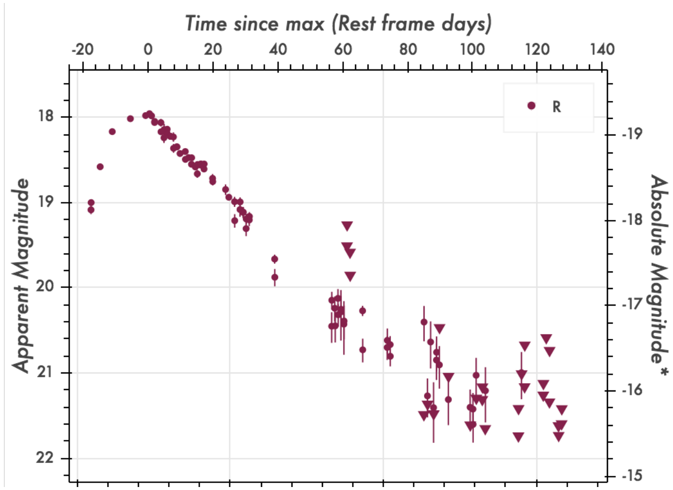
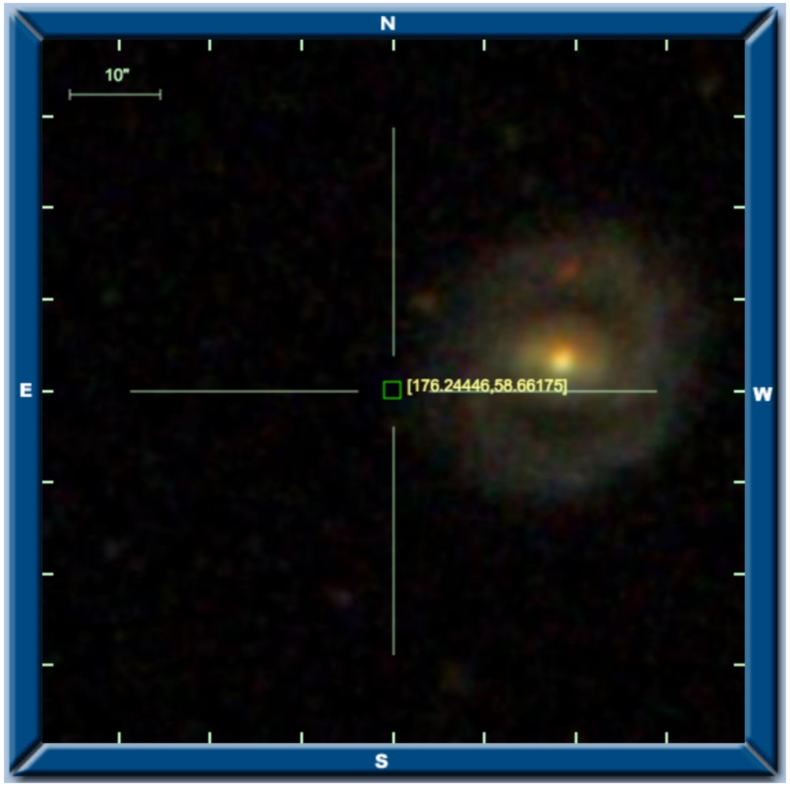




- $m_V(max) = 18.0$
- $M_V(max) = -19.2$

$$m_V - M_V = 5\log d - 5$$

$$\log d = \frac{m_V - M_V + 5}{5} = \frac{18.0 - (-19.2) + 5}{5} = 8.4$$

$$d = 2.5 \times 10^8 \text{ pc}$$

$$= 250 \text{ Mpc}$$

Hubble’s Law

- Redshift of galaxies
- Hubble’s law
- Expansion of the Universe
- Age of the Universe

Redshift

- The radial velocity of a galaxy can be measured using the Doppler shift
- Redshift, *z*, is defined by

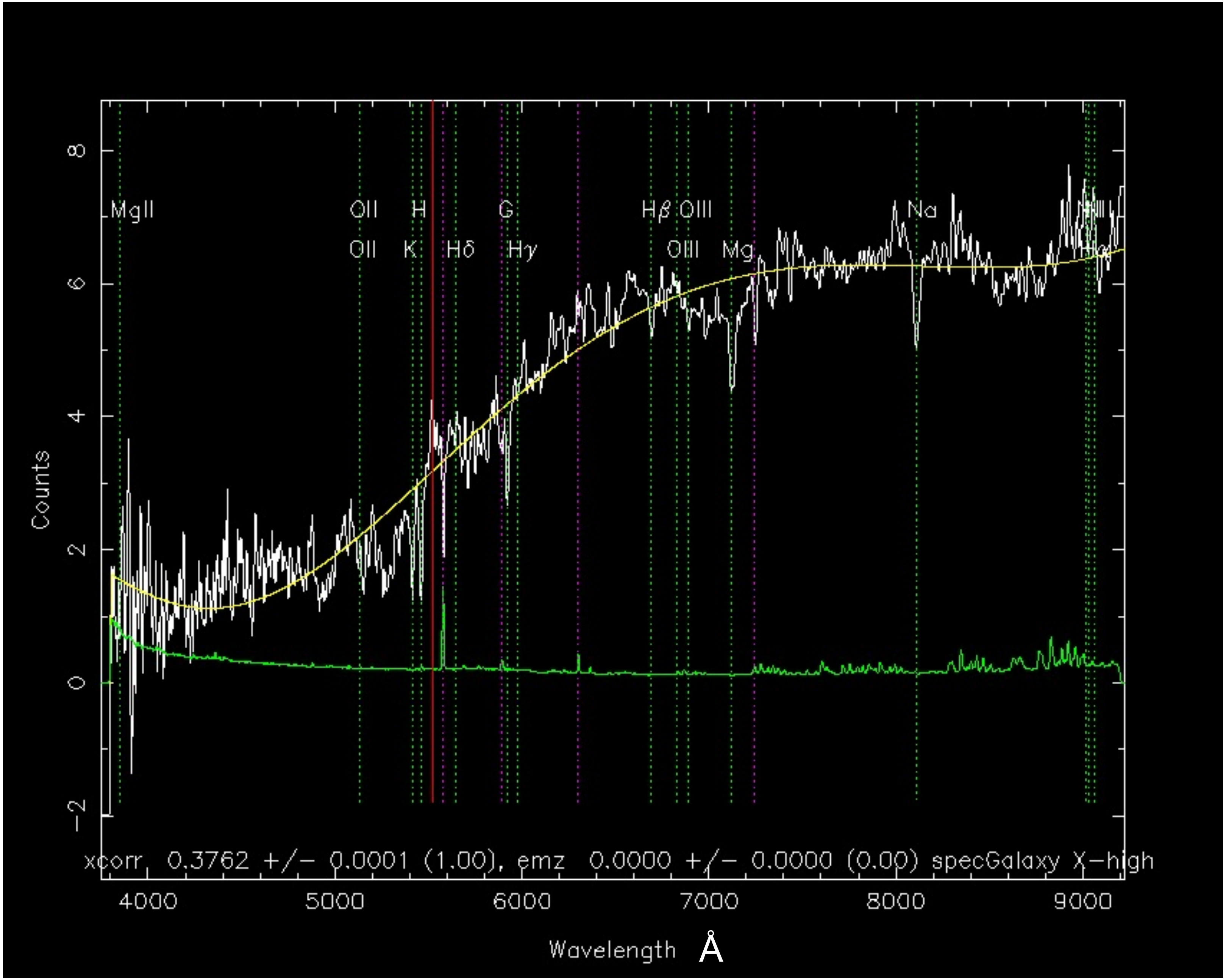
$$z = \frac{\lambda_{obs} - \lambda_0}{\lambda_0} = \frac{\Delta\lambda}{\lambda_0}$$

where the λ_{obs} is the observed wavelength of spectral features in the galaxy spectrum and λ_0 is the rest wavelength

- The radial velocity is related to redshift by

$$v = \frac{\Delta\lambda}{\lambda_0} c = cz$$

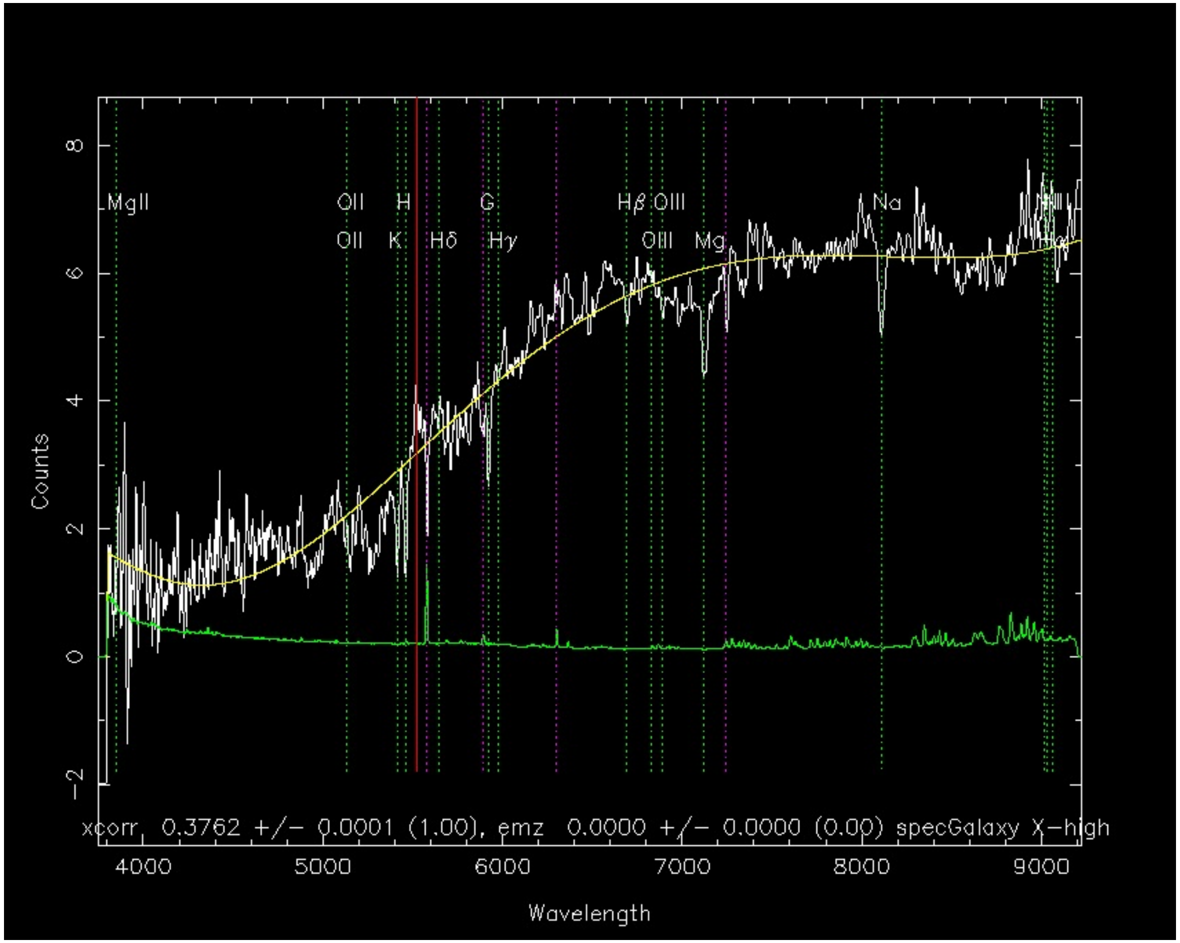
- (Note as velocities become relativistic a different relativistic formula must be used)



A spectrum of a galaxy from the Sloan Digital Sky Survey www.sdss.org

Class Example

- If the rest wavelength of Hβ is 4861 Å (10 Angstroms in 1 nm) what is the redshift of the galaxy on the previous slide?



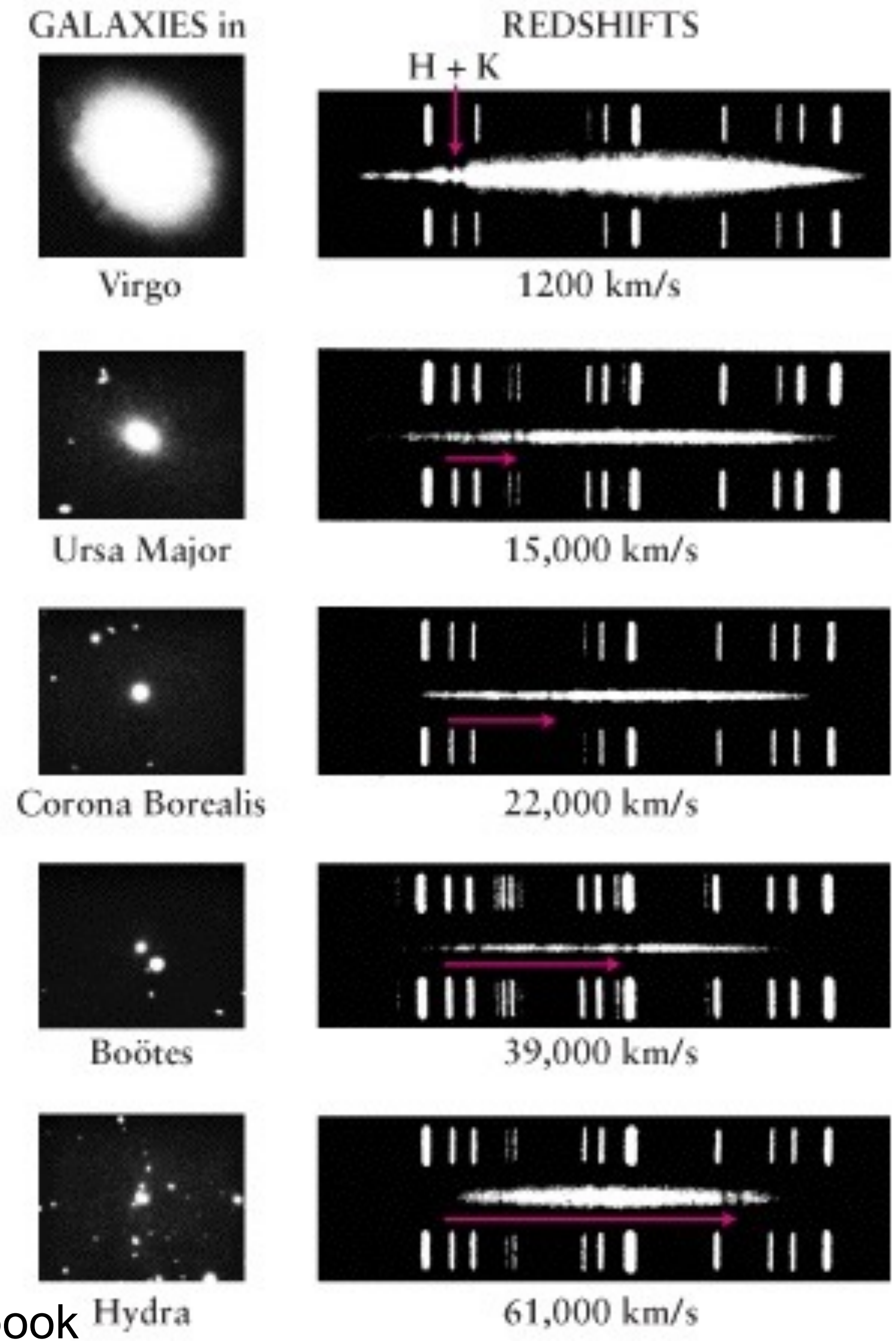
$$z = \frac{\lambda_{obs} - \lambda_0}{\lambda_0} = \frac{6680 - 4861}{4861} = 0.37$$

Hubble's Law

- Hubble found that the majority of galaxies have redshifted lines
- He also found that further away the galaxy the higher the redshift and the radial velocity, i.e.

$$v = H_0 d$$

where H_0 is Hubble's constant



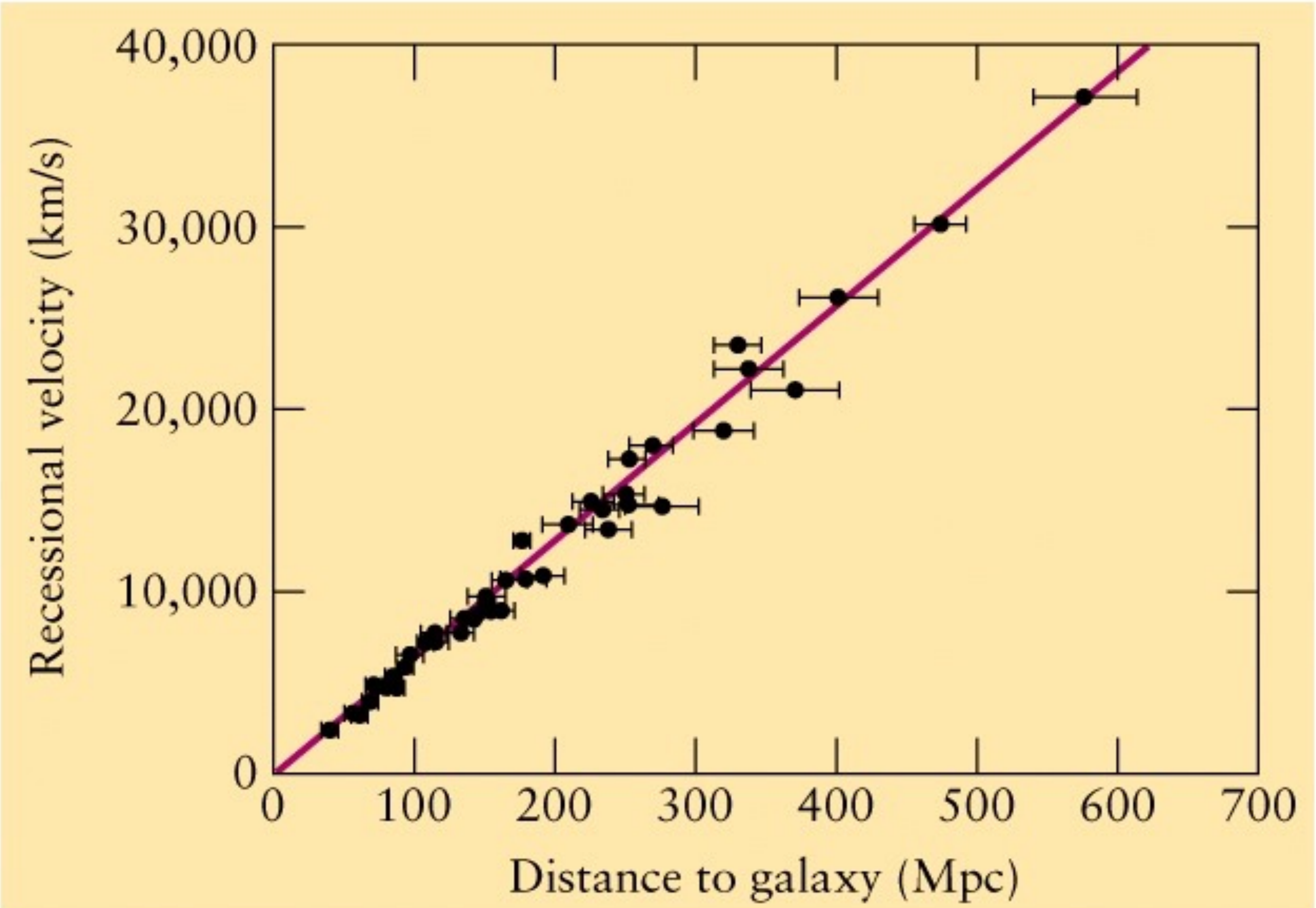
From Universe textbook

Hubble's Constant

- To determine H_0 the distance to galaxies must be found independently
- This is done using standard candles such as Cepheids and Type Ia supernovae
- The current best value is

$$H_0 = 73 \pm 1\,\text{km s}^{-1}\ \text{Mpc}^{-1}$$

- (Note the non-SI units for the constant)



From Universe textbook

Cosmological Distances

- We can now use Hubble's Law to find the distances to very distant galaxies
- Only a spectrum is required to measure the redshift

Class Example

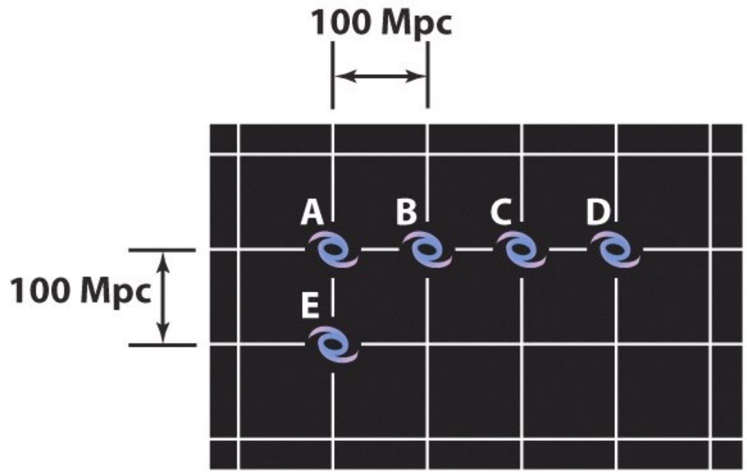
- E.g. What is the distance to the galaxy with redshift z=0.37?

- Distance to a galaxy with redshift z=0.37?

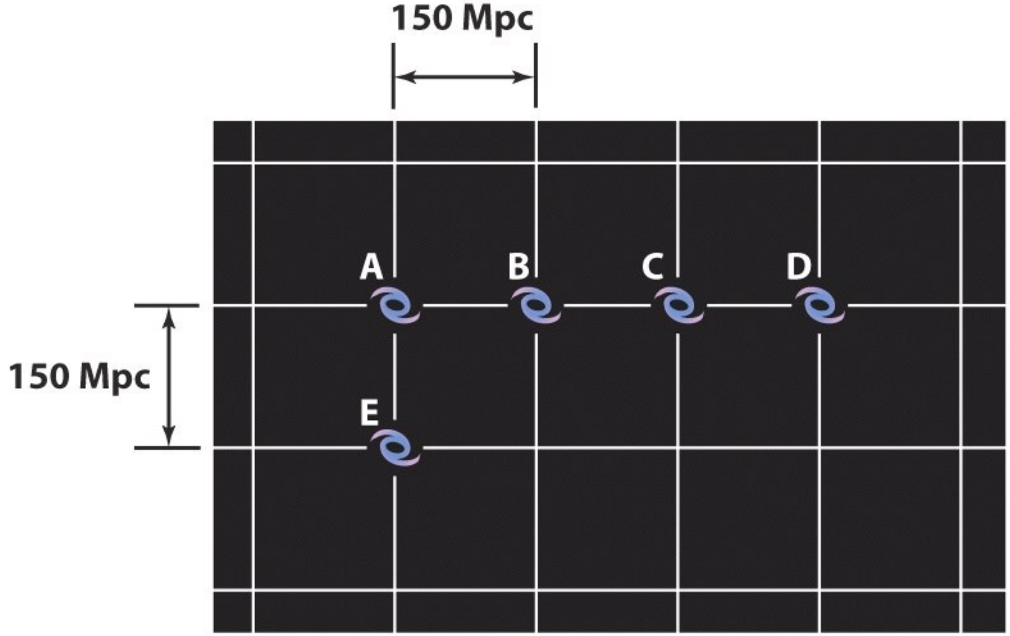
$$d = \frac{v}{H_0} = \frac{cz}{H_0} = \frac{3 \times 10^5 \times 0.37}{73} = 1500 \text{ Mpc}$$

Expansion of the Universe

- The simplest explanation for Hubble’s law is that the Universe is uniformly expanding
- The galaxies are not rushing through space but space itself is expanding
- We are not at a special location
- The universe is not expanding into anything



(a) Five galaxies spaced 100 Mpc apart



(b) The expansion of the universe spreads the galaxies apart

From Universe textbook

The Age of the Universe

- If the Universe has been expanding at a constant rate then we can use the Hubble constant to estimate its age

$$t \approx \frac{d}{v}$$

- Comparing this with Hubble's law gives

$$t \approx \frac{d}{v} \approx \frac{1}{H_0}$$

- Note also that H_0 has units of s^{-1} in S.I.

$$t \approx \frac{1}{H_0} \approx \frac{1}{73} \text{ km}^{-1} \text{ s Mpc}$$

- So what is the age of the Universe?

$$= \frac{1}{73} \times \frac{3.1 \times 10^{22}}{10^3} \text{ s}$$

$$= 4.2 \times 10^{17} \text{ s}$$

$$= 13.7 \text{ billion years}$$

- This is called the Hubble time

The Big Bang

- This age is the time since all galaxies (all matter) were very close together and all of space occupied a very small volume – in fact a singularity (cf a black hole)

Lookback Time

- When we look at distant galaxies we are looking at them as they appeared when the light was emitted, which is along time ago, due to the finite speed of light

Recall the Hubble Extreme Deep Field image from Workshop 4

Summary

- More distant galaxies are receding faster
- More distant galaxies have a greater lookback time
- We live in an expanding Universe that started with a Big Bang

Class Example

- Evaluate how long it takes light to travel from the galaxy at a redshift z=0.37