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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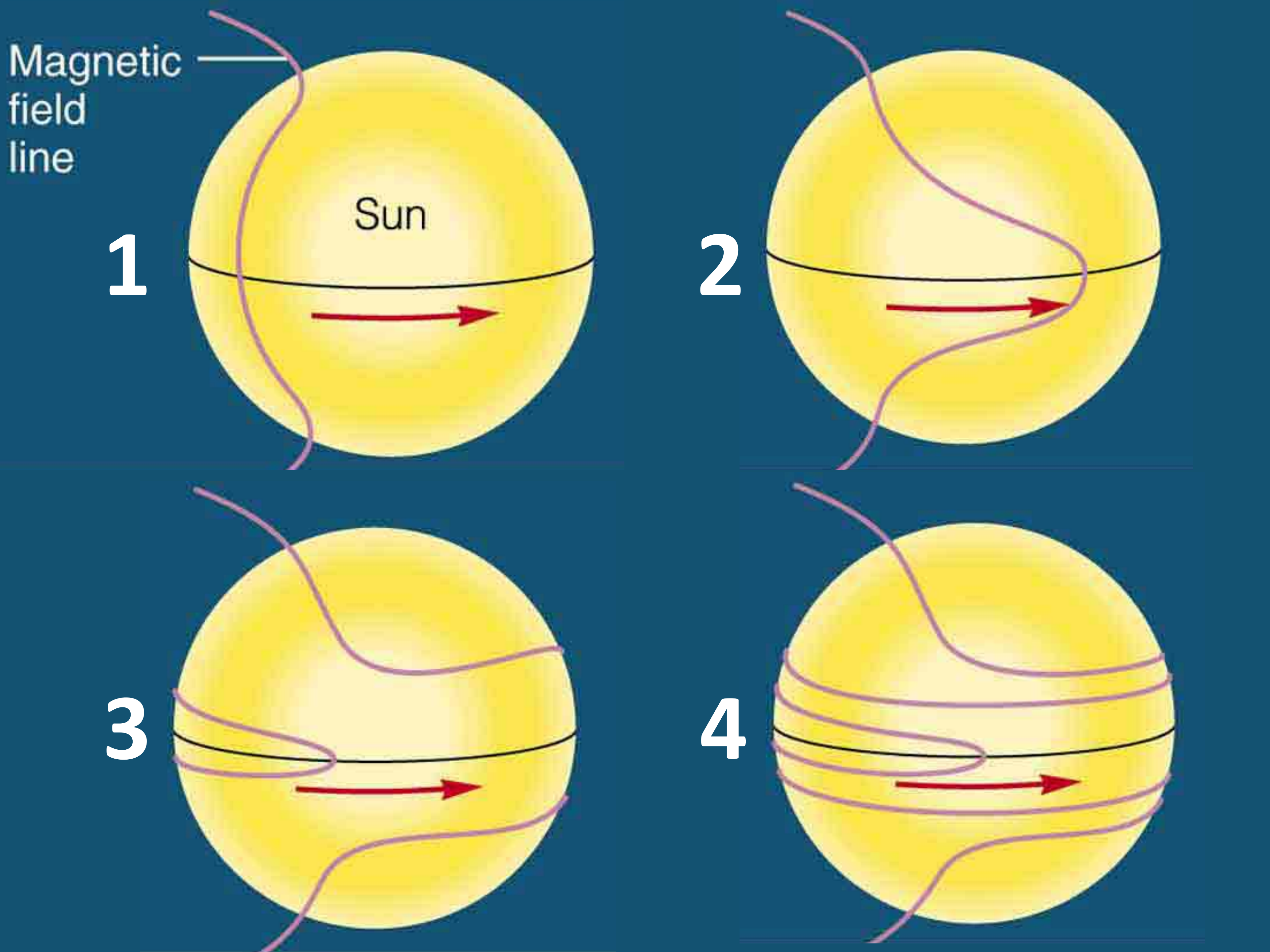
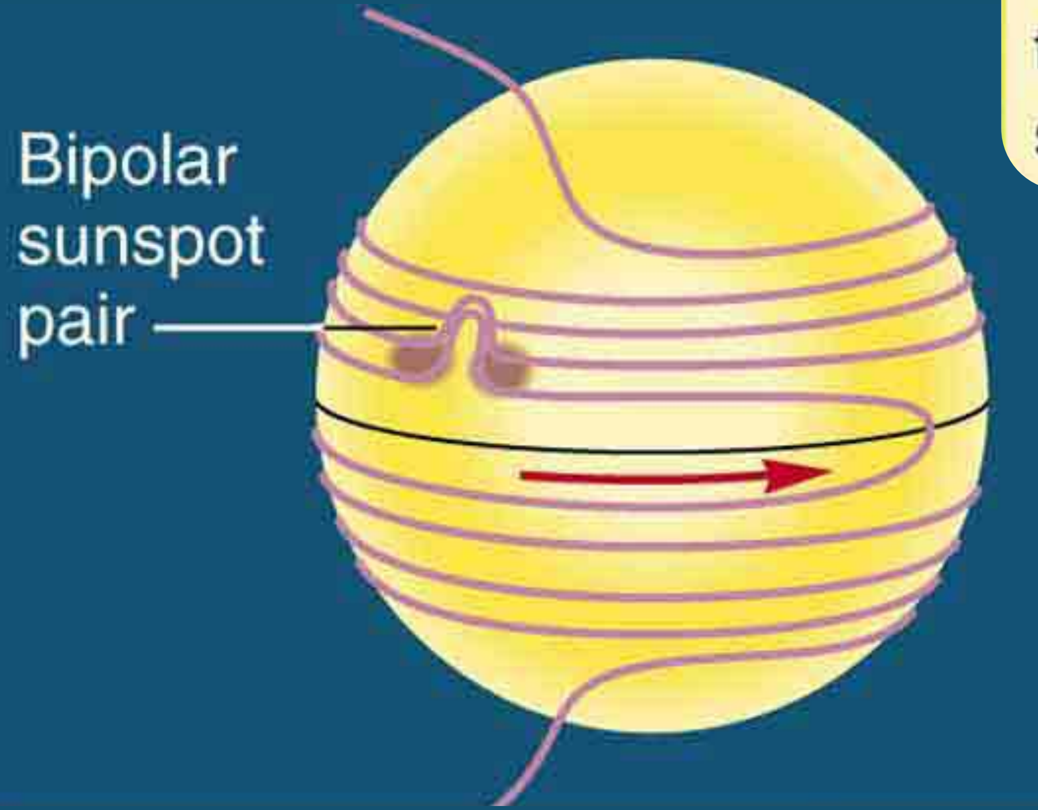
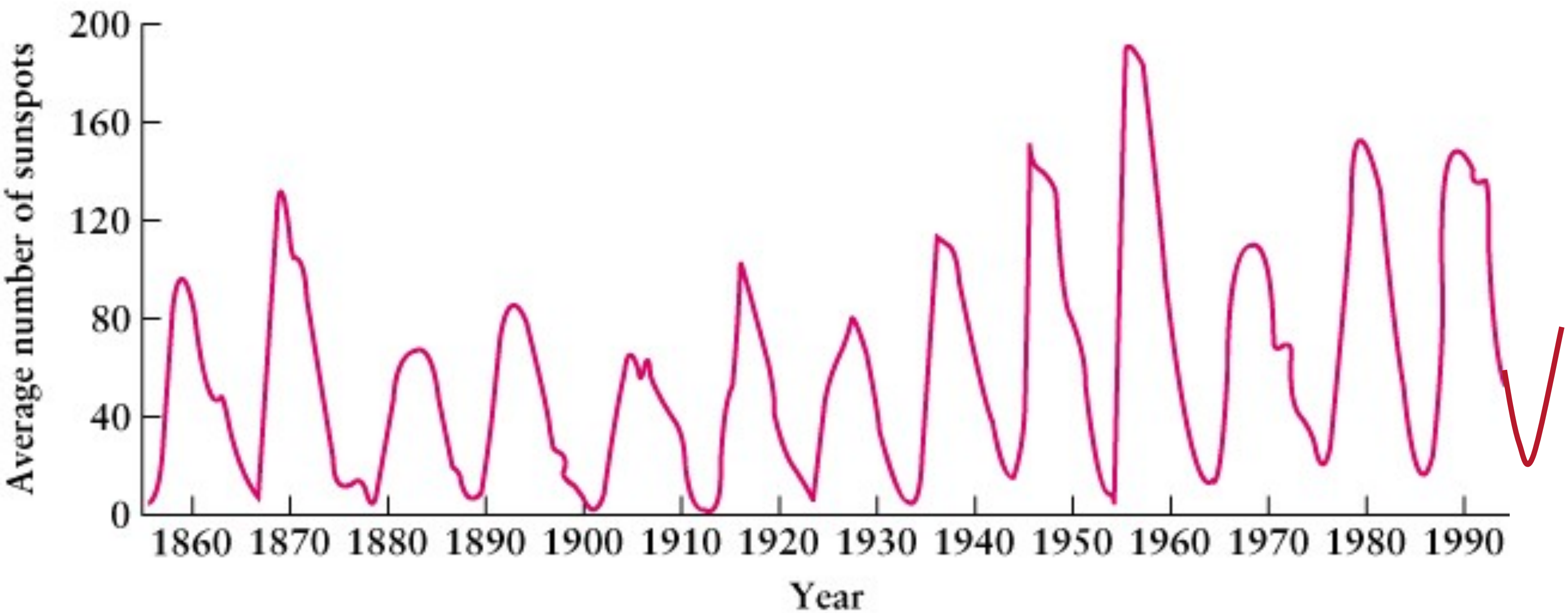

Magnetic field line
Sun
1
2
3
4



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**.

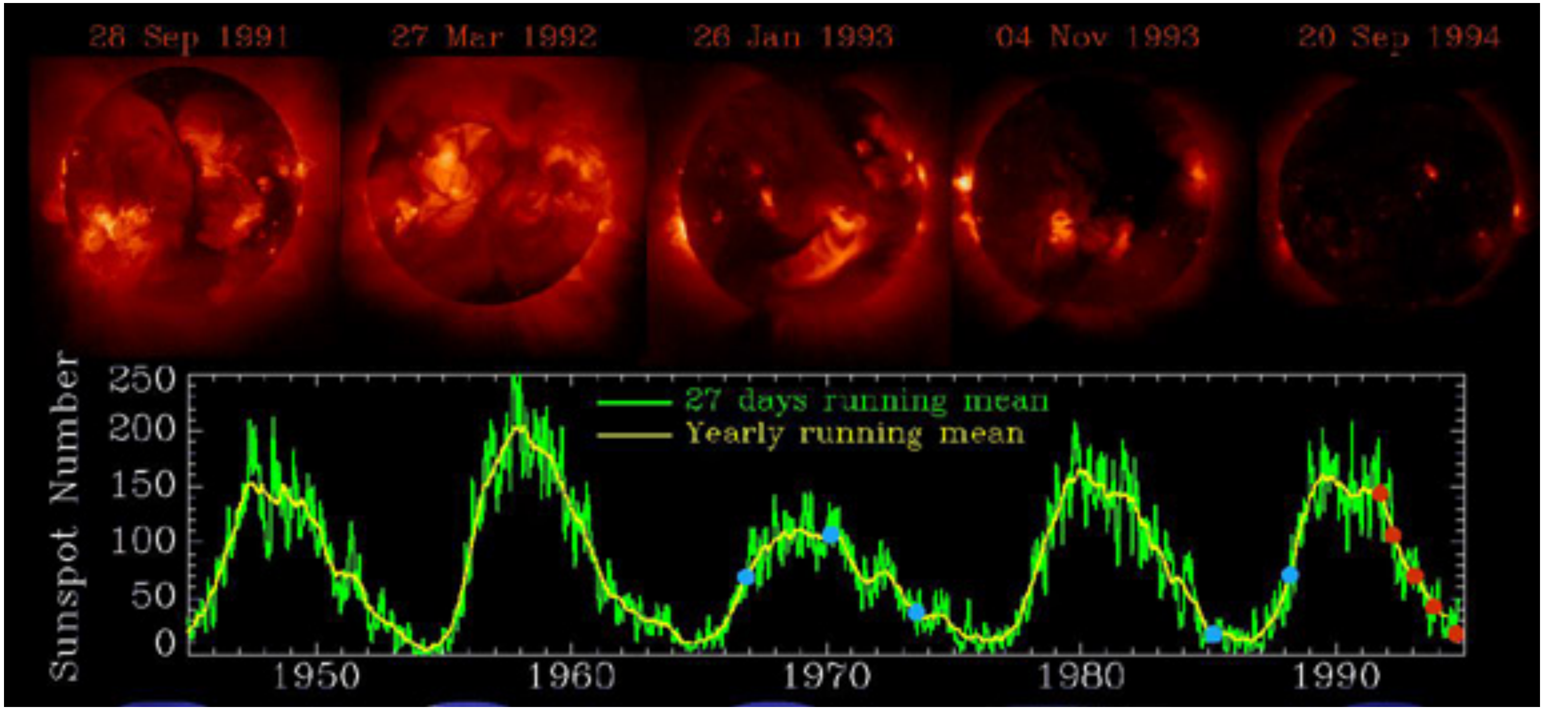


The 11 Year Sunspot Cycle

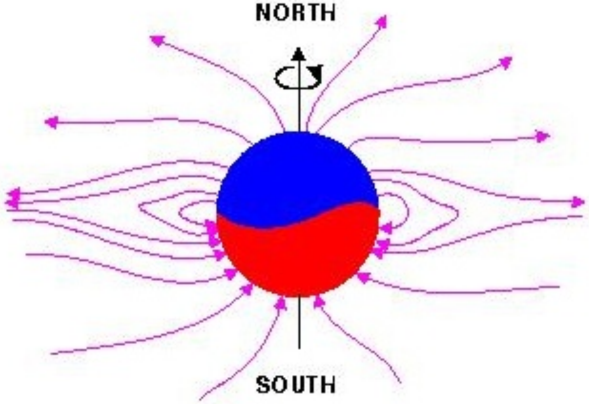
X-ray photos of the Sun from the Yohkoh spacecract for half a cycle, maximum to minimum

solar maximum

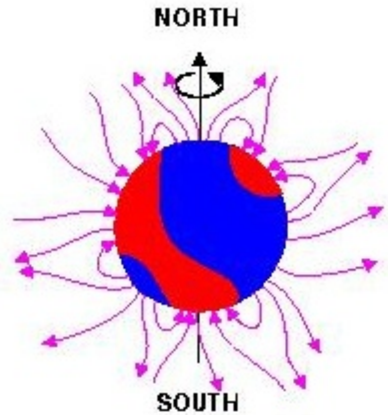
near minimum



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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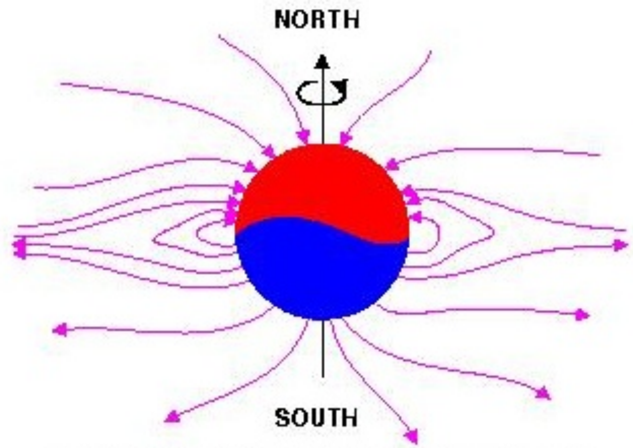
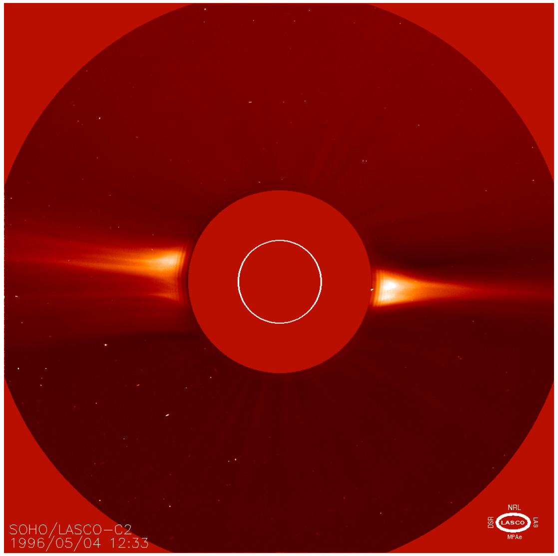
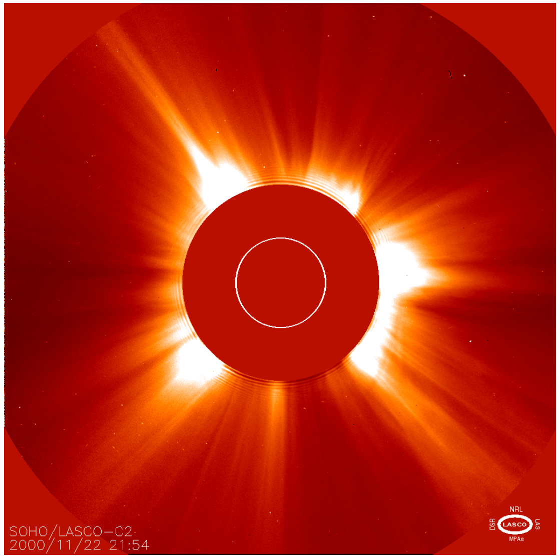


CORONAL MAGNETIC FIELD LINES AT NEXT SOLAR MINIMUM

Solar minimum



Solar maximum

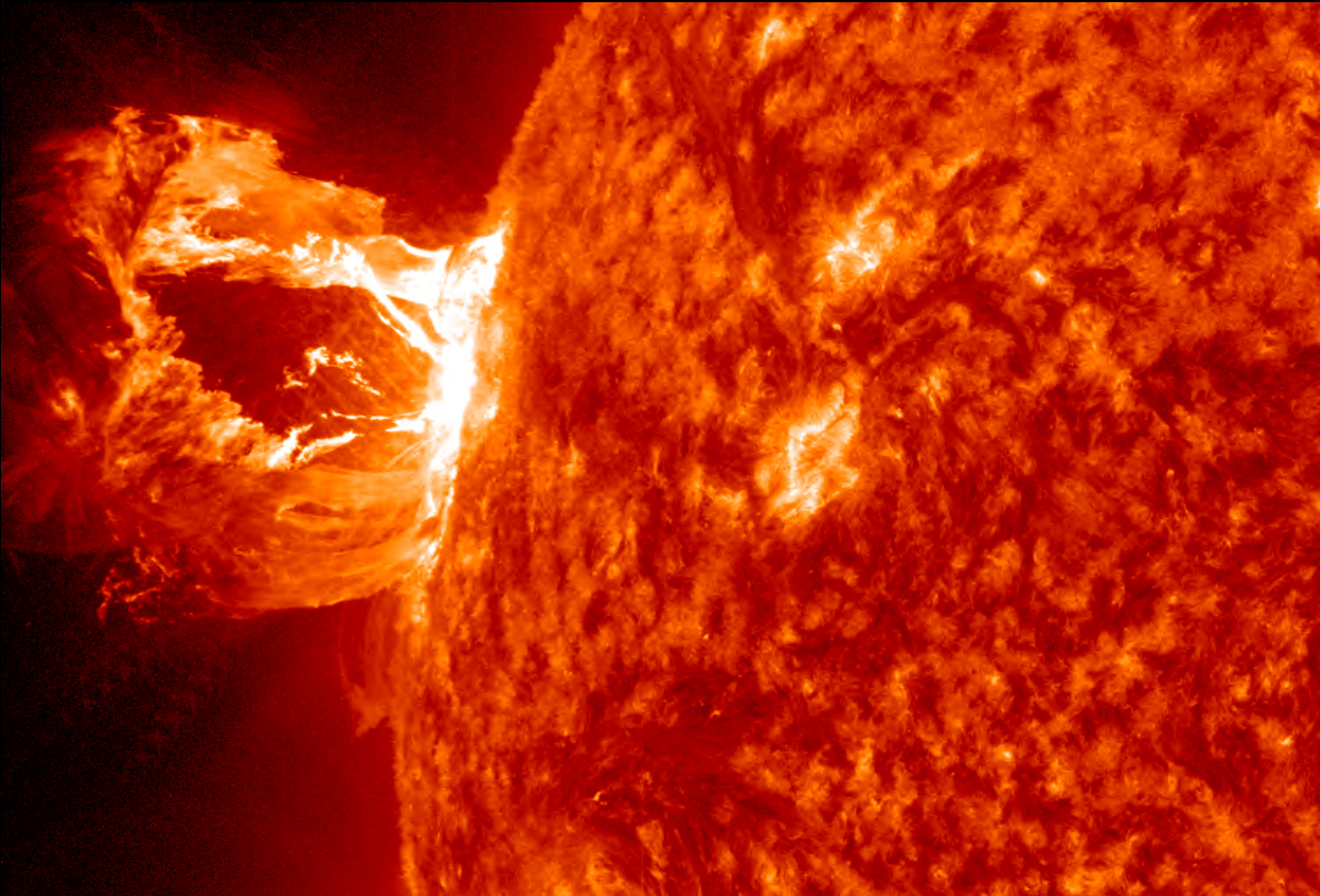


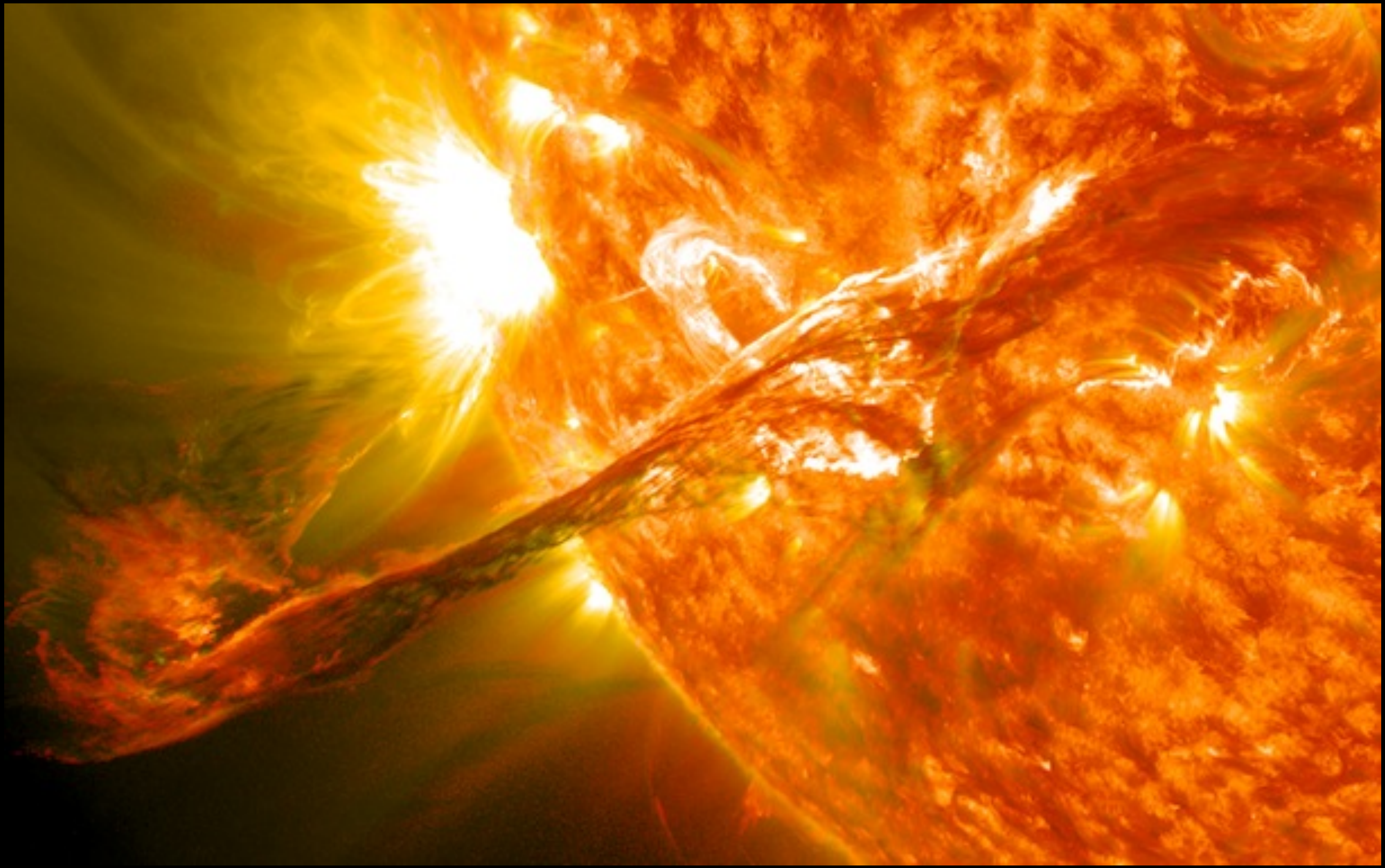
Features Above the Photosphere

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

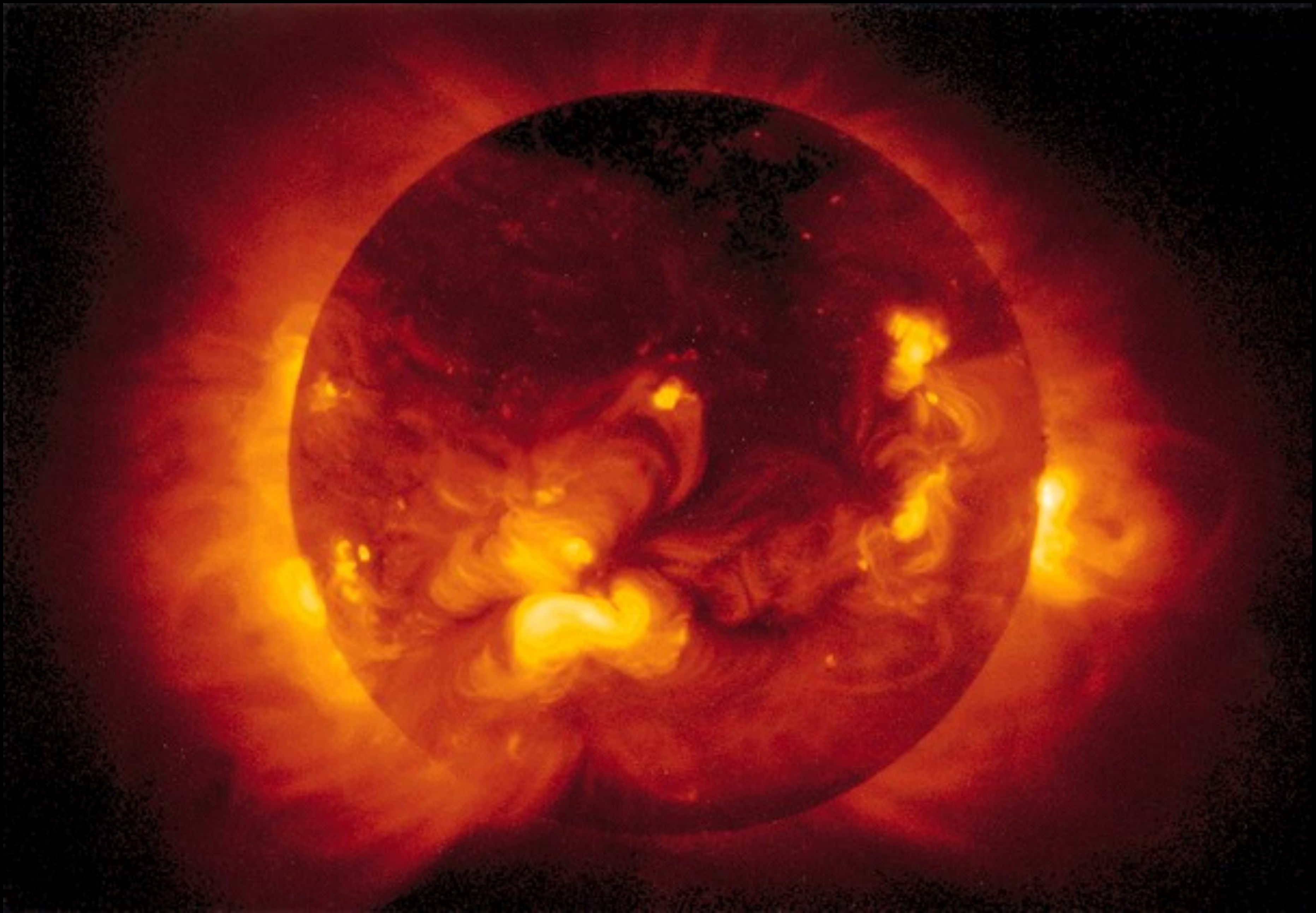
Flares: spectacular, hot explosions that release UV and X-rays and eject electrons and protons from the Sun's surface.

Prominences: Trapped gas from the surface of the sun. Trapped by magnetic fields

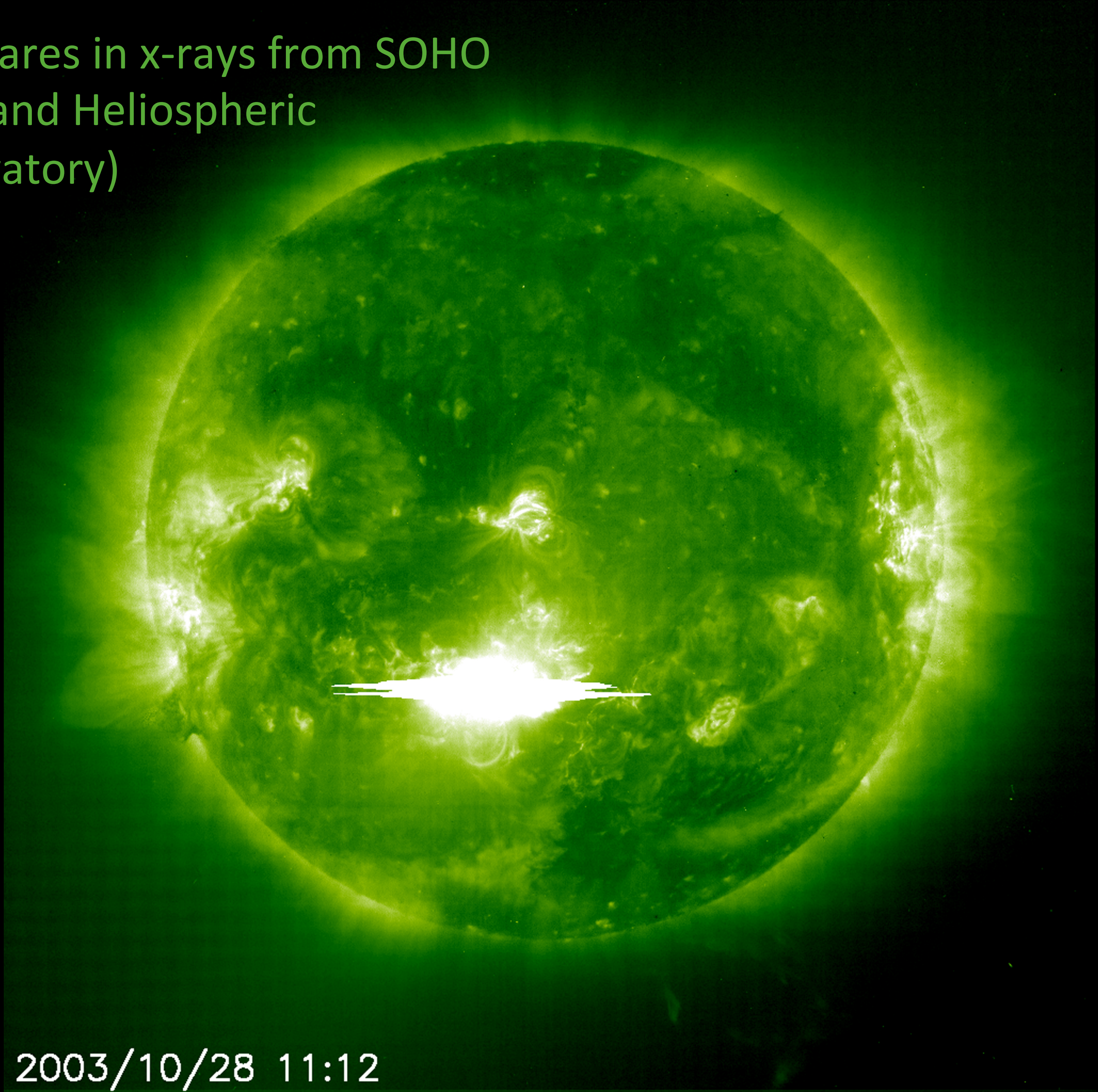




Flares seen in X-ray photo



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**

$$\mathbf{E = mc^2}$$

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

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?

$$E = mc^2 = (4\times10^9)(3\times10^8)(3\times10^8)$$

$$= 36\times10^{25}$$

$$= 4\times10^{26}\text{ watt-seconds}$$

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?

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

$$m = E / c^2 = \frac{(9 \times 10^{26})}{(3 \times 10^{8})(3 \times 10^{8})}$$

$$= 1 \times 10^{10} \text{ kg}$$

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):

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

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)

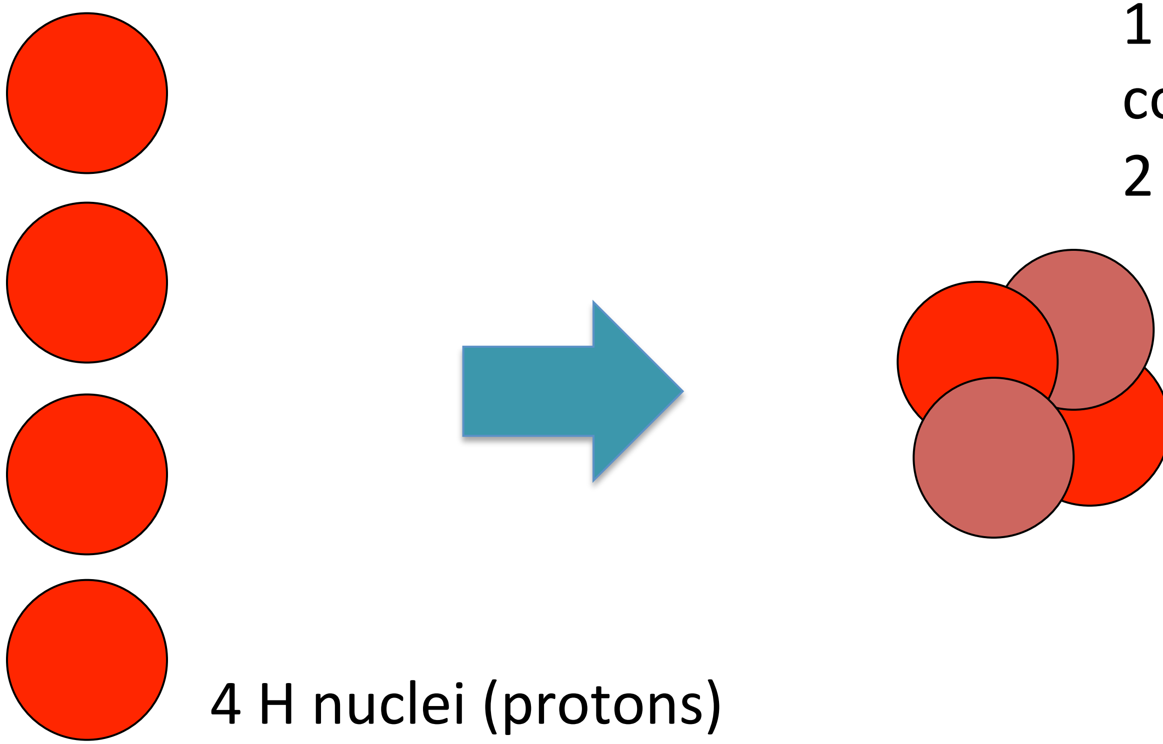
$$4m_H - m_{He} = .007m_H$$

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.

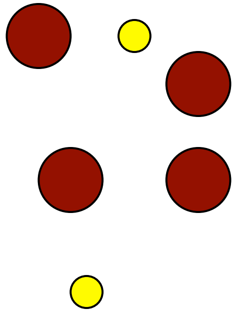


Fusion of H to He in stars like the Sun

Overall reaction:

Proton-proton chain

4 protons + 2 electrons → Helium nucleus



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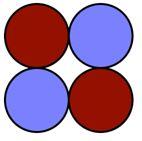

(2 protons, 2 neutrons)

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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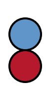

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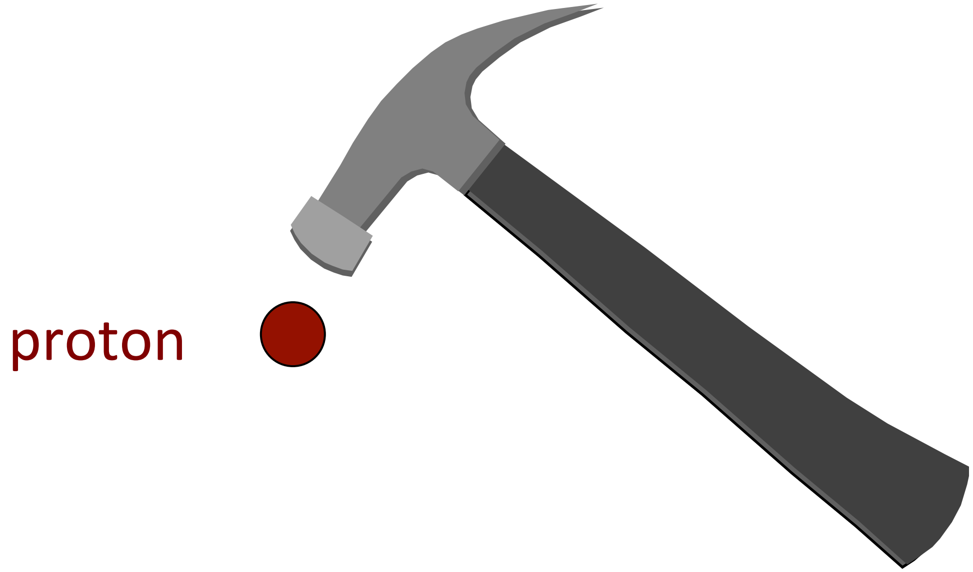
Neutrino

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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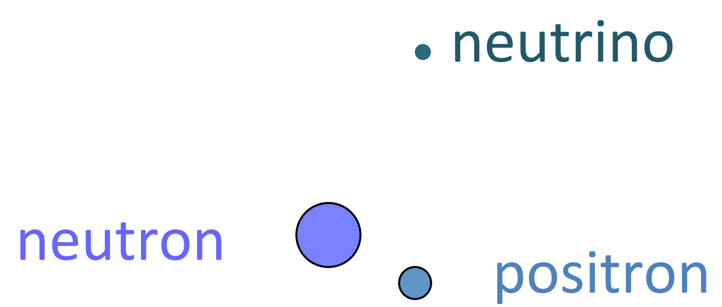
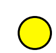


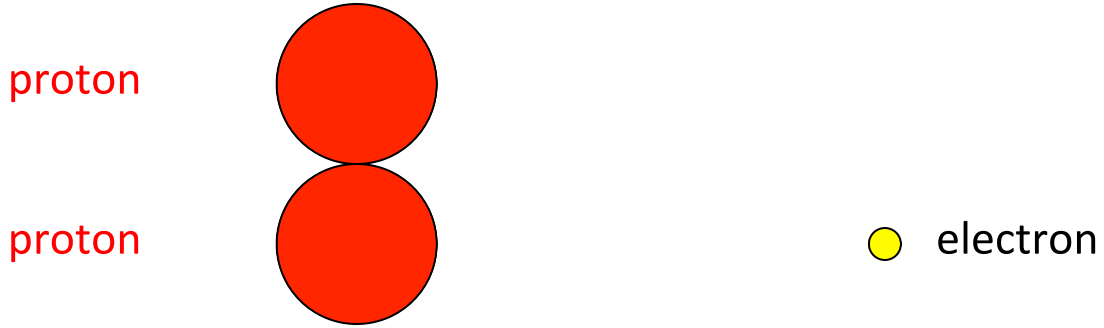
Fusion of H to He in stars like the Sun
Step 1



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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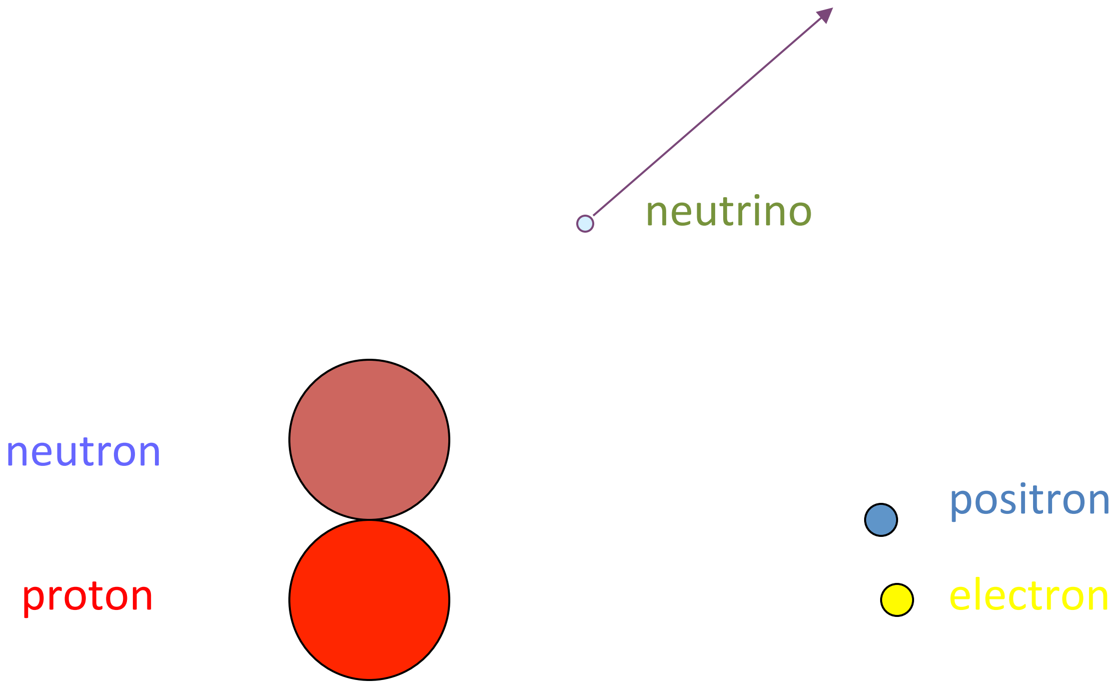

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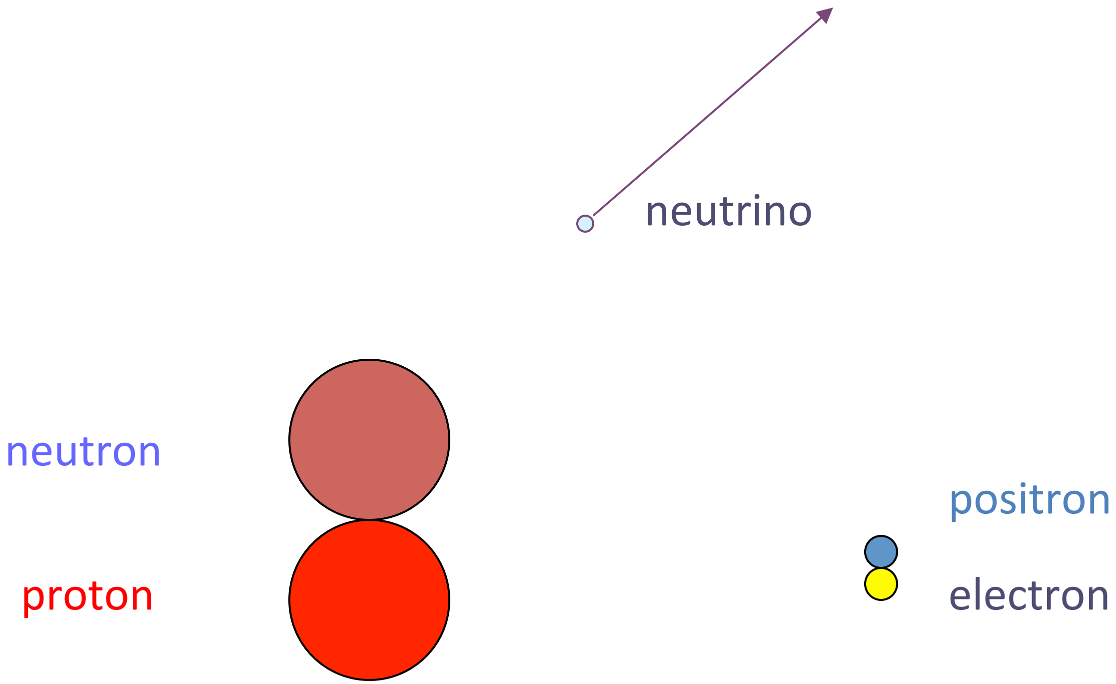

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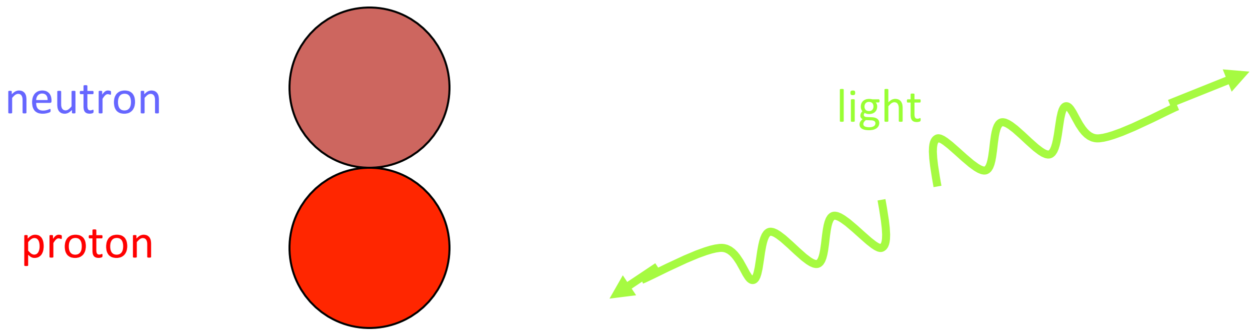

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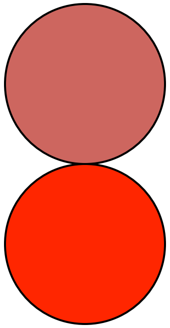
Step 1

H^2



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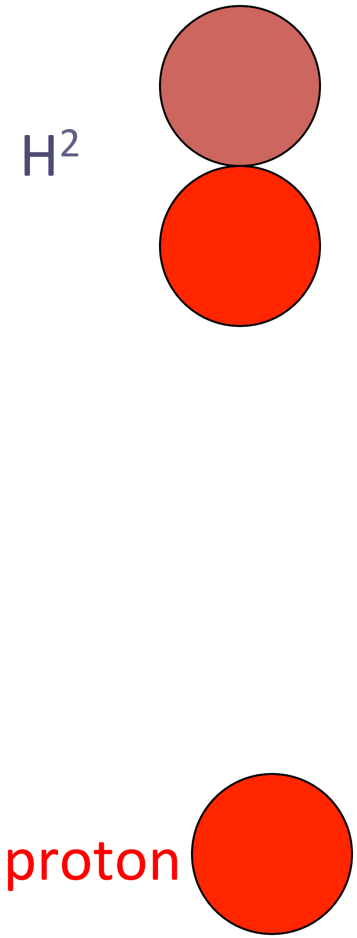
Fusion of H to He in stars like the Sun

Step 2



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

Fusion of H to He in stars like the Sun

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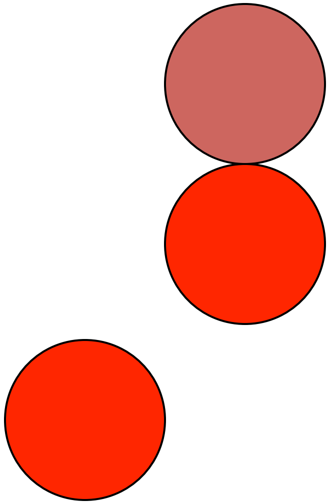

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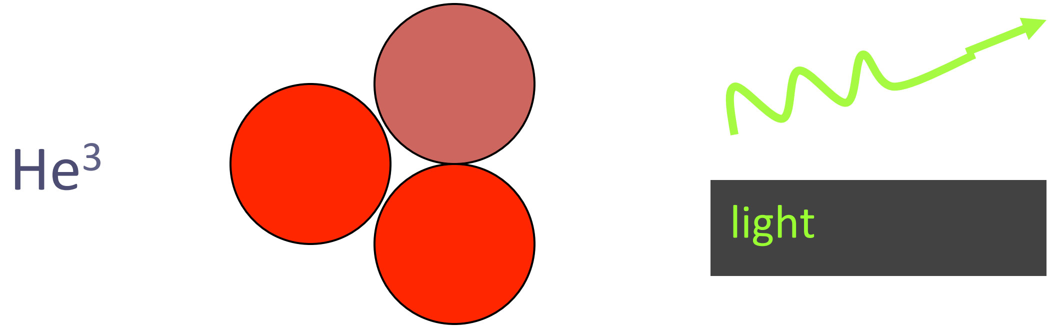

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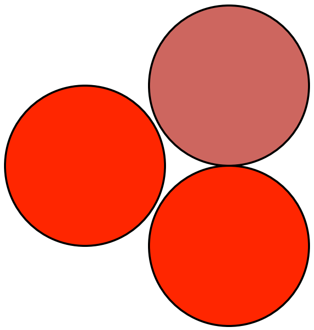
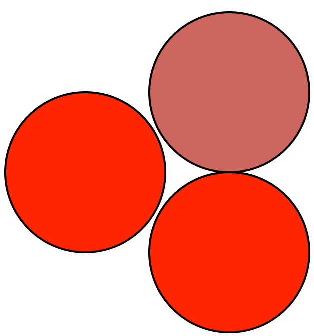
Fusion of H to He in stars like the Sun

Step 3

He^3



He^3



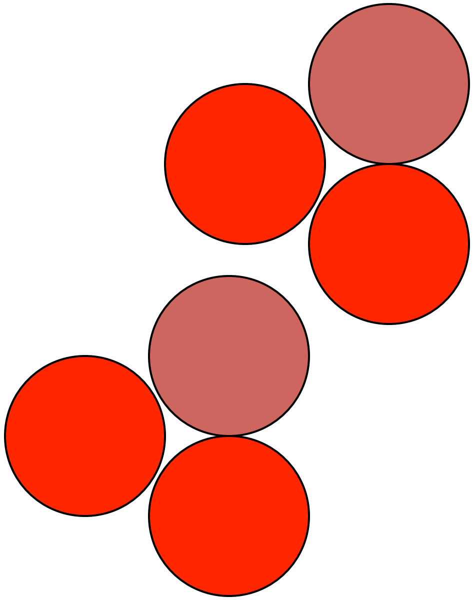
Two helium-3 nuclei combine to form helium-4 (two protons, two neutrons) and two protons

Fusion of H to He in stars like the Sun

Step 3

He^3

He^3



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Fusion of H to He in stars like the Sun

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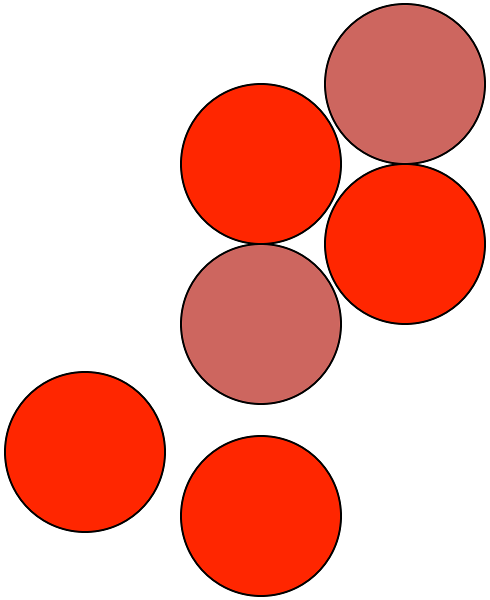

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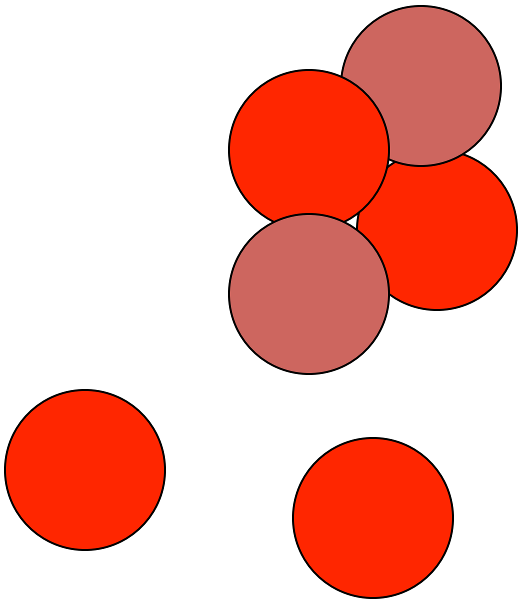

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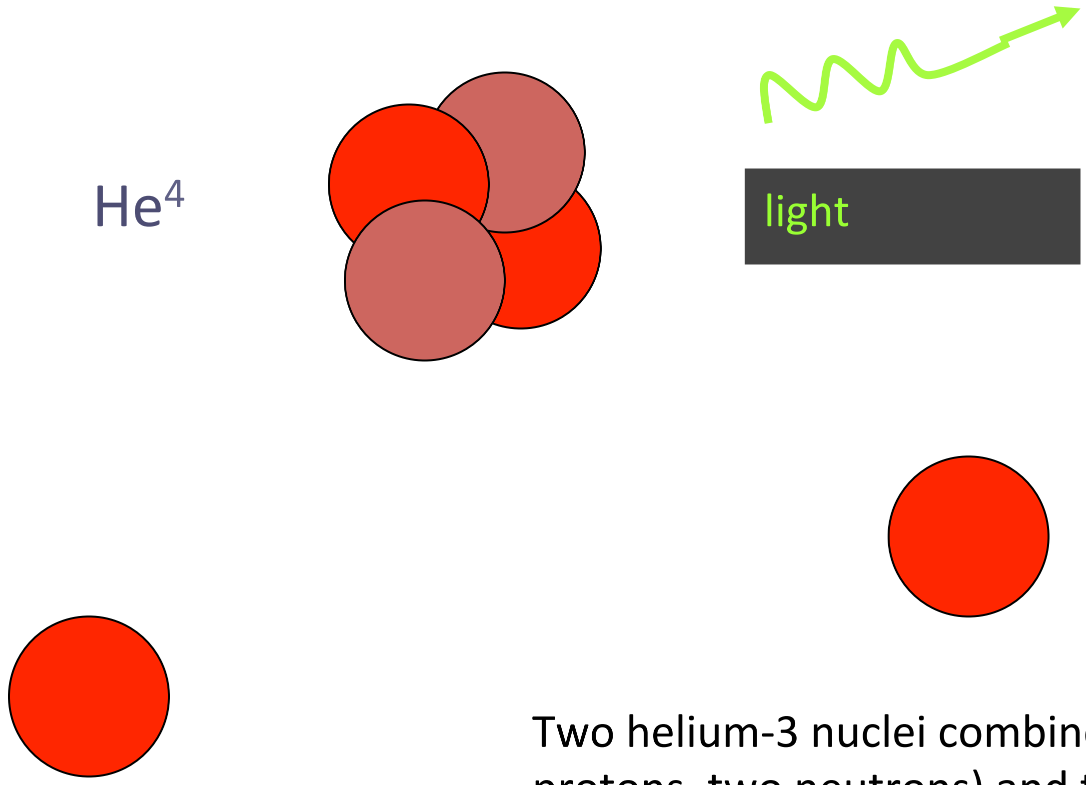

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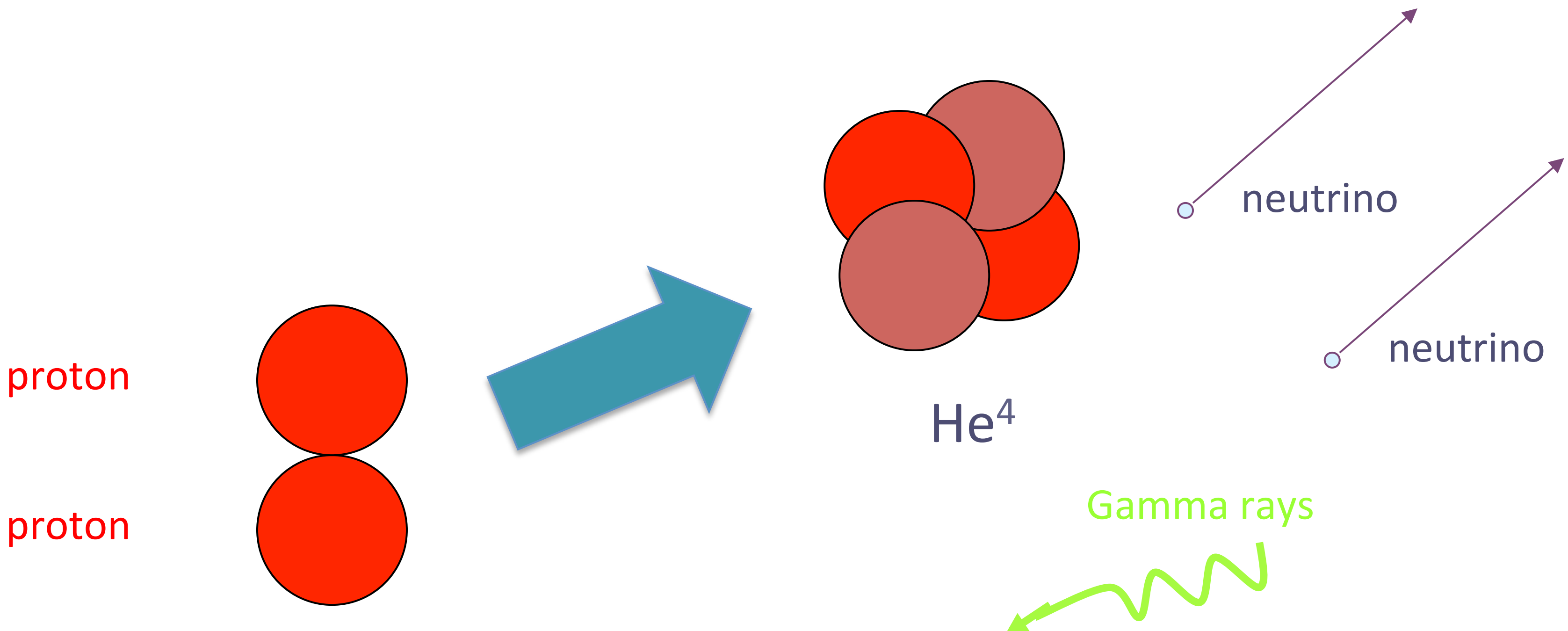
Fusion of H to He in stars like the Sun

Basic process, neglecting intermediate steps:

4 protons → helium-4 + 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

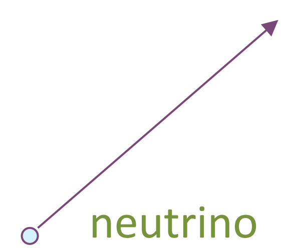
- Light
  - Gamma rays produced in the center are absorbed and re-emitted many many times before they reach the surface of the Sun, more than 10,000 years later
  - As they pass through cooler outer layers blackbody spectrum shifts to lower temperatures
  - We finally see visible radiation from the photosphere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

Solar Neutrinos

Fusion in the Sun produces a lot of neutrinos!

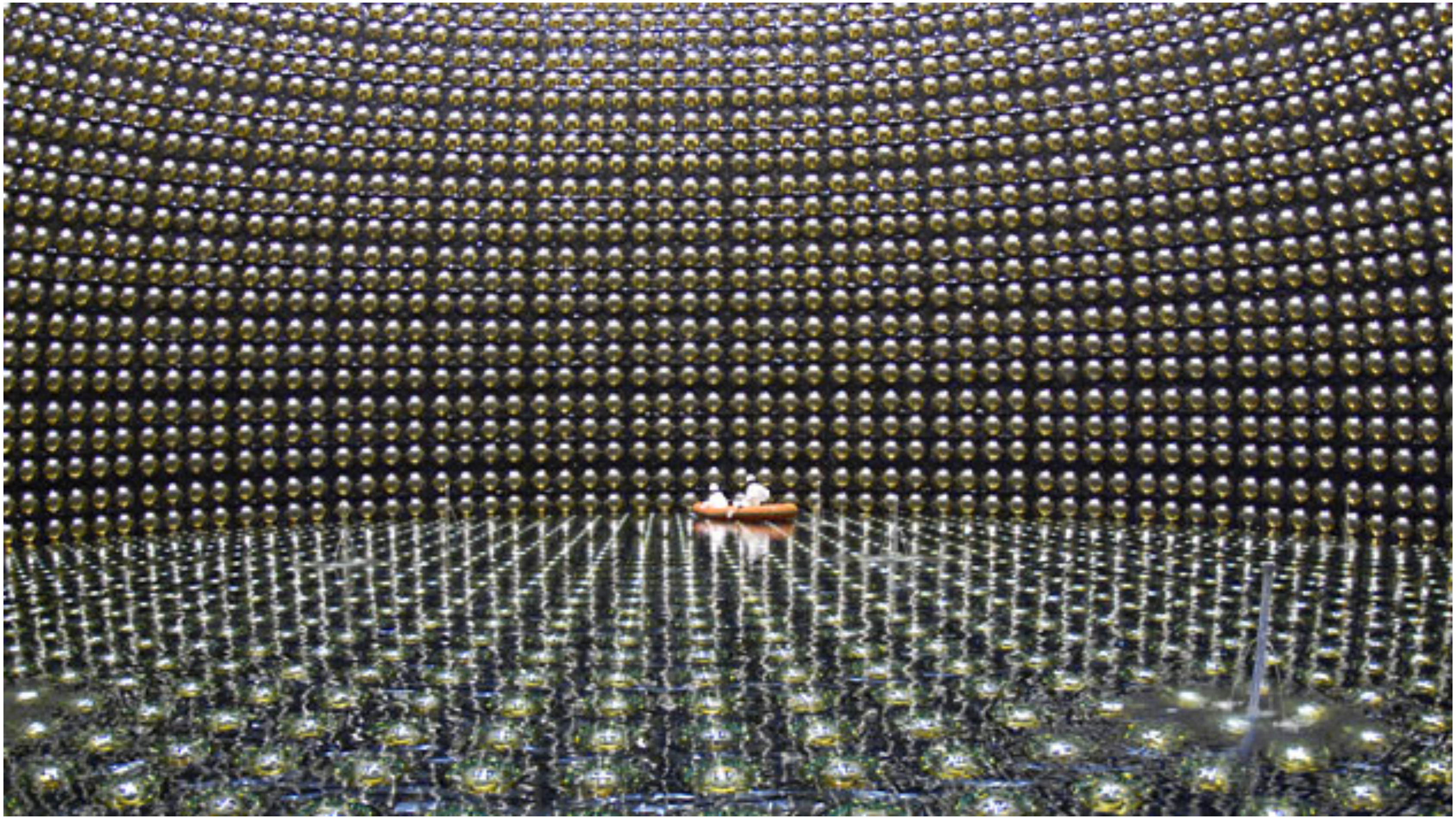
Flux at Earth is about 7×10^{10} neutrinos per square centimeter per second – that's about 70 billion neutrinos passing through your little fingernail every second!

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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