The Hubble Diagram

Hubble used the Cepheid P-L relation to determine distances to local group galaxies. Then using his "tuning fork" galaxy classification system and assuming that certain type galaxies had a "fixed" absolute magnitude (which he "calibrated" from local group galaxies for which he had determined the distances), he determined the distance modulus (hence distance) to galaxies in nearby galaxy clusters. When he plotted these distances verses the radial velocities of these galaxies there was a obvious linear correlation between these parameters.

v = HD Hubble relation

Note: In determining the distances to the so called "spiral nebulae", Hubble helped establish the very existence of other "galaxies".

$$z = \frac{\Delta\lambda}{\lambda_0} = \frac{\lambda - \lambda_0}{\lambda_0}$$

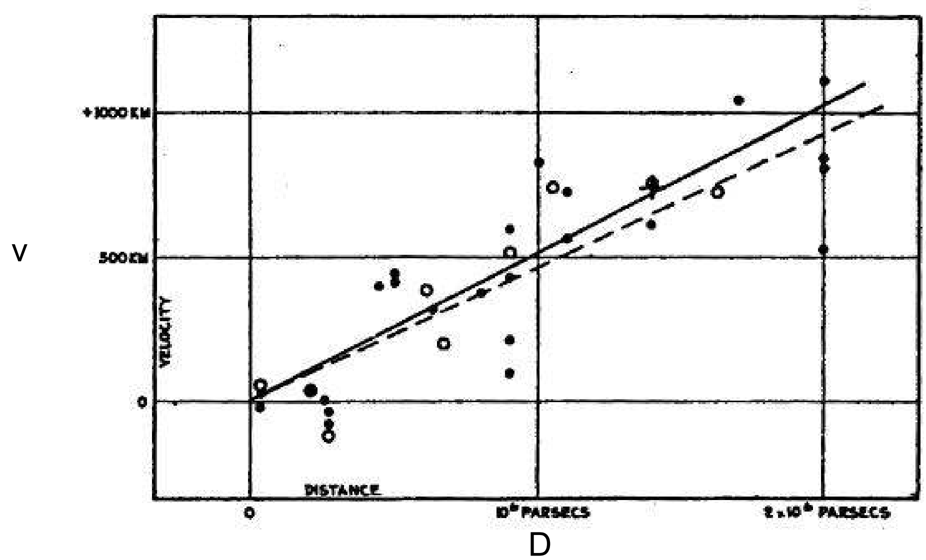
$$\frac{V_r}{c} = \frac{\Delta\lambda}{\lambda_0} \quad \text{or} \quad V_r = cz$$

See separate demo for Doppler effect.

v = HD   H = Hubble's constant

D = distance in Mpc

v = radial velocity of galaxy



Hubble's original Hubble Diagram. Note that the galaxies with the maximum distance are at 2 Mpc. The value of the Hubble Constant was around 500 km/s/Mpc, much larger than current estimates. The main reason for the discrepancy was that Hubble's Cepheid calibration was incorrect for the Cepheids which he observed. The discrepancy was resolved in the early 1950's when it was discovered that there are two types of Cepheid variables, metal rich & metal poor.

For Hubble, this was the ultimate distance measuring technique, once H was determined:

$$D = v/H$$

The Hubble Relation, Interpreted

Einstein used his General Theory of Relativity (still our best description of gravity) to come up with a solution for the dynamics and structure of the Universe (a cosmological model of the Universe). His solutions were all "dynamic", the Universe was either expanding or contracting. But cosmological models of the time held that the Universe was static and unchanging, so Einstein modified his solution with a "repulsive" term called the "cosmological constant". This term could be valued in a way to make his models static.

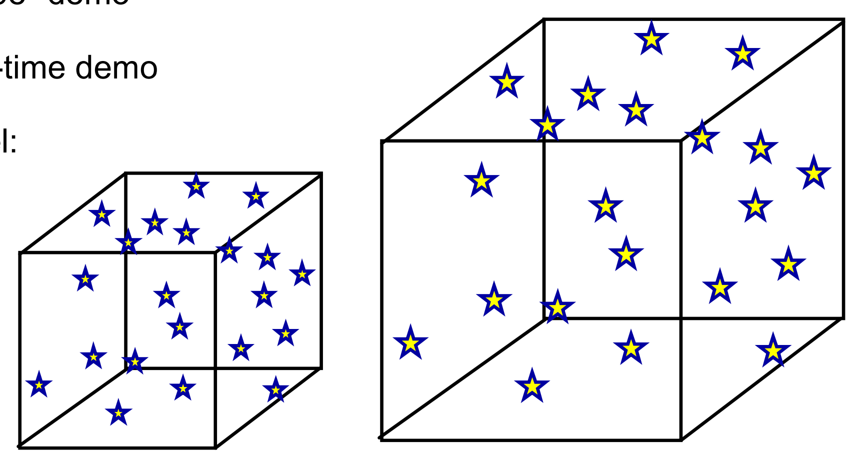
Once Hubble discovered his relation between radial velocity and distance, it was quickly realized that the best interpretation of the Hubble relation was that of an expanding Universe. Einstein realized his cosmological constant was not necessary and he considered its addition to his original solutions one of the worst blunders in his career.

In an expanding Universe, all observers see the Hubble relation and no one has to be in a "special" reference frame to observe the relation.

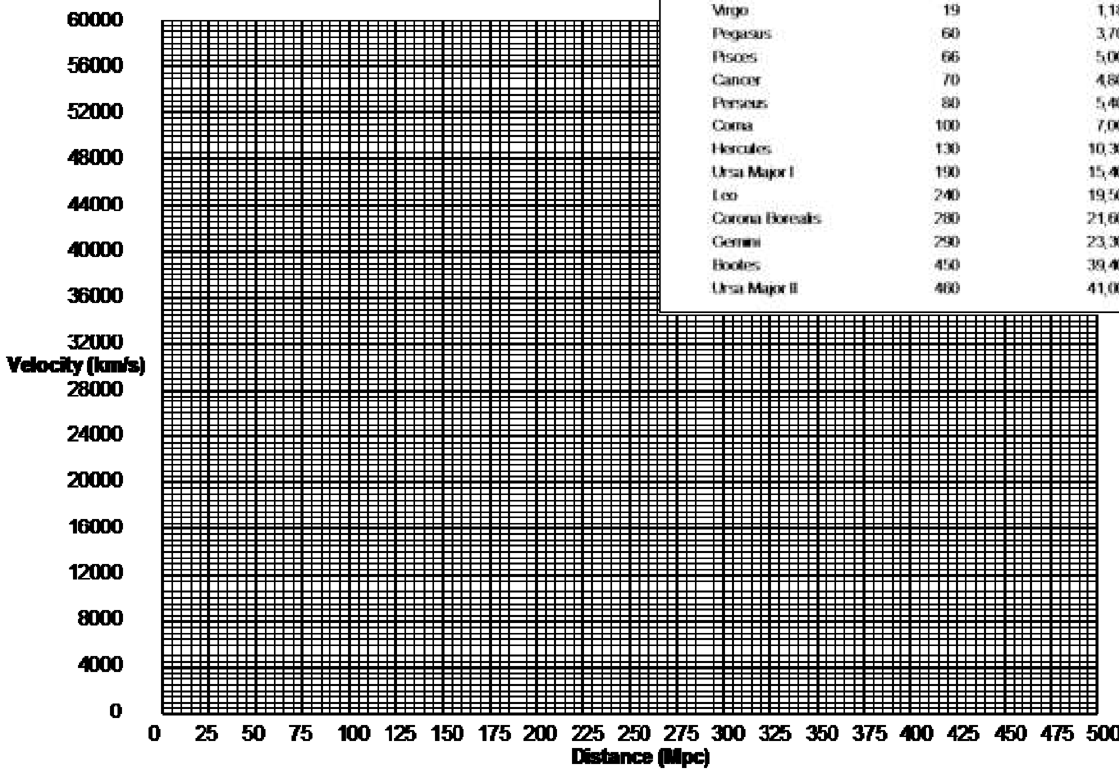
"Galaxies on a rope" demo

3-D closed space-time demo

raisin bread model:



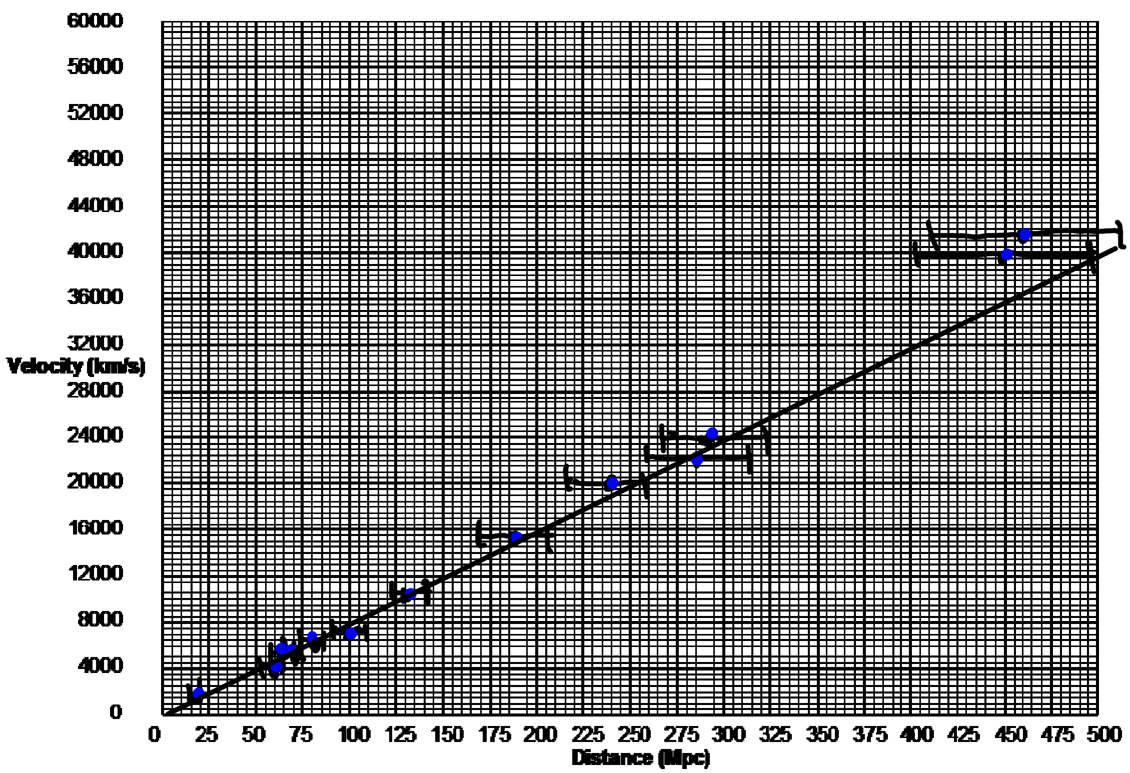
GALAXY CLUSTER	DISTANCE (Mpc)	VELOCITY (km/s)
Virgo	19	1,180
Pegasus	60	3,700
Pisces	66	5,000
Cancer	70	4,800
Perseus	80	5,400
Coma	100	7,000
Hercules	130	10,300
Ursa Major I	190	15,400
Leo	240	19,500
Corona Borealis	280	21,600
Gemini	290	23,300
Bootes	450	39,400
Ursa Major II	460	41,000



To determine Hubble's constant, several distance measuring steps (each of which depended on the closer distance techniques) were used to plot extended Hubble diagrams. From the 50's up through the 70's & 80's, two values immerged as the possible correct value. Let's determine the value of H using the data in the table above. This is an example of data from the 70's which gave a value more consistent with the "long scale" H of around 100 km/s/Mpc.

Next page for plot:

Determine Hubble's constant from the diagram:

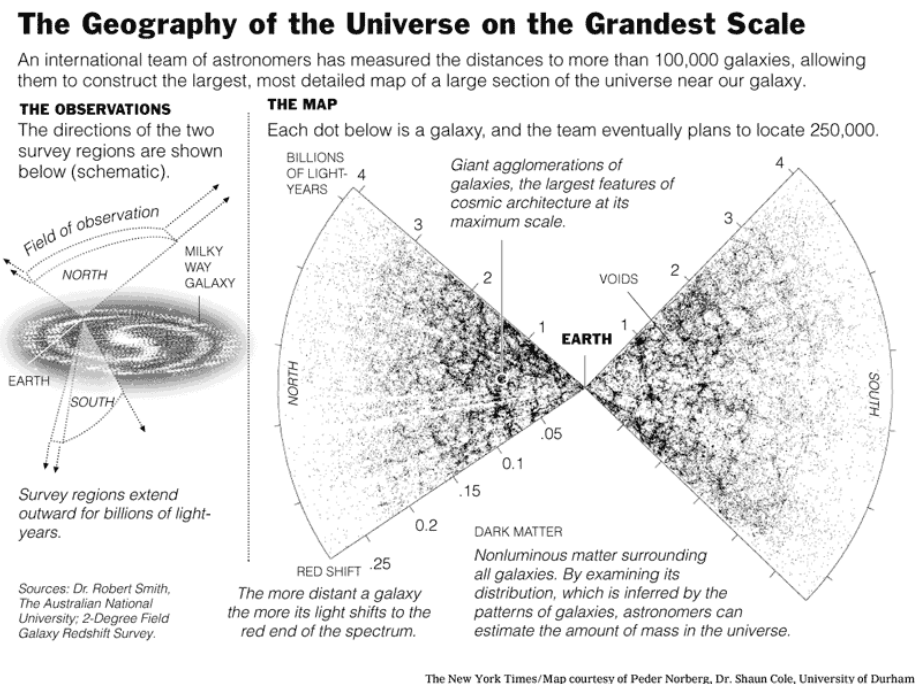


Determine H by measuring the slope of the best-fit line.

v = HD

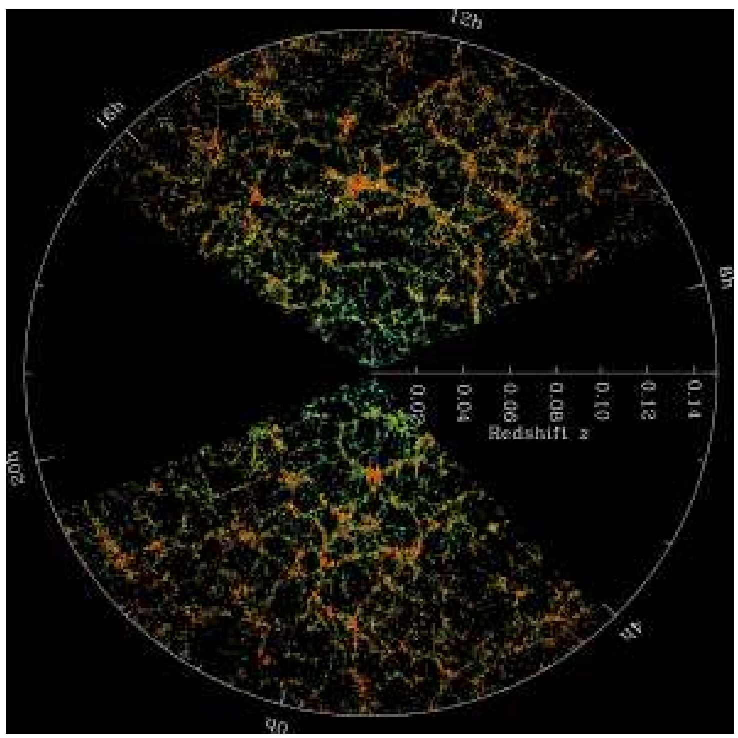
Note, once H is measured it is possible to use the Hubble relation to determine distances to far galaxies by merely measuring their redshift (recessional velocity).

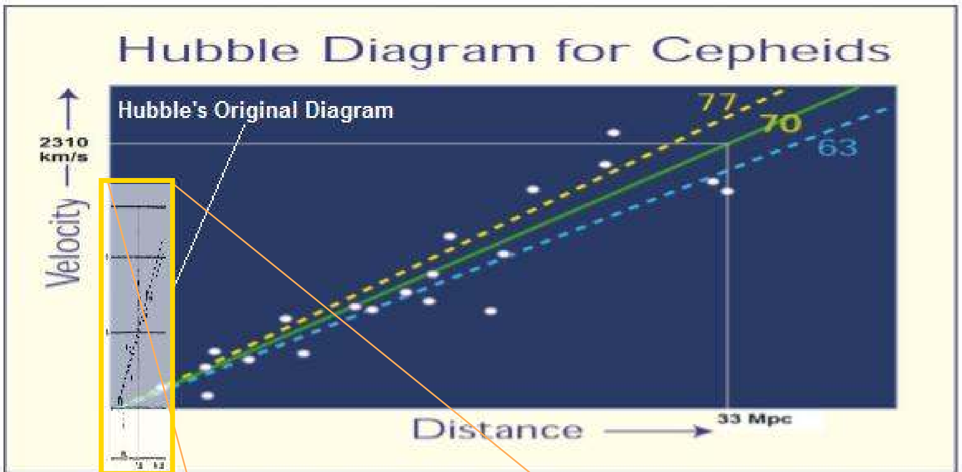
D = v/H

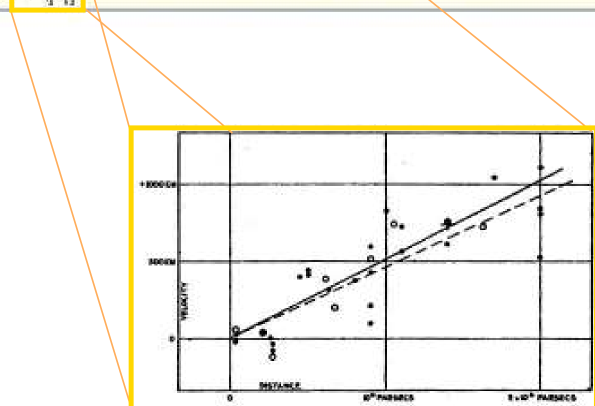


Sloan Digital Sky Survey

The Sloan Digital Sky Survey (SDSS) is one of the most ambitious and influential surveys in the history of astronomy. Over eight years of operations (SDSS-I, 2000-2005; SDSS-II, 2005-2008), it obtained deep, multi-color images covering more than a quarter of the sky and created 3-dimensional maps containing more than 930,000 galaxies and more than 120,000 quasars.



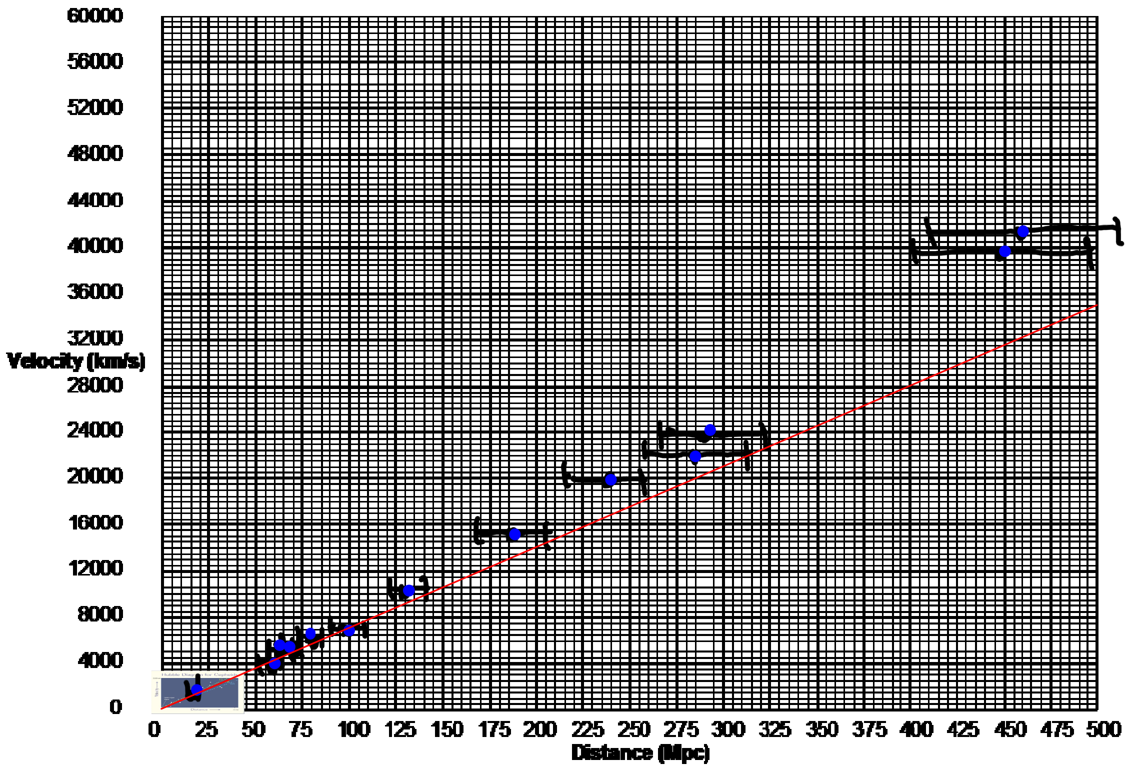




Hubble constant from HST:

70 km/s/Mpc +/- 4 km/s/Mpc

One of the most important missions of the Hubble Space Telescope was to resolve the "long" and "short" cosmic distance scales by accurately measuring the Hubble constant. Hey, why do you think they named the telescope the "Hubble"?



70 km/s/Mpc = red line

Note the HST Hubble diagram in the lower left corner.

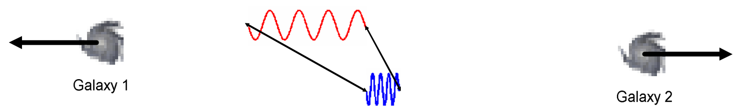
Note that some of the "recessional velocities" are approaching a good fraction of the speed of light. c = 300,000 km/s

Why don't astrophysicists use the relativistic expression for the radial velocities? See next panel and separate demo.

Doppler redshift verses cosmological redshift:

case A: Universe not expanding, galaxies stationary to one another

case B: Universe expanding, galaxies separating due to expanding Universe



case C: Universe not expanding, galaxies stationary to one another

See separate Doppler verses cosmological redshift SMART notebook demo.

Solving the Friedmann-Robertson-Walker (FRW) metric results in 2 coupled differential equations for 3 unknown functions. Given an equation of state and suitable boundary conditions, they can be solved.

1 $$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi}{3}G\rho - \frac{kc^2}{R^2}$$

$\frac{\dot{R}}{R} \equiv H(t) \equiv$ Hubble parameter (time dependent)

$k \equiv$ curvature parameter

$k=+1$ closed

$k=0$ flat

$k=-1$ open

$R(t)$ "scale factor" radius

$\rho(t)$ mass-energy density (written as a "mass density") ie: replace an energy density with ρ/c^2

$P(t)$ pressure

2 $$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3c^2}(\rho c^2 + 3P)$$

3 $$\dot{\rho}c^2 = -3\frac{\dot{R}}{R}(\rho c^2 + P)$$

"energy conservation equation" obtained from a combination of the 2 Friedmann eqns.

$\ell \equiv$ proper distance ("luminosity distance")

$$\ell = R(t)\int_0^r \frac{dr}{\sqrt{1-kr^2}} = \begin{cases} R\sin^{-1}r & k=+1 \\ Rr & k=0 \\ R\sinh^{-1}r & k=-1 \end{cases}$$

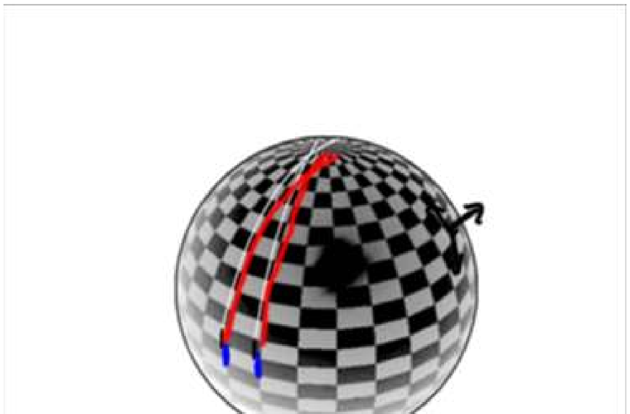


Figure 1. a.

Closed

k = +1

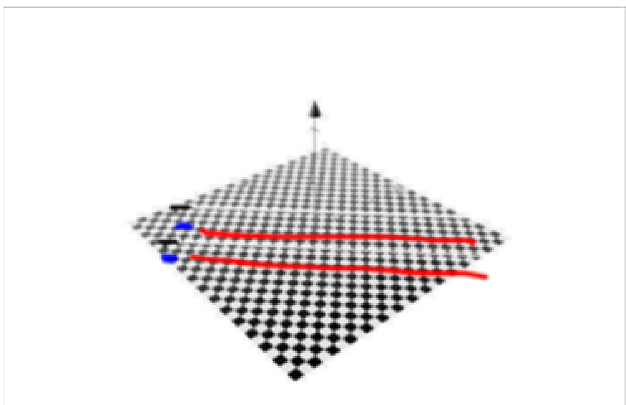


Figure 1. b.

Flat

k = 0

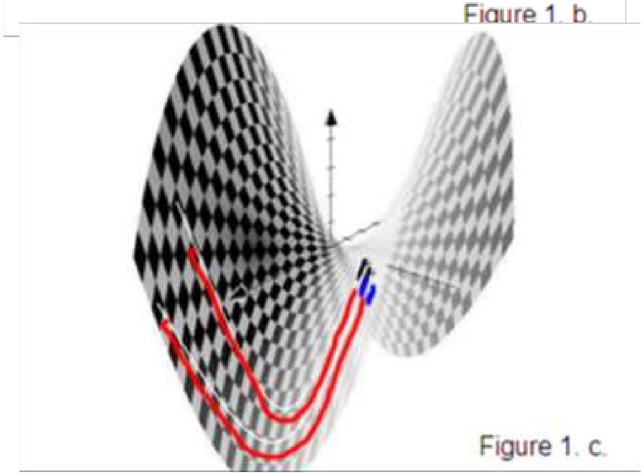


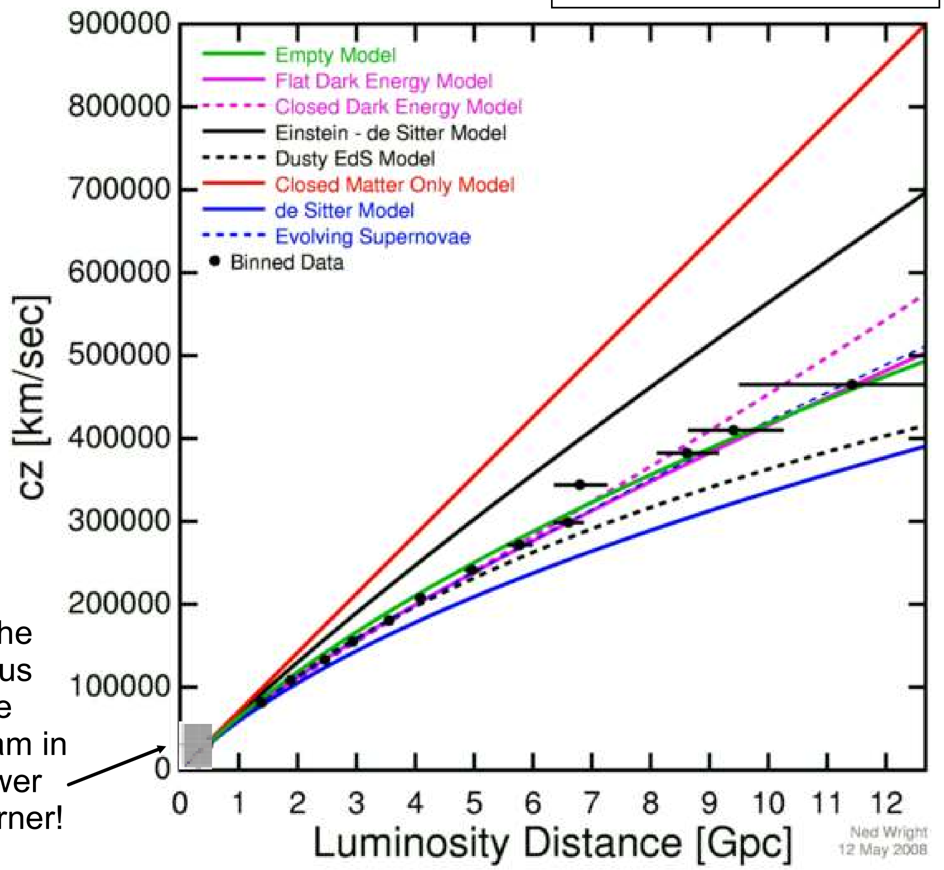
Figure 1. c.

Open

k = -1

Hubble Diagram on "steroids":

Even when Einstein was wrong, he was right!



Note the previous Hubble Diagram in the lower left corner!

Flat Dark Energy Model = non-zero cosmological constant and an accelerating Universe!!

This diagram uses the SN Ia distance measuring technique to extend distance to the edge of the observable Universe! Note the Hubble relation is no longer linear. Different cosmological models can be distinguished between each other depending on the distance accuracy. See the link for an on-line tutorial about this work: http://www.astro.ucla.edu/~wright/sne_cosmology.html