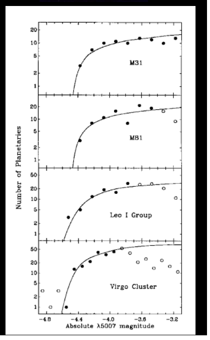
Planetary Nebula

Planetary Nebula Luminosity Function is Universal (Jacoby & Ciardullo)



Advantages:

•Reasonable Physical Understanding

•Works all galaxy types

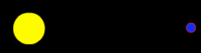
•Precise (0.15 mag)

Disadvantages:

•Only to cz<2000 km/s

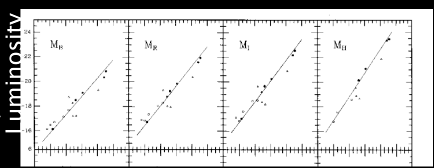
•Moderately observationally expensive

Sun Earth (10 billion years)



Tully-Fisher

Velocity of Galaxy Rotation and Luminosity correlated.



Advantages:

•Observationally inexpensive at low z

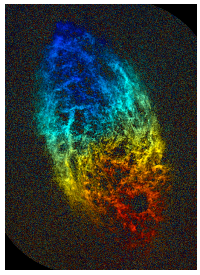
•Useful nearby (M31) and to z~0.1

Disadvantages:

•Moderately Poor Physical Understanding

•Moderately poor precision (0.35 mag)

Tully-Fisher Prescription: Optical Light to measure
Flux and inclination. Radio to measure rotation.
Correct Rotation for inclination (sin i), Apply relation

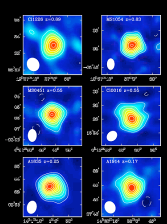


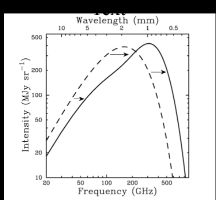
Sunyaev-Zeldovich

Photons scatter off of Hot electrons in clusters.

$$\int \Delta T_{SZ} d\Omega \propto \frac{N_e \langle T_e \rangle}{D_A^2}$$

X-Ray emission proportional to N_e^2. Model X-ray emission - (spherical Isothermal sphere), eliminate N_e, measure T, and solve for distance.





Advantages:

•Physical method

•Works to z>1

•Can be done to large numbers of objects

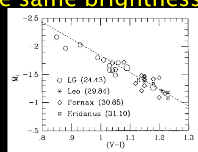
Disadvantages:

•Substructure

•Asphericity makes imprecise

Surface Brightness

Poisson fluctuation of stars cause lumpiness inversely proportional to distance. Assumes stars causing fluctuations are same brightness (Horizontal Branch stars)



Advantages:

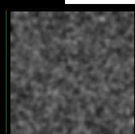
•Precise (0.13 mag)

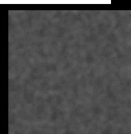
•Can be done to many galaxies

Disadvantages:

•Only to cz<8000 km/s

•Sensitive to Colour (metallicity) and Dust





Supernova Taxonomy

Core Collapse

- **II-P** normal 10-30 Solar Mass Star
- **II-L** massive star with extended envelope?
- **IIn** massive star with dense CSM?
- **IIb** massive star with thin H envelope
- **Ib** massive star with He envelope
- **Ic** massive star without H or He envelope

Thermonuclear Detonations

- **Ia** white dwarf explosion.

The Expanding Photosphere Method

SN II-P Radiate as modified Blackbodies

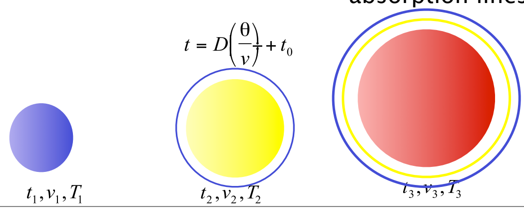
$$\theta_{ph} = \frac{R_{ph}}{D} = \sqrt{\frac{f_\nu}{\zeta^2 \pi B_\nu(T)}}$$

They freely expand

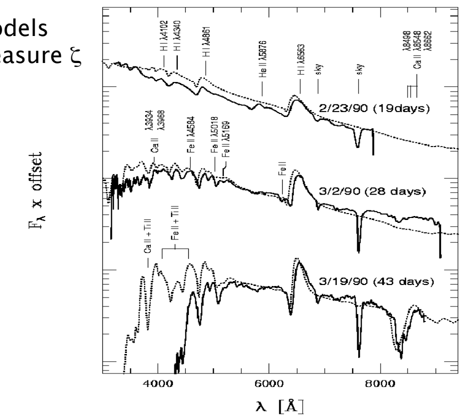
$$R_{ph} = v_{ph}(t - t_0) + R_0$$

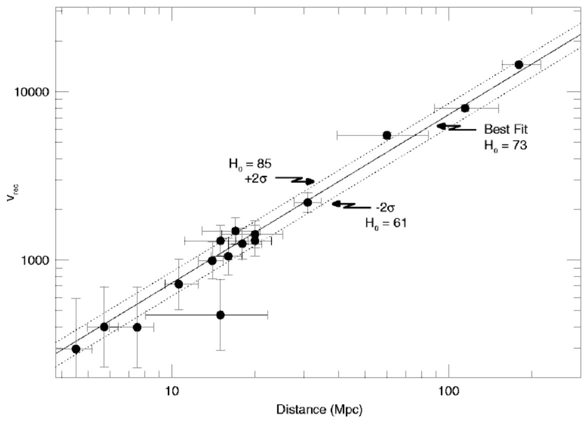
(v measured from absorption lines)

$$t = D\left(\frac{\theta}{v}\right) + t_0$$

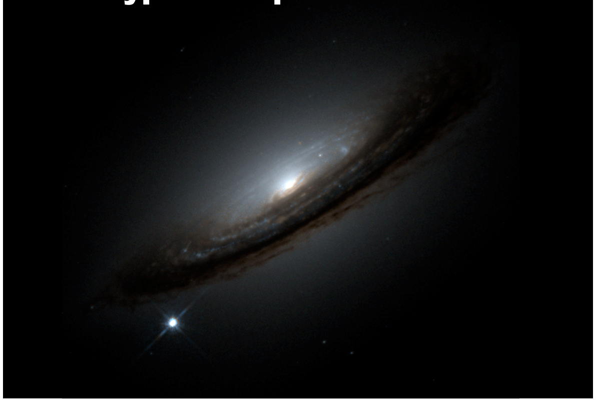


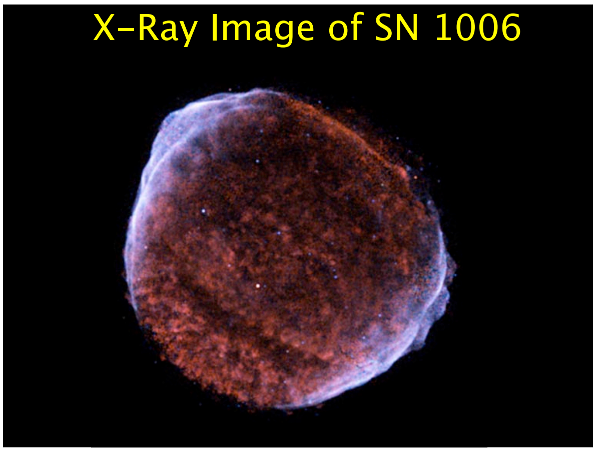
Models
Measure ζ

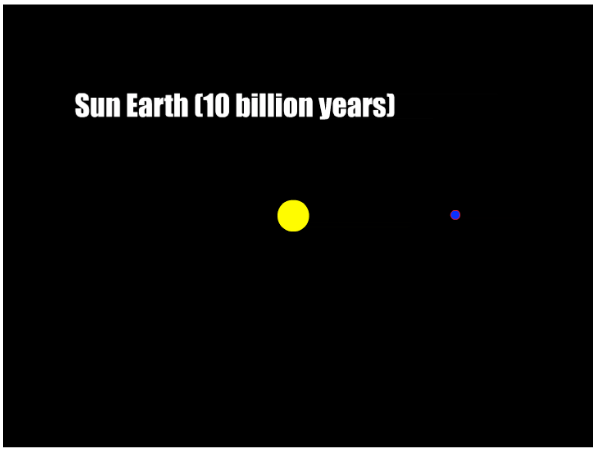


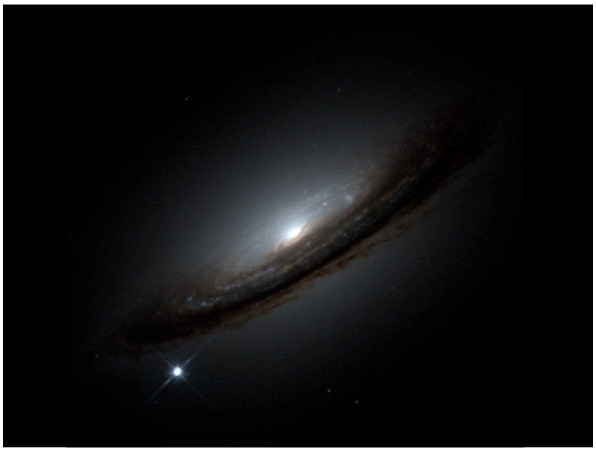


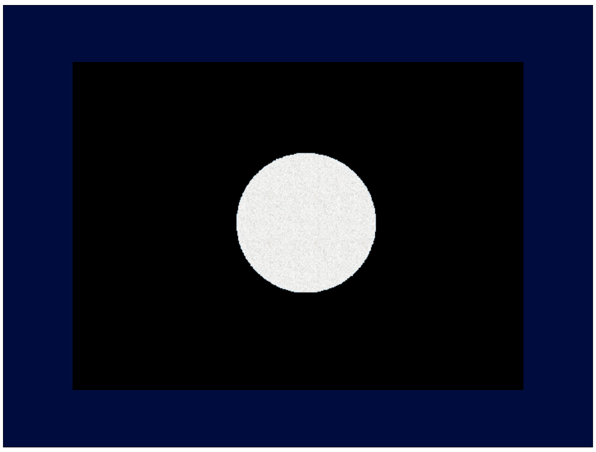
Type Ia Supernovae

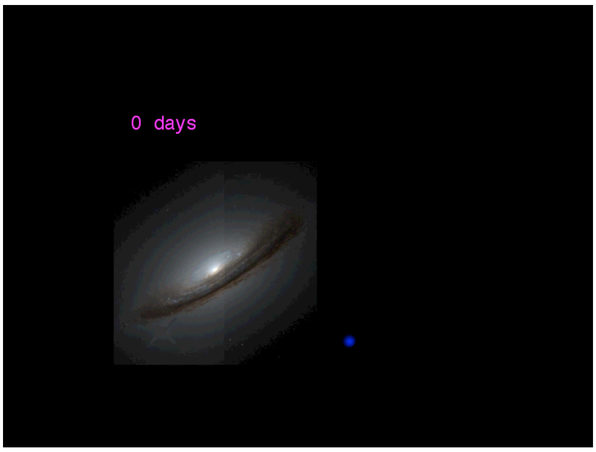



X-Ray Image of SN 1006

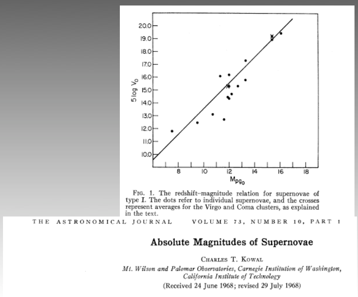

Sun Earth (10 billion years)



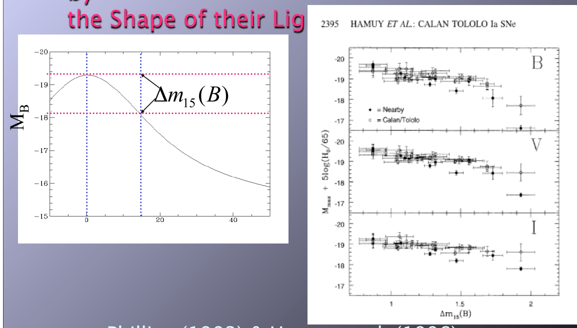



0 days

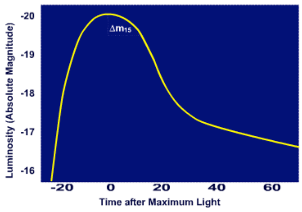
Type Ia SN as Standard Candles

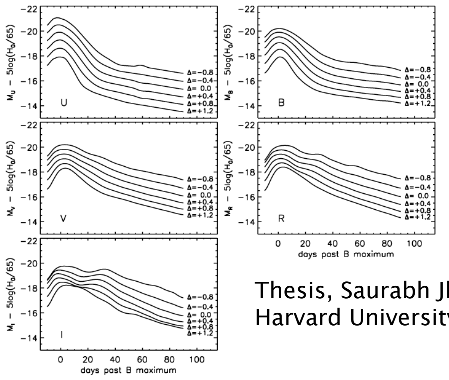


A Most Useful Way of Parameterizing SNe Ia is by the Shape of their Lig

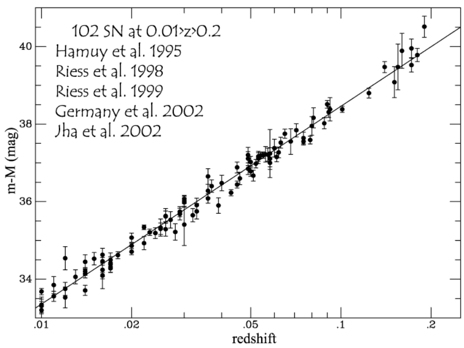


Phillips (1993) & Hamuy et al. (1996)

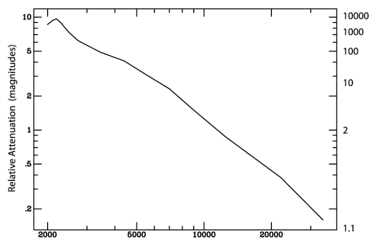




Thesis, Saurabh Jha, Harvard University



Reddening from Dust



Wavelength (Angstroms)

What Causes the Diversity?

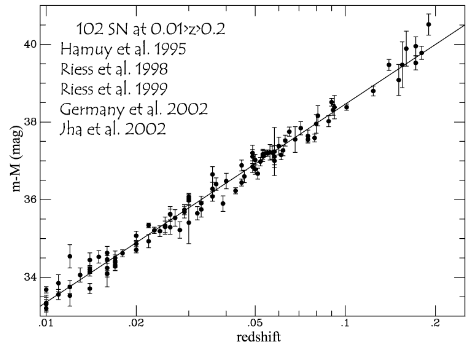
a. Progenitors have different mass.

b. Progenitors have different age or metallicity.

c. Explosion has different mechanism.

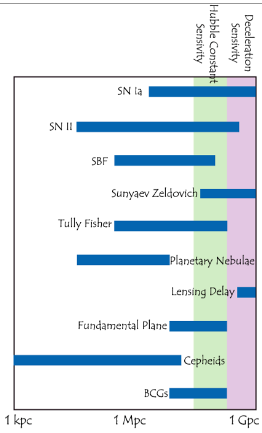
d. all of the above.

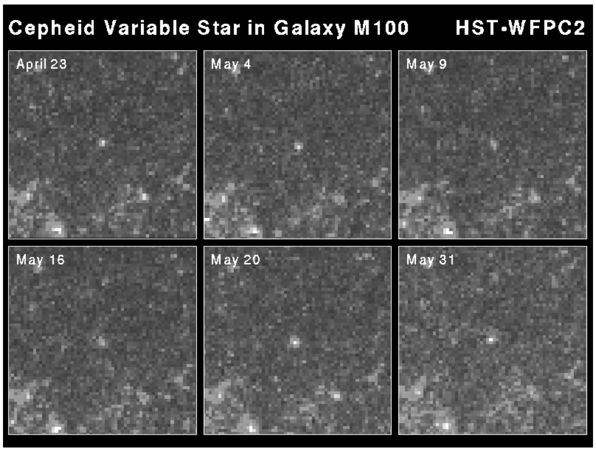
e. none of the above.

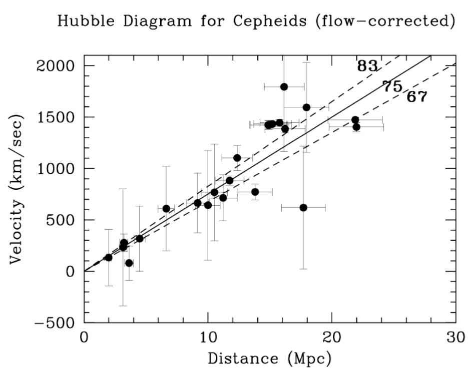


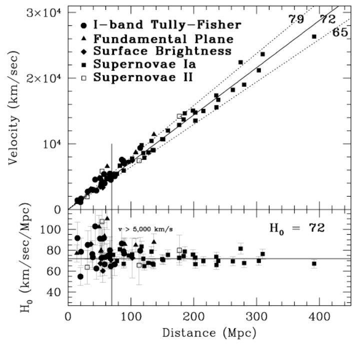
Distance Method Score Card

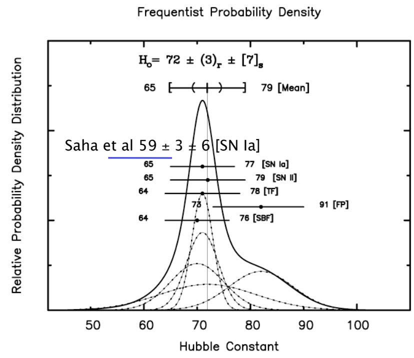
	Precision (mag)	range low Mpc	range hi Mpc	Physical Basis	Comment
BCGs	0.3	15	500	poor	evolution prohibits cosmological use
Cepheids	0.1	0.001	30	moderately good	Cornerstone of Distance Scale
Fundamental Plane	0.4	15	500	moderately poor	evolution prohibits use beyond z>0.1
Lensing Delay	0.3??	1000	3000	good	Very few examples.
Planetary Nebulae	0.15	0.05	15	moderately good	Difficult to increase current sample
Tully-Fisher	0.35	0.5	500	moderately poor	potential cosmological tool
Sunyaev Zeldovich	0.3??	100	3000	good	Potential Powerful Cosmological tool
SBF	0.13	0.5	250	moderately good	Good local tool
SN II	0.25	0.05	1000	good	Expensive, but interesting Cosmological Tool
SN Ia	0.18	4	3000	moderate	Useful Cosmological Probe

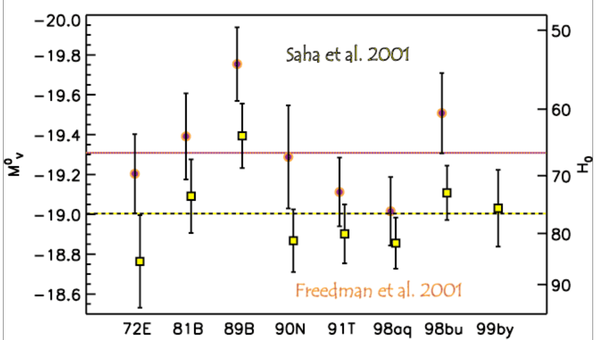




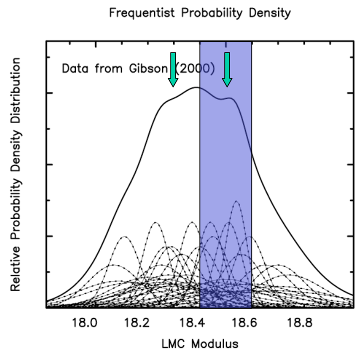








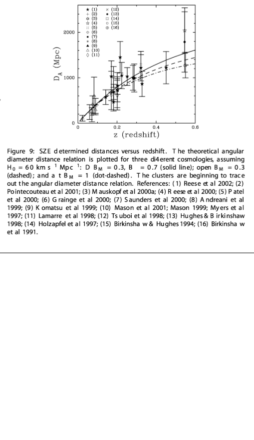
Jha, thesis 2002, Harvard Univ.

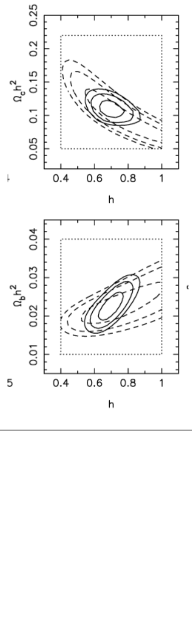


Lensing! Koopmans and Fassnacht (1999)

H^{GL}_0=74+/-8 km s^{-1} Mpc^{-1} for Ω_m=0.3 and Ω_Λ=-0.7.
B0218+357, Q0957+561, B1608+656, and PKS 1830-211 including PG 1115+080, get 68+/-13 km s^{-1} Mpc^{-1}, respectively.
Unfortunately, a more recent analysis (Kochanek and Schechter 2003) gets H_0=48+/-3

S-Z: 38 clusters
Calstrom et al. find
60 ± 3 ± 18 km s^{-1} Mpc^{-1}
For lambda Cosmology



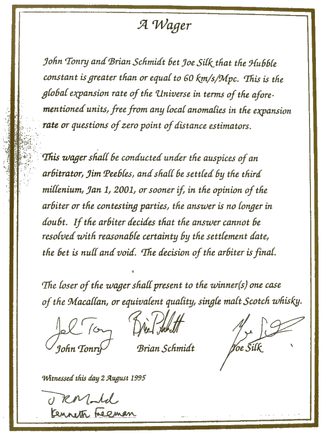


2dF Redshift Survey
+ WMAP (CMB)

72 ± 4 km/s/Mpc

Spergel et al. 2003

Assumes Universe is Flat and Made up of normal matter + Cosmological Constant.



A Wager

John Tonry and Brian Schmidt bet Joe Silk that the Hubble constant is greater than or equal to 60 km/s/Mpc. This is the global expansion rate of the Universe in terms of the aforementioned units, free from any local anomalies in the expansion rate or questions of zero point of distance estimators.

This wager shall be conducted under the auspices of an arbitrator, Jim Peebles, and shall be settled by the third millenium, Jan 1, 2001, or sooner if, in the opinion of the arbiter or the contesting parties, the answer is no longer in doubt. If the arbiter decides that the answer cannot be resolved with reasonable certainty by the settlement date, the bet is null and void. The decision of the arbiter is final.

The loser of the wager shall present to the winner(s) one case of the Macallan, or equivalent quality, single malt Scotch whisky.

John Tonry   Brian Schmidt   Joe Silk

Witnessed this day 2 August 1995

Kenneth Freeman

In Synthesis: Evidence is that H_0=70 km/s/Mpc

Given uncertainties in the
- •Cepheid Distance Scale
- •Distance to LMC

But concordance with the physical distances
- •Lensing
- •S-Z
- •SN II
- •2df+CMB

A good bet that 60 < H_0 < 80 km/s/Mpc, but don't Expect to win any money…