Methods for Measuring Extra-Galactic Distances

- Brightest Cluster Galaxies
- Cepheids
- Fundamental Plane (D_n-σ/Faber Jackson)
- Lensing Delay
- Planetary Nebulae
- Tully-Fisher
- Sunyaev-Zeldovich
- Surface Brightness Fluctuations
- Supernovae Ia
- Supernovae II

Fit Supernova Data with best Shape in many Colors....

Allows you To measure Dust...
Reddening from Dust

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 Comparison

<table>
<thead>
<tr>
<th>Distance Class</th>
<th>Hubble Constant</th>
<th>Redshift Range</th>
<th>Physical Basis</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCGs</td>
<td>0.75</td>
<td>0.05 - 0.2</td>
<td>500, poor</td>
<td>evolution prohibits cosmological use</td>
</tr>
<tr>
<td>DSS</td>
<td>0.75</td>
<td>0.05 - 0.2</td>
<td>500, moderately good</td>
<td>Cornerstone of Distance Scale</td>
</tr>
<tr>
<td>Fundamental Plane</td>
<td>0.75</td>
<td>0.05 - 0.2</td>
<td>500, moderately poor</td>
<td>Evolution prohibits use beyond z=0.1</td>
</tr>
<tr>
<td>Cepheid</td>
<td>0.75</td>
<td>0.05 - 0.2</td>
<td>500, good</td>
<td>Very few examples</td>
</tr>
<tr>
<td>Planetary Nebula</td>
<td>0.75</td>
<td>0.05 - 0.2</td>
<td>1000, good</td>
<td>Difficult to increase current sample</td>
</tr>
<tr>
<td>JMF</td>
<td>0.75</td>
<td>0.05 - 0.2</td>
<td>250, good</td>
<td>Good local tool</td>
</tr>
<tr>
<td>SN II</td>
<td>0.75</td>
<td>0.05 - 0.2</td>
<td>1000 good</td>
<td>Expensive, but interesting Cosmological Tool</td>
</tr>
<tr>
<td>SN Ia</td>
<td>0.75</td>
<td>0.05 - 0.2</td>
<td>3000, moderate</td>
<td>Useful Cosmological Probe</td>
</tr>
</tbody>
</table>
Freedman et al 2001

Frequentist Probability Density

\[ H_0 = 72 \pm 3 \pm [7] \]

Saha et al 59 \pm 3 \pm 5 [SN Ia]

Freedman et al 2001
Eclipsing Binaries (Fitzpatrick et al.)

Frequentist Probability Density

Data from Gibson (2000)

Freedman et al. 2001
Lensing! Koopmans and Fassnacht (1999)
Assuming an isothermal sphere
$H_{0}^{GL}=74+/\kappa 8 \text{ km s}^{-1} \text{ Mpc}^{-1}$ for $\Omega_{m}=0.3$ and $\Omega_{\Lambda}=-0.7$.
B0218+357, Q0957+561, B1608+656, and PKS 1830-211
including PG 1115+080, get 68+/\kappa 13 \text{ km s}^{-1} \text{ Mpc}^{-1}$, respectively.
Unfortunately, a more recent analysis (Kochanek and Schechter 2003)
gets $H_{0}=48+/\kappa 3$
$S-Z$: 38 clusters
Calstron et al. find
$60 \pm 3 \pm 18 \text{ km s}^{-1} \text{ Mpc}^{-1}$
For lambda Cosmology

Figure 8: S2E determined distances versus redshift. The theoretical angular
diameter distance relation is plotted for three different cosmologies: assuming
$H_{0}=60 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_{m}=0.3$, $\Omega_{\Lambda}=0.7$ (solid line), open $\Omega_{m}=0.3$
(dashed), and $\Omega_{m}=1$ (dotted line). The clusters are beginning to break out
the angular diameter distance relation. References: (1) Reas et al. 2002; (2)
Pettit et al. 2003; (3) Brandenburg et al. 2000; (4) Yee et al. 2000; (5) P and
Bennert et al. 2000; (6) C. et al. 1999; (7) A. et al. 1999; (8) A. et al. 1996; (9)

2dF Redshift Survey
+ WMAP (CMB)
$72 \pm 4 \text{ km/s/Mpc}$
Spergel et al. 2003
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…

High-Z SN Ia History
Zwicky’s SN Search from 1930s-1960s giving Kowal’s Hubble Diagram in 1968

Ib/Ic SN Contamination realised in 1984/5

1st distant SN discovered in 1988 by a Danish team ($z = 0.3$)

7 SNe discovered in 1994 by Perlmutter et al. at $z = 0.4$

Calan/Tololo Survey of 29 Nearby SNe Ia completed in 1994
Potential Pitfalls to High-Z SNe Ia Distances

- **Extinction**
  - Are the Extinction Properties of High-Z and low-Z SNe the same?

- **Evolution**
  - Are the SNe Seen today the same as the SNe of yesterday?

- **Selection Effects?**
  - Are the corrections larger than the measurement?

- **K-corrections**
  - How accurately can we transform to the restframe?

- **Gravitational Lensing**
  - Does Weak Lensing significantly bias the measurement?
**SNe Ia Evolve**

Hamuy et al. (1996)

**Comparing Hubble Type with SN Luminosity Provides a Check on Evolution and Extinction**

But can still imagine situations where the SN at high-Z have no nearby analogues.

*long fuses*

*short fuses*