The cosmic distance scale

- Distance is crucial to understand the physics of an object:
  - size and evolution
  - location (effect of environment)
  - cosmology
  - ….

- Distances are derived through:

  - Absolute distance estimators

    Objects for whose distance can be measured directly. They have physical properties which allow such a measurement.

  - Relative distance estimators

    They rely on directly measured distances. Generally these are types of objects that share the same intrinsic luminosity.

- Stars or objects which have the same intrinsic luminosity are known as standard candles.

If the distance to a standard candle has been measured directly, then a relative distance can be derived from

$$\log(D_1/D_2) = 1/5 * [(m_1 - m_2) - (A_1 - A_2)]$$

- $D_{1,2}$ is the distance to the objects
- $m_{1,2}$ the apparent magnitudes of stars
- $A_{1,2}$ corrects for the absorption towards the sources

In such cases, the distance scale derived from this standard candle has been "anchored" to an absolute distance indicator

Plan of the day

- Distance determination for nearby objects
- (Few) Examples of absolute distance estimators
- (Many more) Examples of relative distance estimators
- Important steps in the distance ladder
- Cosmology

Distances in the Solar Neighborhood

- Trigonometric parallax:

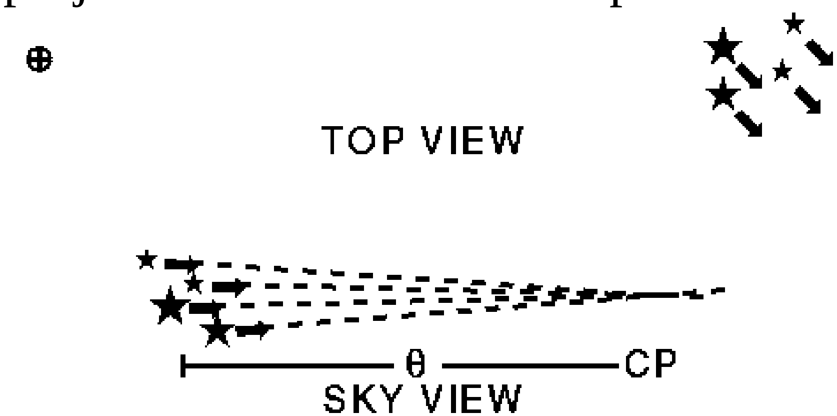
Angular displacement in the position of a star on the celestial sphere as the Earth moves around the Sun: Π [arcsec] = 1/d[pc].

  – Currently restricted to nearby stars, within roughly 200 pc (relative distance error ~ 20%)
  – Revolution to come with GAIA

- Moving cluster method:

The motions of stars in an open cluster when projected onto the celestial sphere are oriented towards a convergence point.

The location of this point combined with proper motions and radial velocities provides the distance to the cluster.



Absolute distance estimators

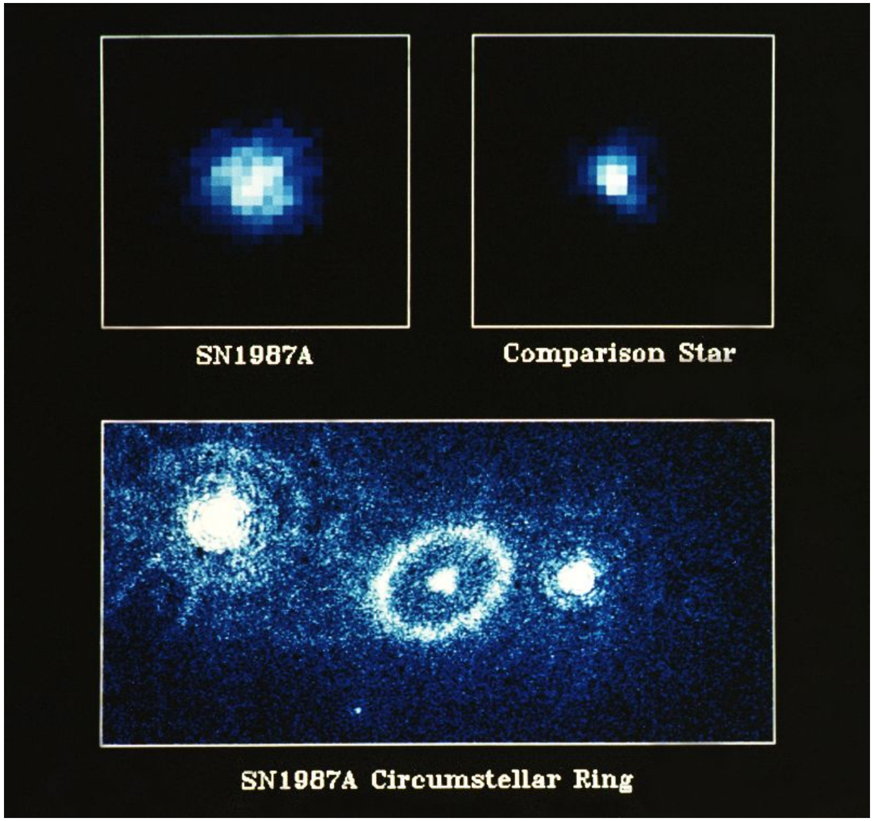
- Baade-Wesselink method
  - The luminosity of a star is given by $L = 4 \pi R^2 \sigma T^4_{eff}$
    If a measurement of R is possible, and T_{eff} and apparent magnitudem are known, then
    $\log D = 0.2 (m - M) + 1$, since $M = -2.5 \log L + M_\odot$
- Supernovae expanding photospheres
- Gravitational lensing
  - both these methods use time delays to measure distances
  - If an object changes its brightness in time Δt, D can be measured from the delay in the arrival of the time-varying signal. If the physical dimension of the source is d, then $d \sim c \Delta t$. If the source angular scale is θ, then $\theta = d/D$, and so $D \sim c \Delta t/\theta$
- Sunyaev - Zel'dovic effect

Distances from time delays: SN 1987A

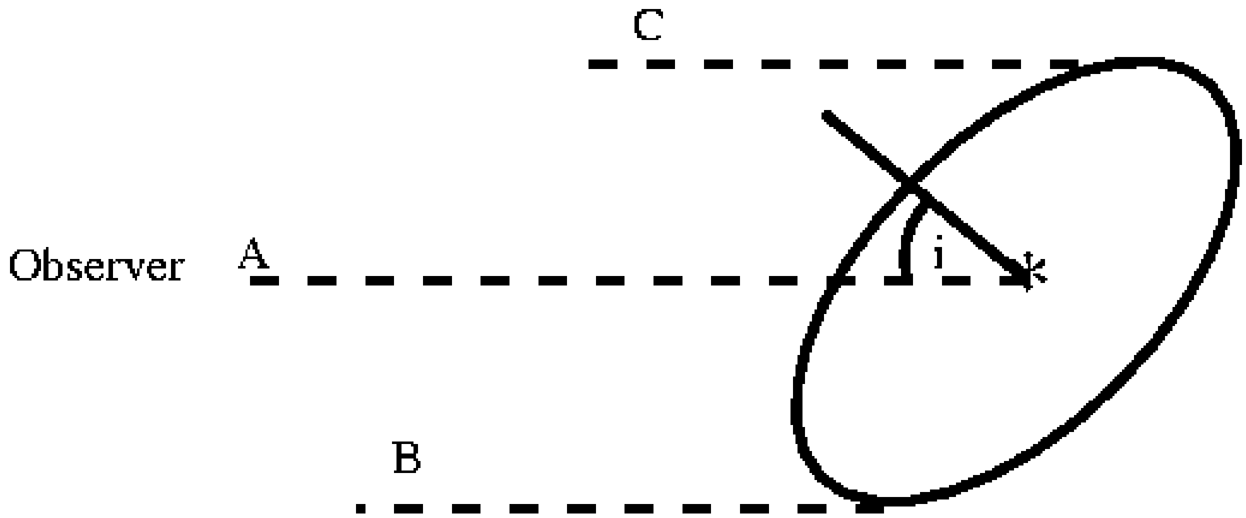
Observations made by the IUE (a UV satellite) showed emission lines from highly ionized atoms in the spectrum of SN1987A in the LMC.

These lines were detected t_0 = 90 days after the initial explosion. Their intensity increased and reached a maximum at t_1= 400 days.

The emission lines come from material that distributed in an inclined ring structure at some distance from the SN.



The delay in the detection of the first emission lines and their maximum intensity can be attributed to different light-paths (from B and C).



$t_o = R_{ring}/c\ (1 – \sin i)$ and $t_1 = R_{ring}/c\ (1 + \sin i)$

Using the values of t_0 and t_1: R_{ring} = 0.42 +/- 0.03 pc and i=42+/- 5 deg.

Since the angular size of the ring is θ = 1.66 +/- 0.03 arcsec, the distance to SN 1987A is 52 +/- 3 kpc

Relative distance indicators

- Luminosities of variable stars: RR Lyrae, cepheids
  - Local Group, nearby groups
- Luminosity functions of globular clusters and planetary nebulae
  - galaxies and nearby clusters
- Novae and supernovae
  - galaxies and cosmological distances
- Kinematics of galaxies: Tully-Fisher and $D_n - \sigma$
  - galaxies, groups of galaxies and clusters

Luminosities of variable stars

- The luminosities of some pulsating variables can be determined accurately from their periods.

- For cepheids: $\langle M_V \rangle \sim -2.78 \log (P/10 \text{ days}) - 4.13$

with a scatter of 0.3 mag.

  - Calibrated for cepheids with known distances (trigonometric parallaxes and the Baade-Wesselink method)

  - Cepheids have absolute magnitudes $M_V \sim -3$, so that they can be observed to large distances (out to the nearest galaxy cluster Virgo)

  - Easy to identify because of their characteristic light curves

- RR Lyrae stars are standard candles; absolute magnitudes $M_V \sim 0.6$.
  - Derived from nearby RR Lyrae (trigonometric parallaxes, and globular clusters main sequence fitting method)
  - RR Lyare are characteristic of metal-poor populations
  - Distances within the Local Group.

Luminosity functions

- Objects that have a spread in intrinsic luminosities cannot be used as standard candles.
- If the luminosity function of these objects is universal, we can compare the distribution of apparent luminosities to derive a relative distance to the systems.

Luminosity function is the number of objects with absolute magnitude in a given range.

- <u>Globular clusters</u>
  - The average luminosity of the globular clusters around the Milky Way, the LMC and M31 seems to be the same.
  - The average luminosity of the globular clusters acts as a standard candle
  - Often used to derive distances to elliptical galaxies.

The globular cluster luminosity function is very similar in all galaxies

$$\phi_{GC} \propto \exp[-(m - \langle m_{GC}\rangle)^2/(2\,\sigma_{GC}^2)]$$

.

•By fitting this functional form to the LF of GC around a given galaxy, we obtain $\langle m_{GC}\rangle$.

•The comparison of this quantity for different galaxies measures their relative distances

•To estimate $\langle m_{GC}\rangle$ reliably, need to reach faint levels so that the turn-over is clearly visible.

• It is tied up to the globular clusters in the Milky Way: only for which <M_{GC}> is accurately known.

•Used to measure distances to the Coma cluster.

LF of globular clusters in four E in Virgo.

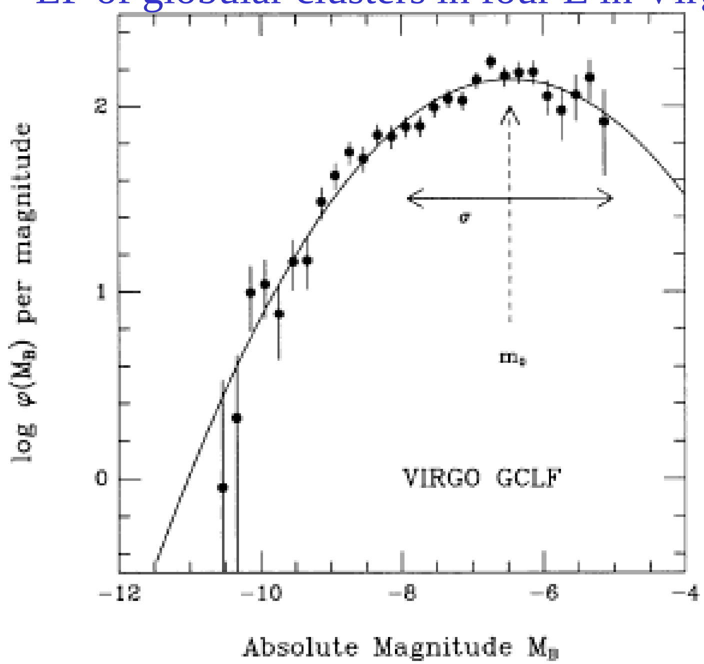


FIG. 7—The luminosity function for the globular clusters in four Virgo ellipticals combined (NGC 4365, 4472, 4486, 4649), from Harris et al. (1991). This composite GCLF was constructed from a total sample of about 2000 clusters brighter than $B=26.2$ (the vertical scale units shown are arbitrary). Here ϕ is the relative number of clusters per unit magnitude interval, plotted against absolute magnitude M_B *assuming* d(Virgo) $\simeq 17$ Mpc. A Gaussian interpolation curve is superimposed, with a "turn-over" or peak indicated by the dashed arrow (m_0), and a standard deviation $\sigma = 1.45$ mag.

Novae

- Novae are very bright, with peak absolute magnitudes of $M_v \sim -7$
- Ideal to probe very large distances

- For novae in our Galaxy distances are directly measured, using the expansion of their shells.
  - If a shell expands with a velocity v_{exp} (doppler shifts in spectral lines), and its angular size is $\delta\theta$, then the distance to the novae is $v_{exp}\, t/\,\delta\theta$.

- Novae are not standard candles
- Show a characteristic rate of decline in brightness

$$M_V(\max) = -10.7 + 2.3 \log(t_2/\text{day})$$

where $M_V(\max)$ is the peak magnitude of the novae, and t_2 is the time to decline in brightness by two magnitudes

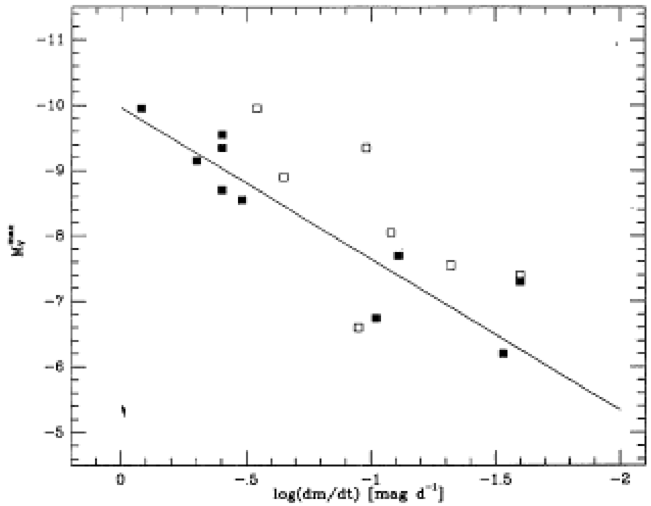


FIG. 9—Maximum magnitude–rate of decline relation for Galactic novae observed by Cohen (1985). Closed symbols represent the novae designated "high quality" by Cohen; the solid line [Eq. (7)] is a least-squares fit to the high-quality data.

Supernovae

•Supernovae type Ia have very similar properties

•They are ideal standard candles because of their extreme intrinsic luminosities, implying that they can be observed to cosmological distances

•Provided the first evidence for a cosmological constant (dark energy)

Distances from galaxy kinematics

Galaxies themselves are not standard candles, since their brightness vary strongly from system to system

They obey certain scaling laws: .

The more massive the galaxy, the larger the average speed of its stars

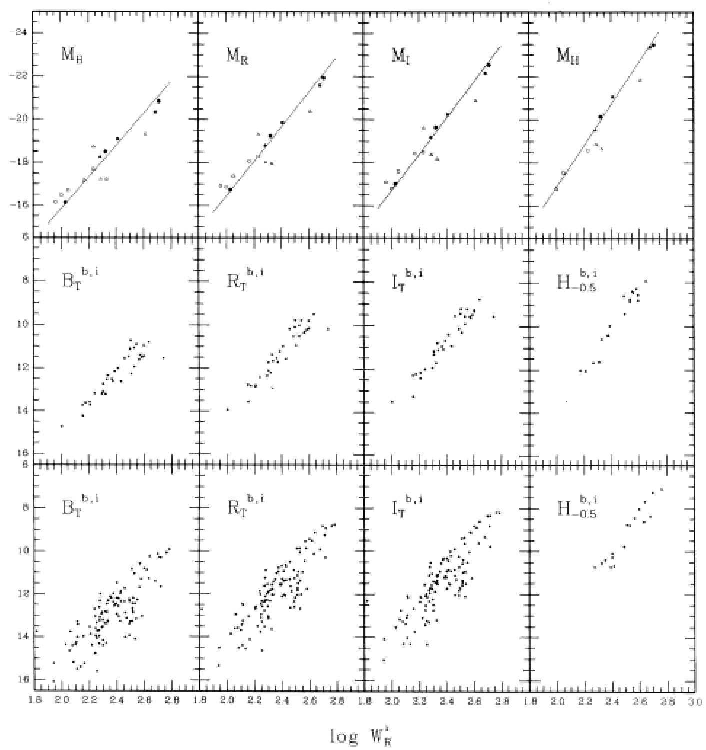


FIG. 11—*B*-, *R*-, *I*-, and *H*-band Tully–Fisher relations for the Local Calibrators (top), Ursa Major cluster members (middle), and Virgo cluster members (bottom). It is apparent from the figures that the slope of the relations increases going to longer wavelengths and the dispersion decreases. The variation in slope is thought to arise from the differing contributions to the observed bandpass made by greater fraction of young stars found in the lower-luminosity systems. The smaller dispersion at longer wavelengths is likely due to a reduction in the sensitivity to these effects, as well as those expected from extinction variations. Note the much larger dispersion found for the Virgo cluster data.

Tully-Fisher relation

The luminosity of a spiral galaxy correlates strongly with its rotational velocity.

The D_n - σ relation

Elliptical galaxies also follow scaling laws which relate their size, velocity dispersion and luminosity (or surface brightness)

To measure distances to elliptical galaxies we use the D_n - σ relation

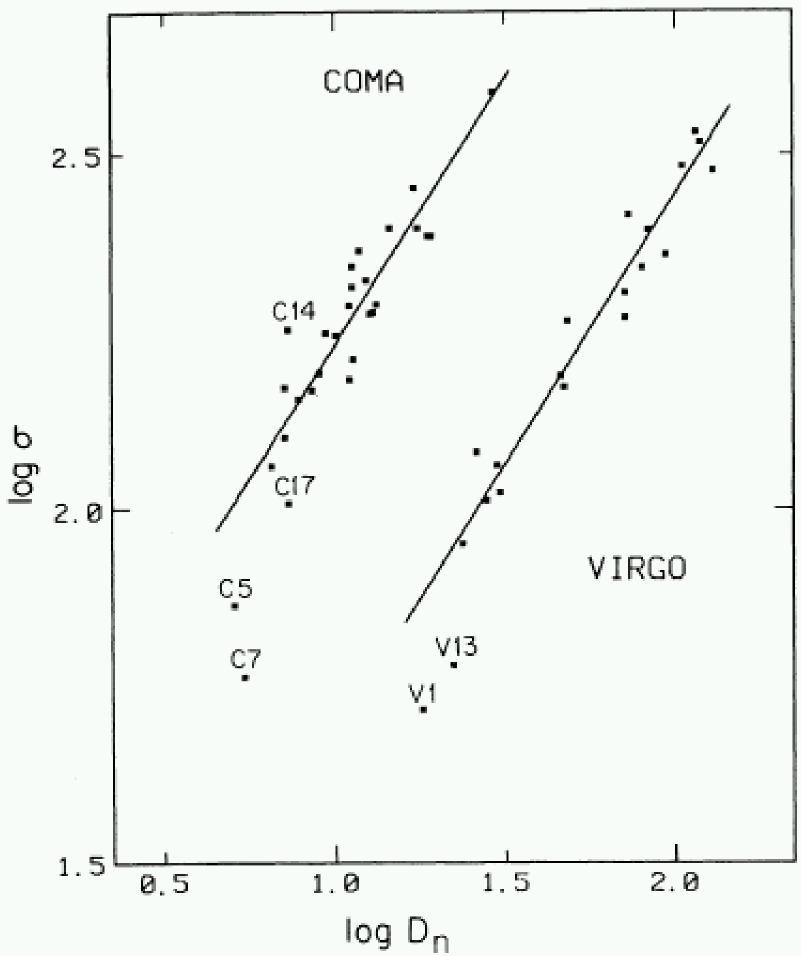


FIG. 1.—(*a*) B_T, the total blue magnitude, vs. log σ, the central velocity dispersion, for ellipticals in the Coma and Virgo clusters. These are the variables of the Faber-Jackson relationship. The lines $\log \sigma = -0.114 B_T + C$, where $C = 3.561$ for Virgo and $C = 3.960$ for Coma, are best median fits, as described in the text. The rms scatters in B_T from these lines are 0.57 mag for Virgo and 0.69 mag for Coma. (*b*) log D_n, the diameter within which the integrated blue surface brightness is 20.75 B mag arcsec^{-2}, vs. log σ for the same galaxies. The horizontal scales correspond to a factor of 10 in distance in both figures. The lines $\log \sigma = 0.750 \log D_n + C$, where $C = 0.934$ for Virgo and $C = 1.475$ for Coma, are best median fits. The rms scatter in log D_n is 0.059 for Virgo and 0.072 for Coma, a factor of 2 smaller scatter than with the Faber-Jackson relationship.

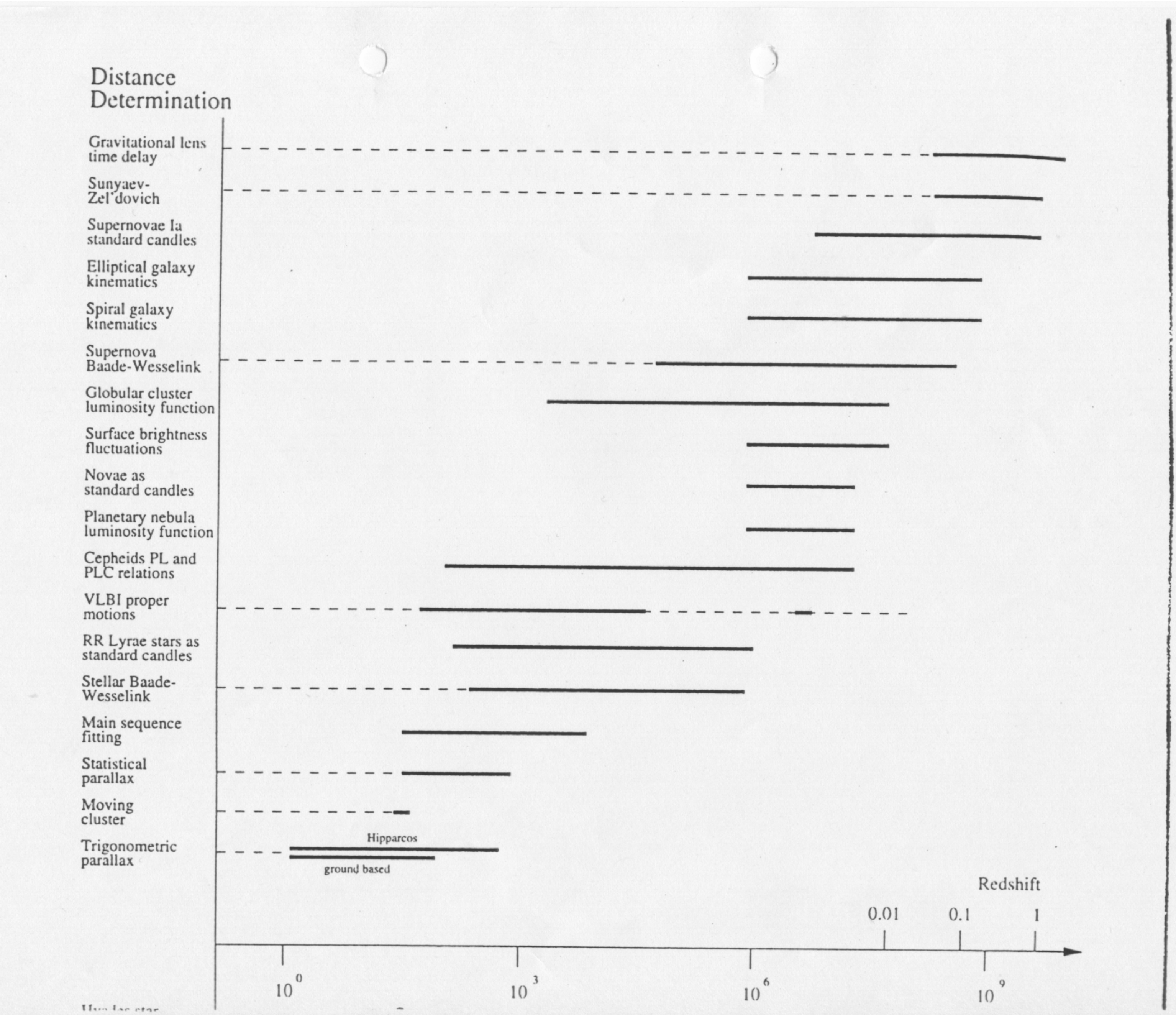
$$D_n \,[\mathrm{kpc}] = 2.05\,(\sigma/100\ \mathrm{km/s})^{1.33}$$

- D_n is the diameter within which the mean surface brightness is $\mu_n = 20.75$ mag/arcsec^2 (in the blue band)
- σ is the central velocity dispersion.

- The distance is $D = D_n\,[\mathrm{kpc}] / D_n\,[\mathrm{arcsec}]$

- There is a 15% scatter in the relation (i.e. uncertainty in the distance to a galaxy)
    - However, the uncertainty in the distance to a cluster of galaxies is reduced by observing large numbers of elliptical galaxies.

Summary


Distance Determination
Gravitational lens time delay
Sunyaev-Zel'dovich
Supernovae Ia standard candles
Elliptical galaxy kinematics
Spiral galaxy kinematics
Supernova Baade-Wesselink
Globular cluster luminosity function
Surface brightness fluctuations
Novae as standard candles
Planetary nebula luminosity function
Cepheids PL and PLC relations
VLBI proper motions
RR Lyrae stars as standard candles
Stellar Baade-Wesselink
Main sequence fitting
Statistical parallax
Moving cluster
Trigonometric parallax
Hipparcos
ground based
Redshift
0.01
0.1
1
10^0
10^3
10^6
10^9

Distances within the Local Group

Distance to the Galactic center

Two absolute distance estimators:

- water masers in star forming regions in SgrB2 (statistical parallax method)
- Star S2 around Sgr A* (SMBH; Kepler problem)

The relative distance estimators that can be used are

- Globular clusters: their density should peak at the location of the Galactic center.
- RR Lyrae in the bulge
- Cepheids

S2 star	7.9 +/- 0.4
RR Lyrae	7.8 +/- 0.4
globular clusters	8.0 +/- 0.8
cepheids	8.0 +/- 0.5

Distance to the LMC: 50 +/- 2 kpc

(It is the extragalactic zero-point of the distance scale)

The absolute distance estimator for the LMC is SN 1987A using time-delay arguments, or the Baade-Wesselink method.

The relative distance estimators that can be used are

- Main sequence fitting of globular clusters
- RR Lyrae stars
- Cepheids

SN 1987 A time delay	52 +/- 3 kpc
SN 1987A Baade-Wesselink	55 +/- 5 kpc
RR Lyrae	44 +/- 2 kpc
Cepheids	50 +/- 2 kpc
main sequence fitting	50 +/- 5 kpc

Distance to the M31: 740 +/- 40 kpc

Its distance is always referred to the LMC

- Cepheids in LMC and M31 show a distance ratio of 15.3 +/- 0.8
- RR Lyraes give a distance ratio of 15 +/- 1.
- The PN luminosity function gives 15 +/- 1.

- The distance using the GCLF is 700 +/- 60 kpc. This is directly calibrated wrt Milky Way rather than the LMC. The fact that there is such good agreement between different estimators and zero-points gives good confidence that the scale is correct.

Novae	710 +/- 80 kpc
RR Lyrae	750 +/- 50 kpc
Cepheids	760 +/- 50 kpc
PNLF	750 +/- 50 kpc
GCLF	700 +/- 60 kpc

Beyond the Local Group

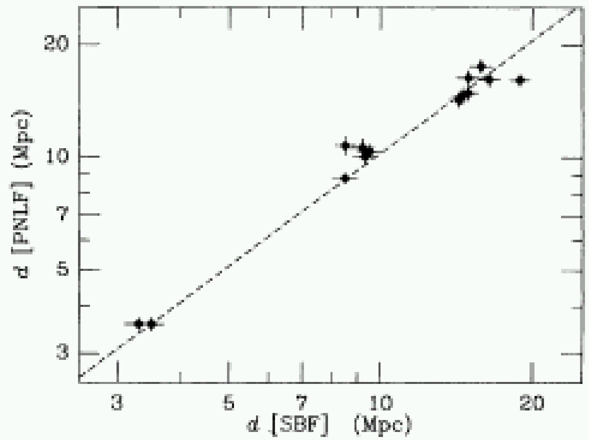
- Good agreement between different methods for distances less than ~ 20 Mpc.

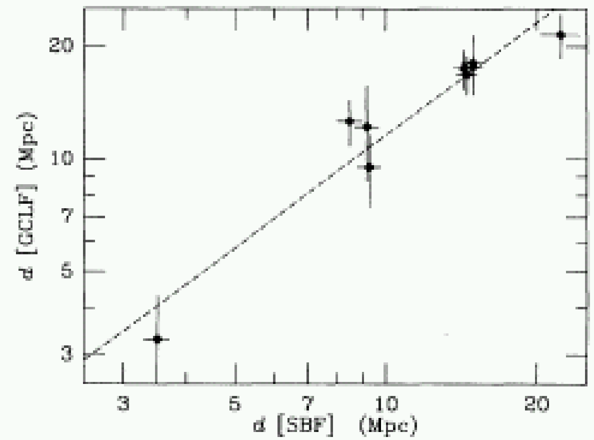
- PNLF and GCLF are generally in good agreement.

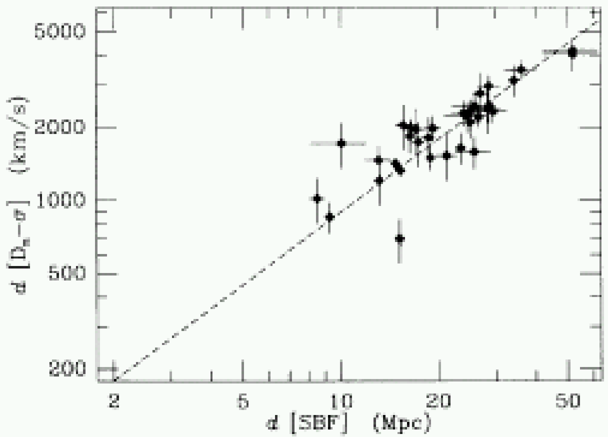
- Tully-Fisher for spiral galaxies in clusters are in worse agreement than distances using elliptical galaxies
  - likely due to their different physical location in the clusters.

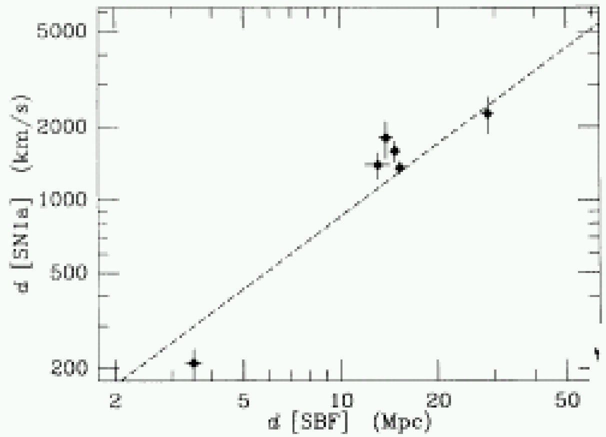
- The distance to the Virgo cluster is crucial in the extragalactic distance scale:
  - nearest galaxy cluster
  - large numbers of spirals and ellipticals
  - has been the site of a few SN
  - it has been recently possible to observe cepheids, and hence to derive a distance which involves less intermediate calibrations
  - it is a fairly average type of cluster: distances beyond it are referred to it.

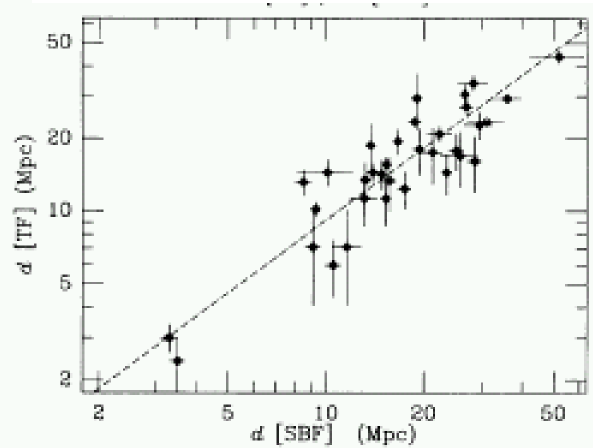
Comparison of various distance determination methods for galaxies in the Virgo cluster











Intro to cosmology

- In a homogeneous and isotropic Universe, the length of path between two points (geodesic) is

$$ds^2 = a^2(t)[dr^2/(1 - k\, r^2) + r^2\, d\theta^2 + r^2 \sin^2\theta\, d\phi^2]$$

  - a(t) is the scale factor
  - the coordinates r, θ, ϕ: comoving coordinate system
  - The distance between two points expands according to a(t)

- k=1 universe is closed
- k = 0 is flat
- k = -1 is open

Hubble expansion

- Two systems separated by a distance D = a * r will move with respect to each other with velocity

$$V = 1/a * da/dt * D + a\, dr/dt =$$
$$V = H * D + a\, v_p$$

- H(t) is the Hubble parameter (note it is not constant)
- v_p is the peculiar velocity of the systems (on top of the expansion)