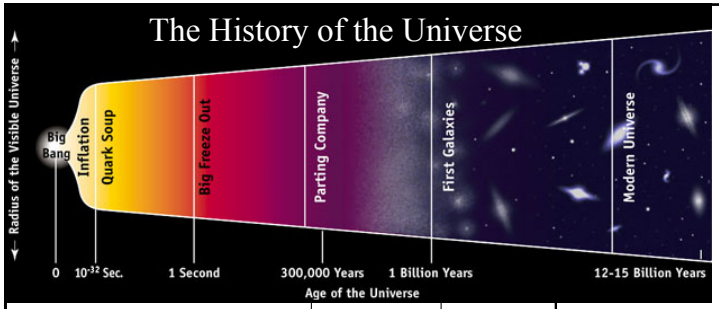
The History of the Universe



Planck time: Gravity separated out	10^{-43} sec	10^{32} °K
Strong nuclear force separated out	10^{-35} sec	10^{27}
Inflation	10^{-32} sec	
Electromagentic, Weak nuclear forces	10^{-12} sec	10^{15}
Nucleosynthesis of H, He, Li	1 sec - 3 min	10^{9}
Decoupling of CMB	300,000 yrs	3000
Galaxy Formation	1 billion years	
Now	13.7 billion yrs	3

hot → cool

high density → low density

The End of the Universe

Continued expansion, forever… (we think).

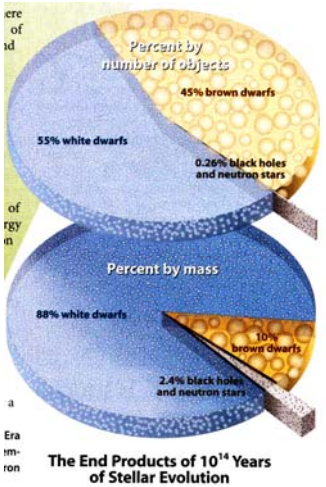
10^{-43} sec	Planck Time
10^{-38} – 10^{-32} sec	Inflation
10^{-32} sec – 10^{4} yrs	Radiation Era
10^{4} – 10^{14} yrs	Stellar Era
10^{14} – 10^{37} yrs	Degenerate Era
10^{37} – 10^{100} yrs	Black Hole Era
> 10^{100} yrs	Dark Era

← Now = 1.4 x 10^{10} yrs

(Extremely speculative: See *Sky & Telescope* magazine, August 1998)

Degenerate Era

- 10^{14} – 10^{37} yrs.
- Almost no further radiation from stars.
  - Cold, dark universe.
- But…
  - Occasional collisions between brown dwarfs ➔ new low-mass stars (10 to 100 in existence per galaxy at any given time).
  - Occasional collisions of degenerate stars ➔ supernova.



Black Hole Era

wild speculation

- 10^{37} – 10^{100} yrs.
- Degenerate stars have all disappeared through proton decay (maybe)
  - p ➔ e^{+} , neutrinos, gamma rays
  - No more atoms
- Dark matter previously swept into degenerate stars and annihilated (??????)
- Only black holes are left.
- But black holes also evaporate
  - *Hawking radiation*: very slow conversion of gravitational energy back to particles or photons.

Dark Era

- Essentially nothing left except hugely redshifted CMB photons.

What's outside the Universe?

- Other universes, not intersecting with our Universe??
- Some magic numbers:
  - At t = 1 second, our Universe defined by:
    - Ratios of
      - **Energy Density.** Matter:Kinetic-energy:Cosmolgical-constant-energy.
      - **Numbers of particles.** Photons:Normal-matter:Dark-matter
    - Amplitude of density fluctuations ~ 10^{-5}
  - Imprinted by Planck Time: ratios of physical constants.
    - Example: electrostatic force 10^{36} x stronger than gravitational force.
  - Different values in other universes?

- ***Anthropic Principle***: our particular universe is suitable for us to live in because otherwise we would not be alive to know about it.

Good book: ***Before the Beginning***, by Martin Rees

Announcements

Homework.

- Set 8 now open.
  - due late at night Friday, Dec 10 (3AM Saturday Nov. 11)
- Set 7 answers on course web site.

Review for Final.

- *Right Now!*

Course Evaluation.

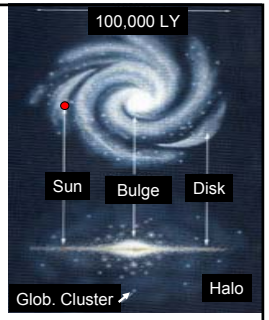
https://rateyourclass.msu.edu

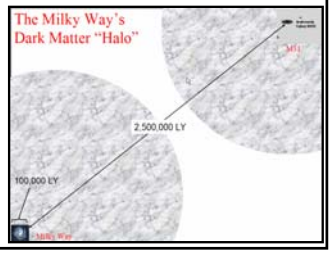
Final Exam.

- Monday December 13.
- 8-10 PM. (PM = in the *evening*!!!).
- In the usual classroom (Natural Resources 158).
- Counts as 1.5 midterms.
- 70 questions.
- 2/3 over material since Midterm 3.
- 1/3 over earlier material.
  - reworded midterm questions.
  - + a few new general questions.
  - + a few about *telescopes*.

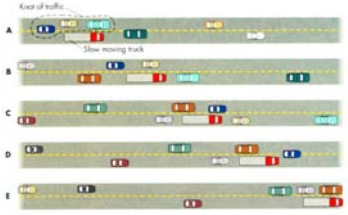
Galaxies

- Composed of 100 billion stars or more.
- Main types are
  - Ellipticals
  - Spirals
    - Regular spirals
    - Barred spirals
  - Irregulars
- Our galaxy (the Milky Way) is a spiral with a weak bar.
- Mass of galaxies dominated by Dark Matter.
  - Detected by studying motions of stars around galactic centers.



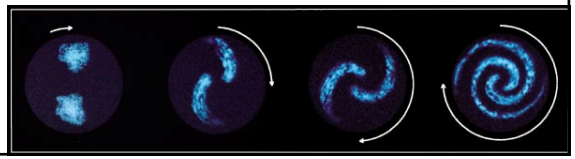


Spiral Arms



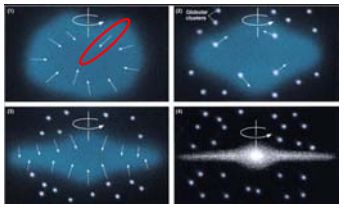
- Density wave
  - Spiral arms have higher density than space between arms
  - Excess gravitational attraction slows down gas, stars when they pass through spiral arm in course of their orbits.
  - ➔ spiral arms are a traffic jam
- But also some effect due to differential rotation.

➔ natural tendency of big star-forming regions to just get wound up into spiral shapes.



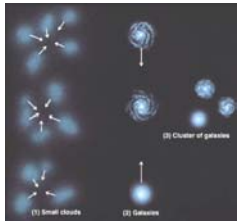
Galaxy Formation:

Top-Down Model



- Collapse ➔ rotating disk
- Halo (Globular clusters & halo stars) formed during collapse.
  - Once formed, stars don't collide.

Bottom-Up Model



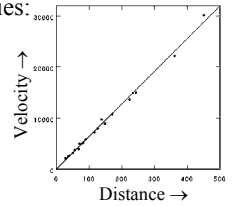
Time → Now

- Small structures form first
  - Dwarf galaxies
  - Globular Clusters
- Galaxies grow by cannibalism
- Ellipticals formed by mergers of spirals (?)

The Cosmic Distance Ladder

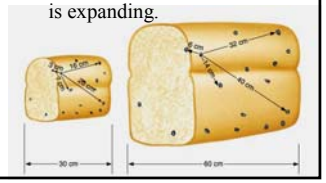
- Parallax
  - Out to 65 LY
  - Calibrate luminosities of Pulsating Variables
- Use pulsating variables to map rest of Milky Way and out to M31.
- In M31, Measure luminosities of
  - Brightest stars 10,000 $L_\odot$
  - Brightest globular clusters 100,000 $L_\odot$
  - Brightest H II regions 100,000 $L_\odot$
  - Etc.
  - ➔ can now measure distances to more distant galaxies

➔ Velocity-distance relation for distant galaxies:

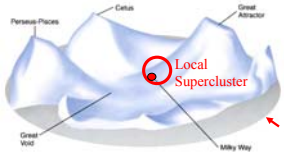


Hubble's Law: $v = H_o d$

- Galaxies all recede from each other.
- ➔ Scale of the whole universe is expanding.

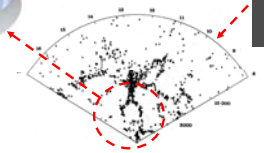


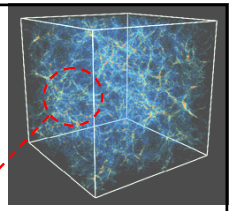
The distribution of matter.



Structure upon Structure.

Bubbles & Voids.





The Cosmic Web.
Structure determined by evolution of *dark* matter.

Location	Fraction of critical density
Gas within galaxies	0.001
Gas in galaxy clusters	0.003
Stars within galaxies	0.004
Gas between galaxy clusters	0.014
Dark Matter	0.3

Total normal matter = **0.022**
Big Bang Nucleosynthesis predicts **0.03**

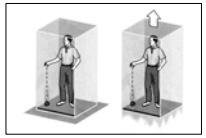
About 90% of all matter is dark matter.

Relativity

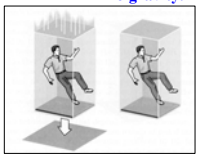
- Special Relativity
  - **The Principal of Relativity.** The laws of physics are the same in all inertial reference frames.
  - **The constancy of the speed of light.** Light travels through a vacuum at a speed *c* which is independent of the light source.

Predicted and then observed effects of Special Relativity:
- $E = mc^2$
- Time Dilation

- General Relativity
  - **The Principle of Equivalence**
    - Can't tell difference between gravity & acceleration
    - …or between freefall & no gravity.
    - So *any* experiment should give same answer in either case.



Gravity **Upwards acceleration, no gravity.**



Falling due to gravity **No gravity**

Curved Space

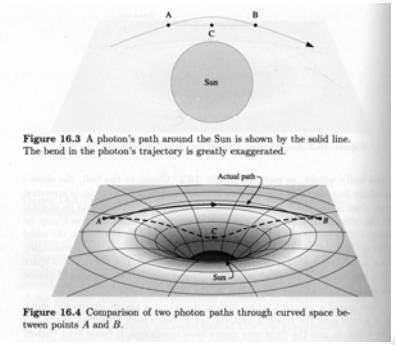


Figure 16.3 A photon's path around the Sun is shown by the solid line. The bend in the photon's trajectory is greatly exaggerated.

Figure 16.4 Comparison of two photon paths through curved space between points *A* and *B*.

- Everything finds shortest path in spacetime.
- Photons (light) find shortest path of all, because they move the fastest.

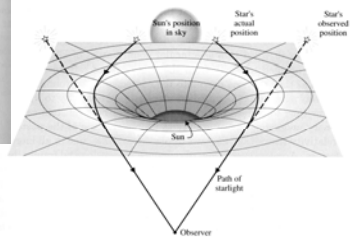
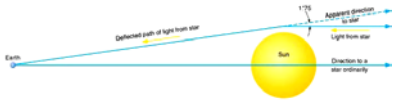


Figure 16.5 Bending of starlight measured during a solar eclipse.

Proofs of General Relativity

- Rapid precession of Mercury's orbit.
  - Phenomenon known before.
  - G.R. offered the explanation.

- Bending of light rays passing near Sun.
  - First measured in 1919



- Time dilation in gravitational fields.
  - Measured using real clocks, on Earth.
- Gravitational redshift in strong gravitational fields
  - Observed in spectra of white dwarfs.

Quasars

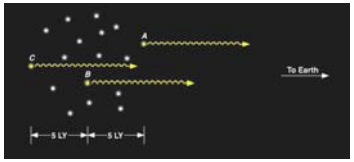
- Large redshift ➔ large distance

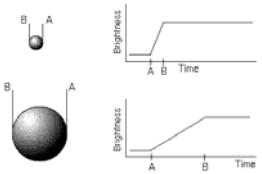
$$F = L/4\pi d^2$$
$$4\pi d^2 F = L$$

- Measured flux + distance ➔ huge luminosity
  - Up to 1000 x luminosity of an entire galaxy of stars.
- Rapid flux variability ➔ small volume.

And also:

- Located in centers of galaxies.
- Happened early in lives of galaxies.





Some luminous quasars vary in *few days* ➔ same size as solar system.

High density ➔ Strong Gravitational Field ➔ Black Hole

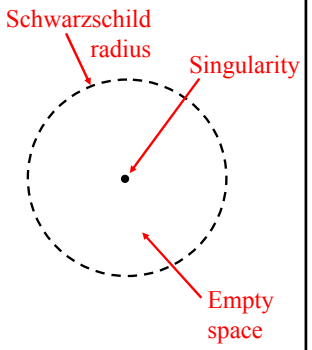
Escape Velocity:

$$v_{escape} = \sqrt{\frac{2GM}{R}}$$

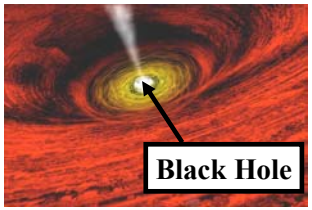
Schwarzschild radius:

$v_{escape} = c$ (speed of light)

$$R_S = \frac{2GM}{c^2}$$



Accretion Disk forms around Black Hole



The Source of the Luminosity:
Gravitational Potential Energy.

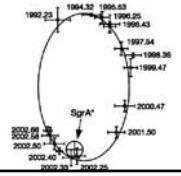
- Matter falls onto accretion disk.
- Disk heats up & glows.

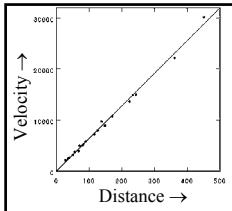
Nearby Galaxies with Mini-Quasars in Center

- Small fraction of nearby galaxies have huge outflows of particles moving at nearly speed of light.

- Massive black holes in most nearby galaxies, but not currently accreting gas.
- Orbits of stars ➔ million solar-mass black hole at center of Milky Way Galaxy.

$P^2 = a^3/(m_1 + m_2)$





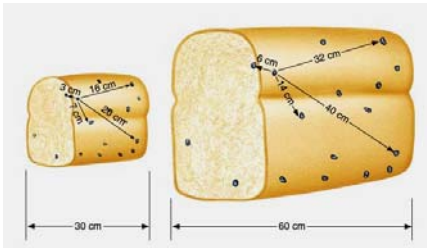
The Expanding Universe

Hubble's Law:
- Galaxies all recede from us.
- Velocity proportional to distance.

$v = H_o\, d$

- We are unlikely to be at exact center.

➔ Scale of the whole universe is expanding.

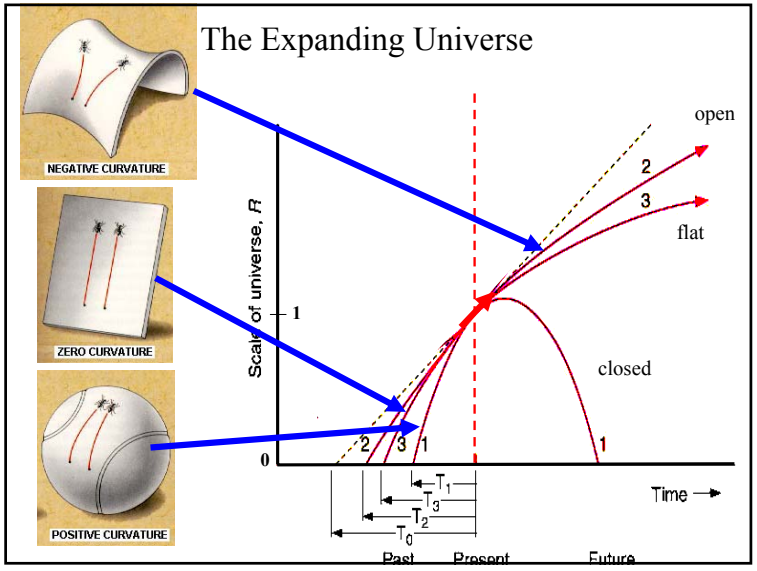


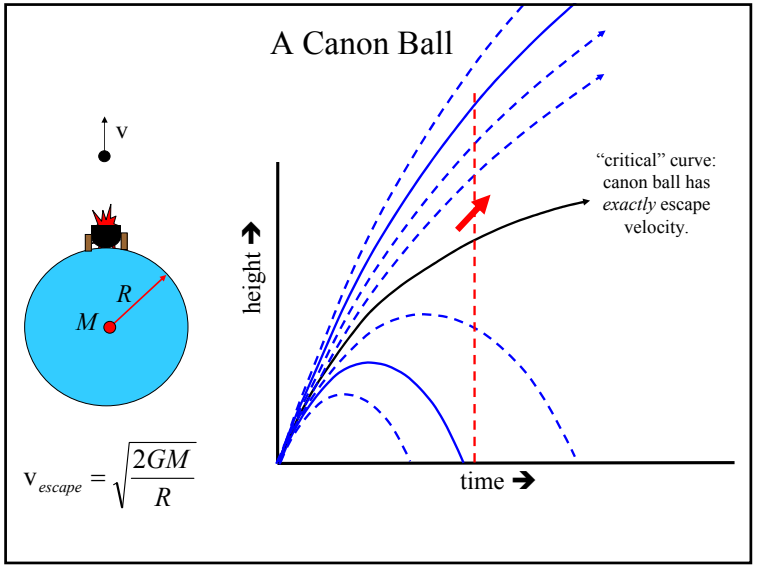
Distance = R(time) x (comoving distance)

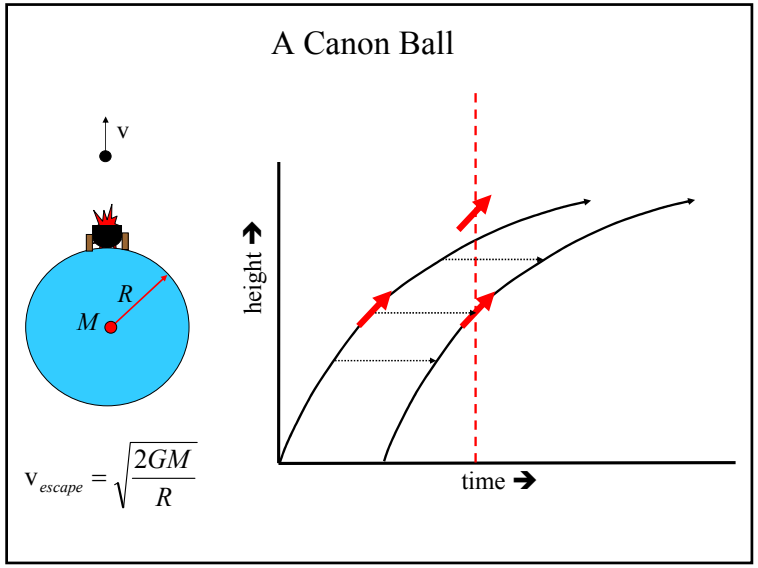
Summary:
How do we know the universe is expanding from a very much smaller size?

- Hubble's Law
  - Everything is moving away from everything else.
- Cosmic Microwave Background (CMB)
  - Universe used to be much hotter than it is now ➔ it has changed and evolved.

The Expanding Universe




A Canon Ball
v
R
M
height
time
"critical" curve: canon ball has *exactly* escape velocity.
$v_{escape} = \sqrt{\frac{2GM}{R}}$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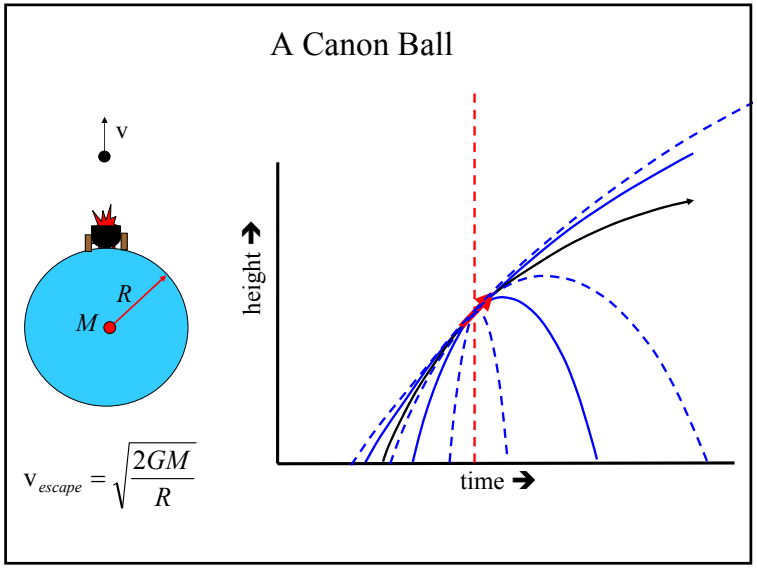
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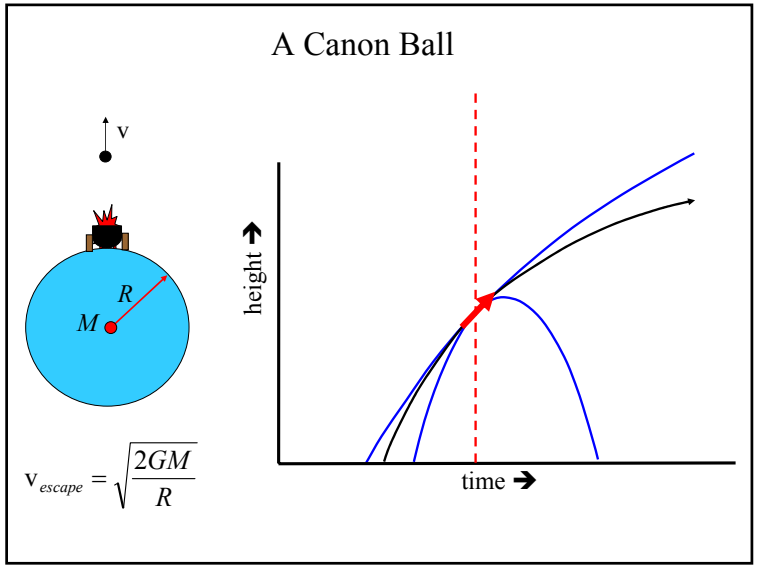
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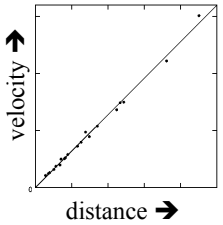
The Expanding Universe



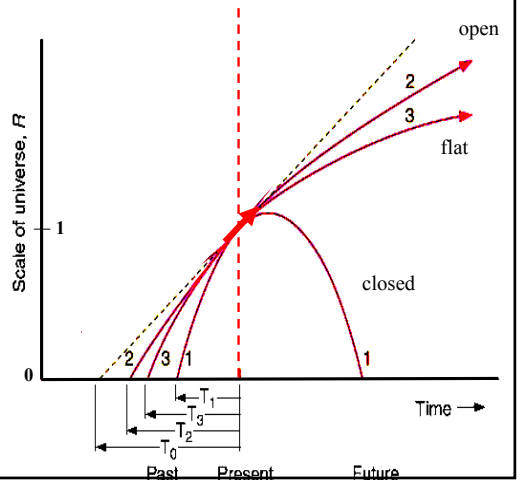
Hubble's law:

$v = H_0 d$

$\frac{d}{v} = \frac{\text{distance}}{\text{velocity}}$

= travel time

$= \frac{1}{H_0}$

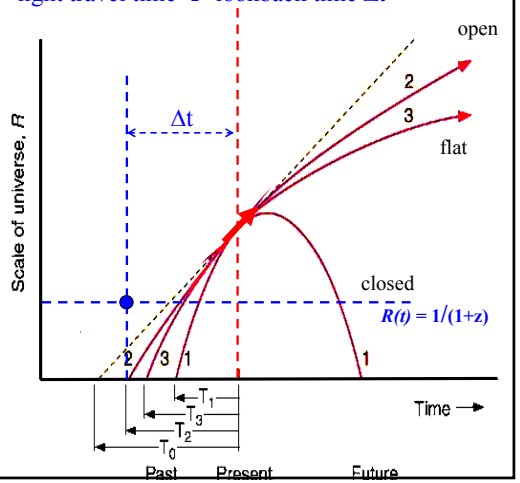


Which Universe Do We Live in?

Distance = light travel time ➔ lookback time Δt

What we can measure for supernovae:

- Redshift
- Distance



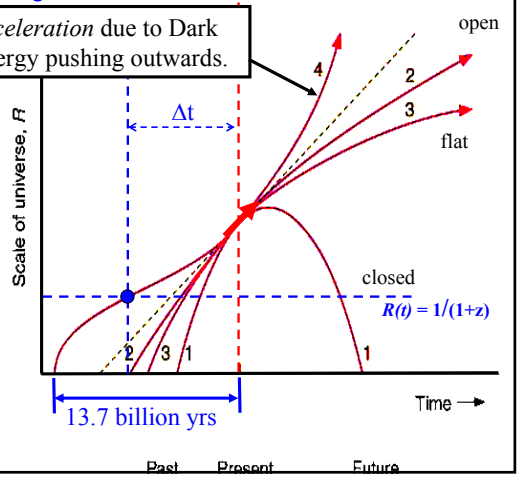
The Accelerating Universe

Distance = light travel time ➔ lookback time Δt

Acceleration due to Dark Energy pushing outwards.

What we can measure for supernovae:

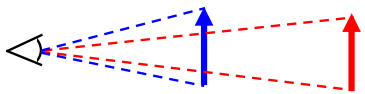
- Redshift
- Distance

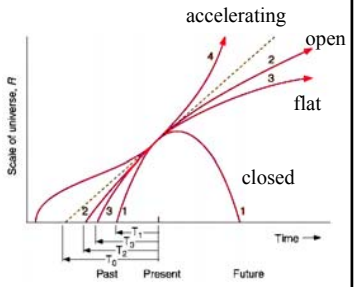


Structure in the Cosmic Microwave Background

What does it tell us?

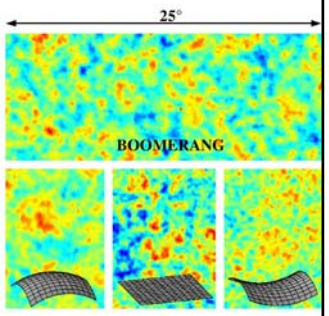
- Sound waves permeated universe just before decoupling of CMB.
- Linear size of largest structure
  = (speed of sound) x (age of universe at that time)
- Distance to surface emitting CMB depends strongly on cosmological model.
- ➔ Angular size depends on cosmological model.

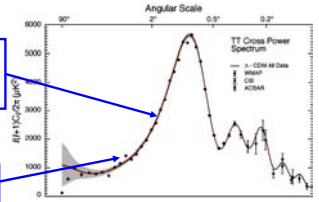




Structure in the CMB

- The result:
  - The universe is FLAT.

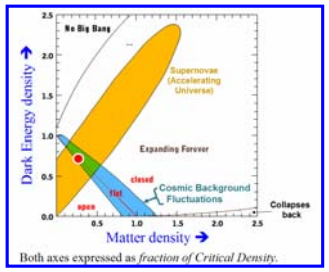




Line shows predicted result for flat universe

Points show measured values

What is the Universe Made Of ?



73% Dark Energy
23% Dark Matter
4% Normal Matter

(using $E = mc^2$)

We infer these are there, but we don't know what they are.

This is the only part we see.

Some Key Numbers

What?	Value	How do we know?
Age of Solar System (& Earth)	4.54 billion years	Direct radioactive decay dating of oldest meteorites.
Lifetime of Sun	10 billion years	Computer simulations of stars.
Age of Universe.	13.7 billion years	Recent measurements that Universe is flat and accelerating.
% of mass of Solar System that is in the Sun.	99.8%	Measuring mass of Sun & planets using Newton's/Kepler's laws.
Number of stars in our Milky Way Galaxy	100 billion	We can count them.
Number of observable galaxies similar to Milky Way	100 billion or more	We can see them with big telescopes.
% of all matter that is unseen Dark Matter	90%	Gravitational effect on normal matter & on path of light.
% of content of Universe that is not any kind of matter	73%	Recent measurements that Universe is flat and accelerating.