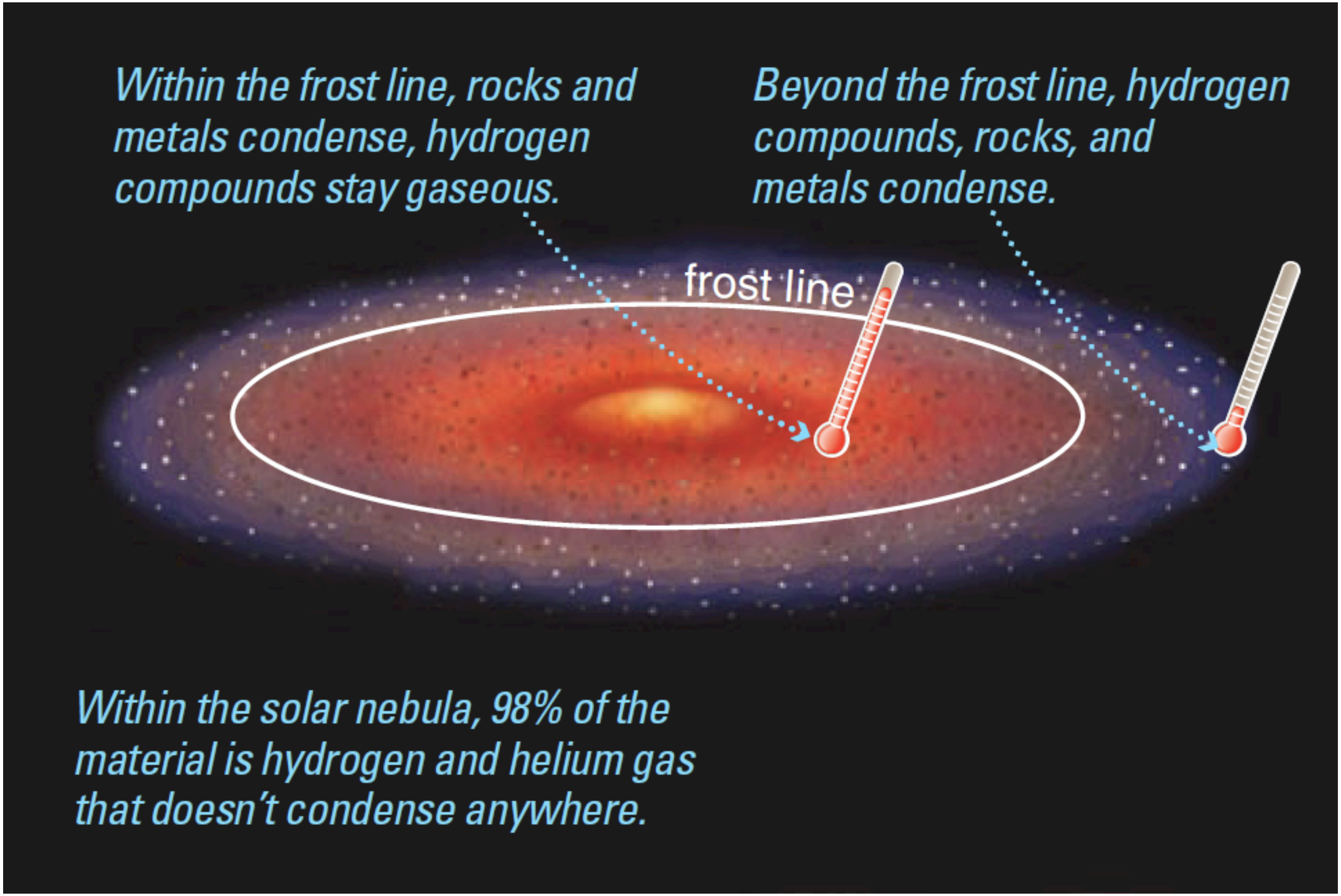
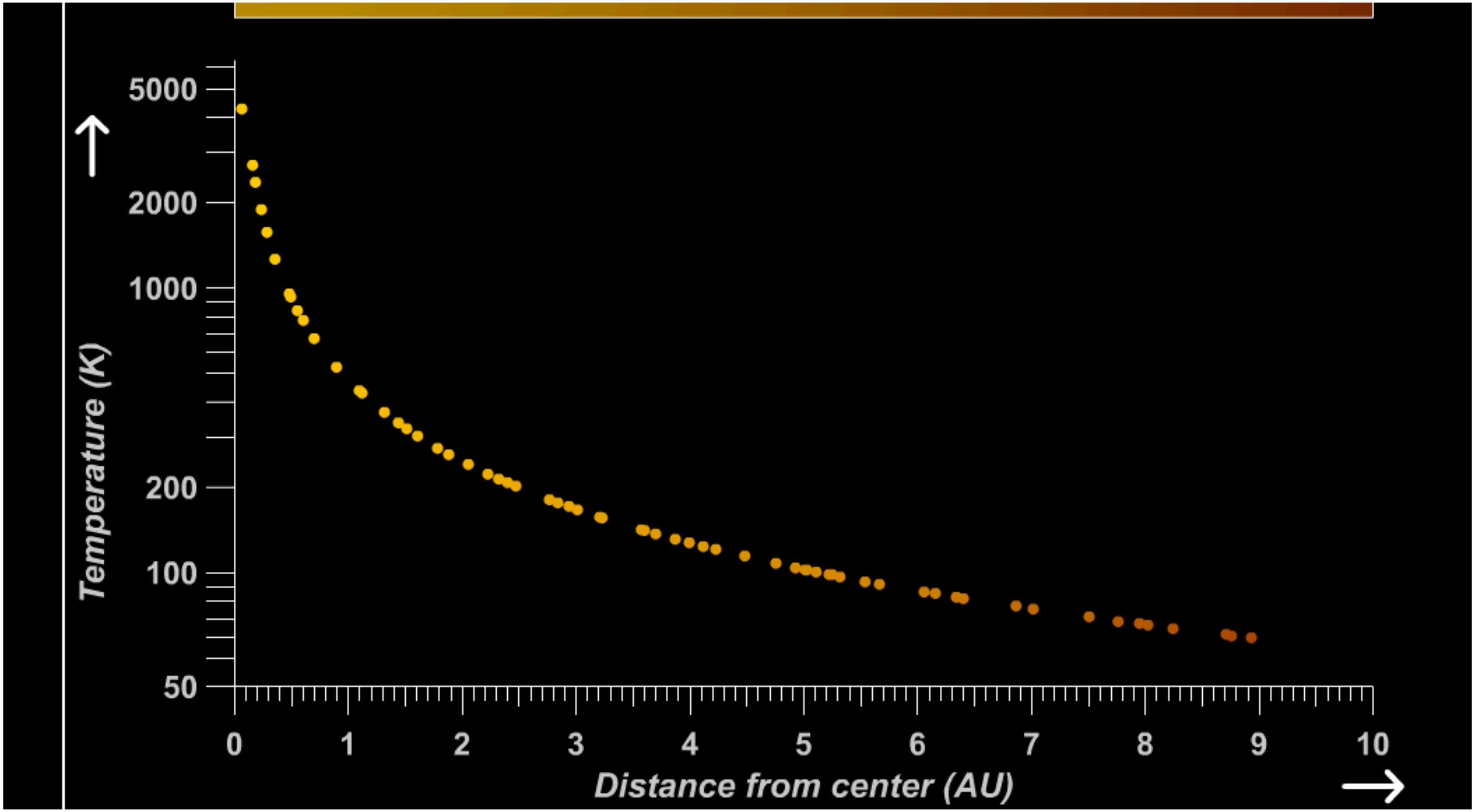
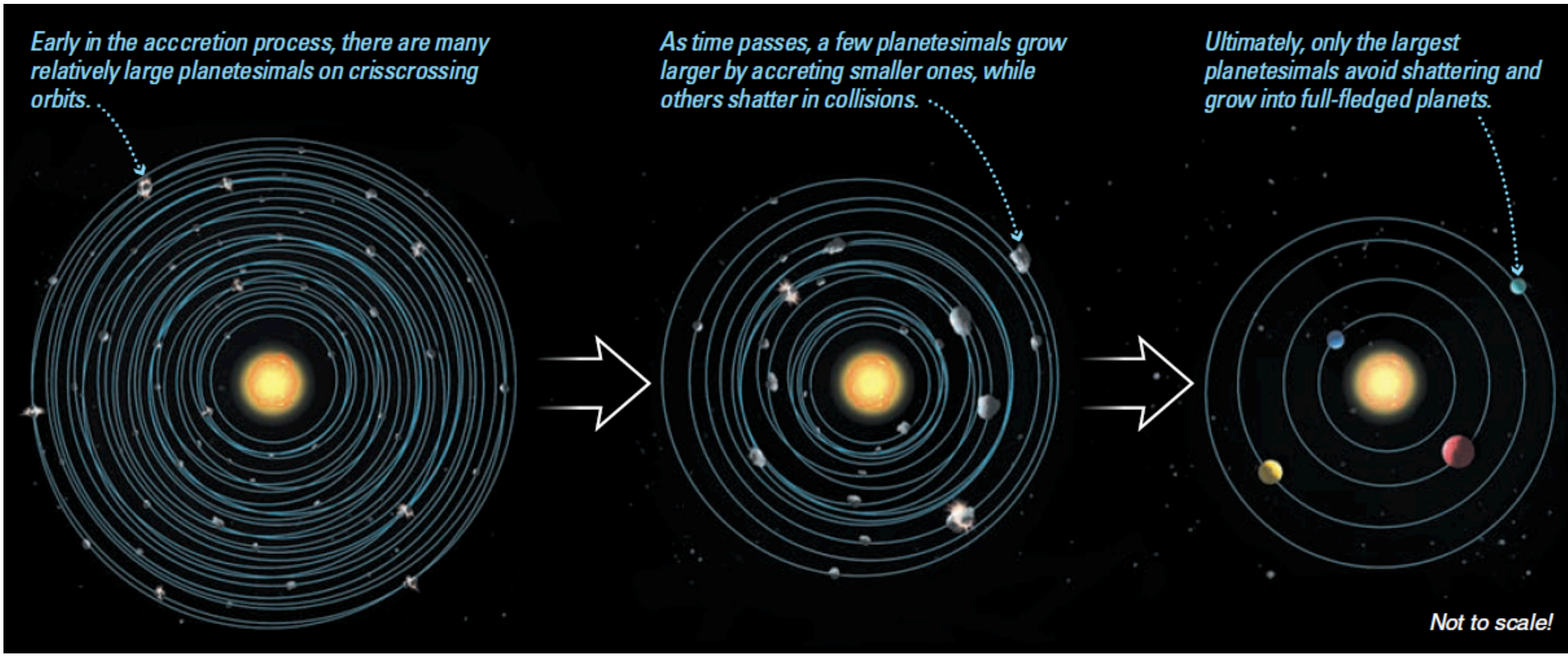
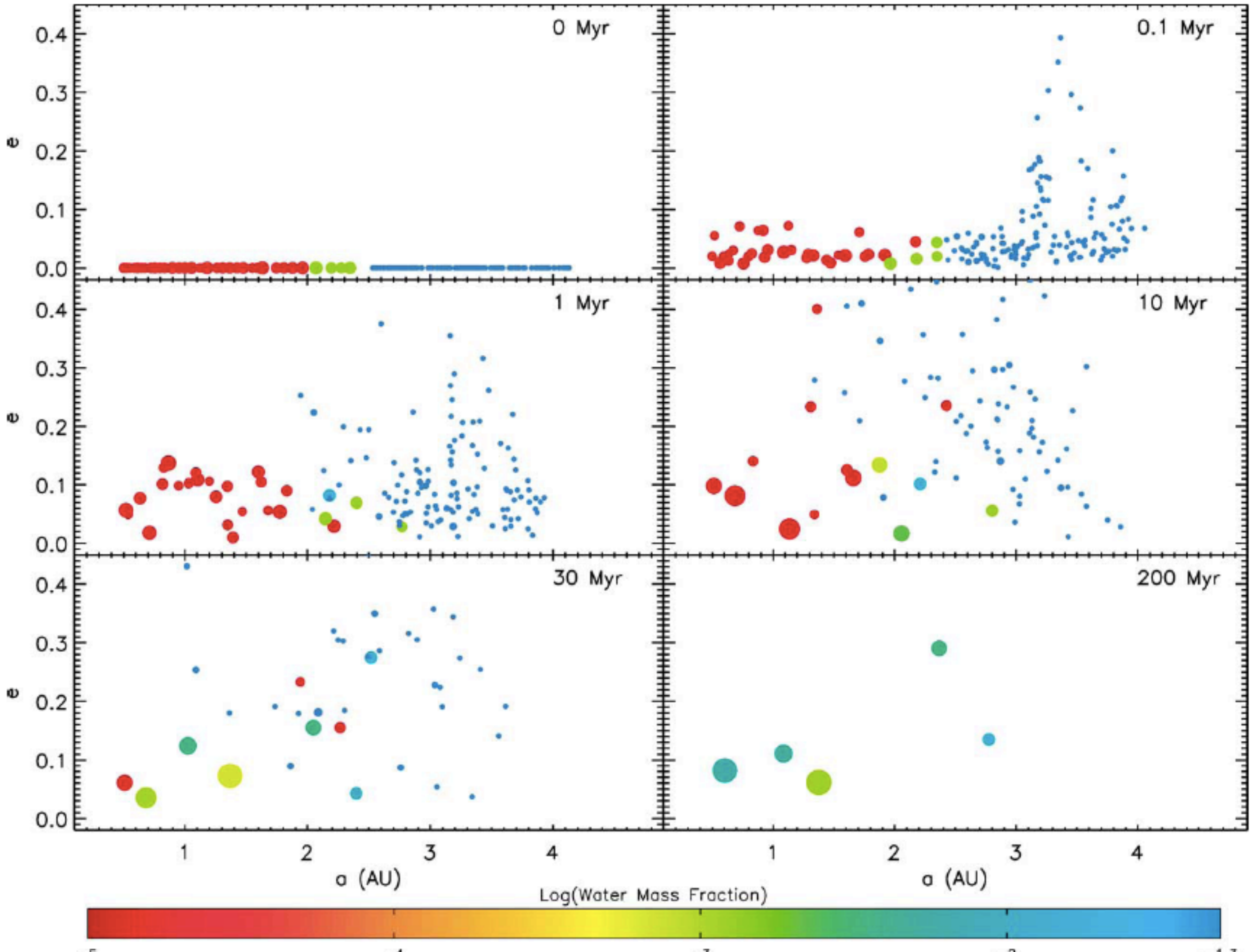


Within the frost line, rocks and metals condense, hydrogen compounds stay gaseous.
Beyond the frost line, hydrogen compounds, rocks, and metals condense.
frost line
Within the solar nebula, 98% of the material is hydrogen and helium gas that doesn't condense anywhere.

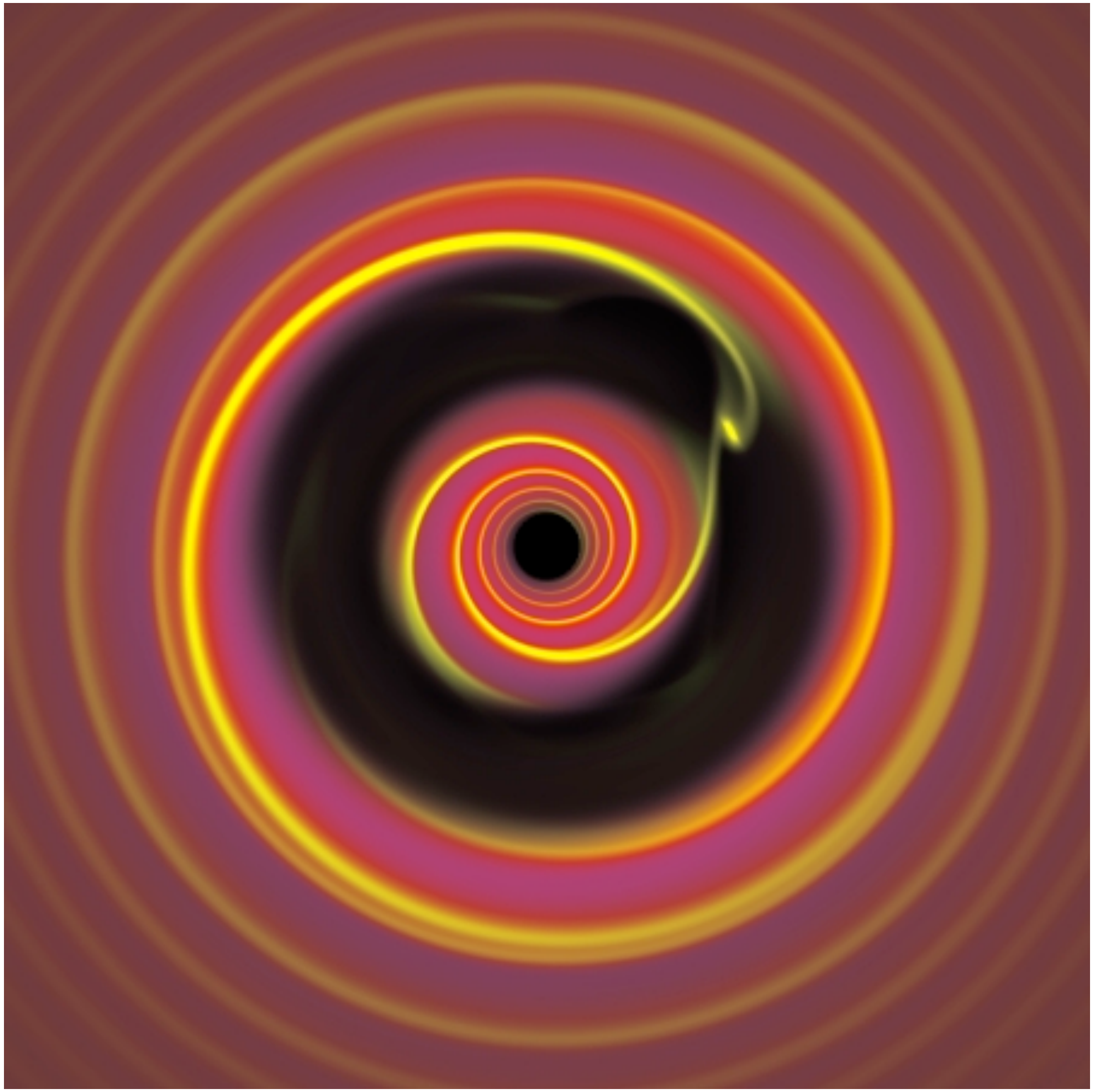
Temperatures in the Solar Nebula




Early in the acccretion process, there are many relatively large planetesimals on crisscrossing orbits.
As time passes, a few planetesimals grow larger by accreting smaller ones, while others shatter in collisions.
Ultimately, only the largest planetesimals avoid shattering and grow into full-fledged planets.
Not to scale!



0 Myr
0.1 Myr
1 Myr
10 Myr
30 Myr
200 Myr
e
0.0
0.1
0.2
0.3
0.4
1
2
3
4
a (AU)
Log(Water Mass Fraction)
-5
-4
-3
-2
-1.3



Beyond the frost line, water is a solid, so there are a lot of solids available

10 M_{Earth} objects can form quickly

Due to gravity, H/He gas, if present, is pulled on, too

Jupiter is 300 M_{Earth} of H/He gas pulled onto a 10-15 M_{Earth} core

Saturn is 85 M_{Earth} of H/He pulled onto a 10-15 M_{earth} core

Uranus/Neptune are several M_{Earth} of H/He pulled onto 15 M_{earth} cores

The Terrestrial Planet / Jovian Planet Connection

Both Terrestrial and Jovian planets form in the same way---the buildup of small planetesimals to form planets, but:

Jovian planets form quickly beyond the frost line, where a lot of solid material is available, while the H/He gas remains (less than 5 Myr)

Terrestrial planets form within the frost line, where rocks and iron are the only solids, and do not reach their final masses until after the gaseous disk is gone. (Tens of Myr)

The large satellites of Jupiter and Saturn formed in a "subnebula," a flattened disk around each giant planet, giving rise to a mini solar system

From stellar pulsations, one can determine that Kepler clearly sees the pole of the parent star, inclined by 45 degrees.

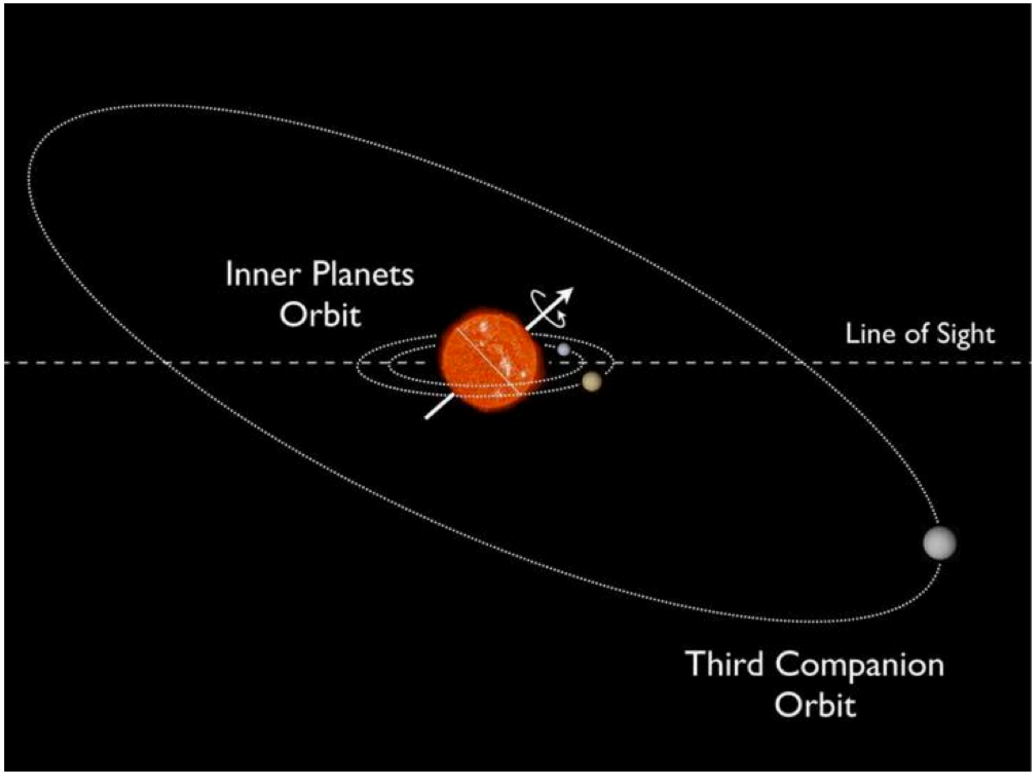
Two close-in planets, with their orbits well-aligned with each other, but mis-aligned with their star's equator

Radial velocity wobble of the parent star indicates a massive companion whose gravitational pull could potentially misalign the smaller planet orbits

Tilt-a-whirl planets throw astronomers for a loop

Alan Boyle, Science Editor, NBC News

Oct. 17, 2013 at 7:59 PM ET

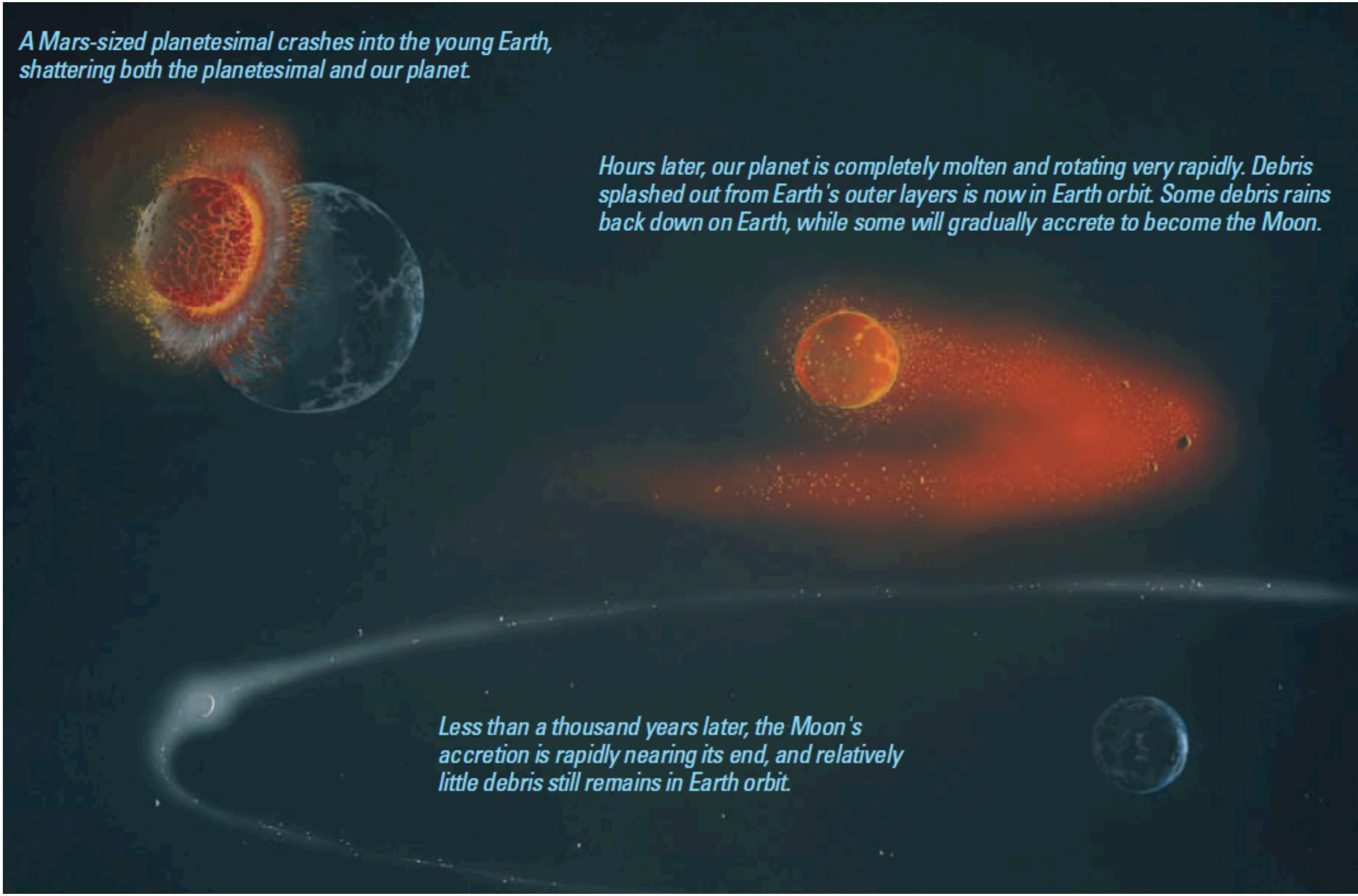


Daniel Huber / NASA Ames

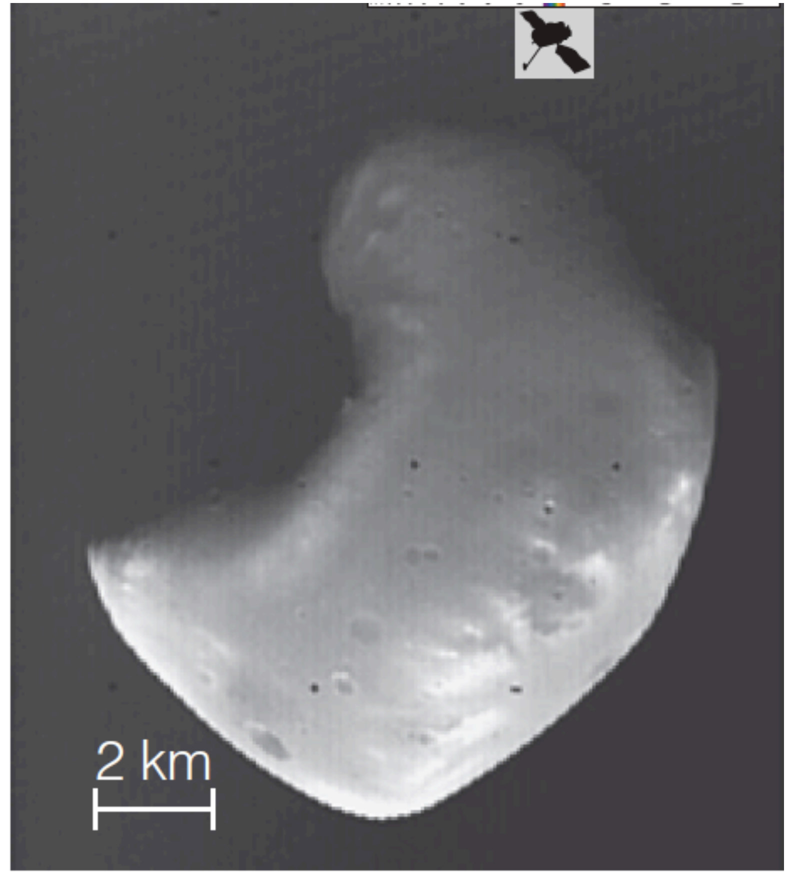
The Kepler-56 planetary system features two inner planets orbiting at a severe tilt to their host star - even though there's no closely orbiting "hot Jupiter" in the system.

Astronomers say they've found a bizarre star system where two of the planetary orbits are 45 degrees out of whack, but do just fine.

How did the Moon form?



a Phobos



b Deimos

The moons of Mars are asteroids the came from the asteroid belt.

Lines of evidence to support giant impact hypothesis:

1)The Moon's overall composition is similar to that of the Earth's crust. Lots of rock, but little iron

- Moon is mostly made up material from the surface of the Earth --- Earth's iron is mostly down in the core

2)Moon rocks are extremely depleted in "volatiles," the easy to vaporize materials, like water

- Stripped off material was so hot that only rocky/metal materials condensed to form solids in Earth's orbit

3) Earth has a mean density of 5.5 g/cm^3, but the moon has a density of only 3.3 g/cm^3. The moon lacks iron.
4) The moon has the same oxygen isotope composition as the Earth, whereas Mars rocks and meteorites from other parts of the solar system have different oxygen isotope compositions. This shows that the moon formed form material formed in Earth's neighborhood.

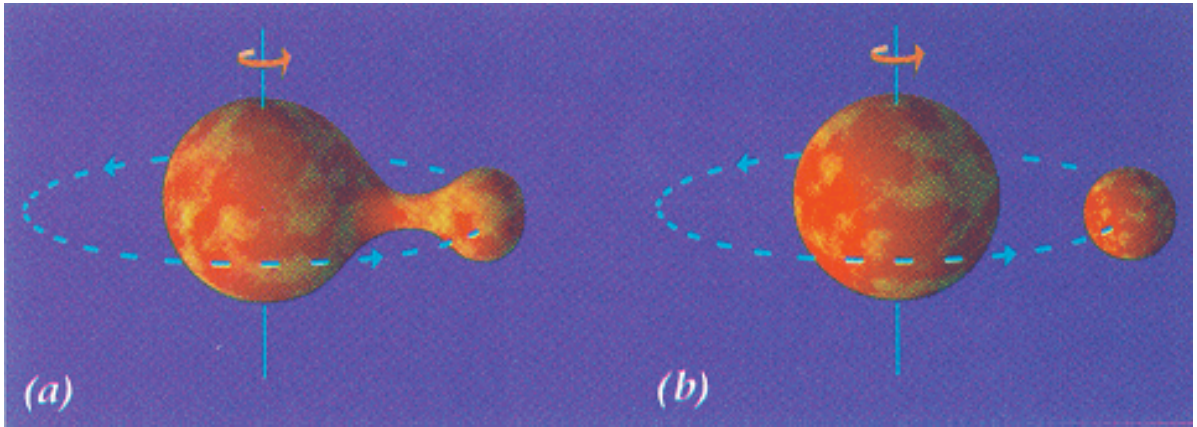
5)If a theory about lunar origin calls for a generic evolutionary process, it has a hard time explaining why other planets do not have similar moons. Our giant impact hypothesis had the advantage of invoking an event that might happen only to one or two planets out of nine.

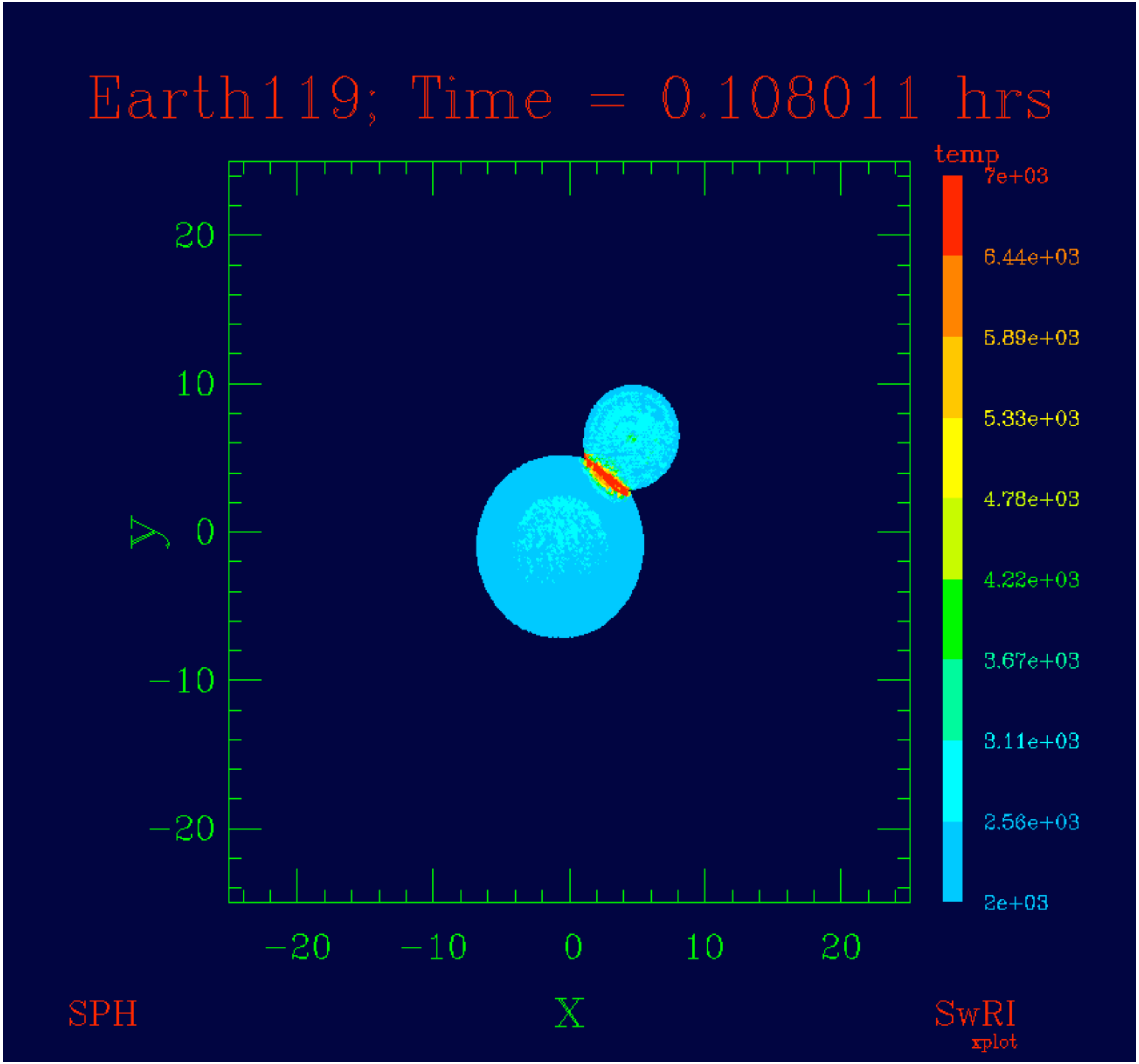
What were some earlier ideas?

1. The moon is a sister world that formed in orbit around Earth as the Earth formed. This theory failed because it could not explain why the moon lacks iron.

2. The moon formed somewhere else in the solar system where there was little iron, and then was captured into orbit around Earth. This failed when lunar rocks showed the same isotope composition as the Earth.

3. Early Earth spun so fast that it spun off the moon. This idea would produce a moon similar to Earth's mantle, but it failed when analysis of the total angular momentum and energy involved indicated that the present Earth-moon system could not form in this way.

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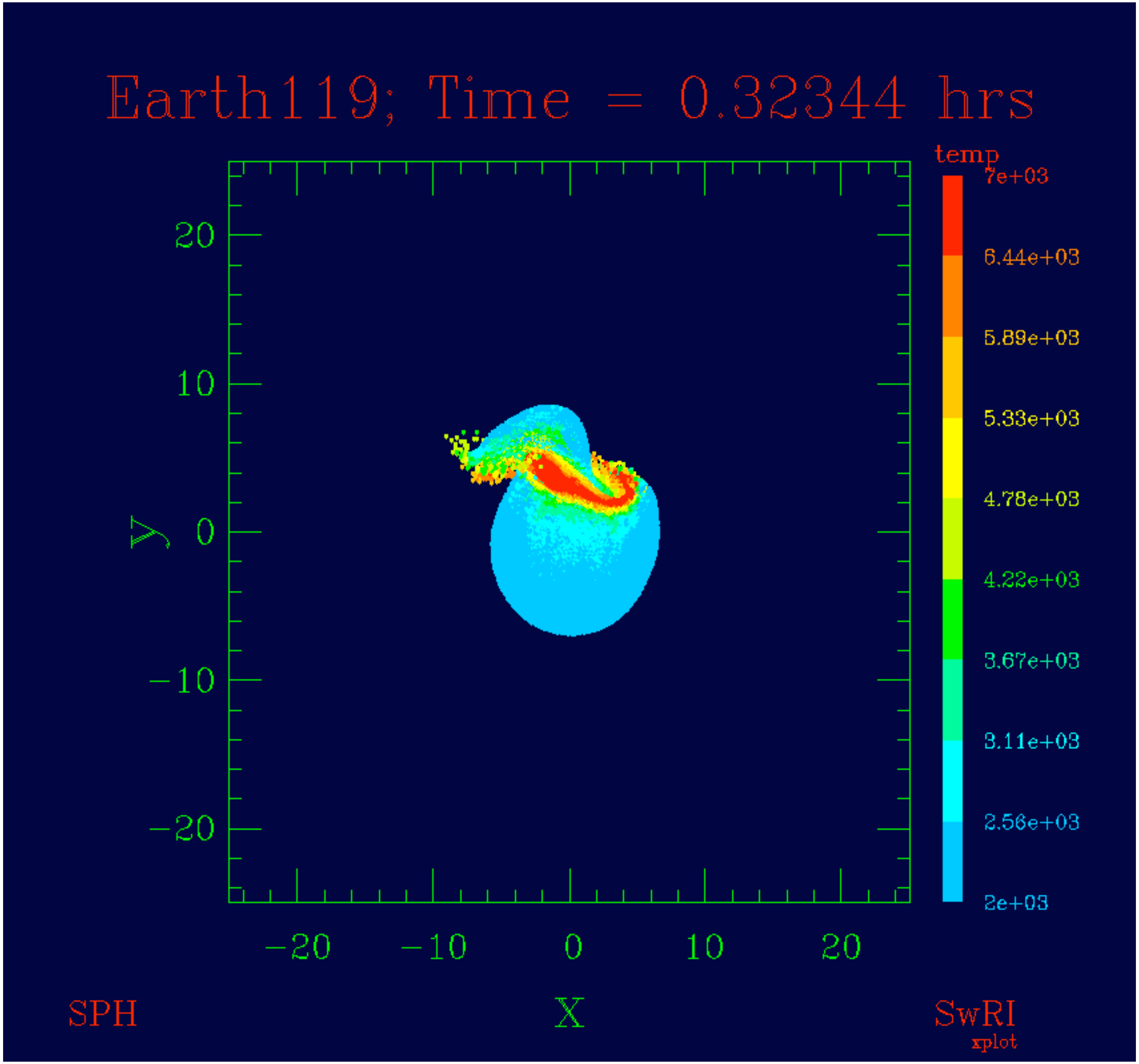
7e+03
6.44e+03
5.89e+03
5.33e+03
4.78e+03
4.22e+03
3.67e+03
3.11e+03
2.56e+03
2e+03
20
10
0
−10
−20
y
−20
−10
0
10
20
X
SPH
SwRI
xplot



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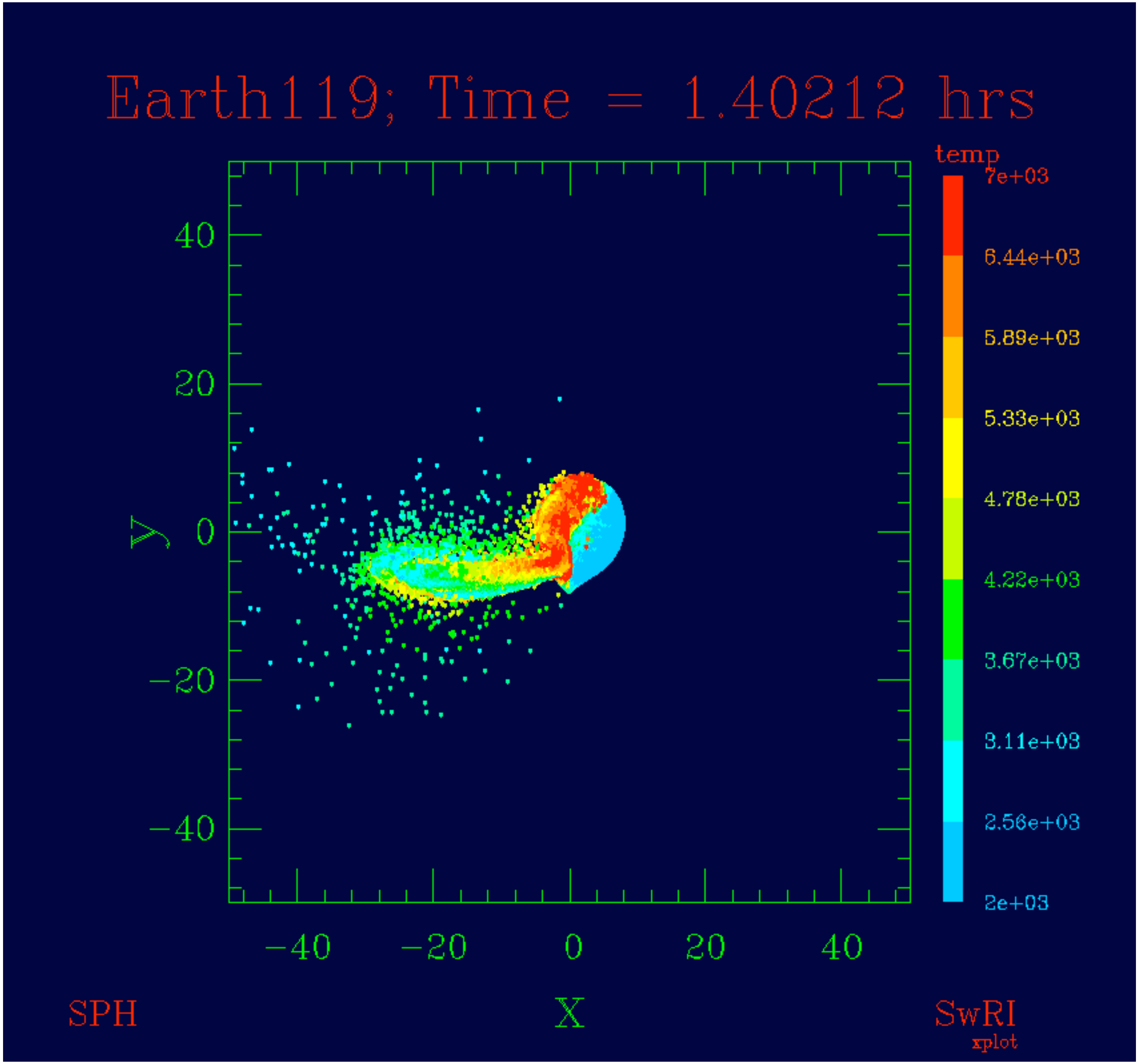
5.33e+03
4.78e+03
4.22e+03
3.67e+03
3.11e+03
2.56e+03
2e+03
20
10
0
−10
−20
y
−20
−10
0
10
20
X
SPH
SwRI
xplot



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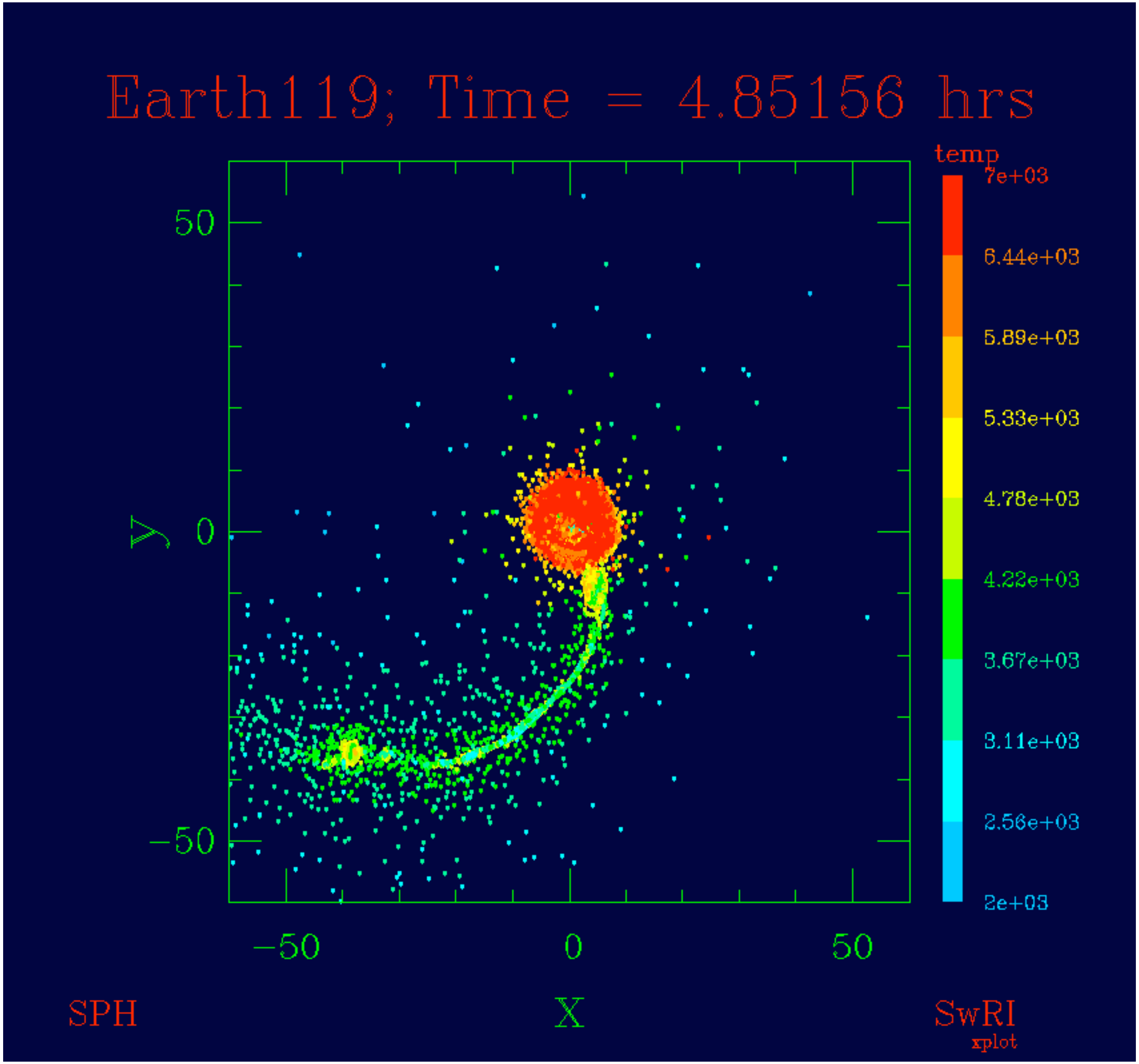
3.67e+03
3.11e+03
2.56e+03
2e+03
40
20
0
−20
−40
y
−40
−20
0
20
40
X
SPH
SwRI
xplot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5.89e+03
5.33e+03
4.78e+03
4.22e+03
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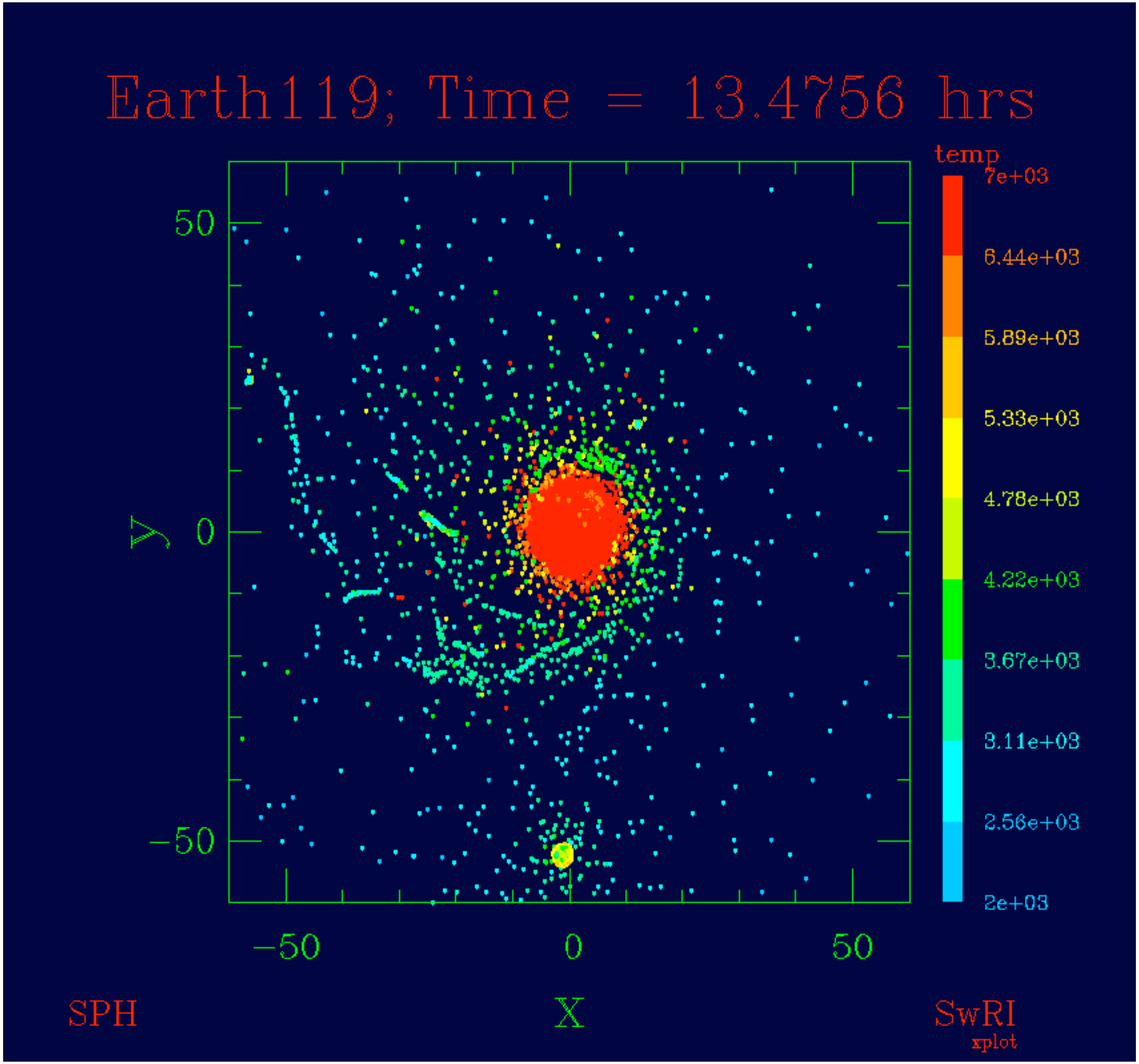
3.11e+03
2.56e+03
2e+03
50
0
−50
y
X
SPH
SwRI
xplot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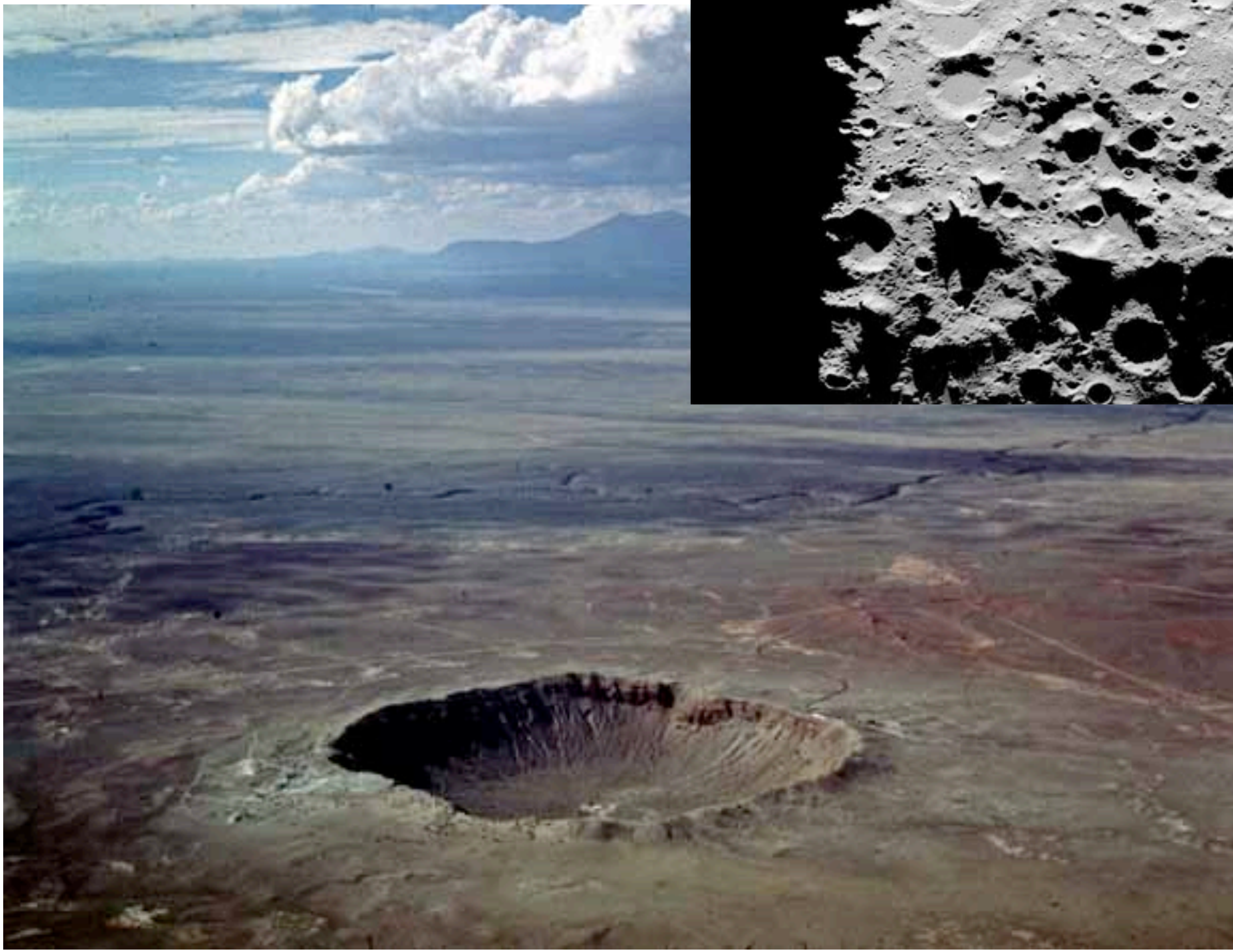
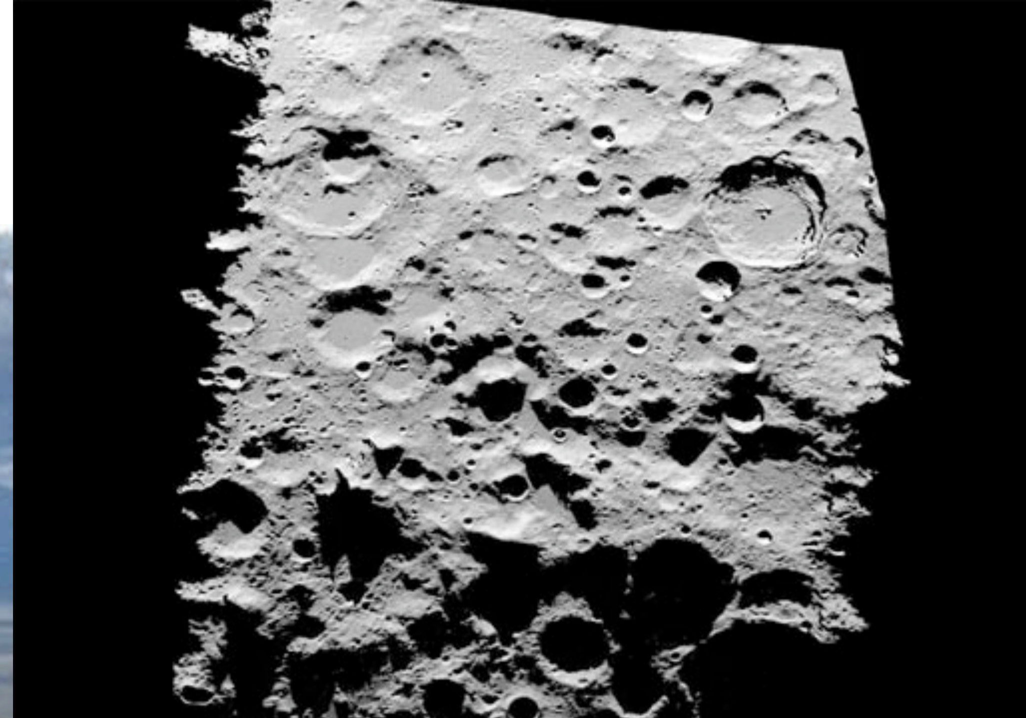
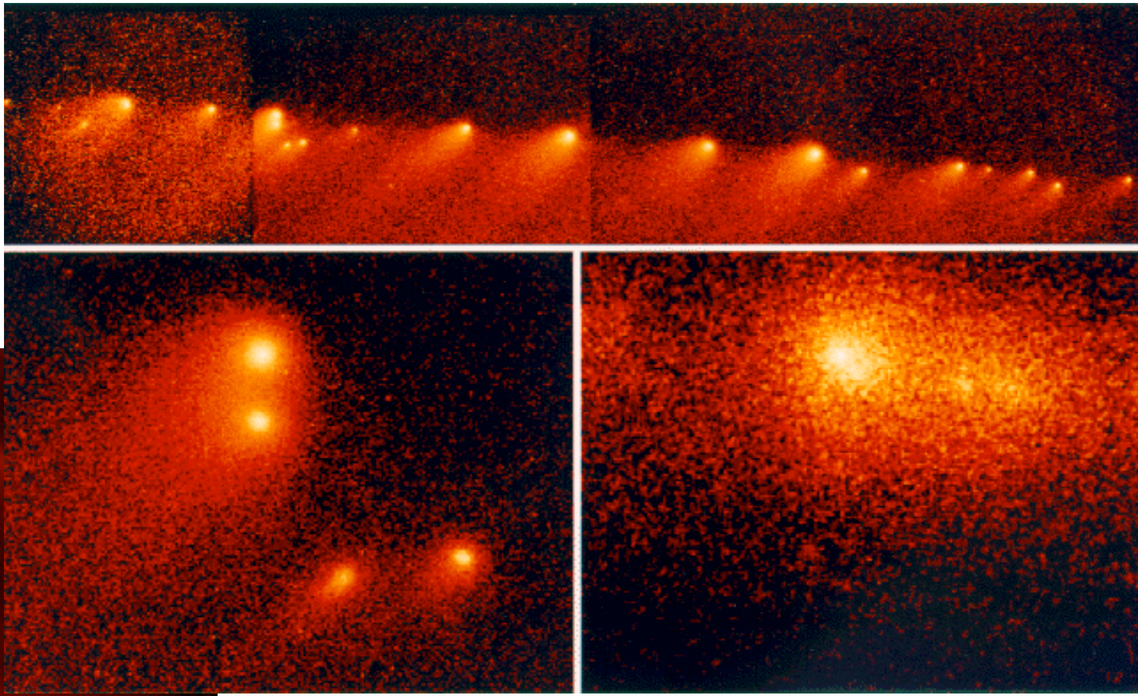
5.89e+03
5.33e+03
4.78e+03
4.22e+03
3.67e+03
3.11e+03
2.56e+03
2e+03
y
50
0
−50
−50
0
50
X
SPH
SwRI
xplot

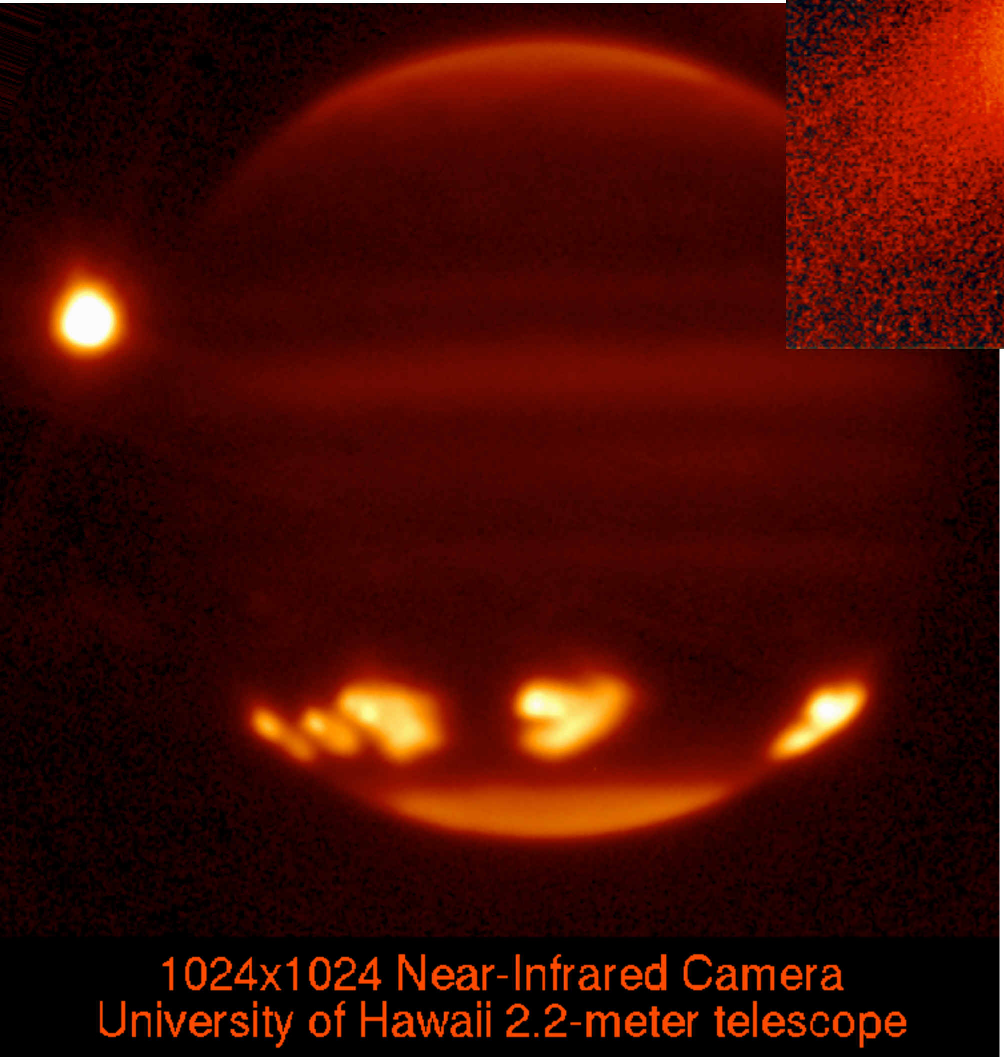
Impacts Happen!



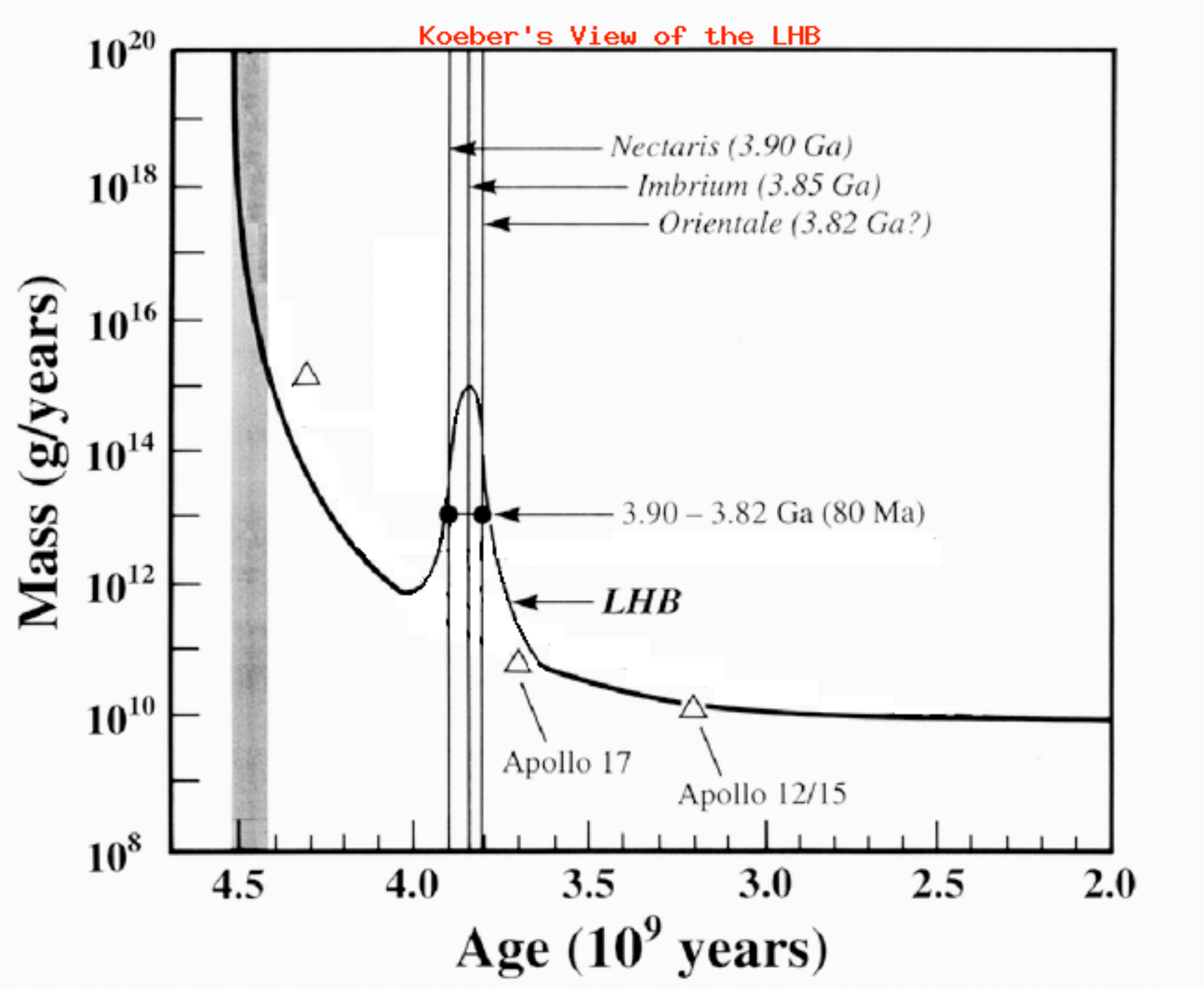


Shoemaker-Levy 9
into Jupiter, 1994





Impacts Happen: The Late Heavy Bombardment



From age dating of rocks, there seems to have been a spike in the impact rate in the inner solar system about 3.9 Gyr ago

Why could the jovian planets grow to be much larger than the terrestrial planets?

A. They were farther from the Sun, where gravity was weaker.
B. They formed beyond the *frost line* where ices could condense, so they included hydrogen compounds.
C. They were far enough from the Sun to escape the *heavy bombardment* that battered the early solar system.

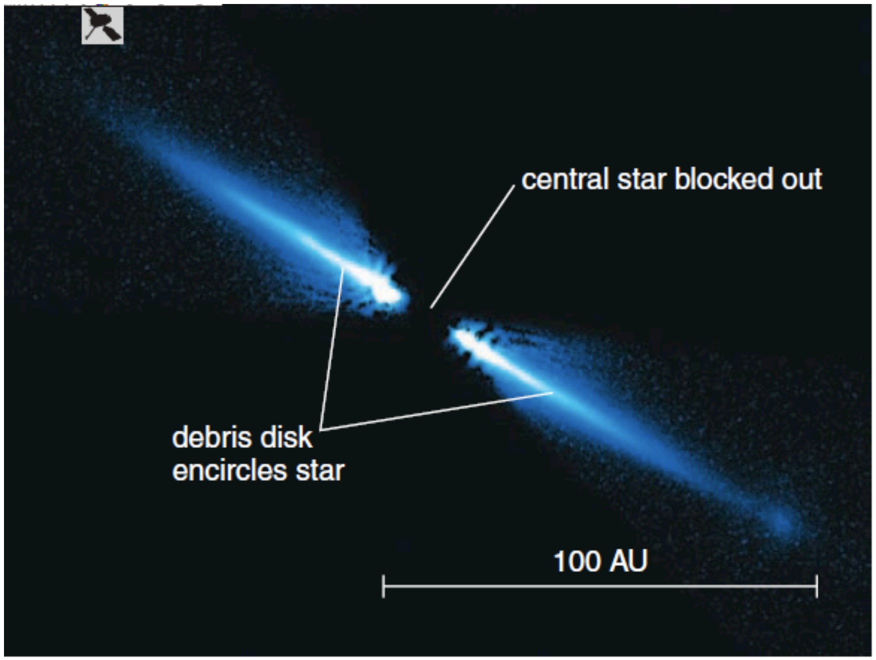
Why could the jovian planets grow to be much larger than the terrestrial planets?

A. They were farther from the Sun, where gravity was weaker.

B. They formed beyond the frost line where ices could condense, so they included hydrogen compounds.

C. They were far enough from the Sun to escape the *heavy bombardment* that battered the early solar system.

We can see “Debris Disk
Larger versions of our K

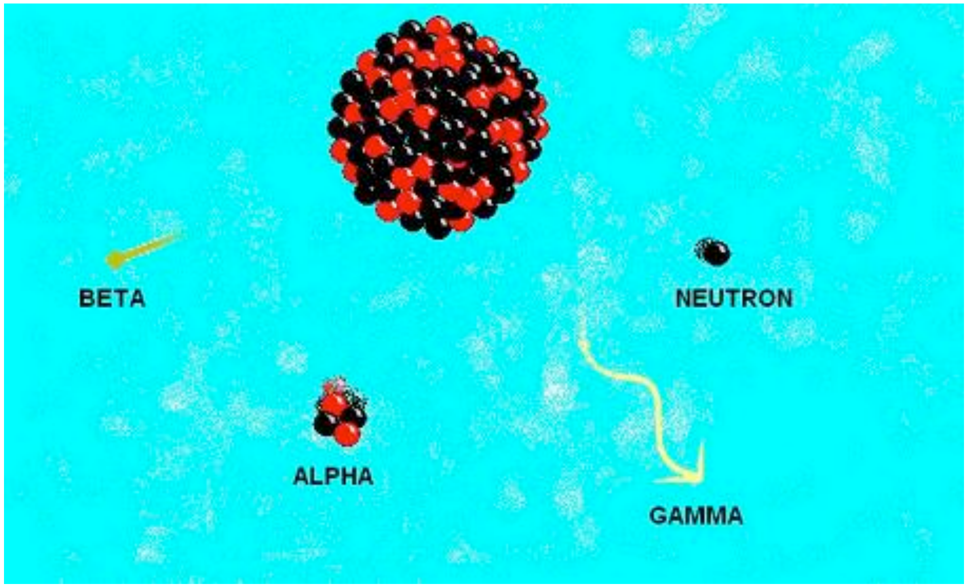


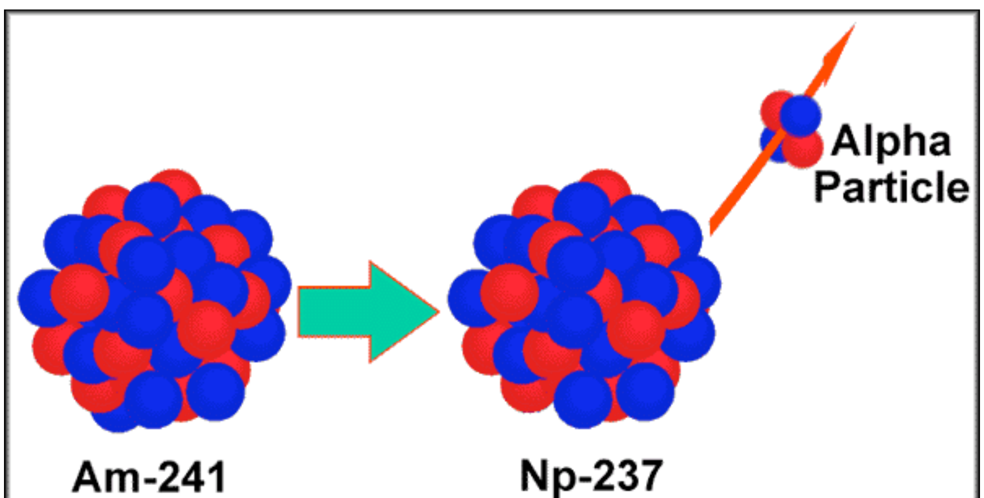
a This edge-on view of the disk around the star AU Microscopii confirms its flattened shape.

•Asteroids and comets are the lef
into forming planets

•Collisions of asteroids/asteroids
lot of “dust,” which can be easily

Age Dating: Radioactive Decay





Decrease of *A* and *Z*, to find a more stable configuration of the nucleus

Age Dating: Radioactive Decay

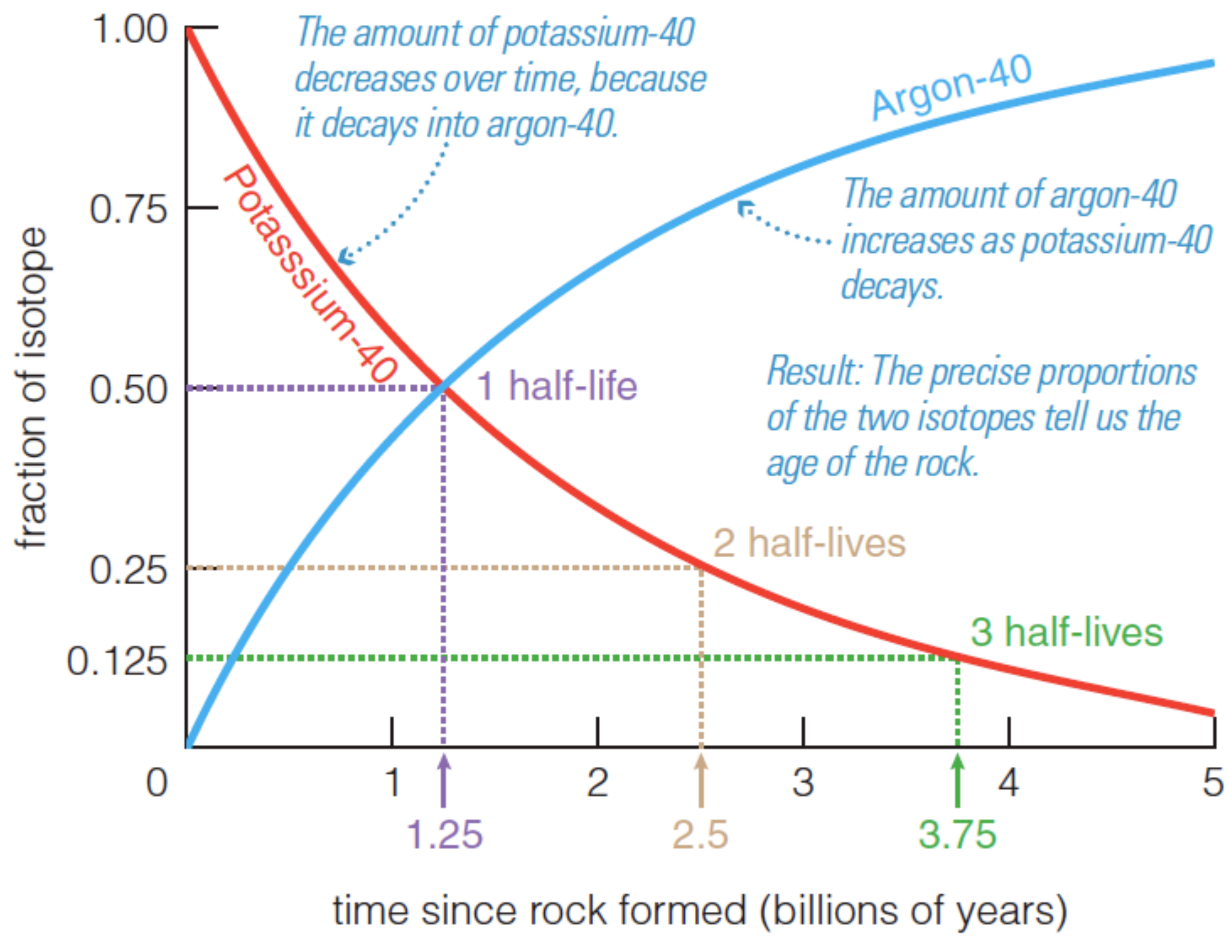


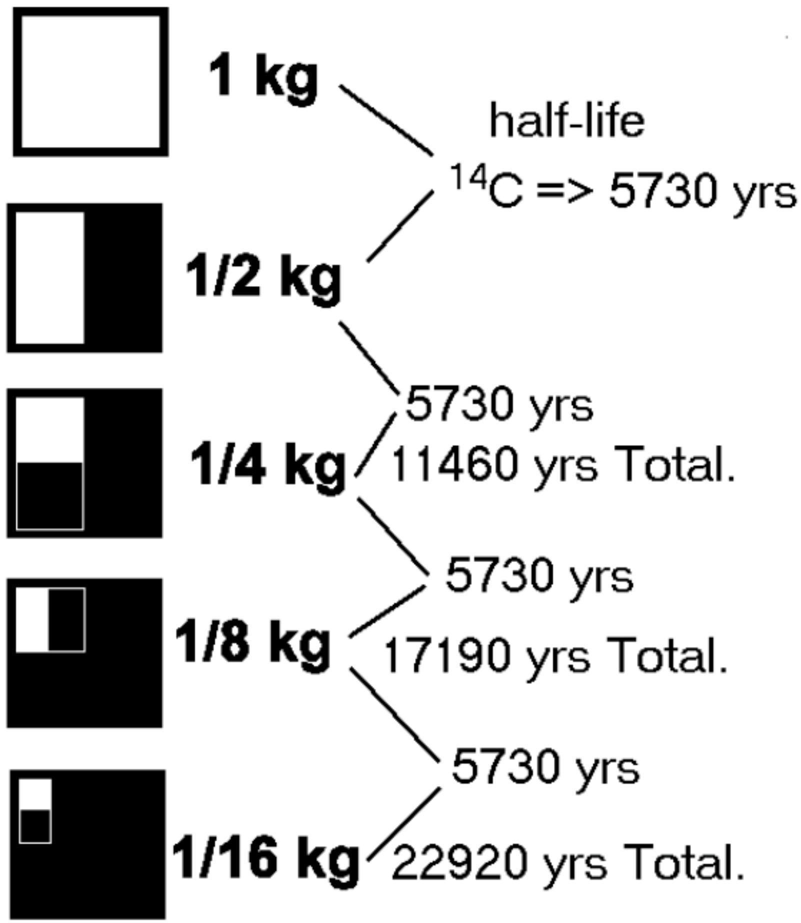
FIGURE 8.14 Potassium-40 is radioactive, decaying into argon-40 with a half-life of 1.25 billion years. The red line shows the decreasing amount of potassium-40, and the blue line shows the increasing amount of argon-40. The remaining amount of potassium-40 drops by half with each successive half-life.

But how much was their to begin with?

We can appeal to chemistry and physics:

•Argon is a noble gas that does not condense. If you see any in a rock sample, it came from decay of potassium-40

•In other rocks, experiments show that lead does not enter into some minerals. So in some cases for specific rocks, all lead must be due to decay of uranium (age dating of moon's surface, for instance)

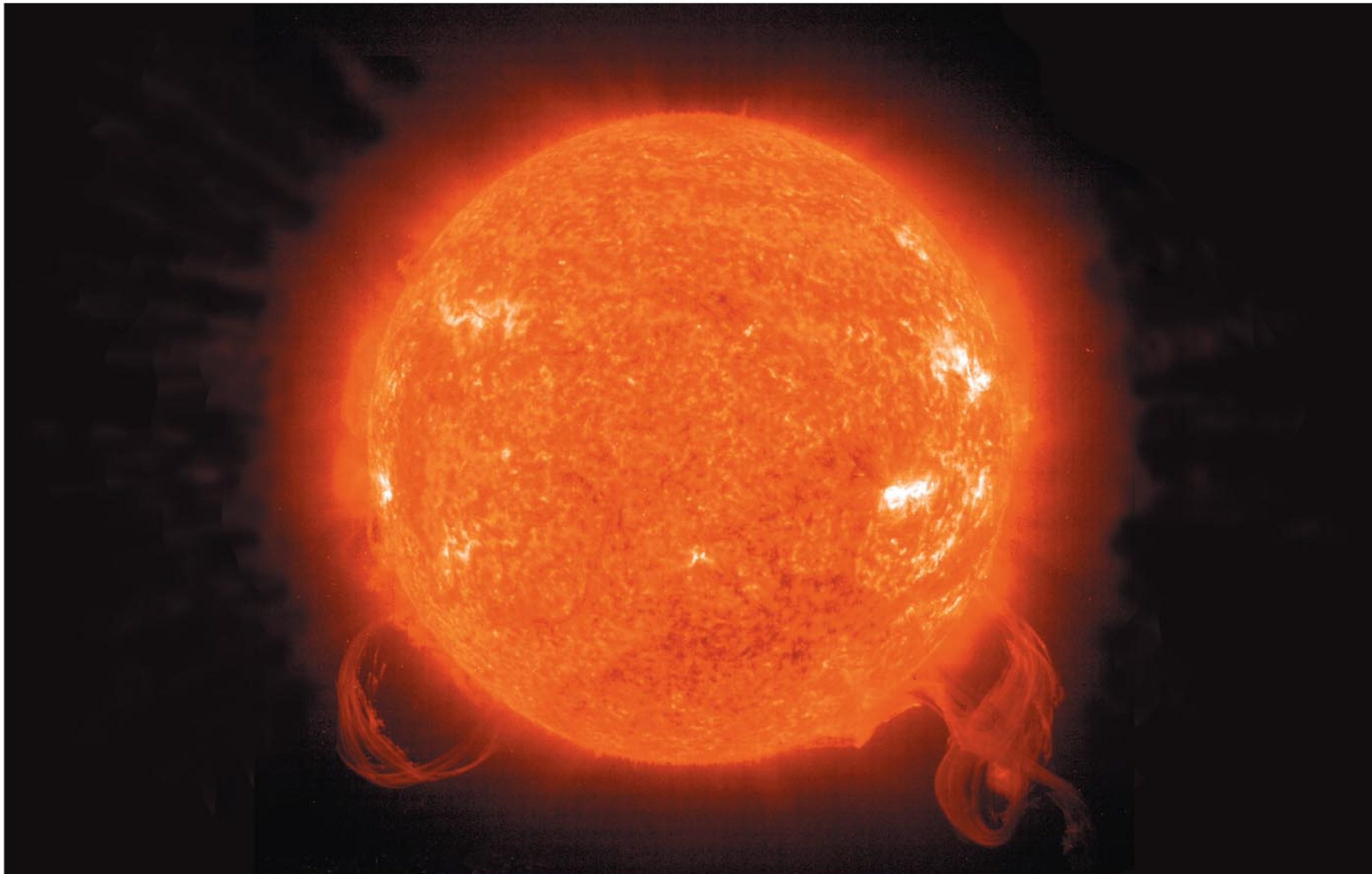


$$\frac{\text{current amount}}{\text{original amount}} = \left(\frac{1}{2}\right)^{t/t_{\text{half}}}$$

$$t = t_{\text{half}} \times \frac{\log_{10}\left(\frac{\text{current amount}}{\text{original amount}}\right)}{\log_{10}\left(\frac{1}{2}\right)}$$

U 238: $4.47\text{x}10^{9}$ years
Th 234: 24.1 days
He 4: Stable
Pa 234: 6.7 hours
C 11: 20.3 minutes
B 11: stable
U 235: $7.04\text{x}10^{8}$years
Xe 140: 13.6 seconds
Po 212: 299 nanoseconds
Se 82: $1.3\text{x}10^{20}$ years

Chapter 14
Our Star

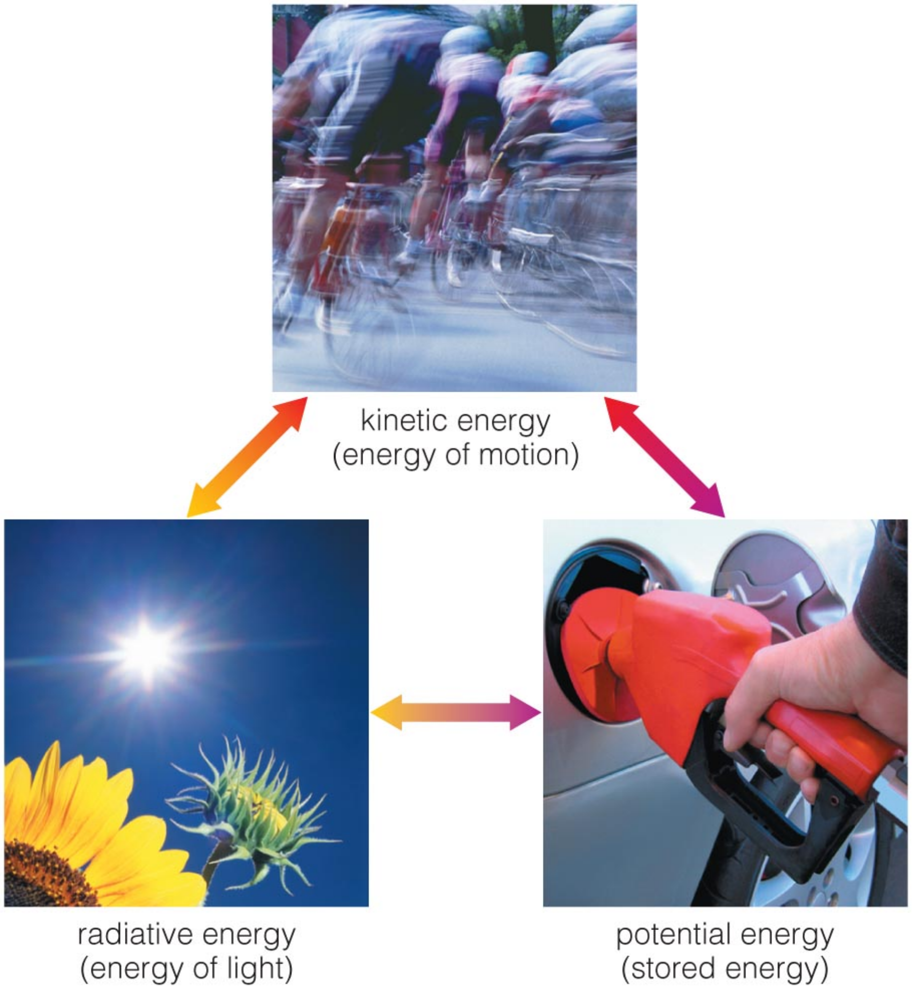


Basic Types of Energy

- Kinetic (motion)
- Radiative (light)
- Potential (stored)

Energy can change type, but cannot be created or destroyed.

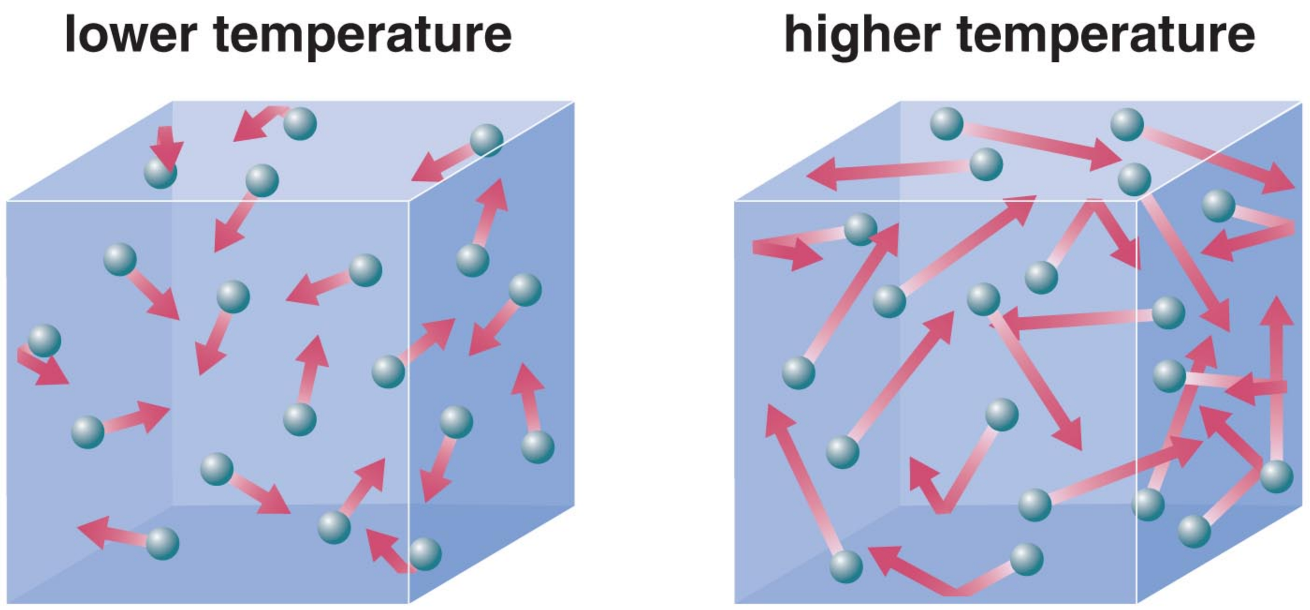
Energy can be converted from one form to another.



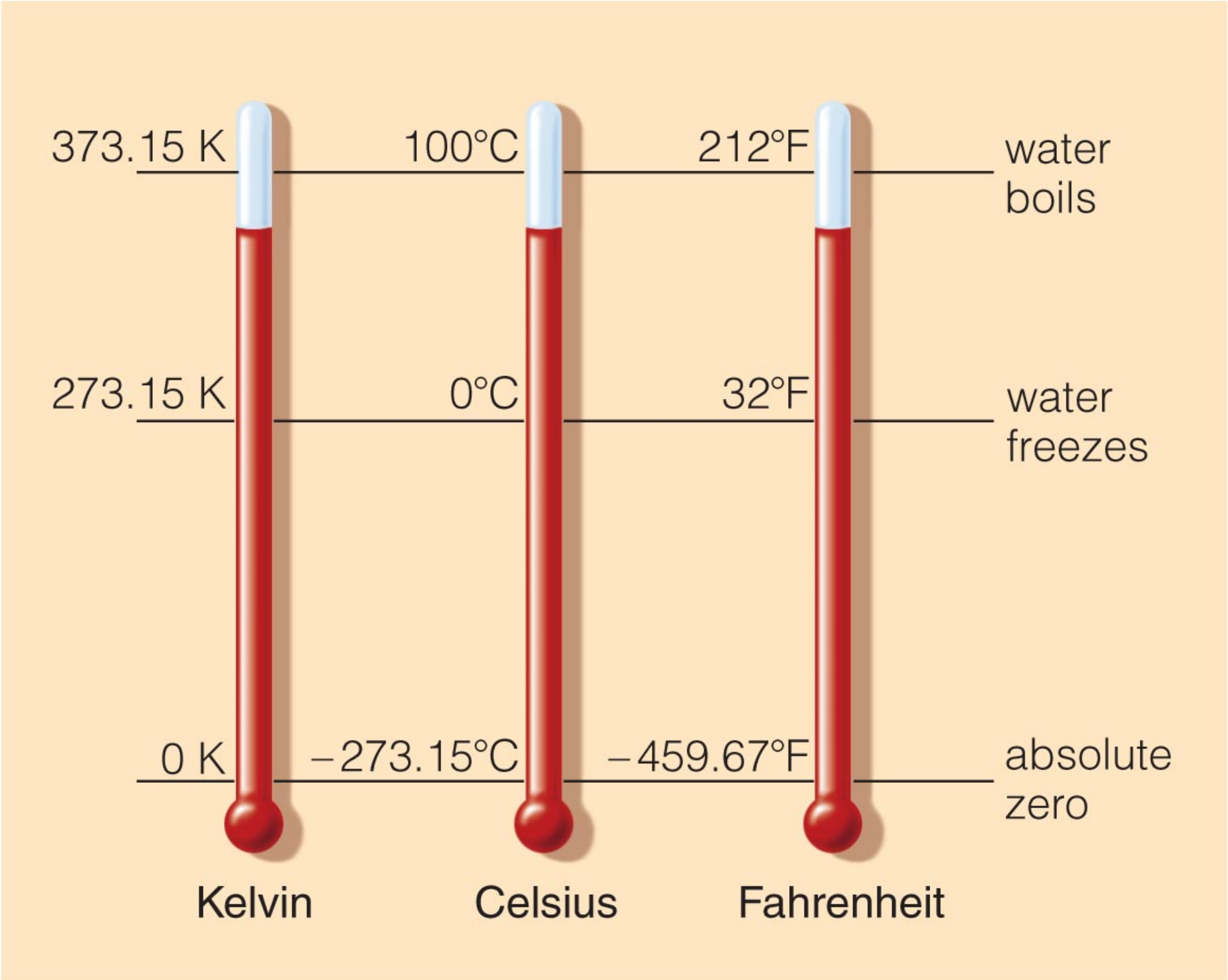
Thermal Energy:

the collective kinetic energy of many particles
(for example, in a rock, in air, in water)

Thermal energy is related to temperature but it is NOT the same.
Temperature is the *average* kinetic energy of the many particles in a substance.

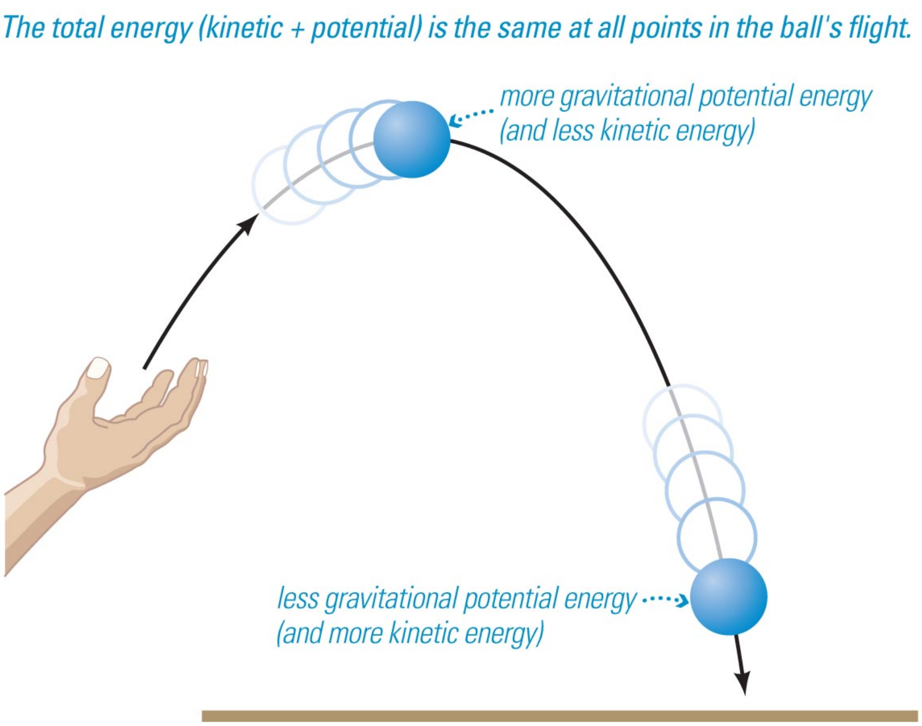


Temperature Scales



Gravitational Potential Energy

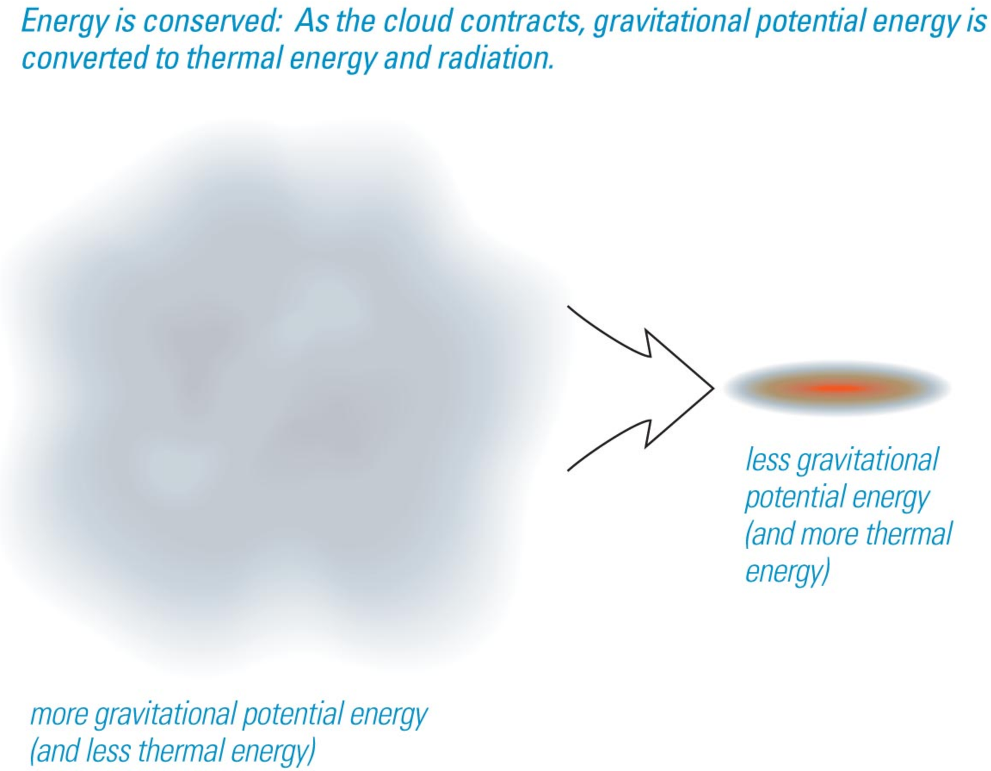
- On Earth, depends on:
  - object's mass (m)
  - strength of gravity (g)
  - distance object could potentially fall



Gravitational Potential Energy

- In space, an object or gas cloud has more gravitational energy when it is spread out than when it contracts.

⇒A contracting cloud converts gravitational potential energy to thermal energy.

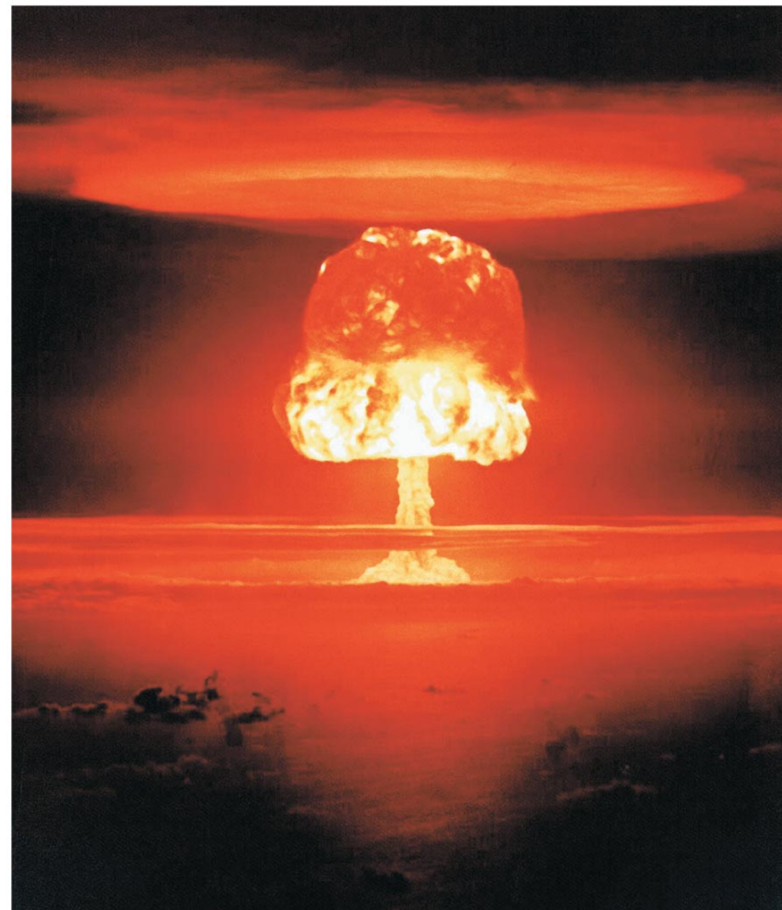


Mass-Energy

Mass itself is a form of potential energy:

$$E = mc^2$$

- A small amount of mass can release a great deal of energy (for example, an H-bomb).
- Concentrated energy can spontaneously turn into particles (for example, in particle accelerators).



Conservation of Energy

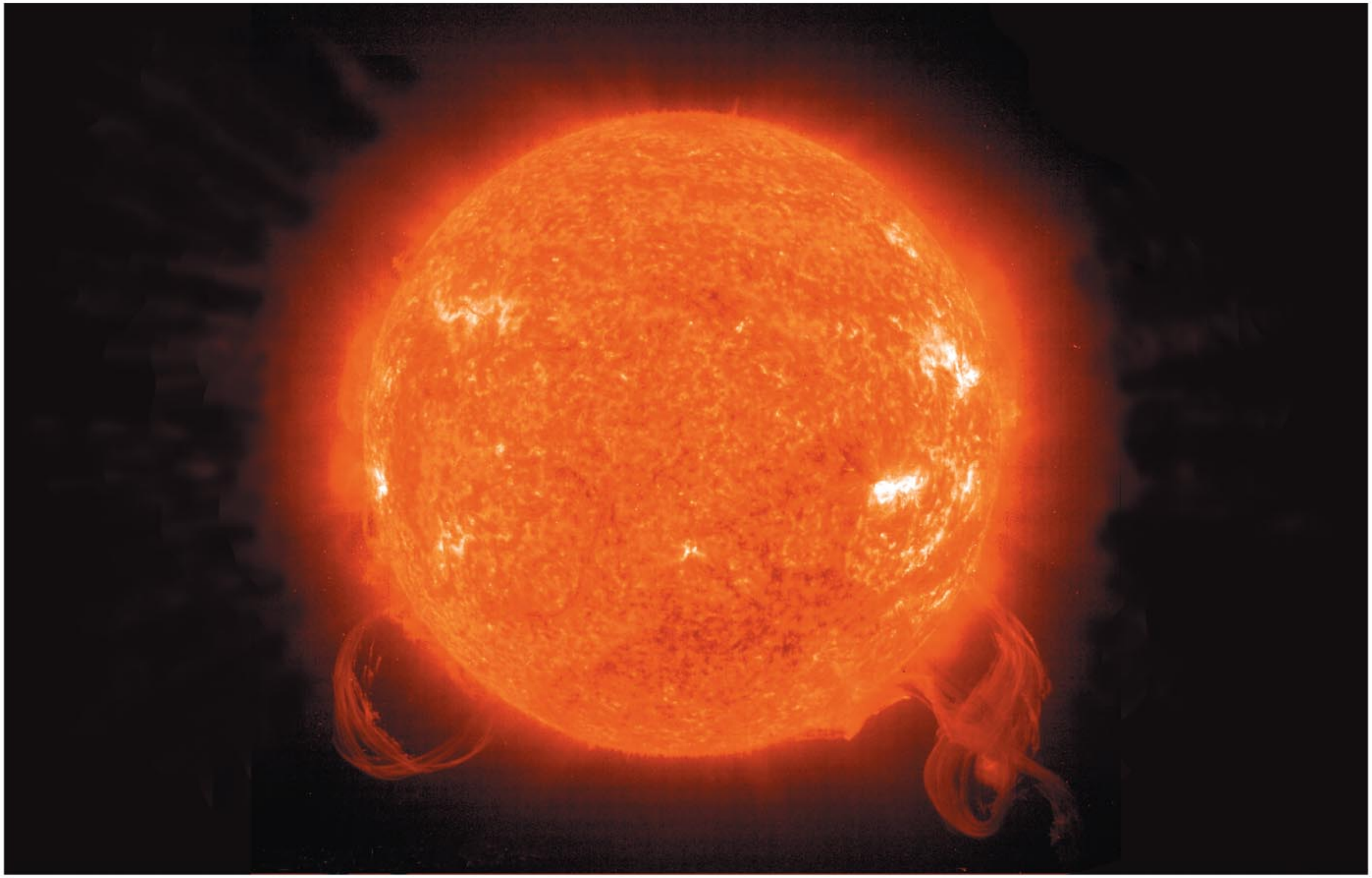
- Energy can be neither created nor destroyed.
- It can change form or be exchanged between objects.
- The total energy content of the universe was determined in the Big Bang and remains the same today.

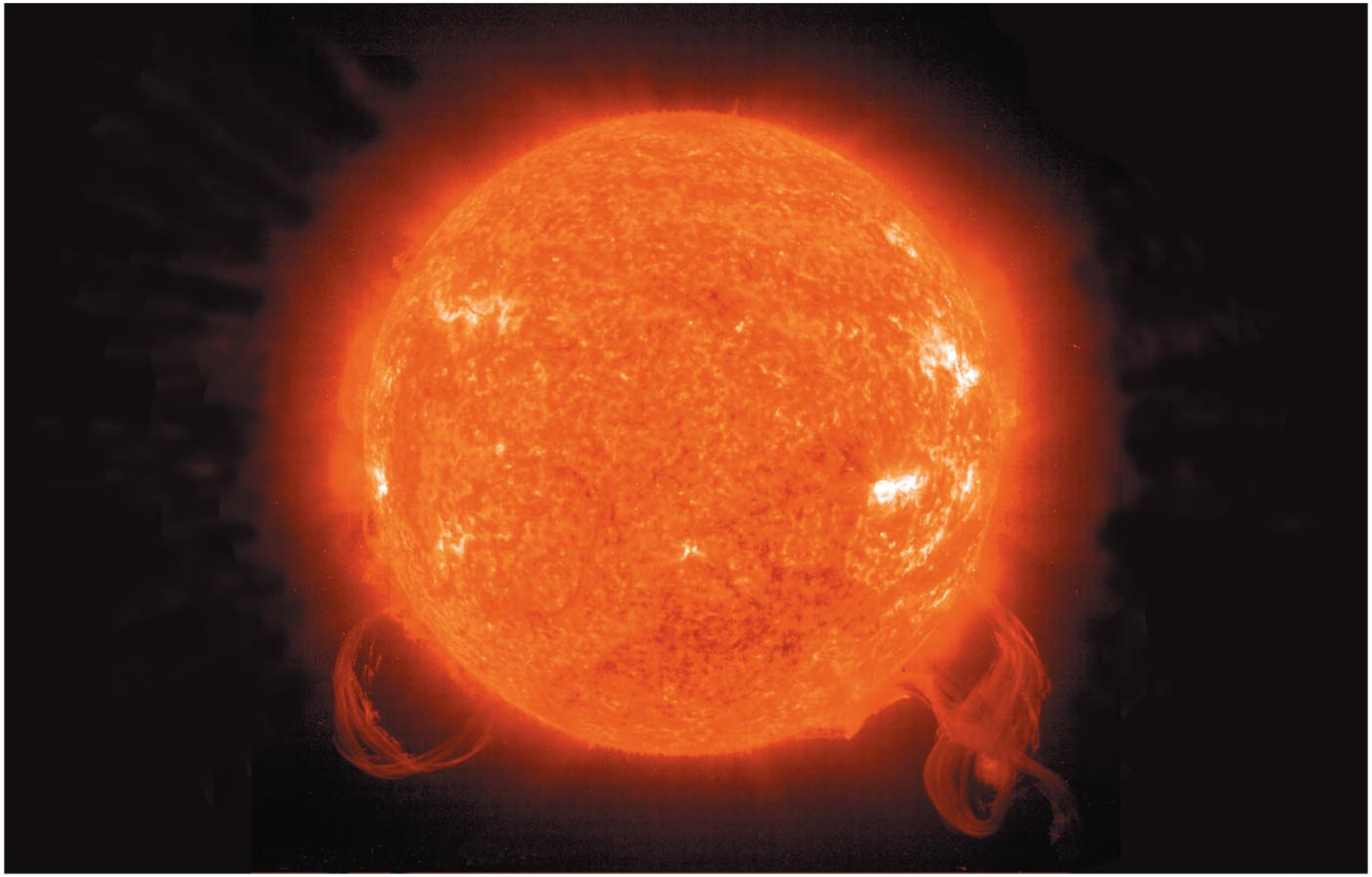
14.1 A Closer Look at the Sun

Our goals for learning:

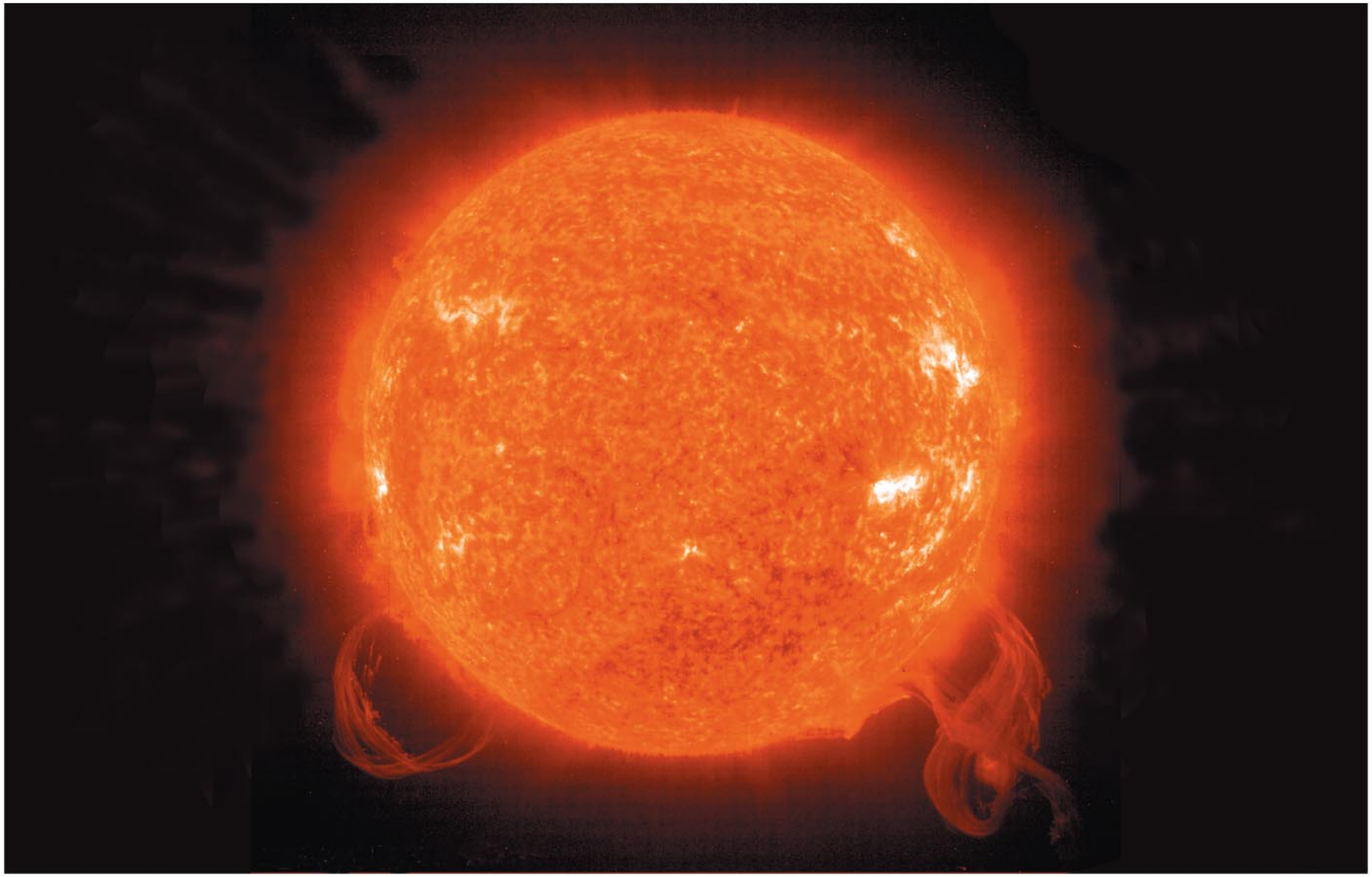
- Why was the Sun's energy source a major mystery?
- Why does the Sun shine?
- What is the Sun's structure?

Why was the Sun's energy source a major mystery?



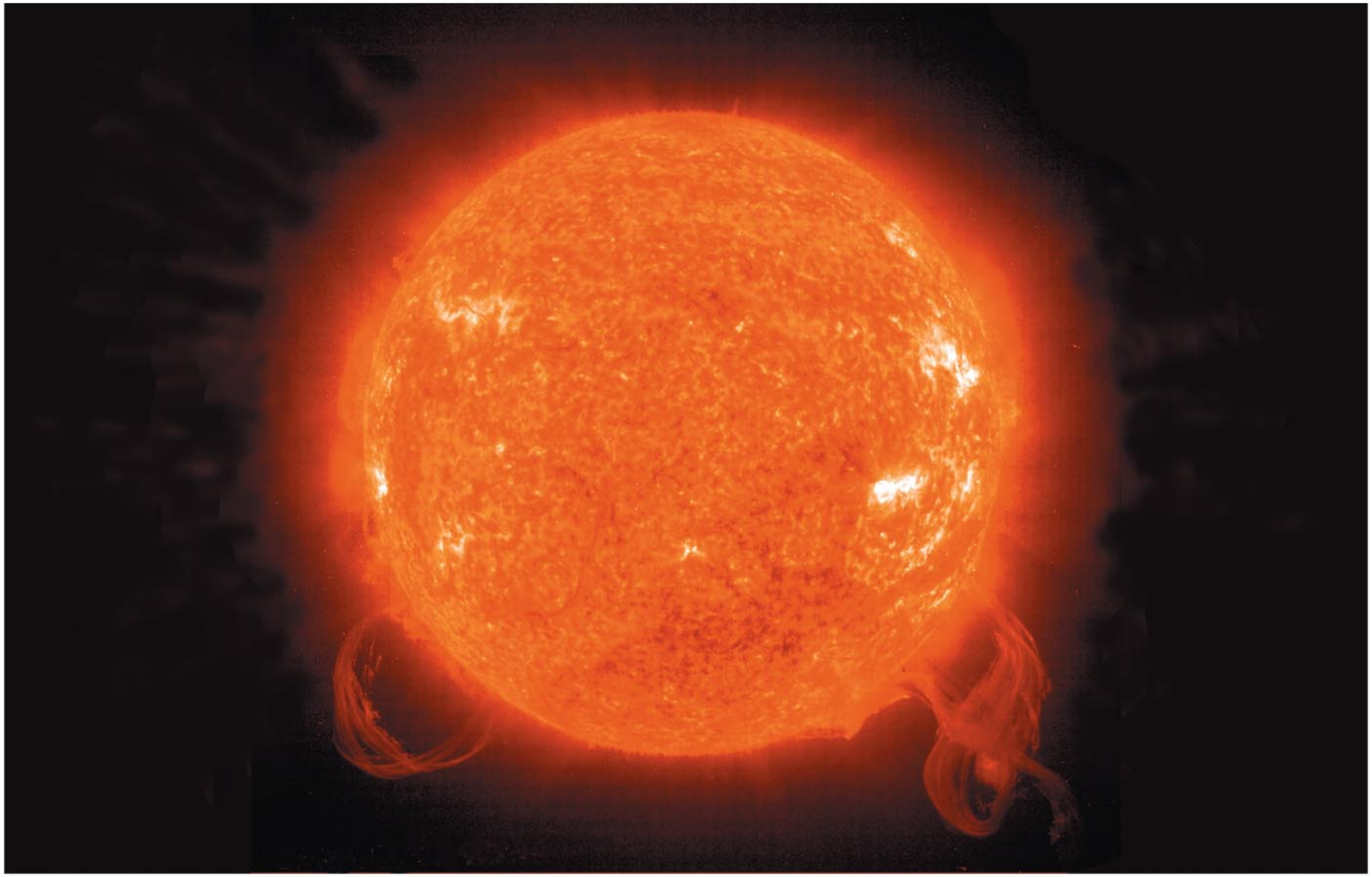


Is it on FIRE?



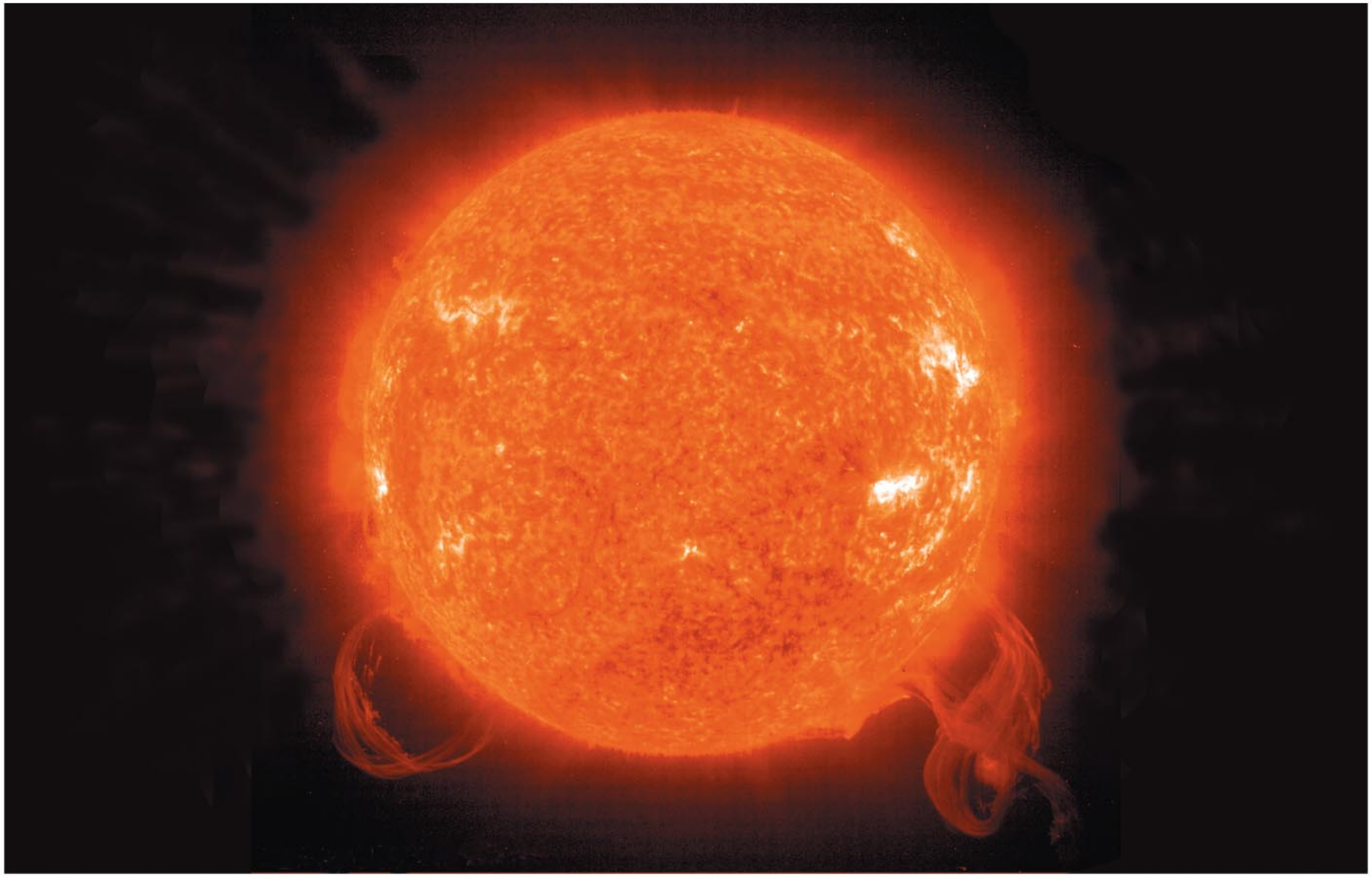
Is it on FIRE?

$$\frac{\text{Chemical energy content}}{\text{Luminosity}} \sim 10{,}000 \text{ years}$$

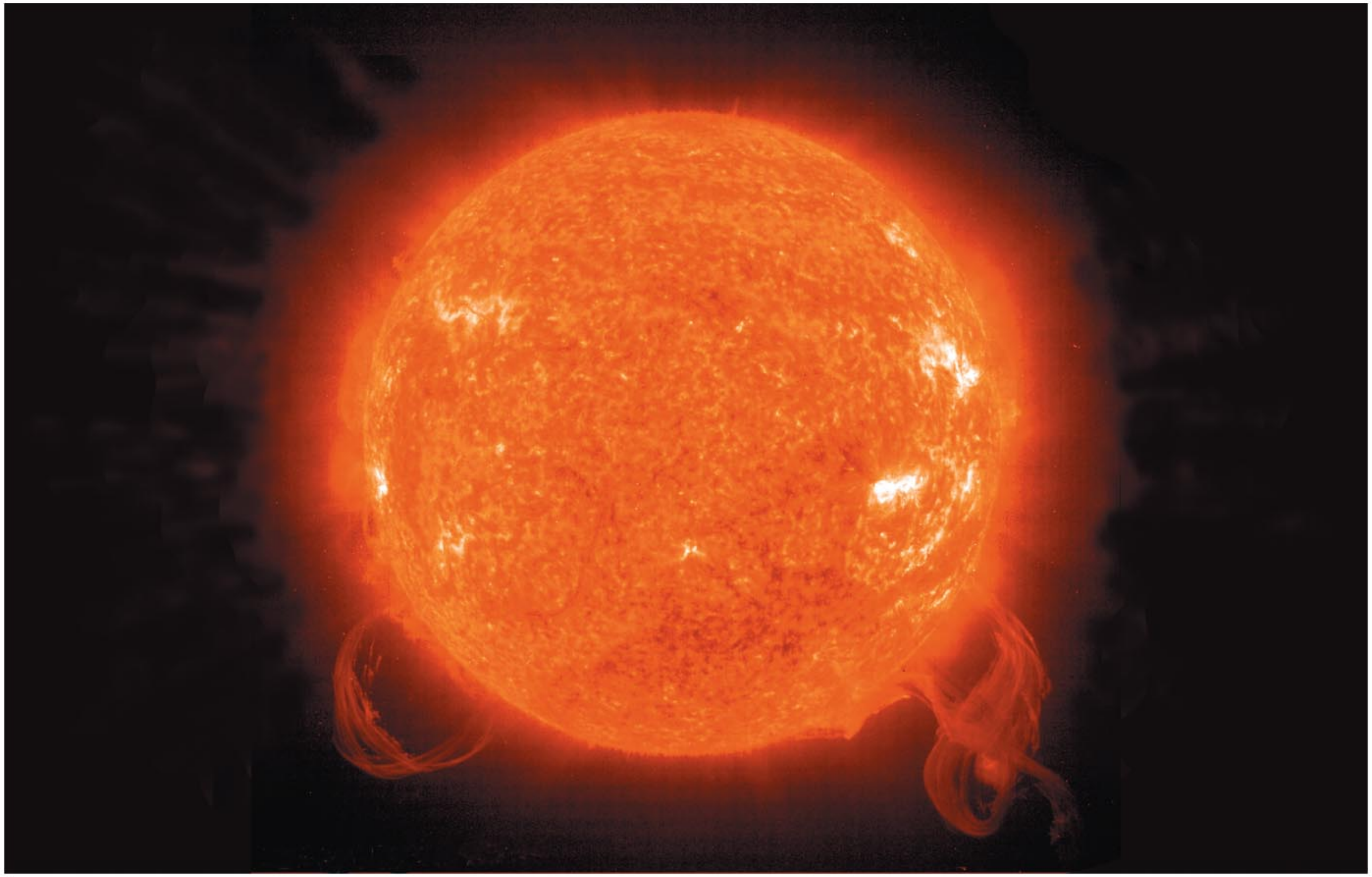


Is it on FIRE? … NO!

$$\frac{\text{Chemical energy content}}{\text{Luminosity}} \sim 10{,}000 \text{ years}$$



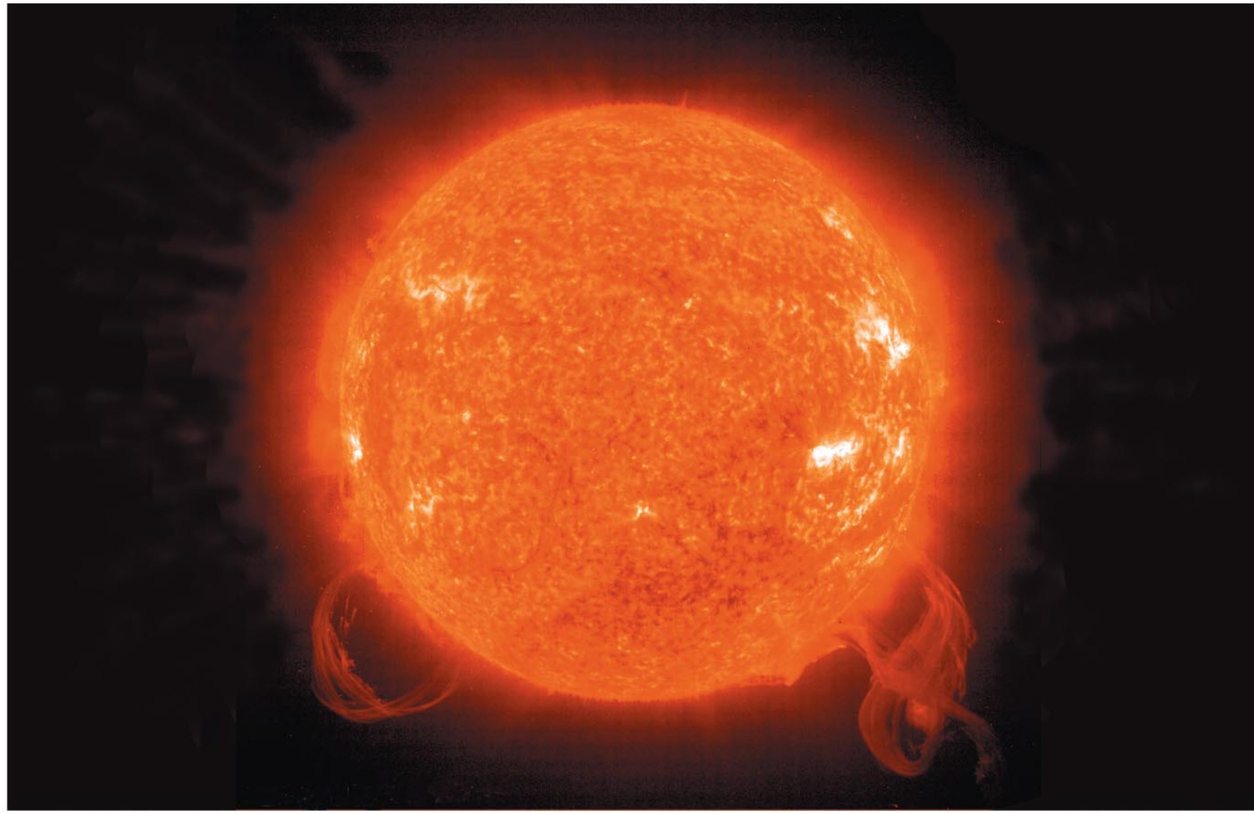
Is it CONTRACTING?



Is it CONTRACTING?

$$\frac{\text{Gravitational potential energy}}{\text{Luminosity}} \sim 25 \text{ million years}$$

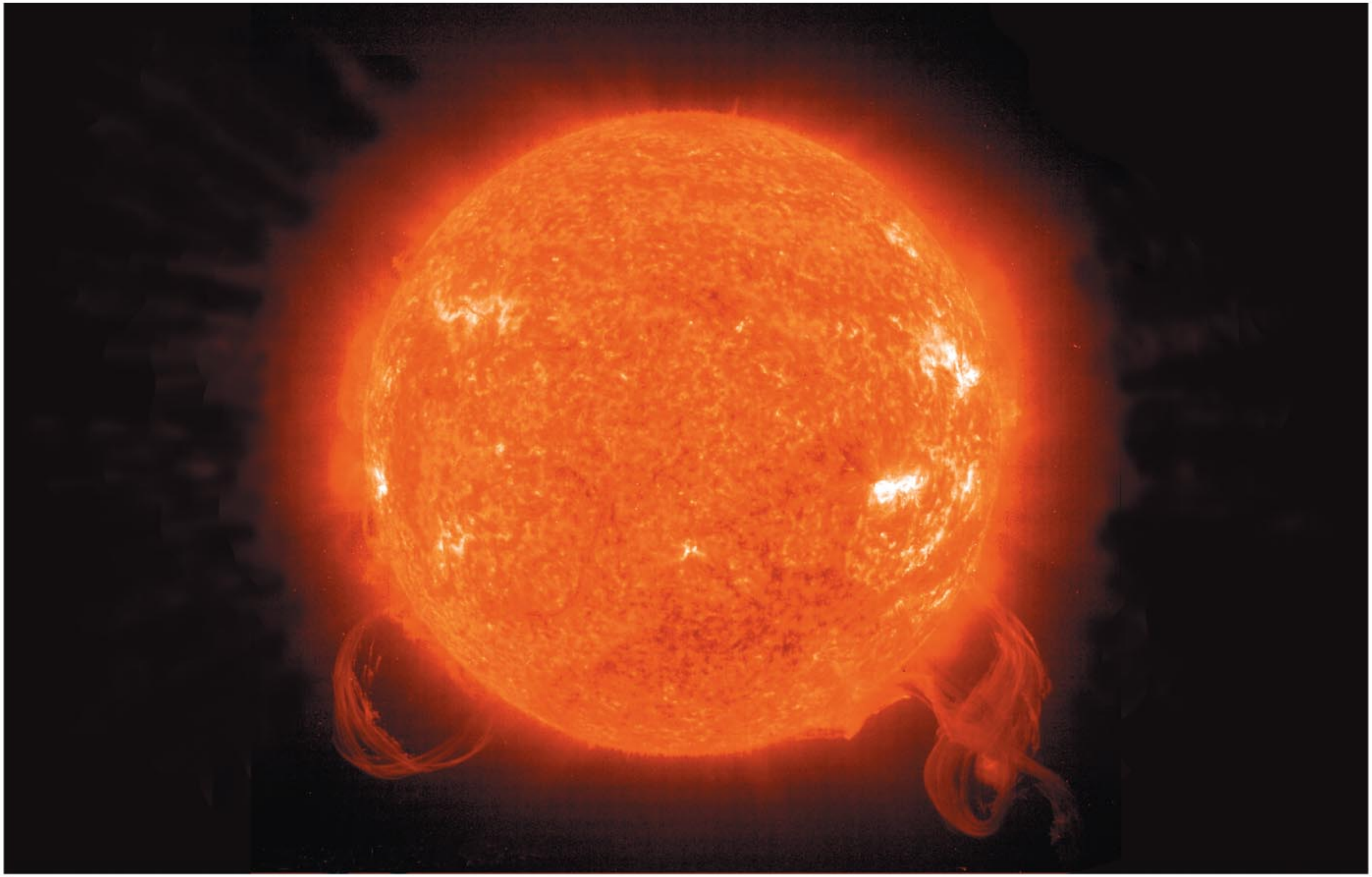
This was one of the great scientific controversies of the late 1800's. Geologists were finding evidence that the Earth was at least 1 Gyr old, but the physicists showed that was *clearly impossible*, as the Sun was only 25 Myr old.



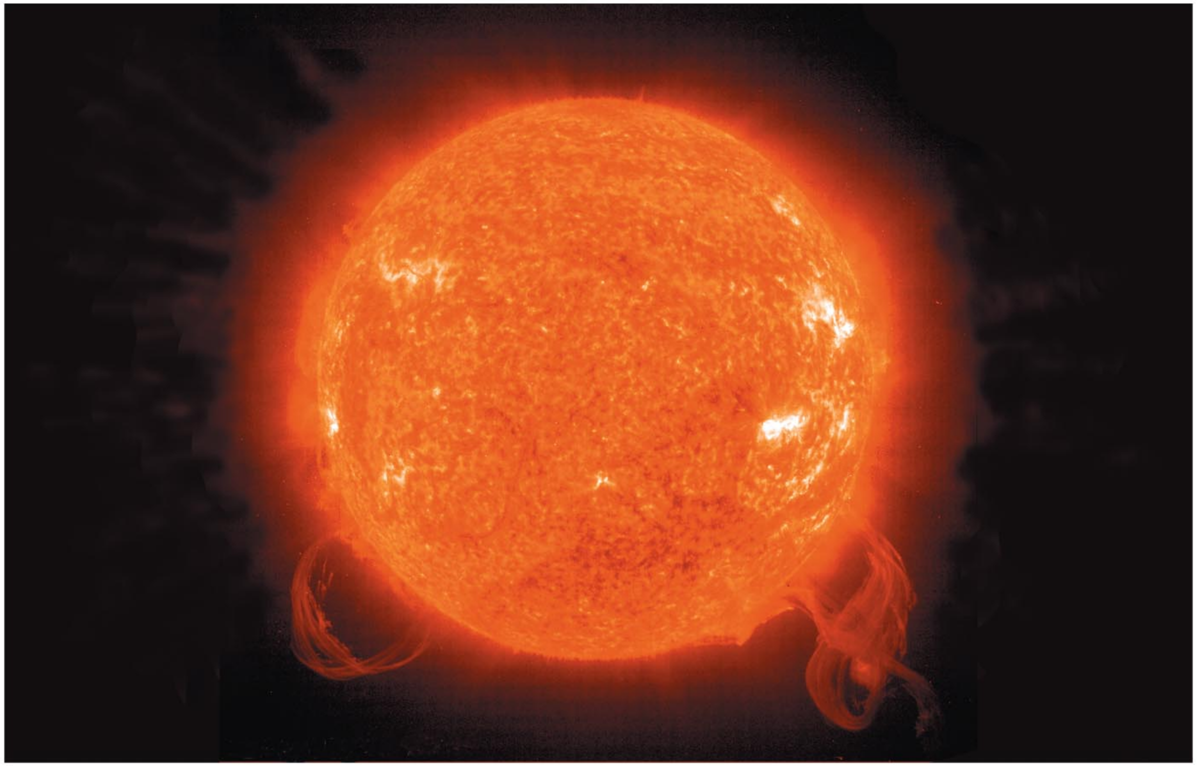
Is it CONTRACTING? … NO!

$$\frac{\text{Gravitational potential energy}}{\text{Luminosity}} \sim 25 \text{ million years}$$

Why does the Sun shine?

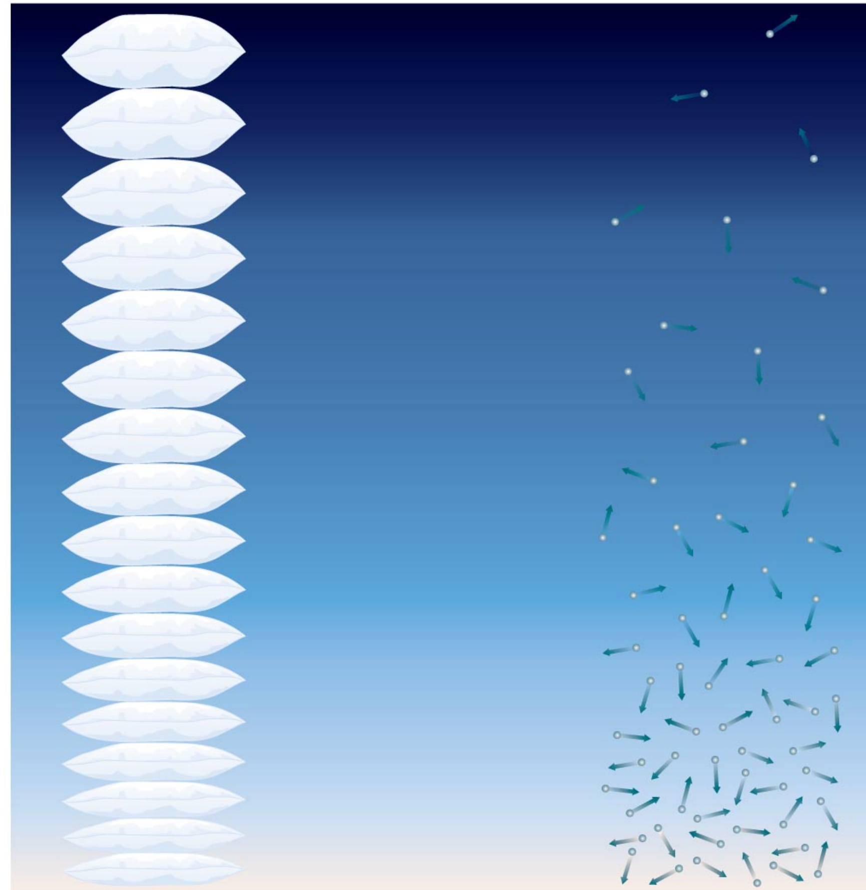


Once Einstein showed that $E=mc^2$, physicists figured that nuclear fusion powered the Sun, but the details were not worked out until the 1940s/1950s.



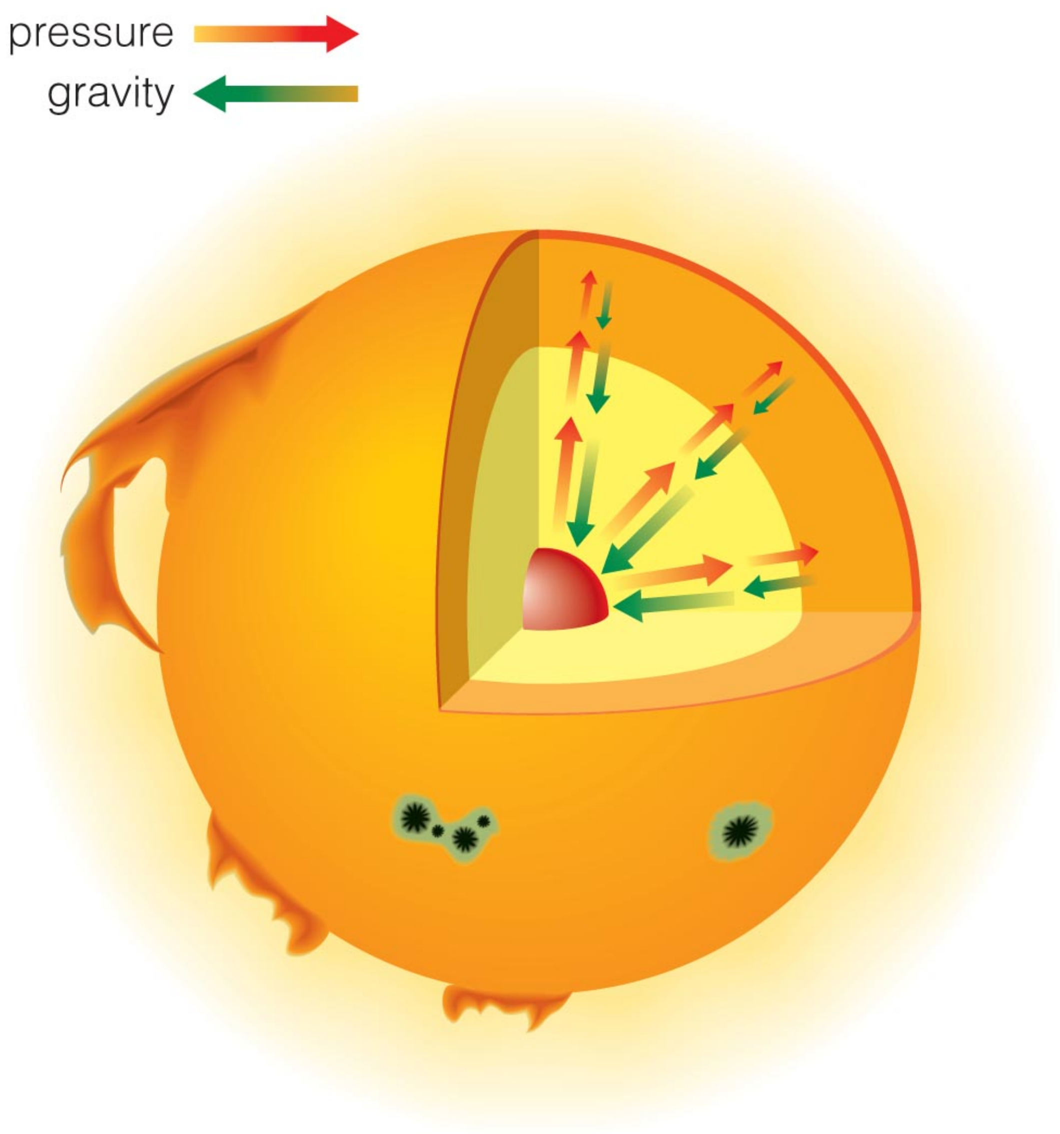
It can be powered by NUCLEAR ENERGY! ($E = mc^2$)

$$\frac{\text{Nuclear potential energy (core)}}{\text{Luminosity}} \sim \text{10 billion years}$$



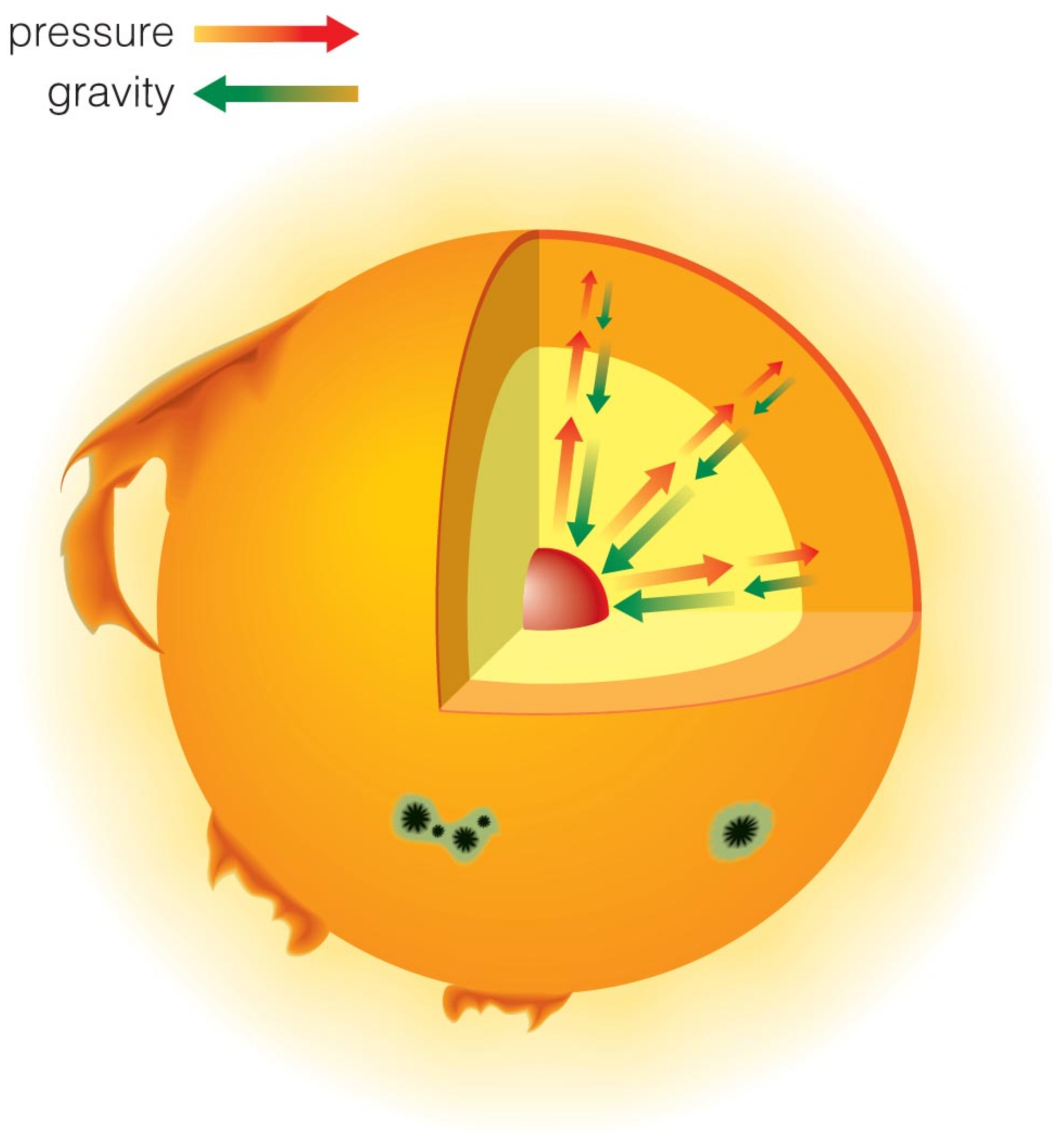
The Sun's core is very high density---over 100 g/cm^3

Weight of upper layers compresses lower layers.



Gravitational equilibrium:

Energy supplied by fusion maintains the pressure that balances the inward crush of gravity.

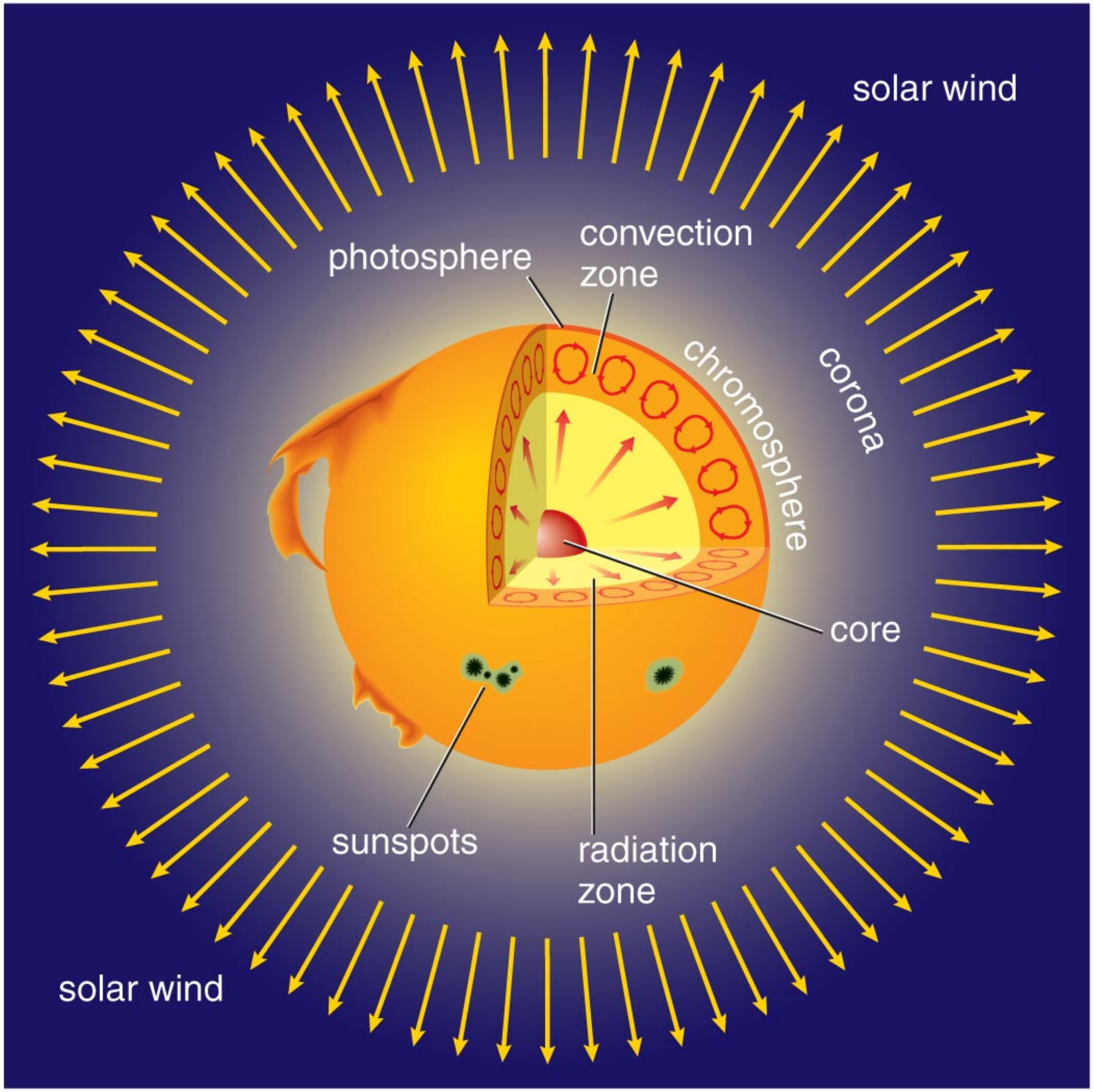


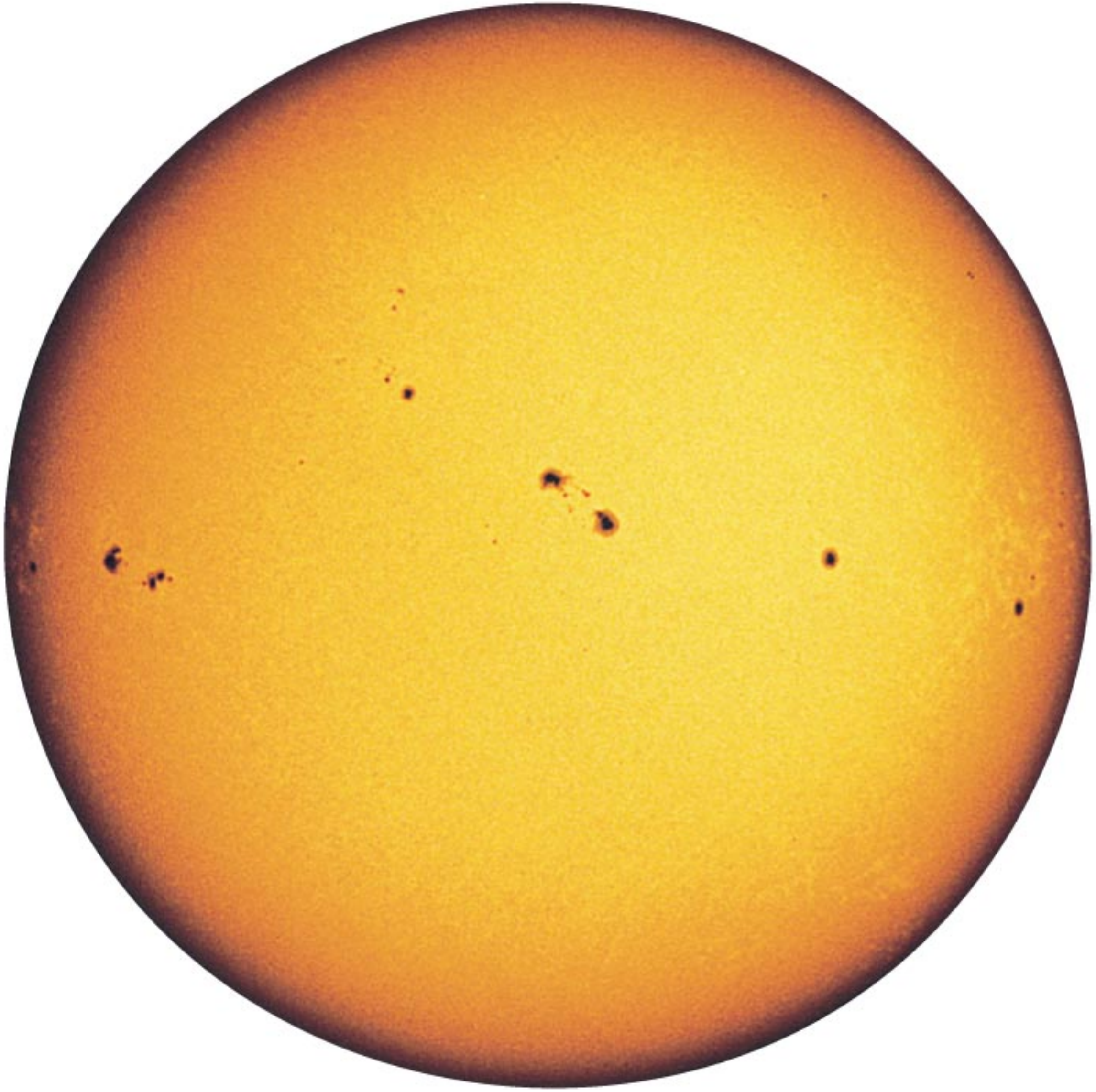
Gravitational contraction:

Provided the energy that heated the core as Sun was forming

Contraction stopped when fusion began.

What is the Sun’s structure?





Radius:

6.9×10^8 m

(10^9 times Earth)

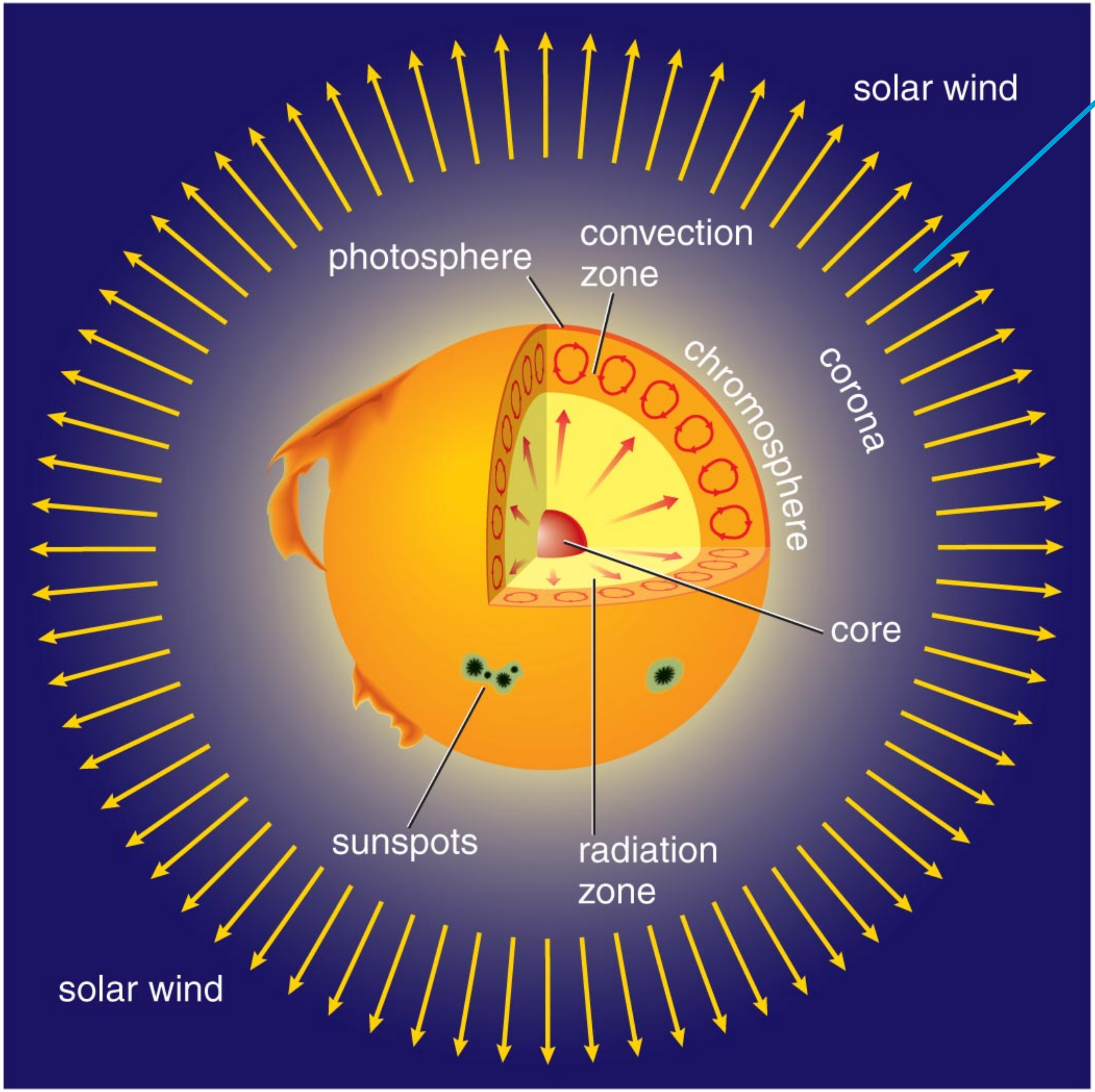
Mass:

2×10^{30} kg

(300,000 Earths)

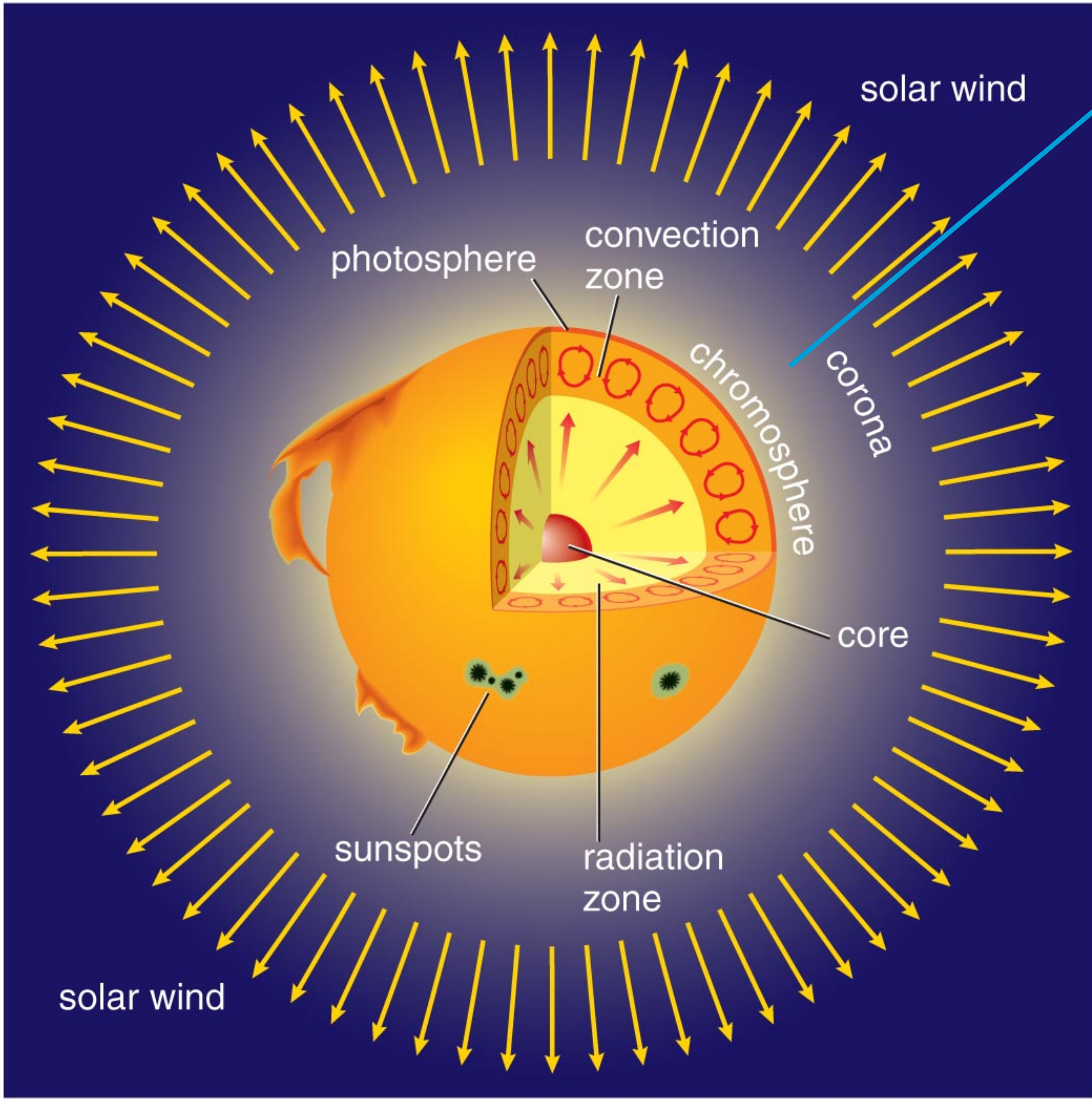
Luminosity:

3.8×10^{26} watts



Solar wind:

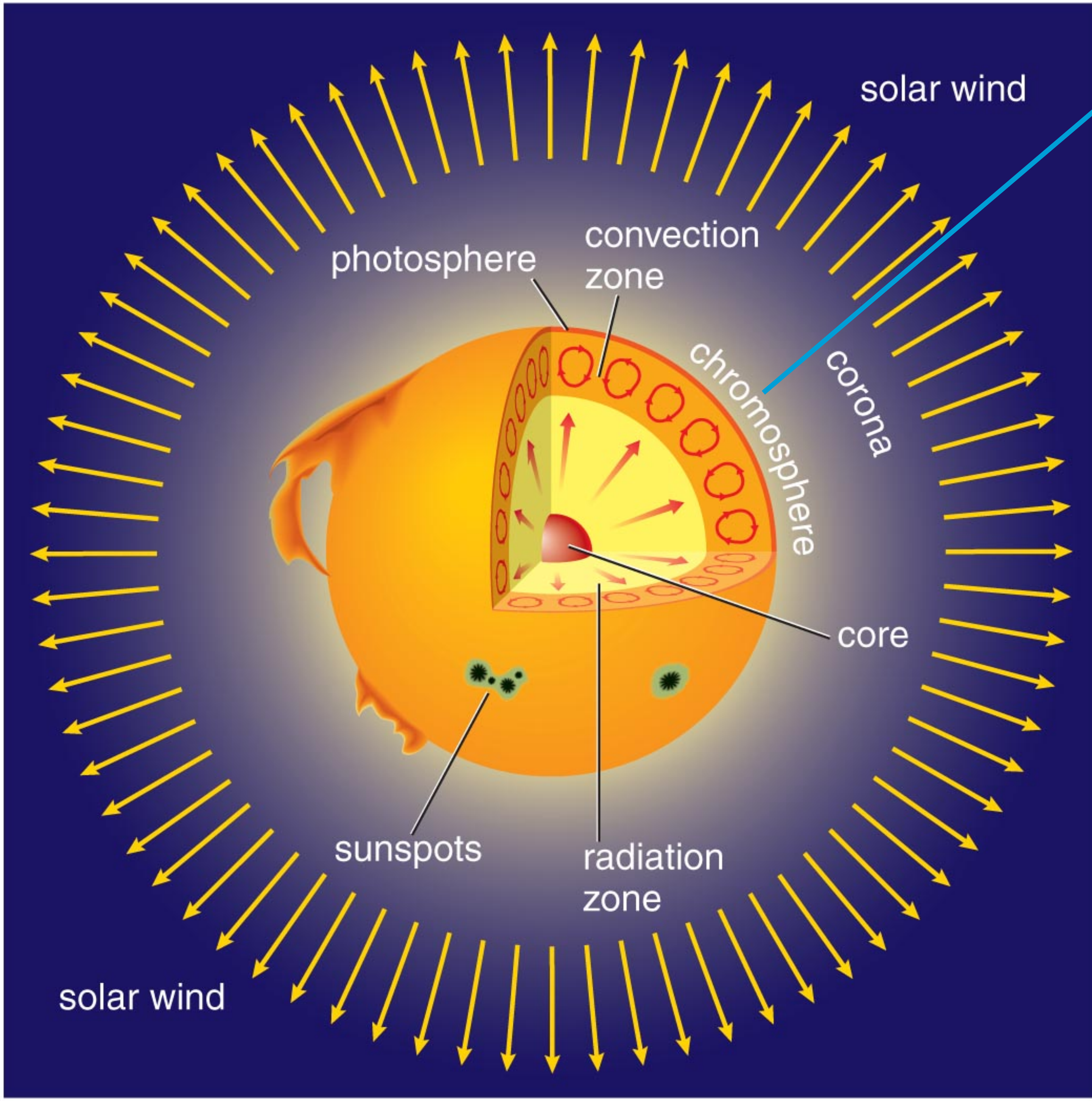
A flow of charged particles from the surface of the Sun



Corona:

Outermost layer of solar atmosphere

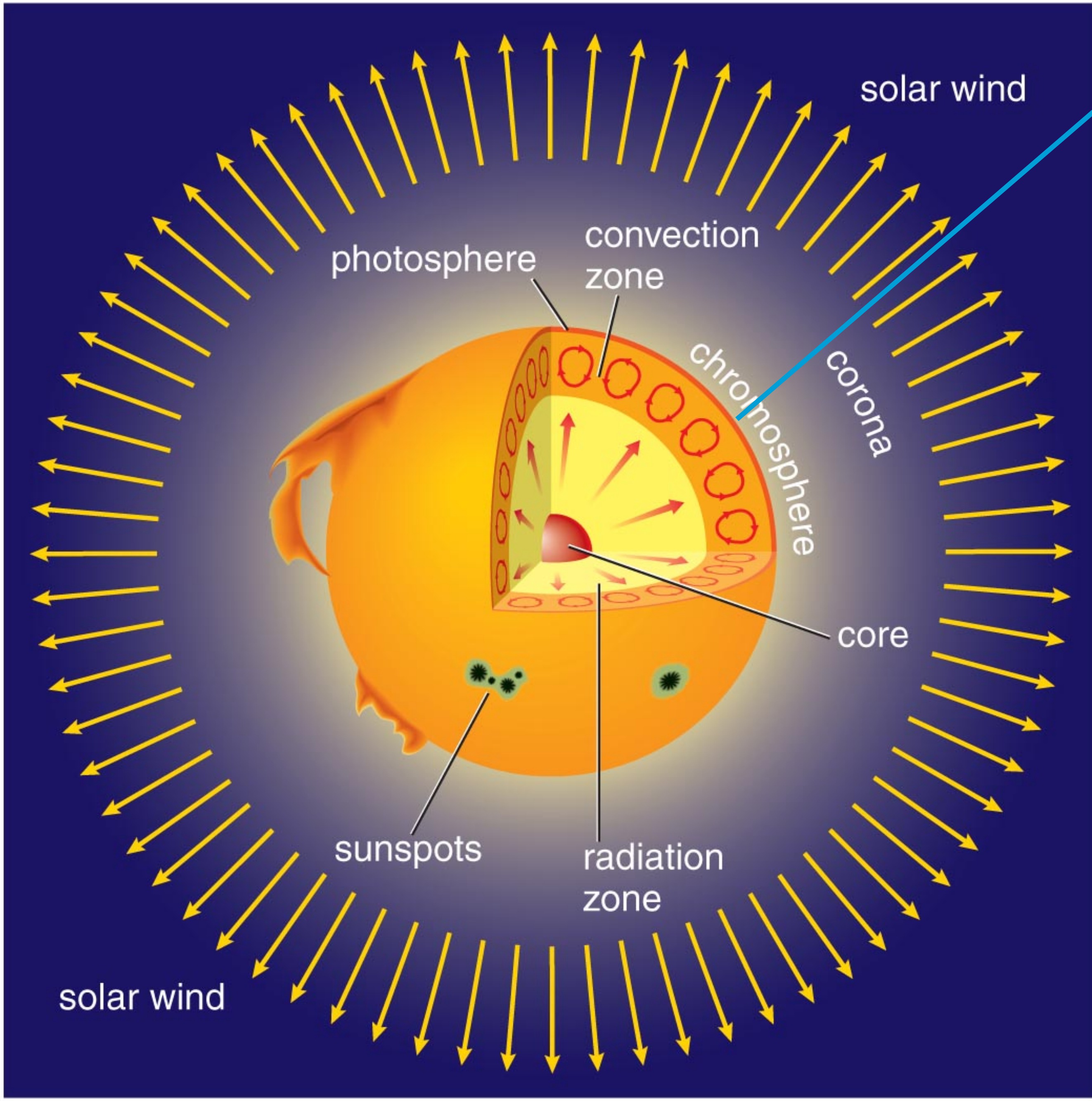
~1 million K



Chromosphere:

Middle layer of solar atmosphere

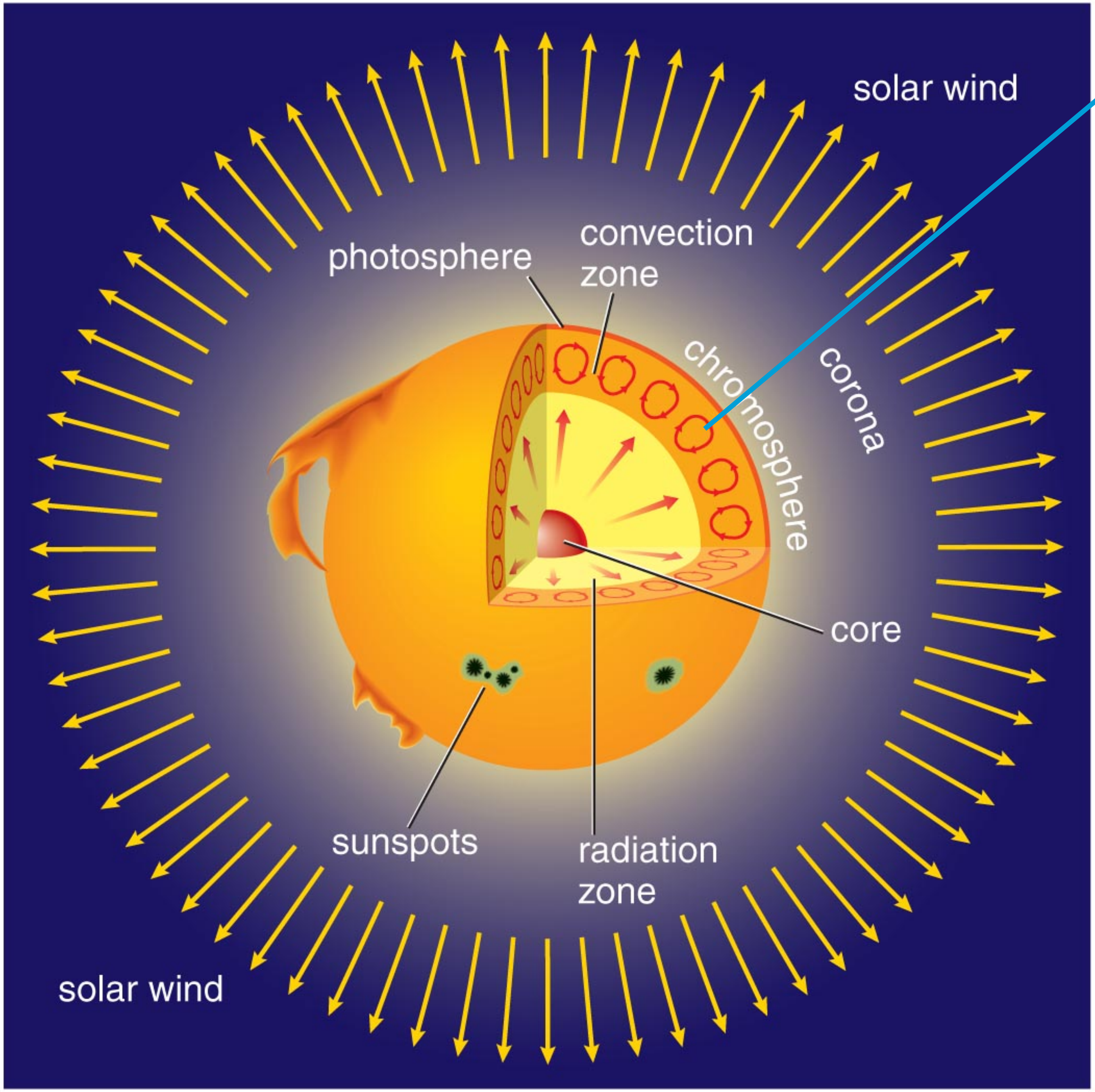
$\sim 10^4$–10^5 K



Photosphere:

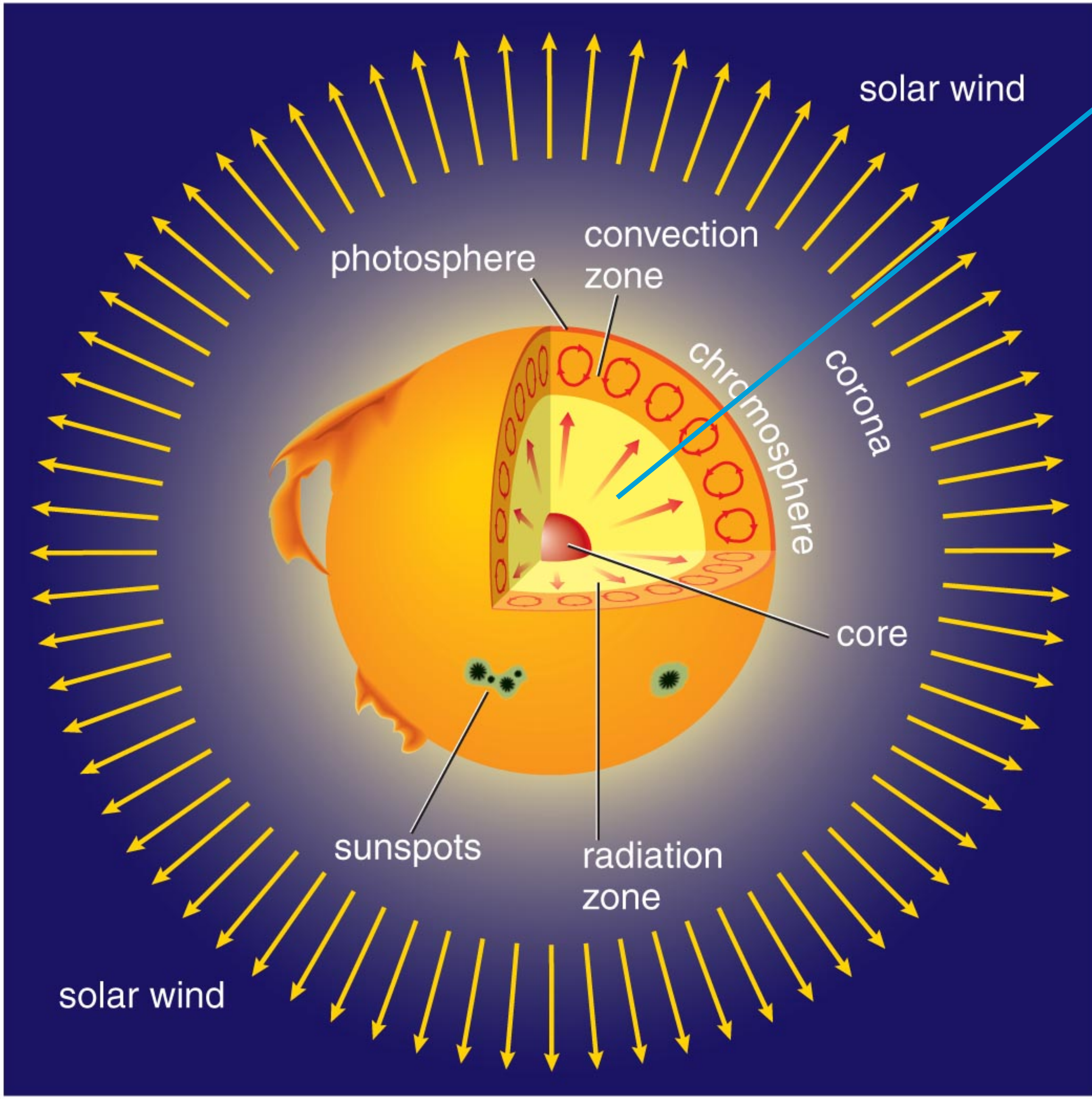
Visible surface of Sun

~ 6000 K



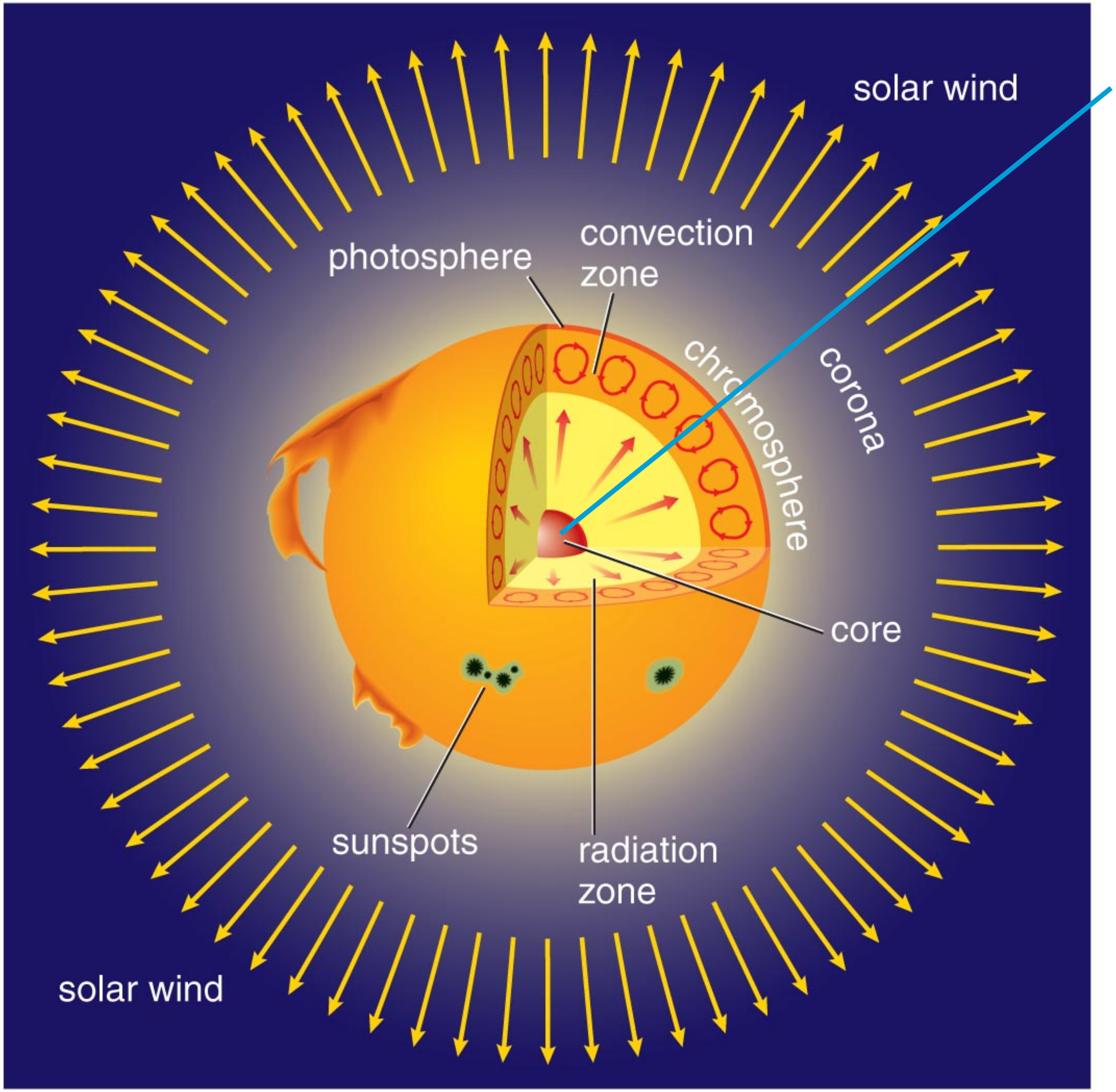
Convection Zone:

Energy transported upward by rising hot gas



Radiation Zone:

Energy transported upward by photons



Core:

Energy generated by nuclear fusion

~ 15 million K

What have we learned?

- Why was the Sun's energy source a major mystery?
  - Chemical and gravitational energy sources could not explain how the Sun could sustain its luminosity for more than about 25 million years.
- Why does the Sun shine?
  - The Sun shines because **gravitational equilibrium** keeps its core hot and dense enough to release energy through nuclear fusion.

What have we learned?

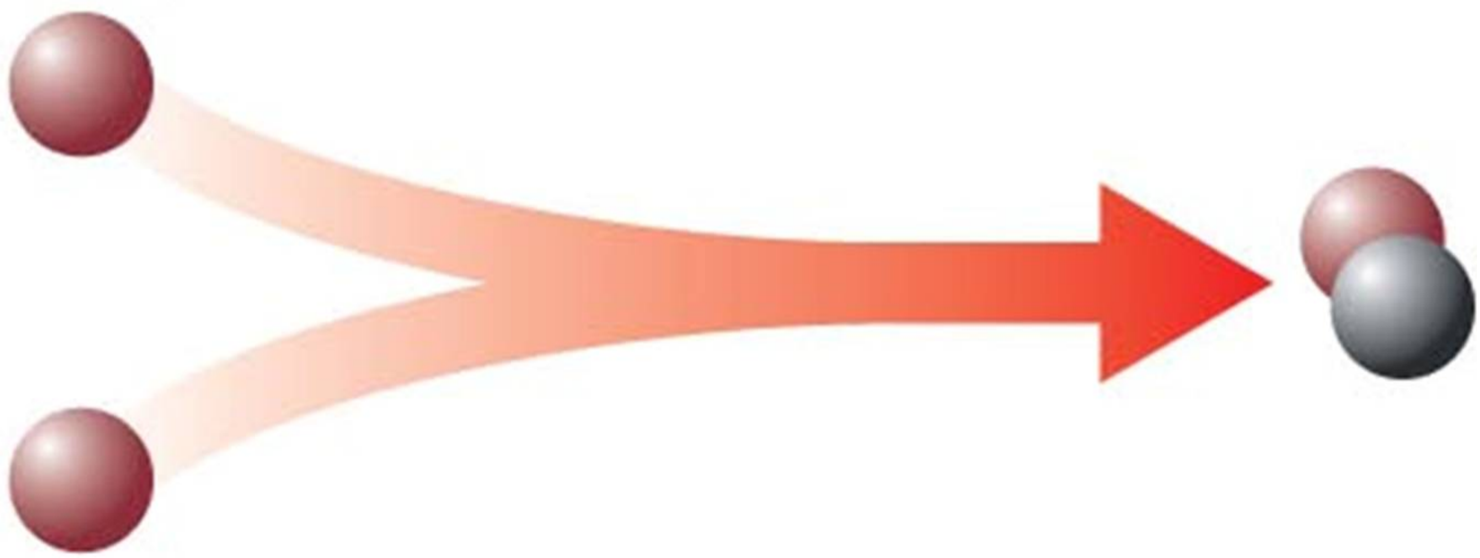
- What is the Sun's structure?
  - From inside out, the layers are:
    - Core
    - Radiation zone
    - Convection zone
    - Photosphere
    - Chromosphere
    - Corona

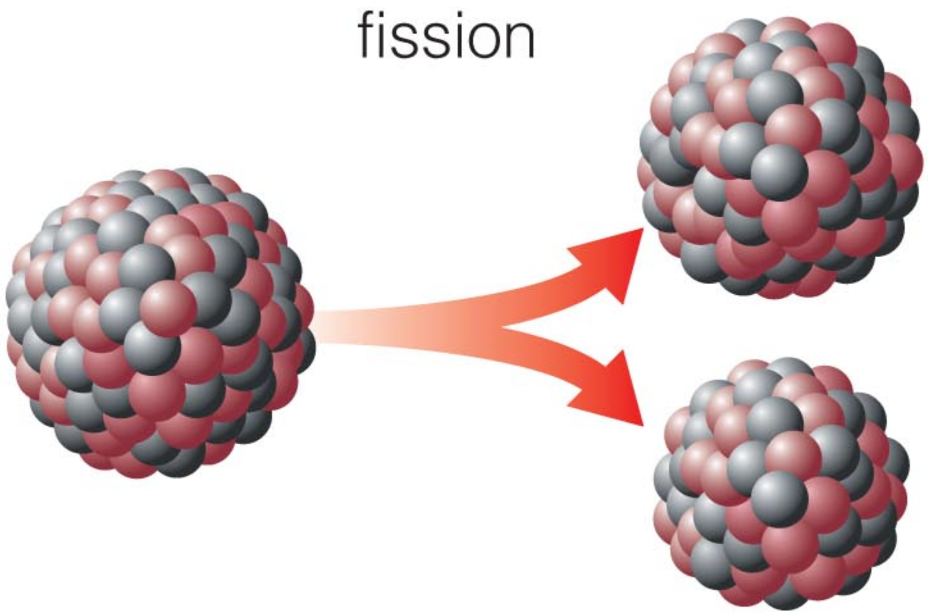
14.2 The Cosmic Crucible

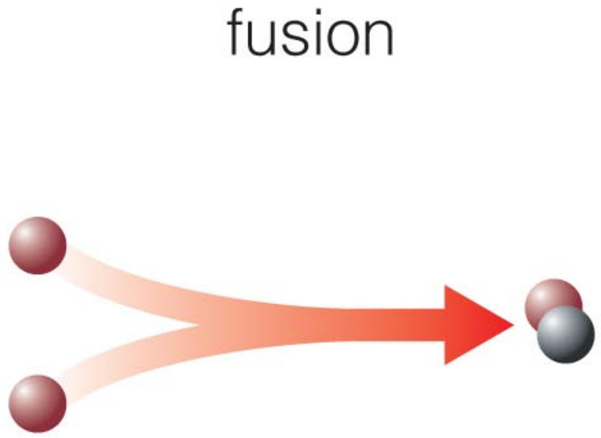
Our goals for learning:

- How does nuclear fusion occur in the Sun?
- How does the energy from fusion get out of the Sun?
- How do we know what is happening inside the Sun?

How does nuclear fusion occur in the Sun?







Fission

Big nucleus splits into smaller pieces.

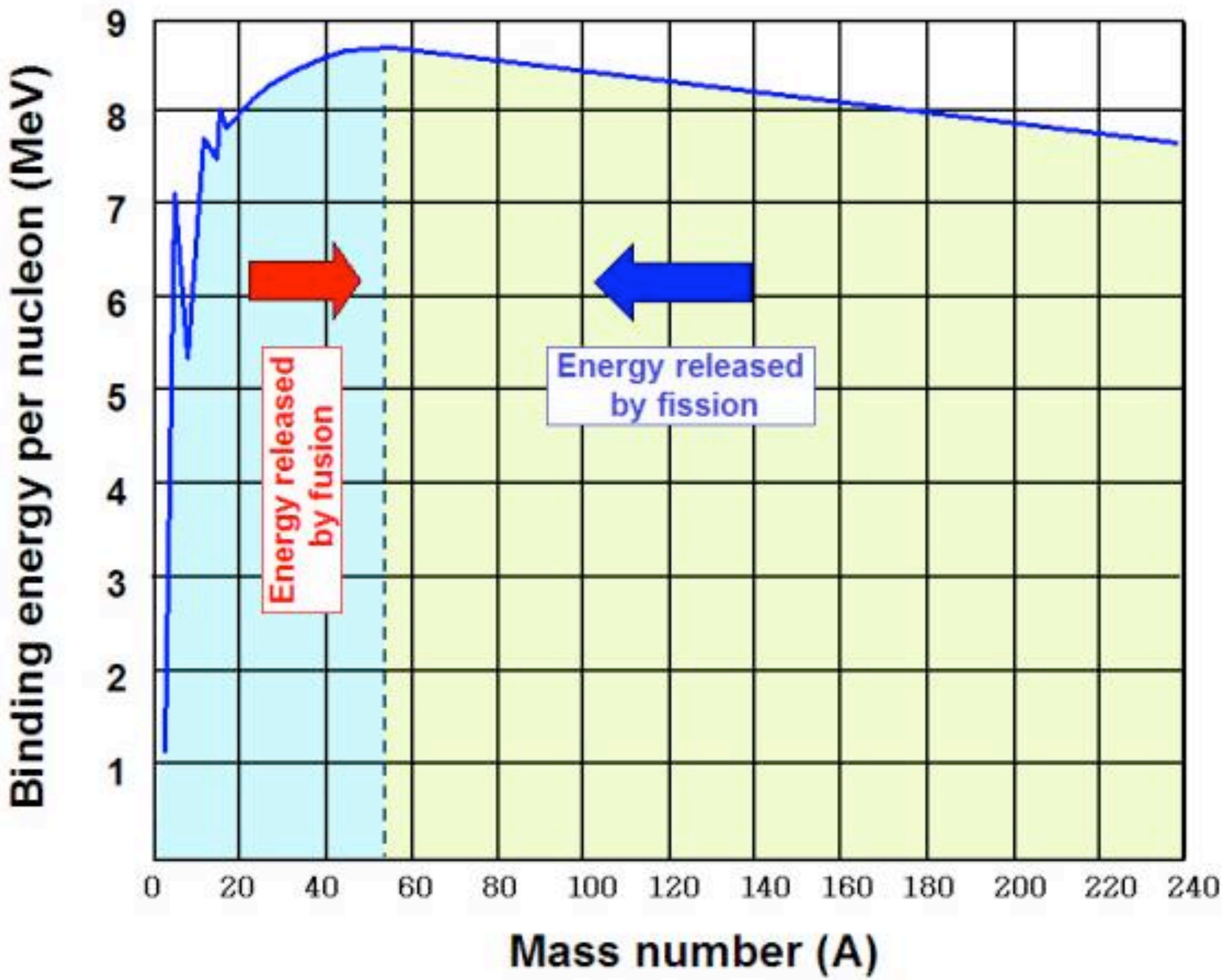
(Example: nuclear power plants)

Fusion

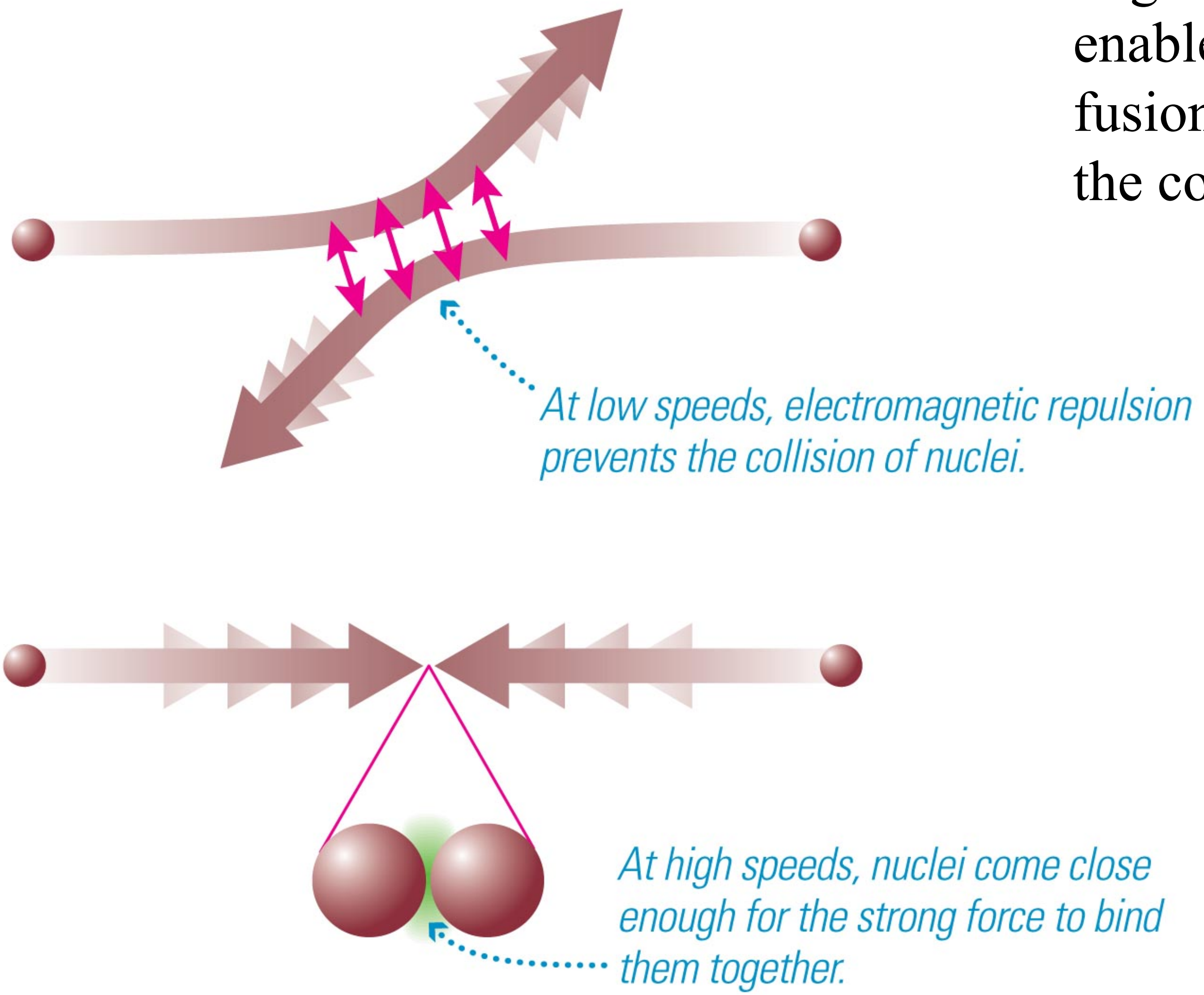
Small nuclei stick together to make a bigger one.

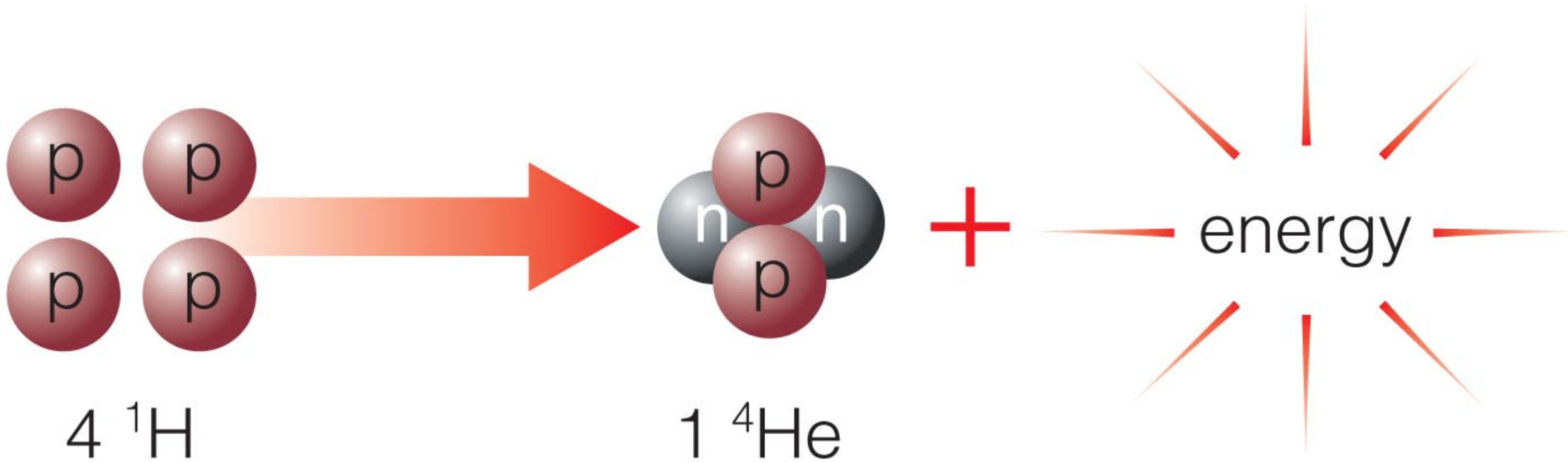
(Example: the Sun, stars)

Nuclear Binding Energy

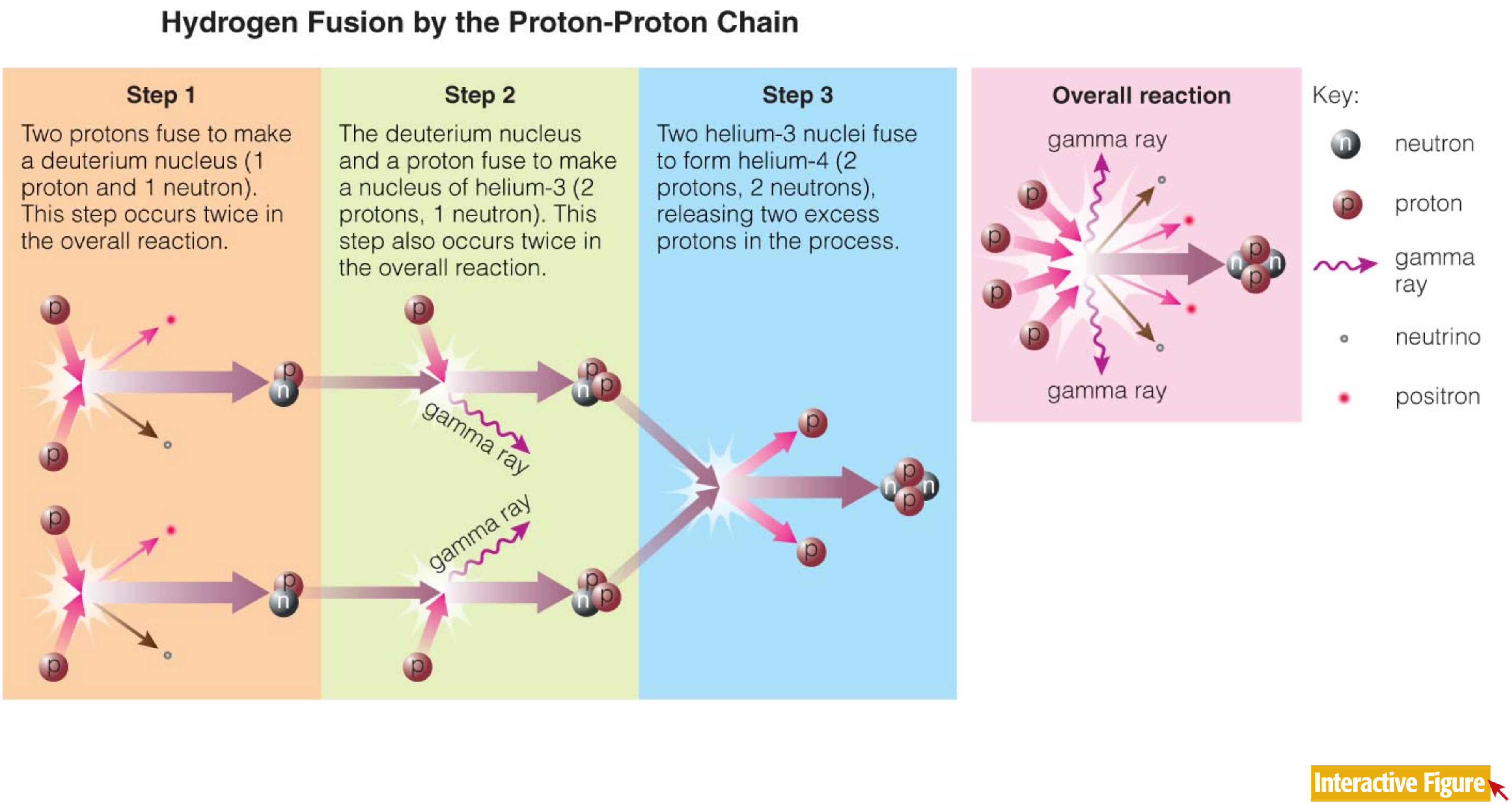


High temperatures enable nuclear fusion to happen in the core.

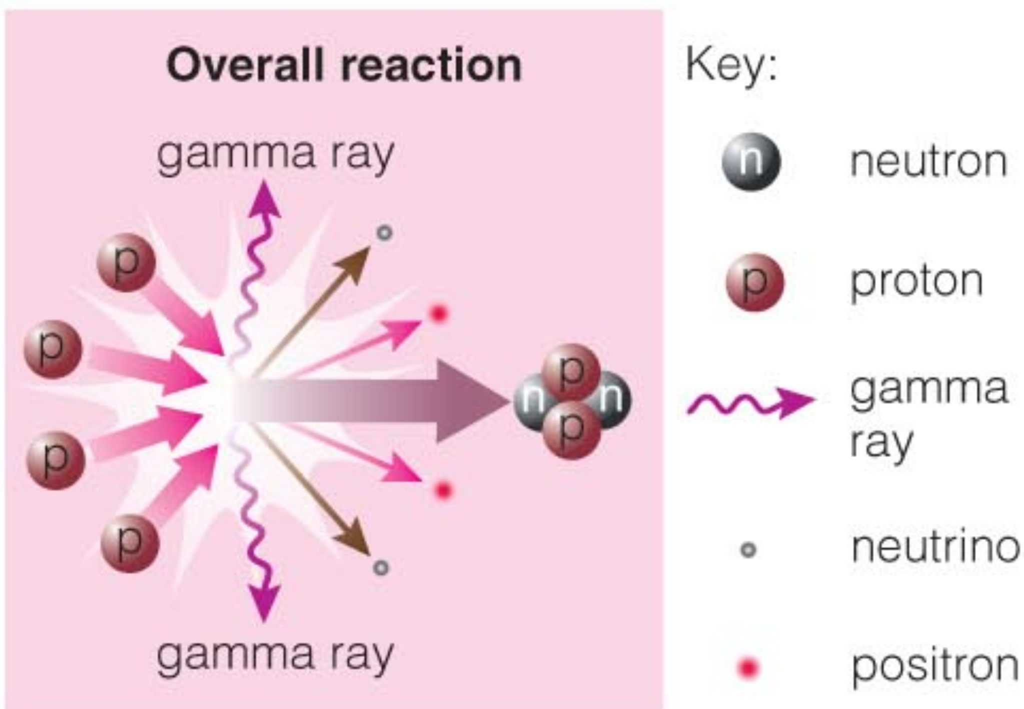




The Sun releases energy by fusing four hydrogen nuclei into one helium nucleus.



The **proton–proton chain** is how hydrogen fuses into helium in Sun.



IN

4 protons

OUT

^{4}He nucleus

2 gamma rays

2 positrons

2 neutrinos

Total mass is 0.7% lower.