Announcements

- **Quiz 5 extended 24 hours**, due Tuesday – includes material that will be covered in lecture today
- Problem Set 5 for practice
- Today: more on the Sun
- We will start Chapter 10 on Wednesday

Astronomy 103

The Sun

Please read chapter 9

Which part of the Sun rotates the fastest?

A The poles

B The equator

C The core

D All parts rotate at the same rate

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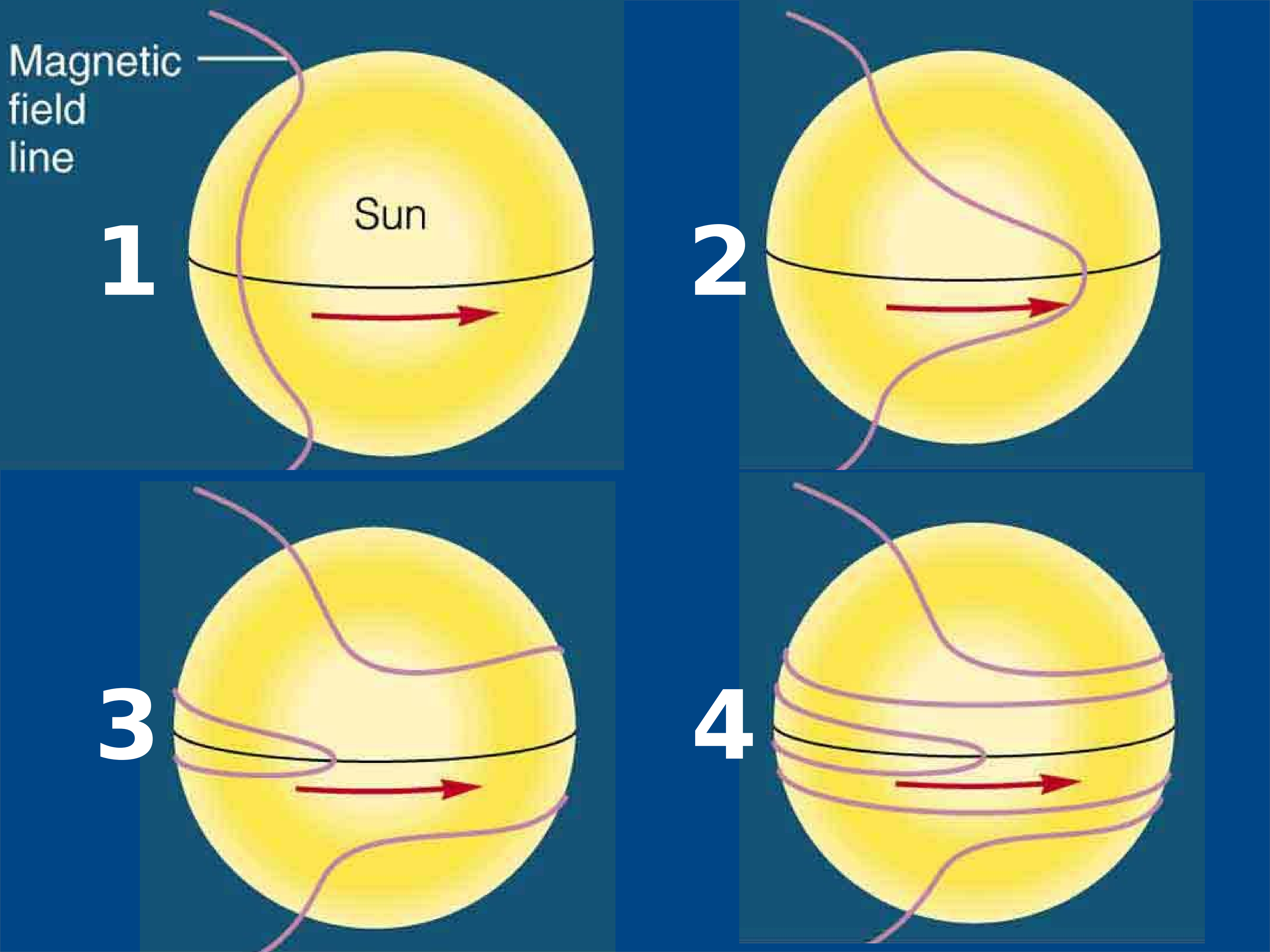
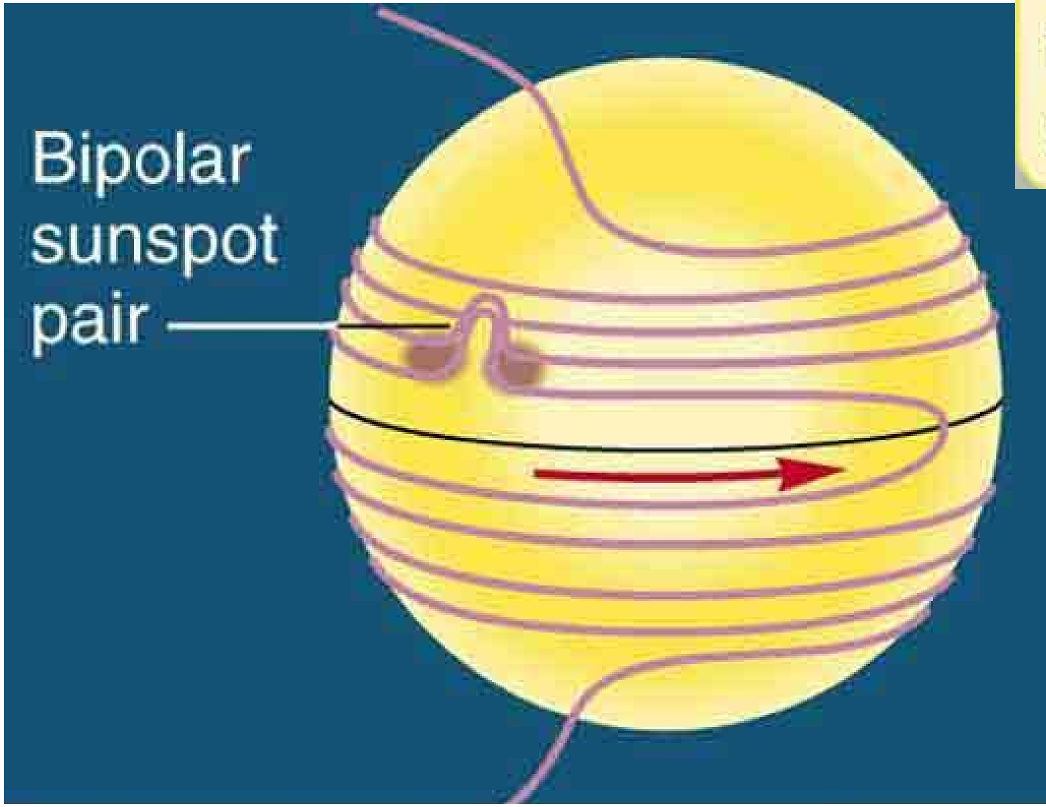
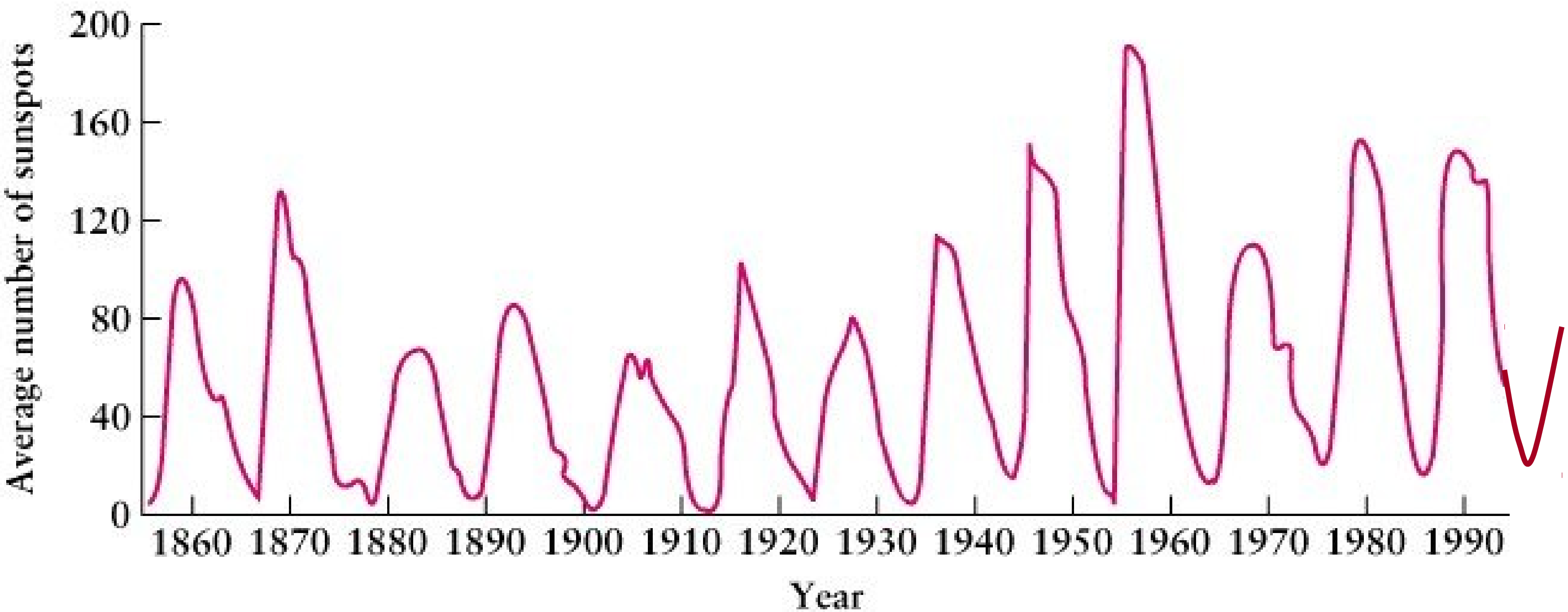

Magnetic field line
Sun
1
2
3
4

Where loops of tangled magnetic field rise through the surface, sunspots occur.



The direction of the Sun’s magnetic field changes with a **22-year cycle**, as if it were a rotating magnet. North and south magnetic poles exchange positions every 11 years.

Sunspots follow this cycle, with the largest number of sunspots (sunspot maxima) occurring every 11 years.

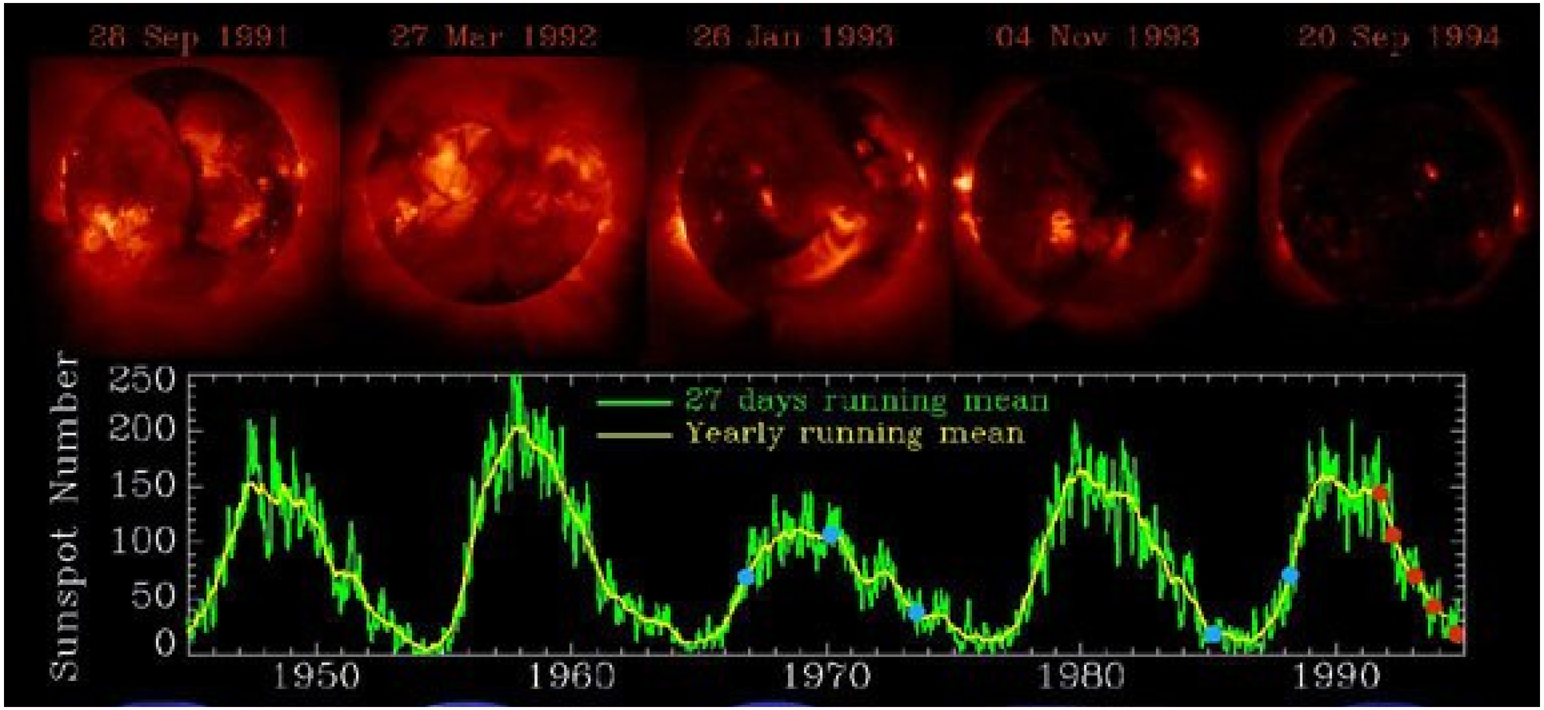


The 11 Year Sunspot Cycle

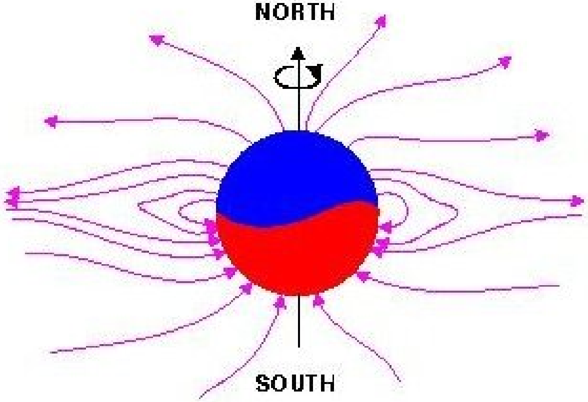
X-ray photos of the Sun from the Yohkoh spacecraft for half a cycle, maximum to minimum

solar maximum

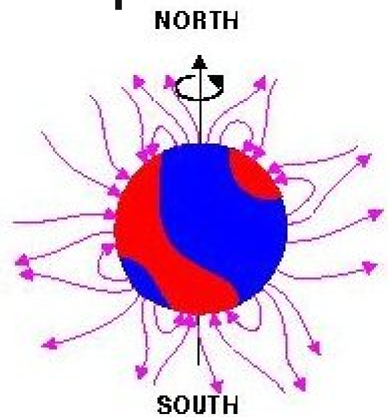
near minimum



The 11 year sunspot cycle corresponds to a magnetic field flip of the sun.



CORONAL MAGNETIC FIELD LINES AT SOLAR MINIMUM ACTIVITY



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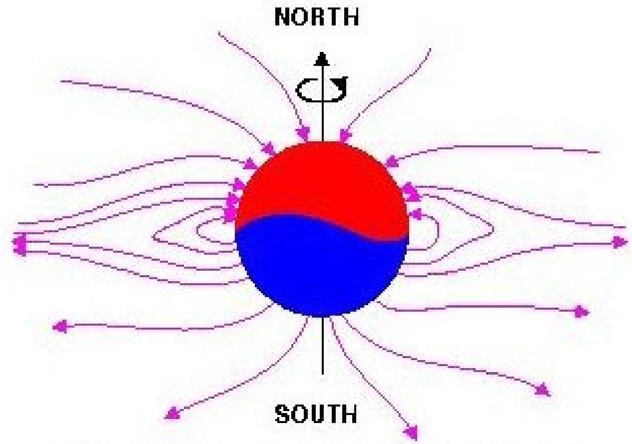
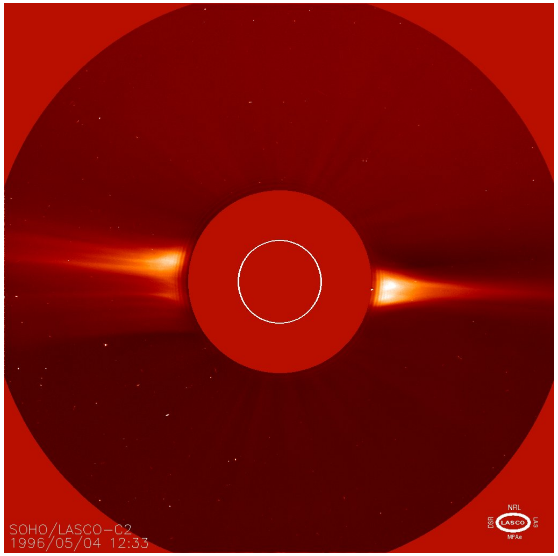
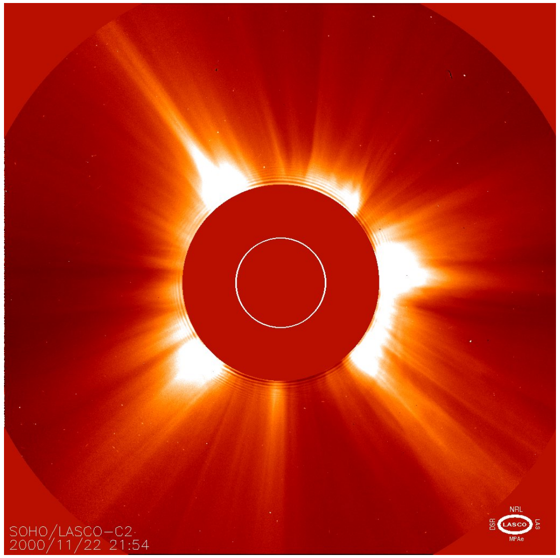


CORONAL MAGNETIC FIELD LINES AT NEXT SOLAR MINIMUM

Solar minimum



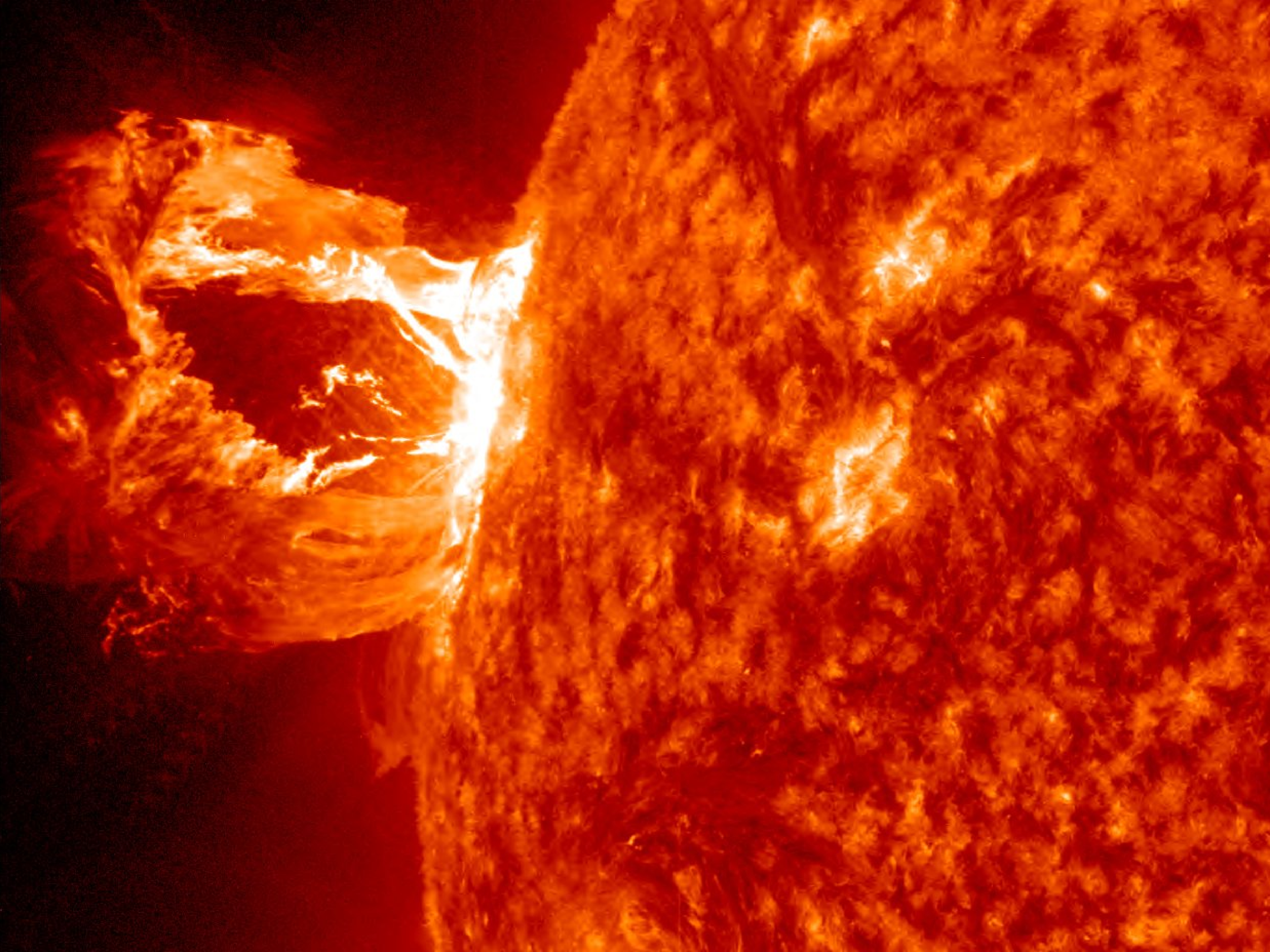
Solar maximum



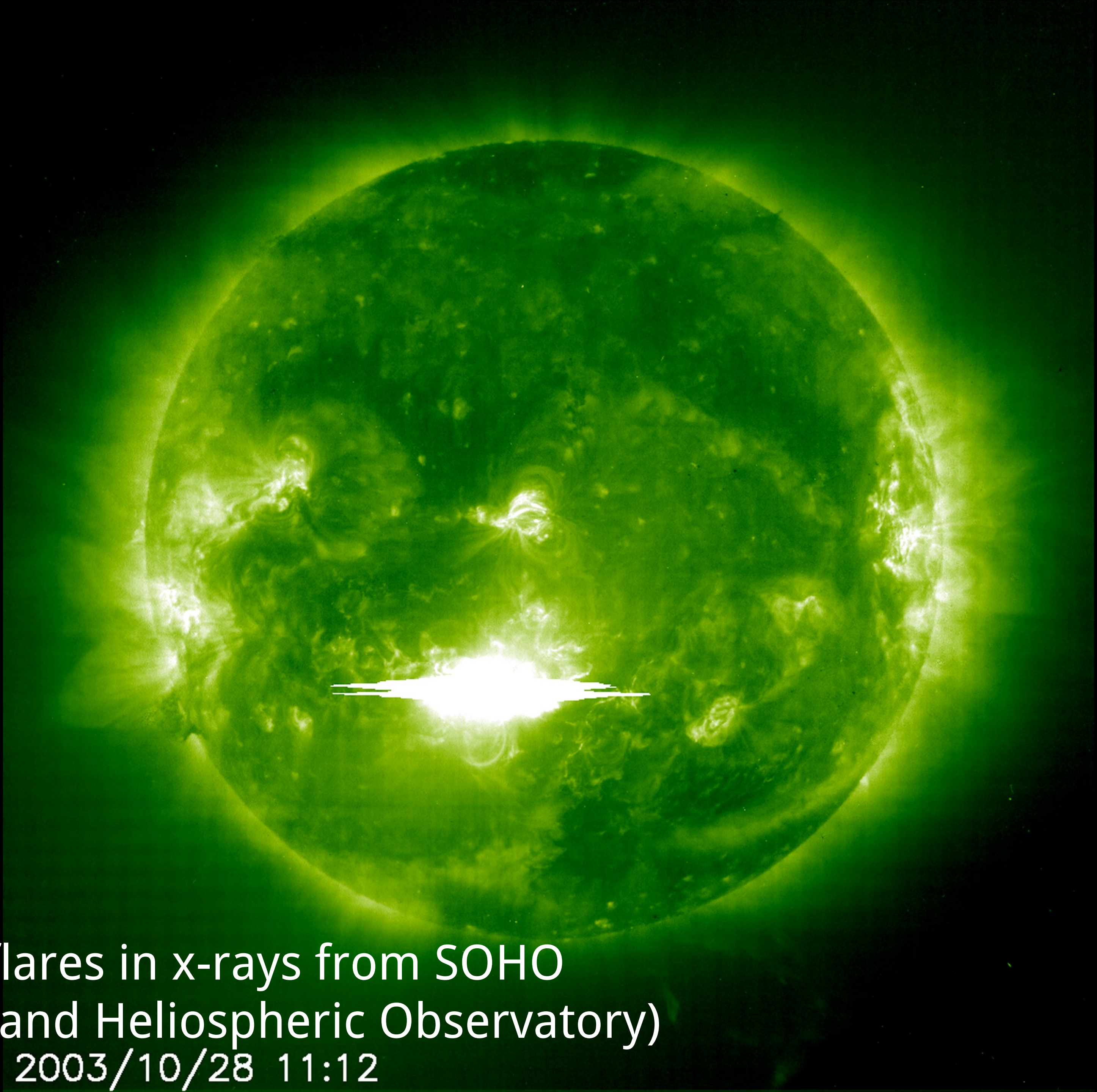
Features Above the Photosphere

Associated with sunspots are **magnetic storms** that give rise to:

- **Flares:** spectacular, hot explosions that release UV and X-rays and eject electrons and protons from the Sun's surface.
- **Prominences:** Trapped gas from the surface of the sun. Trapped by magnetic fields




Flares seen in X-ray photo



Solar flares in x-rays from SOHO
(Solar and Heliospheric Observatory)

Why does the Sun shine?

Only one known process can account for the huge amount of energy generated by the Sun:

Conversion of mass into energy via nuclear fusion

$$E = mc^2$$

Energy = mass x (speed of light)^2

Nuclear fusion vs nuclear fission

Cooling towers of a nuclear fission reactor

- Nuclear reactors on Earth use **fission**: heavy elements are **split** into lighter ones
- Stars generate power through nuclear **fusion**: light elements are **fused** into heavier ones

$E=mc^2$

- Mass m given in kg
- Speed of light c is 3×10^8 meters/second

Example: How much energy do you get if you can change 1 kg of matter entirely to energy?

$$E = mc^2 = (1)(3 \times 10^8)(3 \times 10^8)$$
$$= 9 \times 10^{16} \text{ watt-seconds}$$

This is more than 200 times the energy released by the most powerful nuclear bombs:
(1 kilo-ton TNT → equivalent to mass 46.55 mg)

Example: Luminosity of the Sun

If the Sun changes 4 $x10^9$ kg to energy each second, how much energy does it produce each second?

$$E = mc2 = (4x10^9)\,(3x10^8)\,(3x10^8)$$
$$= 4x3x3 \times 10^9x10^8x10^8 = 36 \times 10^{27}$$
$$= 4 \times 10^{28} \text{ watt-seconds}$$

This is the luminosity of the Sun! Also notice that we've given the answer with the same precision (the same number of digits) we were given in the question.

Example: Luminosity of a star

If the luminosity of a star is 9×10^{26} watts, how much mass does it change into energy each second?

$$E = mc^2 \qquad m = \frac{E}{c^2}$$

$$m = \frac{9x10^{26}}{(3x10^{8})\,x\,(3x10^{8})} = \frac{9x10^{26}}{9\,x\,10^{16}} = 1x10^{10}\,kg$$

Luminosity measures energy per second, so a star with a luminosity of 9 x 10^{26} watts produces 9 x 10^{26} watt-seconds of energy every second

The Energy of Starlight

The mass of a helium atom is slightly less than the mass of 4 hydrogen atoms (by 0.7%=0.007):

$$4m_H - m_{He} = .007\,m_H$$

Mass of Helium precisely measured by Aston, 1920:

This is the apparatus he used. The coil of wire is a large electromagnet. Aston carefully measured how much the magnet bends the paths of helium and hydrogen nuclei . The more massive the nucleus, the less the path bends.

The Energy of Starlight

The Sun turns hydrogen into helium, and the mass of a helium atom is slightly less than the mass of 4 hydrogen atoms (by 0.7%=0.007)

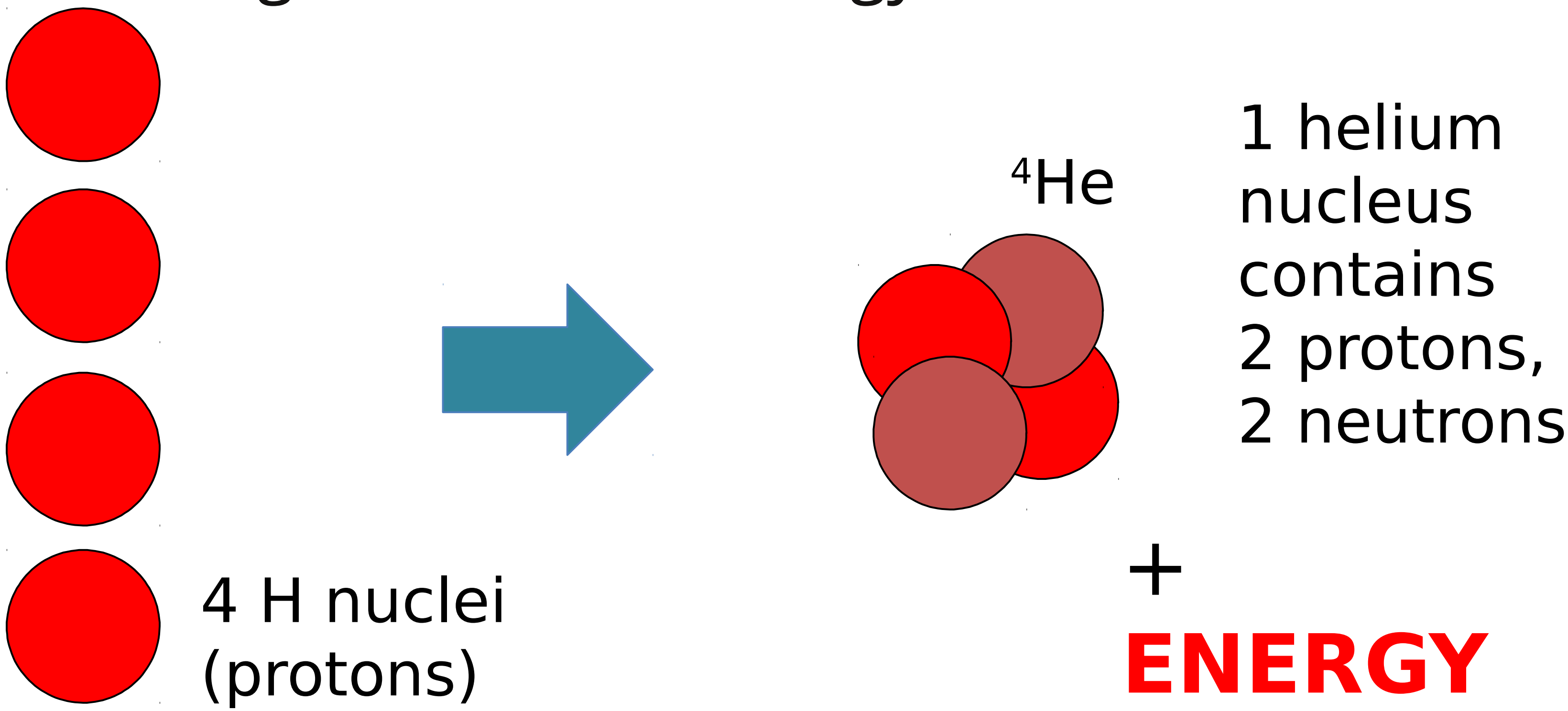
$$4m_H - m_{He} = .007\, m_H$$

Arthur Eddington (1920):
Hydrogen can turn into helium, and when it does, 0.7% of its mass changes to energy, and **that energy powers the Sun**

The whole is less than the sum of the parts

When hydrogen changes to helium, a small fraction of its mass changes into energy.

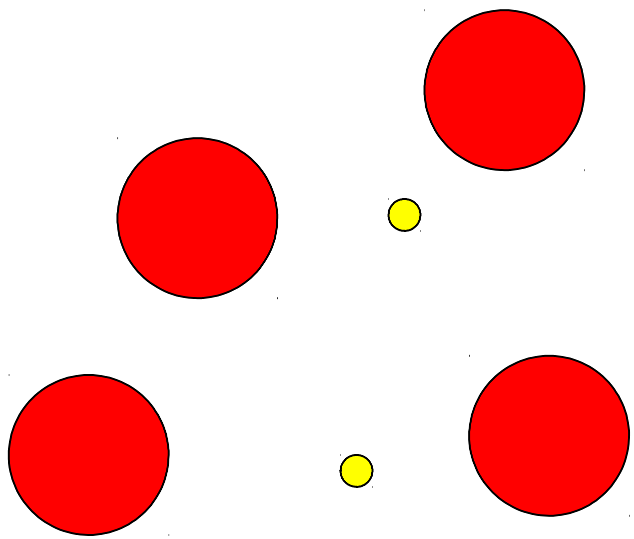
Because c^2 is so large, a small amount of mass produces a large amount of energy.



Fusion of H to He in stars like the Sun

Overall reaction:
Proton-proton chain

4 protons + 2 electrons → 1 Helium nucleus



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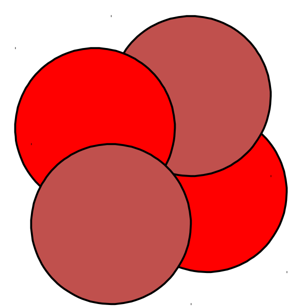


Fusion in the Sun

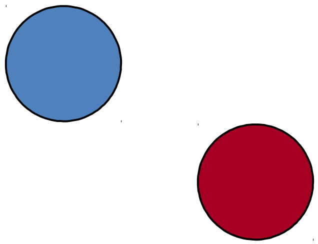
- Protons are positively charged, and things with the same charges repel each other
- So how do protons manage to fuse together?
- Must collide at very high speeds, to get close enough for the **strong nuclear force** to take over
- This is why fusion can only happen at **very very high temperatures**
  - Speed of protons depend on temperature, and temperature of at least 10 million K required for fusion: **only in center of Sun**

Particles and antiparticles

Each particle has a corresponding antiparticle with the same mass and opposite charge.

- E.g. proton and antiproton, electron and positron

When a particle and its antiparticle meet, they annihilate one another and turn into light, with energy given by $E=mc^2$



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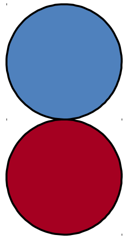

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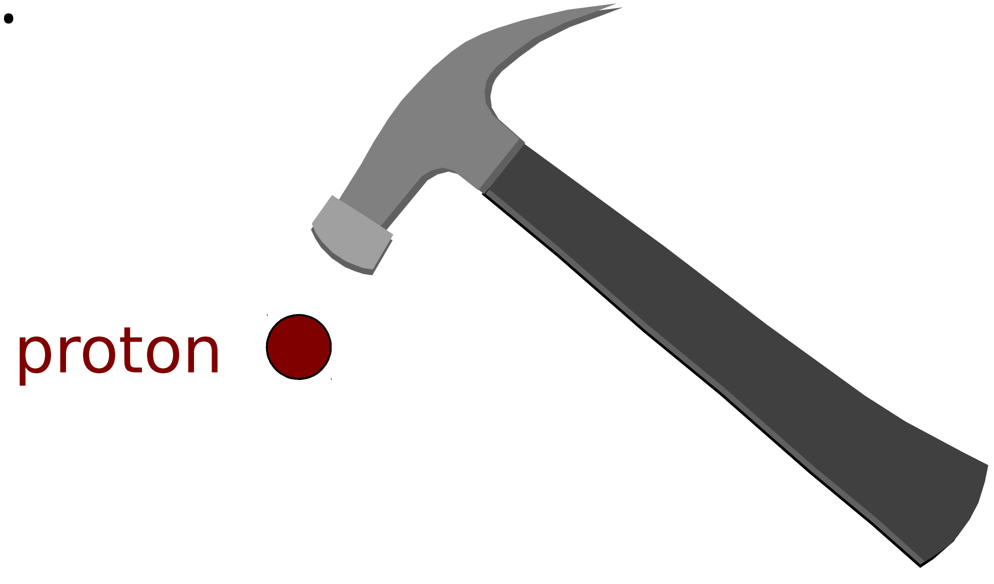
Neutrino

In addition to protons, electrons, and neutrons, there is one other stable, massive, almost invisible particle, the *neutrino*, a neutral (uncharged) particle, with mass much much smaller than that of the electron.

A proton, hit hard enough, can change into a neutron, a positron and a neutrino.



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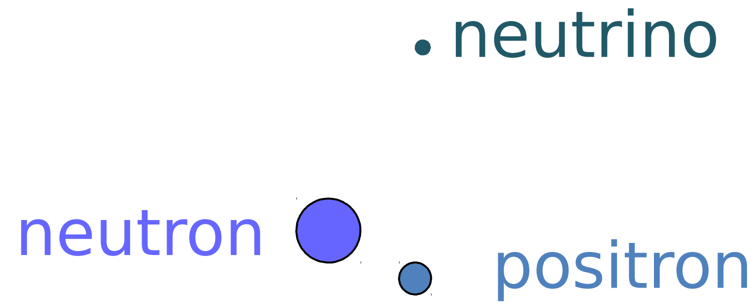
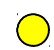


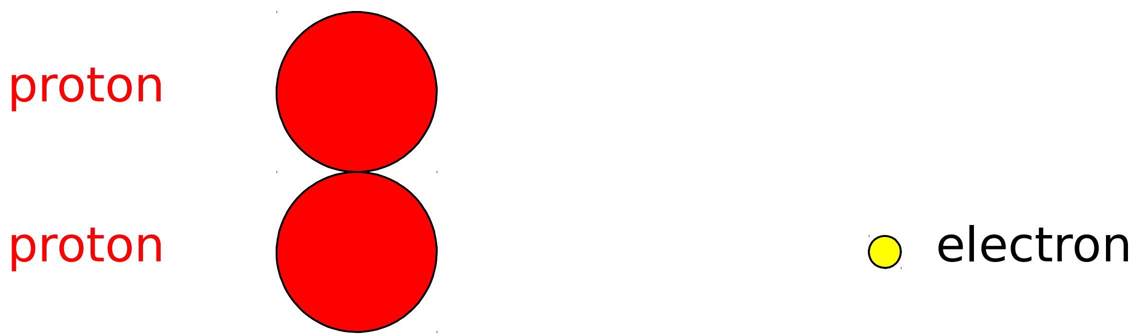
Fusion of H to He in stars like the Sun
Step 1



Two protons combine, forming a deuteron ("heavy hydrogen," proton and neutron) and releasing a positron and a neutrino

The positron annihilates with an electron, producing gamma rays

Fusion of H to He in stars like the Sun
Step 1



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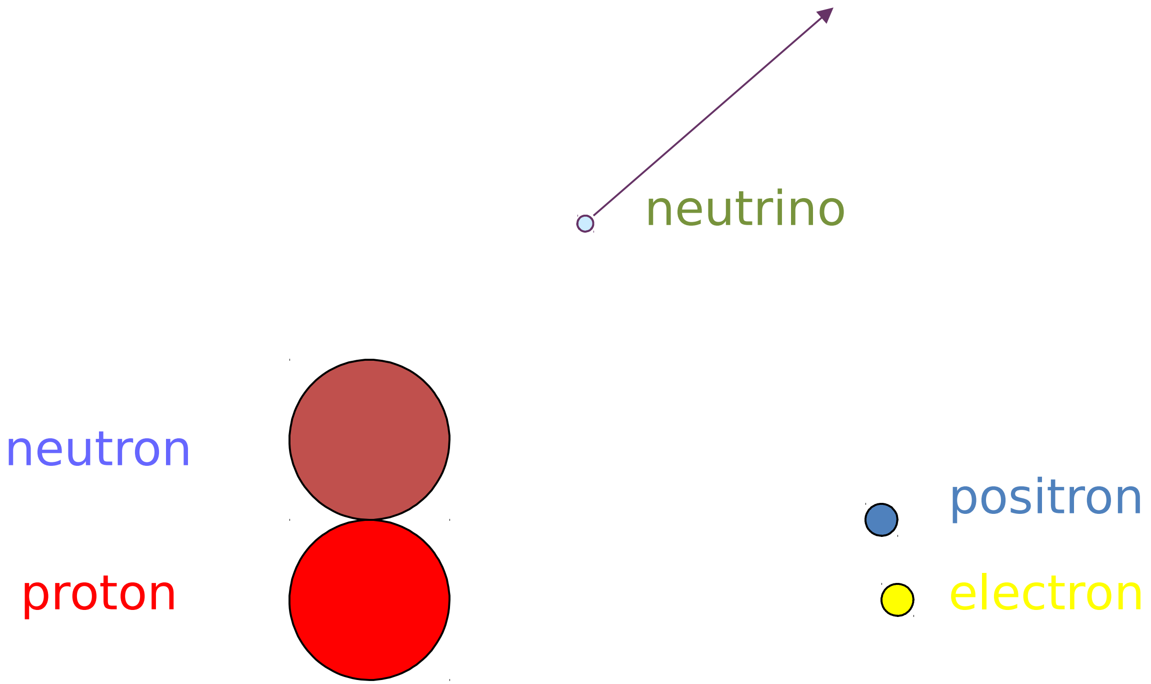

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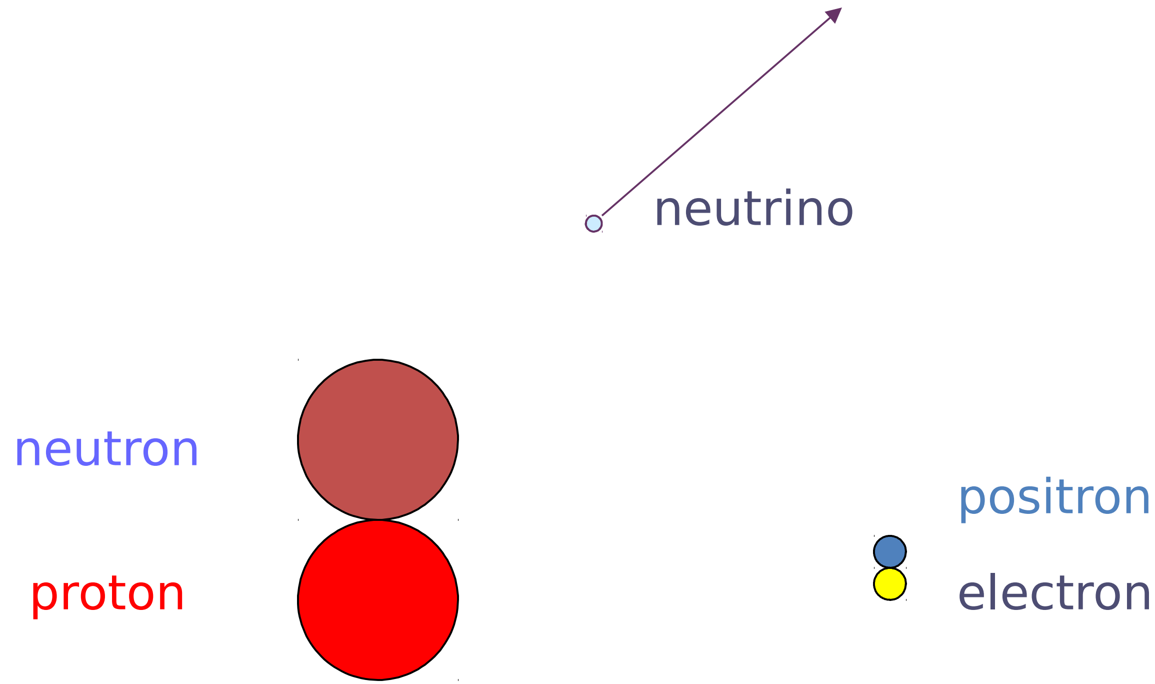

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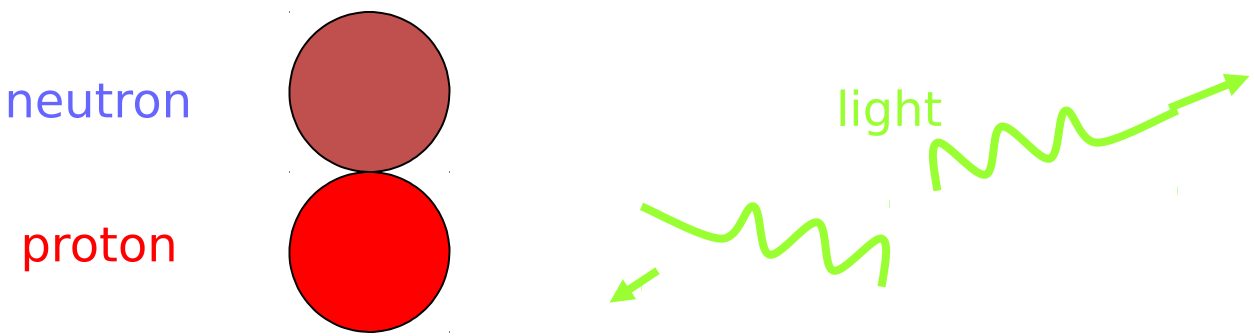

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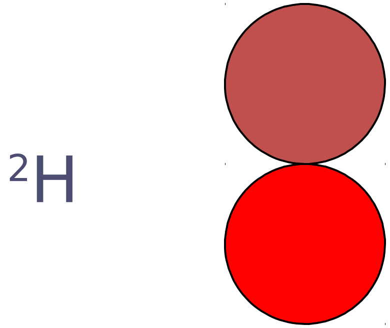

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Fusion of H to He in stars like the Sun
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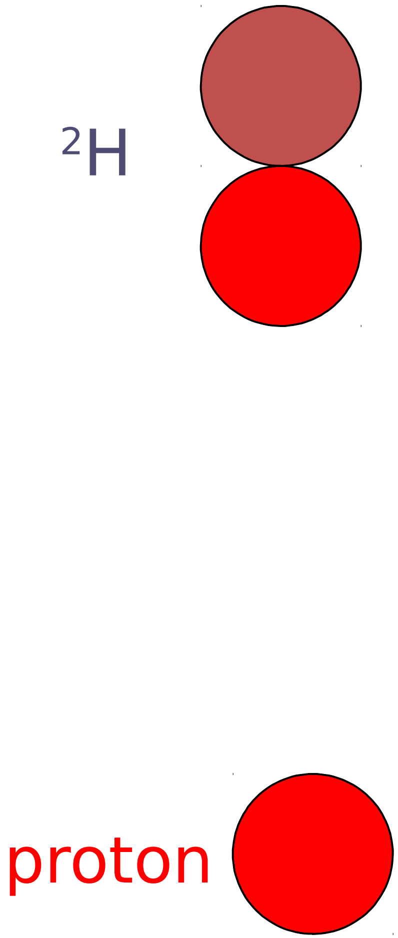

Deuteron then combines with another proton to produce helium-3 (two protons, one neutron)

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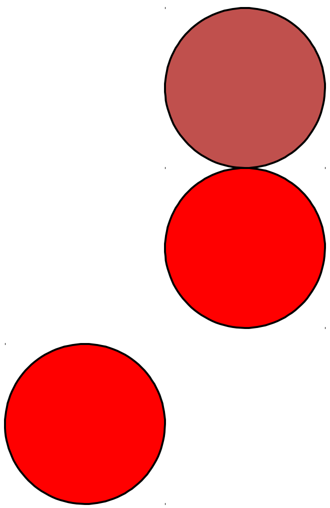

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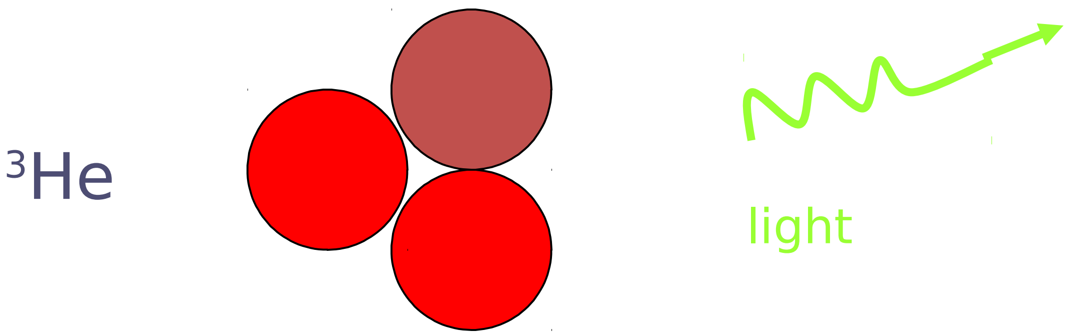

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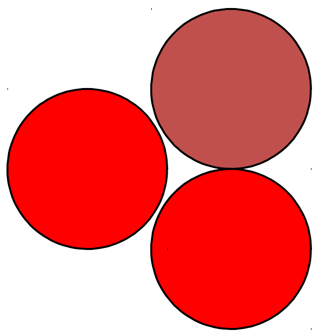
Fusion of H to He in stars like the Sun
Step 3

^{3}He



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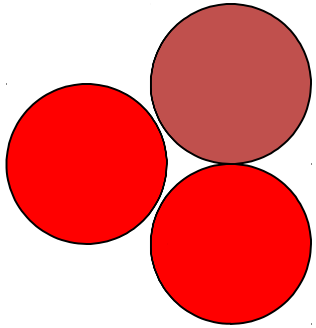
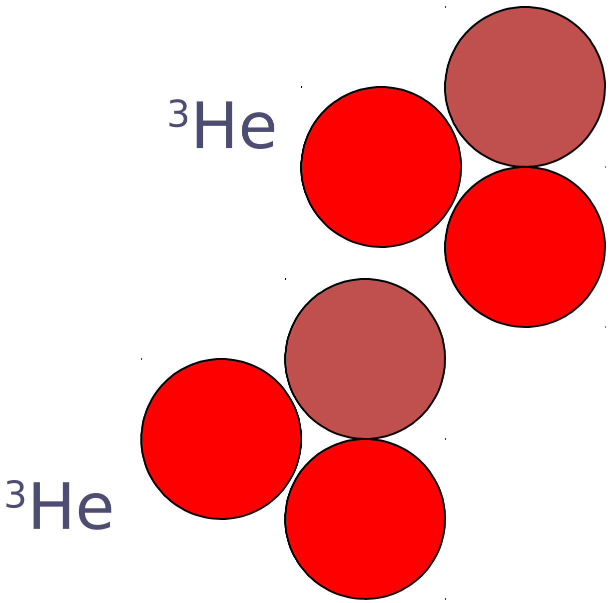


Two helium-3 nuclei combine to form helium-4 (two protons, two neutrons) and two protons

Fusion of H to He in stars like the Sun
Step 3



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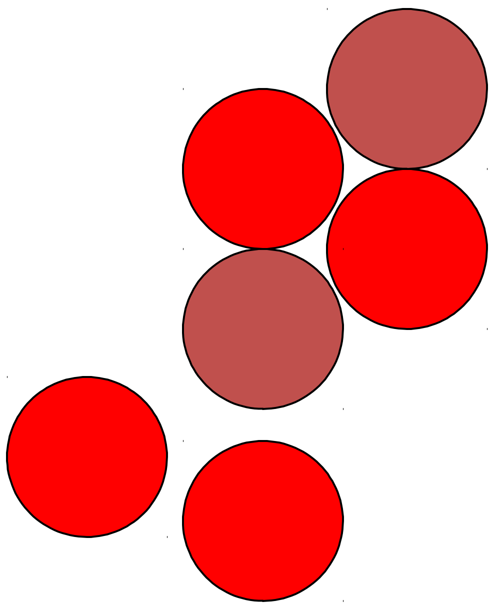

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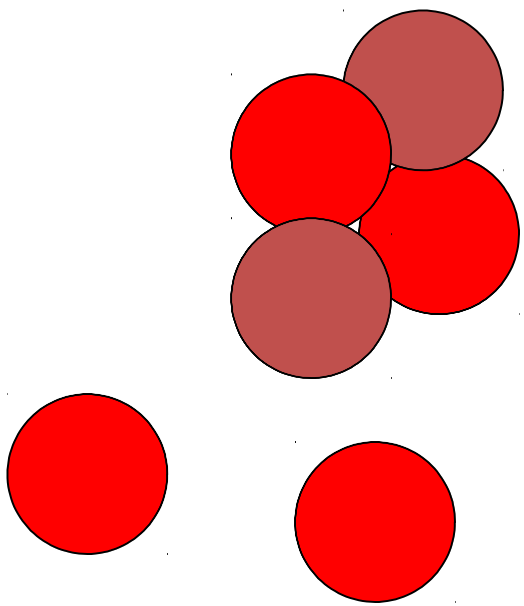

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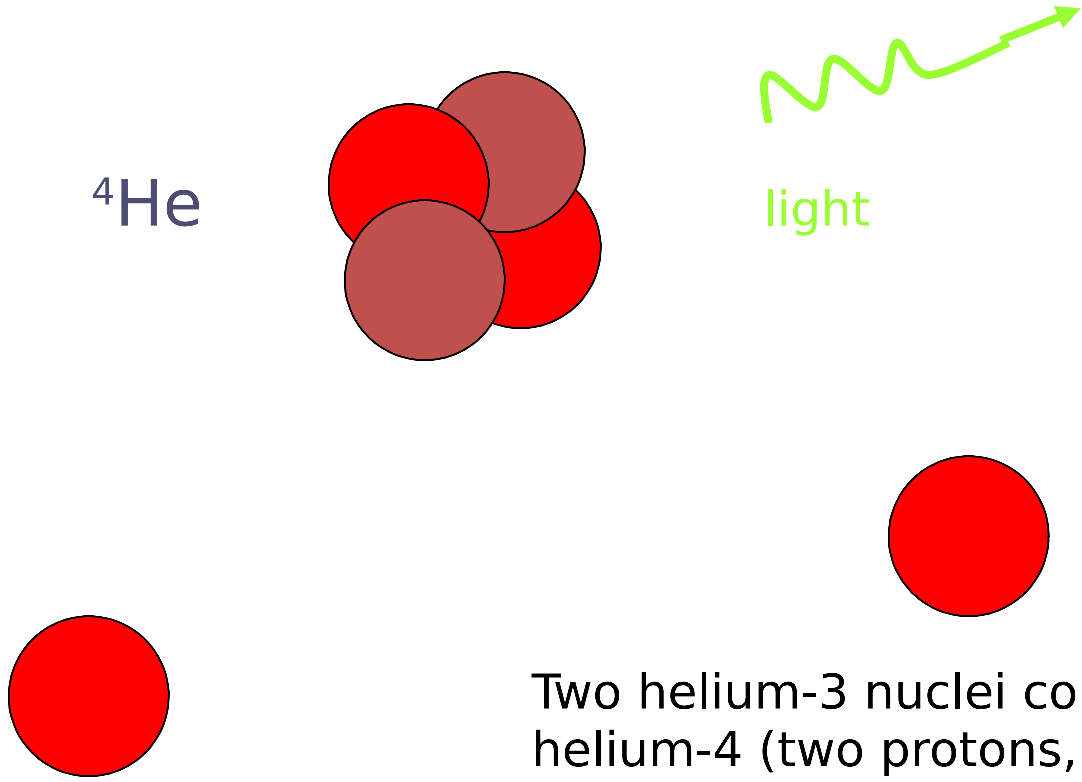

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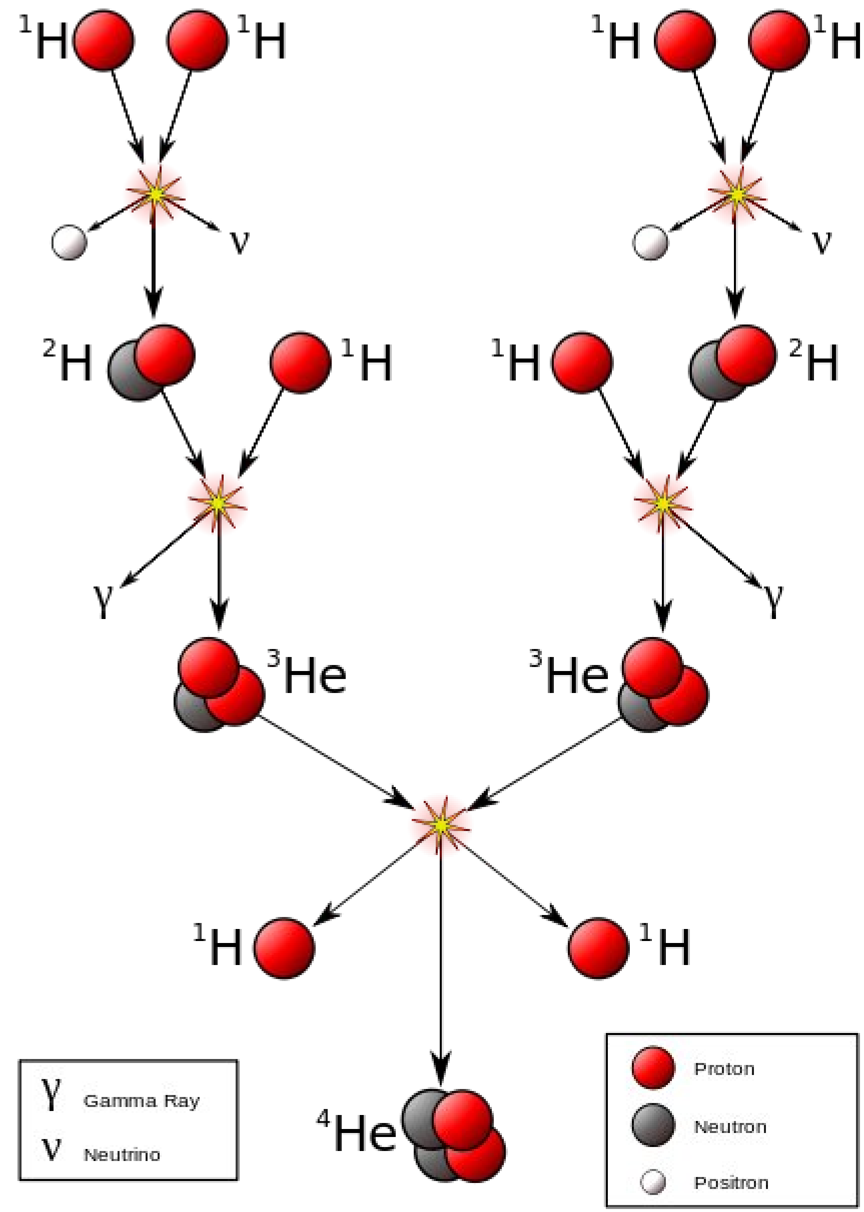
Fusion of H to He in stars like the Sun

Basic process, neglecting intermediate steps:

4 protons →
^{4}He + 2 neutrinos + energy



Powering the Sun

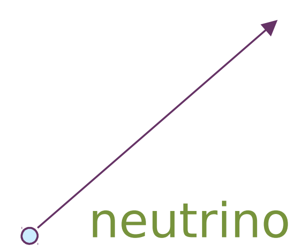
- Current energy output of Sun requires 600 million tons of hydrogen fused into helium every second
- That’s a lot, but only a very tiny fraction of the total mass available
- Sun can sustain this rate of fusion for another 5 billion years

Evidence of fusion in the Sun

- Light
  - Gamma rays produced in the center are absorbed and re-emitted many many times before they reach the surface of the Sun, more than 10,000 years later
  - As they pass through cooler outer layers blackbody spectrum shifts to lower temperatures
  - We finally see visible radiation from the photosphere – this is not direct evidence of fusion
- Neutrinos

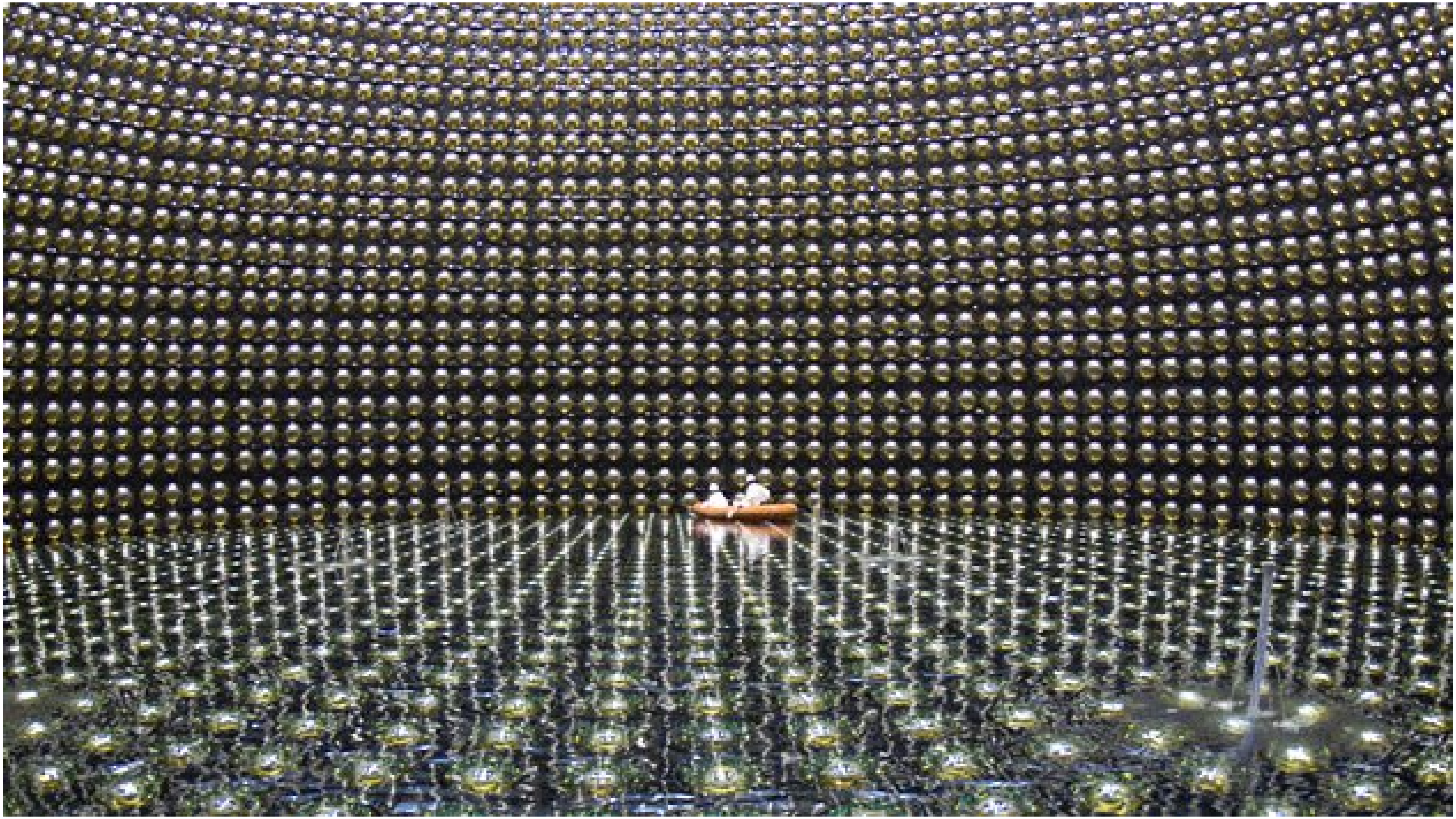
Solar Neutrinos

- Fusion in the Sun produces a lot of neutrinos!
- Flux at Earth is about 7×10^{10} neutrinos per square centimeter per second – that's about 70 billion neutrinos passing through your little fingernail every second!
- But they interact with almost nothing and are very difficult to detect… need a very big, specialized detector.



Solar Neutrinos

Super Kamionkande or Super K in Japan



Solar Neutrinos

- For many years there was a puzzle: we detected only about 1/3 of the number of neutrinos we expected to see from the Sun – the **solar neutrino problem.**
- This was a conflict between reliable experimental results and the very well understood model of the Sun.

Solar Neutrinos

Resolution of the problem: There are 3 kinds of neutrinos – electron neutrino, muon neutrino, tau neutrino.

The sun only produces electron neutrinos, but they can change into other kinds of neutrinos on their way to us – they “change flavor” or “oscillate.”

These other neutrinos were not detected in early experiments, resulting in solar neutrino problem – but now we have seen them, problem is resolved!

How is energy generated in the Sun?

A Gravitational collapse

B Nuclear fission

C Nuclear fusion

D Solar wind power

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