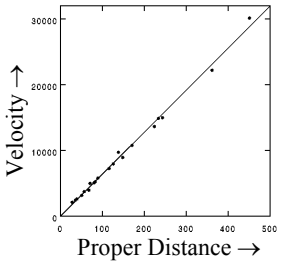
Announcements (this page posted as part of lecture notes on Angel)

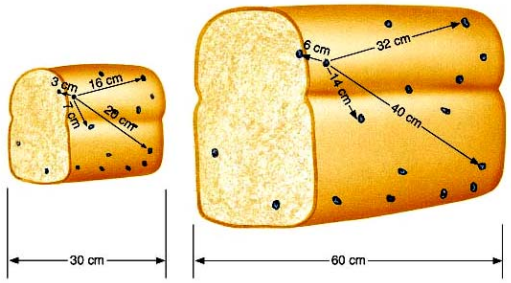
- Homework 7 due late at night Monday April 23 (6:30AM Apr 24)
- Homework 8 now available on Angel
  - Due late at night Friday April 27 (6:30AM Apr 28)

- Final exam info
  - 8-10PM Thursday May 3 in Natural Resources 158
    - SW corner of Farm Lane & Wilson
  - About 50-55 questions.
  - About half on material since Midterm 3 (including my lecture on March 29)
    - Questions provided by Prof. Smith & Baldwin
      - I will only ask about material in lectures or on homework.
      - Sample questions at www.pa.msu.edu/courses/isp205/sec-1
    - Study guide coming next Wednesday
  - About half on material up through Midterm 3
    - Questions provided by Prof. Loh
    - Use same study guides as for midterms
      - already available on syllabus page on Angel

The Expanding Universe

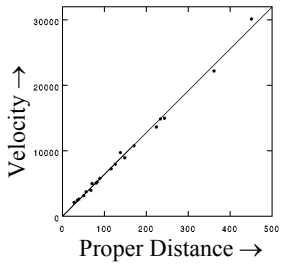


- Cosmological principle
  - Universe looks the same from any point.
- Expanding Universe
  - Hubble's Law
- Scale Factor = R(time) = R(t)
  - Proper Distance = R(t) x (co-moving distance).

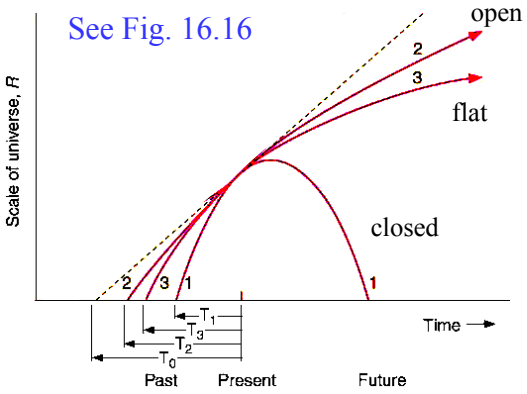


R(t) increased by factor 2

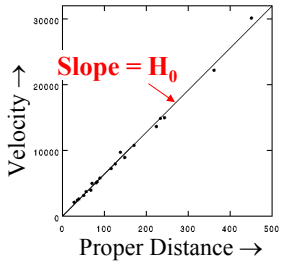
The Evolving Universe



See Fig. 16.16



The Evolving Universe



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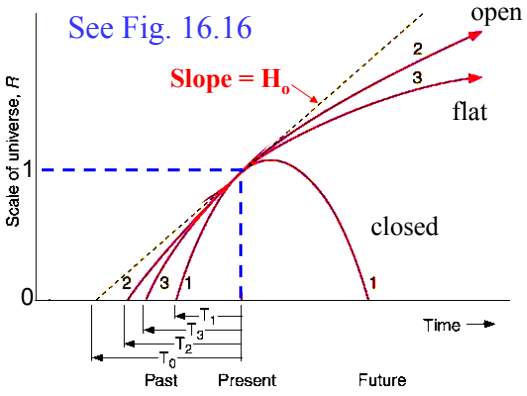


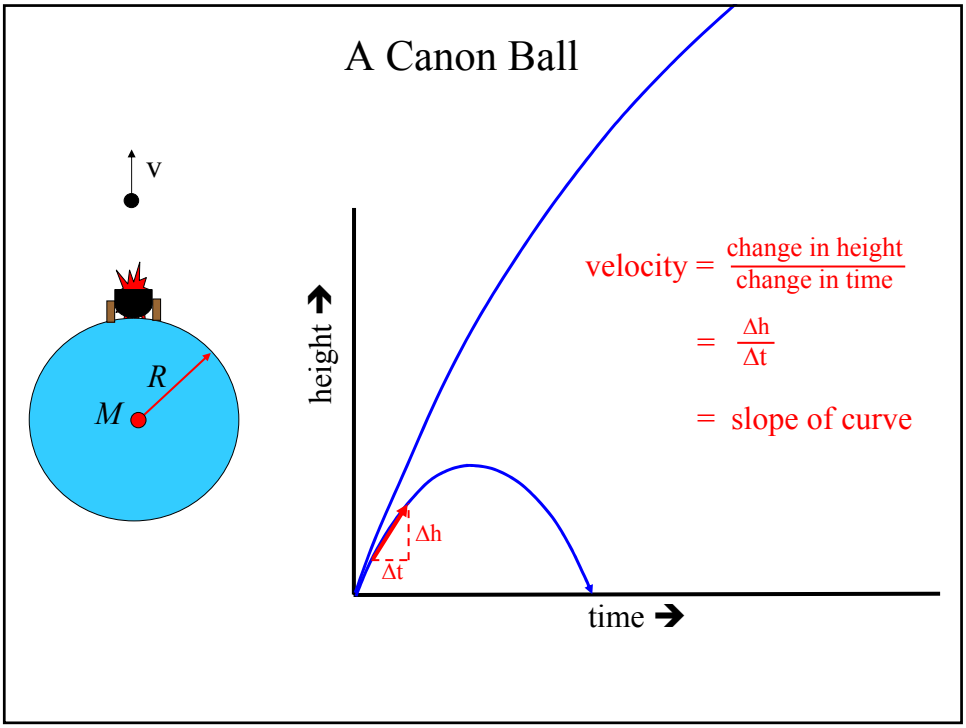
Hubble's law:

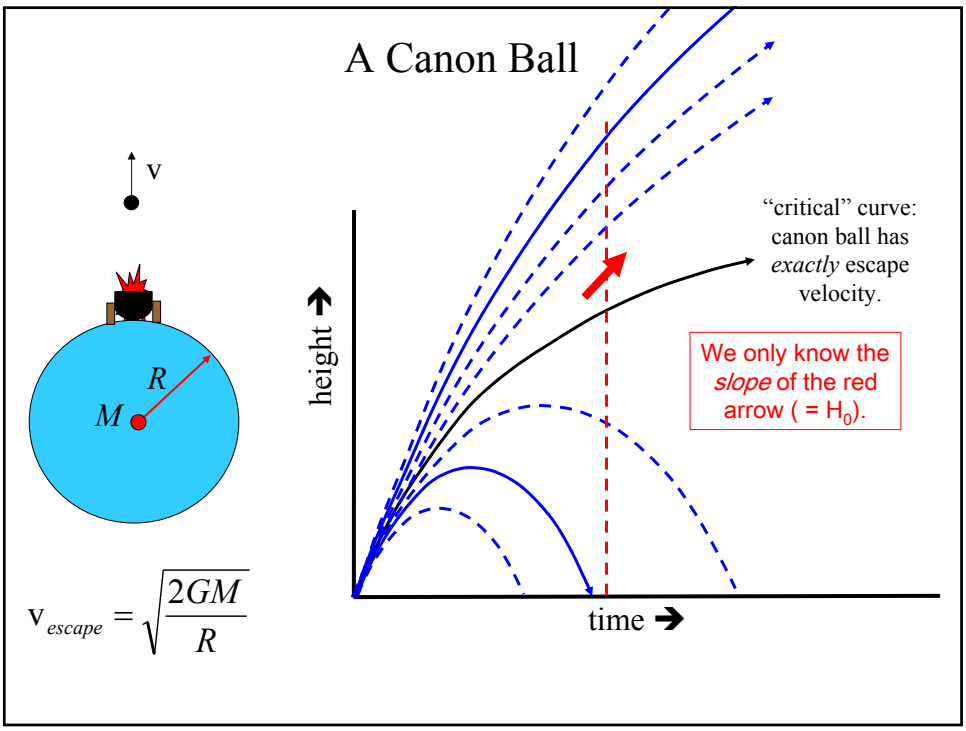
$v = H_0 d$

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

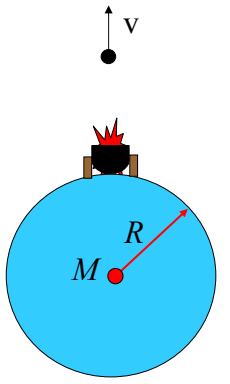
= travel time

$= \frac{1}{H_0}$ = approximate age of Universe


A Canon Ball
v
R
M
height
velocity = change in height / change in time
= Δh / Δt
= slope of curve
Δh
Δt
time


A Canon Ball
v
R
M
height
"critical" curve: canon ball has *exactly* escape velocity.
We only know the *slope* of the red arrow (= H_0).
time
$v_{escape} = \sqrt{\frac{2GM}{R}}$

A Canon Ball



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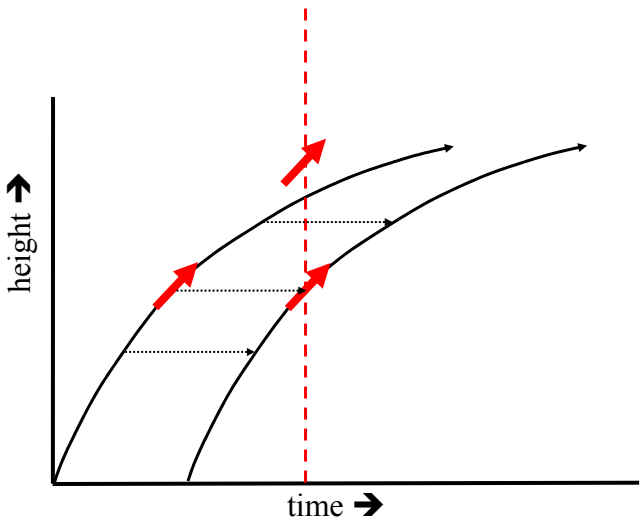
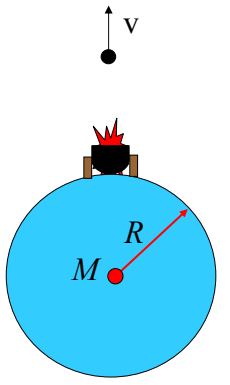


A Canon Ball



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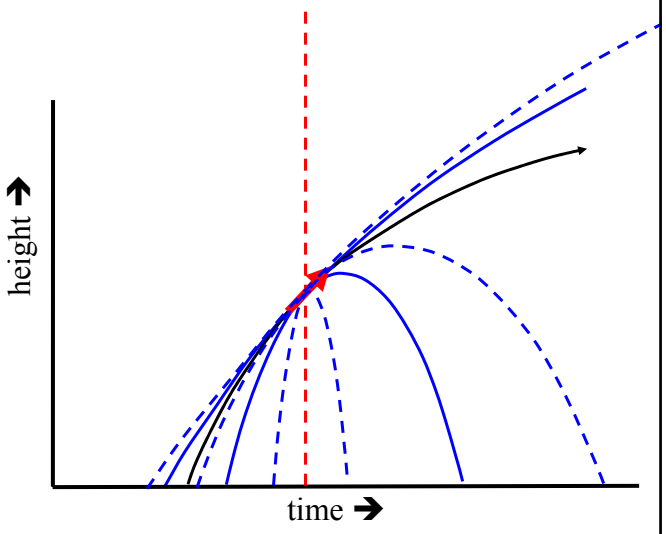

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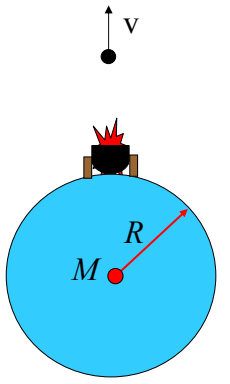

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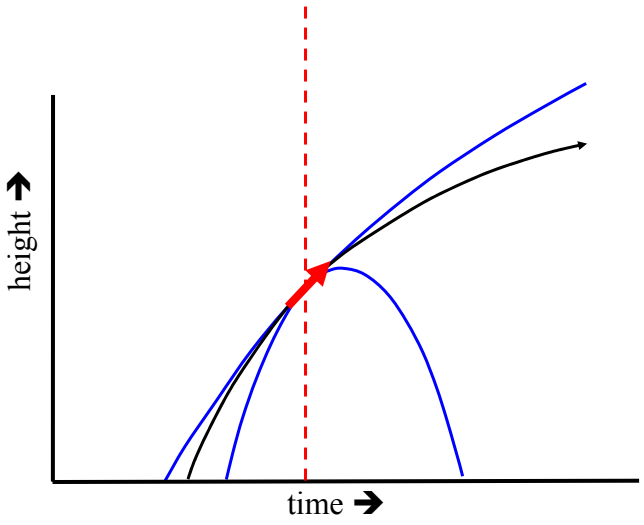
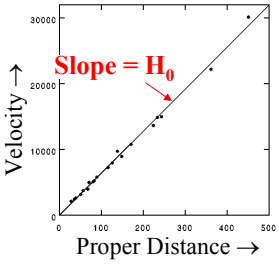


The Expanding Universe



Hubble's law:

$v = H_o d$

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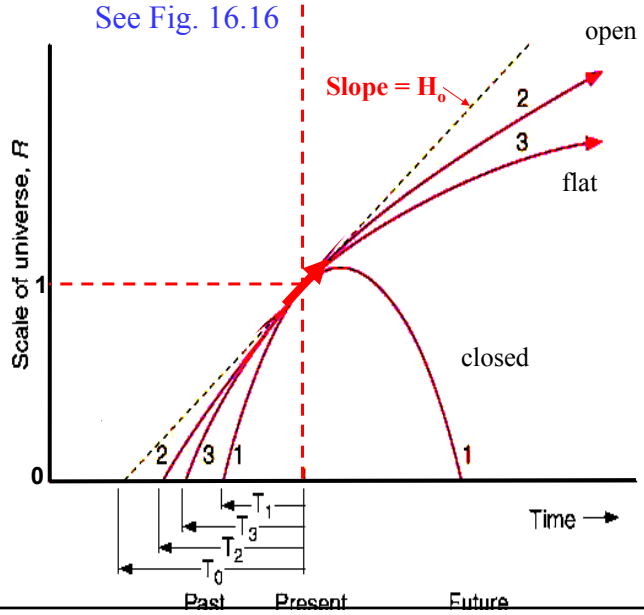
= travel time

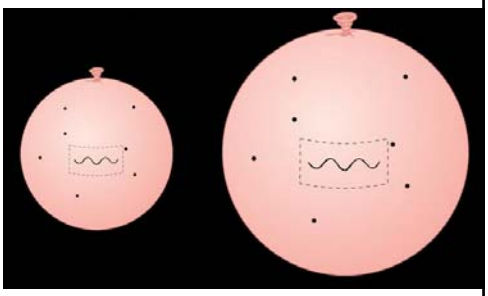
$= \frac{1}{H_o}$

See Fig. 16.16



The Expanding Universe

- Individual galaxies do not get stretched.
- Light waves *do* get stretched ➔ redshift.



doppler demo applet

Redshift ➔ scale factor R(t) at time light was emitted.

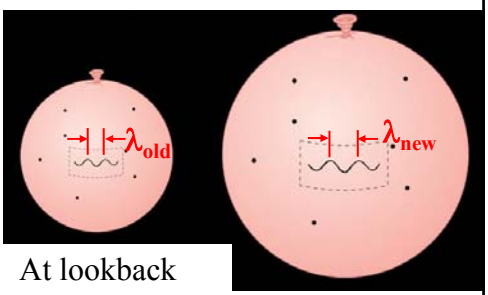
The Expanding Universe

- Individual galaxies do not get stretched.
- Light waves *do* get stretched ➔ redshift.

Redshift

$$z = \frac{\lambda_{new} - \lambda_{old}}{\lambda_{old}} = \frac{\lambda_{new}}{\lambda_{old}} - 1$$

$$R(t) = \frac{\lambda_{old}}{\lambda_{new}} = \frac{1}{1+z}$$



At lookback time corresponding to redshift z

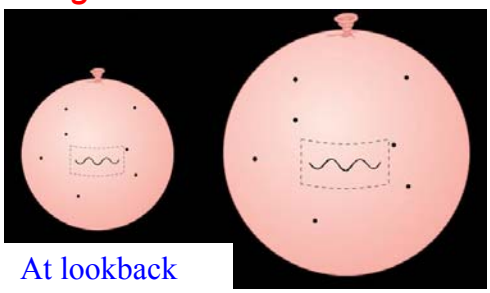
Now

doppler demo applet

Redshift ➔ scale factor R(t) at time light was emitted.

Clicker Question. *The highest redshift galaxies and quasars found so far have redshift z = 6. How many times closer together was all of the material in the universe when the light from them was emitted?*

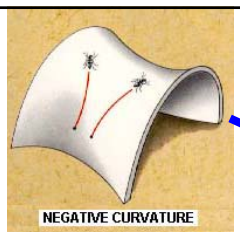
A. 4
B. 5
C. 6
D. 7



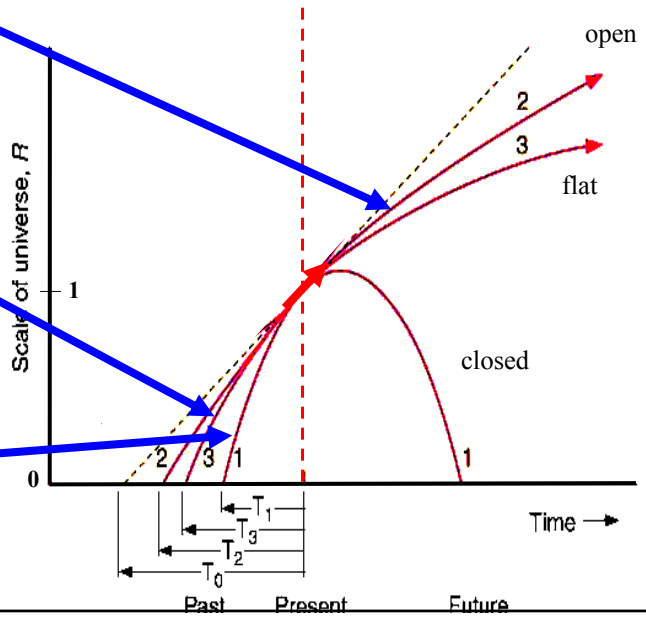
At lookback time corresponding to redshift z

Now

$$R(t) = \frac{\lambda_{old}}{\lambda_{new}} = \frac{1}{1+z}$$



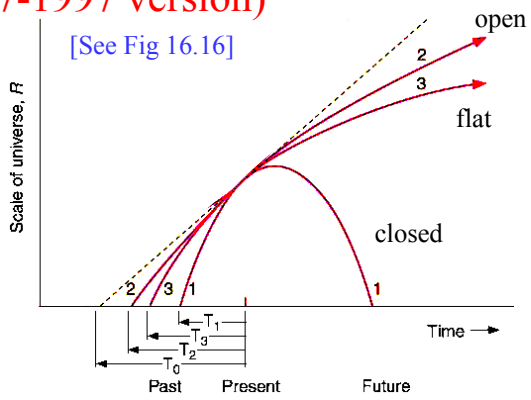
The Evolving Universe (1927-1997 version)



The Evolving Universe (1927-1997 version)

- Formerly concentrated in a tiny volume
- Kinetic energy vs. gravitational attraction
  - ➔ Curvature of space
  - ➔ Evolution

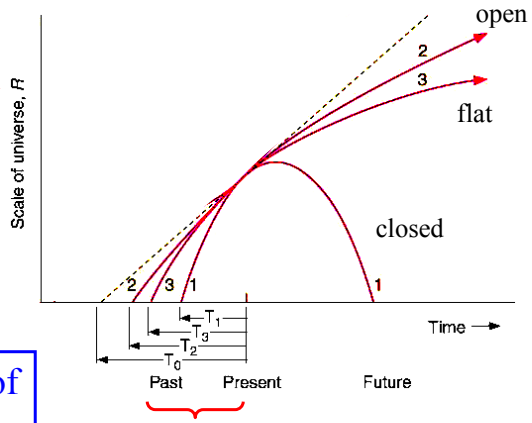
[See Fig 16.16]



Energy balance	Curvature	Future
kinetic > gravitational	negative	open
kinetic = gravitational	flat	critical
kinetic < gravitational	positive	closed

Which Universe do we live in?

$$R(t) = \frac{1}{1+z}$$



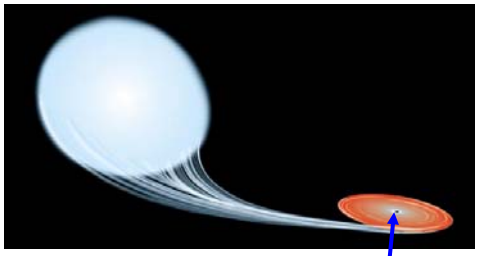
Measure dependence of R on lookback time:

➔ which model of universe is correct?

Lookback time
= distance traveled by photon

Which Universe Do We Live In?

- Type Ia Supernovae
  - Neighbor star dumps too much mass onto a white dwarf.
  - Collapse to neutron star.
  - Supernova explosion.



white dwarf at center of accretion disk

- Type Ia Supernovae as "standard candles".
  - Always happens when mass goes just past limit for white dwarfs.

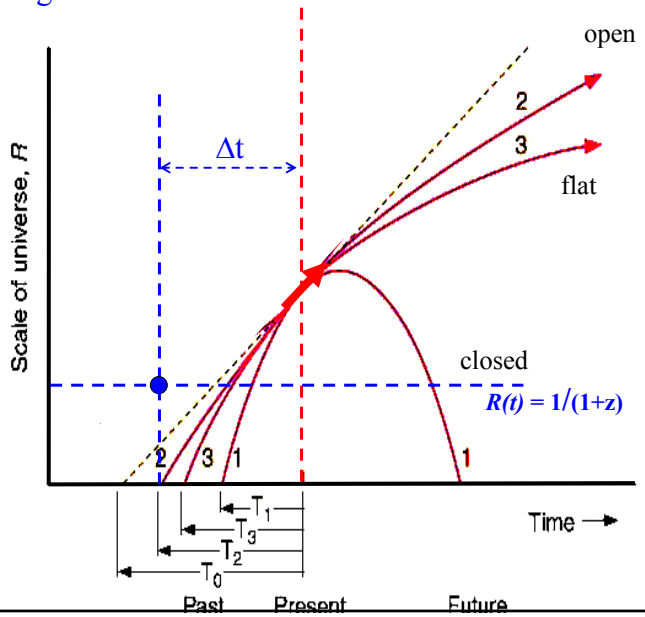
    ➔ Supernova always has same luminosity.
  - Get distance from $\text{Flux} = \frac{L}{4\pi r^2}$

Which Universe Do We Live in?

Distance = light travel time ➔ lookback time Δt

What we can measure for supernovae:

- Redshift
- Distance



Which Universe Do We Live in?

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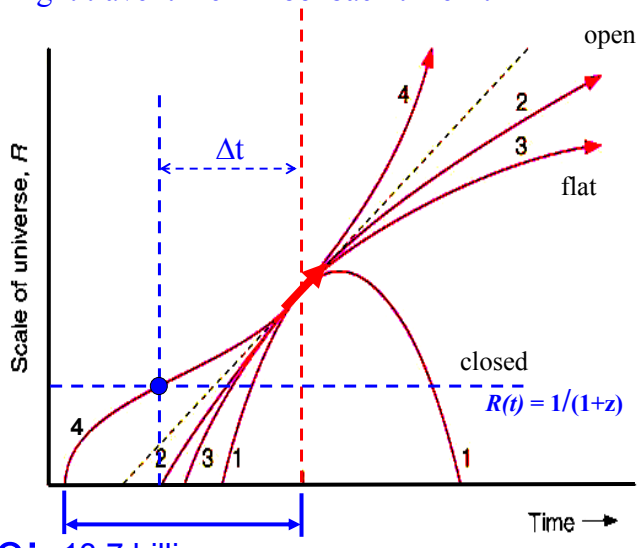


Age of Universe: 13.7 billion years

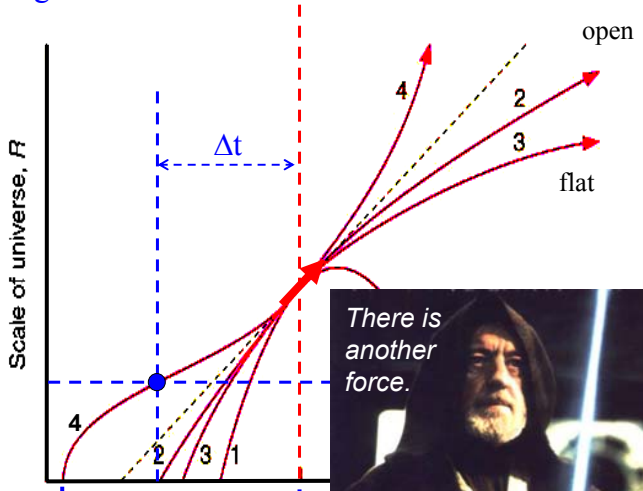
Clicker Question:

What is implied by the upward bend in curve #4?

A. Gravity is the only force at work, but the galaxies have more than the escape velocity.
B. An unknown force is pushing the universe apart.
C. The distances between objects will start to decrease in the future.

Universe Do We Live in?

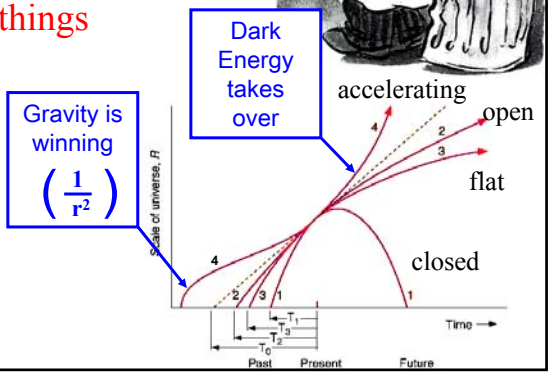
= light travel time ➔ lookback time Δt

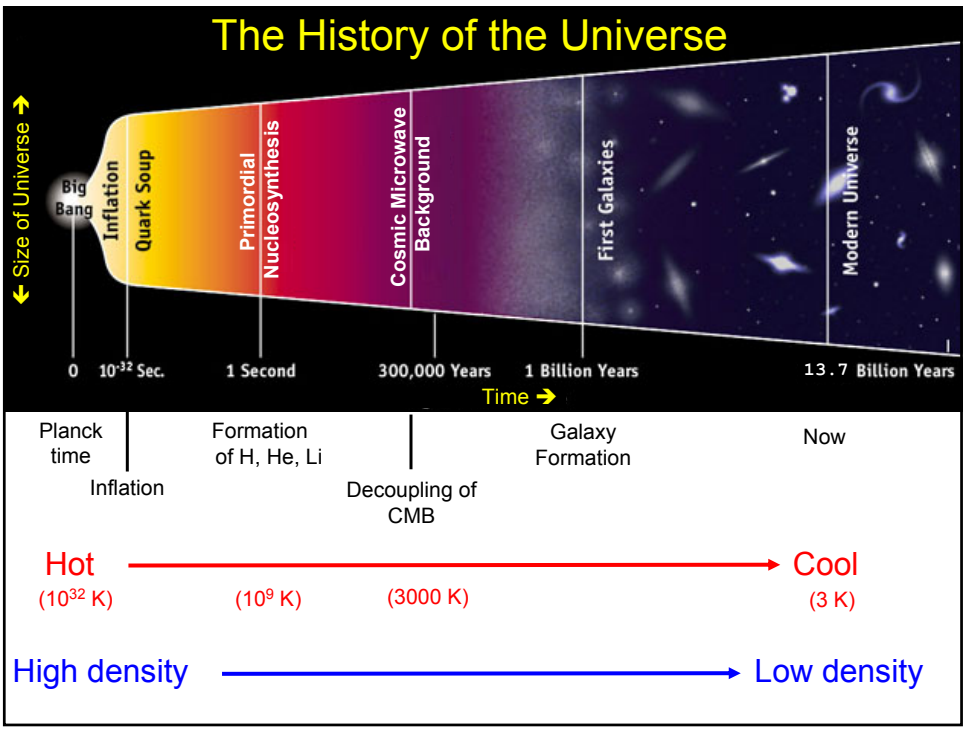


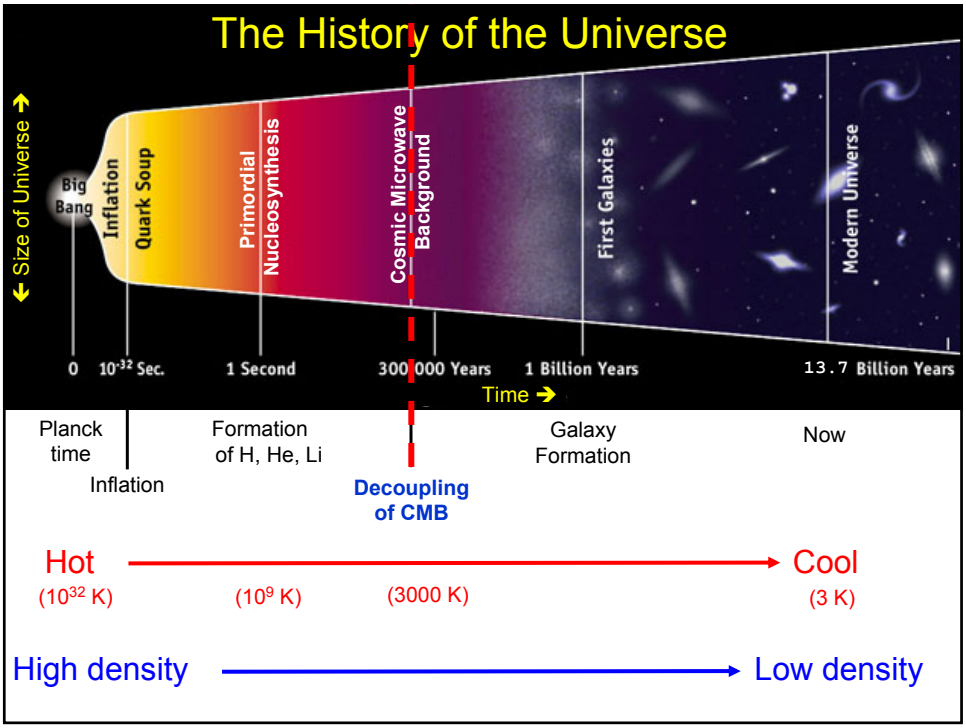
Universe: 13.7 billion years

The Cosmological Constant. (Dark Energy)

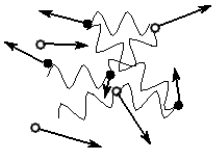
- Einstein's static universe
  - Cosmological constant balanced gravity.
  - Einstein: "My greatest blunder"
- Acts as force pushing things apart.
  - Gets stronger as separation increases
- What is it?
  - Nobody knows.
- Is it really a constant?
  - Nobody knows.







Cosmic Microwave Background



Hotter

- Hydrogen ionized.
  - Universe opaque.
    - Photons travel only short distances.
    - Absorbed, re-emitted by free electrons.

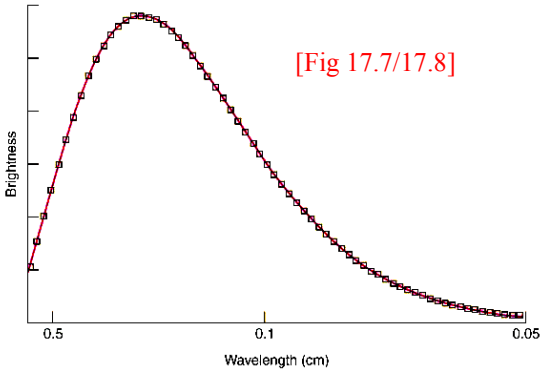
Decoupling { T = 3000°K; 13.7 billion yrs ago; Universe 300,000 yrs old.

- Hydrogen becomes neutral ($p + e^- \rightarrow H$).
  - Universe becomes transparent.
  - Photons decouple from matter, continue in whatever direction they were moving.

Cooler

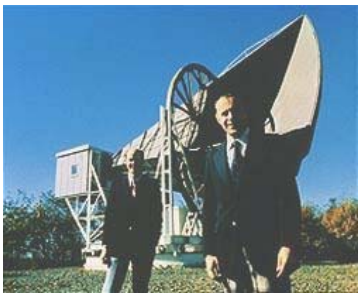
Expansion of universe ➔ redshift

- Photons formed in blackbody with T ~ 3000° K
- Redshifting ➔ lower energy per photon
  - E = hν = hc/λ
  - So we see T = 3° K blackbody spectrum



[Fig 17.7/17.8]

Discovered in 1965



Penzias, Wilson, and their radio telescope.

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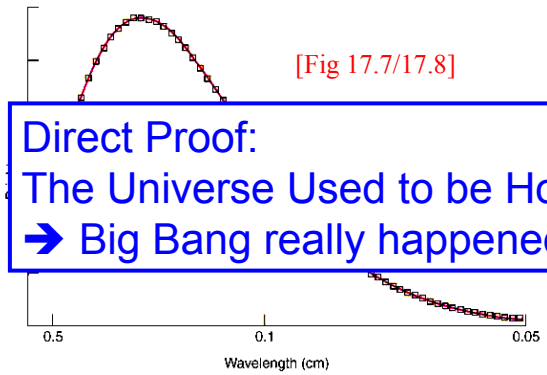

[Fig 17.7/17.8]

Discovered in 1965

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Direct Proof:
The Universe Used to be Hotter.
➔ Big Bang really happened!