The Next 2-3 Weeks

[27.1] The Extragalactic Distance Scale.
[27.2] The Expansion of the Universe.
[29.1] Newtonian Cosmology
[29.2] The Cosmic Microwave Background
[17] General Relativity & Black Holes
[29.3] Relativistic Cosmology

Starting ~ week after next (Oct. 18?)

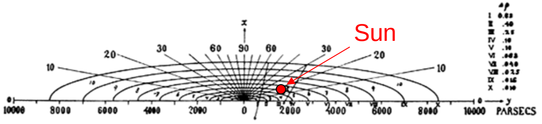
Important to read through Chapter 17 (Relativity) before I start lecturing on it.

Pay particular attention to 17.2 “Intervals & Geodesics”
- What is a metric?
- The Schwarzschild metric (= non-rotating black hole)
- “The orbit of a satellite” (somewhat flakey example)

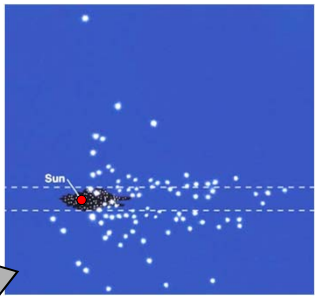
I will present additional material assuming that you have read at least 17.2.

Mapping Our Galaxy

From star counts:

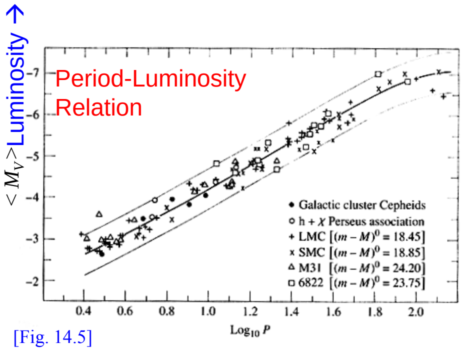


Kapteyn (1922). Surfaces of constant star density.

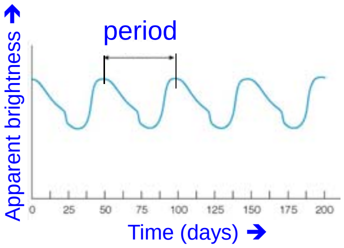


Shapley (1920) Globular Clusters
(distances using RR-Lyraes)

From distribution of Globular Clusters:
- Use pulsating variables to find clusters’ distances.
- Clusters are out of MW disk ➔ little reddening.

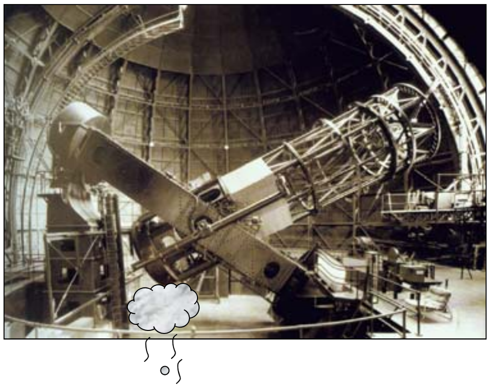


[Fig. 14.5]



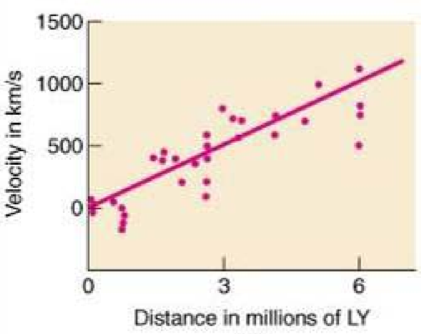
Astronomy in 1929

100 inch telescope
Completed 1918



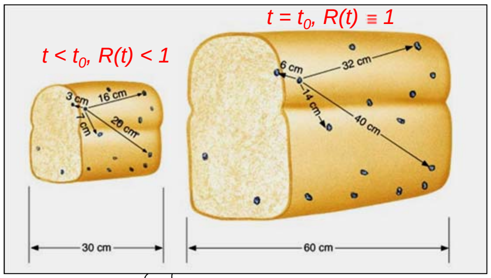
Edwin Hubble

- 1923: Hubble measured distance to M31
  - Pulsating variables
- 1926: Hubble’s E, S, I galaxy classification scheme.
- 1929 Expanding Universe



Astronomy in 1929

A loaf of raisin bread in a 1929 oven



Edwin Hubble

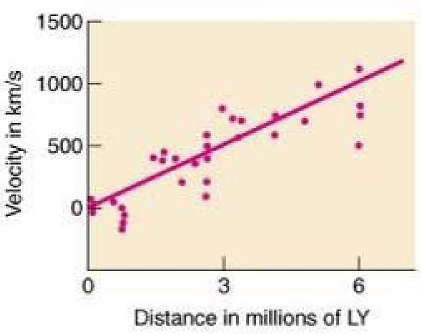
The Scale Factor $R(t)$

Sometimes called $a(t)$

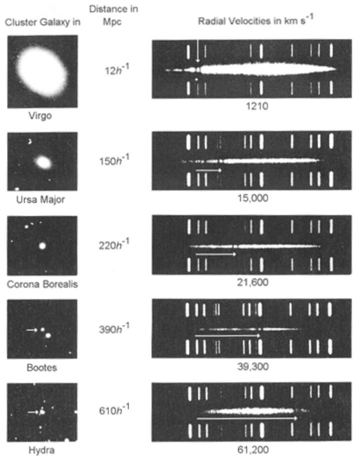
Ratio of size of U. at time t to its current size.

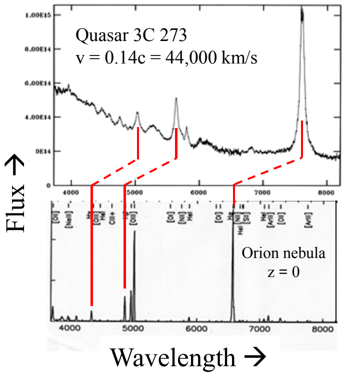
Current time designated $t = t_0$

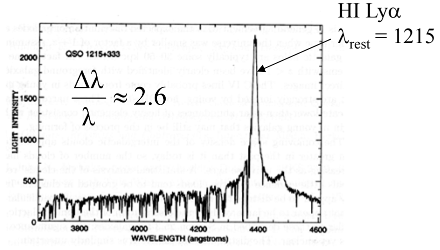
- 1923: Hubble measured distance to M31
  - Pulsating variables
- 1926: Hubble’s E, S, I galaxy classification scheme.
- 1929 Expanding Universe



Velocity from Redshifts







$$\text{Redshift} = z = \frac{\lambda_{obs} - \lambda_{rest}}{\lambda_{rest}} = \frac{\Delta\lambda}{\lambda} \approx \frac{v}{c}$$

$$\cancel{\frac{v}{c} = \frac{(z+1)^2 - 1}{(z+1)^2 + 1}}$$

Special relativistic result [CO eqn. 4.38]

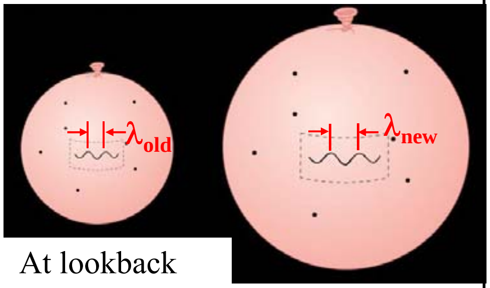
The Expanding Universe

- Individual galaxies do not get stretched.
- Light waves *do* get stretched ➔ redshift.

Redshift

$$z = \frac{\lambda_{new} - \lambda_{old}}{\lambda_{old}} = \frac{\lambda_{new}}{\lambda_{old}} - 1$$

$$R(t) = \frac{\lambda_{old}}{\lambda_{new}} = \frac{1}{1+z}$$



At lookback
time corresponding
to redshift z

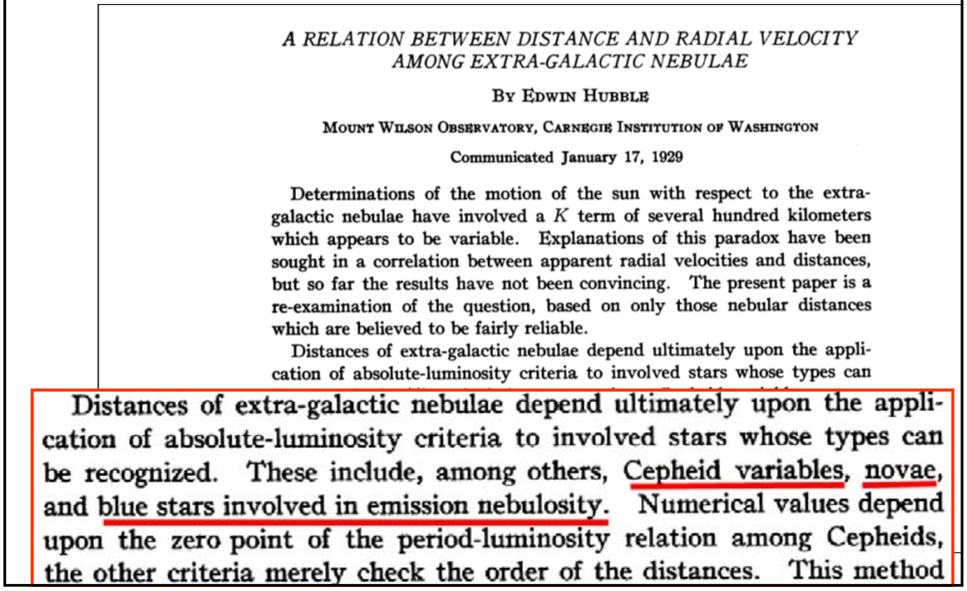
Now

doppler demo
applet

Redshift ➔ scale factor R(t) at time light was emitted.

Hubble's Distance Measurements

From *The Astrophysical Journal*, 1929:



A RELATION BETWEEN DISTANCE AND RADIAL VELOCITY
AMONG EXTRA-GALACTIC NEBULAE

By Edwin Hubble

Mount Wilson Observatory, Carnegie Institution of Washington

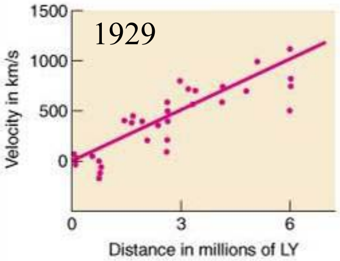
Communicated January 17, 1929

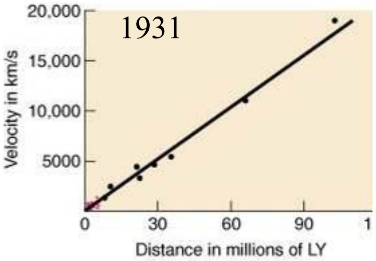
Determinations of the motion of the sun with respect to the extra-galactic nebulae have involved a *K* term of several hundred kilometers which appears to be variable. Explanations of this paradox have been sought in a correlation between apparent radial velocities and distances, but so far the results have not been convincing. The present paper is a re-examination of the question, based on only those nebular distances which are believed to be fairly reliable.

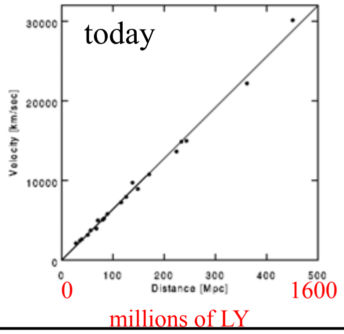
Distances of extra-galactic nebulae depend ultimately upon the application of absolute-luminosity criteria to involved stars whose types can

Distances of extra-galactic nebulae depend ultimately upon the application of absolute-luminosity criteria to involved stars whose types can be recognized. These include, among others, Cepheid variables, novae, and blue stars involved in emission nebulosity. Numerical values depend upon the zero point of the period-luminosity relation among Cepheids, the other criteria merely check the order of the distances. This method

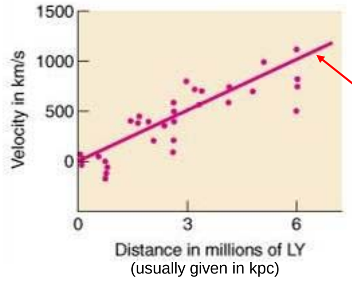
Hubble's Law







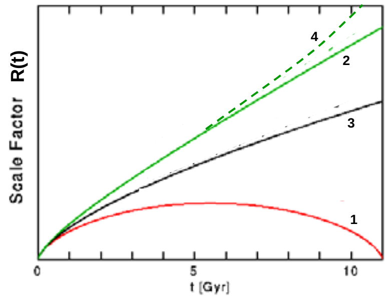
Velocity vs. Distance

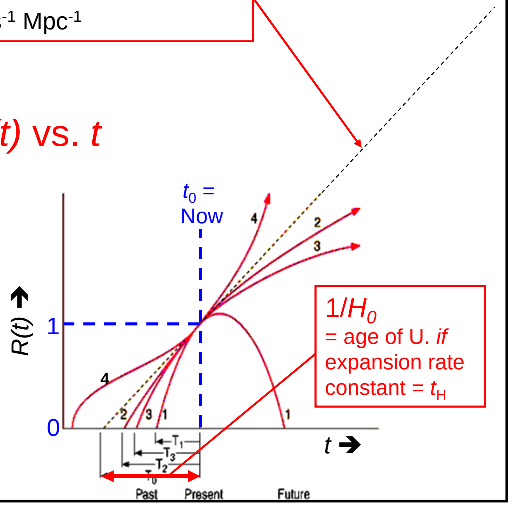


Slope = H_0
(Hubble constant at time t_0)

km s^{-1} Mpc^{-1}

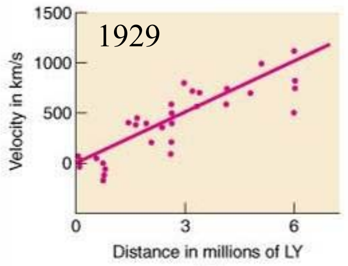
$R(t)$ vs. t

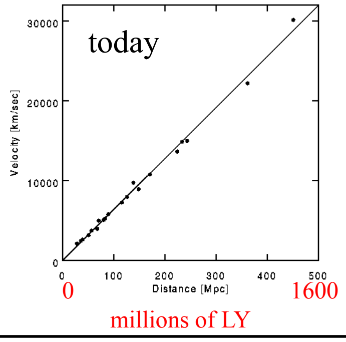




$1/H_0$
= age of U. *if* expansion rate constant = t_H

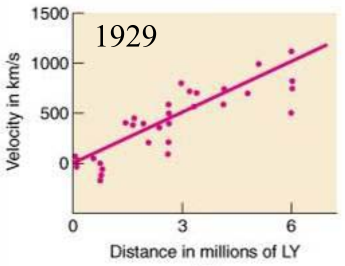
Large Distances Needed

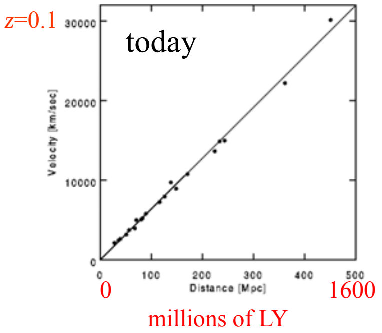




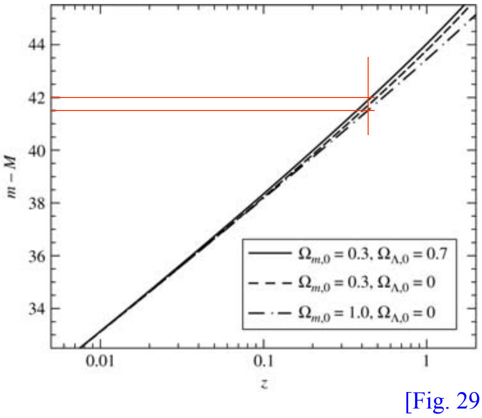
- Hubble flow: $v = H_o d$
  - Peculiar velocities are superimposed on this.

Large Distances Needed



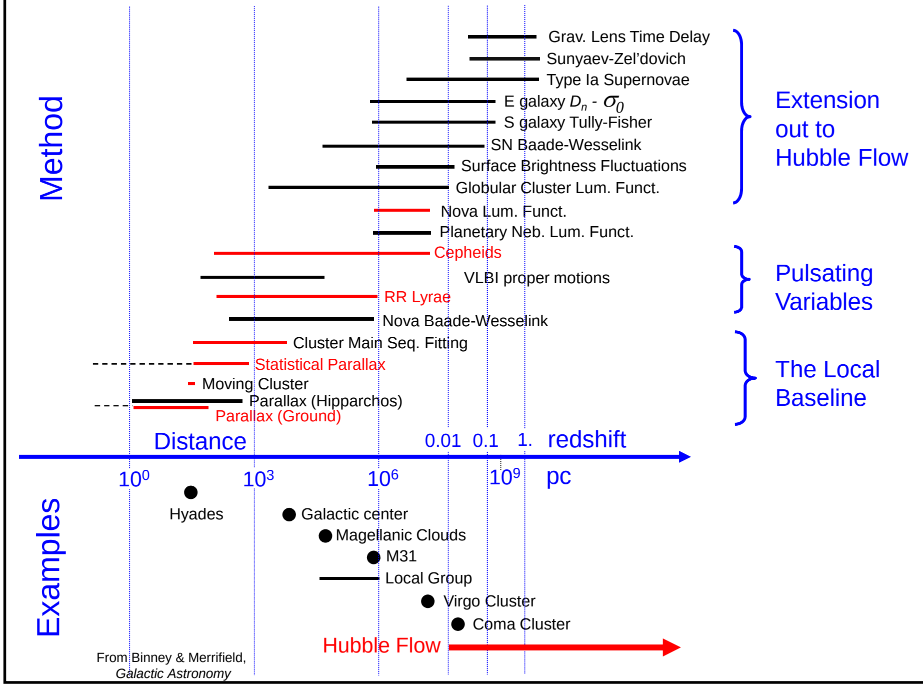


- To distinguish between cosmological models
  - In the example, 0.5 mag accuracy ~ 50% accuracy.



[Fig. 29.26]

The Cosmic Distance Ladder



Method

Grav. Lens Time Delay
Sunyaev-Zel'dovich
Type Ia Supernovae
E galaxy D_n - σ_0
S galaxy Tully-Fisher
SN Baade-Wesselink
Surface Brightness Fluctuations
Globular Cluster Lum. Funct.
Nova Lum. Funct.
Planetary Neb. Lum. Funct.
Cepheids
VLBI proper motions
RR Lyrae
Nova Baade-Wesselink
Cluster Main Seq. Fitting
Statistical Parallax
Moving Cluster
Parallax (Hipparchos)
Parallax (Ground)

Extension out to Hubble Flow

Pulsating Variables

The Local Baseline

Distance
0.01 0.1 1. redshift
10^0 10^3 10^6 10^9 pc

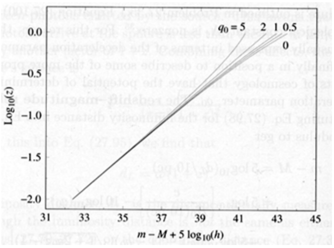
Examples

Hyades
Galactic center
Magellanic Clouds
M31
Local Group
Virgo Cluster
Coma Cluster
Hubble Flow

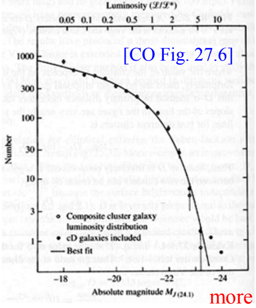
From Binney & Merrifield, *Galactic Astronomy*

Former approach for reaching large distances:
Calibrate Brightest Cluster Galaxies

- To get out to large distances ➔ want most luminous possible objects.

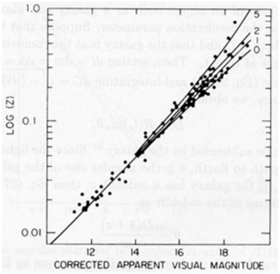


Schecter Luminosity Function



[CO Fig. 27.6]

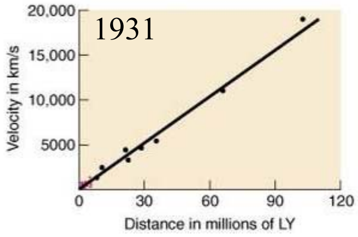
more luminous

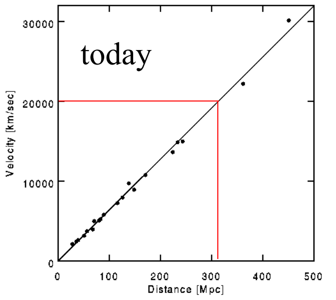


But large distances ➔ large lookback time ➔ evolution effects.

Disaster!

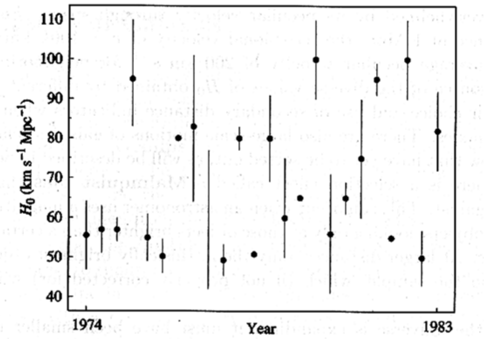
Hubble's Law





0 990 1600

millions of LY



Little *h*

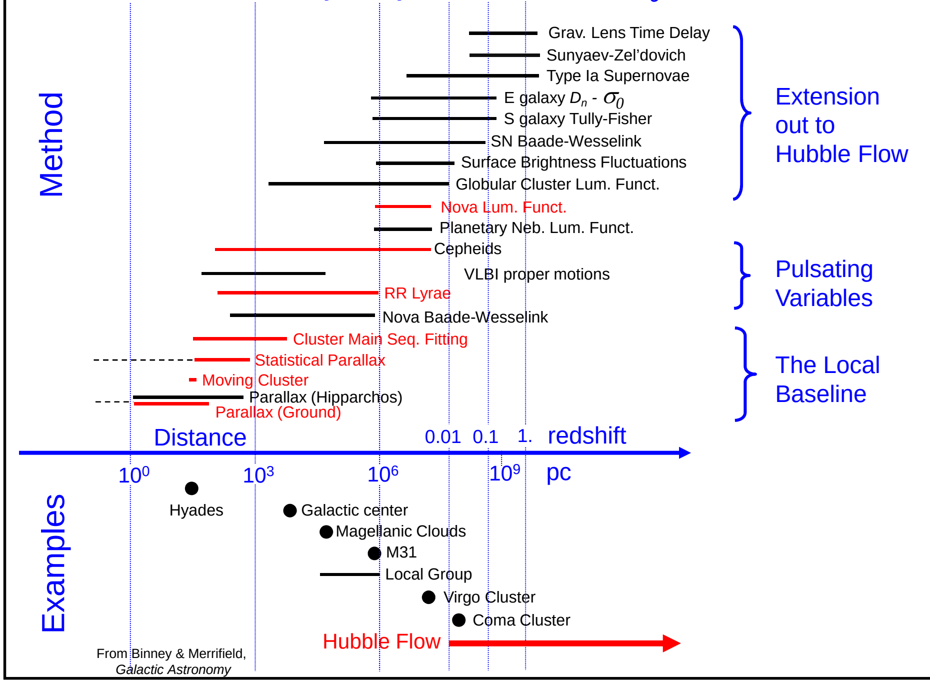
- The Hubble Un-constant (blush)

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

- Hubble time

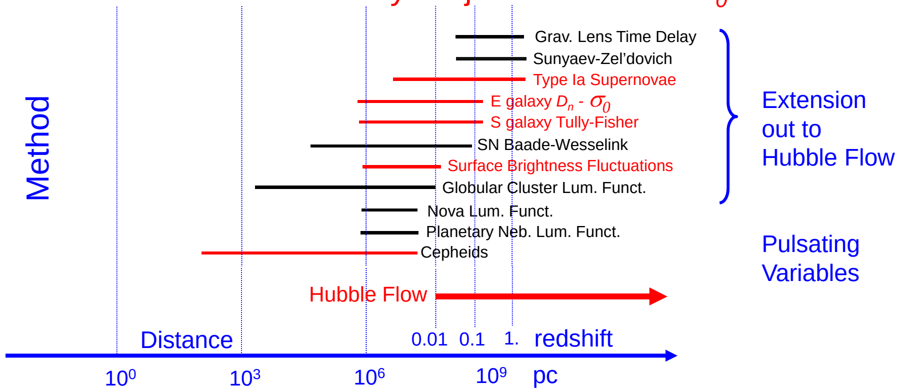
$t_H = 1/H_o = 9.78 \times 10^9\ h^{-1}$ yr.

The HST Key Project to Measure H_0



From Binney & Merrifield, *Galactic Astronomy*

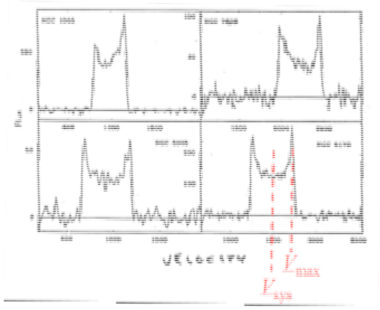
The HST Key Project to Measure H_0

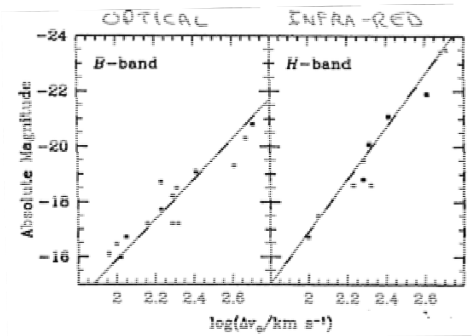


- Mould et al. 2000, ApJ 529, 786
- Measured Cepheids in 18 spirals
  - D < 25 Mpc,   v < 1800 km/s
  - also used 7 more galaxies from other sources
- Distances to Cepheids relative to LMC distance
- Used these to calibrate secondary distance indicators
  - Tully-Fisher
  - Fundamental plane
  - Surface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

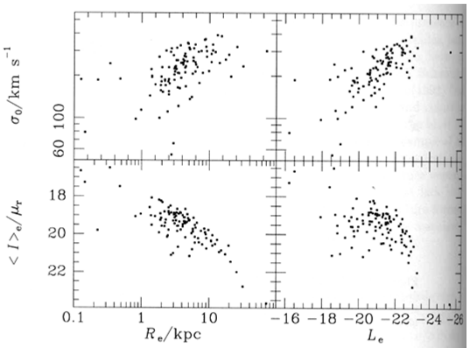
- Observations show that linear size (in kpc) corresponding to D_n is tightly correlated with σ_0

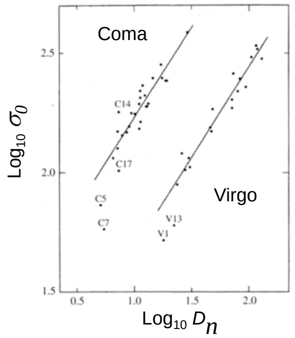
- D_n - σ_0 relation combines radius, surface brightness and internal velocity dispersion σ_0

  ➔ *The Fundamental Plane strikes again!*

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

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

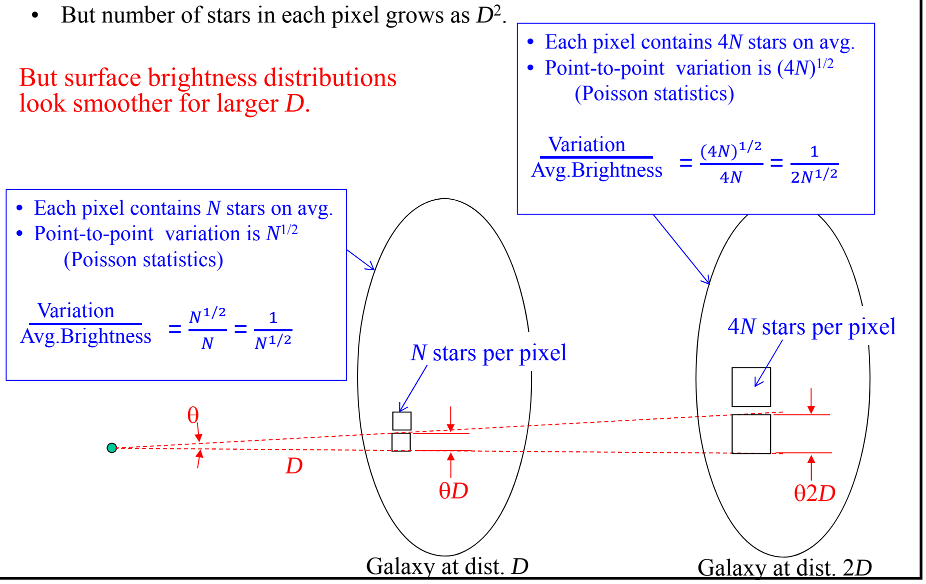




[CO Fig. 27.5]

Surface brightness fluctuations

- Same galaxy seen at any distance will have same surface brightness.
  - Flux from each star drops as $1/D^2$
  - But number of stars in each pixel grows as D^2.
- But surface brightness distributions look smoother for larger D.



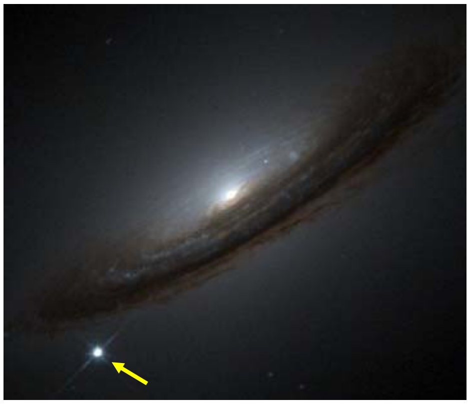
- Each pixel contains N stars on avg.
- Point-to-point variation is $N^{1/2}$ (Poisson statistics)

$$\frac{\text{Variation}}{\text{Avg.Brightness}} = \frac{N^{1/2}}{N} = \frac{1}{N^{1/2}}$$

- Each pixel contains $4N$ stars on avg.
- Point-to-point variation is $(4N)^{1/2}$ (Poisson statistics)

$$\frac{\text{Variation}}{\text{Avg.Brightness}} = \frac{(4N)^{1/2}}{4N} = \frac{1}{2N^{1/2}}$$

Type Ia Supernovae



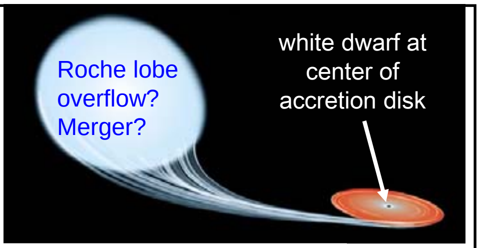
Core collapse supernovae

- 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

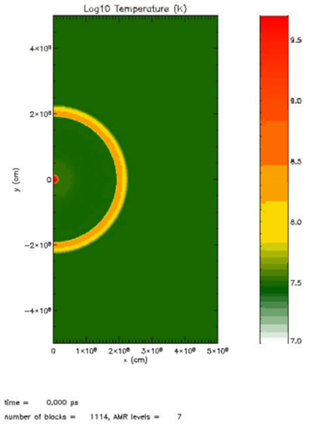


- Something dumps too much mass onto white dwarf.
- Increased density ➔ runaway heating through C + C burning
- Heating rate faster than dynamical timescale
  - White dwarf cannot peacefully respond to pressure increase.
- *Deflagration*
  - leading to *detonation*?

Type Ia Supernovae as "standard candles".

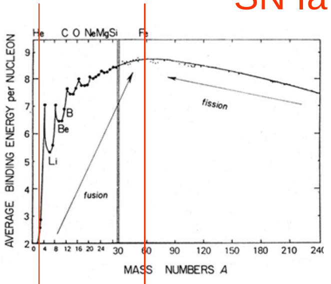
- Always happens when mass goes just past limit for heating-cooling balance.

  ➔ 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

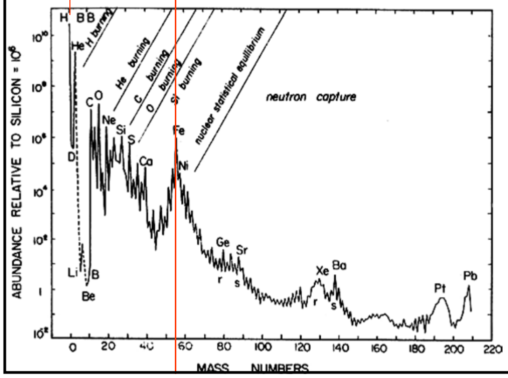


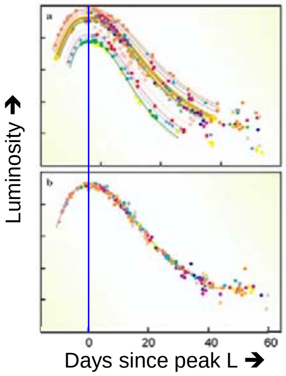
Light output powered by radioactive decay:

$^{56}\text{Ni} \rightarrow {}^{56}\text{Co} \rightarrow {}^{56}\text{Fe}$

Amount of Ni determines both luminosity *and* opacity.

- So luminosity and fading timescale are correlated.

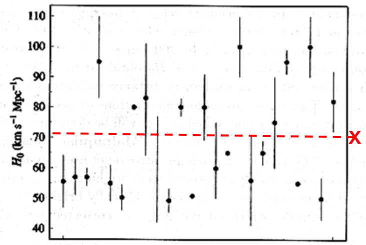




Observed range in L and fading timescale.

After correcting for *L - timescale* correlation.

The HST Key Project to Measure H_0



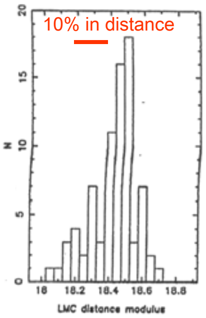
- Measured Distances to Cepheids.
  - relative to LMC distance.
- Used these to calibrate secondary distance indicators in same galaxies.

	value	random	systematic
Tully-Fisher	71	± 4	± 4
D_n - σ_0	78	8	10
Surface Brightness Fluct.	69	4	6
Type Ia SNe	68	2	2

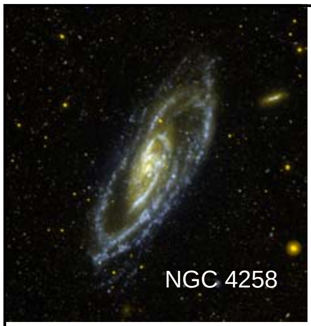
Average: H_0 = 71 ± 6 km/s/Mpc

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

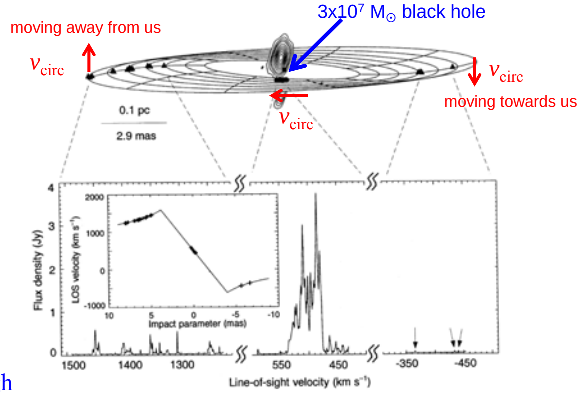
    Taken to be 50 kpc ± 6.5%



Distribution of published LMC distance moduli



Megamaser Galaxies



- Radio telescope observes H_2O emission line.
- Maser (stimulated emission) when there is long path through gas at same radial velocity (as seen by us).

  ➔ Intense brightening of beam.
- Radio VLBI measurements of maser proper motion $d\theta/dt$ and v_r

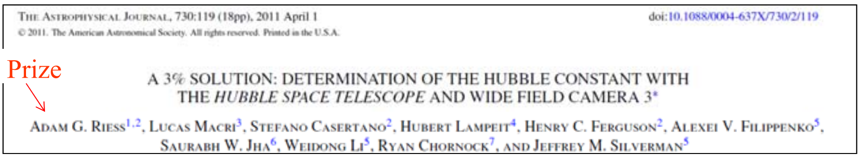
- Keplerian rotation around BH.
- Proper motion of maser knot

  $= d\theta/dt = v_{circ} / D$

D = 7.2 Mpc

Latest Result: $H_0 = 73.8 \pm 2.6$ km s^{-1} Mpc^{-1}

Nobel Prize ↘



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A 3% SOLUTION: DETERMINATION OF THE HUBBLE CONSTANT WITH
THE *HUBBLE SPACE TELESCOPE* AND WIDE FIELD CAMERA 3*

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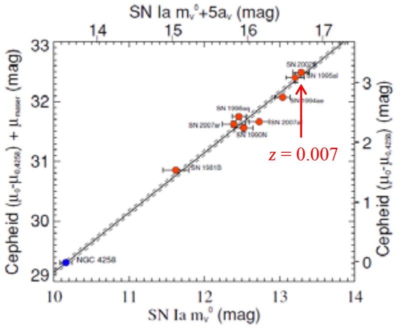
- Recalibrated Cepheid P-L relation in 3 ways:
    - Distance to Megamaser galaxy NGC4258.
    - Better parallaxes to MW Cepheids.
    - Improved distance to LMC.

- Calibrated luminosities of 8 "nearby" SN Ia using Cepheids in same galaxies.

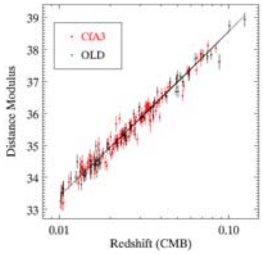
- Determined H_0 from Hubble diagram for existing sample of 253 SN Ia with redshift $z \leq 0.1$



5 log (D) →

$z = 0.007$

constant - 2.5 log(F) →



5 log [D/($L^{1/2}$)] →

Distance modulus:

(m-M) = 5 log(D/10 pc)

$L / F \propto D^2$

[CO pg. 62]