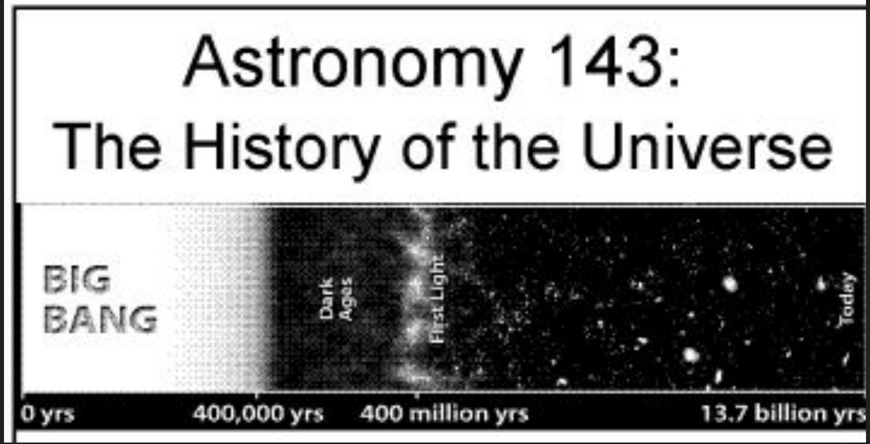
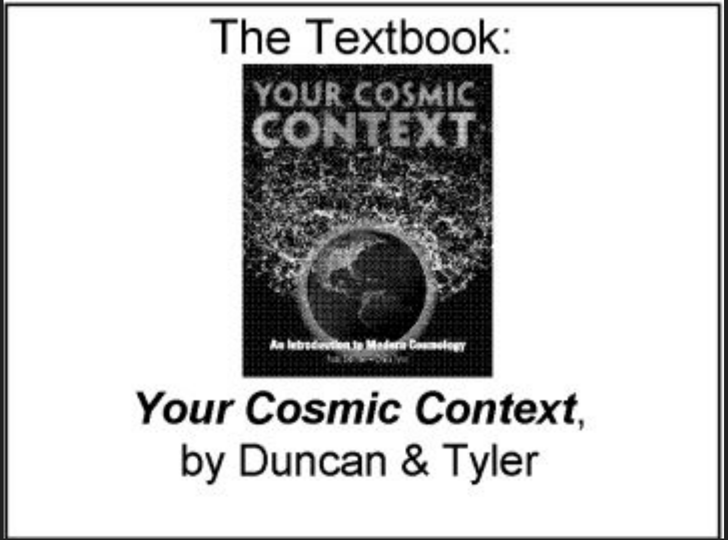
Week 1: Introduction

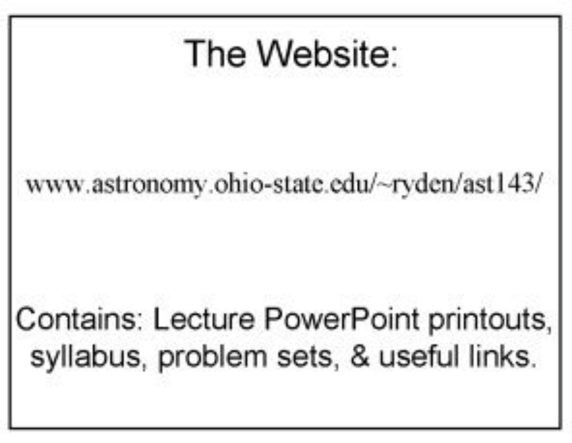


Astronomy 143:
The History of the Universe



The Textbook:

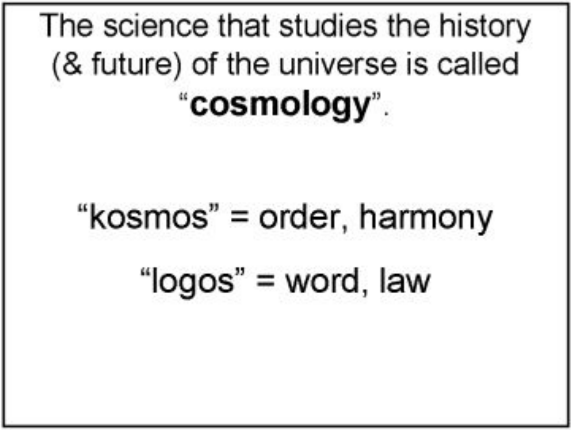
Your Cosmic Context,
by Duncan & Tyler



The Website:

www.astronomy.ohio-state.edu/~ryden/ast143/

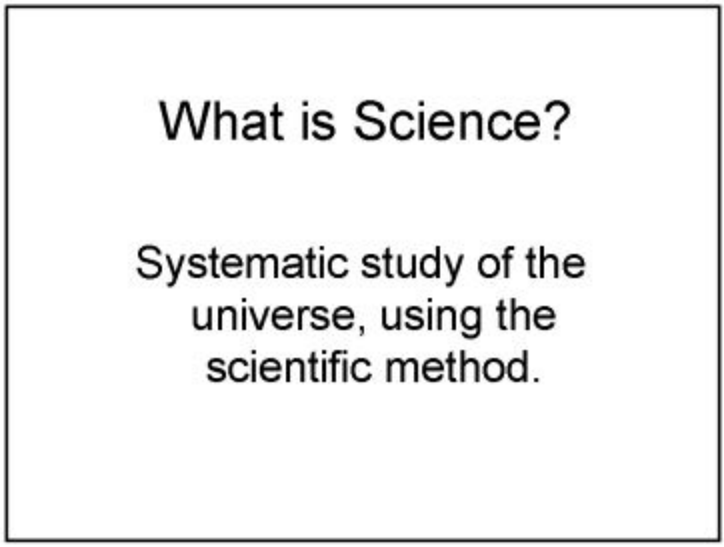
Contains: Lecture PowerPoint printouts, syllabus, problem sets, & useful links.



The science that studies the history (& future) of the universe is called "**cosmology**".

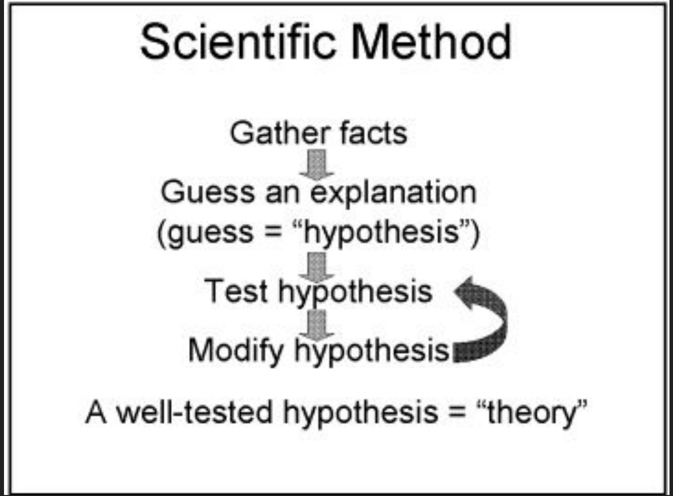
"kosmos" = order, harmony

"logos" = word, law



What is Science?

Systematic study of the universe, using the scientific method.



Scientific Method

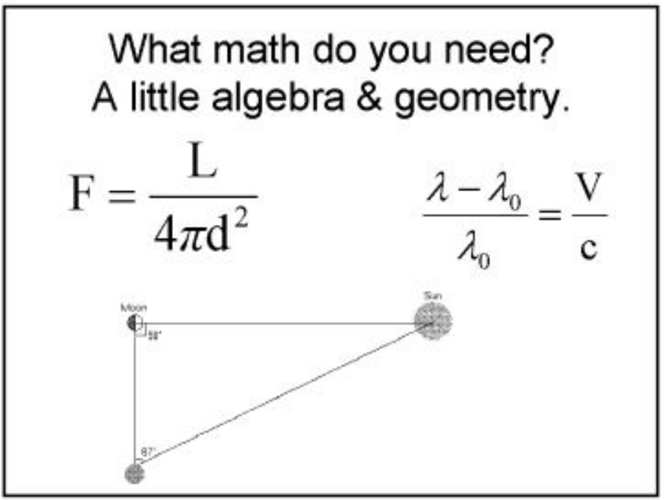
Gather facts

Guess an explanation
(guess = “hypothesis”)

Test hypothesis

Modify hypothesis

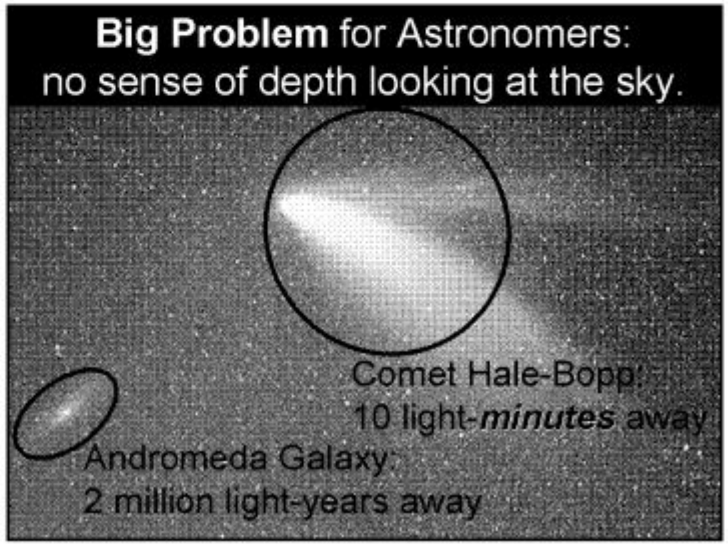
A well-tested hypothesis = “theory”



What math do you need?
A little algebra & geometry.

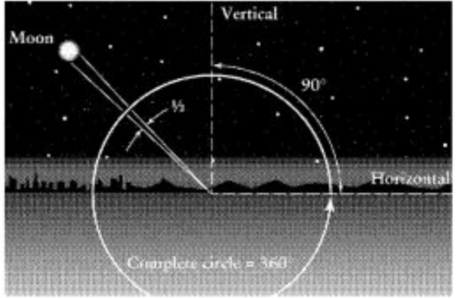
$$F = \frac{L}{4\pi d^2}$$

$$\frac{\lambda - \lambda_0}{\lambda_0} = \frac{V}{c}$$

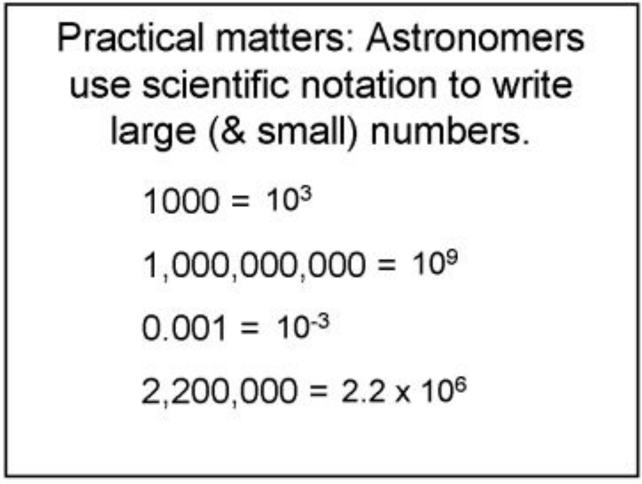


Big Problem for Astronomers:
no sense of depth looking at the sky.

There are 360 degrees in a circle,
60 arcminutes in a degree.



Seen from Earth, both Sun and Moon appear ½ degree across.



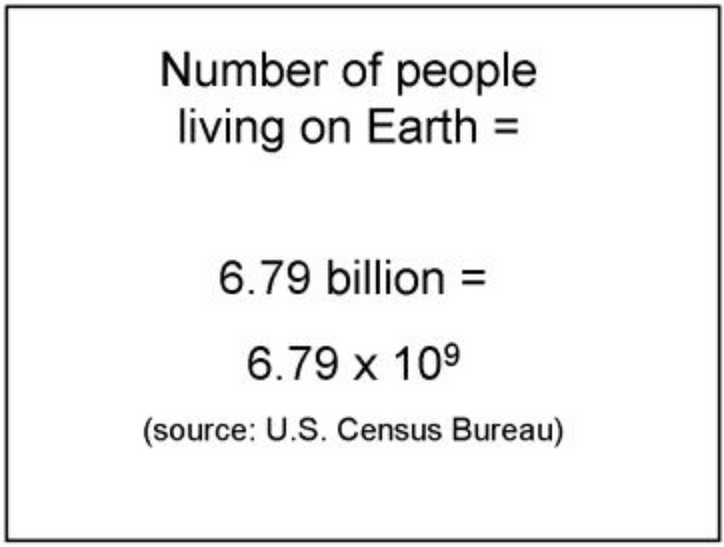
Practical matters: Astronomers use scientific notation to write large (& small) numbers.

$1000 = 10^3$

$1{,}000{,}000{,}000 = 10^9$

$0.001 = 10^{-3}$

$2{,}200{,}000 = 2.2 \times 10^6$

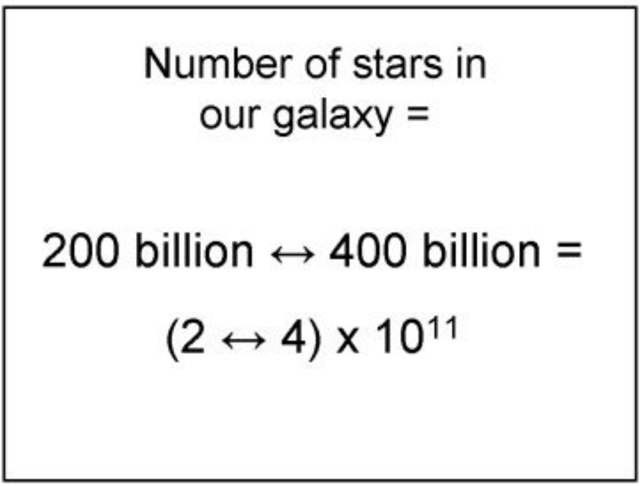


Number of people
living on Earth =

6.79 billion =

6.79 x 10^9

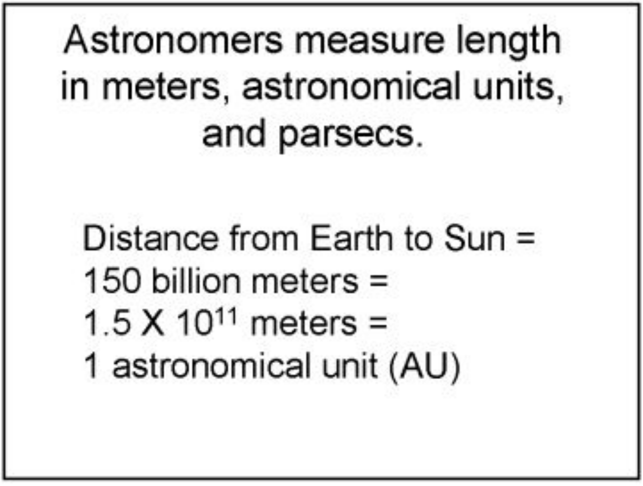
(source: U.S. Census Bureau)



Number of stars in
our galaxy =

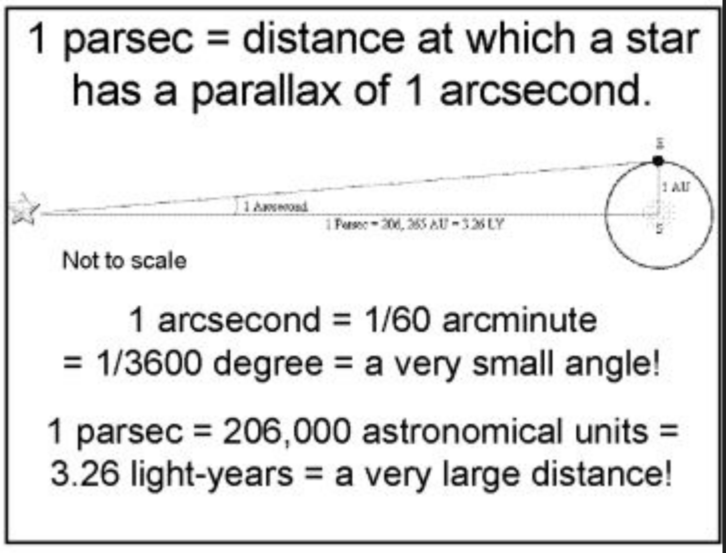
200 billion ↔ 400 billion =

(2 ↔ 4) x 10^{11}



Astronomers measure length in meters, astronomical units, and parsecs.

Distance from Earth to Sun =
150 billion meters =
1.5 X 10^{11} meters =
1 astronomical unit (AU)

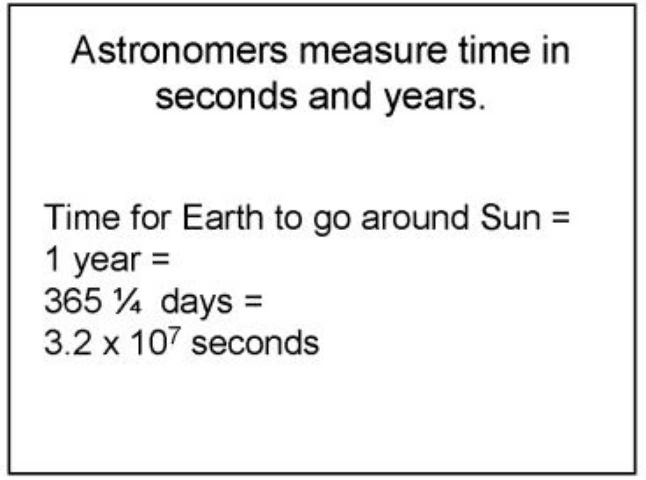


1 parsec = distance at which a star has a parallax of 1 arcsecond.

Not to scale

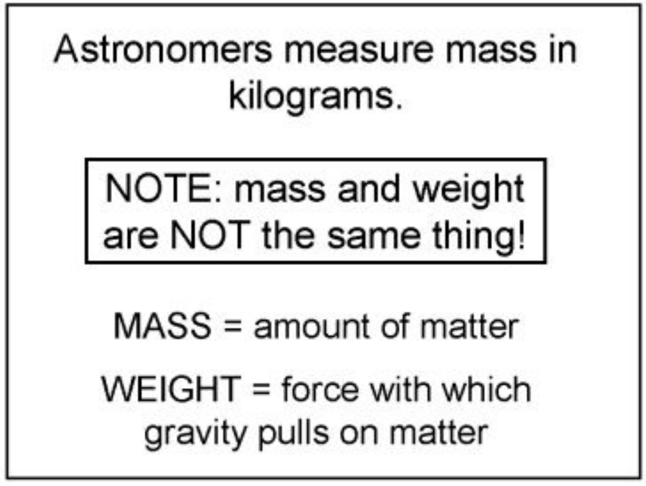
1 arcsecond = 1/60 arcminute
= 1/3600 degree = a very small angle!

1 parsec = 206,000 astronomical units =
3.26 light-years = a very large distance!



Astronomers measure time in seconds and years.

Time for Earth to go around Sun =
1 year =
365 ¼ days =
3.2×10^7 seconds

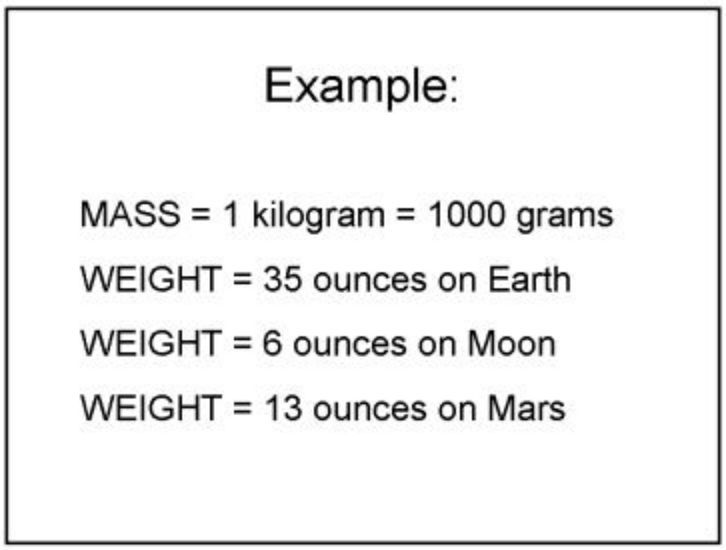


Astronomers measure mass in kilograms.

NOTE: mass and weight are NOT the same thing!

MASS = amount of matter

WEIGHT = force with which gravity pulls on matter



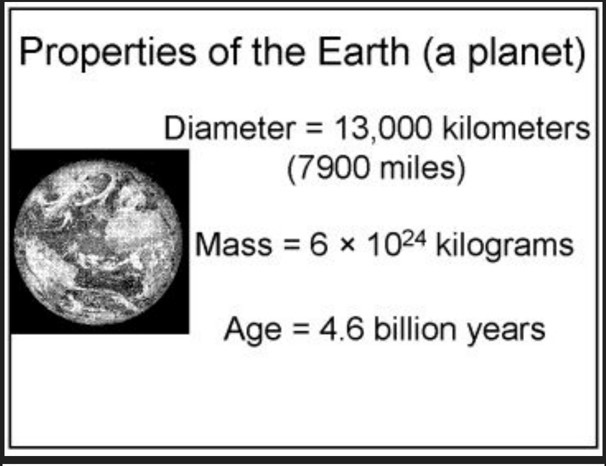
Example:

MASS = 1 kilogram = 1000 grams

WEIGHT = 35 ounces on Earth

WEIGHT = 6 ounces on Moon

WEIGHT = 13 ounces on Mars

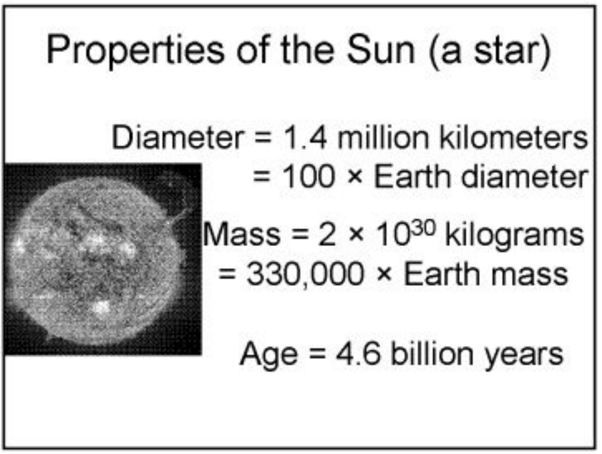


Properties of the Earth (a planet)

Diameter = 13,000 kilometers
(7900 miles)

Mass = 6 × 10^{24} kilograms

Age = 4.6 billion years



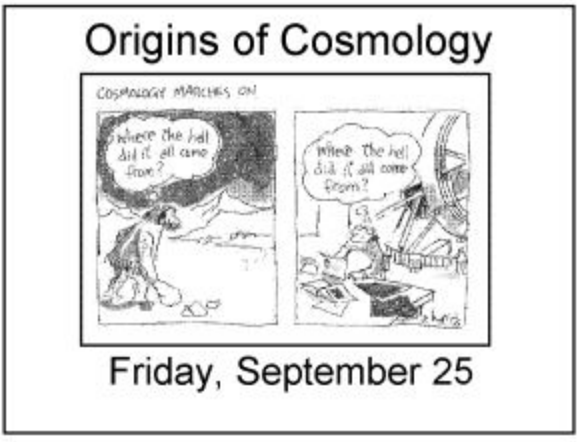
Properties of the Sun (a star)

Diameter = 1.4 million kilometers
= 100 × Earth diameter

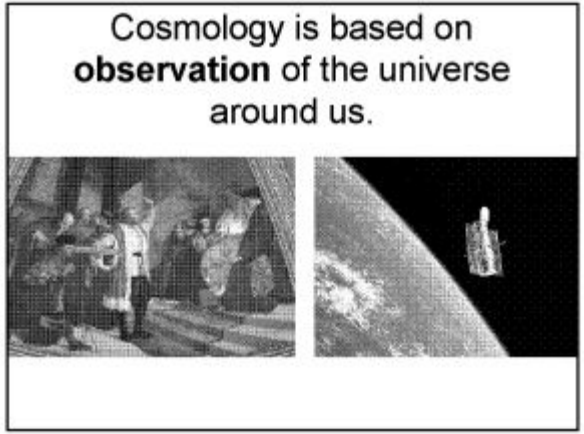
Mass = 2 × 10^{30} kilograms
= 330,000 × Earth mass

Age = 4.6 billion years

Week 1: The Origins of Cosmology


Origins of Cosmology

Friday, September 25


Cosmology is based on **observation** of the universe around us.


Looking WSW, 5:30 pm today

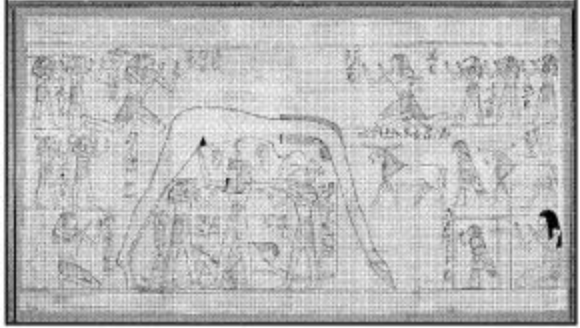
Sun ↑

Sky (blue)

horizon

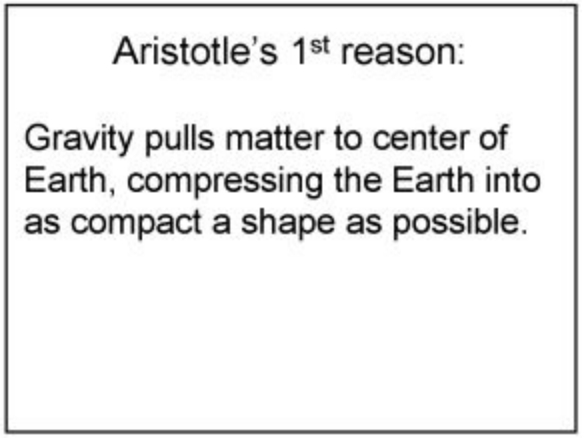
Earth (opaque)

Cosmology version 1.0:
Domed sky over flat earth.



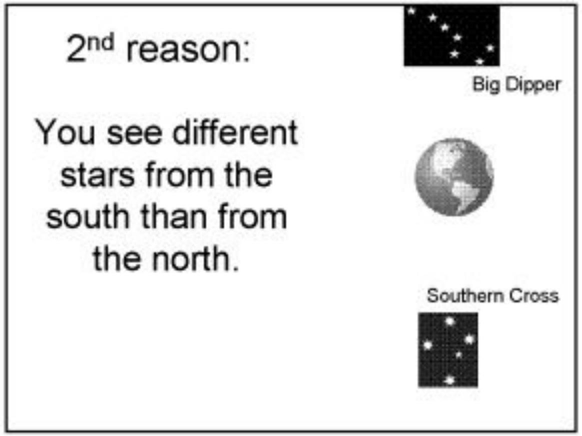
And God said, “Let there be a vault in the midst of the waters, and let it divide water from water.” And God made the vault and it divided the water beneath the vault from the water above the vault, and so it was.
– Genesis 1:6
[Robert Alter translation]

Aristotle (4th century BC): First to give reasons why the Earth is spherical.



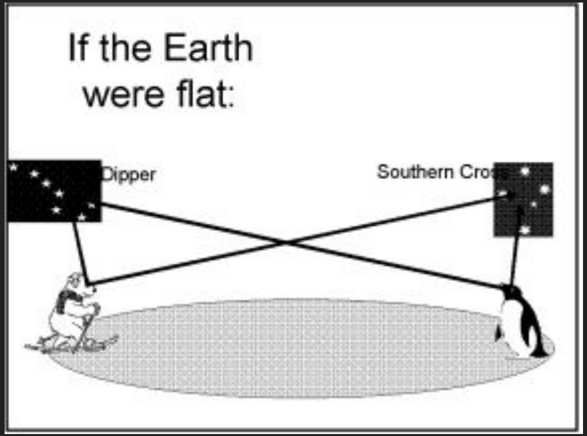
Aristotle's 1st reason:

Gravity pulls matter to center of Earth, compressing the Earth into as compact a shape as possible.

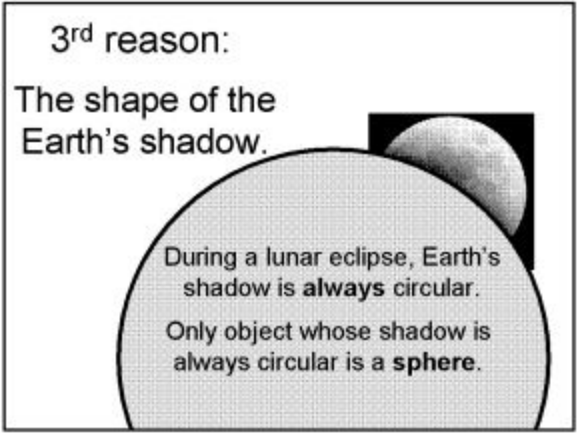


2nd reason:

You see different stars from the south than from the north.



If the Earth were flat:

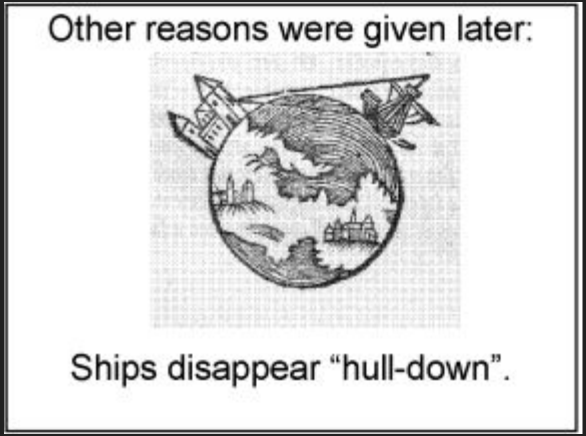


3rd reason:

The shape of the Earth's shadow.

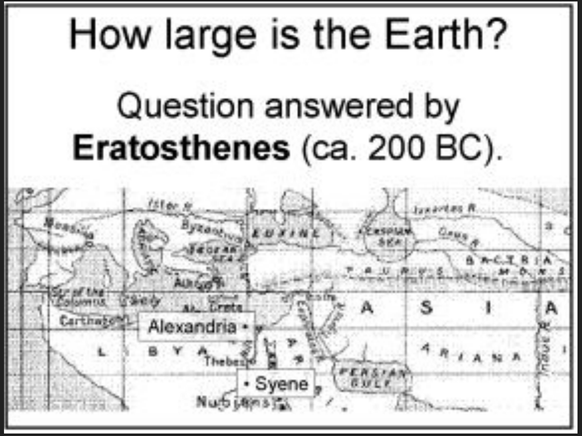
During a lunar eclipse, Earth's shadow is **always** circular.

Only object whose shadow is always circular is a **sphere**.



Other reasons were given later:

Ships disappear "hull-down".



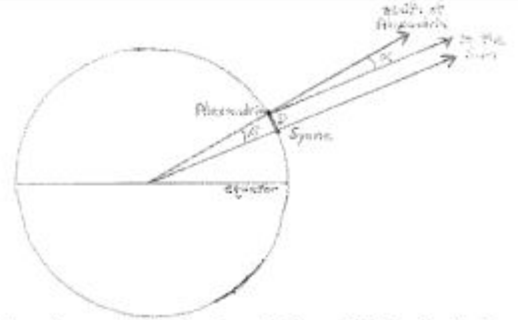
How large is the Earth?

Question answered by **Eratosthenes** (ca. 200 BC).

What Eratosthenes **read**: At noon on June 21, Sun is at zenith seen from Syene.

What he **saw**: At noon on June 21, Sun is 7.2° south of zenith seen from Alexandria.

What he **assumed**: Earth is spherical: Sun is very far away.



Angle α = angle β = 7.2° = 1/50 of circle.

Distance D = 1/50 of circumference.

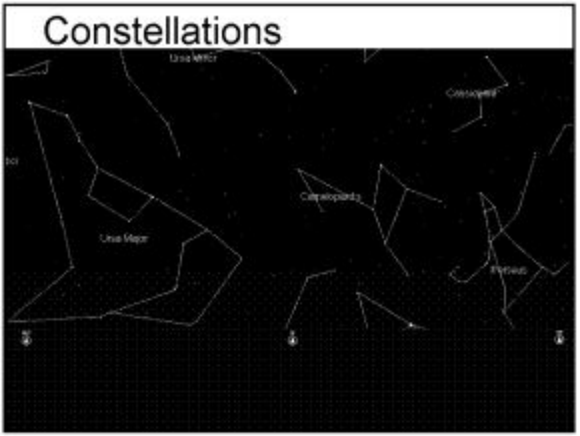
Circumference of Earth = 50 × distance from Alexandria to Syene.

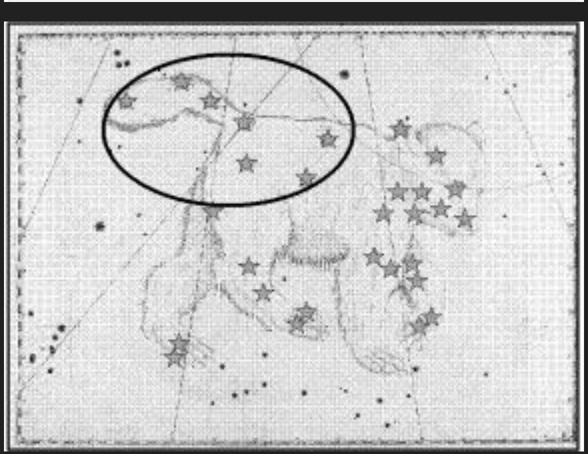
Distance from Alexandria to Syene = 5000 stades

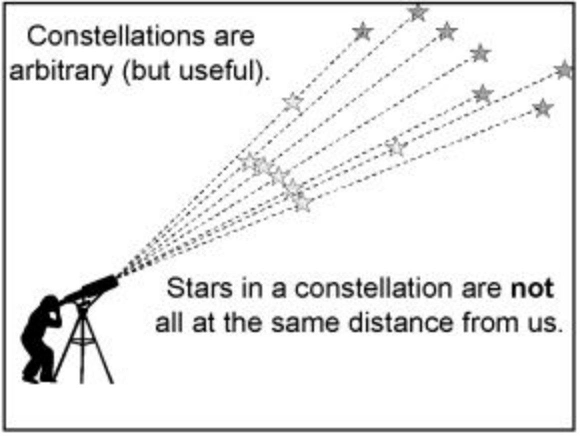
Circumference of Earth = 50 × 5000 stades = 250,000 stades.

(about 46,000 kilometers –
true value is 40,000 kilometers)

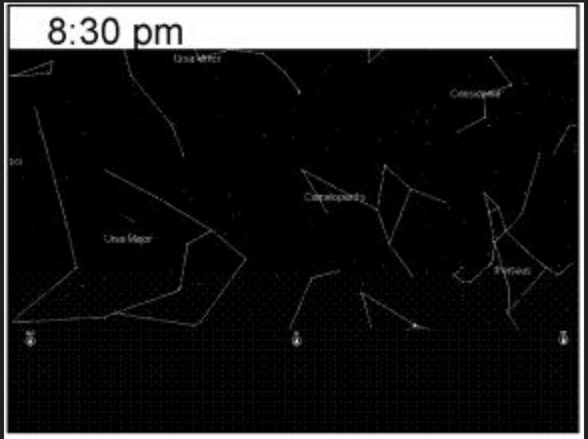

Looking north, 8:30 tonight.

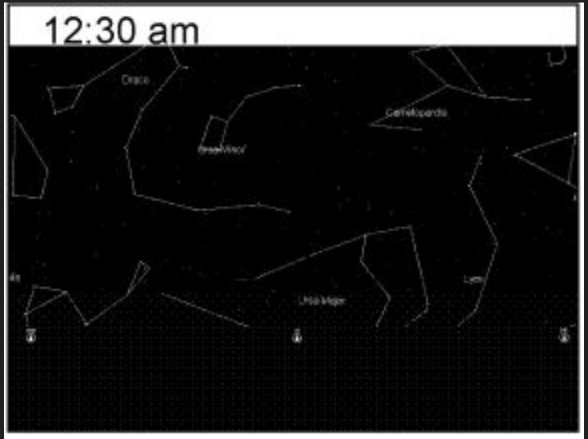

Constellations
Ursa Minor
Cassiopeia
Camelopardalis
Ursa Major
Perseus

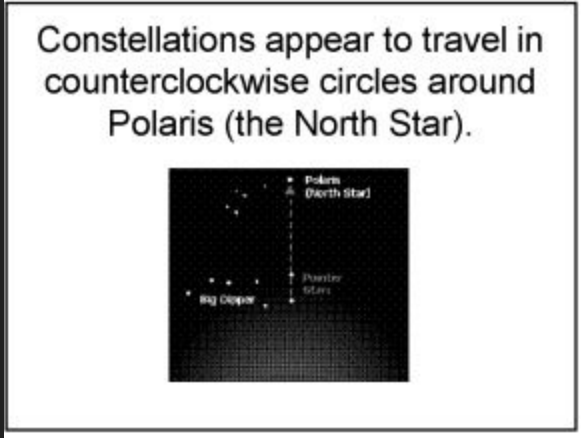



Constellations are arbitrary (but useful).

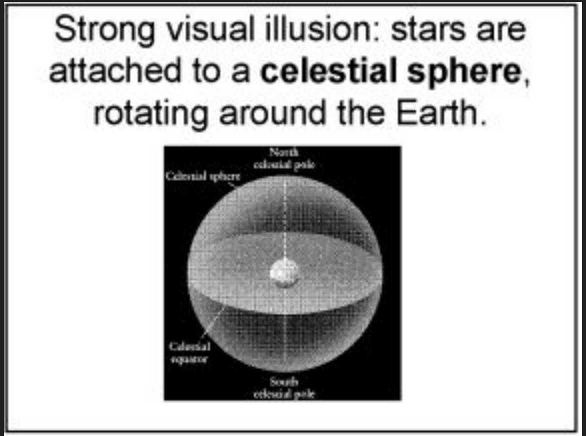
Stars in a constellation are **not** all at the same distance from us.


8:30 pm

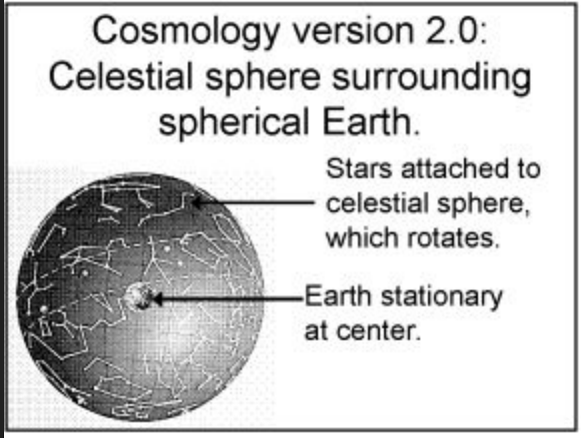

12:30 am



Constellations appear to travel in counterclockwise circles around Polaris (the North Star).



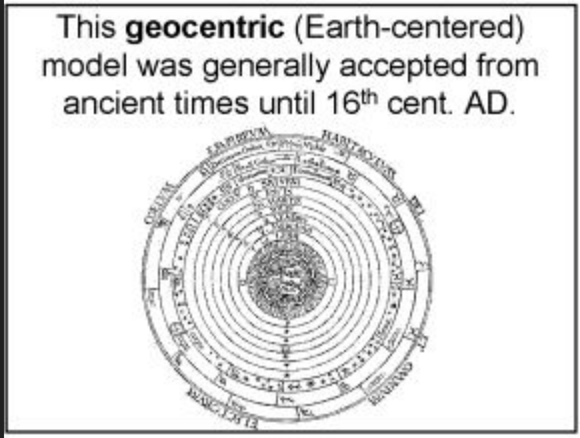
Strong visual illusion: stars are attached to a **celestial sphere**, rotating around the Earth.



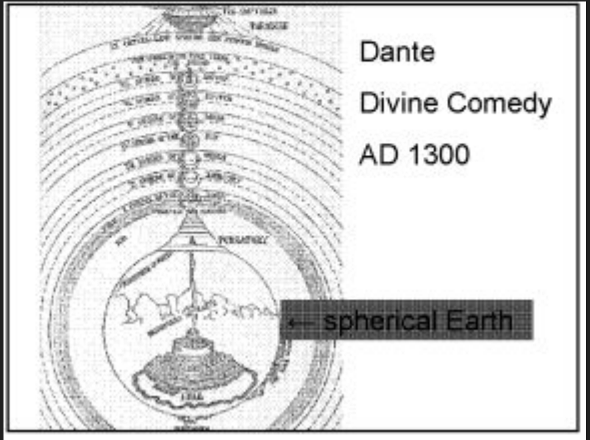
Cosmology version 2.0: Celestial sphere surrounding spherical Earth.

Stars attached to celestial sphere, which rotates.

Earth stationary at center.



This **geocentric** (Earth-centered) model was generally accepted from ancient times until 16th cent. AD.

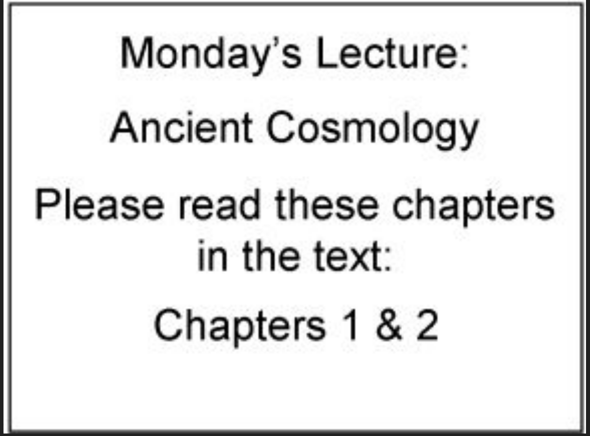


Dante

Divine Comedy

AD 1300

← spherical Earth



Monday's Lecture:

Ancient Cosmology

Please read these chapters in the text:

Chapters 1 & 2

Preparatory Reading Chapters 1 & 2

Week 2: Ancient Cosmology (Not Found)

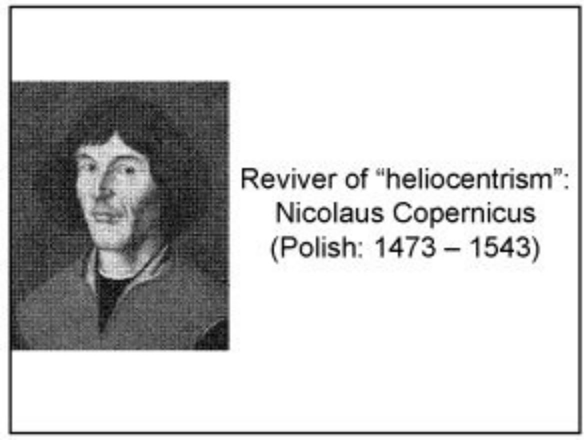
Preparatory Reading Chapters 1 & 2

Week 2: Renaissance Cosmology

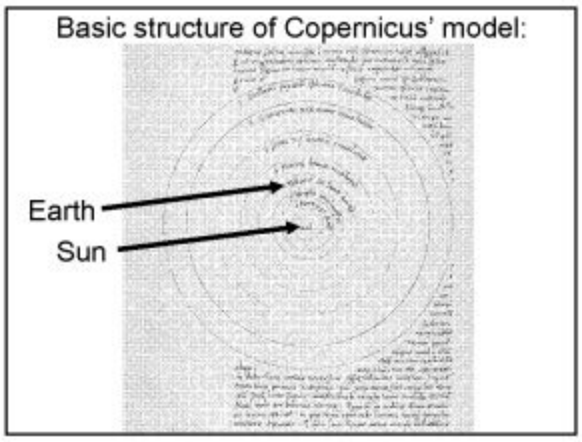
Renaissance Cosmology

Wednesday, September 30

Next Planetarium Shows: Tonight 7 pm, Tomorrow 7 pm



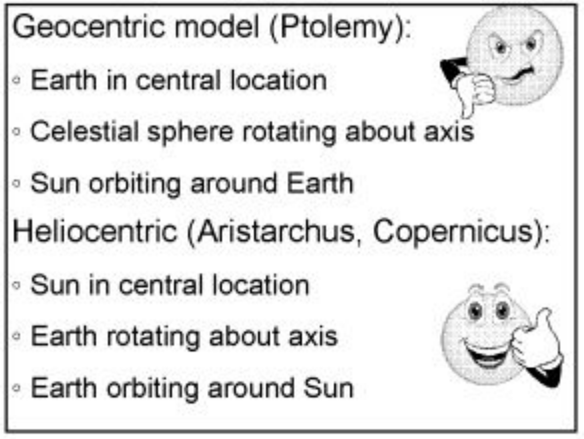
Reviver of “heliocentrism”:
Nicolaus Copernicus
(Polish: 1473 – 1543)



Basic structure of Copernicus’ model:

Earth

Sun

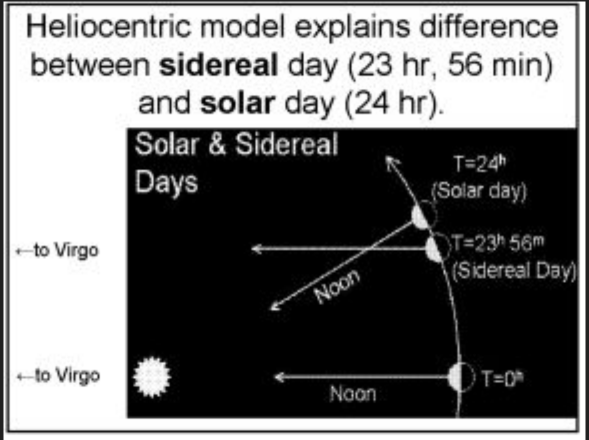


Geocentric model (Ptolemy):

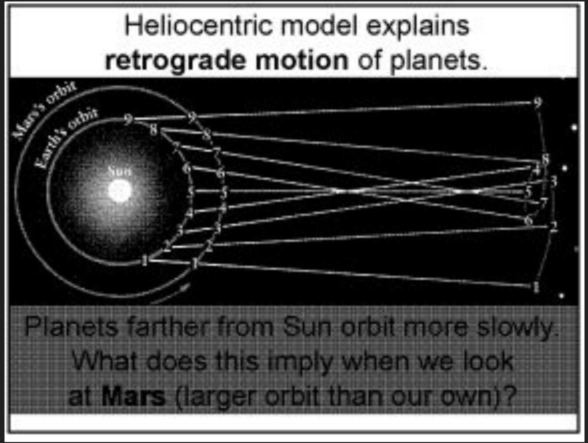
- Earth in central location
- Celestial sphere rotating about axis
- Sun orbiting around Earth

Heliocentric (Aristarchus, Copernicus):

- Sun in central location
- Earth rotating about axis
- Earth orbiting around Sun

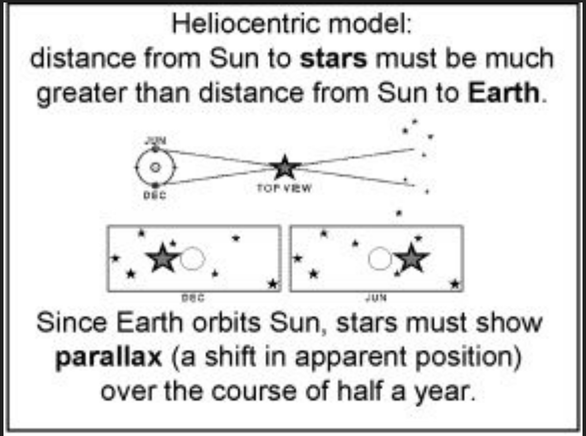


Heliocentric model explains difference between **sidereal** day (23 hr, 56 min) and **solar** day (24 hr).



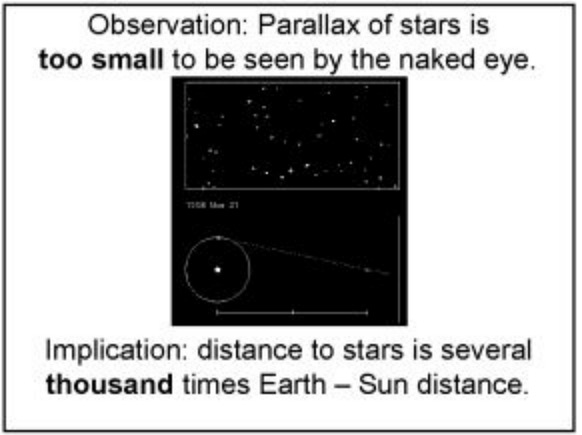
Heliocentric model explains **retrograde motion** of planets.

Planets farther from Sun orbit more slowly. What does this imply when we look at **Mars** (larger orbit than our own)?



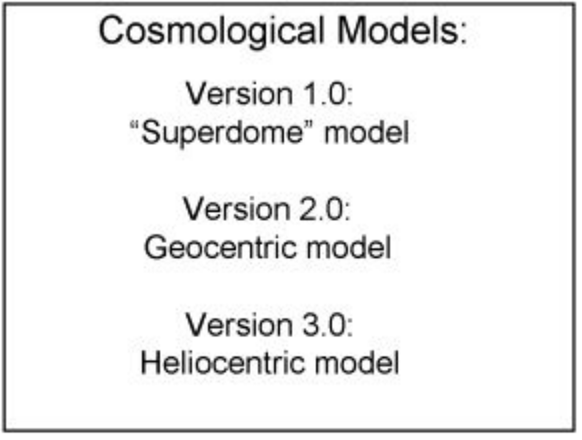
Heliocentric model:
distance from Sun to **stars** must be much greater than distance from Sun to **Earth**.

Since Earth orbits Sun, stars must show **parallax** (a shift in apparent position) over the course of half a year.



Observation: Parallax of stars is **too small** to be seen by the naked eye.

Implication: distance to stars is several **thousand** times Earth – Sun distance.

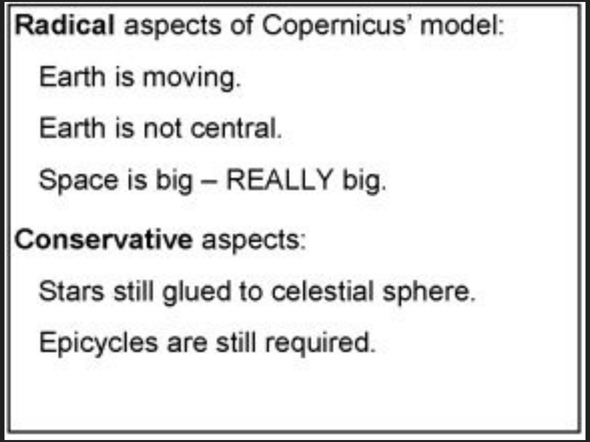


Cosmological Models:

Version 1.0:
"Superdome" model

Version 2.0:
Geocentric model

Version 3.0:
Heliocentric model



Radical aspects of Copernicus' model:

- Earth is moving.
- Earth is not central.
- Space is big – REALLY big.

Conservative aspects:

- Stars still glued to celestial sphere.
- Epicycles are still required.

Startling Realization!

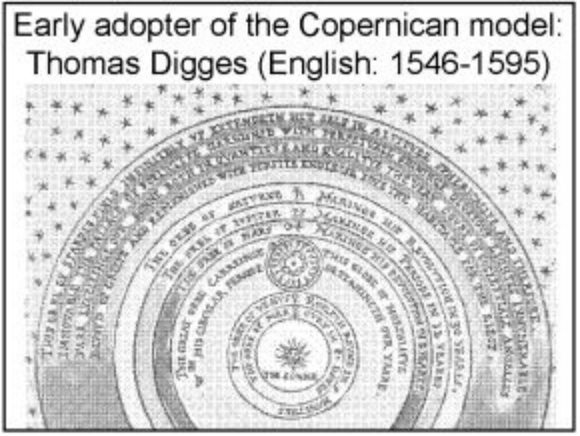
"Planets" (Mercury, Venus, Mars, Jupiter, Saturn) are opaque spheres orbiting the Sun – just like Earth!

Earth is a planet: no division between "perfect" heavens and "corrupt" Earth.

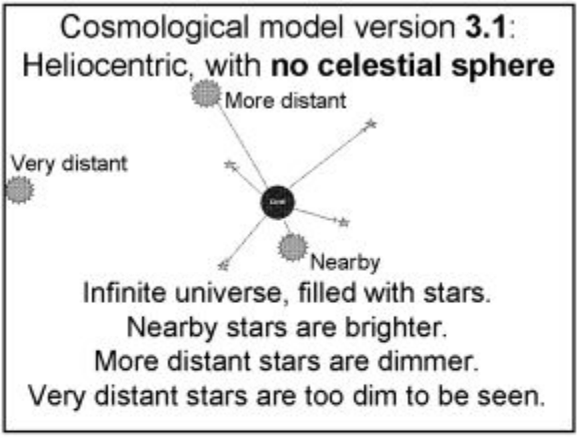
Another Startling Realization!

Stars look small & dim because they're far away; they're actually large, glowing spheres – just like the Sun!

Sun is a star: universe is full of glowing, spherical, Sun-like objects.

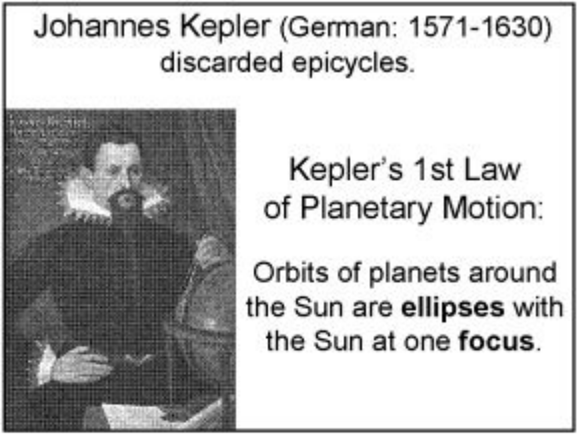


Early adopter of the Copernican model:
Thomas Digges (English: 1546-1595)



Cosmological model version **3.1**:
Heliocentric, with **no celestial sphere**

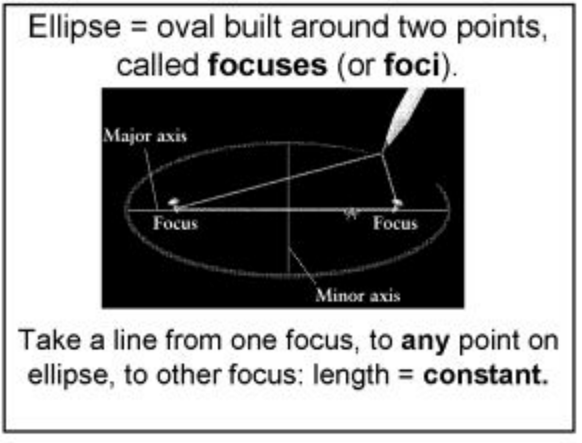
Infinite universe, filled with stars.
Nearby stars are brighter.
More distant stars are dimmer.
Very distant stars are too dim to be seen.



Johannes Kepler (German: 1571-1630)
discarded epicycles.

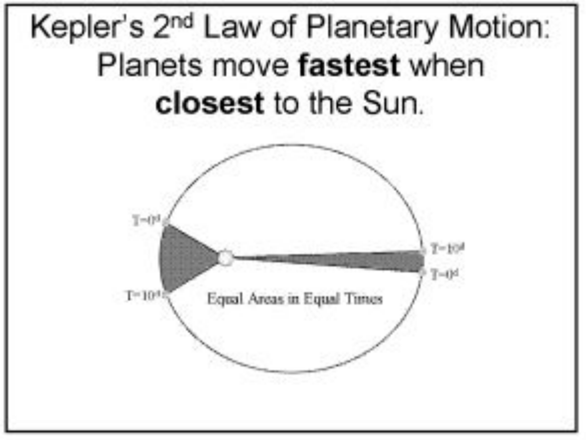
Kepler's 1st Law
of Planetary Motion:

Orbits of planets around the Sun are **ellipses** with the Sun at one **focus**.

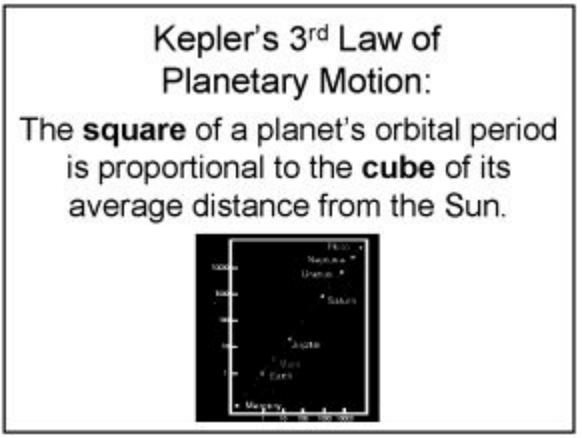


Ellipse = oval built around two points, called **focuses** (or **foci**).

Take a line from one focus, to **any** point on ellipse, to other focus: length = **constant.**



Kepler's 2^{nd} Law of Planetary Motion: Planets move **fastest** when **closest** to the Sun.



Kepler's 3^{rd} Law of Planetary Motion:

The **square** of a planet's orbital period is proportional to the **cube** of its average distance from the Sun.

Preparatory Reading Chapters 1 & 2

Week 2: Ancient Cosmology (Not Found)

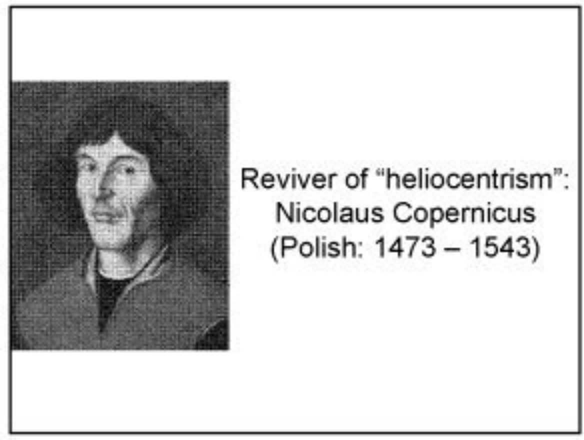
Preparatory Reading Chapters 1 & 2

Week 2: Renaissance Cosmology

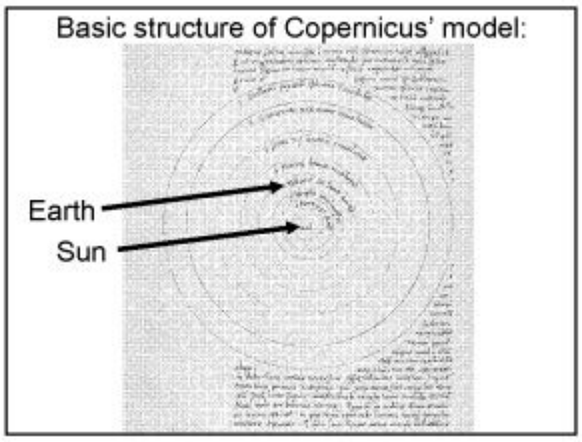
Renaissance Cosmology

Wednesday, September 30

Next Planetarium Shows: Tonight 7 pm, Tomorrow 7 pm



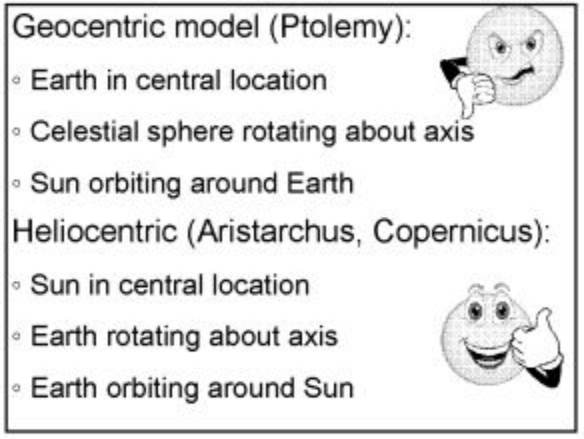
Reviver of “heliocentrism”:
Nicolaus Copernicus
(Polish: 1473 – 1543)



Basic structure of Copernicus’ model:

Earth

Sun

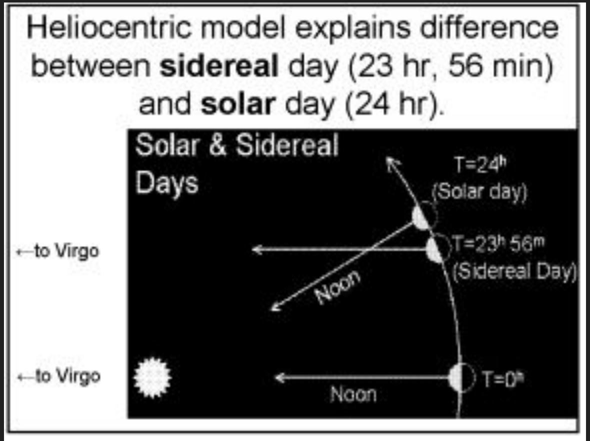


Geocentric model (Ptolemy):

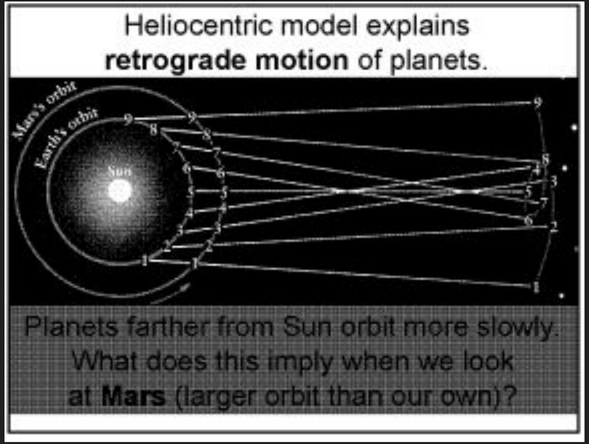
- Earth in central location
- Celestial sphere rotating about axis
- Sun orbiting around Earth

Heliocentric (Aristarchus, Copernicus):

- Sun in central location
- Earth rotating about axis
- Earth orbiting around Sun

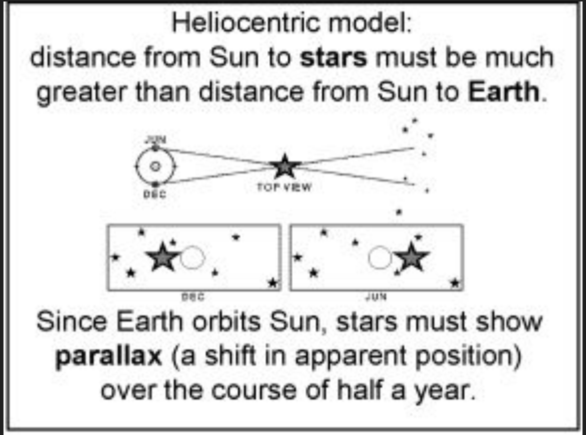


Heliocentric model explains difference between **sidereal** day (23 hr, 56 min) and **solar** day (24 hr).



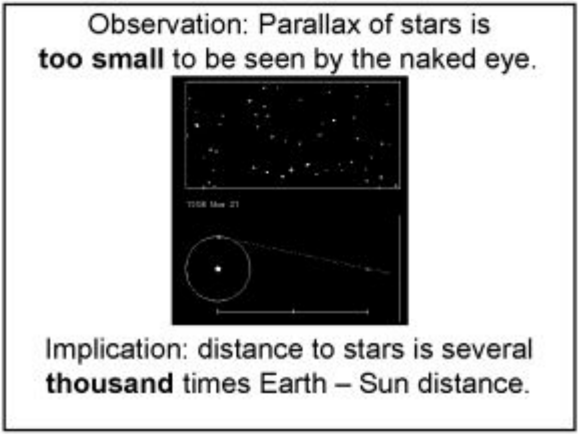
Heliocentric model explains **retrograde motion** of planets.

Planets farther from Sun orbit more slowly. What does this imply when we look at **Mars** (larger orbit than our own)?



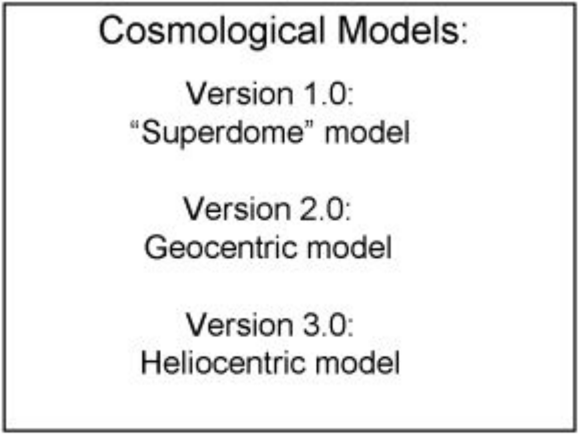
Heliocentric model:
distance from Sun to **stars** must be much greater than distance from Sun to **Earth**.

Since Earth orbits Sun, stars must show **parallax** (a shift in apparent position) over the course of half a year.



Observation: Parallax of stars is **too small** to be seen by the naked eye.

Implication: distance to stars is several **thousand** times Earth – Sun distance.

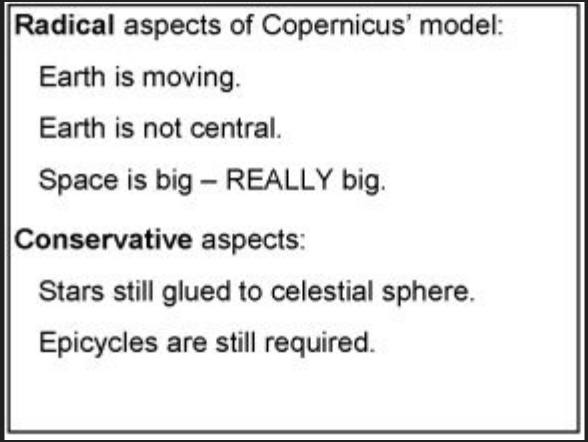


Cosmological Models:

Version 1.0:
“Superdome” model

Version 2.0:
Geocentric model

Version 3.0:
Heliocentric model



Radical aspects of Copernicus' model:

- Earth is moving.
- Earth is not central.
- Space is big – REALLY big.

Conservative aspects:

- Stars still glued to celestial sphere.
- Epicycles are still required.

Startling Realization!

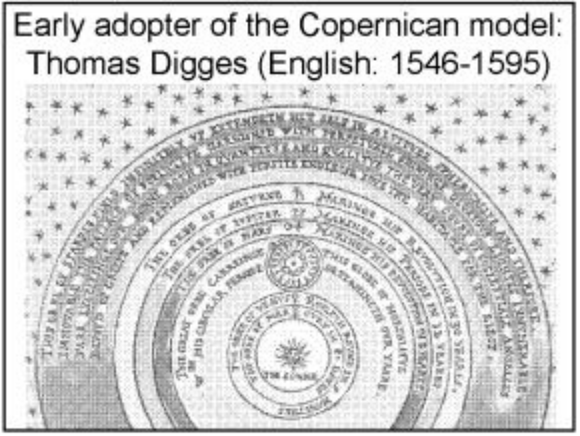
"Planets" (Mercury, Venus, Mars, Jupiter, Saturn) are opaque spheres orbiting the Sun – just like Earth!

Earth is a planet: no division between "perfect" heavens and "corrupt" Earth.

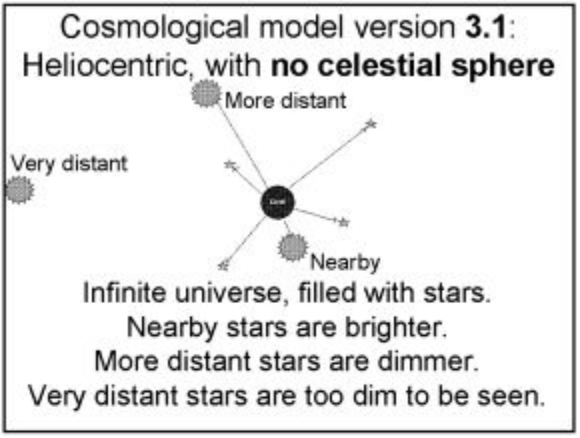
Another Startling Realization!

Stars look small & dim because they're far away; they're actually large, glowing spheres – just like the Sun!

Sun is a star: universe is full of glowing, spherical, Sun-like objects.

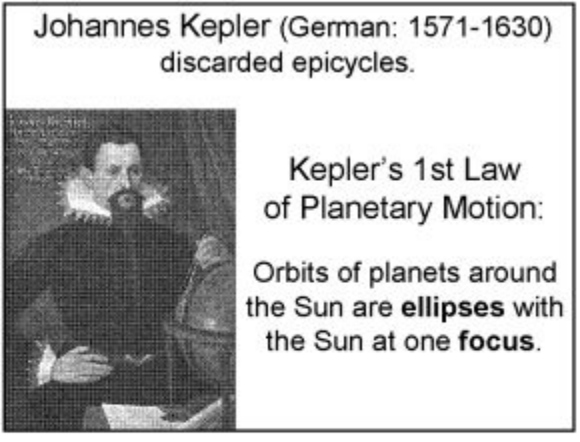


Early adopter of the Copernican model:
Thomas Digges (English: 1546-1595)



Cosmological model version **3.1**:
Heliocentric, with **no celestial sphere**

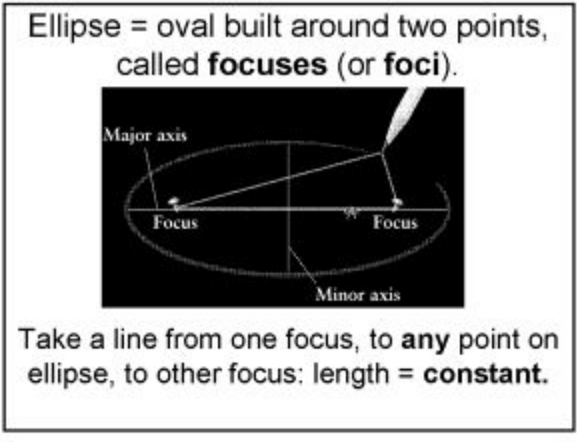
Infinite universe, filled with stars.
Nearby stars are brighter.
More distant stars are dimmer.
Very distant stars are too dim to be seen.



Johannes Kepler (German: 1571-1630)
discarded epicycles.

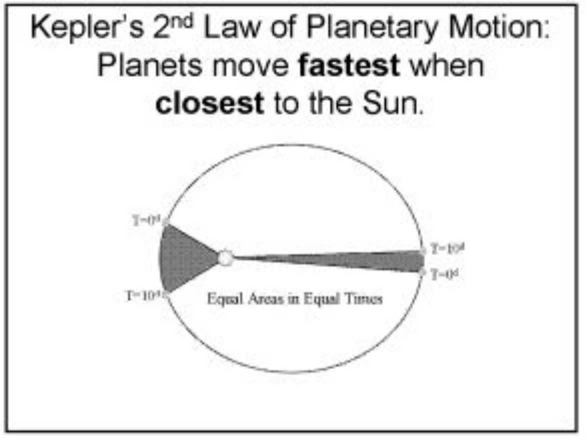
Kepler's 1st Law
of Planetary Motion:

Orbits of planets around the Sun are **ellipses** with the Sun at one **focus**.



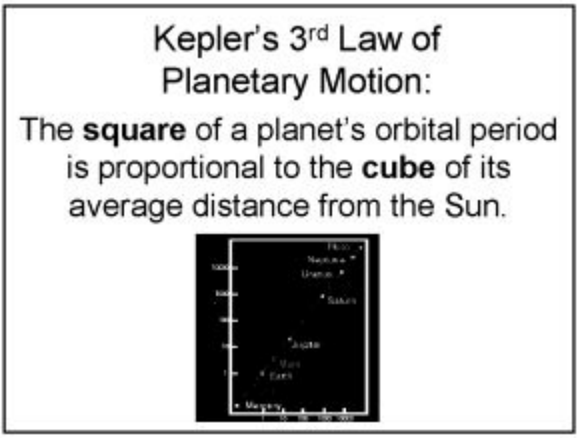
Ellipse = oval built around two points, called **focuses** (or **foci**).

Take a line from one focus, to **any** point on ellipse, to other focus: length = **constant.**



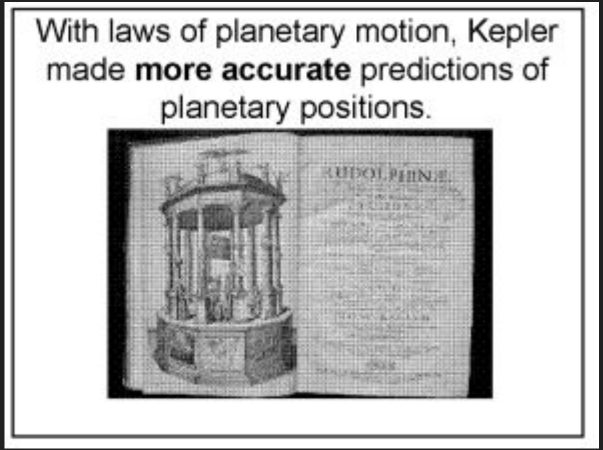
Kepler's 2nd Law of Planetary Motion:

Planets move **fastest** when **closest** to the Sun.

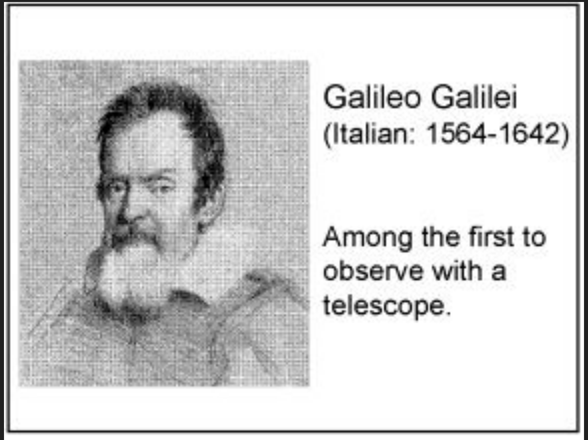


Kepler's 3rd Law of Planetary Motion:

The **square** of a planet's orbital period is proportional to the **cube** of its average distance from the Sun.

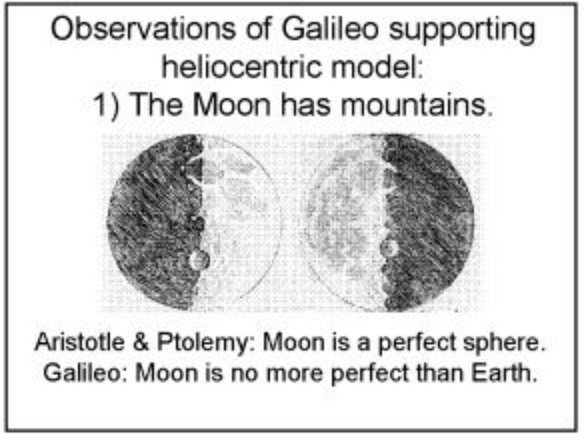


With laws of planetary motion, Kepler made **more accurate** predictions of planetary positions.



Galileo Galilei
(Italian: 1564-1642)

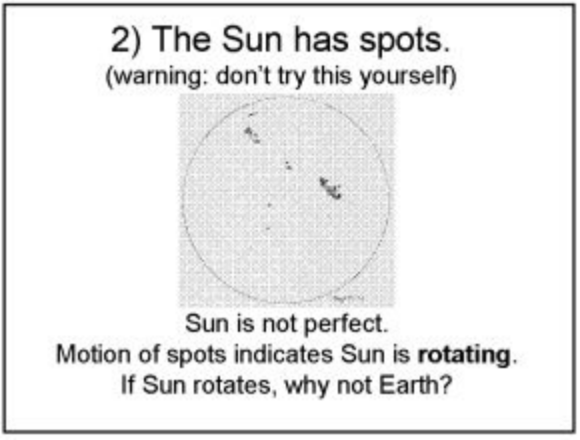
Among the first to observe with a telescope.



Observations of Galileo supporting heliocentric model:

1) The Moon has mountains.

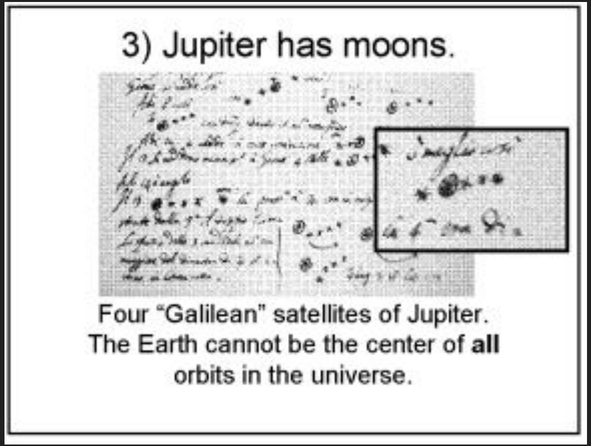
Aristotle & Ptolemy: Moon is a perfect sphere.
Galileo: Moon is no more perfect than Earth.



2) The Sun has spots.

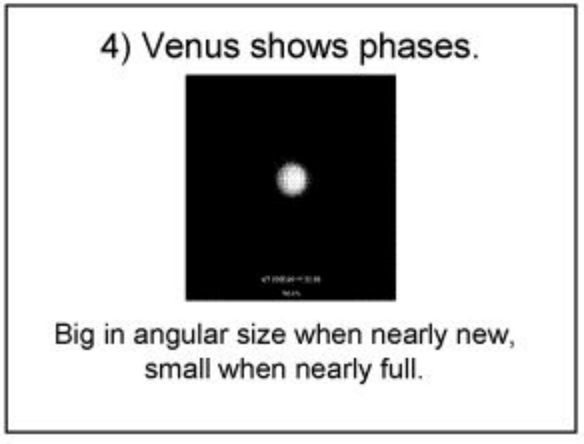
(warning: don't try this yourself)

Sun is not perfect.
Motion of spots indicates Sun is **rotating**.
If Sun rotates, why not Earth?



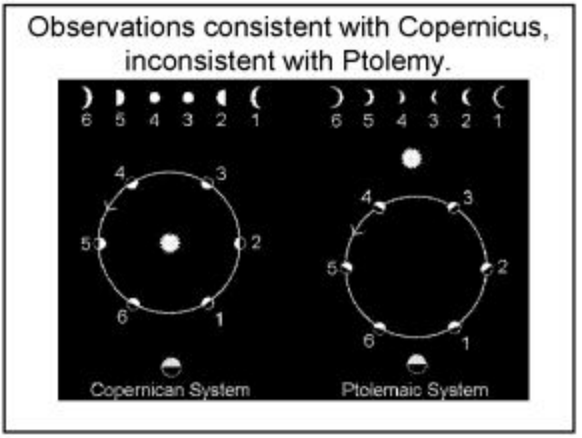
3) Jupiter has moons.

Four "Galilean" satellites of Jupiter.
The Earth cannot be the center of **all** orbits in the universe.

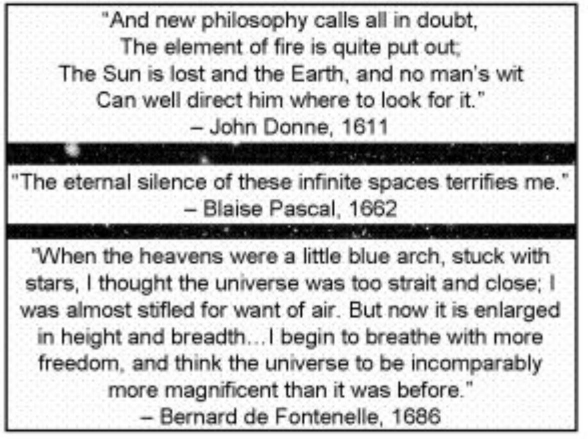


4) Venus shows phases.

Big in angular size when nearly new,
small when nearly full.



Observations consistent with Copernicus, inconsistent with Ptolemy.



"And new philosophy calls all in doubt,
The element of fire is quite put out;
The Sun is lost and the Earth, and no man's wit
Can well direct him where to look for it."
– John Donne, 1611

"The eternal silence of these infinite spaces terrifies me."
– Blaise Pascal, 1662

"When the heavens were a little blue arch, stuck with stars, I thought the universe was too strait and close; I was almost stifled for want of air. But now it is enlarged in height and breadth…I begin to breathe with more freedom, and think the universe to be incomparably more magnificent than it was before."
– Bernard de Fontenelle, 1686

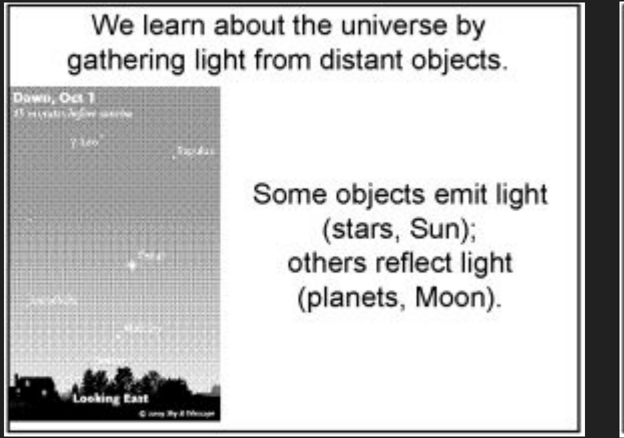
Preparatory Reading Chapters 1 & 2

Week 2: Tools of Modern Cosmology

Tools of Modern Cosmology

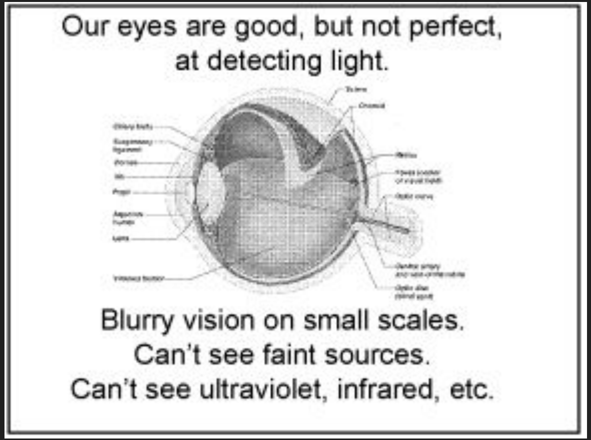
Friday, October 2

Next Planetarium Shows: Mon, Tue, Wed 7 pm



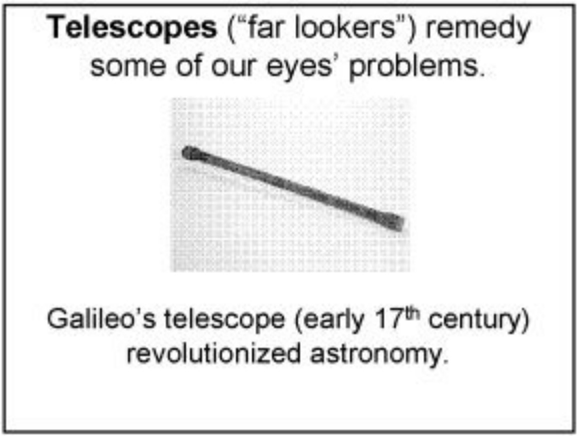
We learn about the universe by gathering light from distant objects.

Some objects emit light (stars, Sun); others reflect light (planets, Moon).



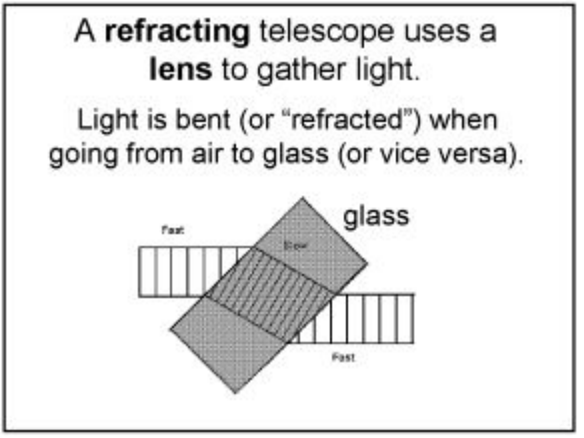
Our eyes are good, but not perfect, at detecting light.

Blurry vision on small scales.
Can't see faint sources.
Can't see ultraviolet, infrared, etc.



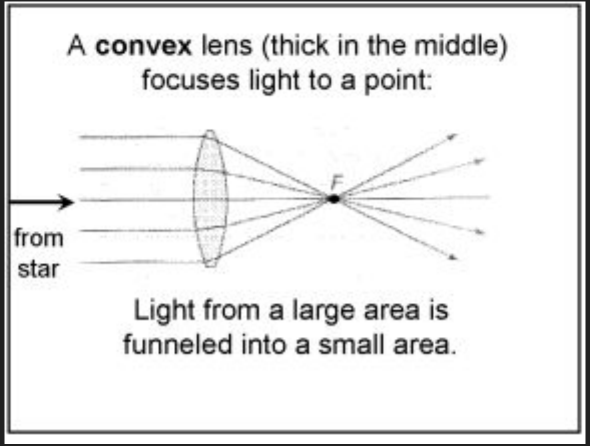
Telescopes ("far lookers") remedy some of our eyes' problems.

Galileo's telescope (early 17th century) revolutionized astronomy.



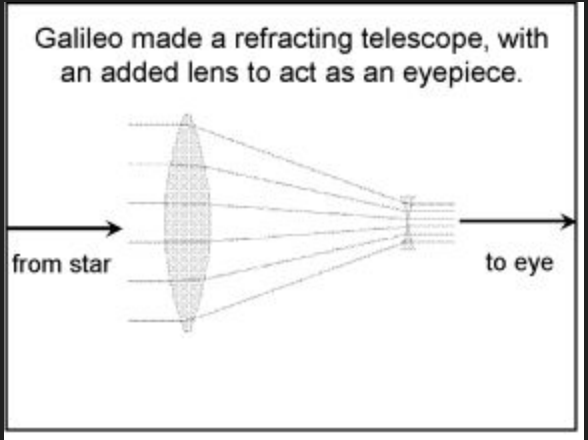
A **refracting** telescope uses a **lens** to gather light.

Light is bent (or "refracted") when going from air to glass (or vice versa).

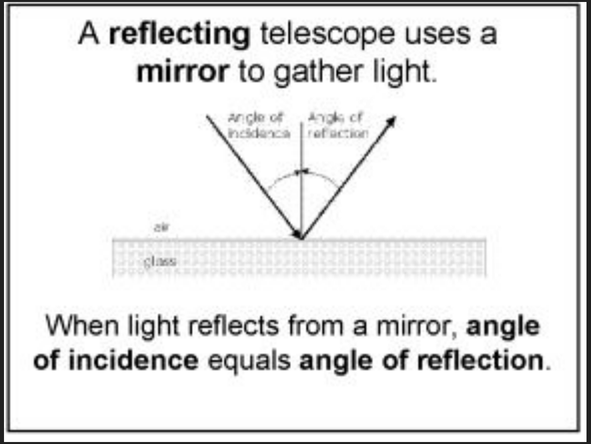


A **convex** lens (thick in the middle) focuses light to a point:

Light from a large area is funneled into a small area.

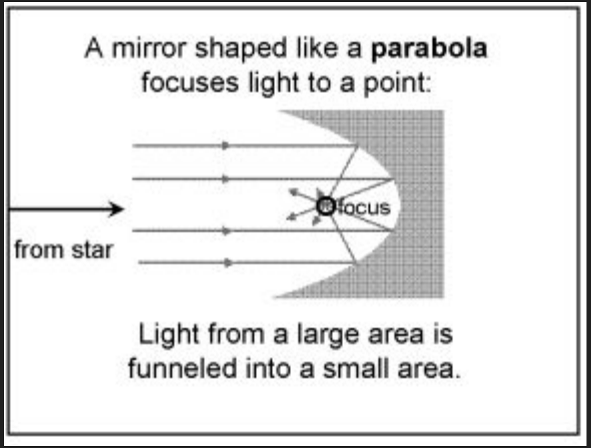


Galileo made a refracting telescope, with an added lens to act as an eyepiece.



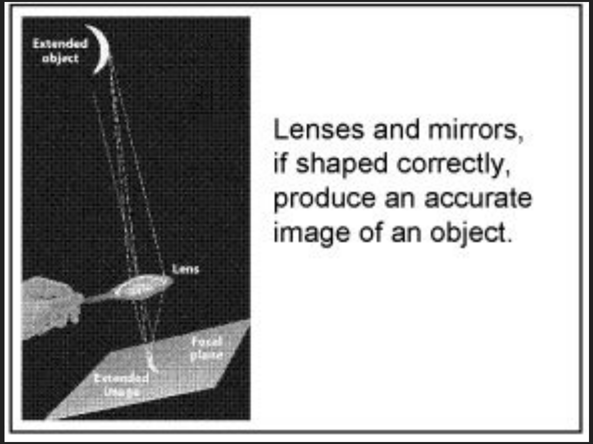
A **reflecting** telescope uses a **mirror** to gather light.

When light reflects from a mirror, **angle of incidence** equals **angle of reflection**.

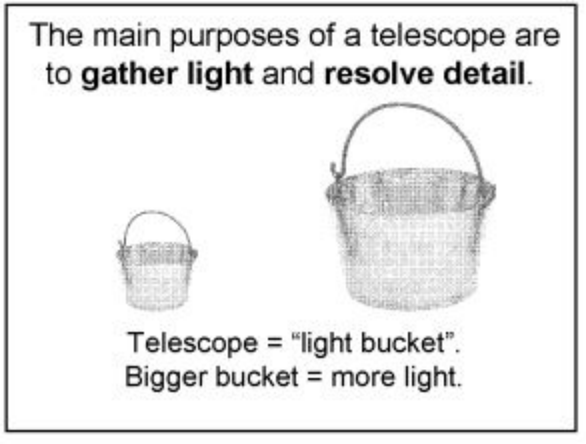


A mirror shaped like a **parabola** focuses light to a point:

Light from a large area is funneled into a small area.

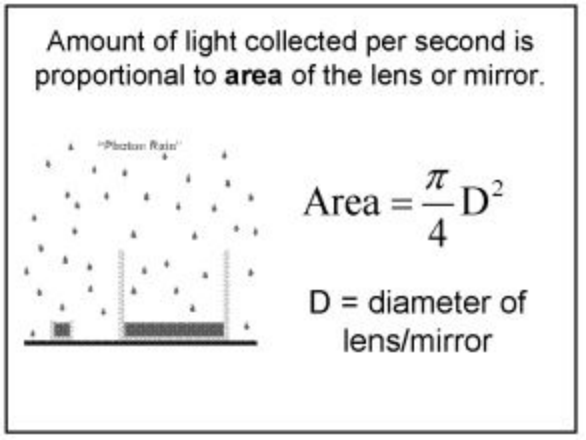


Lenses and mirrors, if shaped correctly, produce an accurate image of an object.



The main purposes of a telescope are to **gather light** and **resolve detail**.

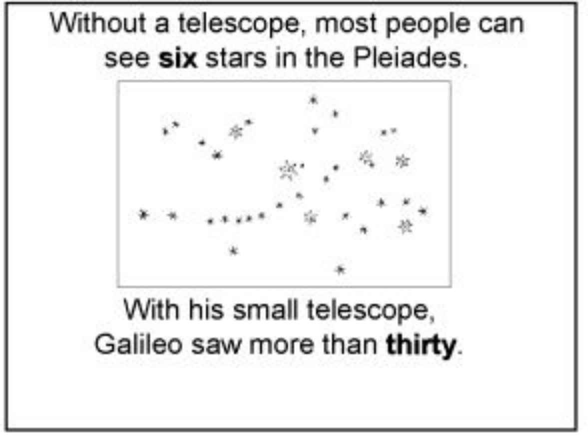
Telescope = “light bucket”.
Bigger bucket = more light.



Amount of light collected per second is proportional to **area** of the lens or mirror.

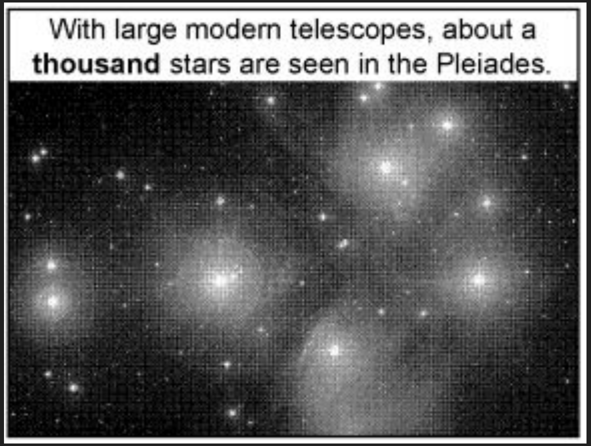
$$\text{Area} = \frac{\pi}{4} D^2$$

D = diameter of lens/mirror

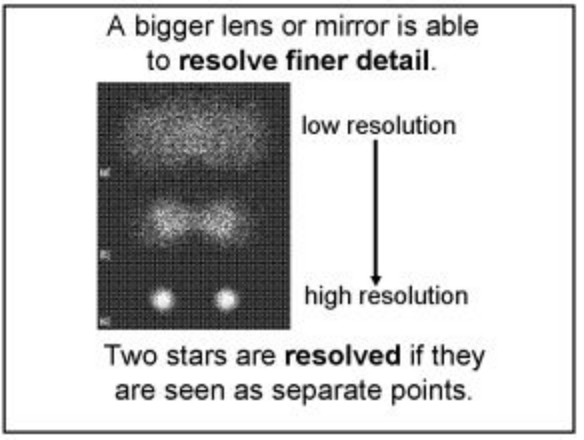


Without a telescope, most people can see **six** stars in the Pleiades.

With his small telescope, Galileo saw more than **thirty**.

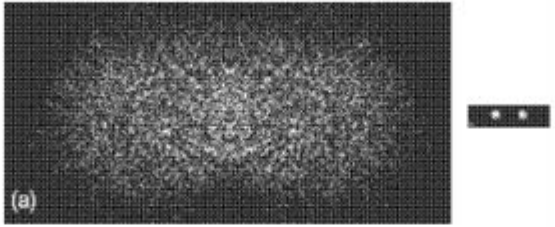


With large modern telescopes, about a **thousand** stars are seen in the Pleiades.



A bigger lens or mirror is able to **resolve finer detail**.

Two stars are **resolved** if they are seen as separate points.



Magnification is not as important:
Big, blurry image is less useful
than small, sharp image.

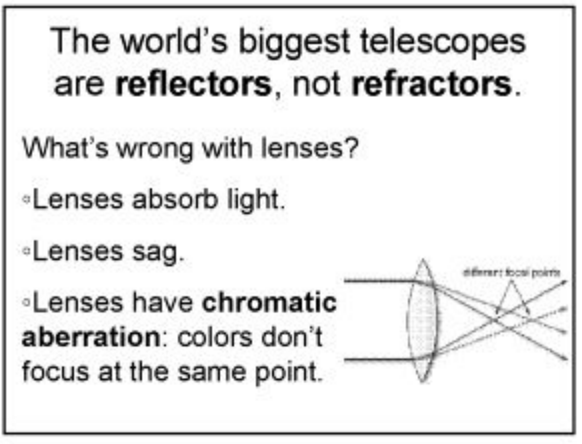
The **Andromeda Galaxy**, as seen by unaided eyes, is a faint oval smudge.

Star atlas of Al Sufi, AD 964.

With large modern telescopes, the Andromeda Galaxy looks like this….

BIGGER IS BETTER!

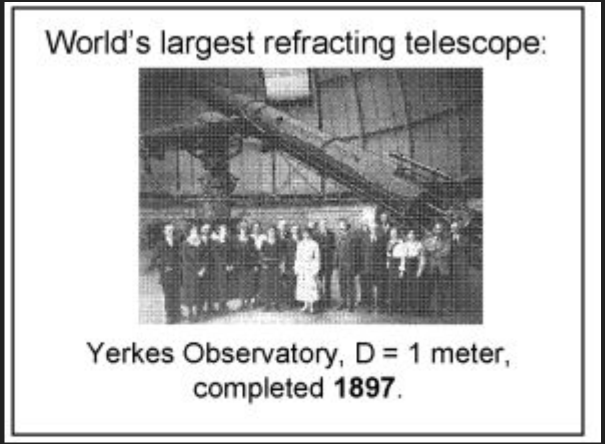
Larger lens or mirror means more light, higher resolution.



The world's biggest telescopes are **reflectors**, not **refractors**.

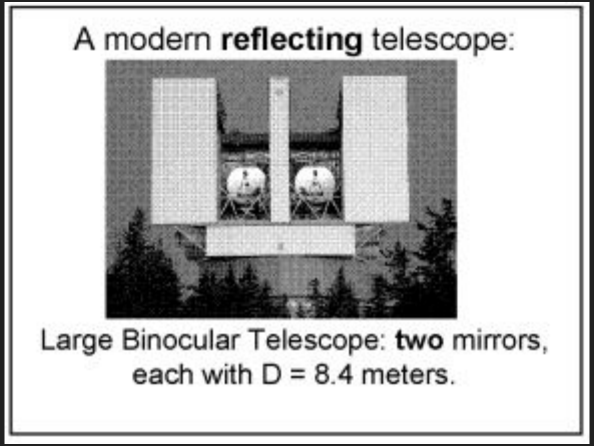
What's wrong with lenses?

- Lenses absorb light.
- Lenses sag.
- Lenses have **chromatic aberration**: colors don't focus at the same point.



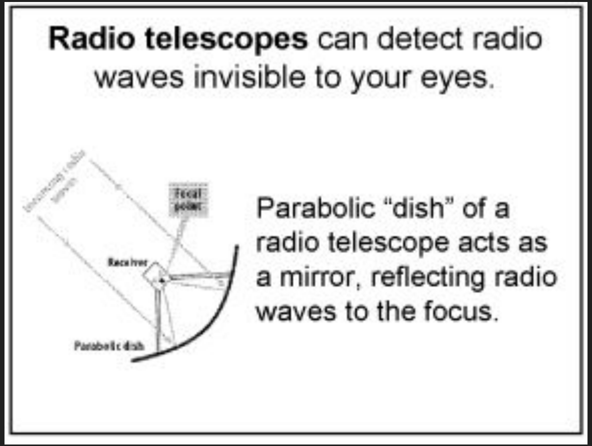
World's largest refracting telescope:

Yerkes Observatory, D = 1 meter, completed **1897**.



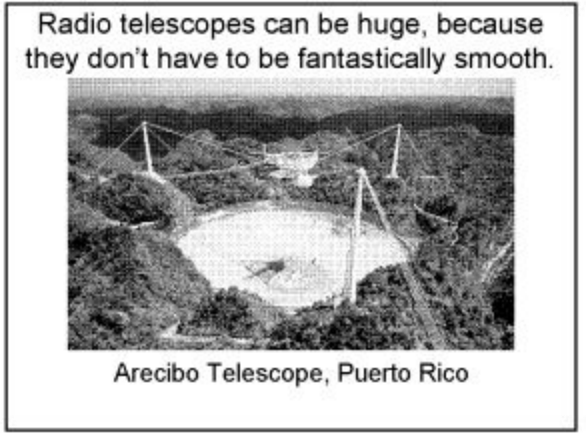
A modern **reflecting** telescope:

Large Binocular Telescope: **two** mirrors, each with D = 8.4 meters.



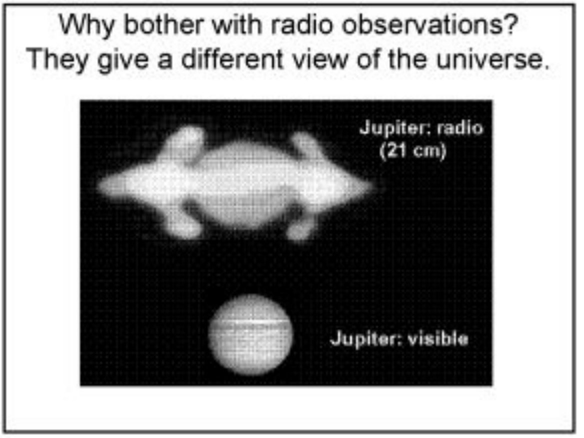
Radio telescopes can detect radio waves invisible to your eyes.

Parabolic “dish” of a radio telescope acts as a mirror, reflecting radio waves to the focus.

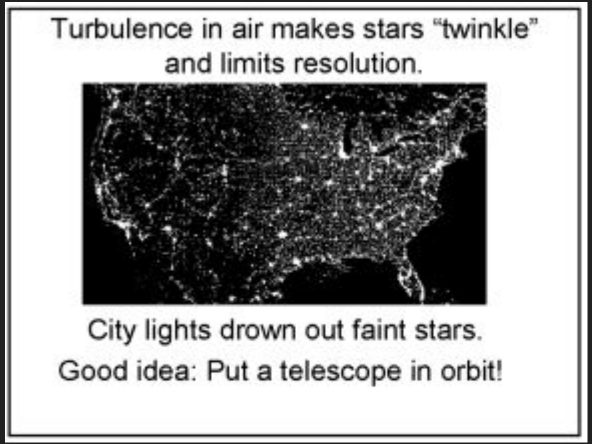


Radio telescopes can be huge, because they don’t have to be fantastically smooth.

Arecibo Telescope, Puerto Rico



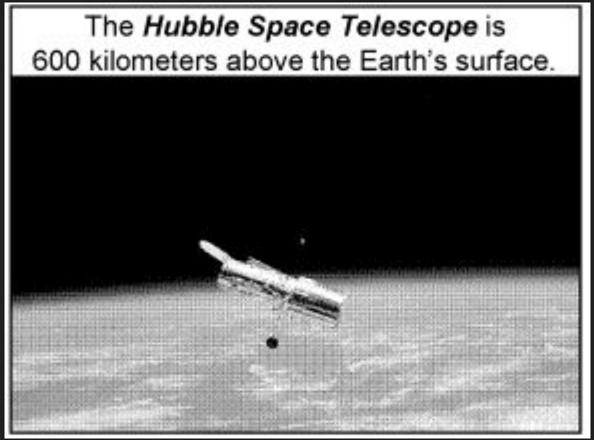
Why bother with radio observations?
They give a different view of the universe.



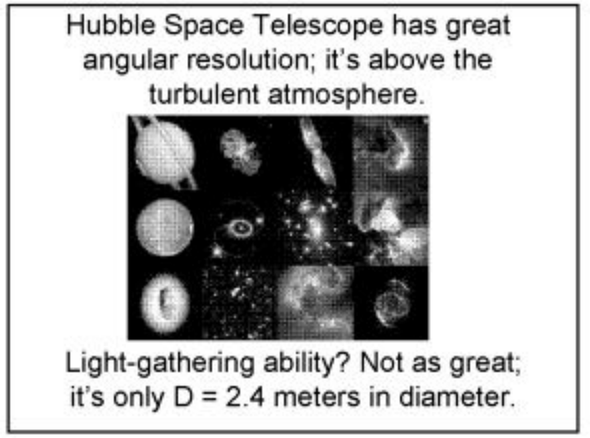
Turbulence in air makes stars “twinkle” and limits resolution.

City lights drown out faint stars.

Good idea: Put a telescope in orbit!



The ***Hubble Space Telescope*** is 600 kilometers above the Earth’s surface.



Hubble Space Telescope has great angular resolution; it's above the turbulent atmosphere.

Light-gathering ability? Not as great; it's only D = 2.4 meters in diameter.

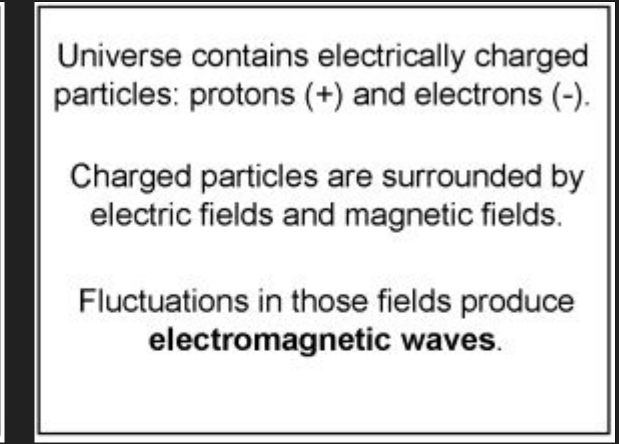
Preparatory Reading Chapter 3

Week 3: Light

Light

Monday, October 5

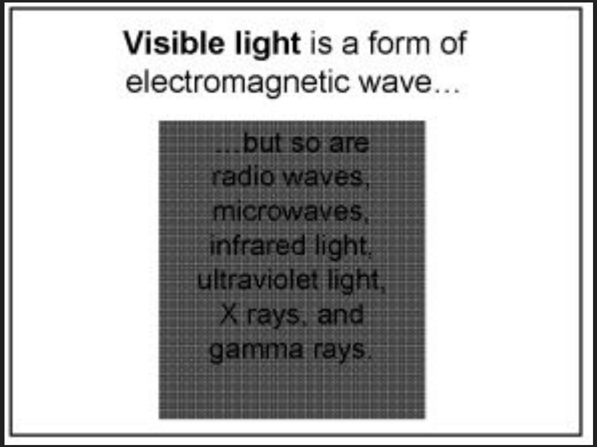
Next Planetarium Shows: Tonight, Tue, Wed 7 pm



Universe contains electrically charged particles: protons (+) and electrons (-).

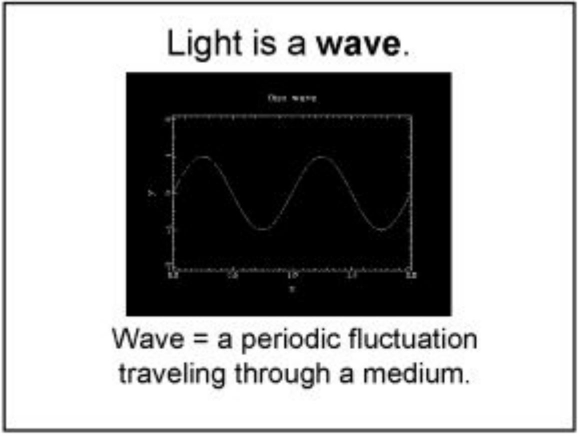
Charged particles are surrounded by electric fields and magnetic fields.

Fluctuations in those fields produce **electromagnetic waves**.



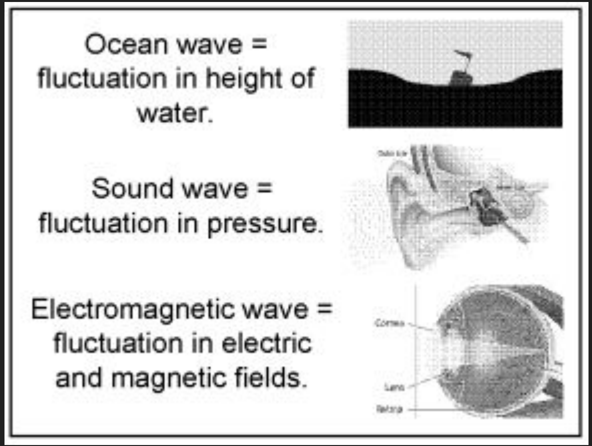
Visible light is a form of electromagnetic wave…

…but so are radio waves, microwaves, infrared light, ultraviolet light, X rays, and gamma rays.



Light is a **wave**.

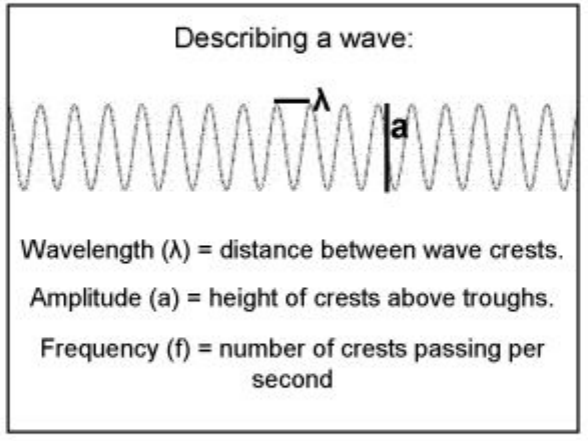
Wave = a periodic fluctuation traveling through a medium.



Ocean wave = fluctuation in height of water.

Sound wave = fluctuation in pressure.

Electromagnetic wave = fluctuation in electric and magnetic fields.

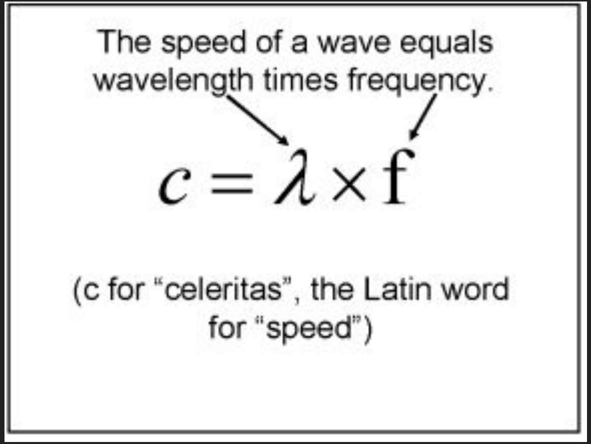


Describing a wave:

Wavelength (λ) = distance between wave crests.

Amplitude (a) = height of crests above troughs.

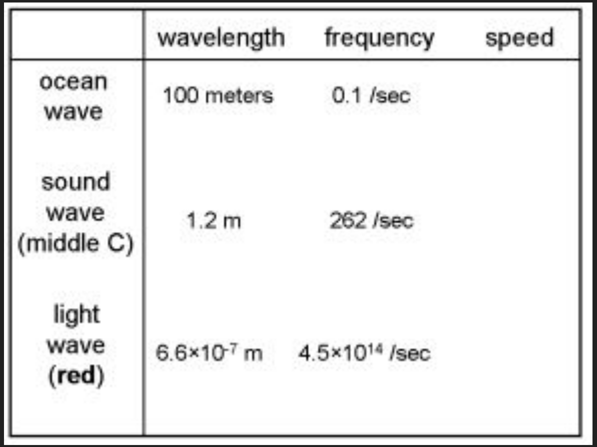
Frequency (f) = number of crests passing per second



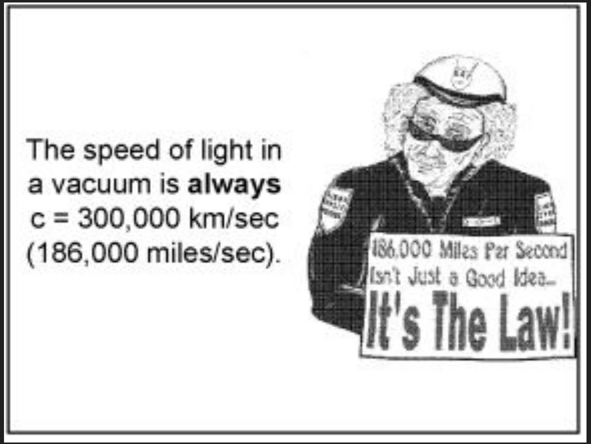
The speed of a wave equals wavelength times frequency.

$$c = \lambda \times \mathrm{f}$$

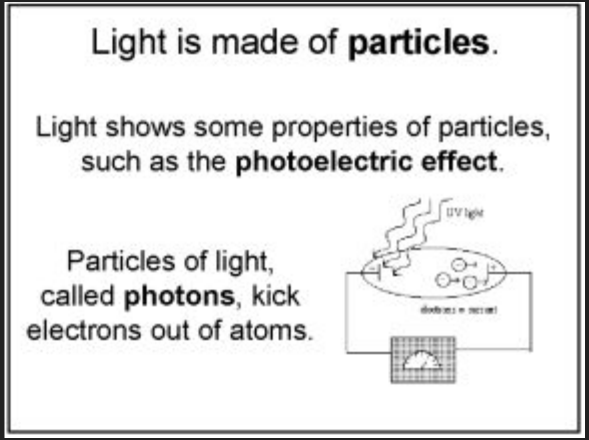
(c for “celeritas”, the Latin word for “speed”)



	wavelength	frequency	speed
ocean wave	100 meters	0.1 /sec	
sound wave (middle C)	1.2 m	262 /sec	
light wave (**red**)	6.6×10^{-7} m	4.5×10^{14} /sec	



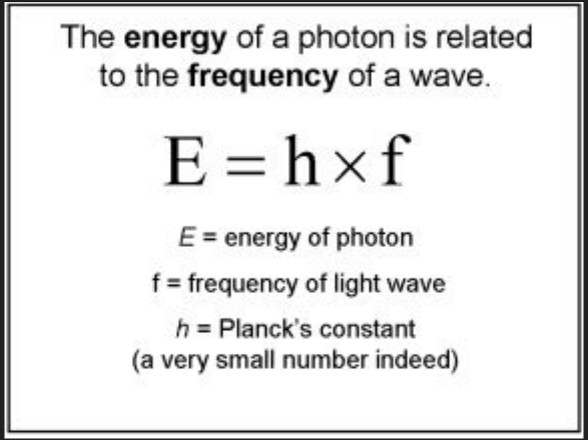
The speed of light in a vacuum is **always** c = 300,000 km/sec (186,000 miles/sec).



Light is made of **particles**.

Light shows some properties of particles, such as the **photoelectric effect**.

Particles of light, called **photons**, kick electrons out of atoms.



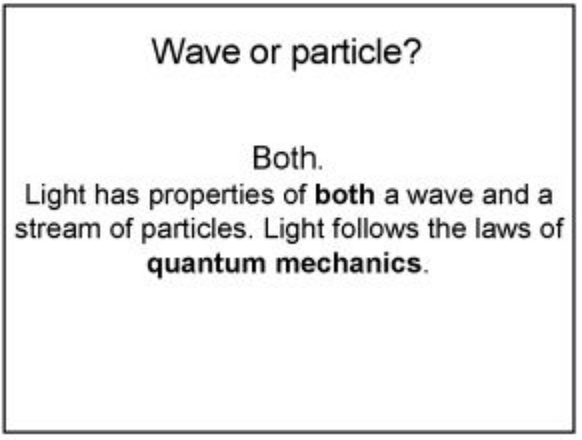
The **energy** of a photon is related to the **frequency** of a wave.

$$E = h \times f$$

E = energy of photon

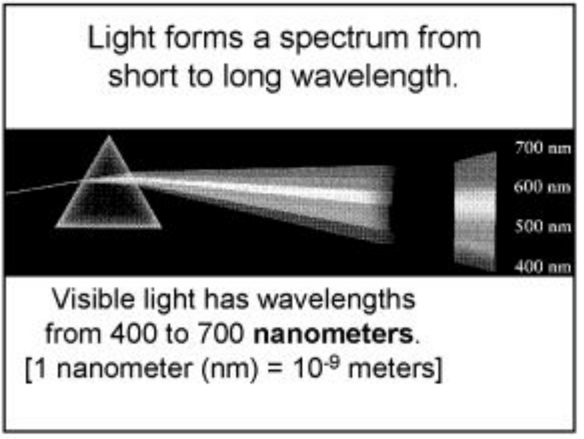
f = frequency of light wave

h = Planck's constant
(a very small number indeed)



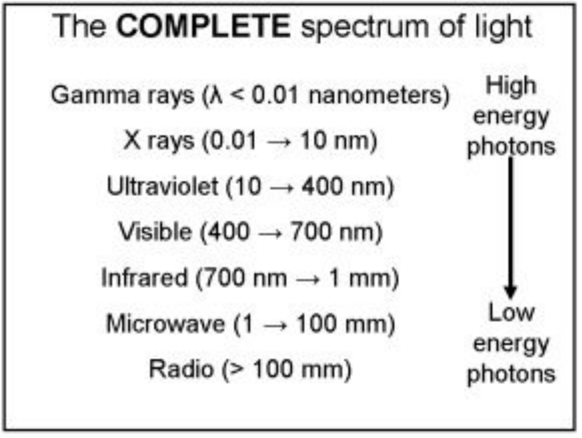
Wave or particle?

Both.
Light has properties of **both** a wave and a stream of particles. Light follows the laws of **quantum mechanics**.



Light forms a spectrum from short to long wavelength.

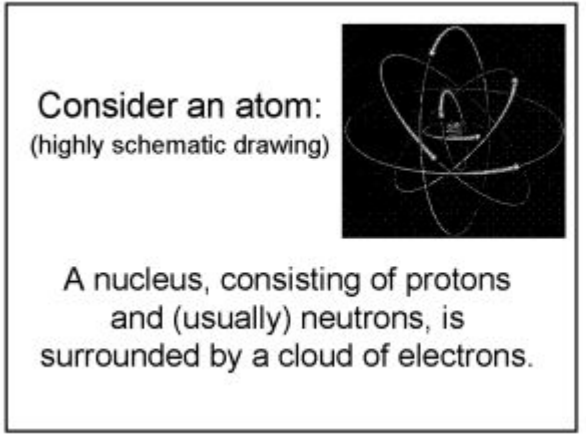
Visible light has wavelengths from 400 to 700 **nanometers**.
[1 nanometer (nm) = 10^{-9} meters]



The **COMPLETE** spectrum of light

Gamma rays (λ < 0.01 nanometers)
X rays (0.01 → 10 nm)
Ultraviolet (10 → 400 nm)
Visible (400 → 700 nm)
Infrared (700 nm → 1 mm)
Microwave (1 → 100 mm)
Radio (> 100 mm)

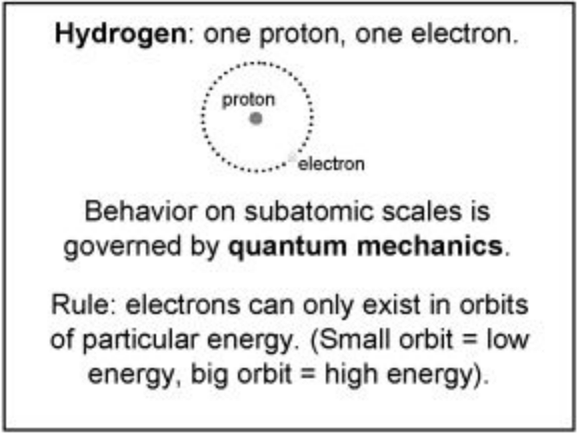
High energy photons
↓
Low energy photons



Consider an atom:

(highly schematic drawing)

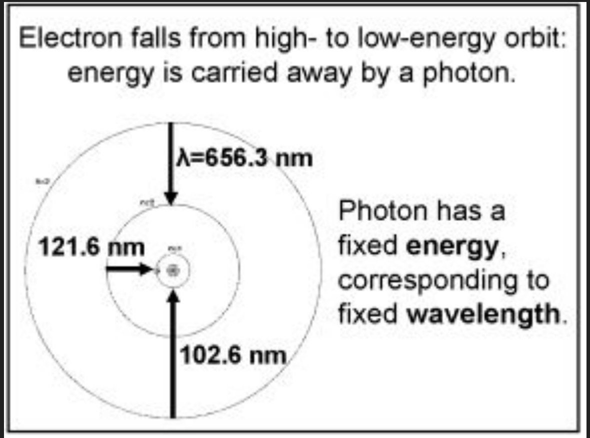
A nucleus, consisting of protons and (usually) neutrons, is surrounded by a cloud of electrons.



Hydrogen: one proton, one electron.

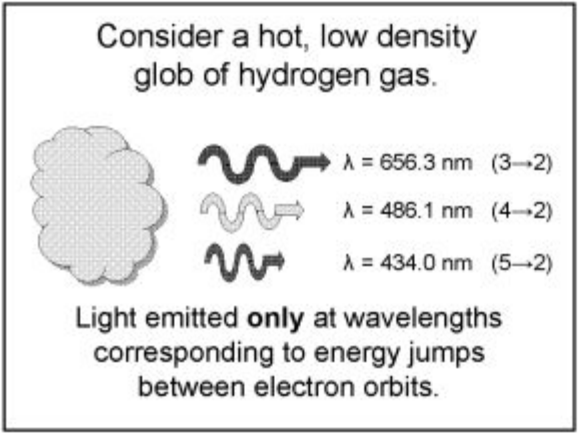
Behavior on subatomic scales is governed by **quantum mechanics**.

Rule: electrons can only exist in orbits of particular energy. (Small orbit = low energy, big orbit = high energy).



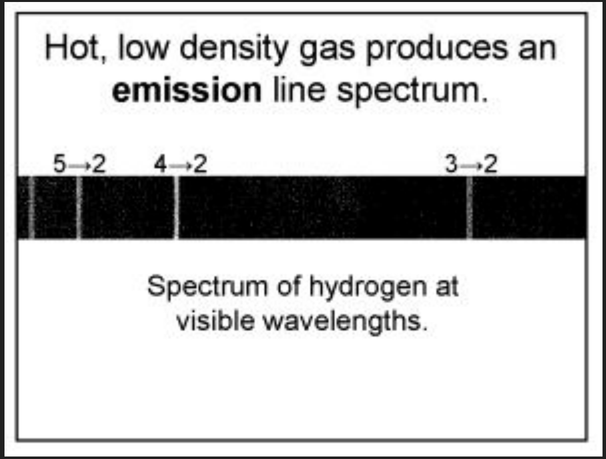
Electron falls from high- to low-energy orbit: energy is carried away by a photon.

Photon has a fixed **energy**, corresponding to fixed **wavelength**.



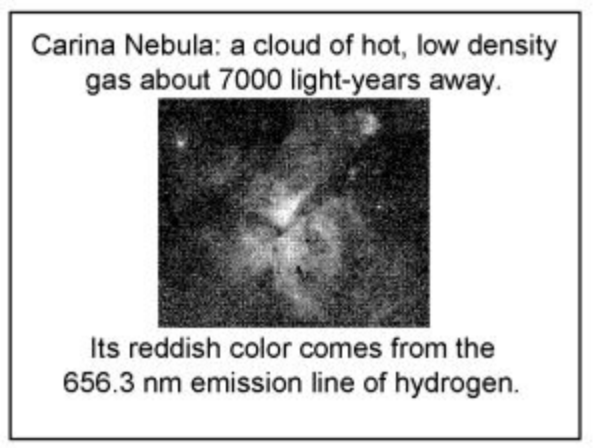
Consider a hot, low density glob of hydrogen gas.

Light emitted **only** at wavelengths corresponding to energy jumps between electron orbits.



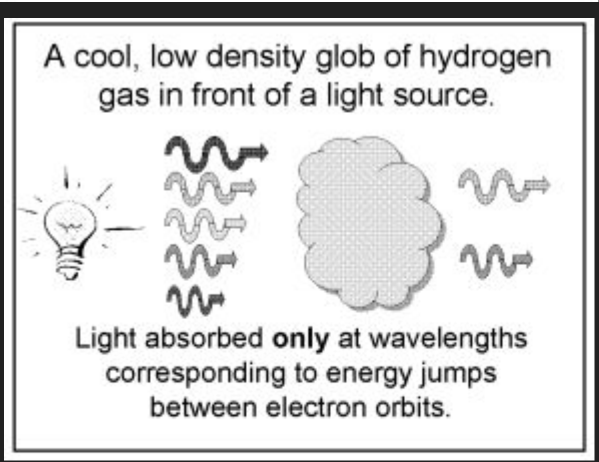
Hot, low density gas produces an **emission** line spectrum.

Spectrum of hydrogen at visible wavelengths.



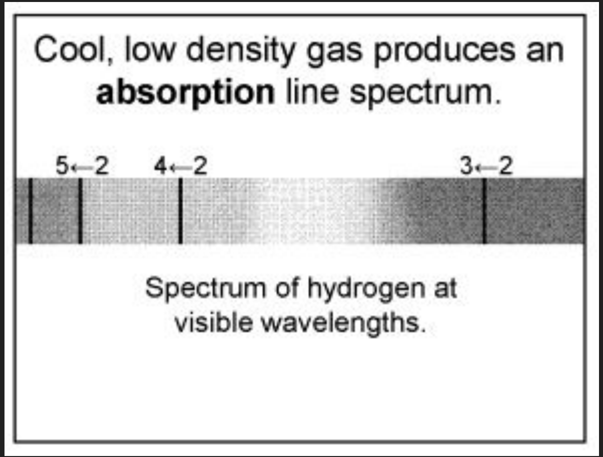
Carina Nebula: a cloud of hot, low density gas about 7000 light-years away.

Its reddish color comes from the 656.3 nm emission line of hydrogen.



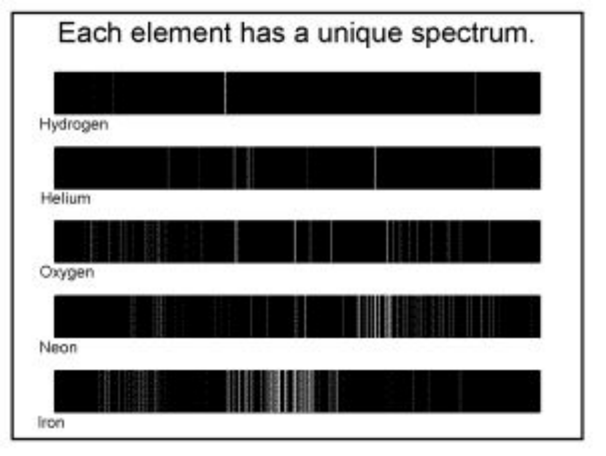
A cool, low density glob of hydrogen gas in front of a light source.

Light absorbed **only** at wavelengths corresponding to energy jumps between electron orbits.

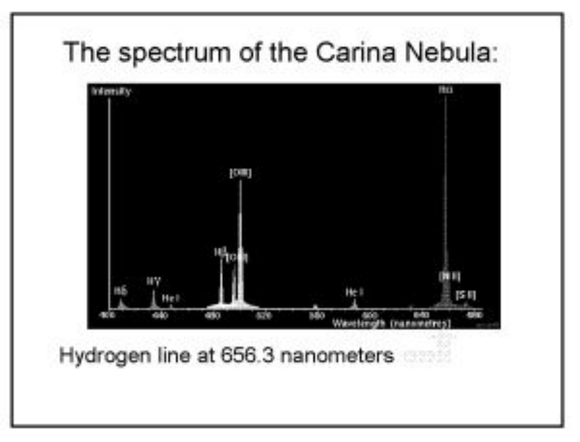


Cool, low density gas produces an **absorption** line spectrum.

Spectrum of hydrogen at visible wavelengths.

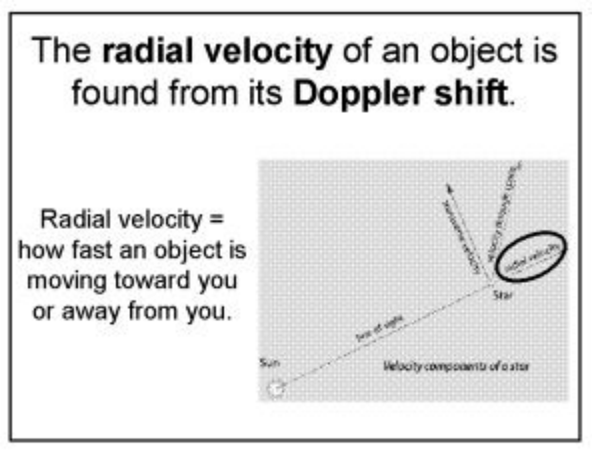


Each element has a unique spectrum.



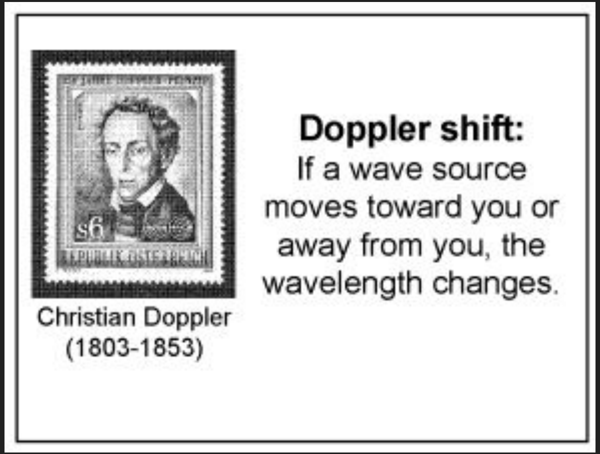
The spectrum of the Carina Nebula:

Hydrogen line at 656.3 nanometers



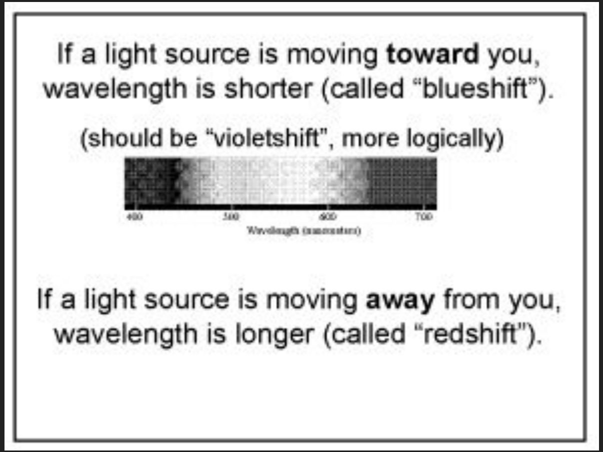
The **radial velocity** of an object is found from its **Doppler shift**.

Radial velocity = how fast an object is moving toward you or away from you.



Christian Doppler
(1803-1853)

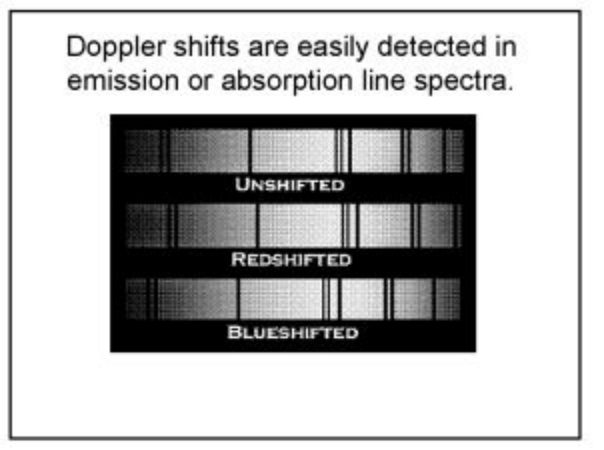
Doppler shift:
If a wave source moves toward you or away from you, the wavelength changes.



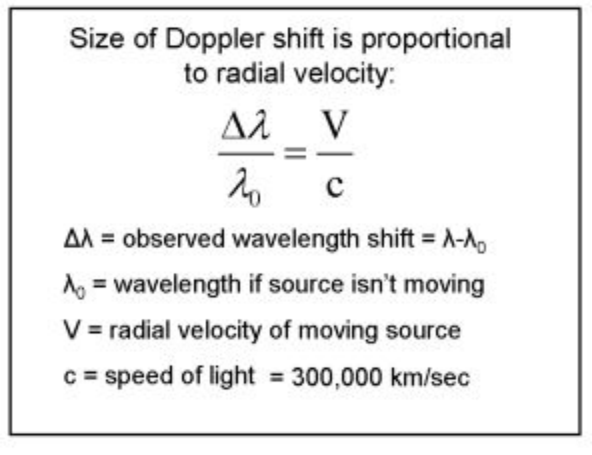
If a light source is moving **toward** you, wavelength is shorter (called “blueshift”).

(should be “violetshift”, more logically)

If a light source is moving **away** from you, wavelength is longer (called “redshift”).



Doppler shifts are easily detected in emission or absorption line spectra.



Size of Doppler shift is proportional to radial velocity:

$$\frac{\Delta\lambda}{\lambda_0} = \frac{V}{c}$$

$\Delta\lambda$ = observed wavelength shift = λ-λ_0

λ_0 = wavelength if source isn't moving

V = radial velocity of moving source

c = speed of light = 300,000 km/sec

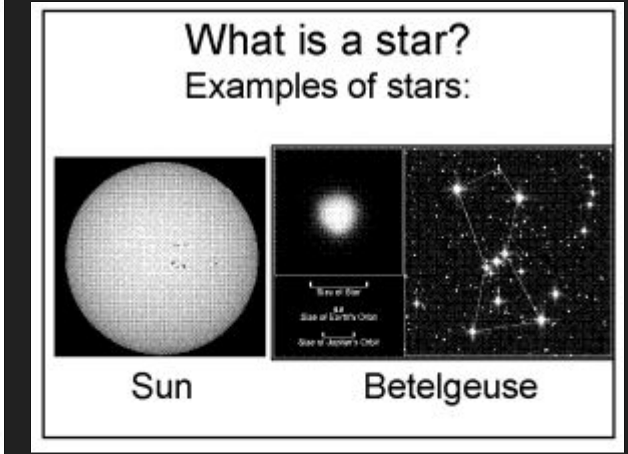
Preparatory Reading Chapter 3

Week 3: What is a Star?

What is a Star?

Wednesday, October 7

Next Planetarium Show: Tonight 7 pm

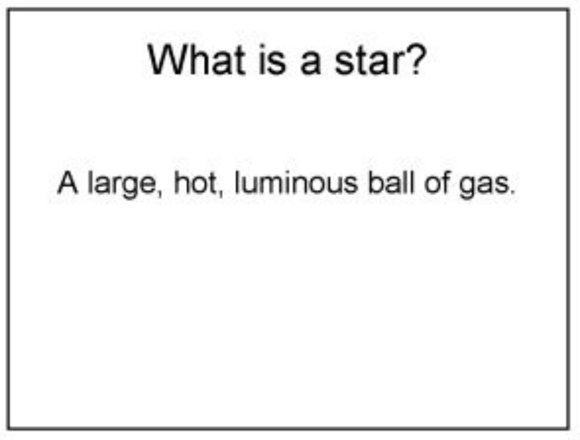


What is a star?

Examples of stars:

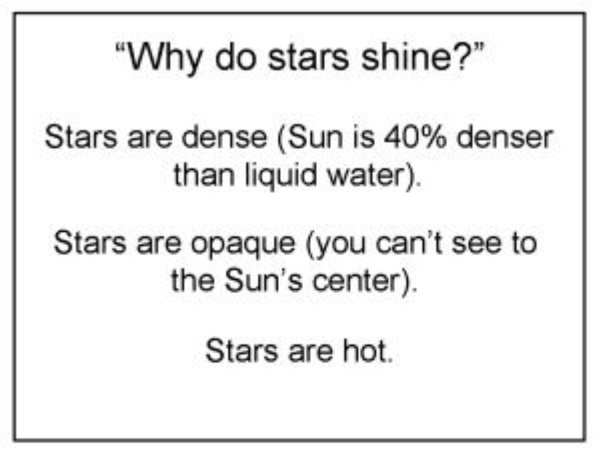
Sun

Betelgeuse



What is a star?

A large, hot, luminous ball of gas.

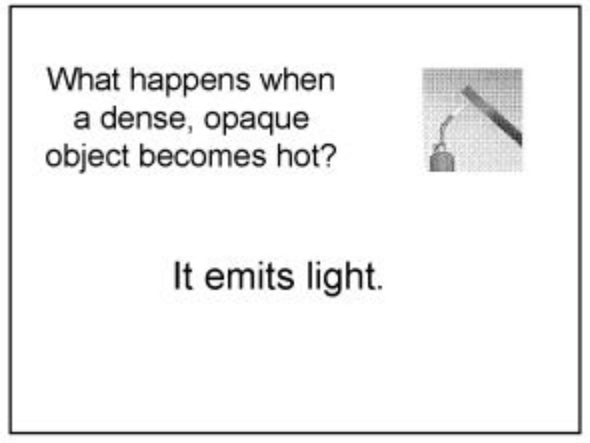


"Why do stars shine?"

Stars are dense (Sun is 40% denser than liquid water).

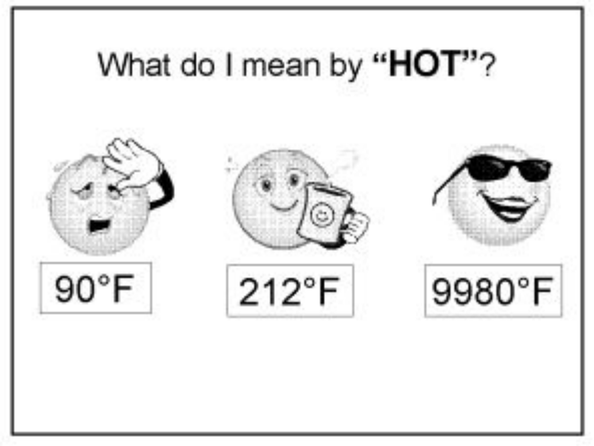
Stars are opaque (you can't see to the Sun's center).

Stars are hot.



What happens when a dense, opaque object becomes hot?

It emits light.

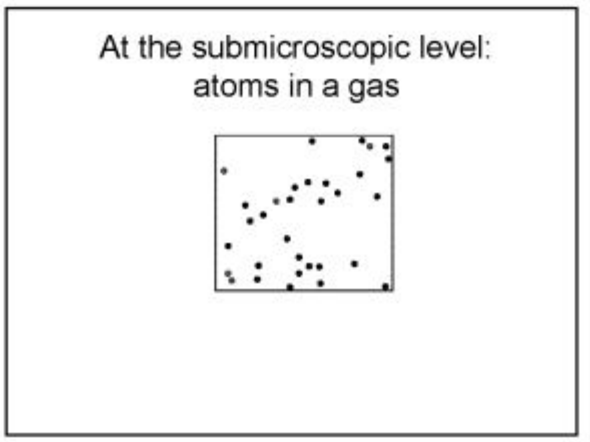


What do I mean by **"HOT"**?

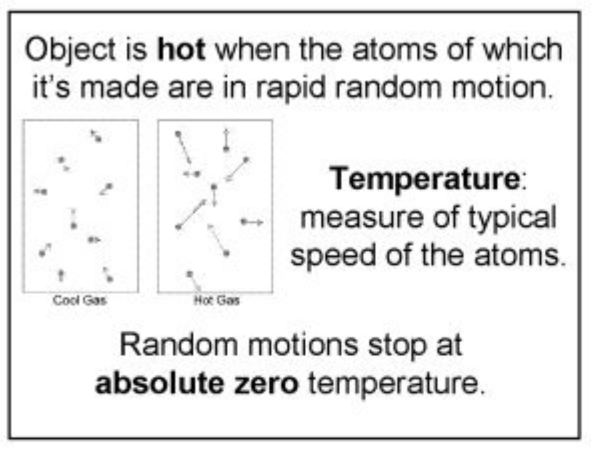
90°F

212°F

9980°F



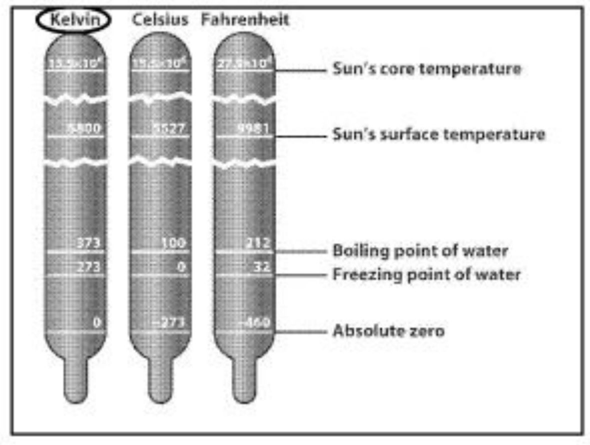
At the submicroscopic level:
atoms in a gas

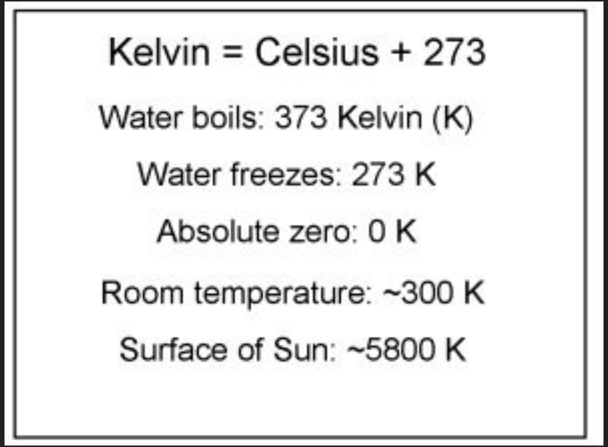


Object is **hot** when the atoms of which it's made are in rapid random motion.

Temperature:
measure of typical speed of the atoms.

Random motions stop at
absolute zero temperature.





Kelvin = Celsius + 273

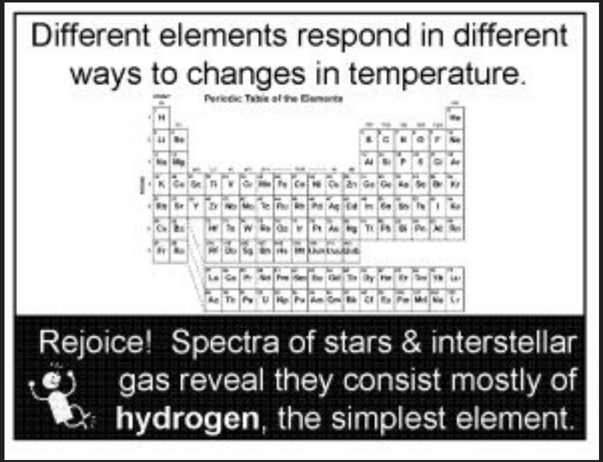
Water boils: 373 Kelvin (K)

Water freezes: 273 K

Absolute zero: 0 K

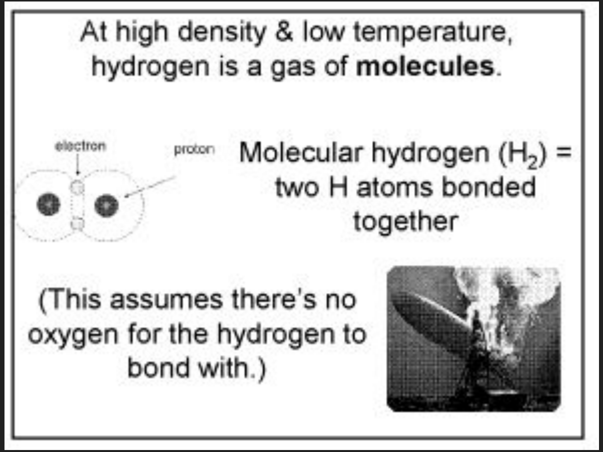
Room temperature: ~300 K

Surface of Sun: ~5800 K



Different elements respond in different ways to changes in temperature.

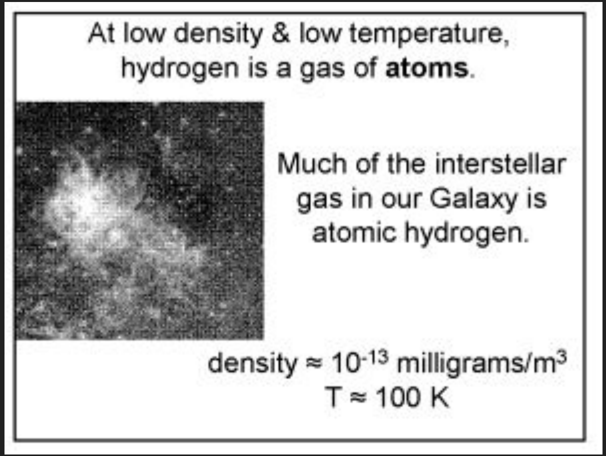
Rejoice! Spectra of stars & interstellar gas reveal they consist mostly of **hydrogen**, the simplest element.



At high density & low temperature, hydrogen is a gas of **molecules**.

Molecular hydrogen (H_2) = two H atoms bonded together

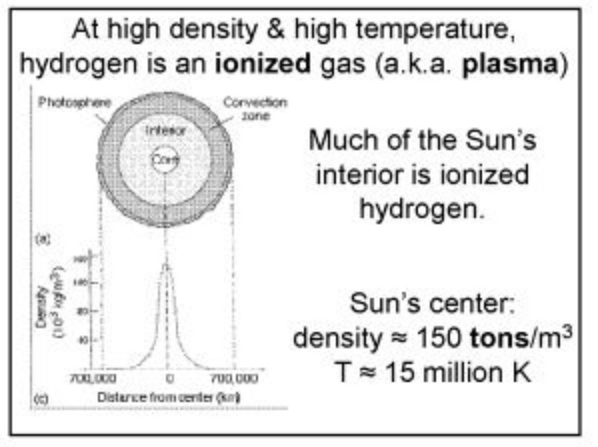
(This assumes there's no oxygen for the hydrogen to bond with.)



At low density & low temperature, hydrogen is a gas of **atoms**.

Much of the interstellar gas in our Galaxy is atomic hydrogen.

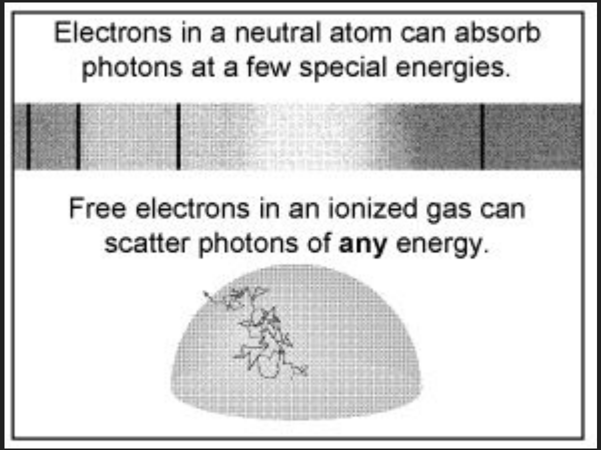
density ≈ 10^{-13} milligrams/m^3
T ≈ 100 K



At high density & high temperature, hydrogen is an **ionized** gas (a.k.a. **plasma**)

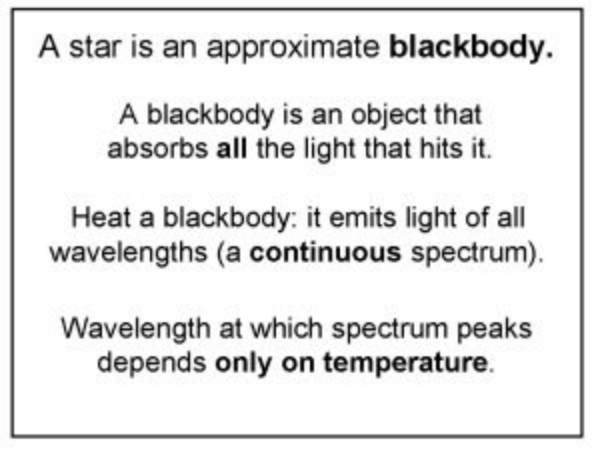
Much of the Sun's interior is ionized hydrogen.

Sun's center:
density ≈ 150 **tons**/m^3
T ≈ 15 million K



Electrons in a neutral atom can absorb photons at a few special energies.

Free electrons in an ionized gas can scatter photons of **any** energy.

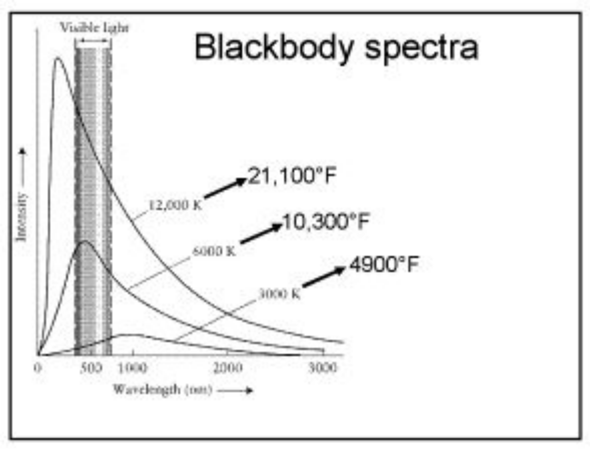


A star is an approximate **blackbody.**

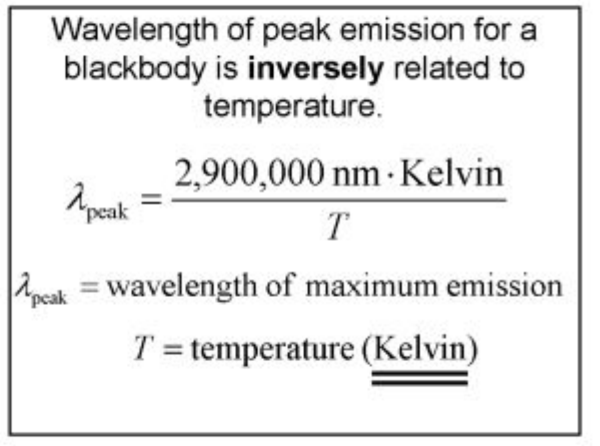
A blackbody is an object that absorbs **all** the light that hits it.

Heat a blackbody: it emits light of all wavelengths (a **continuous** spectrum).

Wavelength at which spectrum peaks depends **only on temperature**.



Blackbody spectra

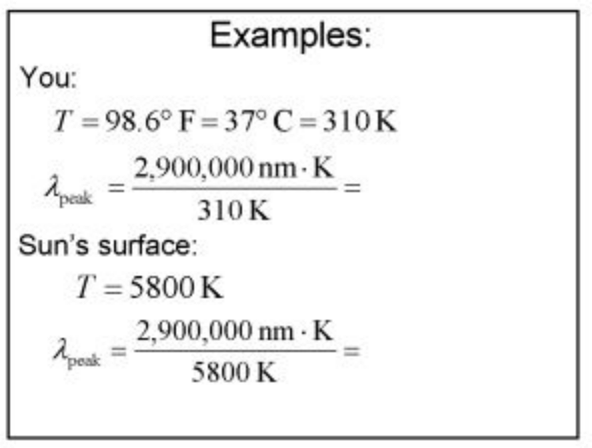


Wavelength of peak emission for a blackbody is **inversely** related to temperature.

$$\lambda_{\text{peak}} = \frac{2{,}900{,}000\ \text{nm} \cdot \text{Kelvin}}{T}$$

λ_{peak} = wavelength of maximum emission

T = temperature (Kelvin)



Examples:

You:

$$T = 98.6° \text{ F} = 37° \text{ C} = 310 \text{ K}$$

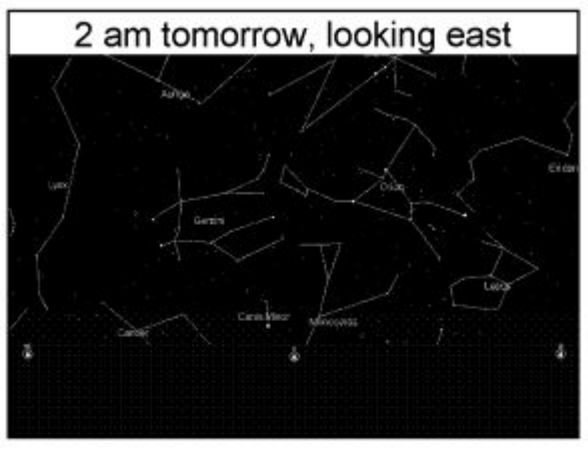
$$\lambda_{\text{peak}} = \frac{2{,}900{,}000 \text{ nm} \cdot \text{K}}{310 \text{ K}} =$$

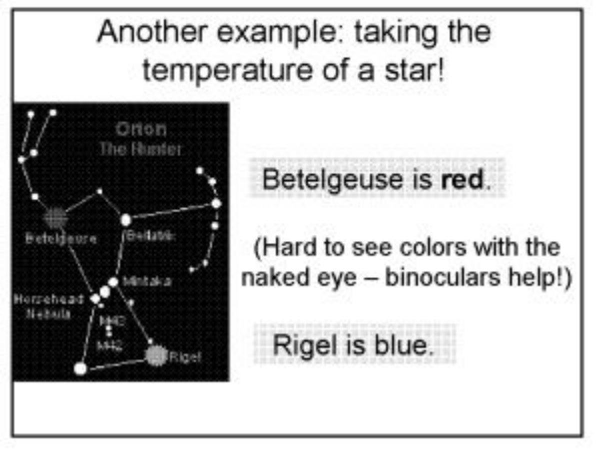
Sun's surface:

$$T = 5800 \text{ K}$$

$$\lambda_{\text{peak}} = \frac{2{,}900{,}000 \text{ nm} \cdot \text{K}}{5800 \text{ K}} =$$

2 am tomorrow, looking east



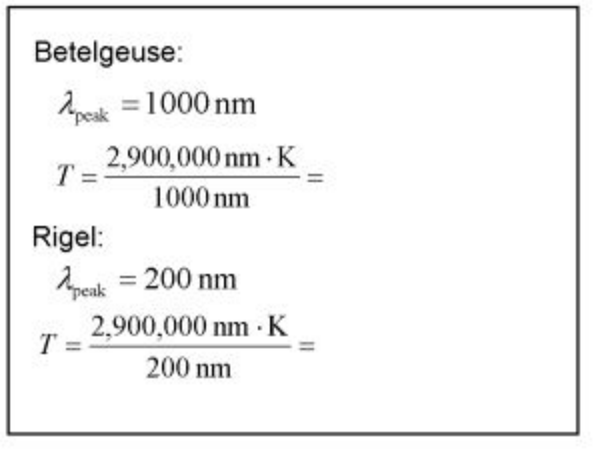


Another example: taking the temperature of a star!

Betelgeuse is **red**.

(Hard to see colors with the naked eye – binoculars help!)

Rigel is blue.



Betelgeuse:

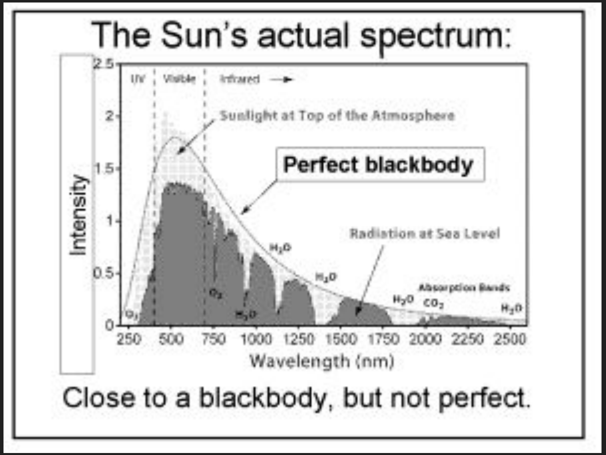
$$\lambda_{\text{peak}} = 1000\,\text{nm}$$

$$T = \frac{2{,}900{,}000\,\text{nm}\cdot\text{K}}{1000\,\text{nm}} =$$

Rigel:

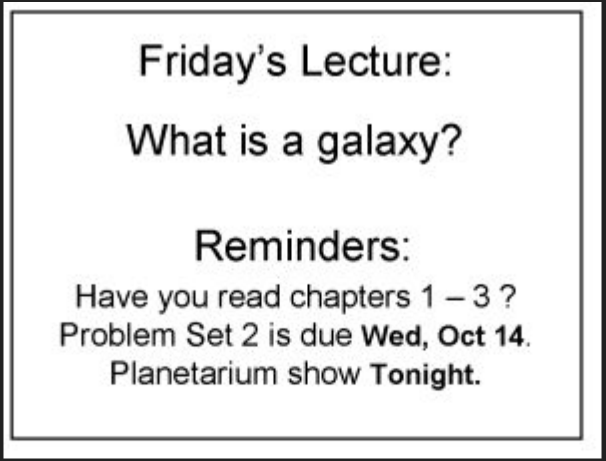
$$\lambda_{\text{peak}} = 200\text{ nm}$$

$$T = \frac{2{,}900{,}000\text{ nm}\cdot\text{K}}{200\text{ nm}} =$$



The Sun's actual spectrum:

Close to a blackbody, but not perfect.



Friday's Lecture:

What is a galaxy?

Reminders:

Have you read chapters 1 – 3 ?
Problem Set 2 is due **Wed, Oct 14**.
Planetarium show **Tonight.**

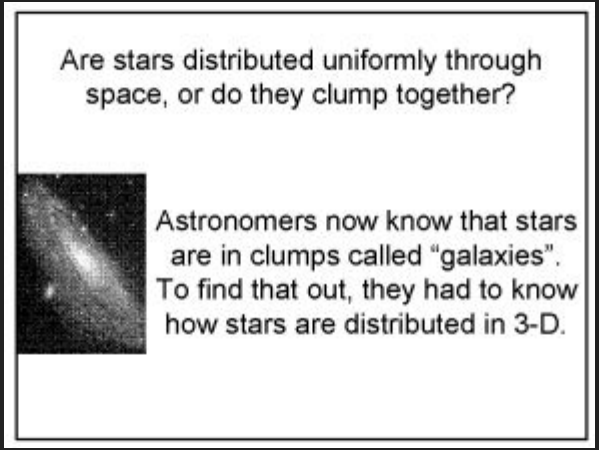
Preparatory Reading Chapter 3

Week 3: What is a Galaxy?

What is a Galaxy?

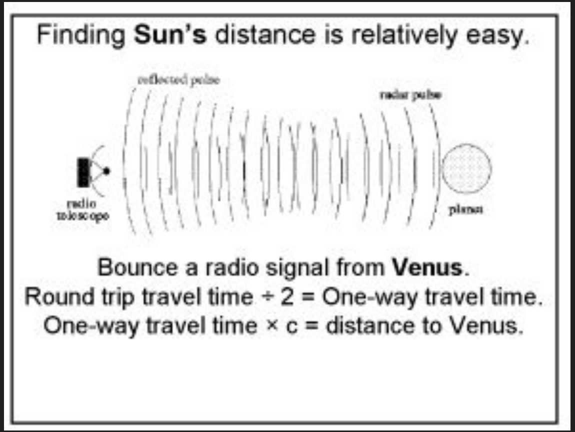
Friday, October 9

Next Planetarium Show: Tues, Oct 27



Are stars distributed uniformly through space, or do they clump together?

Astronomers now know that stars are in clumps called "galaxies". To find that out, they had to know how stars are distributed in 3-D.

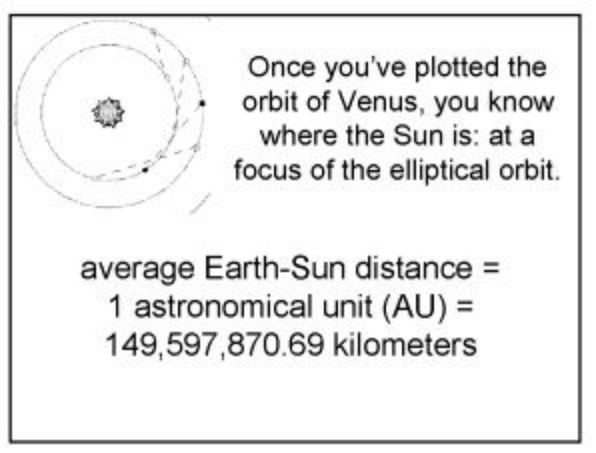


Finding **Sun's** distance is relatively easy.

Bounce a radio signal from **Venus**.

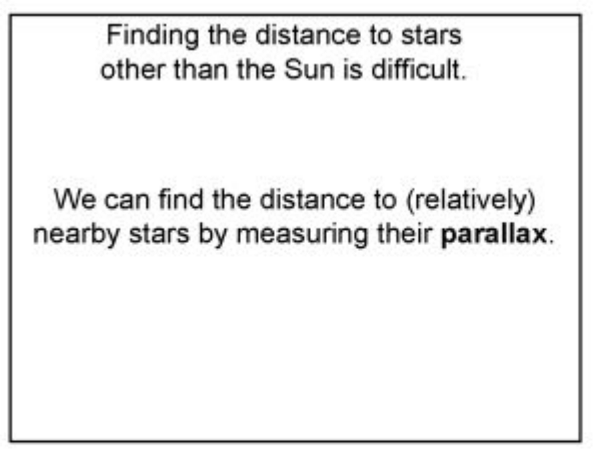
Round trip travel time ÷ 2 = One-way travel time.

One-way travel time × c = distance to Venus.



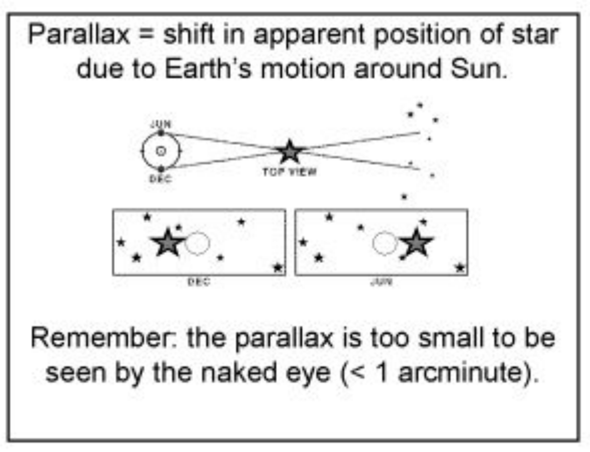
Once you've plotted the orbit of Venus, you know where the Sun is: at a focus of the elliptical orbit.

average Earth-Sun distance =
1 astronomical unit (AU) =
149,597,870.69 kilometers



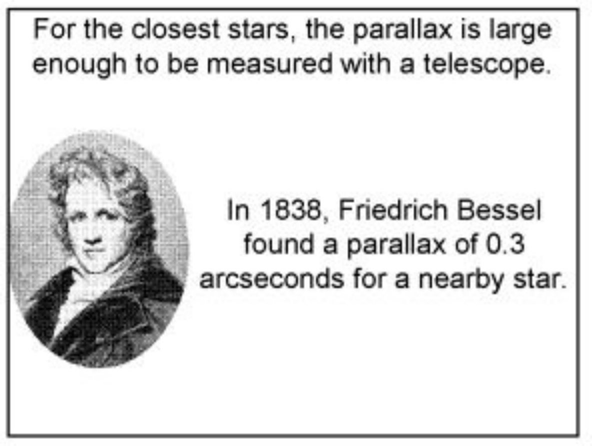
Finding the distance to stars other than the Sun is difficult.

We can find the distance to (relatively) nearby stars by measuring their **parallax**.



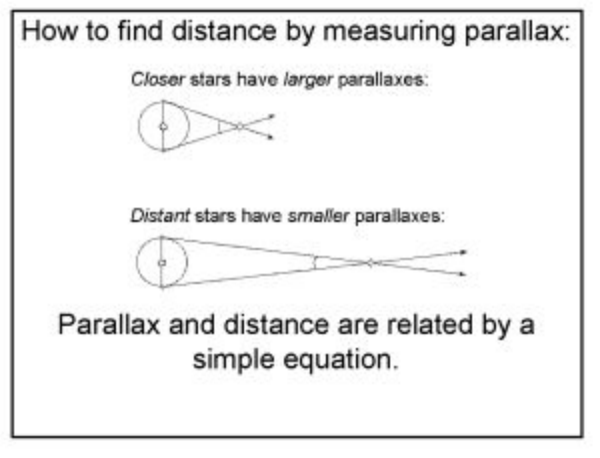
Parallax = shift in apparent position of star due to Earth's motion around Sun.

Remember: the parallax is too small to be seen by the naked eye (< 1 arcminute).



For the closest stars, the parallax is large enough to be measured with a telescope.

In 1838, Friedrich Bessel found a parallax of 0.3 arcseconds for a nearby star.

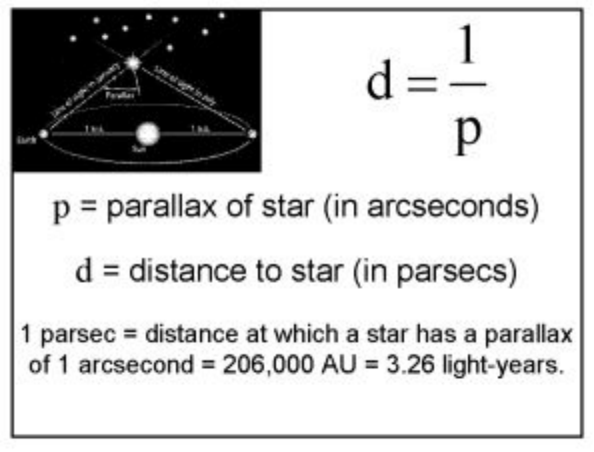


How to find distance by measuring parallax:

Closer stars have *larger* parallaxes:

Distant stars have *smaller* parallaxes:

Parallax and distance are related by a simple equation.

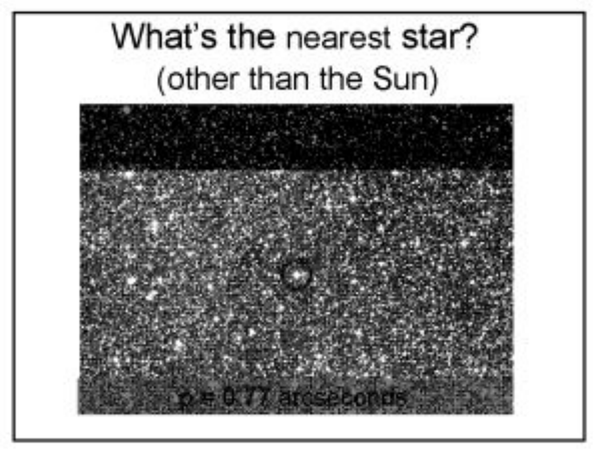


$$d = \frac{1}{p}$$

p = parallax of star (in arcseconds)

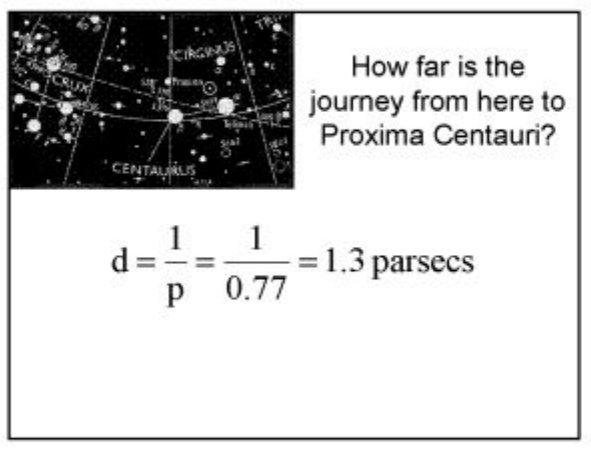
d = distance to star (in parsecs)

1 parsec = distance at which a star has a parallax of 1 arcsecond = 206,000 AU = 3.26 light-years.



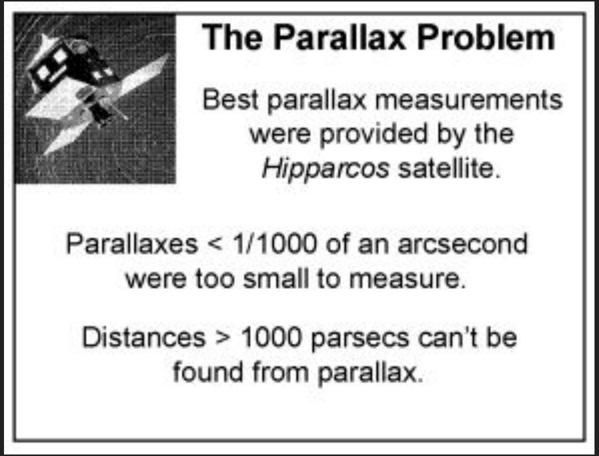
What's the nearest star?

(other than the Sun)



How far is the journey from here to Proxima Centauri?

$$d = \frac{1}{p} = \frac{1}{0.77} = 1.3 \text{ parsecs}$$

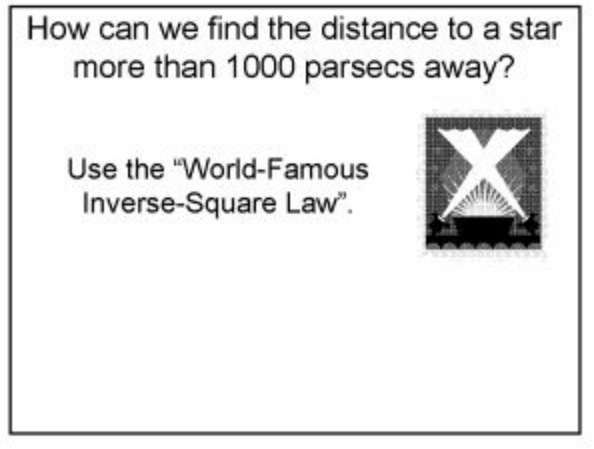


The Parallax Problem

Best parallax measurements were provided by the *Hipparcos* satellite.

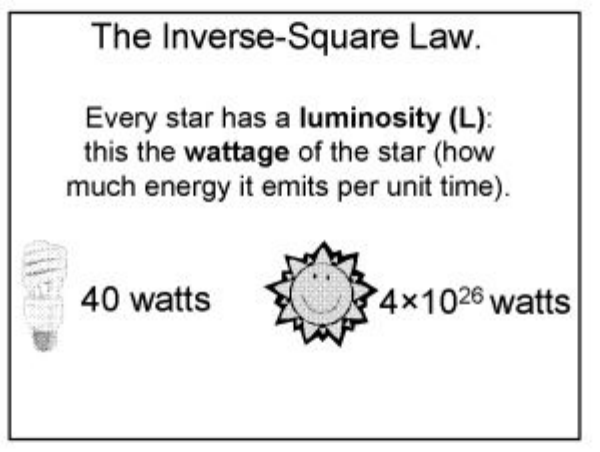
Parallaxes < 1/1000 of an arcsecond were too small to measure.

Distances > 1000 parsecs can't be found from parallax.



How can we find the distance to a star more than 1000 parsecs away?

Use the “World-Famous Inverse-Square Law”.

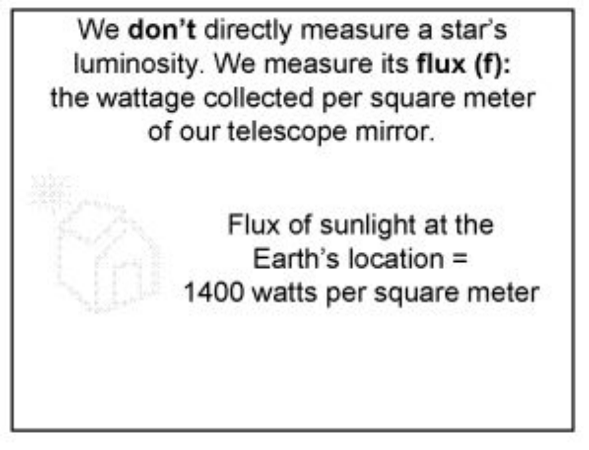


The Inverse-Square Law.

Every star has a **luminosity (L)**: this the **wattage** of the star (how much energy it emits per unit time).

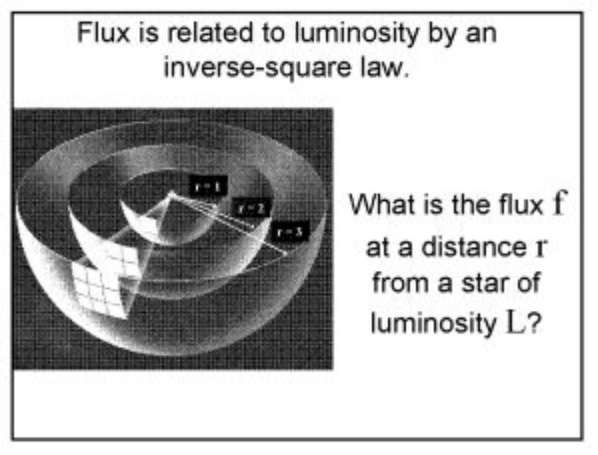
40 watts

4×10^{26} watts



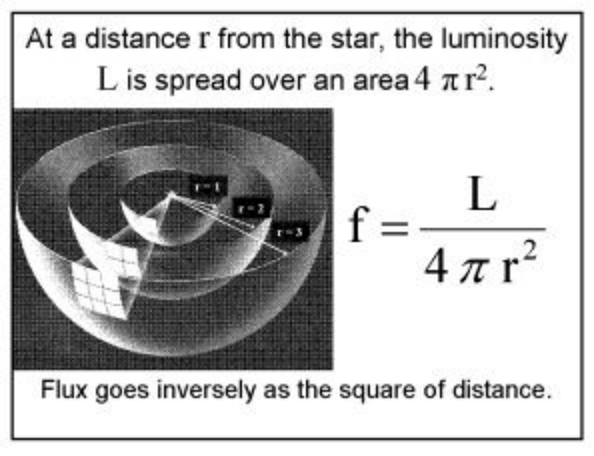
We **don’t** directly measure a star’s luminosity. We measure its **flux (f):** the wattage collected per square meter of our telescope mirror.

Flux of sunlight at the Earth’s location =
1400 watts per square meter



Flux is related to luminosity by an inverse-square law.

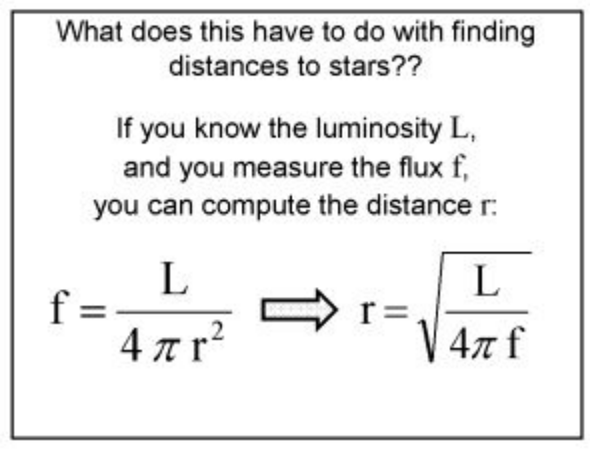
What is the flux f at a distance r from a star of luminosity L?



At a distance r from the star, the luminosity L is spread over an area $4\pi r^2$.

$$f = \frac{L}{4\pi r^2}$$

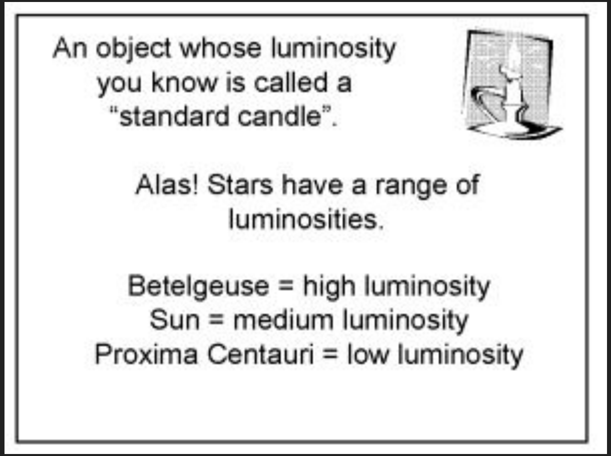
Flux goes inversely as the square of distance.



What does this have to do with finding distances to stars??

If you know the luminosity L,
and you measure the flux f,
you can compute the distance r:

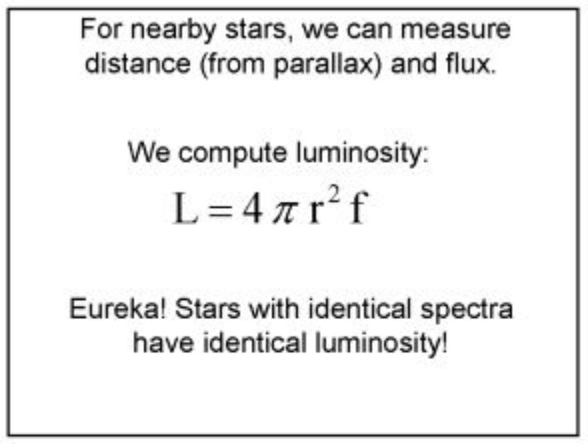
$$f = \frac{L}{4\pi r^2} \Rightarrow r = \sqrt{\frac{L}{4\pi f}}$$



An object whose luminosity you know is called a “standard candle”.

Alas! Stars have a range of luminosities.

Betelgeuse = high luminosity
Sun = medium luminosity
Proxima Centauri = low luminosity

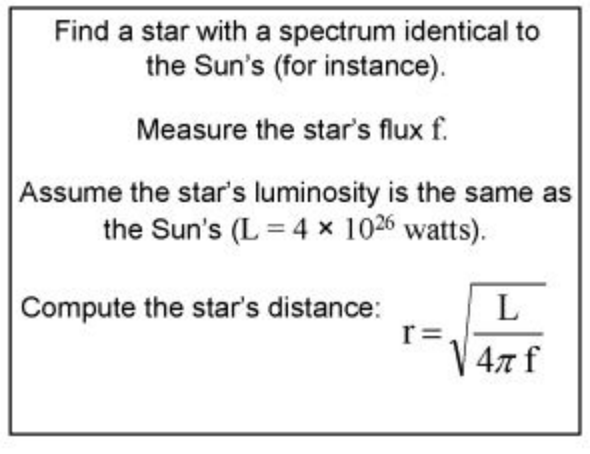


For nearby stars, we can measure distance (from parallax) and flux.

We compute luminosity:

$$L = 4 \pi r^2 f$$

Eureka! Stars with identical spectra have identical luminosity!

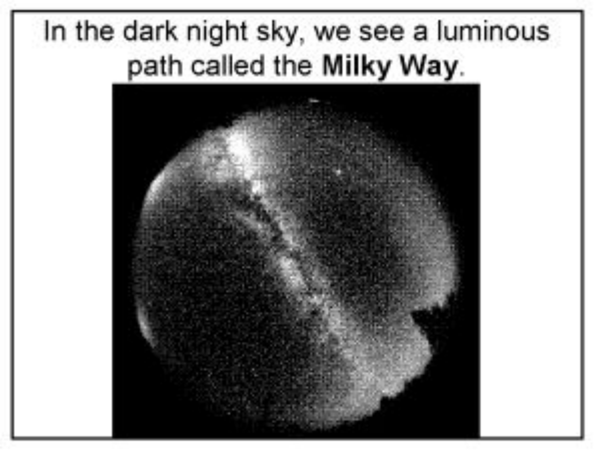


Find a star with a spectrum identical to the Sun’s (for instance).

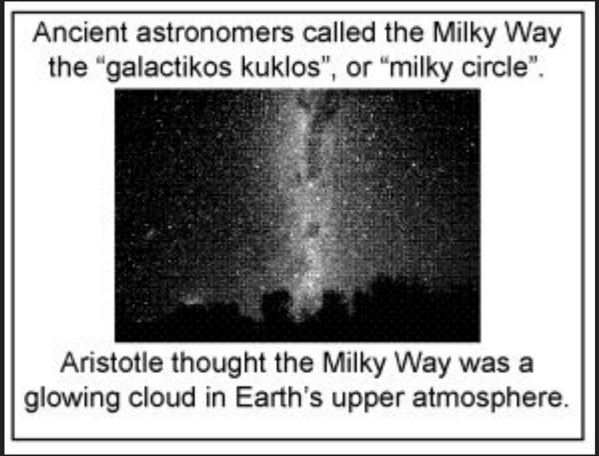
Measure the star’s flux f.

Assume the star’s luminosity is the same as the Sun’s ($L = 4 \times 10^{26}$ watts).

Compute the star’s distance: $r = \sqrt{\frac{L}{4\pi f}}$

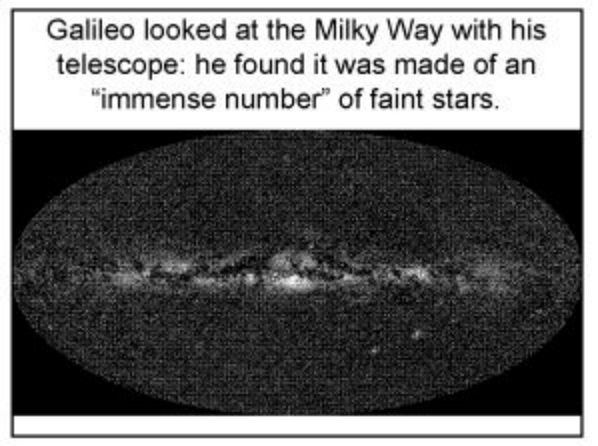


In the dark night sky, we see a luminous path called the **Milky Way**.

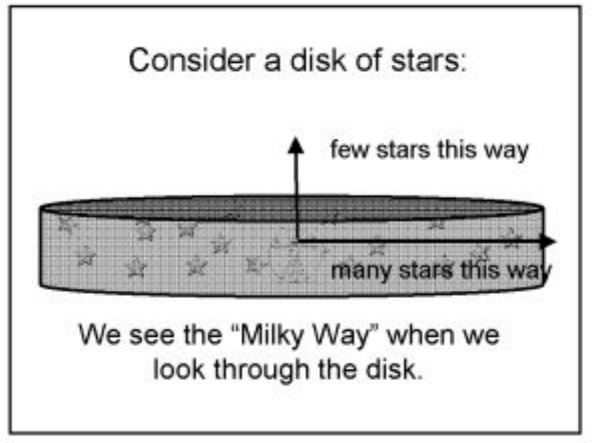


Ancient astronomers called the Milky Way the “galactikos kuklos”, or “milky circle”.

Aristotle thought the Milky Way was a glowing cloud in Earth’s upper atmosphere.

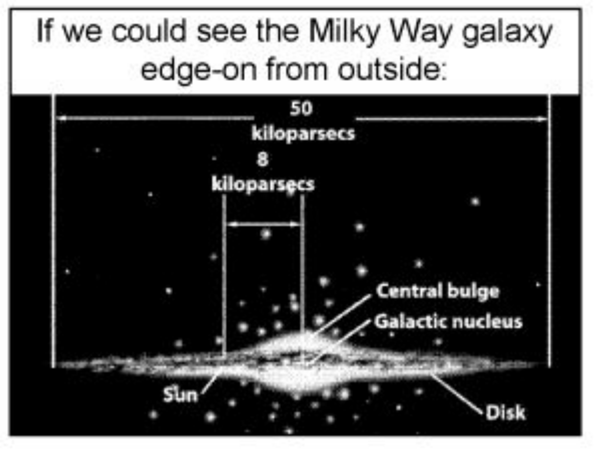


Galileo looked at the Milky Way with his telescope: he found it was made of an “immense number” of faint stars.

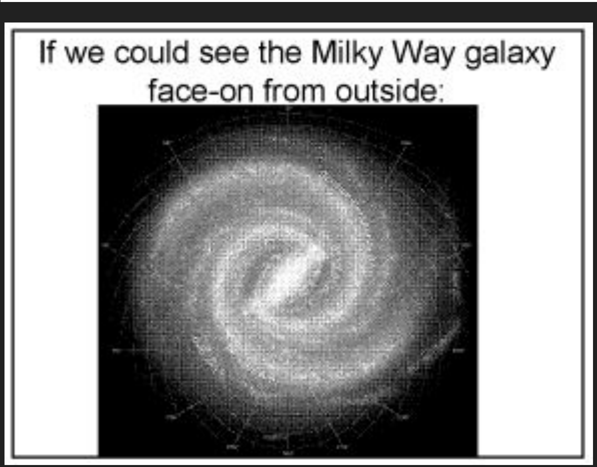


Consider a disk of stars:

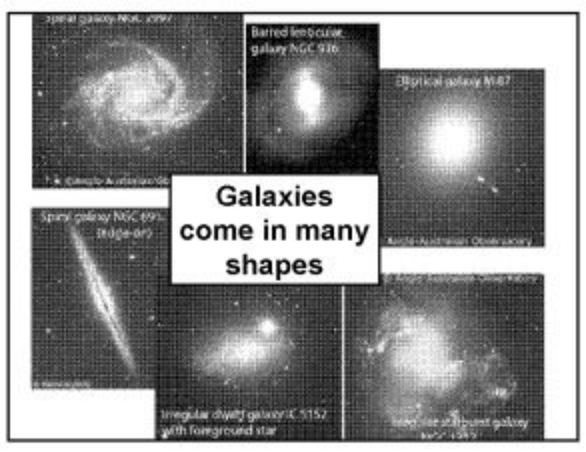
We see the “Milky Way” when we look through the disk.



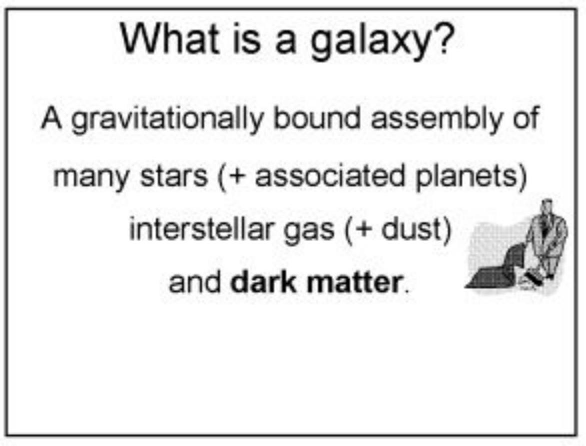
If we could see the Milky Way galaxy edge-on from outside:



If we could see the Milky Way galaxy face-on from outside:



Galaxies come in many shapes



What is a galaxy?

A gravitationally bound assembly of

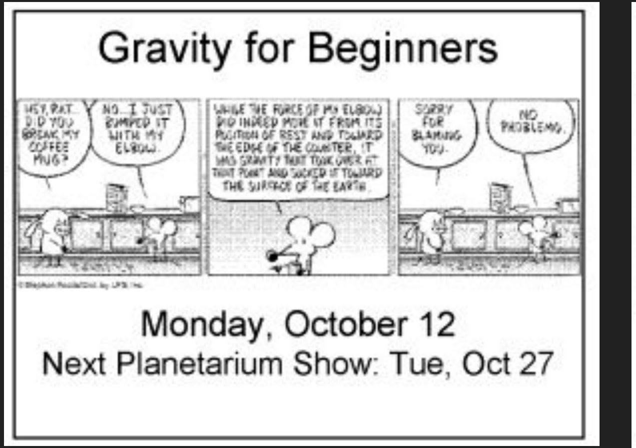
many stars (+ associated planets)

interstellar gas (+ dust)

and **dark matter**.

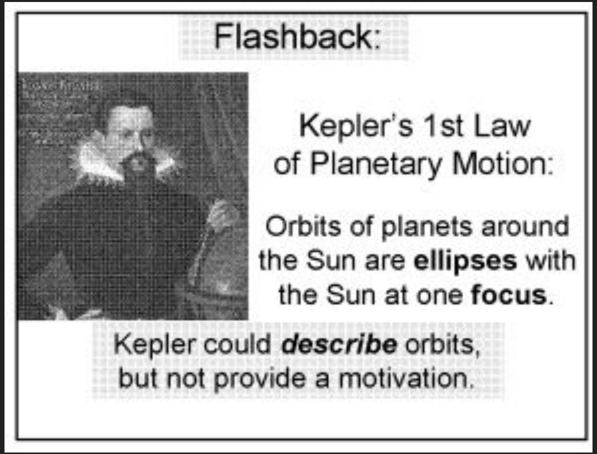
Preparatory Reading Chapter 4

Week 4: Gravity



Gravity for Beginners

Monday, October 12
Next Planetarium Show: Tue, Oct 27

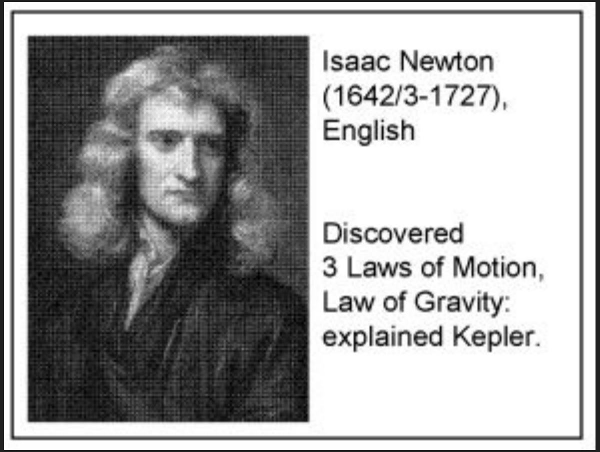


Flashback:

Kepler's 1st Law of Planetary Motion:

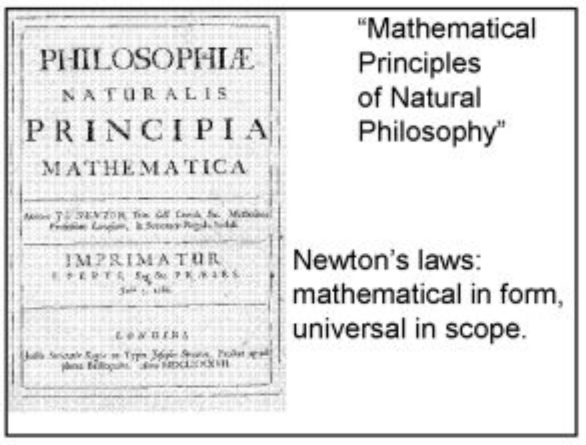
Orbits of planets around the Sun are **ellipses** with the Sun at one **focus**.

Kepler could ***describe*** orbits, but not provide a motivation.



Isaac Newton (1642/3-1727), English

Discovered 3 Laws of Motion, Law of Gravity: explained Kepler.



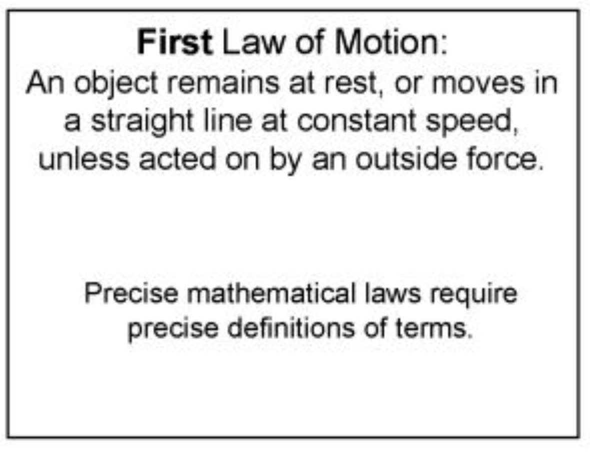
PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA

IMPRIMATUR

LONDINI

"Mathematical Principles of Natural Philosophy"

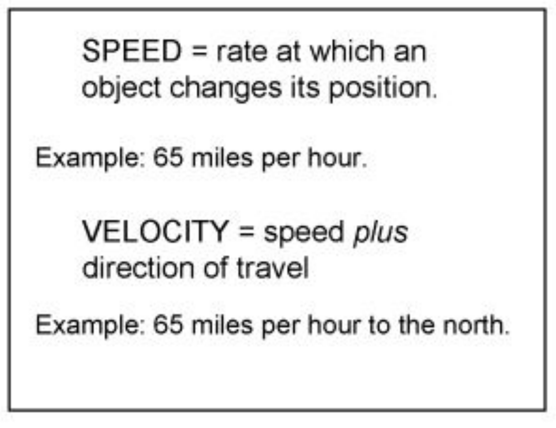
Newton's laws: mathematical in form, universal in scope.



First Law of Motion:

An object remains at rest, or moves in a straight line at constant speed, unless acted on by an outside force.

Precise mathematical laws require precise definitions of terms.

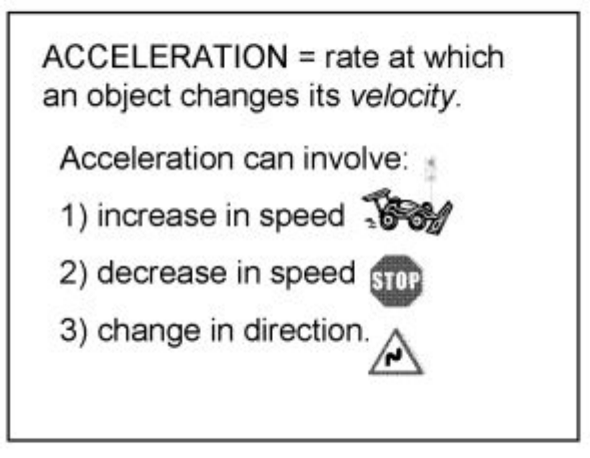


SPEED = rate at which an object changes its position.

Example: 65 miles per hour.

VELOCITY = speed *plus* direction of travel

Example: 65 miles per hour to the north.



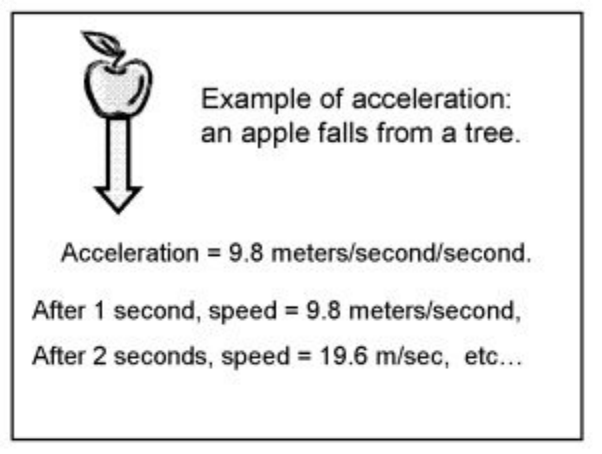
ACCELERATION = rate at which an object changes its *velocity*.

Acceleration can involve:

1) increase in speed

2) decrease in speed

3) change in direction.

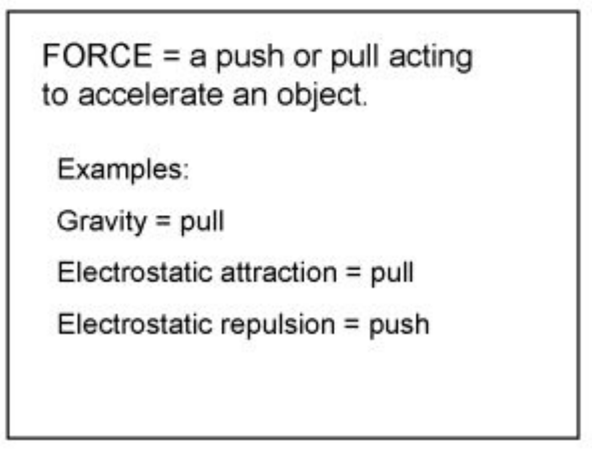


Example of acceleration: an apple falls from a tree.

Acceleration = 9.8 meters/second/second.

After 1 second, speed = 9.8 meters/second,

After 2 seconds, speed = 19.6 m/sec, etc…



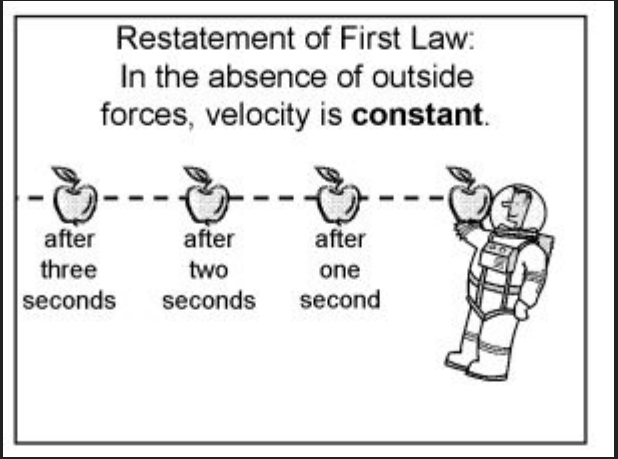
FORCE = a push or pull acting to accelerate an object.

Examples:

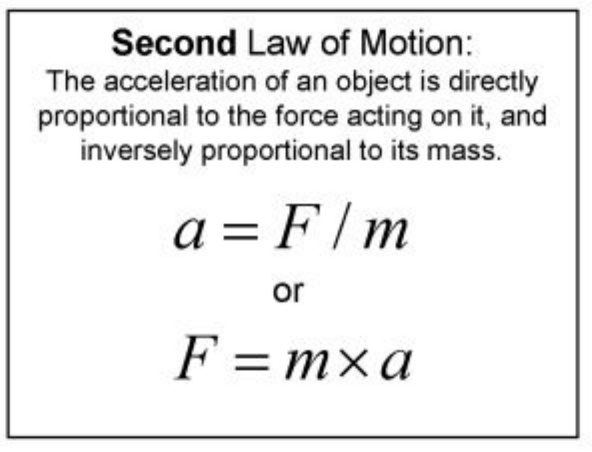
Gravity = pull

Electrostatic attraction = pull

Electrostatic repulsion = push



Restatement of First Law:
In the absence of outside forces, velocity is **constant**.



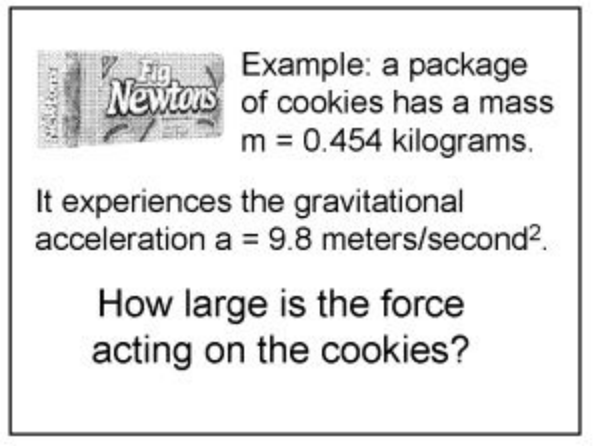
Second Law of Motion:

The acceleration of an object is directly proportional to the force acting on it, and inversely proportional to its mass.

$$a = F / m$$

or

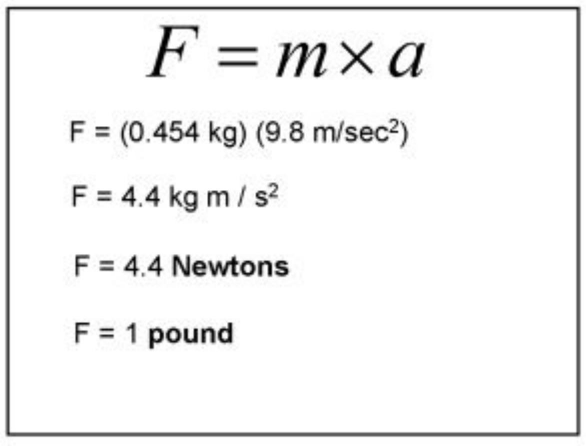
$$F = m \times a$$



Example: a package of cookies has a mass m = 0.454 kilograms.

It experiences the gravitational acceleration a = 9.8 meters/second^2.

How large is the force acting on the cookies?



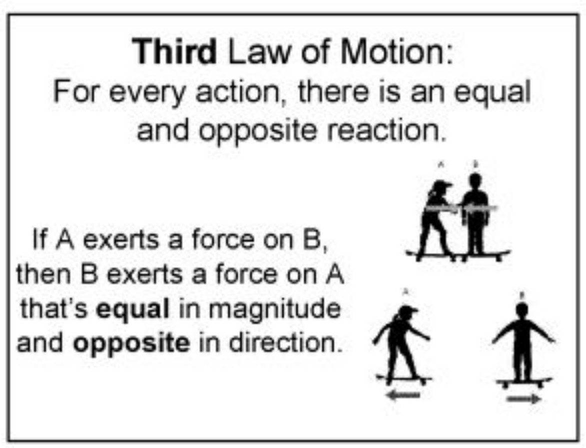
$$F = m \times a$$

F = (0.454 kg) (9.8 m/sec^2)

F = 4.4 kg m / s^2

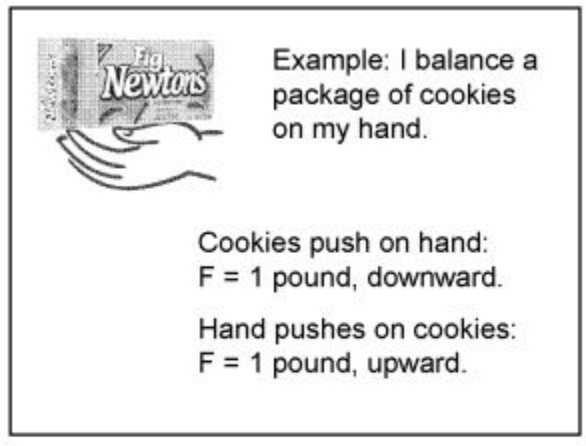
F = 4.4 **Newtons**

F = 1 **pound**



Third Law of Motion:
For every action, there is an equal and opposite reaction.

If A exerts a force on B, then B exerts a force on A that's **equal** in magnitude and **opposite** in direction.



Example: I balance a package of cookies on my hand.

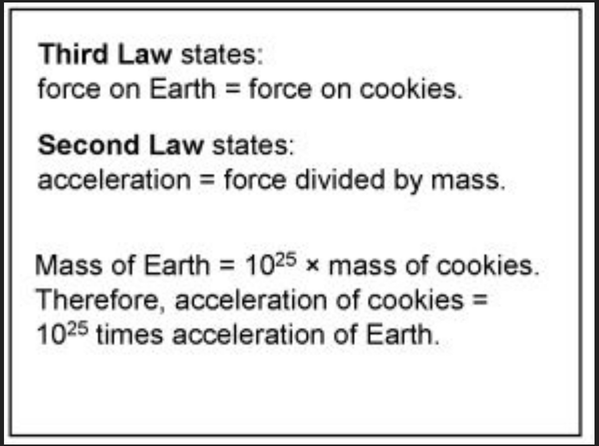
Cookies push on hand:
F = 1 pound, downward.

Hand pushes on cookies:
F = 1 pound, upward.

Example: I remove my hand.

Earth pulls on cookies:
F = 1 pound, downward.

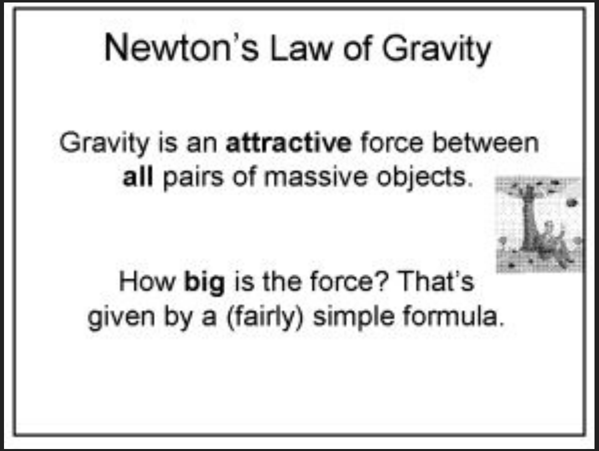
Cookies pull on Earth:
F = 1 pound, upward.



Third Law states:
force on Earth = force on cookies.

Second Law states:
acceleration = force divided by mass.

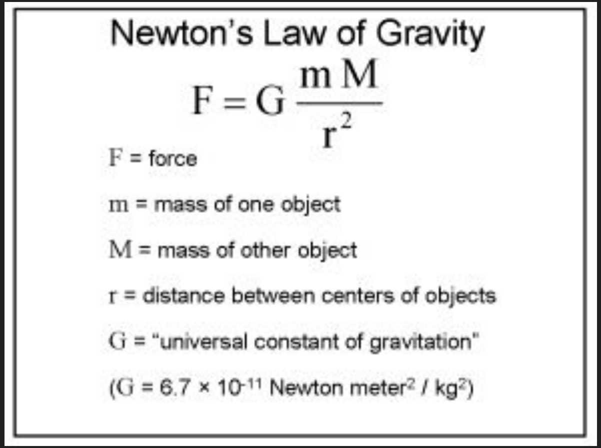
Mass of Earth = 10^{25} × mass of cookies.
Therefore, acceleration of cookies = 10^{25} times acceleration of Earth.



Newton’s Law of Gravity

Gravity is an **attractive** force between **all** pairs of massive objects.

How **big** is the force? That’s given by a (fairly) simple formula.



Newton's Law of Gravity

$$F = G\frac{m\,M}{r^2}$$

F = force

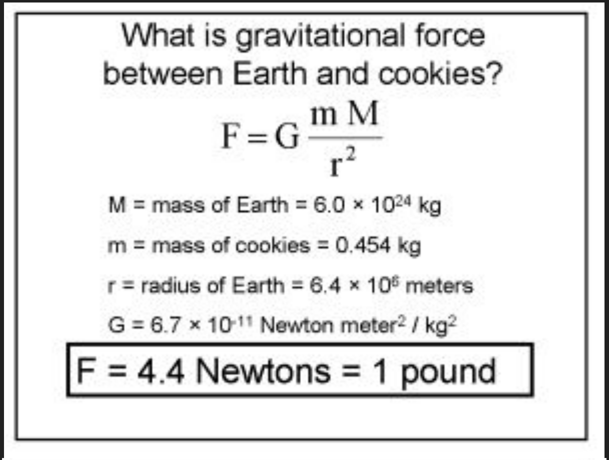
m = mass of one object

M = mass of other object

r = distance between centers of objects

G = "universal constant of gravitation"

(G = 6.7 × 10^{-11} Newton meter^2 / kg^2)



What is gravitational force between Earth and cookies?

$$F = G\frac{m\,M}{r^2}$$

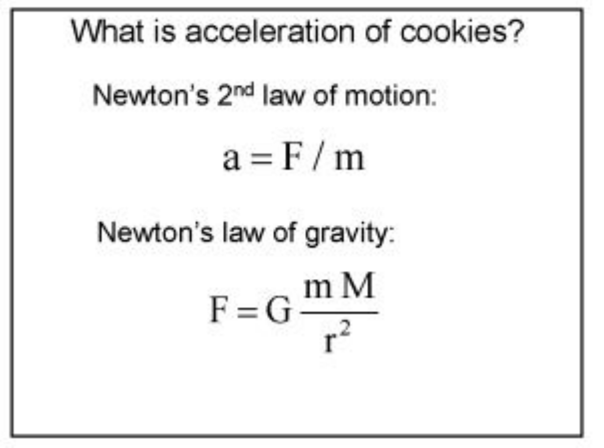
M = mass of Earth = 6.0 × 10^{24} kg

m = mass of cookies = 0.454 kg

r = radius of Earth = 6.4 × 10^6 meters

G = 6.7 × 10^{-11} Newton meter^2 / kg^2

$$\boxed{F = 4.4 \text{ Newtons} = 1 \text{ pound}}$$



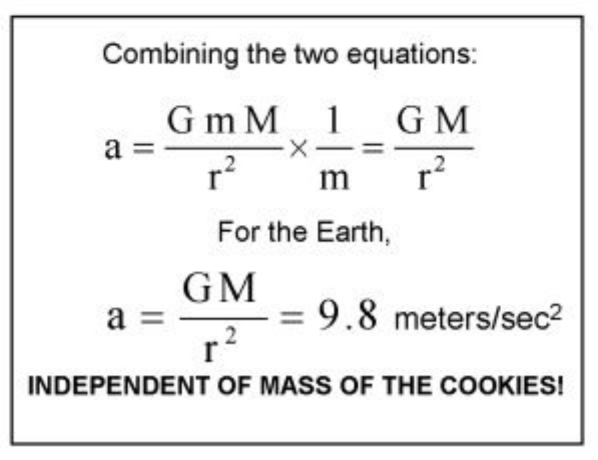
What is acceleration of cookies?

Newton's 2nd law of motion:

$$a = F / m$$

Newton's law of gravity:

$$F = G\frac{m\,M}{r^2}$$



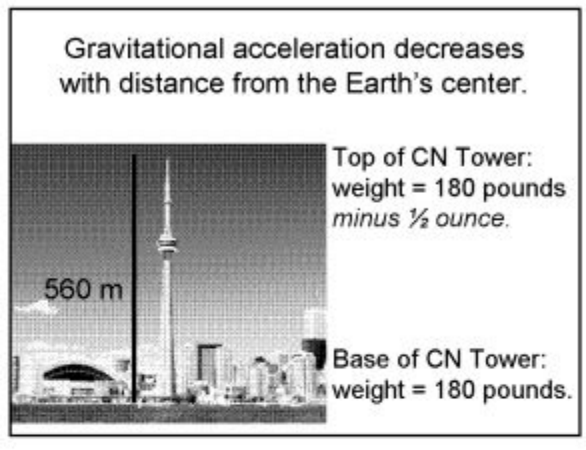
Combining the two equations:

$$a = \frac{G\,m\,M}{r^2} \times \frac{1}{m} = \frac{G\,M}{r^2}$$

For the Earth,

$$a = \frac{G\,M}{r^2} = 9.8 \text{ meters/sec}^2$$

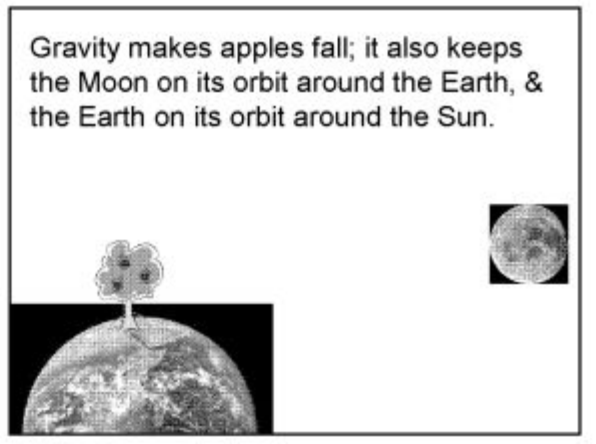
INDEPENDENT OF MASS OF THE COOKIES!



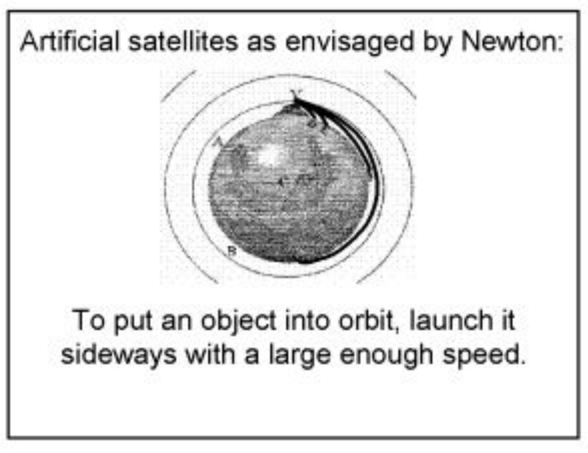
Gravitational acceleration decreases with distance from the Earth’s center.

Top of CN Tower:
weight = 180 pounds
minus ½ ounce.

Base of CN Tower:
weight = 180 pounds.

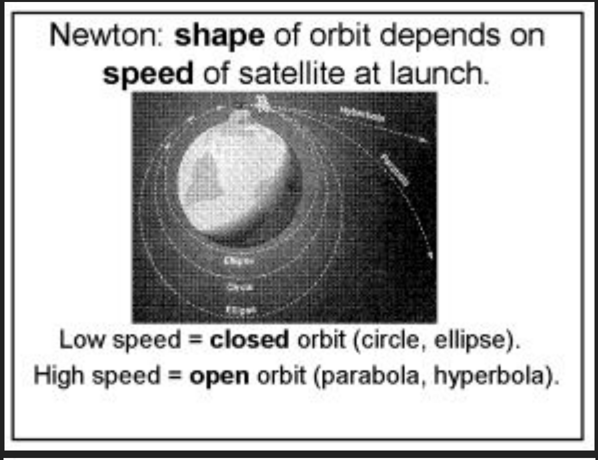


Gravity makes apples fall; it also keeps the Moon on its orbit around the Earth, & the Earth on its orbit around the Sun.



Artificial satellites as envisaged by Newton:

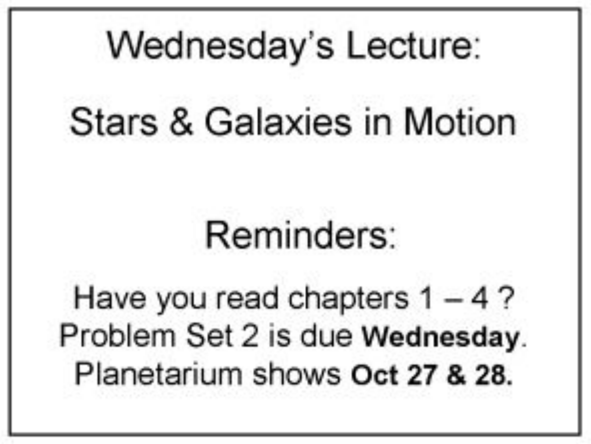
To put an object into orbit, launch it sideways with a large enough speed.



Newton: **shape** of orbit depends on **speed** of satellite at launch.

Low speed = **closed** orbit (circle, ellipse).

High speed = **open** orbit (parabola, hyperbola).



Wednesday's Lecture:

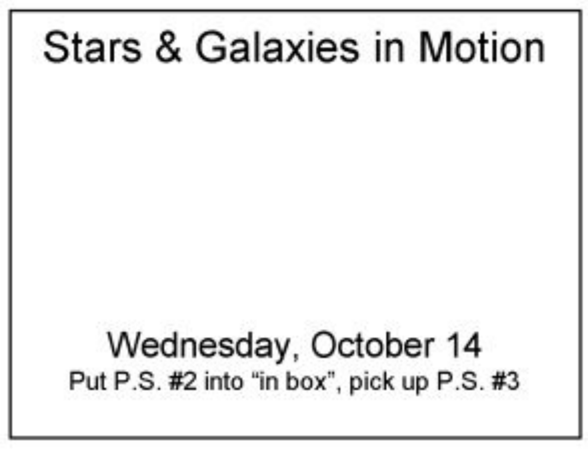
Stars & Galaxies in Motion

Reminders:

Have you read chapters 1 – 4 ?
Problem Set 2 is due **Wednesday**.
Planetarium shows **Oct 27 & 28.**

Preparatory Reading Chapter 4

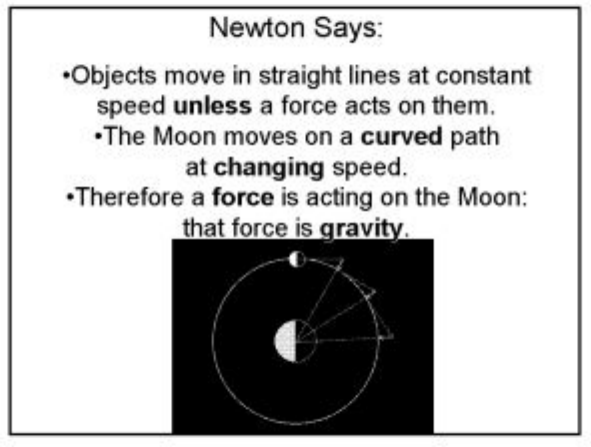
Week 4: Stars & Galaxies in Motion



Stars & Galaxies in Motion

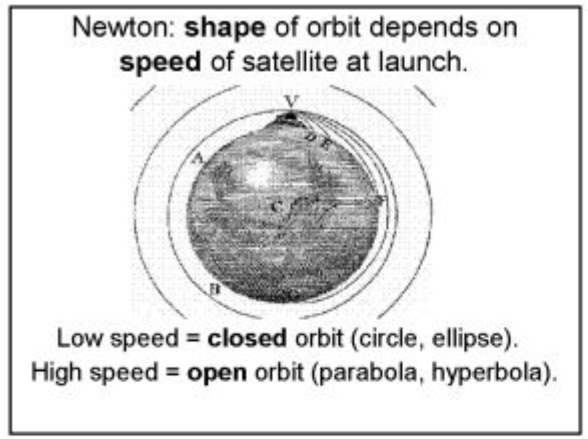
Wednesday, October 14

Put P.S. #2 into "in box", pick up P.S. #3



Newton Says:

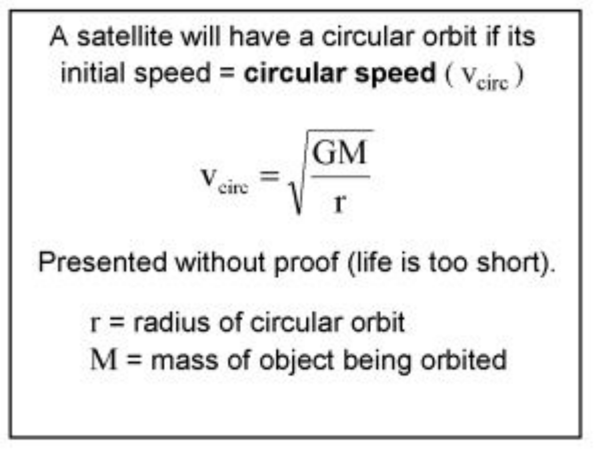
- Objects move in straight lines at constant speed **unless** a force acts on them.
- The Moon moves on a **curved** path at **changing** speed.
- Therefore a **force** is acting on the Moon: that force is **gravity**.



Newton: **shape** of orbit depends on **speed** of satellite at launch.

Low speed = **closed** orbit (circle, ellipse).

High speed = **open** orbit (parabola, hyperbola).

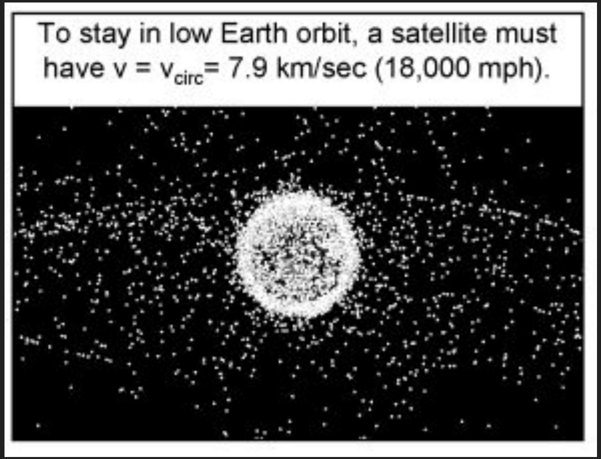


A satellite will have a circular orbit if its initial speed = **circular speed** (v_{circ})

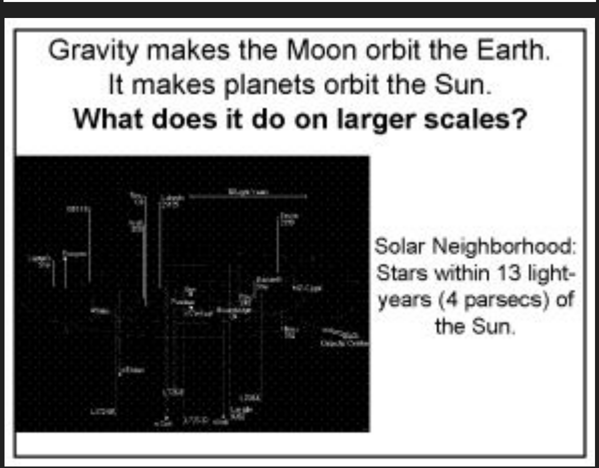
$$v_{circ} = \sqrt{\frac{GM}{r}}$$

Presented without proof (life is too short).

r = radius of circular orbit
M = mass of object being orbited

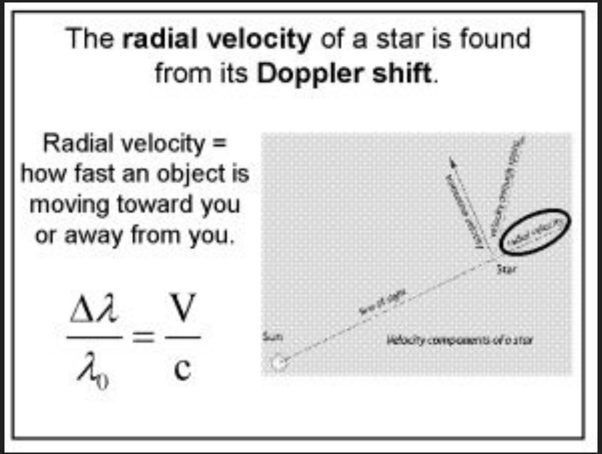


To stay in low Earth orbit, a satellite must have v = v_{circ}= 7.9 km/sec (18,000 mph).



Gravity makes the Moon orbit the Earth.
It makes planets orbit the Sun.
What does it do on larger scales?

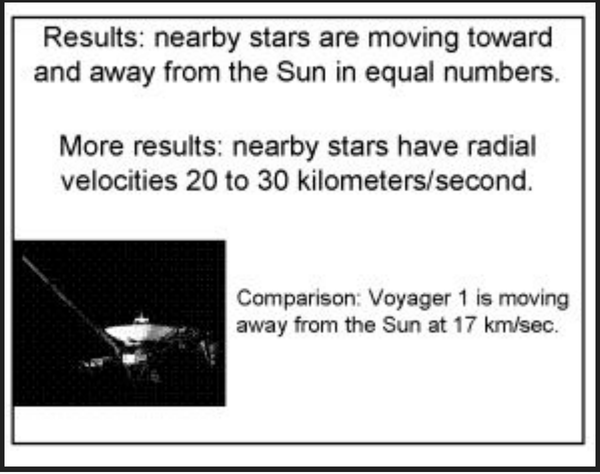
Solar Neighborhood: Stars within 13 light-years (4 parsecs) of the Sun.



The **radial velocity** of a star is found from its **Doppler shift**.

Radial velocity = how fast an object is moving toward you or away from you.

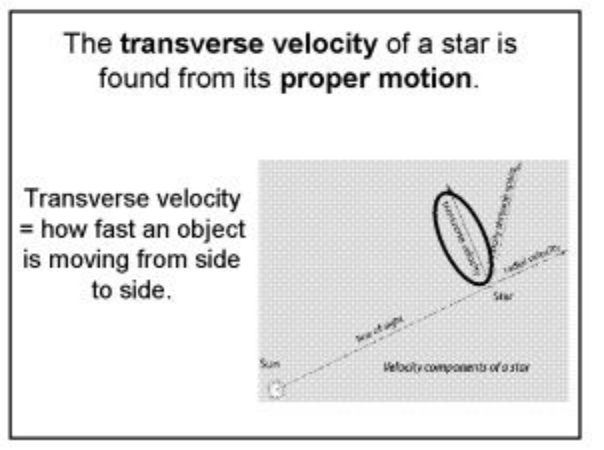
$$\frac{\Delta\lambda}{\lambda_0} = \frac{V}{c}$$



Results: nearby stars are moving toward and away from the Sun in equal numbers.

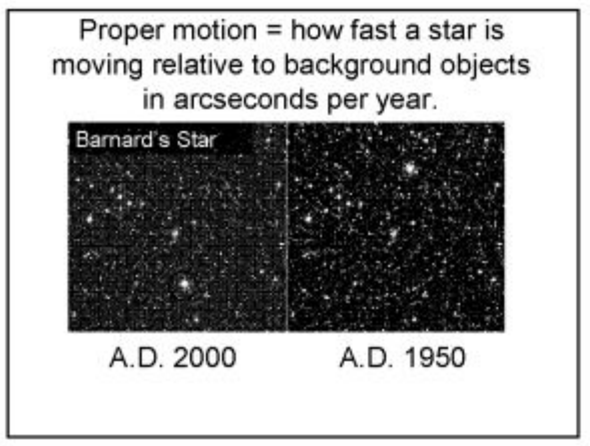
More results: nearby stars have radial velocities 20 to 30 kilometers/second.

Comparison: Voyager 1 is moving away from the Sun at 17 km/sec.

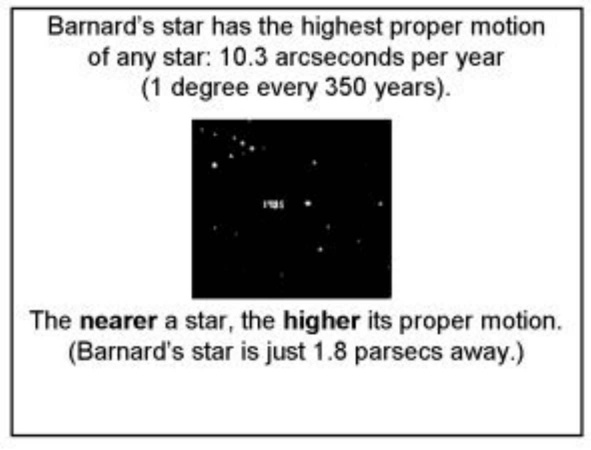


The **transverse velocity** of a star is found from its **proper motion**.

Transverse velocity = how fast an object is moving from side to side.

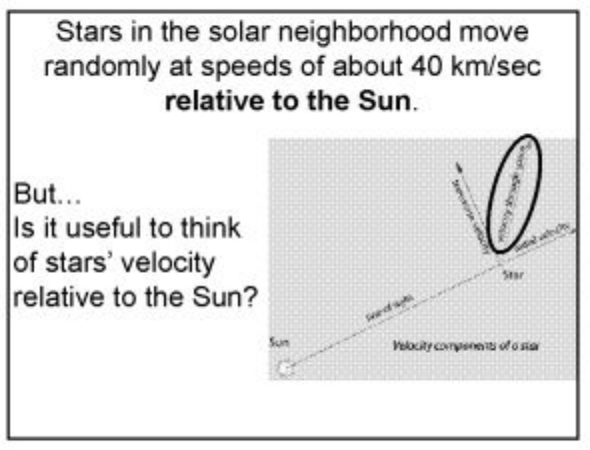


Proper motion = how fast a star is moving relative to background objects in arcseconds per year.



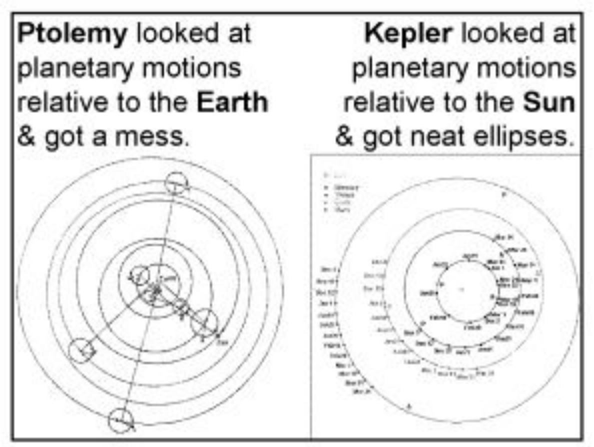
Barnard's star has the highest proper motion of any star: 10.3 arcseconds per year (1 degree every 350 years).

The **nearer** a star, the **higher** its proper motion. (Barnard's star is just 1.8 parsecs away.)



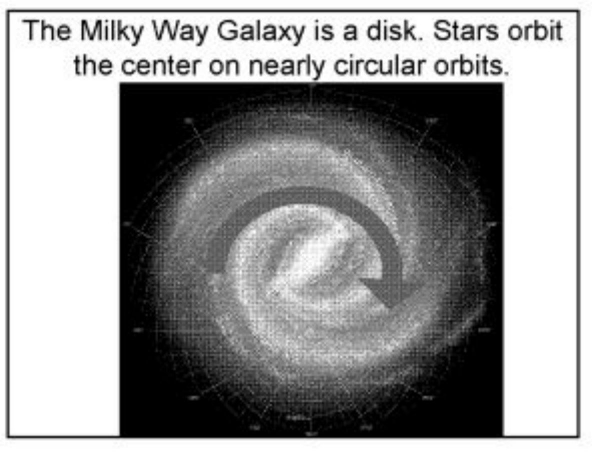
Stars in the solar neighborhood move randomly at speeds of about 40 km/sec **relative to the Sun**.

But…
Is it useful to think of stars' velocity relative to the Sun?

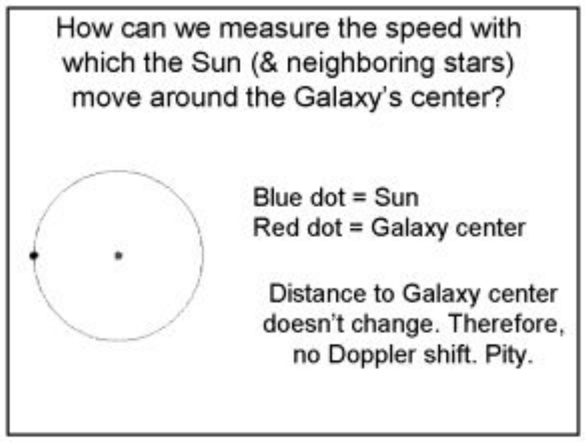


Ptolemy looked at planetary motions relative to the **Earth** & got a mess.

Kepler looked at planetary motions relative to the **Sun** & got neat ellipses.



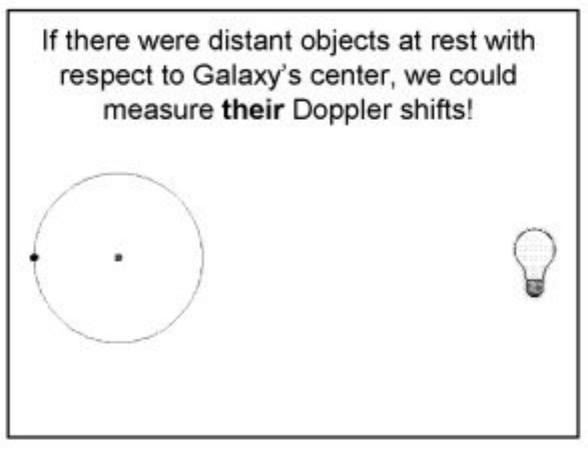
The Milky Way Galaxy is a disk. Stars orbit the center on nearly circular orbits.



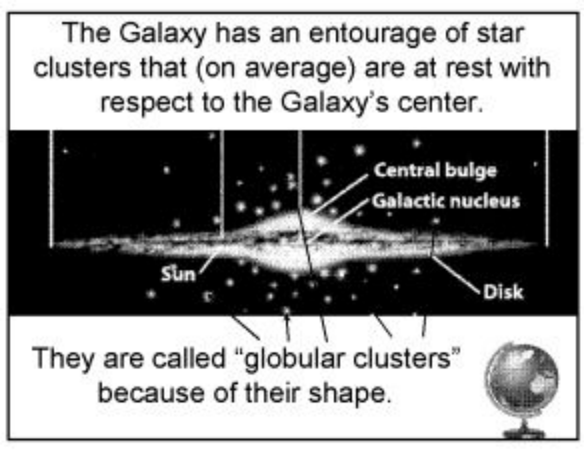
How can we measure the speed with which the Sun (& neighboring stars) move around the Galaxy's center?

Blue dot = Sun
Red dot = Galaxy center

Distance to Galaxy center doesn't change. Therefore, no Doppler shift. Pity.

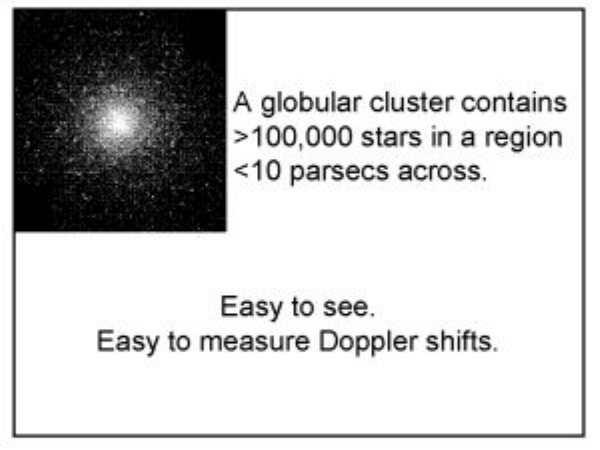


If there were distant objects at rest with respect to Galaxy's center, we could measure **their** Doppler shifts!



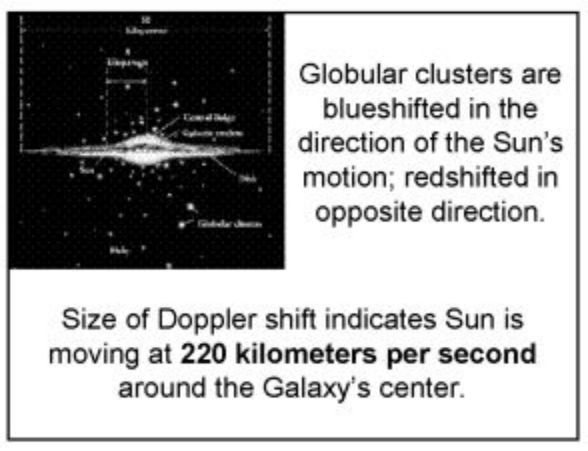
The Galaxy has an entourage of star clusters that (on average) are at rest with respect to the Galaxy's center.

They are called "globular clusters" because of their shape.



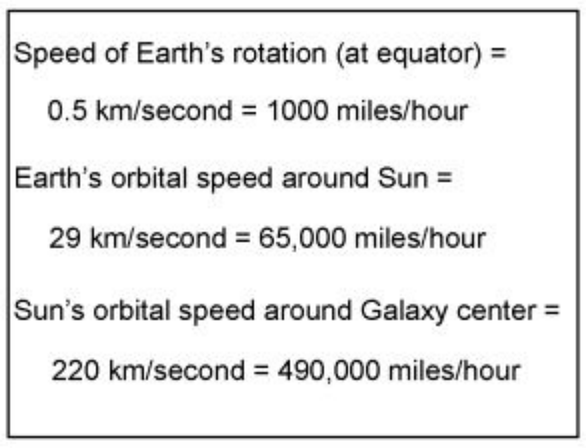
A globular cluster contains >100,000 stars in a region <10 parsecs across.

Easy to see.
Easy to measure Doppler shifts.



Globular clusters are blueshifted in the direction of the Sun's motion; redshifted in opposite direction.

Size of Doppler shift indicates Sun is moving at **220 kilometers per second** around the Galaxy's center.



Speed of Earth's rotation (at equator) =

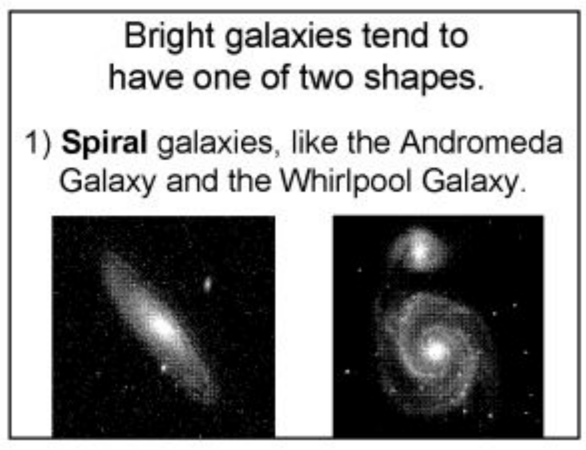
0.5 km/second = 1000 miles/hour

Earth's orbital speed around Sun =

29 km/second = 65,000 miles/hour

Sun's orbital speed around Galaxy center =

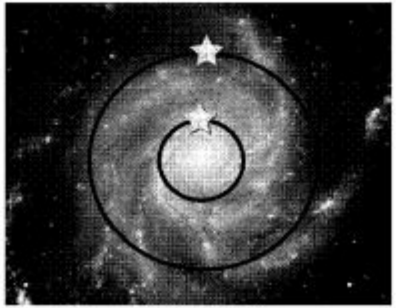
220 km/second = 490,000 miles/hour



Bright galaxies tend to have one of two shapes.

1) **Spiral** galaxies, like the Andromeda Galaxy and the Whirlpool Galaxy.

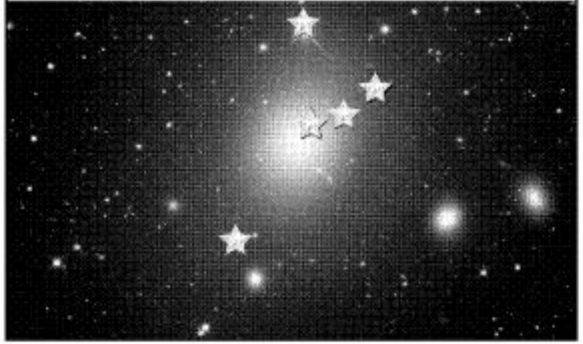
Stars in a spiral galaxy go around on neat (almost) circular orbits.



2) **Elliptical** galaxies, like the galaxy known as M87.

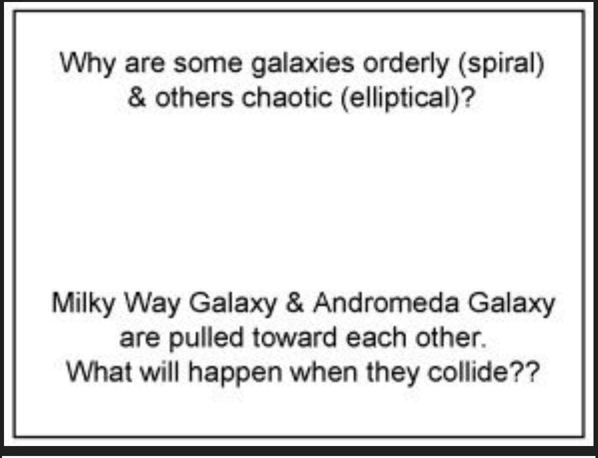
Spiral galaxies are more photogenic, so they appear in all the “coffee table” books.

Stars in an elliptical galaxy are on disordered, randomly oriented orbits.



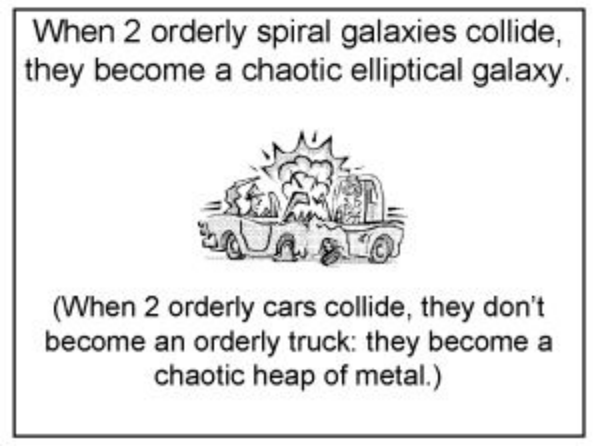
Spiral galaxy: stars are "good citizens", traveling on orderly orbits, all moving in the same direction.

Elliptical galaxy: stars are "individualists", traveling on chaotic orbits, all in different directions.



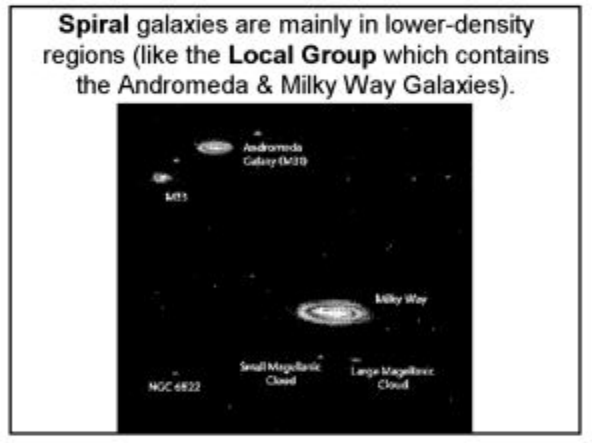
Why are some galaxies orderly (spiral) & others chaotic (elliptical)?

Milky Way Galaxy & Andromeda Galaxy are pulled toward each other.
What will happen when they collide??

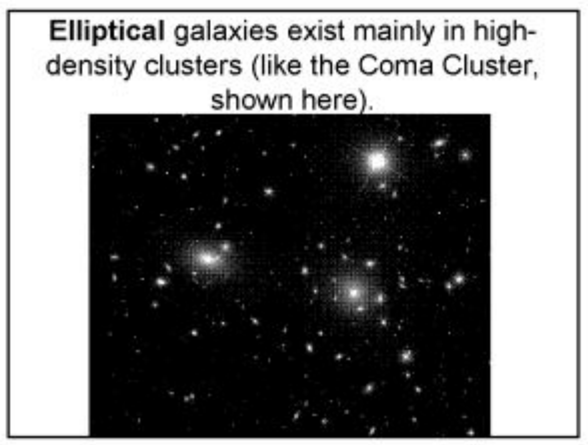


When 2 orderly spiral galaxies collide, they become a chaotic elliptical galaxy.

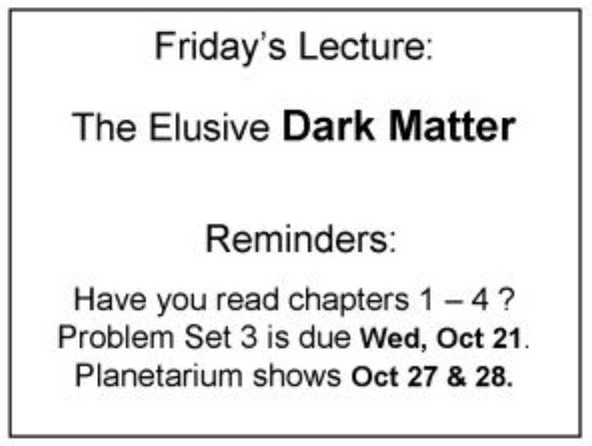
(When 2 orderly cars collide, they don't become an orderly truck: they become a chaotic heap of metal.)



Spiral galaxies are mainly in lower-density regions (like the **Local Group** which contains the Andromeda & Milky Way Galaxies).



Elliptical galaxies exist mainly in high-density clusters (like the Coma Cluster, shown here).



Friday's Lecture:

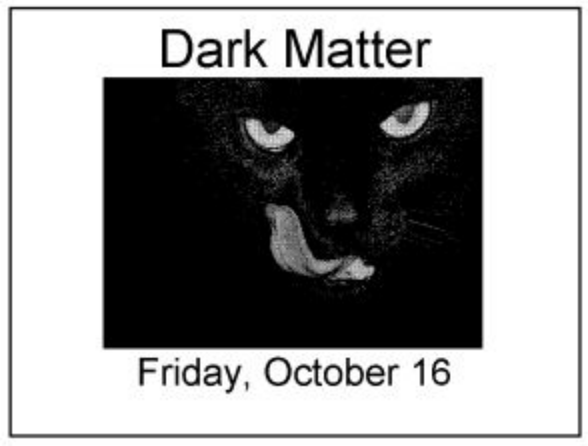
The Elusive **Dark Matter**

Reminders:

Have you read chapters 1 – 4 ?
Problem Set 3 is due **Wed, Oct 21**.
Planetarium shows **Oct 27 & 28.**

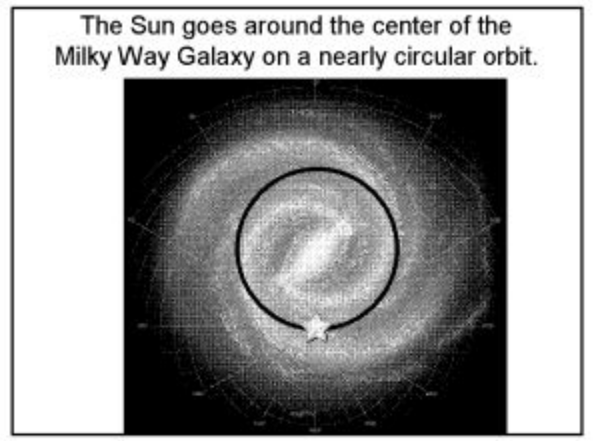
Preparatory Reading Chapter 4

Week 4: The Elusive Dark Matter

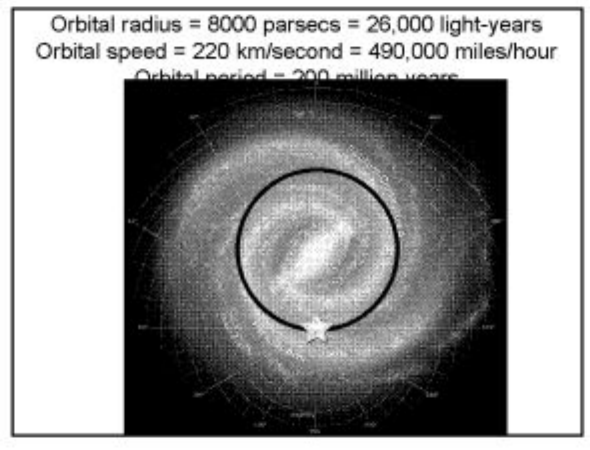


Dark Matter

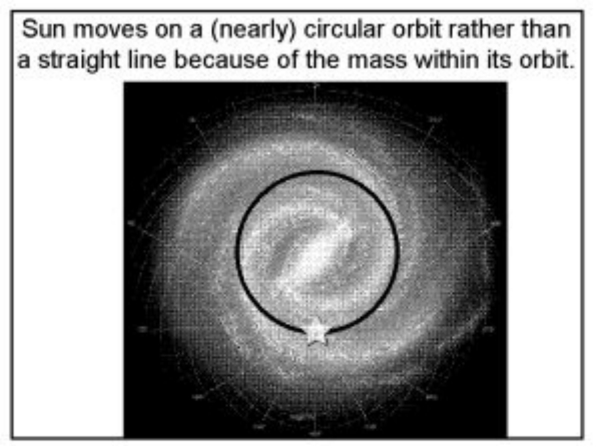
Friday, October 16



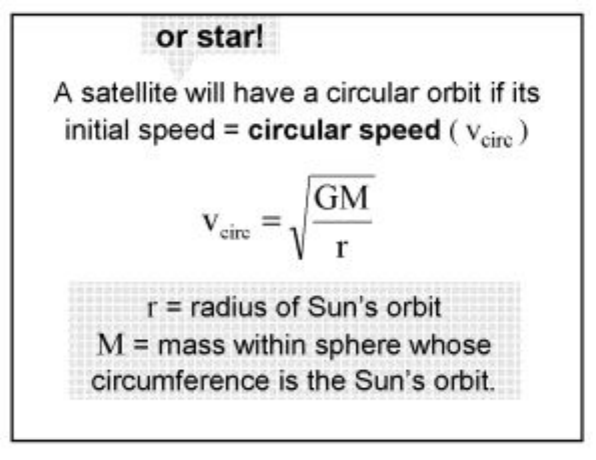
The Sun goes around the center of the Milky Way Galaxy on a nearly circular orbit.



Orbital radius = 8000 parsecs = 26,000 light-years
Orbital speed = 220 km/second = 490,000 miles/hour
Orbital period = 200 million years



Sun moves on a (nearly) circular orbit rather than a straight line because of the mass within its orbit.

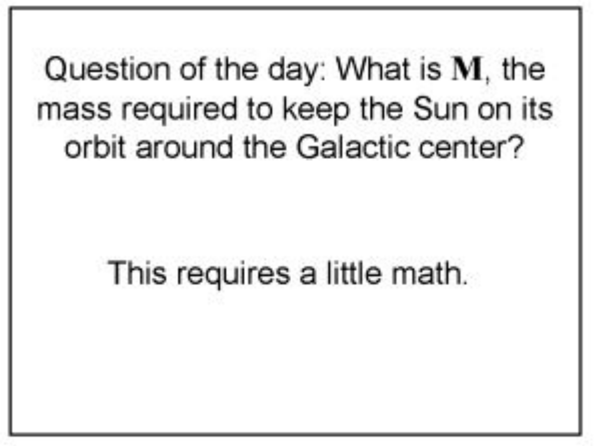


or star!

A satellite will have a circular orbit if its initial speed = **circular speed** (v_{circ})

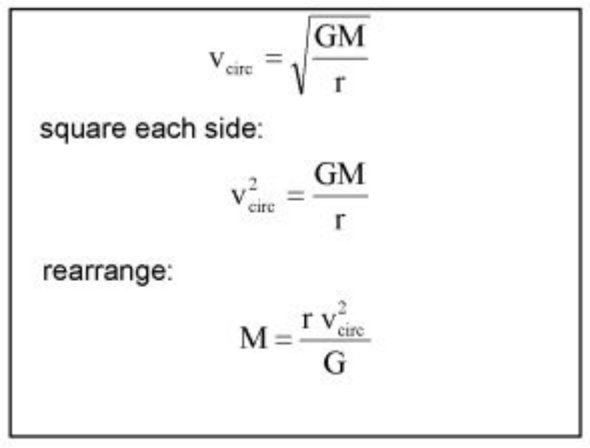
$$v_{circ} = \sqrt{\frac{GM}{r}}$$

r = radius of Sun's orbit
M = mass within sphere whose circumference is the Sun's orbit.



Question of the day: What is **M**, the mass required to keep the Sun on its orbit around the Galactic center?

This requires a little math.



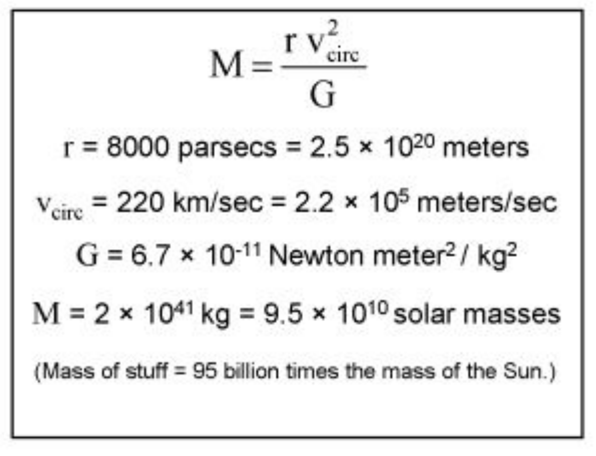
$$v_{circ} = \sqrt{\frac{GM}{r}}$$

square each side:

$$v_{circ}^2 = \frac{GM}{r}$$

rearrange:

$$M = \frac{r\,v_{circ}^2}{G}$$



$$M = \frac{r\,v_{circ}^2}{G}$$

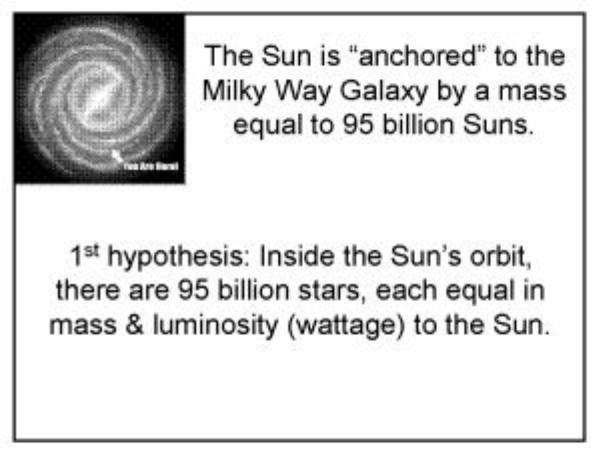
r = 8000 parsecs = 2.5×10^{20} meters

v_{circ} = 220 km/sec = 2.2×10^{5} meters/sec

$G = 6.7 \times 10^{-11}$ Newton meter^2 / kg^2

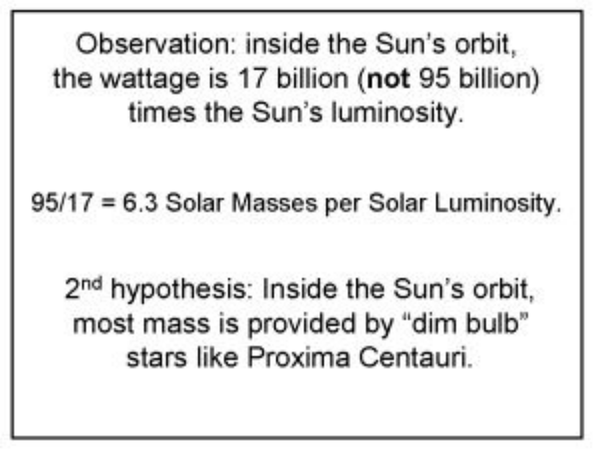
$M = 2 \times 10^{41}$ kg = 9.5×10^{10} solar masses

(Mass of stuff = 95 billion times the mass of the Sun.)



The Sun is "anchored" to the Milky Way Galaxy by a mass equal to 95 billion Suns.

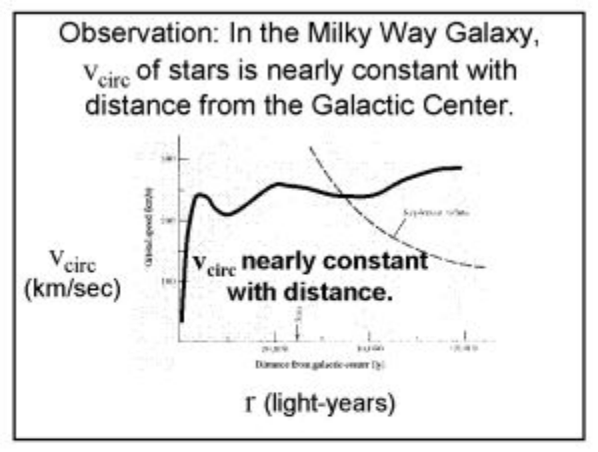
1st hypothesis: Inside the Sun's orbit, there are 95 billion stars, each equal in mass & luminosity (wattage) to the Sun.



Observation: inside the Sun’s orbit, the wattage is 17 billion (**not** 95 billion) times the Sun’s luminosity.

95/17 = 6.3 Solar Masses per Solar Luminosity.

2^{nd} hypothesis: Inside the Sun’s orbit, most mass is provided by “dim bulb” stars like Proxima Centauri.

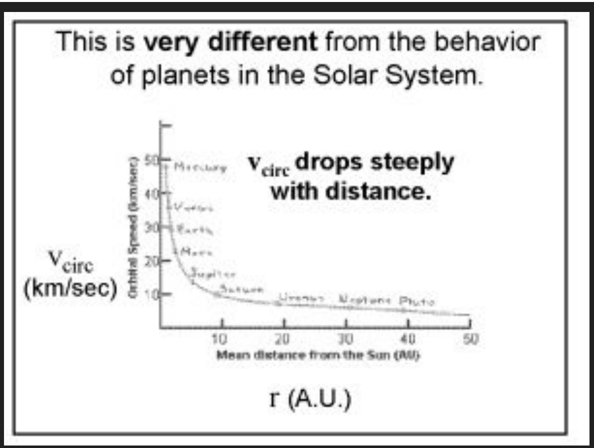


Observation: In the Milky Way Galaxy, v_{circ} of stars is nearly constant with distance from the Galactic Center.

v_{circ} (km/sec)

v_{circ} nearly constant with distance.

r (light-years)

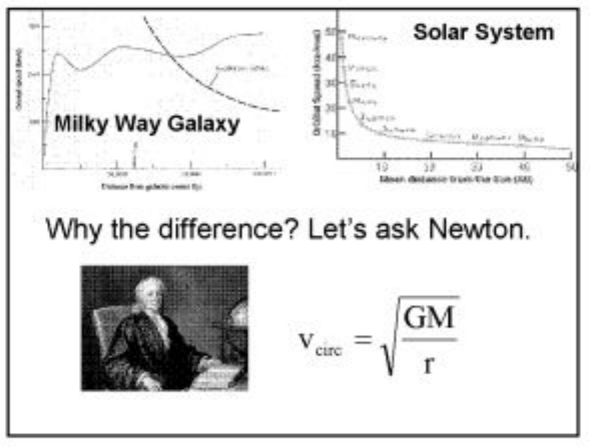


This is **very different** from the behavior of planets in the Solar System.

v_{circ} (km/sec)

v_{circ} drops steeply with distance.

r (A.U.)

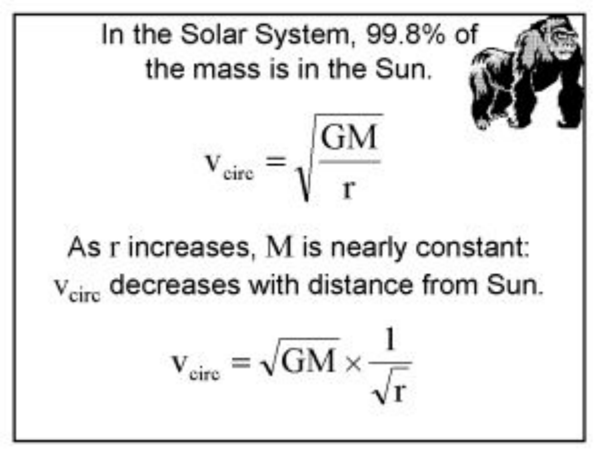


Milky Way Galaxy

Solar System

Why the difference? Let's ask Newton.

$$v_{circ} = \sqrt{\frac{GM}{r}}$$

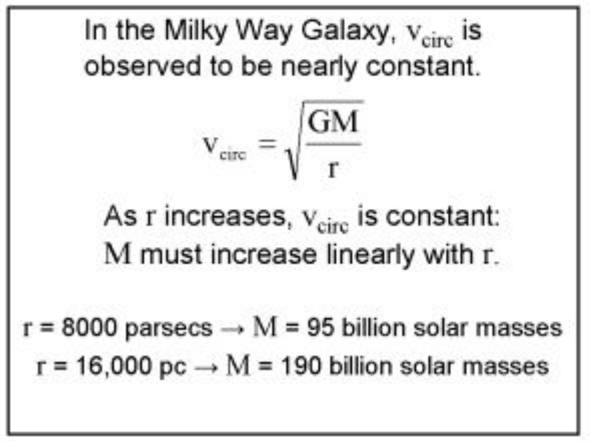


In the Solar System, 99.8% of the mass is in the Sun.

$$v_{circ} = \sqrt{\frac{GM}{r}}$$

As r increases, M is nearly constant: v_{circ} decreases with distance from Sun.

$$v_{circ} = \sqrt{GM} \times \frac{1}{\sqrt{r}}$$



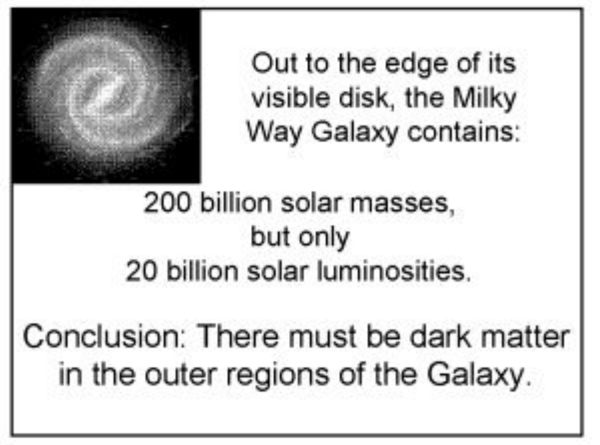
In the Milky Way Galaxy, v_{circ} is observed to be nearly constant.

$$v_{circ} = \sqrt{\frac{GM}{r}}$$

As r increases, v_{circ} is constant: M must increase linearly with r.

r = 8000 parsecs → M = 95 billion solar masses

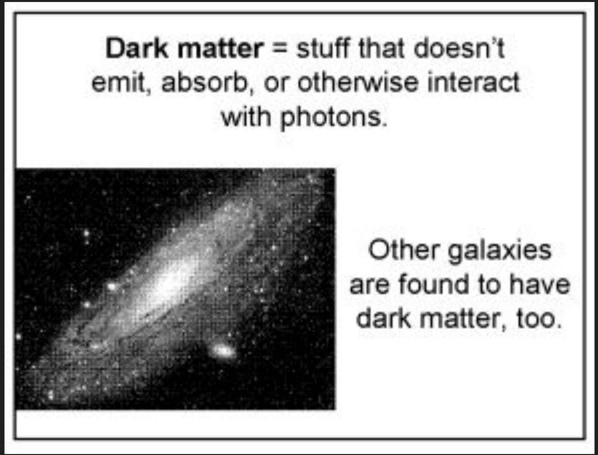
r = 16,000 pc → M = 190 billion solar masses



Out to the edge of its visible disk, the Milky Way Galaxy contains:

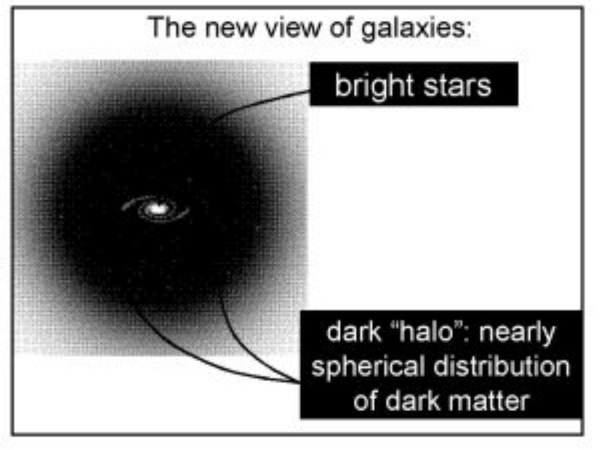
200 billion solar masses,
but only
20 billion solar luminosities.

Conclusion: There must be dark matter in the outer regions of the Galaxy.



Dark matter = stuff that doesn't emit, absorb, or otherwise interact with photons.

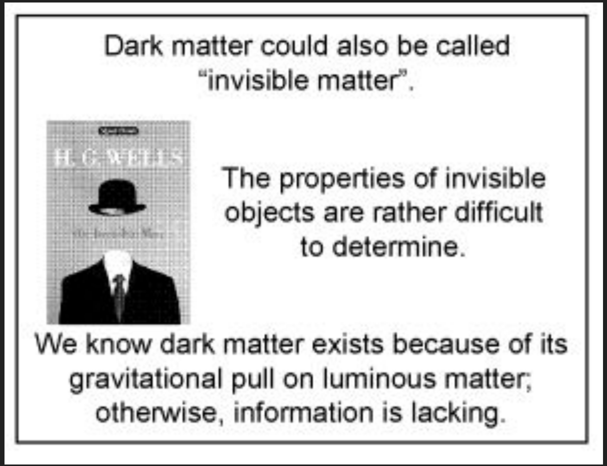
Other galaxies are found to have dark matter, too.



The new view of galaxies:

bright stars

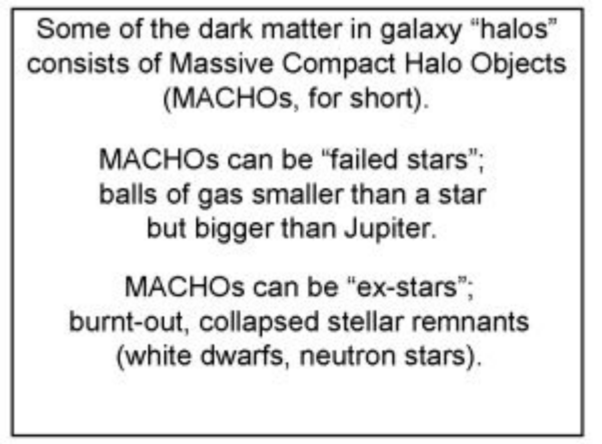
dark "halo": nearly spherical distribution of dark matter



Dark matter could also be called "invisible matter".

The properties of invisible objects are rather difficult to determine.

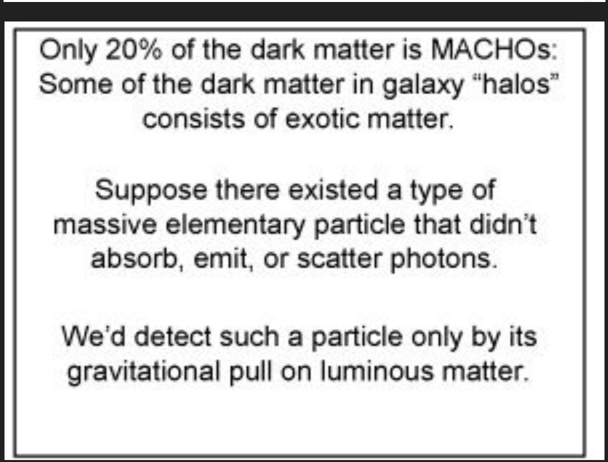
We know dark matter exists because of its gravitational pull on luminous matter; otherwise, information is lacking.



Some of the dark matter in galaxy "halos" consists of Massive Compact Halo Objects (MACHOs, for short).

MACHOs can be "failed stars"; balls of gas smaller than a star but bigger than Jupiter.

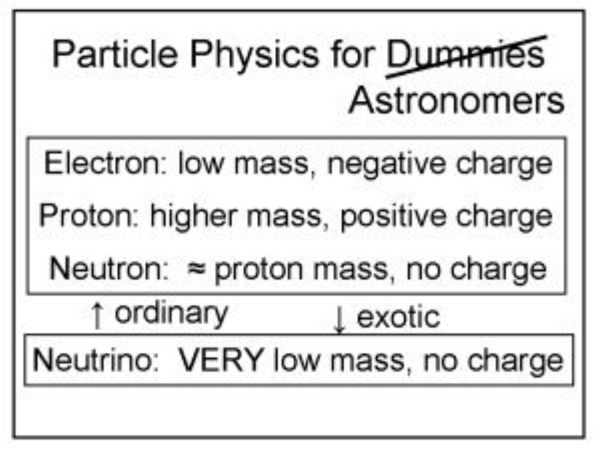
MACHOs can be "ex-stars"; burnt-out, collapsed stellar remnants (white dwarfs, neutron stars).



Only 20% of the dark matter is MACHOs: Some of the dark matter in galaxy "halos" consists of exotic matter.

Suppose there existed a type of massive elementary particle that didn't absorb, emit, or scatter photons.

We'd detect such a particle only by its gravitational pull on luminous matter.



Particle Physics for ~~Dummies~~ Astronomers

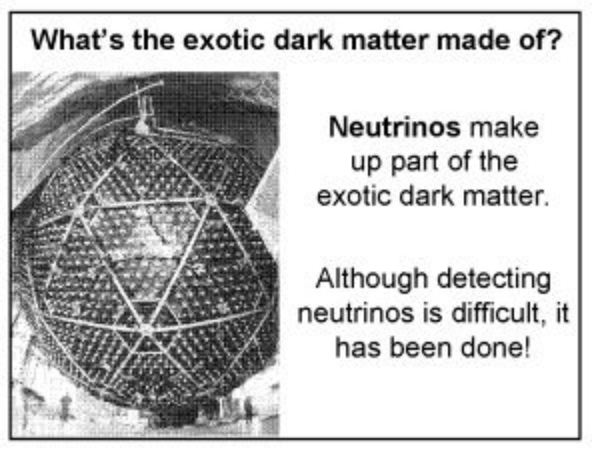
Electron: low mass, negative charge

Proton: higher mass, positive charge

Neutron: ≈ proton mass, no charge

↑ ordinary ↓ exotic

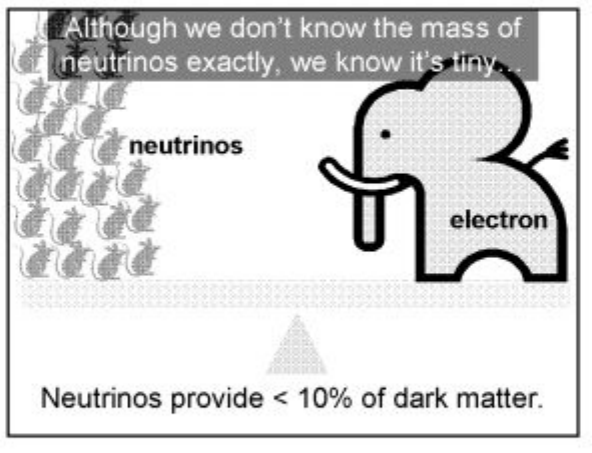
Neutrino: VERY low mass, no charge



What's the exotic dark matter made of?

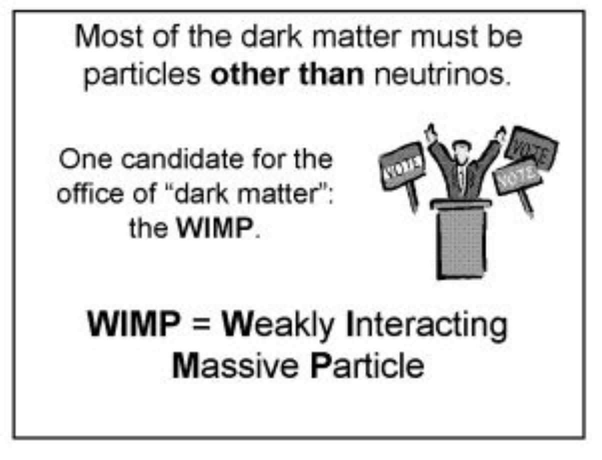
Neutrinos make up part of the exotic dark matter.

Although detecting neutrinos is difficult, it has been done!



Although we don't know the mass of neutrinos exactly, we know it's tiny...

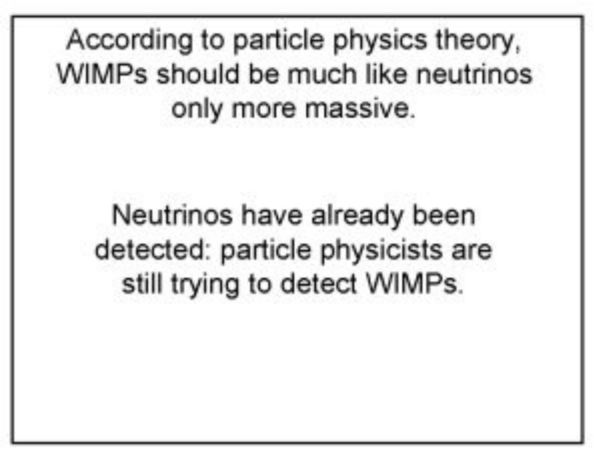
Neutrinos provide < 10% of dark matter.



Most of the dark matter must be particles **other than** neutrinos.

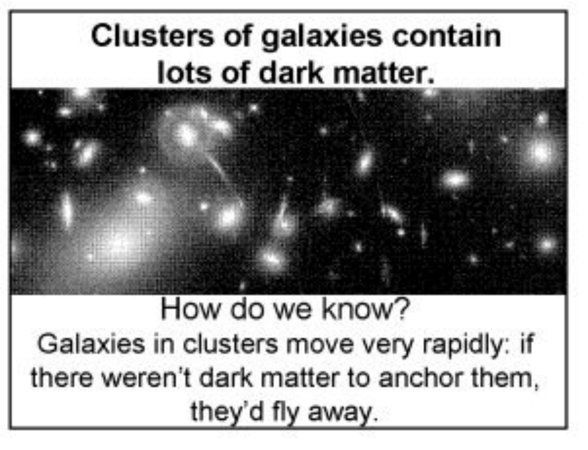
One candidate for the office of "dark matter": the **WIMP**.

WIMP = **W**eakly **I**nteracting **M**assive **P**article



According to particle physics theory, WIMPs should be much like neutrinos only more massive.

Neutrinos have already been detected: particle physicists are still trying to detect WIMPs.



Clusters of galaxies contain lots of dark matter.

How do we know?

Galaxies in clusters move very rapidly: if there weren't dark matter to anchor them, they'd fly away.

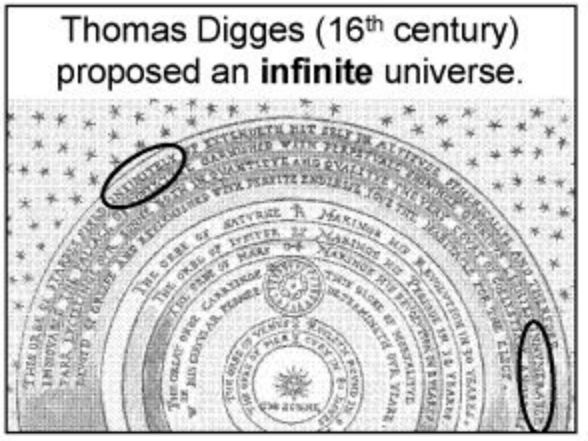
Preparatory Reading Chapter 5 & 6

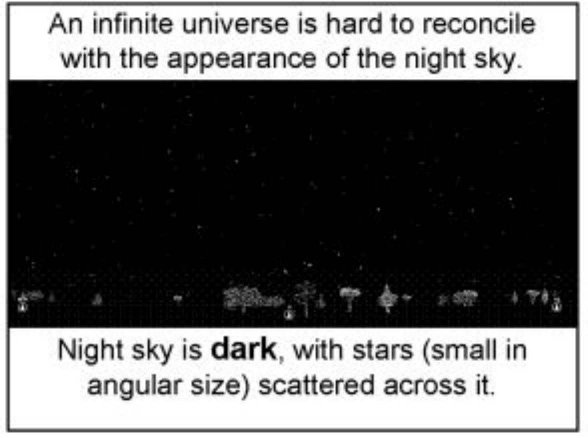
Week 5: Why is it Dark at Night?


Why is it dark at night?

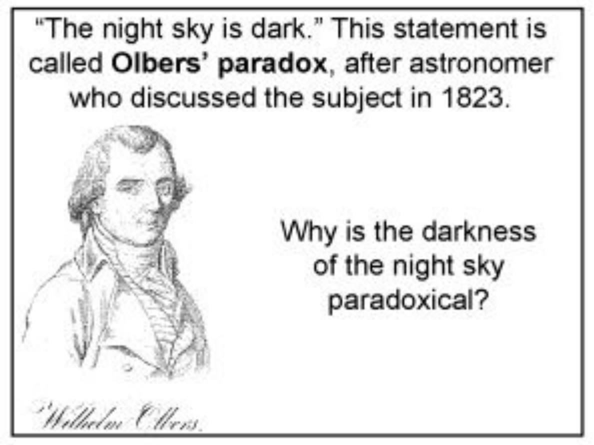
Monday, October 19

Next Planetarium Show: Oct 27 & 28


Thomas Digges (16th century) proposed an **infinite** universe.


An infinite universe is hard to reconcile with the appearance of the night sky.

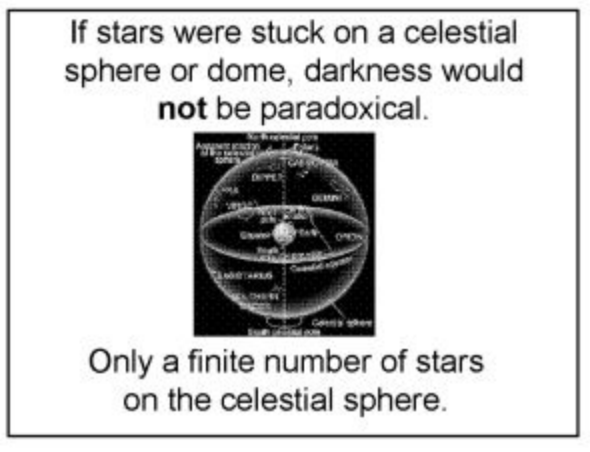
Night sky is **dark**, with stars (small in angular size) scattered across it.



"The night sky is dark." This statement is called **Olbers' paradox**, after astronomer who discussed the subject in 1823.

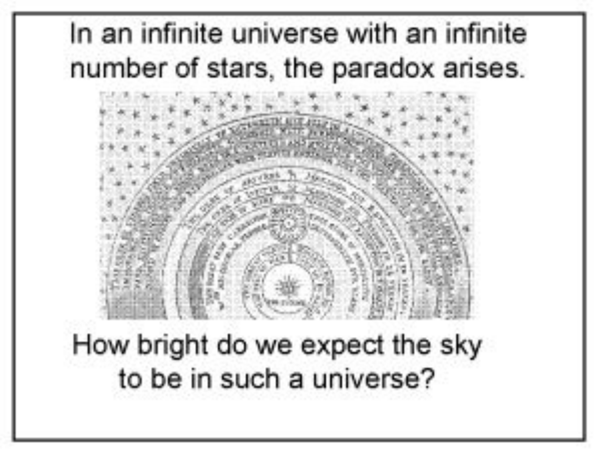
Why is the darkness of the night sky paradoxical?

Wilhelm Olbers.



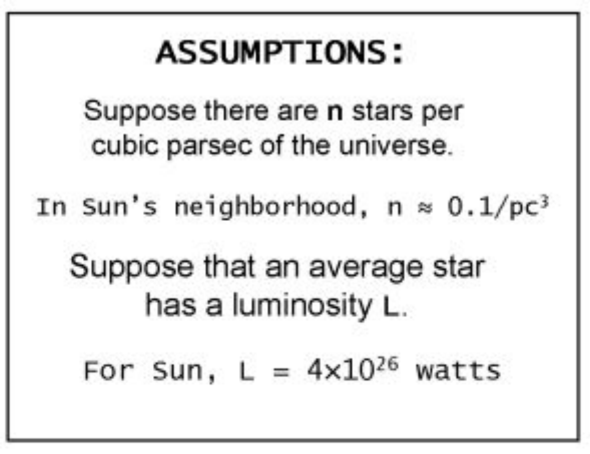
If stars were stuck on a celestial sphere or dome, darkness would **not** be paradoxical.

Only a finite number of stars on the celestial sphere.



In an infinite universe with an infinite number of stars, the paradox arises.

How bright do we expect the sky to be in such a universe?



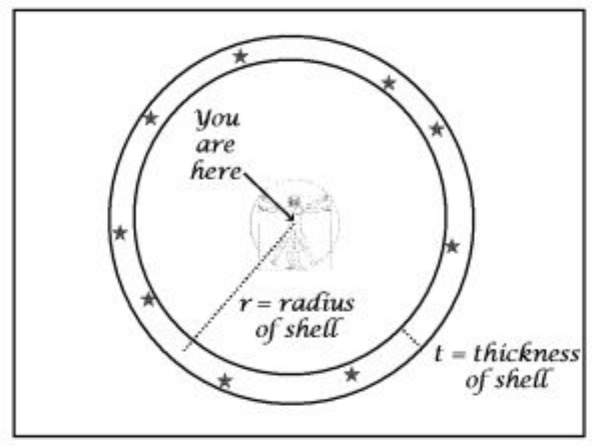
ASSUMPTIONS:

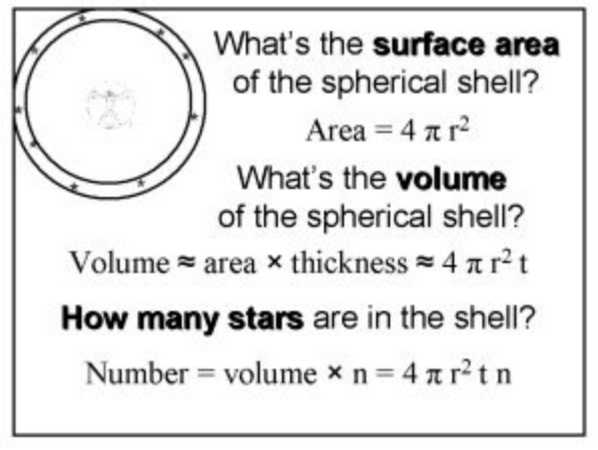
Suppose there are **n** stars per cubic parsec of the universe.

In Sun's neighborhood, $n \approx 0.1/pc^3$

Suppose that an average star has a luminosity L.

For Sun, $L = 4\times10^{26}$ watts





What's the **surface area** of the spherical shell?

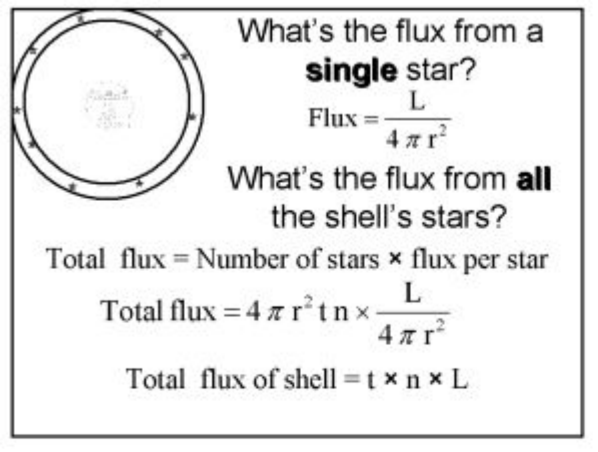
$$\text{Area} = 4\,\pi\,r^2$$

What's the **volume** of the spherical shell?

$$\text{Volume} \approx \text{area} \times \text{thickness} \approx 4\,\pi\,r^2\,t$$

How many stars are in the shell?

$$\text{Number} = \text{volume} \times n = 4\,\pi\,r^2\,t\,n$$



What's the flux from a **single** star?

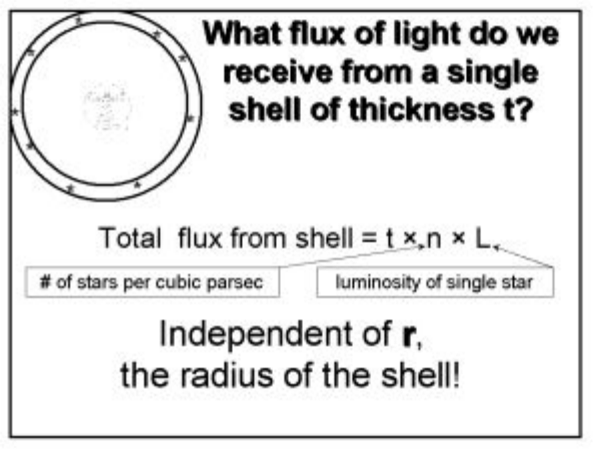
$$\text{Flux} = \frac{L}{4\pi r^2}$$

What's the flux from **all** the shell's stars?

Total flux = Number of stars × flux per star

$$\text{Total flux} = 4\pi r^2 t n \times \frac{L}{4\pi r^2}$$

Total flux of shell = t × n × L



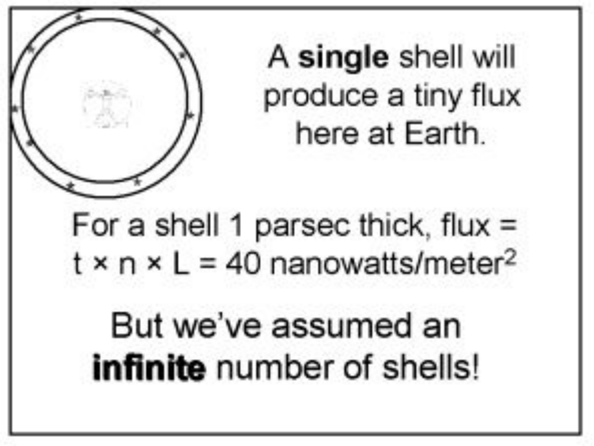
What flux of light do we receive from a single shell of thickness t?

Total flux from shell = t × n × L

# of stars per cubic parsec

luminosity of single star

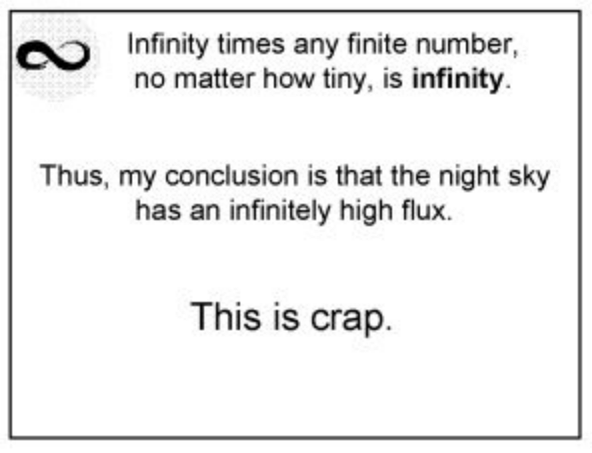
Independent of **r**,
the radius of the shell!



A **single** shell will produce a tiny flux here at Earth.

For a shell 1 parsec thick, flux = t × n × L = 40 nanowatts/meter^2

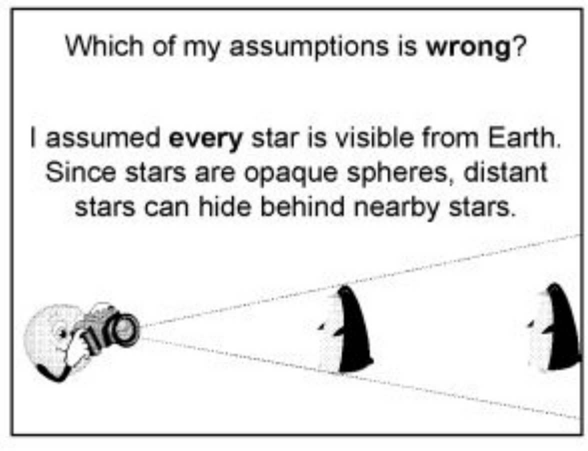
But we've assumed an **infinite** number of shells!



Infinity times any finite number, no matter how tiny, is **infinity**.

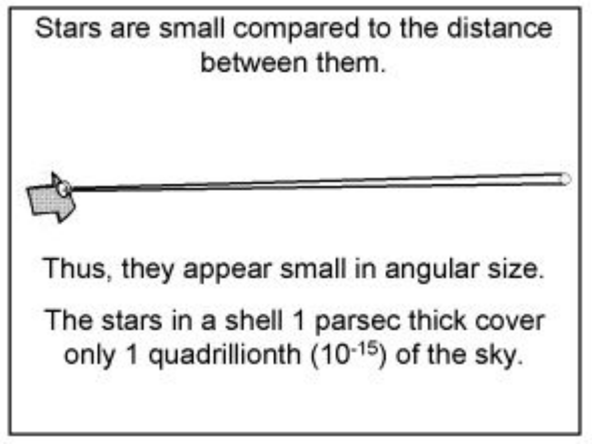
Thus, my conclusion is that the night sky has an infinitely high flux.

This is crap.



Which of my assumptions is **wrong**?

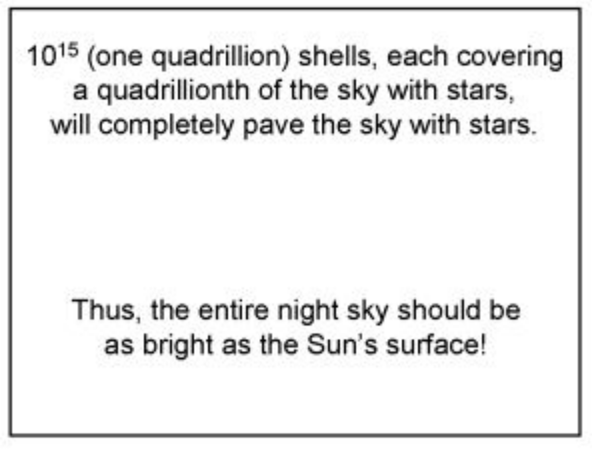
I assumed **every** star is visible from Earth. Since stars are opaque spheres, distant stars can hide behind nearby stars.



Stars are small compared to the distance between them.

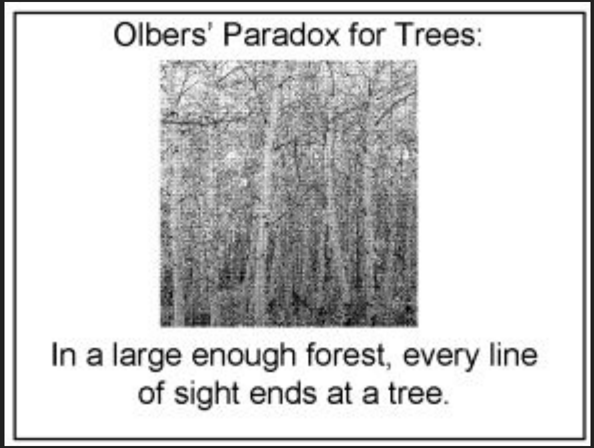
Thus, they appear small in angular size.

The stars in a shell 1 parsec thick cover only 1 quadrillionth (10^{-15}) of the sky.



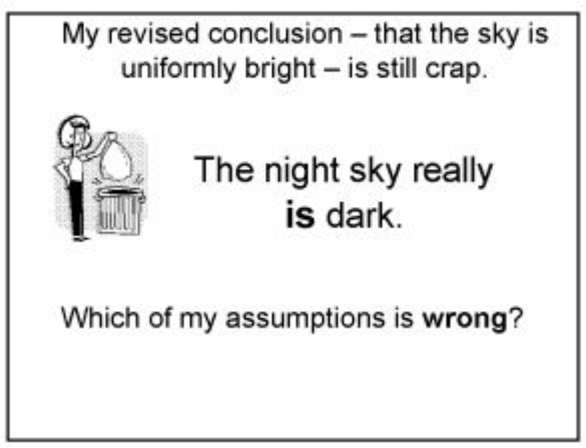
10^{15} (one quadrillion) shells, each covering a quadrillionth of the sky with stars, will completely pave the sky with stars.

Thus, the entire night sky should be as bright as the Sun's surface!



Olbers' Paradox for Trees:

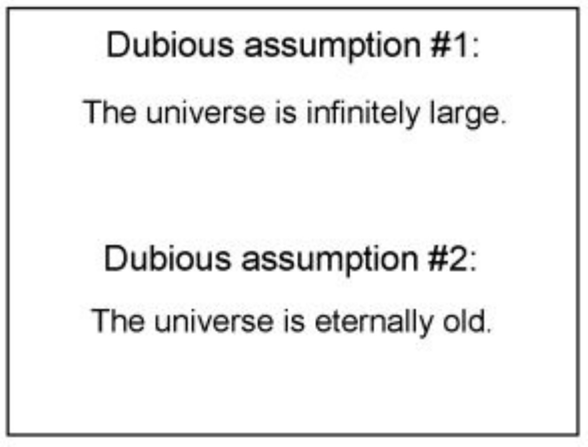
In a large enough forest, every line of sight ends at a tree.



My revised conclusion – that the sky is uniformly bright – is still crap.

The night sky really **is** dark.

Which of my assumptions is **wrong**?

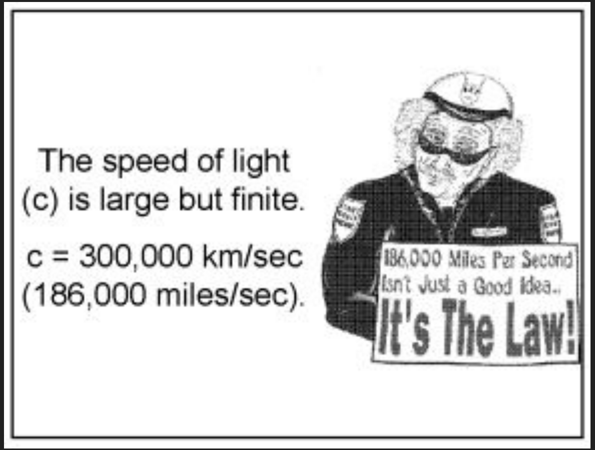


Dubious assumption #1:

The universe is infinitely large.

Dubious assumption #2:

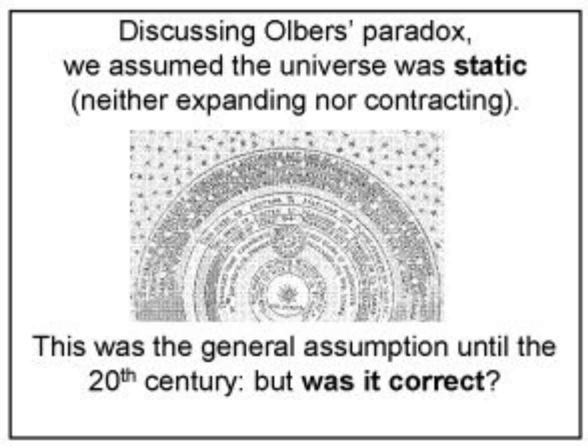
The universe is eternally old.



The speed of light (c) is large but finite.

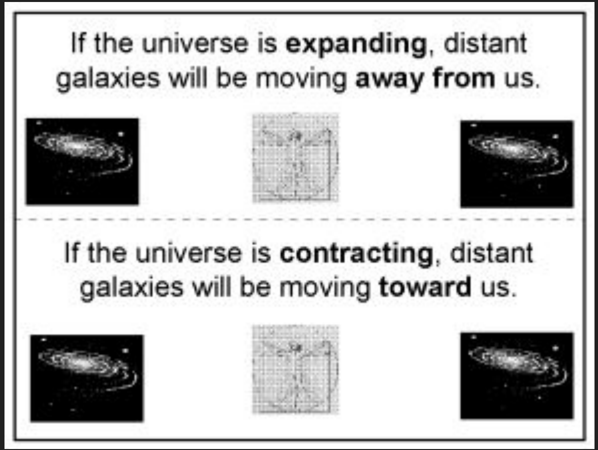
c = 300,000 km/sec (186,000 miles/sec).

If the universe has a finite age,
then distant stars haven't had time to
send us the message "We're here!"



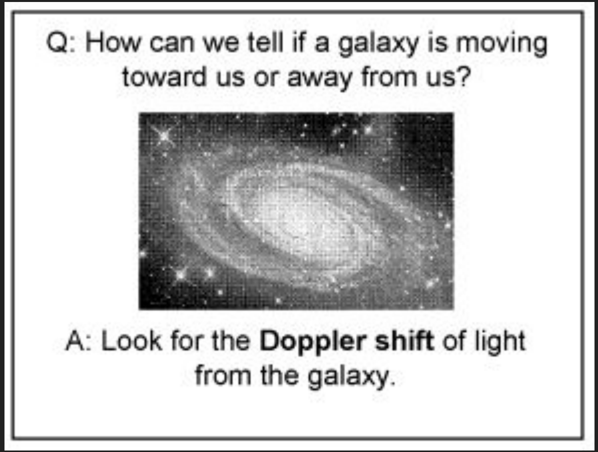
Discussing Olbers' paradox,
we assumed the universe was **static**
(neither expanding nor contracting).

This was the general assumption until the 20th century: but **was it correct**?



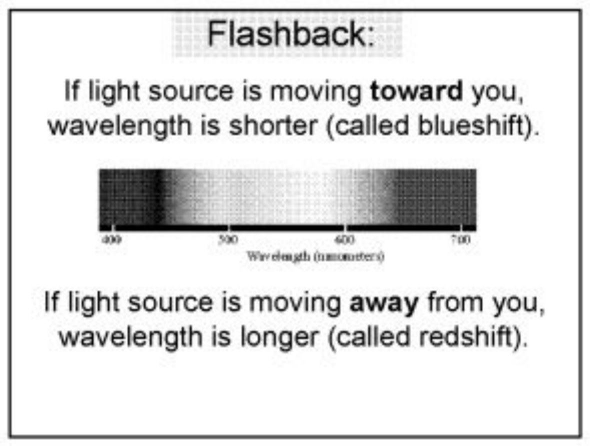
If the universe is **expanding**, distant galaxies will be moving **away from** us.

If the universe is **contracting**, distant galaxies will be moving **toward** us.



Q: How can we tell if a galaxy is moving toward us or away from us?

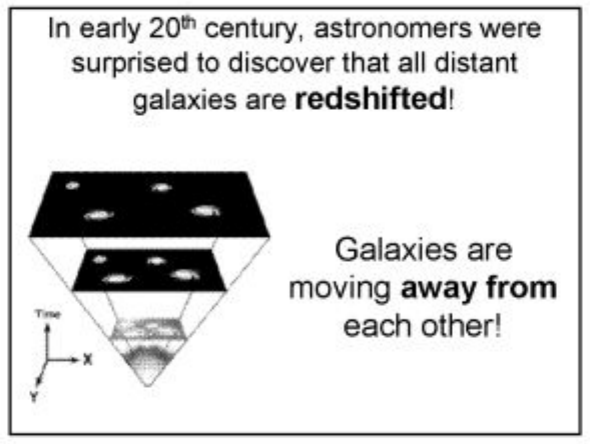
A: Look for the **Doppler shift** of light from the galaxy.



Flashback:

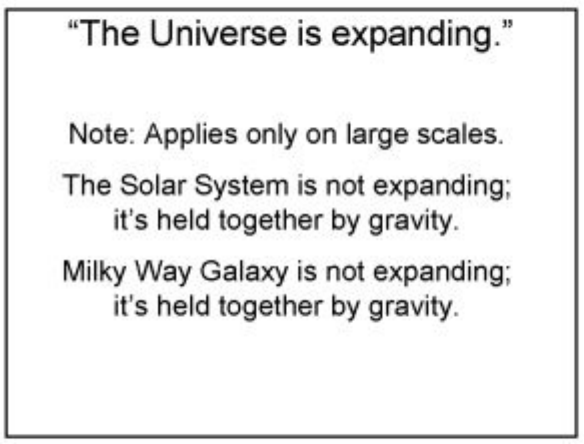
If light source is moving **toward** you, wavelength is shorter (called blueshift).

If light source is moving **away** from you, wavelength is longer (called redshift).



In early 20th century, astronomers were surprised to discover that all distant galaxies are **redshifted**!

Galaxies are moving **away from** each other!



"The Universe is expanding."

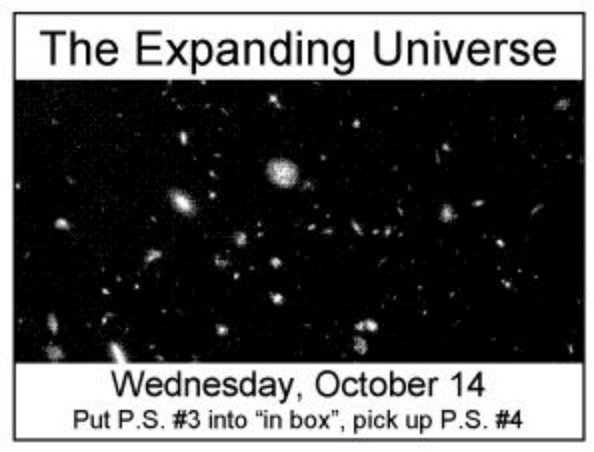
Note: Applies only on large scales.

The Solar System is not expanding; it's held together by gravity.

Milky Way Galaxy is not expanding; it's held together by gravity.

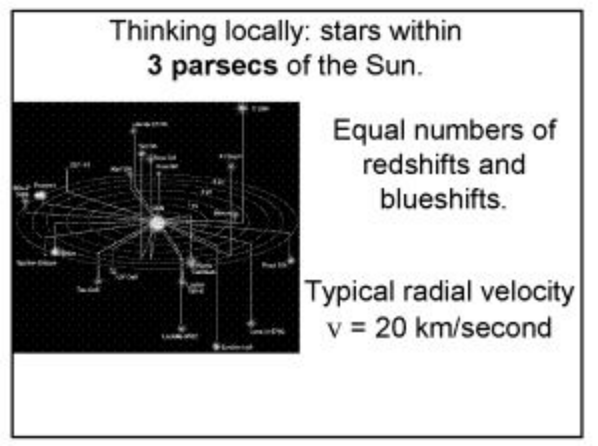
Preparatory Reading Chapter 5 & 6

Week 5: The Expanding Universe


The Expanding Universe

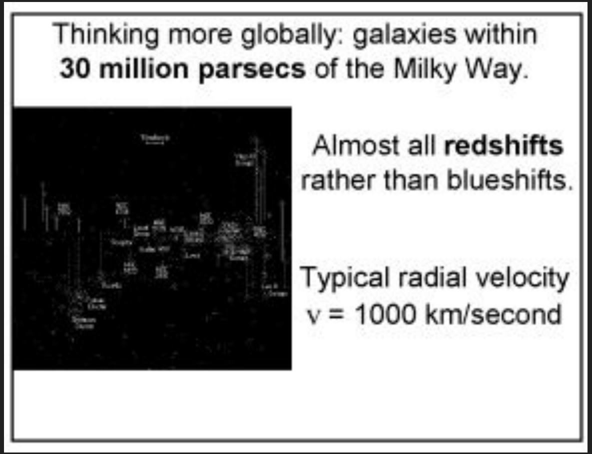
Wednesday, October 14

Put P.S. #3 into “in box”, pick up P.S. #4


Thinking locally: stars within **3 parsecs** of the Sun.

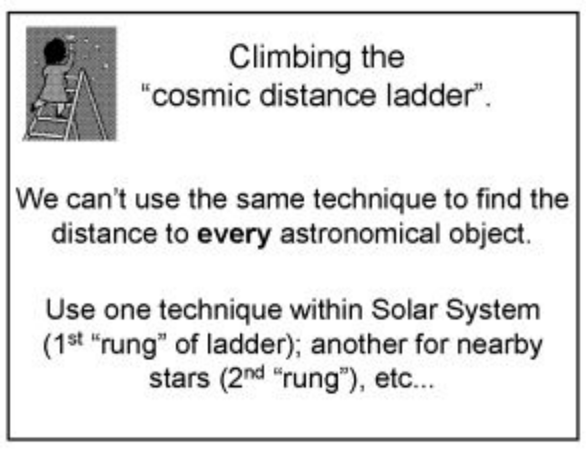
Equal numbers of redshifts and blueshifts.

Typical radial velocity v = 20 km/second


Thinking more globally: galaxies within **30 million parsecs** of the Milky Way.

Almost all **redshifts** rather than blueshifts.

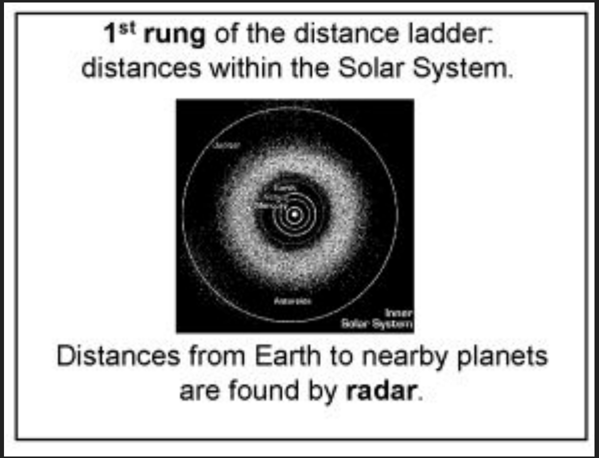
Typical radial velocity v = 1000 km/second



Climbing the “cosmic distance ladder”.

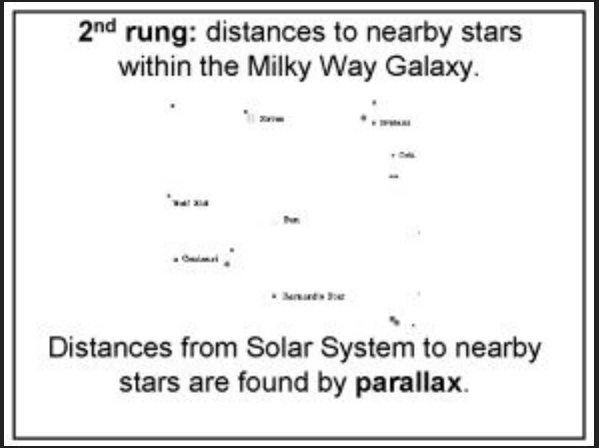
We can’t use the same technique to find the distance to **every** astronomical object.

Use one technique within Solar System (1st “rung” of ladder); another for nearby stars (2nd “rung”), etc...



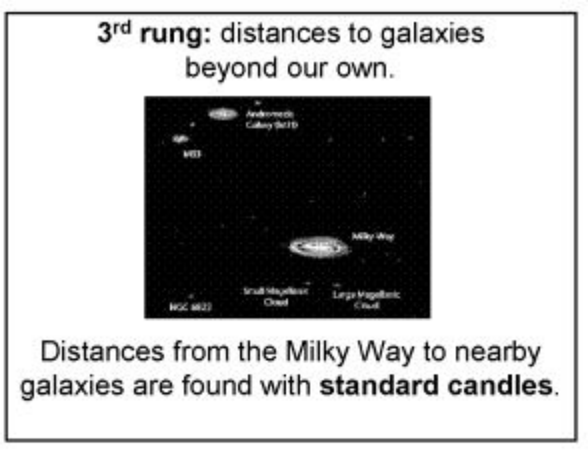
1st rung of the distance ladder: distances within the Solar System.

Distances from Earth to nearby planets are found by **radar**.



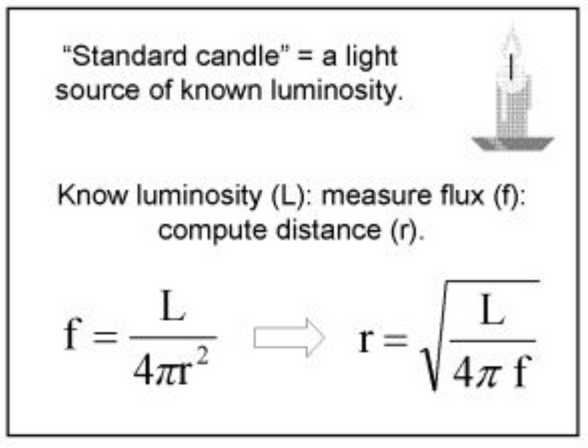
2nd rung: distances to nearby stars within the Milky Way Galaxy.

Distances from Solar System to nearby stars are found by **parallax**.



3^{rd} rung: distances to galaxies beyond our own.

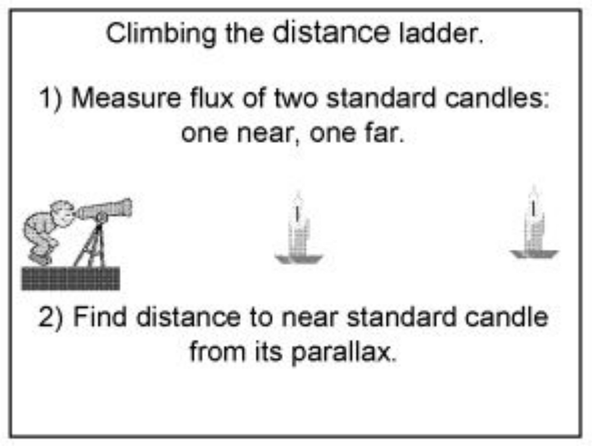
Distances from the Milky Way to nearby galaxies are found with **standard candles**.



"Standard candle" = a light source of known luminosity.

Know luminosity (L): measure flux (f): compute distance (r).

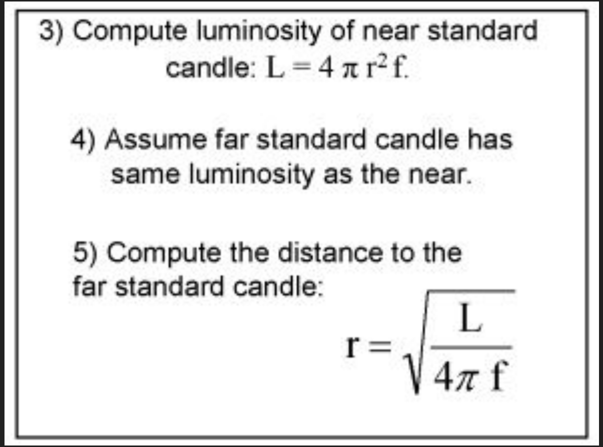
$$f = \frac{L}{4\pi r^2} \Rightarrow r = \sqrt{\frac{L}{4\pi f}}$$



Climbing the distance ladder.

1) Measure flux of two standard candles: one near, one far.

2) Find distance to near standard candle from its parallax.

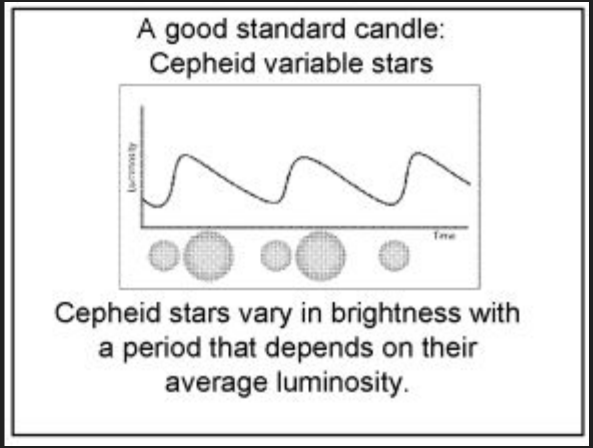


3) Compute luminosity of near standard candle: $L = 4 \pi r^2 f$.

4) Assume far standard candle has same luminosity as the near.

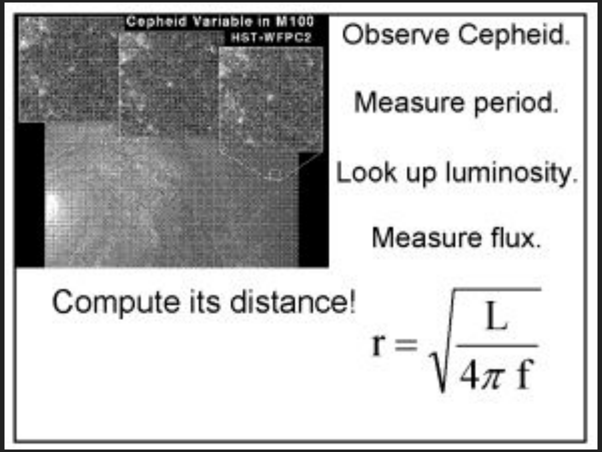
5) Compute the distance to the far standard candle:

$$r = \sqrt{\frac{L}{4\pi f}}$$



A good standard candle:
Cepheid variable stars

Cepheid stars vary in brightness with a period that depends on their average luminosity.



Observe Cepheid.

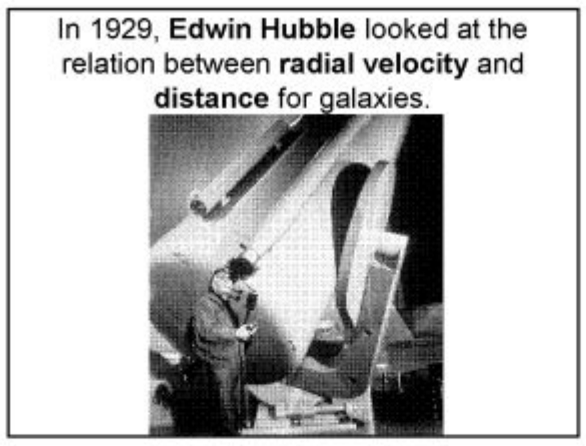
Measure period.

Look up luminosity.

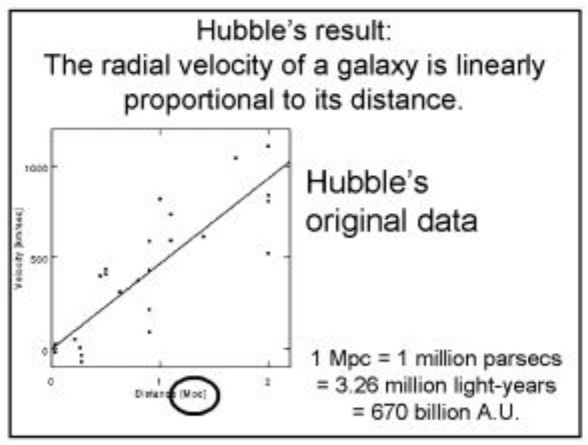
Measure flux.

Compute its distance!

$$r = \sqrt{\frac{L}{4\pi f}}$$



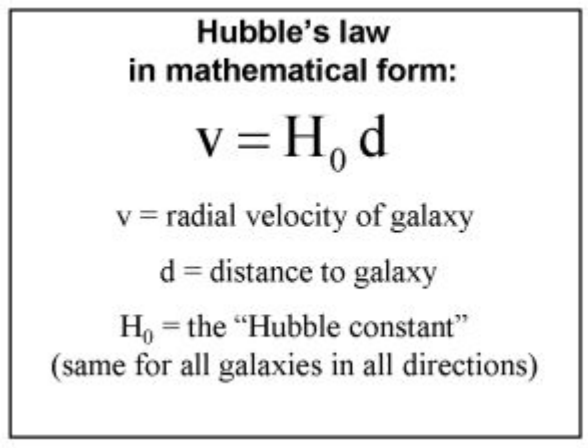
In 1929, **Edwin Hubble** looked at the relation between **radial velocity** and **distance** for galaxies.



Hubble's result:
The radial velocity of a galaxy is linearly proportional to its distance.

Hubble's original data

1 Mpc = 1 million parsecs
= 3.26 million light-years
= 670 billion A.U.



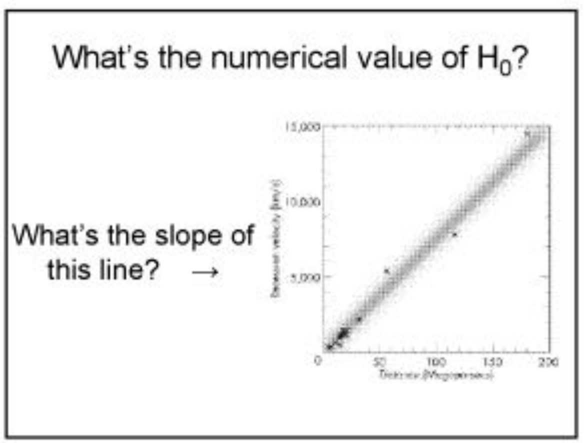
Hubble's law in mathematical form:

$$v = H_0 \, d$$

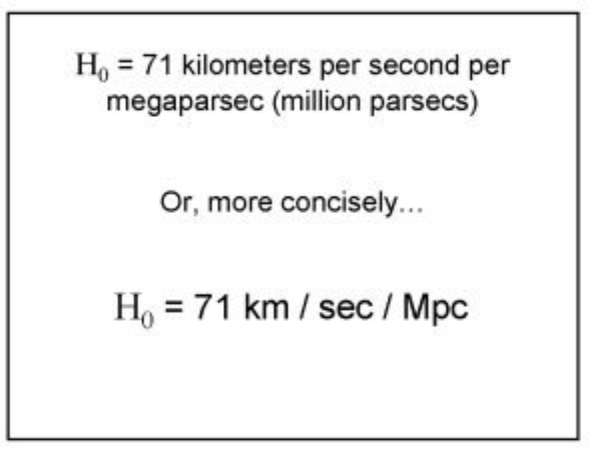
v = radial velocity of galaxy

d = distance to galaxy

H_0 = the "Hubble constant"
(same for all galaxies in all directions)

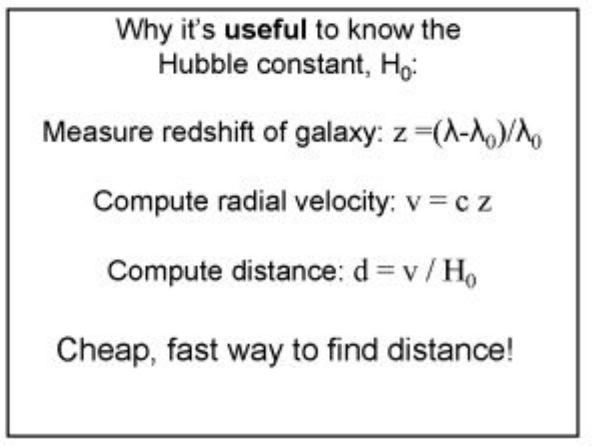

What's the numerical value of H_0?

What's the slope of this line? →


H_0 = 71 kilometers per second per megaparsec (million parsecs)

Or, more concisely…

H_0 = 71 km / sec / Mpc

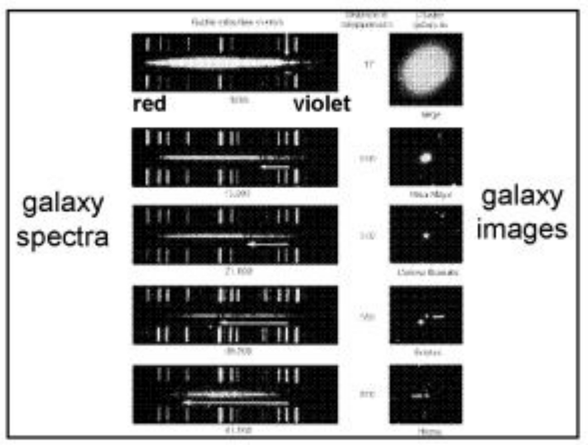

Why it's **useful** to know the Hubble constant, H_0:

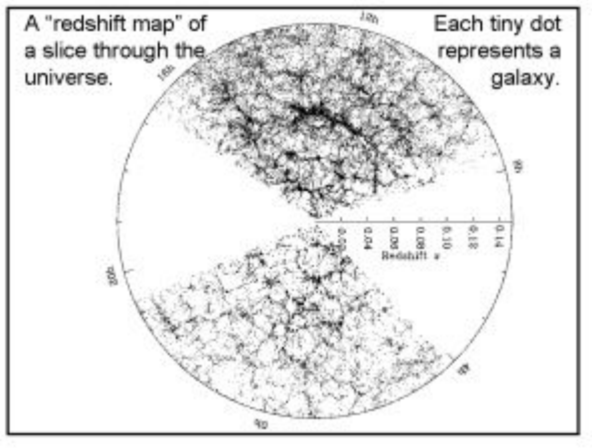
Measure redshift of galaxy: $z = (\lambda - \lambda_0)/\lambda_0$

Compute radial velocity: $v = c\,z$

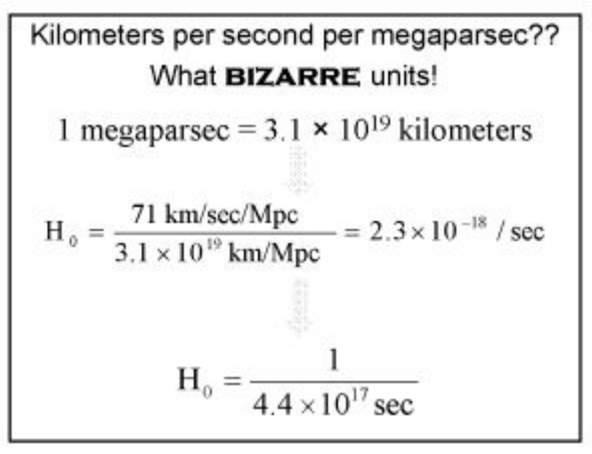
Compute distance: $d = v / H_0$

Cheap, fast way to find distance!




A "redshift map" of a slice through the universe.

Each tiny dot represents a galaxy.

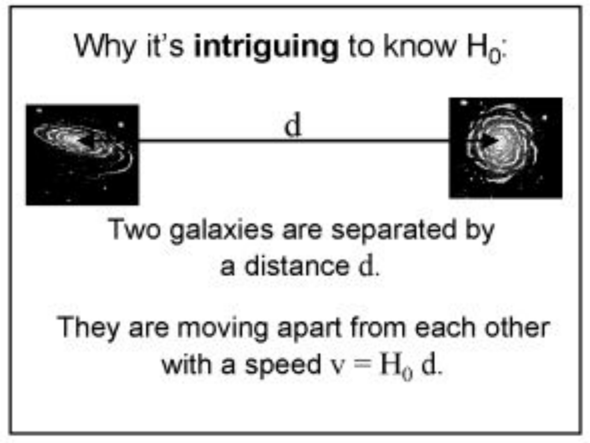

Kilometers per second per megaparsec??

What **BIZARRE** units!

$$1 \text{ megaparsec} = 3.1 \times 10^{19} \text{ kilometers}$$

$$H_0 = \frac{71 \text{ km/sec/Mpc}}{3.1 \times 10^{19} \text{ km/Mpc}} = 2.3 \times 10^{-18} \ / \text{sec}$$

$$H_0 = \frac{1}{4.4 \times 10^{17} \text{ sec}}$$

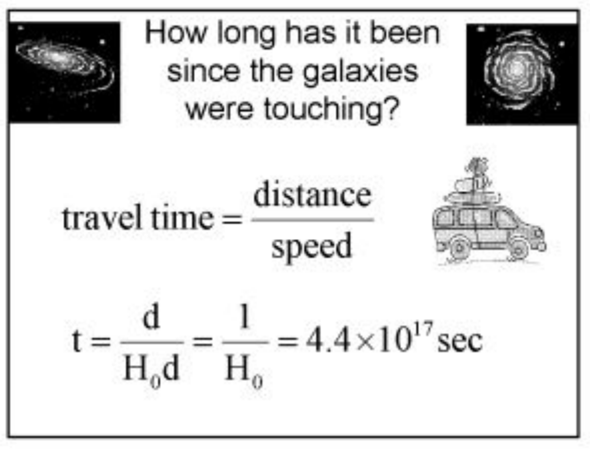


Why it's **intriguing** to know H_0:

d

Two galaxies are separated by a distance d.

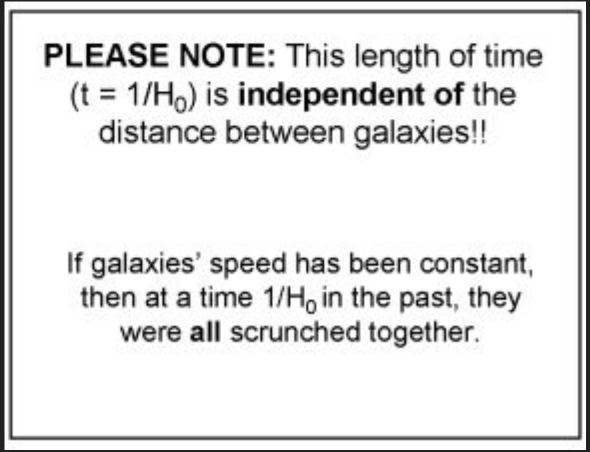
They are moving apart from each other with a speed $v = H_0 d$.



How long has it been since the galaxies were touching?

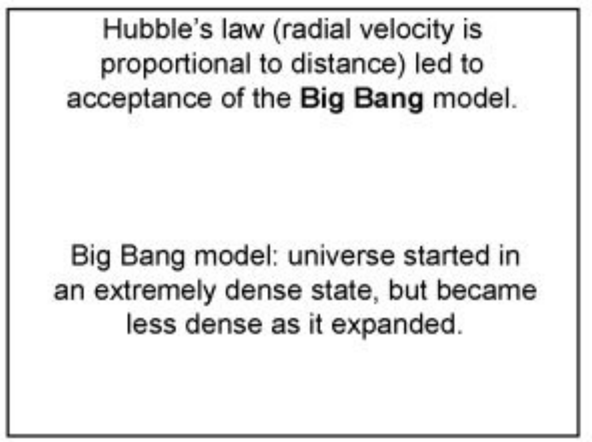
$$\text{travel time} = \frac{\text{distance}}{\text{speed}}$$

$$t = \frac{d}{H_0 d} = \frac{1}{H_0} = 4.4 \times 10^{17}\,\text{sec}$$



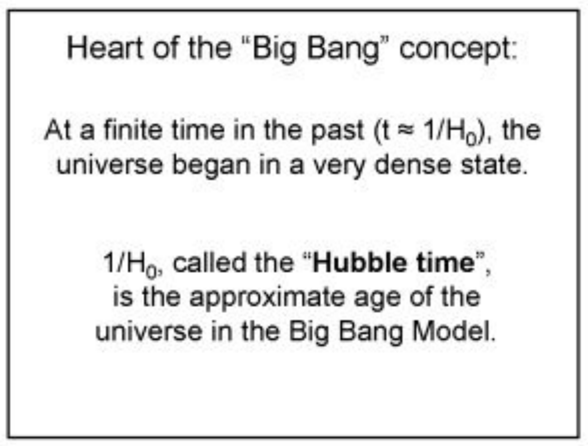
PLEASE NOTE: This length of time ($t = 1/H_0$) is **independent of** the distance between galaxies!!

If galaxies' speed has been constant, then at a time $1/H_0$ in the past, they were **all** scrunched together.



Hubble's law (radial velocity is proportional to distance) led to acceptance of the **Big Bang** model.

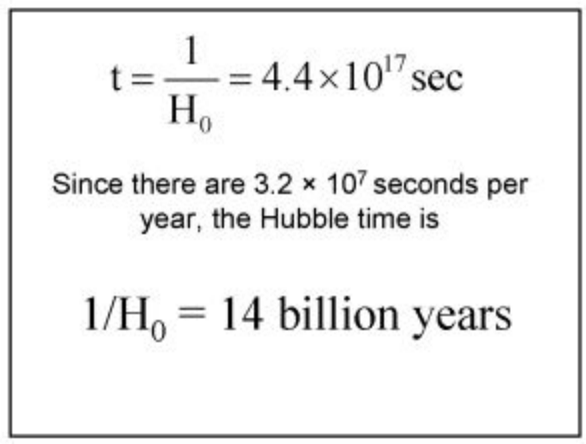
Big Bang model: universe started in an extremely dense state, but became less dense as it expanded.



Heart of the "Big Bang" concept:

At a finite time in the past ($t \approx 1/H_0$), the universe began in a very dense state.

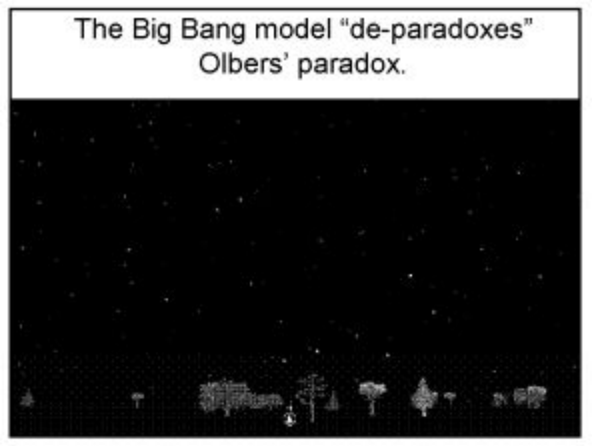
$1/H_0$, called the "**Hubble time**", is the approximate age of the universe in the Big Bang Model.



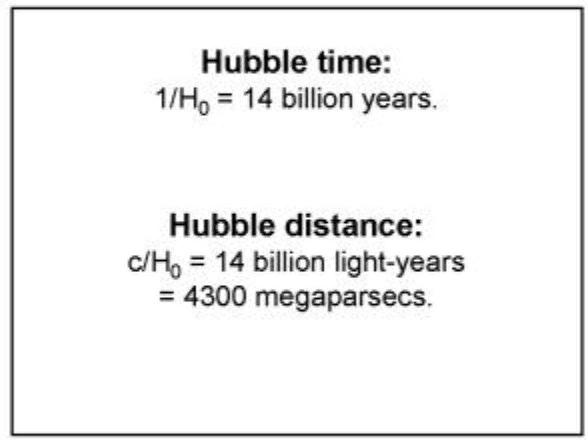
$$t = \frac{1}{H_0} = 4.4 \times 10^{17} \sec$$

Since there are 3.2×10^7 seconds per year, the Hubble time is

$$1/H_0 = 14 \text{ billion years}$$

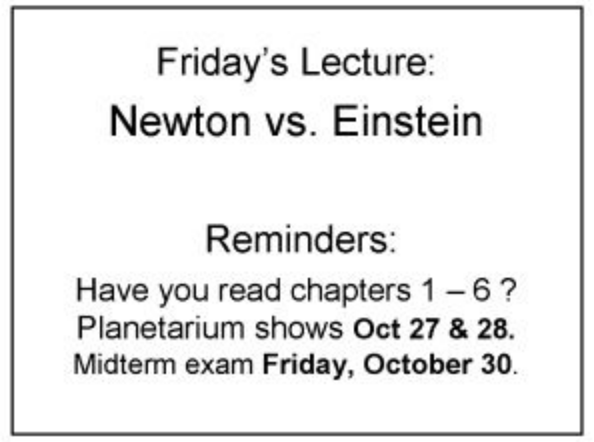


The Big Bang model “de-paradoxes” Olbers’ paradox.



Hubble time:
$1/H_0$ = 14 billion years.

Hubble distance:
c/H_0 = 14 billion light-years
= 4300 megaparsecs.



Friday’s Lecture:

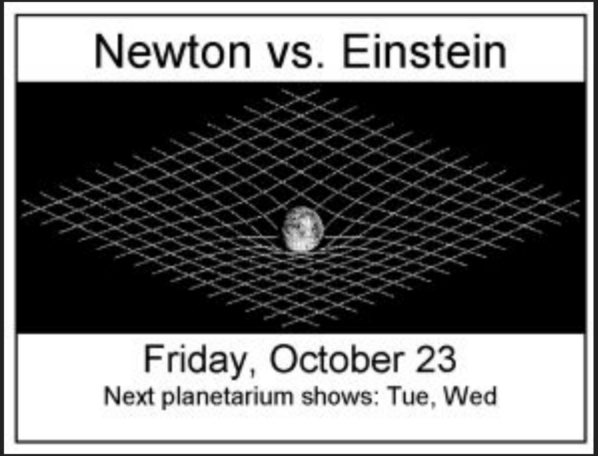
Newton vs. Einstein

Reminders:

Have you read chapters 1 – 6 ?
Planetarium shows **Oct 27 & 28.**
Midterm exam **Friday, October 30**.

Preparatory Reading Chapter 5 & 6

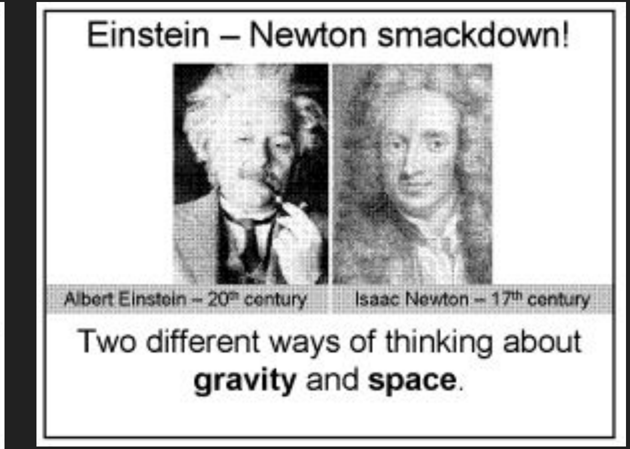
Week 5: Newton vs Einstein



Newton vs. Einstein

Friday, October 23

Next planetarium shows: Tue, Wed

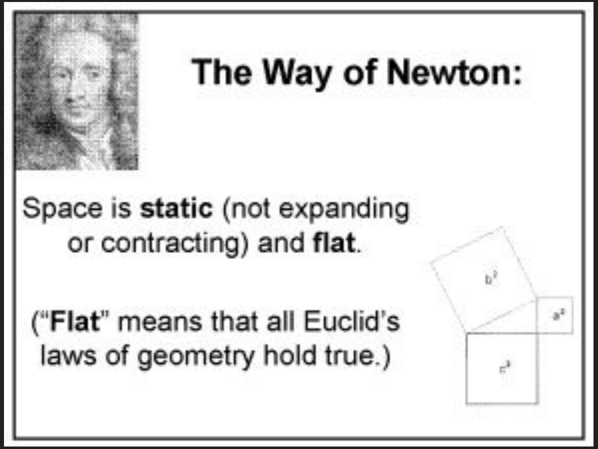


Einstein – Newton smackdown!

Albert Einstein – 20th century

Isaac Newton – 17th century

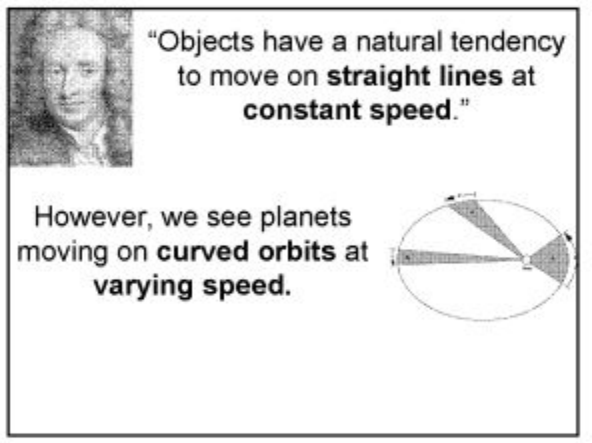
Two different ways of thinking about **gravity** and **space**.



The Way of Newton:

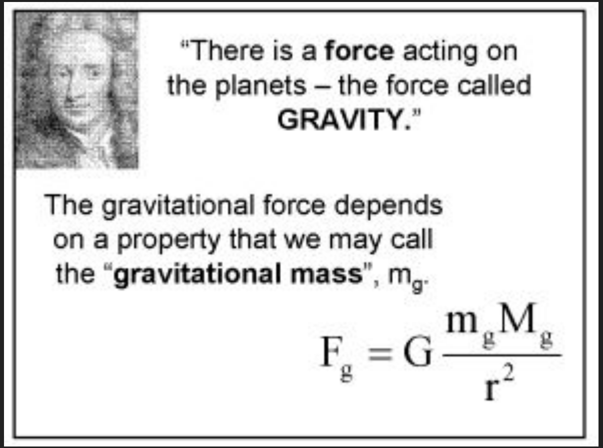
Space is **static** (not expanding or contracting) and **flat**.

(“**Flat**” means that all Euclid’s laws of geometry hold true.)



"Objects have a natural tendency to move on **straight lines** at **constant speed**."

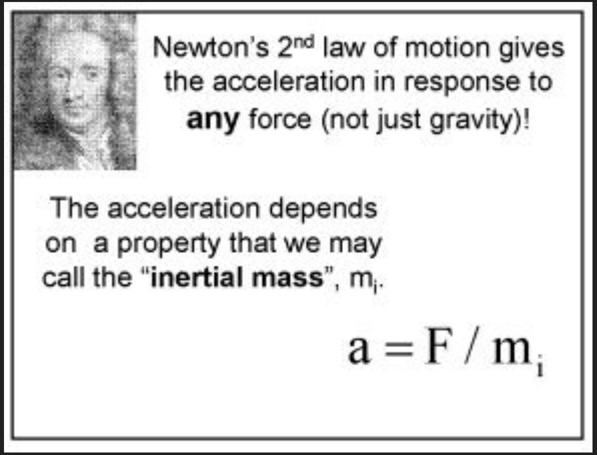
However, we see planets moving on **curved orbits** at **varying speed.**



"There is a **force** acting on the planets – the force called **GRAVITY.**"

The gravitational force depends on a property that we may call the "**gravitational mass**", m_g.

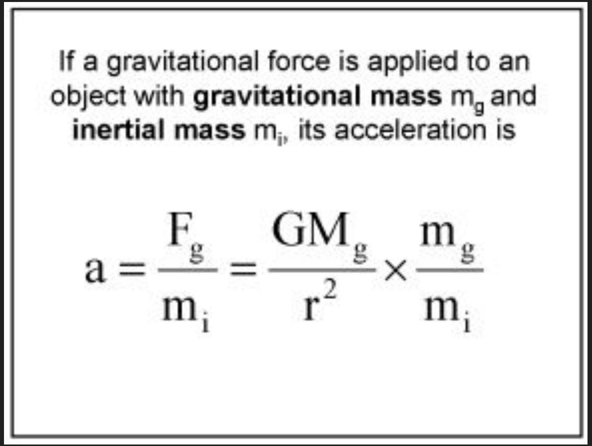
$$F_g = G\frac{m_g M_g}{r^2}$$



Newton's 2nd law of motion gives the acceleration in response to **any** force (not just gravity)!

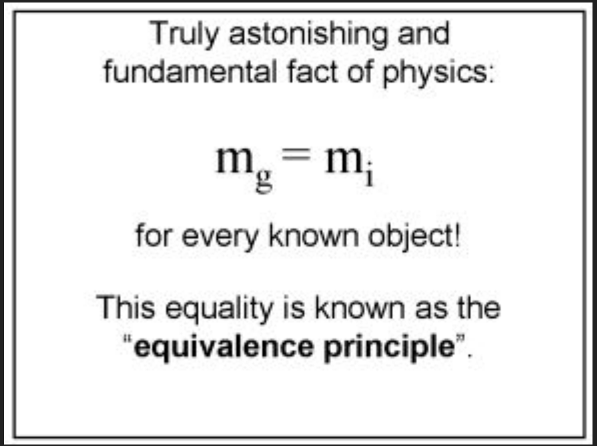
The acceleration depends on a property that we may call the "**inertial mass**", m_i.

$$a = F / m_i$$



If a gravitational force is applied to an object with **gravitational mass** m_g and **inertial mass** m_i, its acceleration is

$$a = \frac{F_g}{m_i} = \frac{GM_g}{r^2} \times \frac{m_g}{m_i}$$

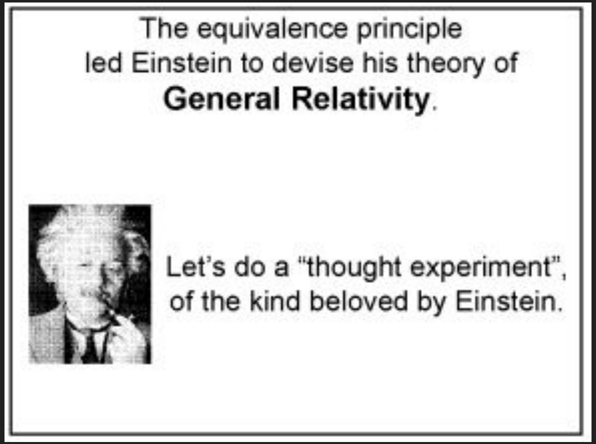


Truly astonishing and
fundamental fact of physics:

$$m_g = m_i$$

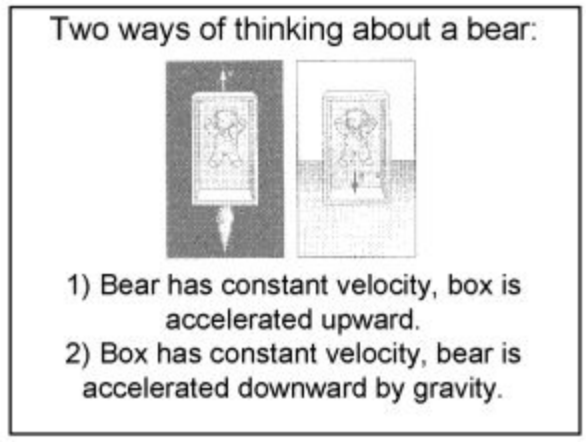
for every known object!

This equality is known as the "**equivalence principle**".



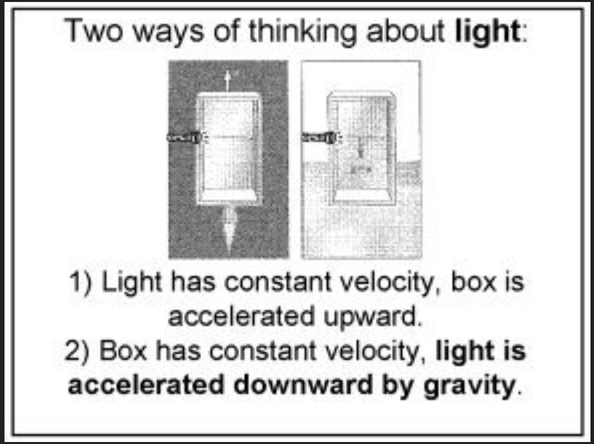
The equivalence principle led Einstein to devise his theory of **General Relativity**.

Let's do a "thought experiment", of the kind beloved by Einstein.



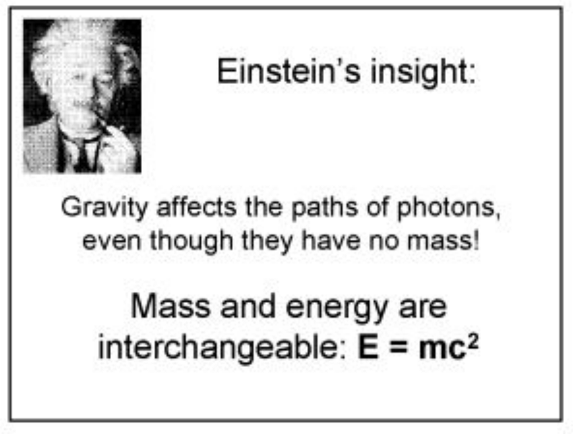
Two ways of thinking about a bear:

1) Bear has constant velocity, box is accelerated upward.
2) Box has constant velocity, bear is accelerated downward by gravity.



Two ways of thinking about **light**:

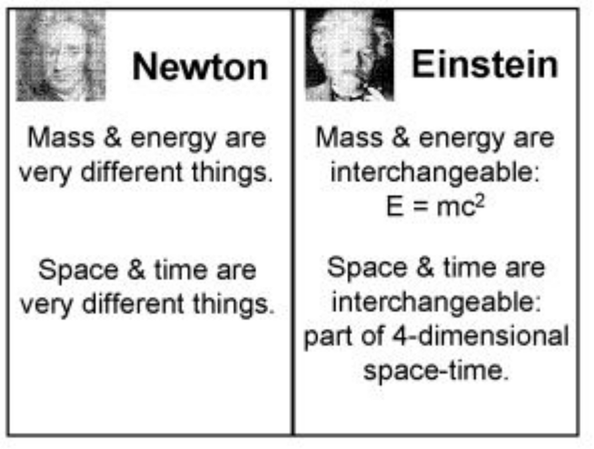
1) Light has constant velocity, box is accelerated upward.
2) Box has constant velocity, **light is accelerated downward by gravity**.



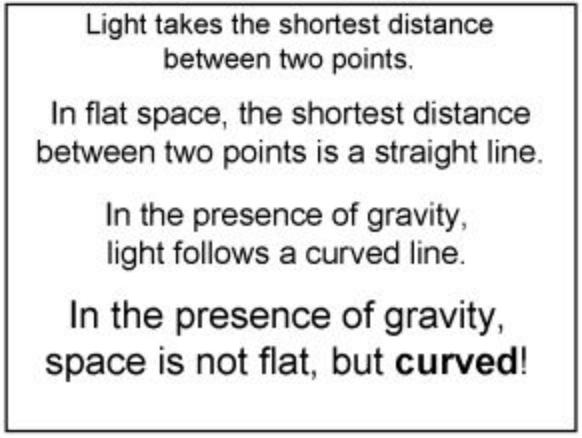
Einstein's insight:

Gravity affects the paths of photons, even though they have no mass!

Mass and energy are interchangeable: $\mathbf{E = mc^2}$



Newton	**Einstein**
Mass & energy are very different things.	Mass & energy are interchangeable: $E = mc^2$
Space & time are very different things.	Space & time are interchangeable: part of 4-dimensional space-time.

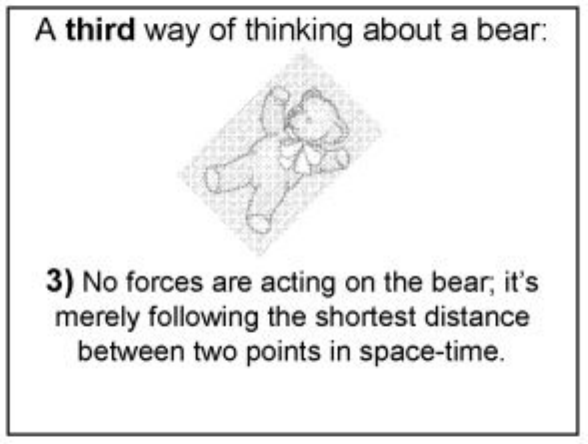


Light takes the shortest distance between two points.

In flat space, the shortest distance between two points is a straight line.

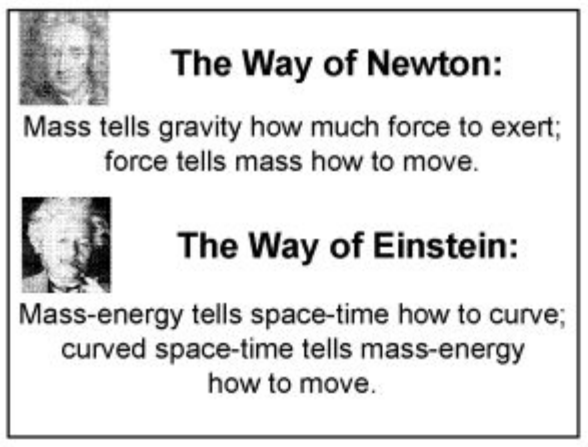
In the presence of gravity, light follows a curved line.

In the presence of gravity, space is not flat, but **curved**!



A **third** way of thinking about a bear:

3) No forces are acting on the bear; it's merely following the shortest distance between two points in space-time.

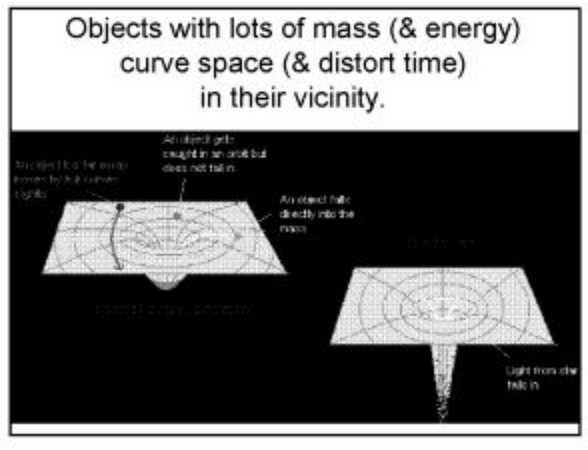


The Way of Newton:

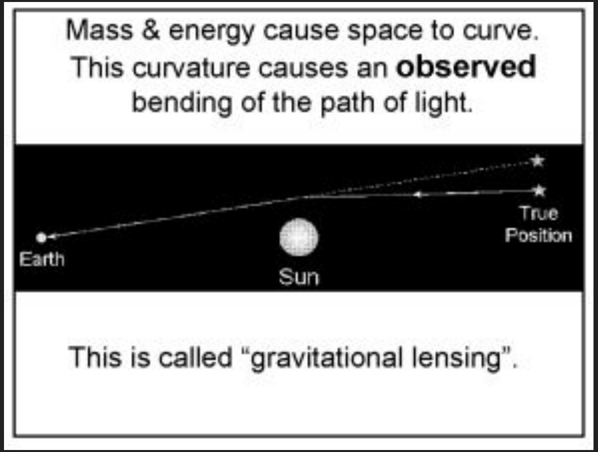
Mass tells gravity how much force to exert; force tells mass how to move.

The Way of Einstein:

Mass-energy tells space-time how to curve; curved space-time tells mass-energy how to move.

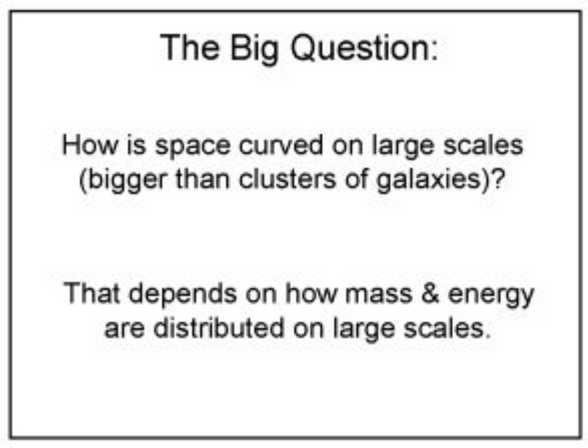


Objects with lots of mass (& energy)
curve space (& distort time)
in their vicinity.



Mass & energy cause space to curve. This curvature causes an **observed** bending of the path of light.

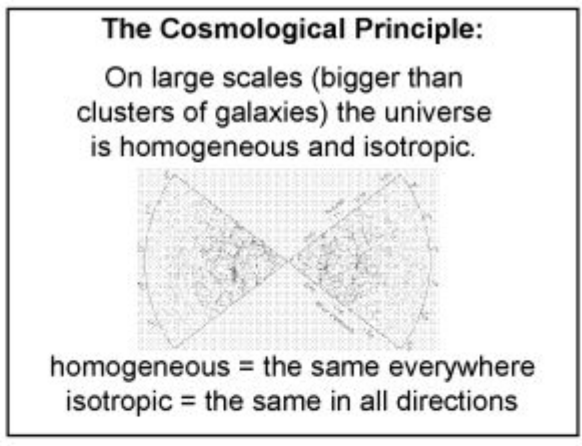
This is called “gravitational lensing”.



The Big Question:

How is space curved on large scales (bigger than clusters of galaxies)?

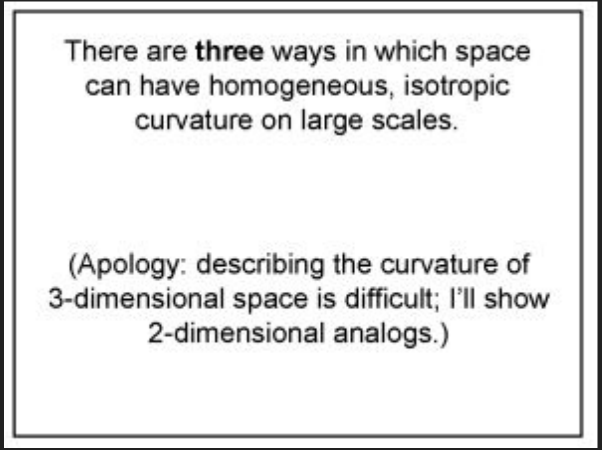
That depends on how mass & energy are distributed on large scales.



The Cosmological Principle:

On large scales (bigger than clusters of galaxies) the universe is homogeneous and isotropic.

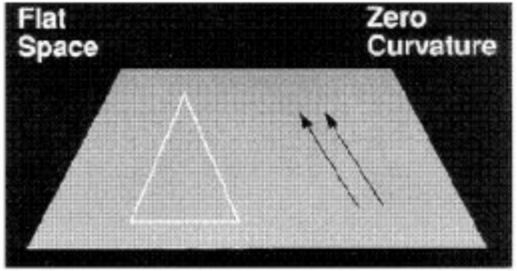
homogeneous = the same everywhere
isotropic = the same in all directions



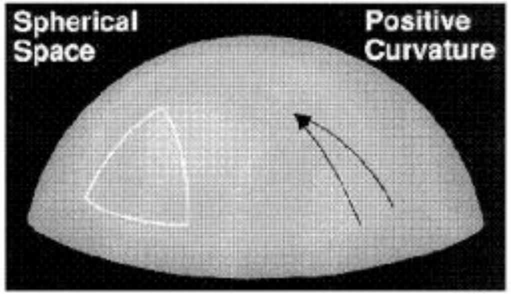
There are **three** ways in which space can have homogeneous, isotropic curvature on large scales.

(Apology: describing the curvature of 3-dimensional space is difficult; I'll show 2-dimensional analogs.)

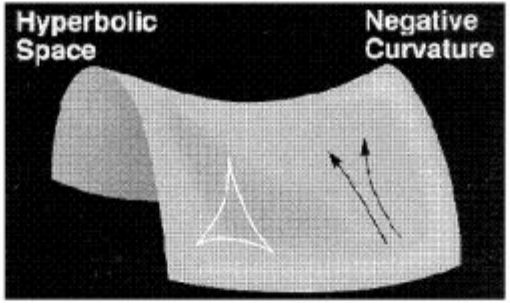
(1) This space is **flat**
(or Euclidean):

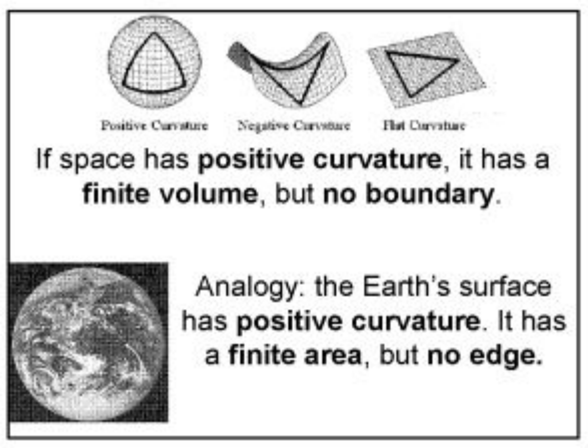


(2) This space is
positively curved:



(3) This space is
negatively curved:

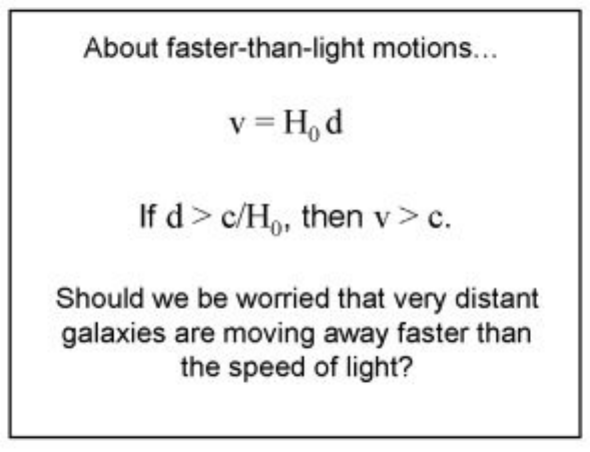




Positive Curvature Negative Curvature Flat Curvature

If space has **positive curvature**, it has a **finite volume**, but **no boundary**.

Analogy: the Earth's surface has **positive curvature**. It has a **finite area**, but **no edge.**

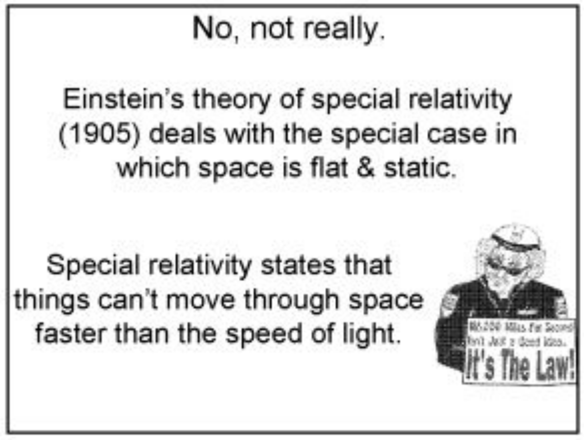


About faster-than-light motions…

$$v = H_0 d$$

If $d > c/H_0$, then $v > c$.

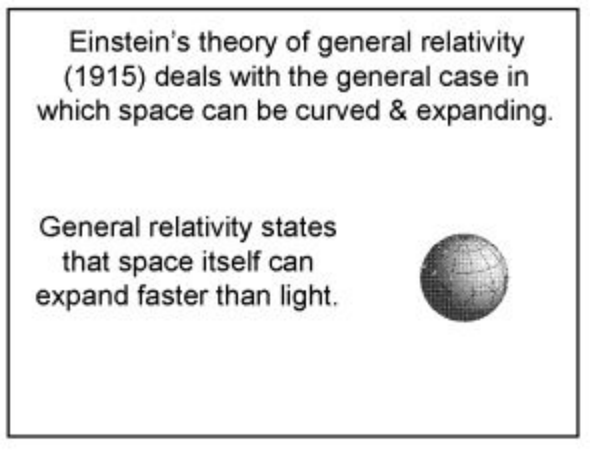
Should we be worried that very distant galaxies are moving away faster than the speed of light?



No, not really.

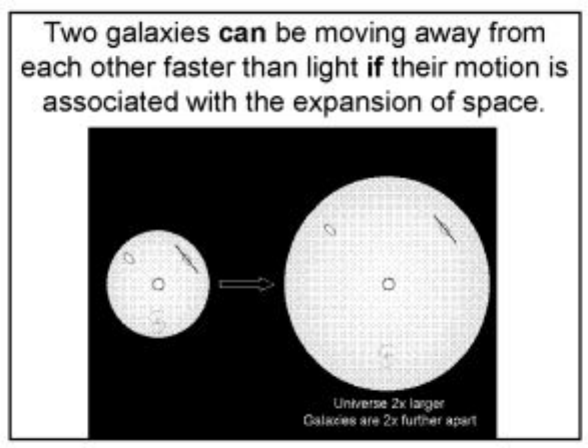
Einstein's theory of special relativity (1905) deals with the special case in which space is flat & static.

Special relativity states that things can't move through space faster than the speed of light.



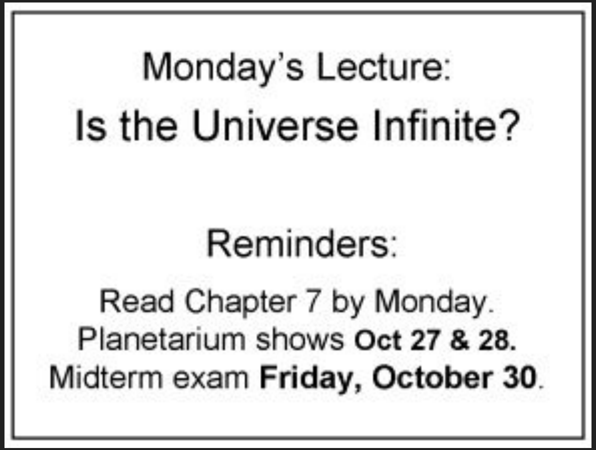
Einstein's theory of general relativity (1915) deals with the general case in which space can be curved & expanding.

General relativity states that space itself can expand faster than light.



Two galaxies **can** be moving away from each other faster than light **if** their motion is associated with the expansion of space.

Universe 2x larger
Galaxies are 2x further apart



Monday's Lecture:

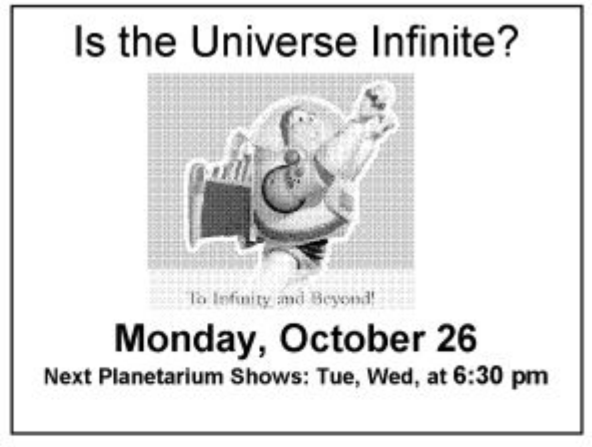
Is the Universe Infinite?

Reminders:

Read Chapter 7 by Monday.
Planetarium shows **Oct 27 & 28.**
Midterm exam **Friday, October 30**.

Preparatory Reading Chapter 7

Week 6: Is the Universe Infinite?

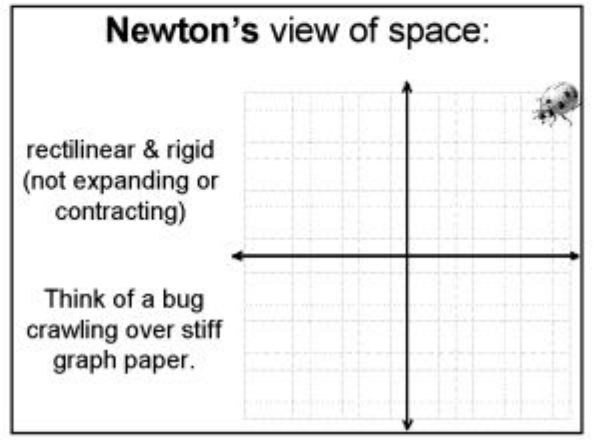


Is the Universe Infinite?

To Infinity and Beyond!

Monday, October 26

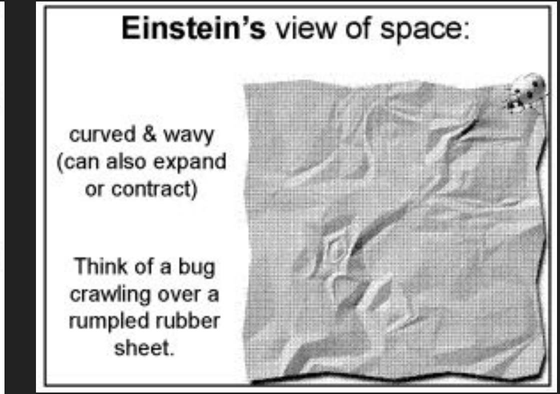
Next Planetarium Shows: Tue, Wed, at 6:30 pm



Newton's view of space:

rectilinear & rigid
(not expanding or
contracting)

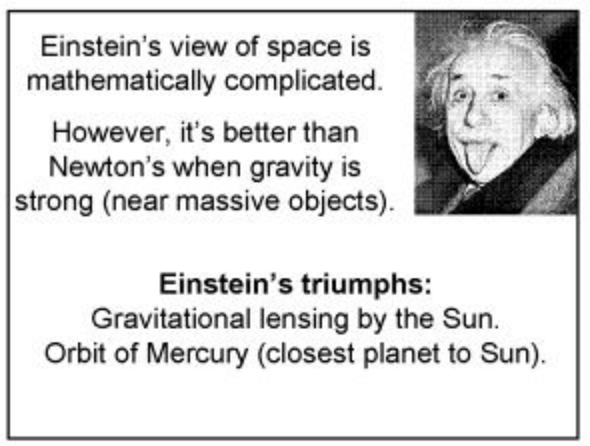
Think of a bug
crawling over stiff
graph paper.



Einstein's view of space:

curved & wavy
(can also expand
or contract)

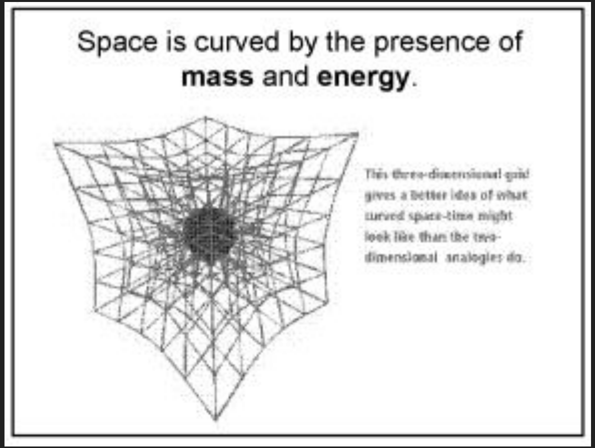
Think of a bug
crawling over a
rumpled rubber
sheet.



Einstein's view of space is mathematically complicated.

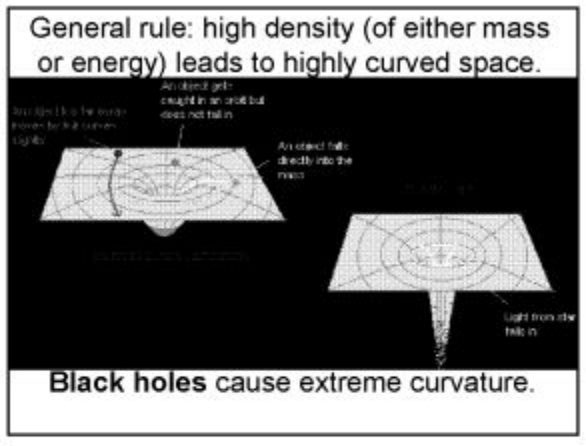
However, it's better than Newton's when gravity is strong (near massive objects).

Einstein's triumphs:
Gravitational lensing by the Sun.
Orbit of Mercury (closest planet to Sun).



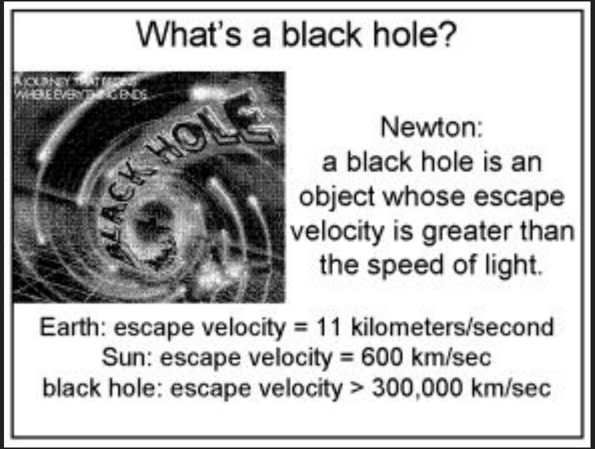
Space is curved by the presence of **mass** and **energy**.

This three-dimensional grid gives a better idea of what curved space-time might look like than the two-dimensional analogies do.



General rule: high density (of either mass or energy) leads to highly curved space.

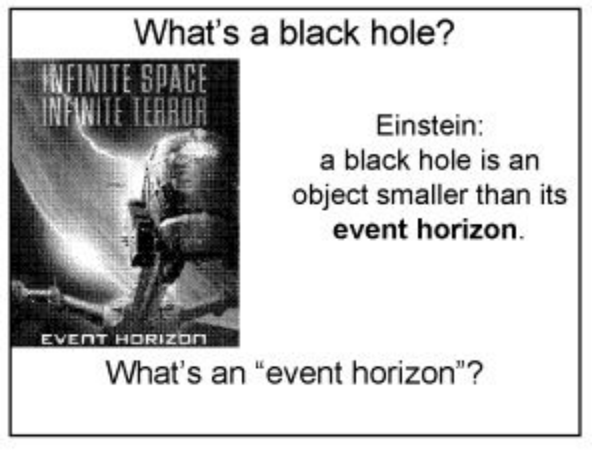
Black holes cause extreme curvature.



What's a black hole?

Newton:
a black hole is an object whose escape velocity is greater than the speed of light.

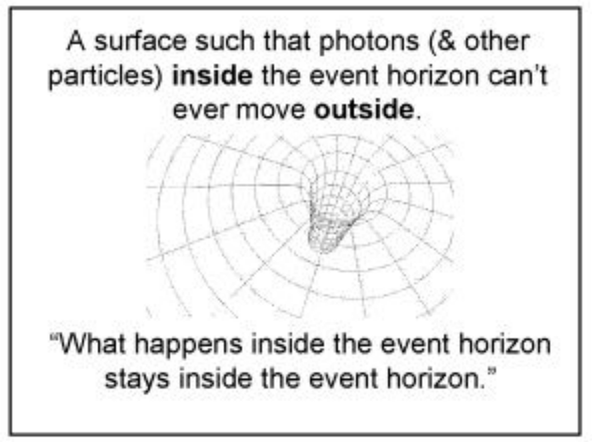
Earth: escape velocity = 11 kilometers/second
Sun: escape velocity = 600 km/sec
black hole: escape velocity > 300,000 km/sec



What's a black hole?

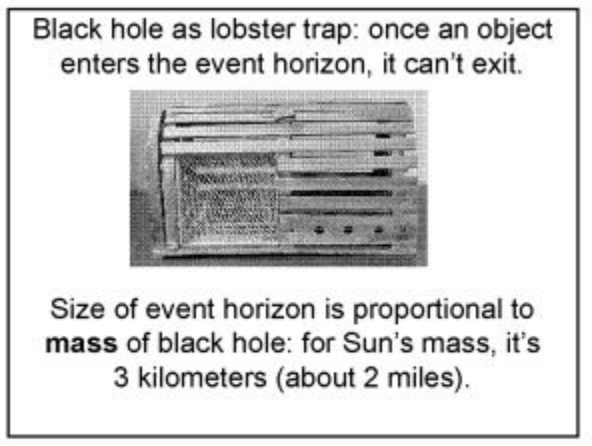
Einstein:
a black hole is an object smaller than its **event horizon**.

What's an "event horizon"?



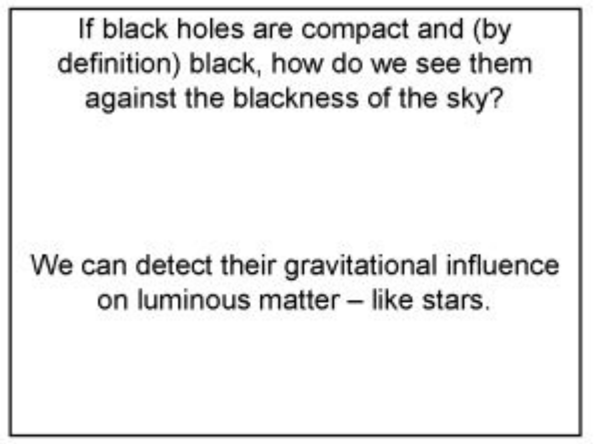
A surface such that photons (& other particles) **inside** the event horizon can't ever move **outside**.

"What happens inside the event horizon stays inside the event horizon."



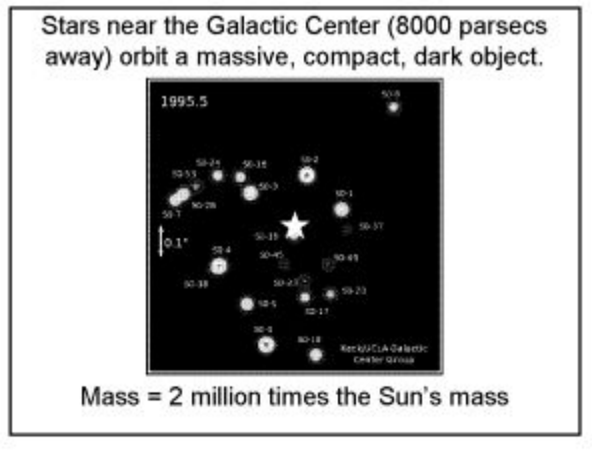
Black hole as lobster trap: once an object enters the event horizon, it can't exit.

Size of event horizon is proportional to **mass** of black hole: for Sun's mass, it's 3 kilometers (about 2 miles).



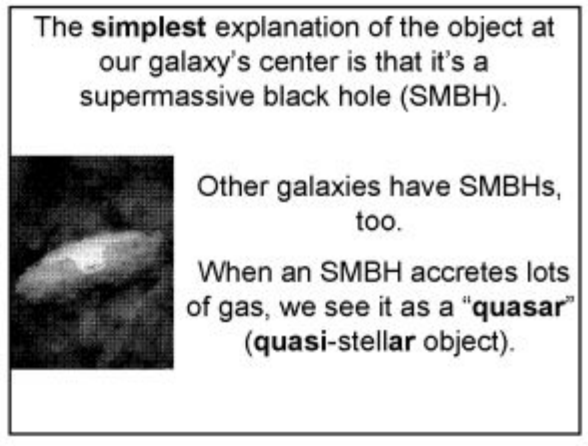
If black holes are compact and (by definition) black, how do we see them against the blackness of the sky?

We can detect their gravitational influence on luminous matter – like stars.



Stars near the Galactic Center (8000 parsecs away) orbit a massive, compact, dark object.

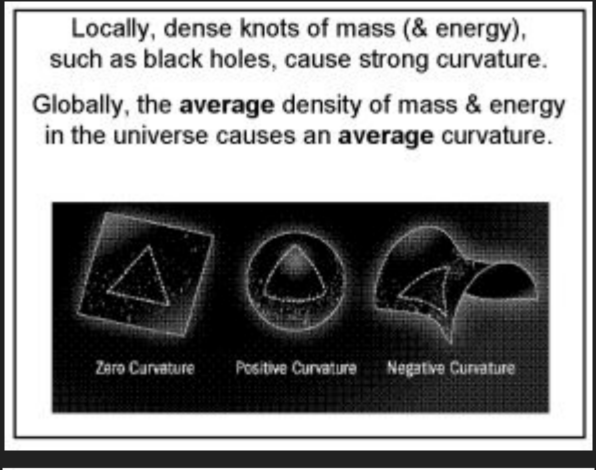
Mass = 2 million times the Sun's mass



The **simplest** explanation of the object at our galaxy's center is that it's a supermassive black hole (SMBH).

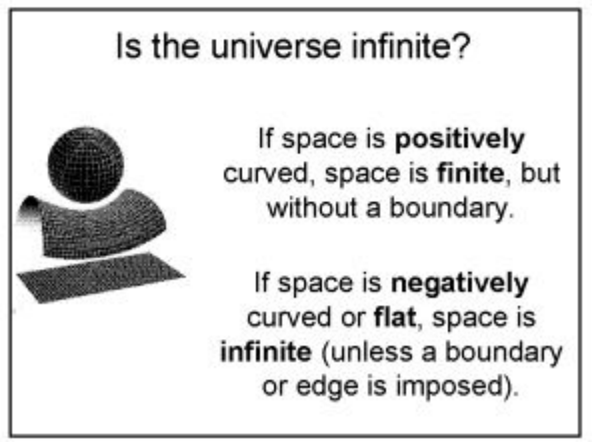
Other galaxies have SMBHs, too.

When an SMBH accretes lots of gas, we see it as a "**quasar**" (**quasi**-stellar object).



Locally, dense knots of mass (& energy), such as black holes, cause strong curvature.

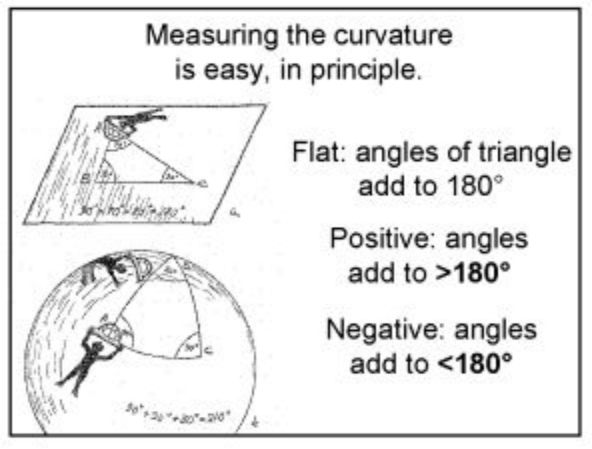
Globally, the **average** density of mass & energy in the universe causes an **average** curvature.



Is the universe infinite?

If space is **positively** curved, space is **finite**, but without a boundary.

If space is **negatively** curved or **flat**, space is **infinite** (unless a boundary or edge is imposed).

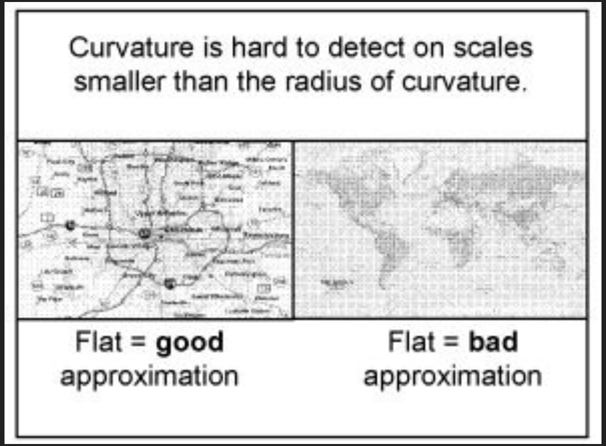


Measuring the curvature is easy, in principle.

Flat: angles of triangle add to 180°

Positive: angles add to **>180°**

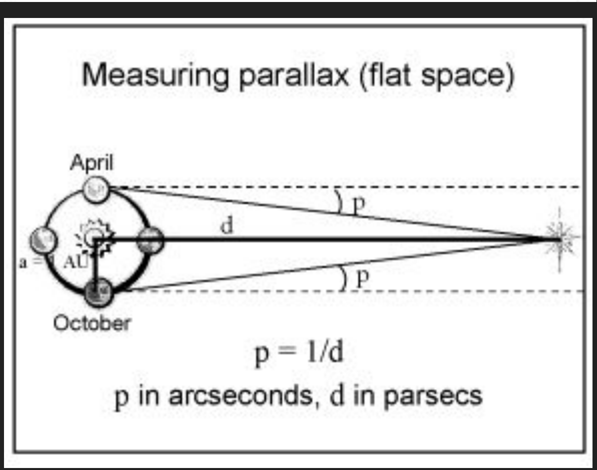
Negative: angles add to **<180°**



Curvature is hard to detect on scales smaller than the radius of curvature.

Flat = **good** approximation

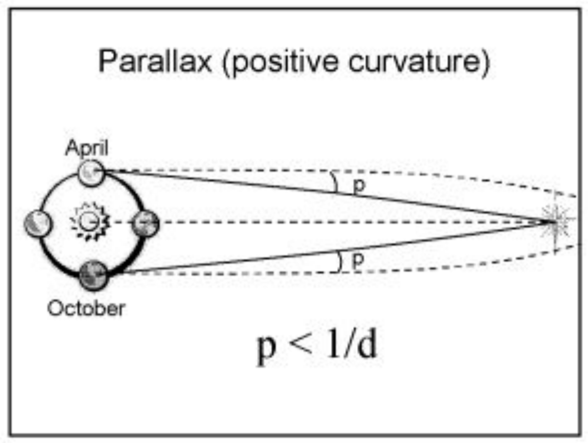
Flat = **bad** approximation



Measuring parallax (flat space)

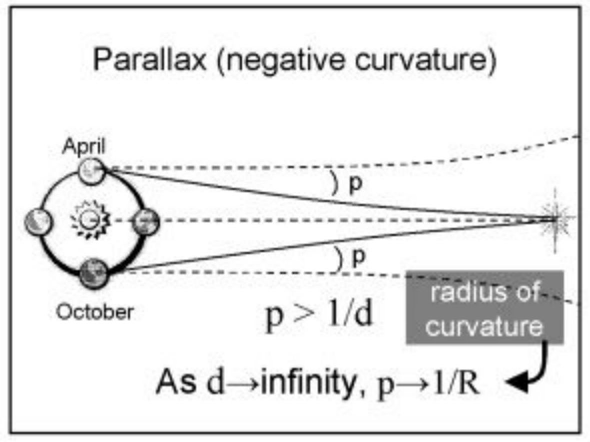
$p = 1/d$

p in arcseconds, d in parsecs



Parallax (positive curvature)

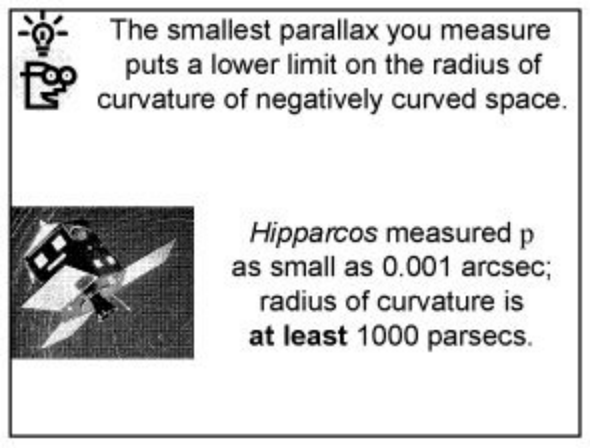
$p < 1/d$



Parallax (negative curvature)

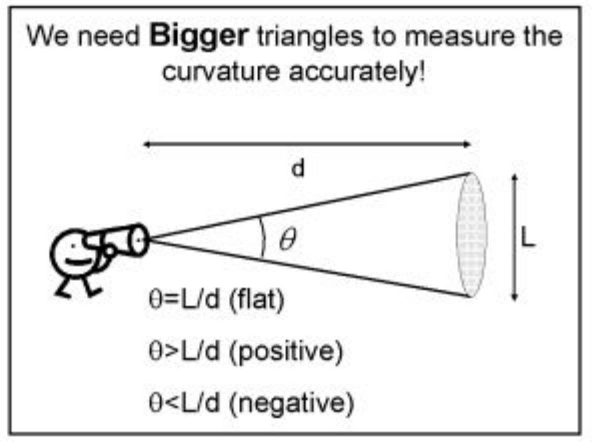
$p > 1/d$

As $d \to$ infinity, $p \to 1/R$



The smallest parallax you measure puts a lower limit on the radius of curvature of negatively curved space.

Hipparcos measured p as small as 0.001 arcsec; radius of curvature is **at least** 1000 parsecs.

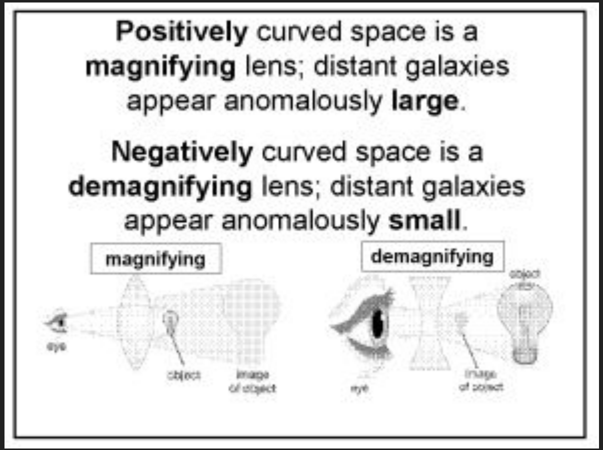


We need **Bigger** triangles to measure the curvature accurately!

$\theta = L/d$ (flat)

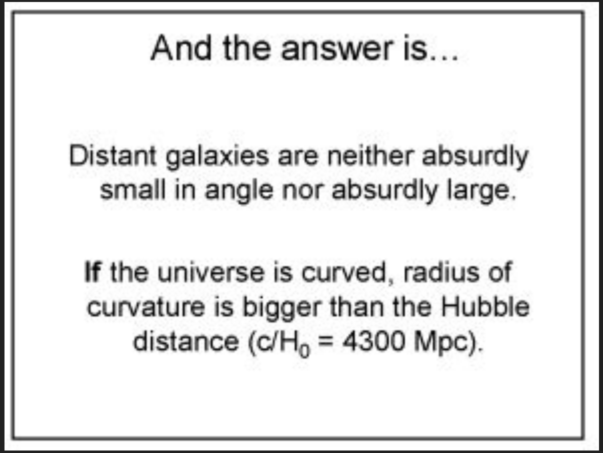
$\theta > L/d$ (positive)

$\theta < L/d$ (negative)



Positively curved space is a **magnifying** lens; distant galaxies appear anomalously **large**.

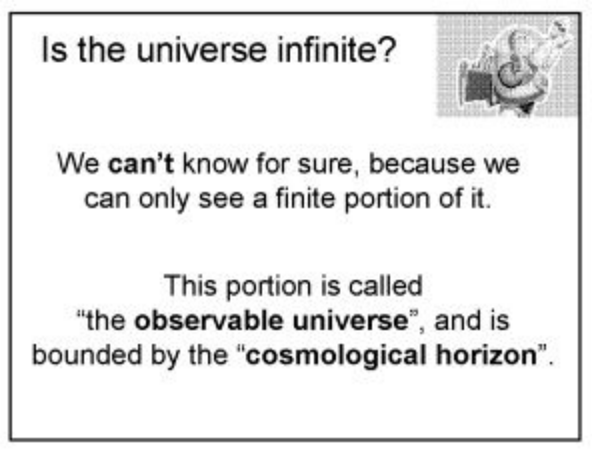
Negatively curved space is a **demagnifying** lens; distant galaxies appear anomalously **small**.



And the answer is…

Distant galaxies are neither absurdly small in angle nor absurdly large.

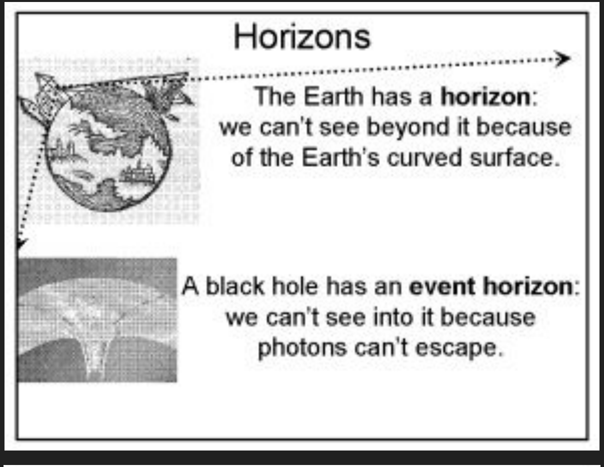
If the universe is curved, radius of curvature is bigger than the Hubble distance (c/H_0 = 4300 Mpc).



Is the universe infinite?

We **can't** know for sure, because we can only see a finite portion of it.

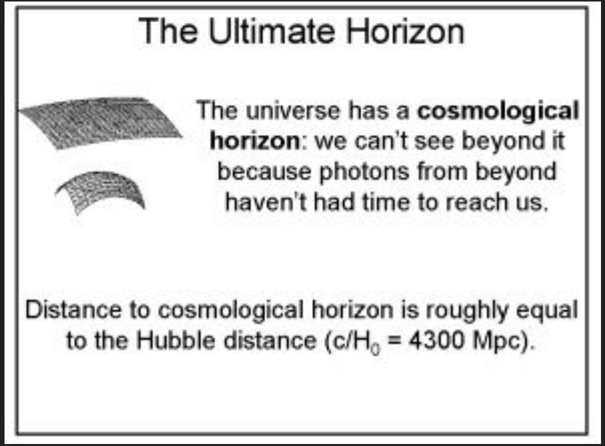
This portion is called "the **observable universe**", and is bounded by the "**cosmological horizon**".



Horizons

The Earth has a **horizon**: we can't see beyond it because of the Earth's curved surface.

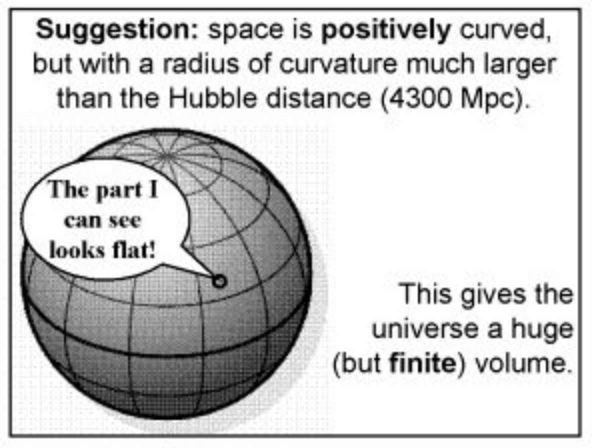
A black hole has an **event horizon**: we can't see into it because photons can't escape.



The Ultimate Horizon

The universe has a **cosmological horizon**: we can't see beyond it because photons from beyond haven't had time to reach us.

Distance to cosmological horizon is roughly equal to the Hubble distance (c/H_0 = 4300 Mpc).

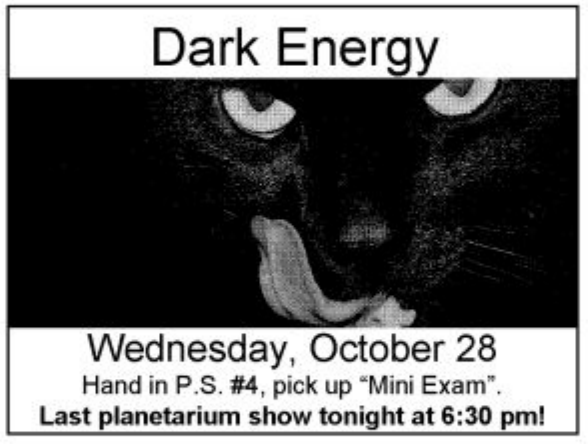


Suggestion: space is **positively** curved, but with a radius of curvature much larger than the Hubble distance (4300 Mpc).

This gives the universe a huge (but **finite**) volume.

Preparatory Reading Chapter 7

Week 6: Dark Energy

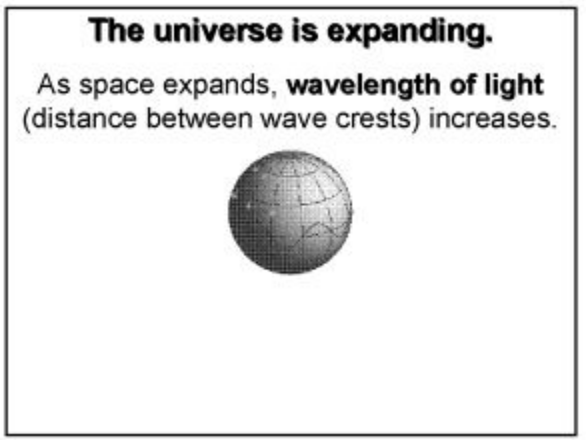


Dark Energy

Wednesday, October 28

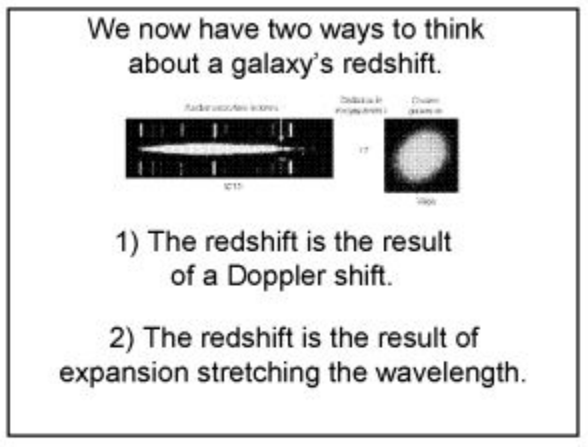
Hand in P.S. **#4**, pick up “Mini Exam”.

Last planetarium show tonight at 6:30 pm!



The universe is expanding.

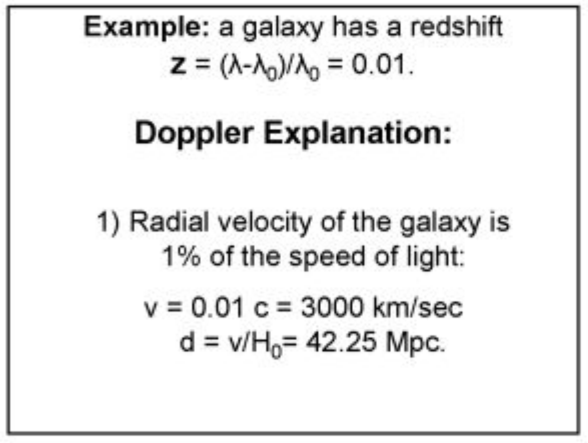
As space expands, **wavelength of light** (distance between wave crests) increases.



We now have two ways to think about a galaxy’s redshift.

1) The redshift is the result of a Doppler shift.

2) The redshift is the result of expansion stretching the wavelength.

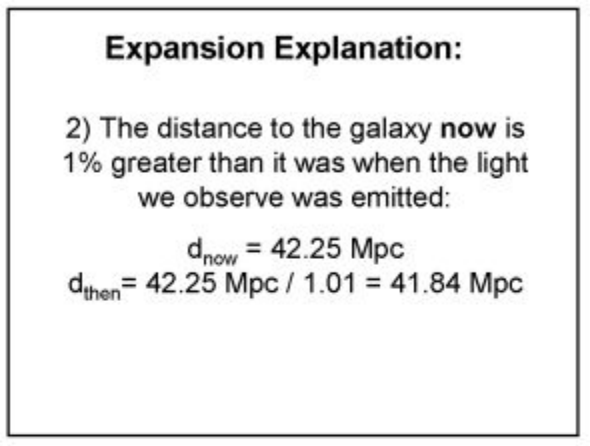


Example: a galaxy has a redshift
$\mathbf{z} = (\lambda-\lambda_0)/\lambda_0 = 0.01$.

Doppler Explanation:

1) Radial velocity of the galaxy is 1% of the speed of light:

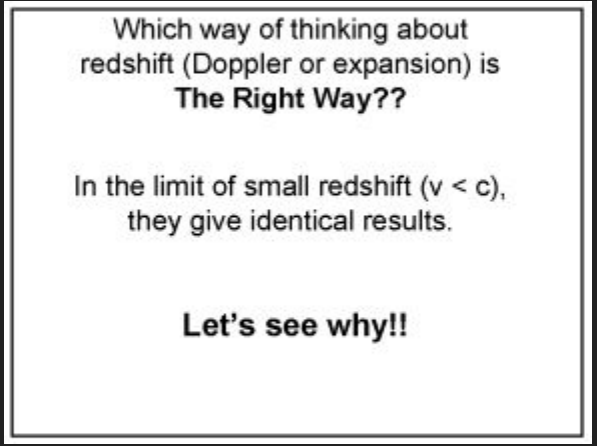
$v = 0.01\ c = 3000$ km/sec
$d = v/H_0 = 42.25$ Mpc.



Expansion Explanation:

2) The distance to the galaxy **now** is 1% greater than it was when the light we observe was emitted:

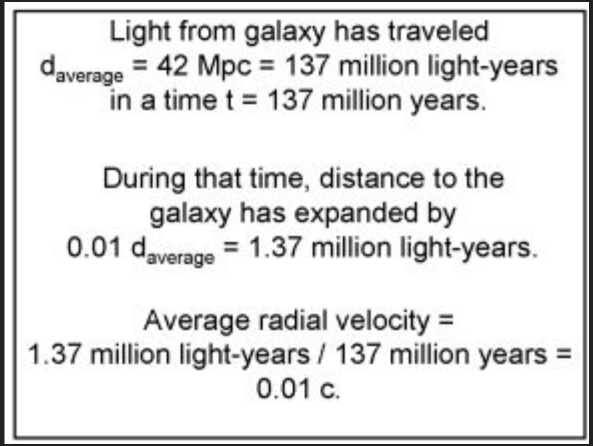
$d_{now} = 42.25$ Mpc
$d_{then} = 42.25$ Mpc / 1.01 = 41.84 Mpc



Which way of thinking about redshift (Doppler or expansion) is
The Right Way??

In the limit of small redshift ($v < c$), they give identical results.

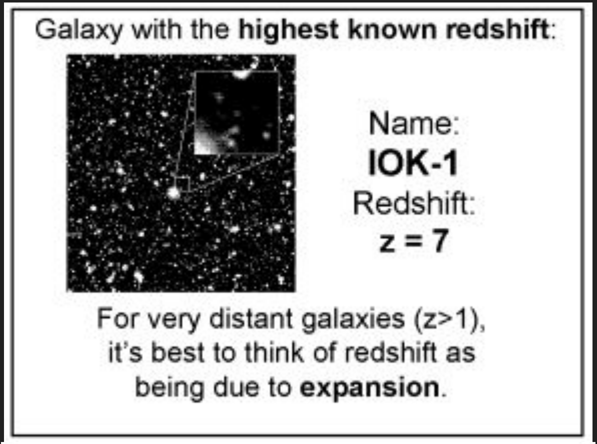
Let's see why!!



Light from galaxy has traveled
$d_{average}$ = 42 Mpc = 137 million light-years
in a time t = 137 million years.

During that time, distance to the
galaxy has expanded by
0.01 $d_{average}$ = 1.37 million light-years.

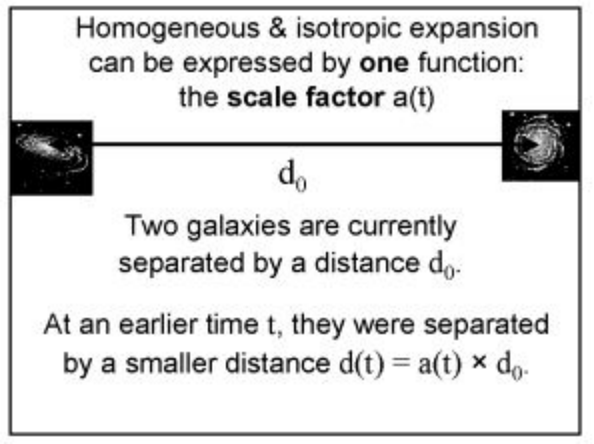
Average radial velocity =
1.37 million light-years / 137 million years =
0.01 c.



Galaxy with the **highest known redshift**:

Name:
IOK-1
Redshift:
z = 7

For very distant galaxies (z>1),
it's best to think of redshift as
being due to **expansion**.

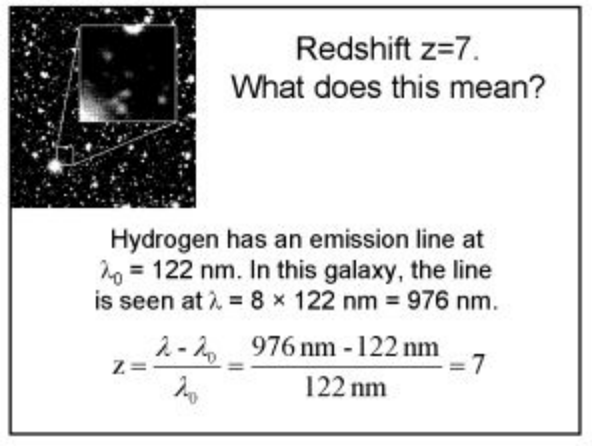


Homogeneous & isotropic expansion
can be expressed by **one** function:
the **scale factor** a(t)

d_0

Two galaxies are currently
separated by a distance d_0.

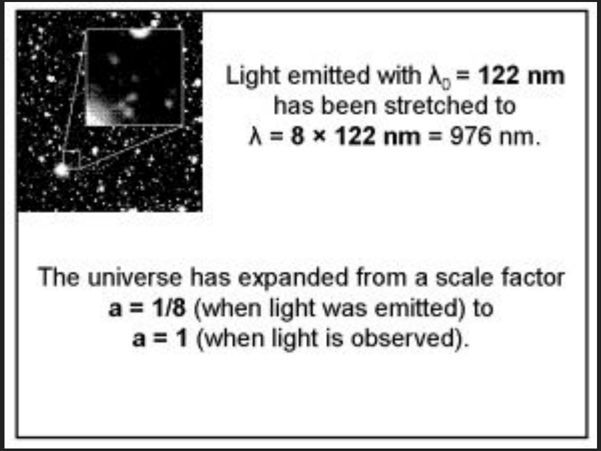
At an earlier time t, they were separated
by a smaller distance $d(t) = a(t) \times d_0$.



Redshift z=7.
What does this mean?

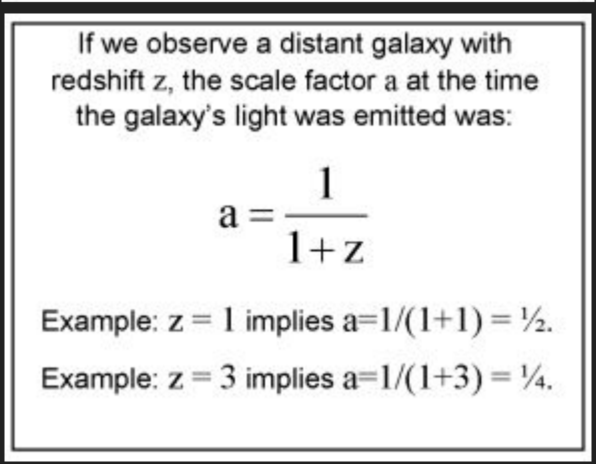
Hydrogen has an emission line at λ_0 = 122 nm. In this galaxy, the line is seen at λ = 8 × 122 nm = 976 nm.

$$z = \frac{\lambda - \lambda_0}{\lambda_0} = \frac{976\,\text{nm} - 122\,\text{nm}}{122\,\text{nm}} = 7$$



Light emitted with λ_0 = **122 nm** has been stretched to
λ = **8 × 122 nm** = 976 nm.

The universe has expanded from a scale factor **a = 1/8** (when light was emitted) to **a = 1** (when light is observed).

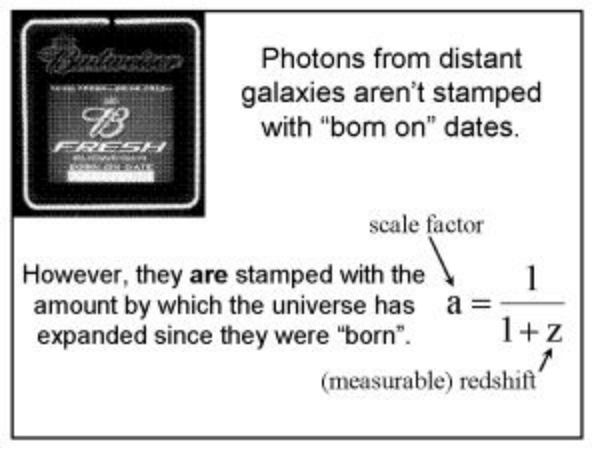


If we observe a distant galaxy with redshift z, the scale factor a at the time the galaxy's light was emitted was:

$$a = \frac{1}{1+z}$$

Example: $z = 1$ implies $a=1/(1+1) = ½$.

Example: $z = 3$ implies $a=1/(1+3) = ¼$.



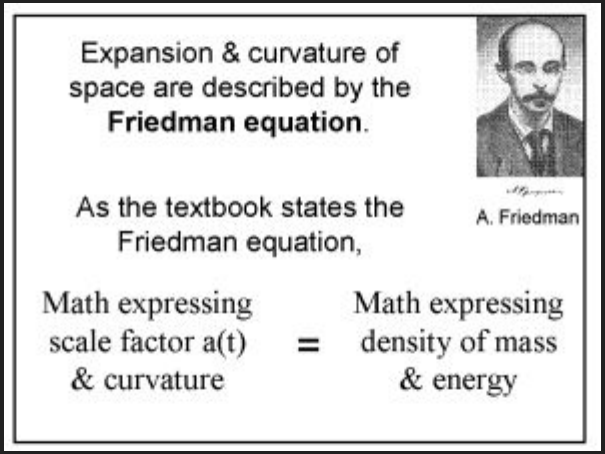
Photons from distant galaxies aren't stamped with "born on" dates.

scale factor

However, they **are** stamped with the amount by which the universe has expanded since they were "born".

$$a = \frac{1}{1+z}$$

(measurable) redshift

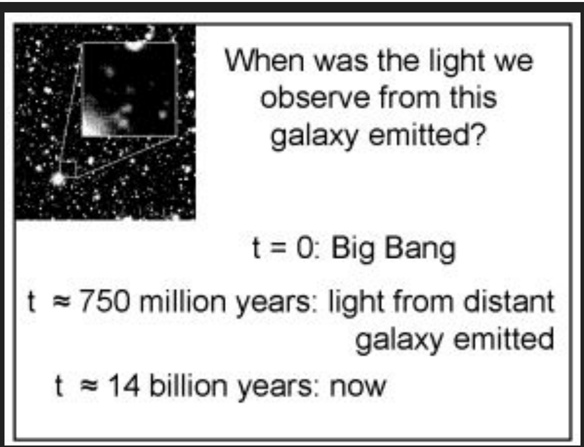


Expansion & curvature of space are described by the **Friedman equation**.

A. Friedman

As the textbook states the Friedman equation,

Math expressing scale factor a(t) & curvature = Math expressing density of mass & energy

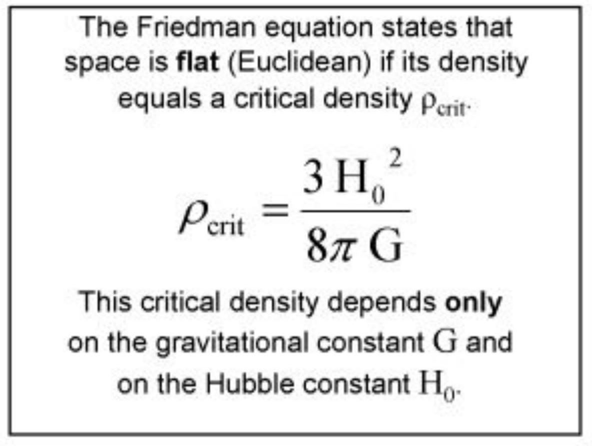


When was the light we observe from this galaxy emitted?

t = 0: Big Bang

t ≈ 750 million years: light from distant galaxy emitted

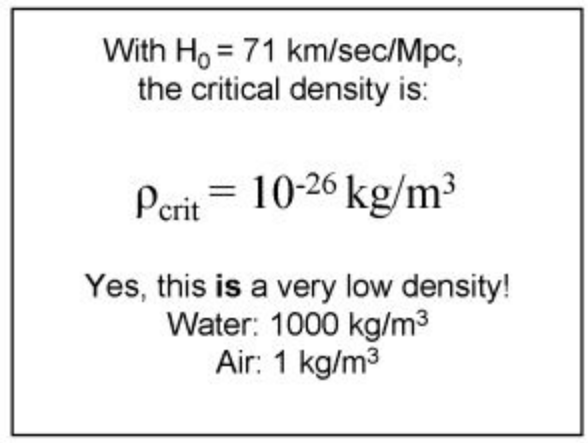
t ≈ 14 billion years: now



The Friedman equation states that space is **flat** (Euclidean) if its density equals a critical density ρ_{crit}.

$$\rho_{crit} = \frac{3\,H_0^{\;2}}{8\pi\,G}$$

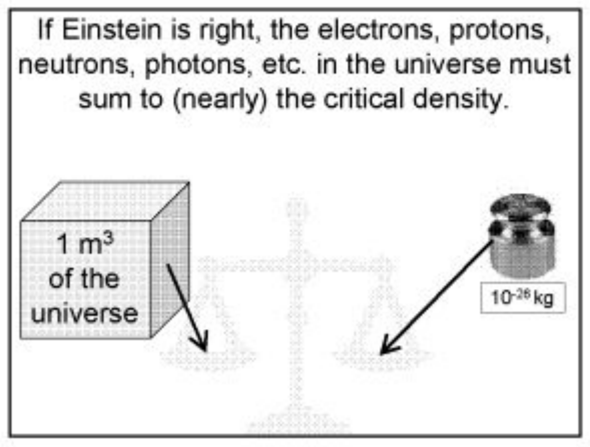
This critical density depends **only** on the gravitational constant G and on the Hubble constant H_0.



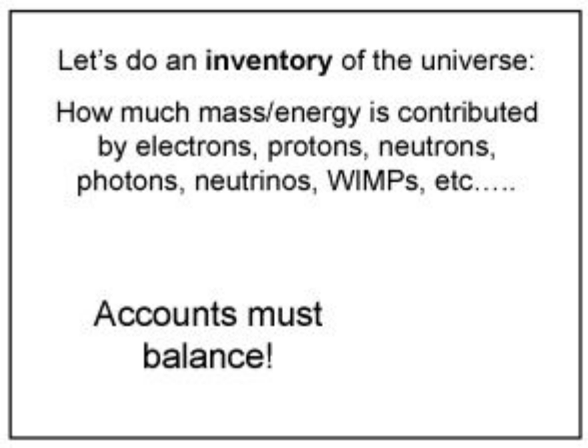
With H_0 = 71 km/sec/Mpc, the critical density is:

$$\rho_{crit} = 10^{-26}\ \mathrm{kg/m^3}$$

Yes, this **is** a very low density!
Water: 1000 kg/m^3
Air: 1 kg/m^3



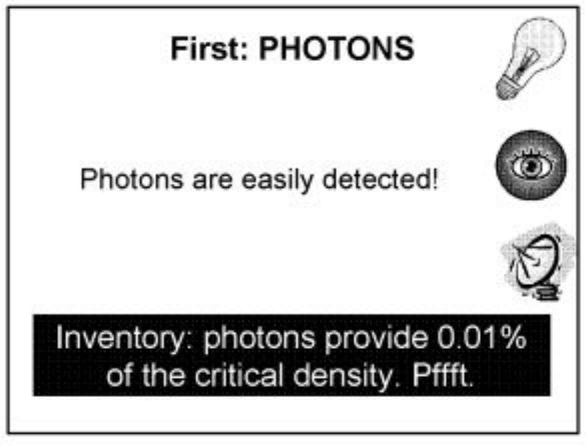
If Einstein is right, the electrons, protons, neutrons, photons, etc. in the universe must sum to (nearly) the critical density.



Let's do an **inventory** of the universe:

How much mass/energy is contributed by electrons, protons, neutrons, photons, neutrinos, WIMPs, etc.….

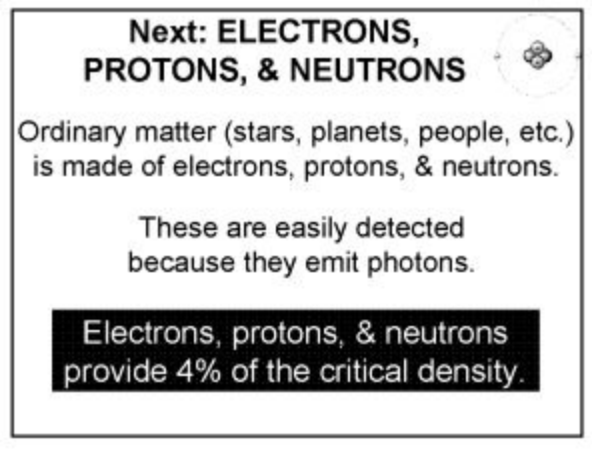
Accounts must balance!



First: PHOTONS

Photons are easily detected!

Inventory: photons provide 0.01% of the critical density. Pffft.

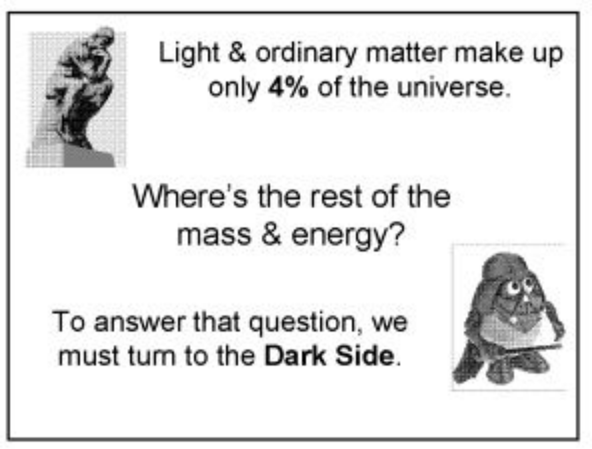


Next: ELECTRONS, PROTONS, & NEUTRONS

Ordinary matter (stars, planets, people, etc.) is made of electrons, protons, & neutrons.

These are easily detected because they emit photons.

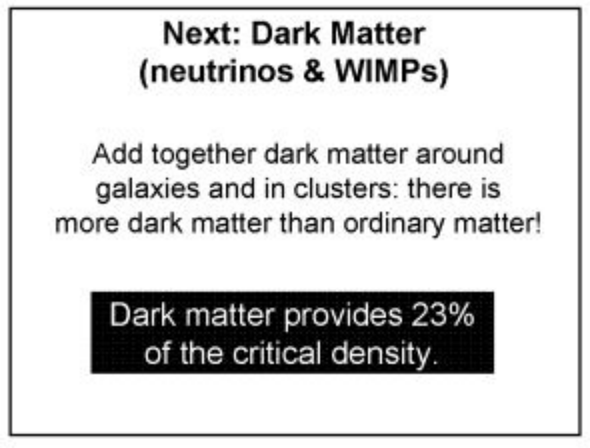
Electrons, protons, & neutrons provide 4% of the critical density.



Light & ordinary matter make up only **4%** of the universe.

Where's the rest of the mass & energy?

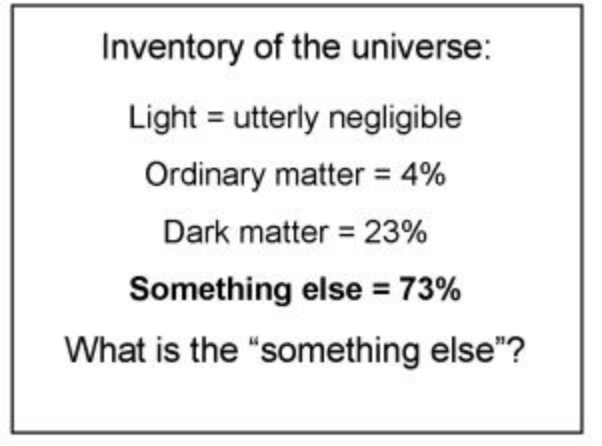
To answer that question, we must turn to the **Dark Side**.



Next: Dark Matter (neutrinos & WIMPs)

Add together dark matter around galaxies and in clusters: there is more dark matter than ordinary matter!

Dark matter provides 23% of the critical density.



Inventory of the universe:

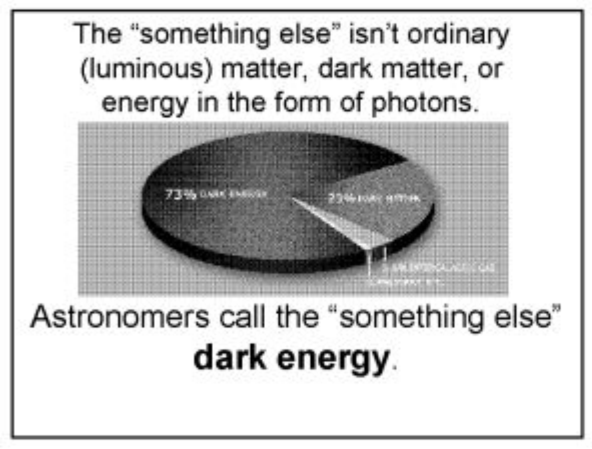
Light = utterly negligible

Ordinary matter = 4%

Dark matter = 23%

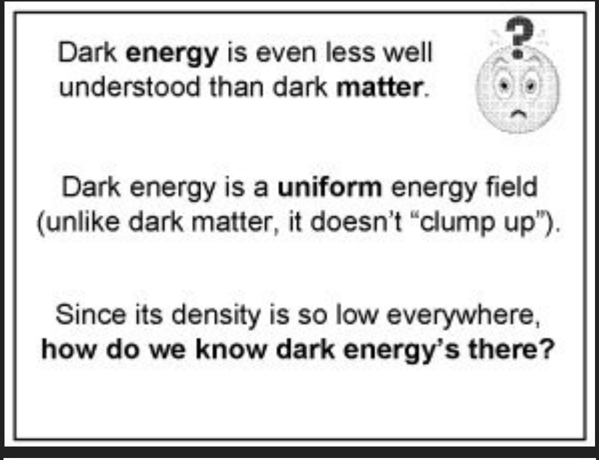
Something else = 73%

What is the “something else”?



The “something else” isn’t ordinary (luminous) matter, dark matter, or energy in the form of photons.

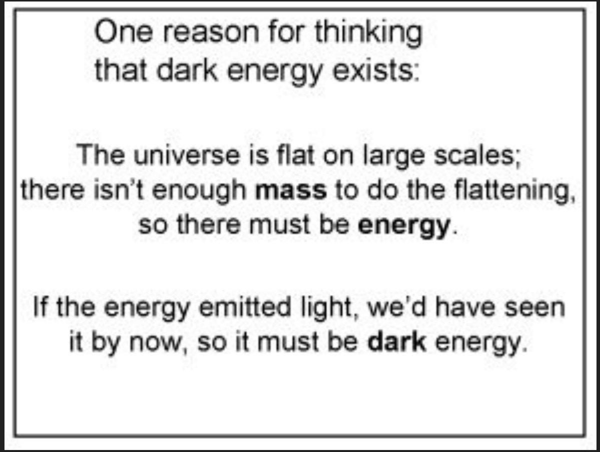
Astronomers call the “something else” **dark energy**.



Dark **energy** is even less well understood than dark **matter**.

Dark energy is a **uniform** energy field (unlike dark matter, it doesn’t “clump up”).

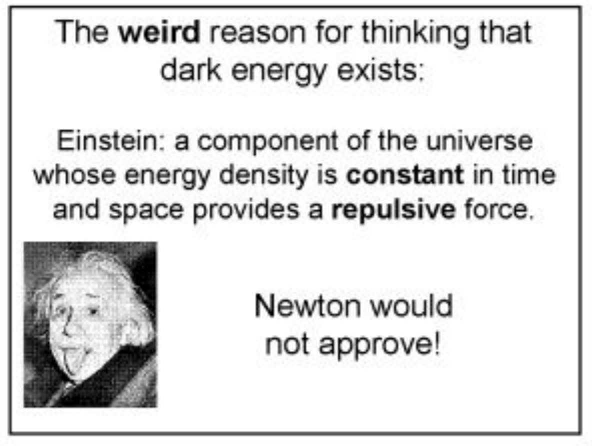
Since its density is so low everywhere, **how do we know dark energy’s there?**



One reason for thinking that dark energy exists:

The universe is flat on large scales; there isn’t enough **mass** to do the flattening, so there must be **energy**.

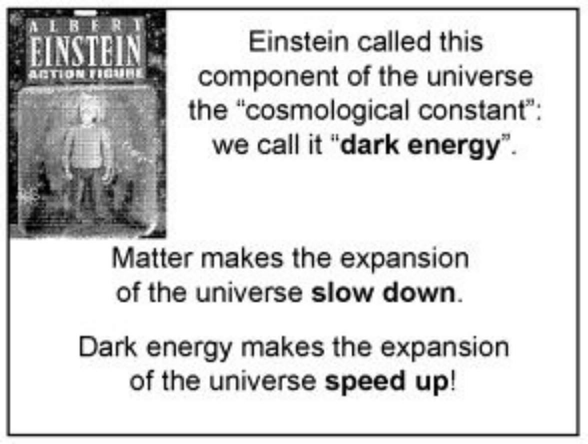
If the energy emitted light, we’d have seen it by now, so it must be **dark** energy.



The **weird** reason for thinking that dark energy exists:

Einstein: a component of the universe whose energy density is **constant** in time and space provides a **repulsive** force.

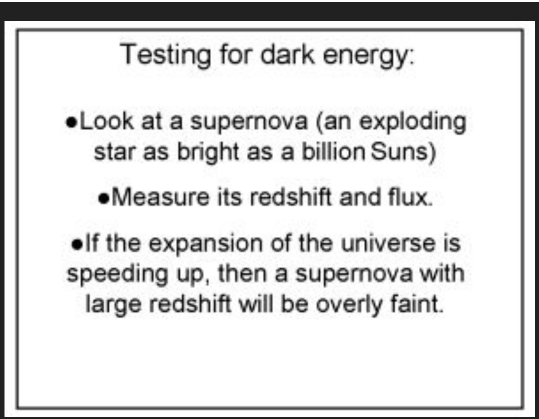
Newton would not approve!



Einstein called this component of the universe the “cosmological constant”: we call it “**dark energy**”.

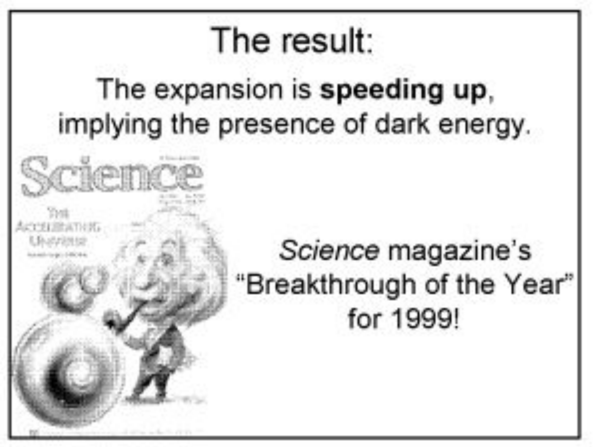
Matter makes the expansion of the universe **slow down**.

Dark energy makes the expansion of the universe **speed up**!



Testing for dark energy:

- Look at a supernova (an exploding star as bright as a billion Suns)
- Measure its redshift and flux.
- If the expansion of the universe is speeding up, then a supernova with large redshift will be overly faint.



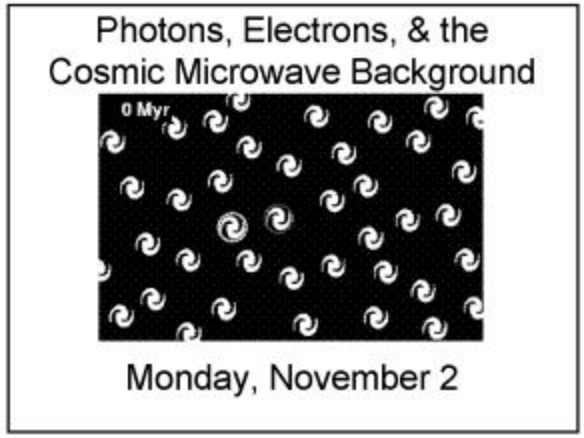
The result:

The expansion is **speeding up**,
implying the presence of dark energy.

Science magazine's
"Breakthrough of the Year"
for 1999!

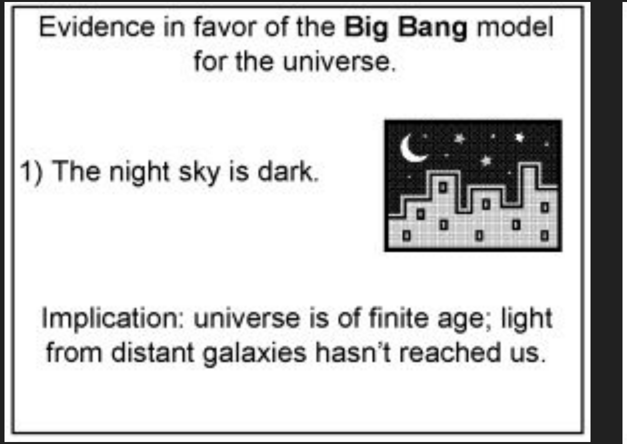
Preparatory Reading Chapter 8

Week 7: The Cosmic Microwave Background



Photons, Electrons, & the Cosmic Microwave Background

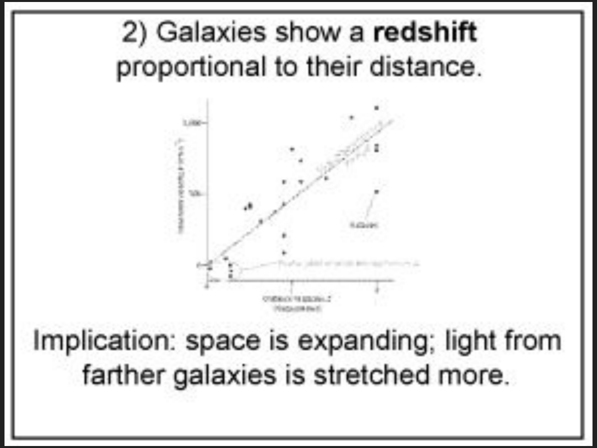
Monday, November 2



Evidence in favor of the **Big Bang** model for the universe.

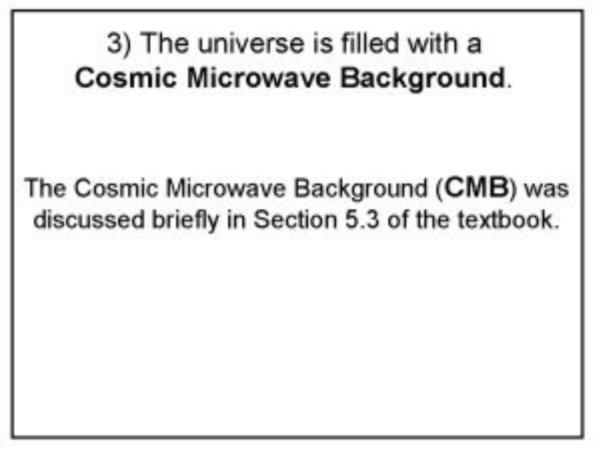
1) The night sky is dark.

Implication: universe is of finite age; light from distant galaxies hasn't reached us.



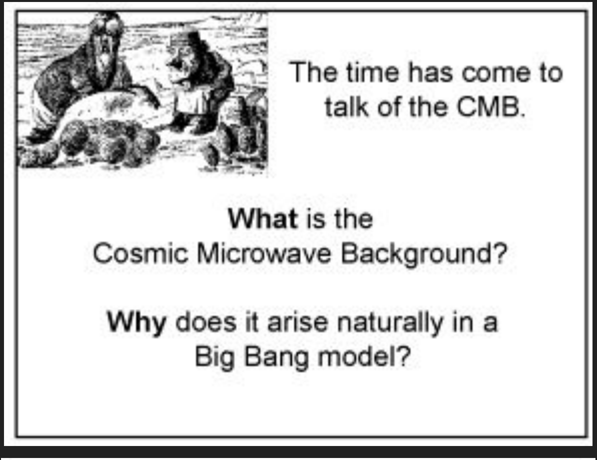
2) Galaxies show a **redshift** proportional to their distance.

Implication: space is expanding; light from farther galaxies is stretched more.



3) The universe is filled with a **Cosmic Microwave Background**.

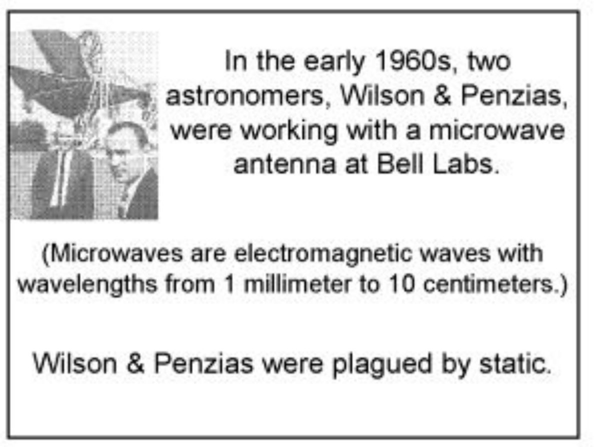
The Cosmic Microwave Background (**CMB**) was discussed briefly in Section 5.3 of the textbook.



The time has come to talk of the CMB.

What is the Cosmic Microwave Background?

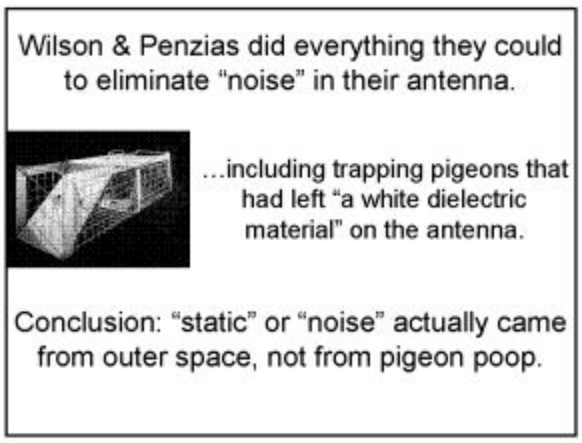
Why does it arise naturally in a Big Bang model?



In the early 1960s, two astronomers, Wilson & Penzias, were working with a microwave antenna at Bell Labs.

(Microwaves are electromagnetic waves with wavelengths from 1 millimeter to 10 centimeters.)

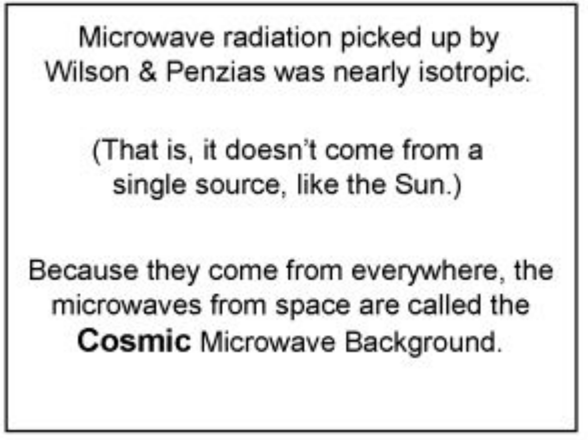
Wilson & Penzias were plagued by static.



Wilson & Penzias did everything they could to eliminate “noise” in their antenna.

…including trapping pigeons that had left “a white dielectric material” on the antenna.

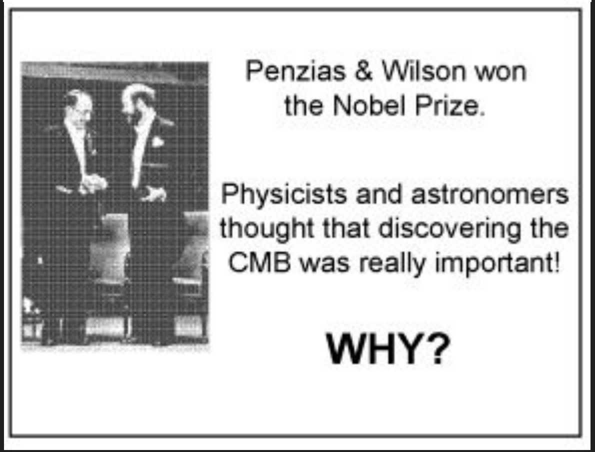
Conclusion: “static” or “noise” actually came from outer space, not from pigeon poop.



Microwave radiation picked up by Wilson & Penzias was nearly isotropic.

(That is, it doesn’t come from a single source, like the Sun.)

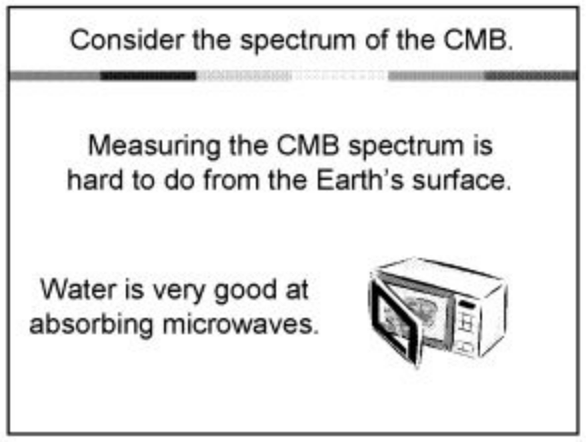
Because they come from everywhere, the microwaves from space are called the **Cosmic** Microwave Background.



Penzias & Wilson won the Nobel Prize.

Physicists and astronomers thought that discovering the CMB was really important!

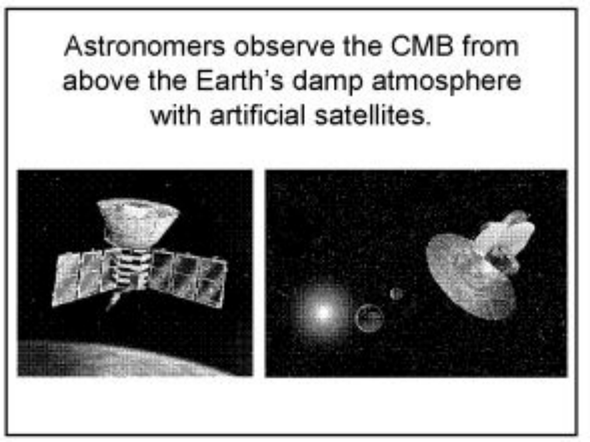
WHY?



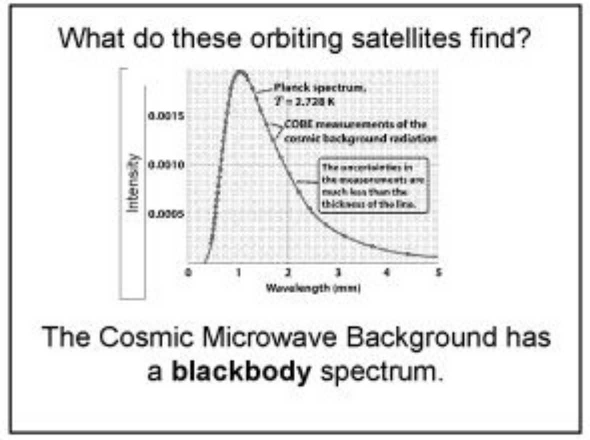
Consider the spectrum of the CMB.

Measuring the CMB spectrum is hard to do from the Earth's surface.

Water is very good at absorbing microwaves.

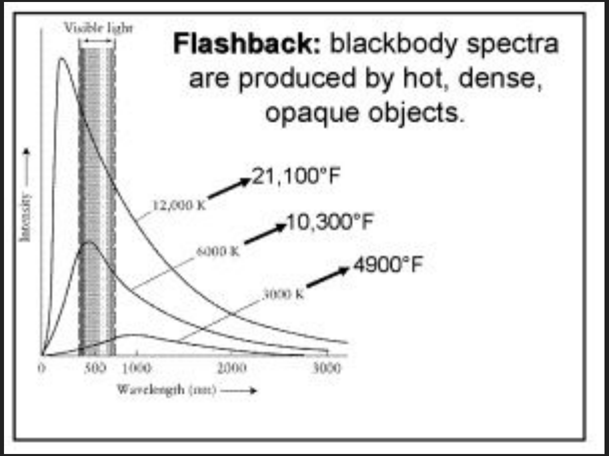


Astronomers observe the CMB from above the Earth's damp atmosphere with artificial satellites.

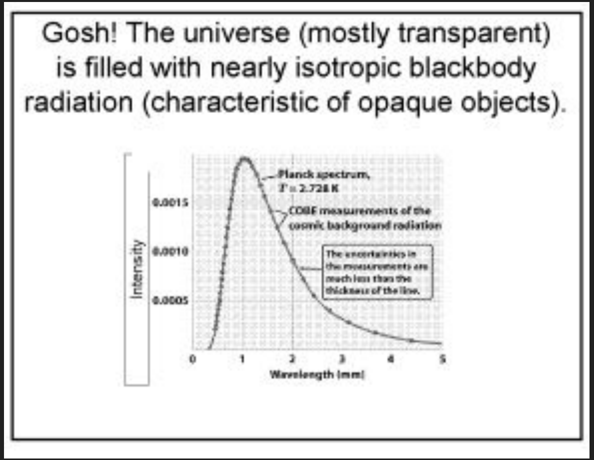


What do these orbiting satellites find?

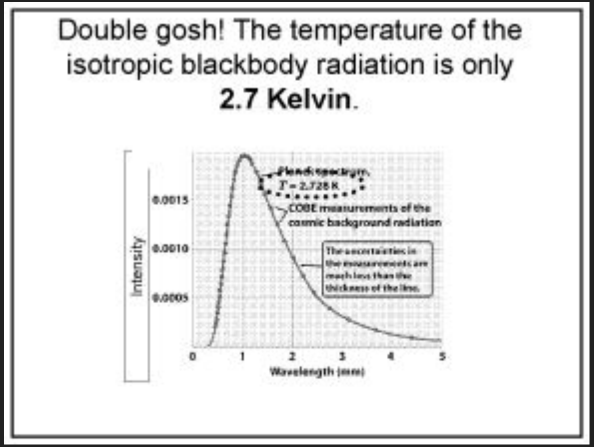
The Cosmic Microwave Background has a **blackbody** spectrum.



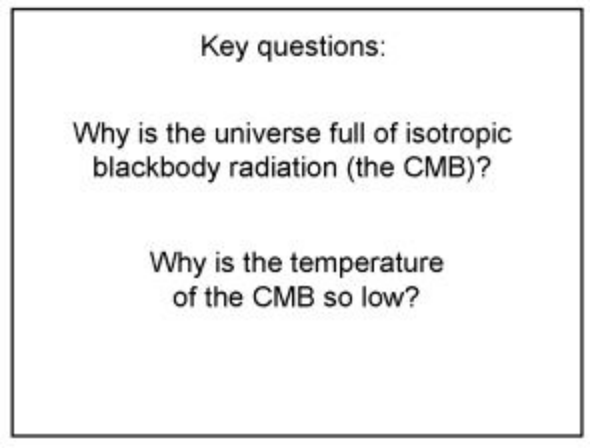
Flashback: blackbody spectra are produced by hot, dense, opaque objects.



Gosh! The universe (mostly transparent) is filled with nearly isotropic blackbody radiation (characteristic of opaque objects).



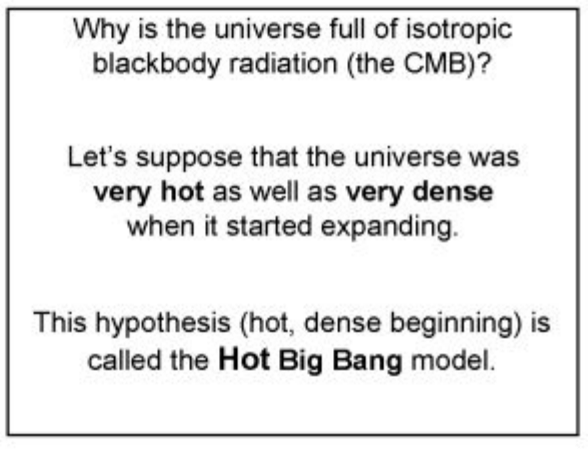
Double gosh! The temperature of the isotropic blackbody radiation is only **2.7 Kelvin**.



Key questions:

Why is the universe full of isotropic blackbody radiation (the CMB)?

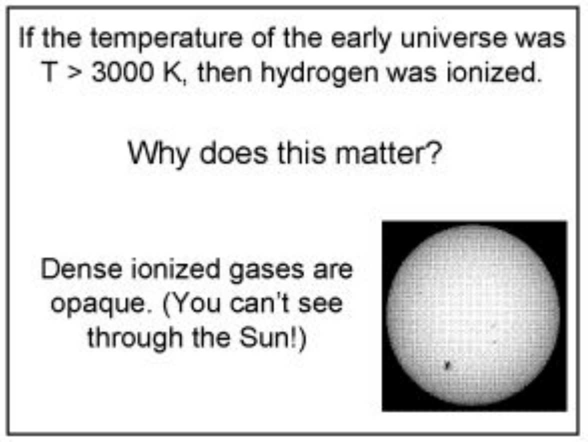
Why is the temperature of the CMB so low?



Why is the universe full of isotropic blackbody radiation (the CMB)?

Let's suppose that the universe was **very hot** as well as **very dense** when it started expanding.

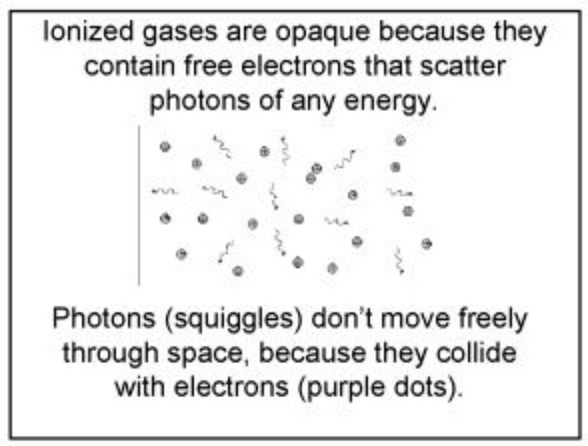
This hypothesis (hot, dense beginning) is called the **Hot Big Bang** model.



If the temperature of the early universe was T > 3000 K, then hydrogen was ionized.

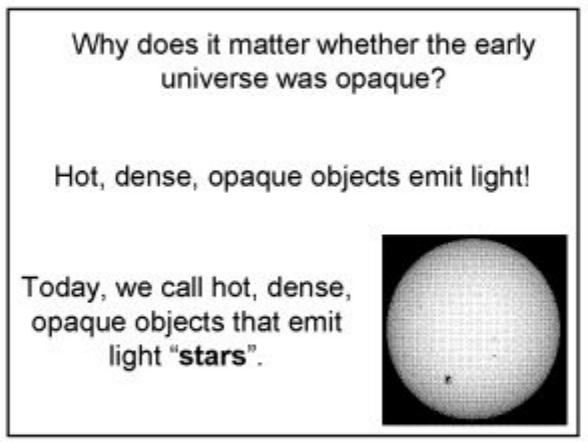
Why does this matter?

Dense ionized gases are opaque. (You can't see through the Sun!)



Ionized gases are opaque because they contain free electrons that scatter photons of any energy.

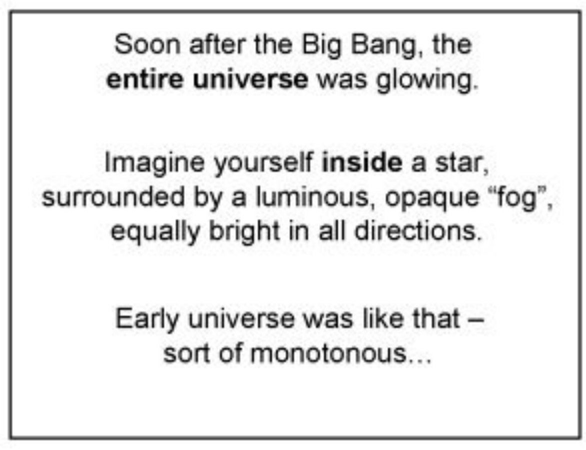
Photons (squiggles) don't move freely through space, because they collide with electrons (purple dots).



Why does it matter whether the early universe was opaque?

Hot, dense, opaque objects emit light!

Today, we call hot, dense, opaque objects that emit light "**stars**".



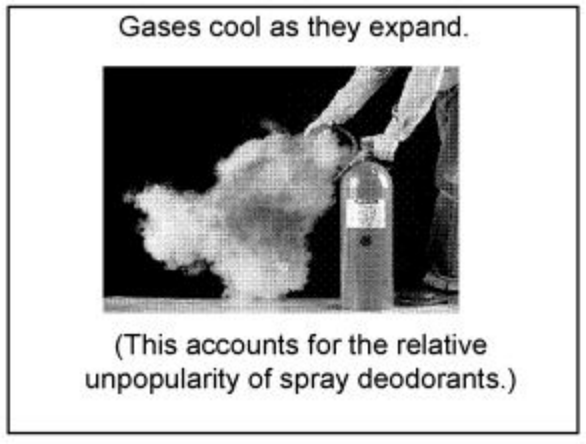
Soon after the Big Bang, the **entire universe** was glowing.

Imagine yourself **inside** a star, surrounded by a luminous, opaque "fog", equally bright in all directions.

Early universe was like that –
sort of monotonous…

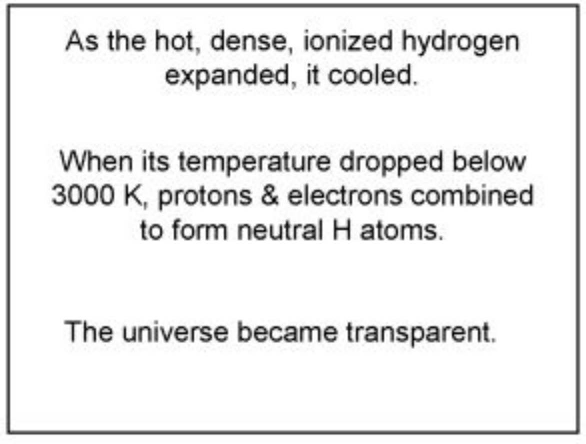
The universe is **NOT** opaque today. We can see galaxies billions of light-years away.

The universe is **NOT** uniformly glowing today. The night sky is dark, with a few glowing stars.



Gases cool as they expand.

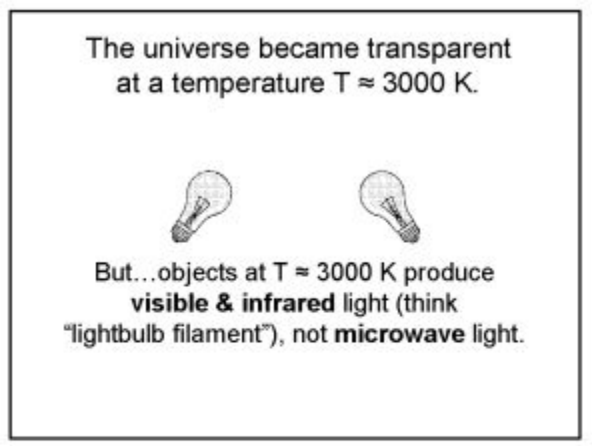
(This accounts for the relative unpopularity of spray deodorants.)



As the hot, dense, ionized hydrogen expanded, it cooled.

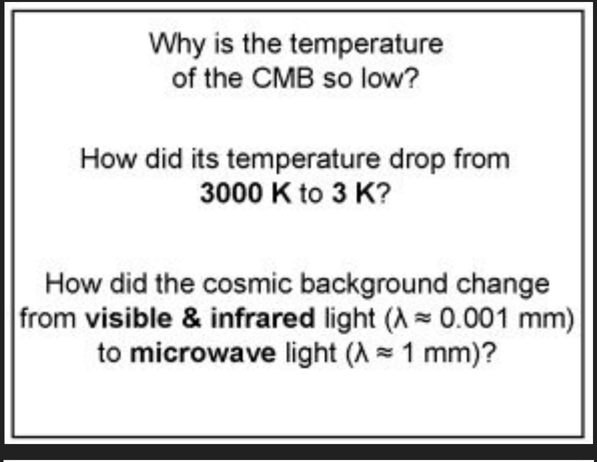
When its temperature dropped below 3000 K, protons & electrons combined to form neutral H atoms.

The universe became transparent.



The universe became transparent at a temperature T ≈ 3000 K.

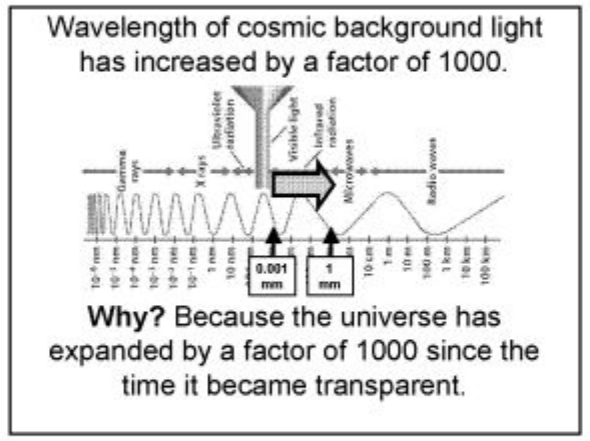
But…objects at T ≈ 3000 K produce **visible & infrared** light (think “lightbulb filament”), not **microwave** light.



Why is the temperature of the CMB so low?

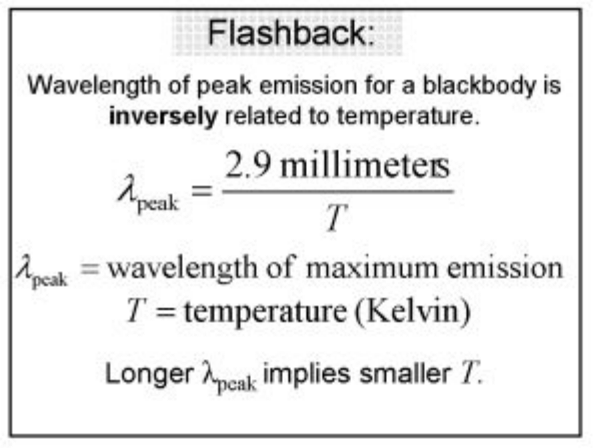
How did its temperature drop from **3000 K** to **3 K**?

How did the cosmic background change from **visible & infrared** light (λ ≈ 0.001 mm) to **microwave** light (λ ≈ 1 mm)?



Wavelength of cosmic background light has increased by a factor of 1000.

Why? Because the universe has expanded by a factor of 1000 since the time it became transparent.



Flashback:

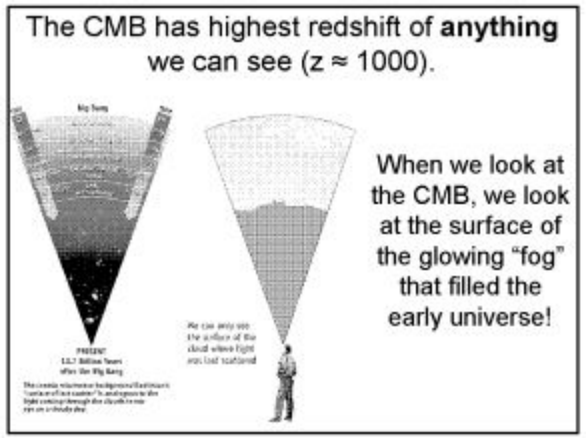
Wavelength of peak emission for a blackbody is **inversely** related to temperature.

$$\lambda_{\text{peak}} = \frac{2.9 \text{ millimeters}}{T}$$

λ_{peak} = wavelength of maximum emission

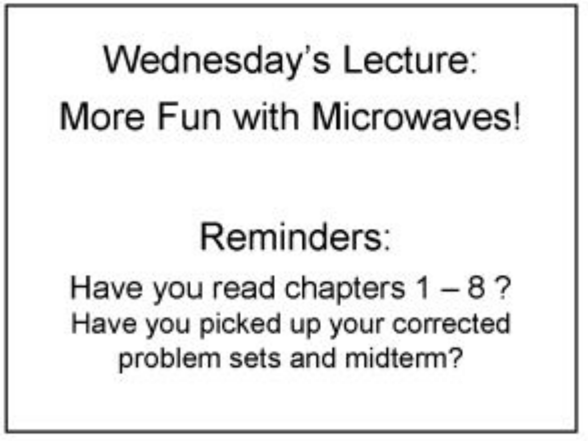
T = temperature (Kelvin)

Longer λ_{peak} implies smaller T.



The CMB has highest redshift of **anything** we can see (z ≈ 1000).

When we look at the CMB, we look at the surface of the glowing "fog" that filled the early universe!



Wednesday's Lecture:

More Fun with Microwaves!

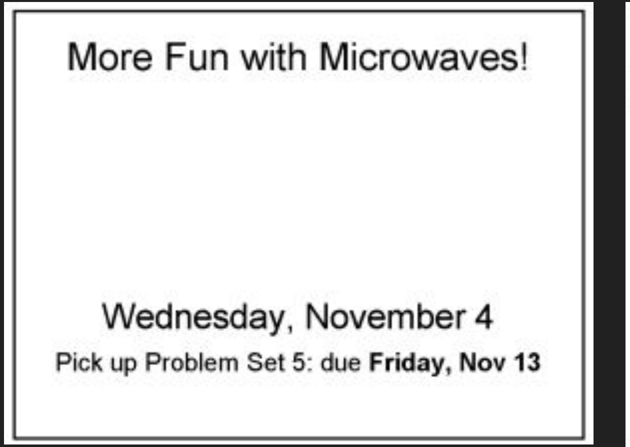
Reminders:

Have you read chapters 1 – 8 ?

Have you picked up your corrected problem sets and midterm?

Preparatory Reading Chapter 8

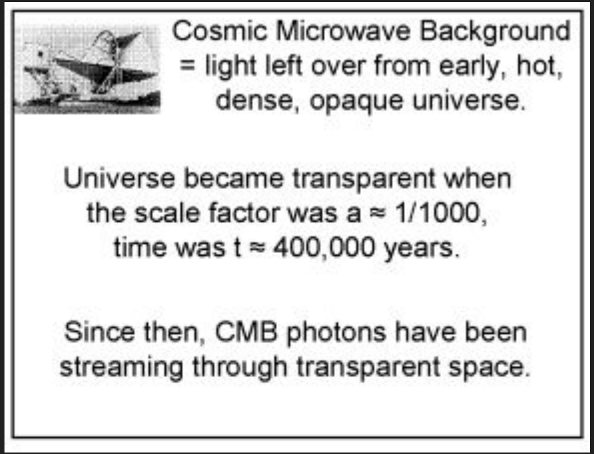
Week 7: More Fun With Microwaves



More Fun with Microwaves!

Wednesday, November 4

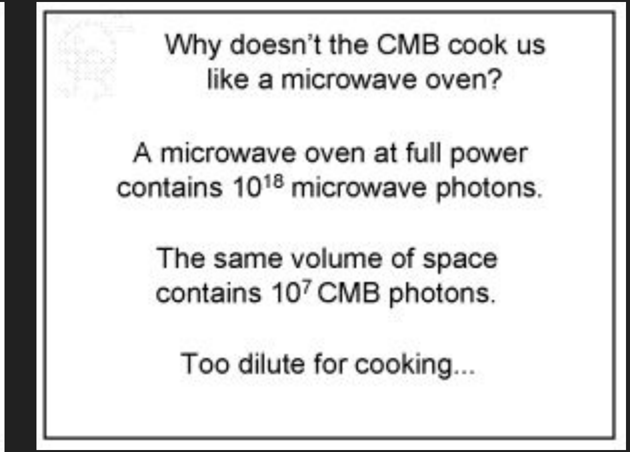
Pick up Problem Set 5: due **Friday, Nov 13**



Cosmic Microwave Background = light left over from early, hot, dense, opaque universe.

Universe became transparent when the scale factor was a ≈ 1/1000, time was t ≈ 400,000 years.

Since then, CMB photons have been streaming through transparent space.

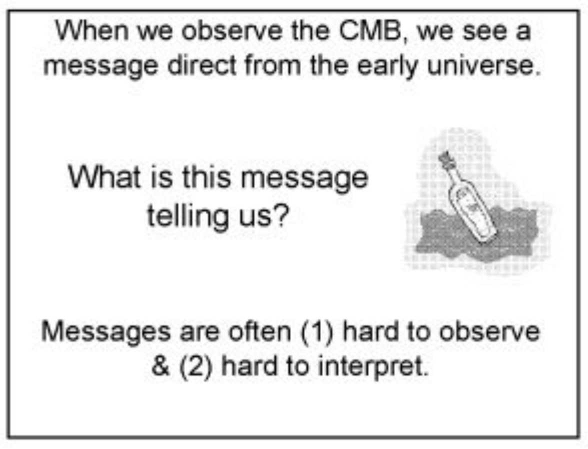


Why doesn't the CMB cook us like a microwave oven?

A microwave oven at full power contains 10^{18} microwave photons.

The same volume of space contains 10^{7} CMB photons.

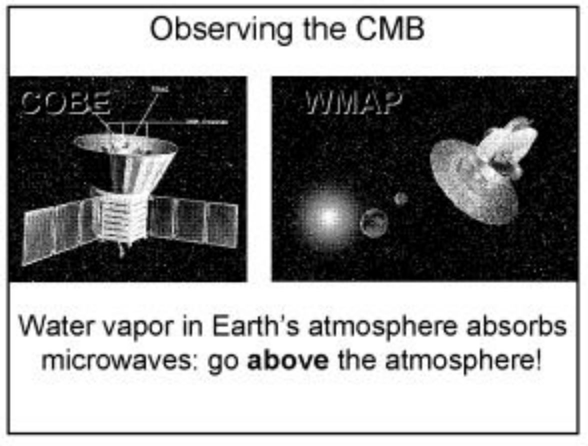
Too dilute for cooking...



When we observe the CMB, we see a message direct from the early universe.

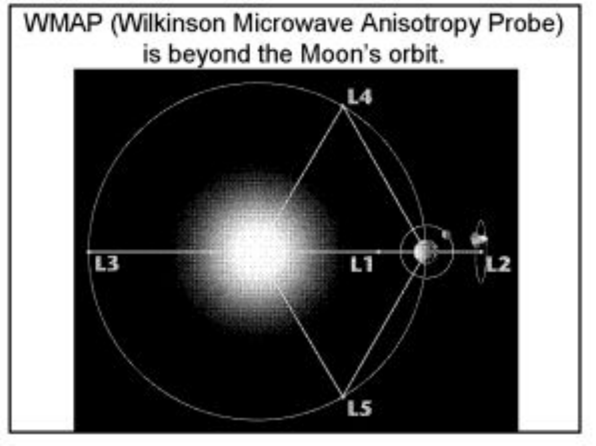
What is this message telling us?

Messages are often (1) hard to observe & (2) hard to interpret.

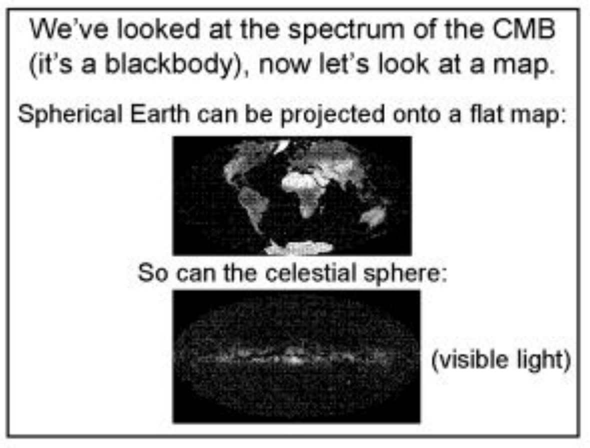


Observing the CMB

Water vapor in Earth's atmosphere absorbs microwaves: go **above** the atmosphere!



WMAP (Wilkinson Microwave Anisotropy Probe) is beyond the Moon's orbit.

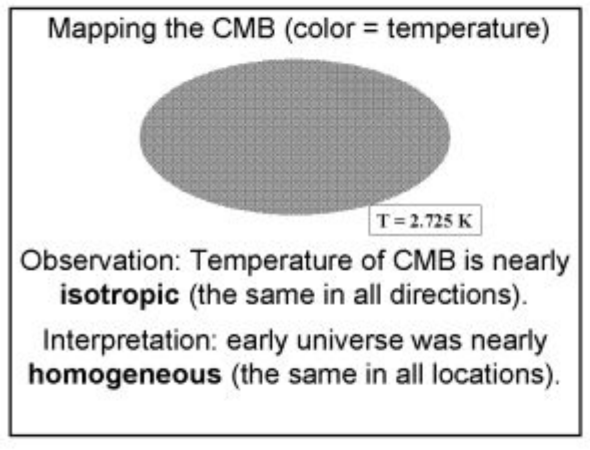


We've looked at the spectrum of the CMB (it's a blackbody), now let's look at a map.

Spherical Earth can be projected onto a flat map:

So can the celestial sphere:

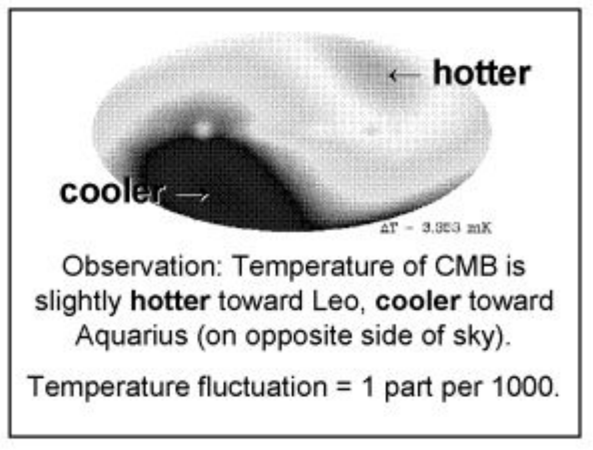
(visible light)



Mapping the CMB (color = temperature)

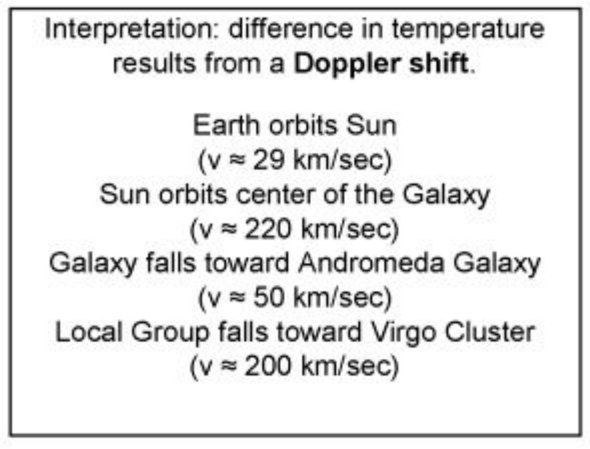
Observation: Temperature of CMB is nearly **isotropic** (the same in all directions).

Interpretation: early universe was nearly **homogeneous** (the same in all locations).



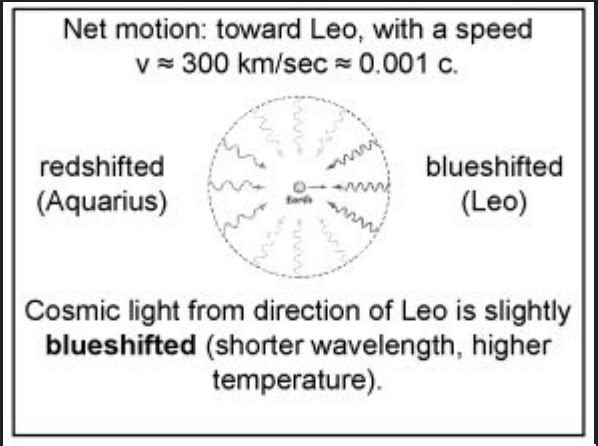
Observation: Temperature of CMB is slightly **hotter** toward Leo, **cooler** toward Aquarius (on opposite side of sky).

Temperature fluctuation = 1 part per 1000.



Interpretation: difference in temperature results from a **Doppler shift**.

Earth orbits Sun
(v ≈ 29 km/sec)
Sun orbits center of the Galaxy
(v ≈ 220 km/sec)
Galaxy falls toward Andromeda Galaxy
(v ≈ 50 km/sec)
Local Group falls toward Virgo Cluster
(v ≈ 200 km/sec)

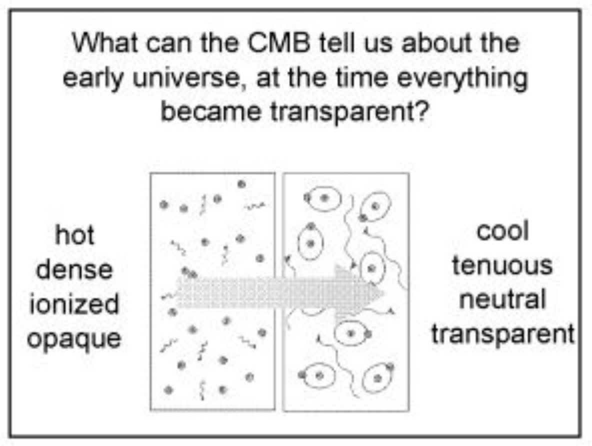


Net motion: toward Leo, with a speed
v ≈ 300 km/sec ≈ 0.001 c.

redshifted
(Aquarius)

blueshifted
(Leo)

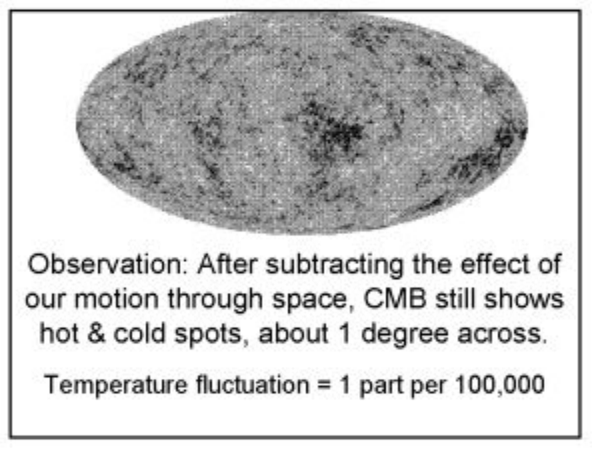
Cosmic light from direction of Leo is slightly **blueshifted** (shorter wavelength, higher temperature).



What can the CMB tell us about the early universe, at the time everything became transparent?

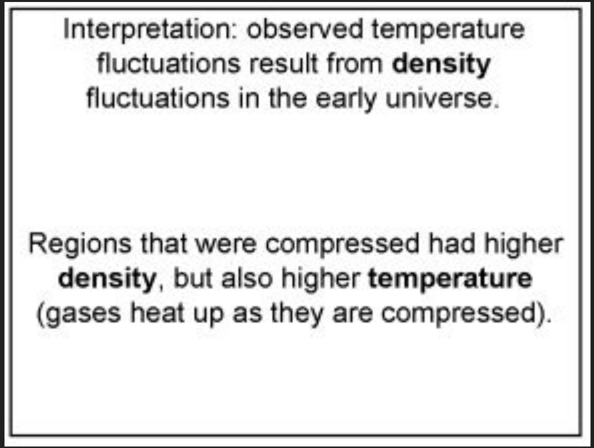
hot
dense
ionized
opaque

cool
tenuous
neutral
transparent



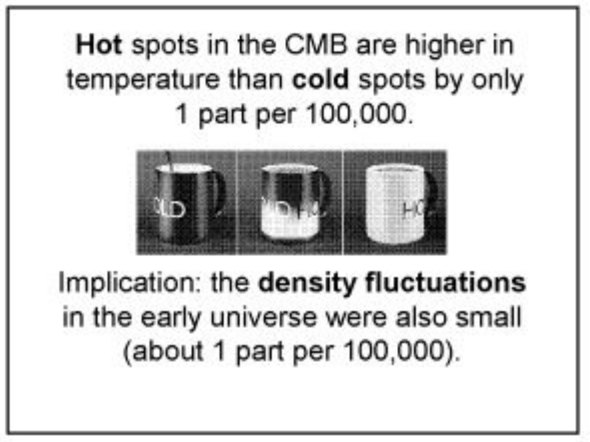
Observation: After subtracting the effect of our motion through space, CMB still shows hot & cold spots, about 1 degree across.

Temperature fluctuation = 1 part per 100,000



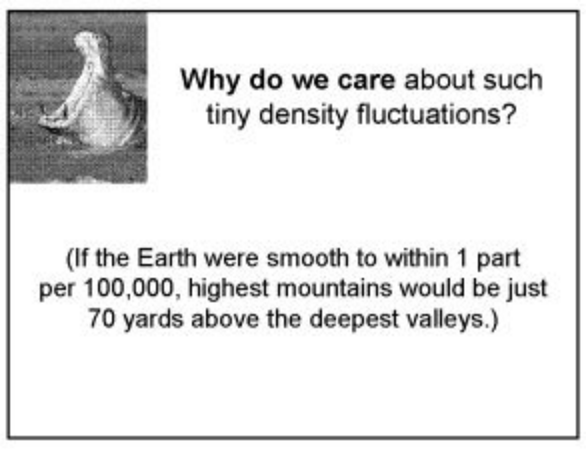
Interpretation: observed temperature fluctuations result from **density** fluctuations in the early universe.

Regions that were compressed had higher **density**, but also higher **temperature** (gases heat up as they are compressed).



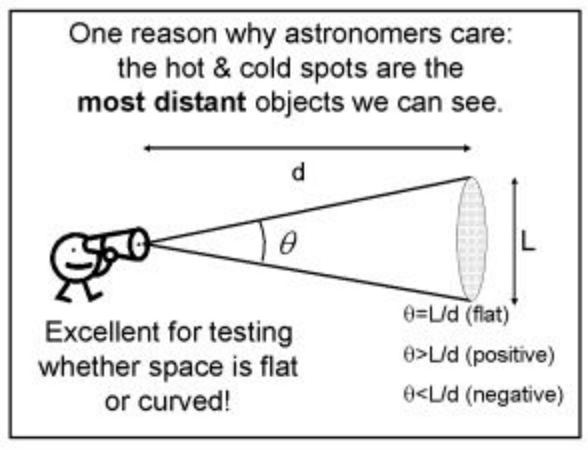
Hot spots in the CMB are higher in temperature than **cold** spots by only 1 part per 100,000.

Implication: the **density fluctuations** in the early universe were also small (about 1 part per 100,000).



Why do we care about such tiny density fluctuations?

(If the Earth were smooth to within 1 part per 100,000, highest mountains would be just 70 yards above the deepest valleys.)



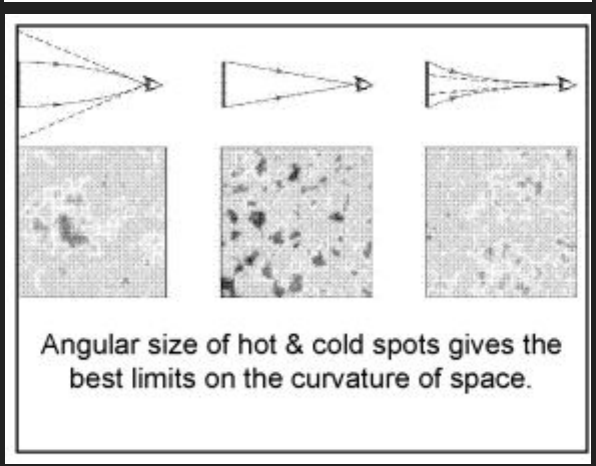
One reason why astronomers care: the hot & cold spots are the **most distant** objects we can see.

Excellent for testing whether space is flat or curved!

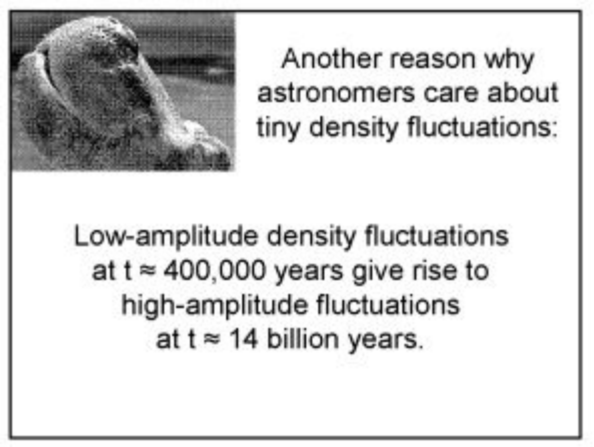
$\theta = L/d$ (flat)

$\theta > L/d$ (positive)

$\theta < L/d$ (negative)

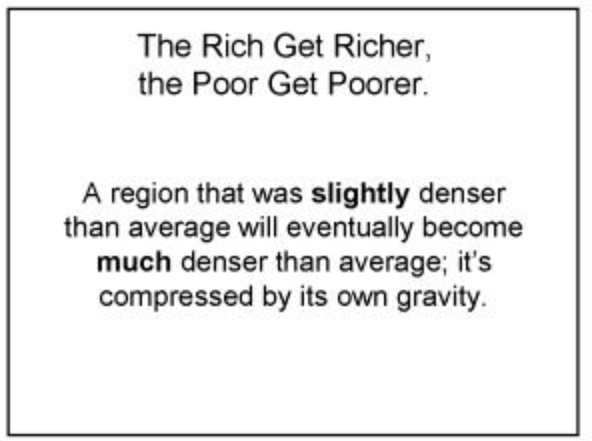


Angular size of hot & cold spots gives the best limits on the curvature of space.



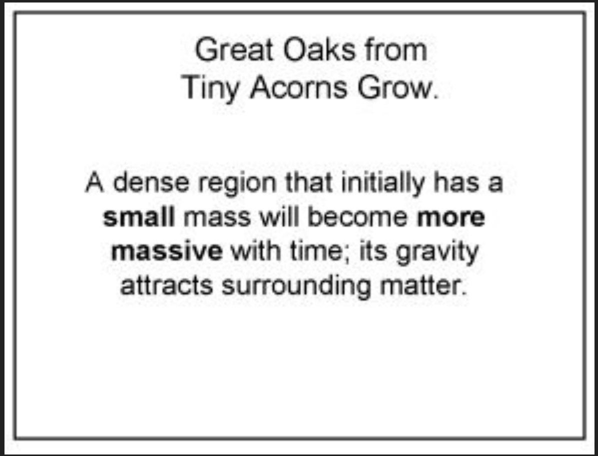
Another reason why astronomers care about tiny density fluctuations:

Low-amplitude density fluctuations at t ≈ 400,000 years give rise to high-amplitude fluctuations at t ≈ 14 billion years.



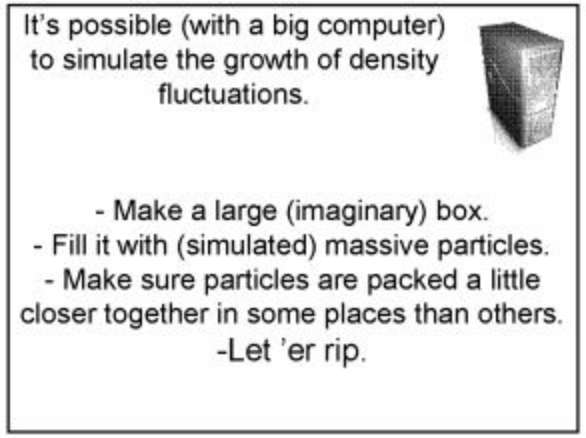
The Rich Get Richer,
the Poor Get Poorer.

A region that was **slightly** denser than average will eventually become **much** denser than average; it's compressed by its own gravity.



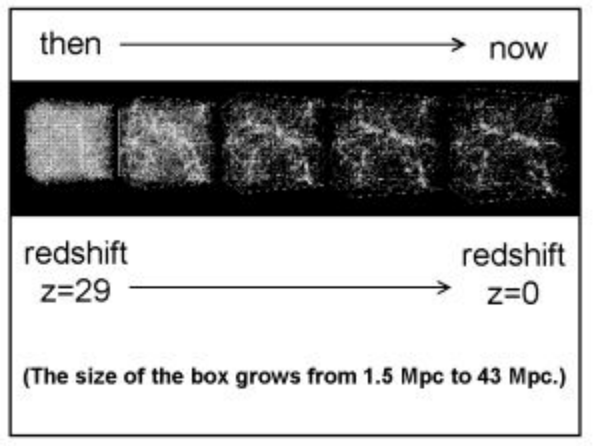
Great Oaks from
Tiny Acorns Grow.

A dense region that initially has a **small** mass will become **more massive** with time; its gravity attracts surrounding matter.



It's possible (with a big computer) to simulate the growth of density fluctuations.

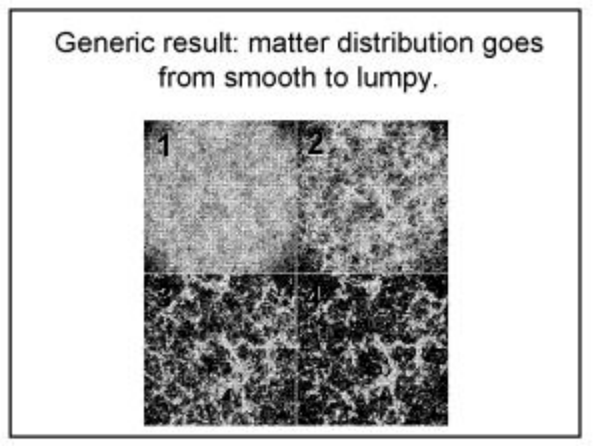
- Make a large (imaginary) box.
- Fill it with (simulated) massive particles.
- Make sure particles are packed a little closer together in some places than others.
-Let 'er rip.



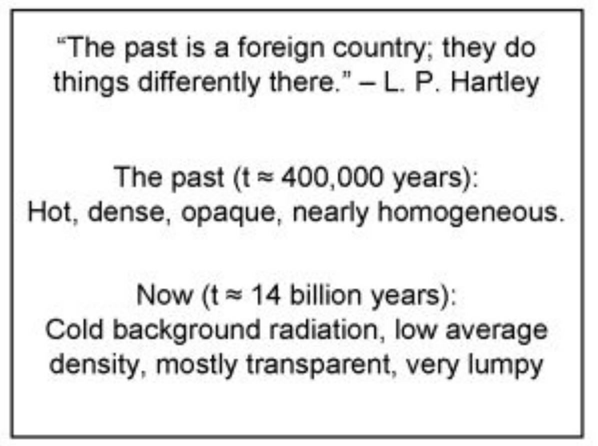
then → now

redshift z=29 → redshift z=0

(The size of the box grows from 1.5 Mpc to 43 Mpc.)



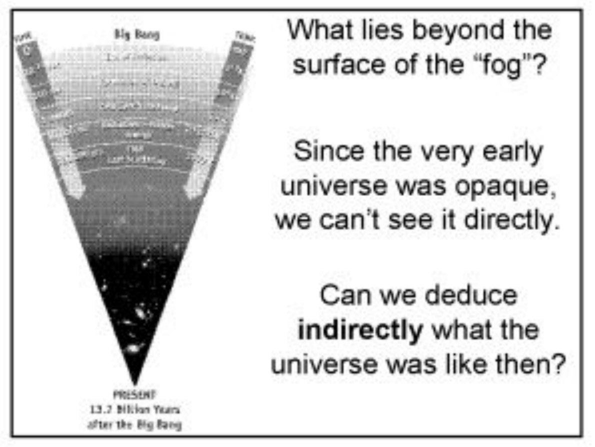
Generic result: matter distribution goes from smooth to lumpy.



“The past is a foreign country; they do things differently there.” – L. P. Hartley

The past (t ≈ 400,000 years):
Hot, dense, opaque, nearly homogeneous.

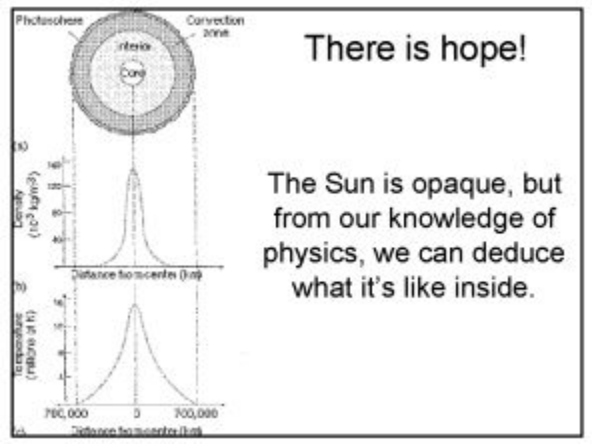
Now (t ≈ 14 billion years):
Cold background radiation, low average density, mostly transparent, very lumpy



What lies beyond the surface of the “fog”?

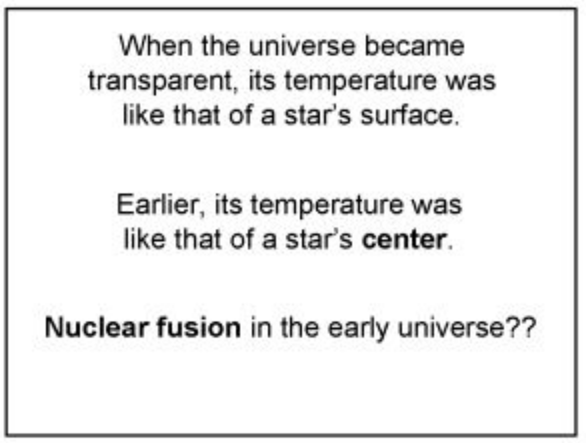
Since the very early universe was opaque, we can’t see it directly.

Can we deduce **indirectly** what the universe was like then?



There is hope!

The Sun is opaque, but from our knowledge of physics, we can deduce what it’s like inside.



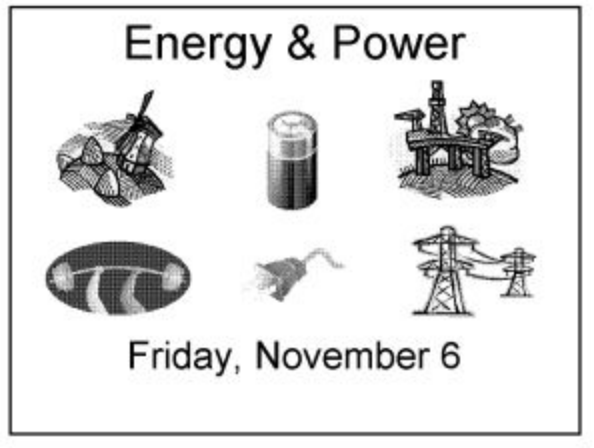
When the universe became
transparent, its temperature was
like that of a star's surface.

Earlier, its temperature was
like that of a star's **center**.

Nuclear fusion in the early universe??

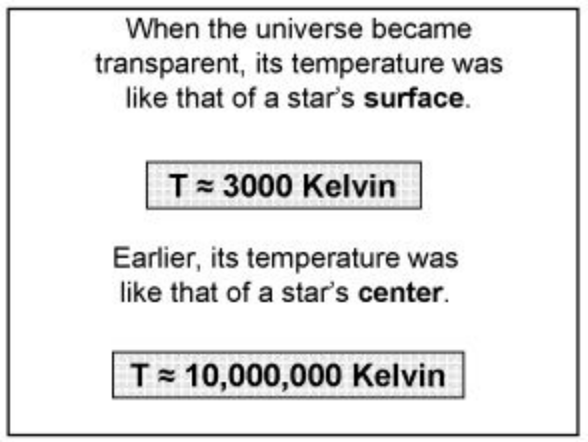
Preparatory Reading Chapter 8

Week 7: Energy & Power



Energy & Power

Friday, November 6

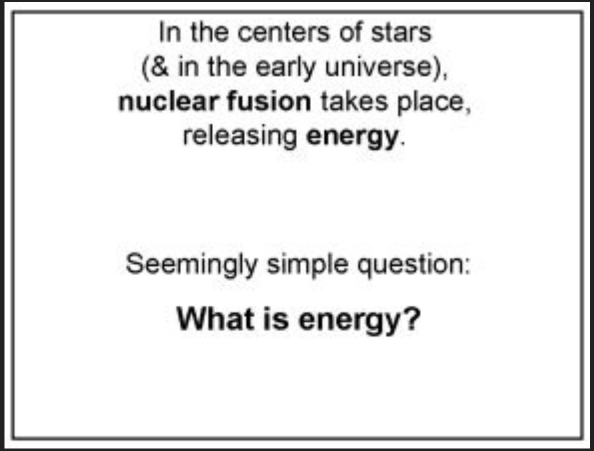


When the universe became transparent, its temperature was like that of a star's **surface**.

T ≈ 3000 Kelvin

Earlier, its temperature was like that of a star's **center**.

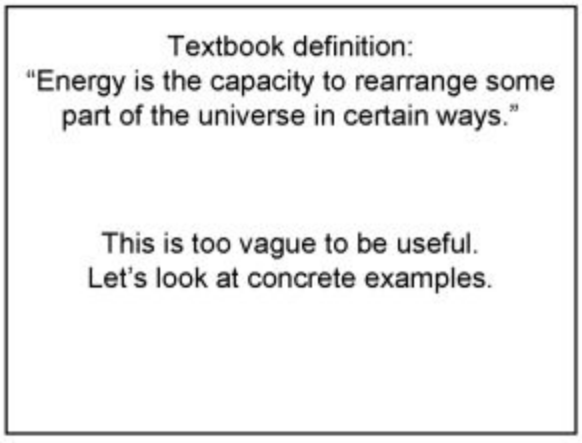
T ≈ 10,000,000 Kelvin



In the centers of stars (& in the early universe), **nuclear fusion** takes place, releasing **energy**.

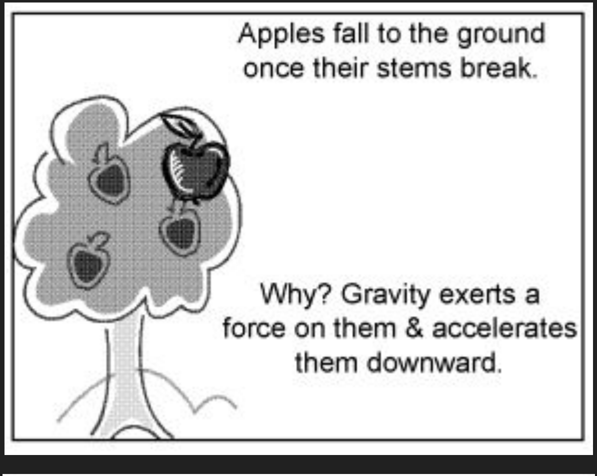
Seemingly simple question:

What is energy?



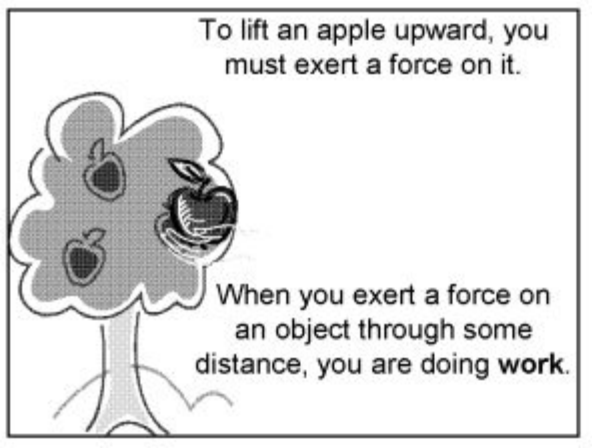
Textbook definition:
“Energy is the capacity to rearrange some part of the universe in certain ways.”

This is too vague to be useful.
Let’s look at concrete examples.



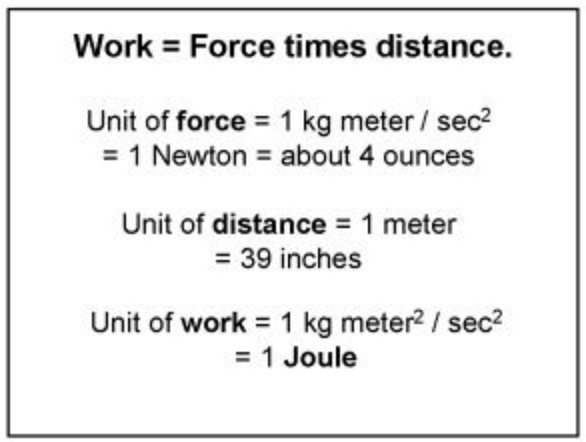
Apples fall to the ground once their stems break.

Why? Gravity exerts a force on them & accelerates them downward.



To lift an apple upward, you must exert a force on it.

When you exert a force on an object through some distance, you are doing **work**.

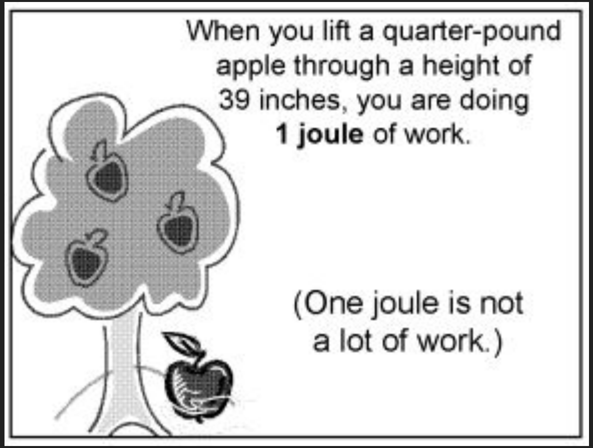


Work = Force times distance.

Unit of **force** = 1 kg meter / sec^2
= 1 Newton = about 4 ounces

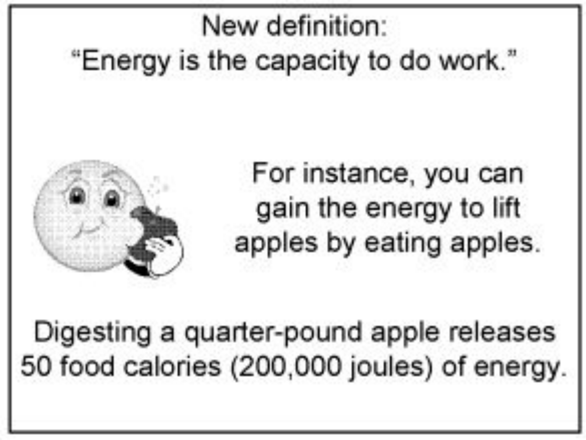
Unit of **distance** = 1 meter
= 39 inches

Unit of **work** = 1 kg meter^2 / sec^2
= 1 **Joule**



When you lift a quarter-pound apple through a height of 39 inches, you are doing **1 joule** of work.

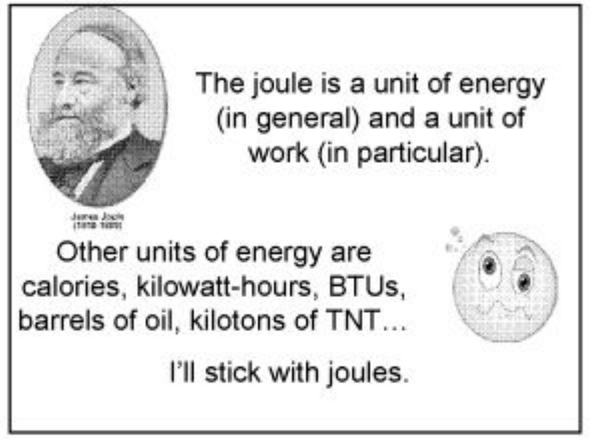
(One joule is not a lot of work.)



New definition:
“Energy is the capacity to do work.”

For instance, you can gain the energy to lift apples by eating apples.

Digesting a quarter-pound apple releases 50 food calories (200,000 joules) of energy.

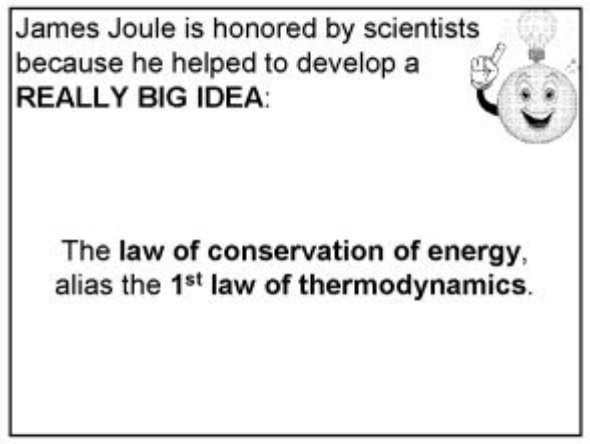


James Joule

The joule is a unit of energy (in general) and a unit of work (in particular).

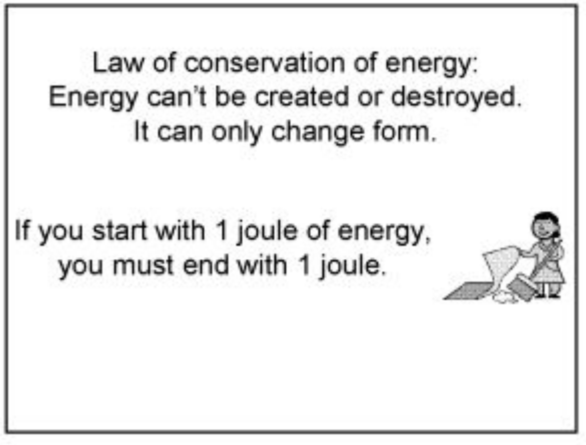
Other units of energy are calories, kilowatt-hours, BTUs, barrels of oil, kilotons of TNT…

I'll stick with joules.



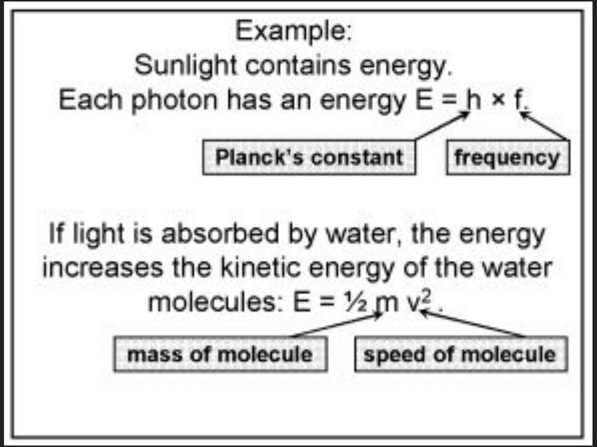
James Joule is honored by scientists because he helped to develop a **REALLY BIG IDEA**:

The **law of conservation of energy**, alias the **1st law of thermodynamics**.



Law of conservation of energy:
Energy can't be created or destroyed.
It can only change form.

If you start with 1 joule of energy, you must end with 1 joule.



Example:

Sunlight contains energy.

Each photon has an energy $E = h \times f$.

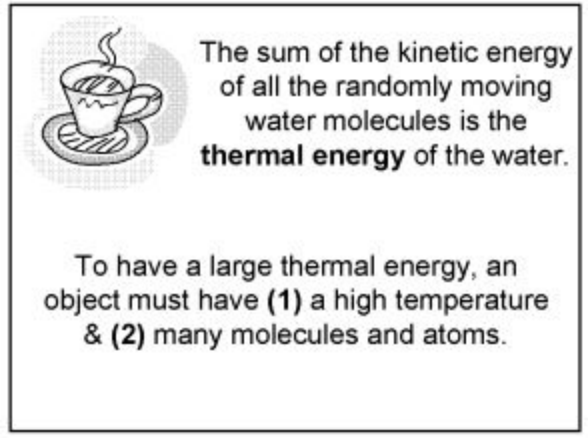
Planck's constant

frequency

If light is absorbed by water, the energy increases the kinetic energy of the water molecules: $E = \frac{1}{2} m v^2$.

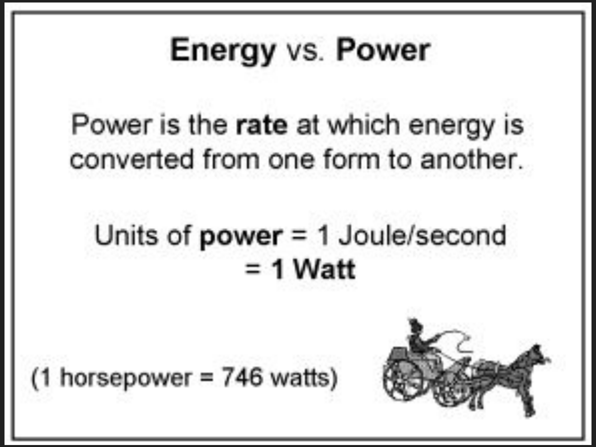
mass of molecule

speed of molecule



The sum of the kinetic energy of all the randomly moving water molecules is the **thermal energy** of the water.

To have a large thermal energy, an object must have **(1)** a high temperature & **(2)** many molecules and atoms.

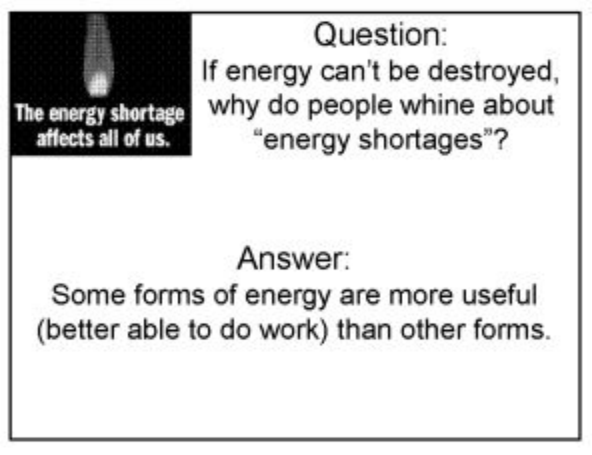


Energy vs. **Power**

Power is the **rate** at which energy is converted from one form to another.

Units of **power** = 1 Joule/second
= **1 Watt**

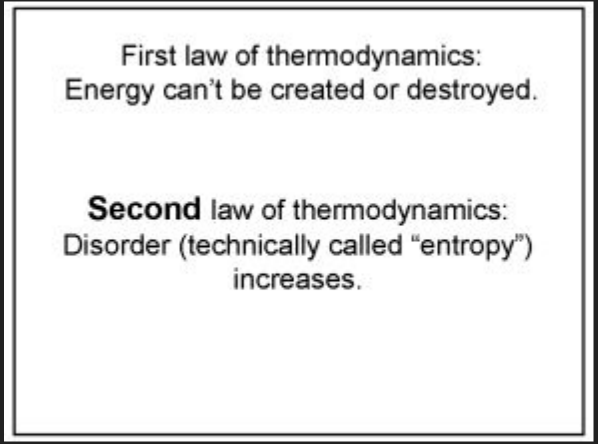
(1 horsepower = 746 watts)



The energy shortage affects all of us.

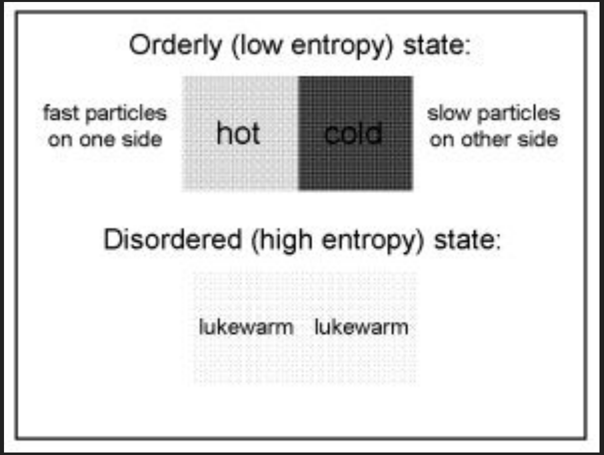
Question:
If energy can't be destroyed, why do people whine about "energy shortages"?

Answer:
Some forms of energy are more useful (better able to do work) than other forms.



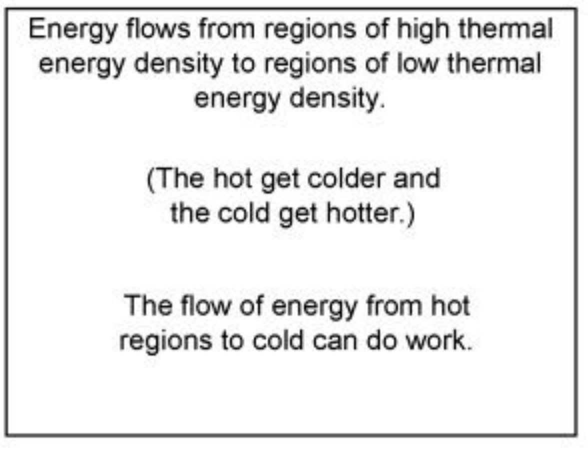
First law of thermodynamics:
Energy can't be created or destroyed.

Second law of thermodynamics:
Disorder (technically called "entropy") increases.



Orderly (low entropy) state:

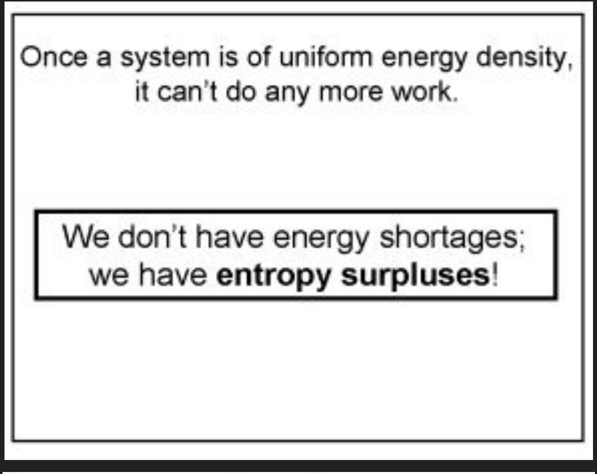
Disordered (high entropy) state:



Energy flows from regions of high thermal energy density to regions of low thermal energy density.

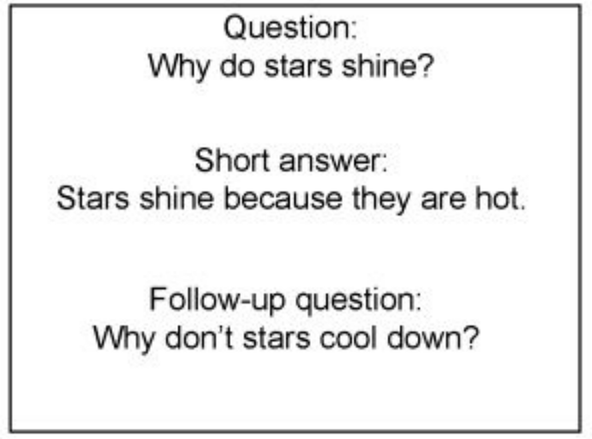
(The hot get colder and
the cold get hotter.)

The flow of energy from hot regions to cold can do work.



Once a system is of uniform energy density, it can't do any more work.

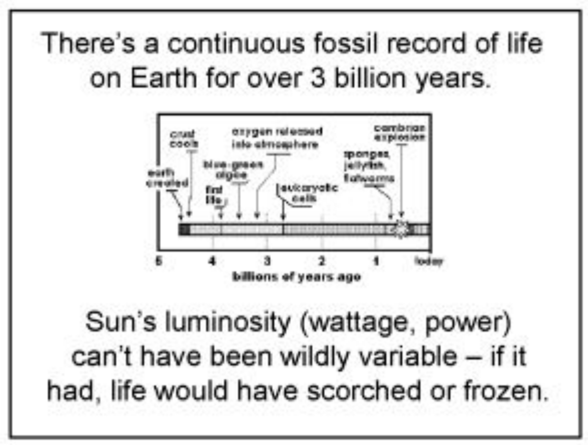
We don't have energy shortages;
we have **entropy surpluses**!



Question:
Why do stars shine?

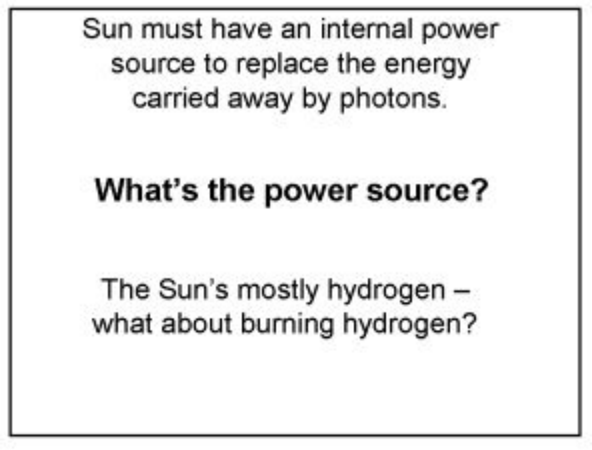
Short answer:
Stars shine because they are hot.

Follow-up question:
Why don't stars cool down?



There's a continuous fossil record of life on Earth for over 3 billion years.

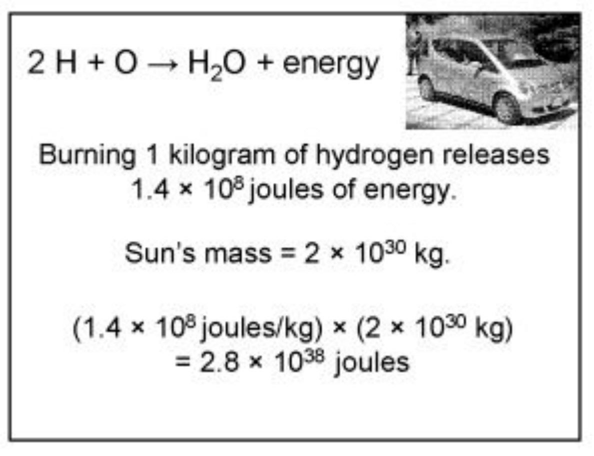
Sun's luminosity (wattage, power) can't have been wildly variable – if it had, life would have scorched or frozen.



Sun must have an internal power source to replace the energy carried away by photons.

What's the power source?

The Sun's mostly hydrogen – what about burning hydrogen?

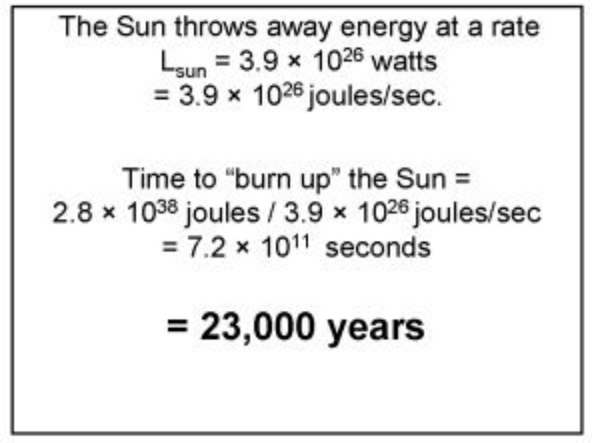


$2\,H + O \rightarrow H_2O$ + energy

Burning 1 kilogram of hydrogen releases 1.4×10^8 joules of energy.

Sun's mass = 2×10^{30} kg.

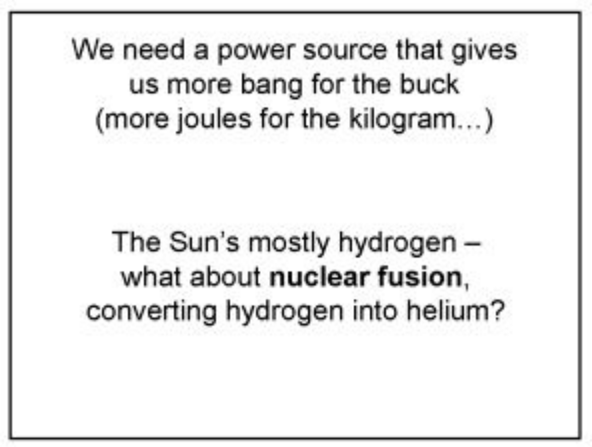
$(1.4 \times 10^8$ joules/kg$) \times (2 \times 10^{30}$ kg$)$
$= 2.8 \times 10^{38}$ joules



The Sun throws away energy at a rate
$L_{sun} = 3.9 \times 10^{26}$ watts
$= 3.9 \times 10^{26}$ joules/sec.

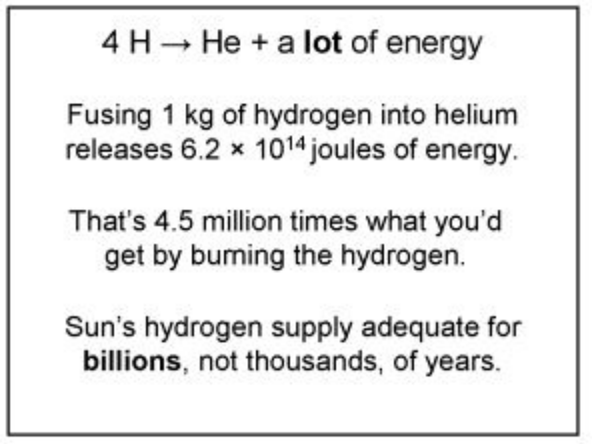
Time to "burn up" the Sun =
2.8×10^{38} joules / 3.9×10^{26} joules/sec
$= 7.2 \times 10^{11}$ seconds

= 23,000 years



We need a power source that gives
us more bang for the buck
(more joules for the kilogram…)

The Sun's mostly hydrogen –
what about **nuclear fusion**,
converting hydrogen into helium?

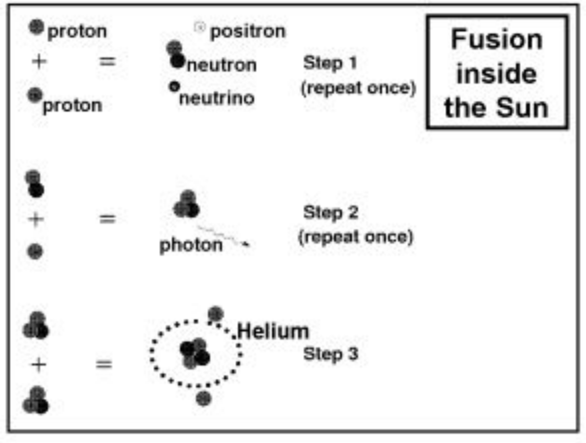


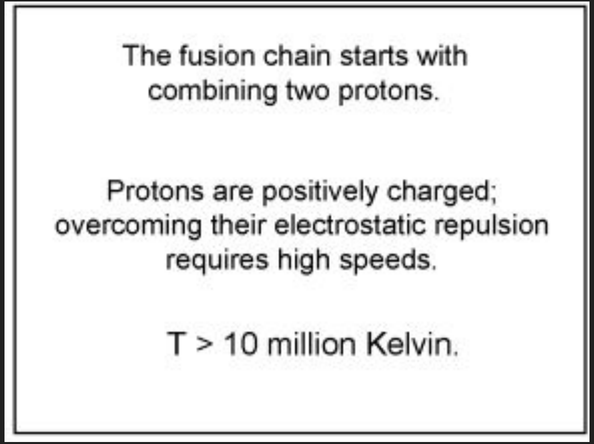
4 H → He + a **lot** of energy

Fusing 1 kg of hydrogen into helium
releases 6.2×10^{14} joules of energy.

That's 4.5 million times what you'd
get by burning the hydrogen.

Sun's hydrogen supply adequate for
billions, not thousands, of years.



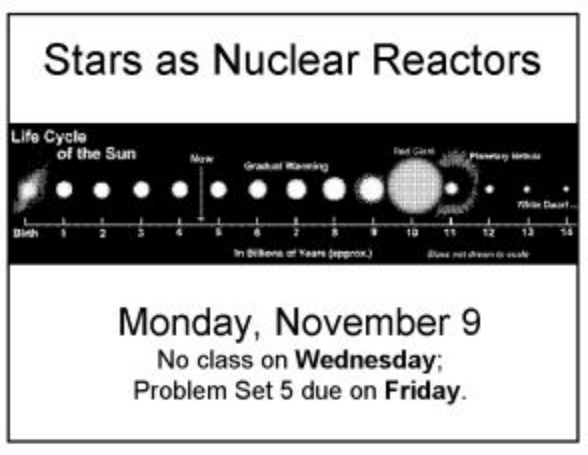

The fusion chain starts with combining two protons.

Protons are positively charged; overcoming their electrostatic repulsion requires high speeds.

T > 10 million Kelvin.

Preparatory Reading Chapter 9

Week 8: Stars as Nuclear Reactors

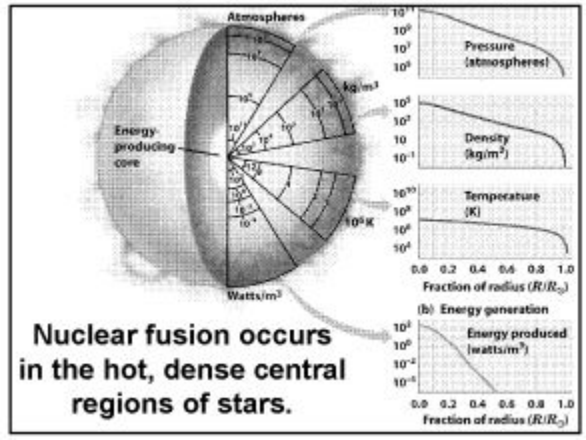


Stars as Nuclear Reactors

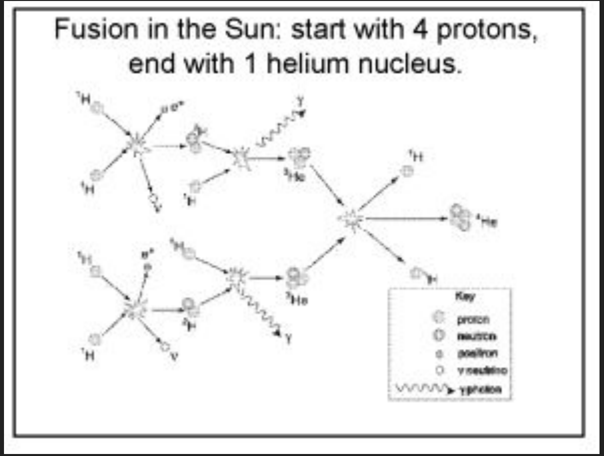
Monday, November 9

No class on **Wednesday**;

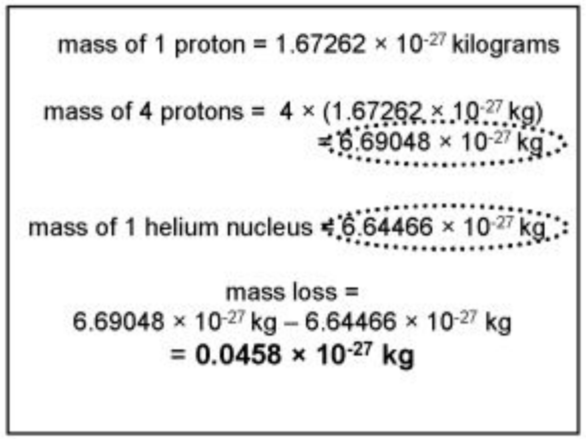
Problem Set 5 due on **Friday**.



Nuclear fusion occurs in the hot, dense central regions of stars.



Fusion in the Sun: start with 4 protons, end with 1 helium nucleus.

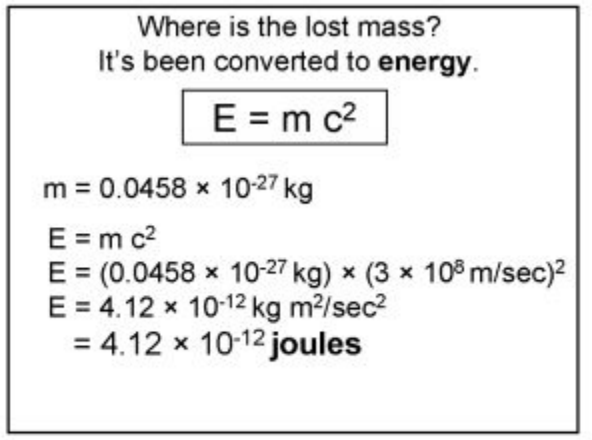


mass of 1 proton = 1.67262×10^{-27} kilograms

mass of 4 protons = $4 \times (1.67262 \times 10^{-27}\ \text{kg})$
$= 6.69048 \times 10^{-27}\ \text{kg}$

mass of 1 helium nucleus = $6.64466 \times 10^{-27}\ \text{kg}$

mass loss =
$6.69048 \times 10^{-27}\ \text{kg} - 6.64466 \times 10^{-27}\ \text{kg}$
$= 0.0458 \times 10^{-27}\ \text{kg}$

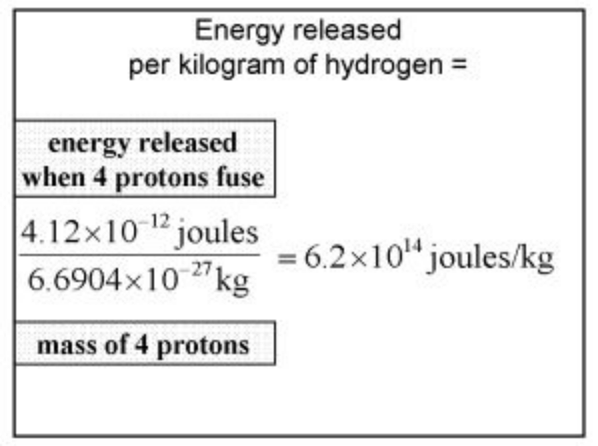


Where is the lost mass?
It's been converted to **energy**.

$$\boxed{E = m c^2}$$

$m = 0.0458 \times 10^{-27}\ \text{kg}$

$E = m c^2$
$E = (0.0458 \times 10^{-27}\ \text{kg}) \times (3 \times 10^8\ \text{m/sec})^2$
$E = 4.12 \times 10^{-12}\ \text{kg m}^2/\text{sec}^2$
$= 4.12 \times 10^{-12}$ **joules**

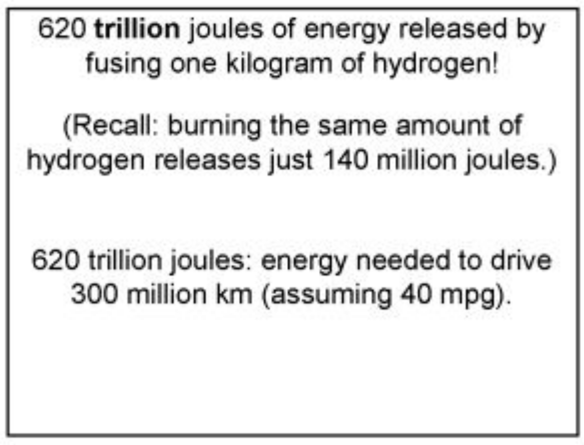


Energy released
per kilogram of hydrogen =

energy released when 4 protons fuse

$$\frac{4.12\times10^{-12}\text{ joules}}{6.6904\times10^{-27}\text{kg}} = 6.2\times10^{14}\text{ joules/kg}$$

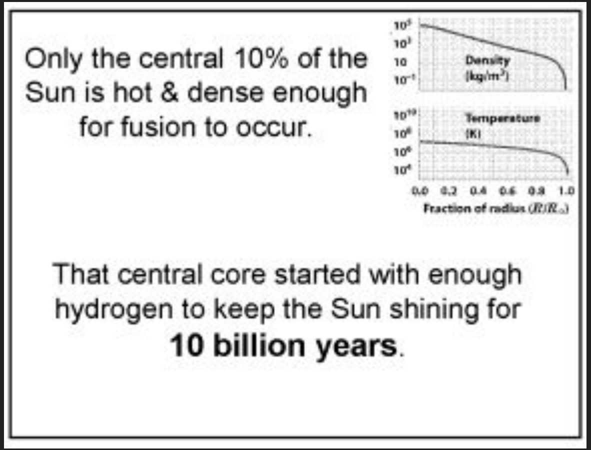
mass of 4 protons



620 **trillion** joules of energy released by fusing one kilogram of hydrogen!

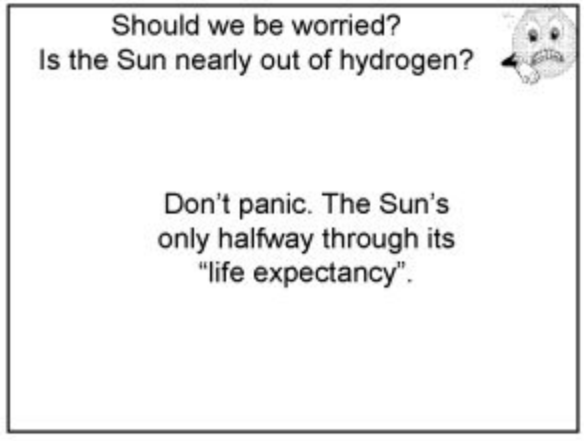
(Recall: burning the same amount of hydrogen releases just 140 million joules.)

620 trillion joules: energy needed to drive 300 million km (assuming 40 mpg).



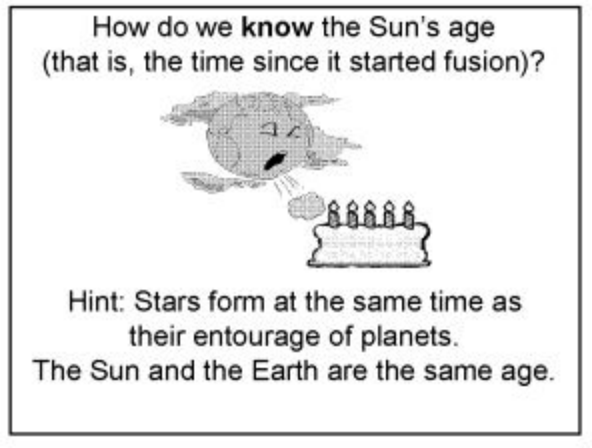
Only the central 10% of the Sun is hot & dense enough for fusion to occur.

That central core started with enough hydrogen to keep the Sun shining for **10 billion years**.



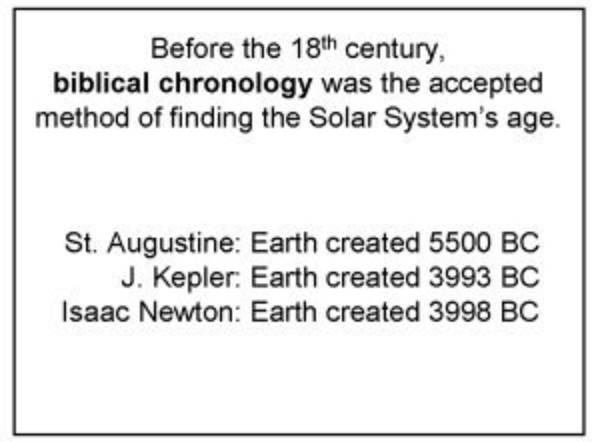
Should we be worried?
Is the Sun nearly out of hydrogen?

Don't panic. The Sun's only halfway through its "life expectancy".



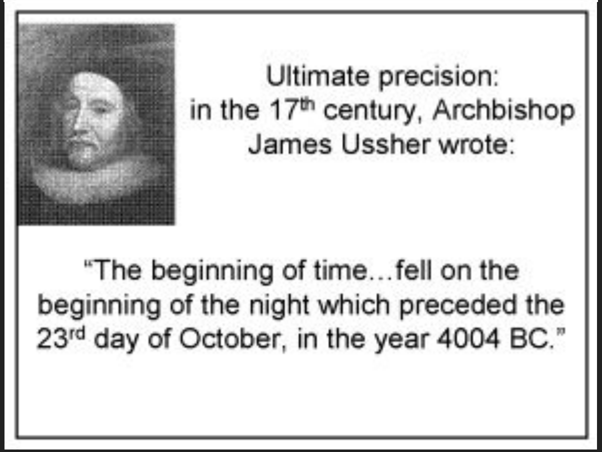
How do we **know** the Sun's age
(that is, the time since it started fusion)?

Hint: Stars form at the same time as
their entourage of planets.
The Sun and the Earth are the same age.



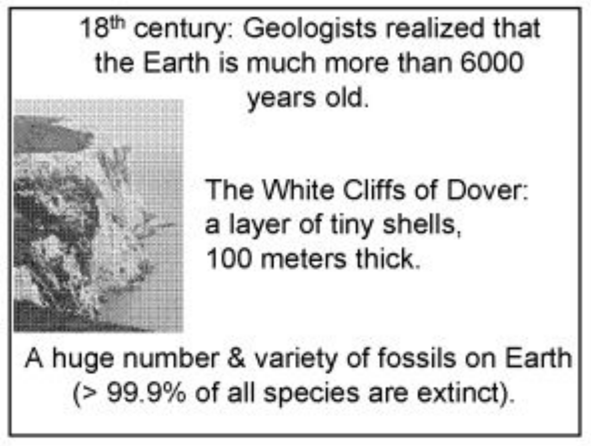
Before the 18th century,
biblical chronology was the accepted
method of finding the Solar System's age.

St. Augustine: Earth created 5500 BC
J. Kepler: Earth created 3993 BC
Isaac Newton: Earth created 3998 BC



Ultimate precision:
in the 17th century, Archbishop
James Ussher wrote:

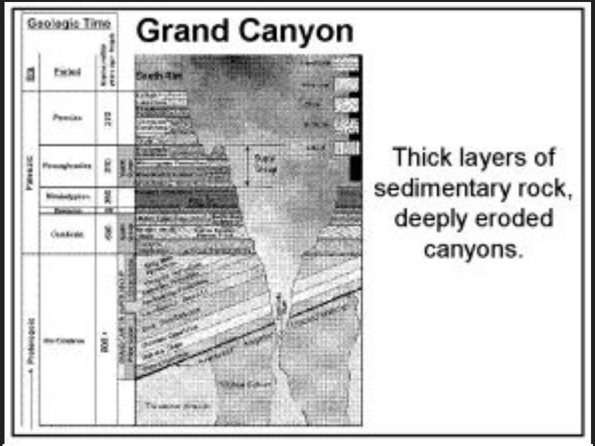
"The beginning of time…fell on the
beginning of the night which preceded the
23rd day of October, in the year 4004 BC."



18th century: Geologists realized that the Earth is much more than 6000 years old.

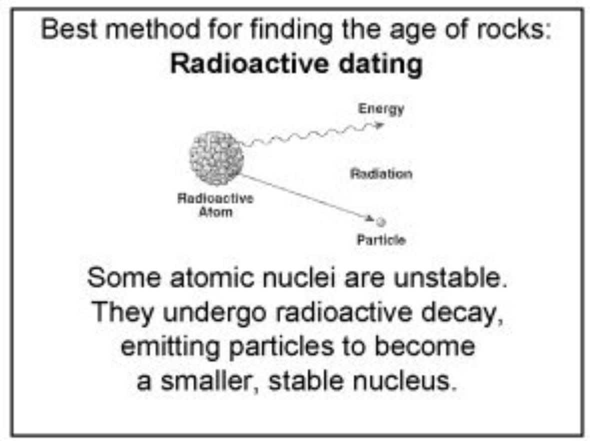
The White Cliffs of Dover:
a layer of tiny shells,
100 meters thick.

A huge number & variety of fossils on Earth (> 99.9% of all species are extinct).



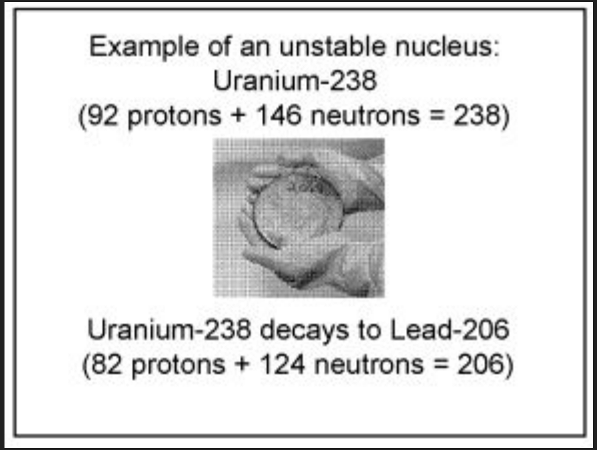
Grand Canyon

Thick layers of sedimentary rock, deeply eroded canyons.



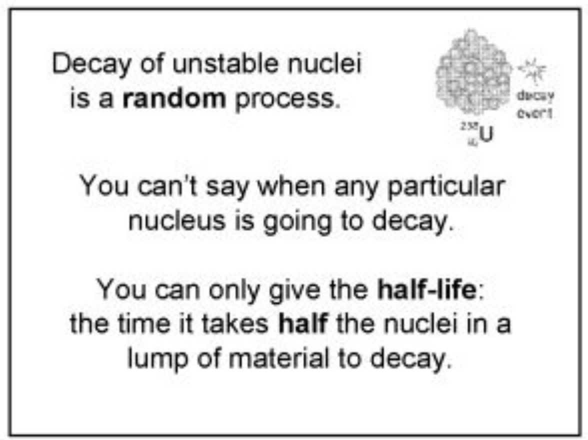
Best method for finding the age of rocks:
Radioactive dating

Some atomic nuclei are unstable. They undergo radioactive decay, emitting particles to become a smaller, stable nucleus.



Example of an unstable nucleus:
Uranium-238
(92 protons + 146 neutrons = 238)

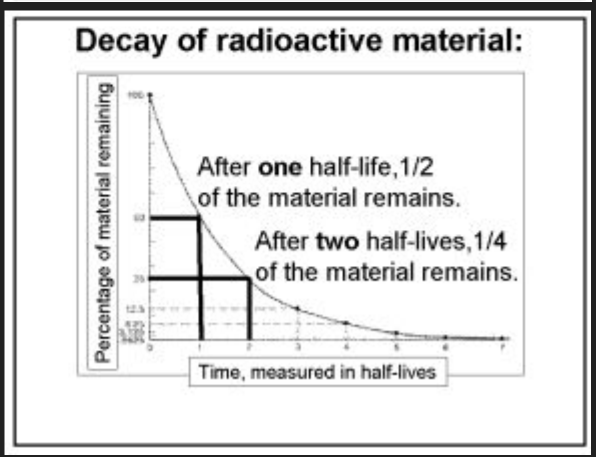
Uranium-238 decays to Lead-206
(82 protons + 124 neutrons = 206)



Decay of unstable nuclei
is a **random** process.

You can't say when any particular nucleus is going to decay.

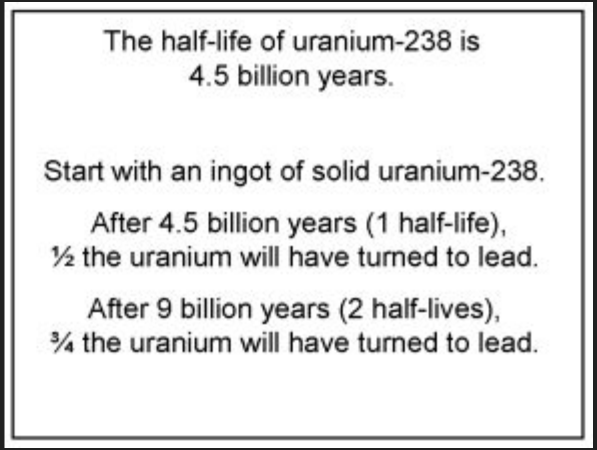
You can only give the **half-life**:
the time it takes **half** the nuclei in a lump of material to decay.



Decay of radioactive material:

After **one** half-life,1/2
of the material remains.

After **two** half-lives,1/4
of the material remains.

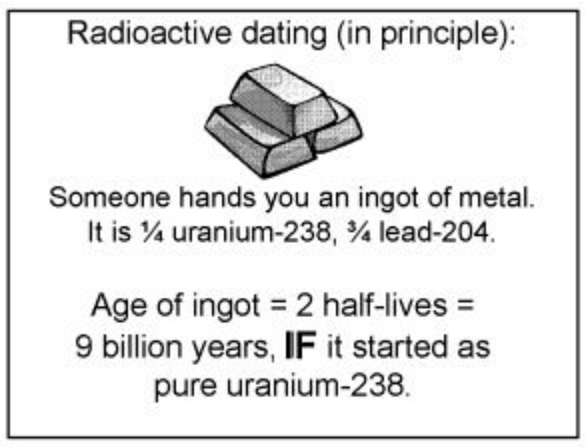


The half-life of uranium-238 is
4.5 billion years.

Start with an ingot of solid uranium-238.

After 4.5 billion years (1 half-life),
½ the uranium will have turned to lead.

After 9 billion years (2 half-lives),
¾ the uranium will have turned to lead.



Radioactive dating (in principle):

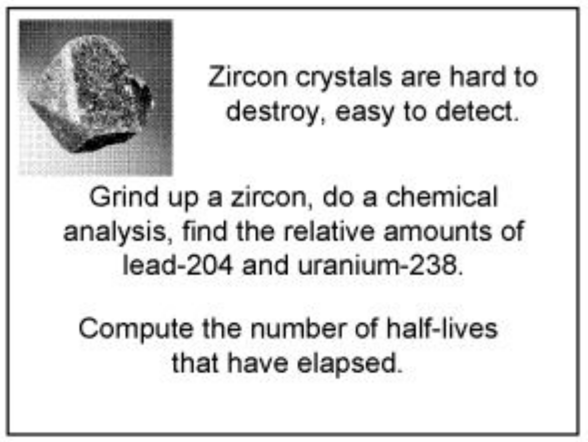
Someone hands you an ingot of metal.
It is ¼ uranium-238, ¾ lead-204.

Age of ingot = 2 half-lives =
9 billion years, **IF** it started as
pure uranium-238.

When it comes to radioactive dating,
zircons are a geologist's best friend.

Zircon = zirconium
silicate, with various
impurities

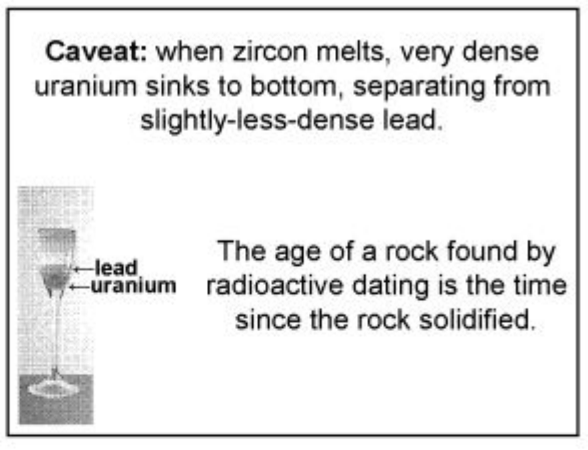
Newly formed zircon crystals are
frequently contaminated with uranium,
never with lead.



Zircon crystals are hard to destroy, easy to detect.

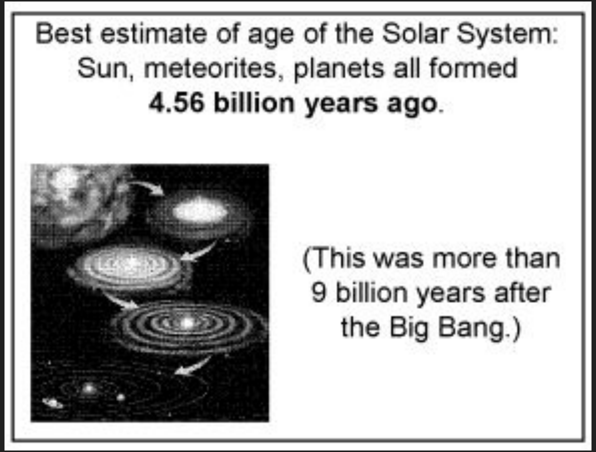
Grind up a zircon, do a chemical analysis, find the relative amounts of lead-204 and uranium-238.

Compute the number of half-lives that have elapsed.



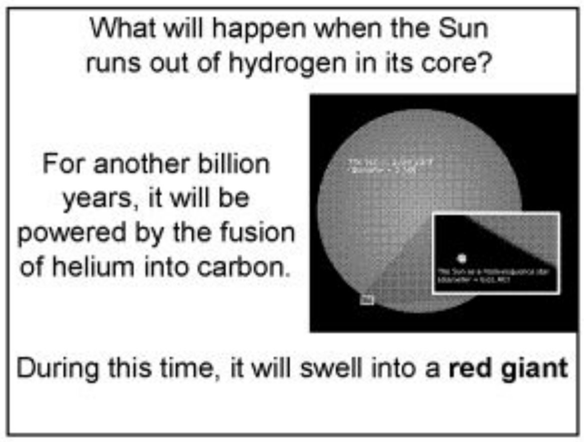
Caveat: when zircon melts, very dense uranium sinks to bottom, separating from slightly-less-dense lead.

The age of a rock found by radioactive dating is the time since the rock solidified.



Best estimate of age of the Solar System: Sun, meteorites, planets all formed **4.56 billion years ago**.

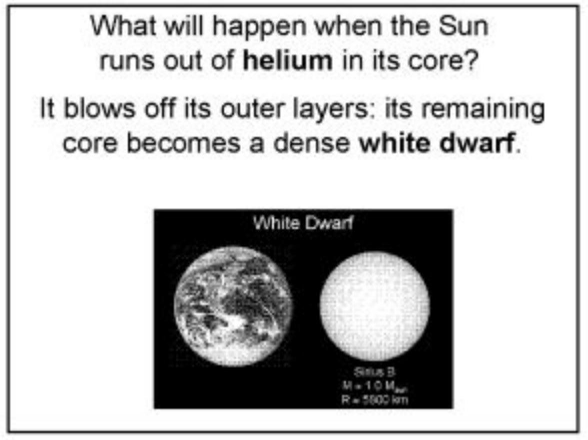
(This was more than 9 billion years after the Big Bang.)



What will happen when the Sun runs out of hydrogen in its core?

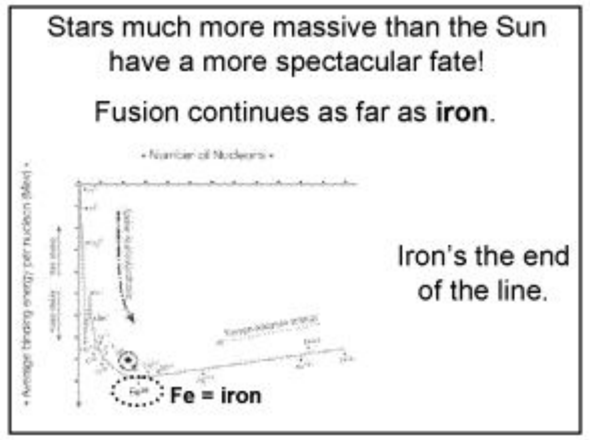
For another billion years, it will be powered by the fusion of helium into carbon.

During this time, it will swell into a **red giant**



What will happen when the Sun runs out of **helium** in its core?

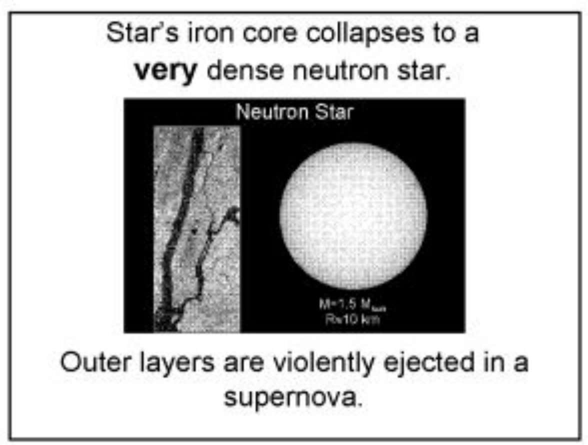
It blows off its outer layers: its remaining core becomes a dense **white dwarf**.



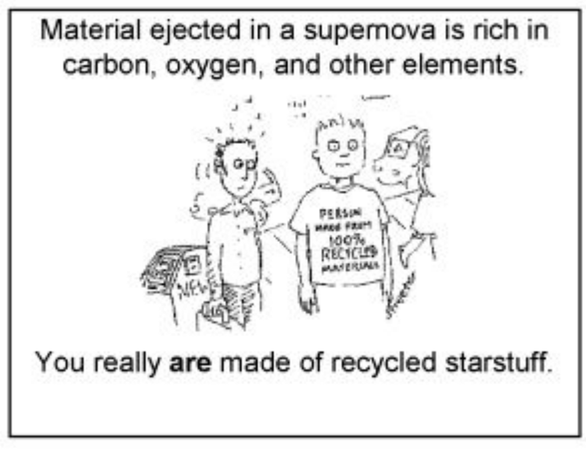
Stars much more massive than the Sun have a more spectacular fate!

Fusion continues as far as **iron**.

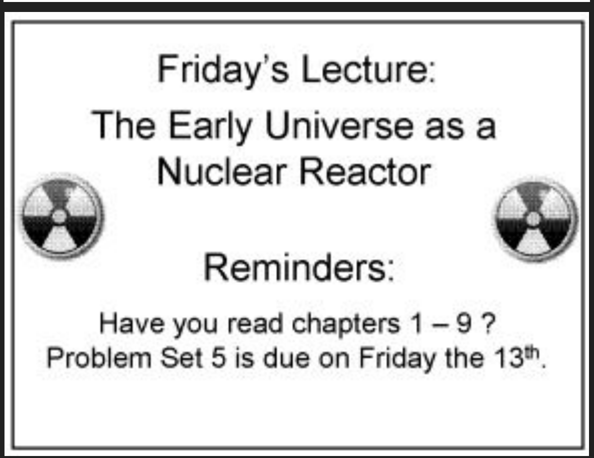
Iron's the end of the line.


Star’s iron core collapses to a **very** dense neutron star.

Outer layers are violently ejected in a supernova.


Material ejected in a supernova is rich in carbon, oxygen, and other elements.

You really **are** made of recycled starstuff.


Friday’s Lecture:

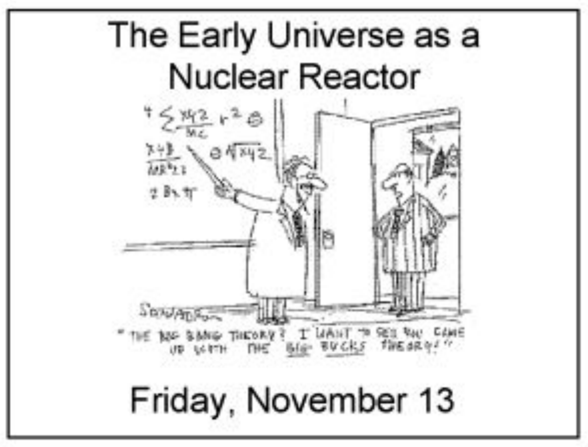
The Early Universe as a Nuclear Reactor

Reminders:

Have you read chapters 1 – 9 ?
Problem Set 5 is due on Friday the 13th.

Preparatory Reading Chapter 9

Week 8: The Early Universe as a Nuclear Reactor



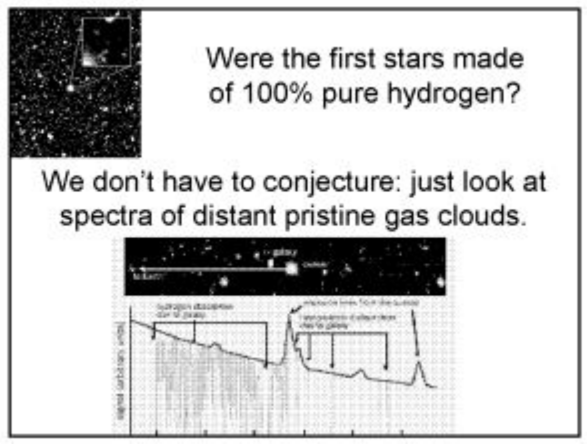
The Early Universe as a Nuclear Reactor

Friday, November 13

The Sun formed over 9 billion years after the Big Bang.

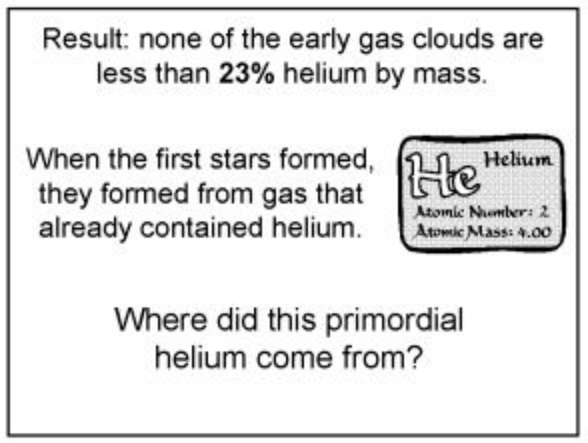
It contains some "recycled" material (gas that had been inside earlier stars).

The first stars formed less than 750 million years after the Big Bang, and contained no recycled material.



Were the first stars made of 100% pure hydrogen?

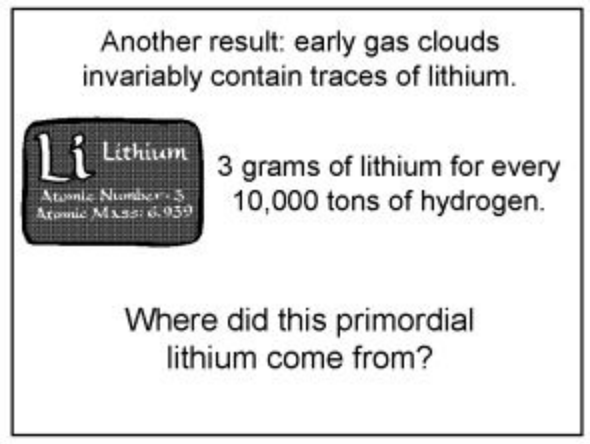
We don't have to conjecture: just look at spectra of distant pristine gas clouds.



Result: none of the early gas clouds are less than **23%** helium by mass.

When the first stars formed, they formed from gas that already contained helium.

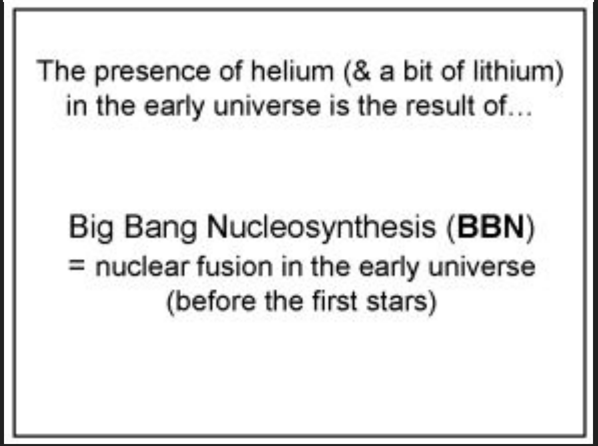
Where did this primordial helium come from?



Another result: early gas clouds invariably contain traces of lithium.

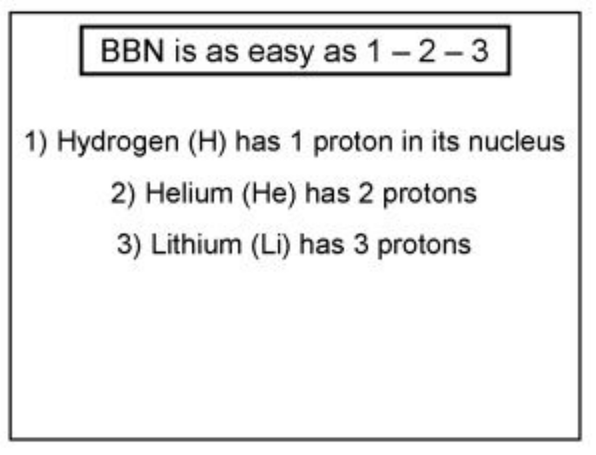
3 grams of lithium for every 10,000 tons of hydrogen.

Where did this primordial lithium come from?



The presence of helium (& a bit of lithium) in the early universe is the result of...

Big Bang Nucleosynthesis (**BBN**)
= nuclear fusion in the early universe
(before the first stars)

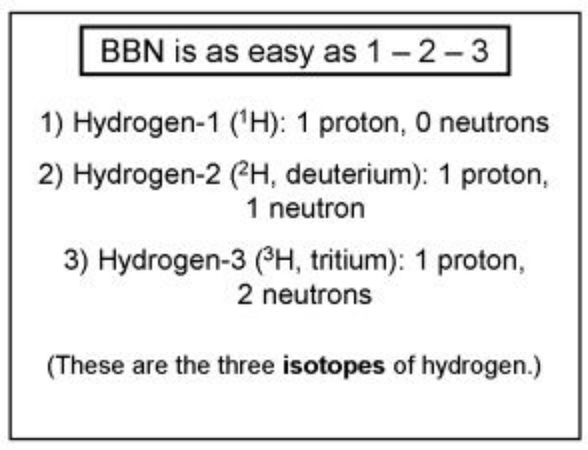


BBN is as easy as 1 – 2 – 3

1) Hydrogen (H) has 1 proton in its nucleus

2) Helium (He) has 2 protons

3) Lithium (Li) has 3 protons



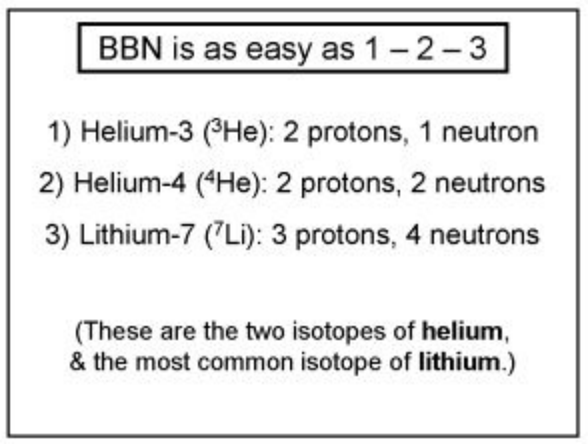
BBN is as easy as 1 – 2 – 3

1) Hydrogen-1 (^{1}H): 1 proton, 0 neutrons

2) Hydrogen-2 (^{2}H, deuterium): 1 proton, 1 neutron

3) Hydrogen-3 (^{3}H, tritium): 1 proton, 2 neutrons

(These are the three **isotopes** of hydrogen.)



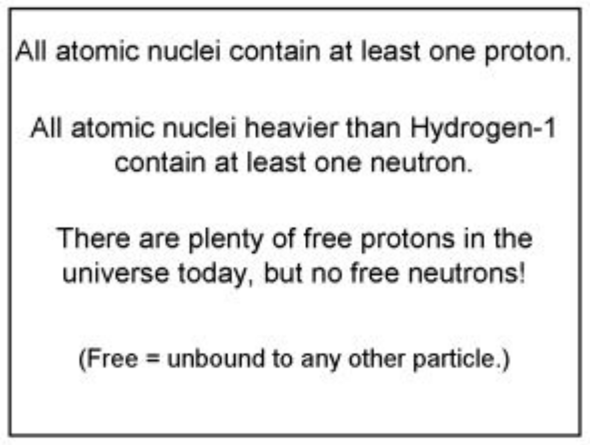
BBN is as easy as 1 – 2 – 3

1) Helium-3 (^{3}He): 2 protons, 1 neutron

2) Helium-4 (^{4}He): 2 protons, 2 neutrons

3) Lithium-7 (^{7}Li): 3 protons, 4 neutrons

(These are the two isotopes of **helium**,
& the most common isotope of **lithium**.)

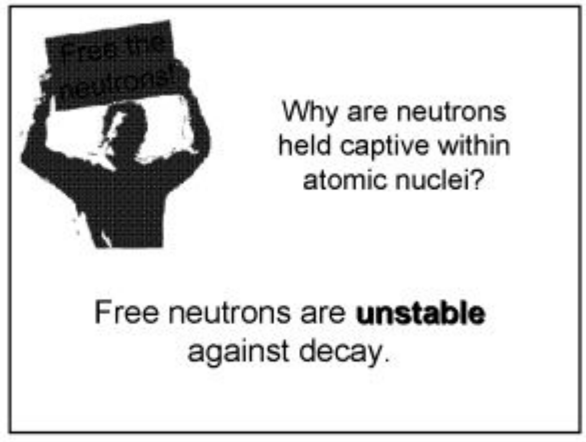


All atomic nuclei contain at least one proton.

All atomic nuclei heavier than Hydrogen-1 contain at least one neutron.

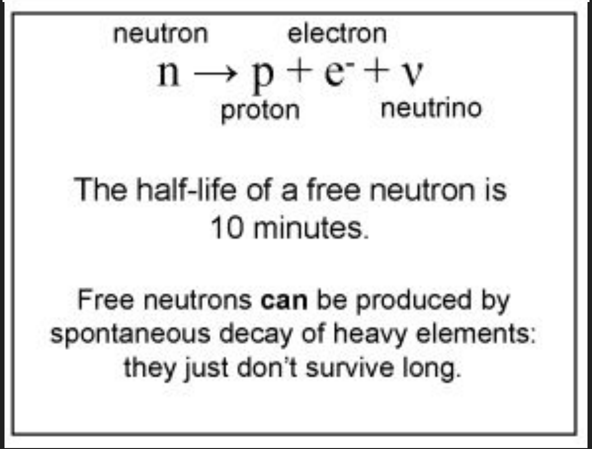
There are plenty of free protons in the universe today, but no free neutrons!

(Free = unbound to any other particle.)



Why are neutrons held captive within atomic nuclei?

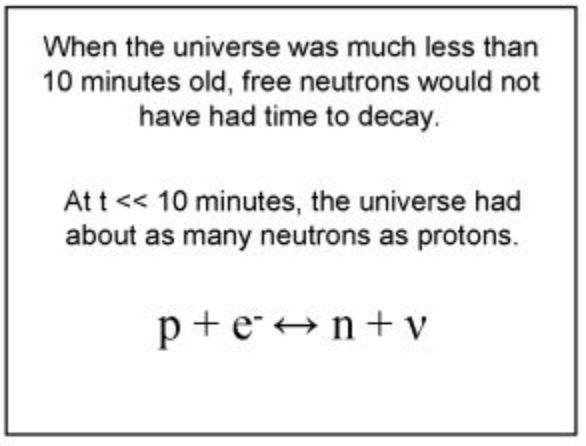
Free neutrons are **unstable** against decay.



$$\overset{\text{neutron}}{n} \rightarrow \underset{\text{proton}}{p} + \overset{\text{electron}}{e^-} + \underset{\text{neutrino}}{\nu}$$

The half-life of a free neutron is 10 minutes.

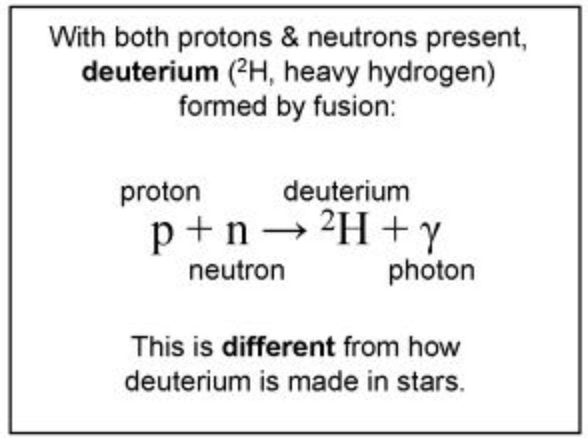
Free neutrons **can** be produced by spontaneous decay of heavy elements: they just don't survive long.



When the universe was much less than 10 minutes old, free neutrons would not have had time to decay.

At t << 10 minutes, the universe had about as many neutrons as protons.

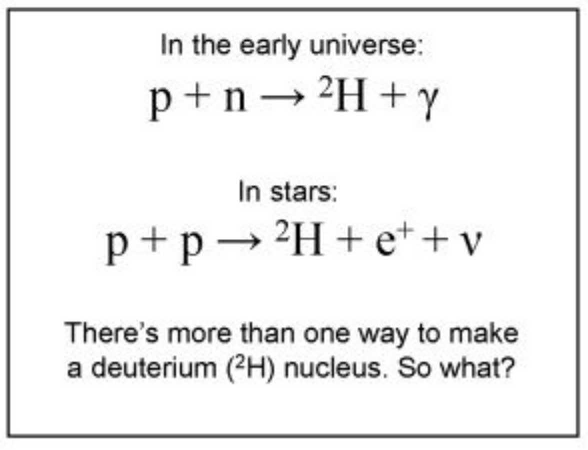
$$p + e^{-} \leftrightarrow n + \nu$$



With both protons & neutrons present, **deuterium** (^{2}H, heavy hydrogen) formed by fusion:

$$\overset{\text{proton}}{p} + \underset{\text{neutron}}{n} \longrightarrow \overset{\text{deuterium}}{{}^{2}H} + \underset{\text{photon}}{\gamma}$$

This is **different** from how deuterium is made in stars.



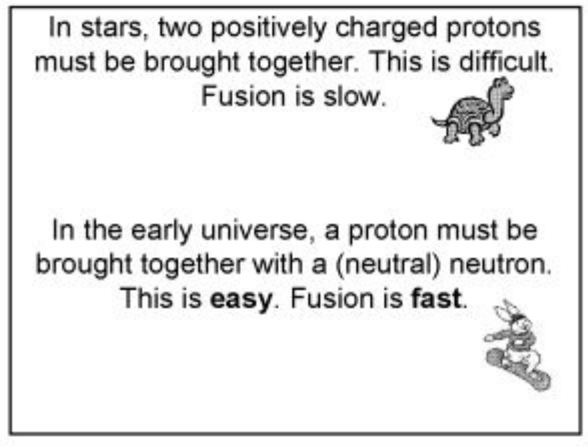
In the early universe:

$$p + n \longrightarrow {}^{2}H + \gamma$$

In stars:

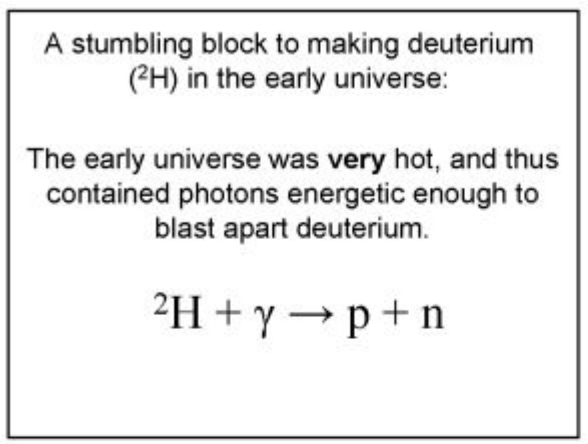
$$p + p \longrightarrow {}^{2}H + e^{+} + \nu$$

There's more than one way to make a deuterium (^{2}H) nucleus. So what?



In stars, two positively charged protons must be brought together. This is difficult. Fusion is slow.

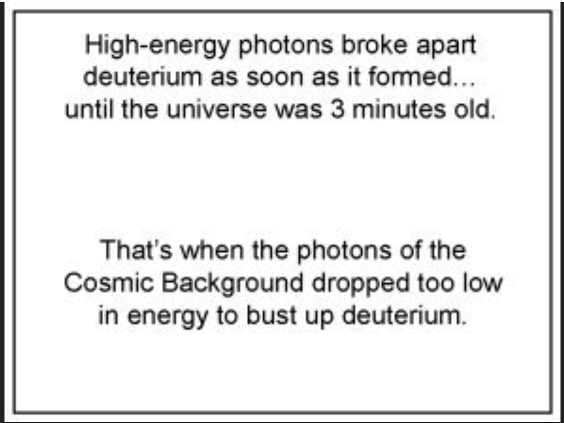
In the early universe, a proton must be brought together with a (neutral) neutron. This is **easy**. Fusion is **fast**.



A stumbling block to making deuterium (^2H) in the early universe:

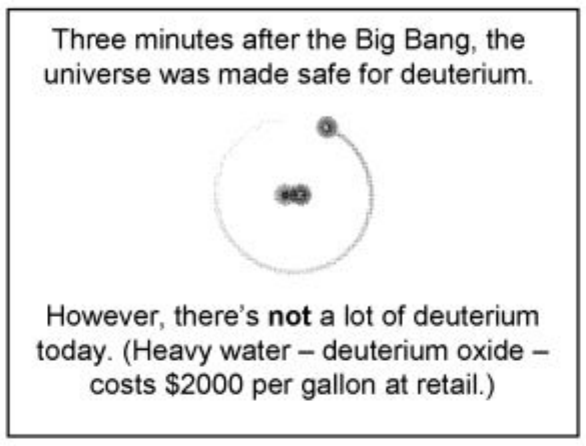
The early universe was **very** hot, and thus contained photons energetic enough to blast apart deuterium.

$$^{2}\mathrm{H} + \gamma \rightarrow \mathrm{p} + \mathrm{n}$$



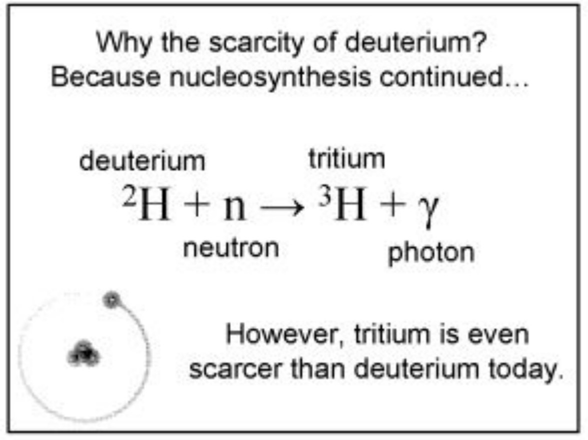
High-energy photons broke apart deuterium as soon as it formed… until the universe was 3 minutes old.

That's when the photons of the Cosmic Background dropped too low in energy to bust up deuterium.



Three minutes after the Big Bang, the universe was made safe for deuterium.

However, there's **not** a lot of deuterium today. (Heavy water – deuterium oxide – costs $2000 per gallon at retail.)



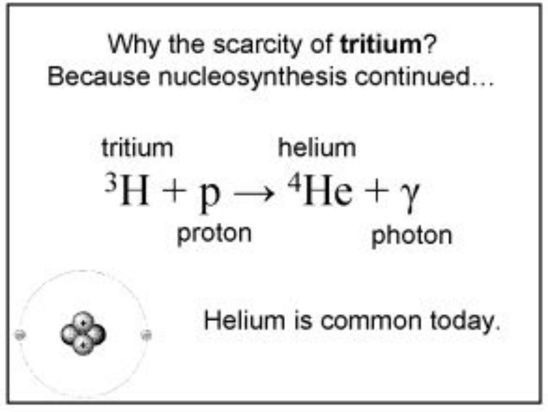
Why the scarcity of deuterium?
Because nucleosynthesis continued…

deuterium tritium

$$^{2}\mathrm{H} + \mathrm{n} \rightarrow {}^{3}\mathrm{H} + \gamma$$

neutron photon

However, tritium is even scarcer than deuterium today.



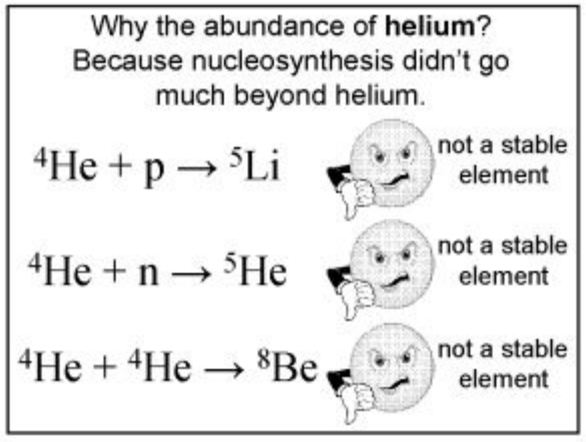
Why the scarcity of **tritium**?
Because nucleosynthesis continued…

tritium helium

$$^{3}\mathrm{H} + \mathrm{p} \rightarrow {}^{4}\mathrm{He} + \gamma$$

proton photon

Helium is common today.

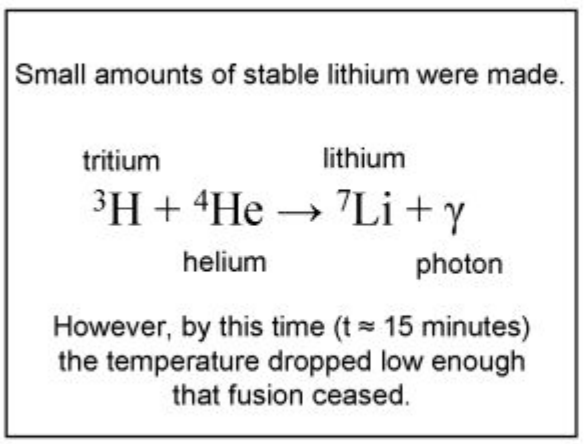


Why the abundance of **helium**?
Because nucleosynthesis didn't go much beyond helium.

$^4\mathrm{He} + p \rightarrow {}^5\mathrm{Li}$ not a stable element

$^4\mathrm{He} + n \rightarrow {}^5\mathrm{He}$ not a stable element

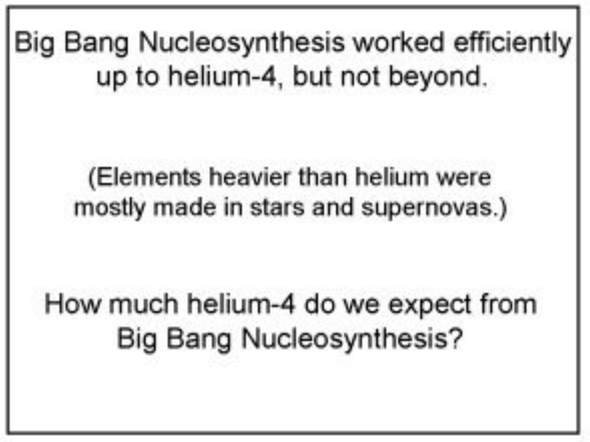
$^4\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^8\mathrm{Be}$ not a stable element



Small amounts of stable lithium were made.

$$\underset{\text{helium}}{\overset{\text{tritium}}{^3\mathrm{H} + {}^4\mathrm{He}}} \rightarrow \underset{\text{photon}}{\overset{\text{lithium}}{^7\mathrm{Li} + \gamma}}$$

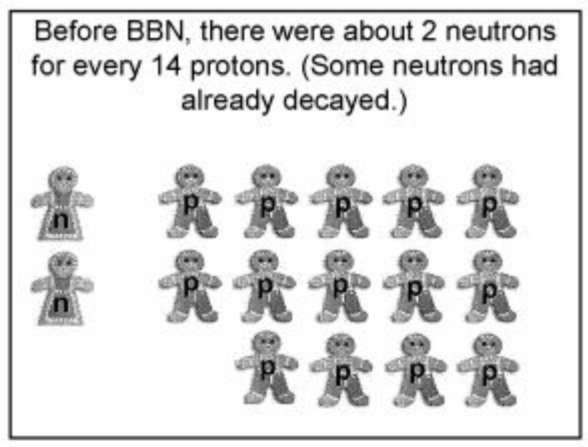
However, by this time (t ≈ 15 minutes) the temperature dropped low enough that fusion ceased.



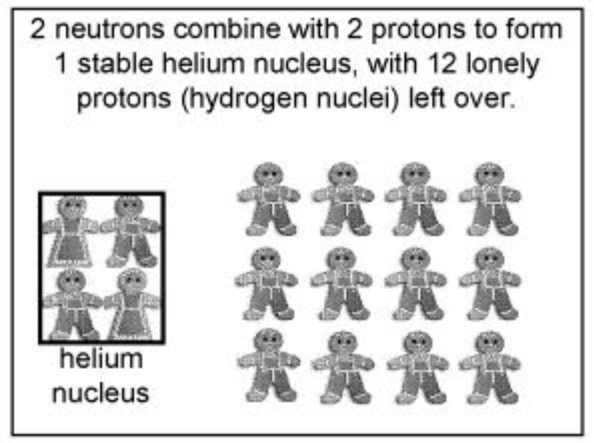
Big Bang Nucleosynthesis worked efficiently up to helium-4, but not beyond.

(Elements heavier than helium were mostly made in stars and supernovas.)

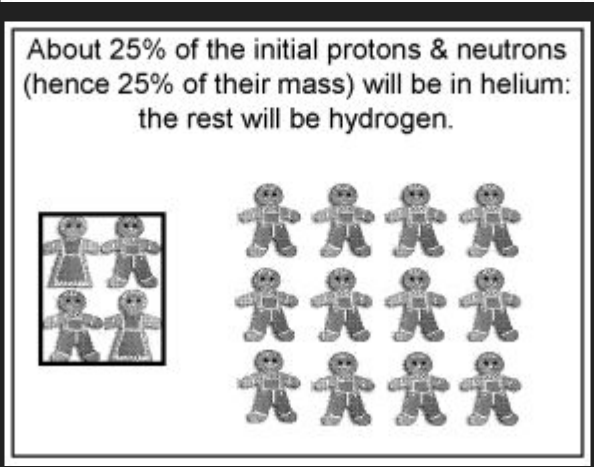
How much helium-4 do we expect from Big Bang Nucleosynthesis?



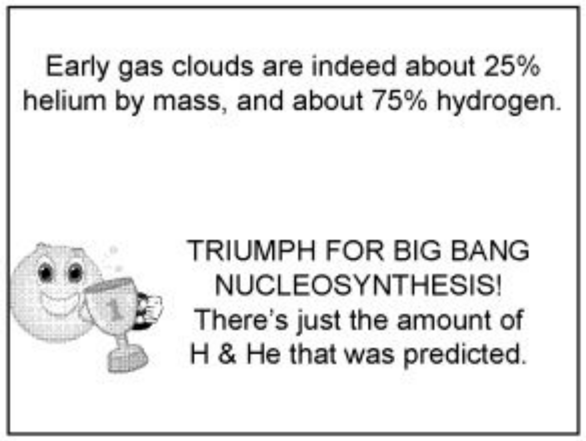
Before BBN, there were about 2 neutrons for every 14 protons. (Some neutrons had already decayed.)



2 neutrons combine with 2 protons to form 1 stable helium nucleus, with 12 lonely protons (hydrogen nuclei) left over.

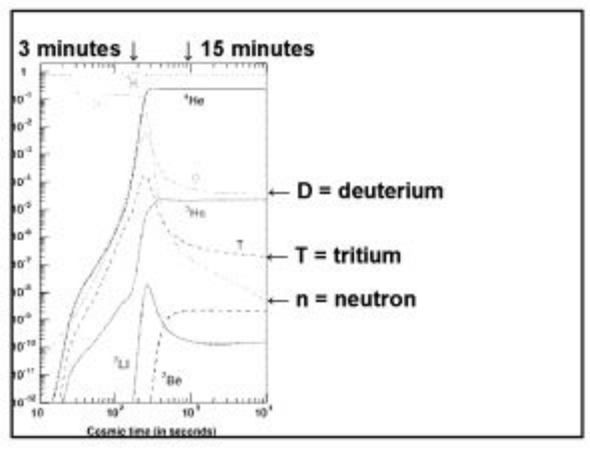


About 25% of the initial protons & neutrons (hence 25% of their mass) will be in helium: the rest will be hydrogen.



Early gas clouds are indeed about 25% helium by mass, and about 75% hydrogen.

TRIUMPH FOR BIG BANG NUCLEOSYNTHESIS!
There's just the amount of H & He that was predicted.

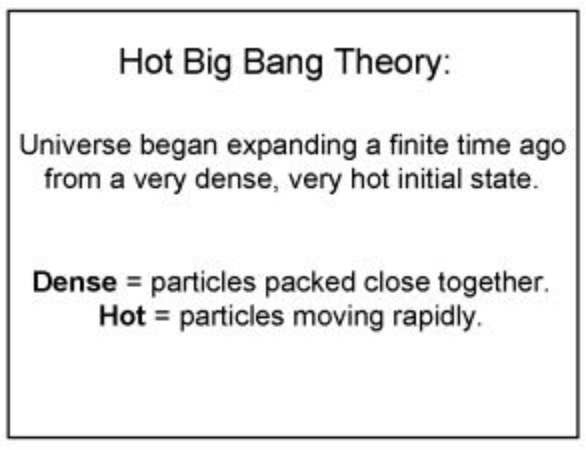


Preparatory Reading Chapter 10 & 11

Week 9: The Hot Big Bang

The Hot Big Bang

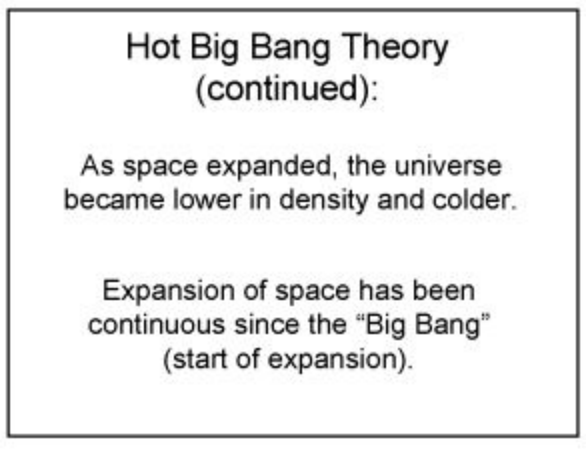
Monday, November 16



Hot Big Bang Theory:

Universe began expanding a finite time ago from a very dense, very hot initial state.

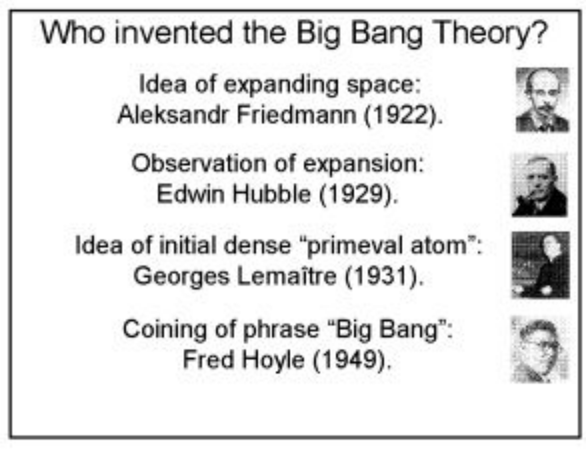
Dense = particles packed close together.
Hot = particles moving rapidly.



Hot Big Bang Theory (continued):

As space expanded, the universe became lower in density and colder.

Expansion of space has been continuous since the “Big Bang” (start of expansion).



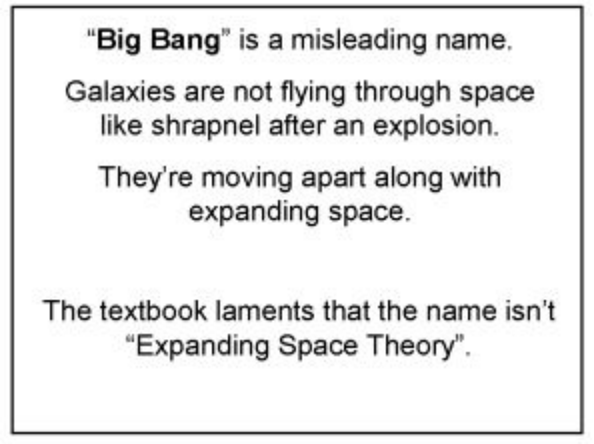
Who invented the Big Bang Theory?

Idea of expanding space:
Aleksandr Friedmann (1922).

Observation of expansion:
Edwin Hubble (1929).

Idea of initial dense “primeval atom”:
Georges Lemaître (1931).

Coining of phrase “Big Bang”:
Fred Hoyle (1949).

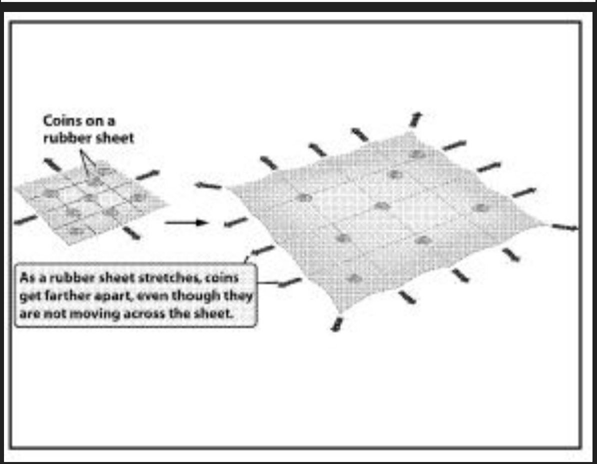


“**Big Bang**” is a misleading name.

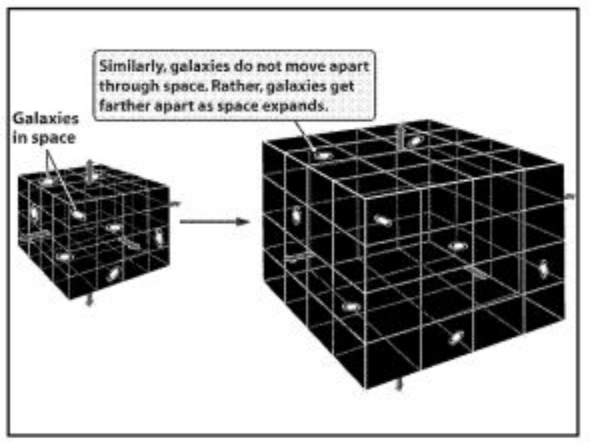
Galaxies are not flying through space like shrapnel after an explosion.

They’re moving apart along with expanding space.

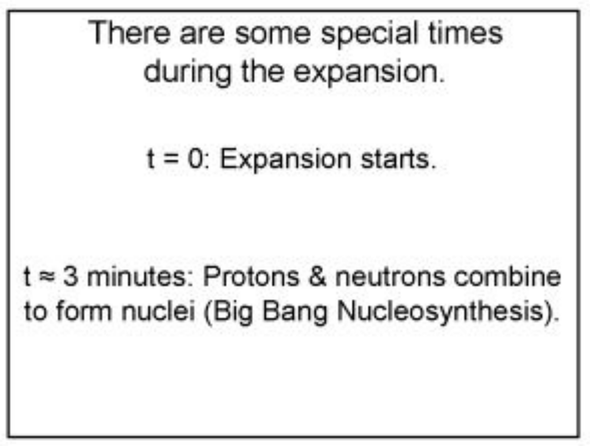
The textbook laments that the name isn’t “Expanding Space Theory”.



As a rubber sheet stretches, coins get farther apart, even though they are not moving across the sheet.



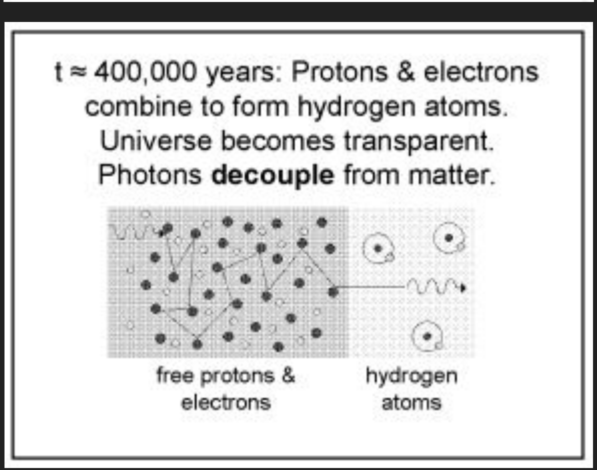
Similarly, galaxies do not move apart through space. Rather, galaxies get farther apart as space expands.



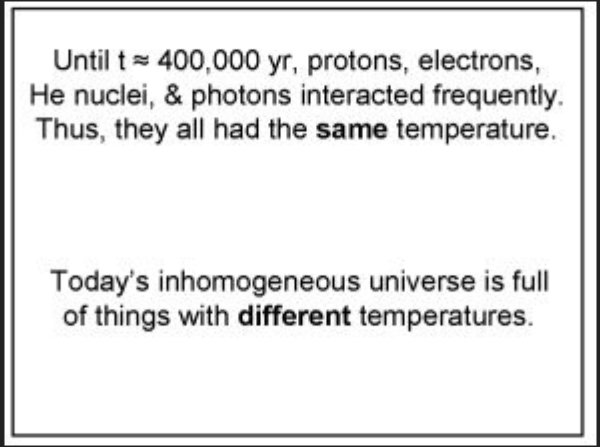
There are some special times during the expansion.

t = 0: Expansion starts.

t ≈ 3 minutes: Protons & neutrons combine to form nuclei (Big Bang Nucleosynthesis).

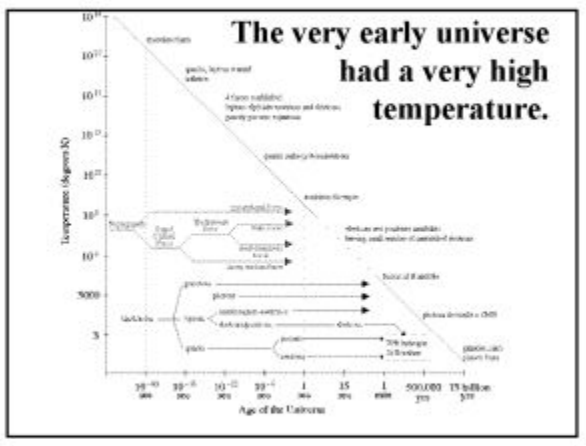


t ≈ 400,000 years: Protons & electrons combine to form hydrogen atoms.
Universe becomes transparent.
Photons **decouple** from matter.

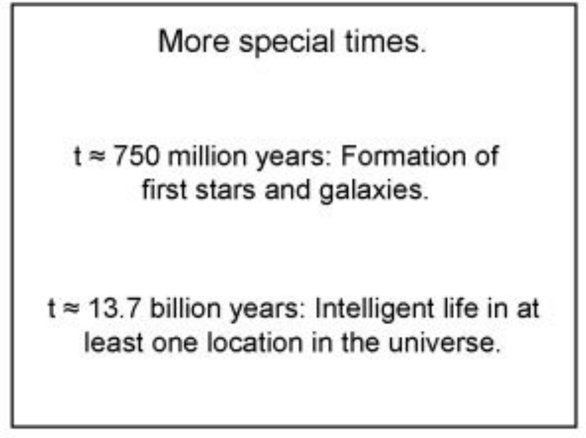


Until t ≈ 400,000 yr, protons, electrons, He nuclei, & photons interacted frequently. Thus, they all had the **same** temperature.

Today's inhomogeneous universe is full of things with **different** temperatures.



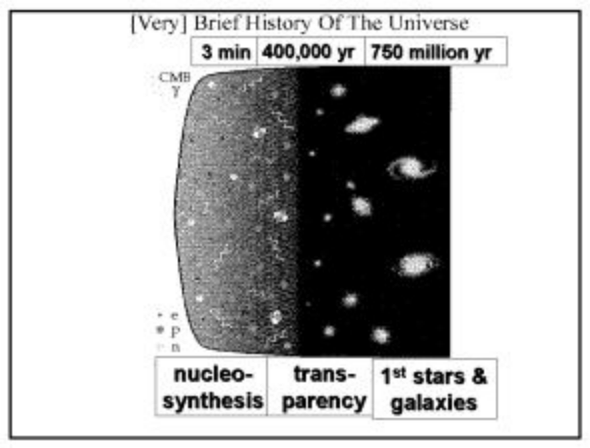
The very early universe had a very high temperature.



More special times.

t ≈ 750 million years: Formation of first stars and galaxies.

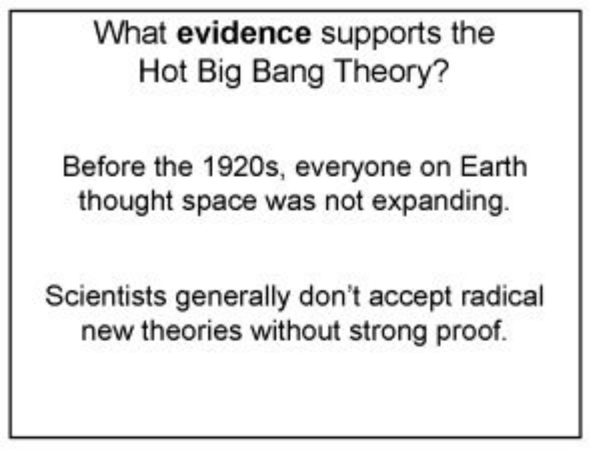
t ≈ 13.7 billion years: Intelligent life in at least one location in the universe.



[Very] Brief History Of The Universe

3 min	400,000 yr	750 million yr

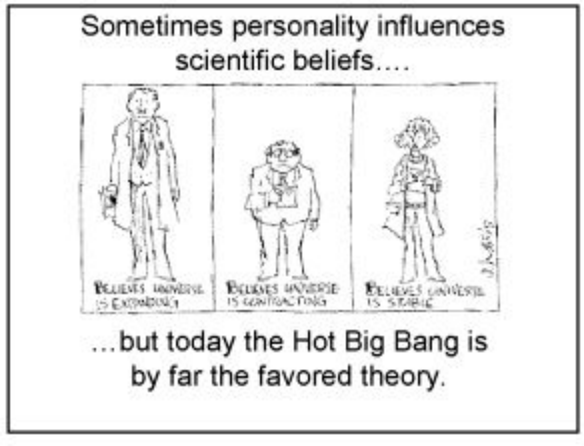
nucleo-synthesis	trans-parency	1st stars & galaxies



What **evidence** supports the Hot Big Bang Theory?

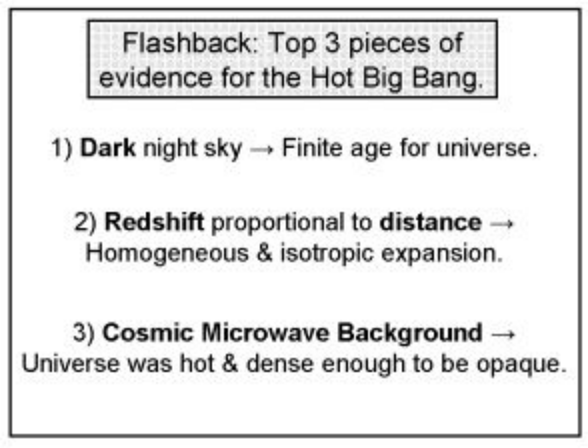
Before the 1920s, everyone on Earth thought space was not expanding.

Scientists generally don't accept radical new theories without strong proof.



Sometimes personality influences scientific beliefs….

…but today the Hot Big Bang is by far the favored theory.

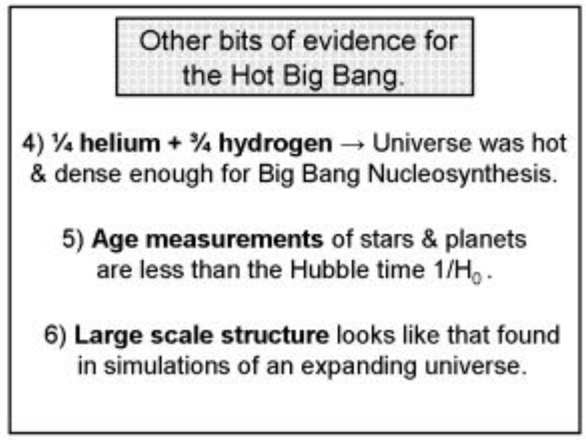


Flashback: Top 3 pieces of evidence for the Hot Big Bang.

1) **Dark** night sky → Finite age for universe.

2) **Redshift** proportional to **distance** → Homogeneous & isotropic expansion.

3) **Cosmic Microwave Background** → Universe was hot & dense enough to be opaque.

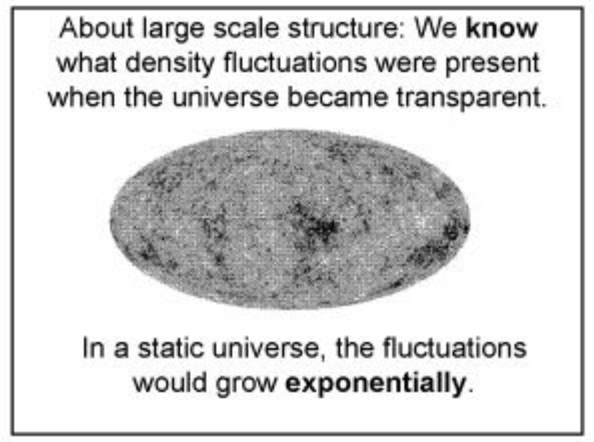


Other bits of evidence for the Hot Big Bang.

4) **¼ helium + ¾ hydrogen** → Universe was hot & dense enough for Big Bang Nucleosynthesis.

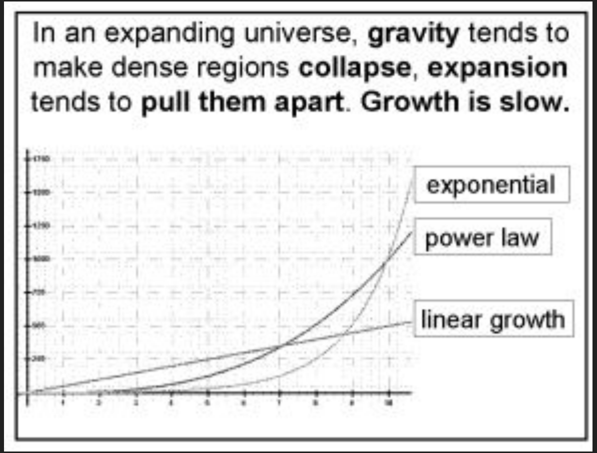
5) **Age measurements** of stars & planets are less than the Hubble time $1/H_0$.

6) **Large scale structure** looks like that found in simulations of an expanding universe.

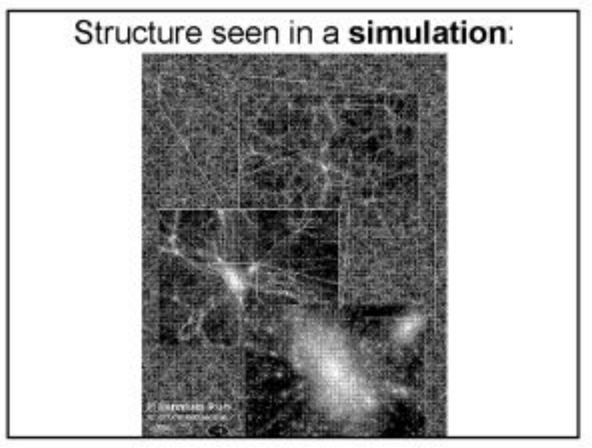


About large scale structure: We **know** what density fluctuations were present when the universe became transparent.

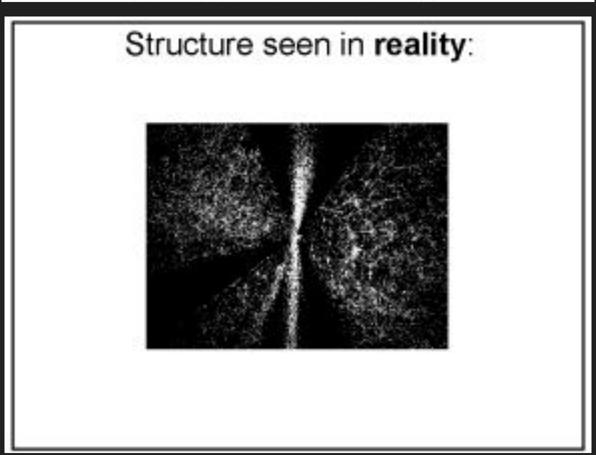
In a static universe, the fluctuations would grow **exponentially**.



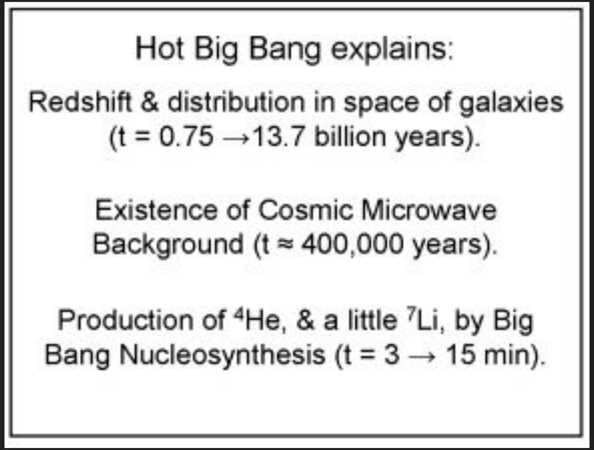
In an expanding universe, **gravity** tends to make dense regions **collapse**, **expansion** tends to **pull them apart**. **Growth is slow.**



Structure seen in a **simulation**:



Structure seen in **reality**:

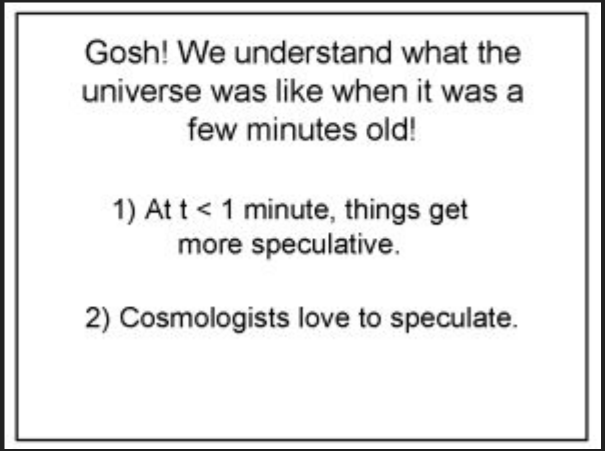


Hot Big Bang explains:

Redshift & distribution in space of galaxies (t = 0.75 →13.7 billion years).

Existence of Cosmic Microwave Background (t ≈ 400,000 years).

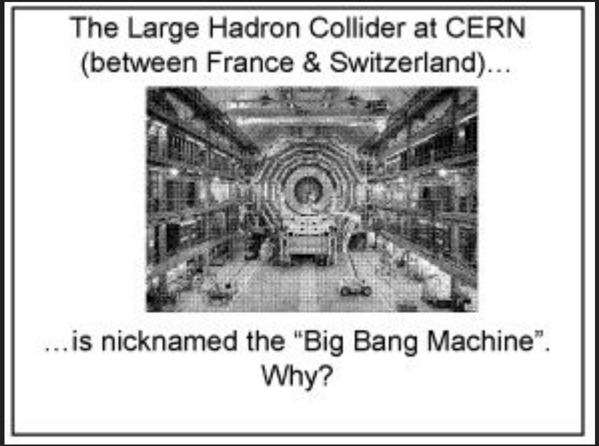
Production of ^{4}He, & a little ^{7}Li, by Big Bang Nucleosynthesis (t = 3 → 15 min).



Gosh! We understand what the universe was like when it was a few minutes old!

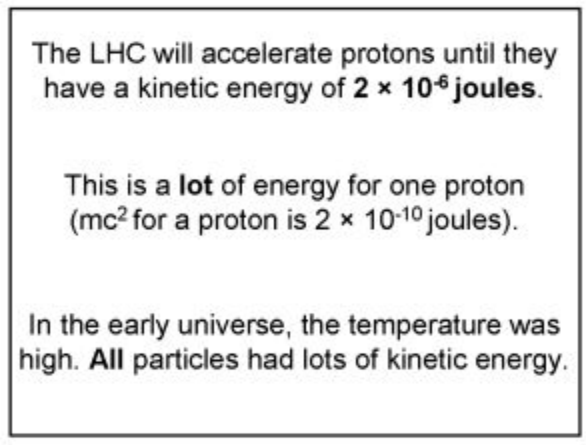
1) At t < 1 minute, things get more speculative.

2) Cosmologists love to speculate.



The Large Hadron Collider at CERN (between France & Switzerland)…

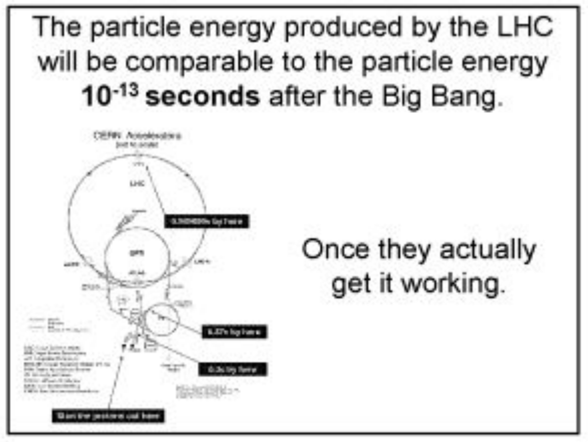
…is nicknamed the “Big Bang Machine”. Why?



The LHC will accelerate protons until they have a kinetic energy of **2×10^{-6} joules**.

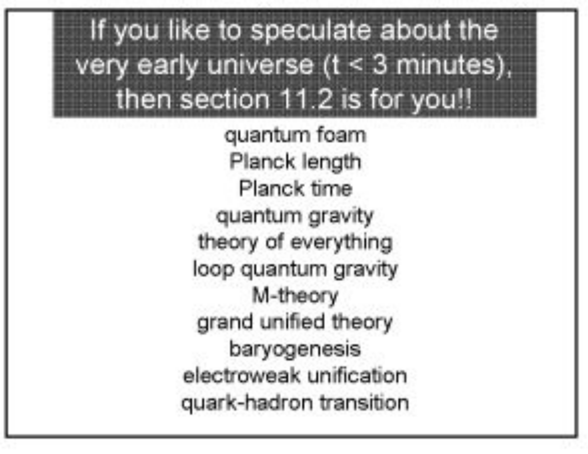
This is a **lot** of energy for one proton (mc^2 for a proton is 2×10^{-10} joules).

In the early universe, the temperature was high. **All** particles had lots of kinetic energy.



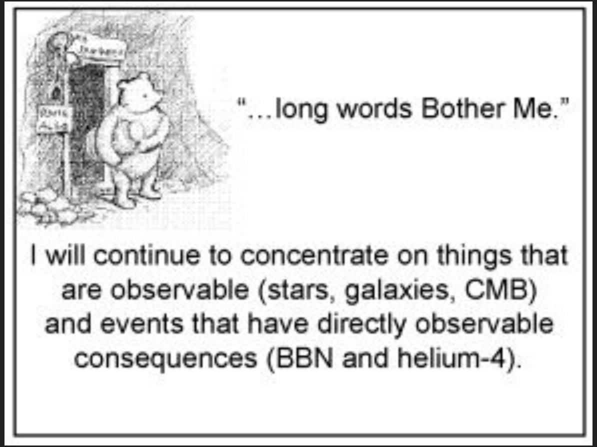
The particle energy produced by the LHC will be comparable to the particle energy **10^{-13} seconds** after the Big Bang.

Once they actually get it working.



If you like to speculate about the very early universe (t < 3 minutes), then section 11.2 is for you!!

quantum foam
Planck length
Planck time
quantum gravity
theory of everything
loop quantum gravity
M-theory
grand unified theory
baryogenesis
electroweak unification
quark-hadron transition

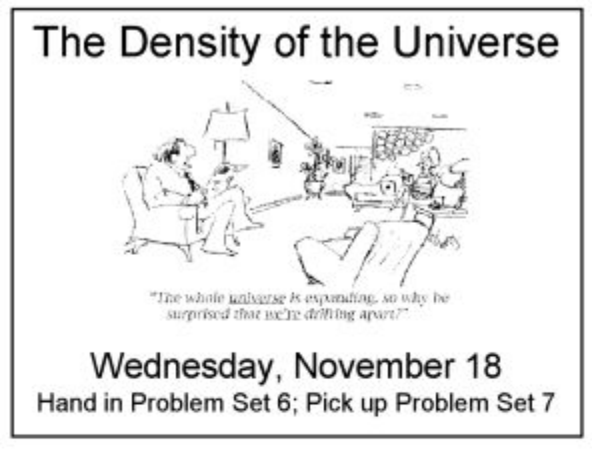


"…long words Bother Me."

I will continue to concentrate on things that are observable (stars, galaxies, CMB) and events that have directly observable consequences (BBN and helium-4).

Preparatory Reading Chapter 10 & 11

Week 9: Density of the Universe

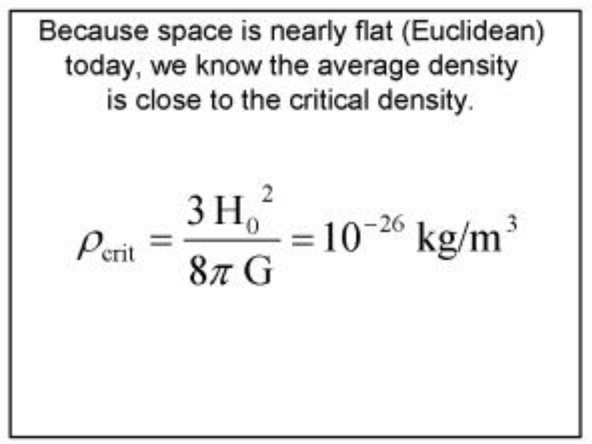


The Density of the Universe

"The whole *universe* is expanding, so why be surprised that *we're* drifting apart?"

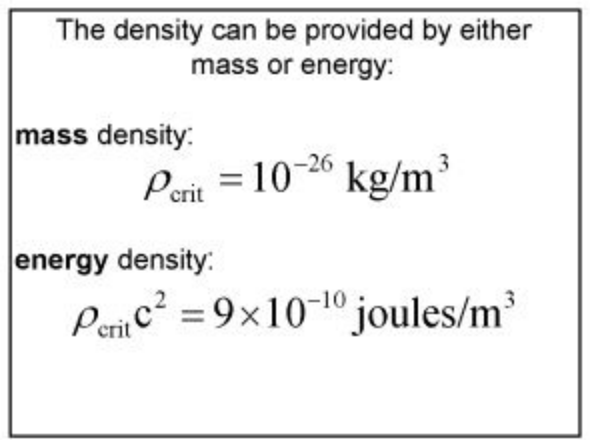
Wednesday, November 18

Hand in Problem Set 6; Pick up Problem Set 7



Because space is nearly flat (Euclidean) today, we know the average density is close to the critical density.

$$\rho_{\text{crit}} = \frac{3\,H_0^{\;2}}{8\pi\,G} = 10^{-26}\ \text{kg/m}^3$$



The density can be provided by either mass or energy:

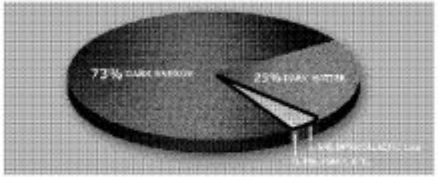
mass density:

$$\rho_{\text{crit}} = 10^{-26}\ \text{kg/m}^3$$

energy density:

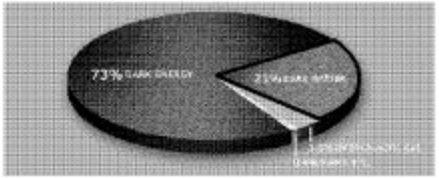
$$\rho_{\text{crit}}c^2 = 9\times10^{-10}\ \text{joules/m}^3$$

Right now, only **4%** of the density is provided by **ordinary matter** (protons, neutrons, electrons).



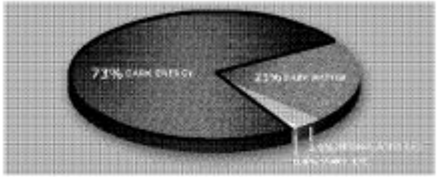
Some ordinary matter is in stars, but most is in low-density intergalactic gas.

Right now, **23%** of the density is provided by **dark matter** (WIMPs, neutrinos).

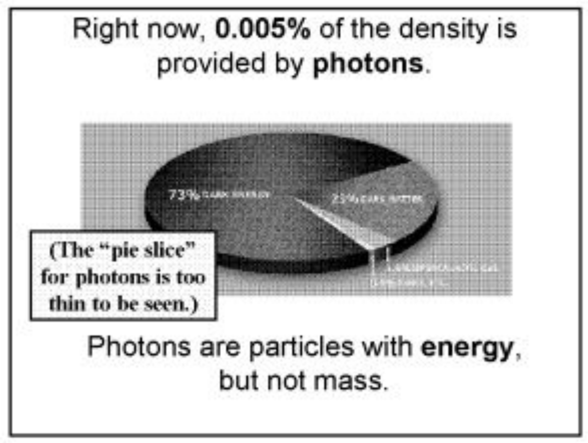


WIMPs, neutrinos, protons, neutrons, & electrons are particles with mass.

Right now, **73%** of the density is provided by **dark energy**.



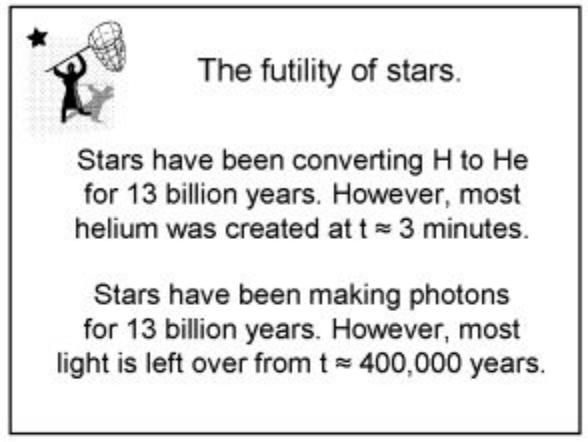
Dark energy is an energy field, and is not made of massive particles.



Right now, **0.005%** of the density is provided by **photons**.

(The "pie slice" for photons is too thin to be seen.)

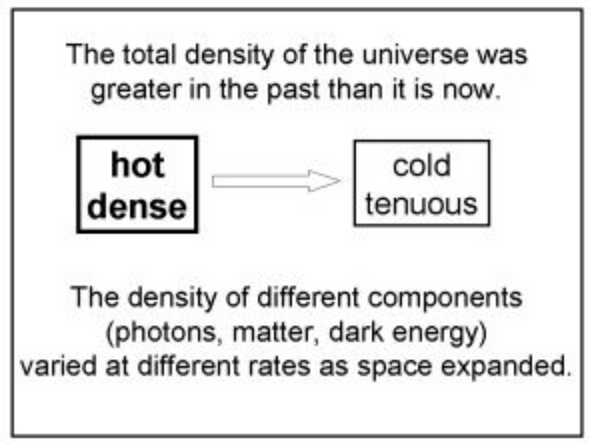
Photons are particles with **energy**, but not mass.



The futility of stars.

Stars have been converting H to He for 13 billion years. However, most helium was created at t ≈ 3 minutes.

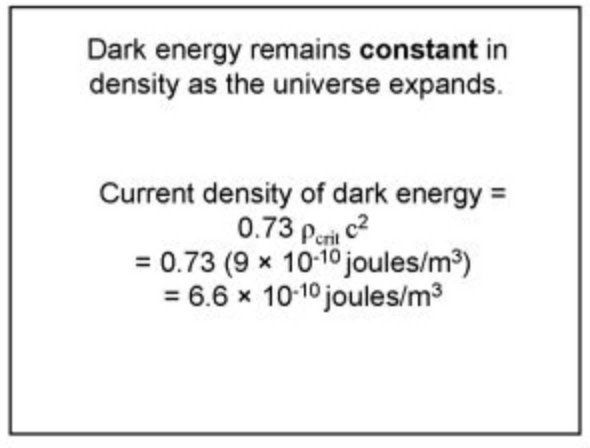
Stars have been making photons for 13 billion years. However, most light is left over from t ≈ 400,000 years.



The total density of the universe was greater in the past than it is now.

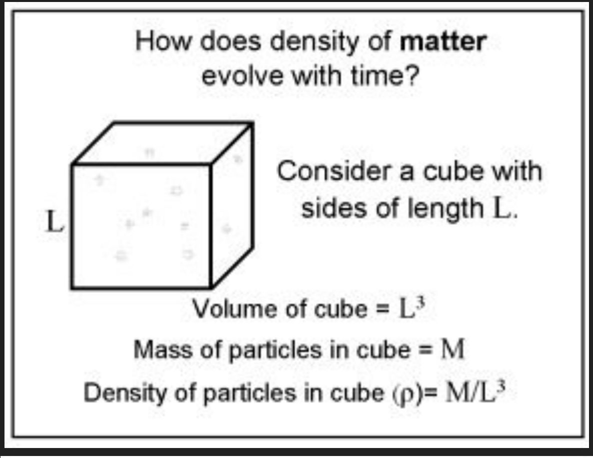
hot dense → cold tenuous

The density of different components (photons, matter, dark energy) varied at different rates as space expanded.



Dark energy remains **constant** in density as the universe expands.

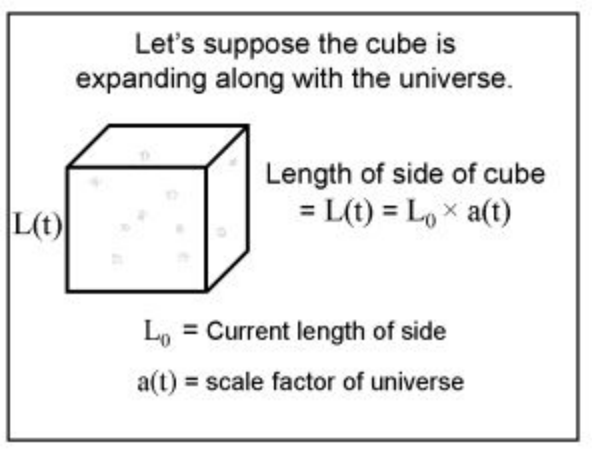
Current density of dark energy =
$0.73\ \rho_{crit}\ c^2$
$= 0.73\ (9 \times 10^{-10}$ joules/m$^3)$
$= 6.6 \times 10^{-10}$ joules/m^3



How does density of **matter** evolve with time?

Consider a cube with sides of length L.

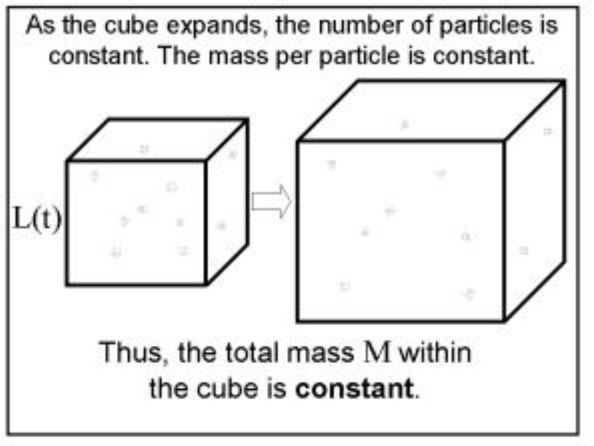
Volume of cube = L^3
Mass of particles in cube = M
Density of particles in cube $(\rho)= M/L^3$



Let's suppose the cube is expanding along with the universe.

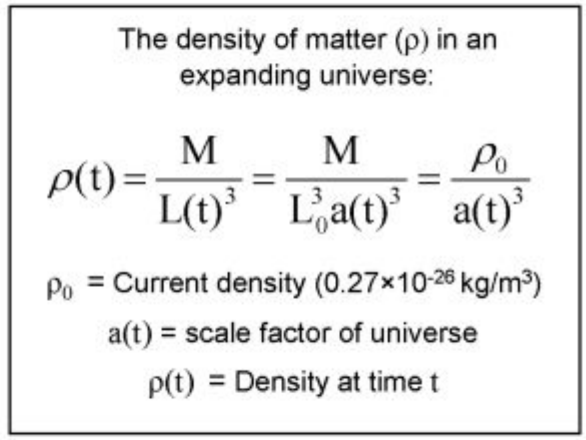
Length of side of cube
$= L(t) = L_0 \times a(t)$

L_0 = Current length of side
$a(t)$ = scale factor of universe



As the cube expands, the number of particles is constant. The mass per particle is constant.

Thus, the total mass M within the cube is **constant**.



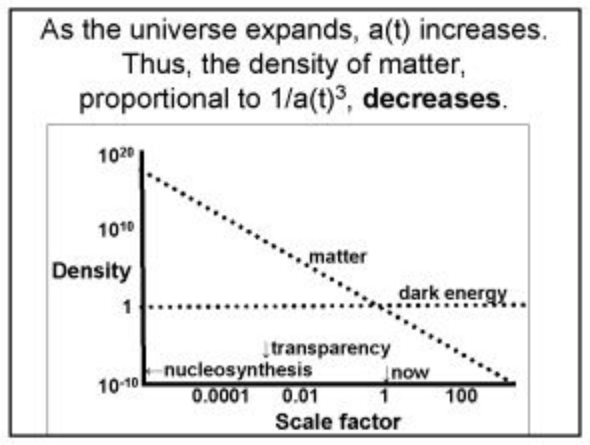
The density of matter (ρ) in an expanding universe:

$$\rho(t) = \frac{M}{L(t)^3} = \frac{M}{L_0^3 a(t)^3} = \frac{\rho_0}{a(t)^3}$$

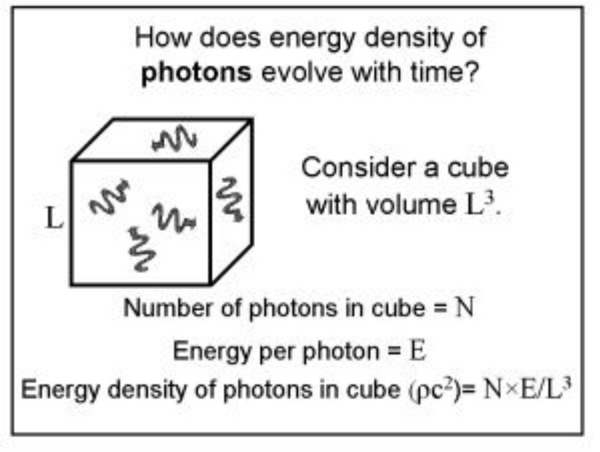
ρ_0 = Current density (0.27×10^{-26} kg/m^3)

$a(t)$ = scale factor of universe

$\rho(t)$ = Density at time t



As the universe expands, a(t) increases. Thus, the density of matter, proportional to $1/a(t)^3$, **decreases**.



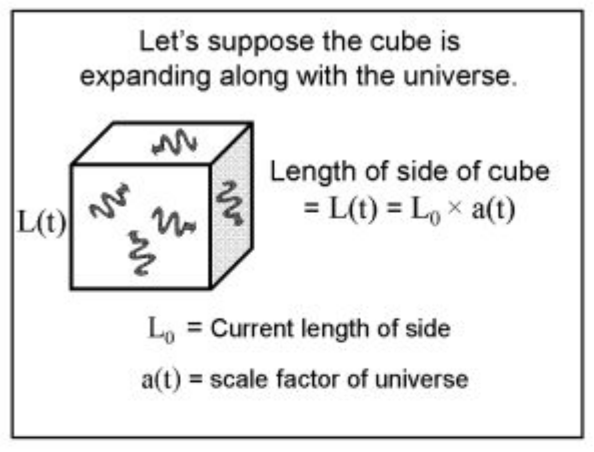
How does energy density of **photons** evolve with time?

Consider a cube with volume L^3.

Number of photons in cube = N

Energy per photon = E

Energy density of photons in cube (ρc^2)= $N \times E/L^3$

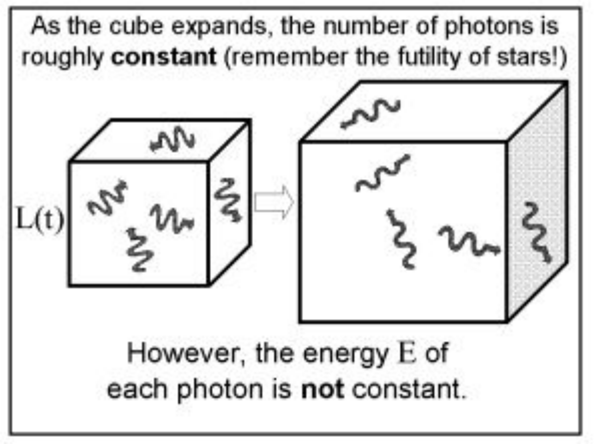


Let's suppose the cube is expanding along with the universe.

Length of side of cube = $L(t) = L_0 \times a(t)$

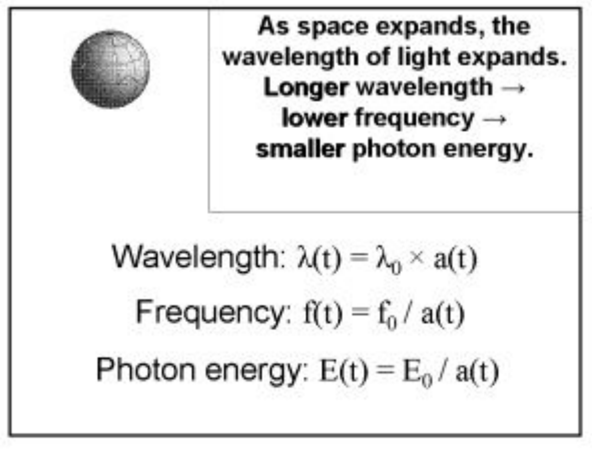
L_0 = Current length of side

$a(t)$ = scale factor of universe



As the cube expands, the number of photons is roughly **constant** (remember the futility of stars!)

However, the energy E of each photon is **not** constant.

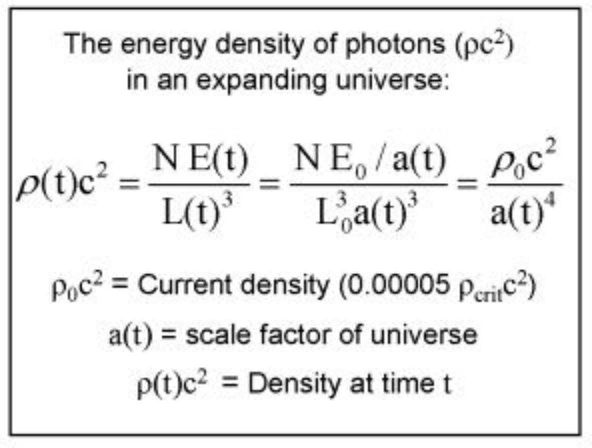


As space expands, the wavelength of light expands. Longer wavelength → lower frequency → smaller photon energy.

Wavelength: $\lambda(t) = \lambda_0 \times a(t)$

Frequency: $f(t) = f_0 / a(t)$

Photon energy: $E(t) = E_0 / a(t)$



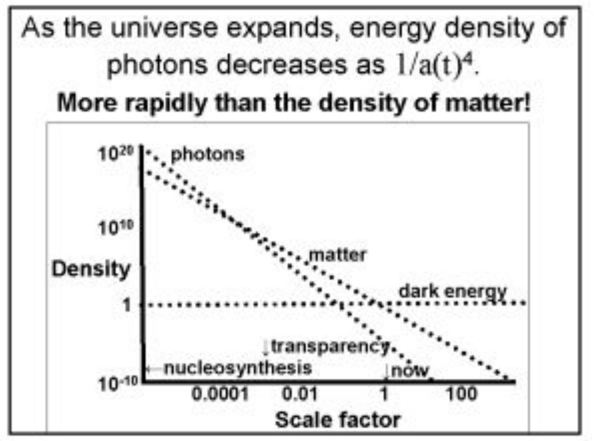
The energy density of photons (ρc^2) in an expanding universe:

$$\rho(t)c^2 = \frac{N\,E(t)}{L(t)^3} = \frac{N\,E_0 / a(t)}{L_0^3 a(t)^3} = \frac{\rho_0 c^2}{a(t)^4}$$

$\rho_0 c^2$ = Current density (0.00005 $\rho_{crit}c^2$)

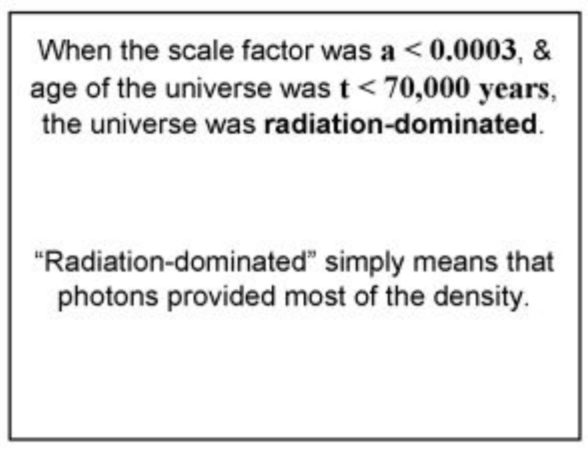
$a(t)$ = scale factor of universe

$\rho(t)c^2$ = Density at time t



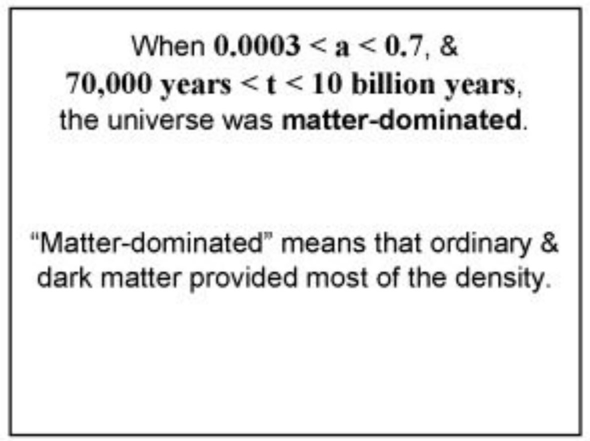
As the universe expands, energy density of photons decreases as $1/a(t)^4$.

More rapidly than the density of matter!



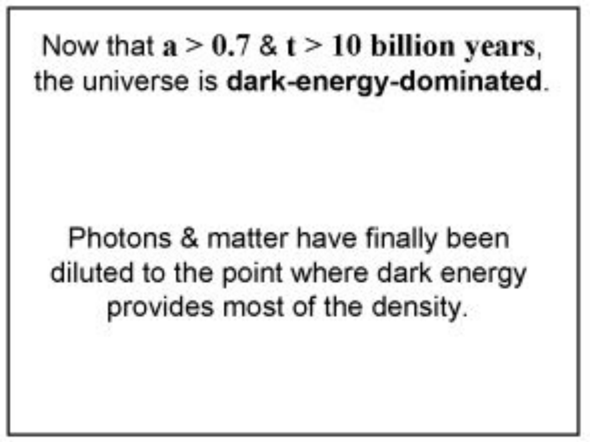
When the scale factor was **$a < 0.0003$**, & age of the universe was **$t < 70{,}000$ years**, the universe was **radiation-dominated**.

“Radiation-dominated” simply means that photons provided most of the density.



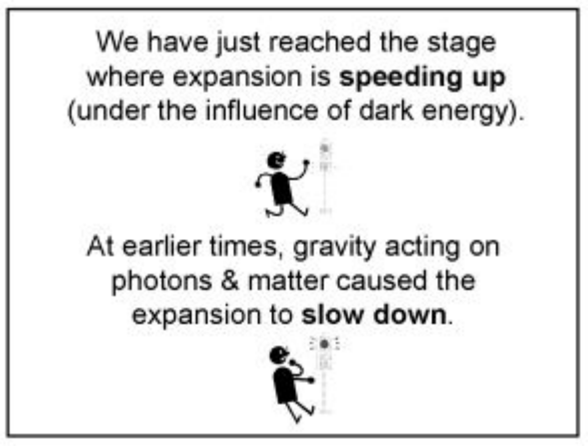
When **$0.0003 < a < 0.7$**, & **70,000 years < t < 10 billion years**, the universe was **matter-dominated**.

“Matter-dominated” means that ordinary & dark matter provided most of the density.



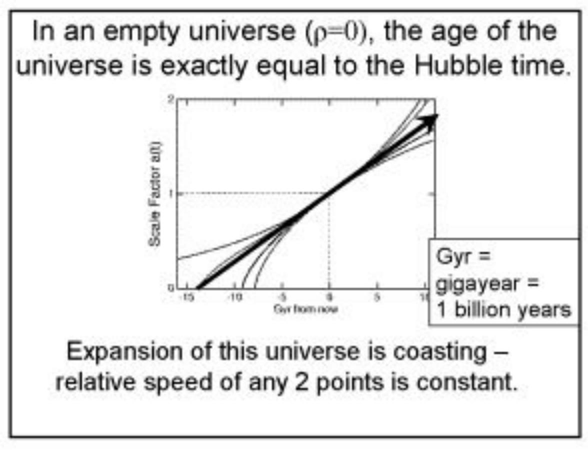
Now that **$a > 0.7$** & **$t > 10$ billion years**, the universe is **dark-energy-dominated**.

Photons & matter have finally been diluted to the point where dark energy provides most of the density.



We have just reached the stage where expansion is **speeding up** (under the influence of dark energy).

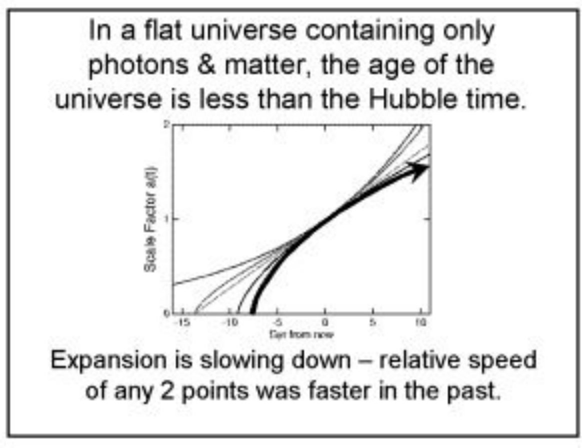
At earlier times, gravity acting on photons & matter caused the expansion to **slow down**.



In an empty universe ($\rho=0$), the age of the universe is exactly equal to the Hubble time.

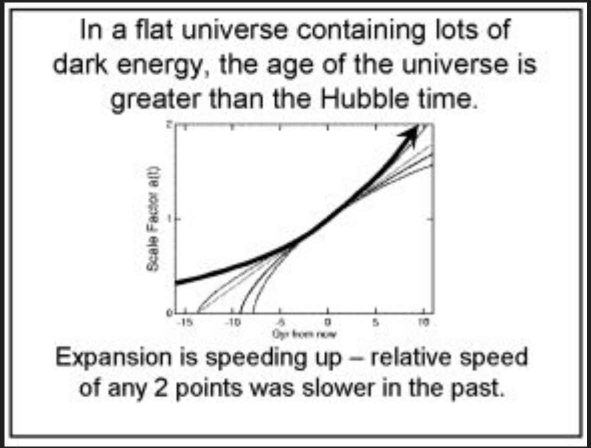
Gyr = gigayear = 1 billion years

Expansion of this universe is coasting – relative speed of any 2 points is constant.



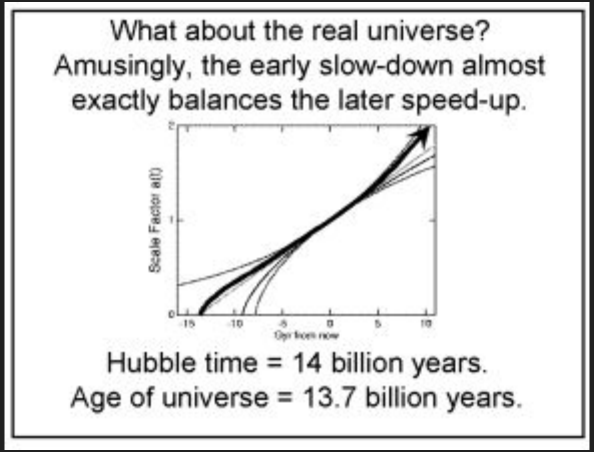
In a flat universe containing only photons & matter, the age of the universe is less than the Hubble time.

Expansion is slowing down – relative speed of any 2 points was faster in the past.



In a flat universe containing lots of dark energy, the age of the universe is greater than the Hubble time.

Expansion is speeding up – relative speed of any 2 points was slower in the past.

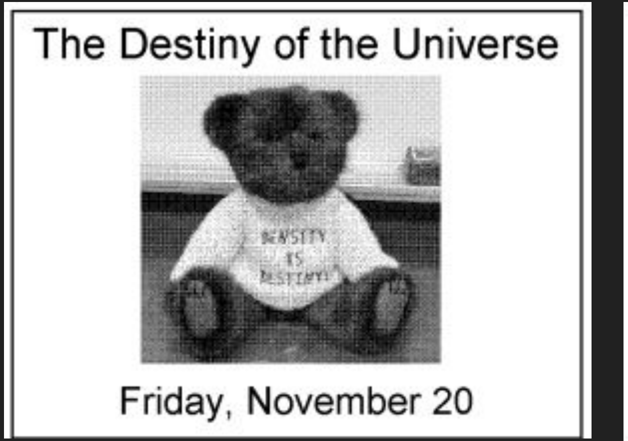


What about the real universe? Amusingly, the early slow-down almost exactly balances the later speed-up.

Hubble time = 14 billion years.
Age of universe = 13.7 billion years.

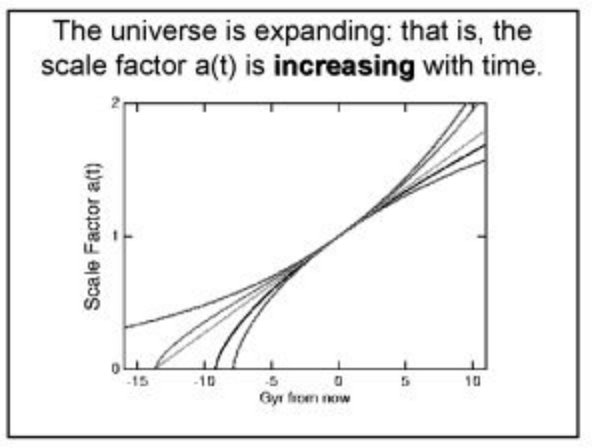
Preparatory Reading Chapter 10 & 11

Week 9: Destiny of the Universe

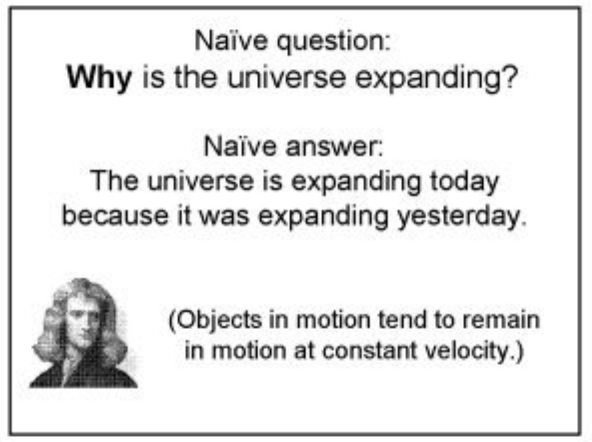


The Destiny of the Universe

Friday, November 20



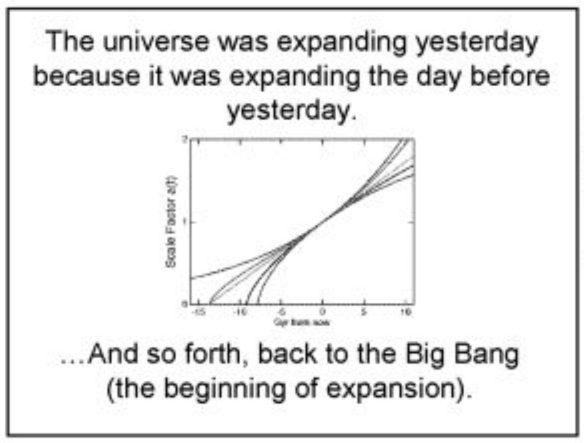
The universe is expanding: that is, the scale factor a(t) is **increasing** with time.



Naïve question:
Why is the universe expanding?

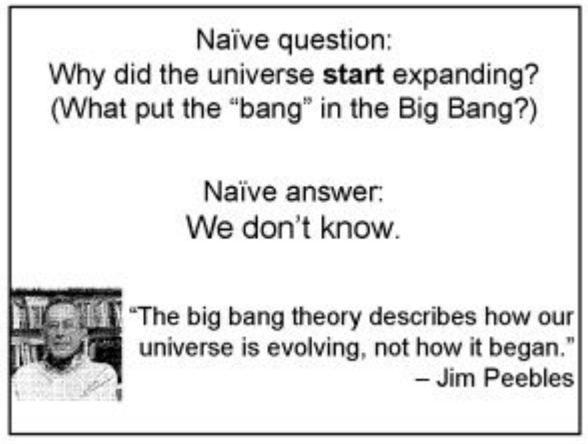
Naïve answer:
The universe is expanding today because it was expanding yesterday.

(Objects in motion tend to remain in motion at constant velocity.)



The universe was expanding yesterday because it was expanding the day before yesterday.

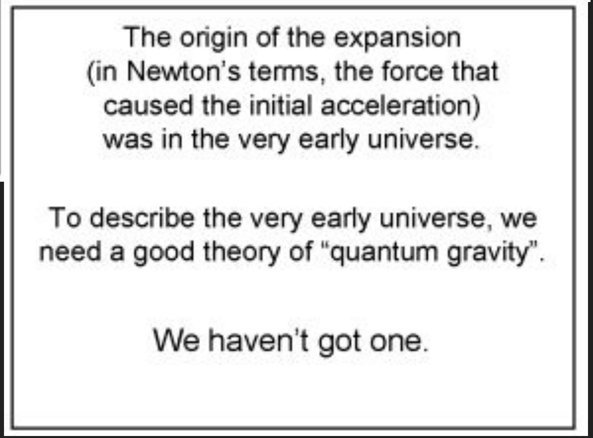
…And so forth, back to the Big Bang (the beginning of expansion).



Naïve question:
Why did the universe **start** expanding?
(What put the "bang" in the Big Bang?)

Naïve answer:
We don't know.

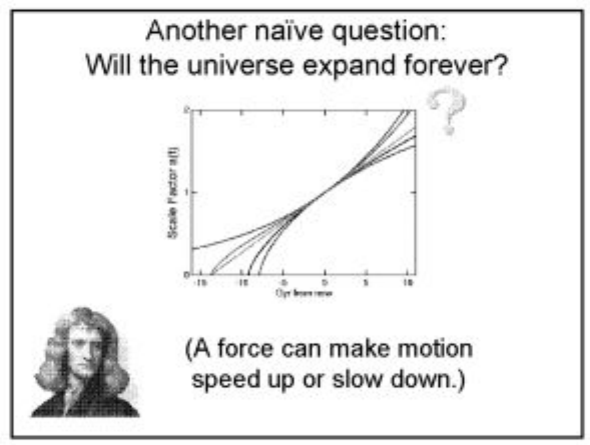
"The big bang theory describes how our universe is evolving, not how it began."
– Jim Peebles



The origin of the expansion
(in Newton's terms, the force that caused the initial acceleration)
was in the very early universe.

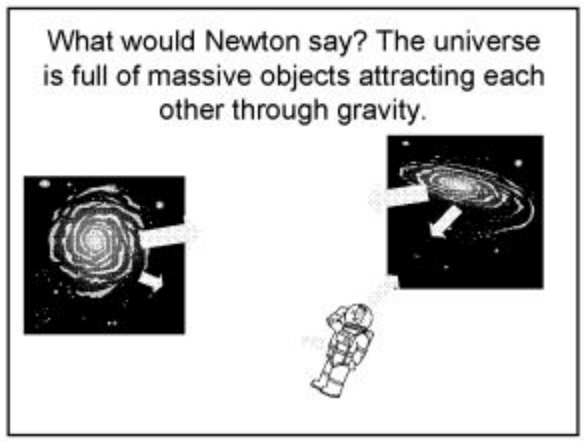
To describe the very early universe, we need a good theory of "quantum gravity".

We haven't got one.

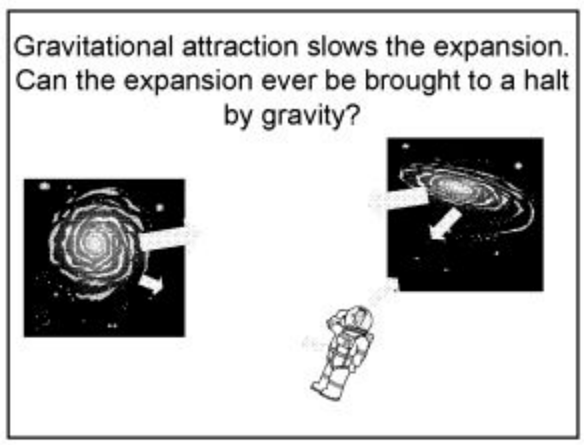


Another naïve question:
Will the universe expand forever?

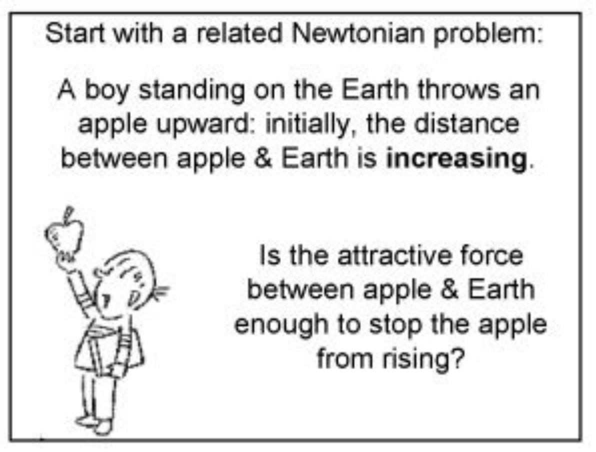
(A force can make motion speed up or slow down.)



What would Newton say? The universe is full of massive objects attracting each other through gravity.



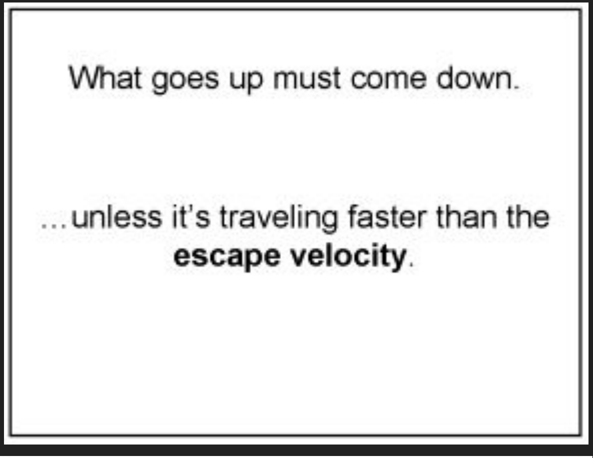
Gravitational attraction slows the expansion. Can the expansion ever be brought to a halt by gravity?



Start with a related Newtonian problem:

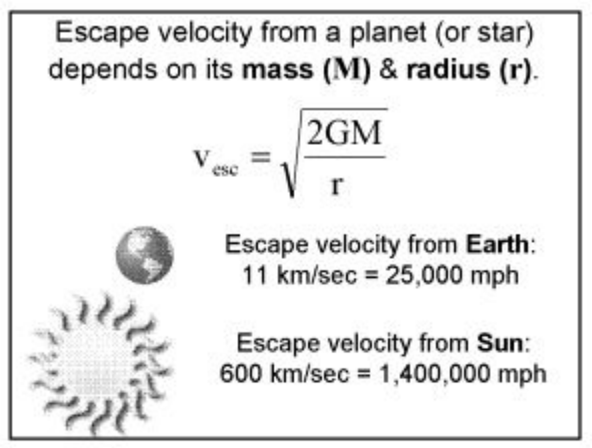
A boy standing on the Earth throws an apple upward: initially, the distance between apple & Earth is **increasing**.

Is the attractive force between apple & Earth enough to stop the apple from rising?



What goes up must come down.

...unless it's traveling faster than the **escape velocity**.

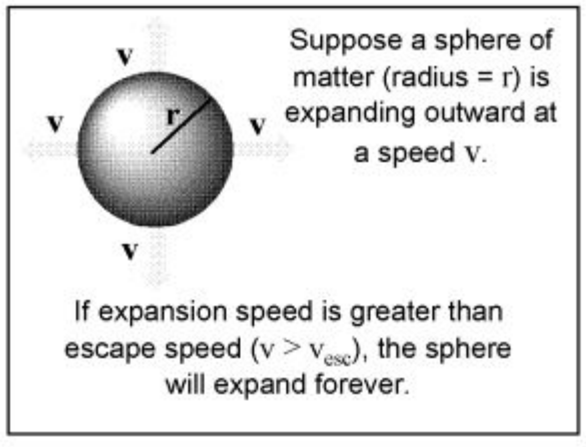


Escape velocity from a planet (or star) depends on its **mass (M)** & **radius (r)**.

$$v_{esc} = \sqrt{\frac{2GM}{r}}$$

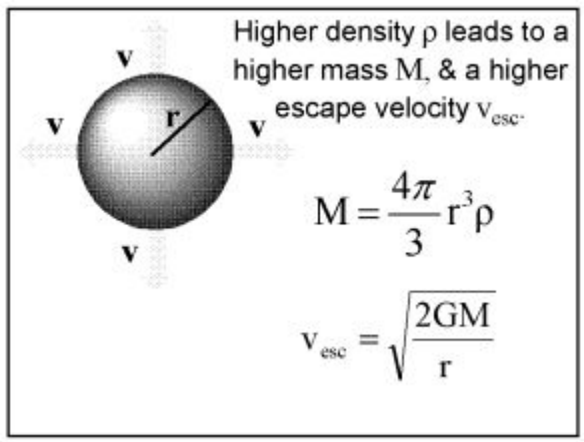
Escape velocity from **Earth**:
11 km/sec = 25,000 mph

Escape velocity from **Sun**:
600 km/sec = 1,400,000 mph



Suppose a sphere of matter (radius = r) is expanding outward at a speed v.

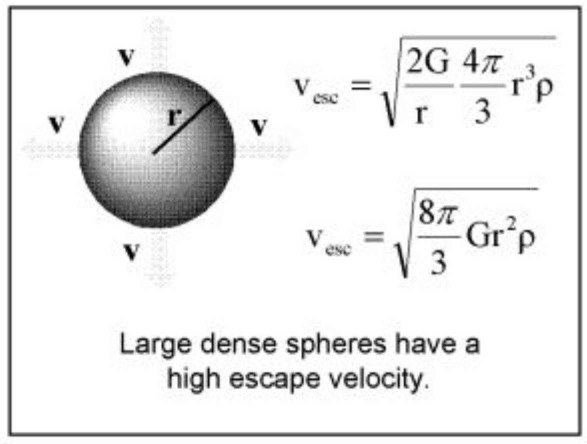
If expansion speed is greater than escape speed ($v > v_{esc}$), the sphere will expand forever.



Higher density ρ leads to a higher mass M, & a higher escape velocity v_{esc}.

$$M = \frac{4\pi}{3} r^3 \rho$$

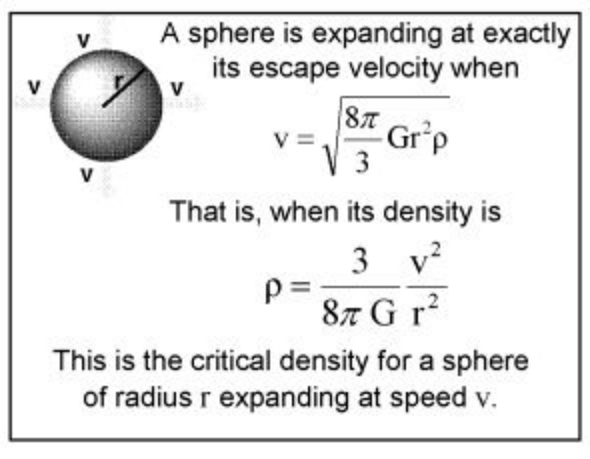
$$v_{esc} = \sqrt{\frac{2GM}{r}}$$



$$v_{esc} = \sqrt{\frac{2G}{r} \frac{4\pi}{3} r^3 \rho}$$

$$v_{esc} = \sqrt{\frac{8\pi}{3} G r^2 \rho}$$

Large dense spheres have a high escape velocity.



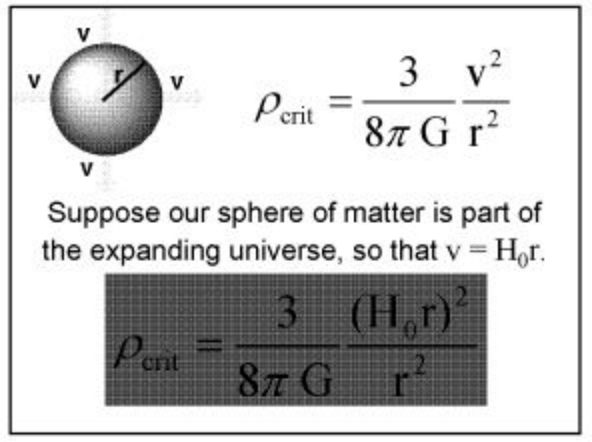
A sphere is expanding at exactly its escape velocity when

$$v = \sqrt{\frac{8\pi}{3} G r^2 \rho}$$

That is, when its density is

$$\rho = \frac{3}{8\pi G} \frac{v^2}{r^2}$$

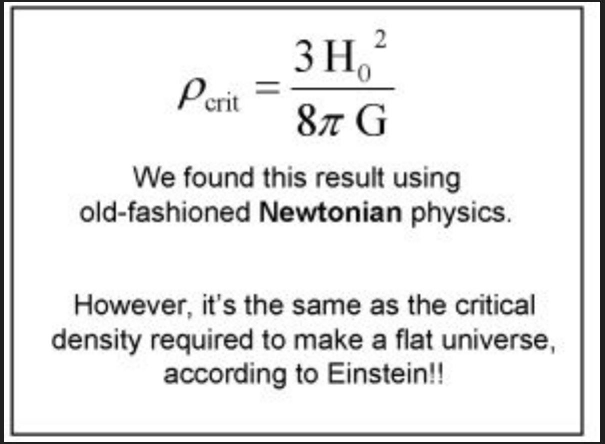
This is the critical density for a sphere of radius r expanding at speed v.



$$\rho_{crit} = \frac{3}{8\pi G} \frac{v^2}{r^2}$$

Suppose our sphere of matter is part of the expanding universe, so that $v = H_0 r$.

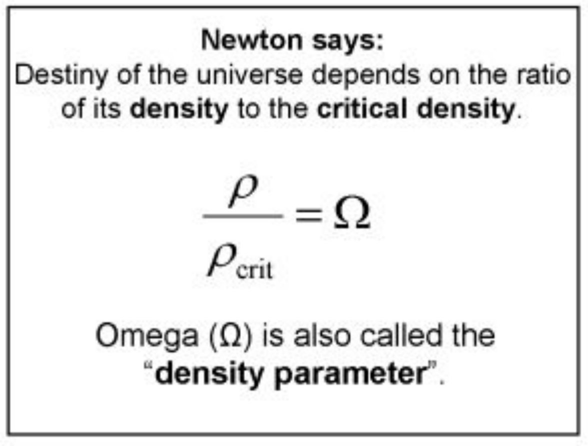
$$\rho_{crit} = \frac{3}{8\pi G} \frac{(H_0 r)^2}{r^2}$$



$$\rho_{crit} = \frac{3 H_0{}^2}{8\pi G}$$

We found this result using old-fashioned **Newtonian** physics.

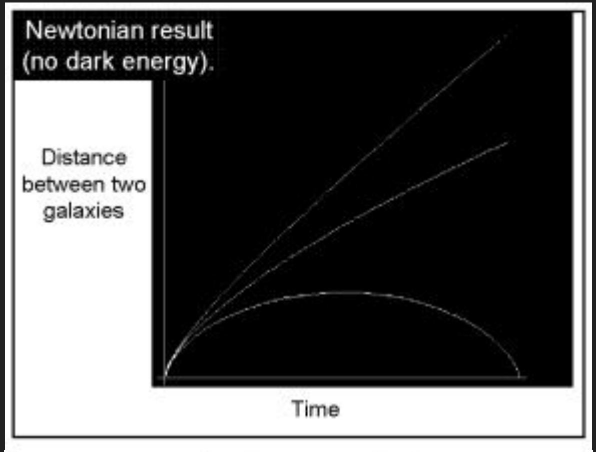
However, it's the same as the critical density required to make a flat universe, according to Einstein!!



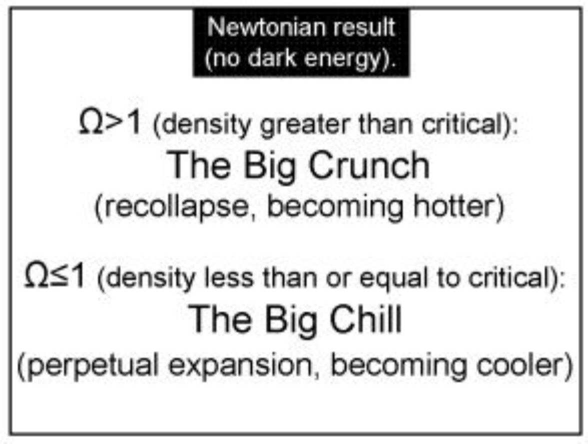
Newton says:
Destiny of the universe depends on the ratio of its **density** to the **critical density**.

$$\frac{\rho}{\rho_{\text{crit}}} = \Omega$$

Omega (Ω) is also called the "**density parameter**".



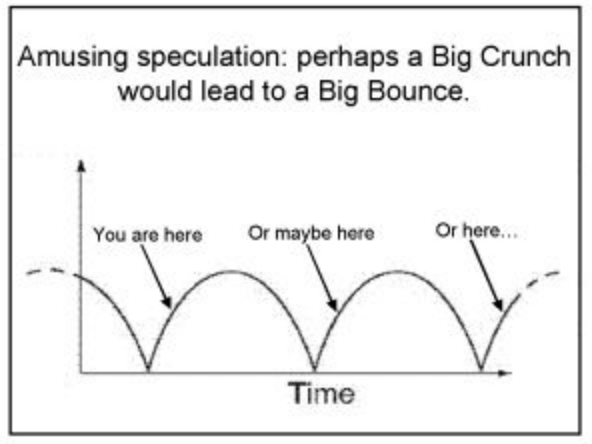
Newtonian result (no dark energy).



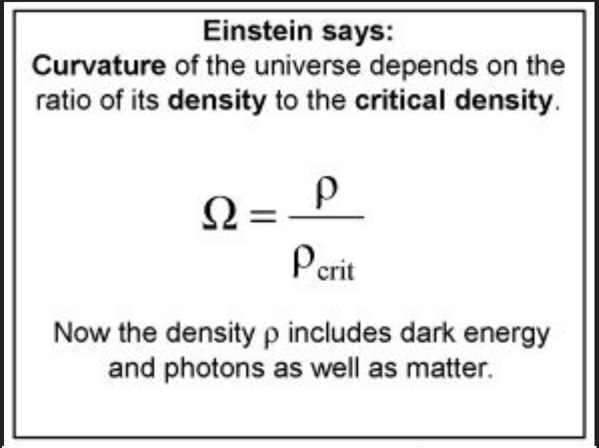
Newtonian result (no dark energy).

Ω>1 (density greater than critical):
The Big Crunch
(recollapse, becoming hotter)

Ω≤1 (density less than or equal to critical):
The Big Chill
(perpetual expansion, becoming cooler)



Amusing speculation: perhaps a Big Crunch would lead to a Big Bounce.

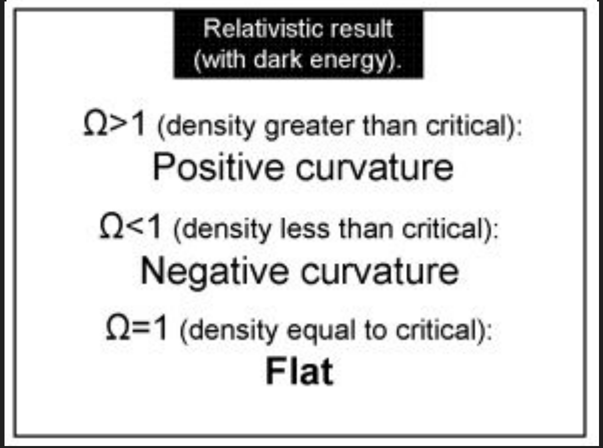


Einstein says:

Curvature of the universe depends on the ratio of its **density** to the **critical density**.

$$\Omega = \frac{\rho}{\rho_{\text{crit}}}$$

Now the density ρ includes dark energy and photons as well as matter.



Relativistic result (with dark energy).

$\Omega>1$ (density greater than critical):

Positive curvature

$\Omega<1$ (density less than critical):

Negative curvature

$\Omega=1$ (density equal to critical):

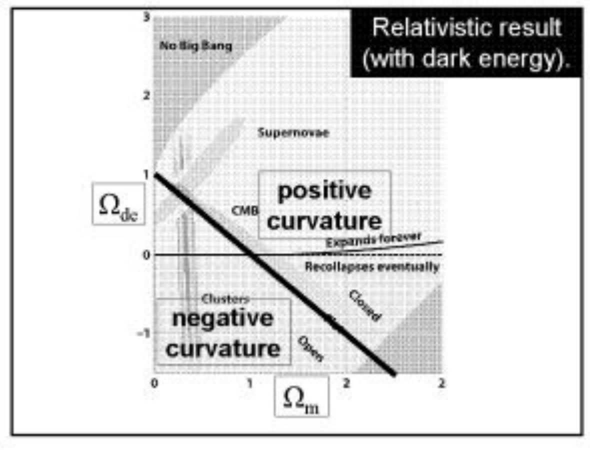
Flat

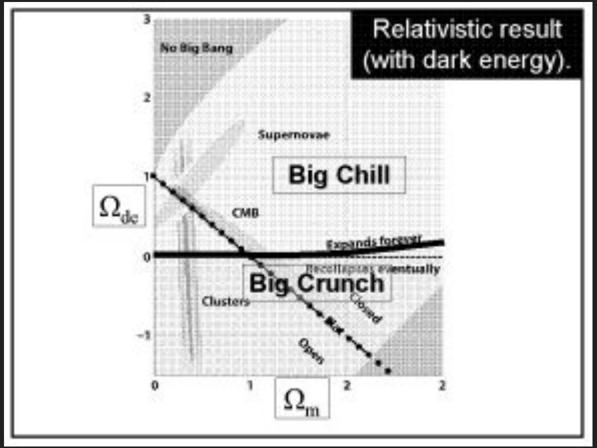
Einstein says:

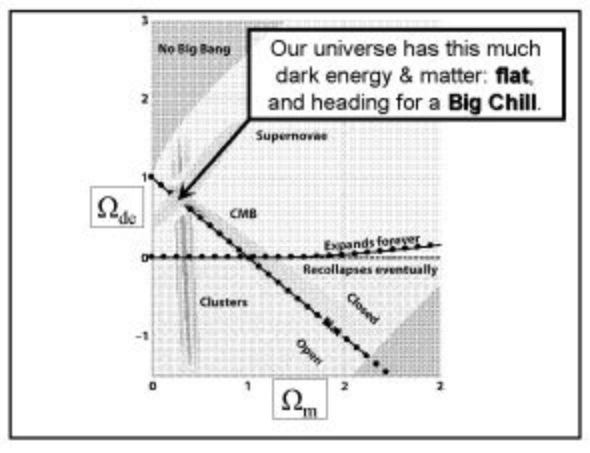
Destiny of the universe depends on the amounts of matter & dark energy today.

$$\Omega_m = \frac{\rho_{matter}}{\rho_{crit}} \qquad \Omega_{de} = \frac{\rho_{dark\,energy}}{\rho_{crit}}$$

Today, $\Omega_m = 0.27$, $\Omega_{de} = 0.73$



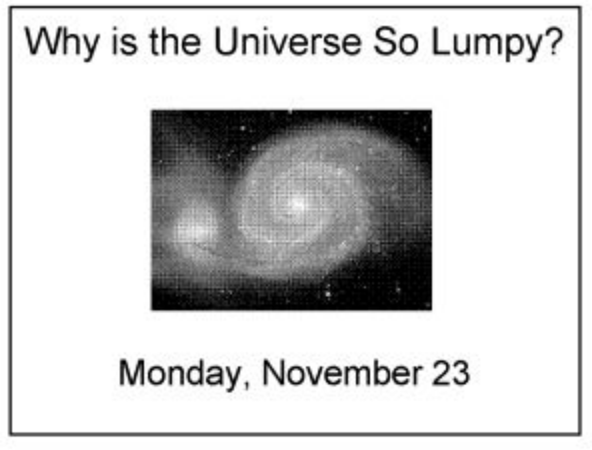




Our universe has this much dark energy & matter: **flat**, and heading for a **Big Chill**.

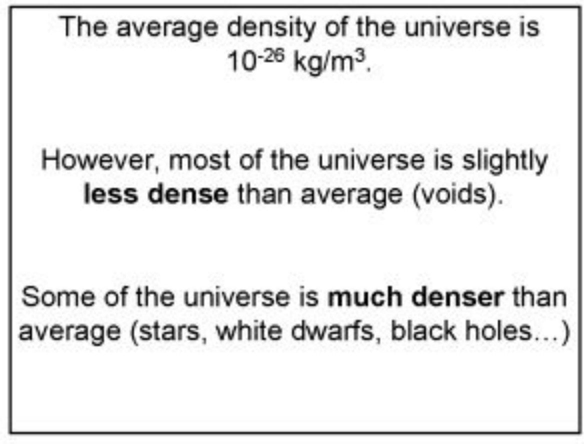
Preparatory Reading Chapter 12

Week 10: Why is the Universe Lumpy?



Why is the Universe So Lumpy?

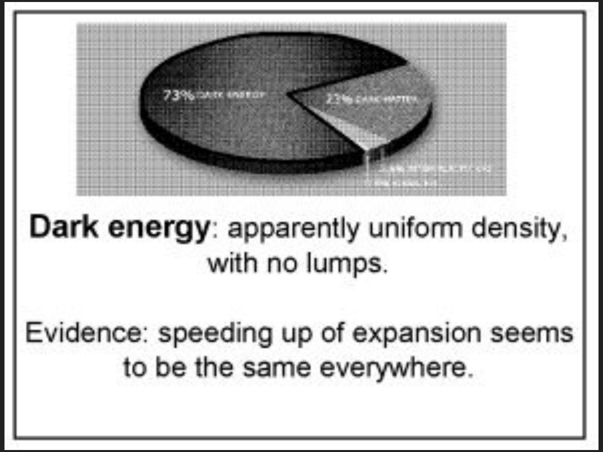
Monday, November 23



The average density of the universe is 10^{-26} kg/m^3.

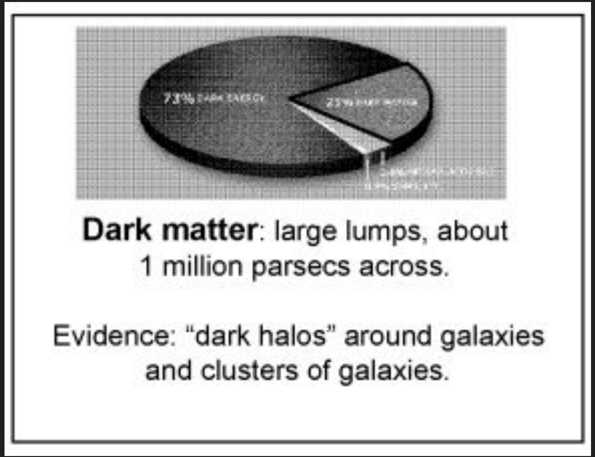
However, most of the universe is slightly **less dense** than average (voids).

Some of the universe is **much denser** than average (stars, white dwarfs, black holes…)



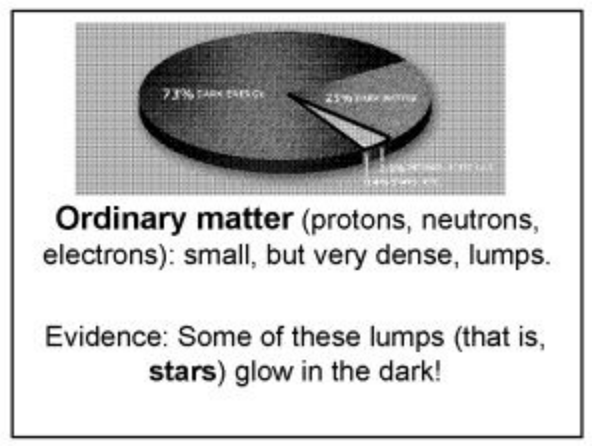
Dark energy: apparently uniform density, with no lumps.

Evidence: speeding up of expansion seems to be the same everywhere.



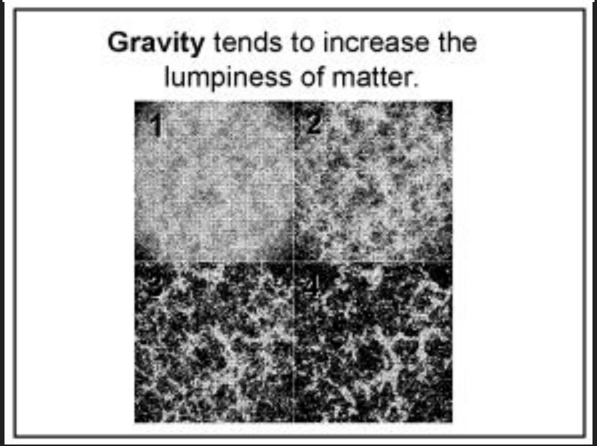
Dark matter: large lumps, about 1 million parsecs across.

Evidence: “dark halos” around galaxies and clusters of galaxies.

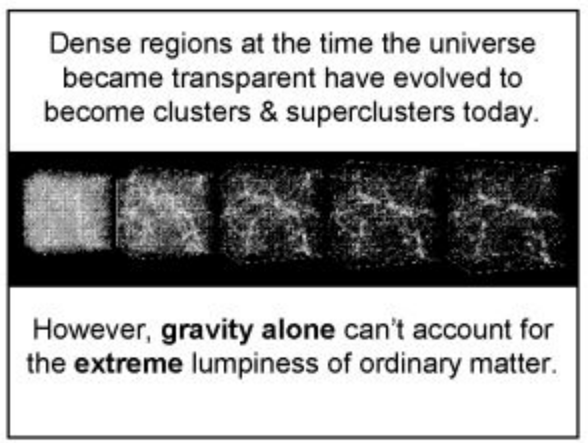


Ordinary matter (protons, neutrons, electrons): small, but very dense, lumps.

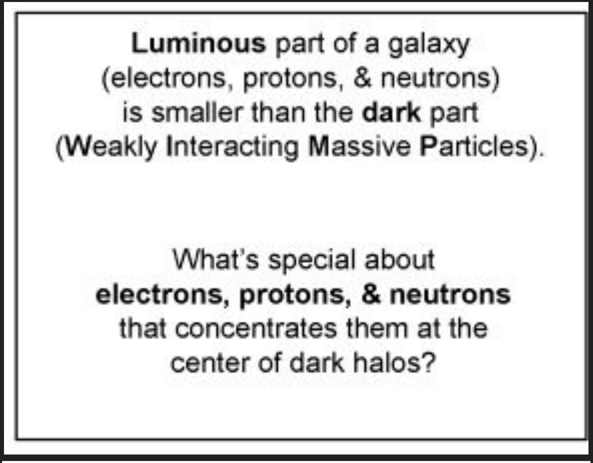
Evidence: Some of these lumps (that is, **stars**) glow in the dark!



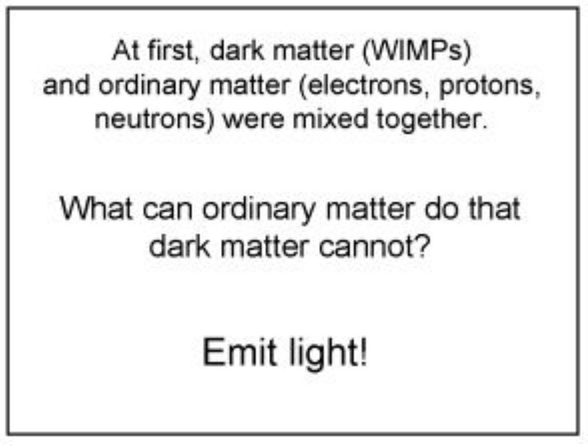
Gravity tends to increase the lumpiness of matter.


Dense regions at the time the universe became transparent have evolved to become clusters & superclusters today.

However, **gravity alone** can't account for the **extreme** lumpiness of ordinary matter.

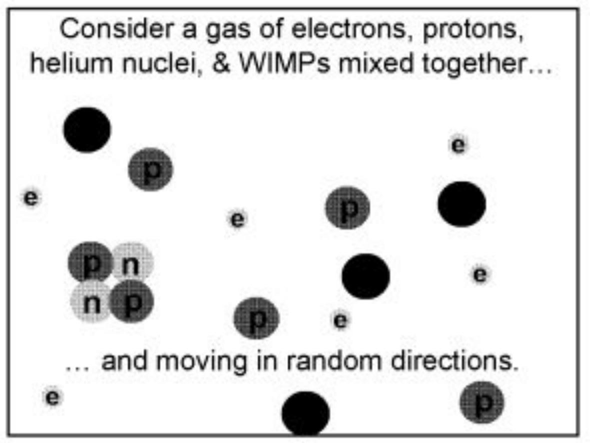

Luminous part of a galaxy
(electrons, protons, & neutrons)
is smaller than the **dark** part
(**W**eakly **I**nteracting **M**assive **P**articles).

What's special about
electrons, protons, & neutrons
that concentrates them at the
center of dark halos?


At first, dark matter (WIMPs) and ordinary matter (electrons, protons, neutrons) were mixed together.

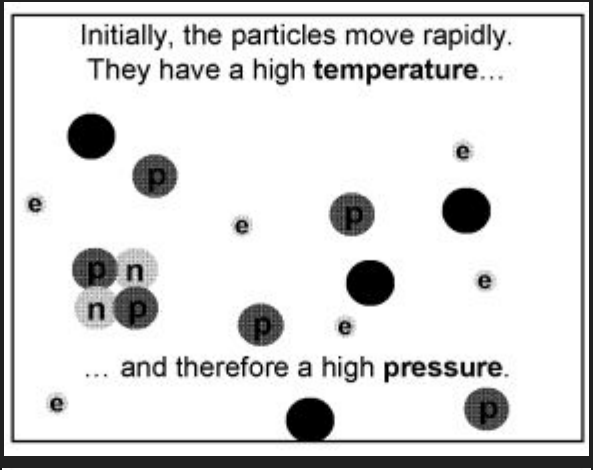
What can ordinary matter do that dark matter cannot?

Emit light!



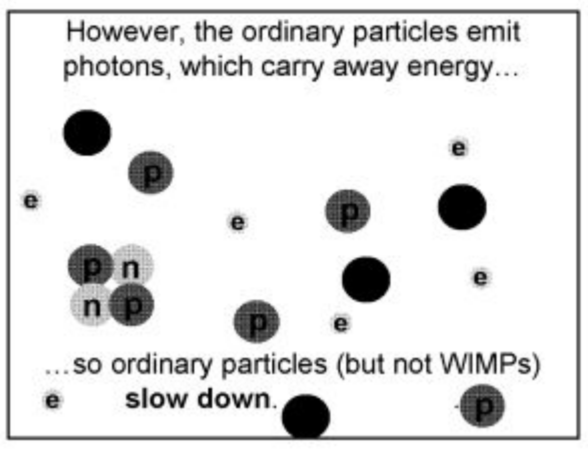
Consider a gas of electrons, protons, helium nuclei, & WIMPs mixed together…

… and moving in random directions.



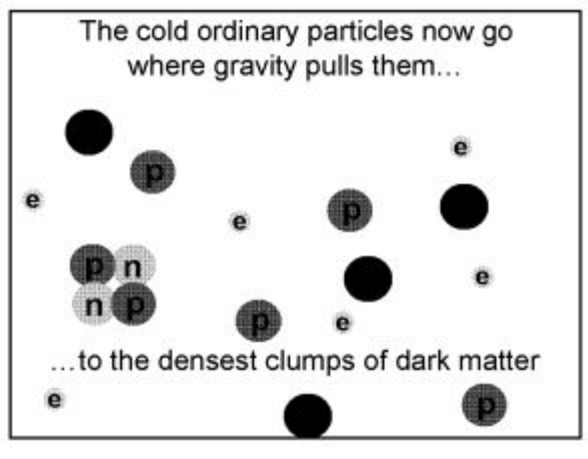
Initially, the particles move rapidly. They have a high **temperature**…

… and therefore a high **pressure**.



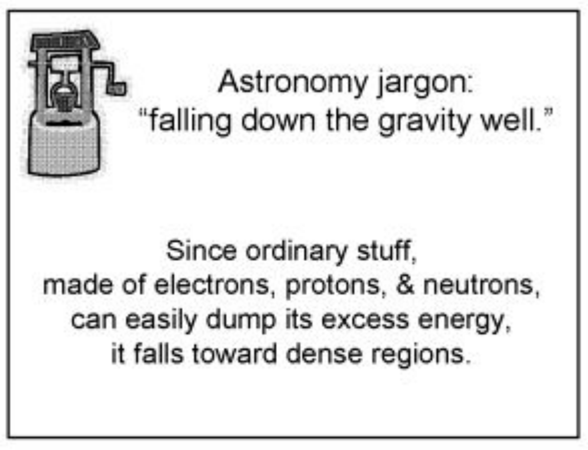
However, the ordinary particles emit photons, which carry away energy…

…so ordinary particles (but not WIMPs) **slow down**.



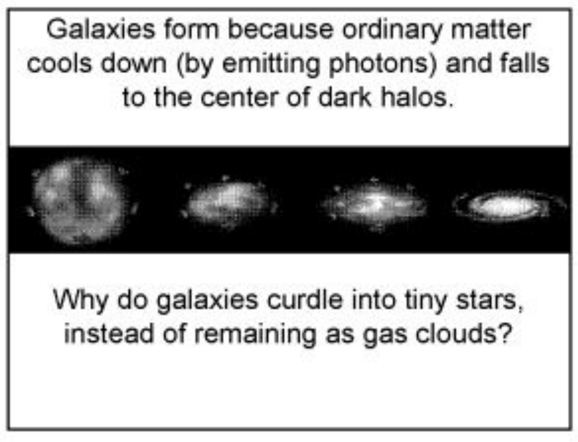
The cold ordinary particles now go where gravity pulls them…

…to the densest clumps of dark matter



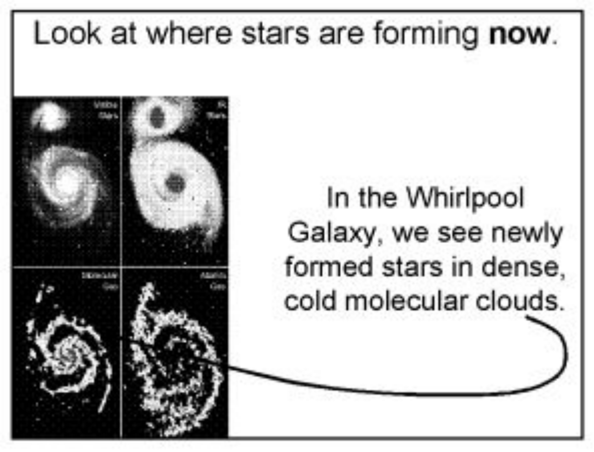
Astronomy jargon:
“falling down the gravity well.”

Since ordinary stuff,
made of electrons, protons, & neutrons,
can easily dump its excess energy,
it falls toward dense regions.



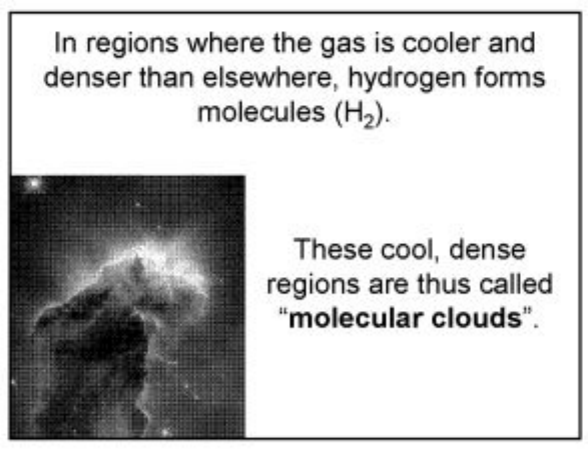
Galaxies form because ordinary matter cools down (by emitting photons) and falls to the center of dark halos.

Why do galaxies curdle into tiny stars, instead of remaining as gas clouds?



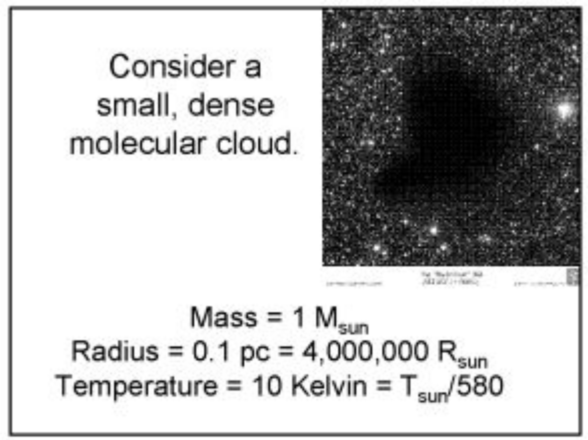
Look at where stars are forming **now**.

In the Whirlpool Galaxy, we see newly formed stars in dense, cold molecular clouds.



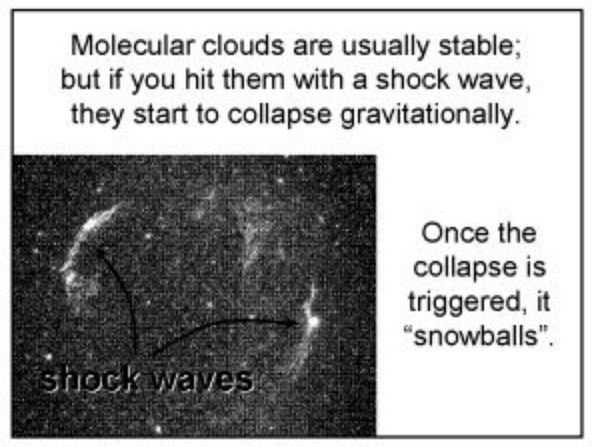
In regions where the gas is cooler and denser than elsewhere, hydrogen forms molecules (H_2).

These cool, dense regions are thus called “**molecular clouds**”.



Consider a small, dense molecular cloud.

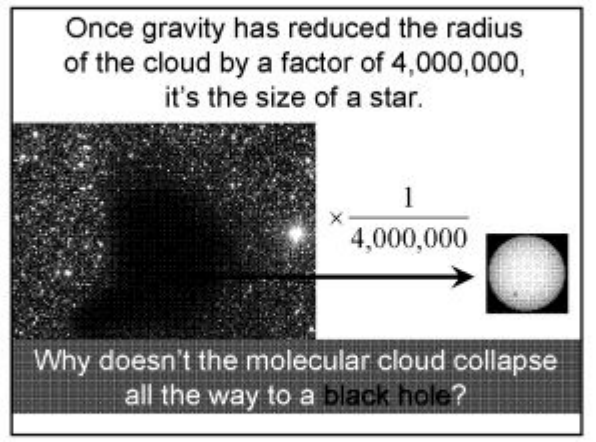
Mass = 1 M_{sun}
Radius = 0.1 pc = 4,000,000 R_{sun}
Temperature = 10 Kelvin = $T_{sun}/580$



Molecular clouds are usually stable; but if you hit them with a shock wave, they start to collapse gravitationally.

shock waves

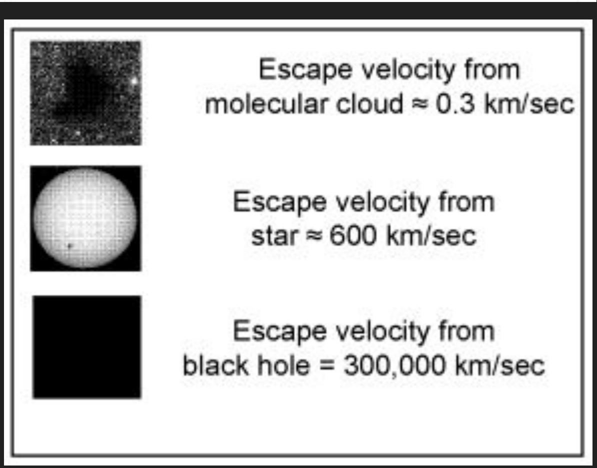
Once the collapse is triggered, it “snowballs”.



Once gravity has reduced the radius of the cloud by a factor of 4,000,000, it’s the size of a star.

$\times \frac{1}{4{,}000{,}000}$

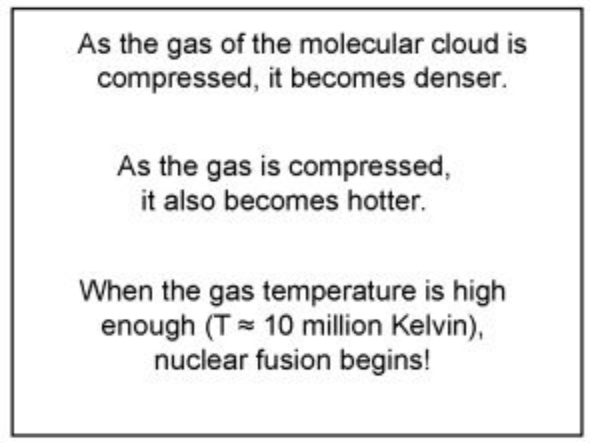
Why doesn’t the molecular cloud collapse all the way to a black hole?



Escape velocity from molecular cloud ≈ 0.3 km/sec

Escape velocity from star ≈ 600 km/sec

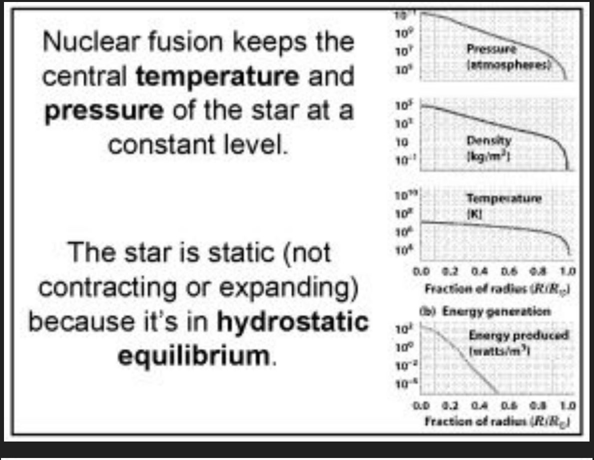
Escape velocity from black hole = 300,000 km/sec



As the gas of the molecular cloud is compressed, it becomes denser.

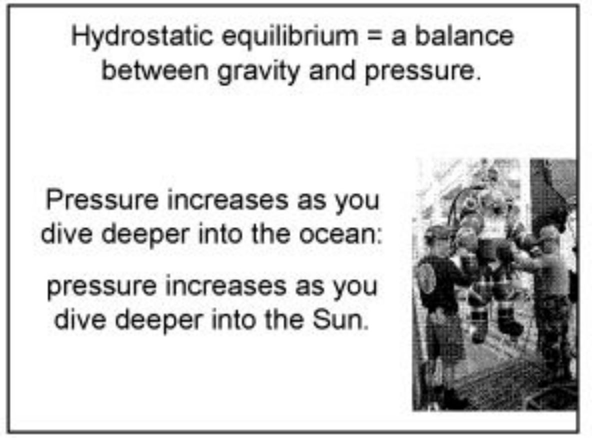
As the gas is compressed,
it also becomes hotter.

When the gas temperature is high enough (T ≈ 10 million Kelvin), nuclear fusion begins!



Nuclear fusion keeps the central **temperature** and **pressure** of the star at a constant level.

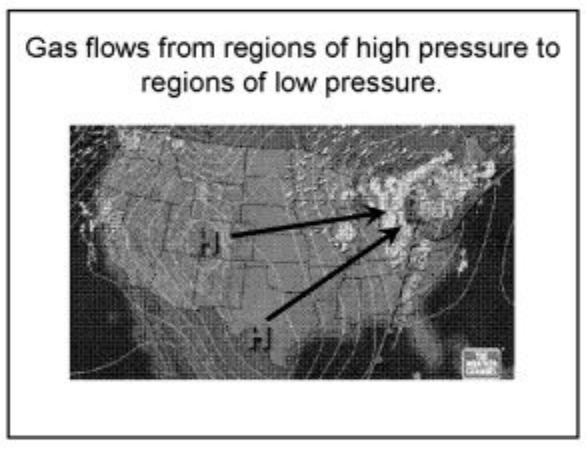
The star is static (not contracting or expanding) because it’s in **hydrostatic equilibrium**.



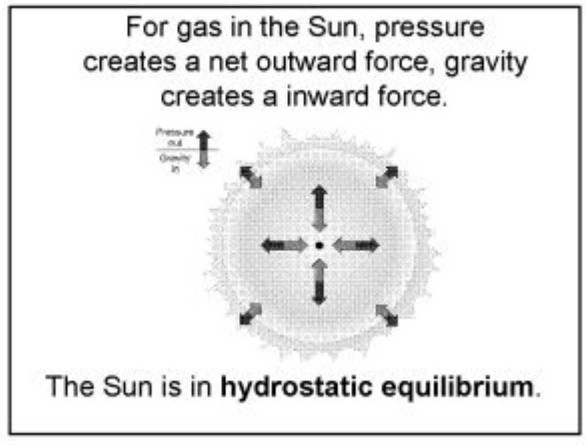
Hydrostatic equilibrium = a balance between gravity and pressure.

Pressure increases as you dive deeper into the ocean:

pressure increases as you dive deeper into the Sun.

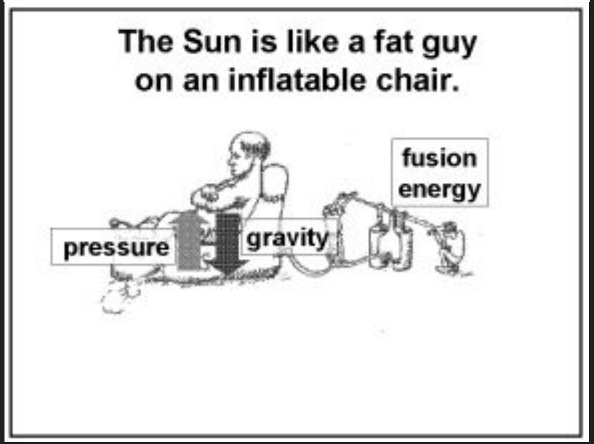


Gas flows from regions of high pressure to regions of low pressure.

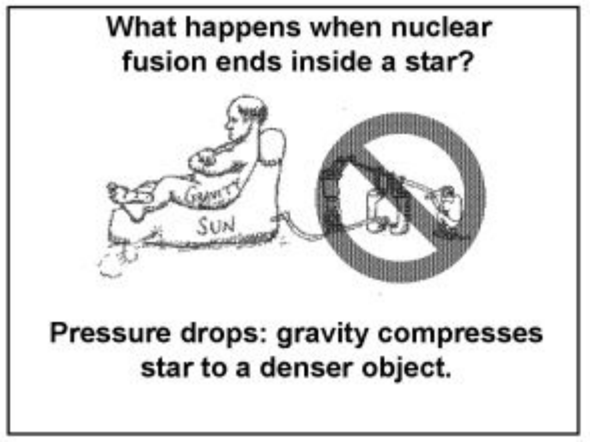


For gas in the Sun, pressure creates a net outward force, gravity creates a inward force.

The Sun is in **hydrostatic equilibrium**.

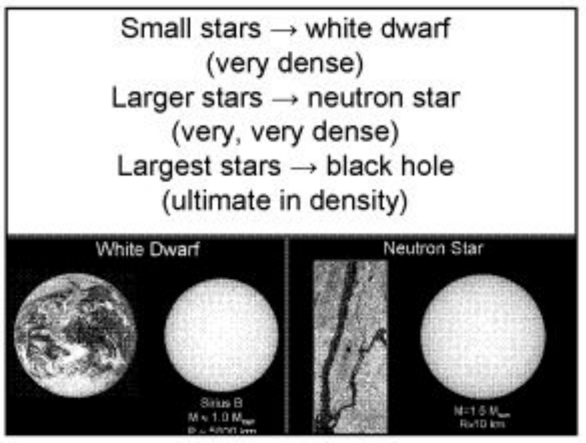


The Sun is like a fat guy on an inflatable chair.



What happens when nuclear fusion ends inside a star?

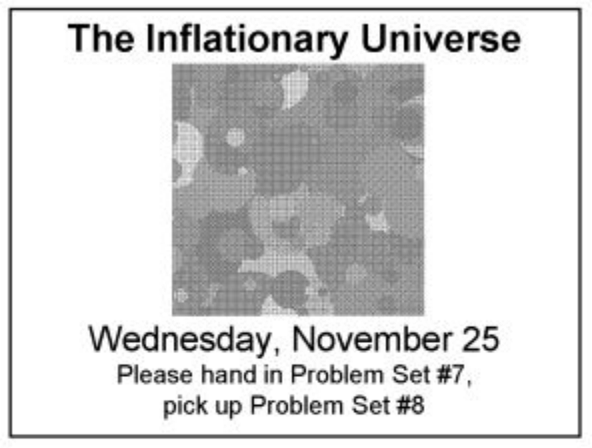
Pressure drops: gravity compresses star to a denser object.



Small stars → white dwarf
(very dense)
Larger stars → neutron star
(very, very dense)
Largest stars → black hole
(ultimate in density)

Preparatory Reading Chapter 12

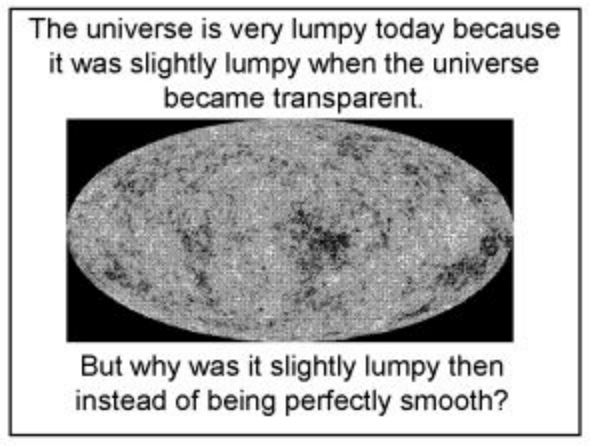
Week 10: The Inflationary Universe



The Inflationary Universe

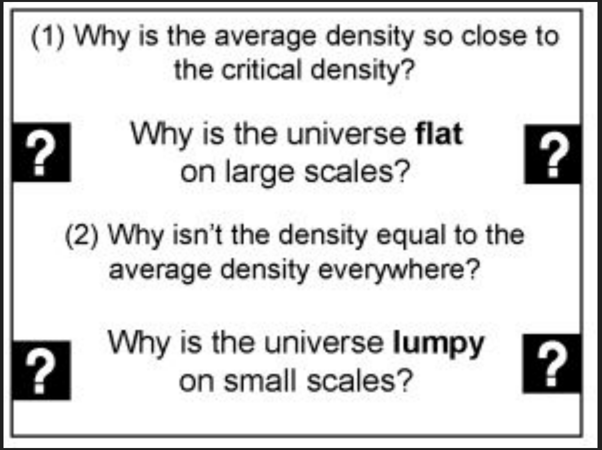
Wednesday, November 25

Please hand in Problem Set #7,
pick up Problem Set #8



The universe is very lumpy today because it was slightly lumpy when the universe became transparent.

But why was it slightly lumpy then instead of being perfectly smooth?

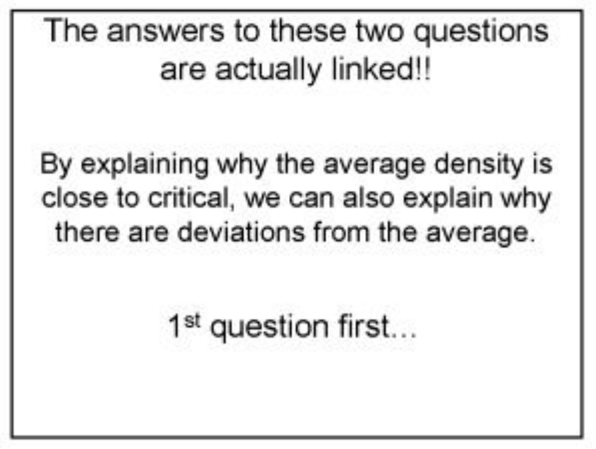


(1) Why is the average density so close to the critical density?

? Why is the universe **flat** on large scales? ?

(2) Why isn't the density equal to the average density everywhere?

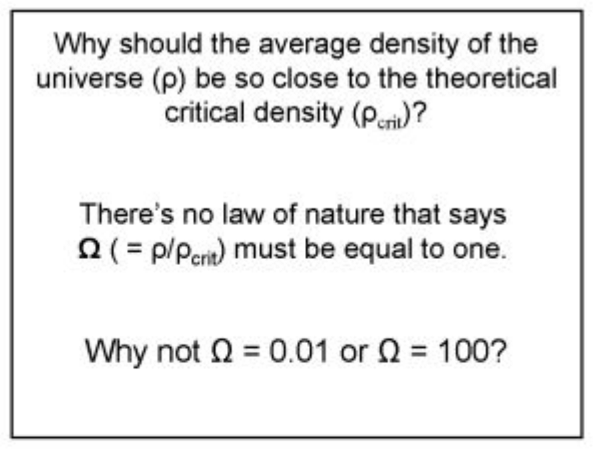
? Why is the universe **lumpy** on small scales? ?



The answers to these two questions are actually linked!!

By explaining why the average density is close to critical, we can also explain why there are deviations from the average.

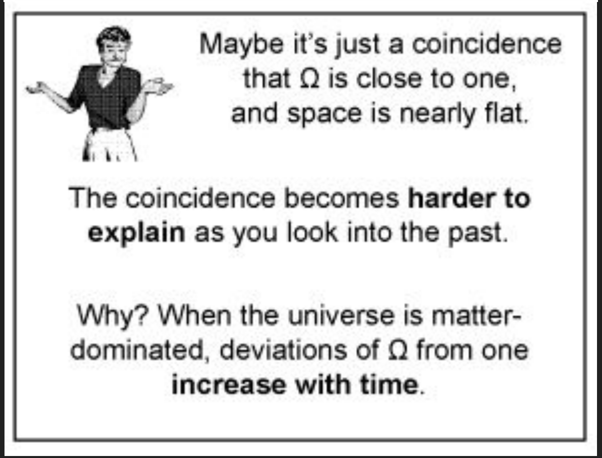
1^{st} question first…



Why should the average density of the universe (ρ) be so close to the theoretical critical density (ρ_{crit})?

There's no law of nature that says $\boldsymbol{\Omega}$ ($= \rho/\rho_{crit}$) must be equal to one.

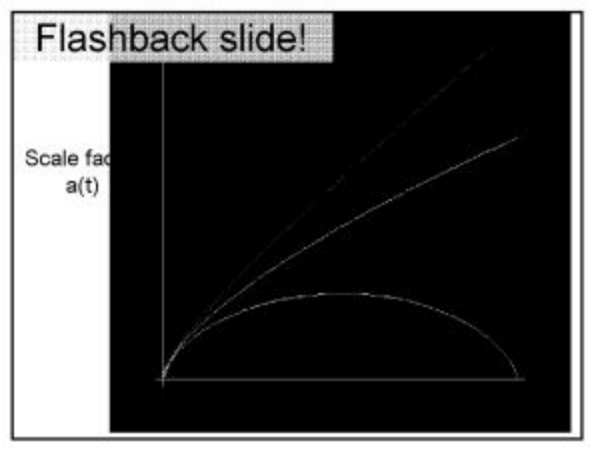
Why not $\Omega = 0.01$ or $\Omega = 100$?



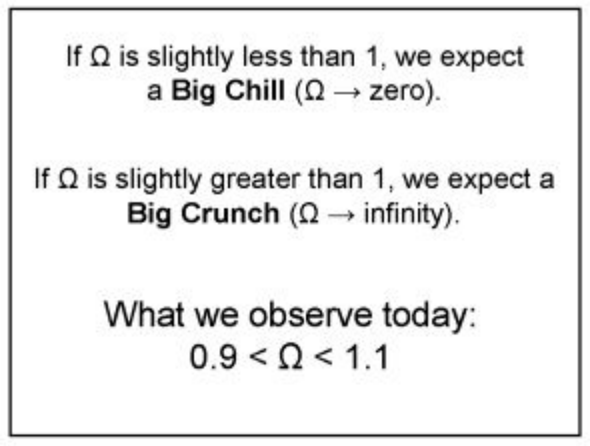
Maybe it's just a coincidence that Ω is close to one, and space is nearly flat.

The coincidence becomes **harder to explain** as you look into the past.

Why? When the universe is matter-dominated, deviations of Ω from one **increase with time**.



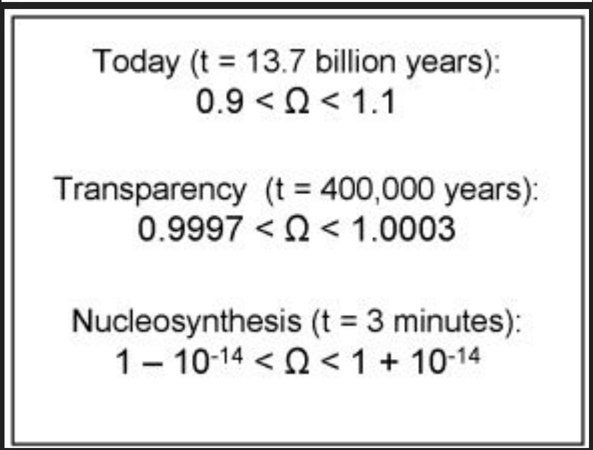
Flashback slide!



If Ω is slightly less than 1, we expect a **Big Chill** (Ω → zero).

If Ω is slightly greater than 1, we expect a **Big Crunch** (Ω → infinity).

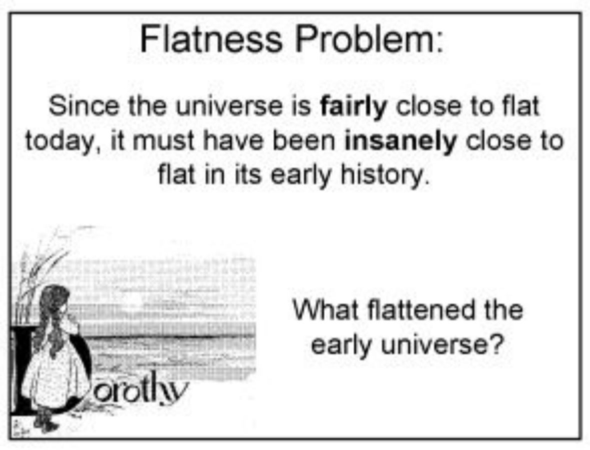
What we observe today:
$0.9 < \Omega < 1.1$



Today (t = 13.7 billion years):
$0.9 < \Omega < 1.1$

Transparency (t = 400,000 years):
$0.9997 < \Omega < 1.0003$

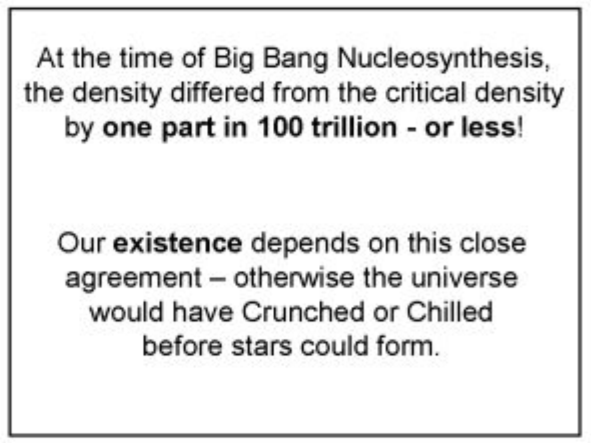
Nucleosynthesis (t = 3 minutes):
$1 - 10^{-14} < \Omega < 1 + 10^{-14}$



Flatness Problem:

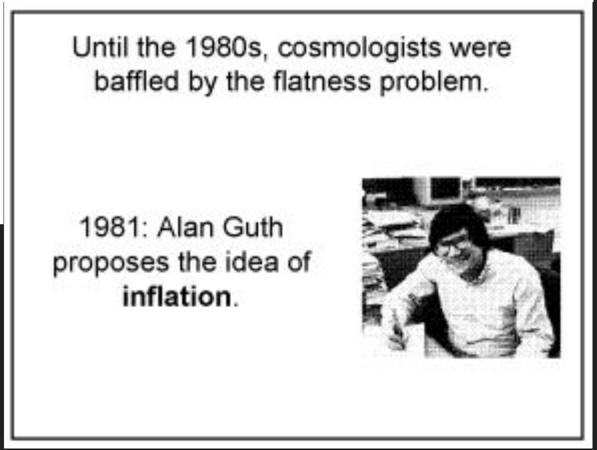
Since the universe is **fairly** close to flat today, it must have been **insanely** close to flat in its early history.

What flattened the early universe?



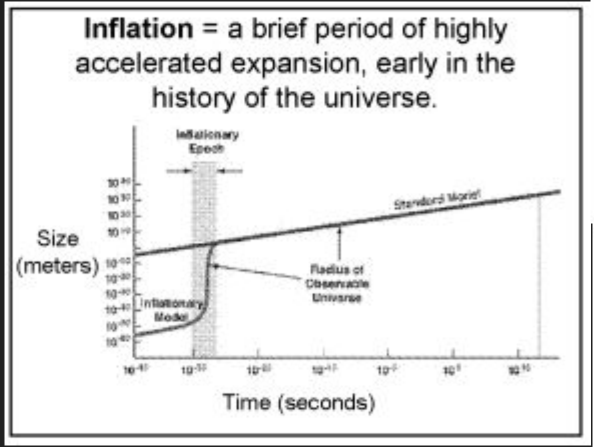
At the time of Big Bang Nucleosynthesis, the density differed from the critical density by **one part in 100 trillion - or less**!

Our **existence** depends on this close agreement – otherwise the universe would have Crunched or Chilled before stars could form.

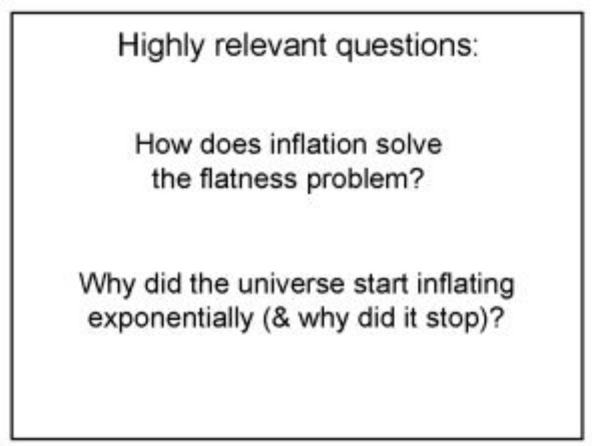


Until the 1980s, cosmologists were baffled by the flatness problem.

1981: Alan Guth proposes the idea of **inflation**.



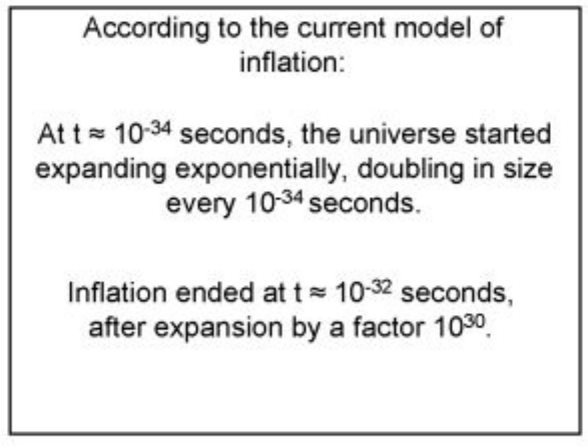
Inflation = a brief period of highly accelerated expansion, early in the history of the universe.



Highly relevant questions:

How does inflation solve the flatness problem?

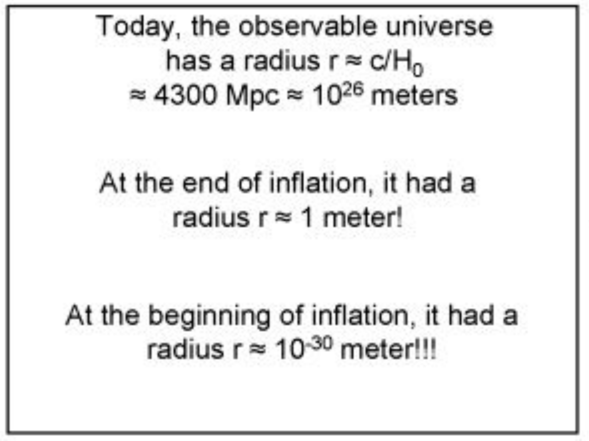
Why did the universe start inflating exponentially (& why did it stop)?



According to the current model of inflation:

At t ≈ 10^{-34} seconds, the universe started expanding exponentially, doubling in size every 10^{-34} seconds.

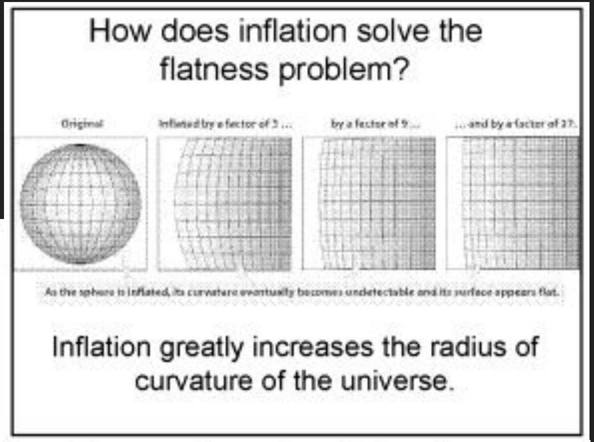
Inflation ended at t ≈ 10^{-32} seconds, after expansion by a factor 10^{30}.



Today, the observable universe has a radius $r \approx c/H_0$ $\approx$ 4300 Mpc $\approx 10^{26}$ meters

At the end of inflation, it had a radius $r \approx 1$ meter!

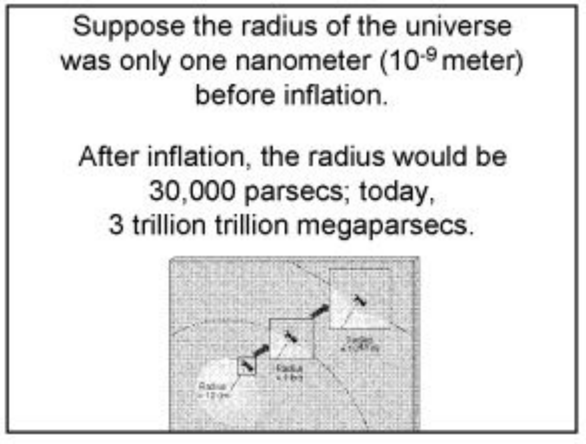
At the beginning of inflation, it had a radius $r \approx 10^{-30}$ meter!!!



How does inflation solve the flatness problem?

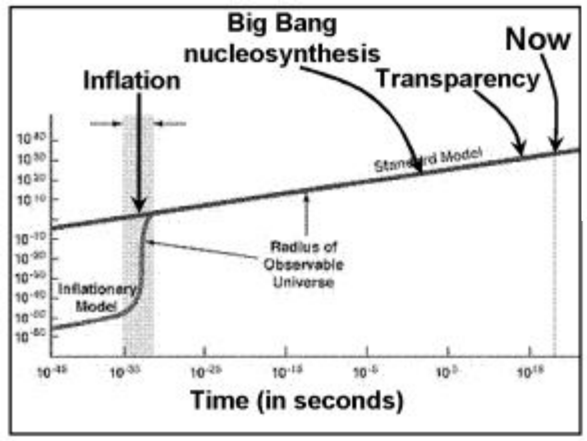
As the sphere is inflated, its curvature eventually becomes undetectable and its surface appears flat.

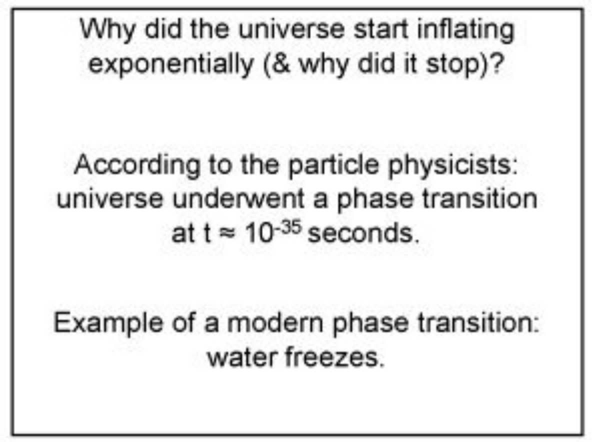
Inflation greatly increases the radius of curvature of the universe.



Suppose the radius of the universe was only one nanometer (10^{-9} meter) before inflation.

After inflation, the radius would be 30,000 parsecs; today,
3 trillion trillion megaparsecs.

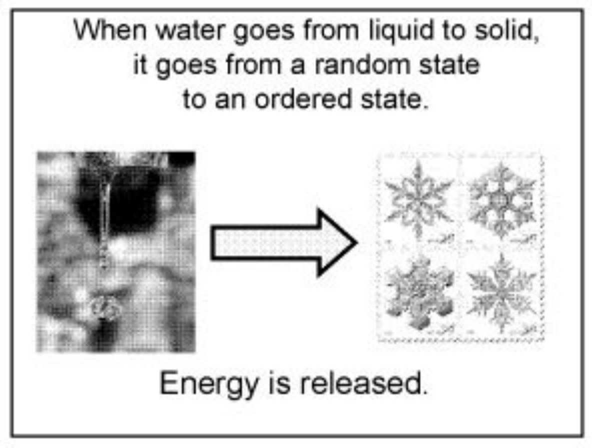




Why did the universe start inflating exponentially (& why did it stop)?

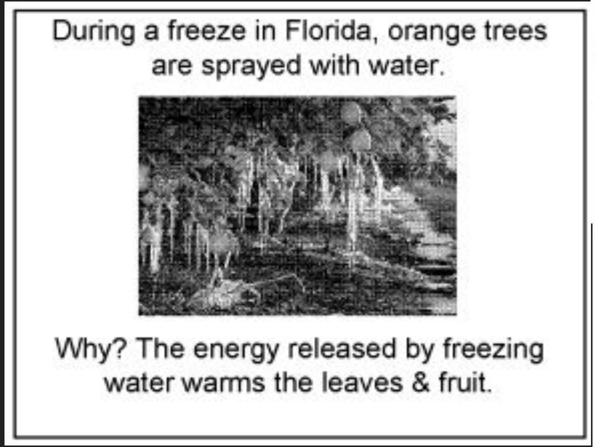
According to the particle physicists: universe underwent a phase transition at t ≈ 10^{-35} seconds.

Example of a modern phase transition: water freezes.



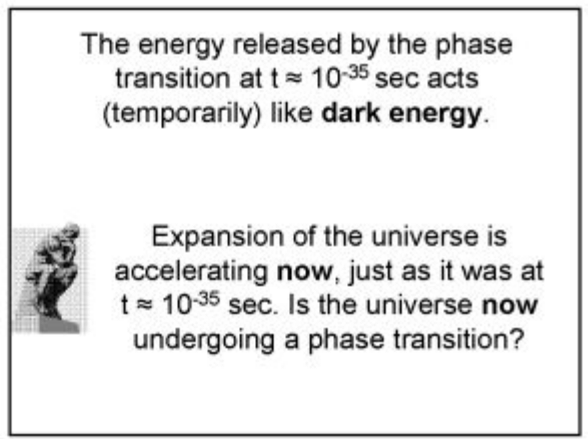
When water goes from liquid to solid, it goes from a random state to an ordered state.

Energy is released.



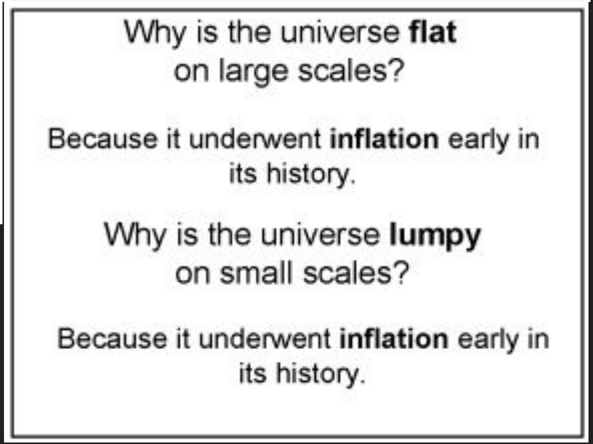
During a freeze in Florida, orange trees are sprayed with water.

Why? The energy released by freezing water warms the leaves & fruit.



The energy released by the phase transition at $t \approx 10^{-35}$ sec acts (temporarily) like **dark energy**.

Expansion of the universe is accelerating **now**, just as it was at $t \approx 10^{-35}$ sec. Is the universe **now** undergoing a phase transition?



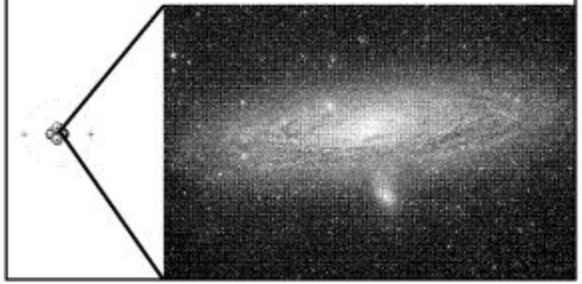
Why is the universe **flat** on large scales?

Because it underwent **inflation** early in its history.

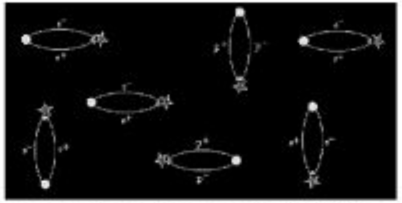
Why is the universe **lumpy** on small scales?

Because it underwent **inflation** early in its history.

Inflation increases a length of
1 nanometer (the size of an atom) to
30,000 parsecs (the size of a galaxy).



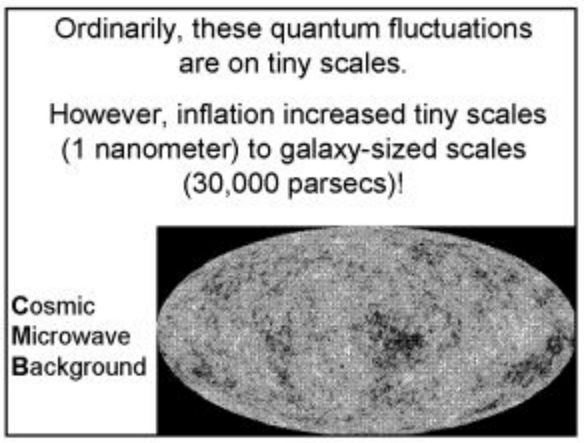
On subatomic scales, the universe is full of quantum fluctuations.



A vacuum looks empty, but it's full of particles & antiparticles being created & destroyed.

This is a result of Heisenberg's Uncertainty Principle: we can't specify exactly the energy of a subatomic patch of the universe.

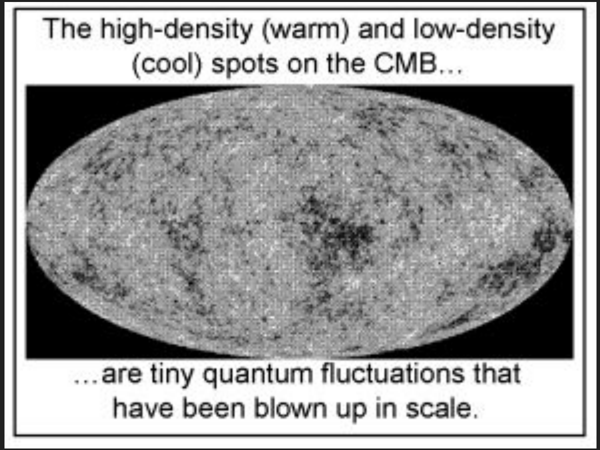
Some patches are higher in energy: some are lower.



Ordinarily, these quantum fluctuations are on tiny scales.

However, inflation increased tiny scales (1 nanometer) to galaxy-sized scales (30,000 parsecs)!

Cosmic
Microwave
Background



The high-density (warm) and low-density (cool) spots on the CMB…

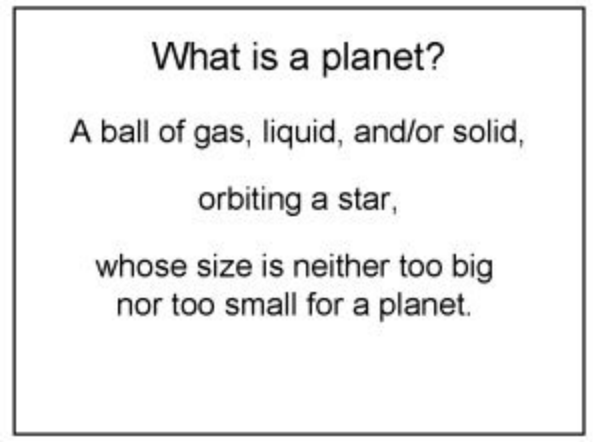
…are tiny quantum fluctuations that have been blown up in scale.

Preparatory Reading Chapter 13 & 14

Week 11: Planets

Planets

Monday, November 30

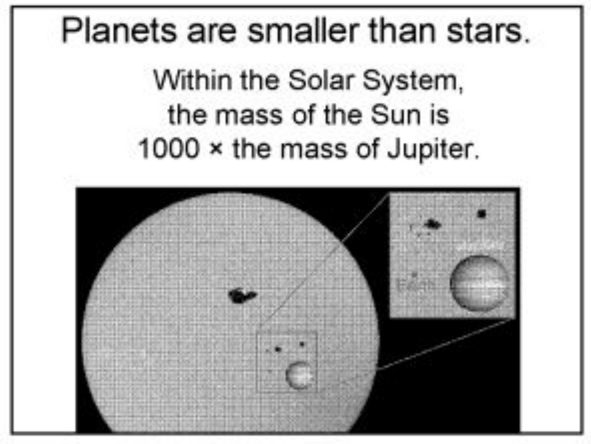


What is a planet?

A ball of gas, liquid, and/or solid,

orbiting a star,

whose size is neither too big
nor too small for a planet.



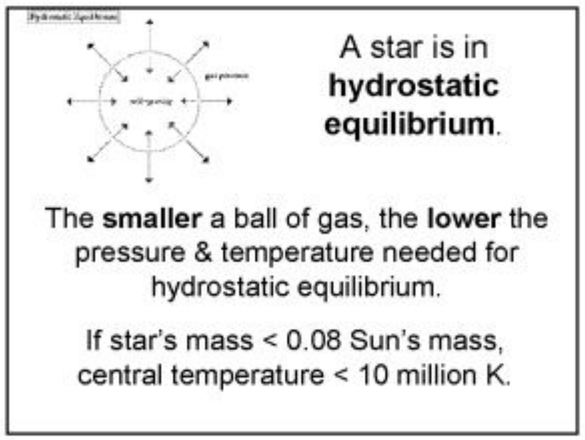
Planets are smaller than stars.

Within the Solar System,
the mass of the Sun is
1000 × the mass of Jupiter.

How small can a ball of gas be and still qualify as a **star**?

A star has **nuclear fusion**
occurring in its interior.

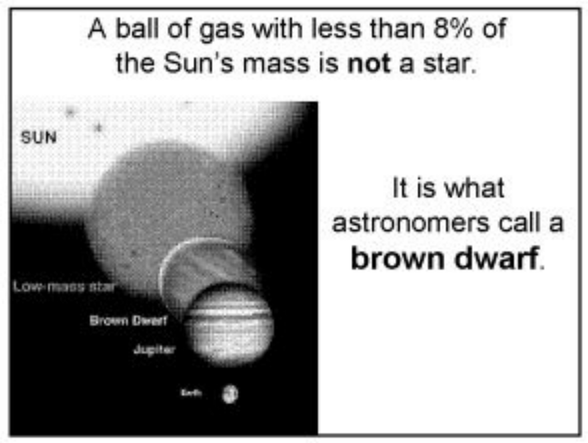
Fusion of hydrogen to helium
requires T > 10 million Kelvin.



A star is in
**hydrostatic
equilibrium**.

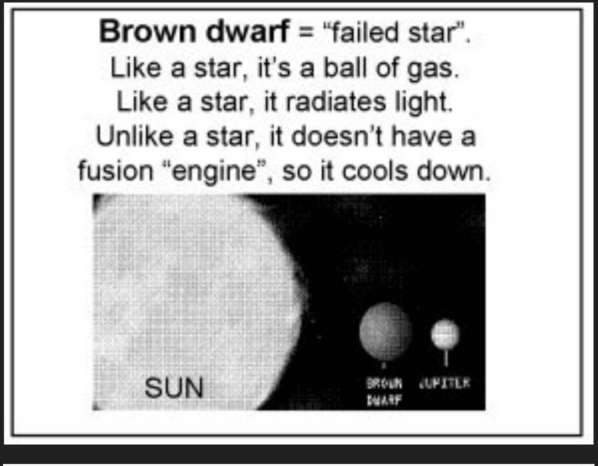
The **smaller** a ball of gas, the **lower** the pressure & temperature needed for hydrostatic equilibrium.

If star's mass < 0.08 Sun's mass,
central temperature < 10 million K.

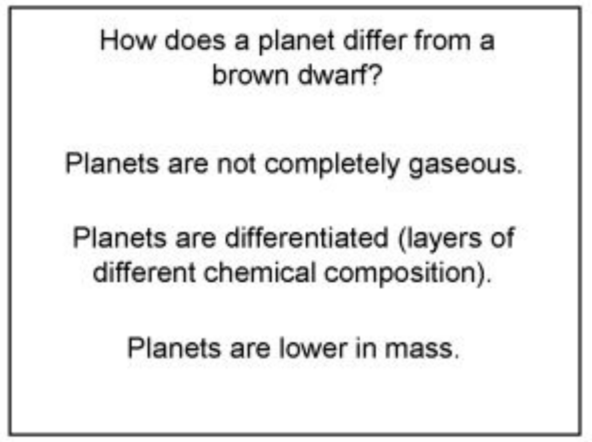


A ball of gas with less than 8% of the Sun's mass is **not** a star.

It is what astronomers call a **brown dwarf**.



Brown dwarf = "failed star".
Like a star, it's a ball of gas.
Like a star, it radiates light.
Unlike a star, it doesn't have a fusion "engine", so it cools down.

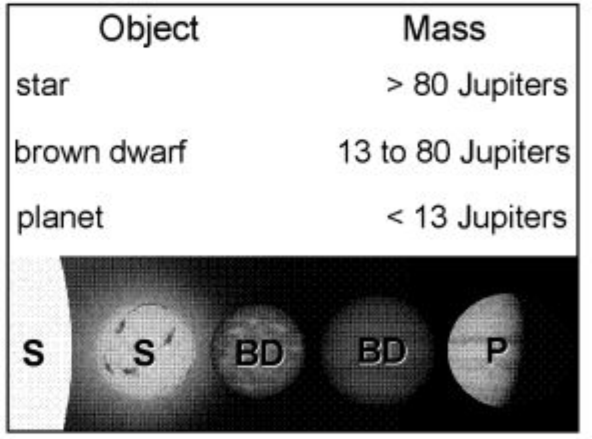


How does a planet differ from a brown dwarf?

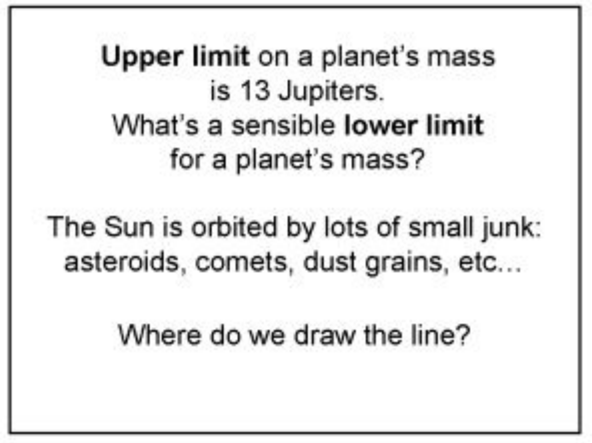
Planets are not completely gaseous.

Planets are differentiated (layers of different chemical composition).

Planets are lower in mass.



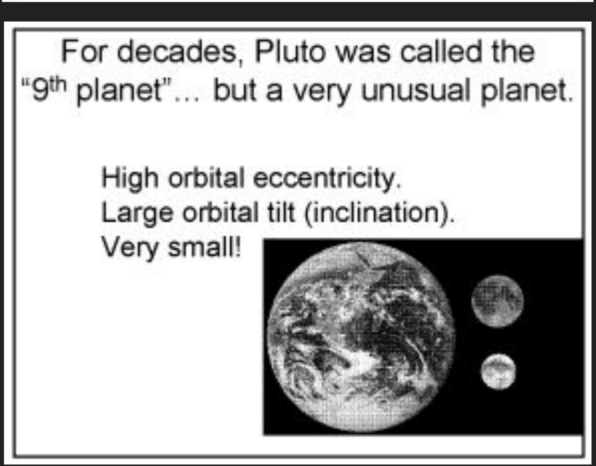
Object	Mass
star	> 80 Jupiters
brown dwarf	13 to 80 Jupiters
planet	< 13 Jupiters



Upper limit on a planet's mass
is 13 Jupiters.
What's a sensible **lower limit**
for a planet's mass?

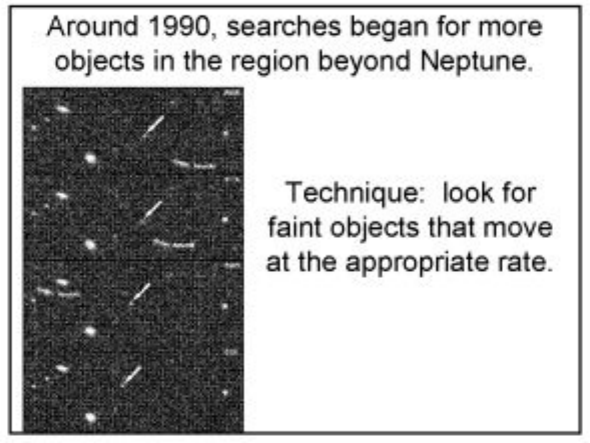
The Sun is orbited by lots of small junk:
asteroids, comets, dust grains, etc…

Where do we draw the line?



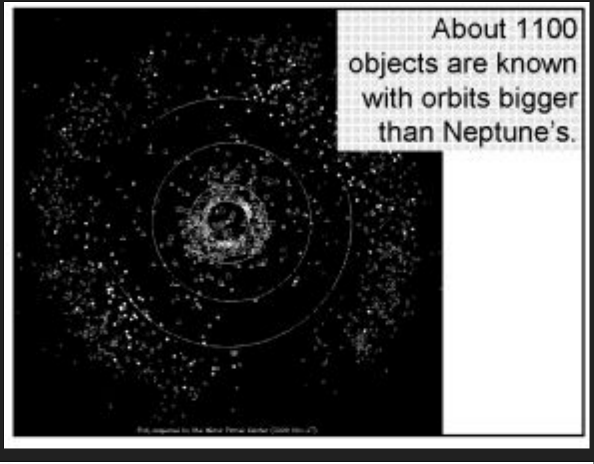
For decades, Pluto was called the "9th planet"… but a very unusual planet.

High orbital eccentricity.
Large orbital tilt (inclination).
Very small!

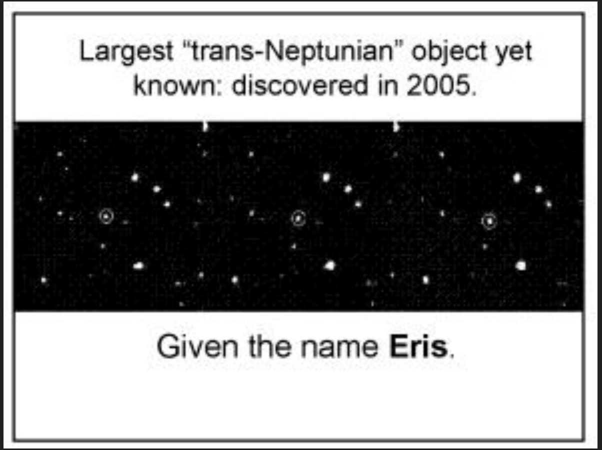


Around 1990, searches began for more objects in the region beyond Neptune.

Technique: look for faint objects that move at the appropriate rate.

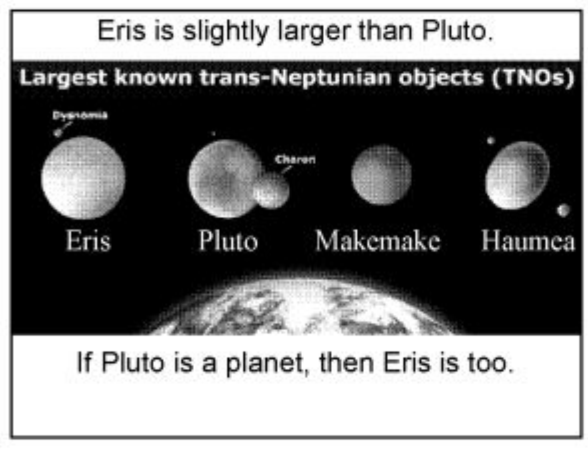


About 1100 objects are known with orbits bigger than Neptune's.



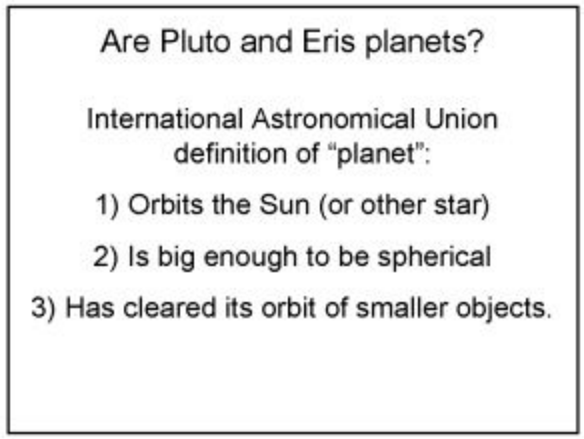
Largest “trans-Neptunian” object yet known: discovered in 2005.

Given the name **Eris**.



Eris is slightly larger than Pluto.

If Pluto is a planet, then Eris is too.



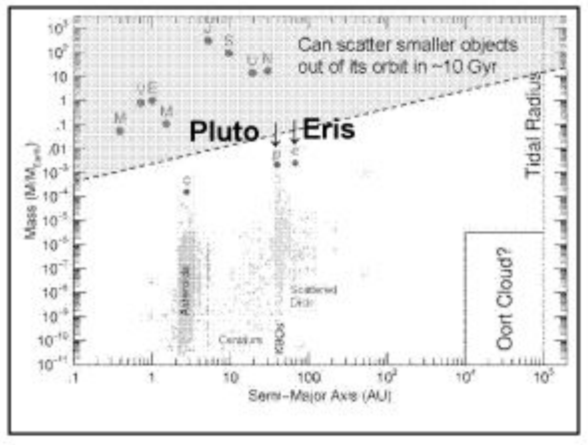
Are Pluto and Eris planets?

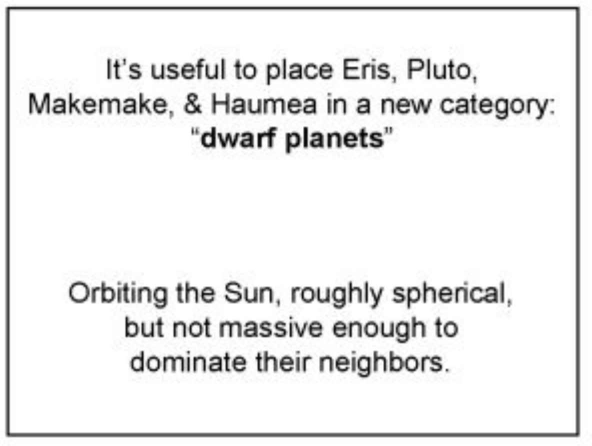
International Astronomical Union definition of "planet":

1) Orbits the Sun (or other star)

2) Is big enough to be spherical

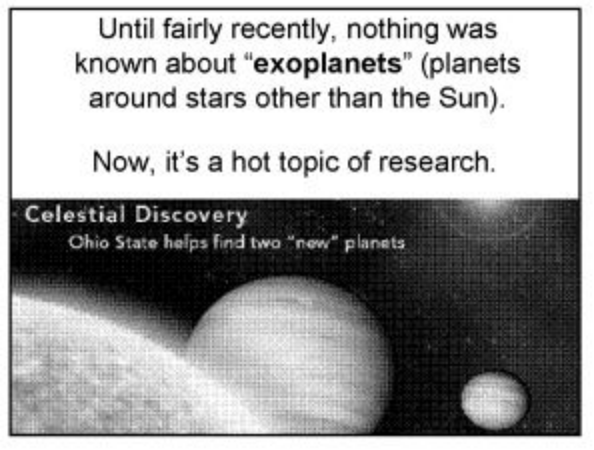
3) Has cleared its orbit of smaller objects.





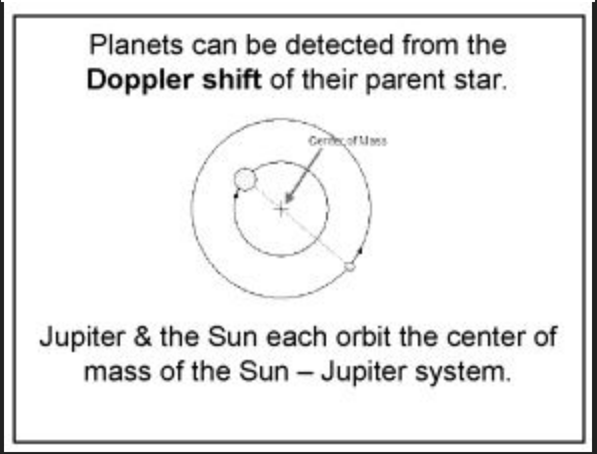
It's useful to place Eris, Pluto, Makemake, & Haumea in a new category: "**dwarf planets**"

Orbiting the Sun, roughly spherical, but not massive enough to dominate their neighbors.



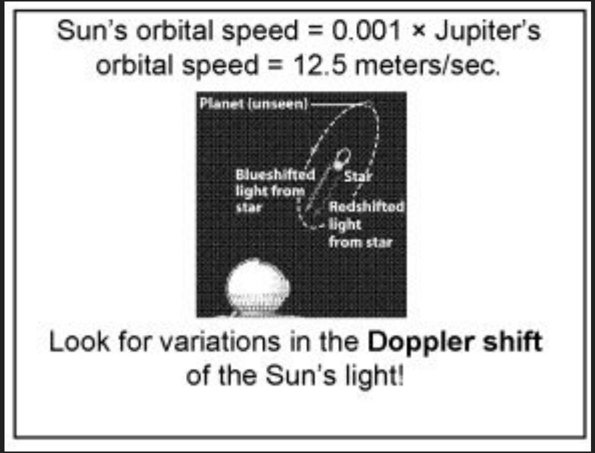
Until fairly recently, nothing was known about "**exoplanets**" (planets around stars other than the Sun).

Now, it's a hot topic of research.



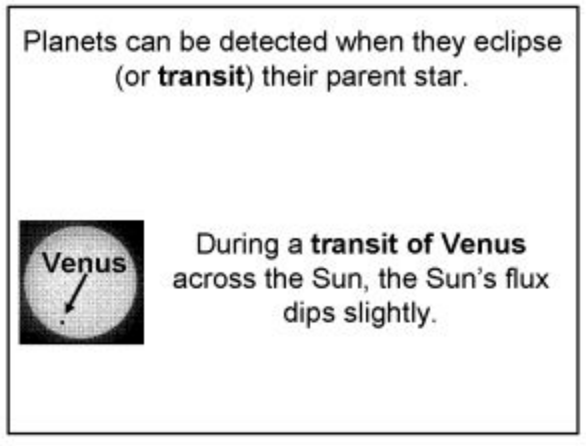
Planets can be detected from the **Doppler shift** of their parent star.

Jupiter & the Sun each orbit the center of mass of the Sun – Jupiter system.



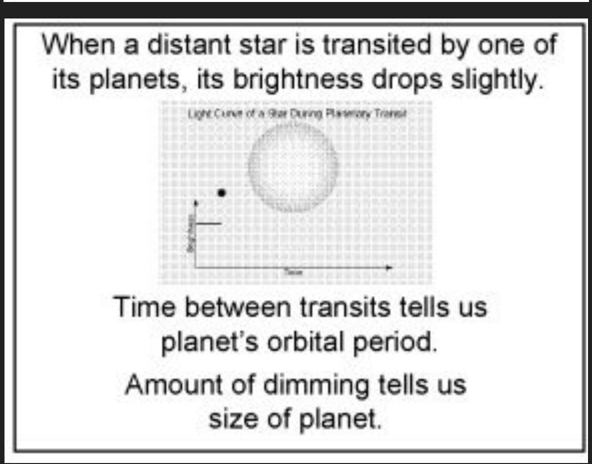
Sun’s orbital speed = 0.001 × Jupiter’s orbital speed = 12.5 meters/sec.

Look for variations in the **Doppler shift** of the Sun’s light!



Planets can be detected when they eclipse (or **transit**) their parent star.

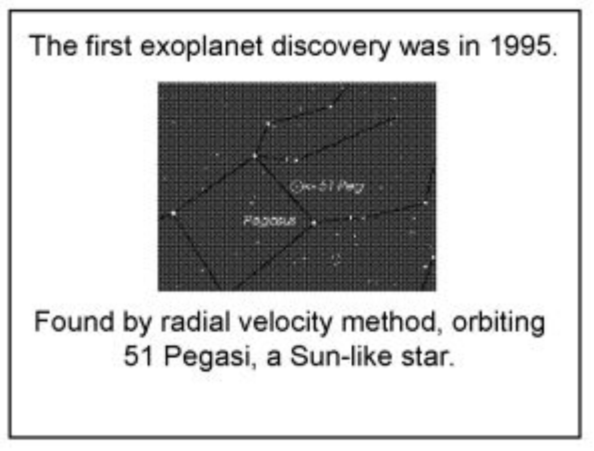
During a **transit of Venus** across the Sun, the Sun’s flux dips slightly.



When a distant star is transited by one of its planets, its brightness drops slightly.

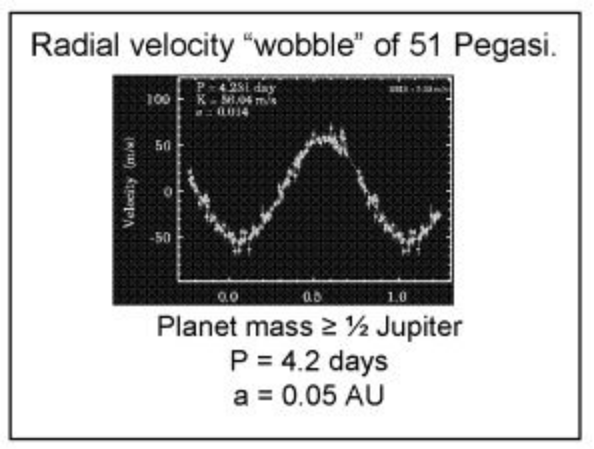
Time between transits tells us planet’s orbital period.

Amount of dimming tells us size of planet.



The first exoplanet discovery was in 1995.

Found by radial velocity method, orbiting 51 Pegasi, a Sun-like star.

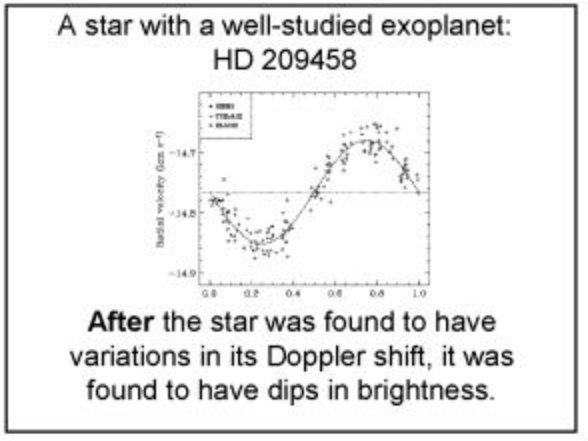


Radial velocity “wobble” of 51 Pegasi.

Planet mass ≥ ½ Jupiter

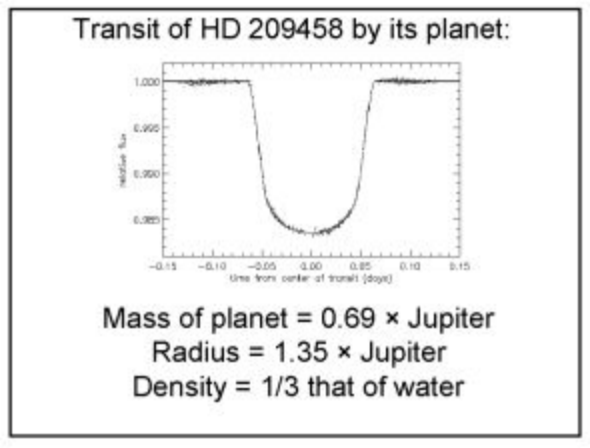
P = 4.2 days

a = 0.05 AU



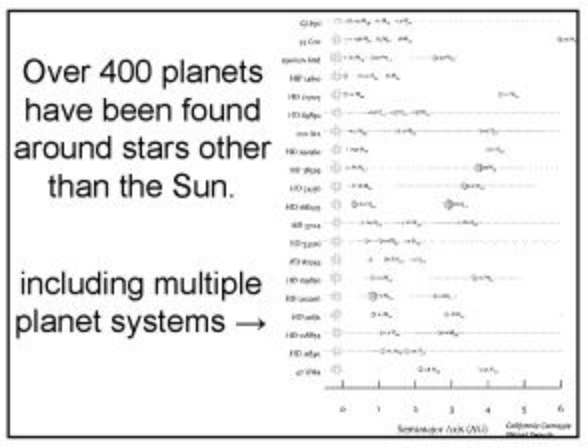
A star with a well-studied exoplanet: HD 209458

After the star was found to have variations in its Doppler shift, it was found to have dips in brightness.



Transit of HD 209458 by its planet:

Mass of planet = 0.69 × Jupiter
Radius = 1.35 × Jupiter
Density = 1/3 that of water

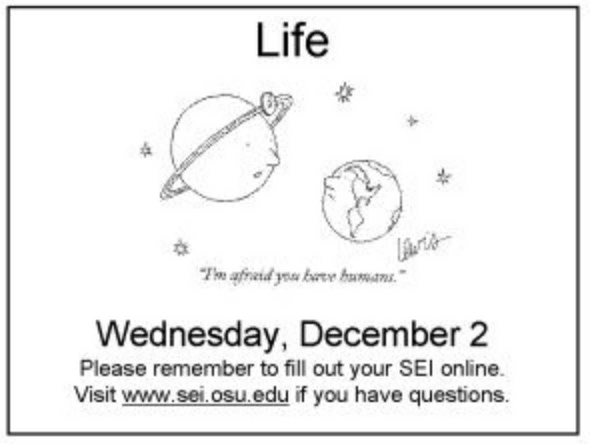


Over 400 planets have been found around stars other than the Sun.

including multiple planet systems →

Preparatory Reading Chapter 13 & 14

Week 11: Life

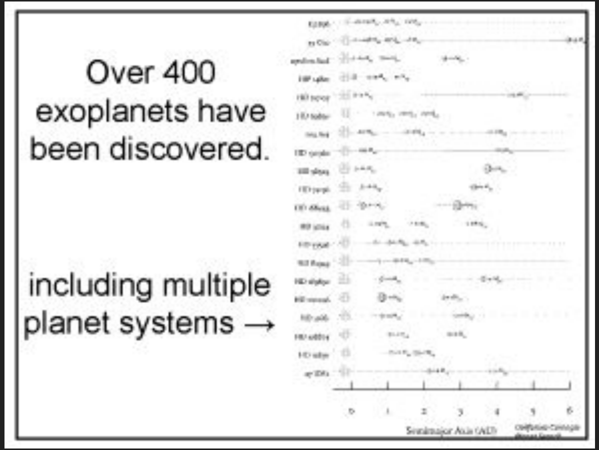


Life

"I'm afraid you have humans."

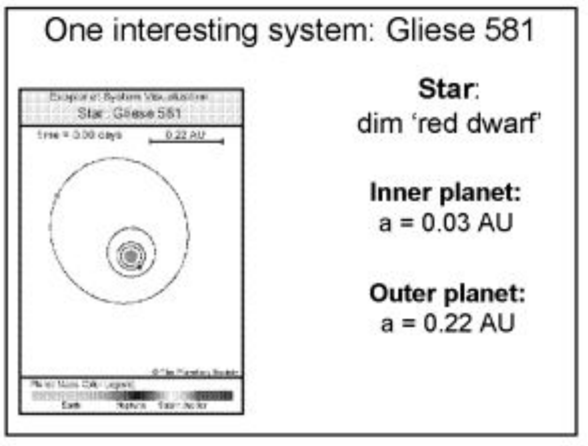
Wednesday, December 2

Please remember to fill out your SEI online.
Visit www.sei.osu.edu if you have questions.



Over 400 exoplanets have been discovered.

including multiple planet systems →

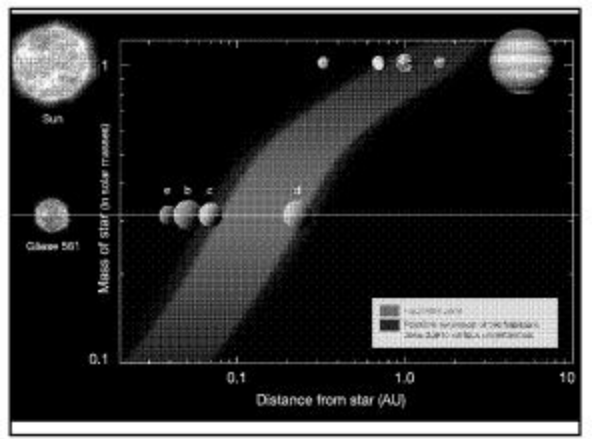


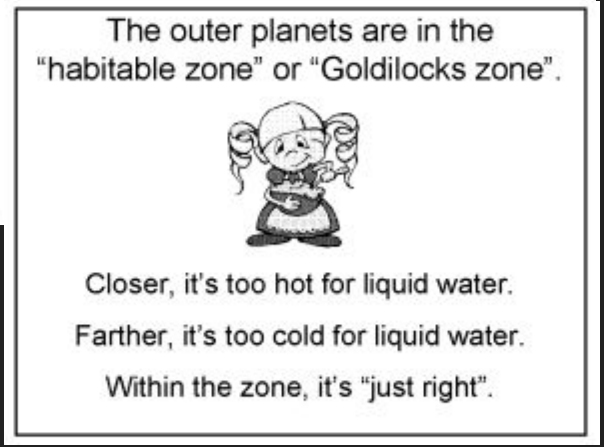
One interesting system: Gliese 581

Star:
dim 'red dwarf'

Inner planet:
a = 0.03 AU

Outer planet:
a = 0.22 AU



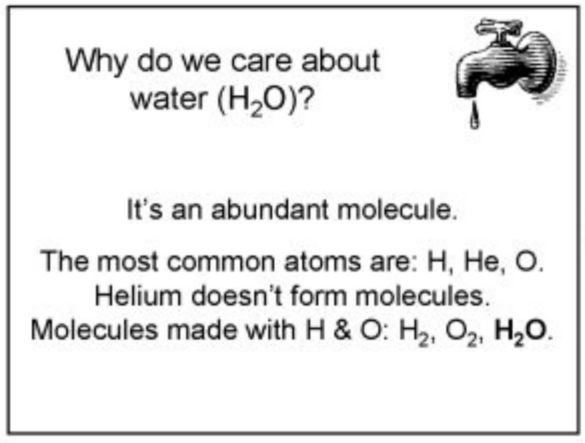


The outer planets are in the "habitable zone" or "Goldilocks zone".

Closer, it's too hot for liquid water.

Farther, it's too cold for liquid water.

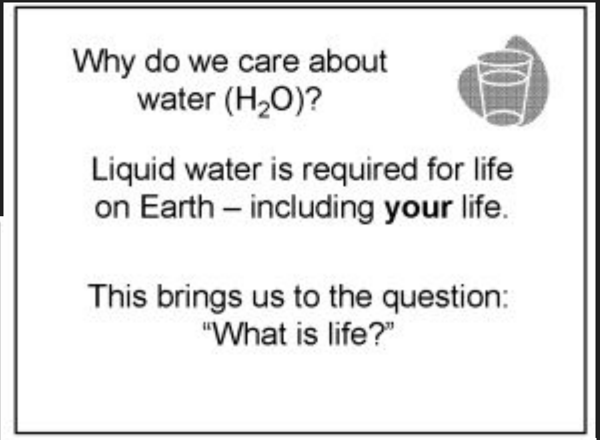
Within the zone, it's "just right".



Why do we care about water (H_2O)?

It's an abundant molecule.

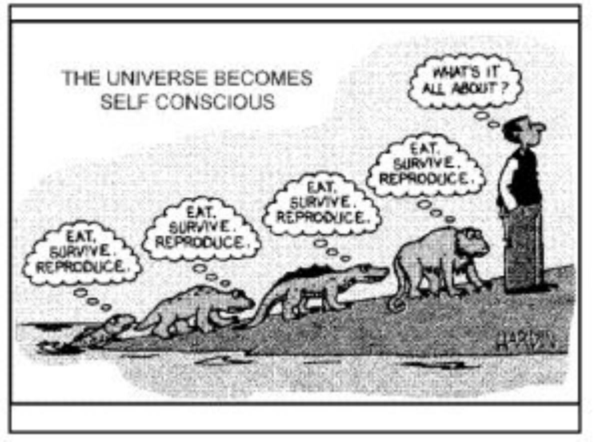
The most common atoms are: H, He, O.
Helium doesn't form molecules.
Molecules made with H & O: H_2, O_2, $\mathbf{H_2O}$.

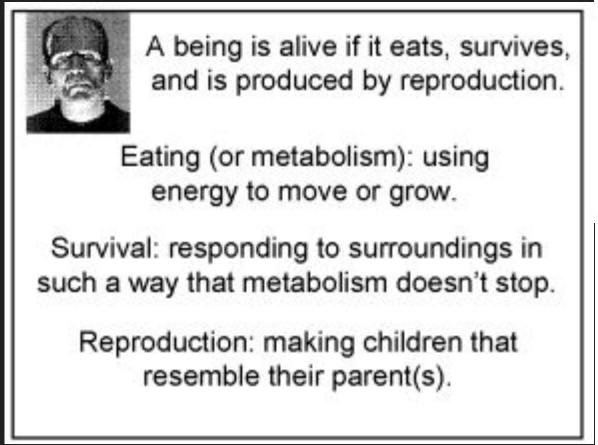


Why do we care about water (H_2O)?

Liquid water is required for life on Earth – including **your** life.

This brings us to the question: "What is life?"



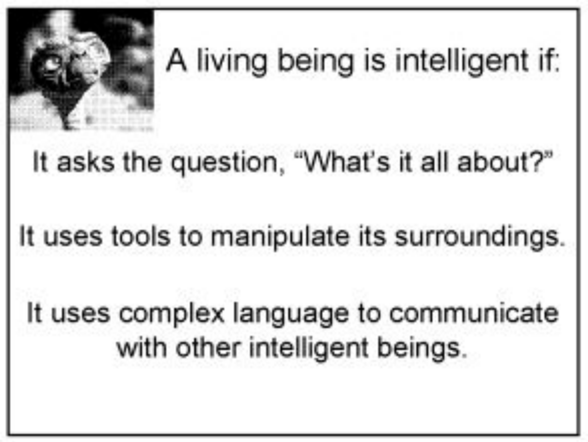


A being is alive if it eats, survives, and is produced by reproduction.

Eating (or metabolism): using energy to move or grow.

Survival: responding to surroundings in such a way that metabolism doesn't stop.

Reproduction: making children that resemble their parent(s).

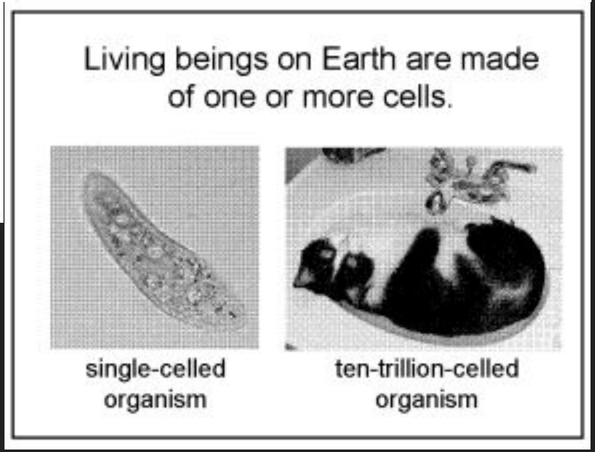


A living being is intelligent if:

It asks the question, "What's it all about?"

It uses tools to manipulate its surroundings.

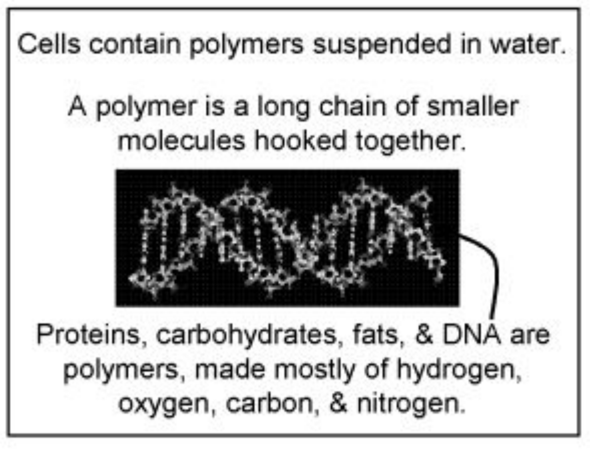
It uses complex language to communicate with other intelligent beings.



Living beings on Earth are made of one or more cells.

single-celled organism

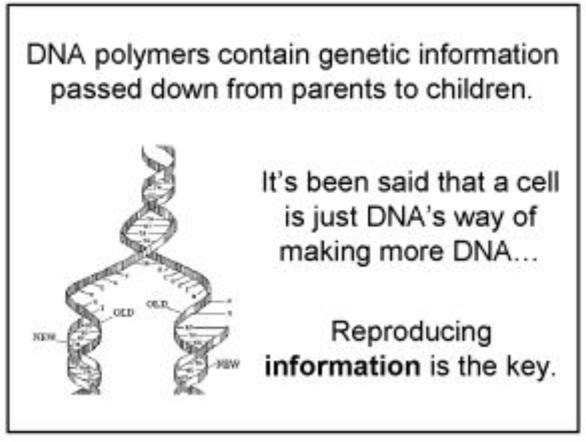
ten-trillion-celled organism



Cells contain polymers suspended in water.

A polymer is a long chain of smaller molecules hooked together.

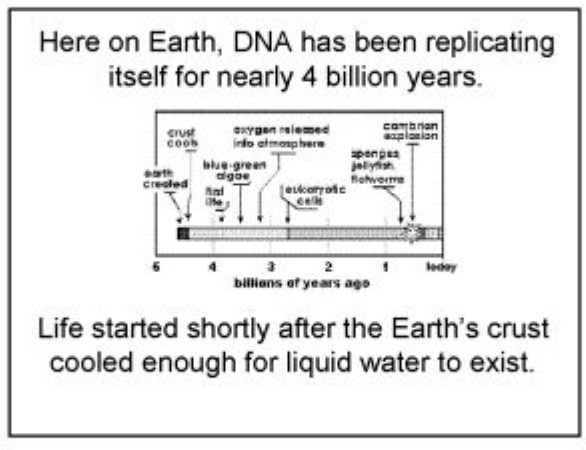
Proteins, carbohydrates, fats, & DNA are polymers, made mostly of hydrogen, oxygen, carbon, & nitrogen.



DNA polymers contain genetic information passed down from parents to children.

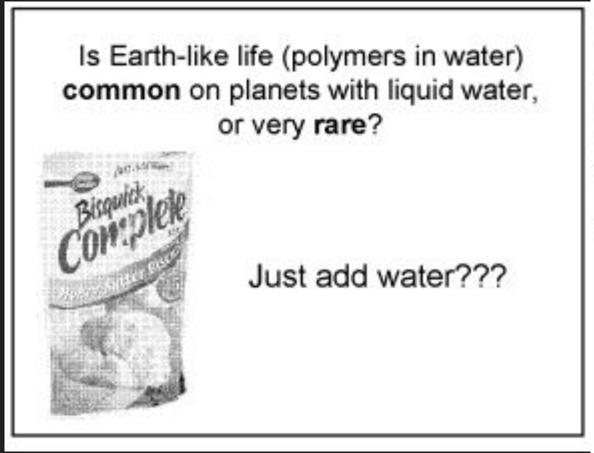
It's been said that a cell is just DNA's way of making more DNA…

Reproducing **information** is the key.



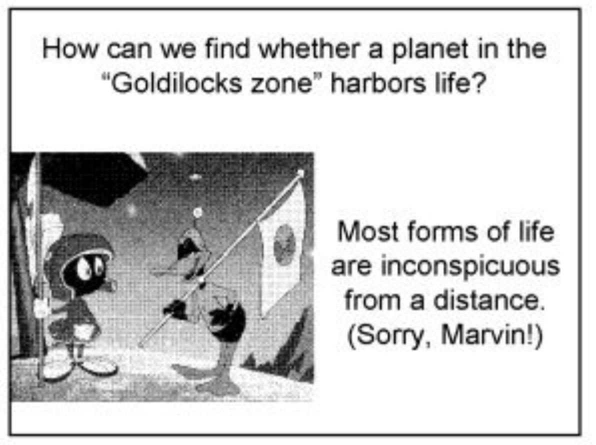
Here on Earth, DNA has been replicating itself for nearly 4 billion years.

Life started shortly after the Earth's crust cooled enough for liquid water to exist.



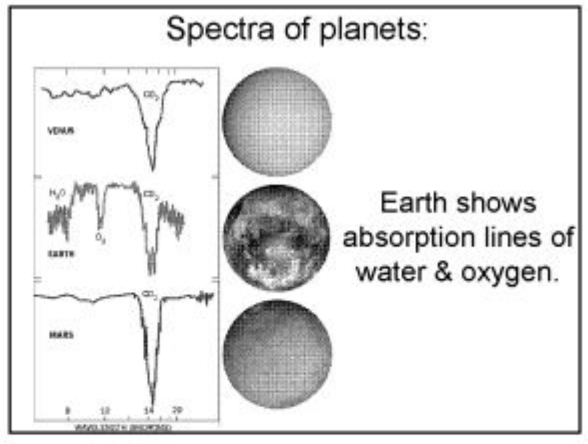
Is Earth-like life (polymers in water) **common** on planets with liquid water, or very **rare**?

Just add water???



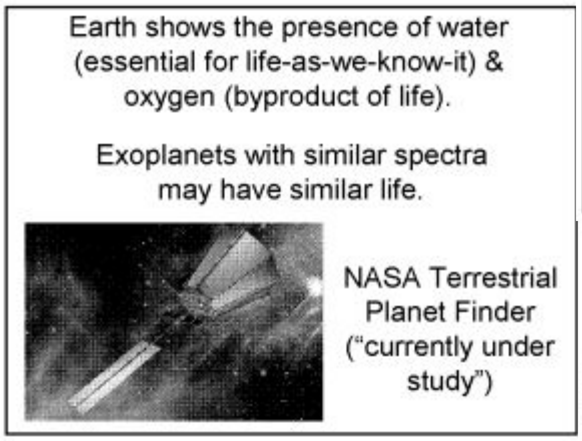
How can we find whether a planet in the "Goldilocks zone" harbors life?

Most forms of life are inconspicuous from a distance. (Sorry, Marvin!)



Spectra of planets:

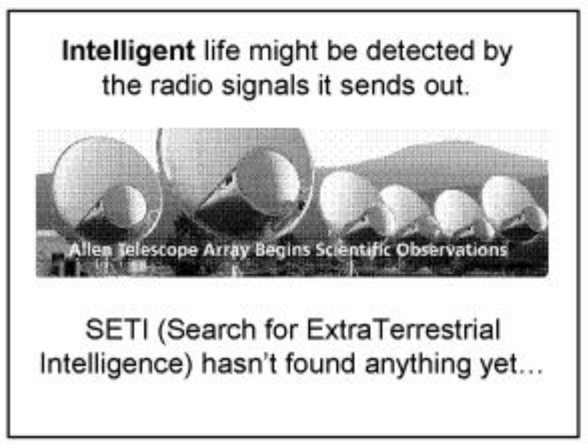
Earth shows absorption lines of water & oxygen.



Earth shows the presence of water (essential for life-as-we-know-it) & oxygen (byproduct of life).

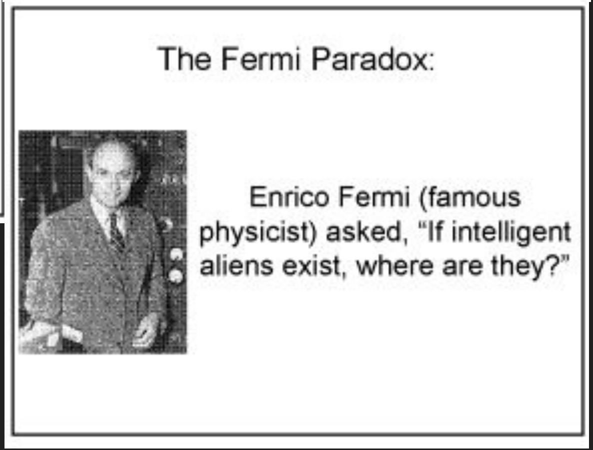
Exoplanets with similar spectra may have similar life.

NASA Terrestrial Planet Finder ("currently under study")



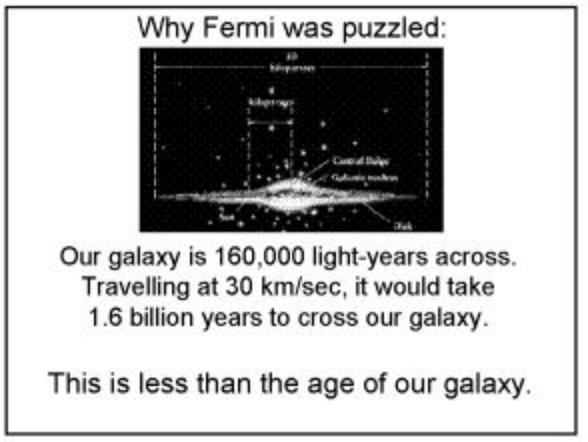
Intelligent life might be detected by the radio signals it sends out.

SETI (Search for ExtraTerrestrial Intelligence) hasn't found anything yet…



The Fermi Paradox:

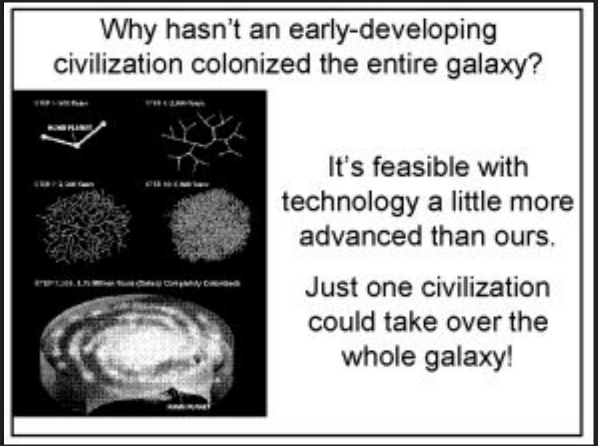
Enrico Fermi (famous physicist) asked, "If intelligent aliens exist, where are they?"



Why Fermi was puzzled:

Our galaxy is 160,000 light-years across.
Travelling at 30 km/sec, it would take
1.6 billion years to cross our galaxy.

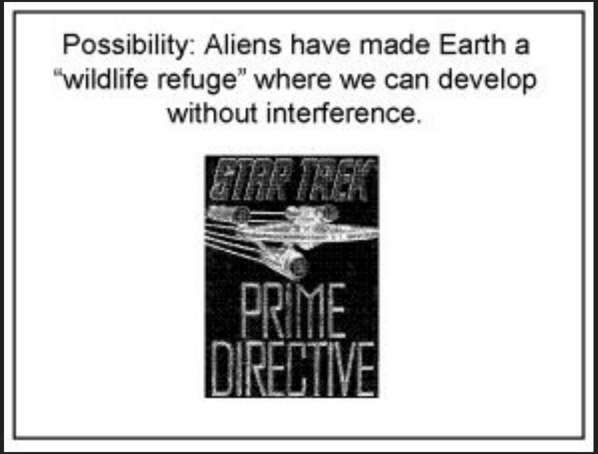
This is less than the age of our galaxy.



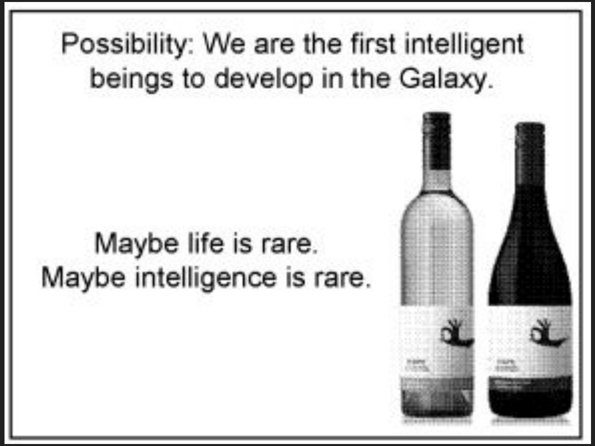
Why hasn't an early-developing civilization colonized the entire galaxy?

It's feasible with technology a little more advanced than ours.

Just one civilization could take over the whole galaxy!

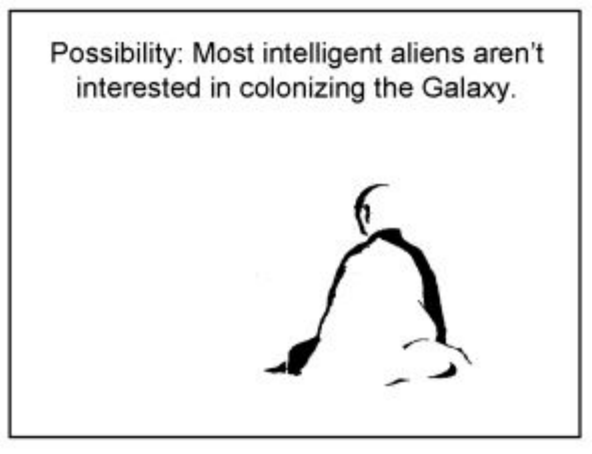


Possibility: Aliens have made Earth a "wildlife refuge" where we can develop without interference.



Possibility: We are the first intelligent beings to develop in the Galaxy.

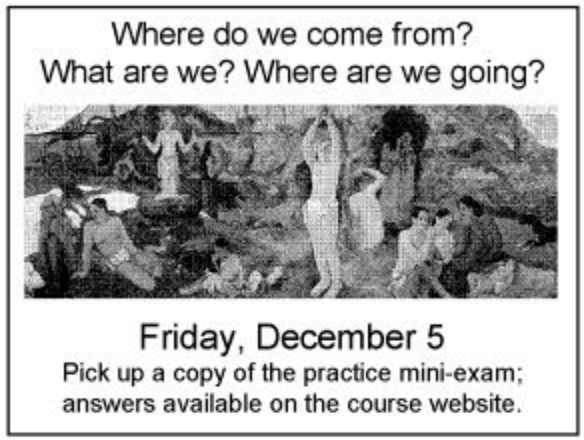
Maybe life is rare.
Maybe intelligence is rare.



Possibility: Most intelligent aliens aren't interested in colonizing the Galaxy.

Preparatory Reading Chapter 13 & 14

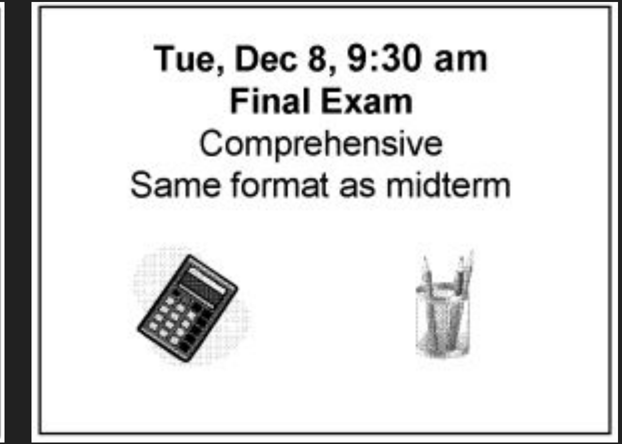
Week 11: Where do we come from? What are we? Where are we going?



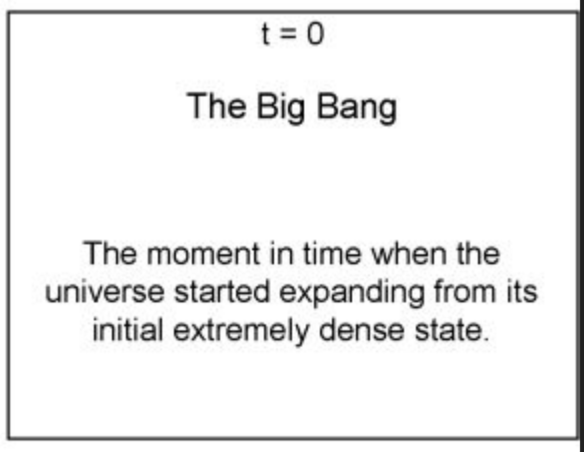
Where do we come from?
What are we? Where are we going?

Friday, December 5

Pick up a copy of the practice mini-exam;
answers available on the course website.



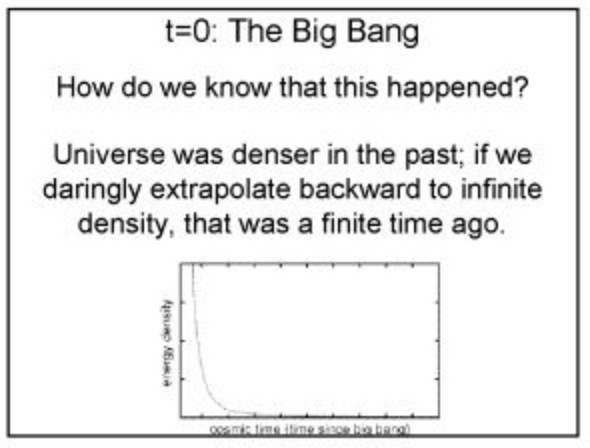
Tue, Dec 8, 9:30 am
Final Exam
Comprehensive
Same format as midterm



t = 0

The Big Bang

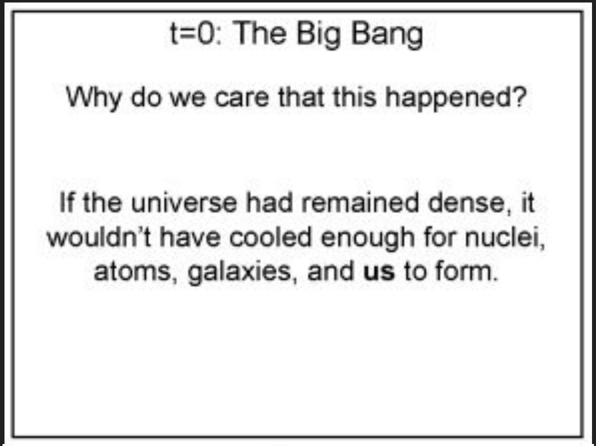
The moment in time when the universe started expanding from its initial extremely dense state.



t=0: The Big Bang

How do we know that this happened?

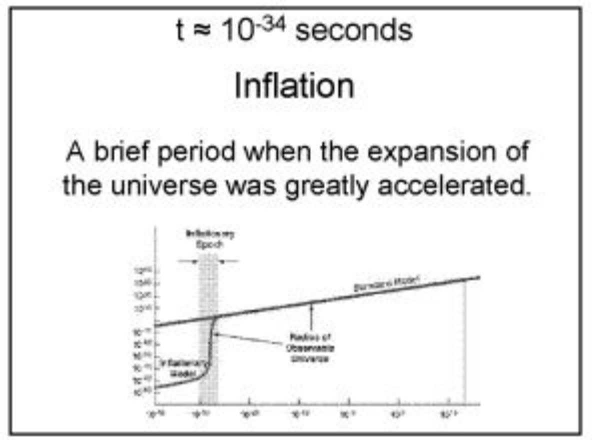
Universe was denser in the past; if we daringly extrapolate backward to infinite density, that was a finite time ago.



t=0: The Big Bang

Why do we care that this happened?

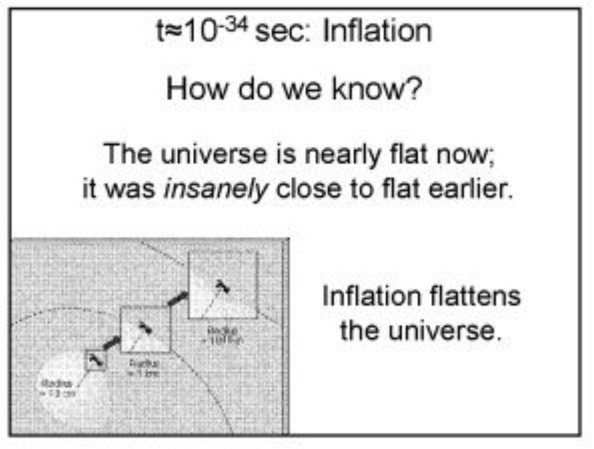
If the universe had remained dense, it wouldn't have cooled enough for nuclei, atoms, galaxies, and **us** to form.



t ≈ 10^{-34} seconds

Inflation

A brief period when the expansion of the universe was greatly accelerated.

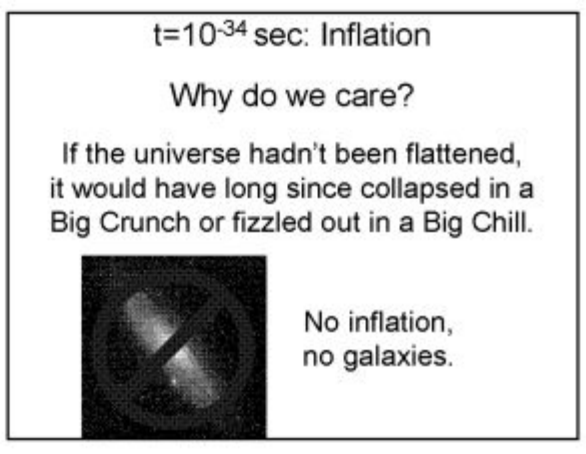


$t \approx 10^{-34}$ sec: Inflation

How do we know?

The universe is nearly flat now;
it was *insanely* close to flat earlier.

Inflation flattens
the universe.

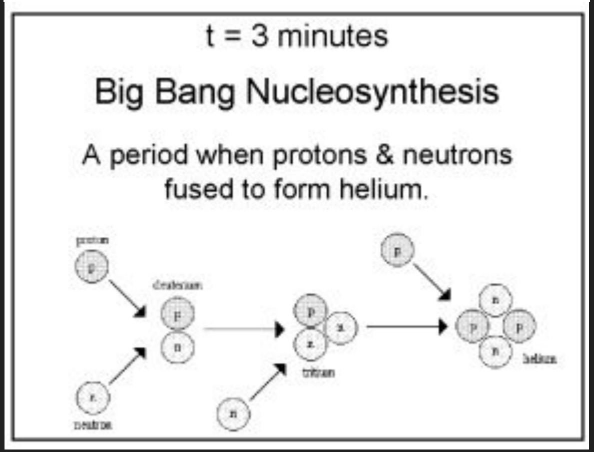


$t=10^{-34}$ sec: Inflation

Why do we care?

If the universe hadn't been flattened,
it would have long since collapsed in a
Big Crunch or fizzled out in a Big Chill.

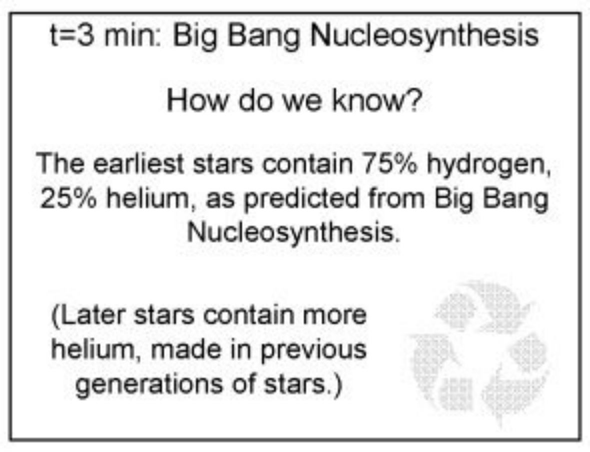
No inflation,
no galaxies.



t = 3 minutes

Big Bang Nucleosynthesis

A period when protons & neutrons
fused to form helium.

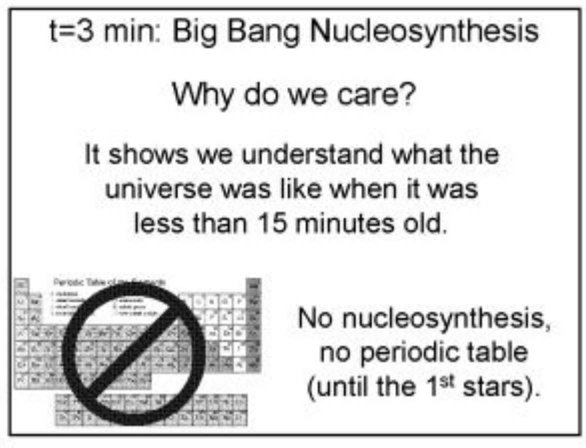


t=3 min: Big Bang Nucleosynthesis

How do we know?

The earliest stars contain 75% hydrogen, 25% helium, as predicted from Big Bang Nucleosynthesis.

(Later stars contain more helium, made in previous generations of stars.)

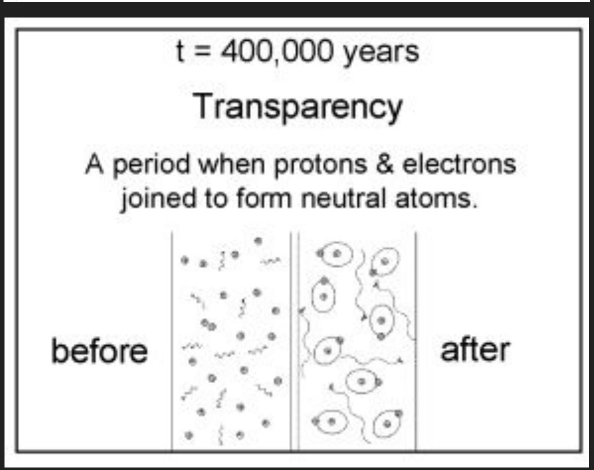


t=3 min: Big Bang Nucleosynthesis

Why do we care?

It shows we understand what the universe was like when it was less than 15 minutes old.

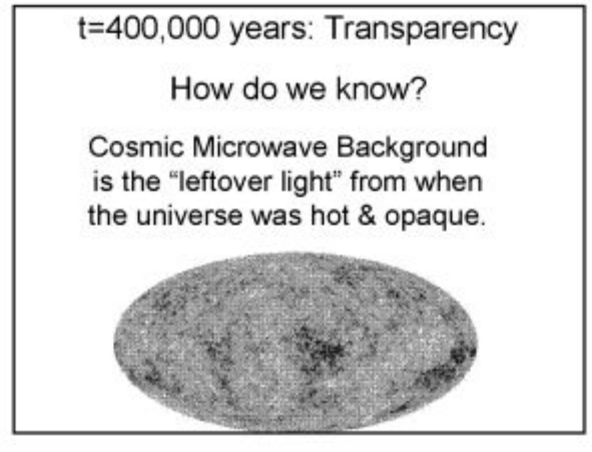
No nucleosynthesis, no periodic table (until the 1st stars).



t = 400,000 years

Transparency

A period when protons & electrons joined to form neutral atoms.



t=400,000 years: Transparency

How do we know?

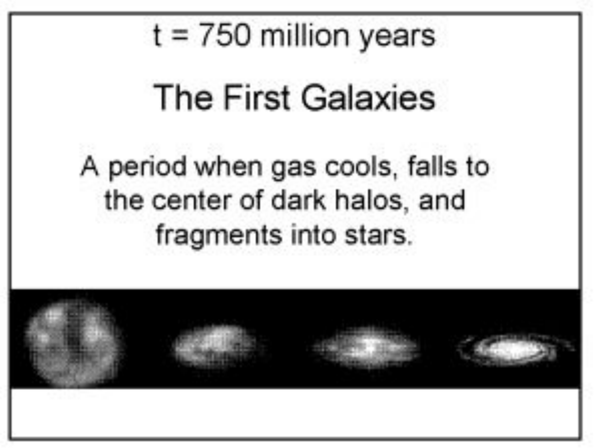
Cosmic Microwave Background
is the “leftover light” from when
the universe was hot & opaque.

t=400,000 years: Transparency

Why do we care?

If the universe were still opaque,
we wouldn’t be able to see
distant galaxies.

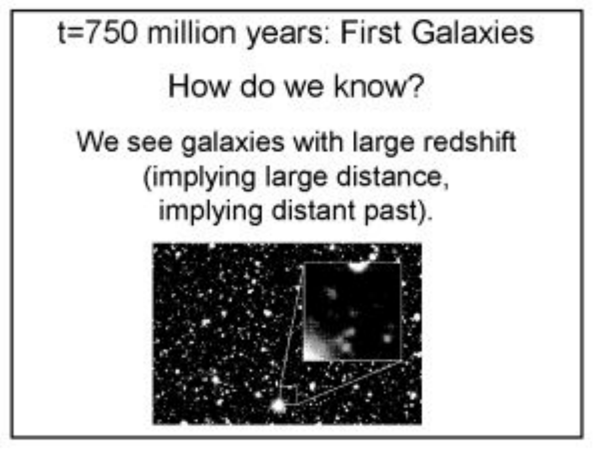
No transparency,
no astronomers.



t = 750 million years

The First Galaxies

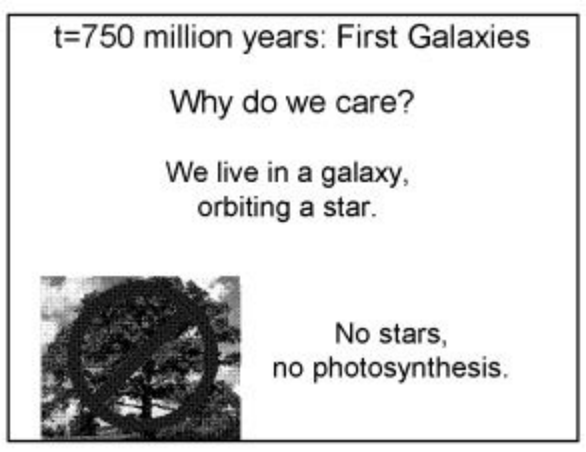
A period when gas cools, falls to
the center of dark halos, and
fragments into stars.



t=750 million years: First Galaxies

How do we know?

We see galaxies with large redshift
(implying large distance,
implying distant past).

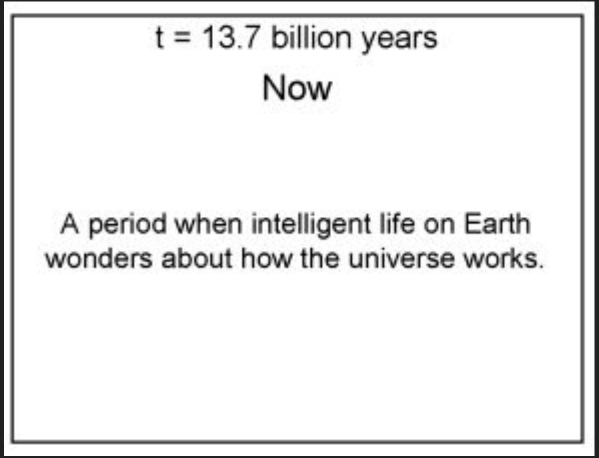


t=750 million years: First Galaxies

Why do we care?

We live in a galaxy,
orbiting a star.

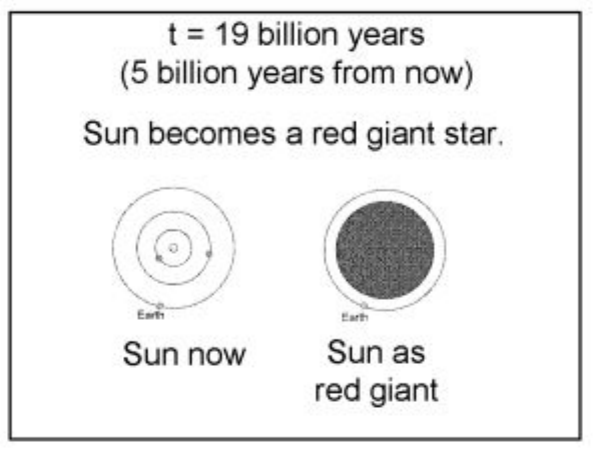
No stars,
no photosynthesis.



t = 13.7 billion years

Now

A period when intelligent life on Earth wonders about how the universe works.

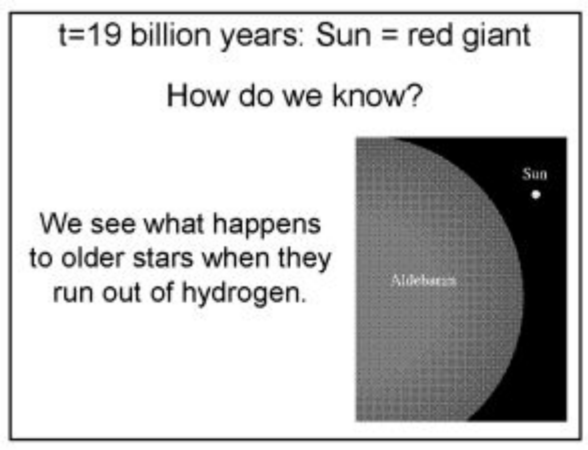


t = 19 billion years
(5 billion years from now)

Sun becomes a red giant star.

Sun now

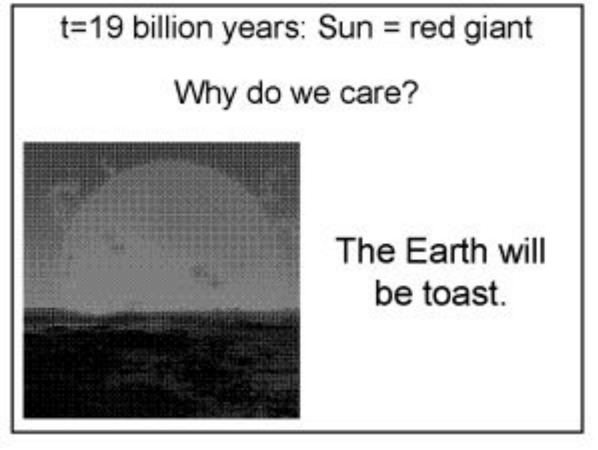
Sun as
red giant



t=19 billion years: Sun = red giant

How do we know?

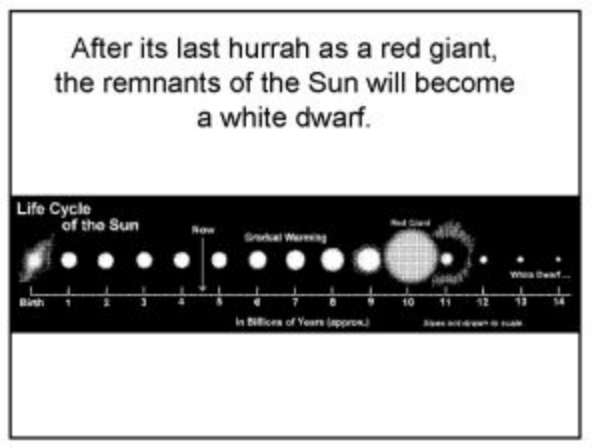
We see what happens to older stars when they run out of hydrogen.



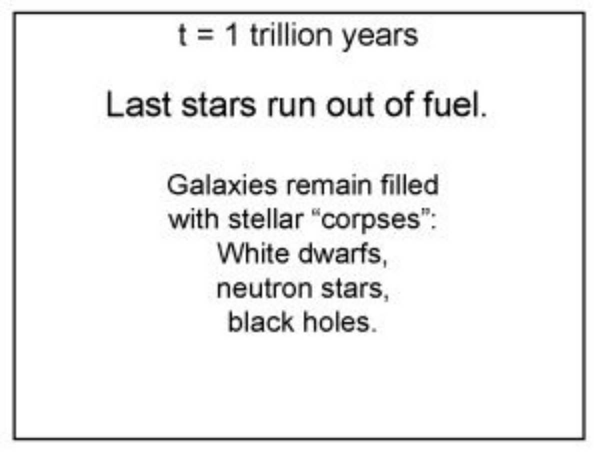
t=19 billion years: Sun = red giant

Why do we care?

The Earth will be toast.



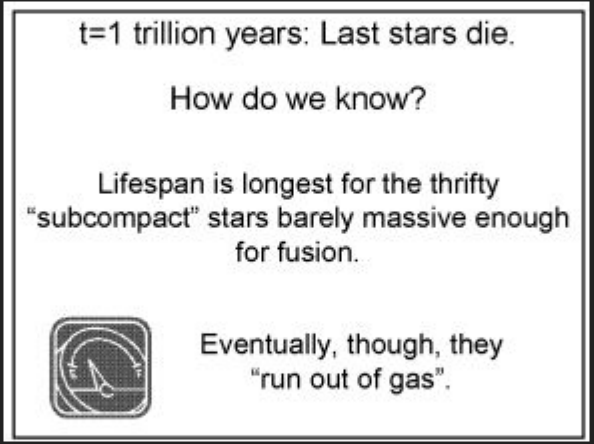
After its last hurrah as a red giant,
the remnants of the Sun will become
a white dwarf.



t = 1 trillion years

Last stars run out of fuel.

Galaxies remain filled
with stellar “corpses”:
White dwarfs,
neutron stars,
black holes.

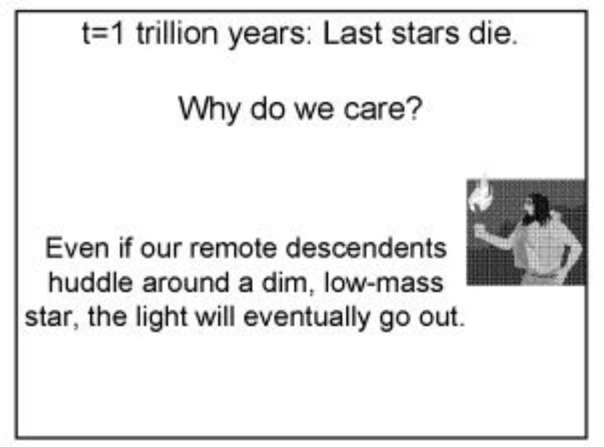


t=1 trillion years: Last stars die.

How do we know?

Lifespan is longest for the thrifty
“subcompact” stars barely massive enough
for fusion.

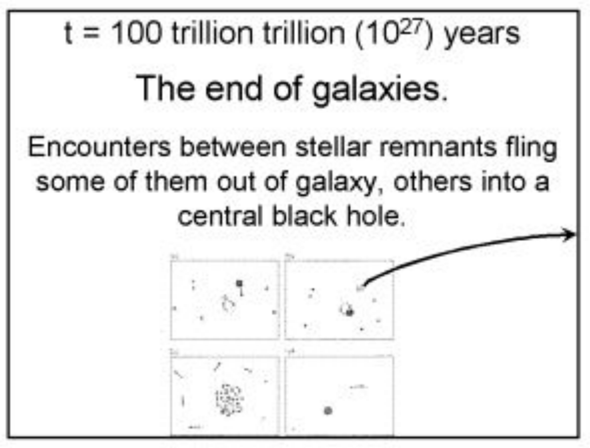
Eventually, though, they
“run out of gas”.



t=1 trillion years: Last stars die.

Why do we care?

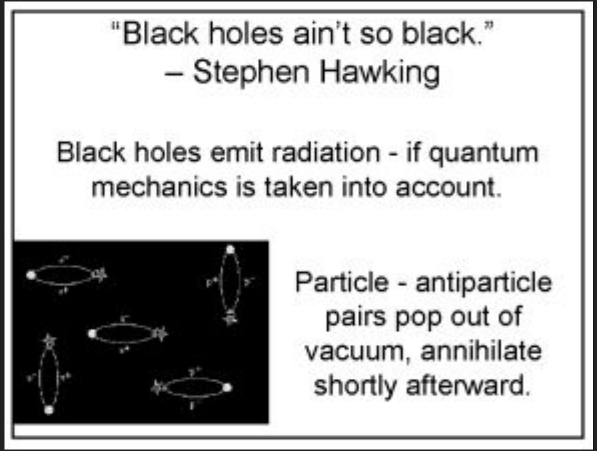
Even if our remote descendents huddle around a dim, low-mass star, the light will eventually go out.



t = 100 trillion trillion (10^{27}) years

The end of galaxies.

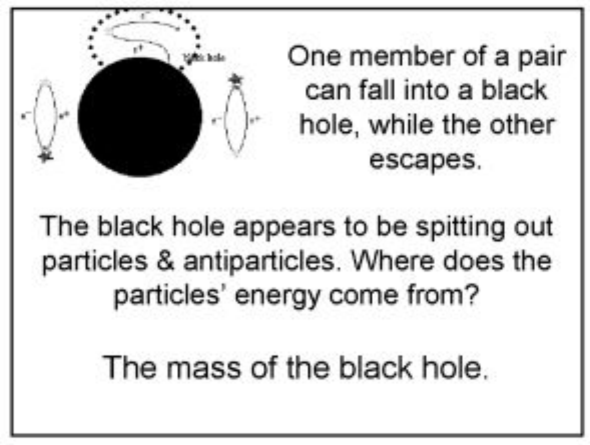
Encounters between stellar remnants fling some of them out of galaxy, others into a central black hole.



"Black holes ain't so black." – Stephen Hawking

Black holes emit radiation - if quantum mechanics is taken into account.

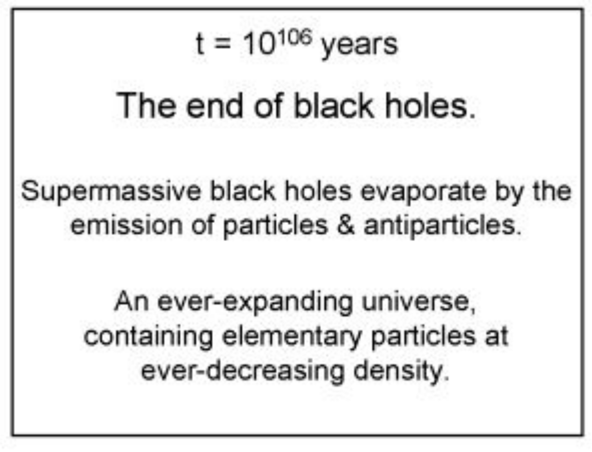
Particle - antiparticle pairs pop out of vacuum, annihilate shortly afterward.



One member of a pair can fall into a black hole, while the other escapes.

The black hole appears to be spitting out particles & antiparticles. Where does the particles' energy come from?

The mass of the black hole.

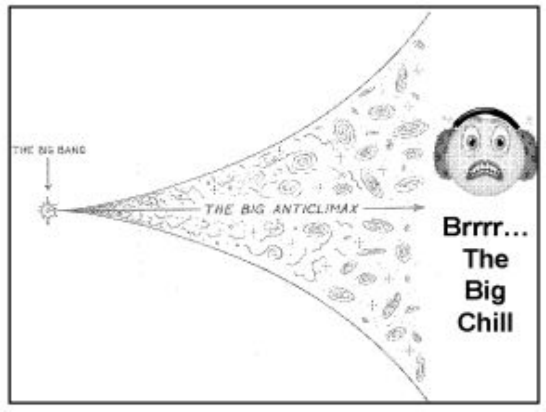


t = 10^{106} years

The end of black holes.

Supermassive black holes evaporate by the emission of particles & antiparticles.

An ever-expanding universe, containing elementary particles at ever-decreasing density.



Brrrr... The Big Chill