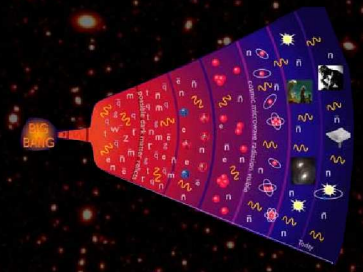
The Expanding Universe



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Hypericon II – 2006 June 23

I. The Shape of the Universe.
   - *Flatland* analogy
   - Non-Euclidean Geometry

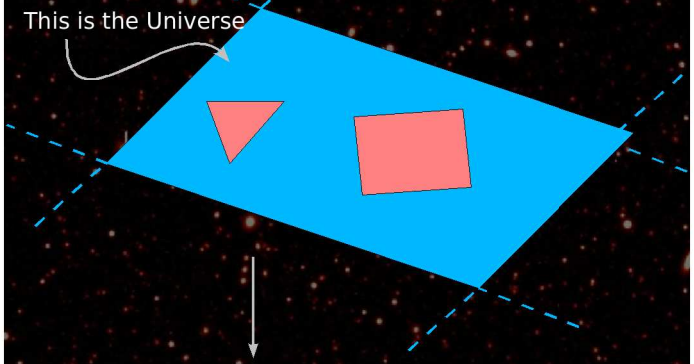
II. The Expansion of Space
   - Measuring Expansion: Redshift
   - Measuring Expansion Rate

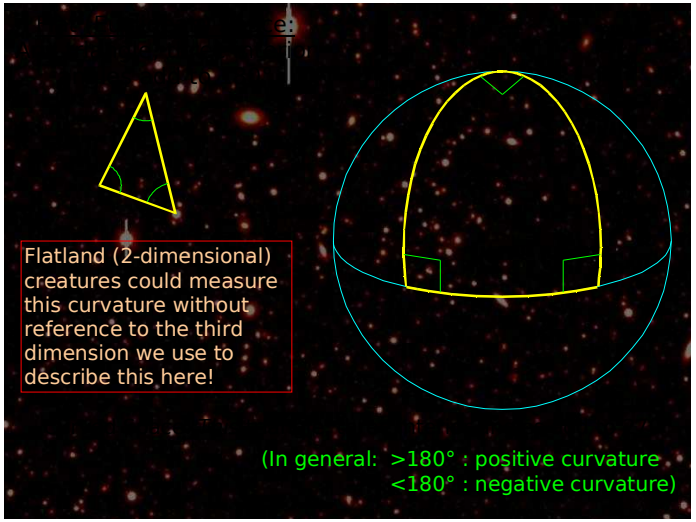
III. A Little Data: how we know
   - A consistent picture of the Whole Universe (!!)

IV. Reality Check: The "old way" of describing the expansion

V. How did we get here? The Big Bang....

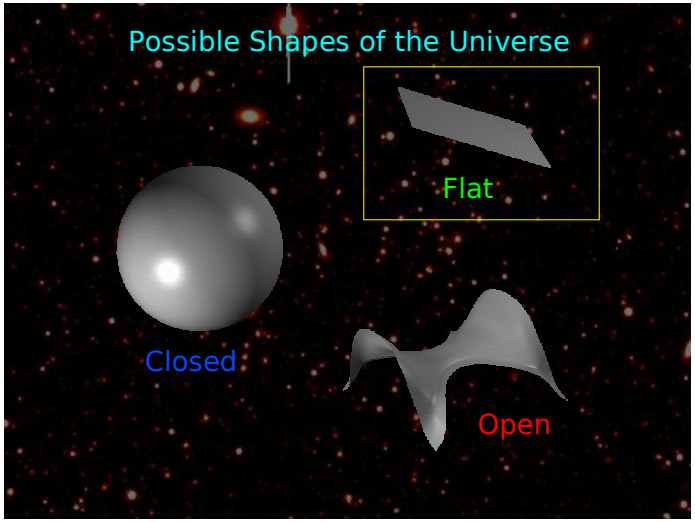
Flatland

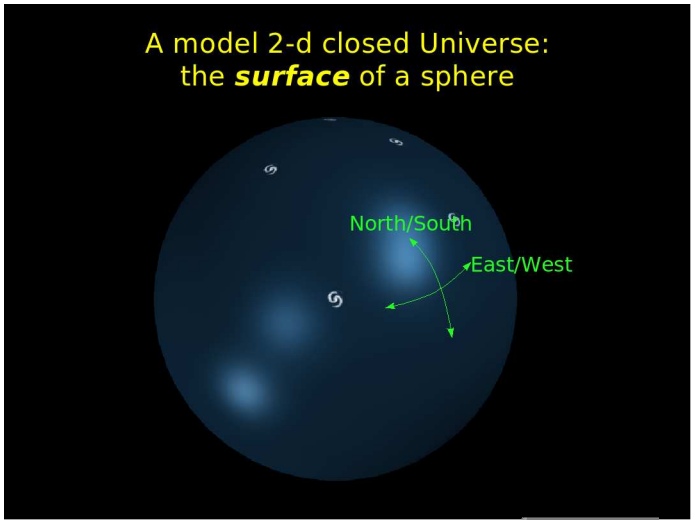


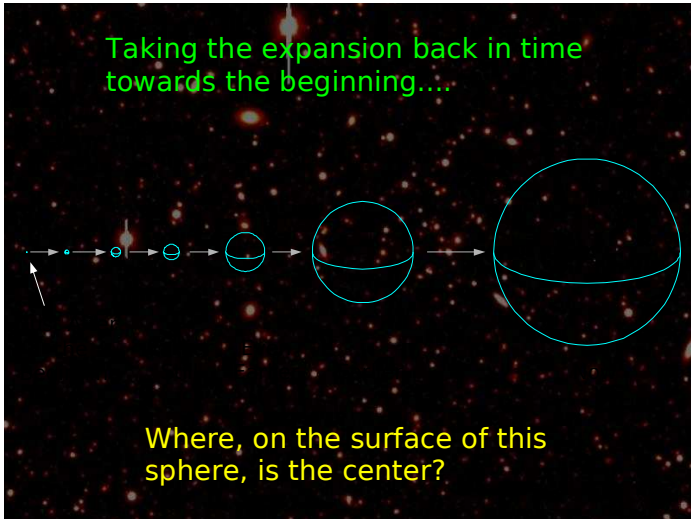


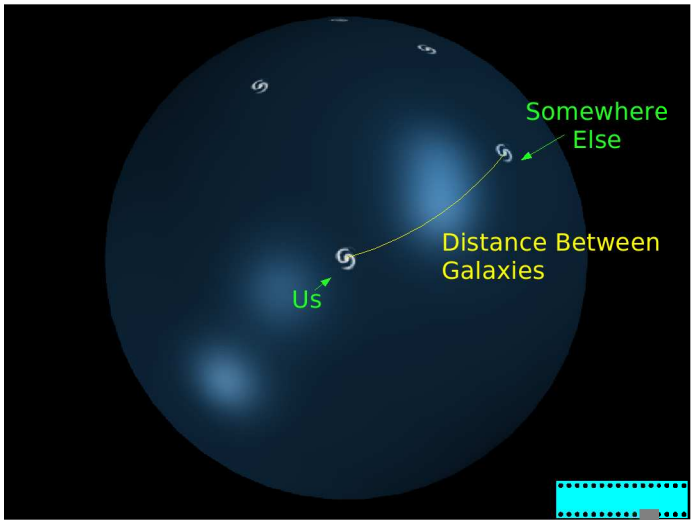
Flatland (2-dimensional) creatures could measure this curvature without reference to the third dimension we use to describe this here!

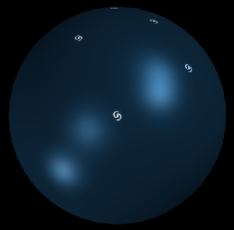
(In general: >180° : positive curvature
<180° : negative curvature)


Possible Shapes of the Universe
Flat
Closed
Open

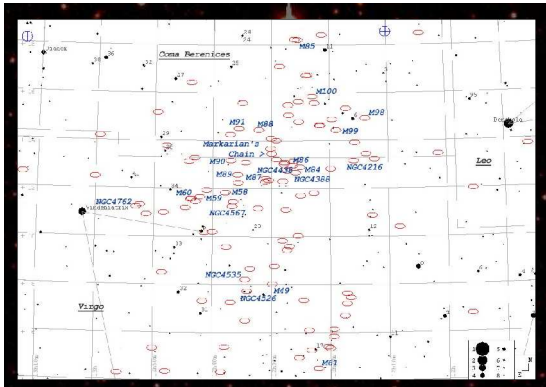

A model 2-d closed Universe:
the *surface* of a sphere
North/South
East/West


Taking the expansion back in time
towards the beginning....
Where, on the surface of this
sphere, is the center?


Somewhere
Else
Distance Between
Galaxies
Us



- As the Universe expands, galaxies get farther apart, but...
- ...galaxies are *not* moving *through space* **
- Galaxies *don't* expand themselves
- This is probably not the explanation you've heard (i.e. galaxies flying apart with greater speeds at greater differences), but better expresses the modern view of how the Universe works.



The Virgo Cluster

Distance today: 20 Mpc (million parsecs)

Distance in 100 years: 20 Mpc + 1×10^{-9} Mpc. (Oh well)

"Look-back" time to Virgo Cluster:

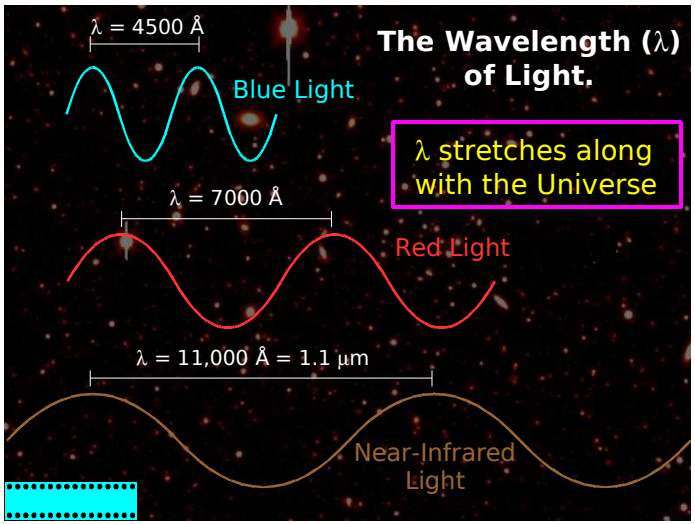
1 parsec = 3.26 light-years

Light goes 1 light-year in one year (surprise!)

20 million parsecs means we see the Virgo clutser as it was 65 million years ago.

Can we find something that has expanded along with the Universe over that time????

Yes! Light!



The Wavelength (λ) of Light.

λ stretches along with the Universe

Cosmological Redshift (z)

Amount wavelength shifts to the red

$$z = \frac{\Delta\lambda}{\lambda}$$

Original emitted wavelength

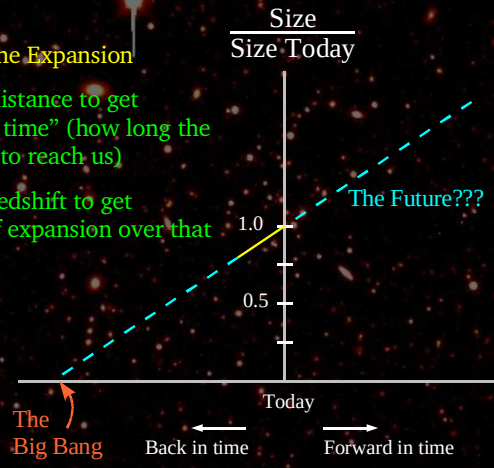
$$1 + z = \frac{\lambda + \Delta\lambda}{\lambda} = \frac{\lambda_{observed}}{\lambda_{original}}$$

$$= \frac{\text{Size of Universe at Detection}}{\text{Size of Universe at Emission}} = \frac{\text{Size Now}}{\text{Size Then}}$$

Redshift tells us directly how much the Universe has expanded while the light was traveling to us.

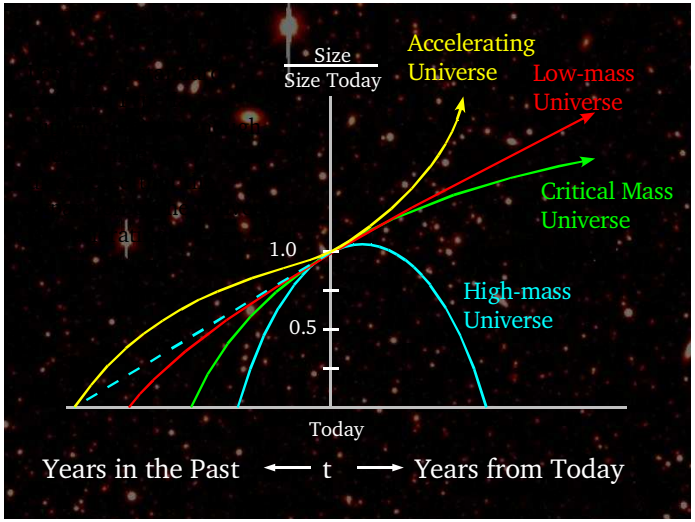
Measuring the Expansion

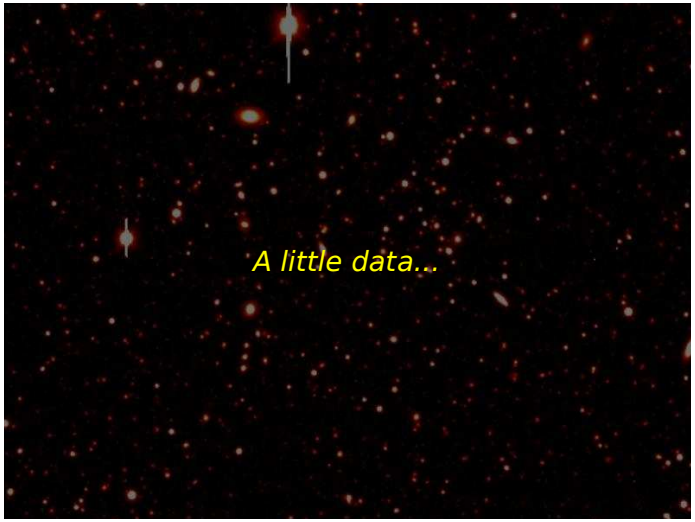
- Measure distance to get "lookback time" (how long the light took to reach us)
- Measure redshift to get amount of expansion over that time.

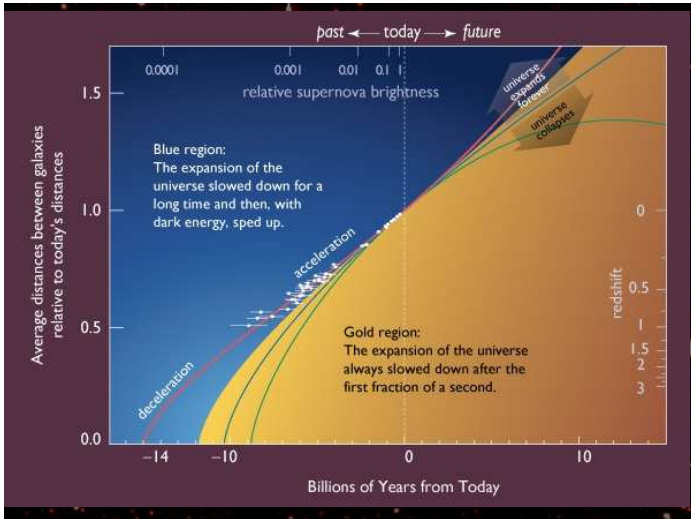


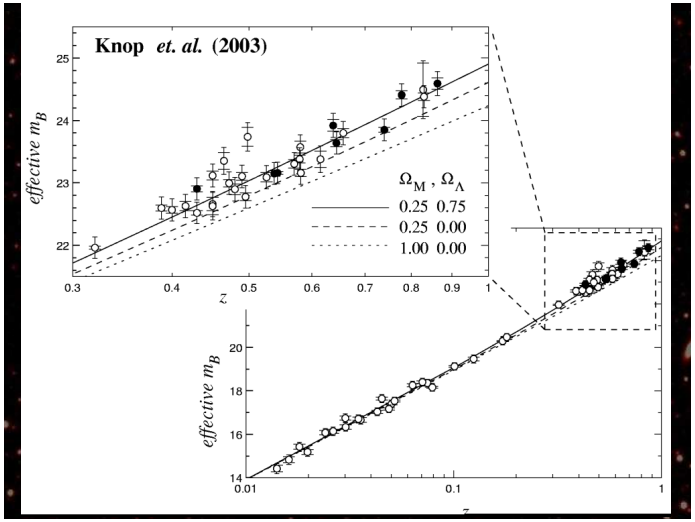
Lookback Times

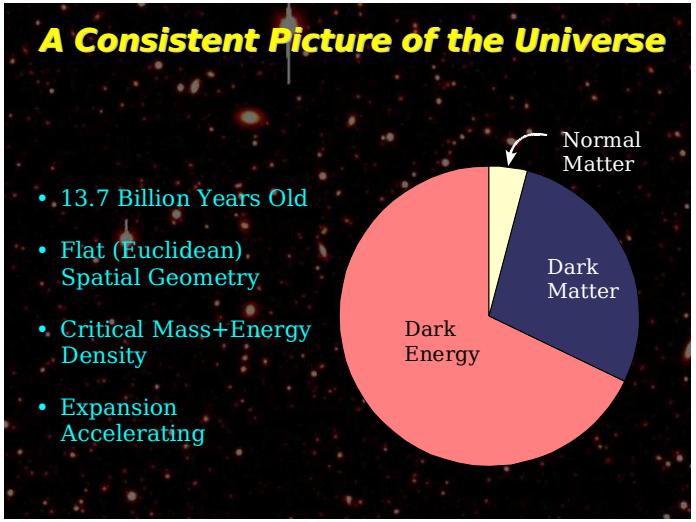
Object	Lookback Time
Sun	8 minutes
Alpha Centauri	4 years
Andromeda Galaxy	2 million years
Seyfert Galaxy NGC1068	16 million years
Quasar 3C273 at z=0.158	2 billion years
Galaxy at z=1	7 billion years
Age of Universe	13 billion years

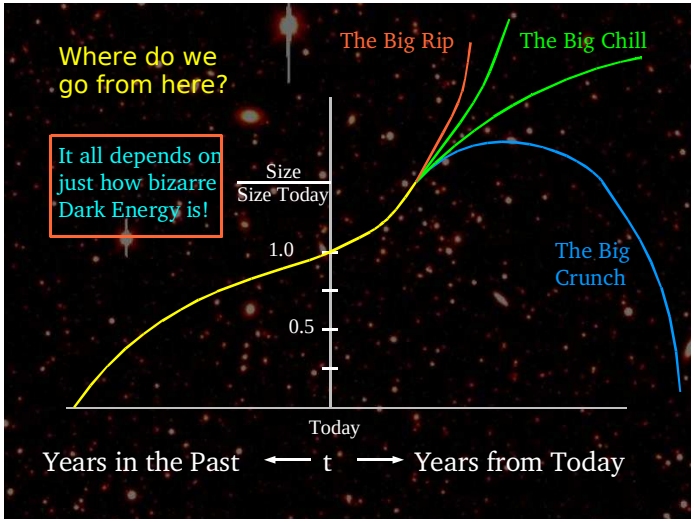


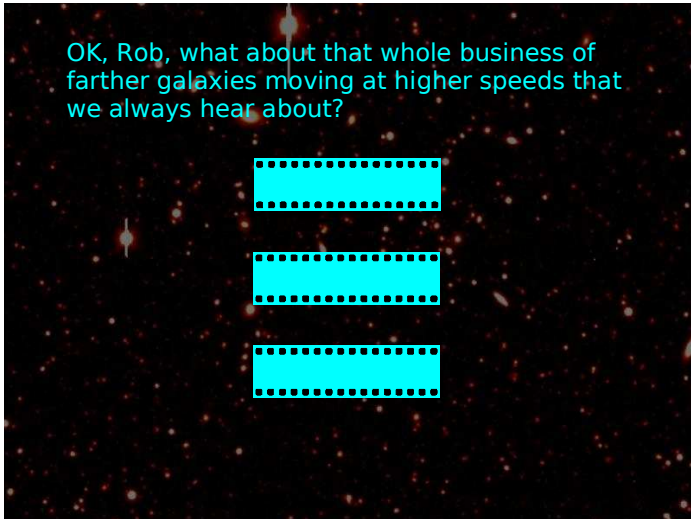

A little data...

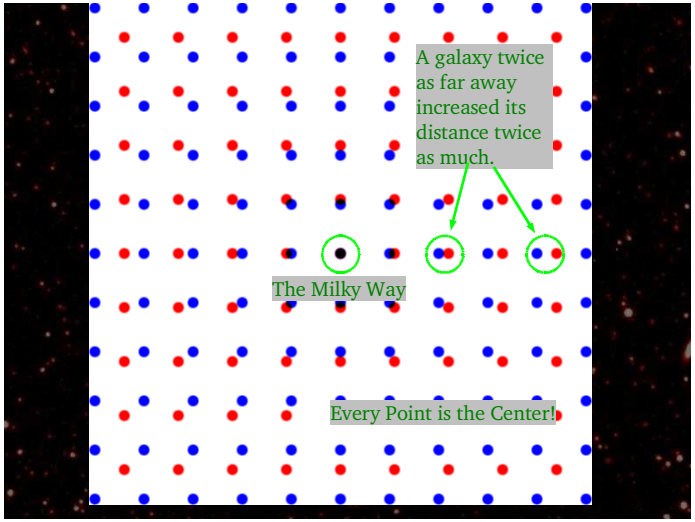

past
today
future
0.0001
0.001
0.01
0.1
1
relative supernova brightness
universe expands forever
universe collapses
Blue region:
The expansion of the universe slowed down for a long time and then, with dark energy, sped up.
acceleration
deceleration
Gold region:
The expansion of the universe always slowed down after the first fraction of a second.
Average distances between galaxies relative to today's distances
1.5
1.0
0.5
0.0
redshift
0
0.5
1
1.5
2
3
−14
−10
0
10
Billions of Years from Today

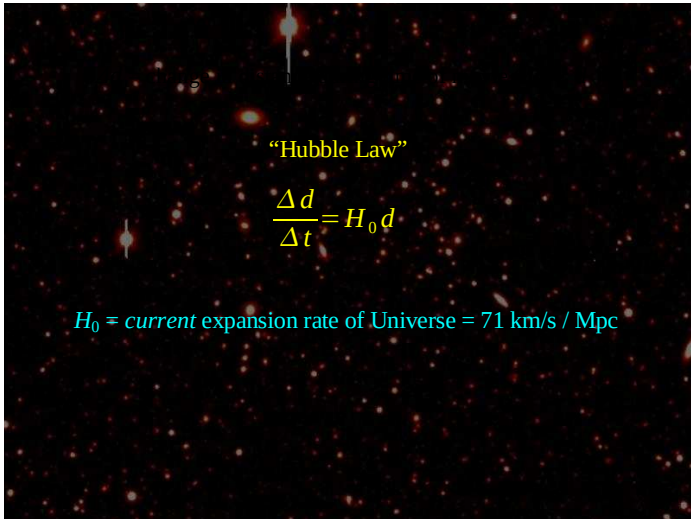

Knop et. al. (2003)
effective m_B
Ω_M , Ω_Λ
0.25 0.75
0.25 0.00
1.00 0.00
z
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
22
23
24
25
effective m_B
14
16
18
20
0.01
0.1
1
z


A Consistent Picture of the Universe
• 13.7 Billion Years Old
• Flat (Euclidean) Spatial Geometry
• Critical Mass+Energy Density
• Expansion Accelerating
Normal Matter
Dark Matter
Dark Energy


Where do we go from here?
The Big Rip
The Big Chill
It all depends on just how bizarre Dark Energy is!
Size
Size Today
1.0
0.5
The Big Crunch
Today
Years in the Past
t
Years from Today


OK, Rob, what about that whole business of farther galaxies moving at higher speeds that we always hear about?


A galaxy twice as far away increased its distance twice as much.
The Milky Way
Every Point is the Center!


"Hubble Law"
$\frac{\Delta d}{\Delta t} = H_0 d$
H_0 = *current* expansion rate of Universe = 71 km/s / Mpc

Doppler Shift (z)

Amount wavelength shifts to the red

$$z = \frac{\Delta\lambda}{\lambda}$$

Original emitted wavelength

$$z \approx \frac{v}{c}$$

Compare to Cosmological redshift:

$$1+z = \frac{\text{Size Now}}{\text{Size Then}} = \frac{d+\Delta d}{d} = \frac{d+vt}{d} = 1+\frac{vt}{d} = 1+\frac{v}{d/t} = 1+\frac{v}{c}$$

Summary

- The expansion of the Universe is an expansion of *space itself*. Galaxies get farther apart, much as do raisins in rising bread, pennies pasted on the surface of an expanding balloon, or paper clips on a stretching elastic band.
- As the Universe expands, the wavelengths of light expand at the same rate.
- The three dimensional space of the Universe can be *intrinsically curved*, but large-scale geometry is flat (Euclidean). (Whew!)
- The expansion of the Universe is accelerating, and indicates that the Universe is filled with *Dark Energy*.

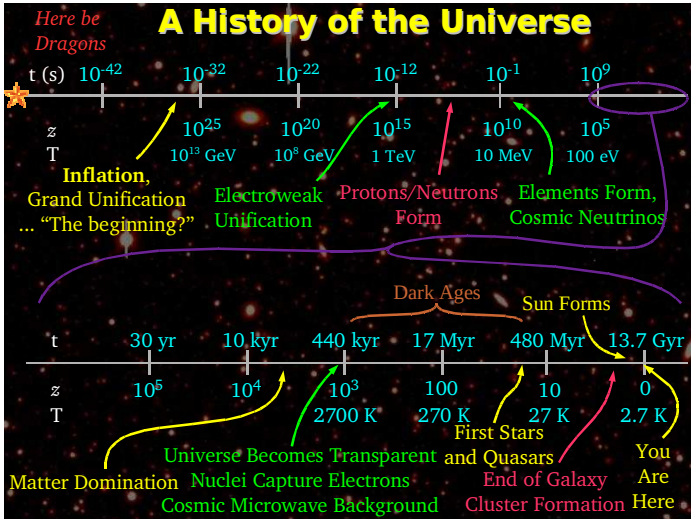
If the Universe is expanding, then in the past it was smaller... far enough back, *much* smaller.

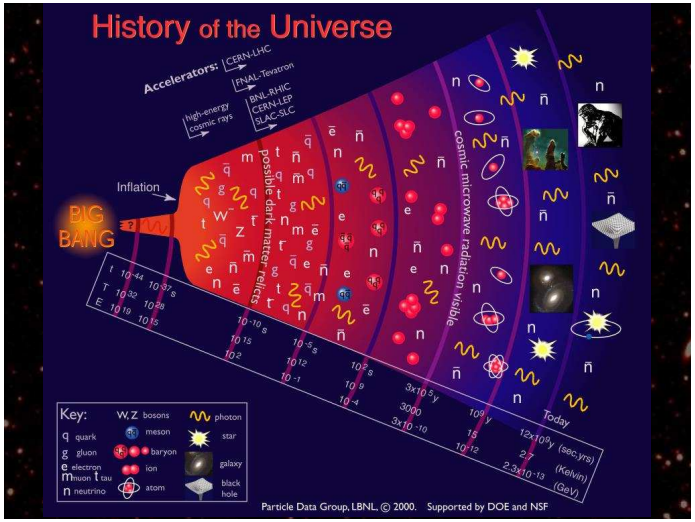
The Big Bang Theory tells us that the Universe has evolved to its present state from a very condensed and hot state over the course of about 14 billion years.

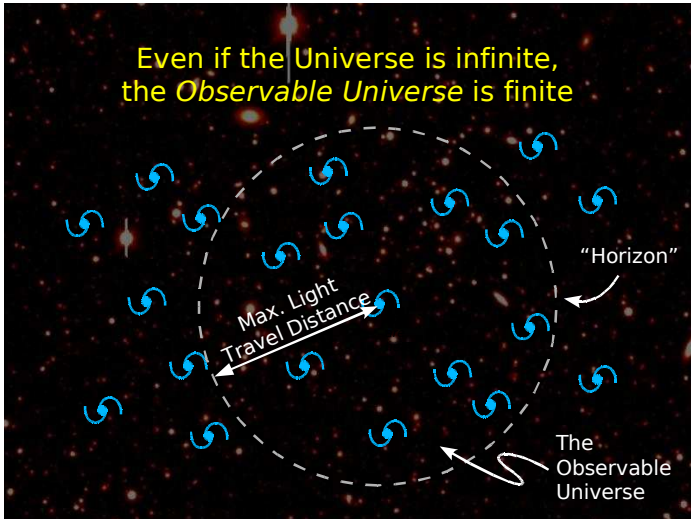
It does not currently tell us about the *actual moment of creation*, or what happened *before* that 14 billion years... there is a point before which our Physics breaks down! (String Theory??)

Evidence for the Big Bang:

- Expanding Universe
- Cosmic Microwave Background
- Fraction of Deuterium and Helium

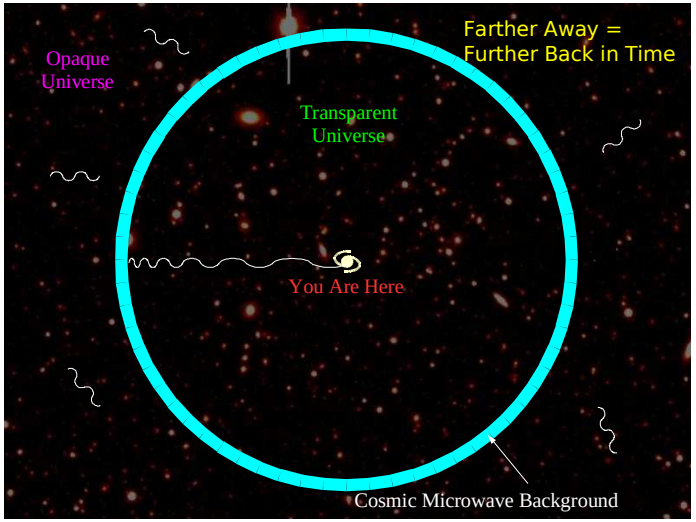




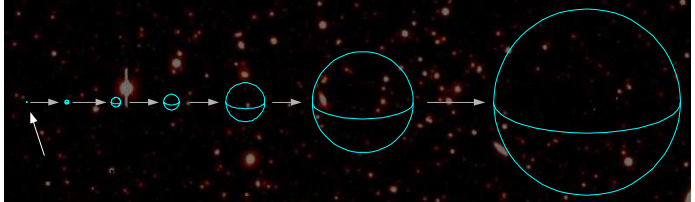


The *observable* Universe, 10^{-43} seconds after the Big Bang:

(Actual Size)



Taking this expansion back in time towards the beginning....

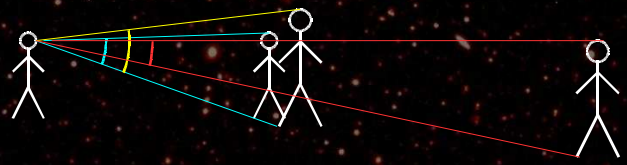


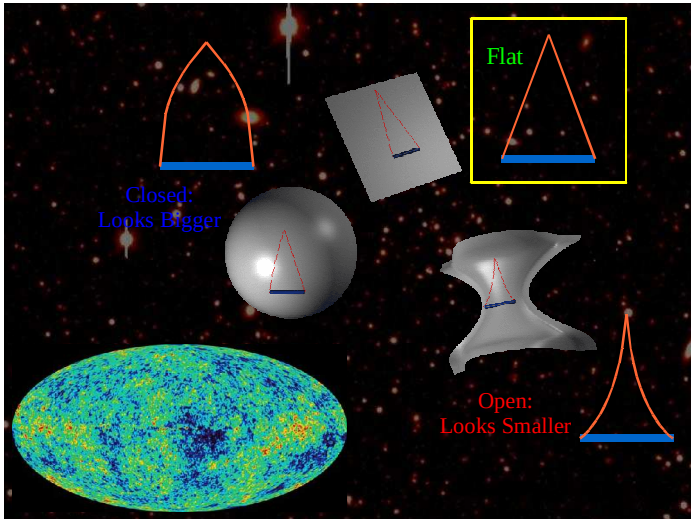
Where, on the surface of this sphere, is the center?

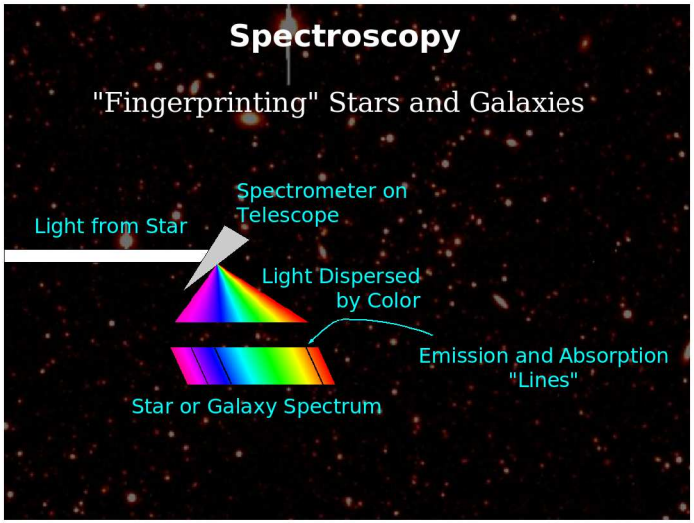
Extra Slides...

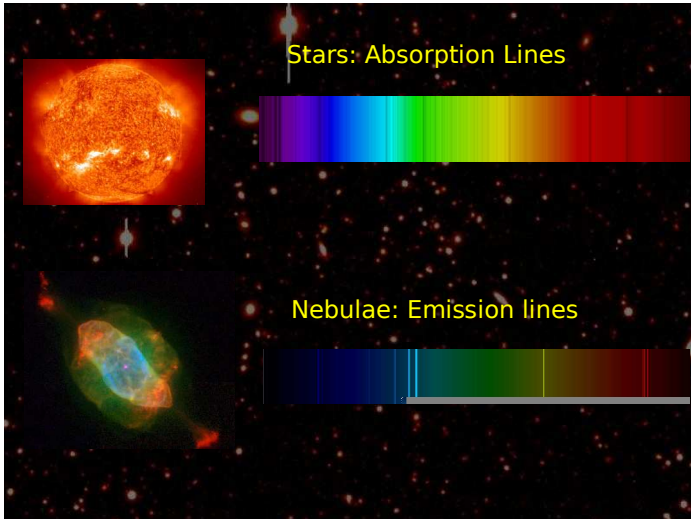
What do we mean when we say how big something looks?

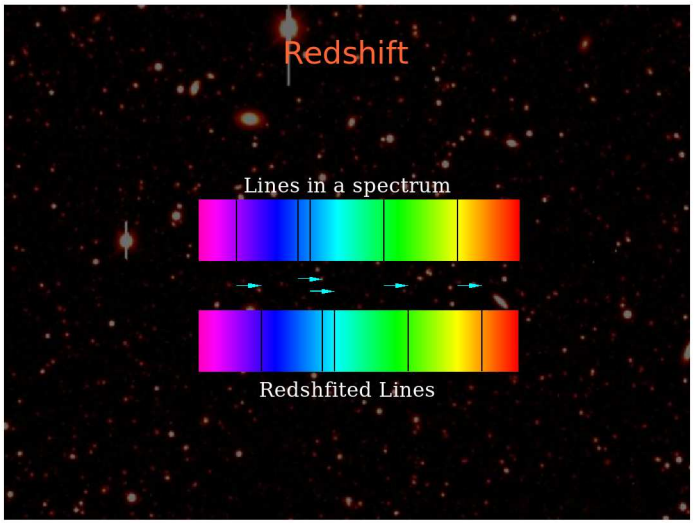
The angle that it *subtends*.






Spectroscopy
"Fingerprinting" Stars and Galaxies
Spectrometer on Telescope
Light from Star
Light Dispersed by Color
Emission and Absorption "Lines"
Star or Galaxy Spectrum


Stars: Absorption Lines
Nebulae: Emission lines


Redshift
Lines in a spectrum
Redshfited Lines