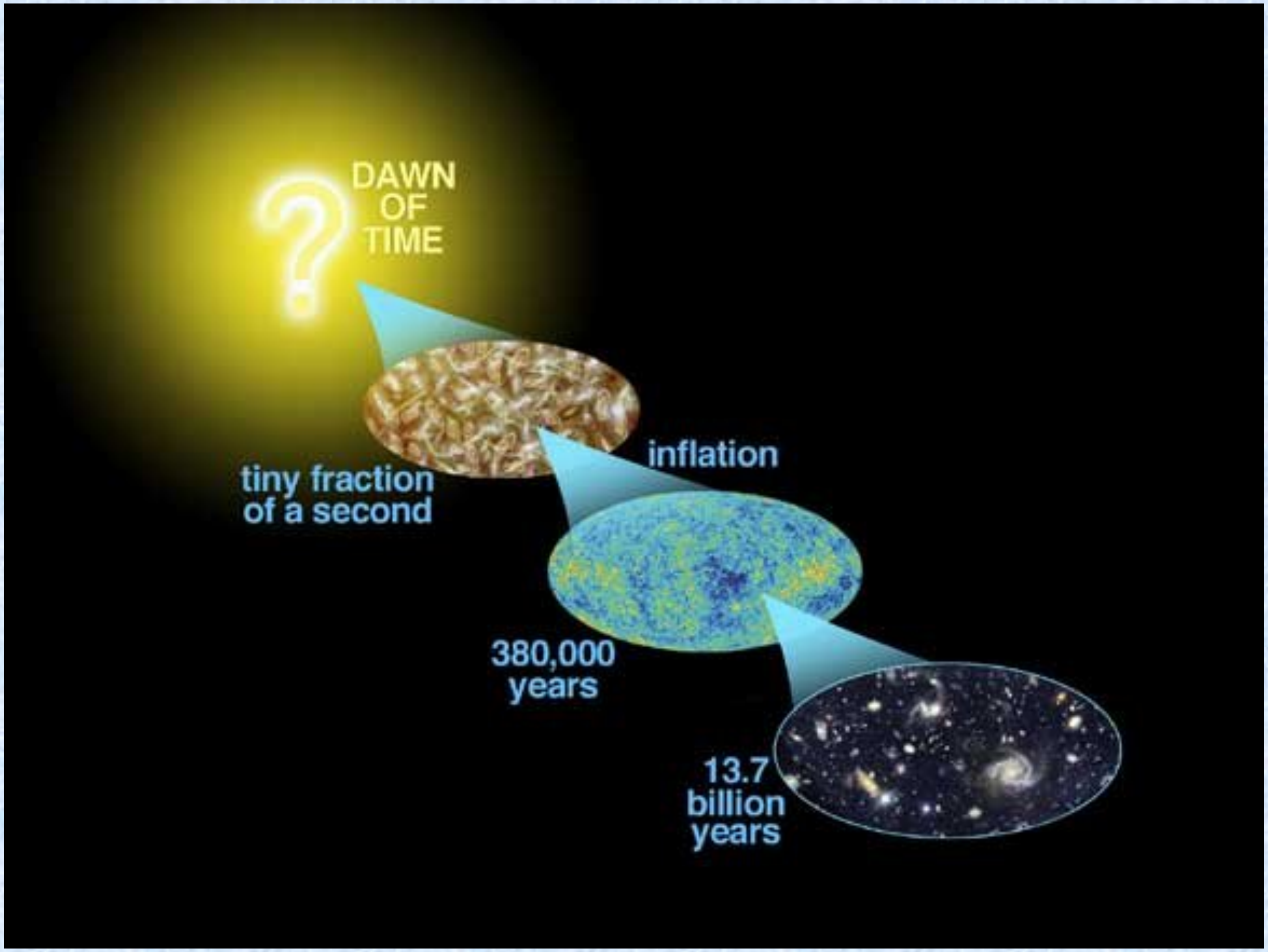
Astro-2: History of the Universe



Lecture 3; April 11 2013

Previously.. On Astro-2

- The universe is much larger than the Milky Way (Gpc vs kpc)
- There are billion of galaxies, the Milky Way is average Joe galaxy
- Most galaxies can be classified based on their appearance as
  - Elliptical
  - Lenticular
  - Spiral
  - Irregular
- Spirals rotate and have young stars, gas and dust
- Ellipticals do not rotate and have old stars, no gas nor dust

Previously.. On Astro-2

- It is difficult but very important to figure out the size and distance of things in the universe
- One way astronomers do that is by using "standard candles".
- Examples of standard candles are cepheids variable stars and supernovae

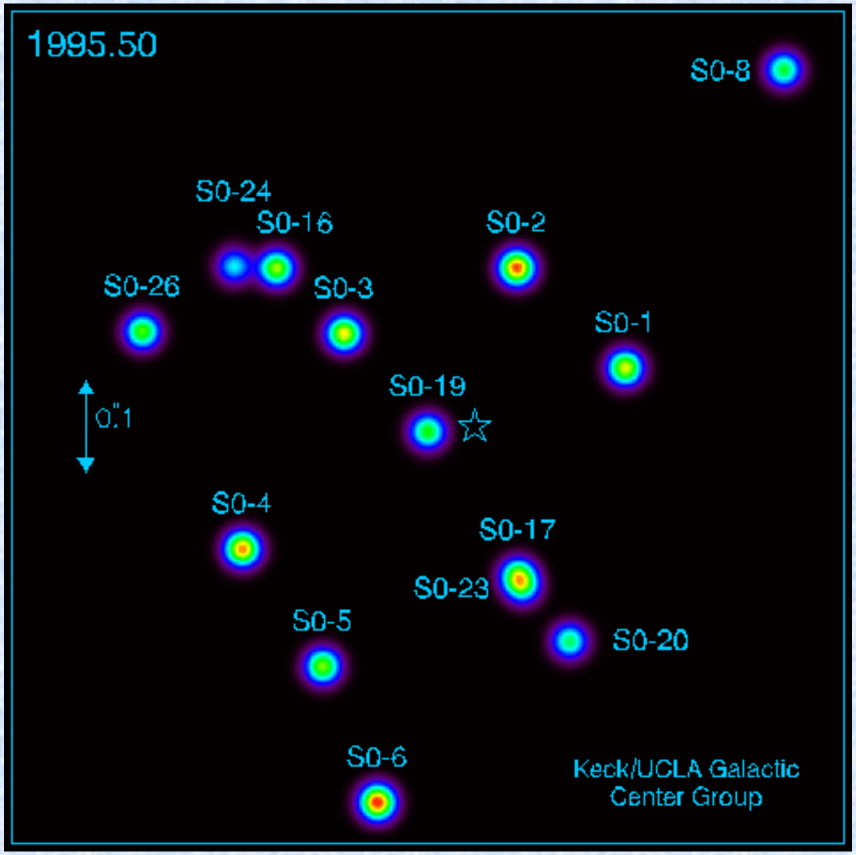
Two important questions

- Are there black holes in galaxies?
- What is a black hole?

"It's black, and it looks like a hole. I'd say it's a black hole."

Two important questions

- How do we know it?
- Exactly in the same way we know the mass of the sun, or the mass of galaxies for that matter!



Two important questions

- If the universe is homogeneous and isotropic how do stars know that there is a center of a galaxy to orbit around?
- It is a matter of scale:
- On scale much larger than a Mpc the universe is homogeneous
- On scales much smaller than a Mpc the universe is NOT homogenous, there are galaxies, for example.

Assignments. Due Friday 4/19 4PM

1. To TA: Universe 24.42 - 24.43 - 24.45
2. On your own: 24.17 thru 24.30

Today.. On Astro-2

1. How far are galaxies?
2. Measuring velocities and “redshifts”.
3. Hubble’s law.
4. The Universe is expanding.

How far are galaxies? Hubble continues to work…

- In 1923 Hubble showed that M31 was 750 kpc away
- But how big was the universe?
- How far were all the other galaxies?
- Using the 100 inch telescope on Mount Wilson, Hubble gets back to work and measures distances to many galaxies, as far as Mpc away
- He uses standard candles, like cepheids.

Measuring velocities. There is more to life than distances, says Hubble..

- Hubble and his colleague Slipher and Humason use big telescopes to take spectra of those galaxies…
- They want to find out what galaxies are made of!
- Surprise, surprise! they discover that most galaxies are moving AWAY from us

Measuring velocities with a spectrum. Doppler Effect

- Like the sound of a police car
- When the car is approaching you hear high pitch, when is running away you hear a low pitch
- The same with light:
- When something is approaching you see “bluer”, more energetic light (blueshift)
- When something is receding you see “redder” light, less energetic, light (redshift)
- This is called “Doppler Effect”

Measuring velocities with a spectrum. Doppler Effect

- Quantitatively, due to the Doppler effect, the WAVELENGTH λ_0 of some spectral feature is moved to a different wavelength λ
- For a receding object, the redshift z is the amount of shift towards longer wavelengths:
- $Z=(\lambda-\lambda_0)/\lambda_0$
- For z much smaller than 1, the line of sight velocity is v=cz, where c is the speed of light (see Universe Chapter 24 for general formula)

Measuring Redshifts, an example.

CaK 3933 Å

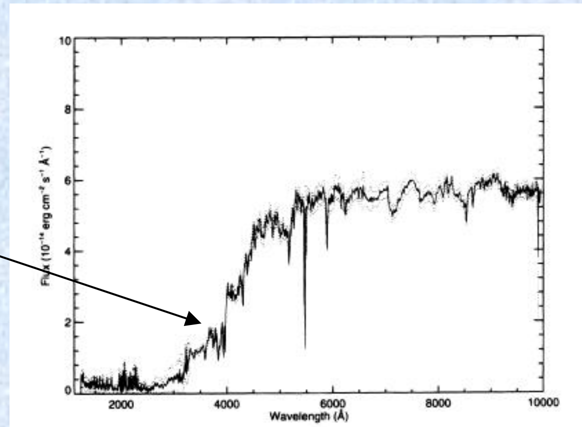
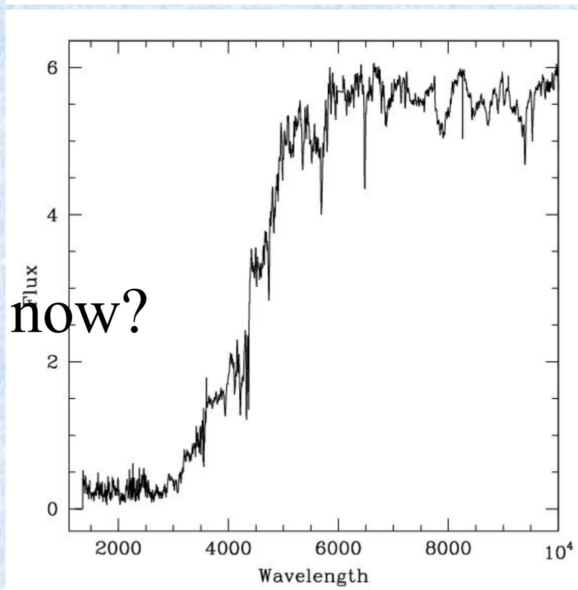


FIG. 2a

Z=0

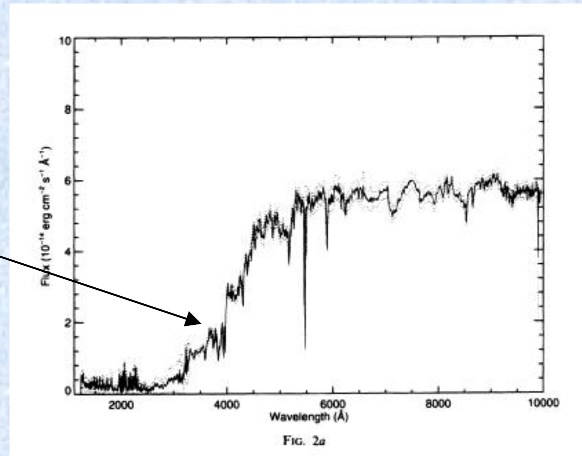
Where is the feature now?



- Z=?
- V=?

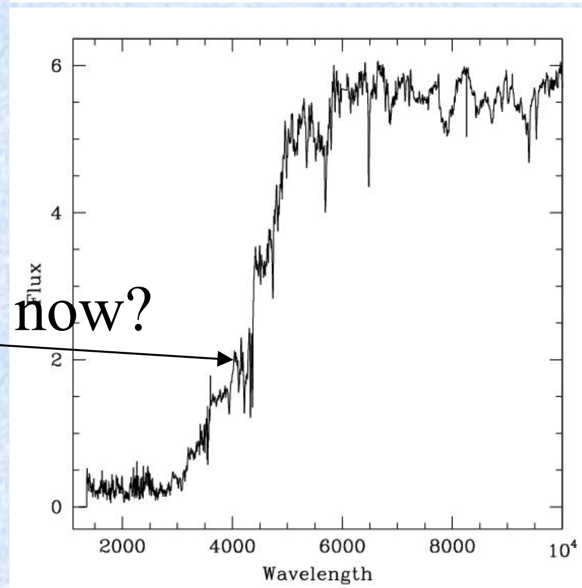
Measuring redshifts, an example.

CaK 3933 Å



Z=0

Where is the feature now?



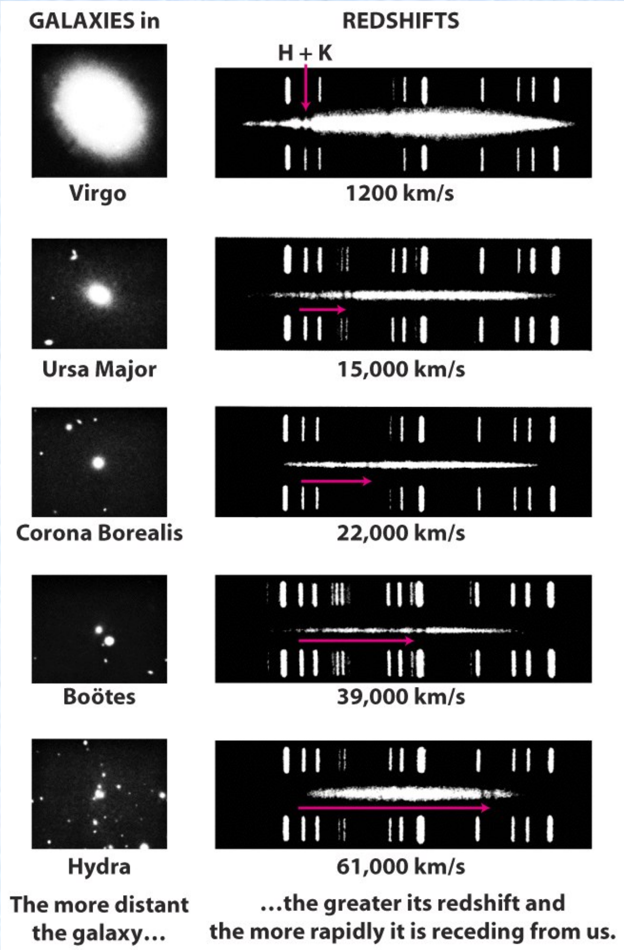
- Z=0.1
- V=30,000 km/s

First summary

- Hubble measured distances to many galaxies out to several Mpc away
- Taking spectra of the nebulae, Hubble and his colleagues were able to measure the relative velocity of galaxies with respect to us
- They found that most galaxies are redshifted, as if they were moving away from us!!

Measuring velocities. Galaxies are moving away from us!

- Hubble found that most galaxies were moving away from us!
- Furthermore, the more distant the galaxy, the larger the redshift



Hubble's law: galaxies are moving away from us!

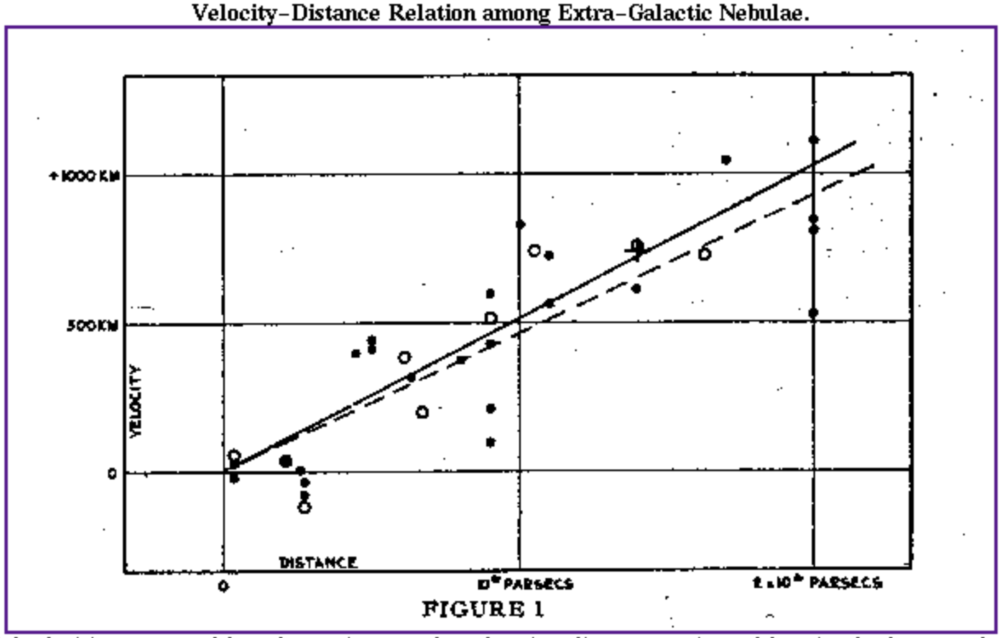


Figure 1: *Radial velocities, corrected for solar motion, are plotted against distances estimated from involved stars and mean luminosities of nebulae in a cluster. The black discs and full line represent the solution for solar motion using the nebulae individually; the circles and broken line represent the solution combining the nebulae into groups; the cross represents the mean velocity corresponding to the mean distance of 22 nebulae whose distances could not be estimated individually.*

- Hubble found that redshift (or velocity) is proportional to distance (Hubble's law): if you measure double speed, you also measure double distance!

Hubble's law: the Hubble constant

Velocity-Distance Relation among Extra-Galactic Nebulae.

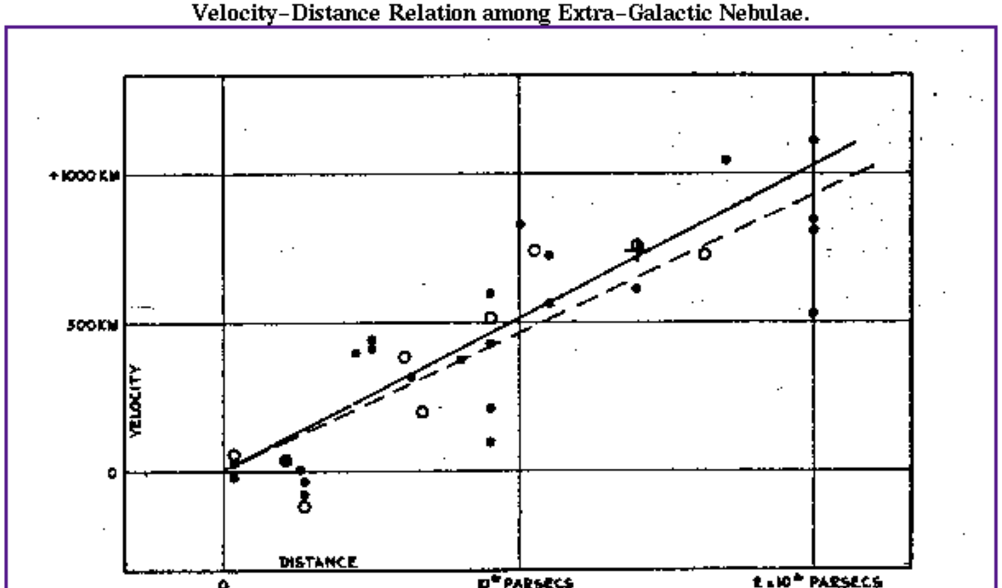


FIGURE 1

Figure 1: *Radial velocities, corrected for solar motion, are plotted against distances estimated from involved stars and mean luminosities of nebulae in a cluster. The black discs and full line represent the solution for solar motion using the nebulae individually; the circles and broken line represent the solution combining the nebulae into groups; the cross represents the mean velocity corresponding to the mean distance of 22 nebulae whose distances could not be estimated individually.*

- The ratio between velocity v and distance d is a constant, called the Hubble Constant or H_0=v/d
- This is phenomenal! If we know H_0 it is sufficient to measure velocity (or redshift), which is easy, as we saw earlier, to find out the distance to any galaxy!!

Even Hubble makes mistakes….

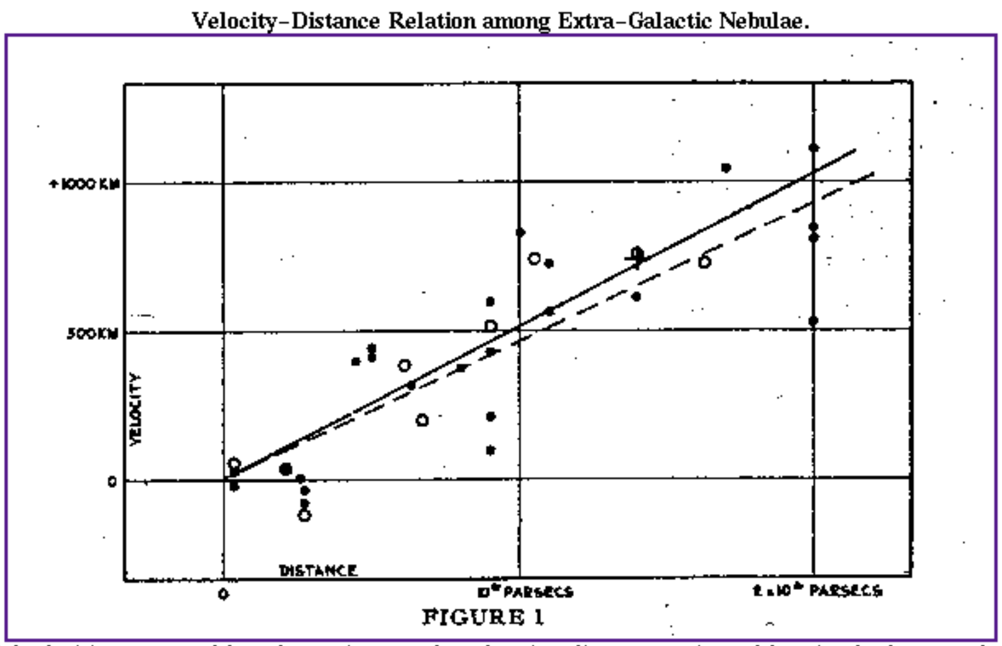


Figure 1: *Radial velocities, corrected for solar motion, are plotted against distances estimated from involved stars and mean luminosities of nebulae in a cluster. The black discs and full line represent the solution for solar motion using the nebulae individually; the circles and broken line represent the solution combining the nebulae into groups; the cross represents the mean velocity corresponding to the mean distance of 22 nebulae whose distances could not be estimated individually.*

- Hubble's first measurement of the Hubble constant was wrong: 500 km/s/Mpc, instead of the current best estimate of 73.8+-2.4 km/s/Mpc

Even Hubble makes mistakes….

Velocity-Distance Relation among Extra-Galactic Nebulae.

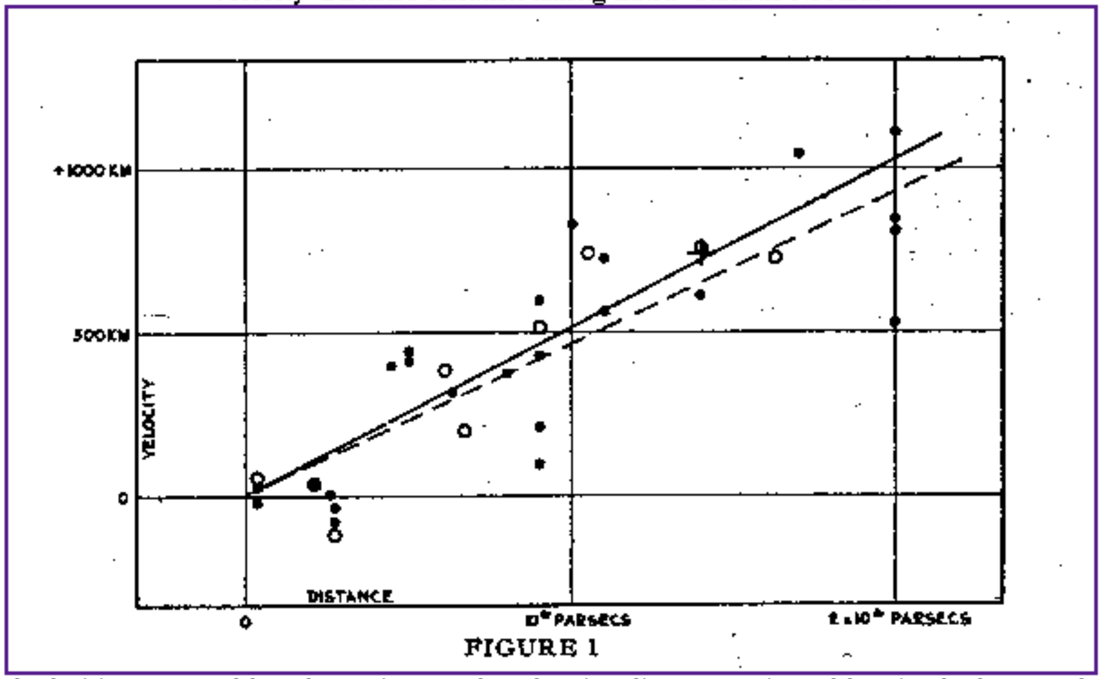


Figure 1: *Radial velocities, corrected for solar motion, are plotted against distances estimated from involved stars and mean luminosities of nebulae in a cluster. The black discs and full line represent the solution for solar motion using the nebulae individually; the circles and broken line represent the solution combining the nebulae into groups; the cross represents the mean velocity corresponding to the mean distance of 22 nebulae whose distances could not be estimated individually.*

- Hubble's mistake was due to various reasons including that he used as standard candles things that were not standard candles

However Hubble's law is valid.. and we can use it to infer distances.

- Astronomers prefer to use redshift instead of velocity because that is what we measure.
- Also redshifts are not properly a measure of speed in the common sense of the world, but a measure of the expansion of the Universe as we will see.
- A generalization of Hubble's law gives you the distance to any galaxy, provided you know the redshift

Hubble's law. The Hubble constant is NOT a solved problem

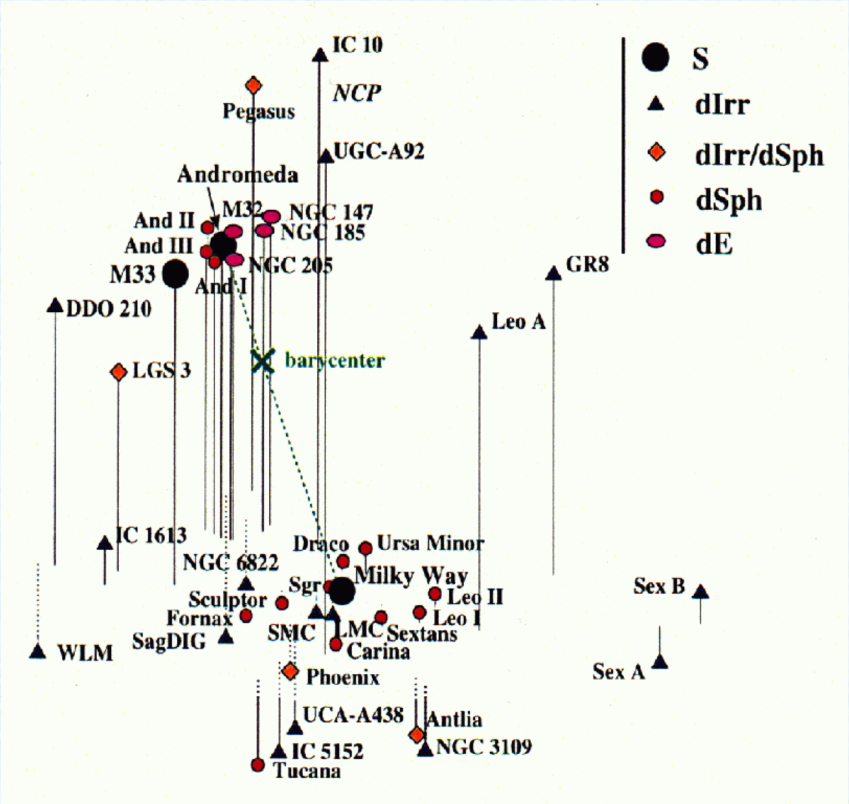
- The Hubble constant is arguably the most important number in cosmology
- Planck recently claimed to have measured a Hubble constant that is somewhat smaller than what previously thought (that depends on some important assumptions)
- What is currently considered the best measurement gives the Hubble constant to within 3% as if you knew your height within with 3 inches or so..
- A lot of people are still working to improve our measurements of the Hubble constant.

Summary 2

- Hubble's Law solves a big problem, providing distances to any object
- If you know the redshift of a galaxy you know its distance with a given precision, equal to the precision with which you know the Hubble Constant
- Redshifts can be measured very precisely, much more precisely than you know your height!!! For this reason astronomers generally say a galaxy is at a redshift z=0.4231, rather than quoting its distance
- Distances can be known only to about 5%
- In cosmology, as in all of physics, measurements also come with an uncertainty, equally important as the number itself

Hubble's Law. Discussion

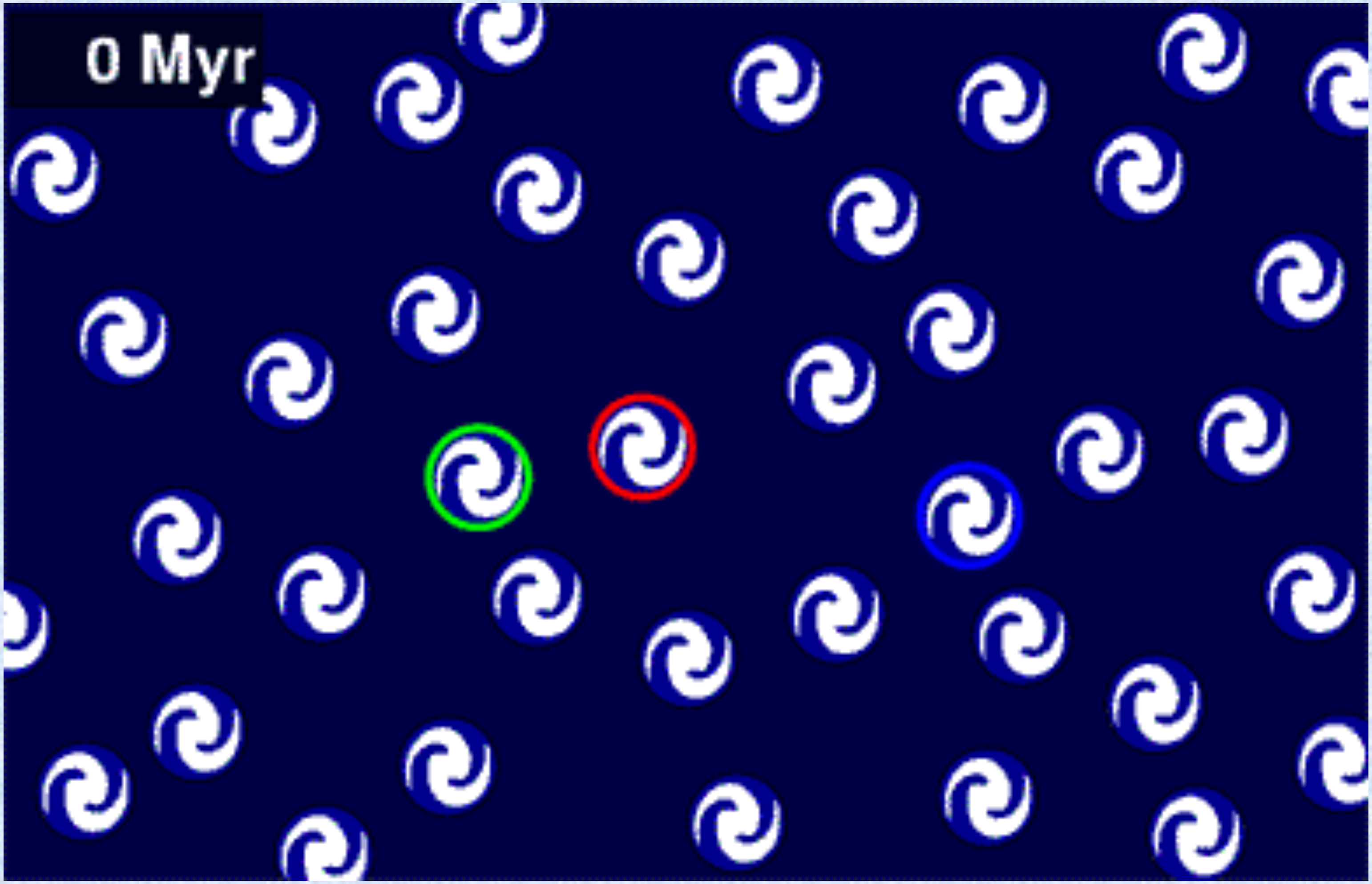
- Are all galaxies redshifted?
- No
- Why?



The Universe is expanding

- Hubble's law is not only a convenient way to obtain distances to galaxies from their redshifts
- Hubble's law has a much more profound significance
- In the current standard cosmological model, Hubble's law is believed to be the result of the expansion of the Universe

The Universe is expanding



The Universe is expanding. Meaning of the Hubble constant

- In our model of the expanding universe the Hubble constant represents the current expansion rate of the Universe
- What is an expansion rate? Think about an interest rate on your savings account.. 3% per year now, next year might be different.

The Universe is expanding. Meaning of the Hubble constant

- The Hubble constant also gives the timescale for the expansion.
- In “normal” units the Hubble Constant is approximately 1/(10 Gyrs)
- This tells us that the age of the Universe is of order 10 Gyrs
- The large value of the Hubble constant obtained by Hubble implied a much shorter life of the Universe, of order 1-2 Gyrs. This caused problems as it was inconsistent with the age of Earth, for example

The universe is expanding. Frequently asked questions…

- What is the universe expanding into?
- Nothing, the universe is all there is, spacetime is expanding itself
- Where is the center of the expansion?
- Nowhere, there is no center, the universe is homogenous and isotropic
- Do we expand as well?
- No, because we are bound by electromagnetic forces
- Do galaxies expand?
- No because they are bound by gravity and they detach from the Hubble Flow

The universe is expanding. More frequently asked questions…

- Are galaxies at z=2 moving faster than the speed of light?
- No, the observed redshift is not really a Doppler effect! It’s only a geometrical effect due to the expansion of the universe. As the universe gets larger wavelengths get stretched, resulting in the observed redshift.
- Nothing moves!

Summary 3

- Hubble's law is interpreted as evidence that the universe is expanding.
- The universe is not expanding into anything, space itself expands.
- The timescale for expansion is given by the inverse of the Hubble constant ~ 10 Gyrs
- The universe is approximately 10 Gyrs old.

The End

See you on thursday!

NO CLASS ON TUESDAY APRIL 16