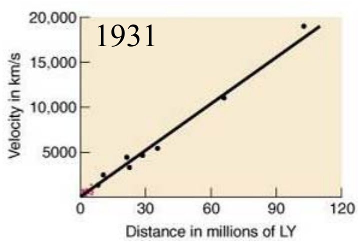
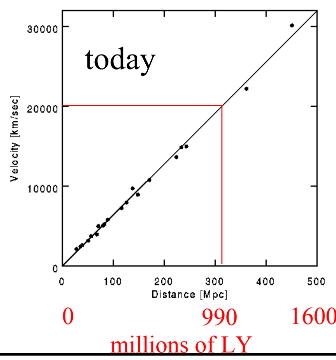
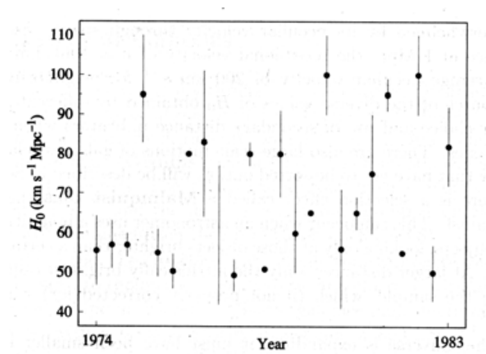
Hubble's Law







Little *h*

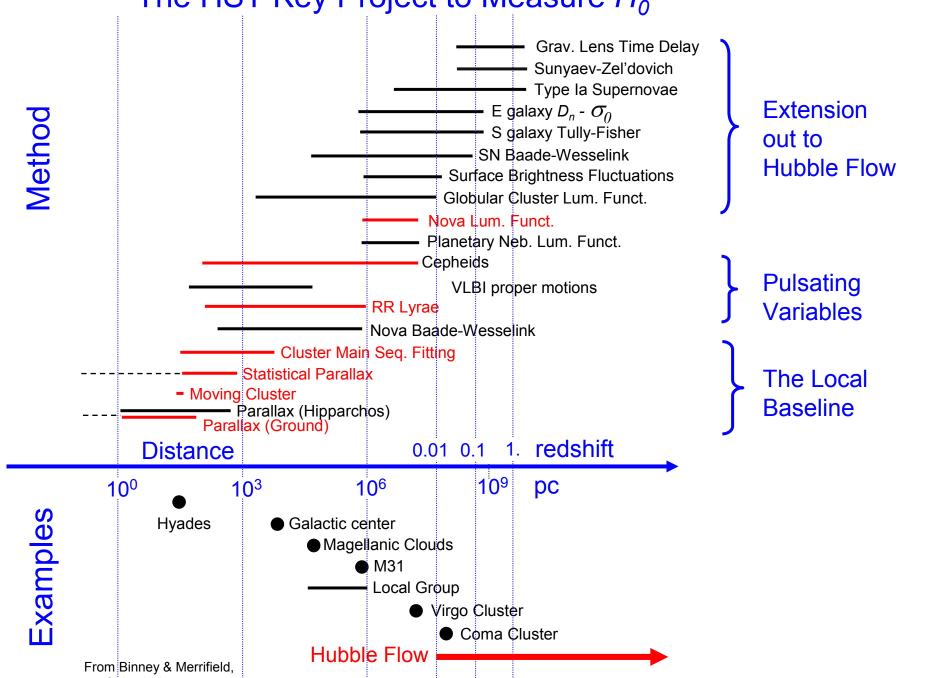
- The Hubble Un-constant (blush)

  $H_o = 100h$ km s^{-1} Mpc^{-1}

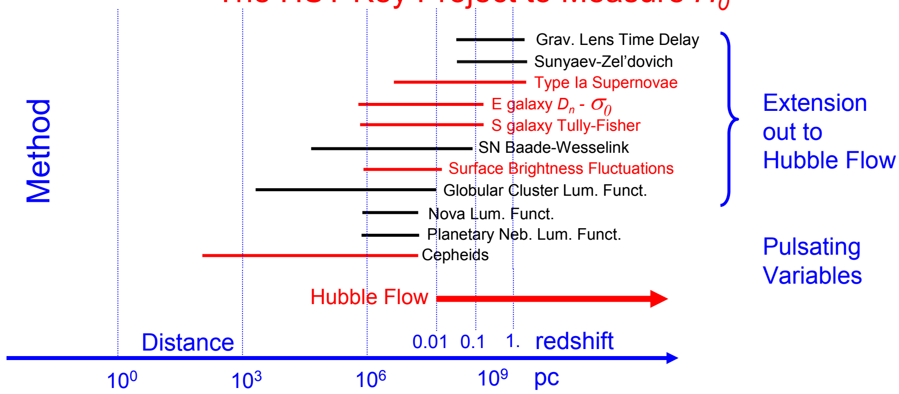
- Hubble time

  $t_H = 1/H_o = 9.78 \times 10^9\ h^{-1}$ yr.

The HST Key Project to Measure H_0



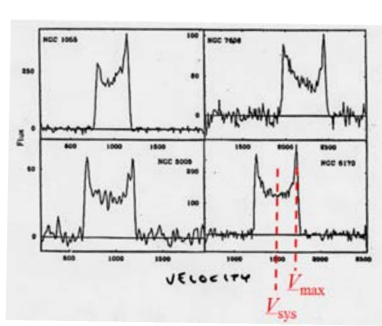
The HST Key Project to Measure H_0

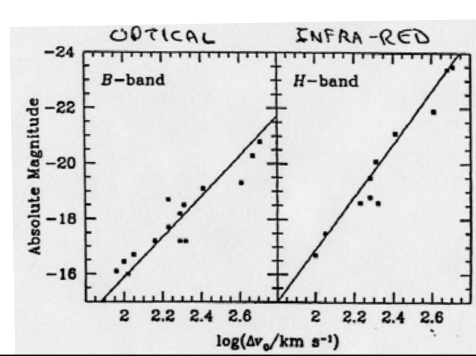


- Mould et al. 2000, ApJ 529, 786
- Measured Cepheids in 18 spirals
  - D < 25 Mpc, v < 1800 km/s
  - also used 7 more galaxies from other sources
- Distances to Cepheids relative to LMC distance
- Used these to calibrate secondary distance indicators
  - Tully-Fisher
  - Fundamental plane
  - Surface brightness fluctuations
  - Type Ia supernovae

Tully-Fisher Relation

- *L*-*v* correlation
- for spiral galaxies, *v* easily measured using H I 21cm (radio) profiles.
- must apply sin *i* correction for inclination.
- infrared Tully-Fisher: IR measurements minimize scatter in *L* due to absorption ==> tighter correlation
- *F*/*L* ➔ distance





E Galaxy Fundamental Plane
The D_n - σ_0 relation

- Define:

  D_n = angular diameter at which surface brightness reaches
  I_n = 20.75 B-mag/arcsec^2

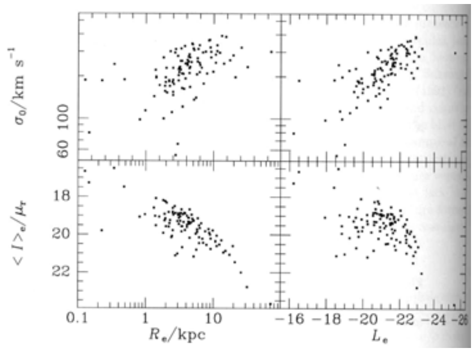
- Observations show that linear size (in kpc) corresponding to D_n is tightly correlated with σ_0

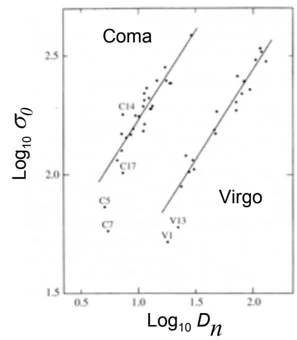
- D_n - σ_0 relation combines radius, surface brightness and internal velocity dispersion σ_0

  ➔ *The Fundamental Plane strikes again!*

- Angular size = D_n = (linear size)/distance

- 15% scatter in resulting distance to any one galaxy.





[CO Fig. 27.5]

Surface brightness fluctuations

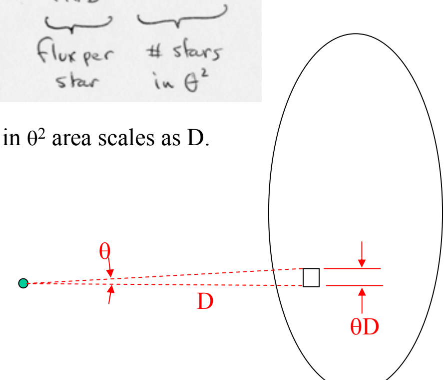
Same galaxy seen at any distance will have same surface brightness.

N = number of stars in angular area θ^2
n = number of stars per unit absolute area
L = luminosity of each star
D = distance

Surface brightness $= I = \underbrace{\left(\frac{L}{4\pi D^2}\right)}_{\text{flux per star}} N = \left(\frac{L}{4\pi D^2}\right) \underbrace{n (D\theta)^2}_{\#\text{ stars in }\theta^2} = \frac{Ln\theta^2}{4\pi}$

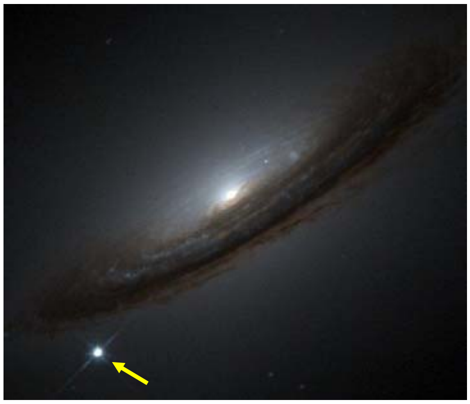
But standard deviation of number of stars in θ^2 area scales as D.

$$N = n(D\theta)^2$$
$$\sigma_N = \sqrt{N} = \sqrt{n}\, D\theta$$
$$\sigma_I = \left(\frac{L}{4\pi D^2}\right)\sigma_N = \frac{L n^{1/2}\theta}{4\pi D}$$
$$\frac{\sigma_I^2}{I} = \frac{\langle L \rangle}{4\pi D^2}$$



So surface brightness distributions look smoother for larger D.

Type Ia Supernovae



Core collapse supernovae

- Massive stars (M > 8 or10 M_{sun})
- Wide range in M ➔ wide range in L
- Not useful as "standard candles"

Type Ia supernovae

- White dwarf with $M \sim 1.4\ M_{sun}$
- L can be precisely calibrated.
- Good standard candles.

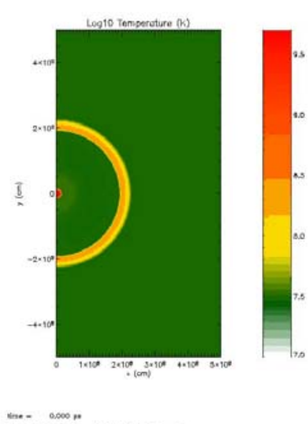
Type Ia Supernovae

- Something dumps too much mass onto white dwarf.
- Increased density ➔ runaway heating through C + C burning
- Heating rate faster than dynamical timescale
  - White dwarf cannot peacefully respond to pressure increase.
- *Deflagration*
  - leading to *detonation*?

Type Ia Supernovae as "standard candles".

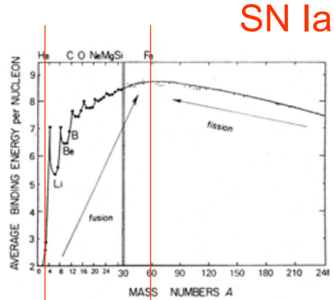
- Always happens when mass goes just past limit for heating-cooling balance.

  ➔ Supernova always has ~ same luminosity (factor 10).
- Get distance from $\text{Flux} = \dfrac{L}{4\pi r^2}$



Deflagration simulation

SN Ia as Standard Candles

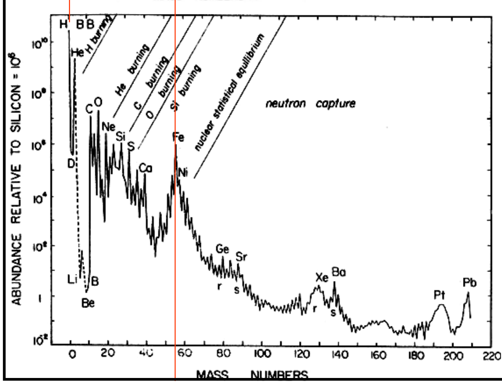


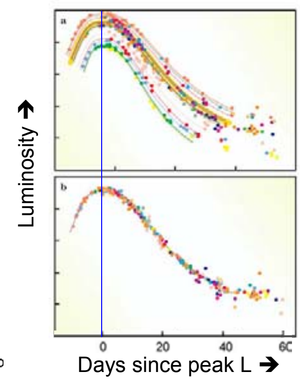
Light output powered by radioactive decay:

^{56}Ni ➔ ^{56}Co ➔ ^{56}Fe

Amount of Ni determines both luminosity *and* opacity.

- So luminosity and fading timescale are correlated.



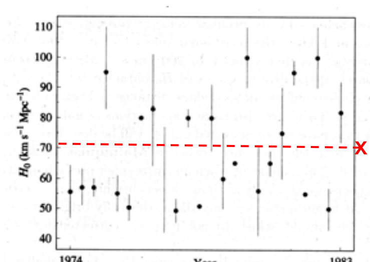


Observed range in *L* and *fading timescale.*

After correcting for *L - timescale* correlation.

The HST Key Project to Measure H_0

- Measured Distances to Cepheids.
  - relative to LMC distance.
- Used these to calibrate secondary distance indicators in same galaxies.

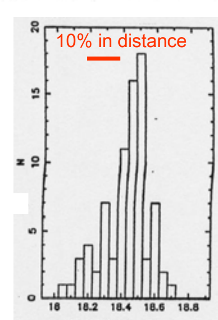


	value	random	systematic
Tully-Fisher	71	± 4	± 4
$D_n - \sigma_0$	78	8	10
Surface Brightness Fluct.	69	4	6
Type Ia SNe	68	2	2

Average: H_0 = 71 ± 6 km/s/Mpc

- Uncertainties:
  - Correction for large scale flows
  - Distance to LMC.

    Taken to be 50 kpc ± 6.5%

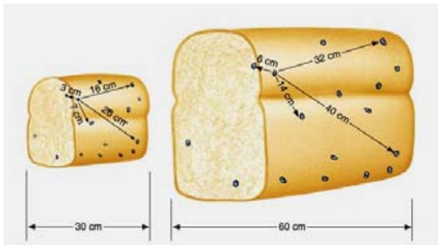


Distribution of published LMC distance moduli

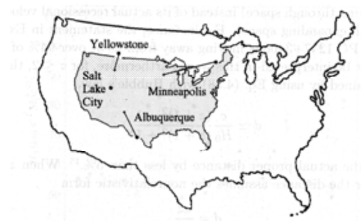
The Expanding Universe

Homogeneous * Isotropic

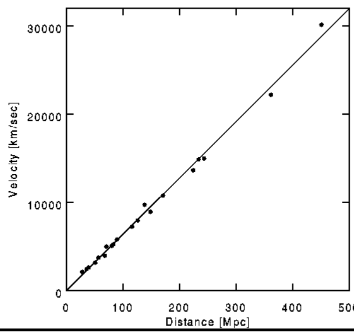
[CO 29.1]



As seen from a Wonder Bread raisen



As seen from Utah



The Cosmological Principle:

At any given time, the universe is the same everywhere.

Cosmological Principle: Universe is homogeneous & isotropic

Newtonian Cosmology

- Energy:

Kinetic + Potential = Total

[29.1]

$$\frac{1}{2}mv^2 - \frac{GM_r m}{r} = -\frac{1}{2}mkc^2\varpi^2$$

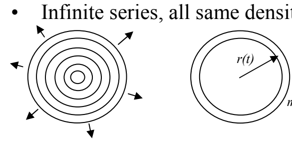
$$\frac{1}{2}mv^2 - \frac{G\frac{4}{3}\pi r^3 \rho m}{r} = -\frac{1}{2}mkc^2\varpi^2$$

$$v^2 - \frac{8}{3}\pi G \rho r^2 = -kc^2\varpi^2 \quad [29.2]$$

$$\left(\left(\frac{1}{R}\frac{dR}{dt}\right)^2 - \frac{8}{3}\pi G\rho\right)R^2 = -kc^2 \quad [29.10]$$

Friedman eq'n:

- Nested, expanding shells
  - Infinite series, all same density $\rho(t)$



  - Follow single shell, mass m [29.3]

- ***r(t)* = (Scale factor) x (co-moving coordinate)**

$$r(t) = R(t)\,\varpi$$

Define: Total Energy $= -\frac{1}{2}mkc^2\varpi^2$

Why???

Cosmological principle ➔

For bound universe, each nested shell must simultaneously have KE➔0

$$E = -G\frac{4}{3}\pi r^2 \rho m \propto m\varpi^2$$