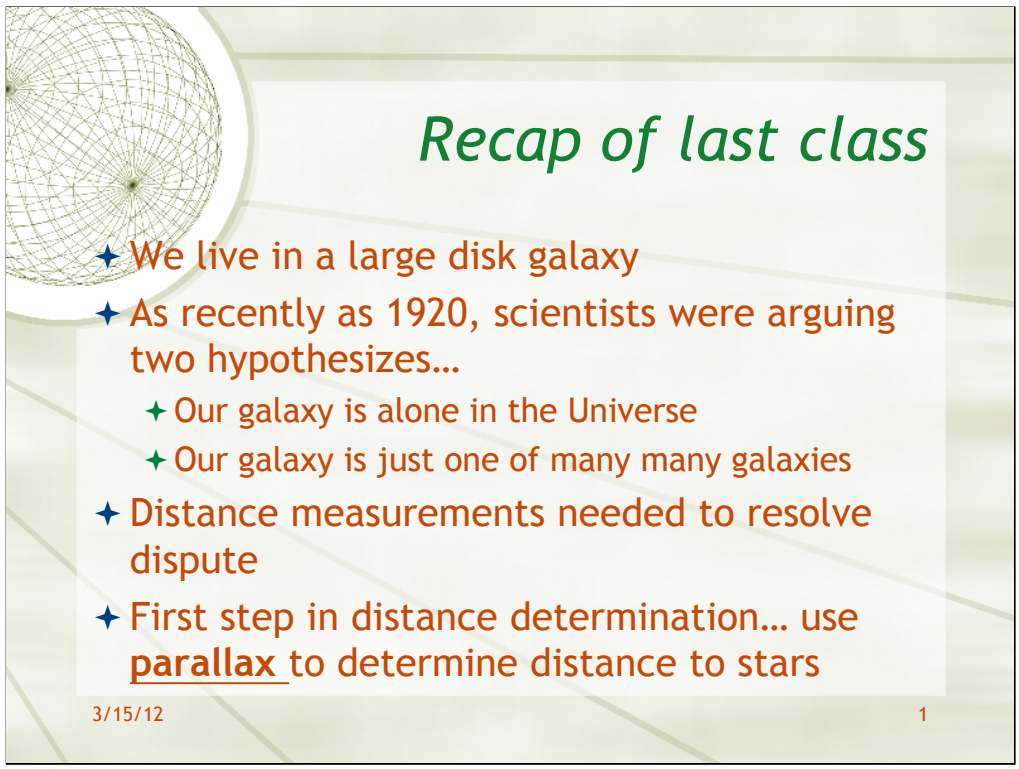
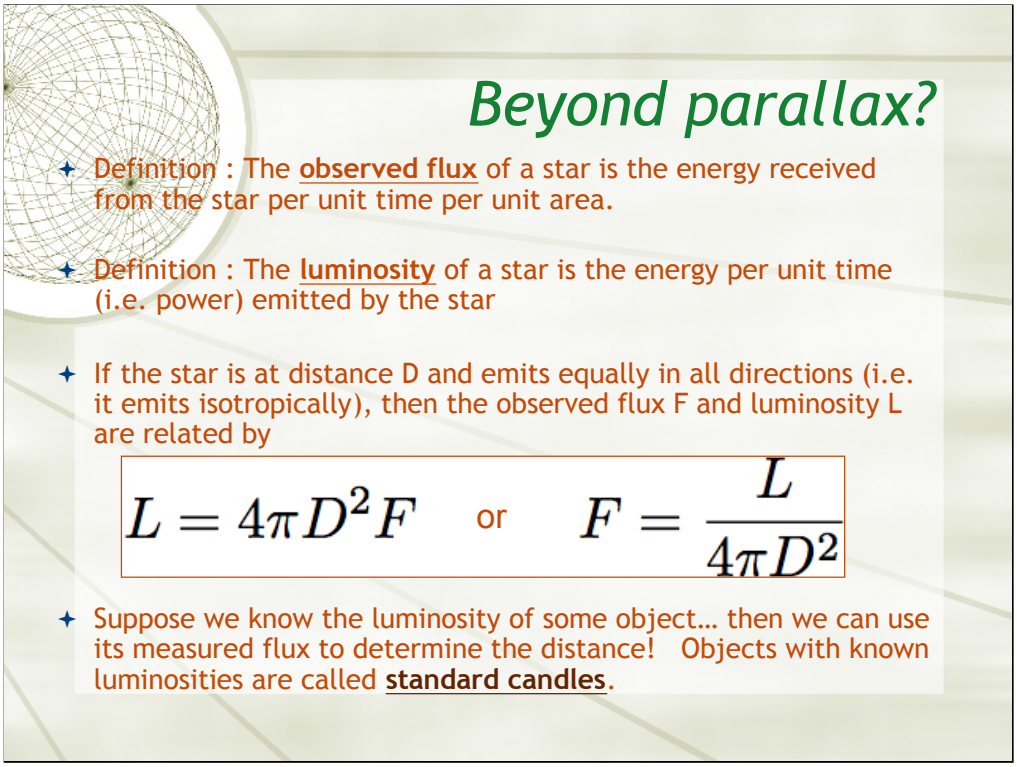
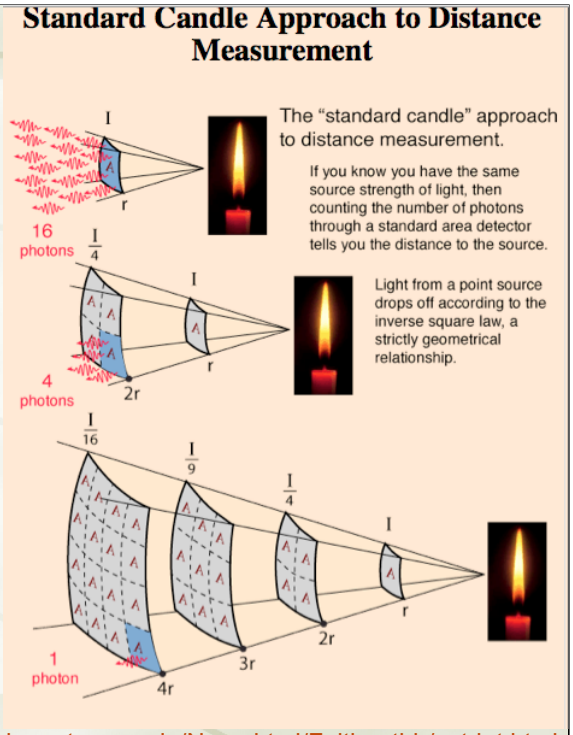

Recap of last class
We live in a large disk galaxy
As recently as 1920, scientists were arguing two hypothesizes…
Our galaxy is alone in the Universe
Our galaxy is just one of many many galaxies
Distance measurements needed to resolve dispute
First step in distance determination… use parallax to determine distance to stars
3/15/12
1



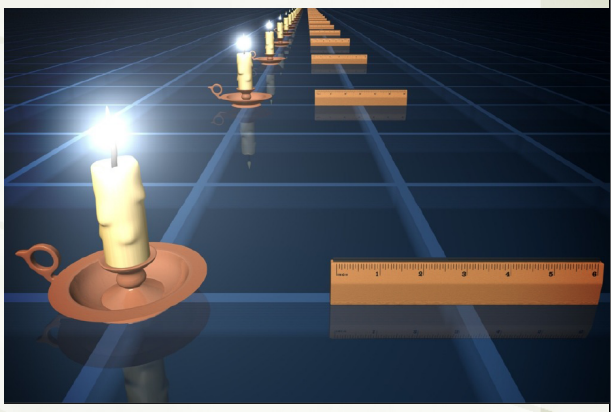
Let's formalize this…

- So the problem boils down to how to find and define a standard candle
- Question: how would you do this??



http://hyperphysics.phy-astr.gsu.edu/Nave-html/Faithpathh/astdat.html

Standard Rulers and Candles



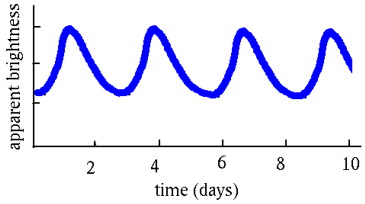
Brian Schmidt

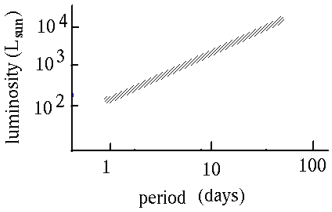
Henrietta Leavitt
ph.credit: AAVSO

Cepheid variables

http://universe-review.ca/R02-07-candle.htm

- Henrietta Leavitt discovered (1912) that a certain class of variable stars called Cepheids had properties that meant they could be used as standard candles
  - She studied Cepheids in the Magellenic Clouds (and assumed that they were all at the same distance)… found that the luminosity is related to the period of fluctuations in brightness
  - So, if you measure the period of a Cepheid, you can determine its luminosity. Measuring flux then gives you distance, even if its too far for parallax!



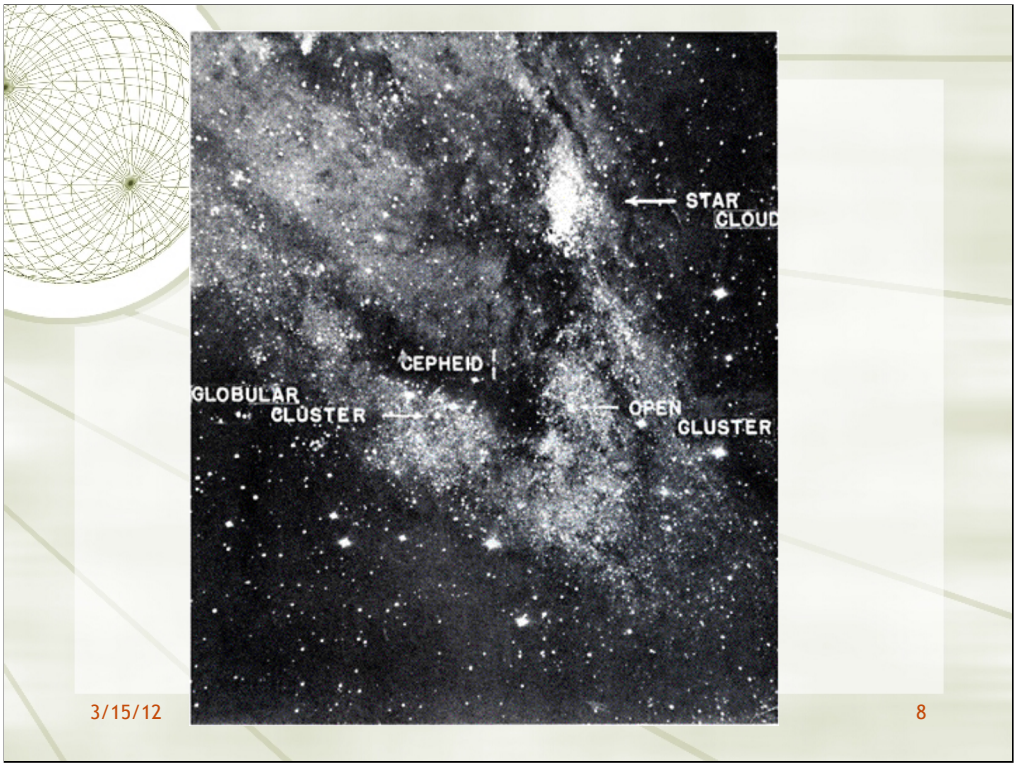


graphics: University of Oregon Astronomy Dept

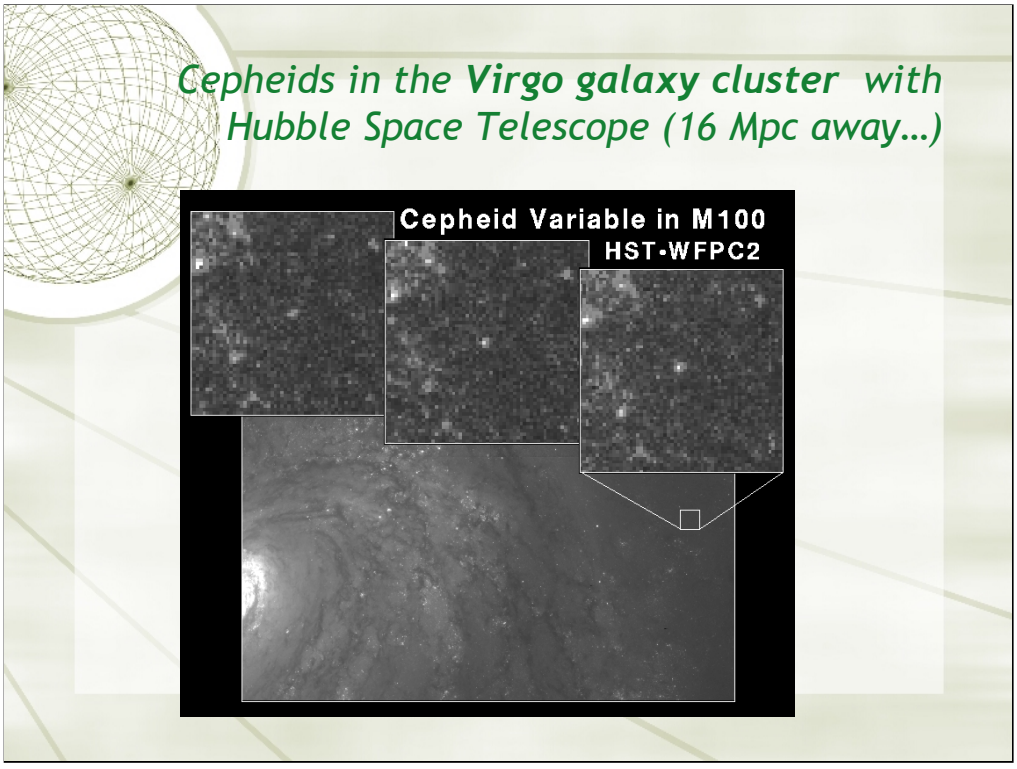
Edwin Hubble

Hubble's observations

- Hubble found Cepheid Variables in Andromeda
  - Measured period and flux, and hence distance
  - Concluded that Andromeda must be well outside of the Milky Way Galaxy
  - Thus, the Great Debate was settled… the MW is just one of many many many galaxies
- Modern measurements
  - Distance to Andromeda 2 million lyr
  - About 20x MW diameter



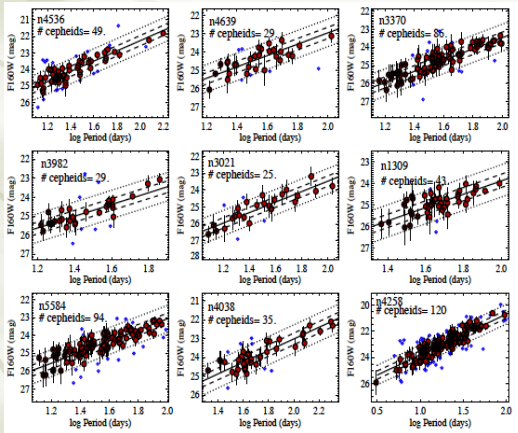
Hubble's photo


Cepheids in the Virgo galaxy cluster with Hubble Space Telescope (16 Mpc away…)
Cepheid Variable in M100
HST·WFPC2

Modern data…

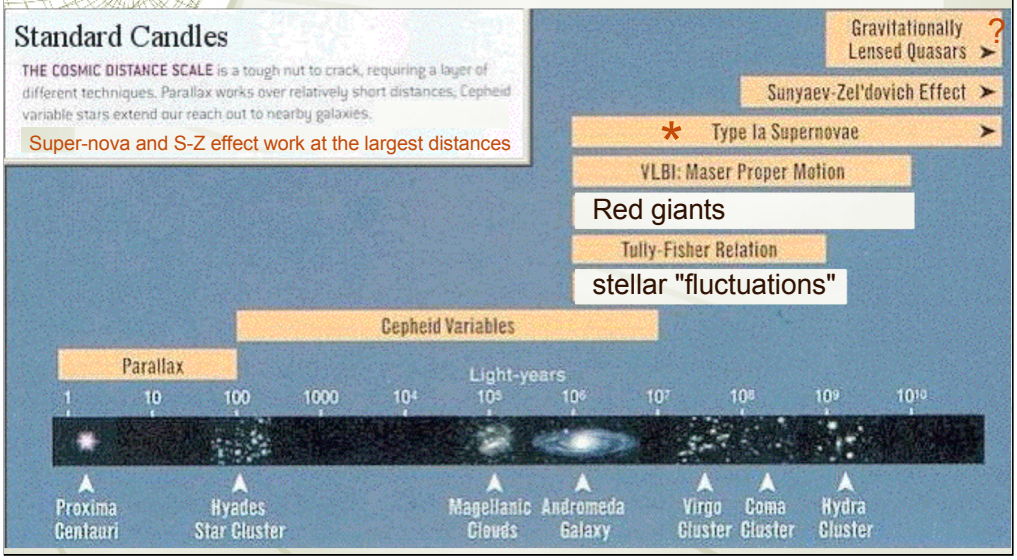
Modern Cepheid Data

Have 30-300 Cepheids per galaxy- Reiss et al 2011



Other techniques include eclipsing binaries, planetary nebulae, long-period variables, RR Lyrae stars,

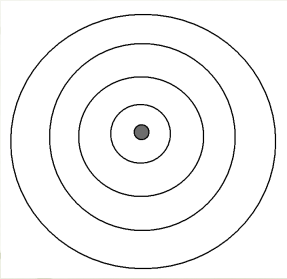
Distance Ladder- *While Cepheids are great they only work to ~20Mpc*



I : THE DOPPLER EFFECT-Recap of a few lectures ago

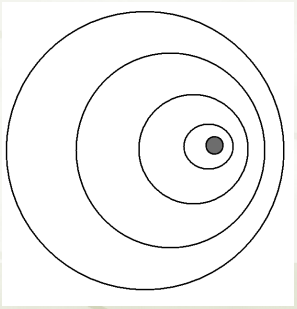
- Think about sound waves
  - Let ν=frequency (number of waves passing certain fixed point in one second)
  - Let L=wavelength (distance between two "crests" of the wave)
  - Let c_s=speed of the wave

$$c_s = \lambda\nu$$

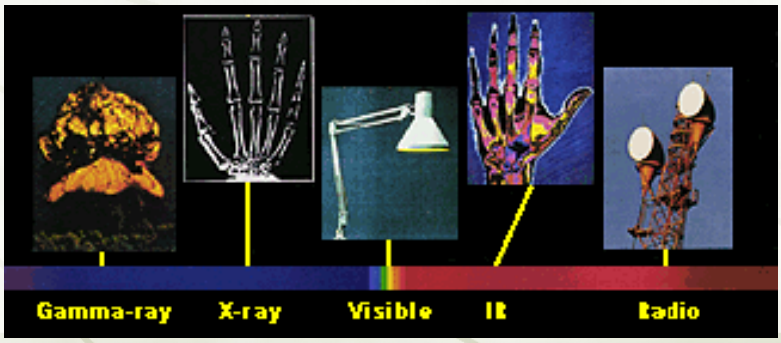


- Suppose source is moving towards you with speed V
  - Waves get squeezed in direction of motion (I.e., λ decreases)
  - c_s stays same (i.e. speed of sound fixed)
  - So, frequency must go up

$$\frac{\lambda_{moving}}{\lambda_{still}} = \frac{c_s - V}{c_s}$$

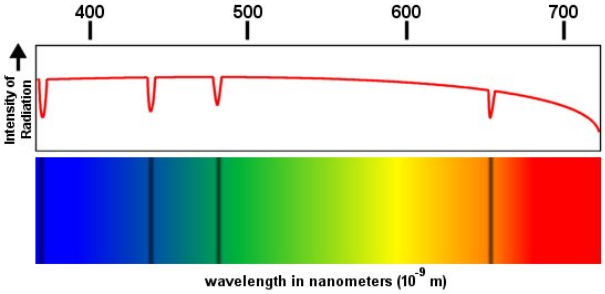


- The Doppler effect works on any wave – including light waves!

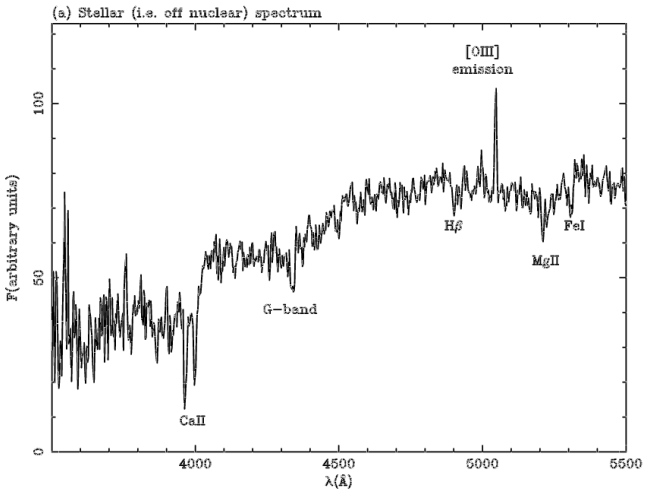


II : MEASURING APPARENT VELOCITIES OF GALAXIES

- Technique for measuring a galaxies velocity:
  - Measure the spectrum of light from the galaxy
  - Look for characteristic features in the spectrum



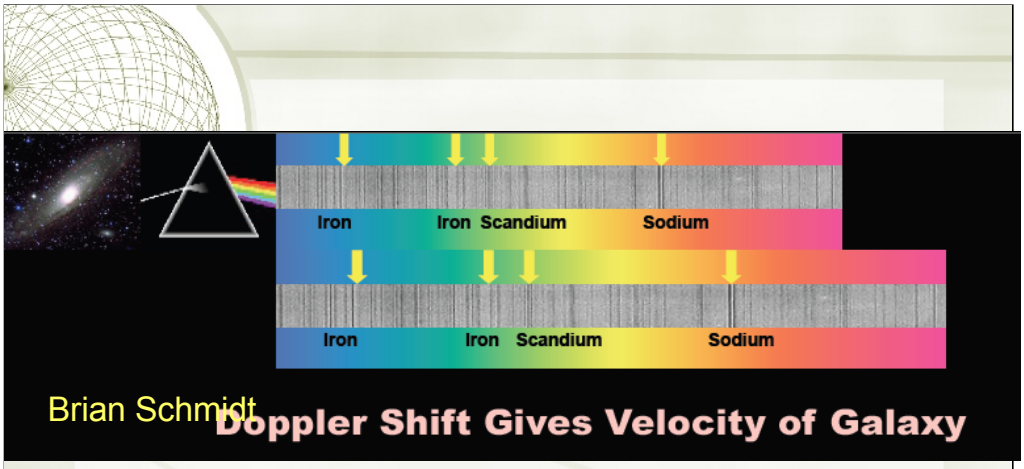
Example of a real galaxy spectrum…



http://www.phys.unsw.edu.au/astro/wwwlabs/hdfSize/hdfSize_intro.html#Ho

Redshift of this galaxy is z=0.008… so lines are only slightly shifted

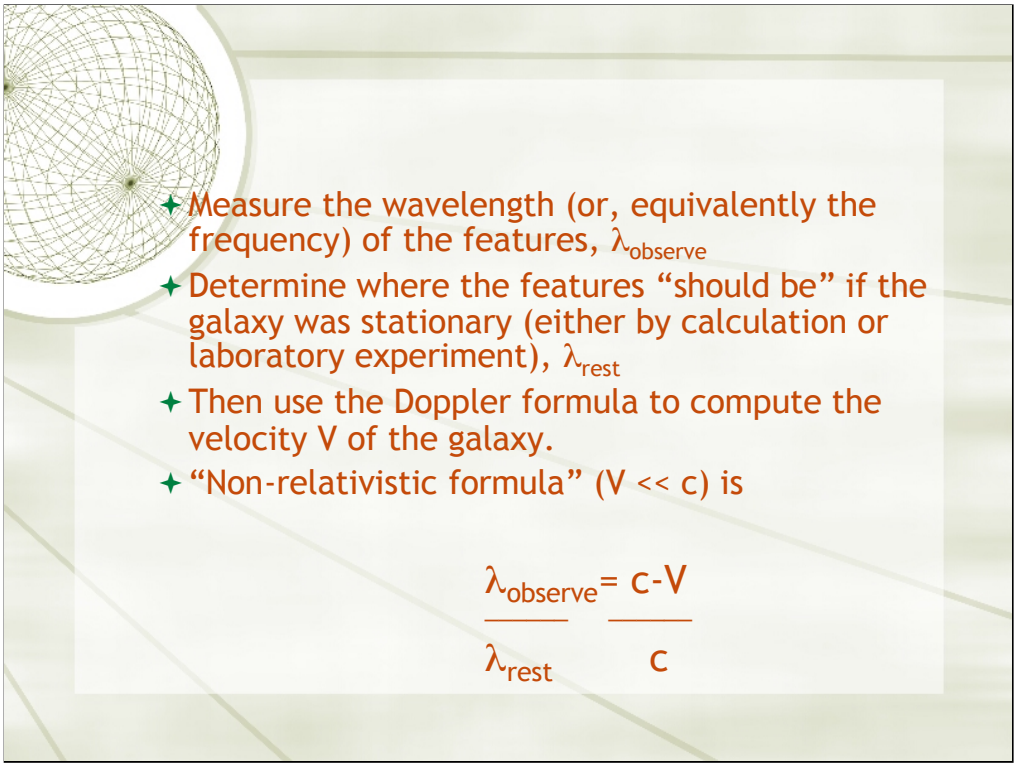
p.s. *I* took this spectrum… my only real observing run ☺



Brian Schmidt

Doppler Shift Gives Velocity of Galaxy

- Multiple spectral features allow a unique redshift solution


Measure the wavelength (or, equivalently the frequency) of the features, $\lambda_{observe}$
Determine where the features "should be" if the galaxy was stationary (either by calculation or laboratory experiment), λ_{rest}
Then use the Doppler formula to compute the velocity V of the galaxy.
"Non-relativistic formula" (V << c) is
$\frac{\lambda_{observe}}{\lambda_{rest}} = \frac{c-V}{c}$

Blueshifts and Redshifts

- If galaxy is moving towards us, wavelengths are shortened ⇒ **spectrum blueshifted**
- If galaxy is receding from us, wavelenths are lengthened ⇒ **spectrum redshifted**

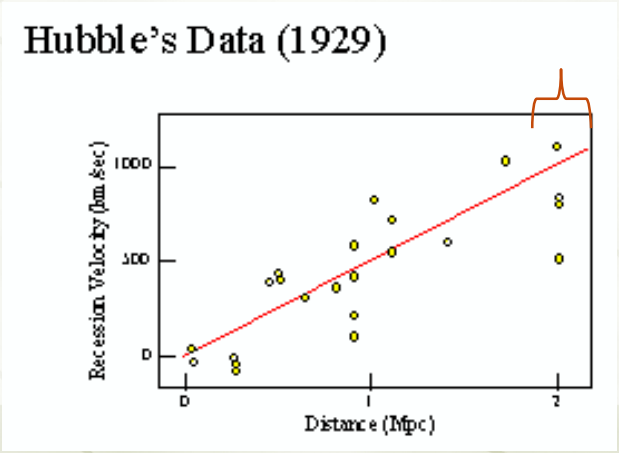
- Slipher measured velocities of nearby galaxies (spiral nebulae) – by 1922, he found that 36 out of 41 were moving away from us!-

"For us to have such motion and the stars not show it means that our whole stellar system moves and carries us with it. It has for a long time been suggested that the spiral nebulae are stellar systems seen at great distances ... This theory, it seems to me, gains favor in the present observations". This, was 8 years before Hubble.

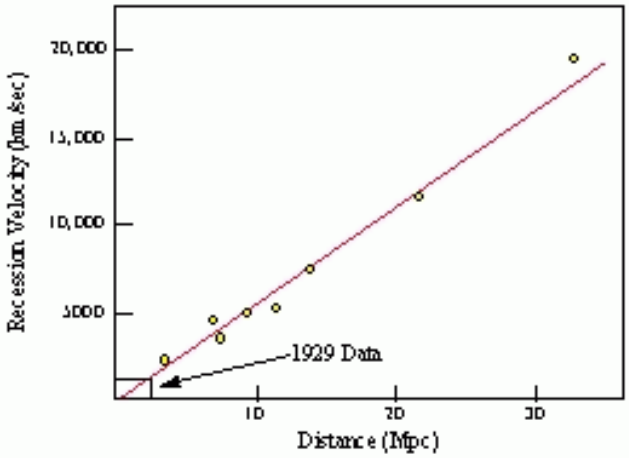
- The first hint of Hubble's remarkable result

III : HUBBLE'S RESULTS

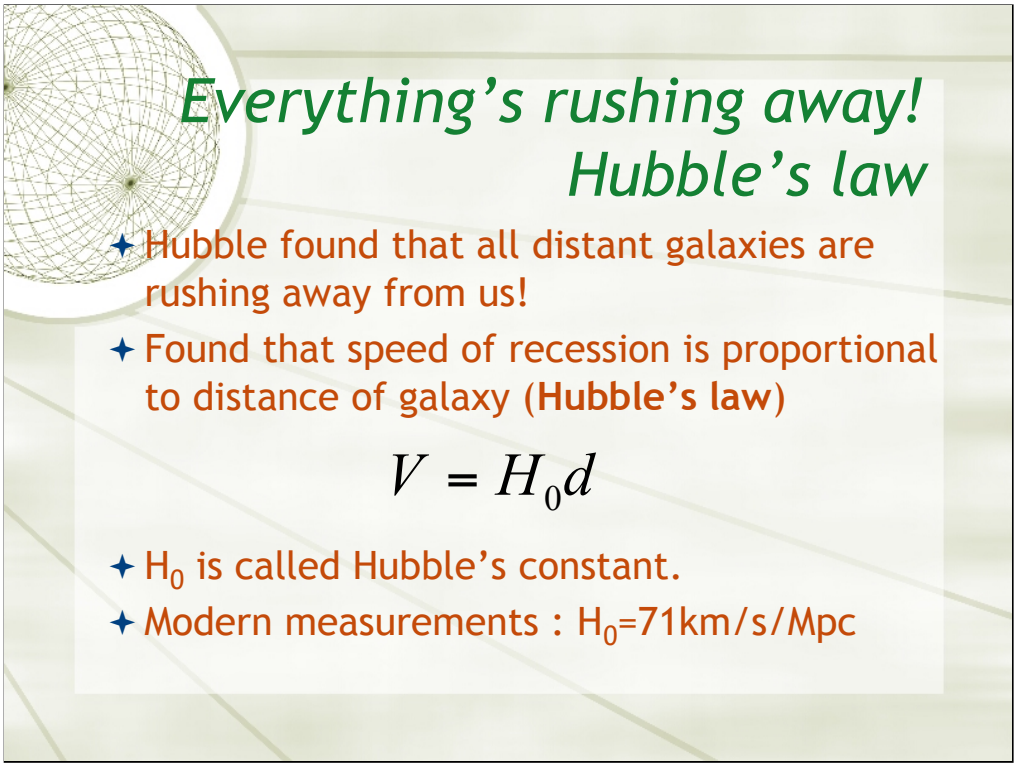
- Hubble measured distance (some derived from Cepheids, some less accurate estimates) and plotted it against velocity…



Hubble & Humason (1931)



http://www.aip.org/history/cosmology/ideas/hubble-work.htm



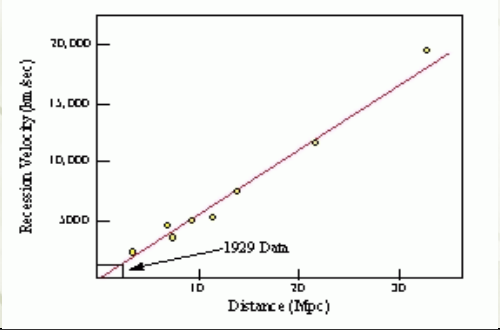
Discussion… why is everything moving away from US?

What's wrong with US?

What would an observer in another galaxy see?

Recession Velocity and Redshift

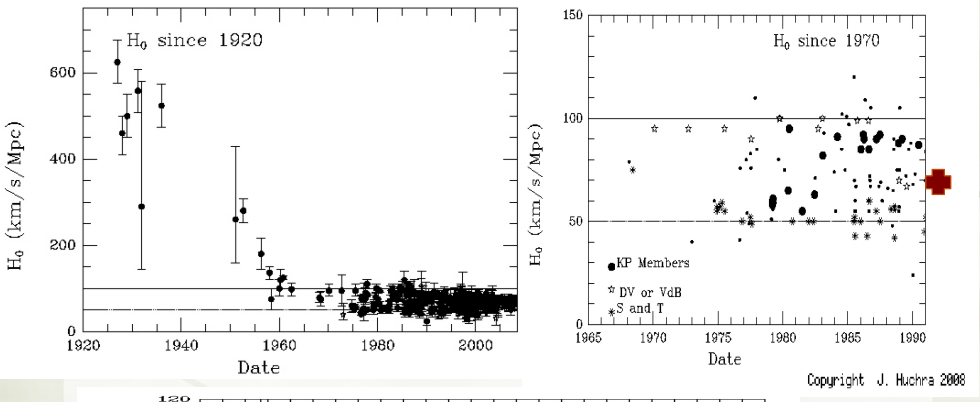
- Hubble's original value was H=500km/s/Mpc… way off the real value. He had mistakenly identified bright nebulae in other galaxies with bright stars, thereby making them seem closer.
- Redshift $z = (\lambda_{observed}-\lambda_{emited})/\lambda_{emited}$;
- $1+z= \mathrm{sqrt}\{(1+v/c)/(1-v/c)\}$ or for $v<<c$ $-(v/c)$.
- or $1+z=\gamma\{1+(v/c)\}$

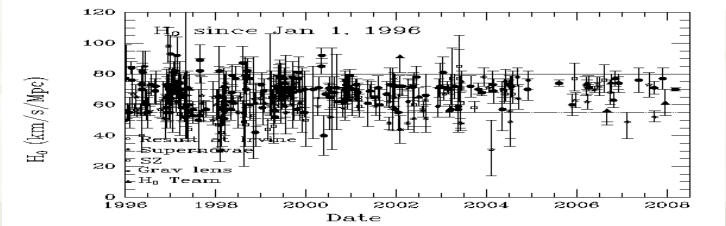


Hubble Expansion

we will later show that the redshift is related to the scale factor change of the universe (how big the universe is at different times)

Its Hard to Measure the Hubble Constant



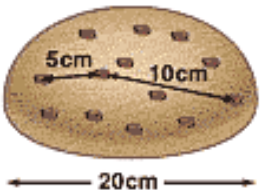


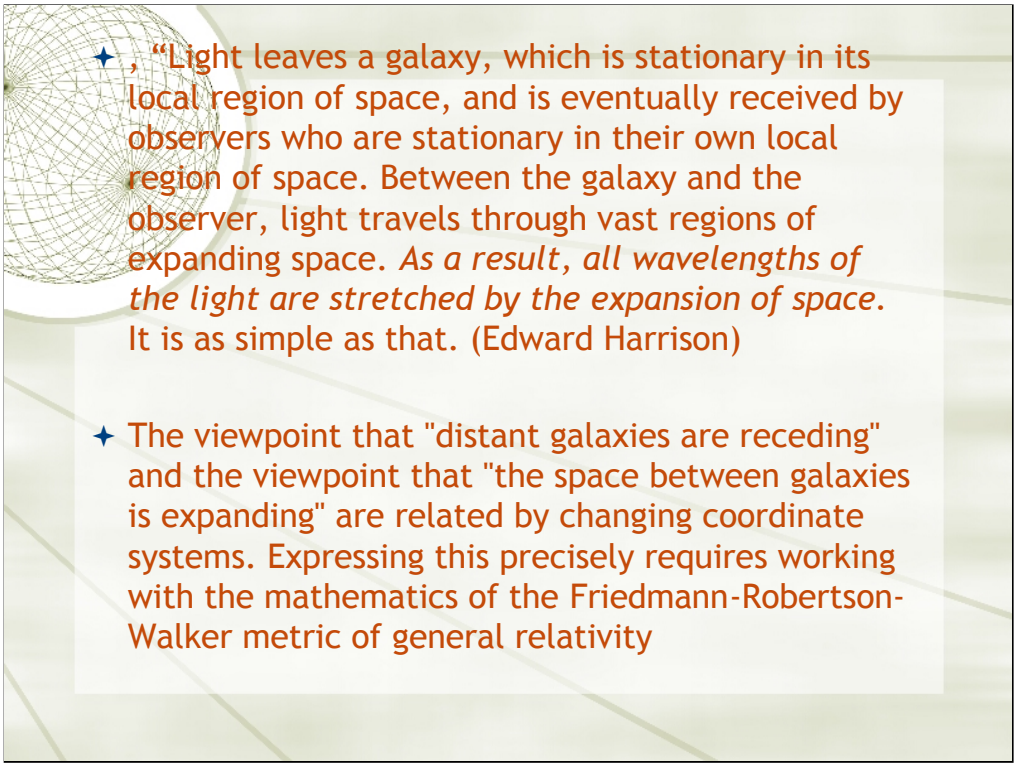
https://www.cfa.harvard.edu/~dfabricant/huchra/hubble/

Cosmological and Gravitational Redshift

- Doppler shifts imply a certain **velocity**
- Gravitational redshifts a certain mass and size

  $1+z = \sqrt{1/1 - 2GM/Rc^2}$
- The cosmological redshift is due to the **expansion of space itself**- every galaxy is moving away from every other- there is no center
- Because this is NOT a velocity effect galaxies can move apart from each other faster than the speed of light- this is not a violation of Einstein





- , “Light leaves a galaxy, which is stationary in its local region of space, and is eventually received by observers who are stationary in their own local region of space. Between the galaxy and the observer, light travels through vast regions of expanding space. *As a result, all wavelengths of the light are stretched by the expansion of space*. It is as simple as that. (Edward Harrison)

- The viewpoint that "distant galaxies are receding" and the viewpoint that "the space between galaxies is expanding" are related by changing coordinate systems. Expressing this precisely requires working with the mathematics of the Friedmann-Robertson-Walker metric of general relativity

Not An Explosion

- An explosion has a center and an edge. But every galaxy is moving away from every other galaxy and an observer on any galaxy will measure the same expansion

- In an explosion, the fragments fly through space, and their motion can be defined relative to the center of the explosion and the medium through which the fragments travel. In the expanding universe, galaxies are carried apart by the expansion of space itself, not by the forces of an explosion!

- In the expanding universe, galaxies are carried apart by the expansion of space itself, not by the forces of an explosion!

http://www.galaxyzoo.org/cosmology

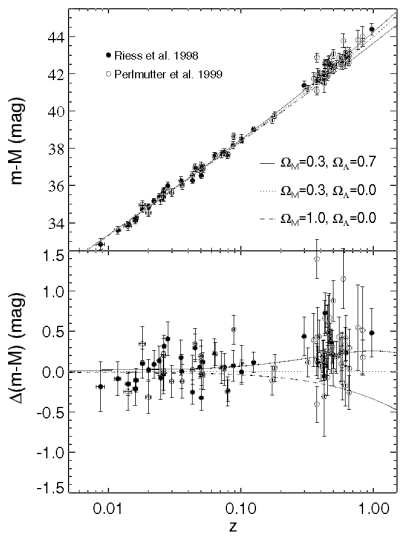
Something to Think About

- If the Universe is in fact expanding what would happen if you "rewound" things... at some point should it have been much denser (and hotter)??

- Some modern data
  - In terms of redshift

$$z = \frac{(\lambda_{Galaxy} - \lambda_{rest})}{\lambda_{rest}}$$

  - … and m-M which is one way that some astronomers measure distance (we don't need the details of this)
  - Clearly, we are seeing some very fast galaxies!



A Redshift Digression

- As shown later the cosmological redshift is related to the expansion of the universe

$1+z=R_{then}/R_{now}$

Where R is the size of the universe at different times

Calculation of redshift, z

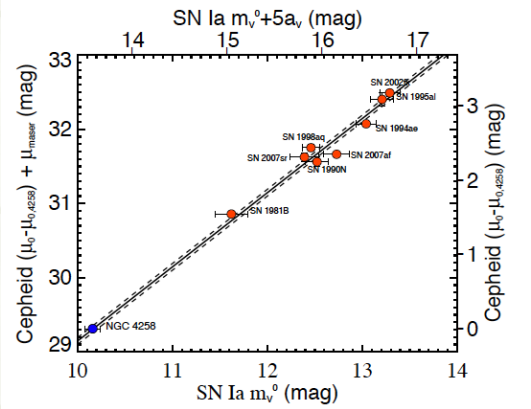
Based on wavelength	Based on frequency
$z = \frac{\lambda_{obsv} - \lambda_{emit}}{\lambda_{emit}}$	$z = \frac{\nu_{emit} - \nu_{obsv}}{\nu_{obsv}}$
$1 + z = \frac{\lambda_{obsv}}{\lambda_{emit}}$	$1 + z = \frac{\nu_{emit}}{\nu_{obsv}}$

Doppler redshift $1 + z = \left(1 + \frac{v}{c}\right)\gamma.$

Gravitational redshift $1 + z = \frac{1}{\sqrt{1 - \frac{2GM}{rc^2}}},$

What About Going Further

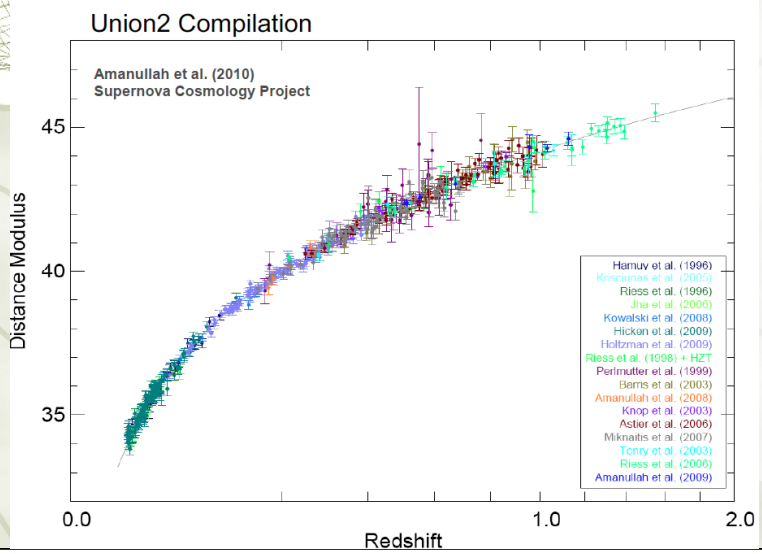
- Need brigher 'standardizable' candles
- Turns out that type I SuperNova (SNIa) can be made standard candles (Nobel Prize 2011*)-"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae".
- This allow 'absolute' distances to ~5000 Mpc



Comparison of SN Ia and Cepheid distances

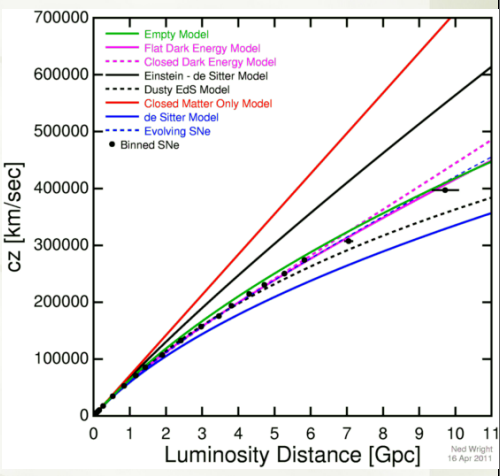
*http://www.nobelprize.org/nobel_prizes/physics/laureates/2011/

Data Have Gotten Very Good !

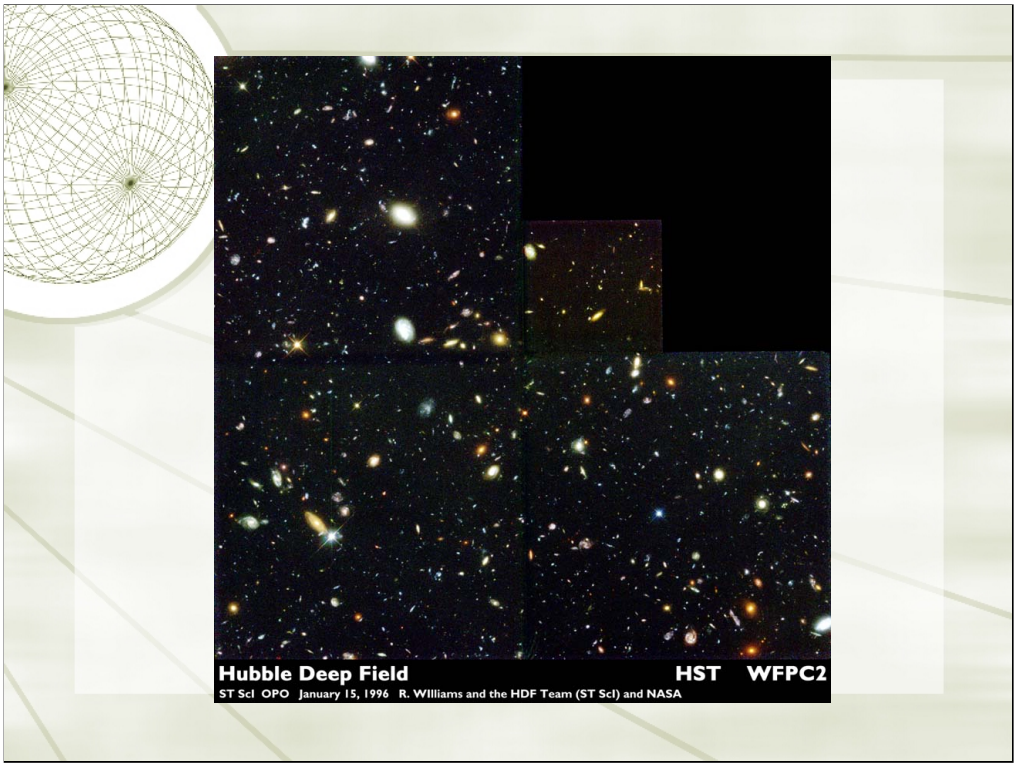


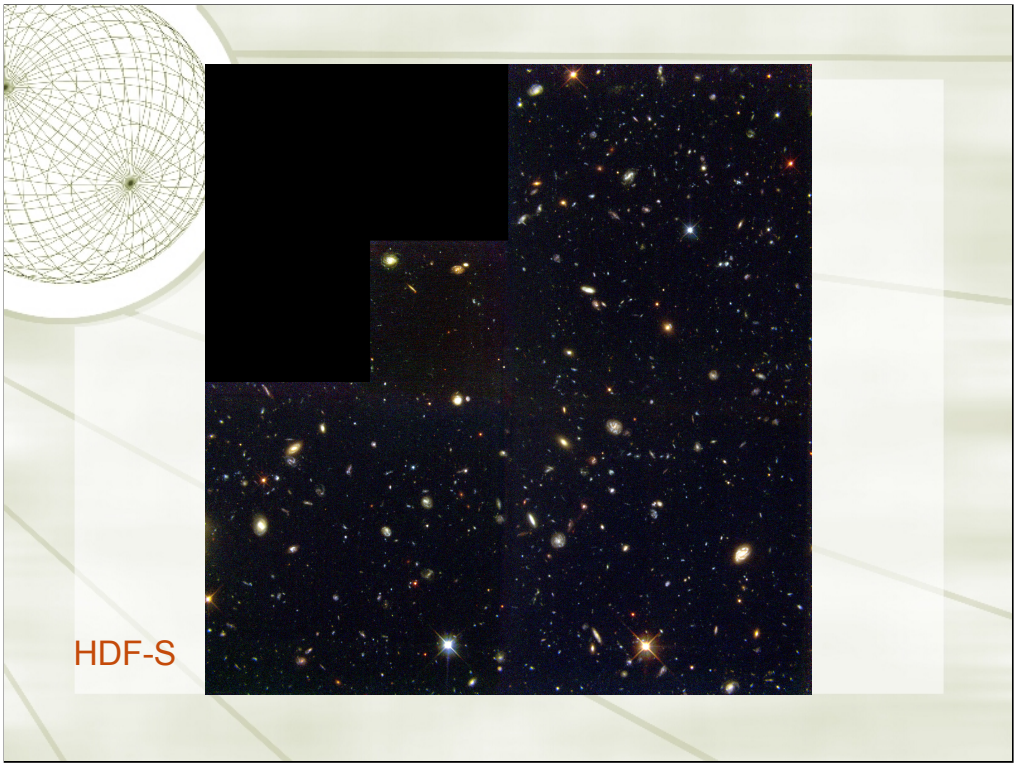
Hubble's Relation at the Largest Scales

- Using type Ia SN to determine relationship between redshift and distance
- At huge distances Hubble law is no longer linear- clue to the shape of space-time
- Hubble constant is not really constant. It has the same value everywhere in the universe at one instant, but it does change over time



http://www.astro.ucla.edu/~wright/sne_cosmology.html


Hubble Deep Field
HST WFPC2
ST ScI OPO January 15, 1996 R. WIlliams and the HDF Team (ST ScI) and NASA


HDF-S