The Cosmic Distance Scale

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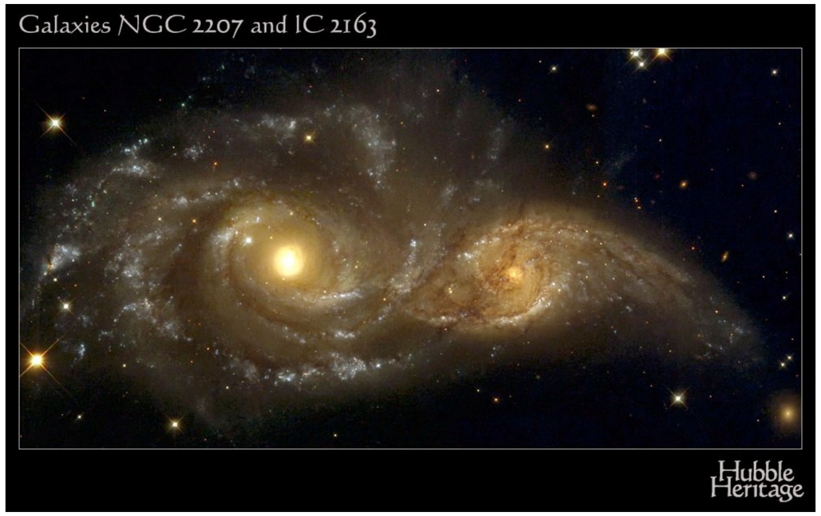
Why is this important?

Knowing the distances to galaxies is fundamental for a lot of problems.

e.g., are two galaxies going to interact? or are they just conicidental on the sky?



or

understanding the large scale structure in the Universe, and whether the Universe has always expanded at the same rate.

or

simply determining absolute luminosities

Some numbers to keep in mind…

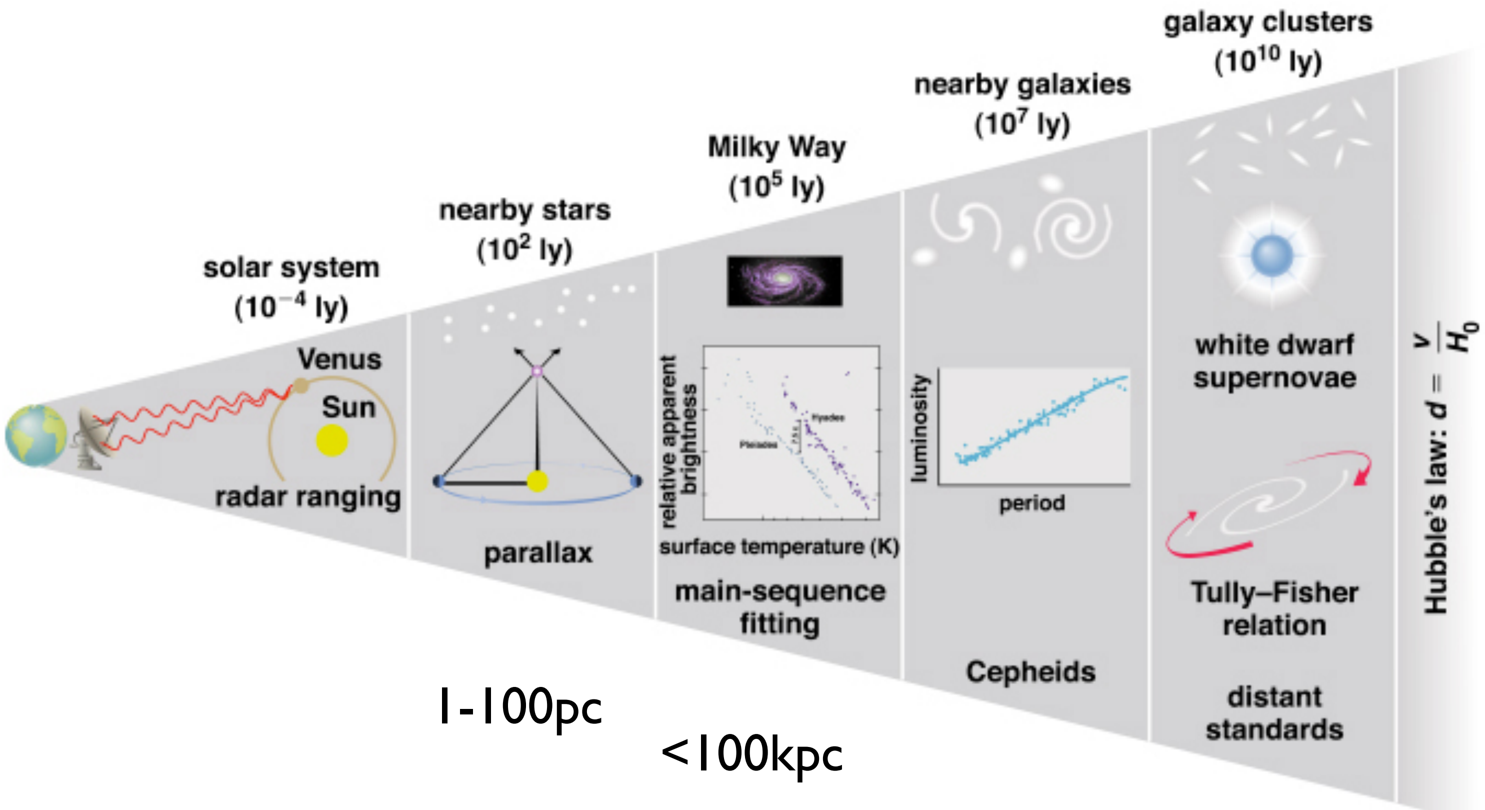
- Sun’s distance from centre of Galaxy: ~ 8 kpc
- diameter of Galaxy: ~ 30 kpc

- nearest (non-satellite) galaxies: ~750 kpc
- sizes of groups and clusters: 1-3 Mpc

- nearest rich clusters: 20-100 Mpc
- sizes of ‘walls’ and large-scale structure: 100’s Mpc

The cosmological distance ladder

The Cosmological Distance Ladder: starts with distances to the nearest stars, ends with distances to the furthest galaxies



1-100pc

<100kpc

<3Mpc

<3000Mpc

Two main groups of distance measures

ABSOLUTE METHODS

those in which distances can be determined quite directly

typically involve geometrical measurements

mostly work for nearby sources (within MW)

RELATIVE METHODS

they refer to a **standard candle** or **standard ruler**

apply to larger distances

Distance indicators

- Primary DIs are single step methods
- Secondary DIs rely on a primary DI
- Tertiary Dis rely on a secondary DI etc

PRIMARY

PARALLAX
SUNYAEV-ZELDOVICH *
LENSING TIME DELAY*

* cosmological

SECONDARY

CEPHEIDS
MS-FITTING
RR-LYRAE
SNIa*

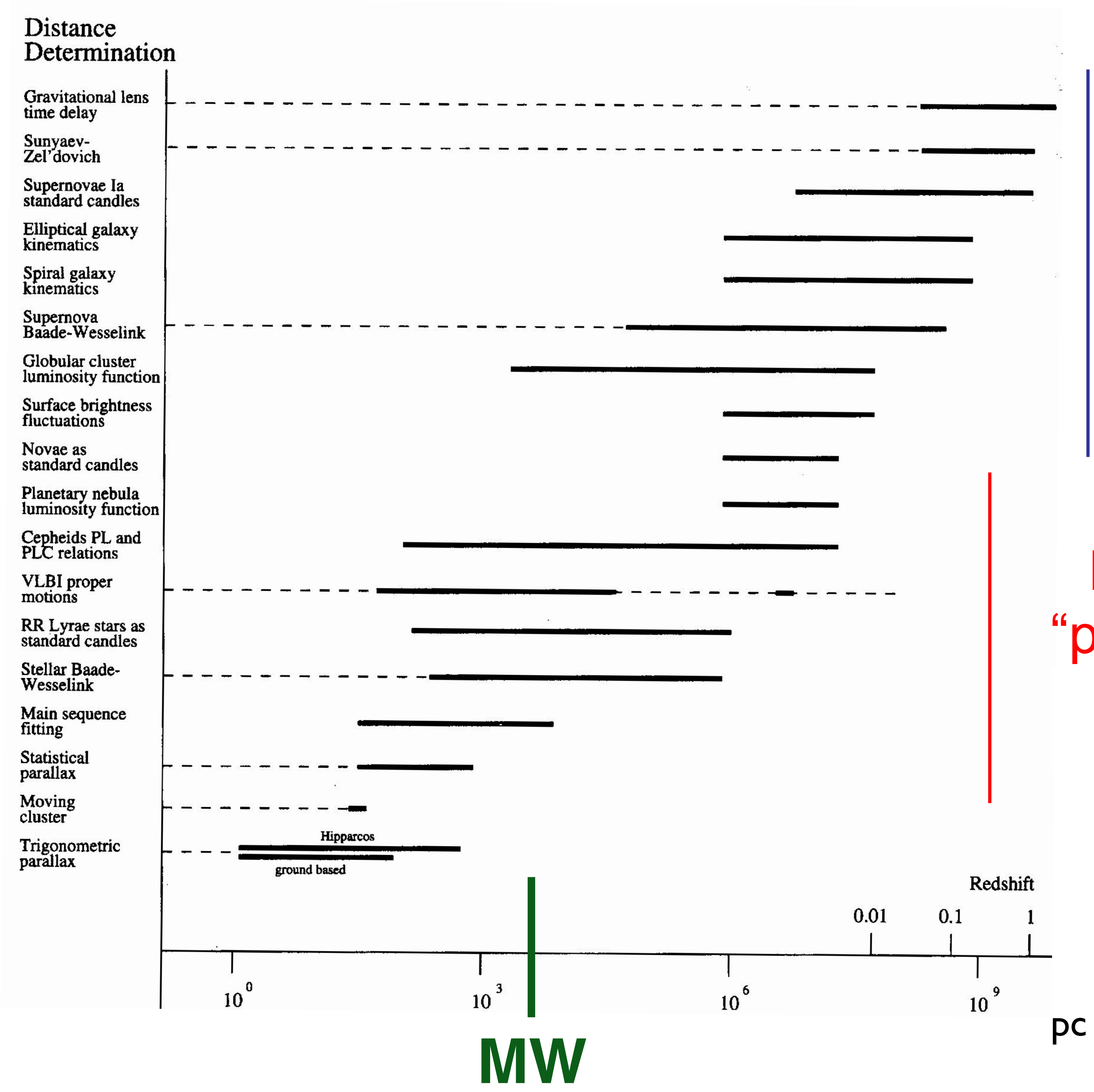
Stellar based

TERTIARY

TULLY_FISHER
FABER-JACKSON
SBF
GC LF
PN LF

Galaxy based

Typical scales for distance indicators



Mostly
“secondary or
tertiary”

Mostly
“primary”

Primary Methods

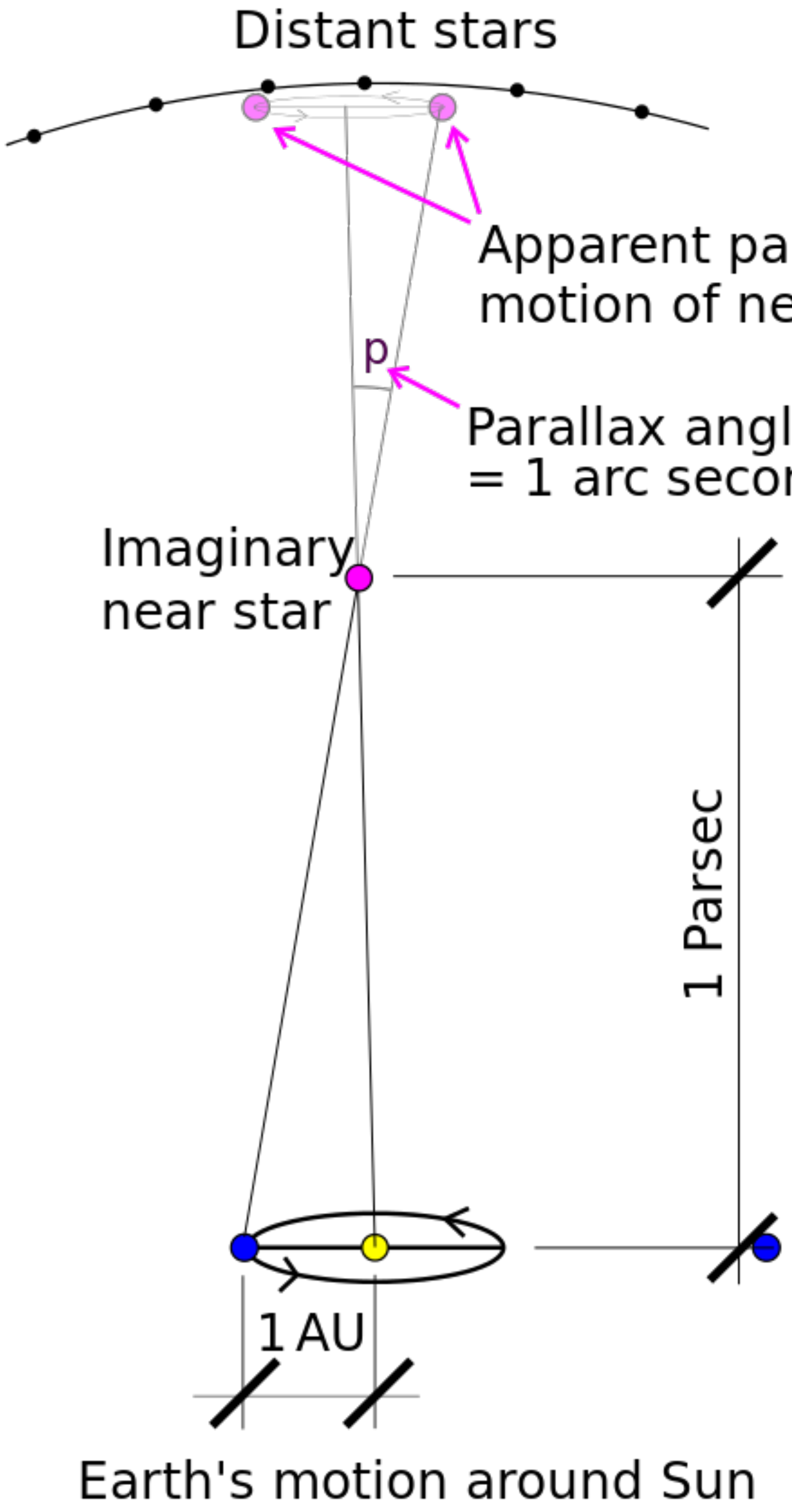
Distances within the MW

Stellar Parallax

In1838 using a heliometer Bessel measured the first parallax of a star, 61 Cygni, of 0.314 arcseconds, indicating that the star is 10.3 ly away (current measurement 11.4 ly).

Friedrich Wilhelm Bessel (1784-1846)

There are ~25 stars within 3.5pc of us.



Measuring stars apparent motion (parallax)

*The **parallax** is the apparent motion of stars produced by the orbital motion of the Earth*

Astronomical Unit (AU)

=

mean distance between Sun and Earth

(150 million km or 8.3 light minutes)

As the Earth orbits the Sun, our viewing position changes, and closer stars appear to move relative to more distant objects. In the course of a year, a nearby star traces out an elliptical path against the background of distant stars. The angle ϖ on the sky is the parallax.

$$\frac{r}{d} = \tan\varpi \approx \varpi\,\mathrm{rad} \xrightarrow{\varpi\ \text{small}} \varpi'' = 206265\varpi\,\mathrm{rad}$$

defining 1 AU $$d = \frac{206265}{\varpi''}\,\mathrm{AU}$$

1 parsec is the distance at which a star would have a parallax of 1″:

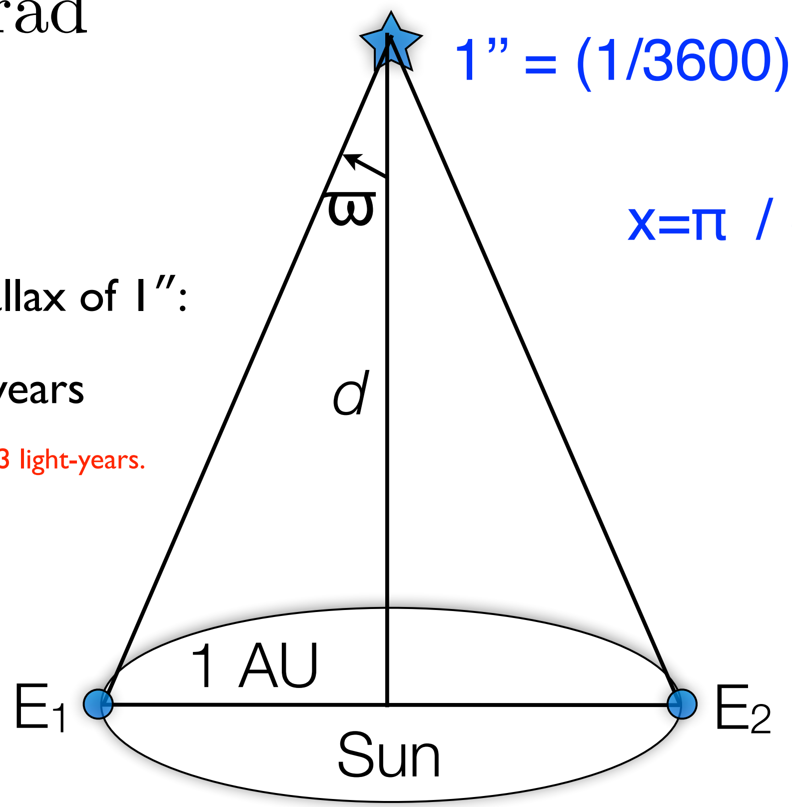
1 rad =1pc = 206265 AU = 3.086 x 10^{13} km = 3.26 light years

Proxima Centauri, the nearest star, has ϖ = 0.8″, so its distance is 1.3 pc or 4.3 light-years.

The distance to a star with observed parallax ϖ″ is then

$$\boxed{d = \frac{1}{\varpi''}\,\mathrm{pc}}$$

$$(m - M)_0 \equiv 5\log_{10}\left(\frac{d}{10\,\mathrm{pc}}\right) = 5\log_{10}\left(\frac{0.1''}{\varpi}\right)$$



180° ____π rad

1” = (1/3600)° ____x rad

x=π / (180x3600)

currently limited to ~100 pc for bright stars

Secular parallax

Secular parallax: Instead of using the Earth's motion around the Sun, use the Sun's motion relative to nearby stars: $v_\odot \approx 20$ km/s, so the Sun moves about 4 AU/year, which is twice as large a distance as the Earth moves in six months! and can use long time baselines to get very long distance baselines.

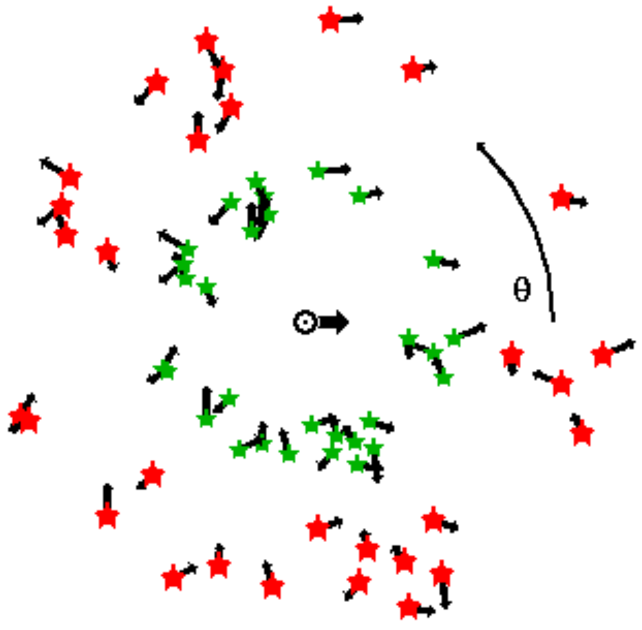
Problem: the other stars move too!

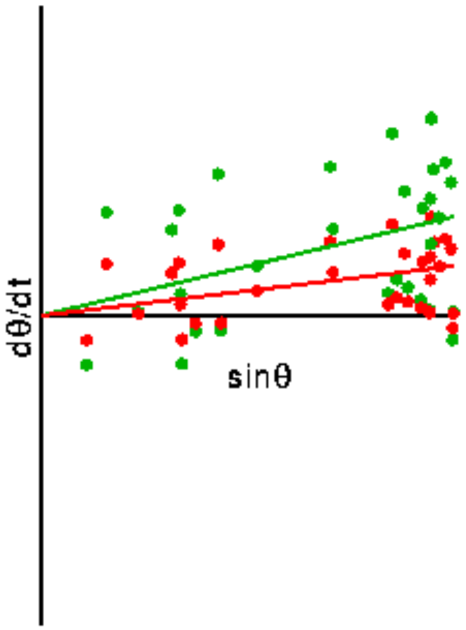
Thus, the position of any one star changes on the celestial sphere both because of the Sun's motion and because of the motion of the star and we can't disentangle the two without further information

The mean proper motion of the stars, $d\theta/dt$, will have a mean component proportional to $\sin\theta$, if the slope of this line is, μ, then the distance D is

$$D[\text{in pc}] = 4.16/(\mu\ [\text{in "/yr}])$$

4.16 is the Solar motion in au/yr

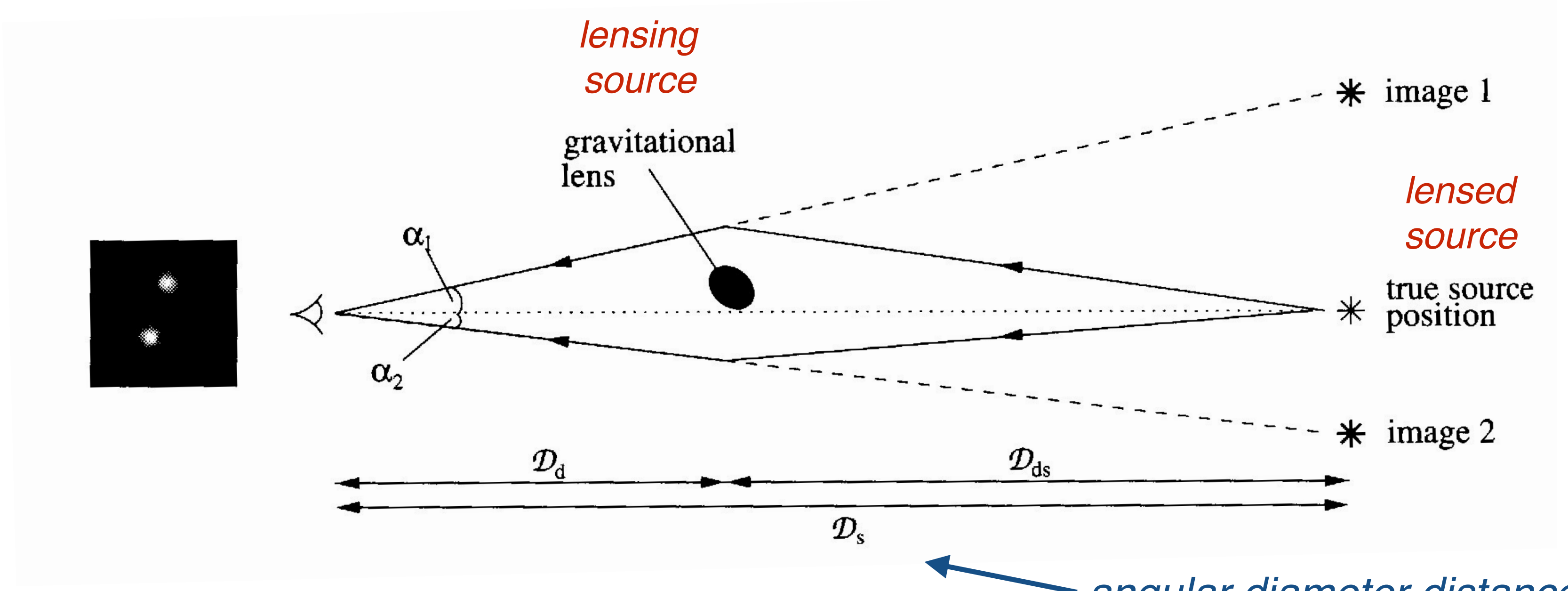




Primary Methods

Cosmological Distances

Gravitational Lensing



lensing source

lensed source

angular diameter distances

- ➢ the path of light is bent as it passes a gravitating mass (General Relativity)
- ➢ this effect can cause an amplification of the light source as well as multiple images of the background source (eg. Q0957+561 and another ~40 systems)

$$t^{(i)}_{\rm lens} = (1+z_d)\left[\frac{1}{2c}\frac{D_d D_s}{D_{ds}}\alpha_i^2 - \frac{2}{c^3}\int_{\gamma_i} ds\,\Phi(s)\right]$$

light time delay due to larger travel path

z of lensing source

gravitational potential (lensing source)

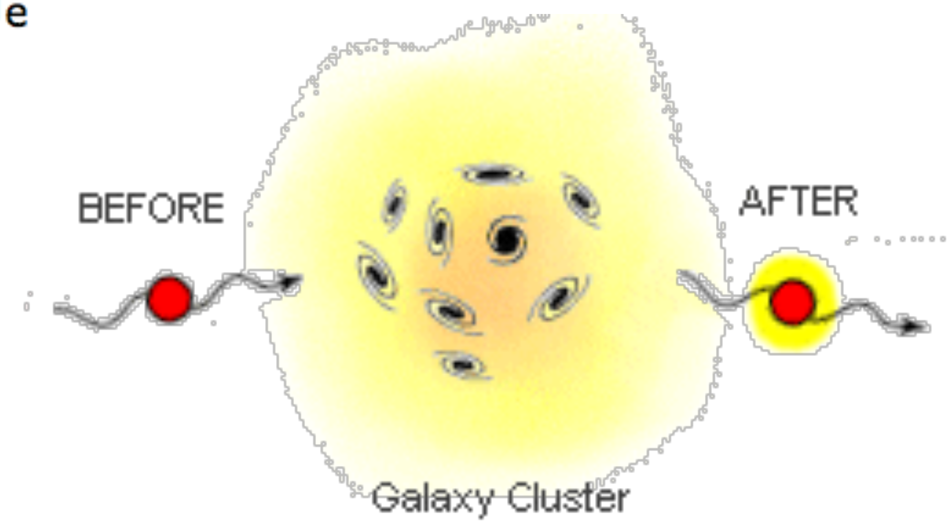
- ➢ if the source varies in intrinsic brightness (i.e. flickers), then the differing light paths of multiple images leads to a time lag in their light curves
- ➢ this method can be applied at any distance but requires knowledge of the mass distribution in the lensing galaxy and difficult/uncertain observations

The Sunyaev-Zeldovich Method

If the cluster is spherical then $R = D\theta$

$$\tau_S = \sigma_T 2 R n_e$$

optical depth for scattering



$$D = \frac{\tau_s}{\theta n_e \sigma_T}$$

$$D = \frac{1.78\times10^{-40}\tau_s^2\theta T^{1/2}}{24\sigma_T^2 F}$$

n_e = electron density
T = electron temperature in the intracluster medium

- ➢ cosmic microwave background is weak radio emission that pervades the sky
- ➢ clusters of galaxies contain large amounts of hot ionized gas (~$10^{6\text{-}7}$ K)
- ➢ as CMB photons pass through the cluster, hot gas e^- scatter the microwave photons in random directions (inverse compton scattering)
- ➢ result that CMB photons generally increase in energy

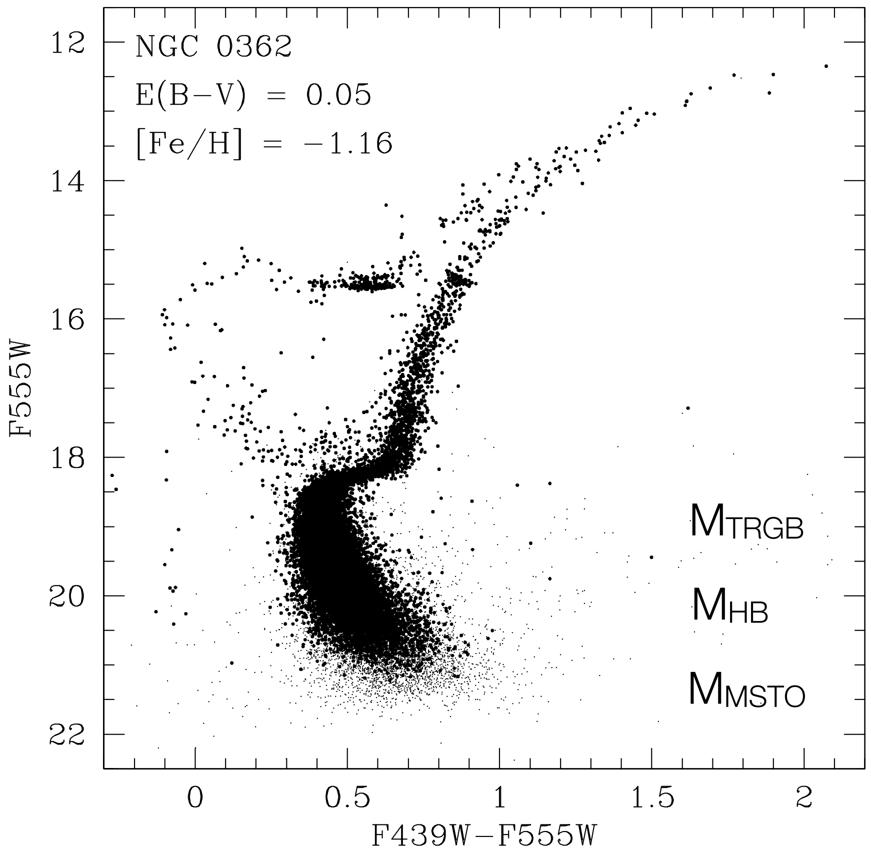
Relative Methods

(Secondary, tertiary)

General idea

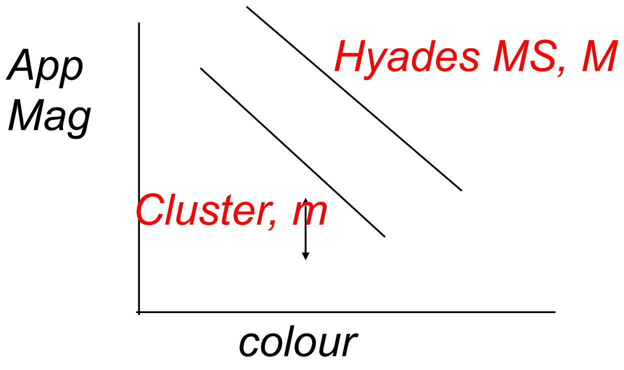
- the general idea is to measure something that doesn't vary with the distance to a galaxy, e.g.
  - flux of specific phenomenon
  - period of a regular phenomenon
- relate this velocity or period to the luminosity, using local objects (with distances known from other methods)
- then we use $F = L / 4 \pi d^2$
  - measure F, know L....work out d
- or use the *distance modulus*:
  - calculate the absolute magnitude M for the luminosity L, measure m... use $m - M = 5 \log_{10} (d / 10 \text{ pc})$

Stellar main sequence fitting



Main Sequence Fitting:

- ➢ given distance to Hyades (from trig parallax), can calibrate its main sequence in terms of magnitude and colour; compare apparent magnitude of other cluster main sequences with Hyades and derive distance
- ➢ requires accurate knowledge of extinction, and to a lesser extent metallicity of cluster

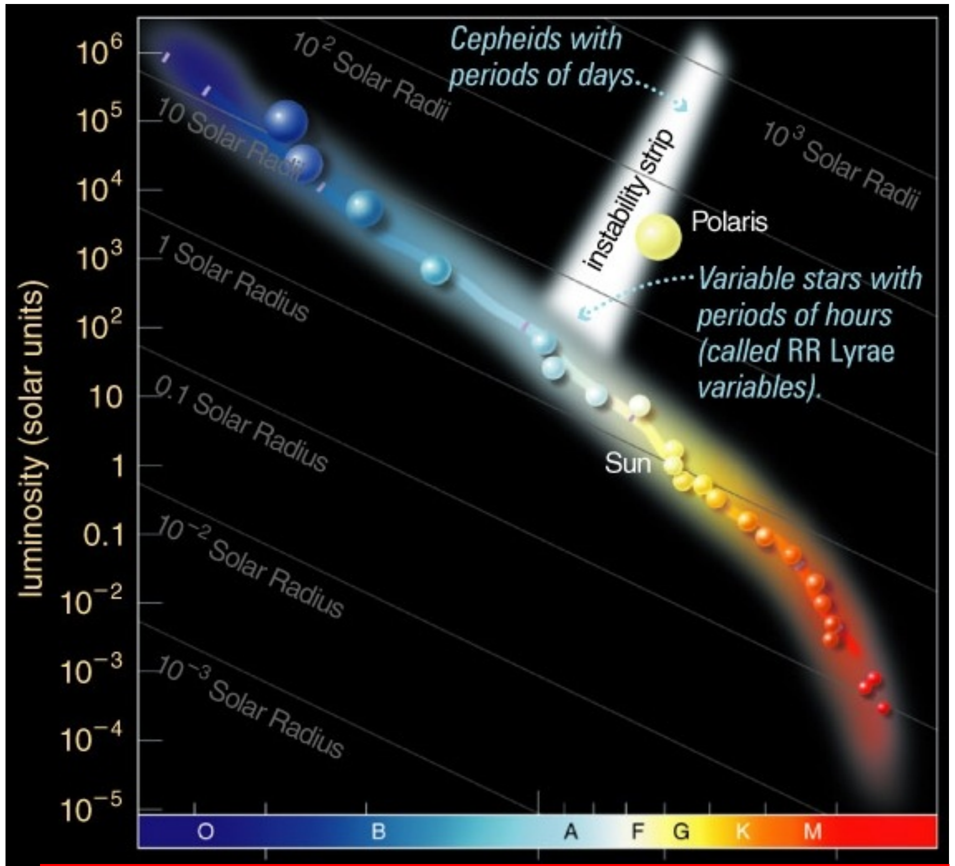


$$\boxed{m_{cluster}-M_{Hyades}=5\log D(pc)-5 + A}$$

extinction!

Variable stars and the distance scale

Variable Stars & The Distance Scale



Variable stars are fundamental to
the distance scale as they are standard candles!!

- ➢ some stars vary in luminosity due to pulsations in their interiors
- ➢ these stars are found in the "instability strip" of the CMD (transient phase of their evolution)
- ➢ Cepheids (young, luminous M_V~-6, Pop I, P~2-100 days)
- ➢ RR Lyrae (old, faint M_V~ +0.6, Pop II, P~1.5-24 hr)

Time-delay methods

Supernova light echo

A supernova explosion at time t is seen at position A

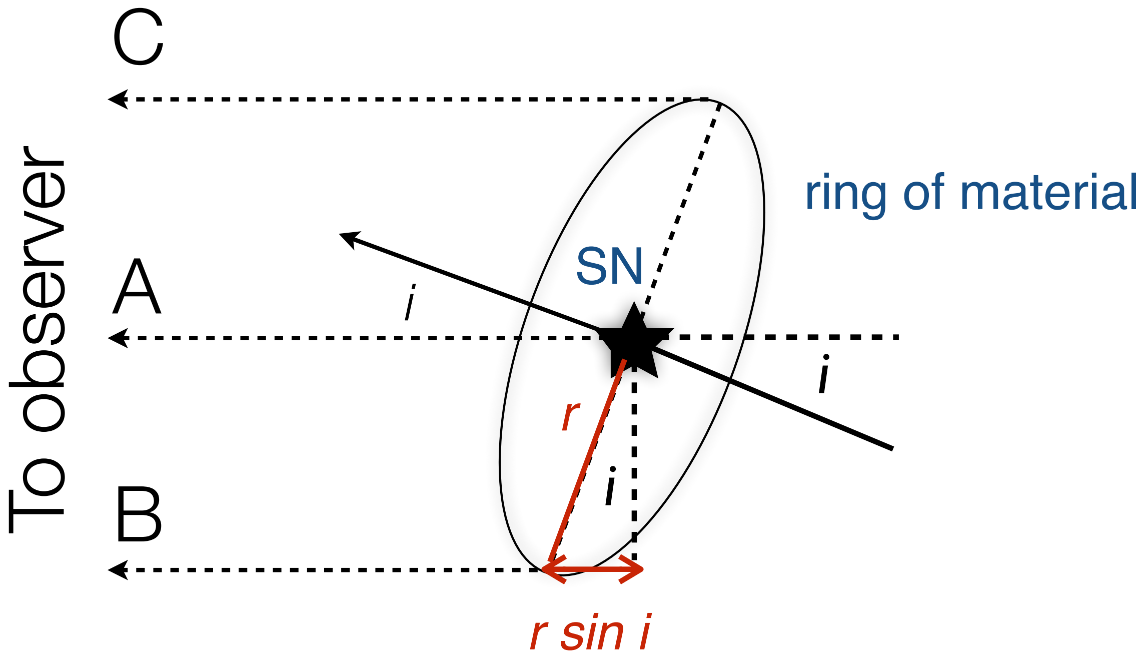
At some time later, t_0 light from the SN is seen at position B, and at an even later time t_1 exactly the same signal is seen at position C

this light has been reprocessed by an inclined ring, in the case of SN1987A, as seen by HST.

HST image

$$t_B - t_A = \frac{r_{\rm ring}}{c}(1 - sin\, i)$$

$$t_C - t_A = \frac{r_{\rm ring}}{c}(1 + sin\, i)$$



Common methods in extragalactic sources

- standard candle
  - Cepheid variable stars, that have longer periods when more luminous
- in elliptical galaxies:
  - luminosity versus velocity dispersion

    (Faber-Jackson relation)
- in spiral galaxies:
  - luminosity versus rotation velocity

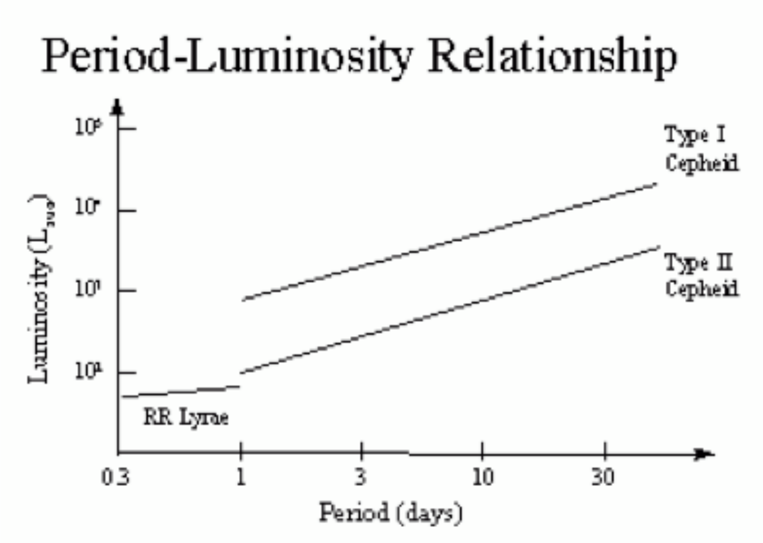
    (Tully-Fisher relation)

Standard candles

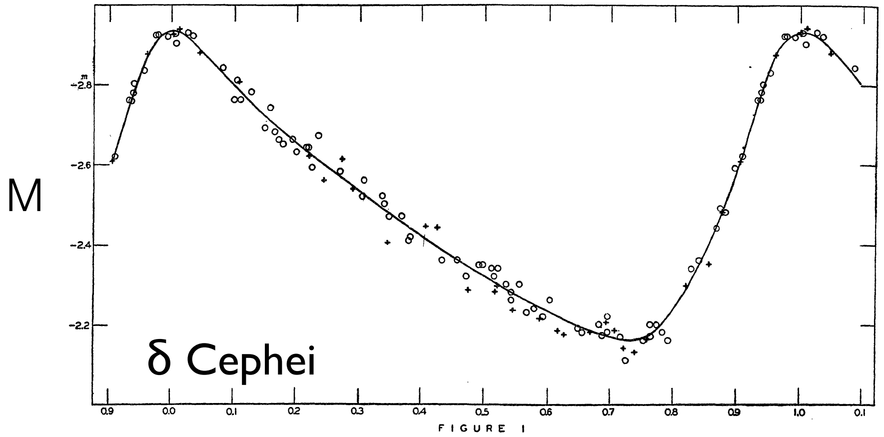
A standard candle is anything that has a predictable brightness, usually related to changes with time, e.g., pulsating stars

In fact, the entire cosmic distance scale (i.e., beyond the Local Group) is based on one kind of pulsating star: the Cepheid variables

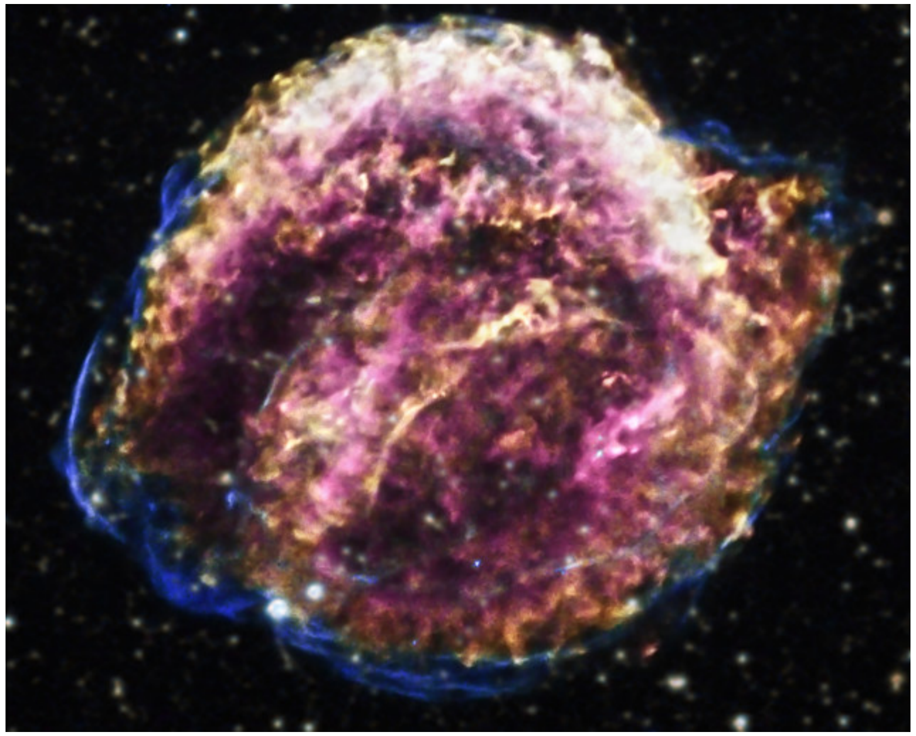
- Cepheid variable stars are very useful for nearby galaxies
  - very luminous
  - several-day periods
  - distance record is ~ 30 Mpc



NGC 4603 (HST)



Supernovae as distance estimators



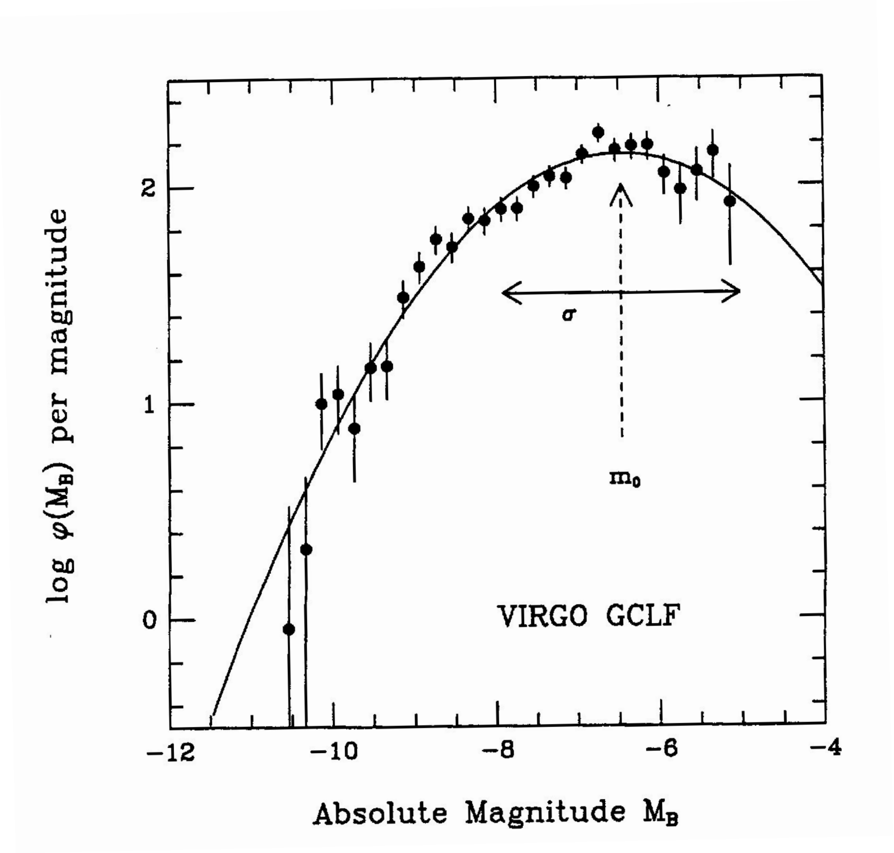
Picture credit: NASA/CXC/SAO/SDSS

➢ supernovae come in a variety of types:

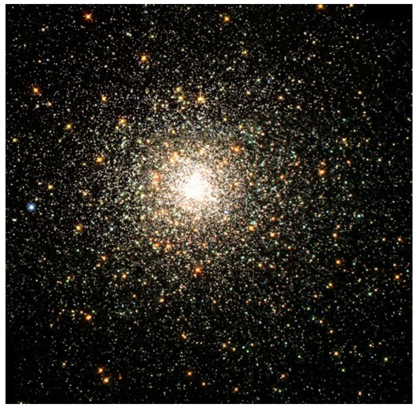
Type I (a,b,c)	Type II
- spectra show no H lines	- spectra show H lines
- same lightcurves	- variety of lightcurves
- occur Spiral and Ell	- occur only Spiral
- progenitors low mass white dwarf in close binary	- progenitors high mass
- accretes enough mass from secondary to initiate runaway nuclear reaction in CO core	- core collapse at end of nuclear burning

⇒ Type Ia supernovae are particularly interesting because they appear to have same $M_B(max)=-19.3\pm0.03$ and the same time evolution thereafter

Globular cluster LF



- ➢ number of GCs per unit magnitude in galaxy has universal Gaussian form
- ➢ well-defined peak at turnover magnitude (M_0=-6.5)
- ➢ value of turnover magnitude is standard candle that works out to ~50 Mpc

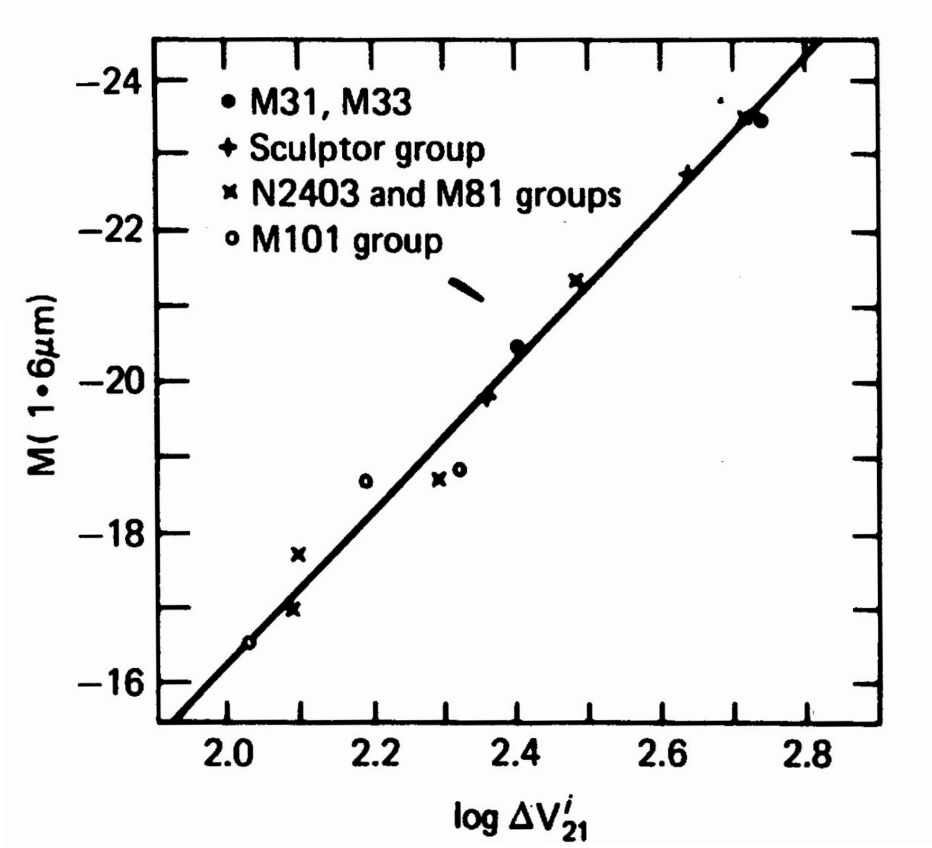


Tully-Fisher relation

relation between absolute magnitude and rotational velocity in spiral galaxies

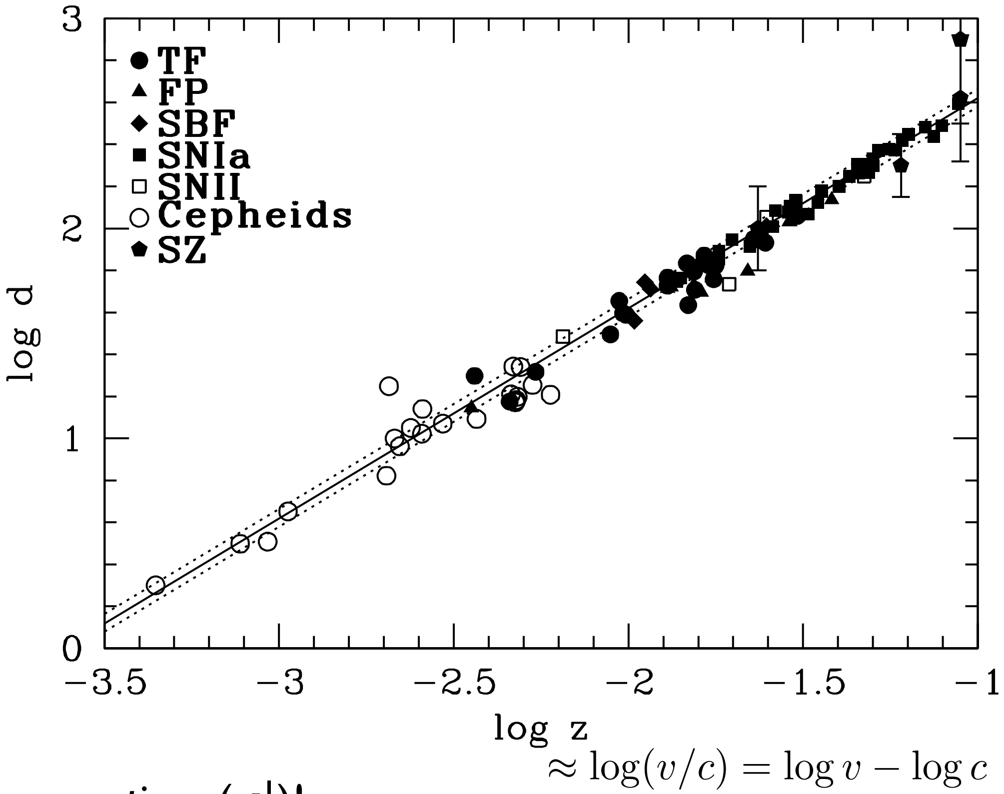
combined with apparent magnitudes allows for determining distance

H-band TF Relation for Local Universe galaxies (with good Cepheid distances)



The Hubble Law

- Today this relation as **Hubble's Law** and H_0 is known as the **Hubble Constant**
- Typically, v is in km/s and d is in Mpc, so H_0 is in km s^{-1} Mpc^{-1}
    - The currently favored value of the Hubble constant is H_0=100 h km s^{-1} Mpc^{-1} = 69 km s^{-1} Mpc^{-1}, where h=0.69 is used to parameterize the Hubble constant



- Note that the Hubble constant has units of *inverse time* (s^{-1})!
- The inverse of the Hubble constant thus gives a timescale, called the **Hubble time**:

$$t_H \equiv \frac{1}{H_0} = 4.35 \times 10^{17}\,\mathrm{s} = 13.8\,\mathrm{Gyr}$$

- If the Universe has been expanding uniformly since the Big Bang (which it hasn't), then the Hubble time should equal the age of the Universe (which it nearly does!)