The Cosmic Distance Scale

Sterrenstelsels en Kosmos deel 5

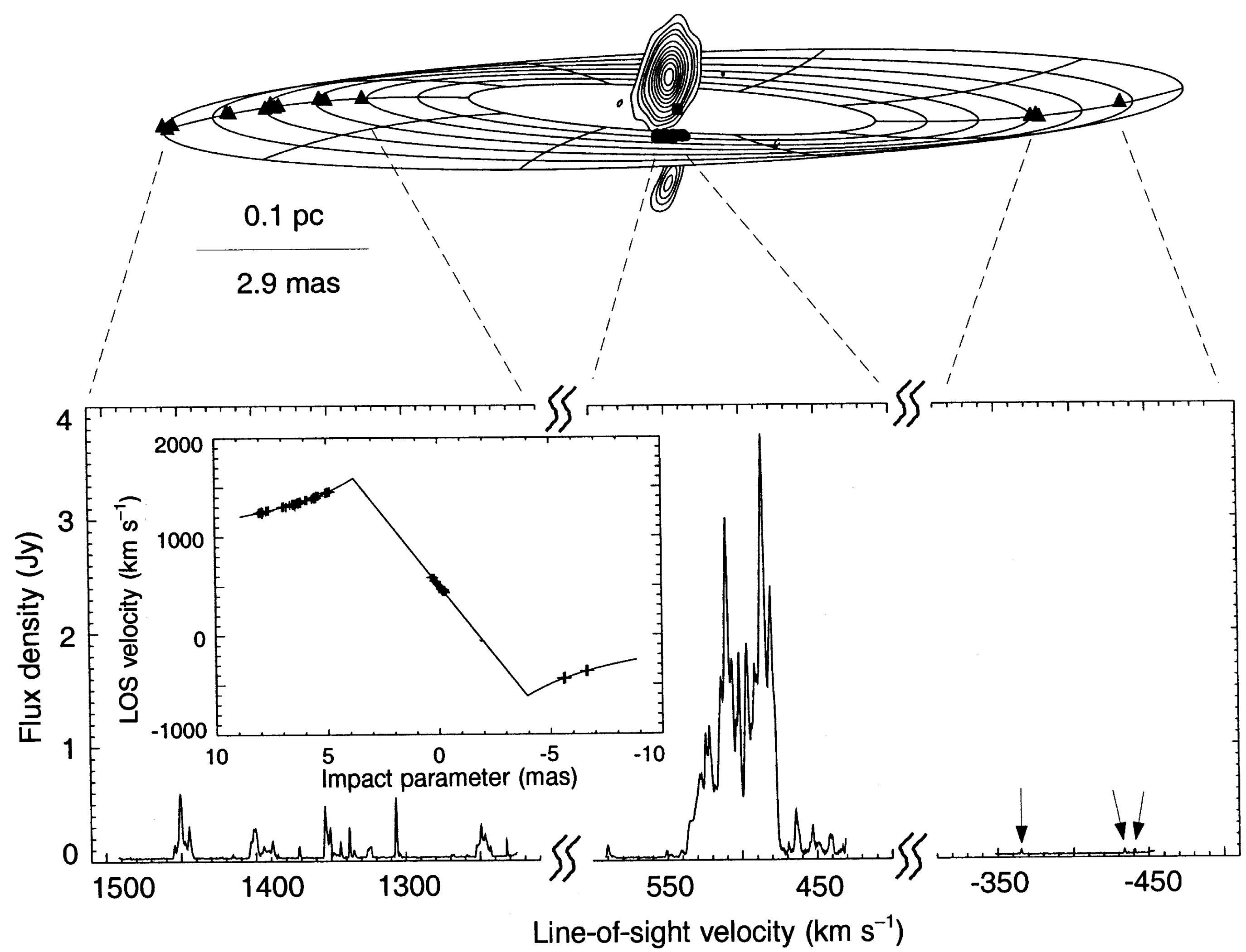
How big is the Universe?

- We want to understand how big the Universe is!
- Why?
    - *Scale*: how big are distant things, like galaxies?
    - *Time*: we'll see that recession speed is proportional to distance, so our estimate of the *age of the Universe depends on how far apart galaxies are!*

Direct geometrical distance measures

- Parallax: apparent motion of distant stars caused by orbital motion of earth
  - currently limited to <1 kpc for bright stars
  - after Gaia (~2018 or so), will reach out to ~1 Mpc for the brightest stars

- Maser distance
    - The nearby active galaxy NGC 4258 shows that it possesses an accretion disk containing *water masers* orbiting in a thin disk, nearly on the plane of the sky
    - By measuring the *velocity* and *acceleration* of these masers over time, one can derive a *direct* distance to this galaxy: 7.2±0.3 Mpc



And also a black hole mass: $3.9(\pm 0.1)\times 10^7\ M_\odot$

- Gravitational lensing
    - Quasars lensed into multiple images by foreground galaxies (usually ellipticals) show *correlated brightness variations* in the light of each component
    - The *delay time* of these variations with respect to each other is another geometrical distance measurement
        - But! Uncertainty in *mass profiles* of lens galaxies means large uncertainties in distance determinations

Indirect distance measures

- Because direct measurements generally lie well within our own MW, we need other means of reaching out to cosmic distances
- These methods are called *indirect distance measures* and they fall into two classes:
  - *Standard candles* --- based on objects with known (or calibratable) luminosities
  - *Dynamical measures* --- based on scaling relations like TF and FP

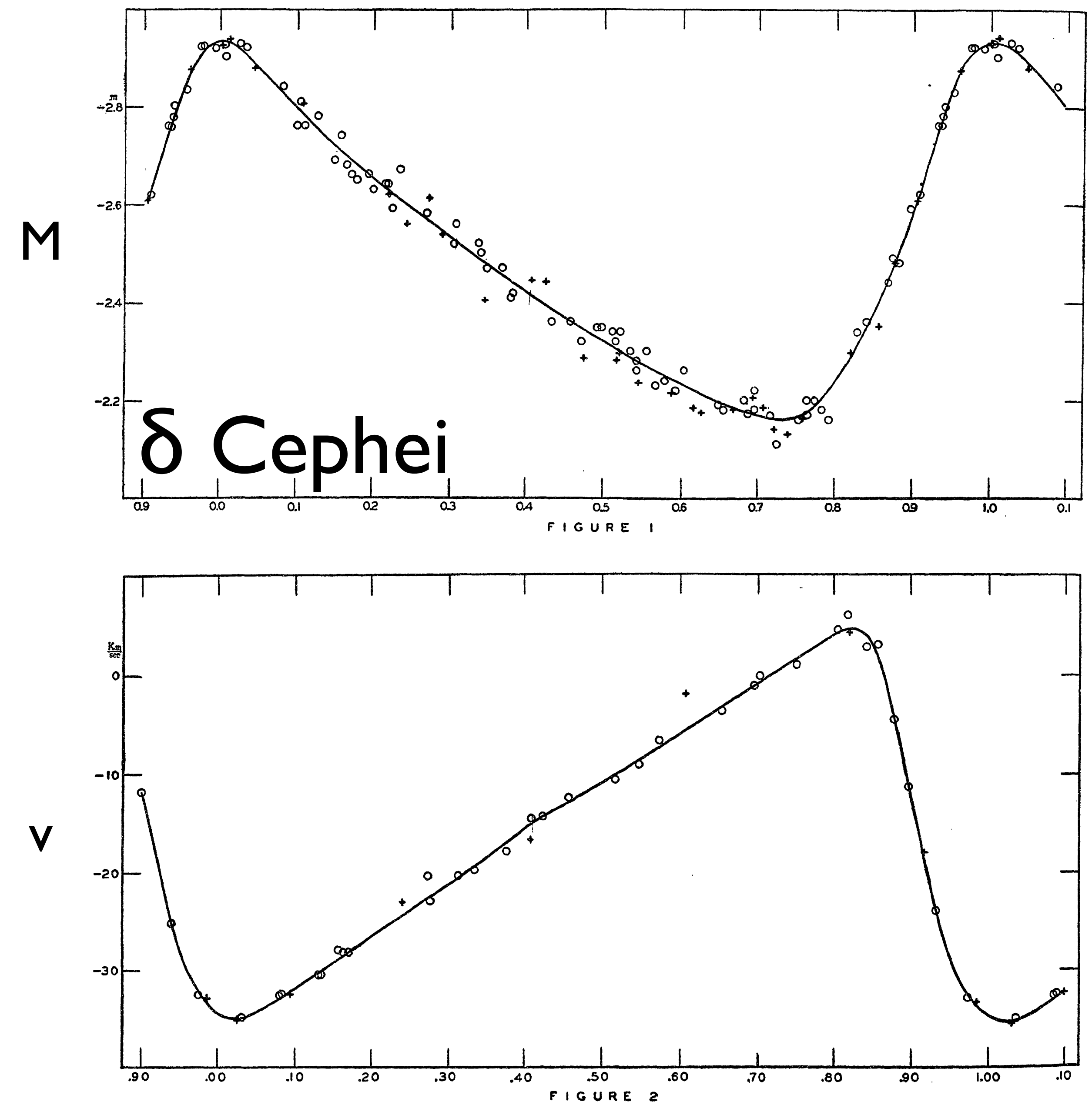
Standard candles

- *All* indirect distance measurements depend on the calibration of standard candles, and one in particular: pulsating stars
  - In fact, the entire cosmic distance scale is based on **one** kind of pulsating star: the Cepheid variables

Cepheid variables

- Cepheids are pulsating stars which "breathe" due to their surface opacities and specific heats *increasing* as they compress, due to partial ionization of H and He

- This means the pulsations that occur in *all* stars are *much bigger* in Cepheids



FIGURES 1 and 2. — Light curve (Stebbins o, Danjon +) and radial velocity curve (Jacobsen o, Henroteau +) of δ Cephei.

pulsation phase

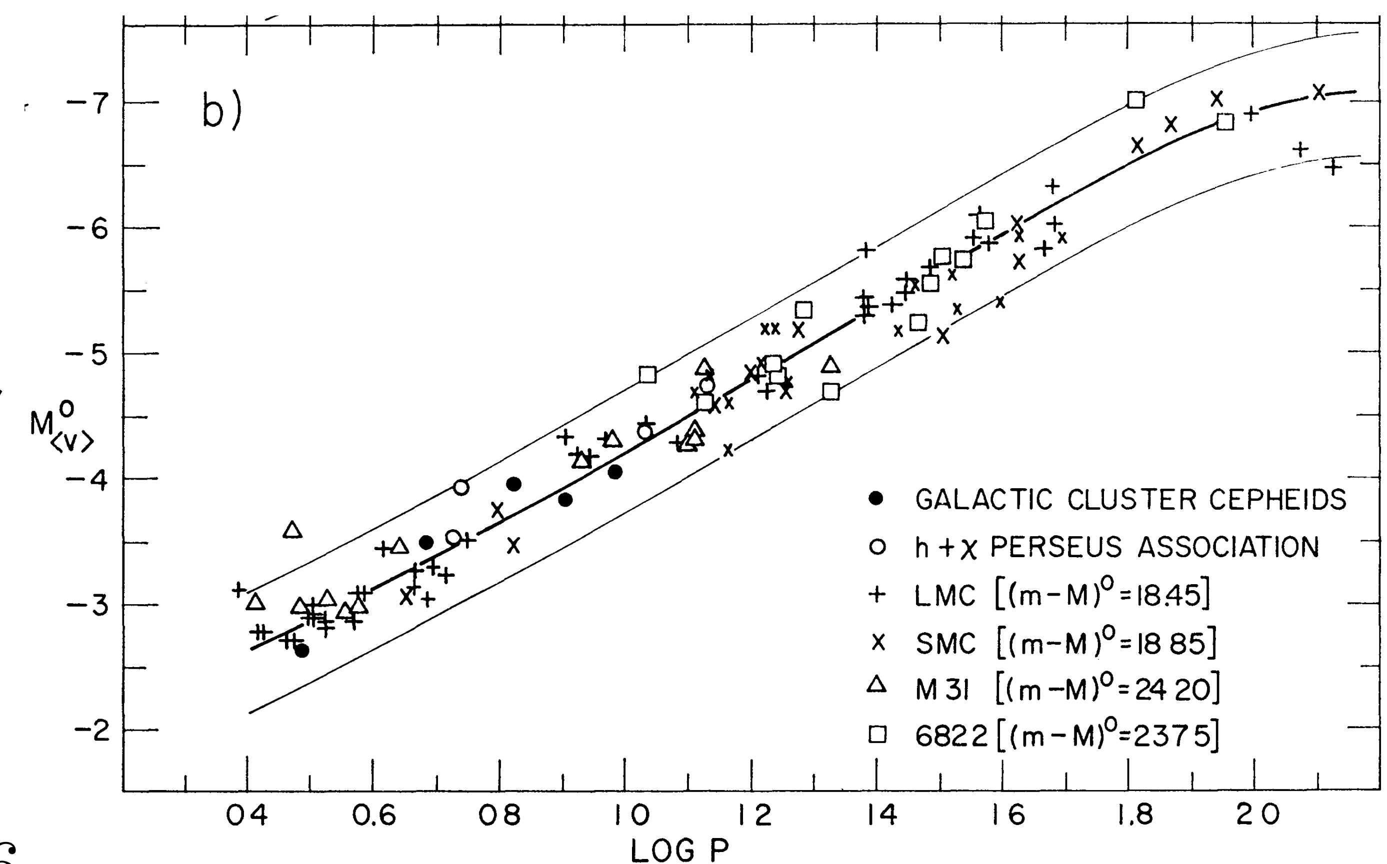
- The nearest Cepheid is *Polaris* (the pole star), about 200 pc away, too distant for parallax measurements until the Hipparcos satellite in the 1990s
    - In 1913, Hertzsprung (of the HRD!) came up with the ingenious idea to use the variation of the Sun's motion with respect to the *Local Standard of Rest* as a secular parallax and determined the distances to Cepheids that way

- In the beginning of the 20th century, Henrietta Swan Leavitt, a “computer” for Harvard Observatory, discovered that the Cepheids in the Small Magellanic Cloud pulsated with periods that were *directly proportional* to their *average* luminosities

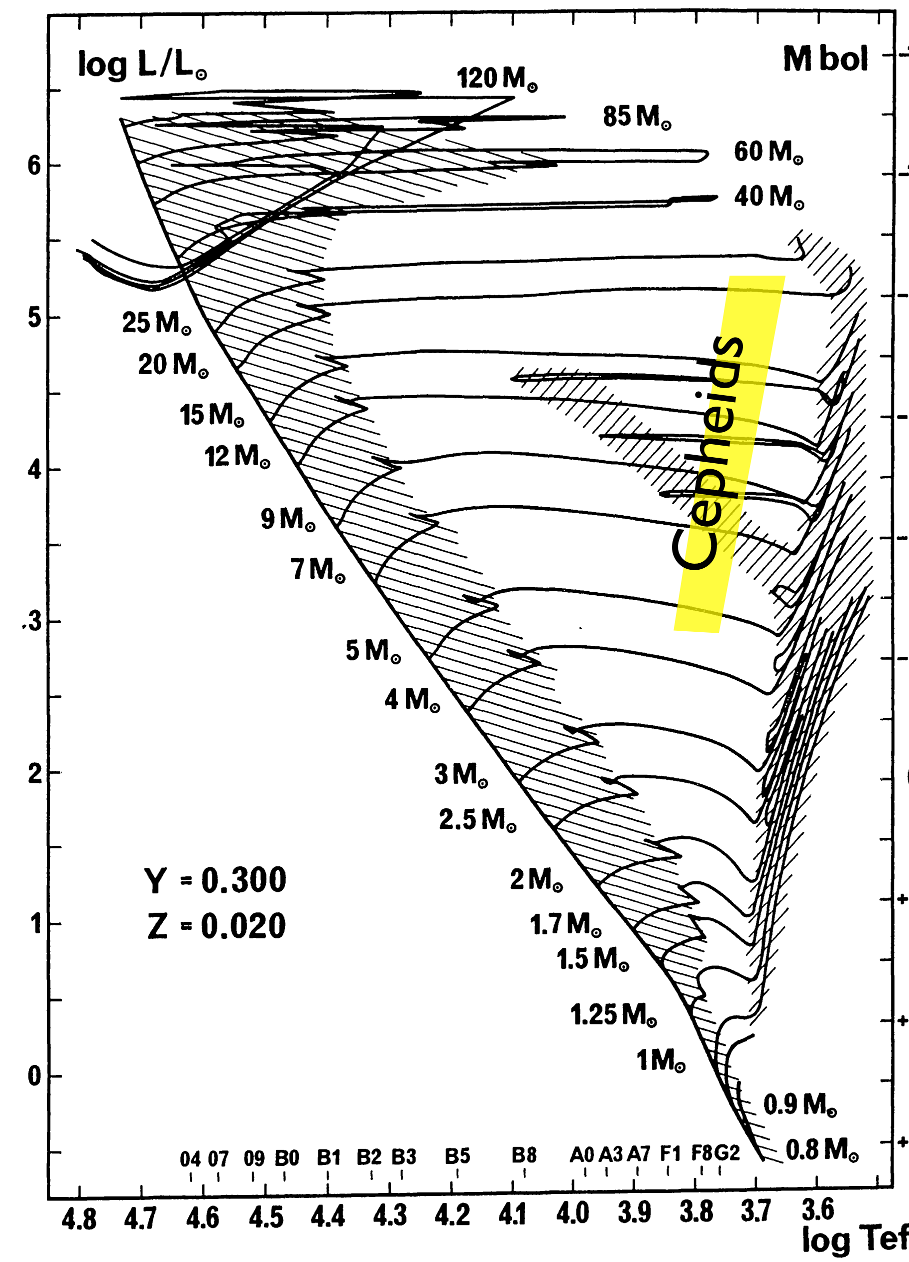
- Recent period-luminosity relations for Cepheids give

$$M_V = -2.76 \log P - 1.46$$

- The trend is even tighter when the *colour* of the Cepheid is included



- Cepheids are *massive* stars with temperatures near ~7000 K (~F stars)



- Because Cepheids are so bright --- the brightest Cepheids reach $\langle M_V \rangle$~-8 (!) --- Cepheids can be used for indirect distances out to ~20 Mpc
  - Note that this is well beyond this distance of NGC 4258, allowing for a direct comparison of the Cepheid distance with the maser distance for this galaxy --- with a difference within the error bars of both methods, confirming that the Cepheid scale is reasonable for local galaxies

- Note also that the reason that Hubble got the distance to M31 (Andromeda) wrong was that Cepheids actually come in *two* (well, three!) flavors:
  - “Classical” Cepheids
  - Metal-poor Cepheids, also called *W Virginis* stars, which are less luminous by a factor of 4 --- and it was these that Hubble thought he was using

- There are also even fainter Population II (i.e., metal-poor) pulsating stars that can be used as standard candles: these are called *RR Lyrae* stars

    - The calibration for the Cepheid distance scale actually rested in large part on the calibration of the RR Lyrae distance to the LMC until recently

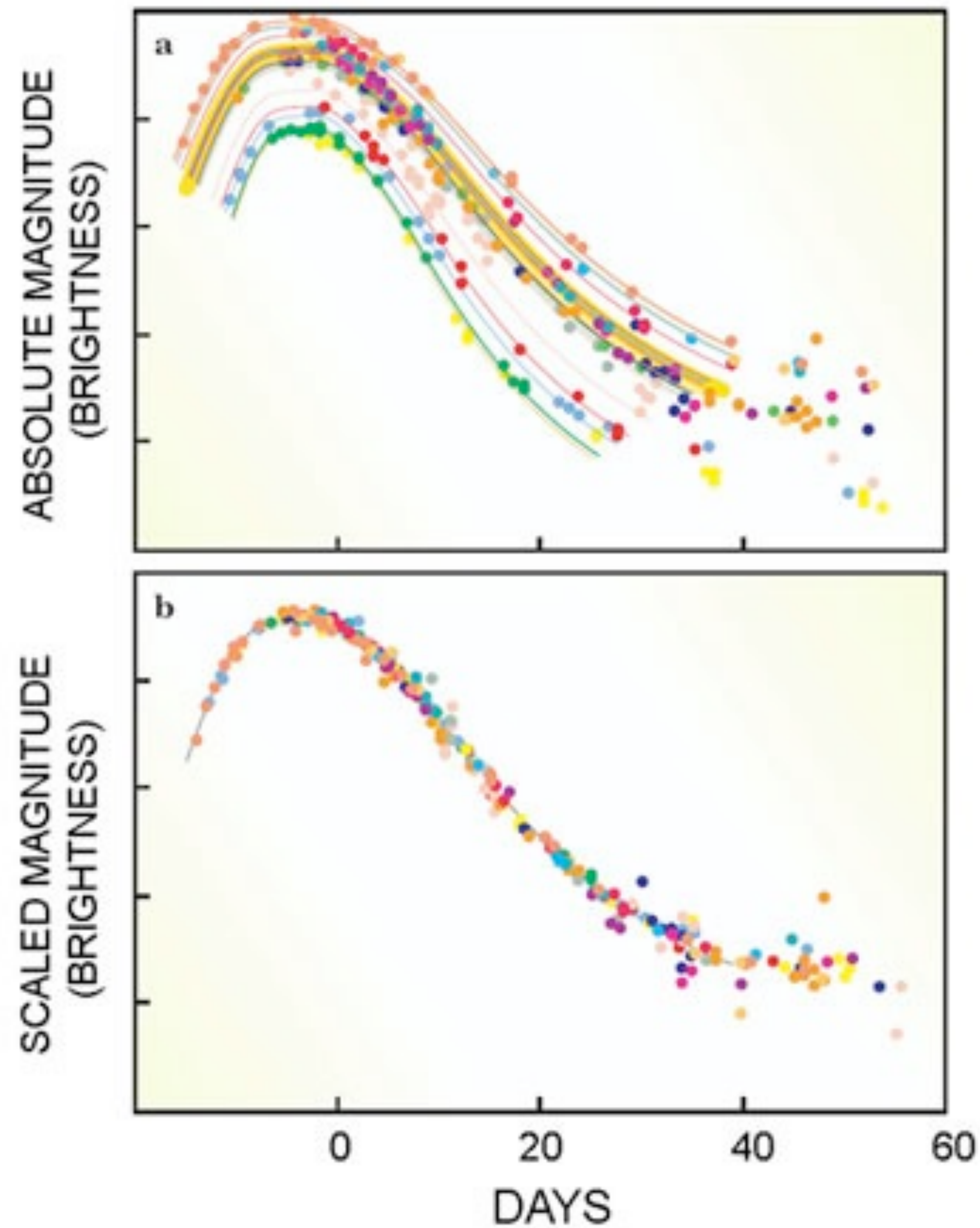
Supernovae

- The distance to a supernova can be measured by measuring the temperature and the expansion velocity of its photosphere:

$$L = 4\pi R^2(t)\sigma T_{\rm eff}^4$$

where the radius $R(t)=v_{\rm ph}t$ and t is the time since the explosion, assuming constant expansion velocity

- For type Ia supernovae, this method allows us to estimate that their peak brightness is $\langle M_B \rangle \approx \langle M_V \rangle \approx -19.3 \pm 0.03$
  - But it has been determined that *not all SNe Ia* have this peak brightness!
  - However, the *width* or *shape* of the light curve of the SN is correlated with the peak brightness, allowing for a correction



- Type Ia supernovae can be used as distance indicators to (staggeringly!) high distances: the record holder for the redshift of a SN Ia is at $z \sim 1.6$ (!)

  - In fact, the distances to SNe Ia are the reason we believe the Universe is presently *accelerating* and therefore is one of the observations that suggest that *dark energy* is a major contributor to the energy density of the Universe!

Other sort-of-standard candles

- Two other classes of objects used to be used:
  - Planetary nebula have a sharp(ish) cutoff in their *luminosity function* --- that is, the number of objects per decade in luminosity --- with a maximum brightness that appears to be ~constant
    - However, it's really only possible to see PNe out to distances of ~50 Mpc, and SNe Ia are easier to observe!

- Globular clusters have a ~Gaussian-shaped luminosity function that peaks at a magnitude of M~-6.6
  - Two problems:
    - Fainter than the brightest Cepheids!
    - Not clear if the peak is *always* at the same magnitude

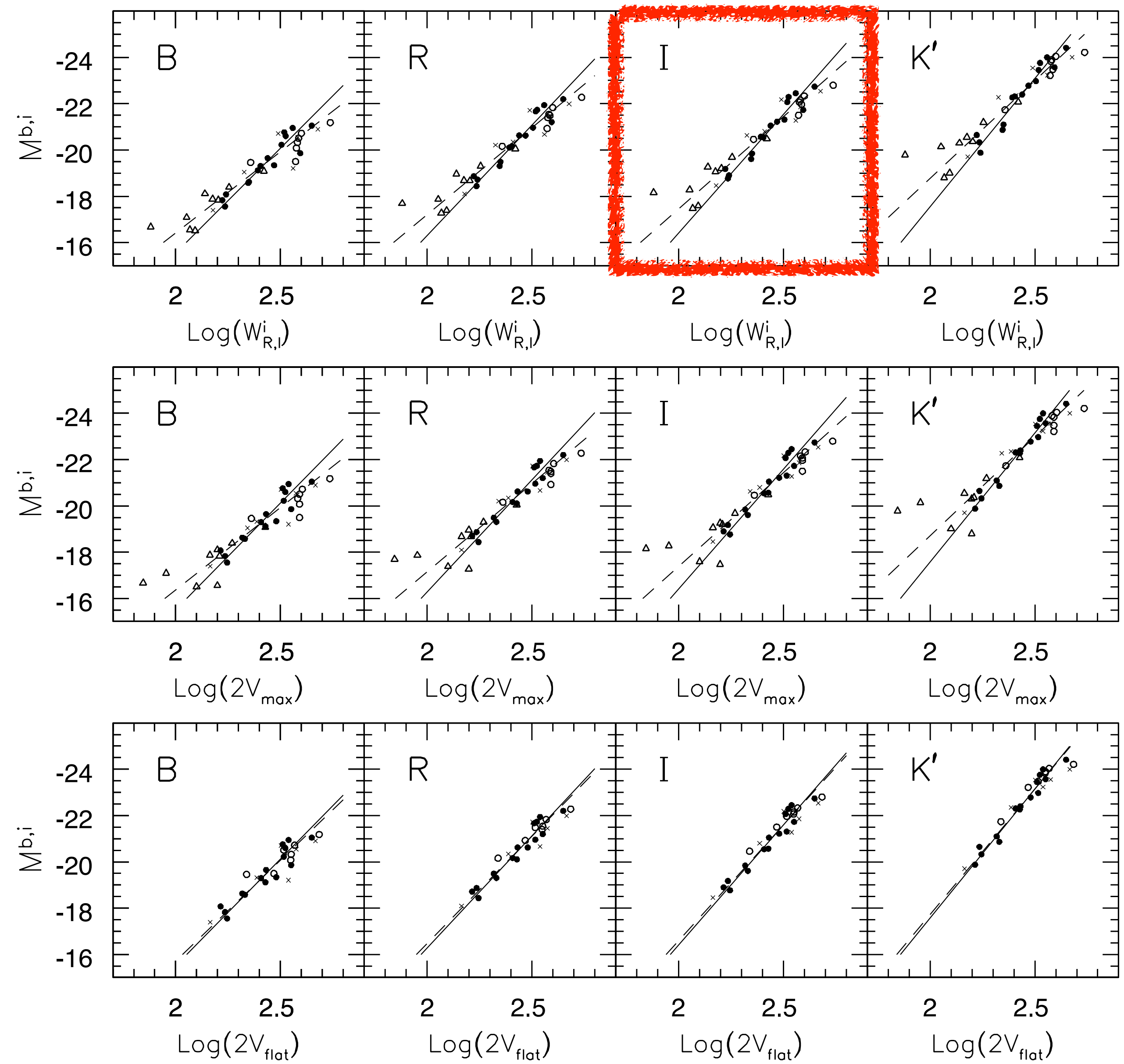
“Dynamical” distance indicators

- Both the Tully-Fisher (TF) relation and the Fundamental Plane (FP) and its projection, the D_n-σ relation, can be used to measure the distances to galaxies, because they all (roughly) depend on luminosity as

$$L \propto v^4$$

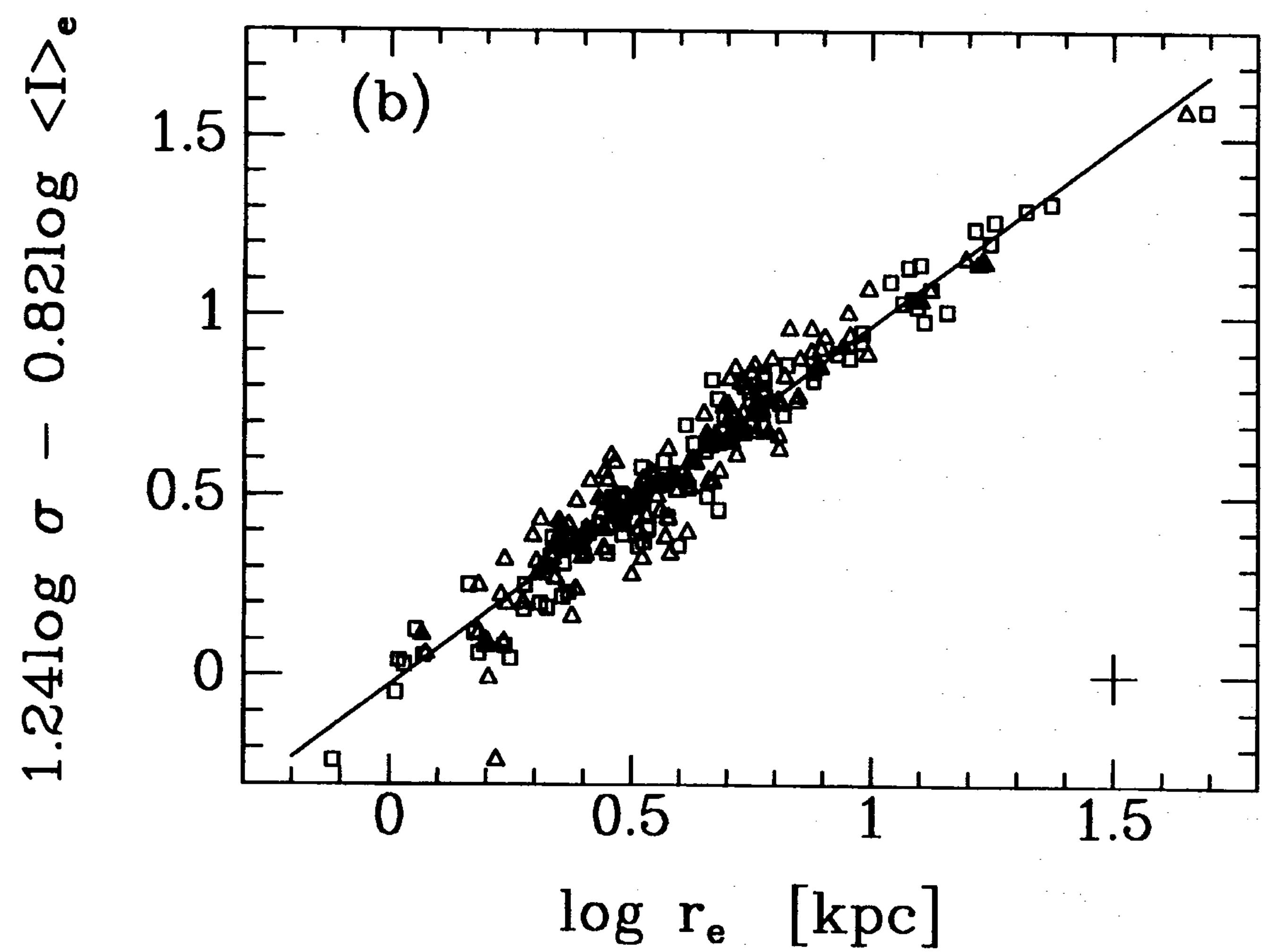
TF as a distance indicator

- *If* you can calibrate a large enough number of spiral galaxies with good rotation curves, you can use the TF relation as a distance indicator
  - Problems: need to have excellent radio and optical data; need to "weed out" galaxies that don't fit; only Sc galaxies really fit; need to choose bandpass and velocity measurement correctly; not that many Sc's with good Cepheid distances



The FP as a distance indicator

- Recall that the Fundamental Plane is a relation between velocity dispersion, surface brightness, and effective radius
    - The first two of those are *distance-indepedent*, so the FP actually gives you a *standard ruler*, not a standard candle

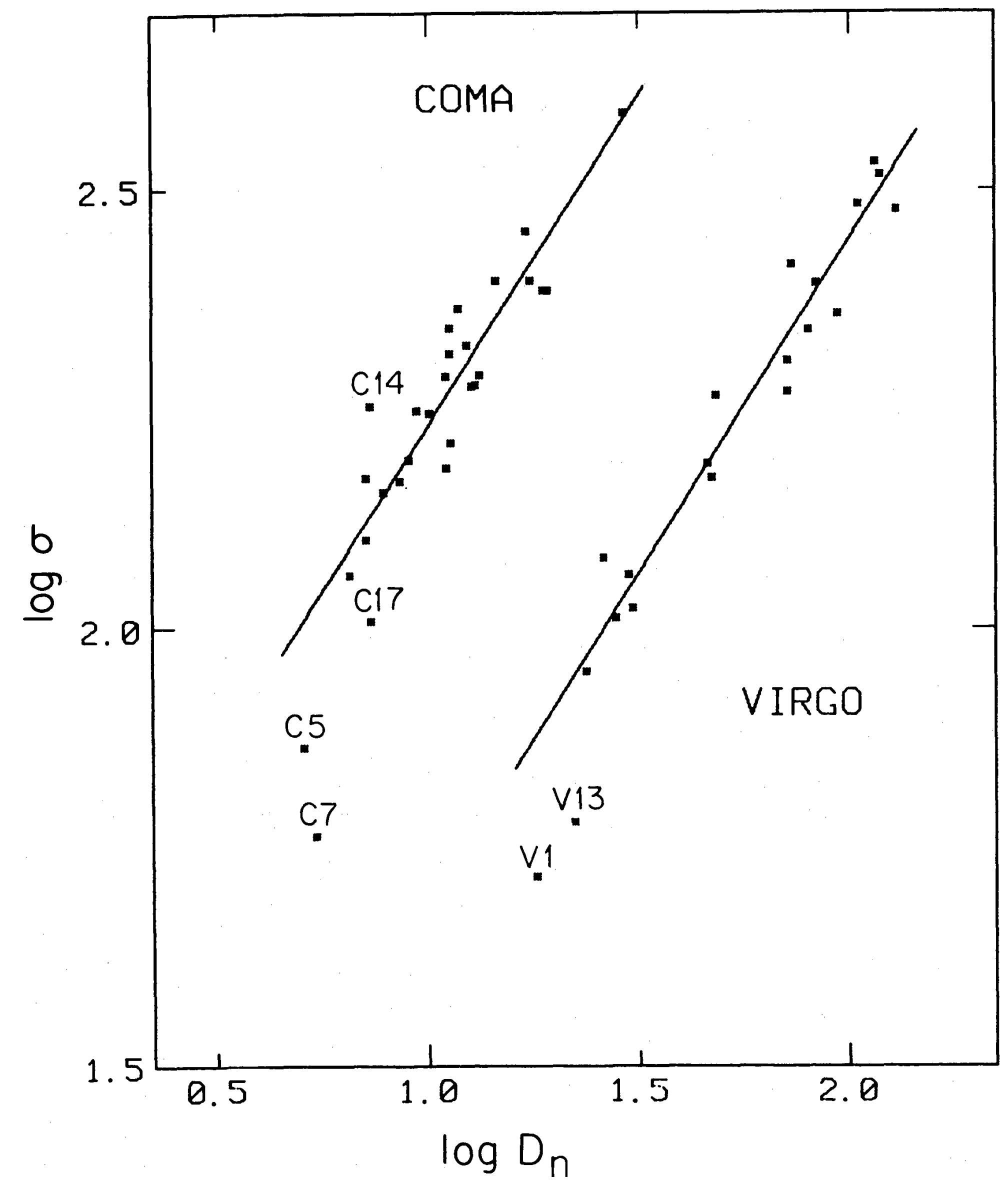


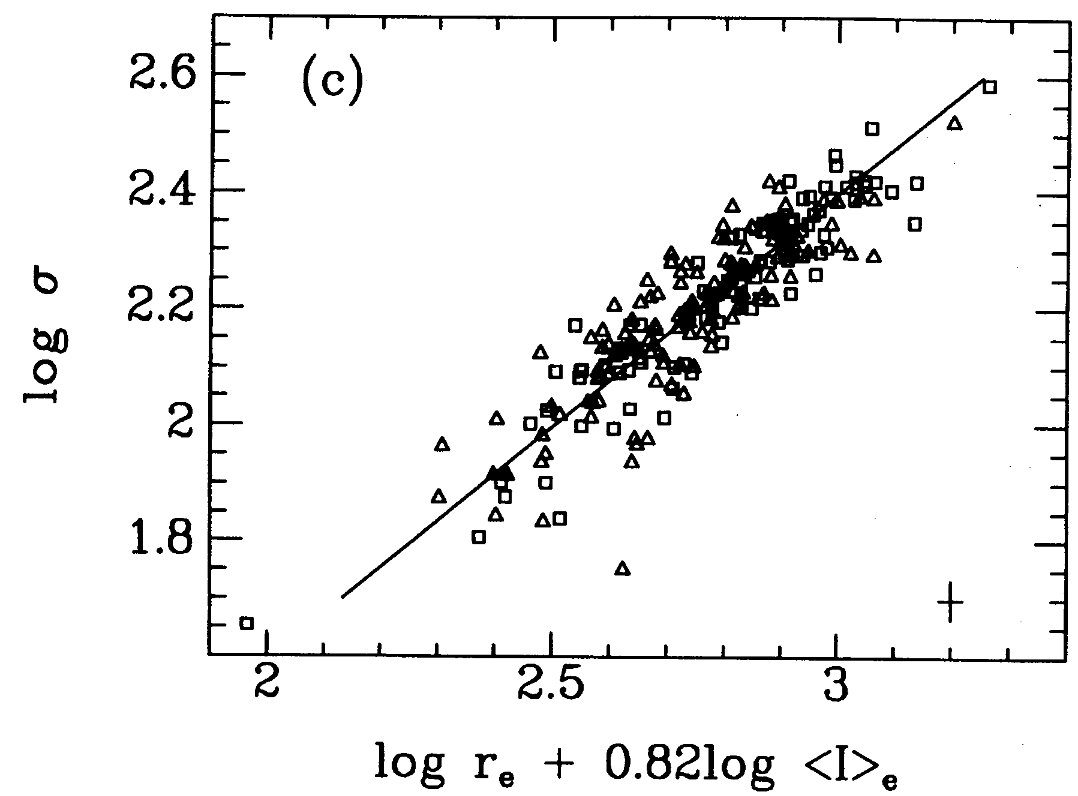
- In fact, a combination of surface brightness and radius, called D_n, the radius at a surface brightness of 20.75 in the *B* band, is very well correlated with the velocity dispersion:

$$\log D_n = 1.33 \log \sigma + C$$

- This makes D_n a standard length

- The problem is that Cepheids don't occur in elliptical galaxies (which have *old* populations) and other variables (like RR Lyraes) are too faint
    - Need either *clusters of galaxies* with spirals with known Cepheid distances or SN Ia to calibrate





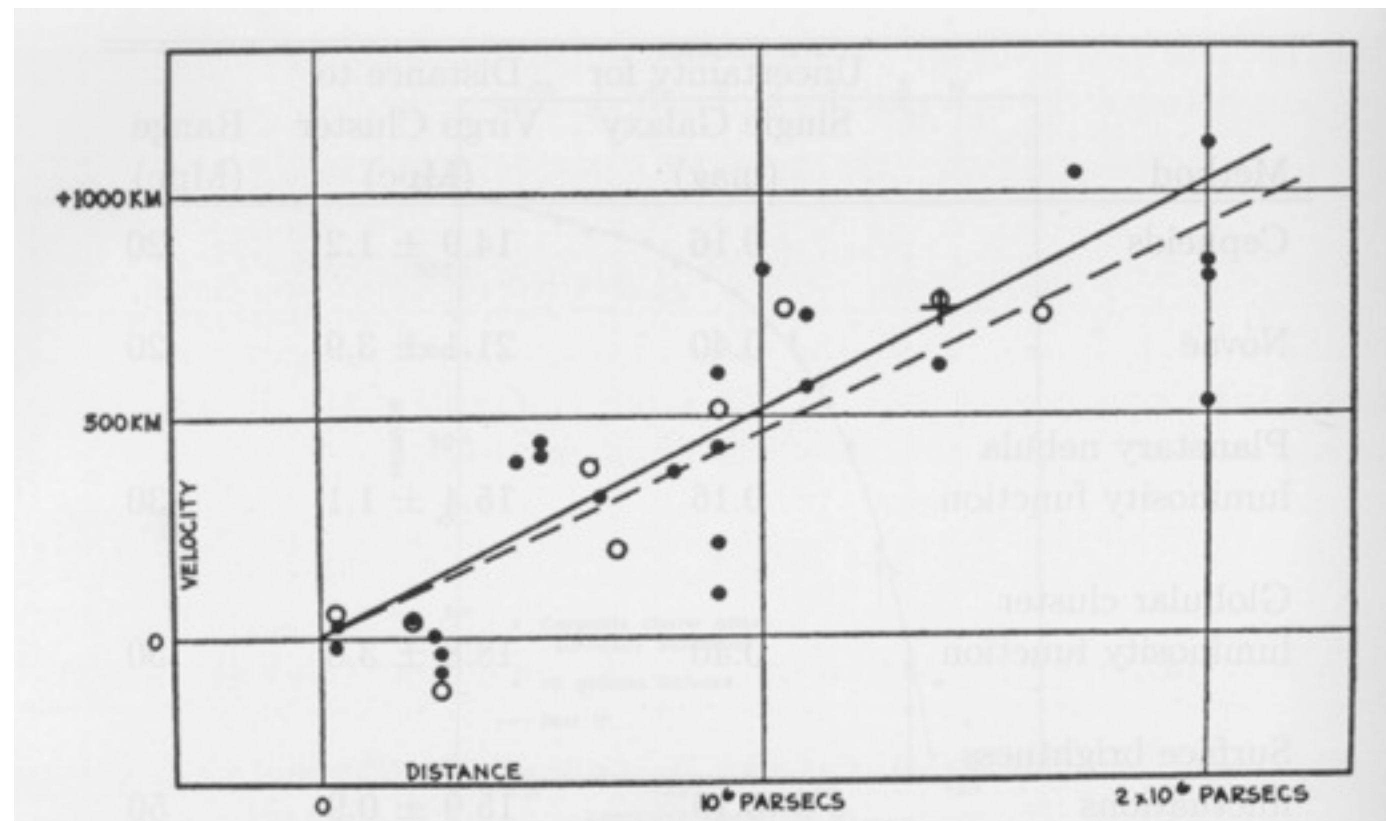
- In fact, distances to *individual galaxies* using D_n-σ (or the full FP) or TF are pretty uncertain, so entire clusters of galaxies (or at least *groups* of galaxies) are used to get accurate distances

The Hubble Law and the Hubble Constant

- In 1912, V.M. Slipher announced that he had computed radial velocities for 12 spiral nebulae and found that they were all (except for M31) moving away from the Milky Way, because their spectra were redshifted
  - by 1925, he had found that nearly every one of 40 nearby galaxies with redshifts were redshifted and moving away from us

- In 1929, Edwin Hubble presented a paper in which he showed that the *distances* to 18 galaxies inferred from Cepheid variables *were directly proportional to their velocities* (as measured by Slipher):

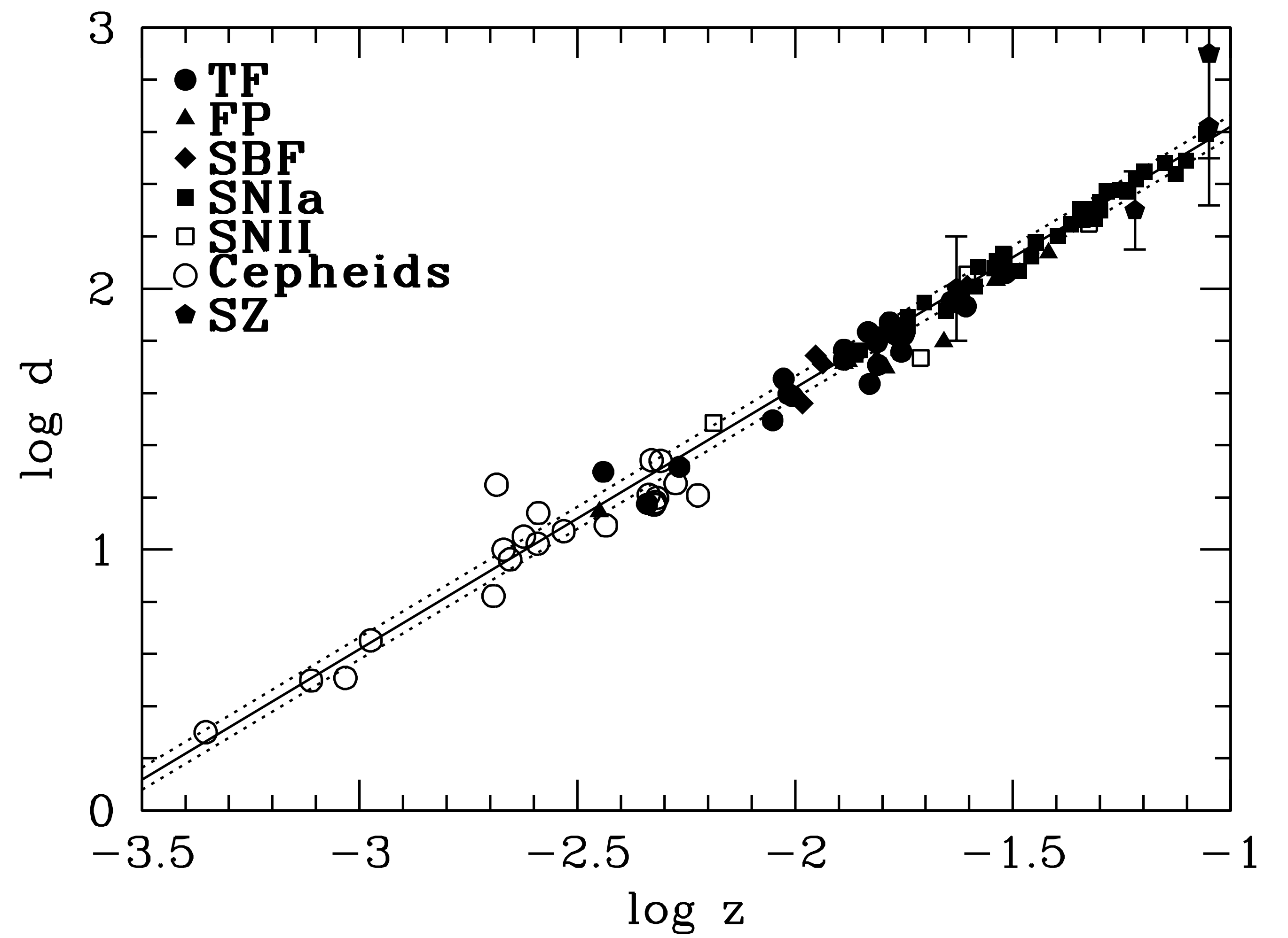
$$v = H_0 d$$



- 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} = 72±8 km s^{-1} Mpc^{-1}, where *h*=0.72 is used to parameterize the Hubble constant



$$\approx \log(v/c) = \log v - \log c$$

Note how each method takes you out a little further: That's why this is often called the "Cosmic Distance Ladder"

- 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!)