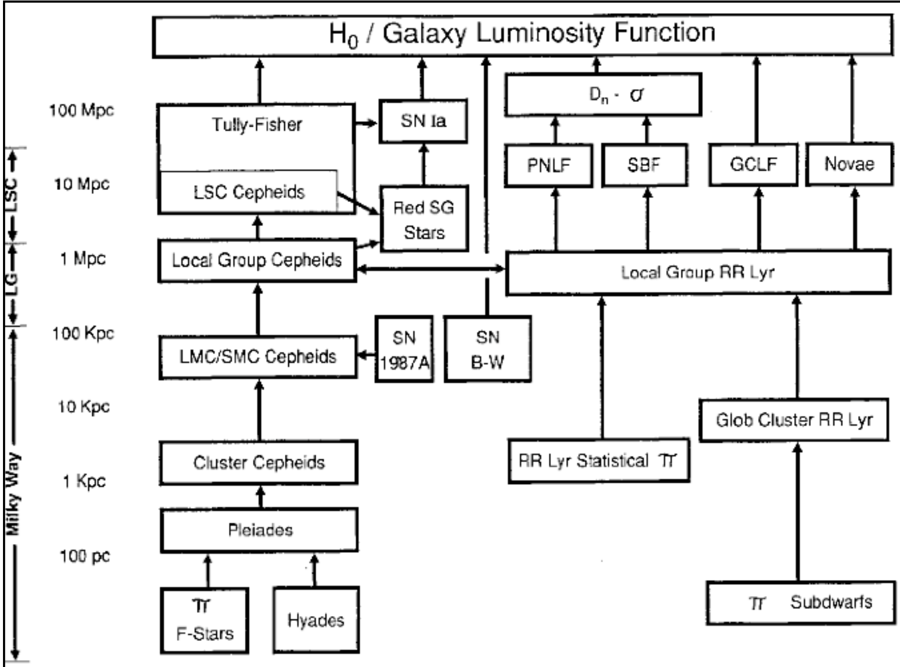
Lecture 9: The Hubble Constant

- Definition
- What is the fuss ?
- What does it mean ?
- How accurately do we know it ?
- Problems with the distance ladder
  - – Peculiar velocities
  - – Infall velocities
  - – Bootstrapping
  - – Examples

•Supernova Type Ia



Pathways to Extragalactic Distances

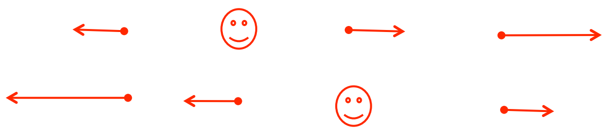
The Hubble Constant (H_o)

Rate by which galaxies are receding, in units of km/s per Mpc: $H_o = \frac{v}{d}$

NOTE: h NOTATION

$h_1 = \frac{H_o}{100}, h_{0.75} = \frac{H_o}{75}$

Consistent with Cosmological Principal (no special location/ direction):



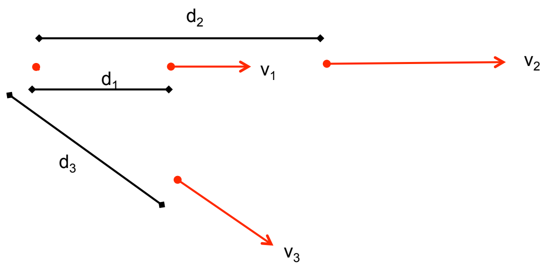
Observer sees objects further away recede faster

Implication 1: The Universe is expanding (empirical result)

Implication 2: At some time t_o everything was at one point (defines a key event some time ago)

Naive age of the Universe

- How long ago was t_o ?



- If each object is moving at a constant velocity (I.e., ignoring cosmological deceleration/acceleration)

$$t_o = \frac{d_1}{V_1} = \frac{d_2}{V_2} = \frac{d_3}{V_3} = \frac{d_n}{V_n} \qquad t_o = \frac{1}{H_o}$$

(Cosmological solution for a zero mass universe: Milne Universe)

Age of the Universe

- E.g., H_o=75km/s/Mpc

$$\therefore t_o = \frac{1}{\left(\frac{75\times10^3}{3\times10^{22}}\right)} = 4\times10^{17}s$$

$$t_o = \frac{4\times10^{17}}{365.25\times24\times60\times60} = 12.7\times10^9 yrs = 13Gyrs$$

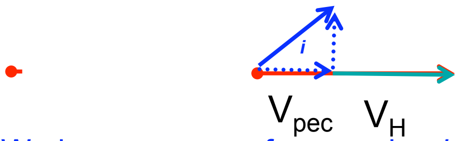
- and we know globular clusters ~12-14Gyrs
- In reality H_o is not constant but changes according to the contents of the universe (matter, energy, radiation)
- Full solution requires cosmology course = 13.6 Gyrs.

The distance ladder revisited

- To measure H_o we need distances and velocities
- Methods:
  - Cepheids
  - Tully-Fisher
  - Faber-Jackson
  - Globular Cluster LF
  - PNe LF
  - Surface Brightness Fluctuations
  - Supernova Type Ia (end of this lecture)
- Problems:
  - Accuracy of distance indicators (~10-20%)
  - Accuracy of redshift measurement (~50km/s)
  - Peculiar velocities (~300 km/s)
  - Bulk flows (~1000km/s)
  - Location of object if in cluster

Velocities

- Hubble flow:
  - A galaxy is said to be at rest (co-moving) if its V_{pec}=0 I.e., it is in the Hubble Flow



$V_T = V_H + V_{pec}$

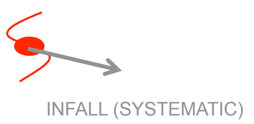
  - We have no way of measuring *i* but only the radial component of the peculiar velocity (V_{pec}) is relevant anyway:

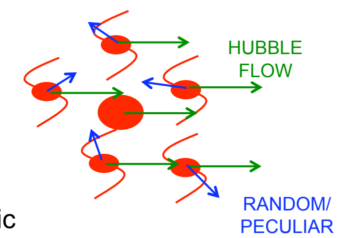
$$H_o = \frac{V_H}{d}, z = \frac{V_T}{c}$$

$$\therefore H_o = \frac{cz}{d} - \frac{V_{pec}}{d}$$

Peculiar velocities and Infall velocities

- Can attempt to remove peculiar velocities of sample out by observing large samples:

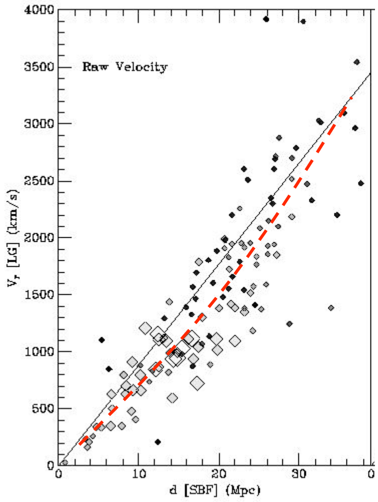




- However infall velocity is a systematic
- Measuring large numbers reduces the random peculiar velocities but not the systematic infall (I.e., our galaxies motion relative to local space-time).
- Thankfully CMB dipole provides an accurate measure.

Virgo infall

- Local Group is falling towards the Virgo cluster
  - can see that in fact nearby groups of galaxies are all doing this, V_{Infall} up to ~300 km/s
  - called 'Virgocentric infall'
- this is why H_0 has been very difficult to measure
  - galaxies within this volume have best values of d!
  - now have H_0 from WMAP study of cosmic background



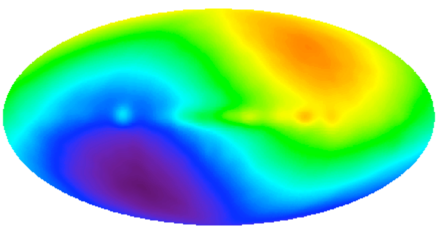
J. Tonry

Absolute motion through space

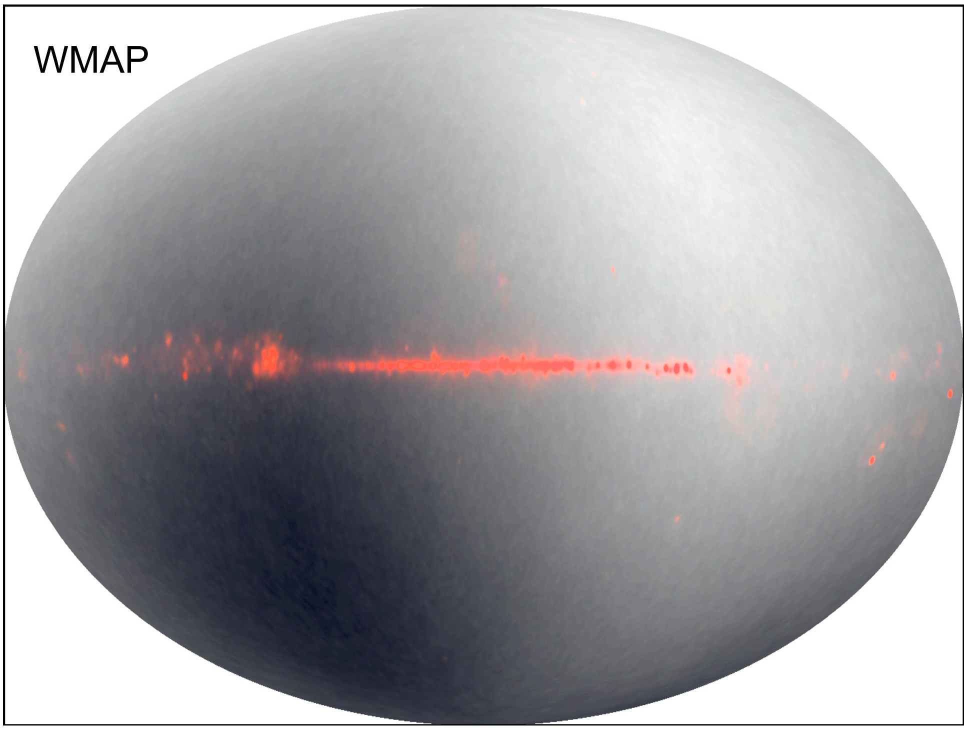
- maps of the cosmic microwave background have also shown that the Local Group is moving through it
  - speed of ~600 km/s

  (NB, Einstein said there is no absolute reference point, all velocities are relative…however the sum of all matter+radiation does define a preferred reference frame: Mach's Principle)

COBE map of cosmic background radiation– we are moving towards the blue-shifted side of the sky



WMAP



Measuring Ho

Q) At what z do random and infall velocities become < 10% ?

$$z = \frac{V}{c}$$

$$\frac{V_R}{V_H} = 10\%, \text{when}, V_H = 3000$$

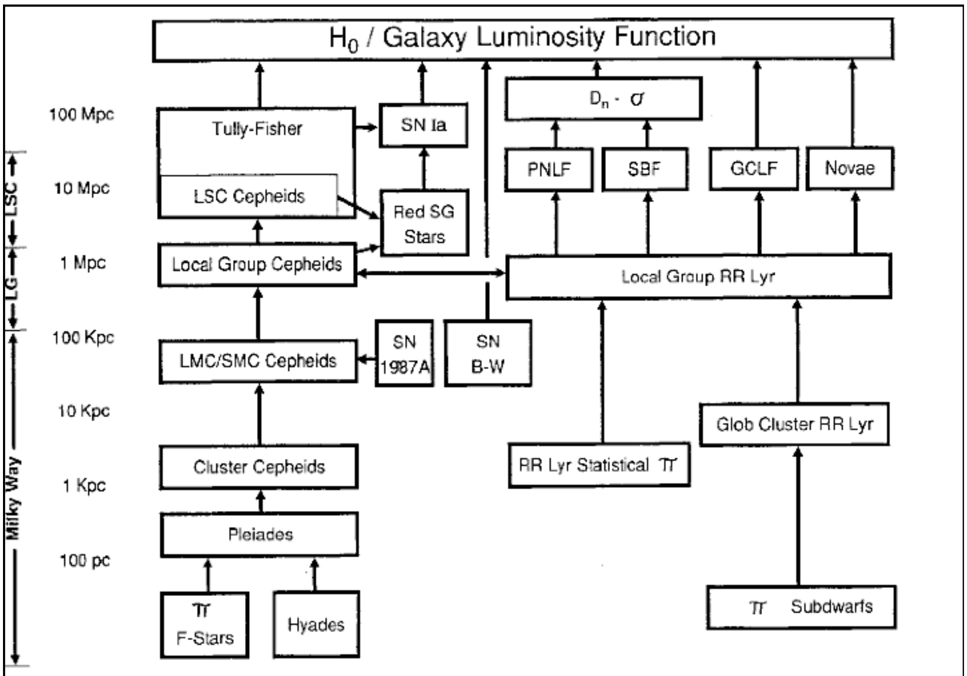
$$\frac{V_I}{V_H} = 10\%, \text{when}, \text{V}_\text{H} = 6000$$

$$z^R_{10\%} = 0.01(d = 43\text{Mpc}, \text{for}, H_o = 70\text{km/s/Mpc})$$

$$z^I_{10\%} = 0.02(d = 86\text{Mpc}, \text{for}, H_o = 70\text{km/s/Mpc})$$

What distance indicators work over these distance ?

Could Ho have evolved during the light travel time ?



Pathways to Extragalactic Distances

Bootstrapping to get Ho

- 1) Measure z to M101 in Virgo via Cepheids:
  - Estimate V_{pec}
  - Estimate V_{infall}
- 2) Boostrap via Coma:

$$H_o = \frac{cz}{d} + \frac{V_{infall}}{d} - \frac{V_{pec}}{d}$$

- If ratio d_1/d_2 is known (e.g., TF or FJ) we can use d_1 to get d_2, then the redshift to Coma will yield a more accurate Ho value.
- I.e., V_{infall} and V_{pec} comparable but V_H x 10 larger => error in H_o lower

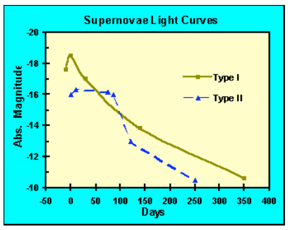
Supernovae Type Ia

- an ideal standard candle is very bright, and of known brightness (at least for some observable time)
- type Ia supernovae fit this description:
  - when they explode, they reach a large absolute magnitude that varies little from supernova to supernova
- a type Ia supernova occurs in a binary star system where gas from a red giant overflows onto a white dwarf
  - when a critical mass is reached the white dwarf can no longer be supported and collapses, then rebounds

    (type II supernovae are single stars that collapse when nuclear fusion ceases... Ia vs Ib depends on if the companion has hydrogen in the atmosphere)

Acceleration of the Universe

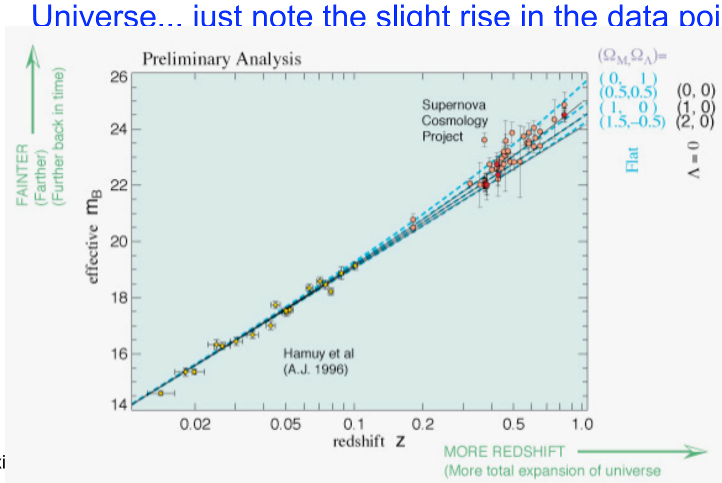
- Type Ias can be seen over such large distances one can measure the change in H with t (or z)
  - assume their peak luminosity L is constant
  - then the measured flux is just $F = L / 4 \pi d^2$
  - from Hubble's law: $d = v / H_0$



W. Johnson

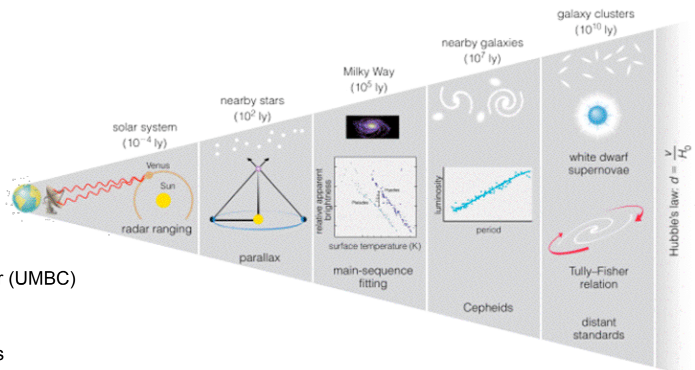
  - if Hubble's law applies at large distances, i.e. the Universe has always expanded at the same rate, then the flux should decrease steadily with redshift
- the Supernova Cosmology project set out to discover if this is actually the case (http://www-supernova.lbl.gov/public/)

- in fact, the most distant Ia supernovae appear to be a bit *fainter* than predicted (distance to large)
  – results for 42 supernovae shown in the plot
  – the lines show different ideas about the history of the Universe... just note the slight rise in the data points



the distance ladder

- Lastly... remember that absolute distances can have big errors! Most of the methods are ‘bootstrapped’ to another method for closer objects (e.g. Hubble’s law). When we get to the scale of the whole Universe, this series of potential errors could build up to be pretty big!



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