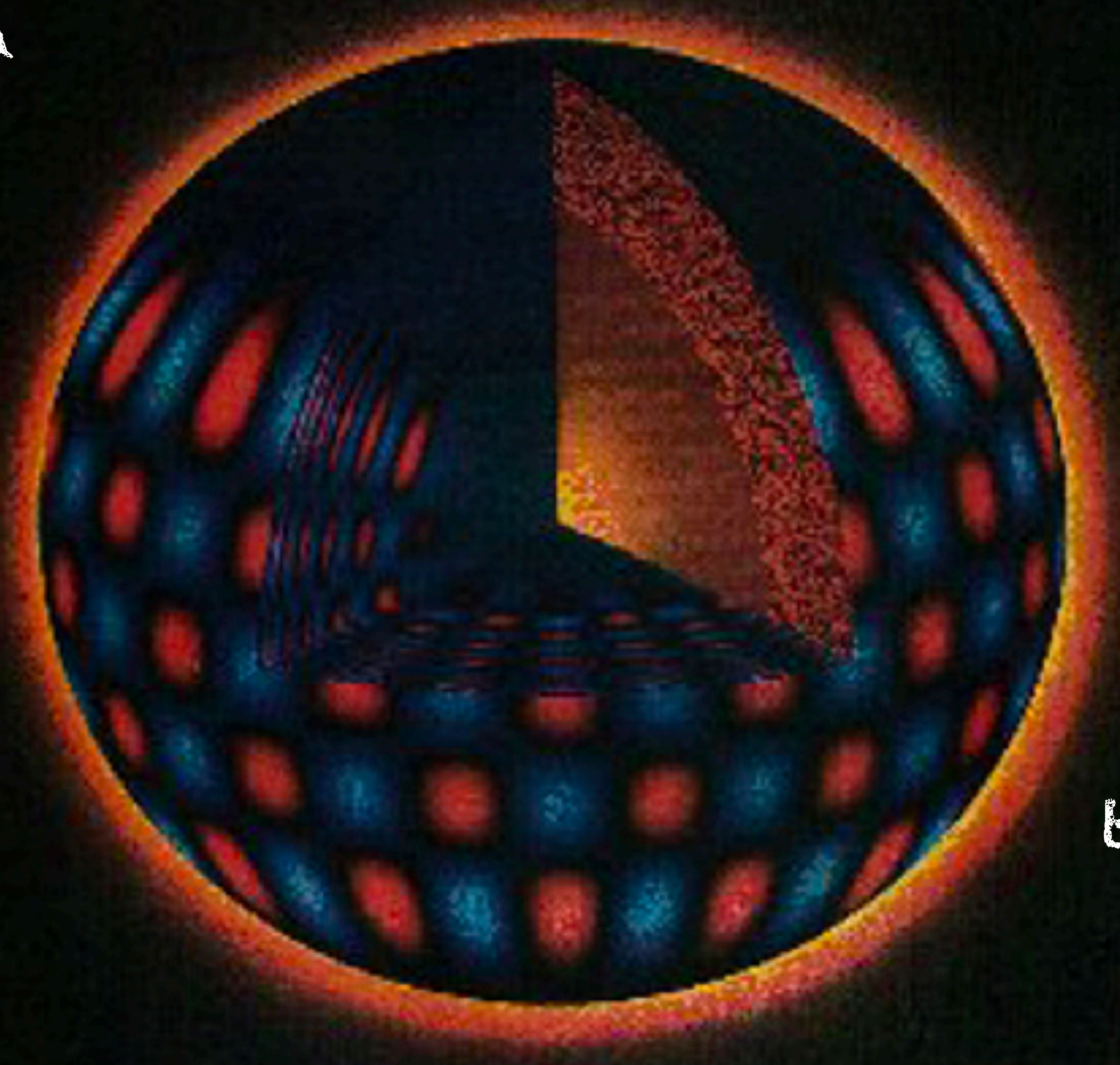
Solar Observations

- In spite of the fact that we can't 'see' into the sun past the photosphere we can make observations to support our theory for the interior.

- solar pulsations - the sun pulsates and has waves travel through it like earthquakes. This is called helioseismology, and can tell us about the inside of the sun

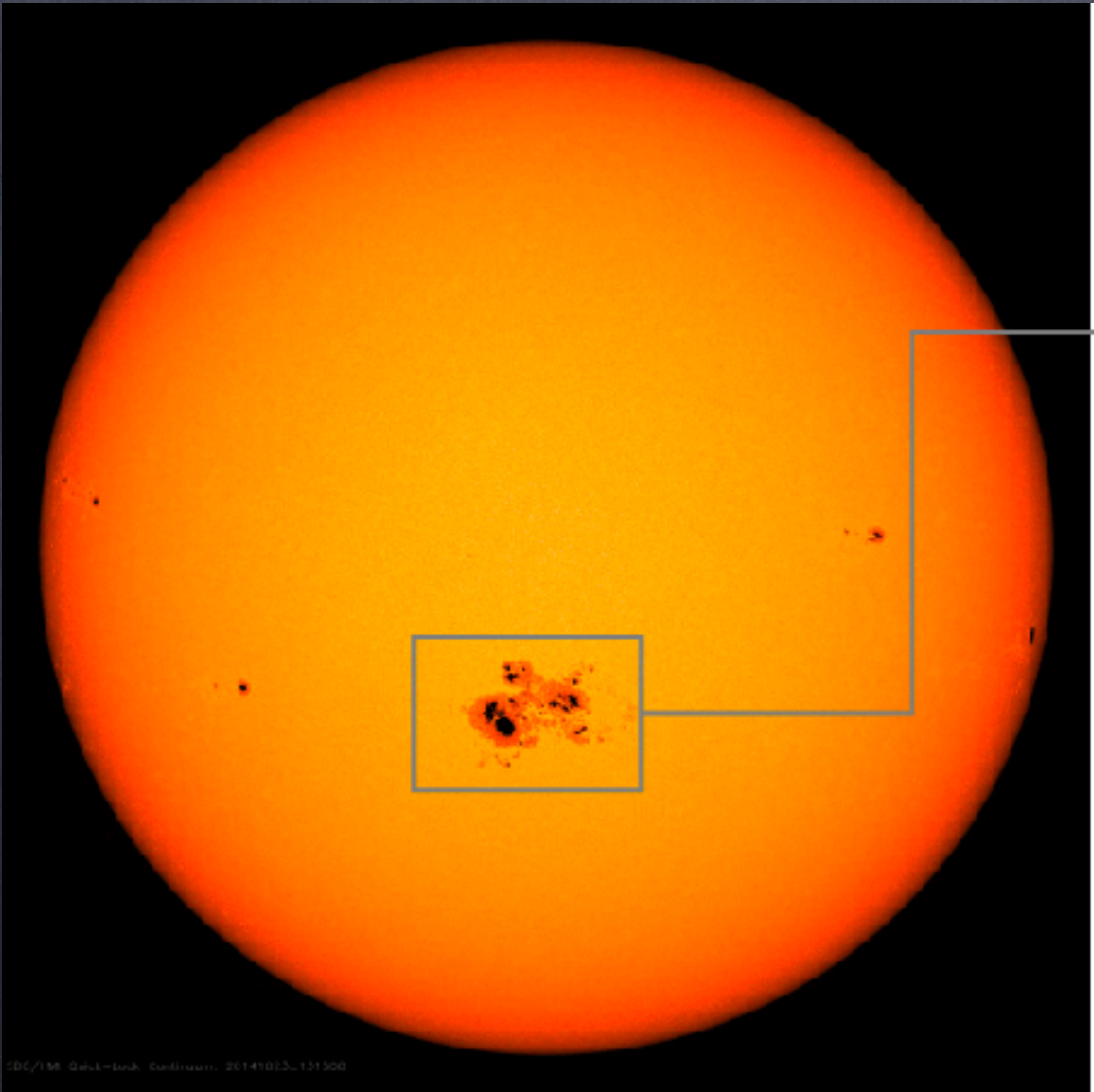
- solar neutrinos - neutrinos come directly from the center of the sun, this is away to 'see' directly into the core.

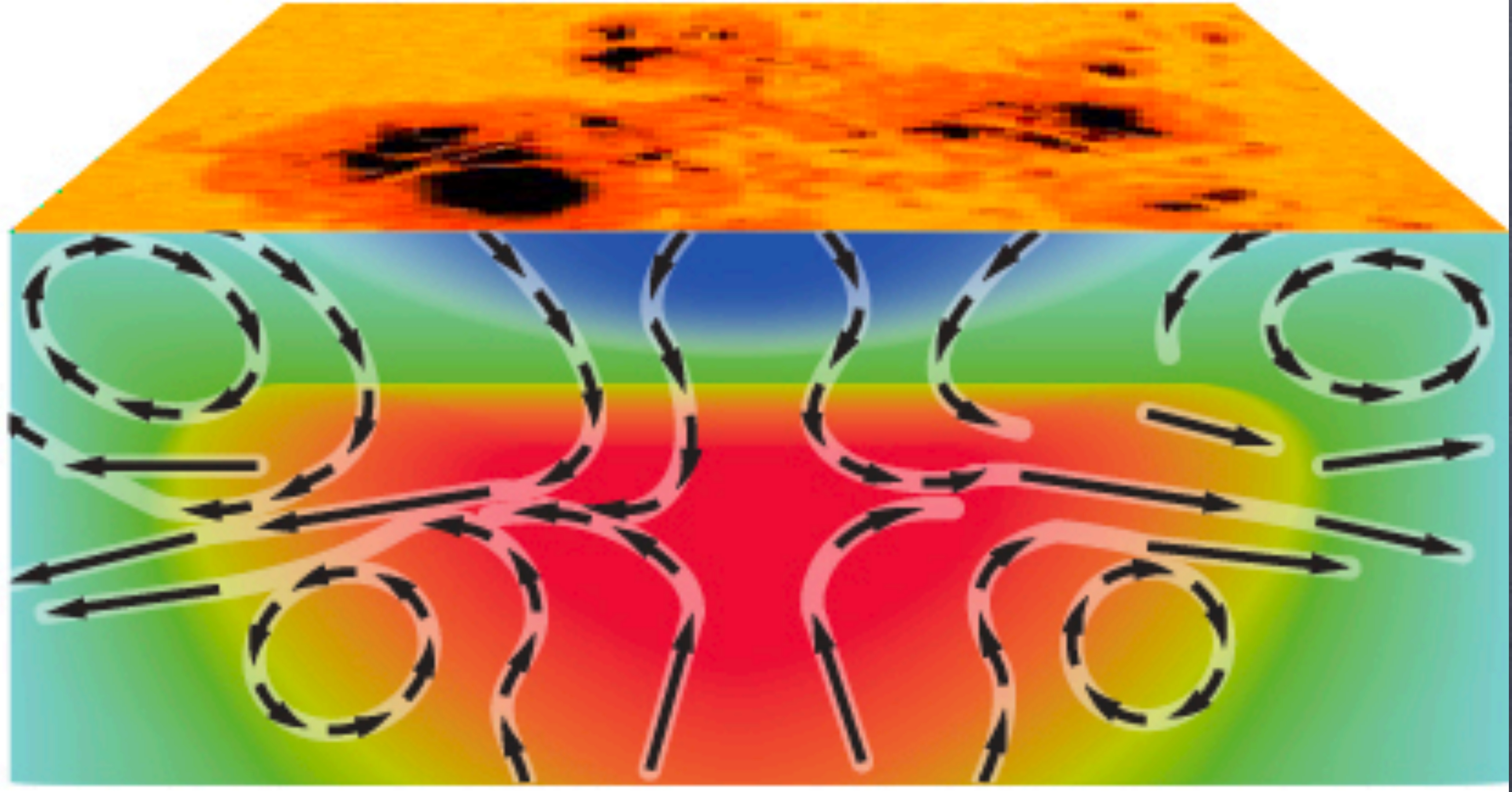
pulsations seen in the photosphere these are only motion of a few 100 m/s



These waves only take an hour or so to get from the sun's center to the surface

Helioseismology lets us understand how sunspots work





We see under the sunspot the gas flows down but below that gas is flowing up. The gas gets pushed to the side.

Solar Neutrinos

- One way to look directly at the sun is to detect neutrinos that come directly from the sun's core.
- This is very difficult because the whole reason neutrinos come directly from the sun is that they hardly ever interact with anything. This makes them very hard to detect, but with lots of hard work over many years scientist have managed to detect neutrinos from the sun.

Detecting Neutrinos

- The first detector in the 1970s was made of 400,000 liters of ammonia. Only one atom a year would interact with a neutrino and the experiment had to find that atom.
- This experiment only found 1/3 of the neutrinos expected from the sun.
- There were two possible explanations for this. We didn't understand the sun, or we didn't understand neutrinos.

Detecting Neutrinos

- One possibility is that neutrinos come in 3 flavors, maybe the sun's neutrinos were changing flavor before they got to Earth. This would only happen if neutrinos have mass.
- New experiments were built to measure all 3 flavors. After many decades of work all 3 flavors were detected and it was found that combined you get the predicted number of neutrinos.
- In turned out that our model for the sun is correct, and we discovered that neutrinos have mass.