Review: Properties of the Sun
Properties of the Sun
Energy Transport
The Heart of the Sun
The Forces and Particles in the Universe
Nuclear Fusion
Measuring the Stars
Stellar Parallax
Stellar Motion

The Sun and the Stars

The Heart of the Sun

Giants, Dwarfs, and the Main Sequences

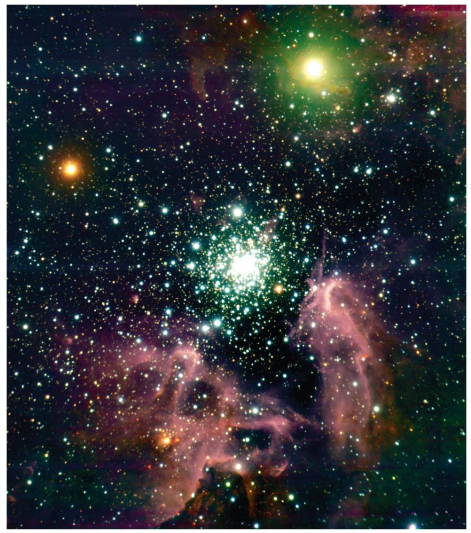
10/20/2009

My Office Hours:
Tuesday 3:30 PM - 4:30 PM
206 Keen Building

Review: Properties of the Sun
Properties of the Sun
Energy Transport
The Heart of the Sun
The Forces and Particles in the Universe
Nuclear Fusion
Measuring the Stars
Stellar Parallax
Stellar Motion

Outline

1. Review: Properties of the Sun
   - Properties of the Sun
   - Energy Transport
2. The Heart of the Sun
   - The Forces and Particles in the Universe
   - Nuclear Fusion
3. Measuring the Stars
   - Stellar Parallax
   - Stellar Motion



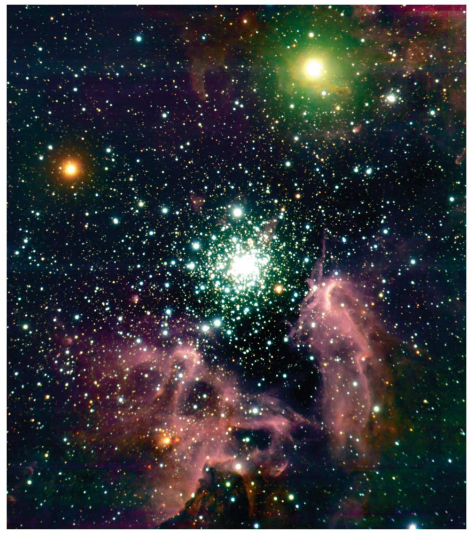
Review: Properties of the Sun
Properties of the Sun
Energy Transport
The Heart of the Sun
The Forces and Particles in the Universe
Nuclear Fusion
Measuring the Stars
Stellar Parallax
Stellar Motion

Outline

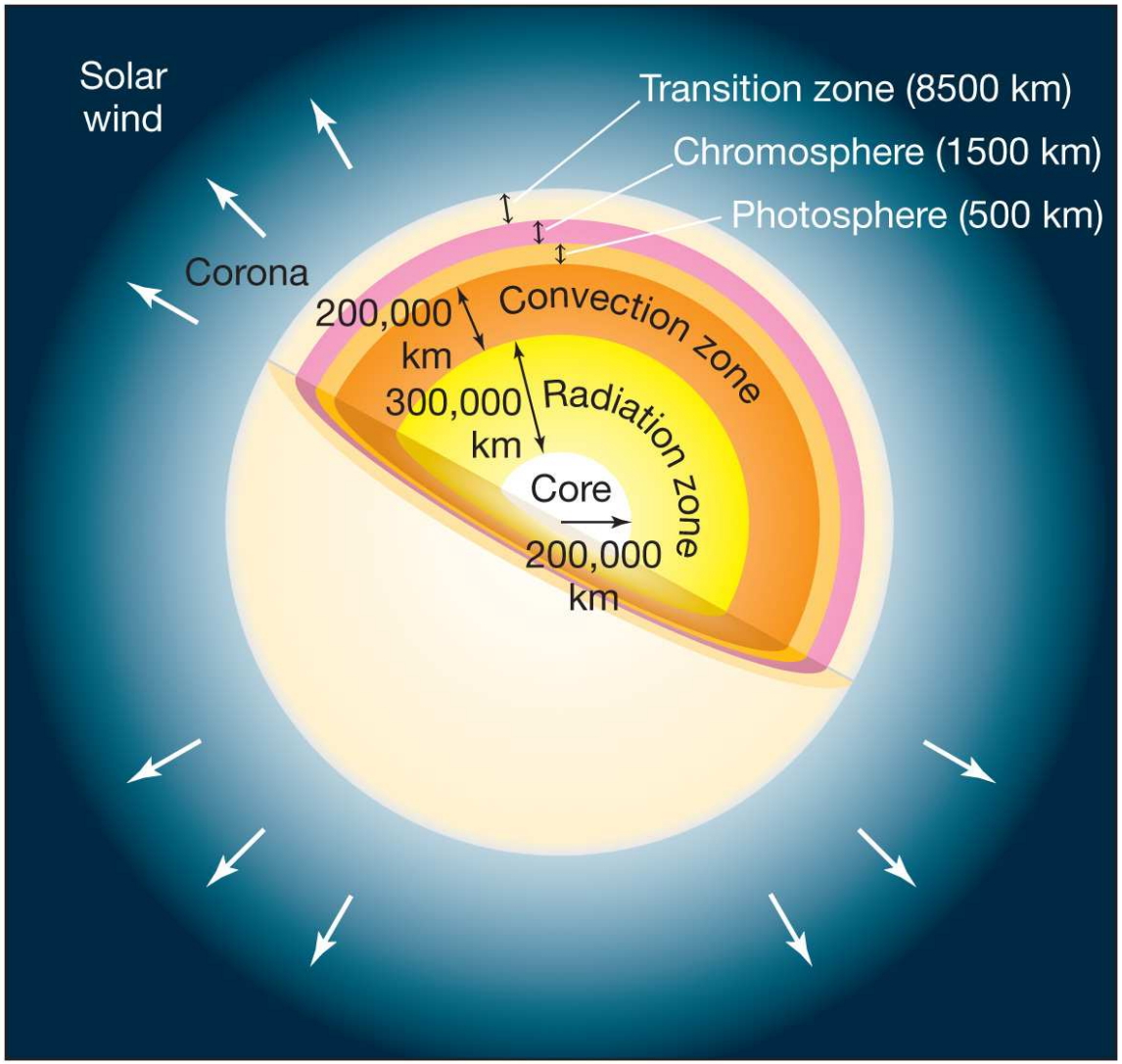
1 Review: Properties of the Sun
- Properties of the Sun
- Energy Transport

2 The Heart of the Sun
- The Forces and Particles in the Universe
- Nuclear Fusion

3 Measuring the Stars
- Stellar Parallax
- Stellar Motion



Solar Structure



Interior structure of the Sun

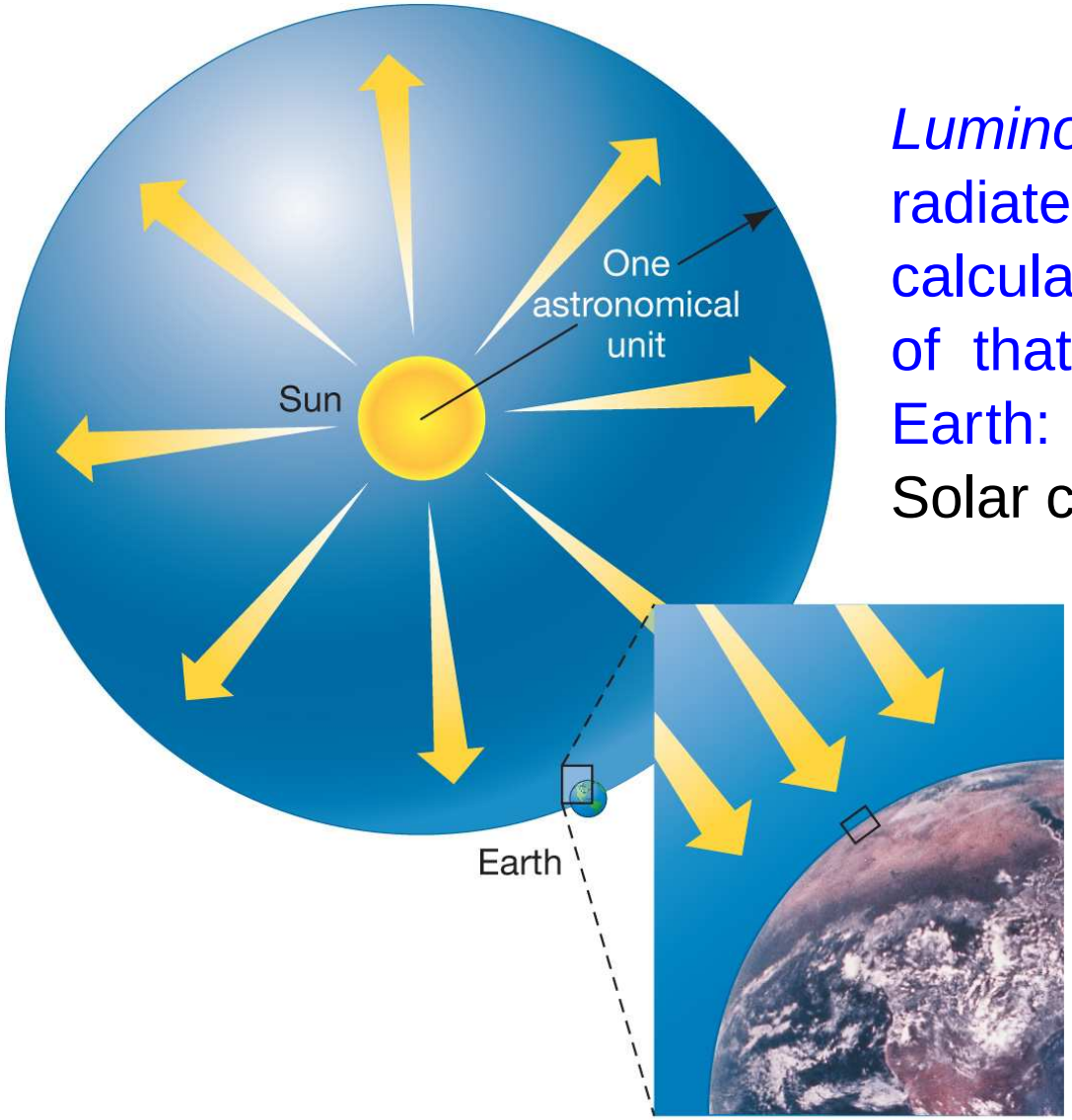
➜ Outer layers are not to scale

Convection Zone

Radiation Zone

Core

Solar Luminosity

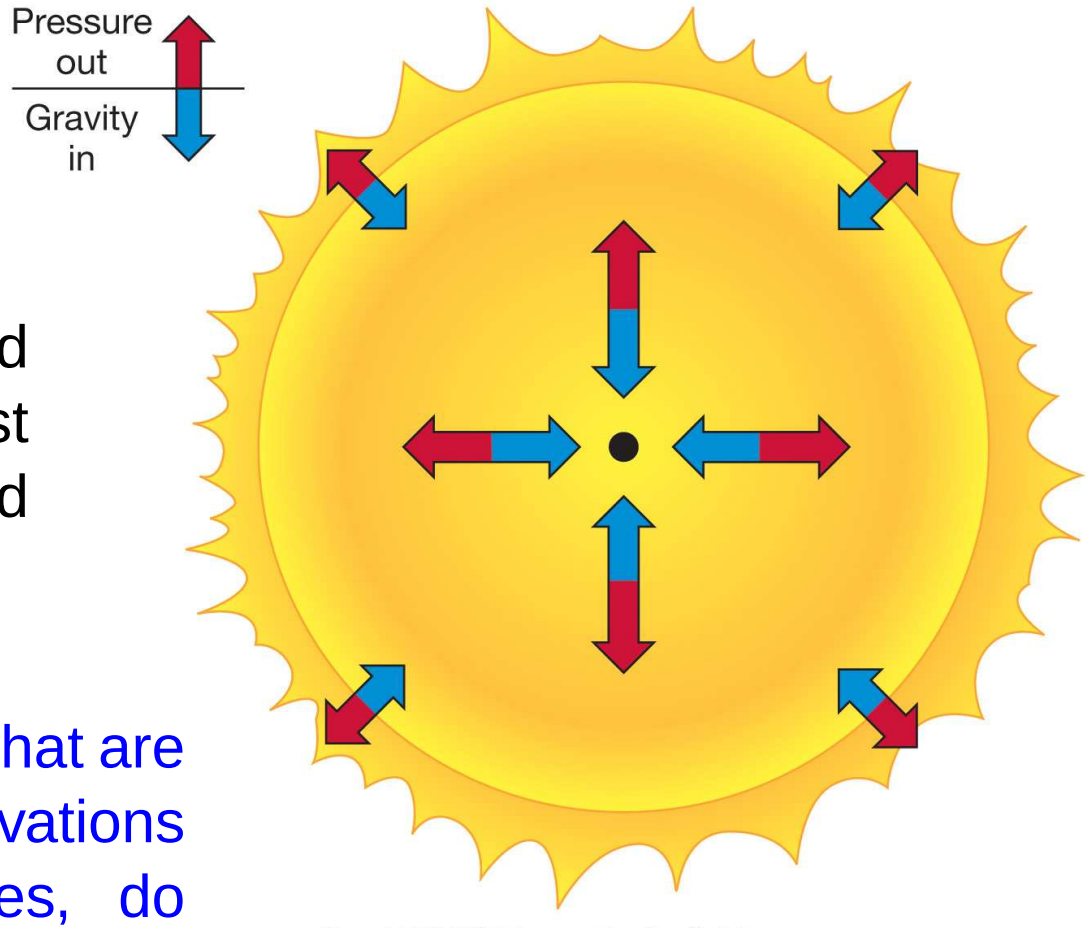


Luminosity: the total energy radiated by the Sun – can be calculated from the fraction of that energy that reaches Earth:

Solar constant ≈ 1400 W/m^2

The total *luminosity* is about $4 \cdot 10^{26}$ W – the equivalent of 10 billion 1-megaton nuclear bombs per second.

Stellar Balance



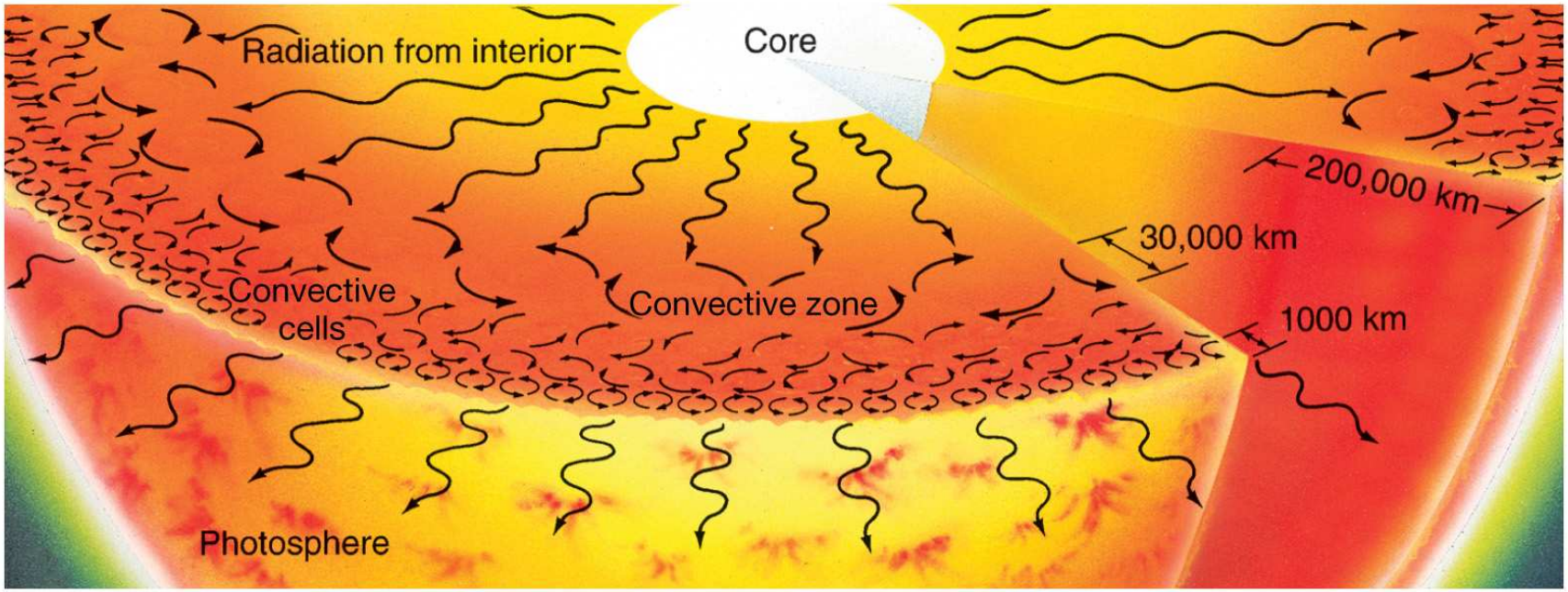
In equilibrium, inward gravitational force must be balanced by outward pressure.

Mathematical models that are consistent with observations and physical principles, do provide information about the Sun's interior.

Solar Convection

Physical transport of energy

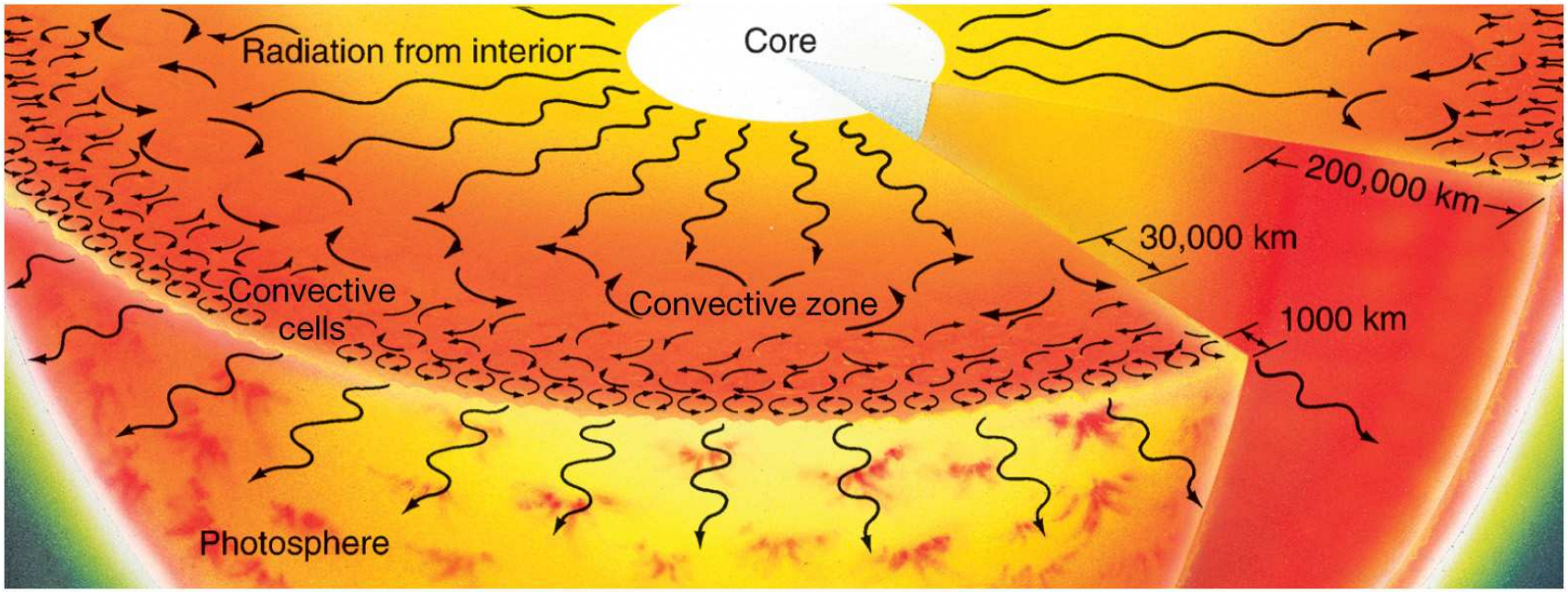
1. The *radiation zone* is relatively transparent.



Solar Convection

Physical transport of energy

1. The *radiation zone* is relatively transparent.
2. The cooler *convection zone* is opaque:
   - Each convective cell is about 1000 km across.
   - Cell sizes become progressively smaller closer to surface.

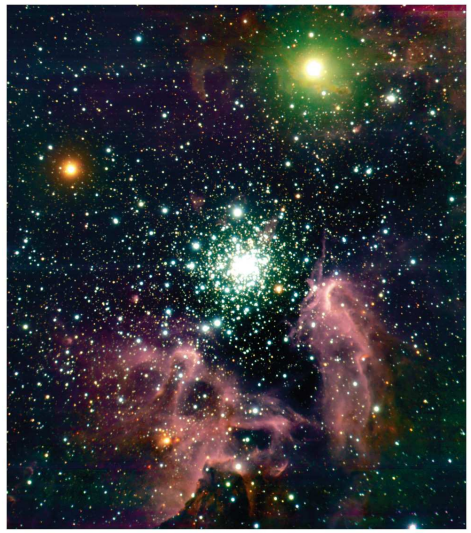


Outline

1 Review: Properties of the Sun
- Properties of the Sun
- Energy Transport

2 The Heart of the Sun
- The Forces and Particles in the Universe
- Nuclear Fusion

3 Measuring the Stars
- Stellar Parallax
- Stellar Motion



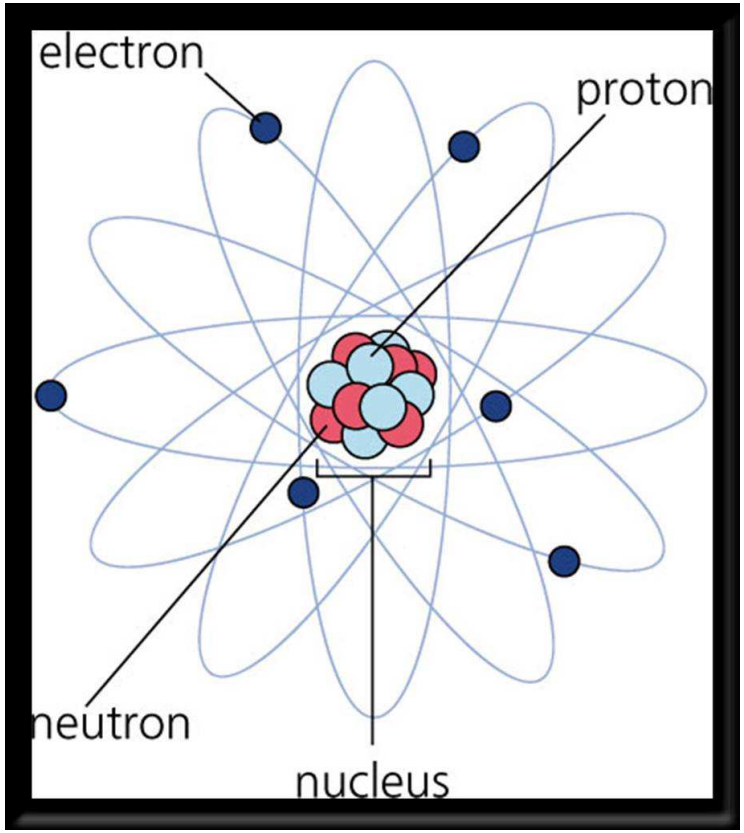
Review: Properties of the Sun
Properties of the Sun
Energy Transport
The Heart of the Sun
The Forces and Particles in the Universe
Nuclear Fusion
Measuring the Stars
Stellar Parallax
Stellar Motion

Getting to the Bottom of Things

Is the atom fundamental?

Getting to the Bottom of Things

Is the atom fundamental? No!



Review: Properties of the Sun
Properties of the Sun
Energy Transport
The Heart of the Sun
The Forces and Particles in the Universe
Nuclear Fusion
Measuring the Stars
Stellar Parallax
Stellar Motion

Getting to the Bottom of Things

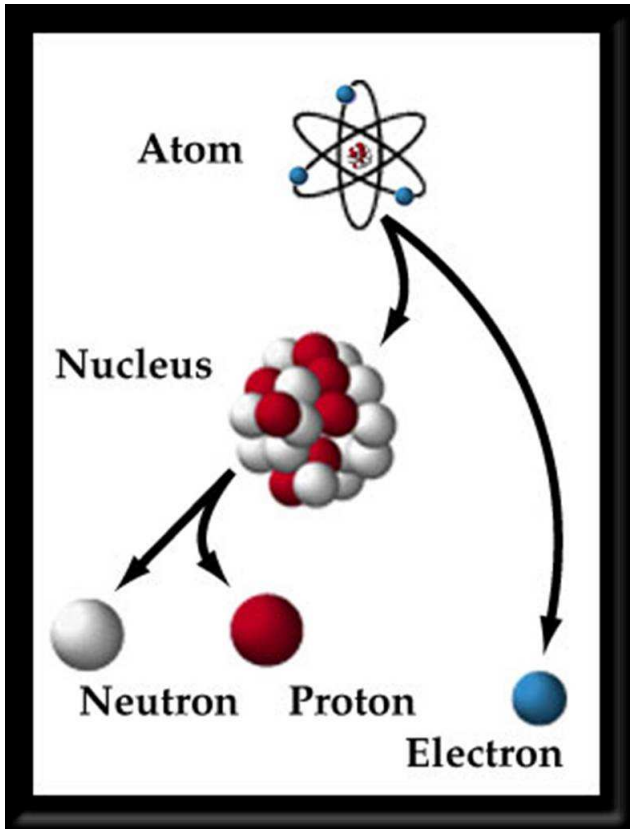
Is the atom fundamental? No!

Is the nucleus fundamental?

Getting to the Bottom of Things

Is the atom fundamental? No!

Is the nucleus fundamental? No!



Review: Properties of the Sun
Properties of the Sun
Energy Transport
The Heart of the Sun
The Forces and Particles in the Universe
Nuclear Fusion
Measuring the Stars
Stellar Parallax
Stellar Motion

Getting to the Bottom of Things

Is the atom fundamental? No!

Is the nucleus fundamental? No!

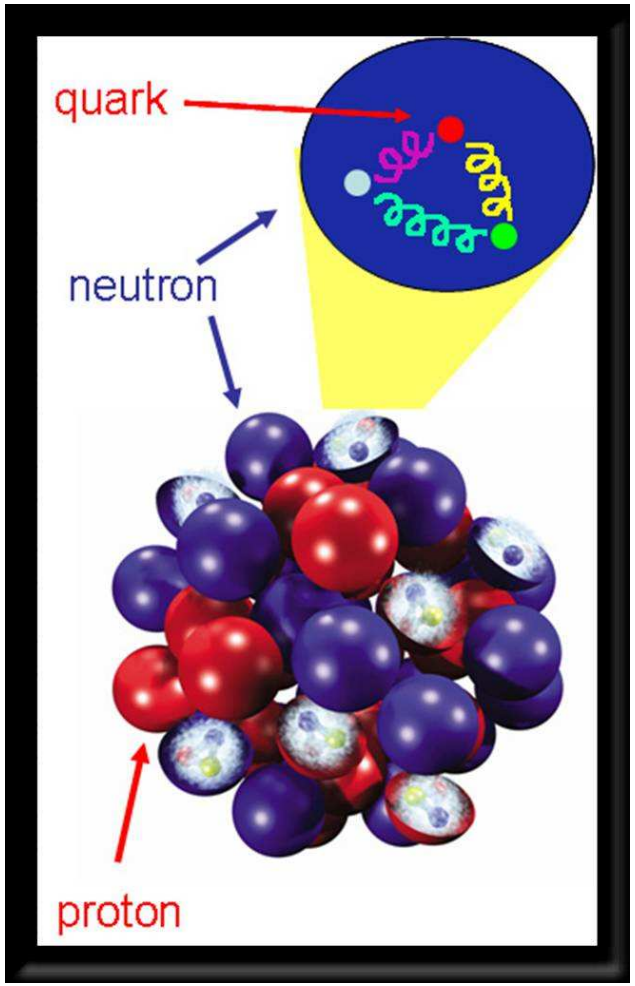
Is the nucleon fundamental?

Getting to the Bottom of Things

Is the atom fundamental? No!

Is the nucleus fundamental? No!

Is the nucleon fundamental? No!



Review: Properties of the Sun
Properties of the Sun
Energy Transport
The Heart of the Sun
The Forces and Particles in the Universe
Nuclear Fusion
Measuring the Stars
Stellar Parallax
Stellar Motion

Getting to the Bottom of Things

Is the atom fundamental? No!

Is the nucleus fundamental? No!

Is the nucleon fundamental? No!

Is a quark fundamental?

Review: Properties of the Sun
Properties of the Sun
Energy Transport
The Heart of the Sun
The Forces and Particles in the Universe
Nuclear Fusion
Measuring the Stars
Stellar Parallax
Stellar Motion

Getting to the Bottom of Things

Is the atom fundamental? No!

Is the nucleus fundamental? No!

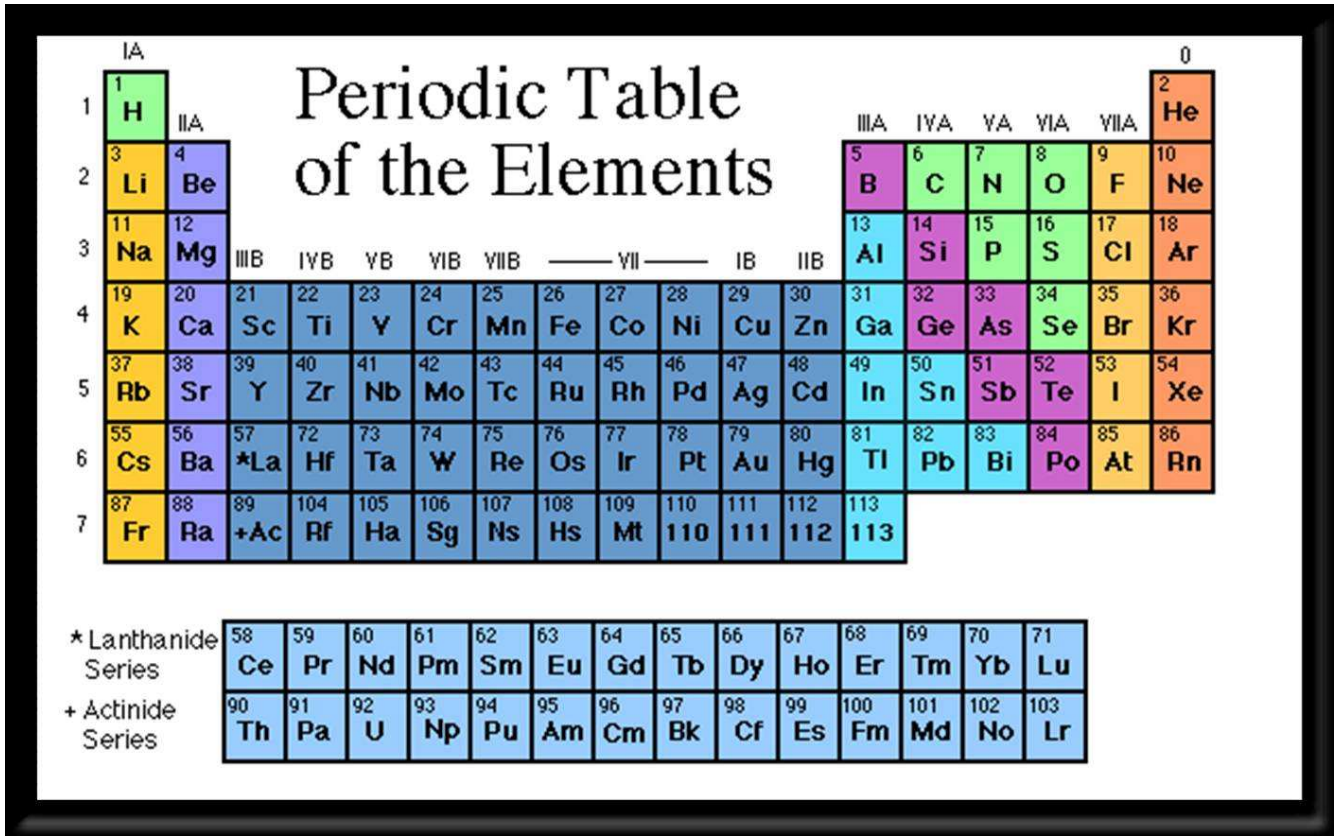
Is the nucleon fundamental? No!

Is a quark fundamental? Maybe ...

Chemistry, Alchemy, Atomics, ...

Chemistry: The action is in the electrons.

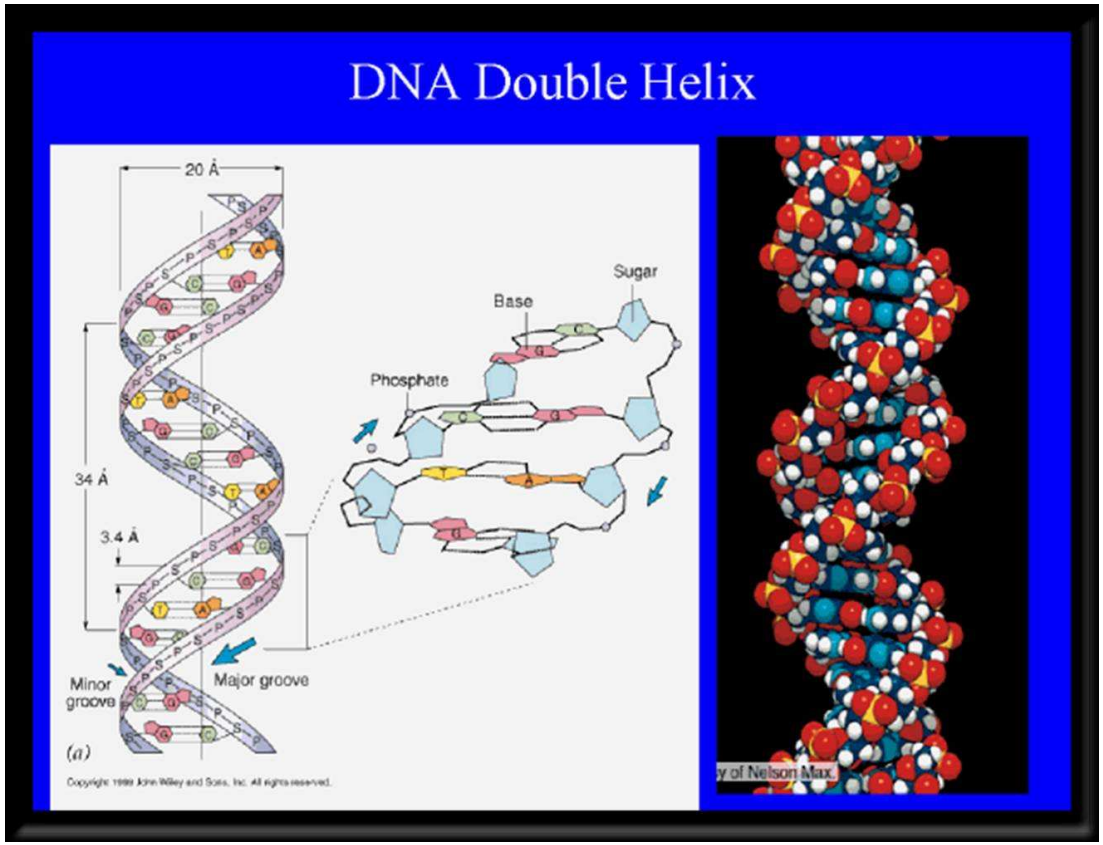
Nuclear Physics: The action is in the nuclei.



Chemistry, Alchemy, Atomics, ...

Chemistry: The action is in the electrons.

Nuclear Physics: The action is in the nuclei.

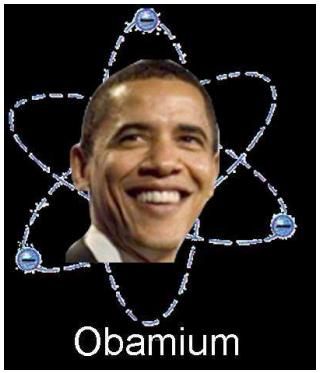


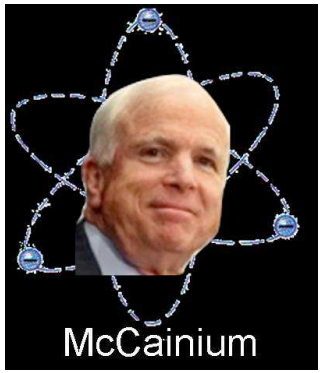
Review: Properties of the Sun
Properties of the Sun
Energy Transport
The Heart of the Sun
The Forces and Particles in the Universe
Nuclear Fusion
Measuring the Stars
Stellar Parallax
Stellar Motion

Chemical Reactions

Chemistry: The action is in the electrons.

Nuclear Physics: The action is in the nuclei.



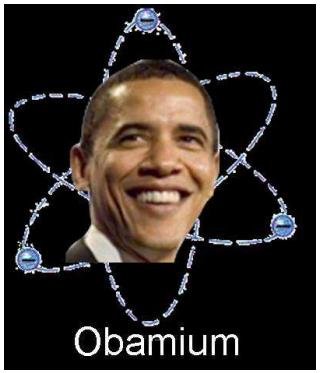


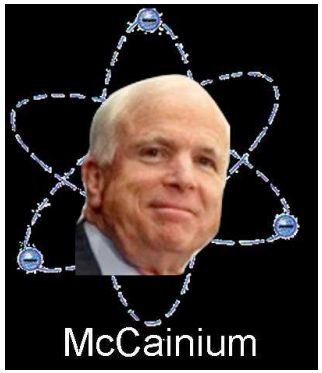
Chemical Reactions

Chemistry: The action is in the electrons.

Nuclear Physics: The action is in the nuclei.

Maverick McNitrate



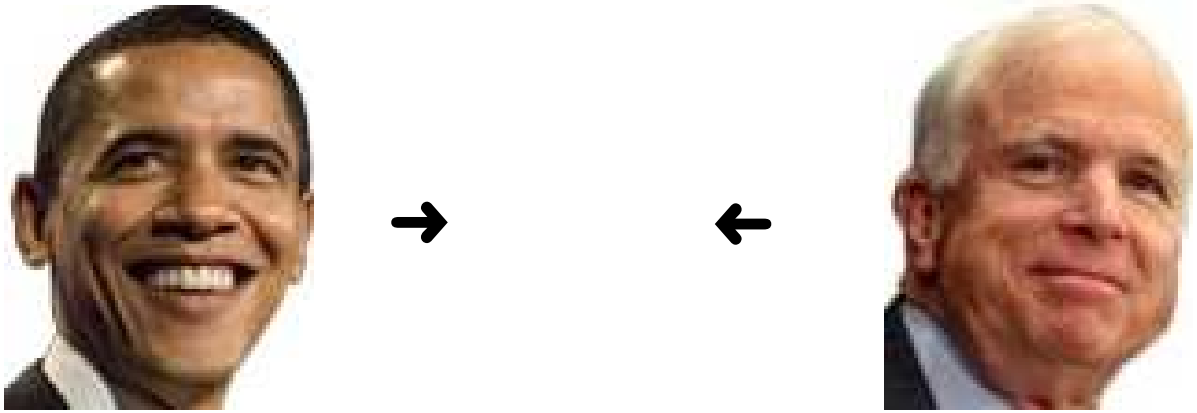


Changehope Dioxide

Chemical Reactions

Chemistry: The action is in the electrons.

Nuclear Physics: The action is in the nuclei.



Review: Properties of the Sun
Properties of the Sun
Energy Transport
The Heart of the Sun
The Forces and Particles in the Universe
Nuclear Fusion
Measuring the Stars
Stellar Parallax
Stellar Motion

Chemical Reactions

Chemistry: The action is in the electrons.

Nuclear Physics: The action is in the nuclei.

Chemical Reactions

Chemistry: The action is in the electrons.

Nuclear Physics: The action is in the nuclei.

Question

How many fundamental interactions (forces) are there in the universe?

1. 2
2. 4
3. 10
4. infinite
5. constantly changing

Review: Properties of the Sun
Properties of the Sun
Energy Transport
The Heart of the Sun
The Forces and Particles in the Universe
Nuclear Fusion
Measuring the Stars
Stellar Parallax
Stellar Motion

Fundamental Interactions

There are *only* 4 fundamental forces in the universe.

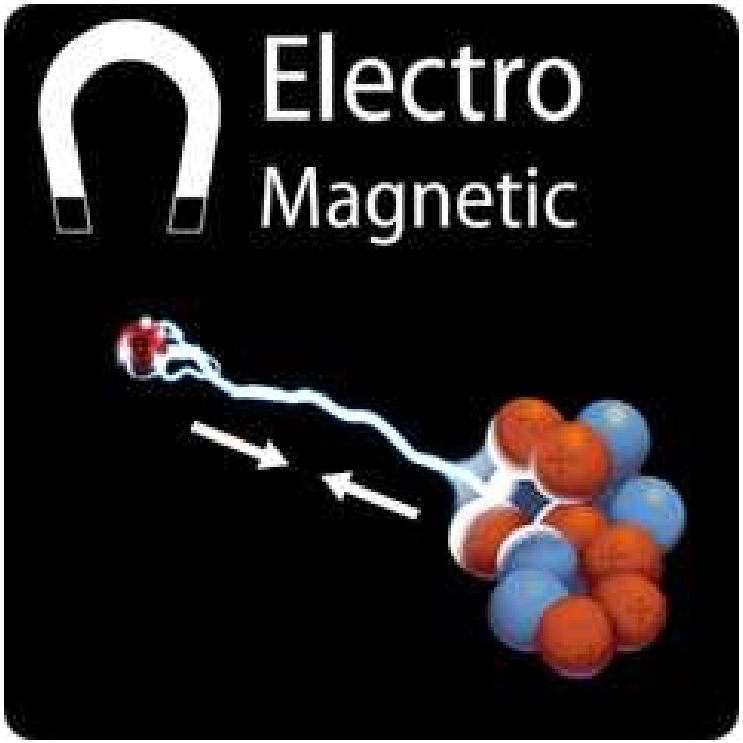
Fundamental Interactions

There are *only* 4 fundamental forces in the universe.

The effect of gravity on fundamental particles is really tiny. So we don't really consider it for the moment.

Fundamental Interactions

There are *only* 4 fundamental forces in the universe.



The electromagnetic force affects any electrically charged fundamental particle (that's half of the leptons and all the quarks). It's the same force that makes lightning strike and different poles of bar magnets attract each other.

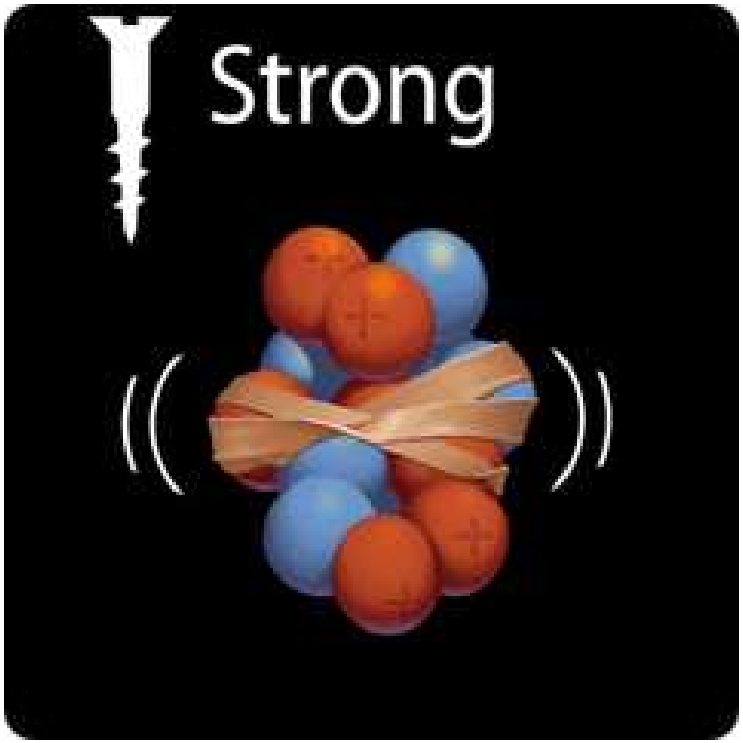
Fundamental Interactions

There are *only* 4 fundamental forces in the universe.

The weak force is responsible for radioactive decay. It actually makes neutrons turn into protons, amongst other things, and every type of matter particle experiences it.

Fundamental Interactions

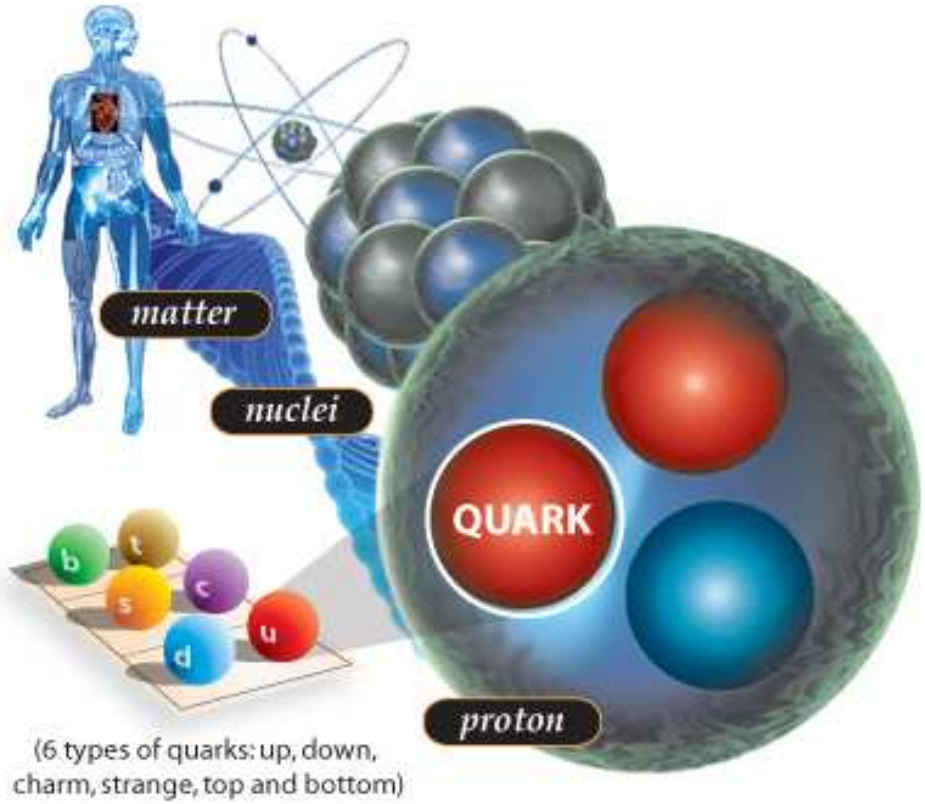
There are *only* 4 fundamental forces in the universe.



The strong force (so-called because it is stronger than the weak force) is only felt by quarks. It behaves like elastic, because the further apart you pull two quarks, the stronger the strong force gets between them.

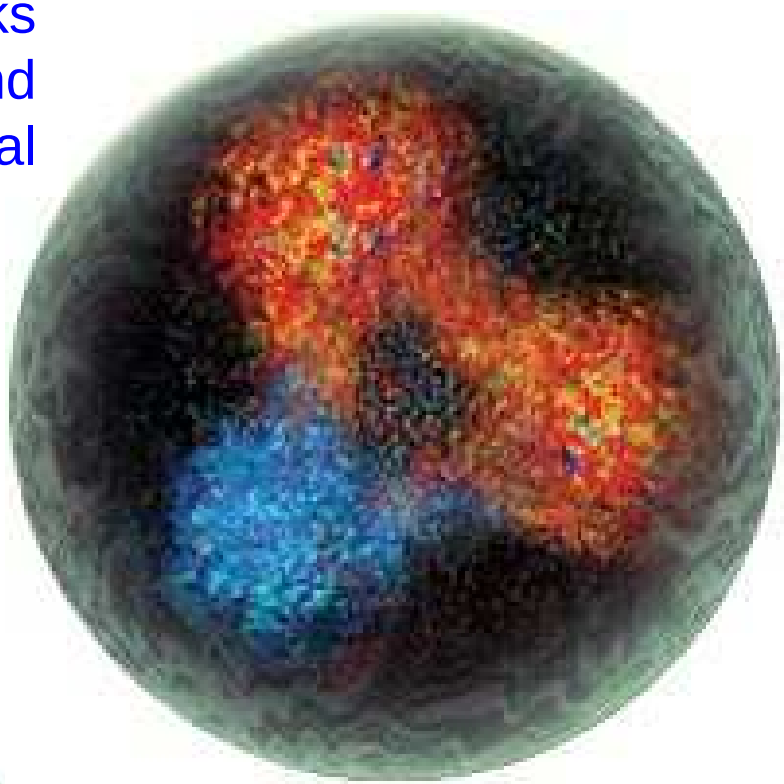
Review: Properties of the Sun
Properties of the Sun
Energy Transport
The Heart of the Sun
The Forces and Particles in the Universe
Nuclear Fusion
Measuring the Stars
Stellar Parallax
Stellar Motion

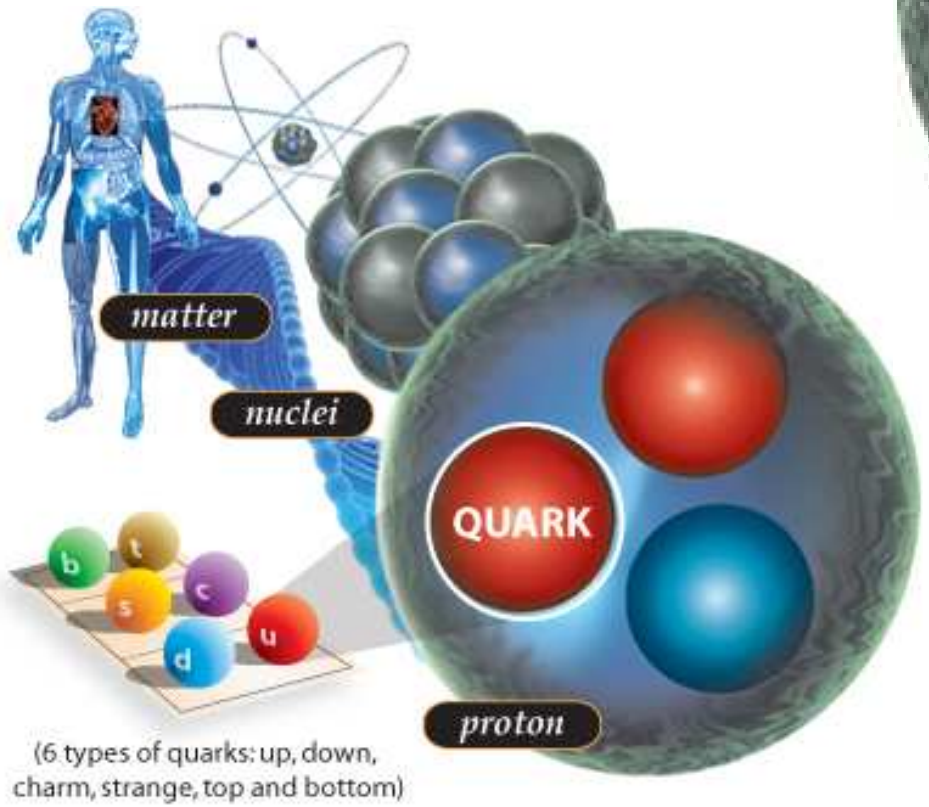
The Proton



The Proton

On a sub-microscopic level, the quarks in a proton appear as shared force and energy rather than as three individual "billiard balls."

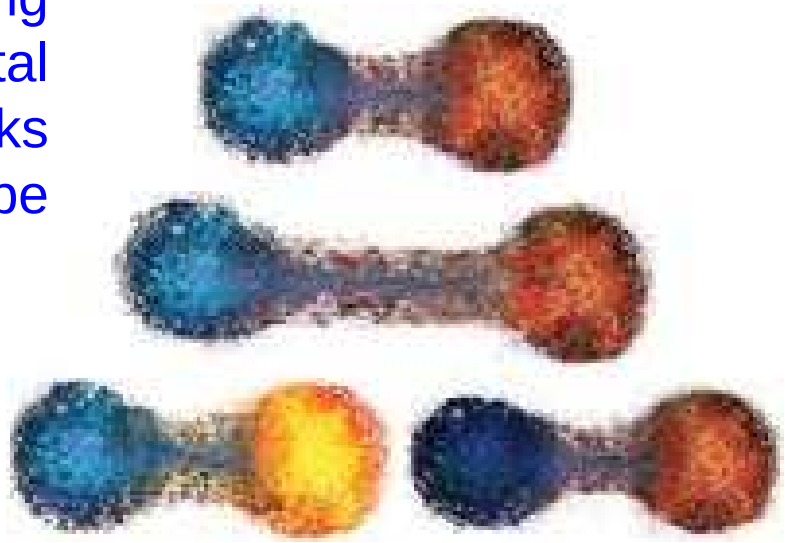


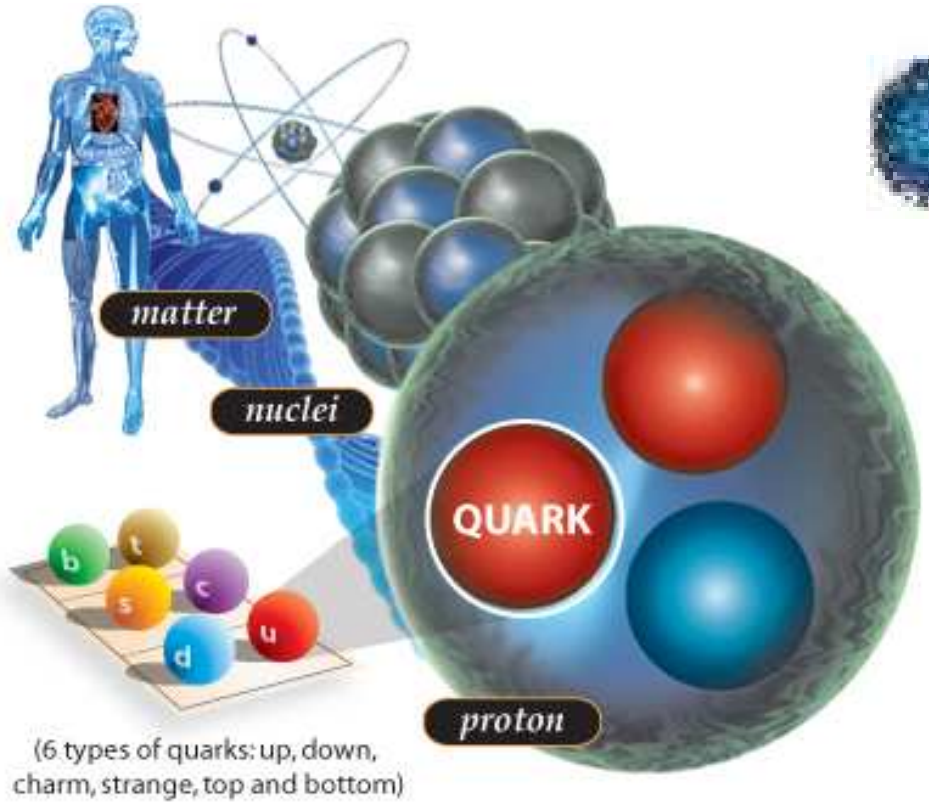


(6 types of quarks: up, down, charm, strange, top and bottom)

Confinement

We observe the crucial phenomenon of *confinement* yet remain baffled by its underlying cause. Understanding confinement is one of the fundamental questions in physics today. If quarks were not confined, the world would be a very different place.

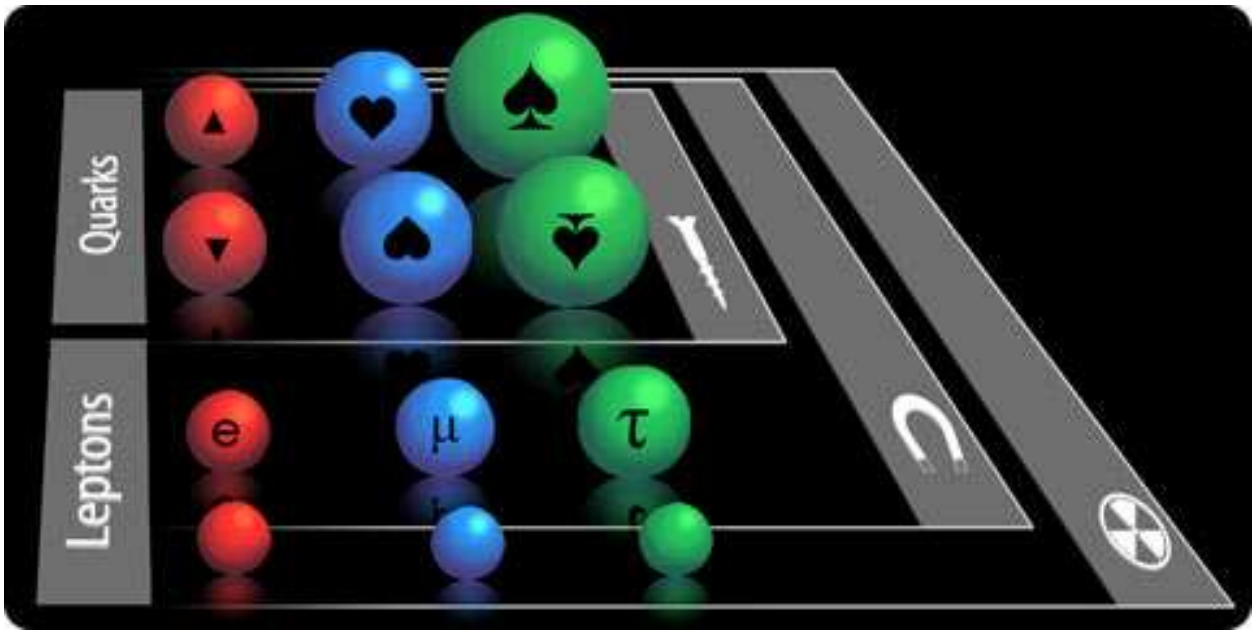




(6 types of quarks: up, down, charm, strange, top and bottom)

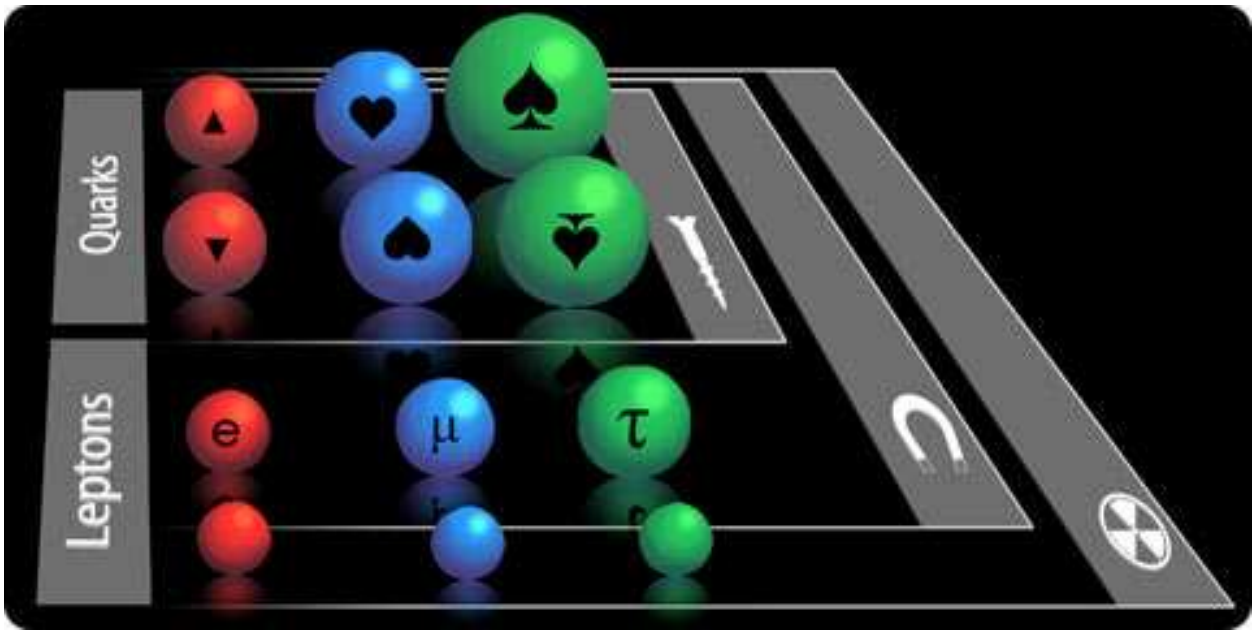
Fundamental Particles

1. Why are there exactly twelve fundamental matter particles?



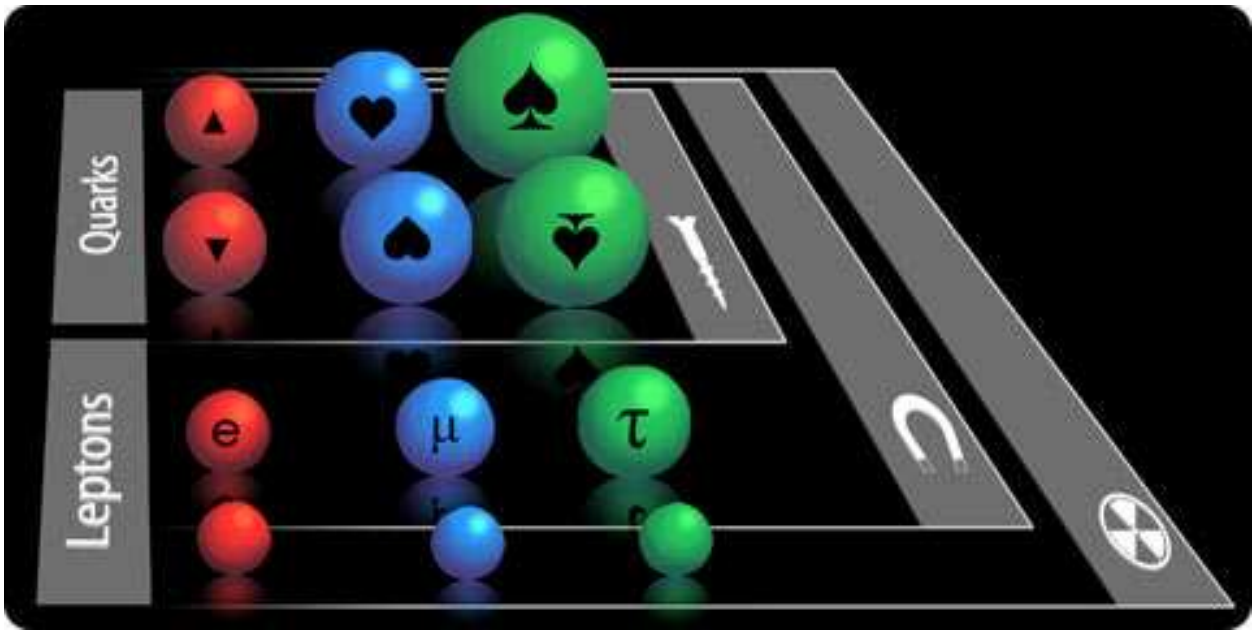
Fundamental Particles

1. Why are there exactly twelve fundamental matter particles?
2. Are these twelve particles fundamental, or are they in turn made up of other, smaller particles?



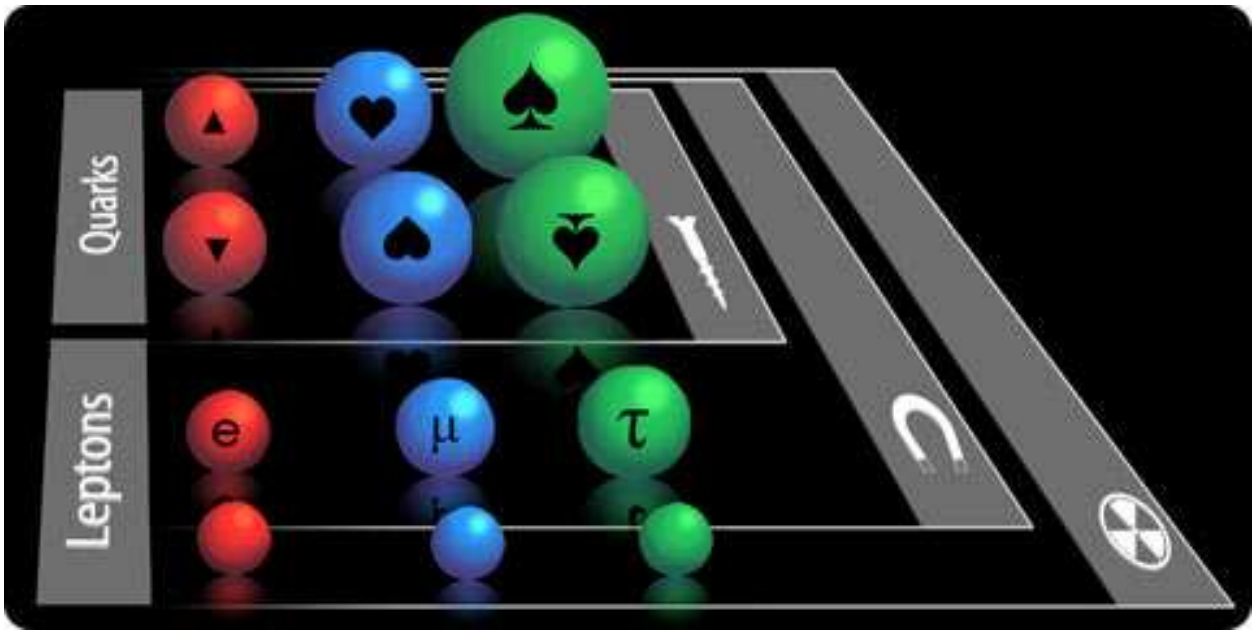
Fundamental Particles

1. Why are there exactly twelve fundamental matter particles?
2. Are these twelve particles fundamental, or are they in turn made up of other, smaller particles?
3. What is mass - how do particles get heavy?

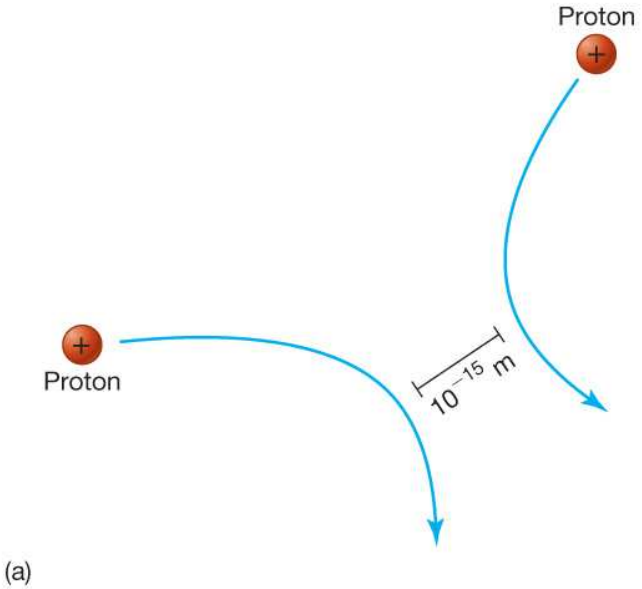


Fundamental Particles

1. Why are there exactly twelve fundamental matter particles?
2. Are these twelve particles fundamental, or are they in turn made up of other, smaller particles?
3. What is mass - how do particles get heavy?
4. Where does gravity fit into the Standard Model?

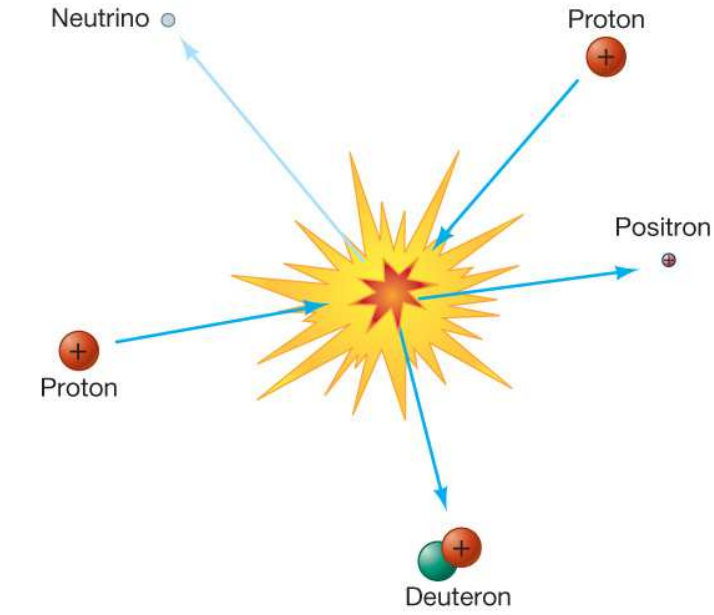


Proton Interactions



Nuclear fusion requires that like-charged nuclei get close enough to each other to fuse:

nucleus 1 + nucleus 2
➜ nucleus 3 + energy



1. Total mass decreases:

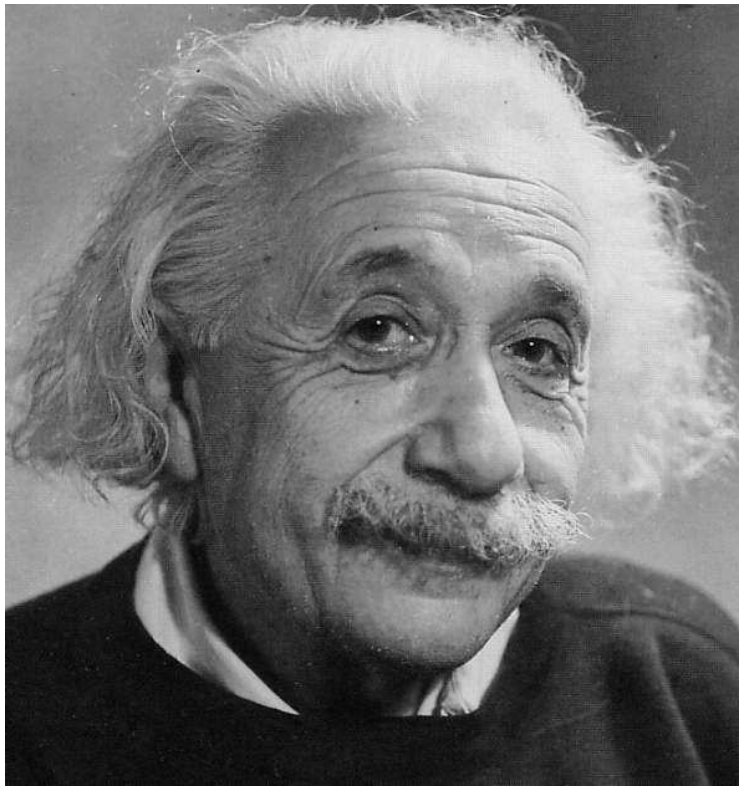
$$E = mc^2$$

2. $\mathrm{p} + \mathrm{p} \rightarrow \mathrm{d} + \mathrm{e}^+ + \nu$

Review: Properties of the Sun
Properties of the Sun
Energy Transport
The Heart of the Sun
The Forces and Particles in the Universe
Nuclear Fusion
Measuring the Stars
Stellar Parallax
Stellar Motion

Hydrogen Bomb

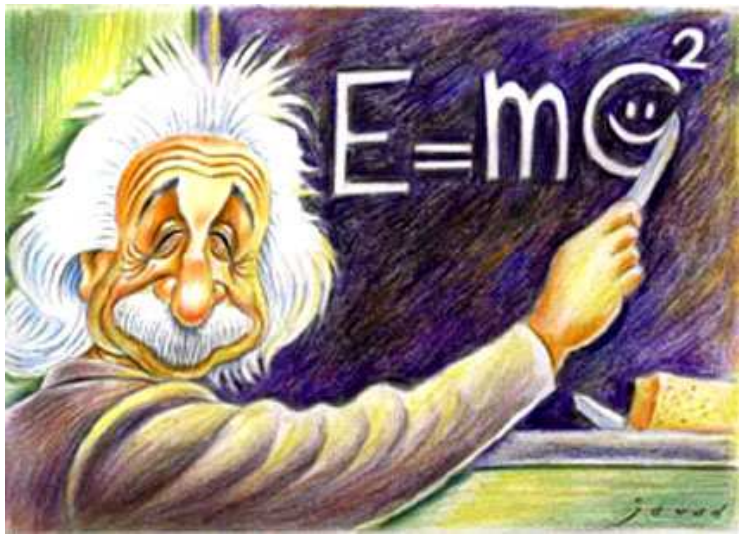
Review: Properties of the Sun
Properties of the Sun
Energy Transport
The Heart of the Sun
The Forces and Particles in the Universe
Nuclear Fusion
Measuring the Stars
Stellar Parallax
Stellar Motion

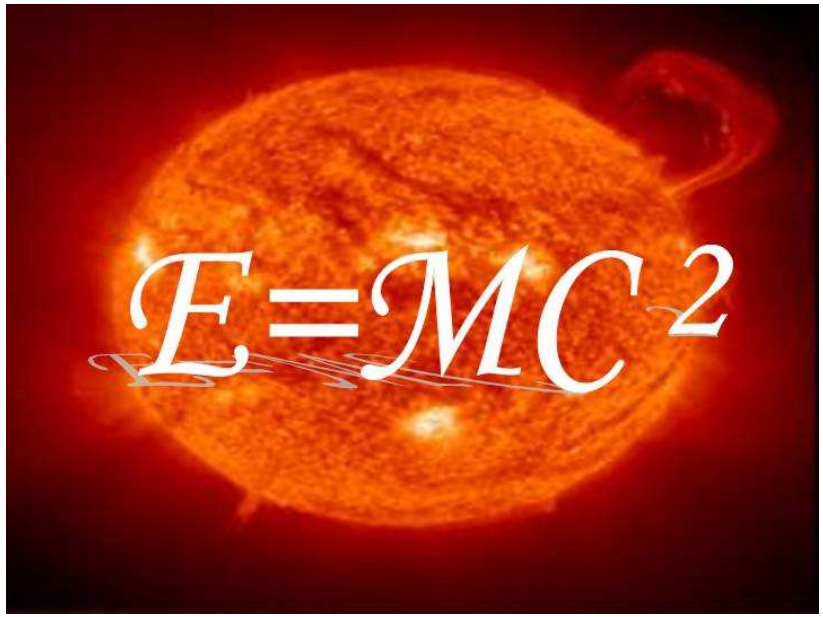


Albert Einstein

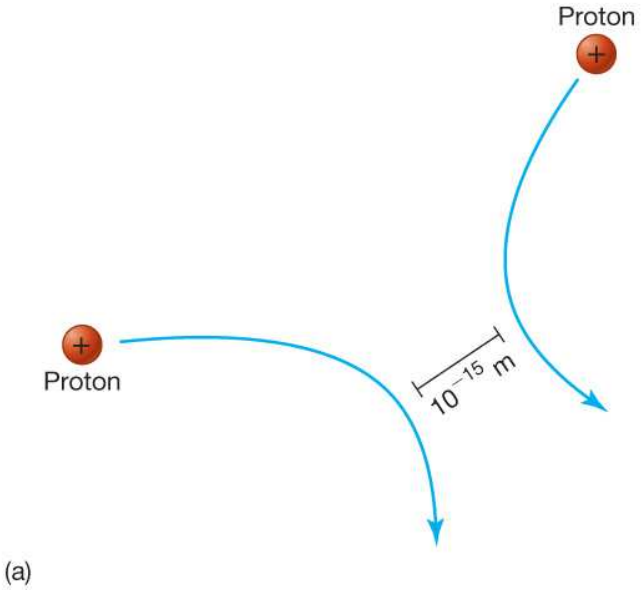
Result of

"Theory of General Relativity"

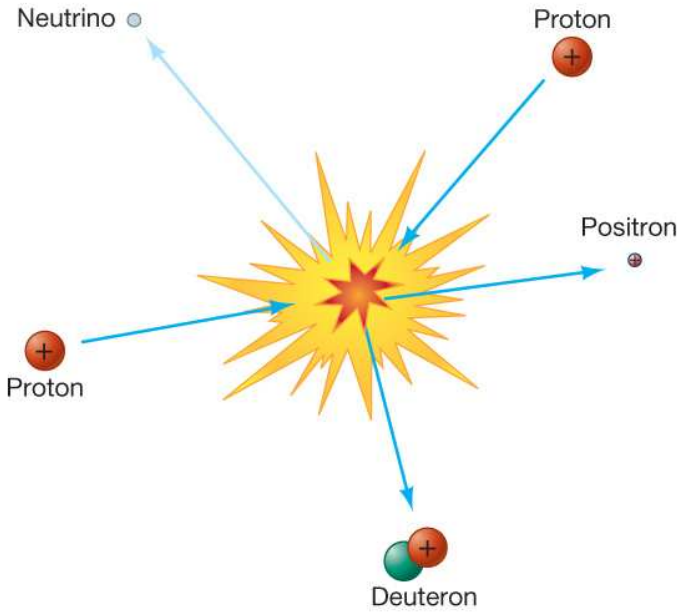




Proton Interactions



(a)

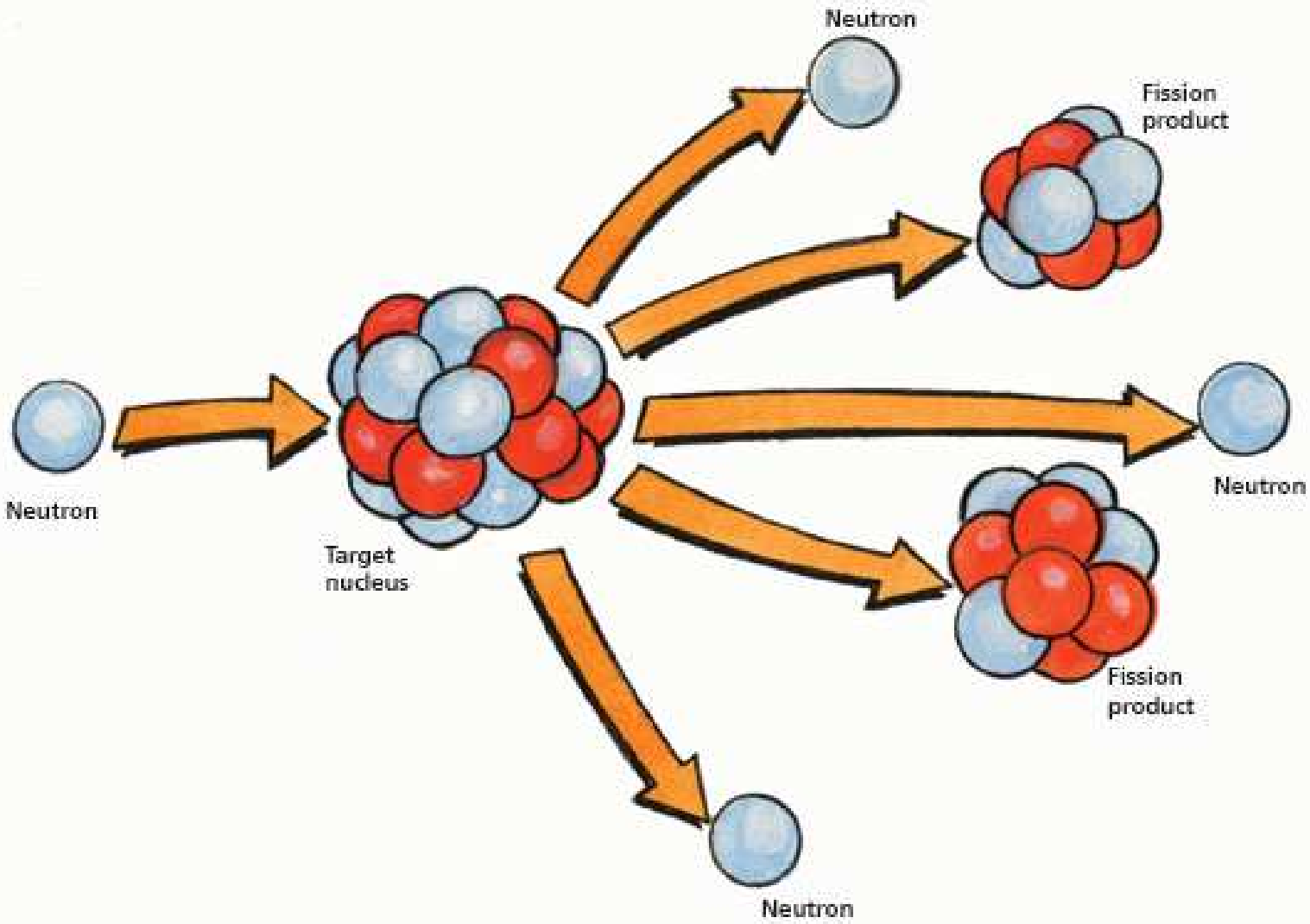


(b)

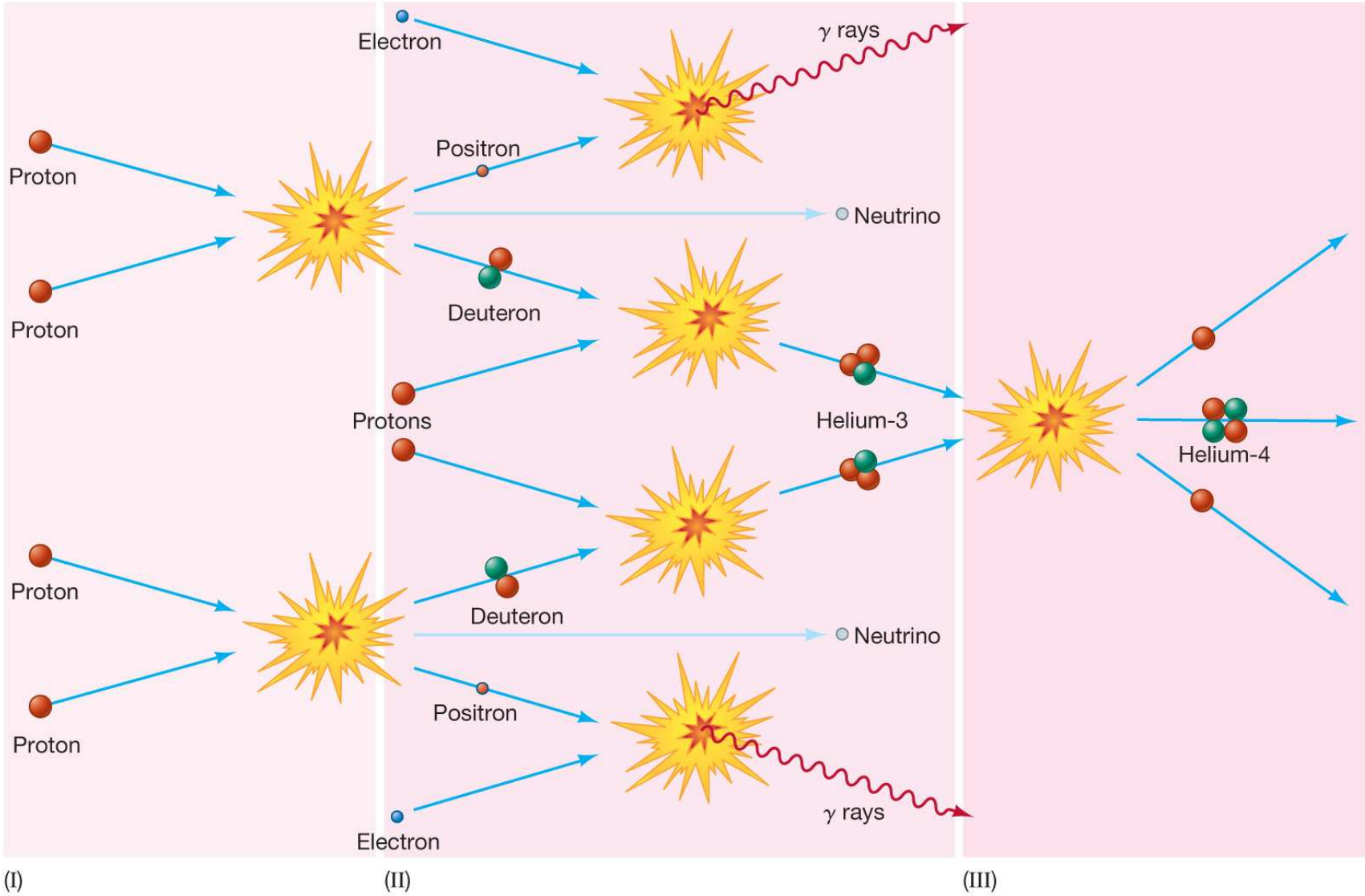
Nuclear fusion requires that like-charged nuclei get close enough to each other to fuse.

This can happen only if the temperature is extremely high – over 10 million K.

Nuclear Fission



Solar Fusion



http://www.jinaweb.org/movies/pp_chain.html

The Particle Zoo

Review: Properties of the Sun
Properties of the Sun
Energy Transport
The Heart of the Sun
The Forces and Particles in the Universe
Nuclear Fusion
Measuring the Stars
Stellar Parallax
Stellar Motion

Energy Balance

Energy Generation in the Proton-Proton Chain

1. $m_{4\,\text{protons}} = 6.6943 \cdot 10^{-27}$ kg
2. $m_{\text{helium}-4} = 6.6466 \cdot 10^{-27}$ kg

➜ $\Delta m = 0.0477 \cdot 10^{-27}$ kg

Energy Balance

Energy Generation in the Proton-Proton Chain

1. $m_{4\,\text{protons}} = 6.6943 \cdot 10^{-27}$ kg
2. $m_{\text{helium}-4} = 6.6466 \cdot 10^{-27}$ kg

➜ $\Delta m = 0.0477 \cdot 10^{-27}$ kg

energy = mass · (speed of light)^2

$E = 0.0477 \cdot 10^{-27}\ \text{kg} \cdot (3 \cdot 10^8\ \text{m/s})^2 = 4.28 \cdot 10^{-12}\ \text{J}$

➜ The process converts about 0.71 % of the original mass into pure energy.

Energy Balance

Energy Generation in the Proton-Proton Chain

1. $m_{4\,\text{protons}} = 6.6943 \cdot 10^{-27}$ kg
2. $m_{\text{helium}-4} = 6.6466 \cdot 10^{-27}$ kg

➜ $\Delta m = 0.0477 \cdot 10^{-27}$ kg

energy = mass · (speed of light)^2

$E = 0.0477 \cdot 10^{-27}\ \text{kg} \cdot (3 \cdot 10^8\ \text{m/s})^2 = 4.28 \cdot 10^{-12}\ \text{J}$

➜ The process converts about 0.71 % of the original mass into pure energy.

Sun has a luminosity of $3.86 \cdot 10^{26}$ W

➜ Mass consumption rate of roughly 600 million tons of hydrogen every second

Neutrinos

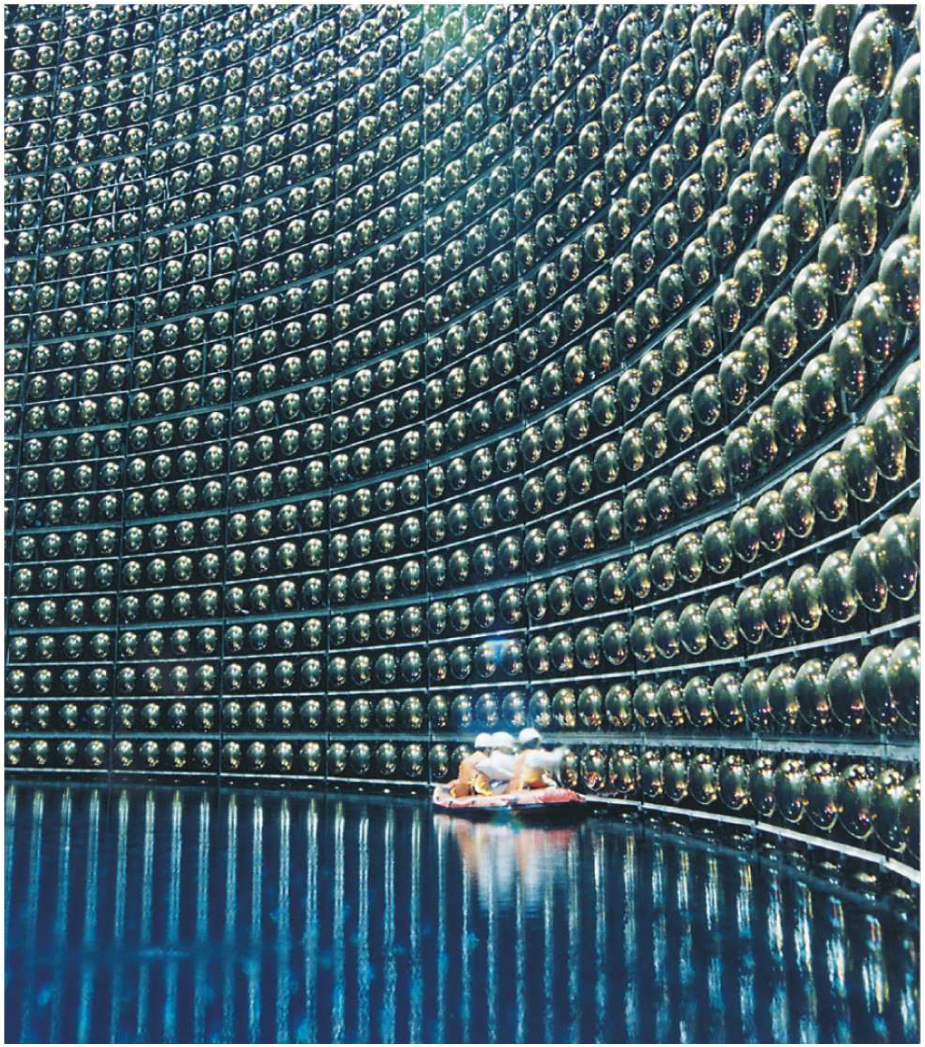
Neutrinos are emitted directly from the core of the Sun, and escape, interacting with virtually nothing. Being able to observe these neutrinos would give us a direct picture of what is happening in the core.

Unfortunately, they are no more likely to interact with Earth-based detectors than they are with the Sun; the only way to spot them is to have a huge detector volume and to be able to observe single interaction events.

Solar Neutrino Problem:

The number of solar neutrinos that reach our Earth is substantially less (by 30 to 50 %) than the prediction of the standard solar model.

Neutrino Telescopes: Super Kamiokande



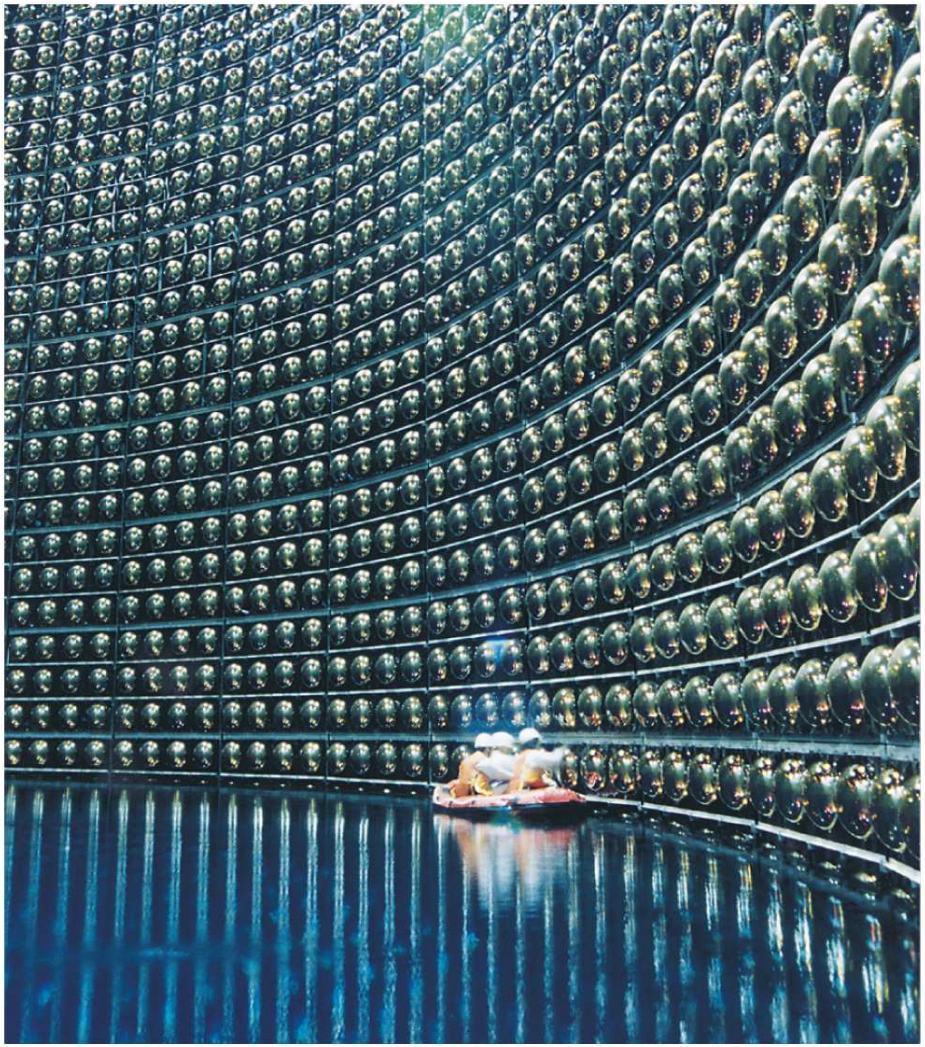
Buried beneath a mountain near Tokyo, Japan

- 50,000 tons of purified water
- 13,000 light detectors

In November 2001, one detector imploded

➜ Shock wave destroyed about half the detectors

Neutrino Telescopes: Super Kamiokande



Buried beneath a mountain near Tokyo, Japan

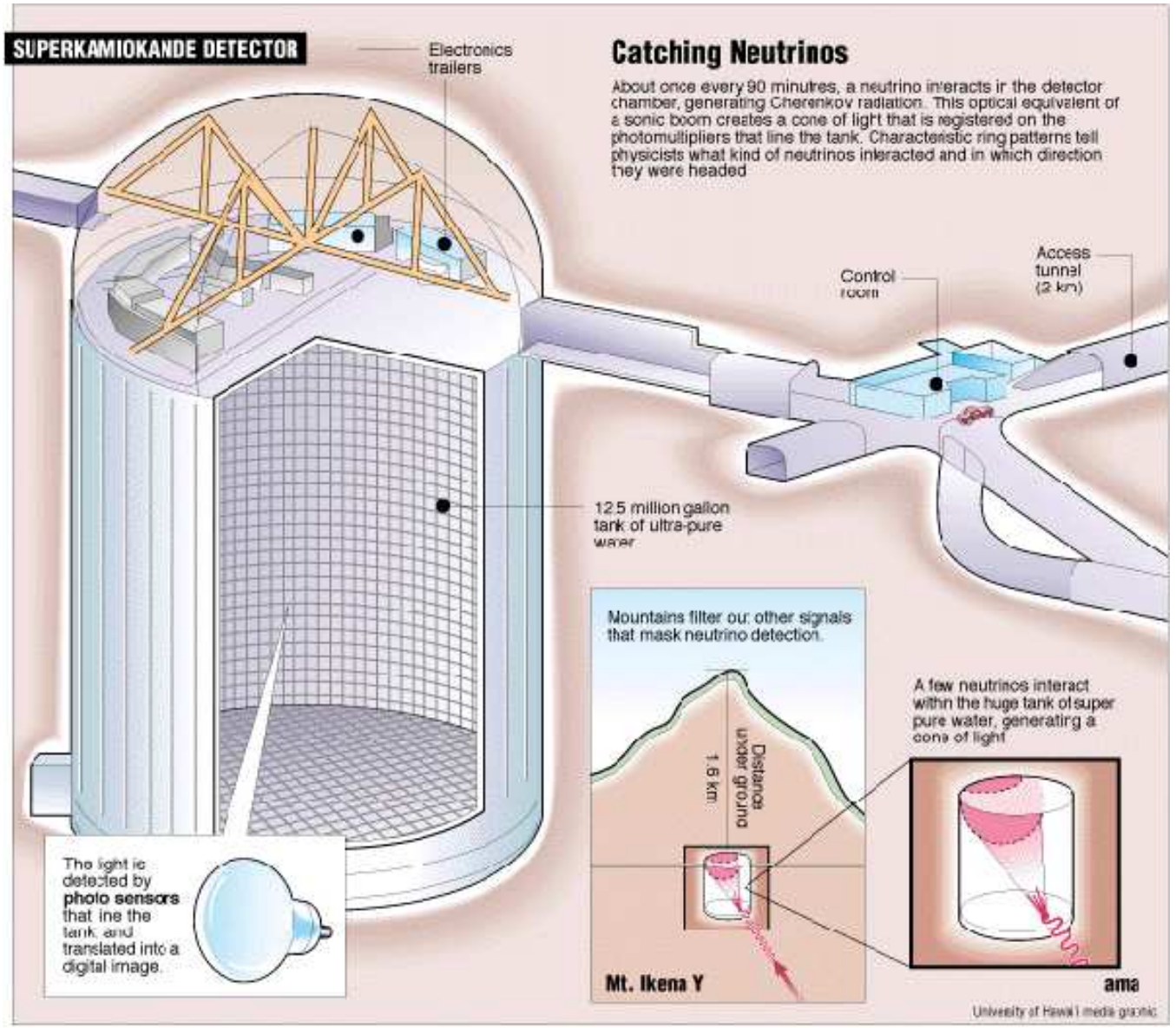
- 50,000 tons of purified water
- 13,000 light detectors

Experimental Program

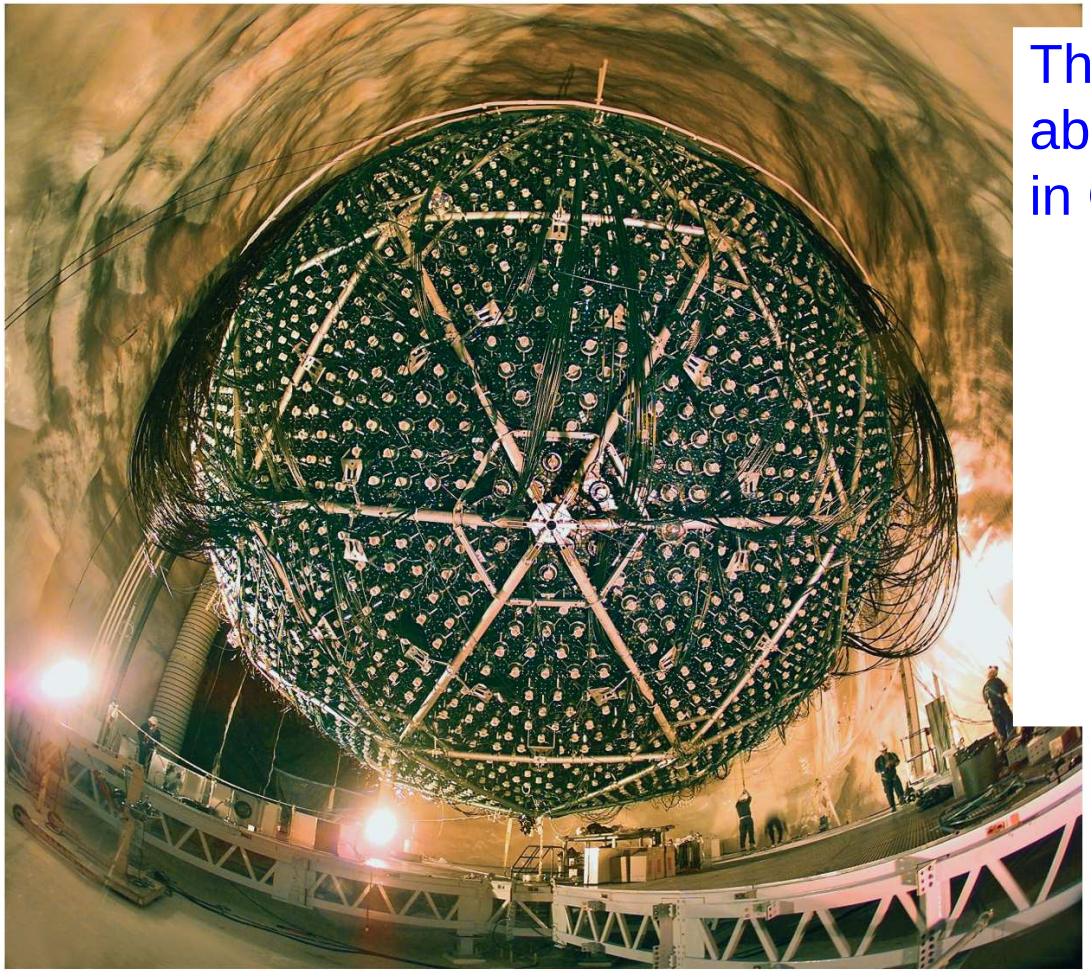
- Proton decay
  ➜ Grand Unification Theory (GUT)
- Observation of neutrinos (solar, super novae, etc.)
- Cosmic rays (mostly μ's)

Review: Properties of the Sun
Properties of the Sun
Energy Transport
The Heart of the Sun
The Forces and Particles in the Universe
Nuclear Fusion
Measuring the Stars
Stellar Parallax
Stellar Motion

Super Kamiokande: $\nu e^- \rightarrow \nu e^-$



Sudbury Neutrino Observatory



The detector is situated about 2 km underground in Ontario, Canada:

- D_2O instead of H_2O *(Heavy Water)*
- Additional two tons of salt (➜ sensitivity)
- 10,000 light-sensitive detectors

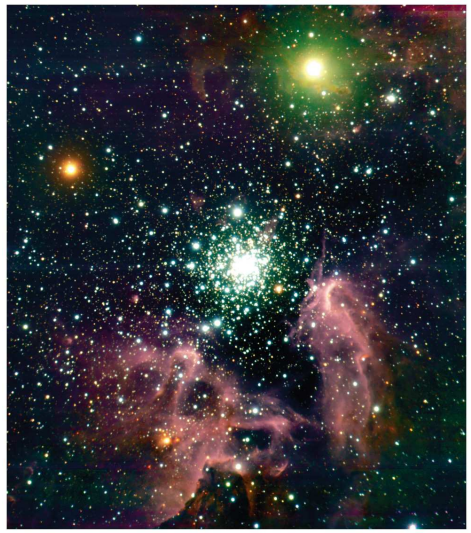
Review: Properties of the Sun
Properties of the Sun
Energy Transport
The Heart of the Sun
The Forces and Particles in the Universe
Nuclear Fusion
Measuring the Stars
Stellar Parallax
Stellar Motion

Outline

1 Review: Properties of the Sun
- Properties of the Sun
- Energy Transport

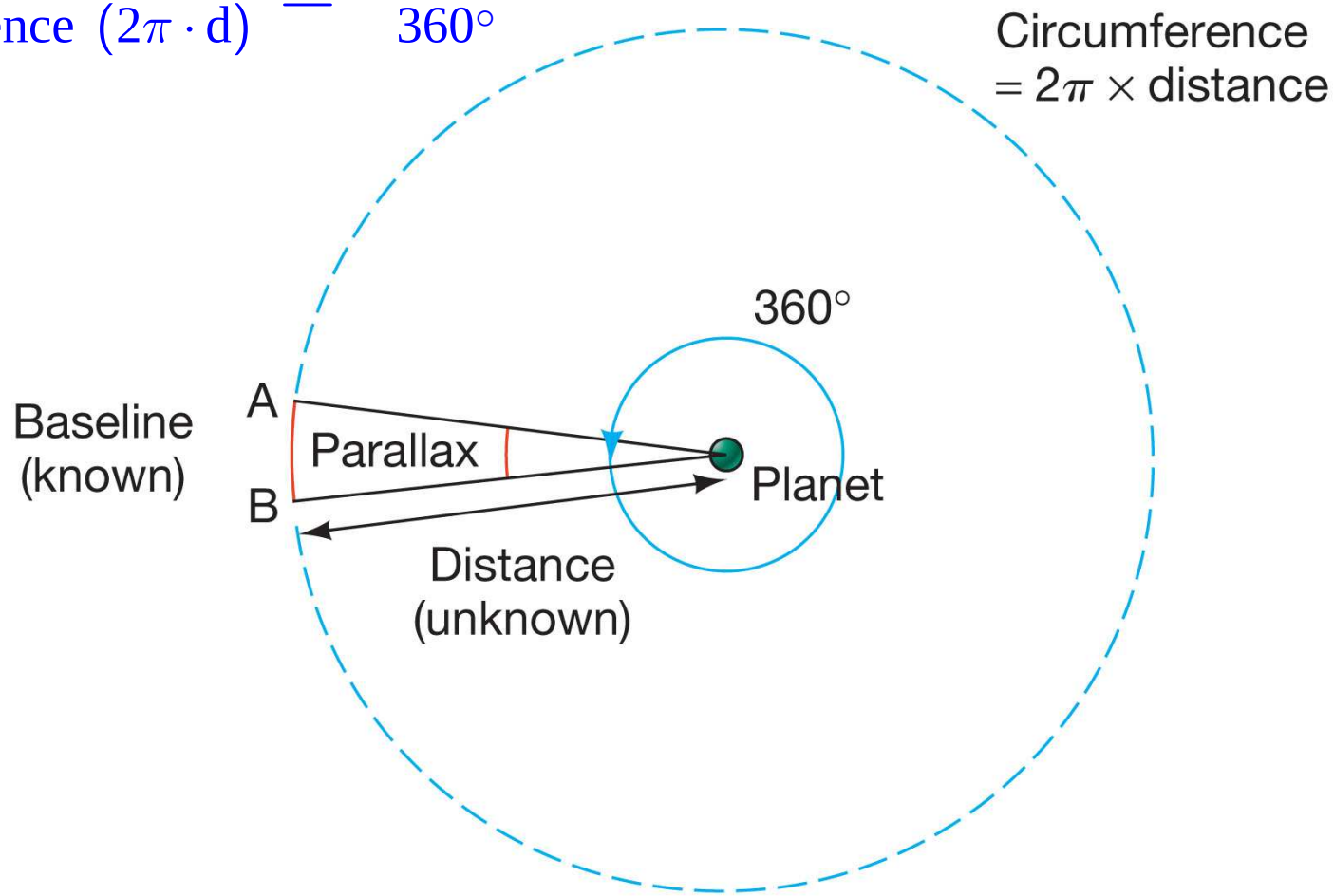
2 The Heart of the Sun
- The Forces and Particles in the Universe
- Nuclear Fusion

3 Measuring the Stars
- Stellar Parallax
- Stellar Motion

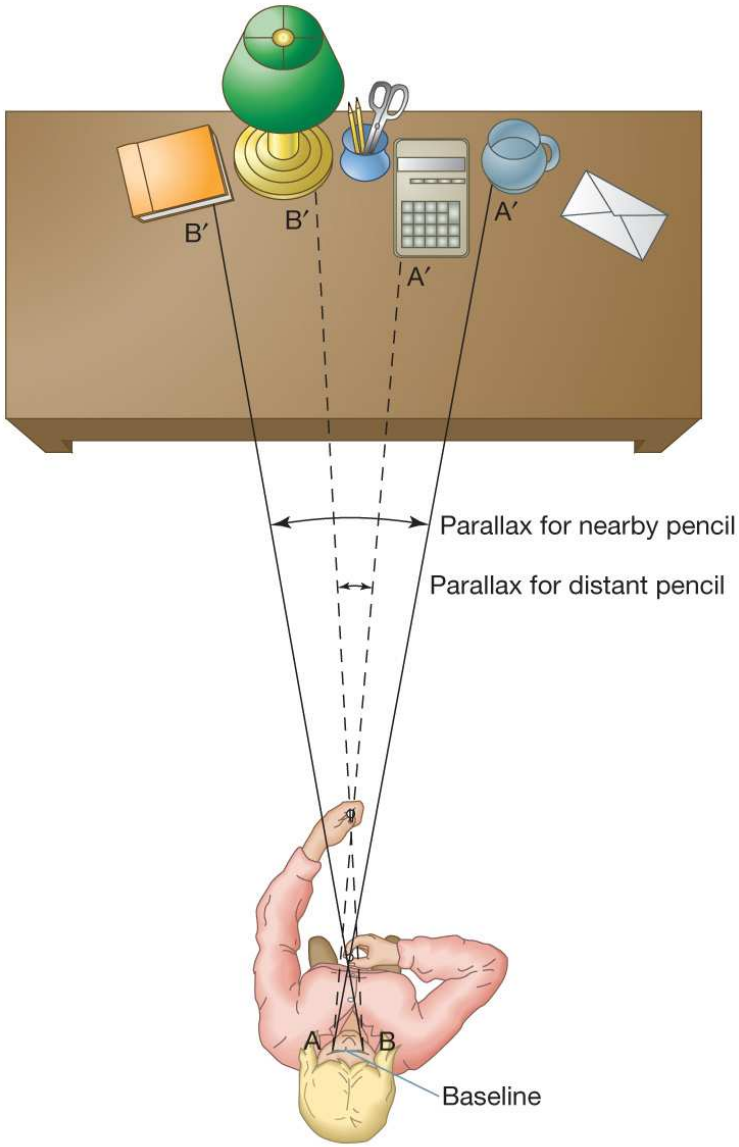


Measuring Distances with Geometry

$$\frac{\text{baseline (A – B)}}{\text{circumference } (2\pi \cdot \text{d})} = \frac{\text{parallax}}{360^\circ}$$



Parallax Geometry

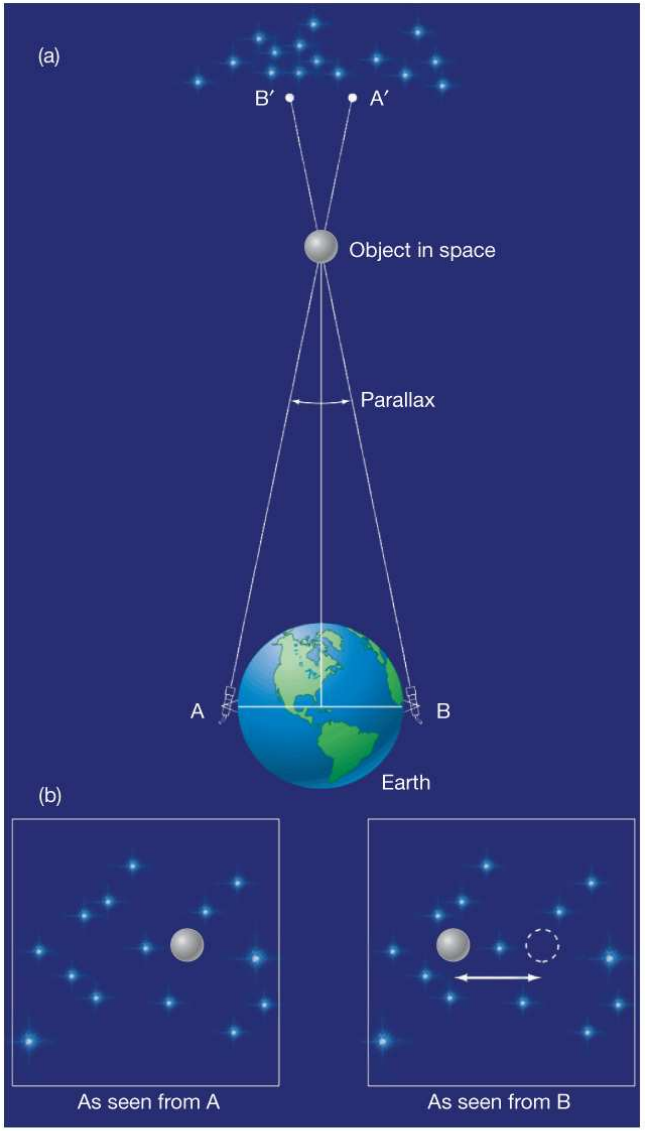


An object near your nose has a much larger parallax than an object held at arm's length.

Review: Properties of the Sun
Properties of the Sun
Energy Transport
The Heart of the Sun
The Forces and Particles in the Universe
Nuclear Fusion
Measuring the Stars
Stellar Parallax
Stellar Motion

The Measurement of Distance

Parallax: similar to triangulation, but look at apparent motion of object against distant background from two vantage points



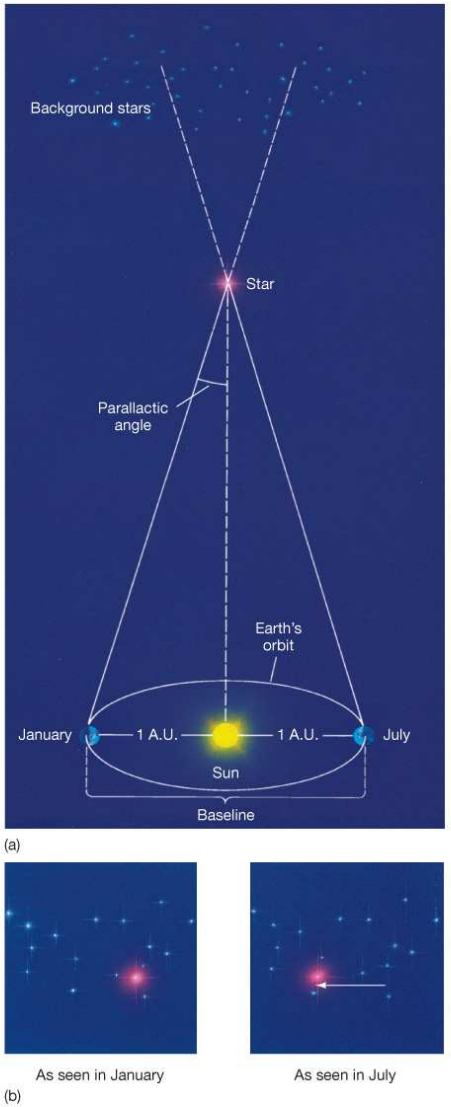
The Measurement of Distance

Parallax: similar to triangulation, but look at apparent motion of object against distant background from two vantage points

The baseline can be effectively extended to the diameter of Earth's orbit around the Sun, two astronomical units (AU).

Observed parallax of $1''$ corresponds to an object's distance from Sun of 206,265 AU or $3.1 \cdot 10^{16}$ m:

parsec (1 pc) $\approx$ 3.3 lightyears



The Measurement of Distance

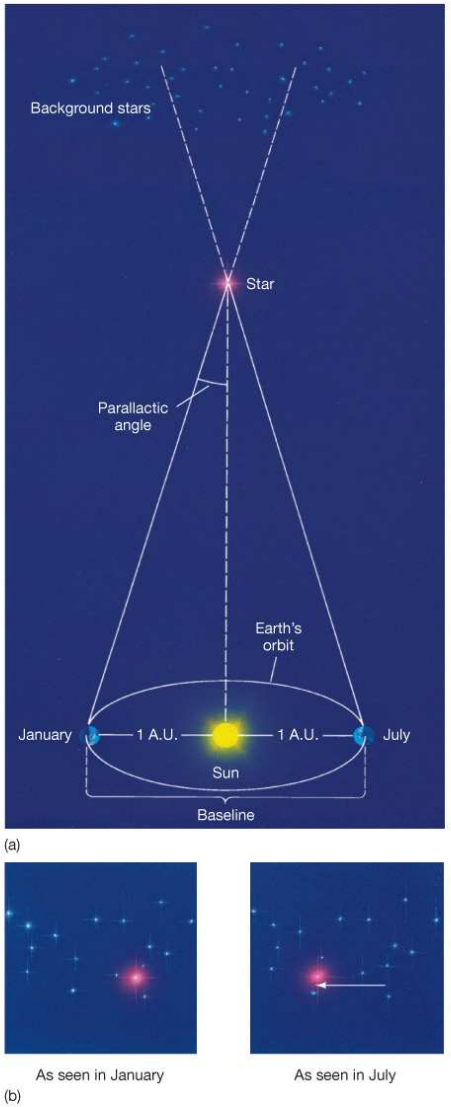
Parallax: similar to triangulation, but look at apparent motion of object against distant background from two vantage points

The baseline can be effectively extended to the diameter of Earth's orbit around the Sun, two astronomical units (AU).

distance (in parsecs)

= 1 / parallax (in arcseconds)

Example: parallax of $0.5''$ $\longrightarrow$ 2 pc



The Measurement of Distance

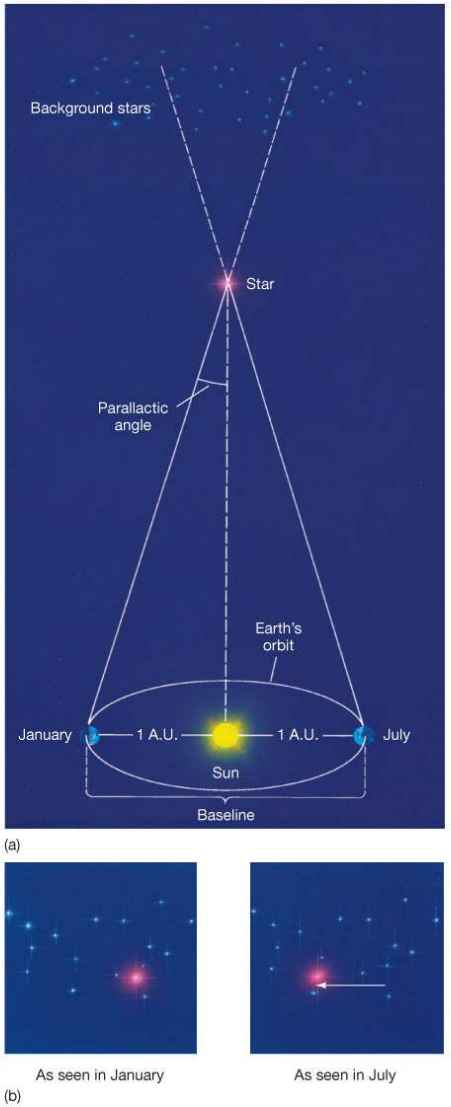
Parallax: similar to triangulation, but look at apparent motion of object against distant background from two vantage points

The baseline can be effectively extended to the diameter of Earth's orbit around the Sun, two astronomical units (AU).

distance (in parsecs)

= 1 / parallax (in arcseconds)

Example: parallax of $0.1''$ $\longrightarrow$ 10 pc



Review: Properties of the Sun
Properties of the Sun
Energy Transport
The Heart of the Sun
The Forces and Particles in the Universe
Nuclear Fusion
Measuring the Stars
Stellar Parallax
Stellar Motion

Example

How far away is the star *Spica*, whose parallax is $0.013''$?

Example

How far away is the star *Spica*, whose parallax is $0.013''$?

distance (in parsecs) = 1 / parallax (in arcseconds)

$$d = \frac{1}{0.013} \approx 77 \text{ pc}$$

The Solar Neighborhood

Nearest star to the Sun: *Proxima Centauri*, which is a member of a 3-star system (Alpha Centauri complex)

Simple model of distances:

1. Sun is a marble
   ➜ Earth is a grain of sand orbiting 1 m away

The Solar Neighborhood

Nearest star to the Sun: *Proxima Centauri*, which is a member of a 3-star system (Alpha Centauri complex)

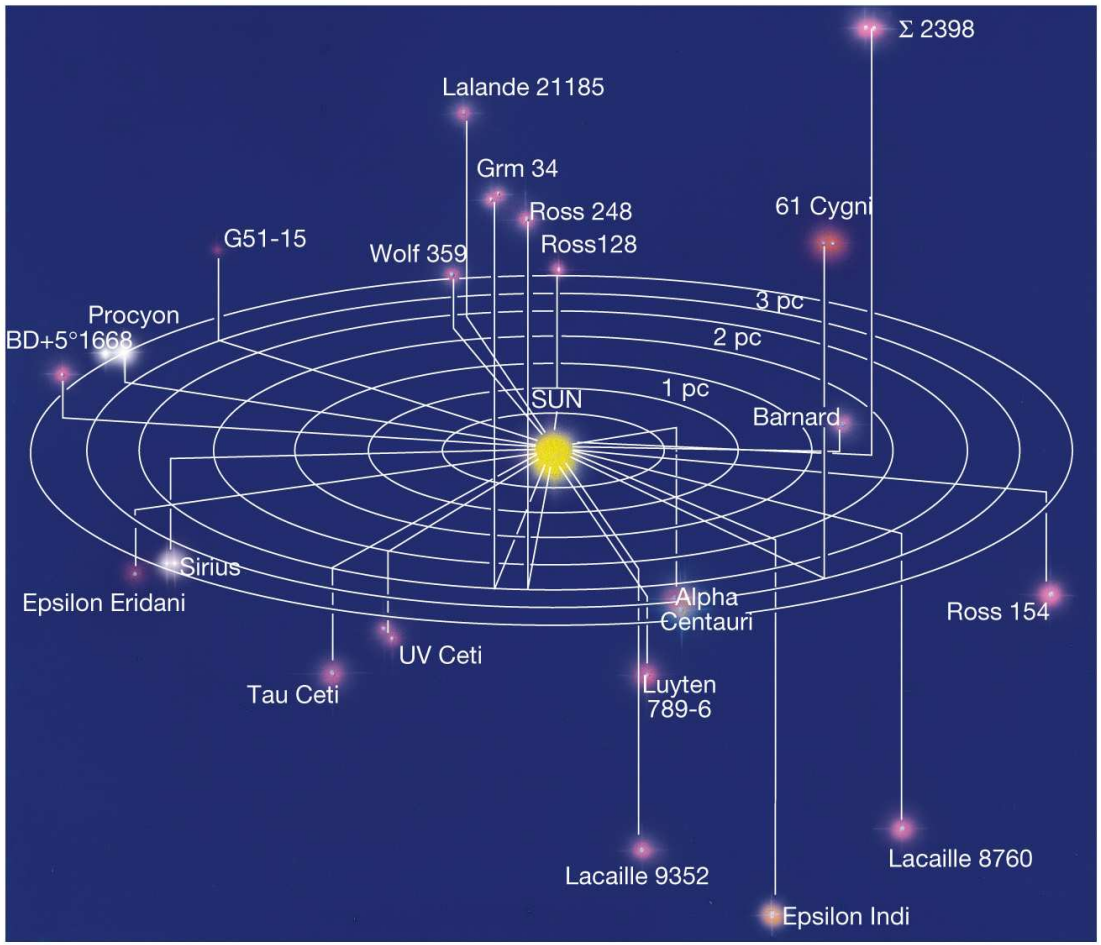
Simple model of distances:

1. Sun is a marble
   ➜ Earth is a grain of sand orbiting 1 m away
2. Nearest star is also a marble, but 270 km away
3. Solar system extends about 50 m from Sun; rest of distance to nearest star is essentially empty.

Sun's Neighborhood

The 30 closest stars to the Sun.

All lie within 4 pc (about 13 light-years) of Earth.



The Solar Neighborhood

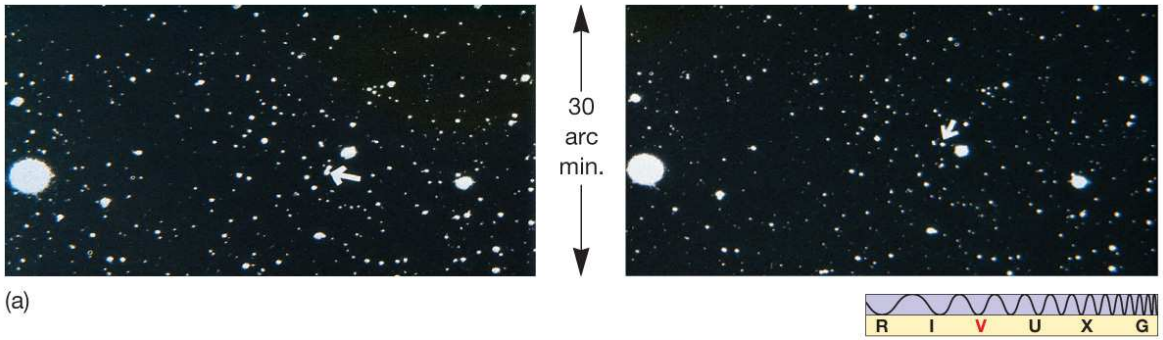
Nearest star to the Sun: *Proxima Centauri*, which is a member of a 3-star system (Alpha Centauri complex)

Simple model of distances:

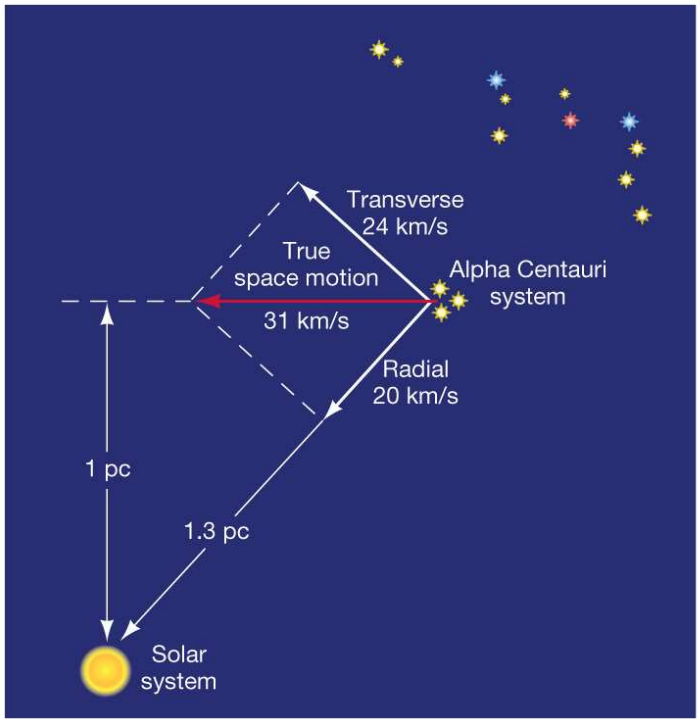
1. Sun is a marble
   ➜ Earth is a grain of sand orbiting 1 m away
2. Nearest star is also a marble, but 270 km away
3. Solar system extends about 50 m from Sun; rest of distance to nearest star is essentially empty.

- Adaptive optics systems allow parallax range to over 100 pc
- European *Hipparcos* stellite extended range to over 200 pc
- Next-generation space missions: $\approx$ 25,000 pc (our galaxy)

Real Space Motion



(a)



(b)

Barnard's Star (top) has the largest *proper motion* – *proper motion* is the actual shift of the star in the sky, after parallax correction (pictures taken 22 years apart).

⇐ Actual motion of *Alpha Centauri* complex