But, only see enough events to account for ≤ 2% of dark matter in these regions. 14.11.3

Additional evidence from the abundance ratios of elements & isotopes from the big bang (Big Bang Nucleosynthesis) which suggests dark matter cannot be baryonic.

→ 3rd yr cosmology.

3rd alternative, that dark matter doesn't exist, and is inferred through relying on incorrect theories of gravity, e.g. modified Newtonian ~~gravity~~ dynamics MOND, $F_g \not\propto \frac{1}{R^2}$

---

3. Distances to galaxies

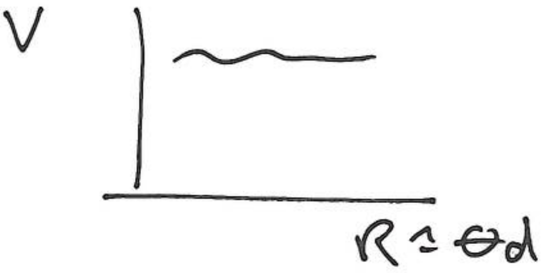
Need distances in order to measure all main properties:

→ size, $R \simeq \theta d$
(θ ← angular size.)

→ luminosity, $L = f 4\pi d^2$
(f ← flux)

14.11.4

→ mass, – e.g. via rotation curves.



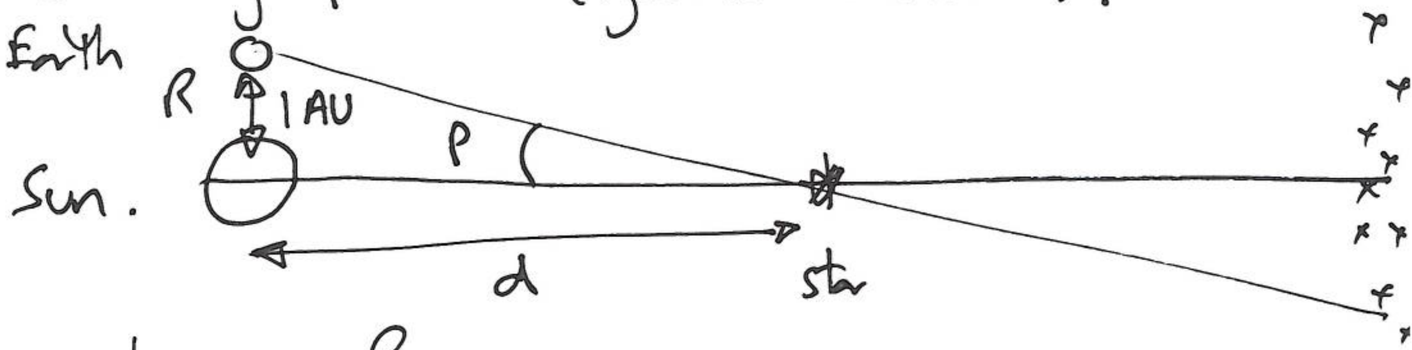
Two types of methods, both relying on independent knowledge. ~~of the target object.~~

1) Geometric methods rely on an indepent measurement/estimate of a length scale

2) Standard candle methods rely on an independent measurent/estimate of luminosity.

Taken together, all the methods build into a cosmic distance ladder.

① Trig. parallax (geometric method).



$$\tan p = \frac{R}{d} \simeq p$$

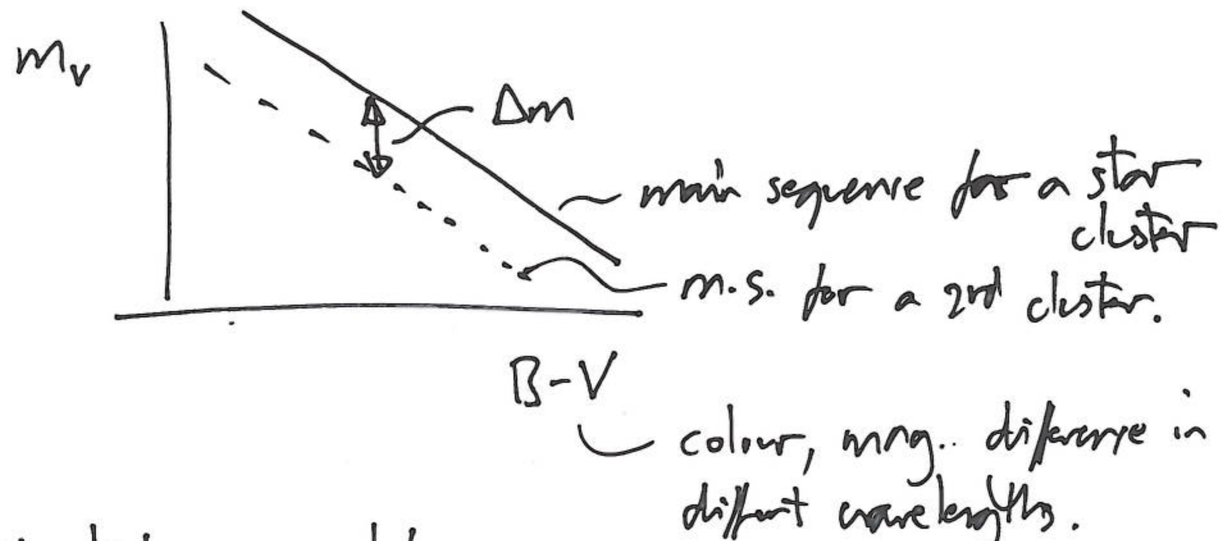
14.11.5

By definition, a parsec is the distance at which a star has $p = 1''$.

② Spectroscopic parallax (standard candle).

Using H-R diagram to estimate L of M.S. stars (colour ⇒ luminosity).

③ main sequence fitting (standard candle).



Recall, distance modulus

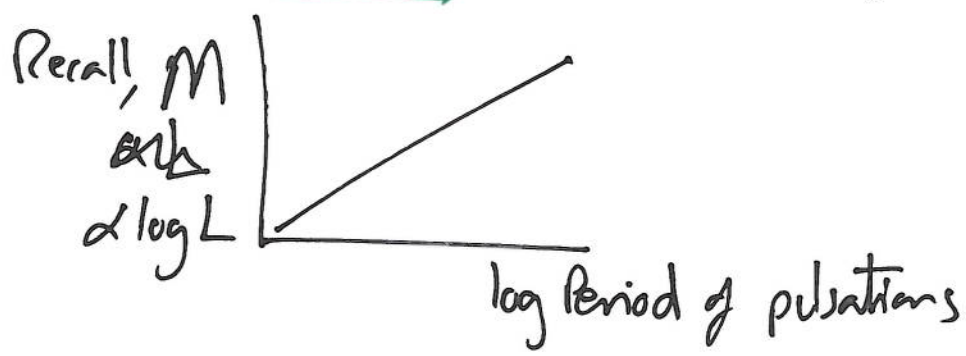
$$m - M = 5\log_{10}(d) - 5 \quad (+A)$$

A: dust extinction.

$$\Rightarrow \quad \Delta m = 5\log_{10}\left(\frac{d_1}{d_2}\right)$$

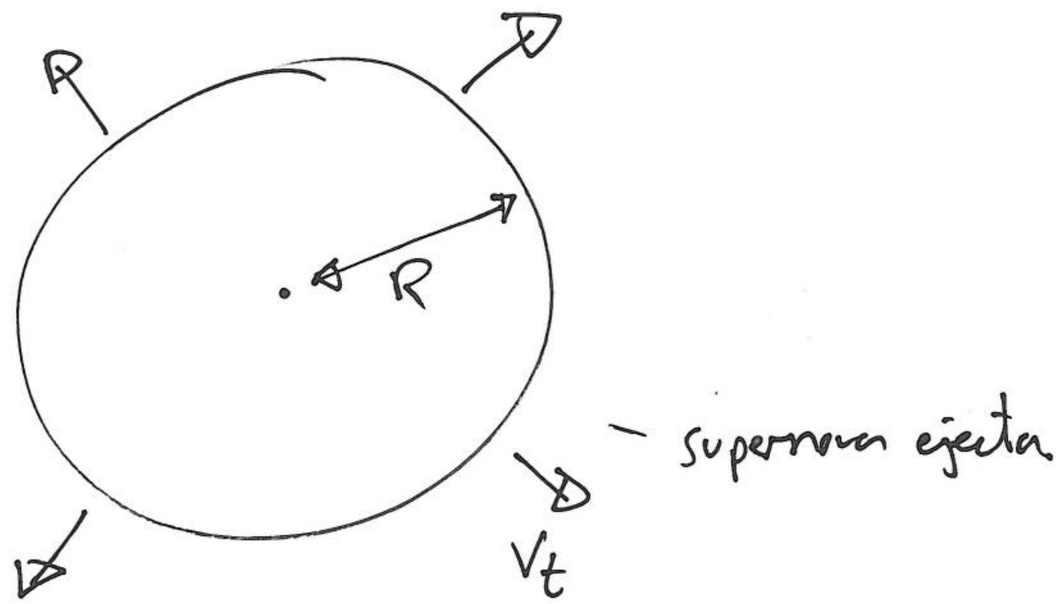
provides v. precise distance for a distant cluster based on e.g. parallax for a nearby cluster.

④ Cepheid variables (standard candle)



Cepheids are luminous giants, so detected in external galaxies at relatively large distances.

(5) Supernova shell expansion (geometric)



$$R \simeq \theta d \simeq \text{age} \times V_t$$

can measure, V_r, radial velocity using Doppler shift of spectral lines.

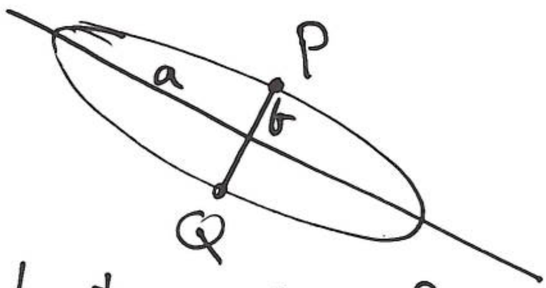
Assume symmetry $\Rightarrow V_r = V_t$

$$\Rightarrow d = \frac{\text{age} \times V_r}{\theta}$$

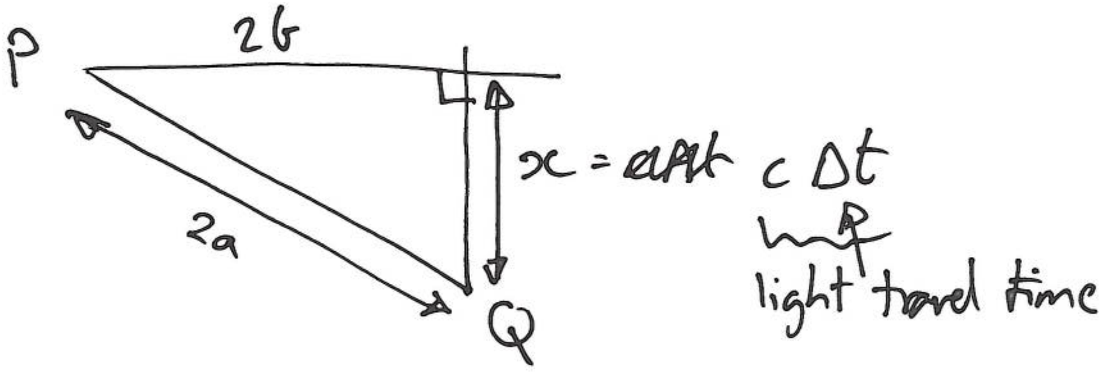
Provides ~~not~~ an independent check of parallax distances. *

⑥ Ring around SN1987A in the LMC (geometric).

Ring brightened around the SNe, interpreted as an inclined circular ring of ejected material (pre-SN) illuminated by the SN. Once side brightened first, interpreted as the light travel time difference across the inclined ring.



Ring brightened at Q, before P.



$$x^2 = (2a)^2 - (2b)^2$$

$$\Rightarrow 2a = \frac{c\Delta t}{\sqrt{1-\left(\frac{b}{a}\right)^2}}$$

$\frac{b}{a}$ estimated from the image. Δt ~~fr~~ is the measured time delay. 2a is the standard ruler.

$$d = \frac{2a}{\theta} = 52 \pm 3\,\text{kpc}.$$

Independent of all the other methods.

⑦ SN as standard candles

Useful because $L_{SN} \simeq L_{galaxy}$, so detectable at v. large distance.

But, core-collapse SN are very poor standard candles (too many factors in the properties and histories of the individual stars).

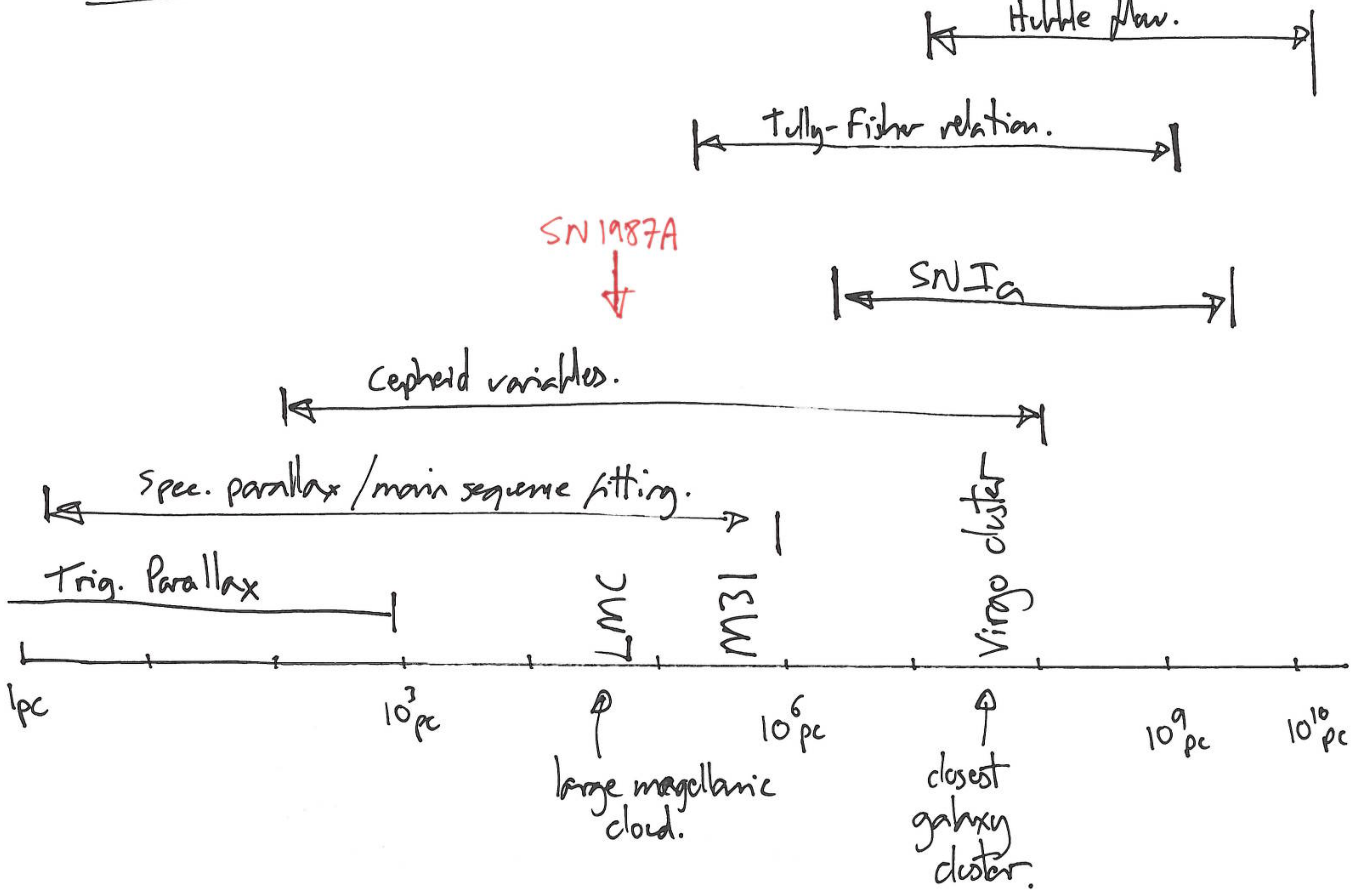
However, type Ia SN are useful standard candles. H free spectra. Believed to thermonuclear ignition of a white dwarf star, when its mass reaches the chandrasaker limit ($1.4 M_\odot$)

Peak $L \simeq 6 \times 10^9 L_\odot$ - calibrate this to a standard candle based on the light curve.

But, can only measure distances to the few galaxies in which SNIas are detected. 14.12.6

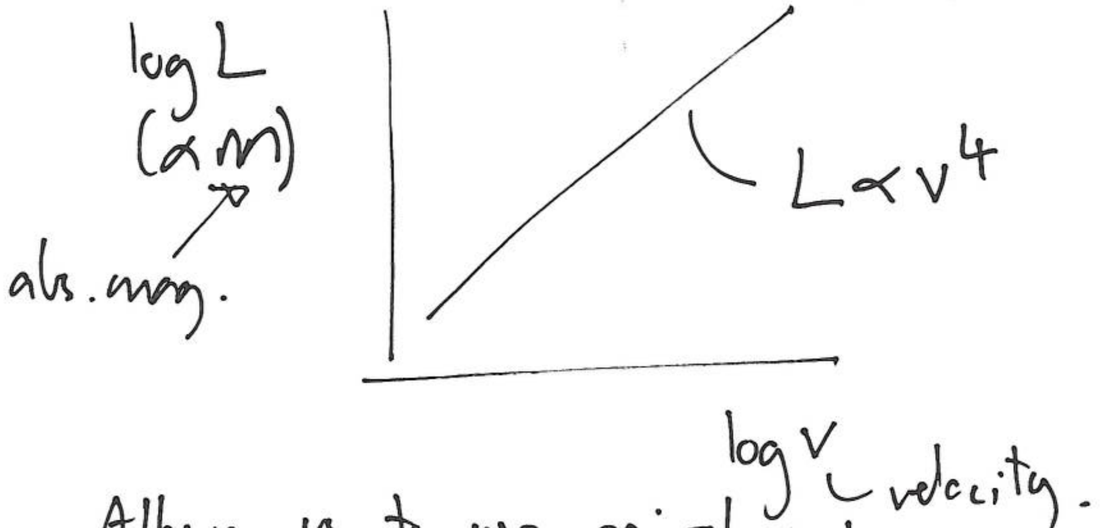
Distance ladder.

14.12.1
+ 14.13.0



⑧ Tully-Fisher relation (standard candle)

Empirical correlation between luminosity and rotational velocity for spiral galaxies.



Allows us to use spiral galaxies as standard candles.

why?

Assume constant mass-to-light ratio in spiral discs

$$\frac{M}{L} = \text{const} \Rightarrow L \propto M \quad (M\text{: mass})$$

Recall, $M(<R) = \frac{V^2 R}{G}$

$$\Rightarrow L \propto V^2 R$$

Further assume surface brightness of spiral discs are the same,

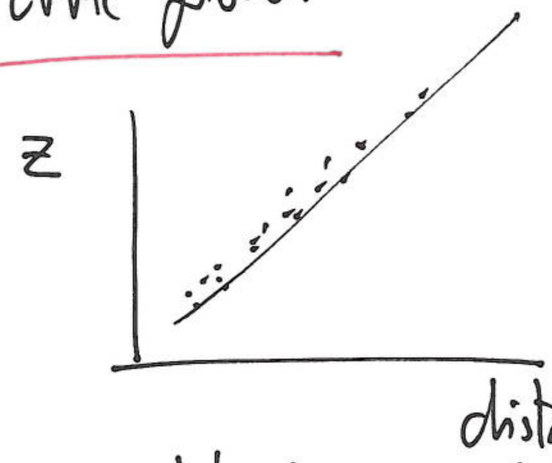
$$\Rightarrow \frac{L}{R^2} \simeq \text{const} \Rightarrow L \propto R^2$$

$\Rightarrow$ $L \propto v^4$ as observed!

So the Tully-Fisher relation ~~sugg~~ suggests these assumptions are valid.

---

(9) Hubble flow.



using redshift & Hubble constant calibration to estimate distances.

Not v. precise, but it is universal.

For nearby galaxies, expansion is slow compared with their peculiar velocities.

For distant galaxies, depends on the assumed cosmology.