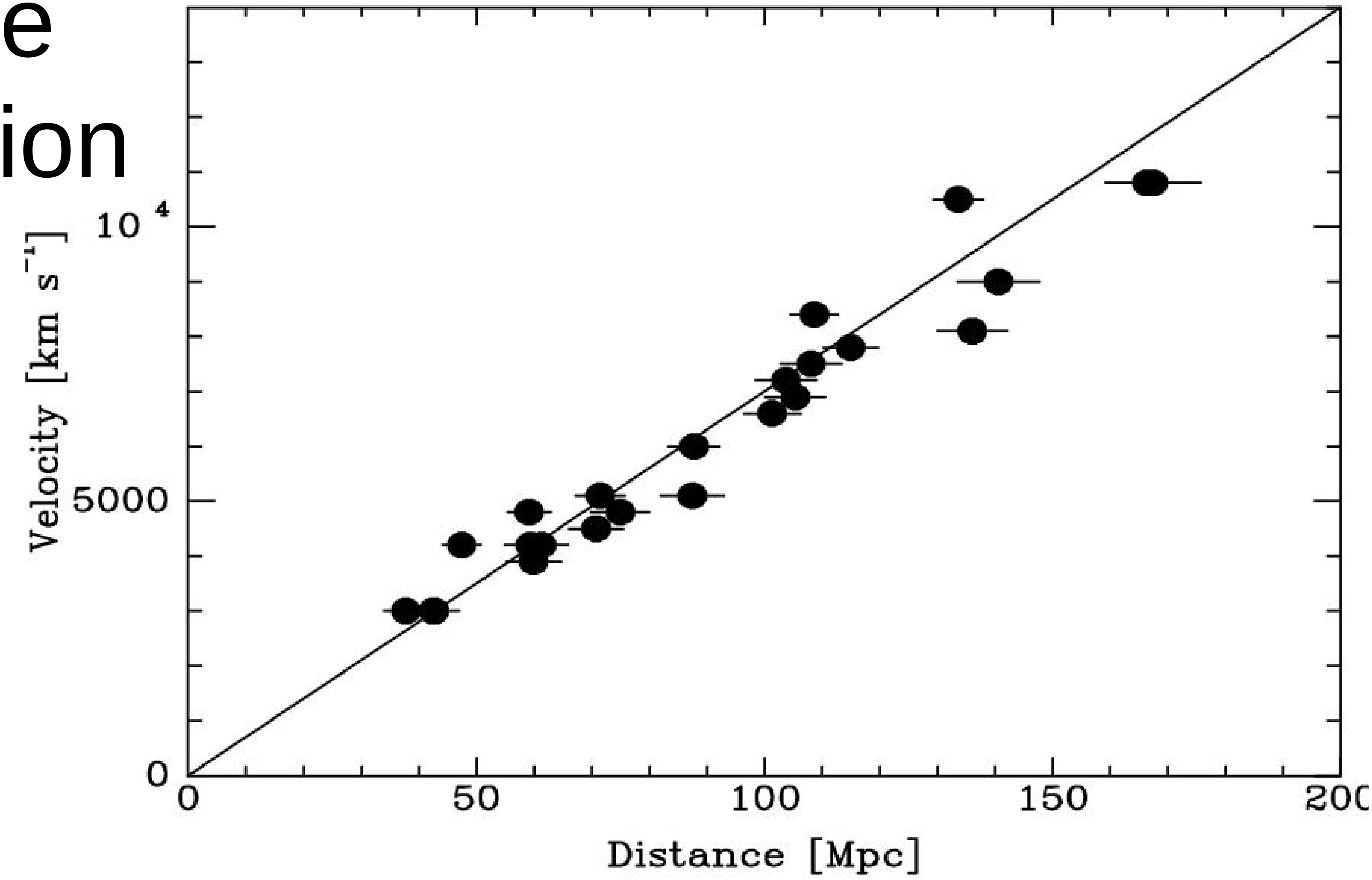
Outline

- Go over problem 8.5
- Redshift in the FRW metric
- Distances: luminosity, surface brightness, proper motion

Hubble Expansion



- Galaxies are moving away with speed, v, proportional to distance, D,

$$v = H_0 D$$

- H_0 = 70 km/s/Mpc = Hubble “constant” – not actually a constant.

Cosmological Redshift

- Consider a crest of a wave emitted at t_e then one emitted at $t_e + \Delta t_e$
- These arrive at us at t_0 and $t_0 + \Delta t_0$
- The ratio $\Delta t_0/\Delta t_e$ gives the redshift

$$\frac{\Delta t_0}{\Delta t_e} = \frac{\lambda_0}{\lambda_e} = \frac{\nu_e}{\nu_0} = 1+z$$

  - Nearby universe has $z \approx 0$.
  - $z = 1$ means photons have half their original energy.
- To calculate t_0 and $t_0 + \Delta t_0$, need to look at propagation of light in the FRW metric, $ds = 0$.

Friedmann-Robertson-Walker Metric

- Spacetime with constant density and constant curvature is described by the Friedmann-Robertson-Walker metric, interval is:

$$(ds)^2 = c^2 dt^2 - R^2 \left(\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta \, d\varphi^2 \right)$$

- where *R* = “scale factor”, all distances scale with *R*.
- (r, θ, φ) are “co-moving” coordinates – as *R* changes as the universe expands, (r, θ, φ) of each galaxy are unchanged.
- Note *r* is dimensionless.
- *k* = “curvature parameter”,
  - 0 = flat, +1 = hypersphere, -1 = hyperboloid

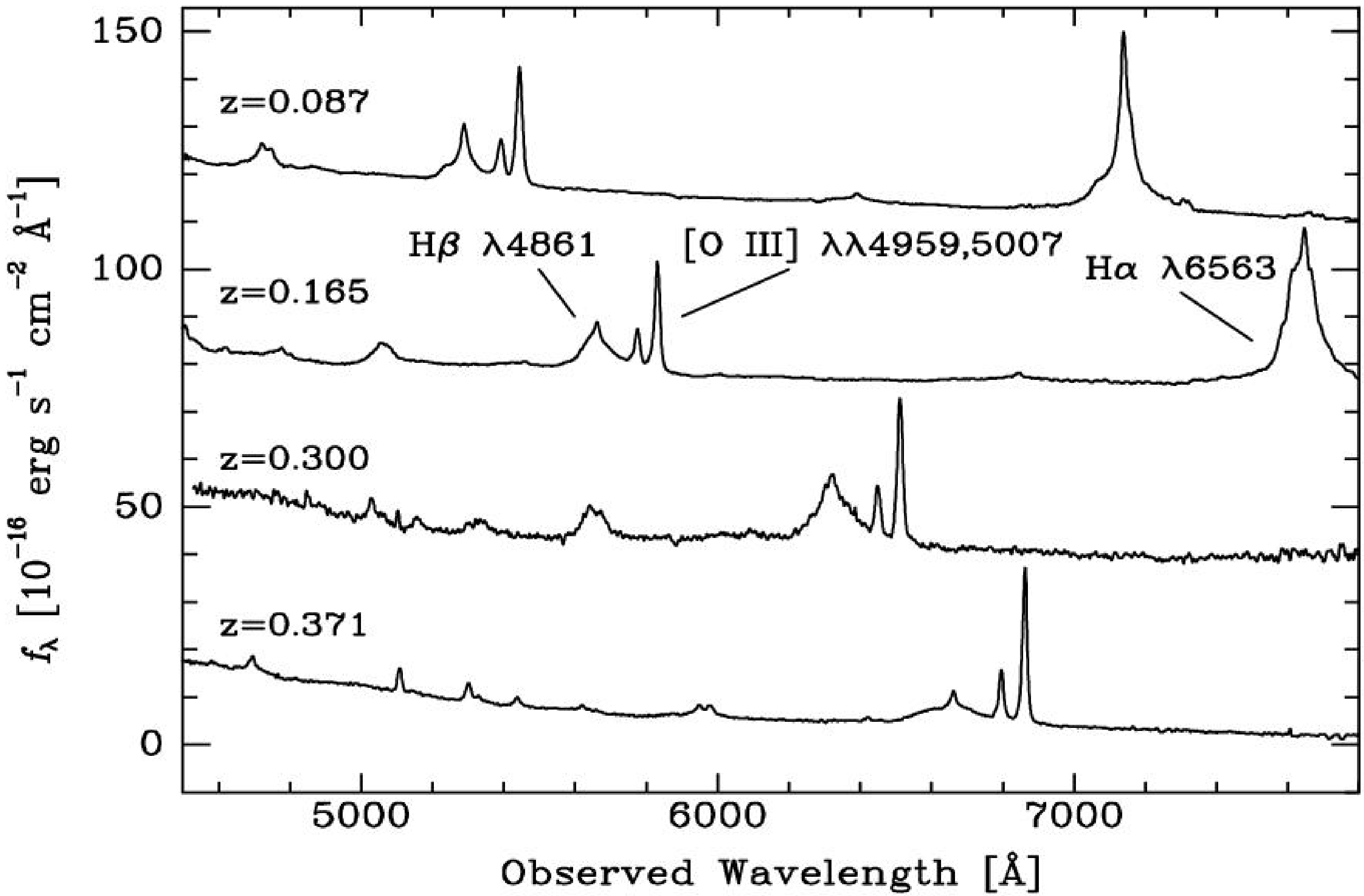
Cosmological Redshift

- The ratio $R(t_0)/R(t_e)$ gives the redshift

$$\frac{\Delta t_0}{\Delta t_e} = \frac{R(t_0)}{R(t_e)} = \frac{\lambda_0}{\lambda_e} = \frac{\nu_e}{\nu_0} = 1+z$$

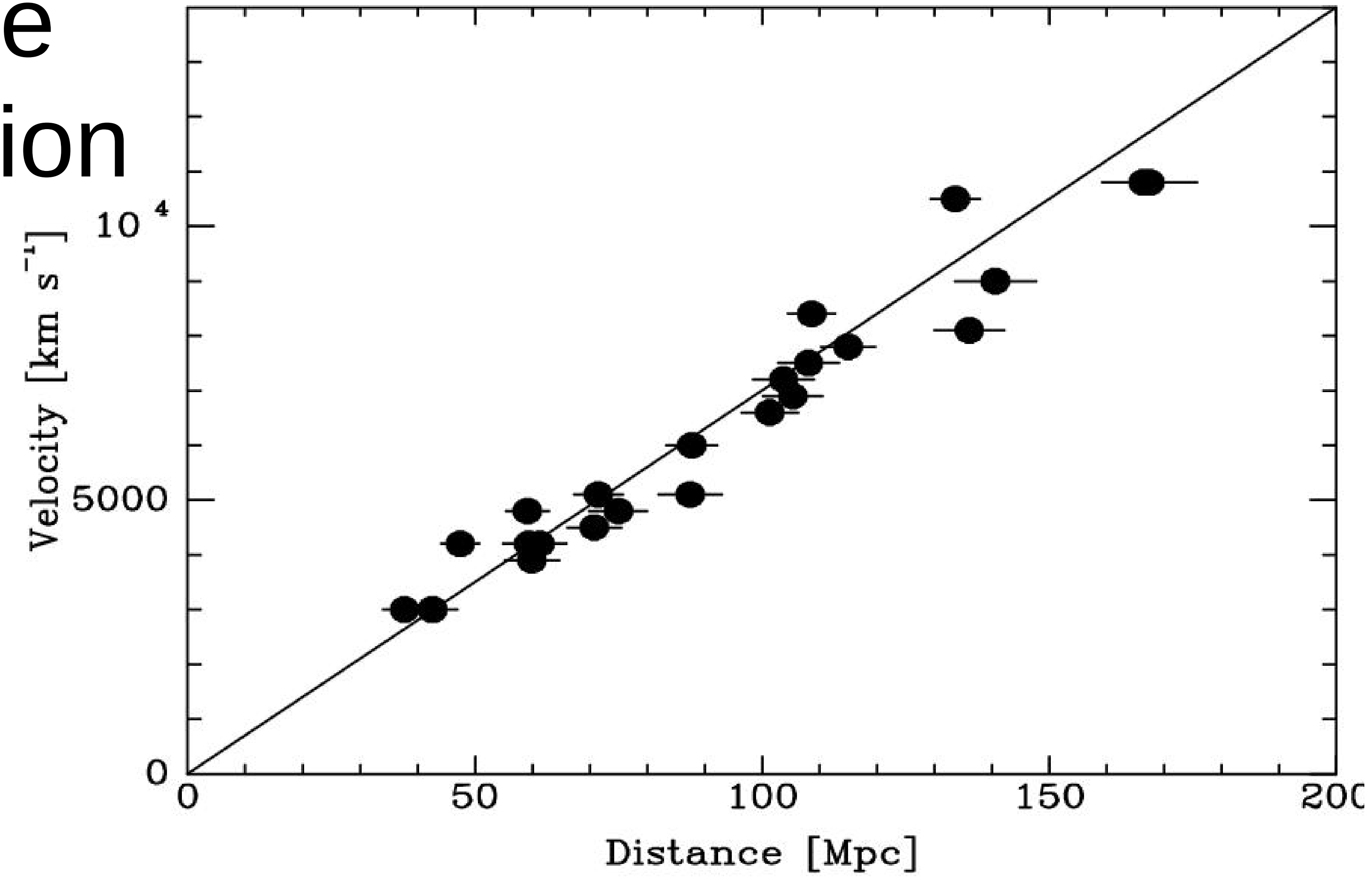
- Redshift is due to expansion of universe, $R(t)$
- Can also have redshift due relative motions (Doppler and transverse Doppler) and gravity.
- Redshift usually measured by identifying spectral lines.

Cosmological Redshift



- Identify lines via wavelength ratios, which are unchanged by redshift
- Usually need several lines (Balmer series, Oxygen lines, ...)

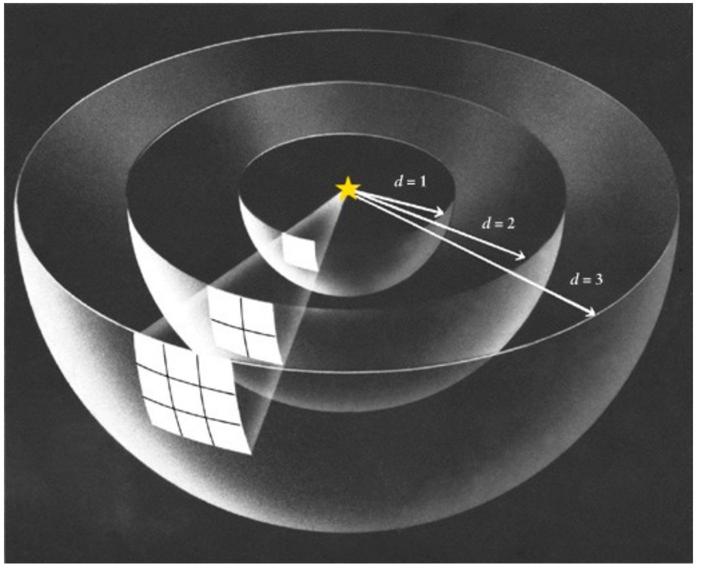
Hubble Expansion



- Now have cosmological redshift instead of velocity.
- Distance is calculated from the measured flux assuming a known luminosity, but is the relation F = $L/(4\pi D^2)$ still valid?

Flux and Luminosity

- Flux is energy per unit surface area per unit time.
- Flux decreases as light spreads out into space.
- Flux is inversely proportional to the surface area of a sphere with radius equal to the distance between observer and source.
- The appropriate distance is the product $R_0 \times r$ which is called the "proper motion distance" or "co-moving distance". It is the ratio of the transverse velocity (in distance per unit time) of an object to its proper motion (in radians per unit time).
- What else affects the observed flux?

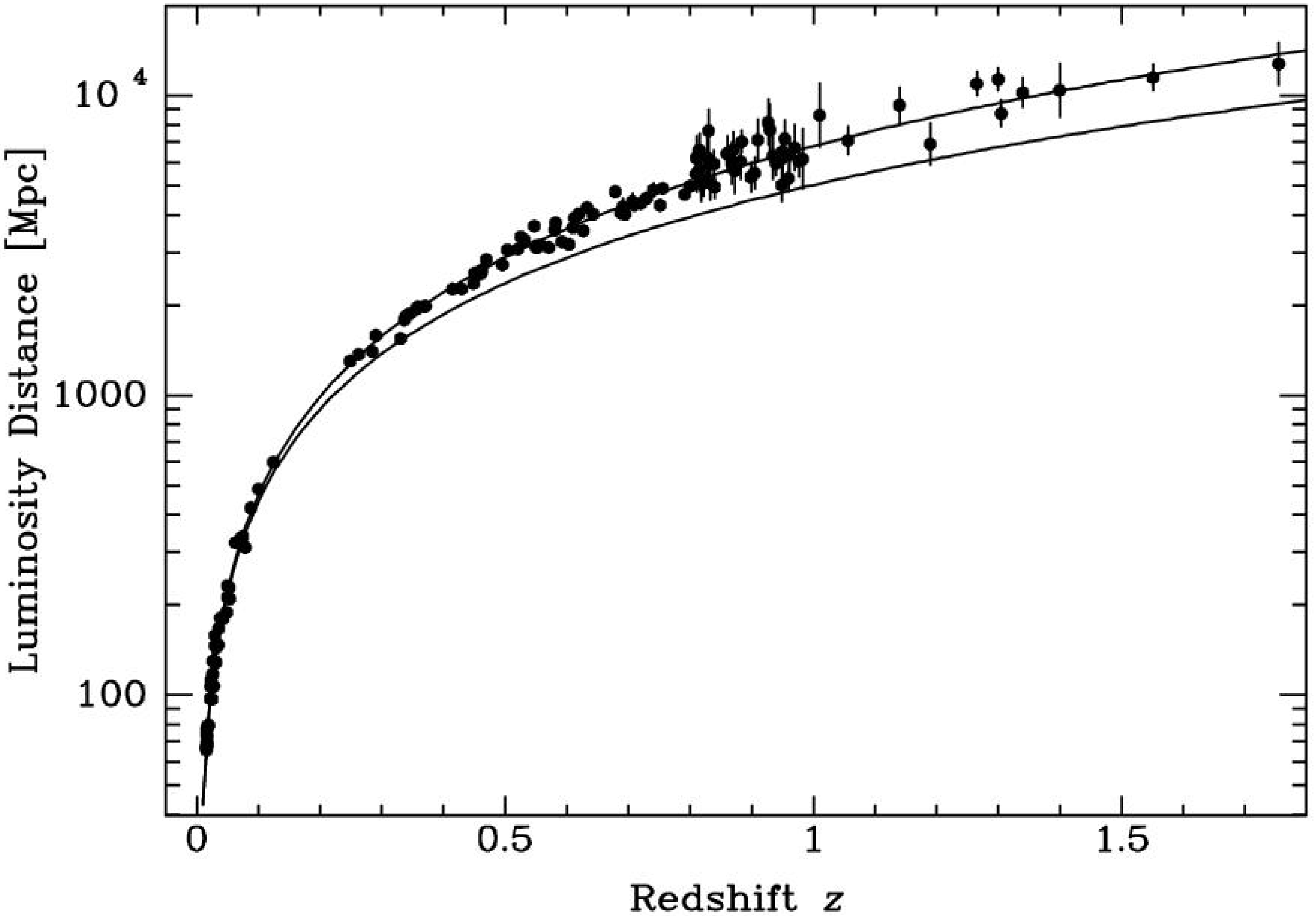


Luminosity Distance

- Light will be red-shifted
  - Decreases frequency, hence energy, hence flux
  - Flux decreases by factor $1/(1+z)$
- There is also cosmological time dilation – the observed duration of an event is longer by a factor of $\Delta t_0/\Delta t_\mathrm{e} = R(t_0)/R(t_e)$.
  - Energy is spread over greater time interval
  - Decreases energy per unit time, hence flux
  - Flux decreases by factor 1/(1+z)
- Overall, flux decreases by factor $(1+z)^{-2}$

- Luminosity distance, $D_\mathrm{L} = rR_0(1+z)$ is defined so $F = L/(4\pi D_\mathrm{L}^2)$

Hubble Expansion



- Hubble diagram is now plot of luminosity distance versus redshift.
- Can use Hubble diagram to determine $R(t)$, hence cosmological parameters.
  - Upper curve has $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$
  - Lower curve has $\Omega_m = 1$, $\Omega_\Lambda = 0$

Homework

For next class: problem 9.2