Classical Cosmology

Classical Cosmology

To understand what universe we live in, we need to determine observationally the following numbers:

1. The Hubble constant, H_0
   $\Longrightarrow$ Requires distance measurements.
2. The current density parameter, Ω_0
   $\Longrightarrow$ Requires measurement of the mass density.
3. The cosmological constant, Λ
   $\Longrightarrow$ Requires acceleration measurements.
4. The age of the universe, t_0, for consistency checks
   $\Longrightarrow$ Requires age measurements.

The determination of these numbers is the realm of classical cosmology.

First part: Distance determination and H_0!

Introduction, I

Distances are required for determination of H_0.

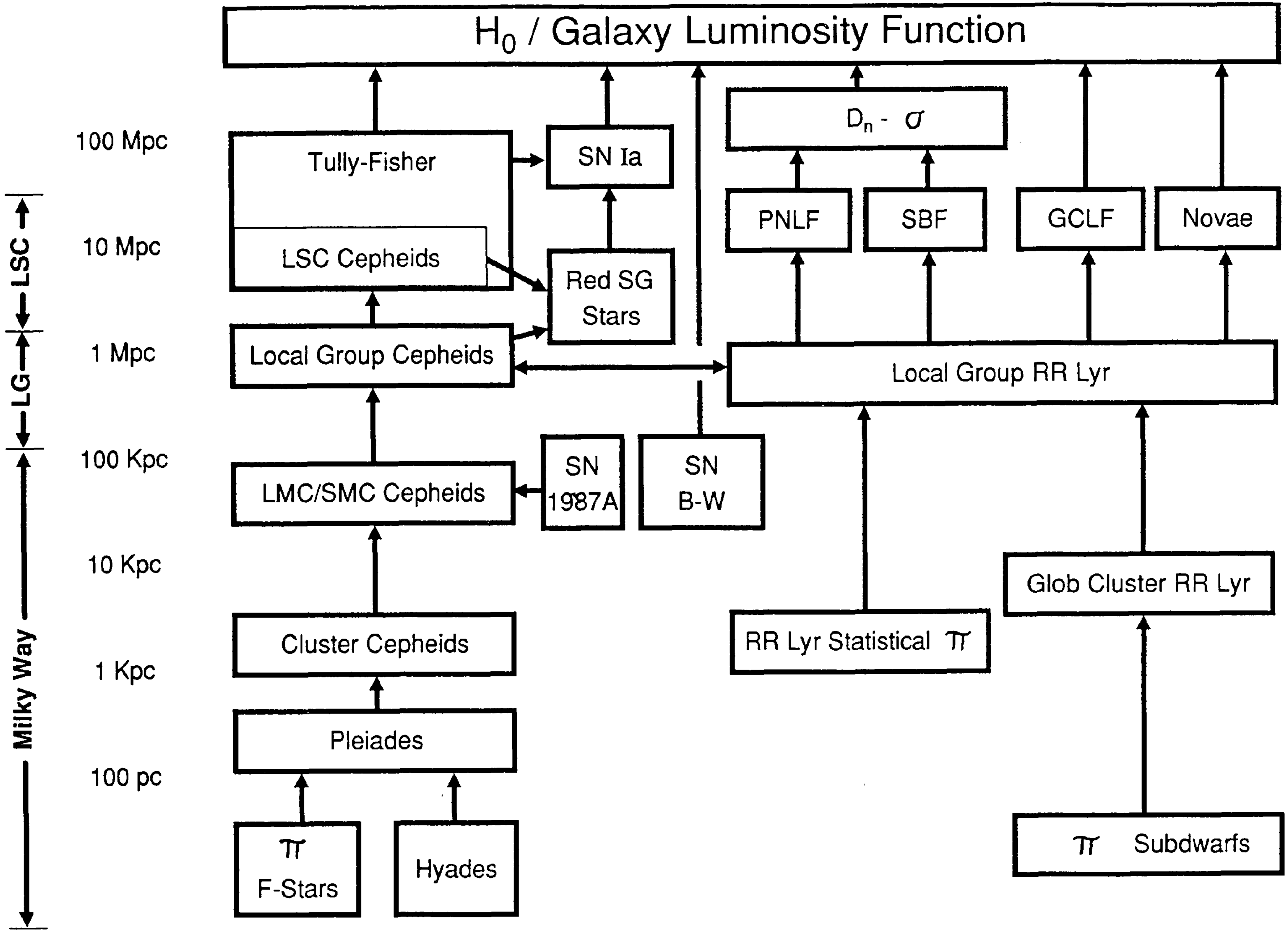
$\Longrightarrow$ Need to measure distances out to ~200 Mpc to obtain reliable values.

To get this far: cosmological distance ladder.

1. Trigonometric Parallax
2. Moving Cluster
3. Main Sequence Fitting
4. RR Lyr
5. Baade-Wesselink
6. Cepheids
7. Light echos
8. Luminosity function of planetary nebulae
9. Brightest Stars
10. Type Ia Supernovae
11. Tully-Fisher
12. D_n-σ for ellipticals
13. Brightest Cluster Galaxies
14. Gravitational Lenses

The best reference is

Rowan-Robinson, M., 1985, The Cosmological Distance Ladder, New York: Freeman



Pathways to Extragalactic Distances

(Jacoby et al., 1992, Fig. 1)

Units

Basic unit of length in astronomy: Astronomical Unit (AU).

Colloquial Definition: 1 AU$=$mean distance Earth–Sun.

Measurement: (Venus) radar ranging, interplanetary satellite positions, χ^2 minimization of N-body simulations of solar system

1 AU $\sim$ 149.6 $\times$ 10^6 km

In the astronomical system of units (IAU 1976), the AU is defined via Gaussian gravitational constant (k).

Acceleration:

$$\ddot{\mathbf{r}} = -\frac{k^2(\mathbf{1}+m)\mathbf{r}}{r^3}$$

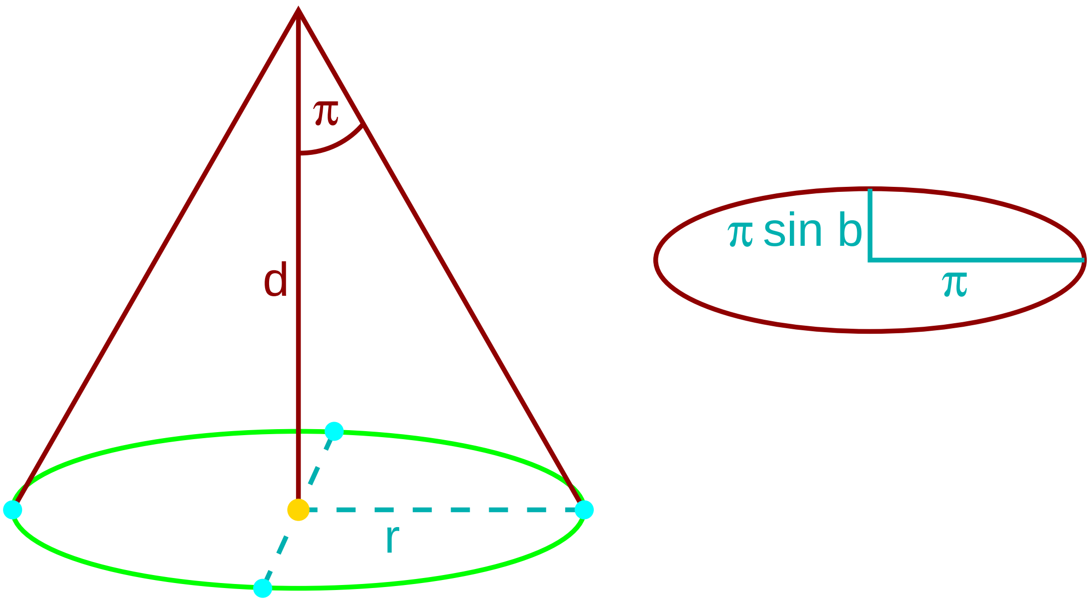
where $k = 0.01720209895$, leading to

$a_{♁} = 1.00000105726665$, and

1 AU=1.4959787066 $\times$ 10^{11} m (Seidelmann, 1992).

Reason for this definition: k much better known than G.

Trigonometric Parallax, I



after Rowan-Robinson (1985, Fig. 2.1)

Motion of Earth around Sun $\Longrightarrow$ Parallax

produces apparent motion by amount

$$\tan\pi \sim \pi = \frac{r_\male}{d} \qquad (5.1)$$

π is called the trigonometric parallax, and *not* 3.141!

If star is at ecliptic latitude b, then ellipse with axes π and $\pi\sin b$.

Measurement difficult: $\pi \lesssim 0.76''$ (α Cen).

Define unit for distance:

Parsec: Distance where 1 AU has $\pi = 1''$.

$1\,\text{pc} = 206265\,\text{AU} = 3.08\times10^{18}\,\text{cm} = 3.26\,\text{ly}$

Trigonometric Parallax, II

Best measurements to date: Hipparcos satellite (with Tübingen participation).

- systematic error of position: $\sim$0.1 mas
- effective distance limit: 1 kpc
- standard error of proper motion: $\sim$1 mas/yr
- broad band photometry
- narrow band: $B - V$, $V - J$
- magnitude limit: 12
- complete to mag: 7.3–9.0

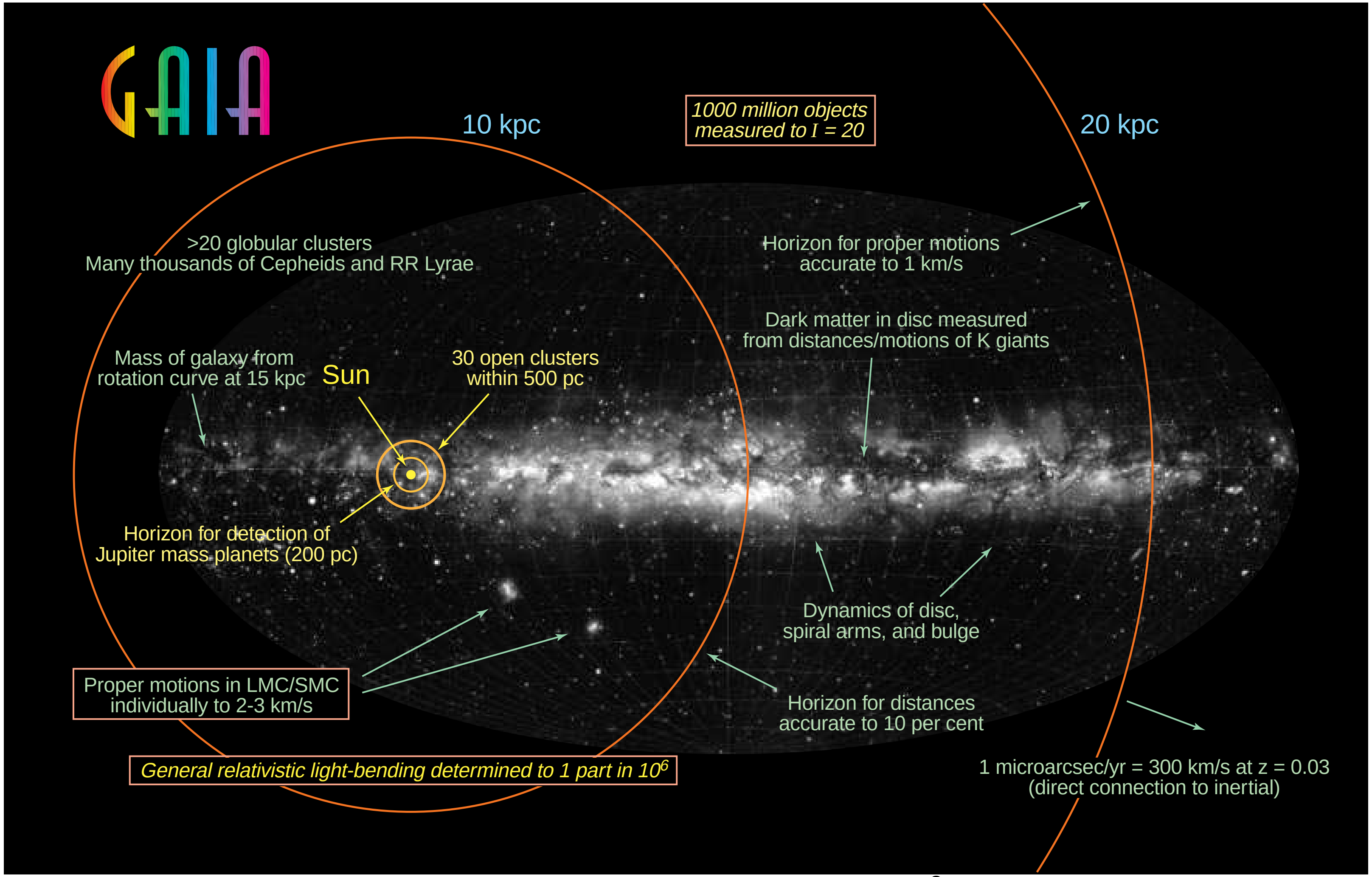
Results available at `http://astro.estec.esa.nl/Hipparcos/`:

Hipparcos catalogue: 120000 objects with milliarcsecond precision.

Tycho catalogue: 10^6 stars with 20–30 mas precision, two-band photometry

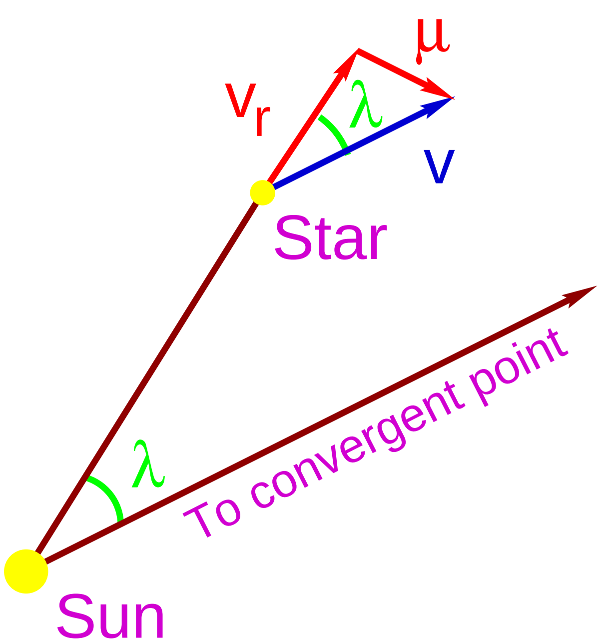
Trigonometric Parallax, III

Plans for the future: GAIA (ESA mission, ∼2010–2012):



GAIA: $\sim 4\mu$arcsec precision, 4 color to $V = 20$ mag, 10^9 objects.

Moving Cluster, I



Perspective effect of spatial motion towards convergent point:

$$\tan\lambda = \frac{v_\mathrm{t}}{v_\mathrm{r}} = \frac{\mu d}{v_\mathrm{r}} \tag{5.2}$$

or

$$\frac{d}{1\,\mathrm{pc}} = \frac{v_\mathrm{r}/(1\,\mathrm{km/s})\tan\lambda}{4.74\,\mu/(1''/\mathrm{a})} \tag{5.3}$$

Problem: determination of convergent point

Less error prone: moving cluster method = rate of variation of angular diameter of cluster:

$$\dot{\theta} d = \theta v_\mathrm{r} \tag{5.4}$$

Observation of proper motions gives

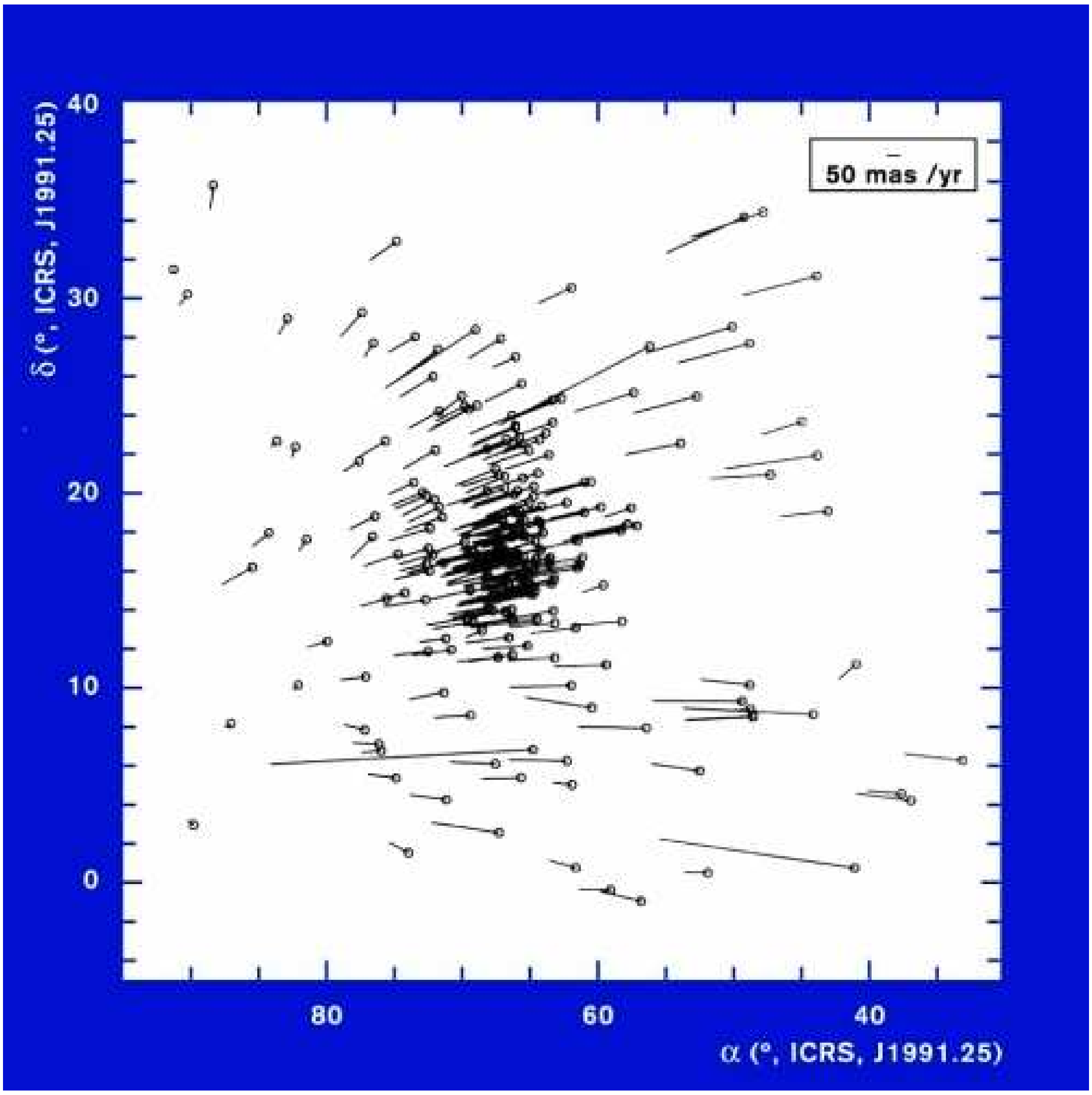
$$\frac{\dot{\theta}}{\theta} = \frac{\mathrm{d}\mu_\alpha}{\mathrm{d}\alpha} = \frac{\mathrm{d}\mu_\delta}{\mathrm{d}\delta} \tag{5.5}$$

where $\mu_{\alpha,\delta}$ proper motion in α and δ, and from Eq. (5.4),

$$d = v_\mathrm{r}\,\frac{\dot{\theta}}{\theta} \tag{5.6}$$

v_r from spectroscopical radial velocity measurements.

Moving Cluster, II



Source: ESA

Application: Distance to Hyades.

Tip of "arrow": Position of stars in 100000 a.

Moving cluster (Hanson): DM $\sim$ 3.3.

Hipparcos: geometric distance to Hyades is $d = 46.34 \pm 0.27$ pc, i.e., DM $= 3.33 \pm 0.01$ mag $\Longrightarrow$ Moving cluster method only of historic interest.

Interlude

Parallax and Moving Cluster: geometrical methods.

All other methods (exception: light echoes): standard candles.

Requirements for standard candles (Mould, Kennicutt, Jr. & Freedman, 2000):

1. Physical basis should be understood.
2. Parameters should be measurable objectively.
3. No corrections (“fudges”) required.
4. Small intrinsic scatter ($\Longrightarrow$ requiring small number of measurements!).
5. Wide dynamic range in distance.

Magnitudes, I

Assuming isotropic emission, distance and luminosity are related ("inverse square law")
$\Longrightarrow$ luminosity distance:

$$F = \frac{L}{4\pi d_{\mathrm{L}}^2} \tag{5.7}$$

where F is the measured flux ($\mathrm{erg\,cm^{-2}\,s^{-1}}$) and L the luminosity ($\mathrm{erg\,s^{-1}}$).

Definition also true for flux densities, I_ν ($\mathrm{erg\,cm^{-2}\,s^{-1}\,Å^{-1}}$).

The magnitude is defined by

$$m = A - 2.5\log_{10} F \tag{5.8}$$

where A is a constant used to define the zero point (defined by $m = 0$ for Vega).

For a filter with transmission function ϕ_ν,

$$m_i = A_i - 2.5\log \int \phi_\nu F_\nu \,\mathrm{d}\nu \tag{5.9}$$

where, e.g., $i = U, B, V$.

Magnitudes, II

To enable comparison of luminosities: define

absolute magnitude M = magnitude at distance 10 pc

Thus, since $m = A - 2.5\log(L/4\pi d^2)$,

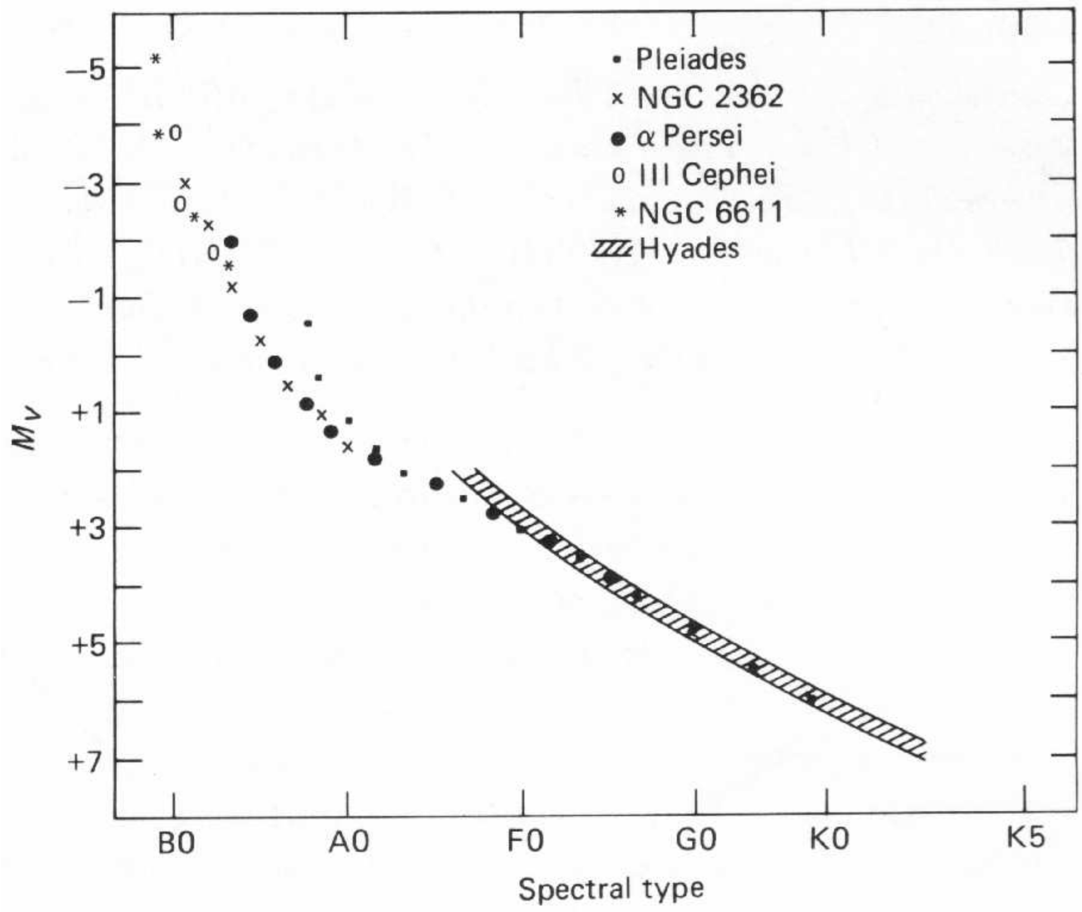
$$M = m - 5\log\left(\frac{d_\mathrm{L}}{10\,\mathrm{pc}}\right) \qquad (5.10)$$

The difference $m - M$ is called the distance modulus, μ_0:

$$\mu_0 = \mathrm{DM} = m - M = 5\log\left(\frac{d_\mathrm{L}}{10\,\mathrm{pc}}\right) \qquad (5.11)$$

Often, distances are given in terms of $m - M$, and not in pc.

Main Sequence Fitting, I



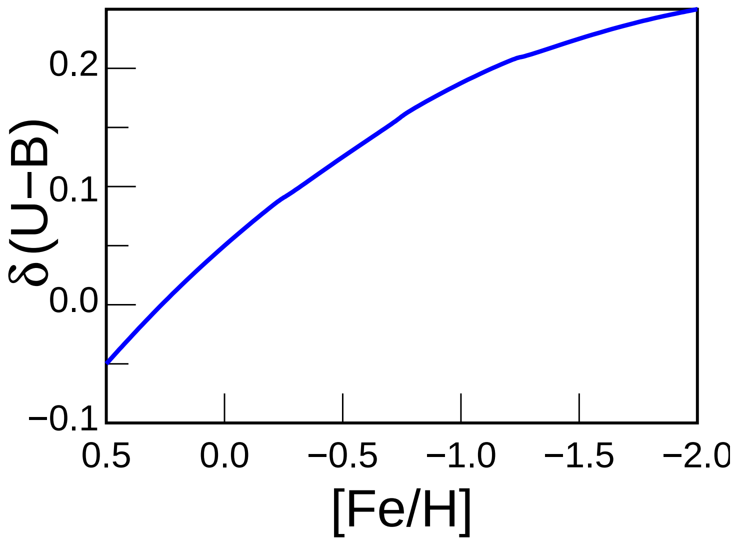
after Rowan-Robinson (1985, Fig. 2.11)

All open clusters are comparably young

$\Longrightarrow$ Hertzsprung Russell Diagram (HRD) dominated by Zero Age Main Sequence (ZAMS).

$\Longrightarrow$ Measure HRD (or Color Magnitude Diagram; CMD), shift magnitude scale until main sequence aligns $\Longrightarrow$ distance modulus.

Main Sequence Fitting, II



(after Rowan-Robinson, 1985, Fig. 2.12)

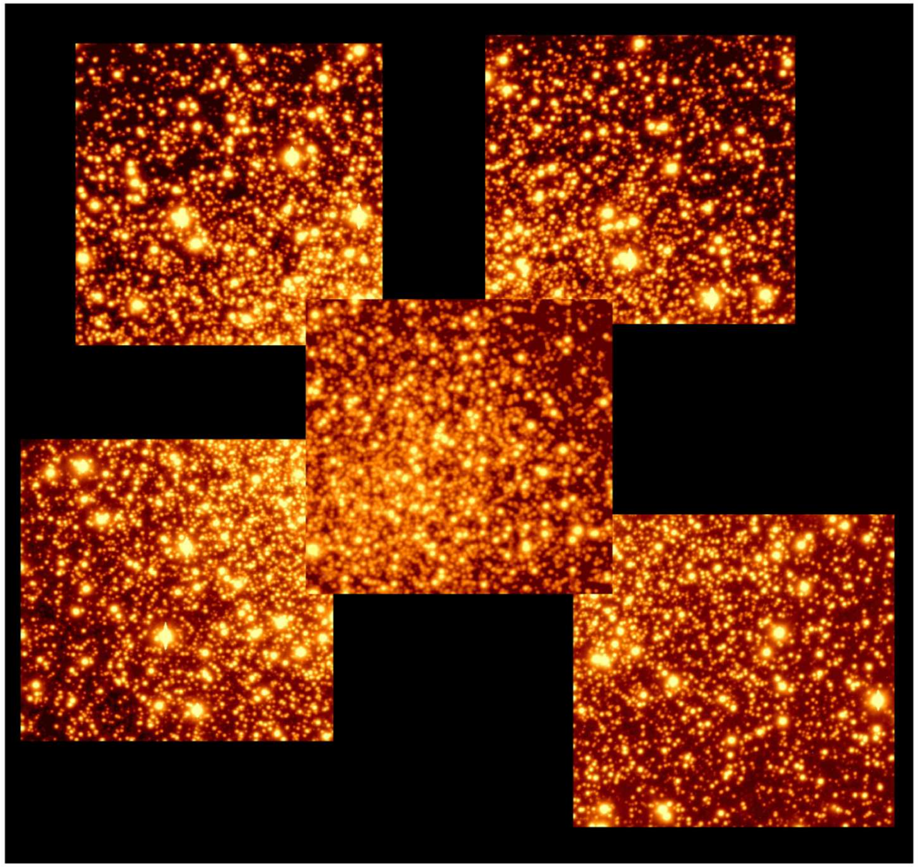
Caveats:

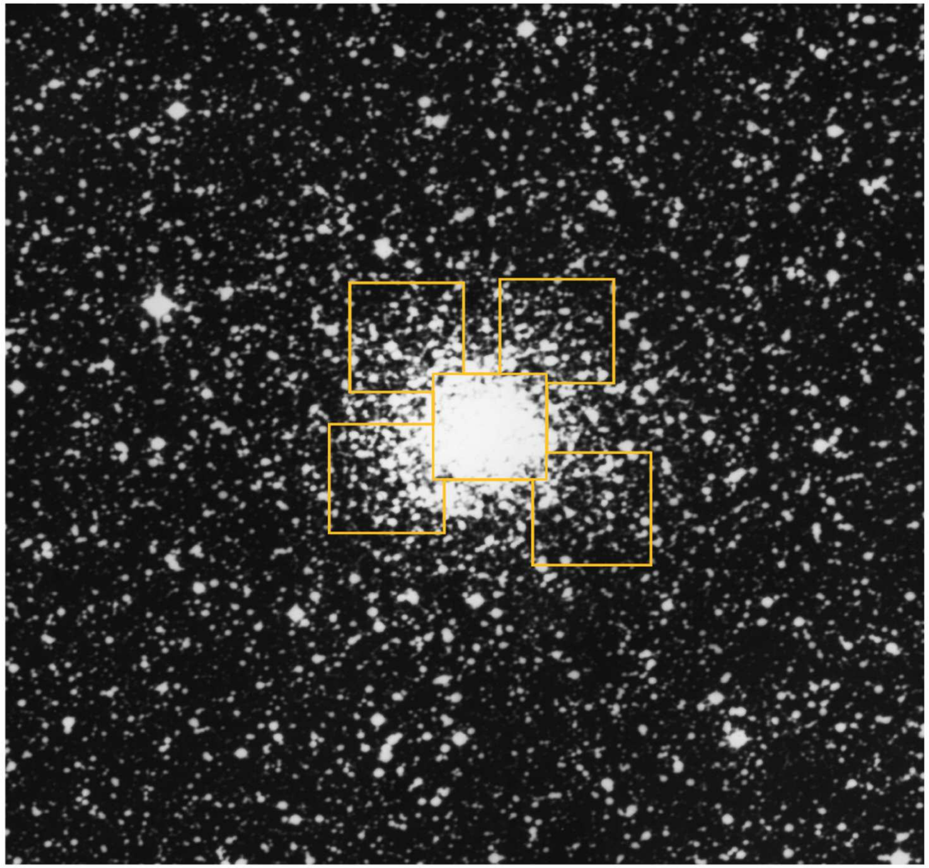
1. Location of ZAMS more age dependent than expected (van Leeuwen, 1999).
2. interstellar extinction $\Longrightarrow \mu_0 = \mu_\mathrm{V} - A_\mathrm{V}$, where μ_V, A_V DM/extinction measured in V-band.
3. metals: line blanketing (change in stellar continuum due to metal absorption lines, see figure) $\Longrightarrow$ Changes color $\Longrightarrow$ horizontal shift in CMD.

   van den Bergh (1977): $Z_\text{Hyades} \sim 1.6 Z_\odot$, while other open clusters have solar metallicity $\Longrightarrow$ Cepheid DM were overestimated by 0.15 mag.
4. identification of unevolved stars crucial (evolution to larger magnitudes on MS during stellar life).

Currently: distances to ∼200 open clusters known (Fenkart & Binggeli, 1979).

Distance limit ∼7 kpc.

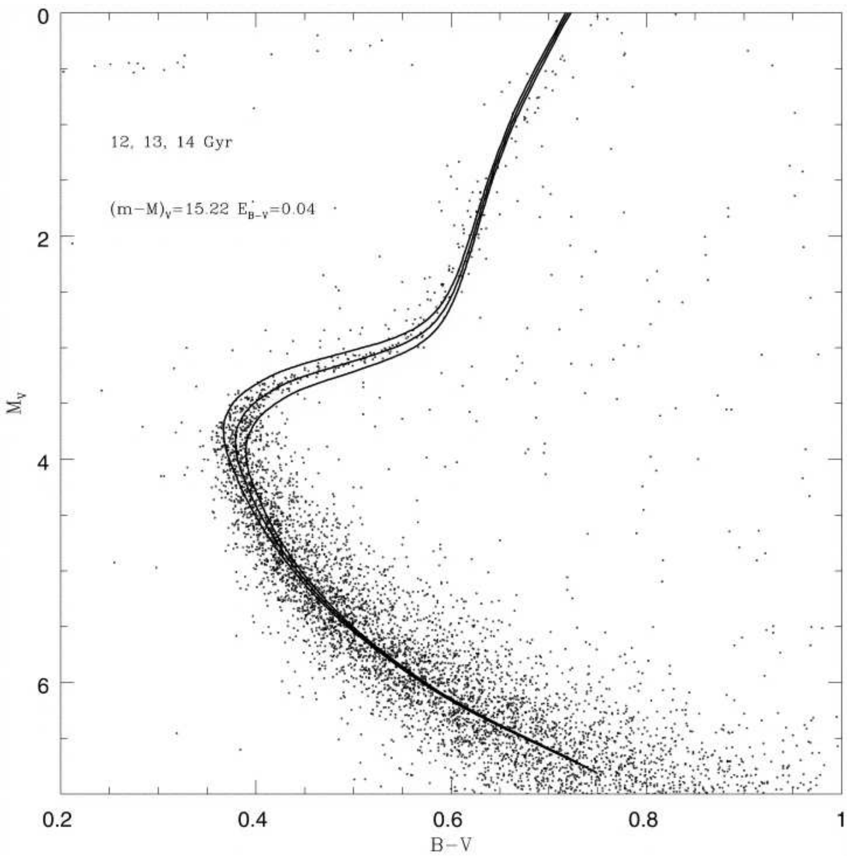




Globular Cluster NGC 6712

ESO PR Photo 06a/99 (18 February 1999)

Main Sequence Fitting, IV



(M68, Straniero, Chieffi & Limongi, 1997, Fig. 11)

Globular clusters: HRD different from open clusters:

- population II $\Longrightarrow Z \ll Z_\odot$
- evolved

Use theoretical HRDs (isochrones) to obtain distance.

For distant clusters: MS unobservable $\Longrightarrow$ position of horizontal branch.

Baade-Wesselink

Basic principle (Baade, 1926): Assume black body $\Longrightarrow$ Use color/spectrum to get kT_{eff} $\Longrightarrow$ Emitted intensity is Planckian $\Longrightarrow$ Observed Intensity is $I_\nu \propto \pi r_*^2 B_\nu$.

Radius from integrating velocity profile of spectral lines:

$$R_2 - R_1 = p \int_1^2 v \, \mathrm{d}t \tag{5.12}$$

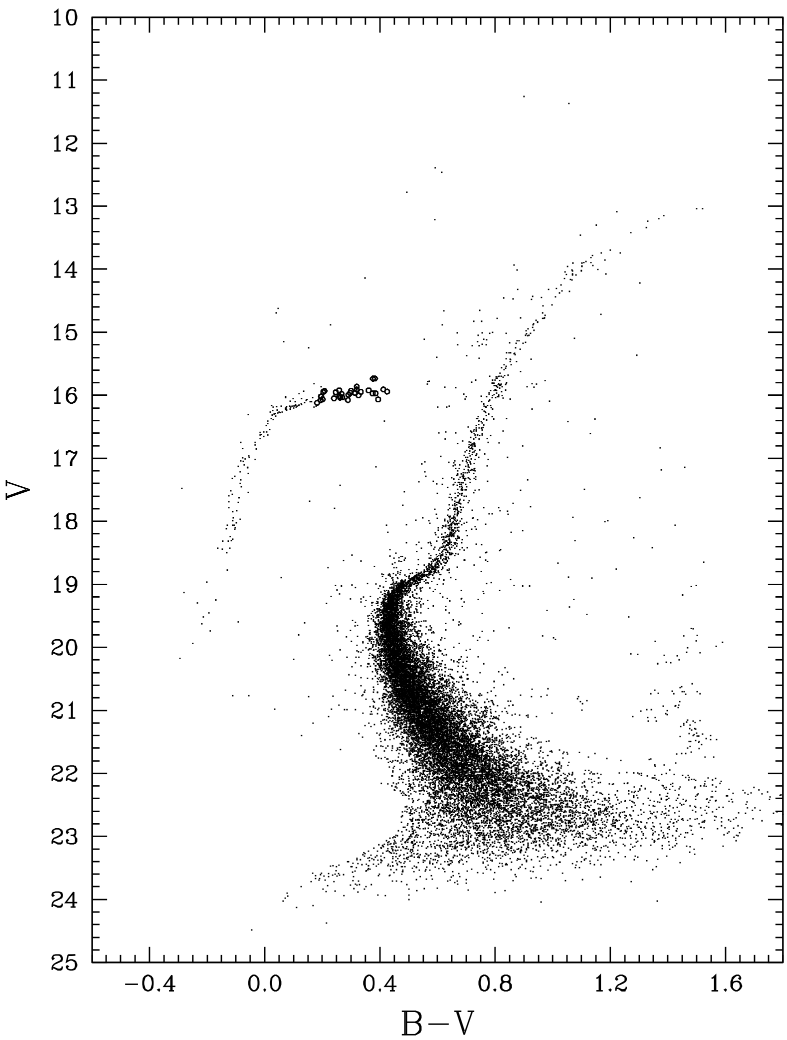
(p: projection factor between velocity vector and line of sight).

Wesselink (1947): Determine brightness for times of same color $\Longrightarrow$ rather independent of knowledge of stellar spectrum (deviations from B_ν).

Stars: Calibration using interferometric diameters of nearby giants.

Baade-Wesselink works for pulsating stars such as RR Lyr, Cepheids, Miras, and expanding supernova remnants.

RR Lyr, I



M2: Lee & Carney (1999, Fig. 2)

RR Lyrae variables: Stars crossing instability strip in HRD

$\Longrightarrow$ Variability ($P \sim 0.2\ldots1\,\mathrm{d}$)

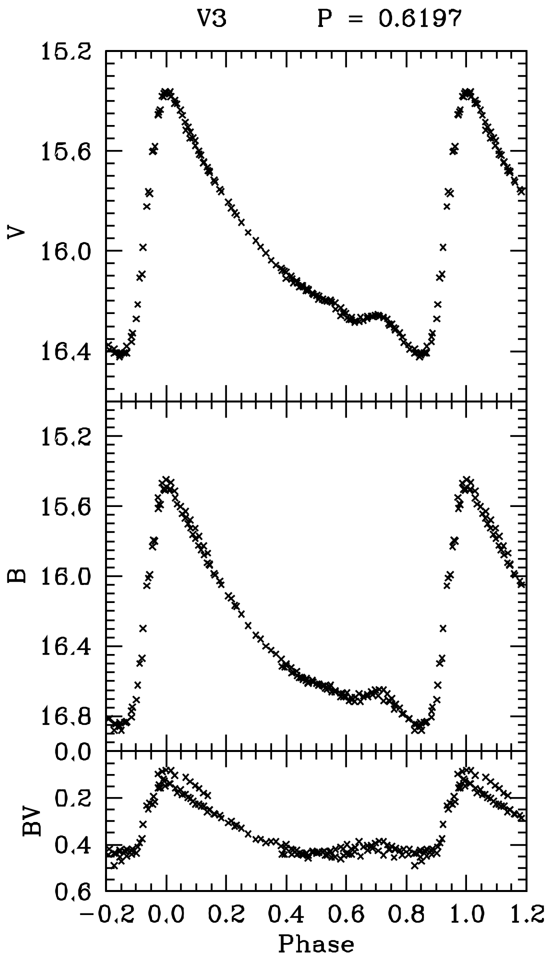
$\Longrightarrow$ RR Lyr gap (change in color!).

Absolute magnitude of RR Lyr gap:

$M_\mathrm{V} = 0.6$, $M_\mathrm{B} = 0.8$, i.e., $L_\mathrm{RR} \sim 50\,L_\odot$).

M determined from ZAMS fitting, statistical parallax, and Baade-Wesselink method.

RR Lyr, II



Lightcurve (here: Lee & Carney, 1999, Fig. 5) shows characteristic color variations over pulsation (temperature change!), and a fast rise, slow decay behavior.

RR Lyr in GCs show bimodal number distribution: RRab with $P > 0.5$ d and most probable period of $P_{ab} \sim 0.7$ d, and RRc, with $P < 0.5$ d and $P_c \sim 0.3$ d (metallicity effect).

Caveat: M dependent on metallicity: larger for higher Z (i.e., metal-rich RR Lyr are *fainter*, i.e., difference in RR Lyr from population I and II).

Works out to LMC and other dwarf galaxies of local group, however, used mainly for globular clusters.

Interlude, I

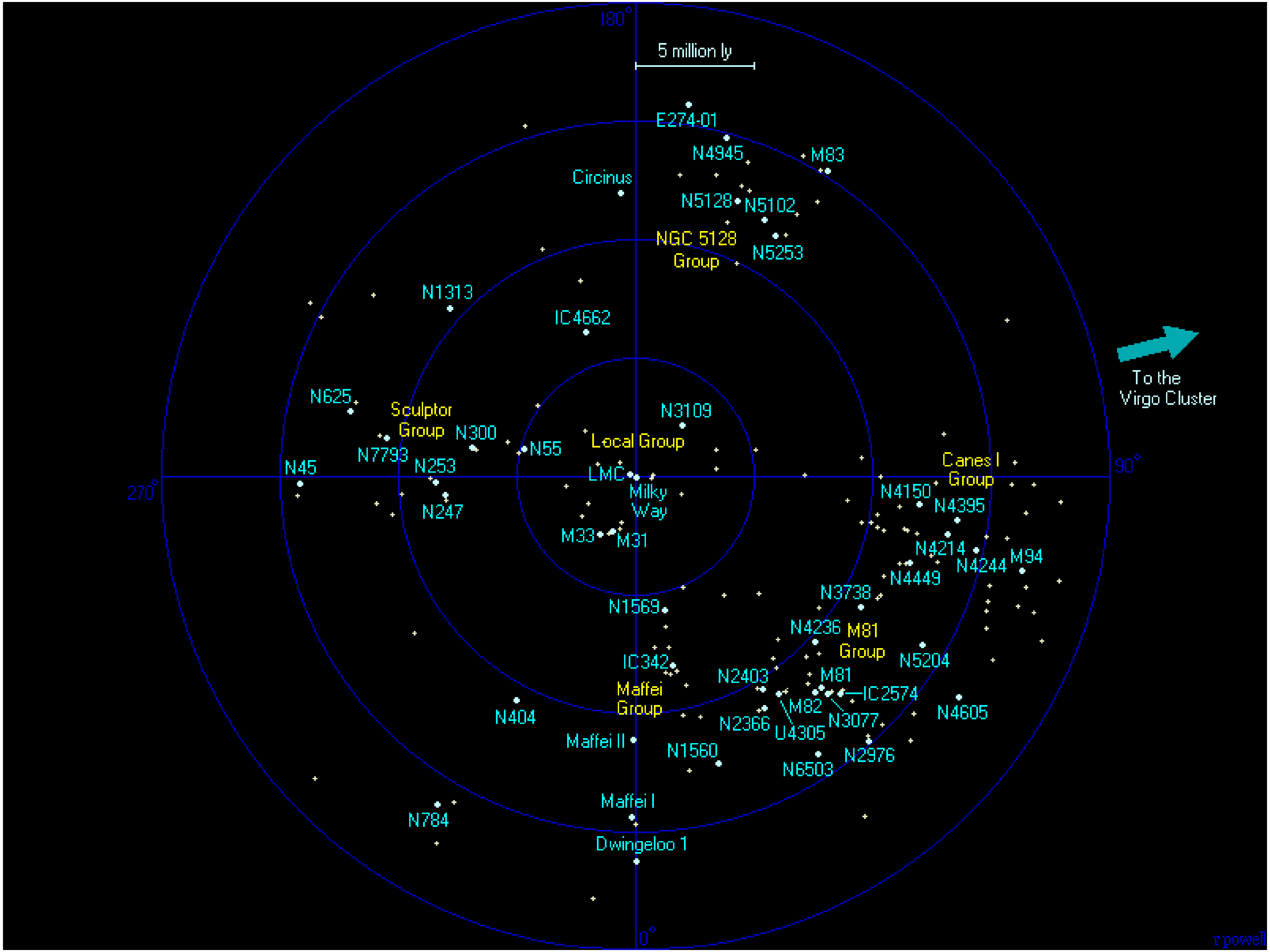
Previous methods: Selection of methods for distances within Milky Way (and Magellanic Clouds): Basis for extragalactic distance scale.

Primary extragalactic distance indicators:
Distance can be calibrated from observations *within* milky way or from theoretical grounds.

Primary indicators usually work within our neighborhood (i.e., out to Virgo cluster at 15–20 Mpc).
Examples: Cepheids, light echos,. . .

Secondary extragalactic distance indicators:
Distance calibrated from primary distance indicators.

Examples: Type Ia SNe, methods based on integral galaxy properties.



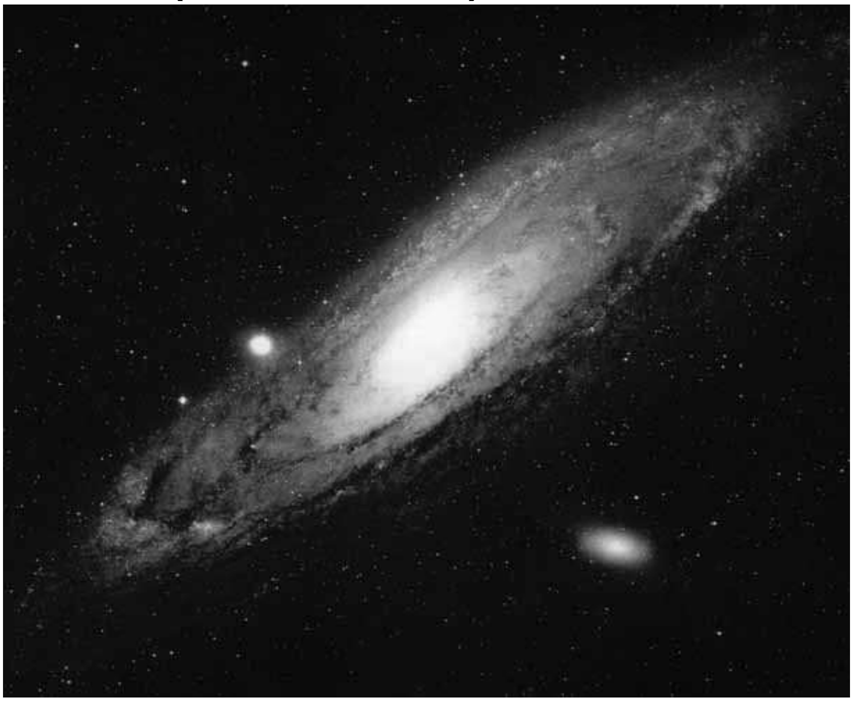
source: `http://anzwers.org/free/universe/galgrps.html`

Interlude, III

To get a feel for the distances in our "neighborhood":

50 kpc: LMC, SMC, some other dwarf galaxies

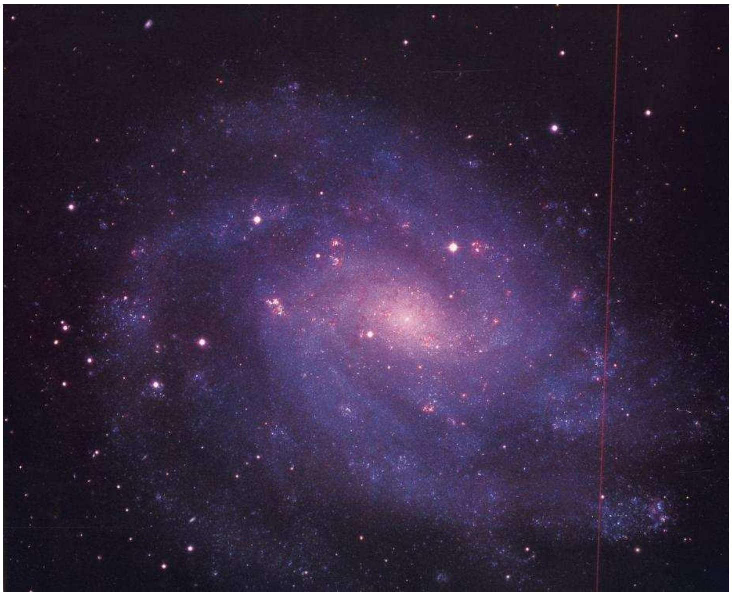
700 kpc: M31 (Andromeda)



Palomar Schmidt

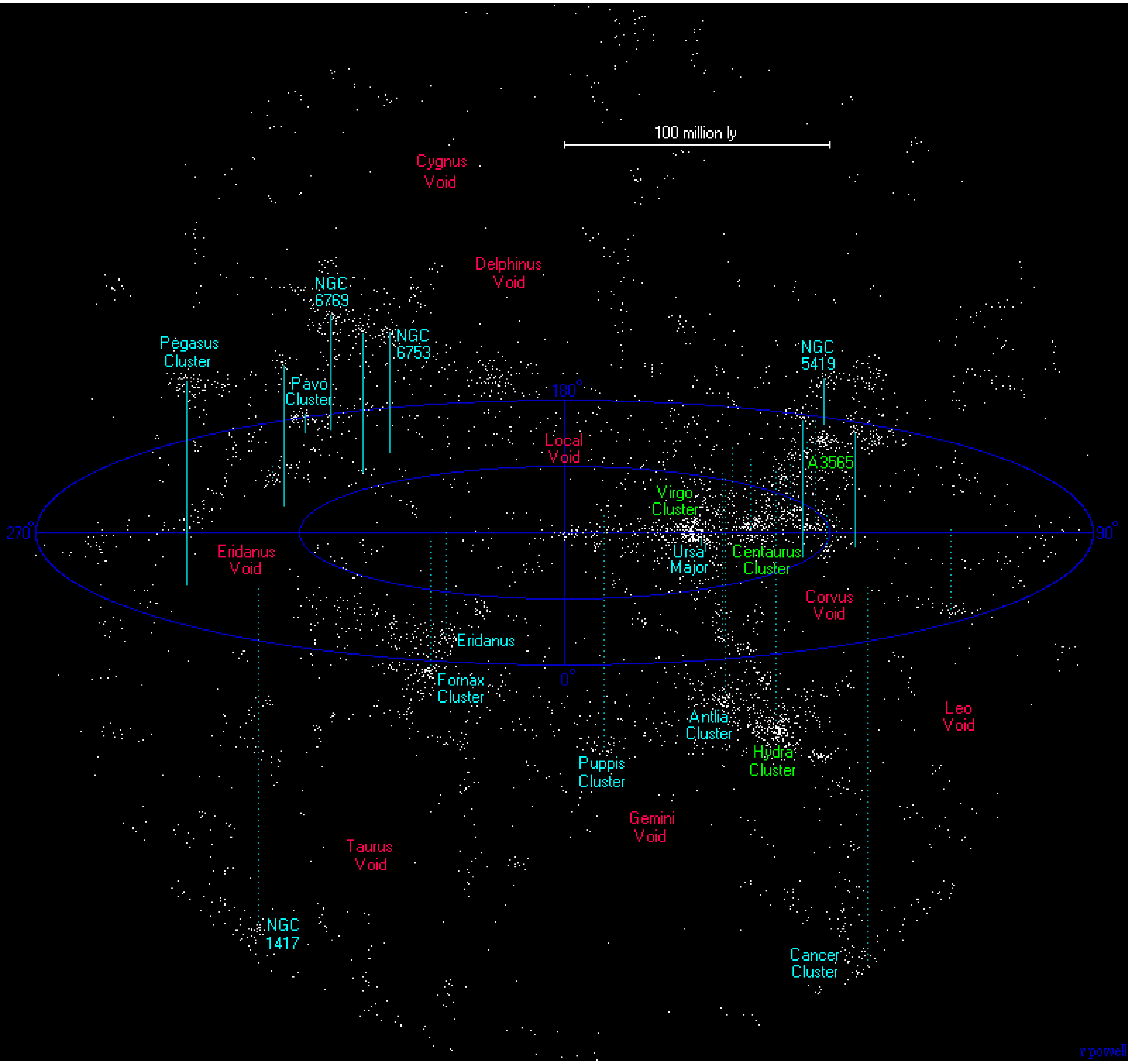
Interlude, IV

2–3 Mpc: Sculptor, M81 group (groups similar to local group: a few large spirals, plus smaller stuff).



NGC 300 (Sculptor; Laustsen, Madsen, West, 1991)

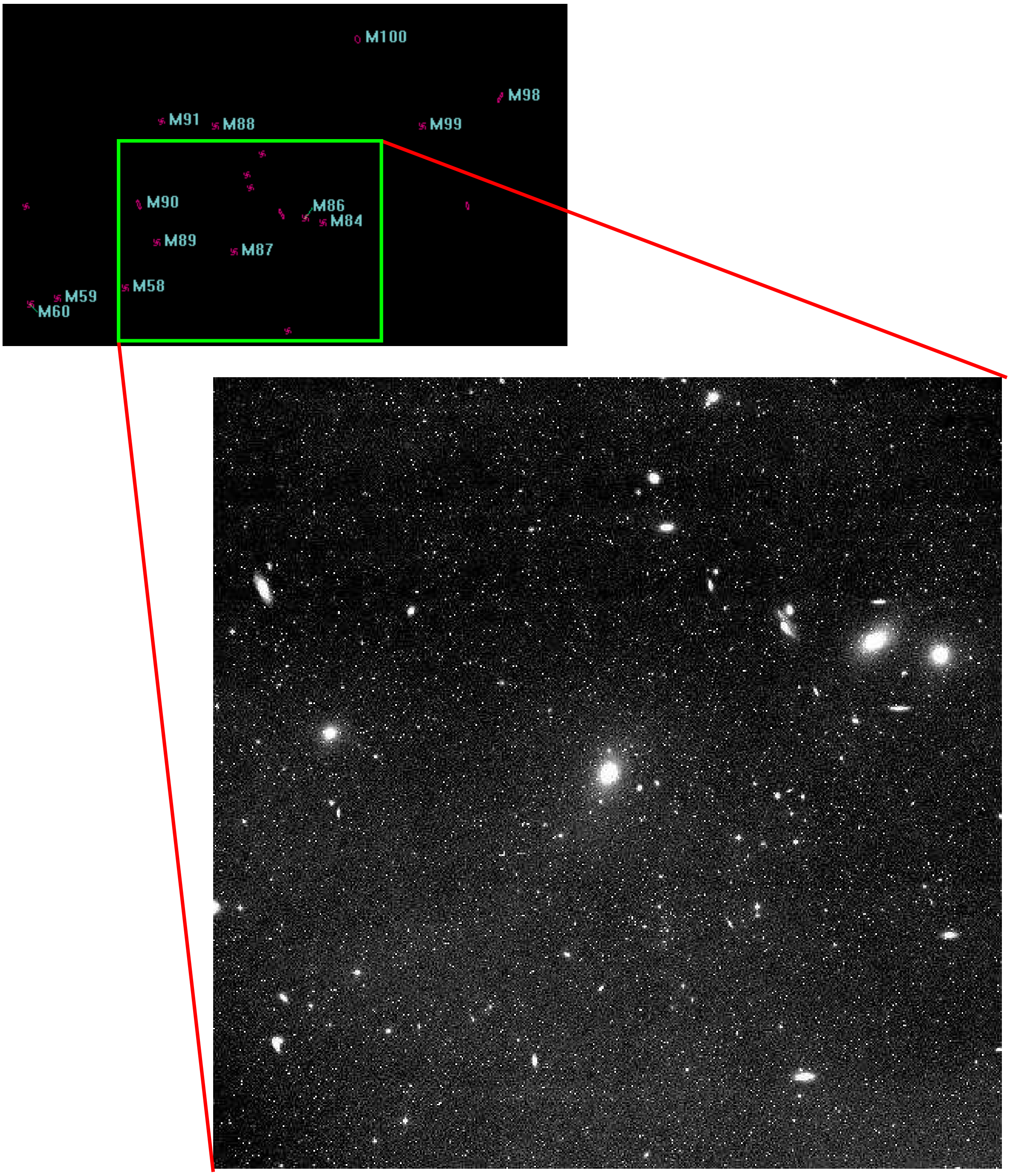
5–7 Mpc: M101 group ("pinwheel galaxy").
Important because of high L.



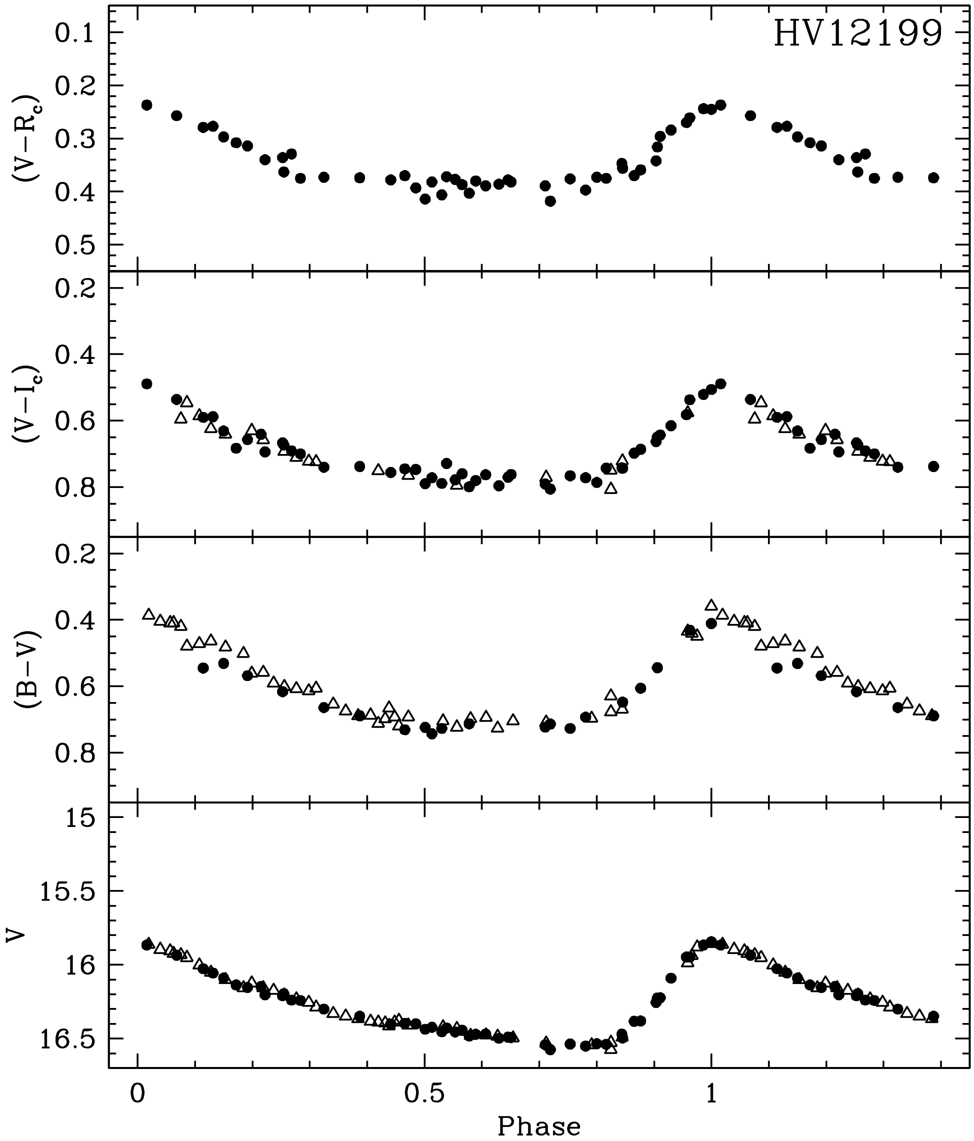
source: `http://anzwers.org/free/universe/200mill.html`

Interlude, VI

15–20 Mpc: Virgo cluster.

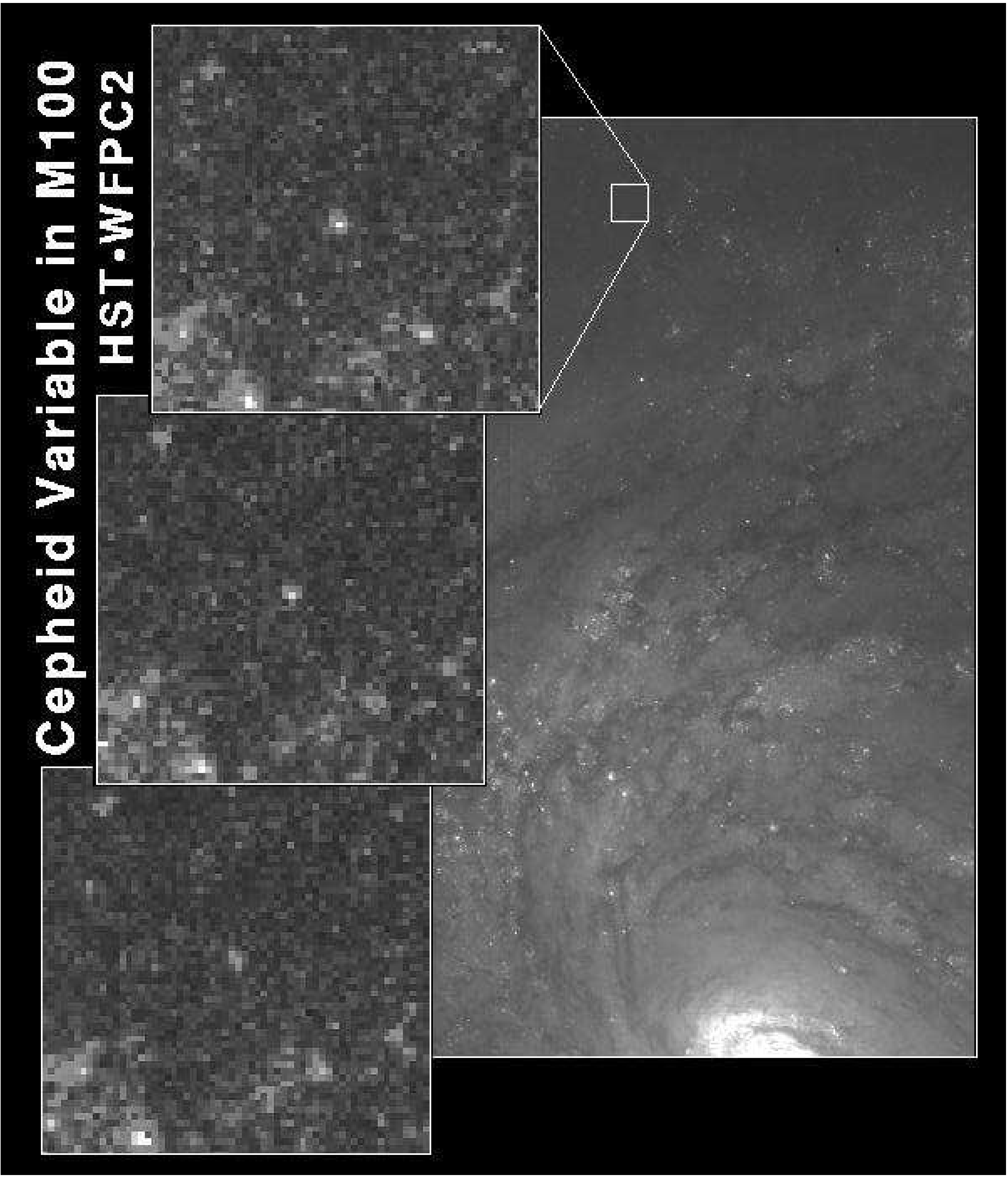


Cepheids, I



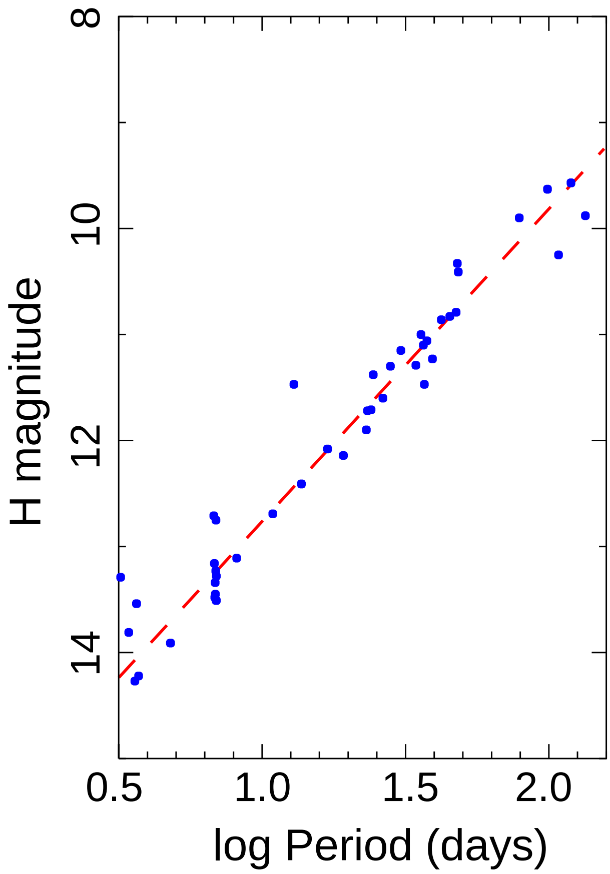
(Gieren et al., 2000, Fig. 3)

Cepheids: Luminous stars ($L \sim 1000\,L_\odot$) in instability strip (He II–He III ionization) with large amplitude variation, $P \sim 2\ldots150\,\mathrm{d}$ (easily measurable). Recent review: Feast (1999).



STScI PR94-49

Cepheids, III



PL relation for the LMC Cepheids (after Mould, Kennicutt, Jr. & Freedman, 2000, Fig. 2).

Henrietta Leavitt (1907): Period-Luminosity (PL) relation: $M_\mathrm{V} \propto -2.76 \log P$.

Low luminosity Cepheids have lower periods.

Good indications that also influence of color

$\Longrightarrow$ Period-Luminosity-Color (PLC) relation

Cepheids, IV

Physics of Period-Luminosity-Color relation:

Star pulsates such that outer parts remain bound:

$$\frac{1}{2}\left(\frac{R}{P}\right)^2 \lesssim \frac{GM}{R} \implies \frac{M}{R^3} \propto P^{-2} \tag{5.13}$$

where P period. Therefore:

$$P \propto \rho^{-1/2} \iff P\rho^{1/2} = Q \tag{5.14}$$

(Q: pulsational constant, $\rho \propto MR^{-3}$ mean density). But Radius R related to luminosity L:

$$L = 4\pi R^2 \sigma T^4 \implies R \propto L^{1/2} T^{-2} \tag{5.15}$$

Inserting everything into Eq. (5.14) gives:

$$PL^{-3}T^3 = \text{const.} \tag{5.16}$$

$$\iff \log P - 3\log L + 3\log T = \text{const.} \tag{5.17}$$

But:

bolometric magnitude: $M_{\mathrm{bol}} \propto -\log L$;

colors: $\mathrm{B} - \mathrm{V} \propto \log T$

such that

$$c_1 \log P + c_2 M_{\mathrm{bol}} + c_3(\mathrm{B} - \mathrm{V}) = \text{const.} \tag{5.18}$$

where $c_{1,2,3}$ calibration constants.

Cepheids, V

Calibration: Need slope and zero point of PLC.

Slope is easy: Observations of nearby galaxies (e.g., open clusters in LMC, see previous slide).

Zero point is difficult:

- Cepheids in galactic clusters, distance to these via ZAMS fitting $\Longrightarrow$ problematic due to age dependency of ZAMS.
- Hipparcos: geometrical distances $\Longrightarrow$ problematic due to low SNR (resulting in 9% systematic error.
- Baade-Wesselink using IR info (low metallicity dependence).

Typical relations (Mould et al., 2000, 32 Cepheids):

$$\begin{aligned} M_{\mathrm{V}} &= -2.76 \log P - 1.40 + C(Z) \\ M_{\mathrm{I}} &= -3.06 \log P - 1.81 + C(Z) \end{aligned} \tag{5.19}$$

The metallicity (color) dependence is roughly

$$(m - M)_{\mathrm{true}} = (m - M)_{\mathrm{PL}} - \gamma \log Z/Z_{\mathrm{LMC}} \tag{5.20}$$

where $\gamma = -0.11 \pm 0.03\,\mathrm{mag}/\mathrm{dex}$ (Z: metallicity) (=Cepheids with larger Z are fainter).

Cepheids, VI

Notes:

1. Pulsational constant $Q = Q(\rho, P)$? $\Longrightarrow$ possible deviation from PLC, especially at high luminosity $\Longrightarrow$ adds uncertainty at large distances.
2. M_{V} depends on metallicity (LMC Cepheids *are* bluer [$Z_{\mathrm{LMC}} < Z_{\odot}$]), but γ very uncertain.

   For V and I magnitudes, most probably $\delta(m - M)_0/\delta[\mathrm{O/H}] \lesssim -0.4\,\mathrm{mag\,dex}^{-1}$, however, others find $+0.75\,\mathrm{mag\,dex}^{-1}$, see Ferrarese et al. (2000) for details. . .
3. Stellar evolution unclear (multiple crossings of instability strip possible).

W Vir Stars

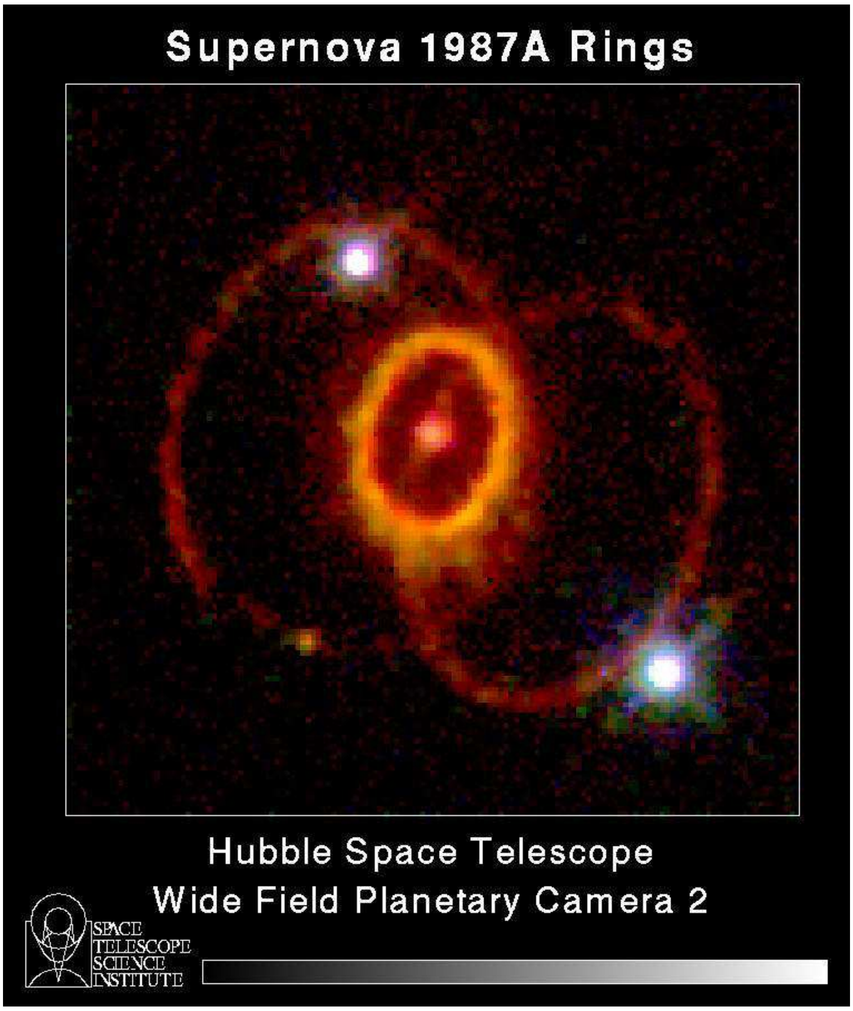
W Vir stars, also called type II Cepheids = “little brother of Cepheids” (present in globular clusters).

Less luminous than normal Cepheids, similar PLC relation, first confused with Cepheids $\Longrightarrow$ Cause for early thoughts of much smaller universe.

Cause for early confusion with Cepheids by Hubble (realization vastly increased assumed size of universe).

Light echos, I

Light echo: specialized way to determine distance to LMC using Supernova 1987A.



STScI PR94-22

February 1987: Supernova in Large Magellanic Cloud.

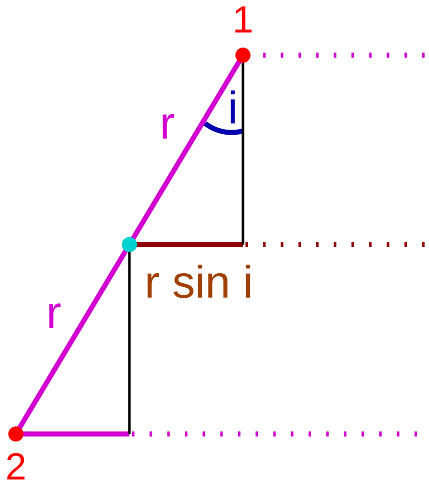
87 d after explosion: Ring of ionized C and N around SN

$\Longrightarrow$ Excitation of C, N in ring-like shell (ejecta from stars equator during red giant phase?).

Observed size: $1.66'' \times 1.21''$

Light echos, II

Assuming ring-geometry: direct geometrical determination of distance to LMC possible:



Time delay SN – close side of ring:

$$\begin{aligned} ct_1 &= r(1-\sin i) \\ &= 86 \pm 6\,\mathrm{d} \end{aligned} \tag{5.21}$$

Time delay SN – far side of ring:

$$\begin{aligned} ct_2 &= r(1+\sin i) \\ &= 413 \pm 24\,\mathrm{d} \end{aligned} \tag{5.22}$$

The radius is (Eq. 5.21+Eq. 5.22):

$$r = c\,\frac{t_1+t_2}{2} = 250 \pm 12\,\mathrm{lt\,d} \tag{5.23}$$

and the inclination is (Eq. 5.21+Eq. 5.22):

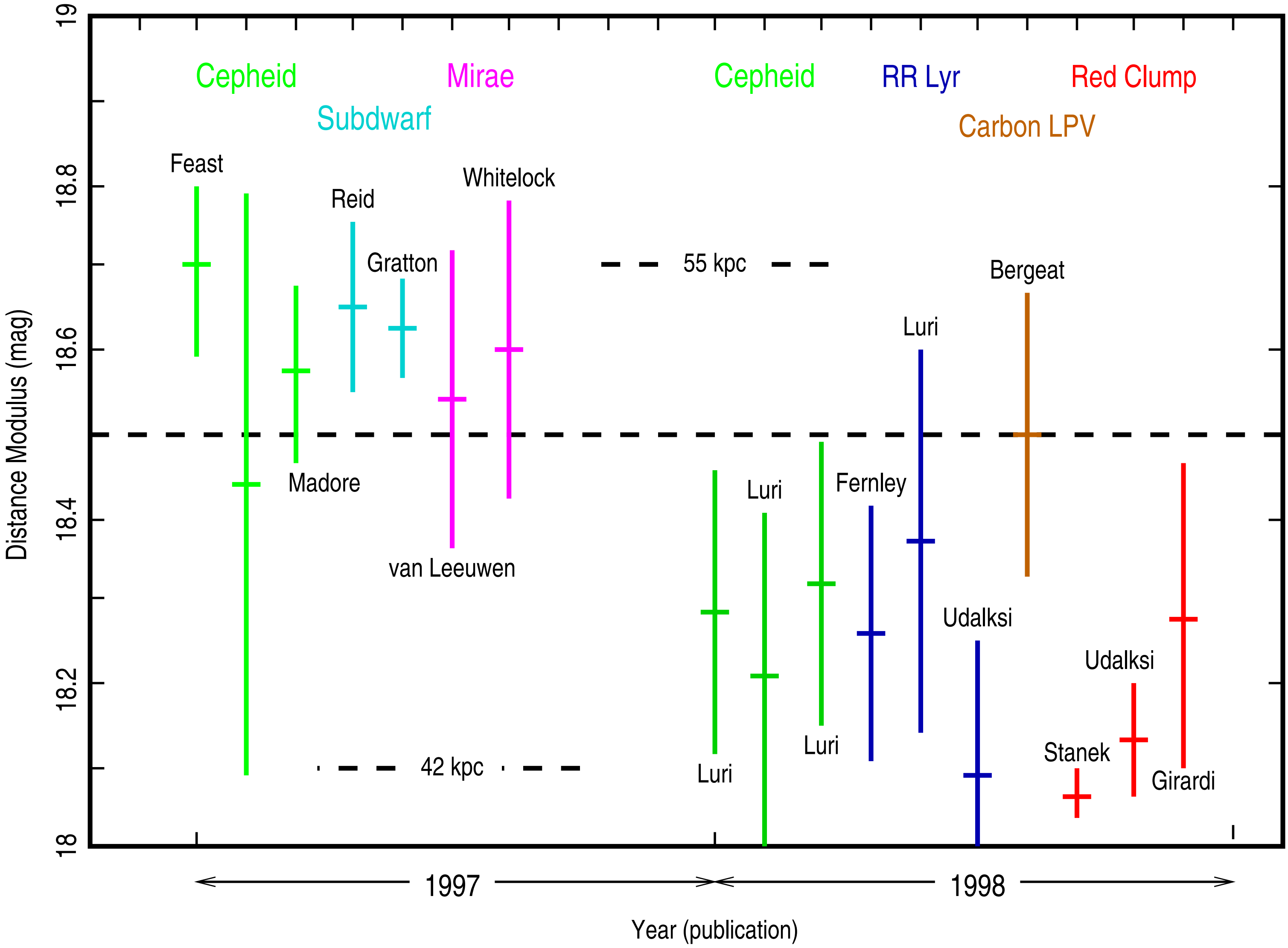
$$\sin i = \frac{t_2-t_1}{t_1+t_2} \quad\Longrightarrow\quad i \sim 41^\circ \tag{5.24}$$

From ring-geometry: $\cos i = 1.21''/1.66'' \Longrightarrow i \sim 43^\circ$).
Thus from angular size of ring:

$$1.66'' = \frac{r\cos i}{d} \quad\Longrightarrow\quad d = 52 \pm 3\,\mathrm{kpc} \tag{5.25}$$

UWarwick

Large Magellanic Cloud (LMC) distance: “anchor point” of extragalactic distance scale.



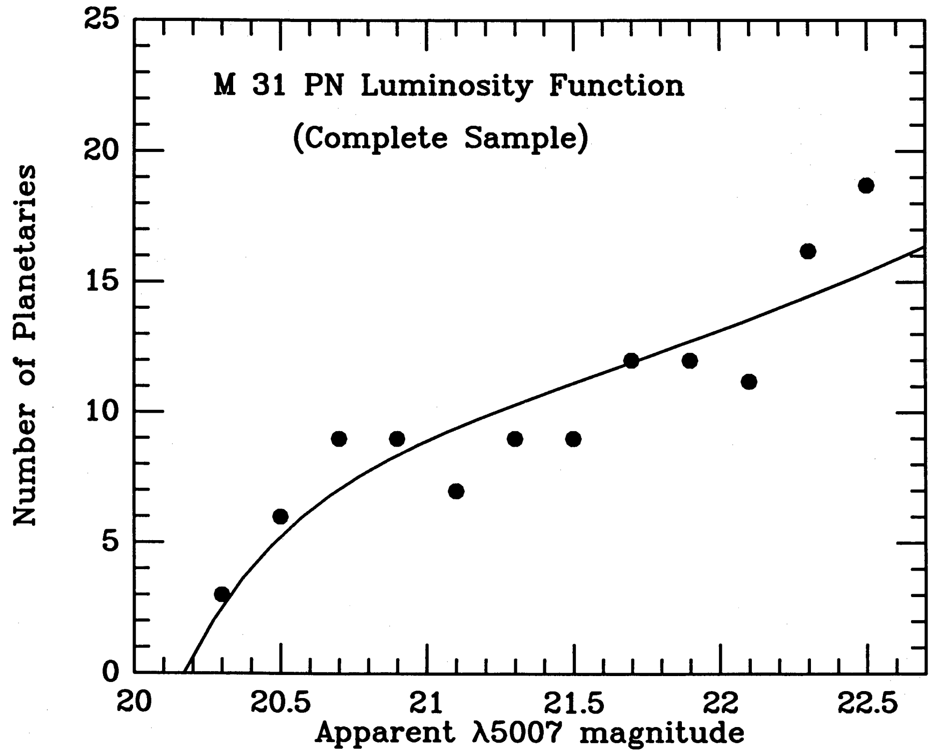
After Gaia Science Workgroup

Problems that are still not understood:

- Strong dependence on Hipparcos calibration. Values between 18.7 $\pm$ 0.1 (Feast & Catchpole) and 18.57 $\pm$ 0.11 (Madore & Freedman) obtained.
- Eclipsing binaries and red clump stars: $\mu_{\rm LMC} \sim$ 18.23 (Mould, Kennicutt, Jr. & Freedman, 2000) $\Longrightarrow$ Inconsistent with other methods!?!

Currently, the distance to the LMC is less well known than desirable.

PN Luminosity Function, I



(Ciardullo et al., 1989, Fig. 4)

Planetary Nebulae have empirical universal luminosity function:

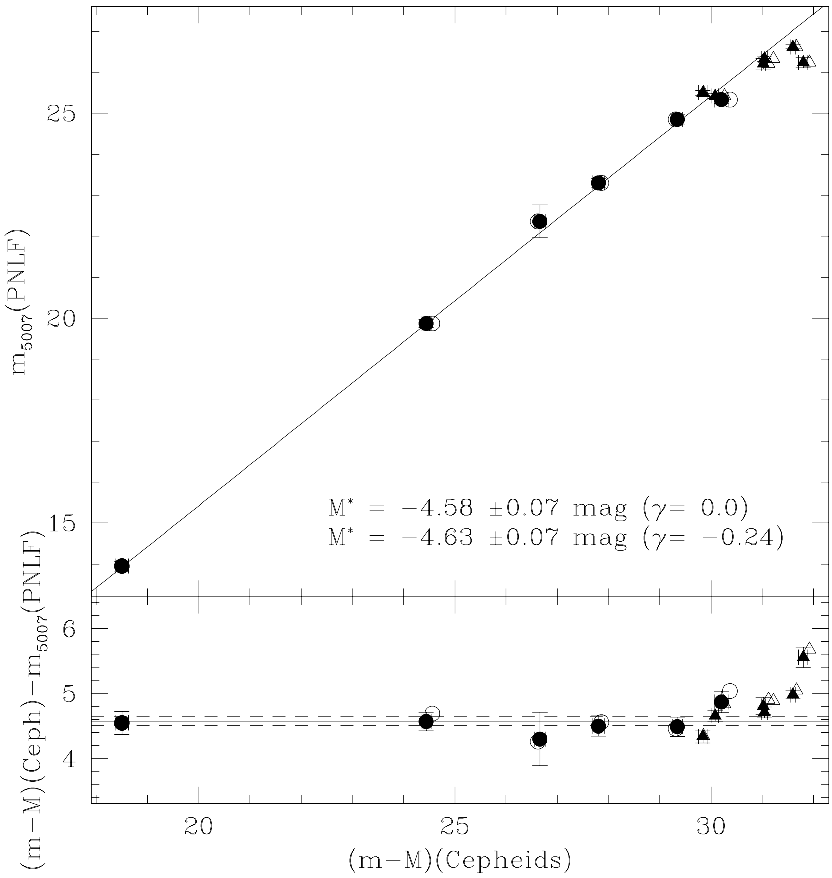
$$N(M) \propto \mathrm{e}^{0.307M} \left(1 - \mathrm{e}^{3(M_{\mathrm{PN}}-M)}\right) \qquad (5.26)$$

Measurement of "cutoff magnitude" $M_{\mathrm{PN}} \Longrightarrow$ Standard candle!

PN detection with narrow band filter of O[III] λ5007Å.

UWarwick

PN Luminosity Function, II



(Ferrarese et al., 2000, Fig. 3), left to right: LMC, M31, NGC 300, M81, M101, NGC 3368, and several galaxy groups.

Result of calibration using Cepheid distances (Ferrarese et al., 2000):

Cutoff of luminosity function:

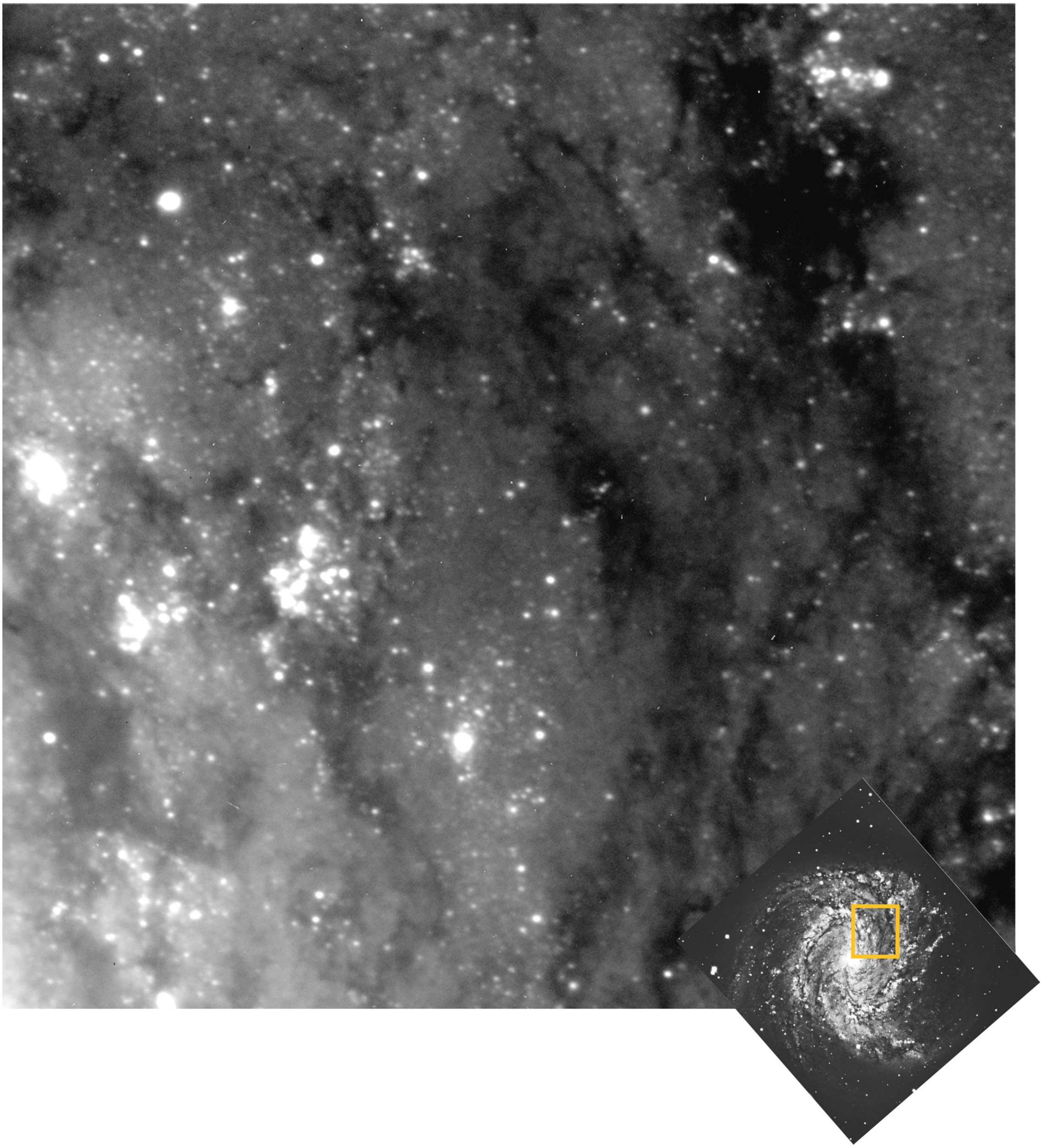
$$M_{\mathrm{PN}} = -4.58 \pm 0.13\,\mathrm{mag} \qquad (5.27)$$

Out to ∼40 Mpc with 8 m class telescope.

PN Luminosity Function, III

Caveats: Effects of metallicity, population age, parent galaxy most probably small, but

- Contamination by H II regions (but distinguish using Hα/[O III] ratio.
- Background emission-line galaxies at $z = 3.1$
- intraclustser PNe (i.e., PNe outside galaxies)



The VLT Looks Deep into a Spiral Galaxy

ESO PR Photo 20/98 (23 June 1998)

M83

Brightest Stars, II

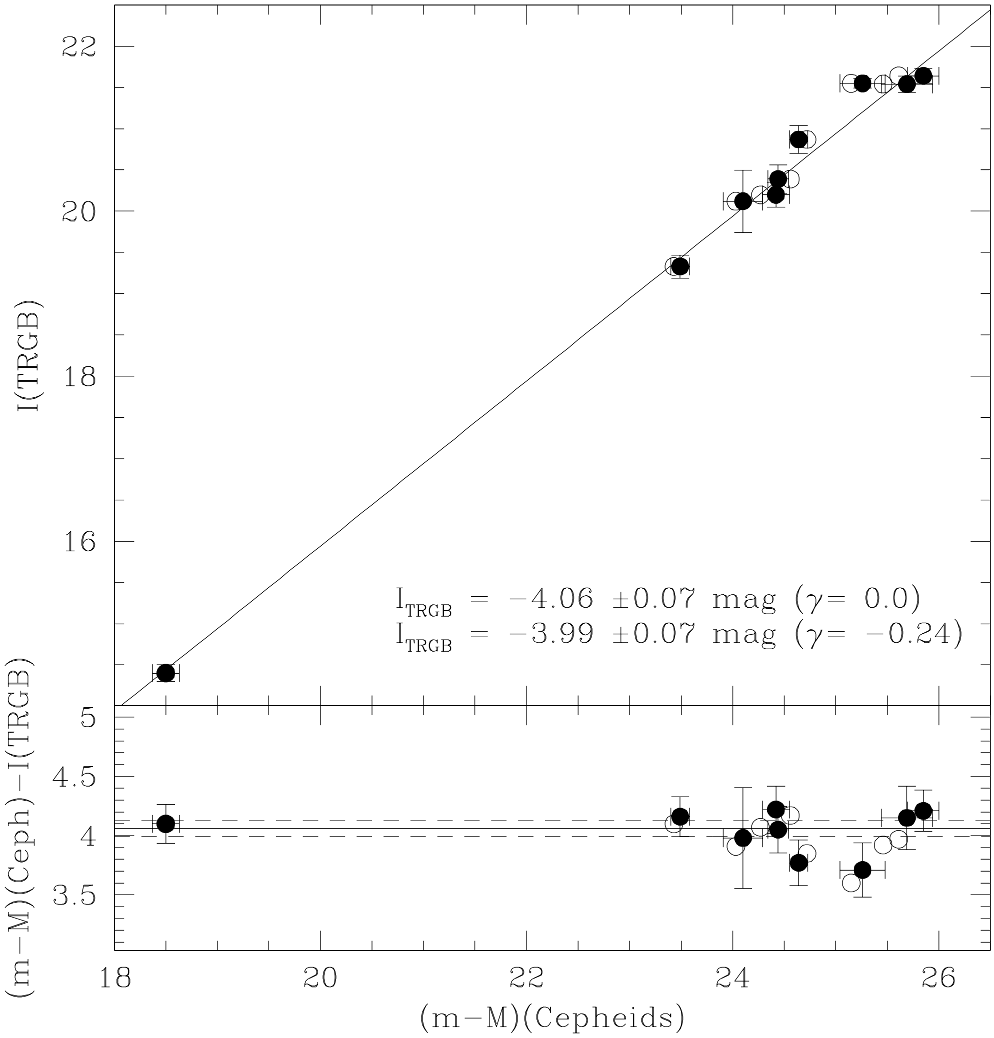
Brightest Stars= O, B, A supergiants, absolute magnitudes usable in local group, large scatter. Brightest stars possible: upper limit to stellar luminosity due to mass loss in supergiants

Possible Improvement: Strength of Balmer series lines. Hα and Hβ appear biased (class of supergiants with anomalously strong Balmer lines?).

Problems:

- Contamination by foreground halo stars $\Longrightarrow$ Choose stars with unusual color (rare, i.e. less foreground contamination): B $-$ V $<$ 0.4 or B $-$ V $>$ 2.0 $\Longrightarrow$ Tip of Red Giant Branch
- Internal extinction.
- Scatter in max. $L \Longrightarrow$ Average over brightest N stars (Sandage, Tammann: $N =$ 3).
- Metallicity dependence.

Brightest Stars, III



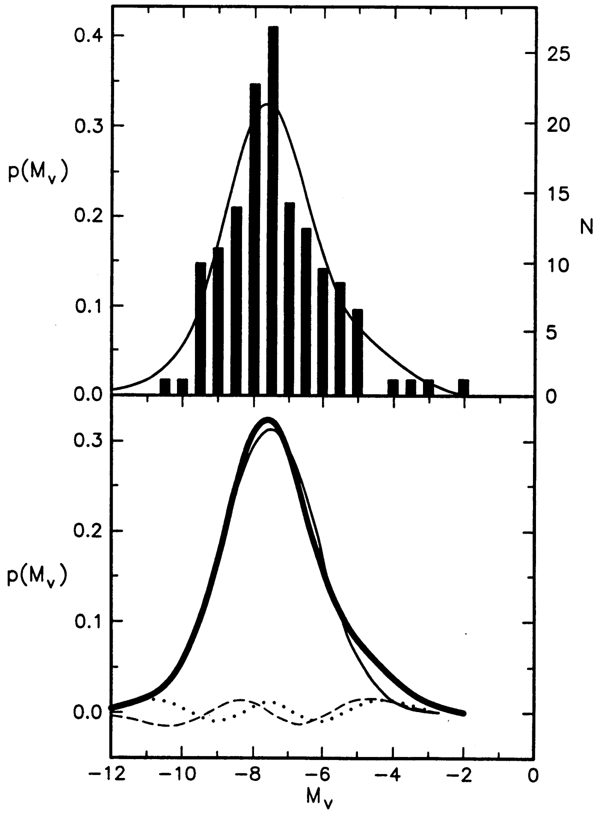
(Ferrarese et al., 2000, Fig. 1)

Tip of Red Giant Branch: Usable within local group, possibly out to Virgo.

Calibration:

$$M_{\mathrm{I}} = -4.06 \pm 0.13\,\mathrm{mag} \qquad (5.28)$$

Globular Cluster



Globular Cluster Luminosity Function very stable ≈Gaussian $\Longrightarrow$ Use maximum of distribution ("turnover magnitude", M_T) as standard candle.

(MW GCs, Abraham & van den Bergh, 1995, Fig. 1)

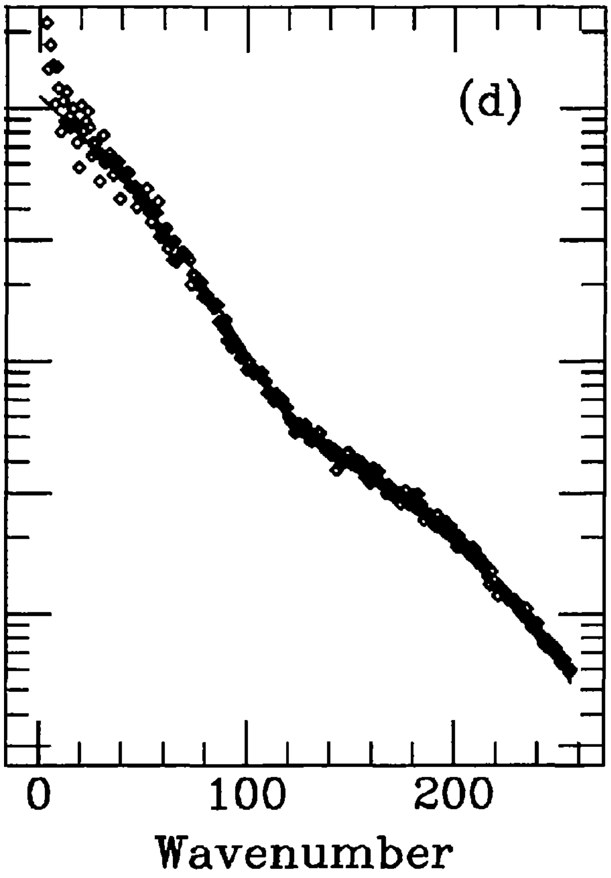
From Virgo and Fornax Cepheid distances (Ferrarese et al., 2000):

$$M_\mathrm{T,V} = -7.60 \pm 0.25\,\mathrm{mag} \qquad (5.29)$$

Caveats:

1. M_T depends on luminosity and type of host galaxy (GC of dwarf galaxies weaker by $\sim$ 0.3 in V).
2. Metallicity of galaxy cluster influences M_T.
3. Measurement difficult (need the weak GCs!).
4. Large scatter in data $\Longrightarrow$ Method rather unreliable.

Surface Brightness Fluctuations, I



(Ajhar et al., 1997, Fig. 3d)

For early type galaxies: Assume N stars in picture element (pixel), with average flux f.

$\Longrightarrow$ Mean pixel intensity:

$$\mu = Nf \tag{5.30}$$

μ independent of distance, since $N \propto r^2$ and $f \propto r^{-2}$.

Standard Deviation (Poisson):

$$\sigma = \sqrt{N} f \propto r^{-1} \tag{5.31}$$

Therefore:

$$f = \frac{\sigma^2}{\mu} = \frac{L}{4\pi r^2} \tag{5.32}$$

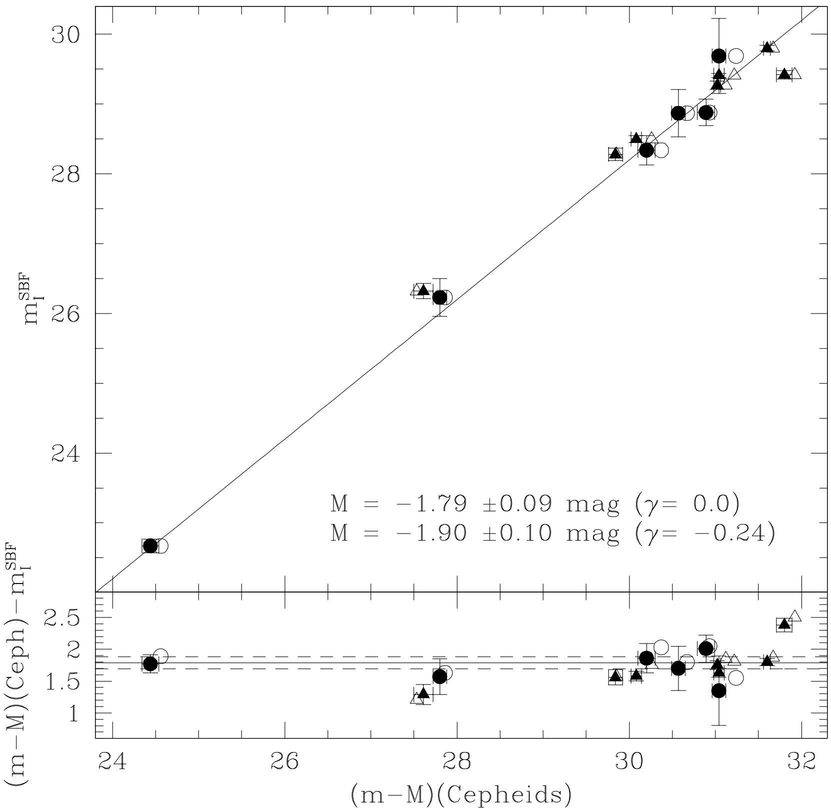
which gives the distance r.

Review: Blakeslee, Ajhar & Tonry (1999).

Complication: Adjacent pixels not independent (point spread function of telescope!)

$\Longrightarrow$ Use radial power spectrum to obtain σ^2 and μ.

Surface Brightness Fluctuations, II



(Ferrarese et al., 2000, Fig. 5)

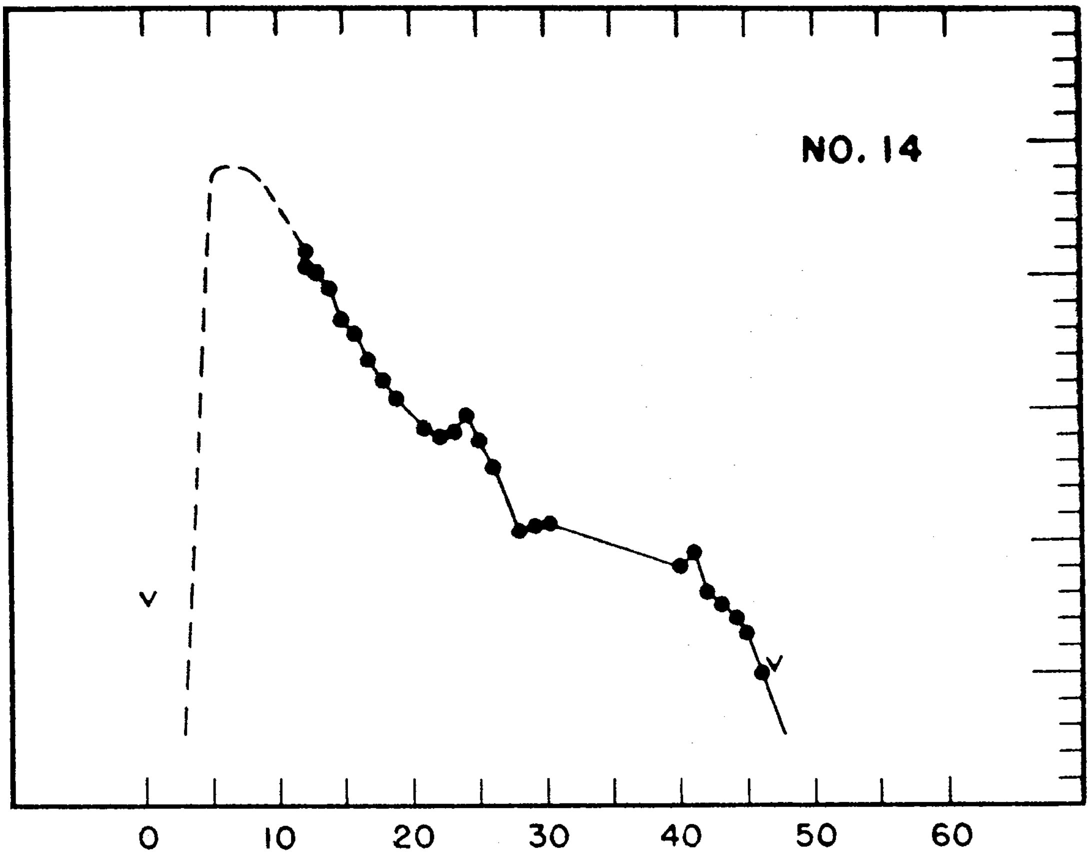
Luminosity of galaxy dominated by Red Giant Branch stars $\Longrightarrow$ Strong wavelength and color dependence $\Longrightarrow$ Primary calibration: I-band plus broad-band color dependency to give standard candle.

Often also used: HST WFPC2 plus F814W filter (close to I-band),

$$M_{\mathrm{F814W}} = (-1.70 \pm 0.16) + (4.5 \pm 0.3)\left[(\mathrm{V}-\mathrm{I})_0 - 1.15\right] \quad (5.33)$$

Works out to $\sim 70\,\mathrm{Mpc}$ with HST.

Novae, I



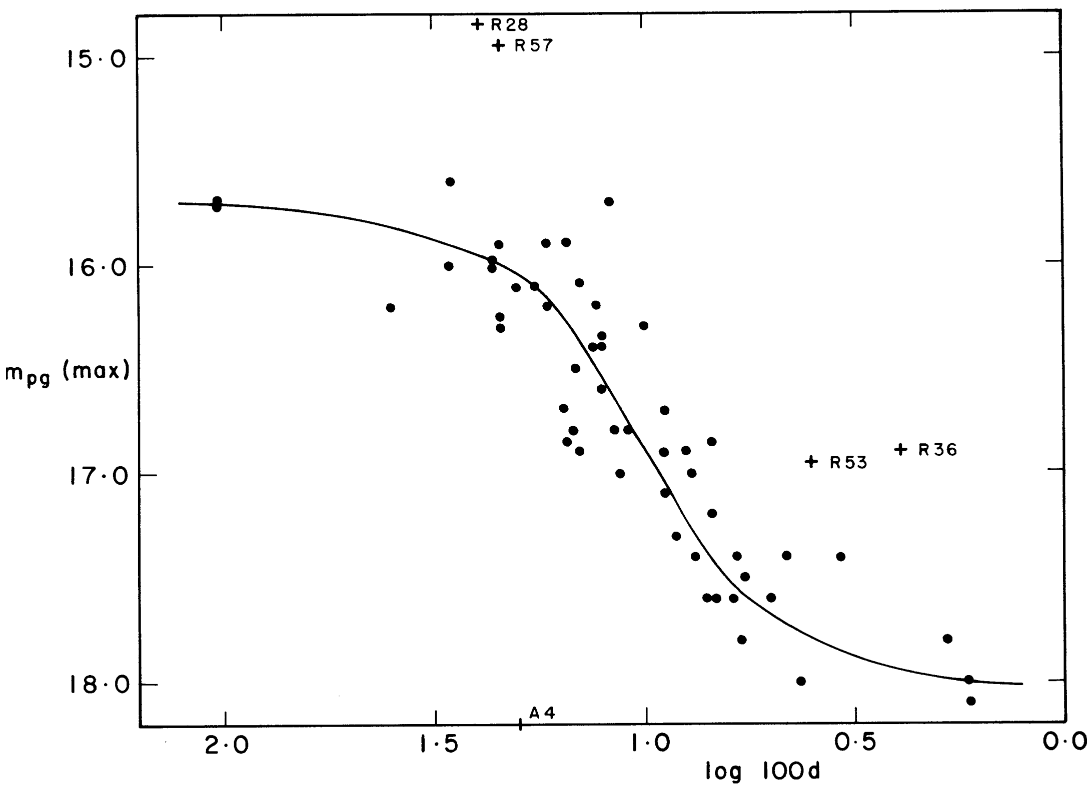
(Nova in M31, Arp, 1956, p. 18)

"classical nova"= explosion on surface of white dwarf

Novae only in binary systems $\Longrightarrow$ slow accretion of material onto WD $\Longrightarrow$ outer skin reaches M_{crit} for fusion $\Longrightarrow$ explosion $\Longrightarrow$ ejection of $10^{-6} \dots 10^{-4}\,M_\odot$ with $v \sim 500\,\mathrm{km/s}$

Explosion produces characteristic lightcurve.

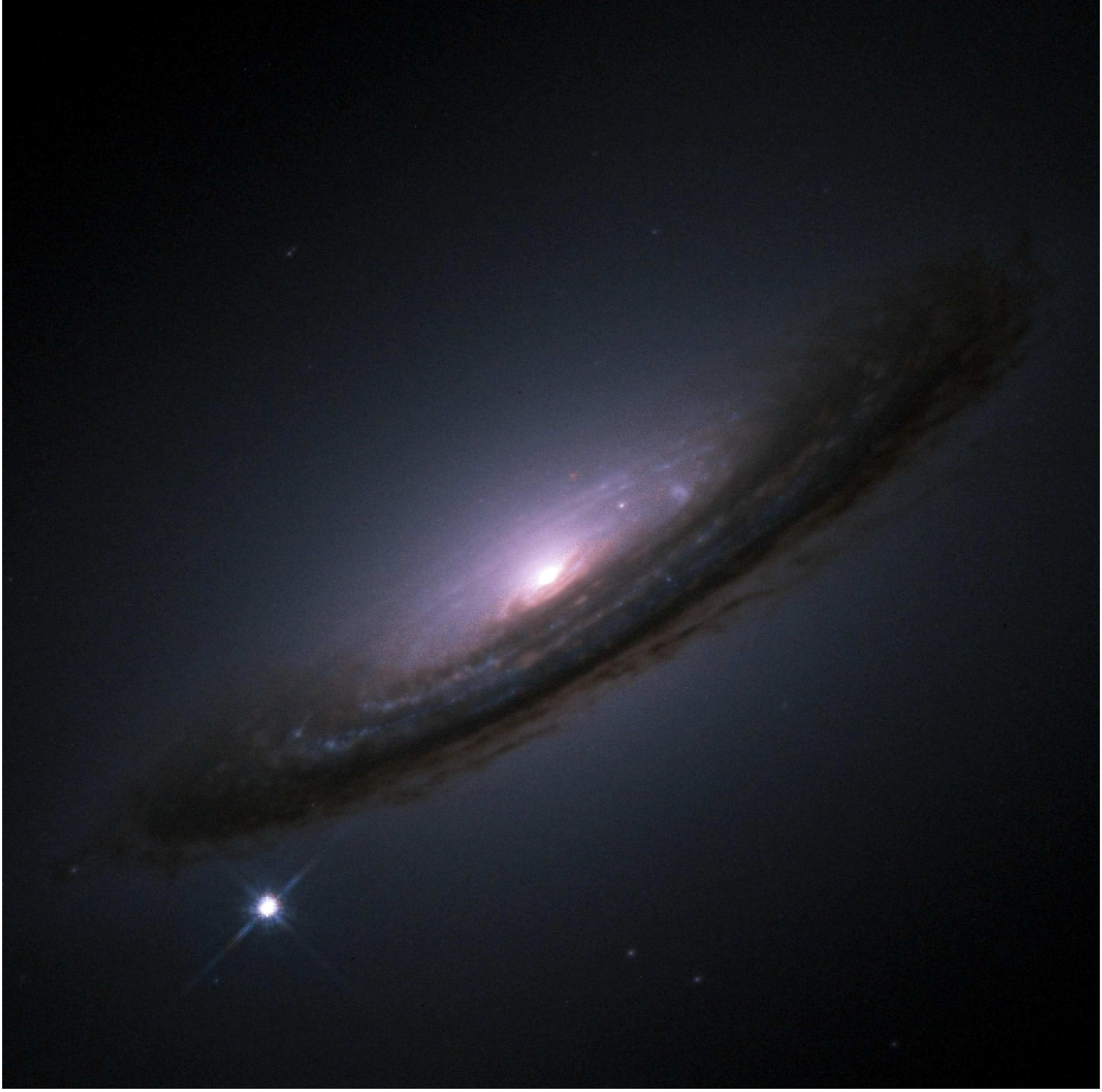
Novae, II



(van den Bergh & Pritchet, 1986, Fig. 1).

Strong scatter in lightcurves (higher $L_{\max} \Longrightarrow$ faster decline, but typically $\sim 3\times$ brighter than Cepheids), but good Correlation luminosity vs. decline timescale (t_i, time to reach $m(t_i) = m_{\max} + i$).

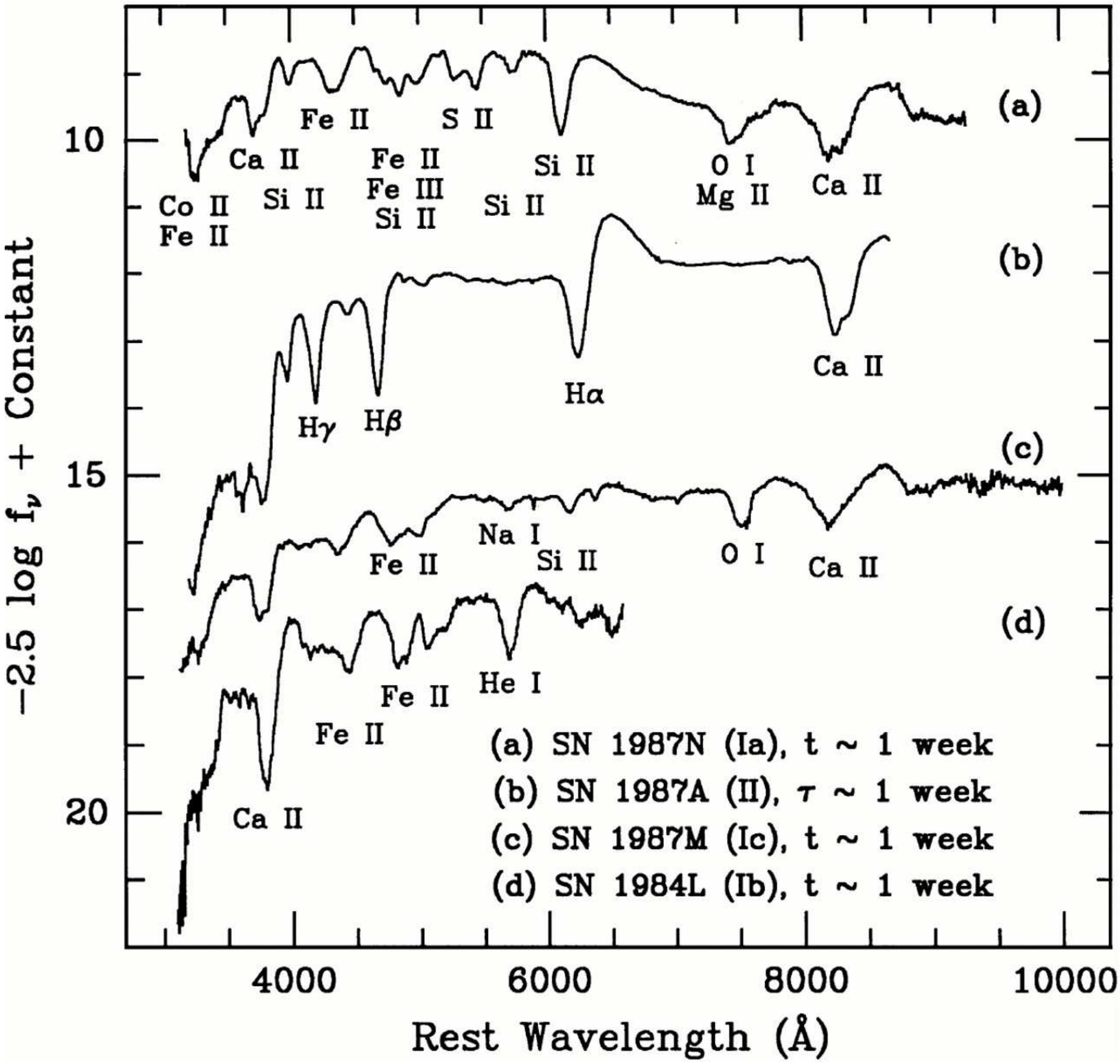
Calibration: galactic novae.



SN1994d (HST WFPC)

Supernovae have luminosities comparable to whole galaxies: $\sim 10^{51}$ erg/s in light, $100\times$ more in neutrinos.

Type Ia Supernovae, II



(Filippenko, 1997, Fig. 1); t: time after maximum light; τ: time after core collapse; P Cyg profiles give $v \sim 10000\,\mathrm{km\,s^{-1}}$

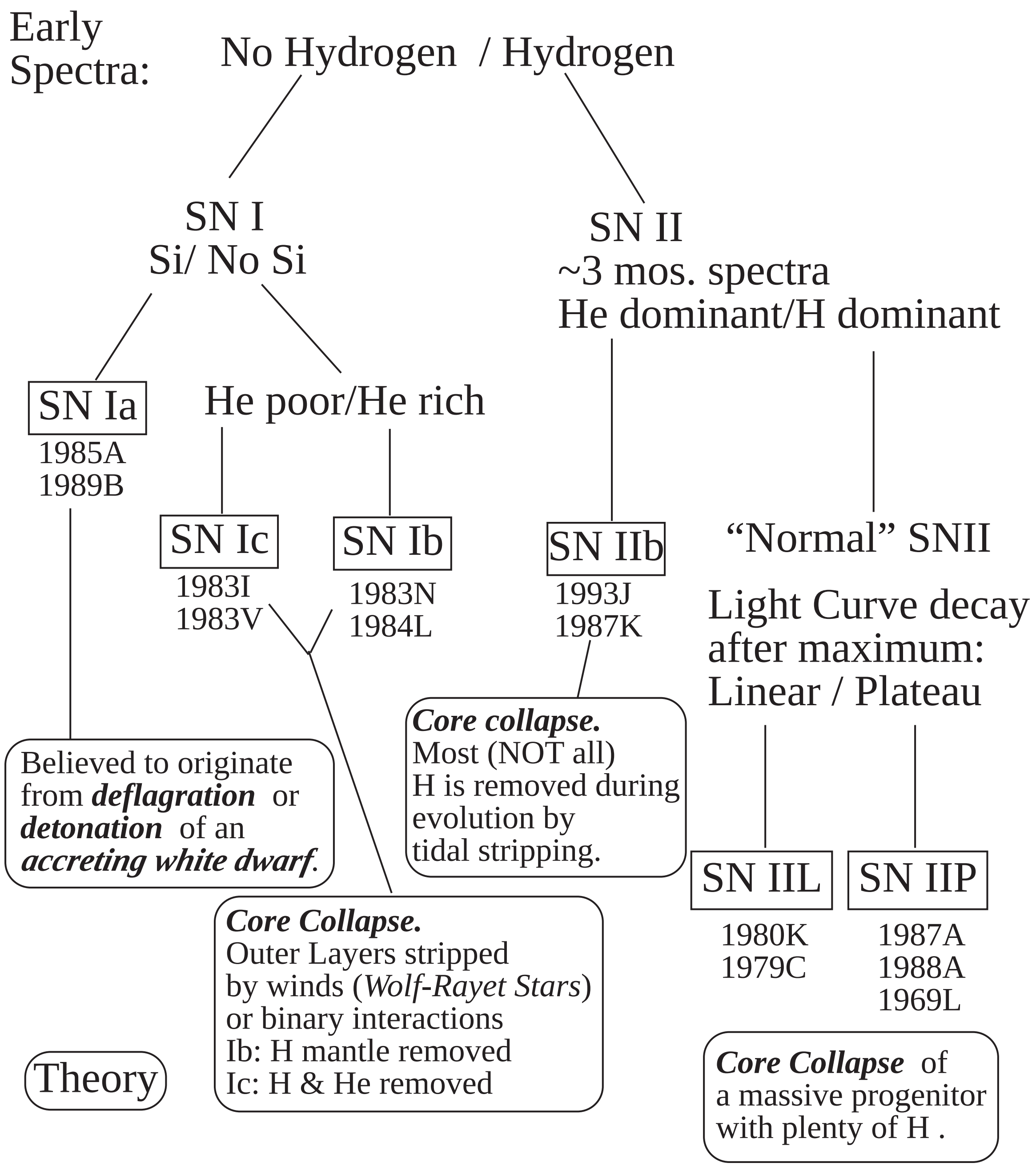
Rough classification (Minkowski, 1941):

Type I: no hydrogen in spectra; subtypes Ia, Ib, Ic

Type II: hydrogen present, subtypes II-L, II-P

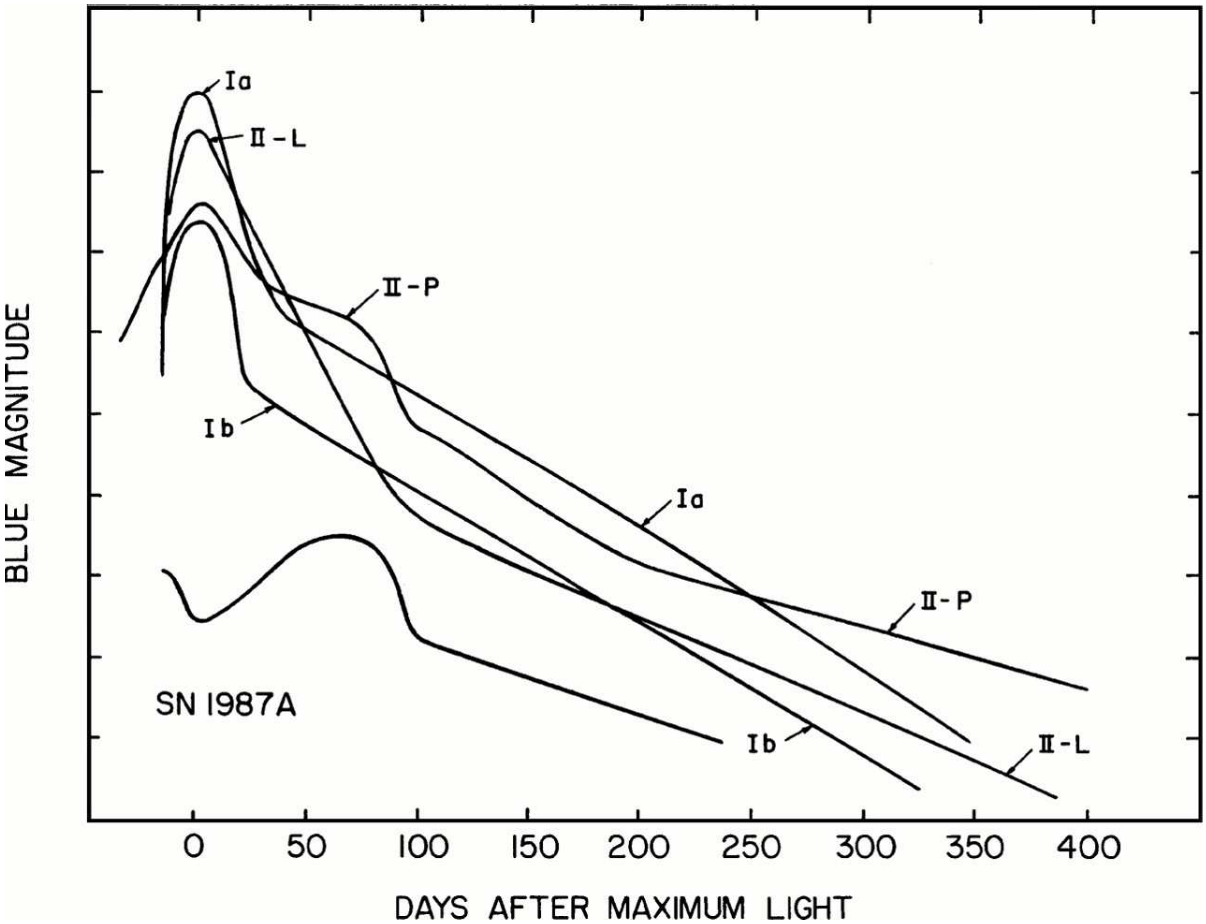
Note: pre 1985 subtypes Ia, Ib had different definition than today $\Longrightarrow$ beware when reading older texts.

Type Ia Supernovae, III



courtesy M.J. Montes

Type Ia Supernovae, IV

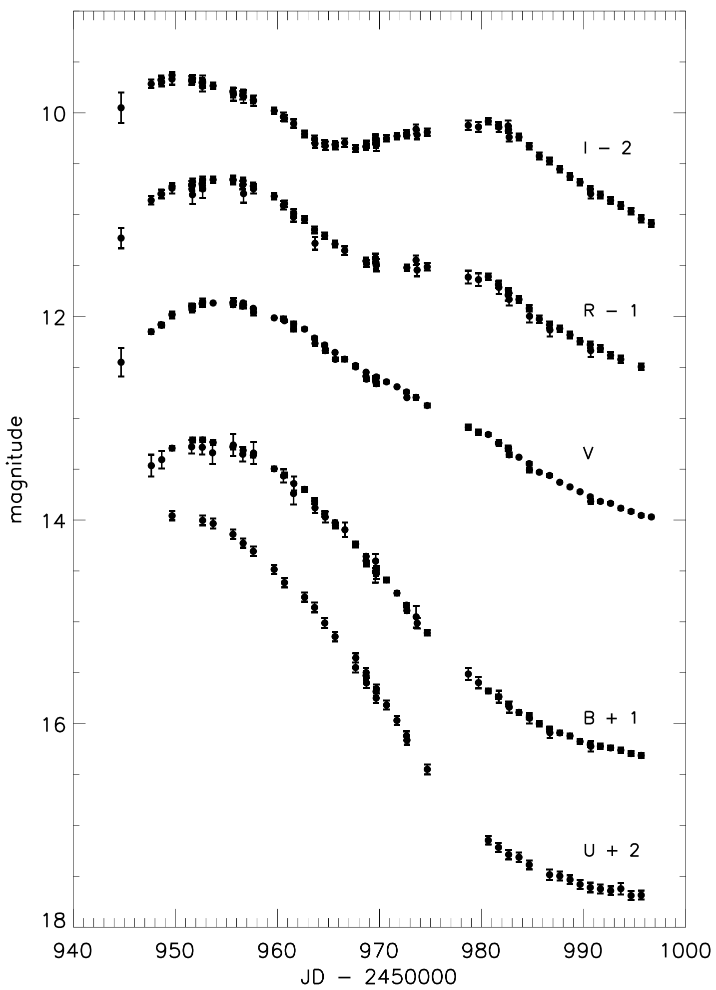


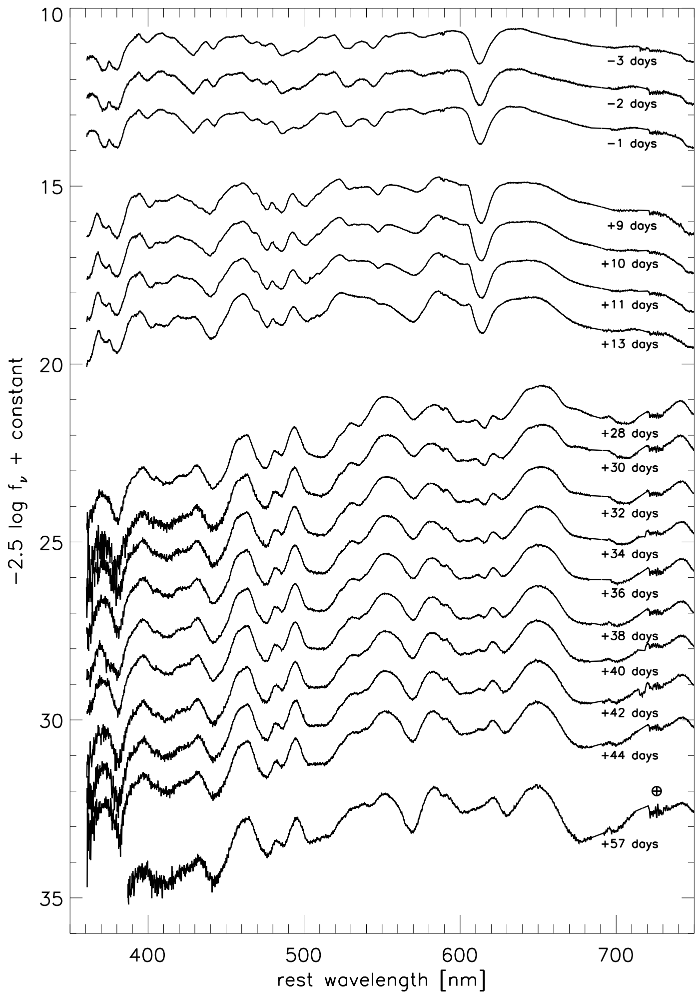
(Filippenko, 1997, Fig. 3)

Light curves of SNe I all very similar, SNe II have much more scatter.

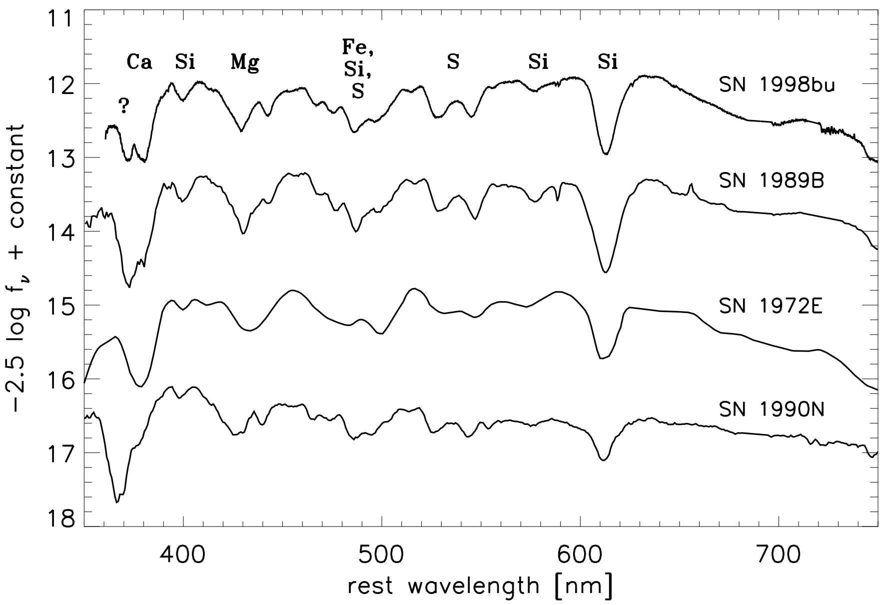
SNe II-L ("linear") resemble SNe I

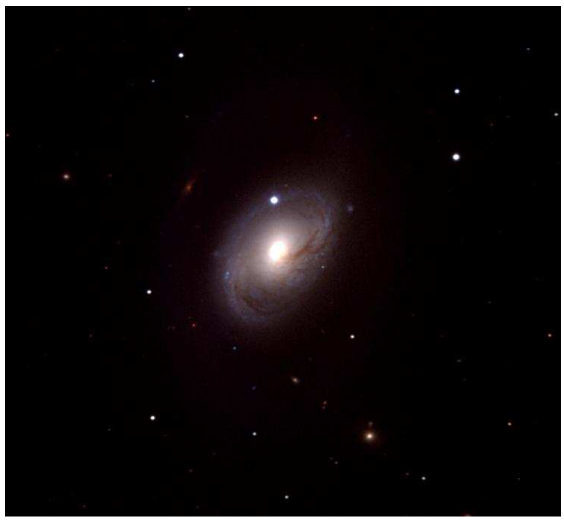
SNe II-P ("plateau") have const. brightness to within 1 mag for extended period of time.





(SN 1998bu in M96, Jha et al., 1999, Figs. 2 and 4)





(SN 1998bu, Jha et al., 1999, Fig. 6)

90 cm CTIO, N. Suntzeff

Type Ia Supernovae, VI

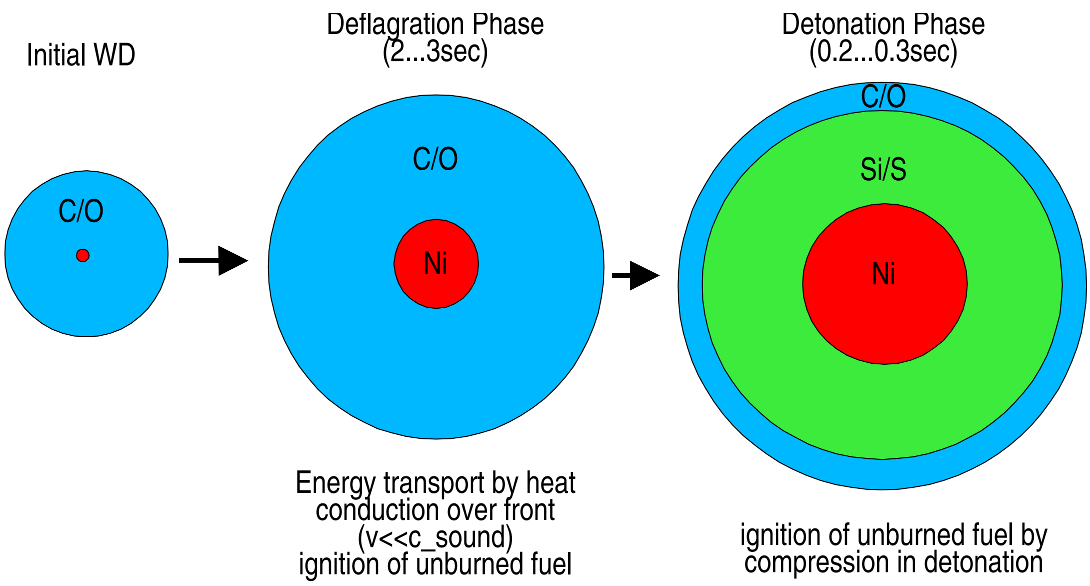
Clue on origin from supernova statistics:

- SNe II, Ib, Ic: never seen in ellipticals; rarely in S0; generally associated with spiral arms and H II regions.

$\Longrightarrow$ progenitor of SNe II, Ib, Ic: massive stars ($\gtrsim 8\,M_\odot$) $\Longrightarrow$ core collapse

- SNe Ia: all types of galaxies, no preference for arms.

$\Longrightarrow$ progenitor of SNe Ia: accreting carbon-oxygen white dwarfs, undergoing thermonuclear runaway



after P. Höflich

Type Ia Supernovae, VII

SN Ia = Explosion of CO white dwarf when pushed over Chandrasekhar limit (1.4 $M_\odot$) (via accretion?).

$\Longrightarrow$ Always similar process

$\Longrightarrow$ Very characteristic light curve: fast rise, rapid fall, exponential decay with half-time of 60 d.

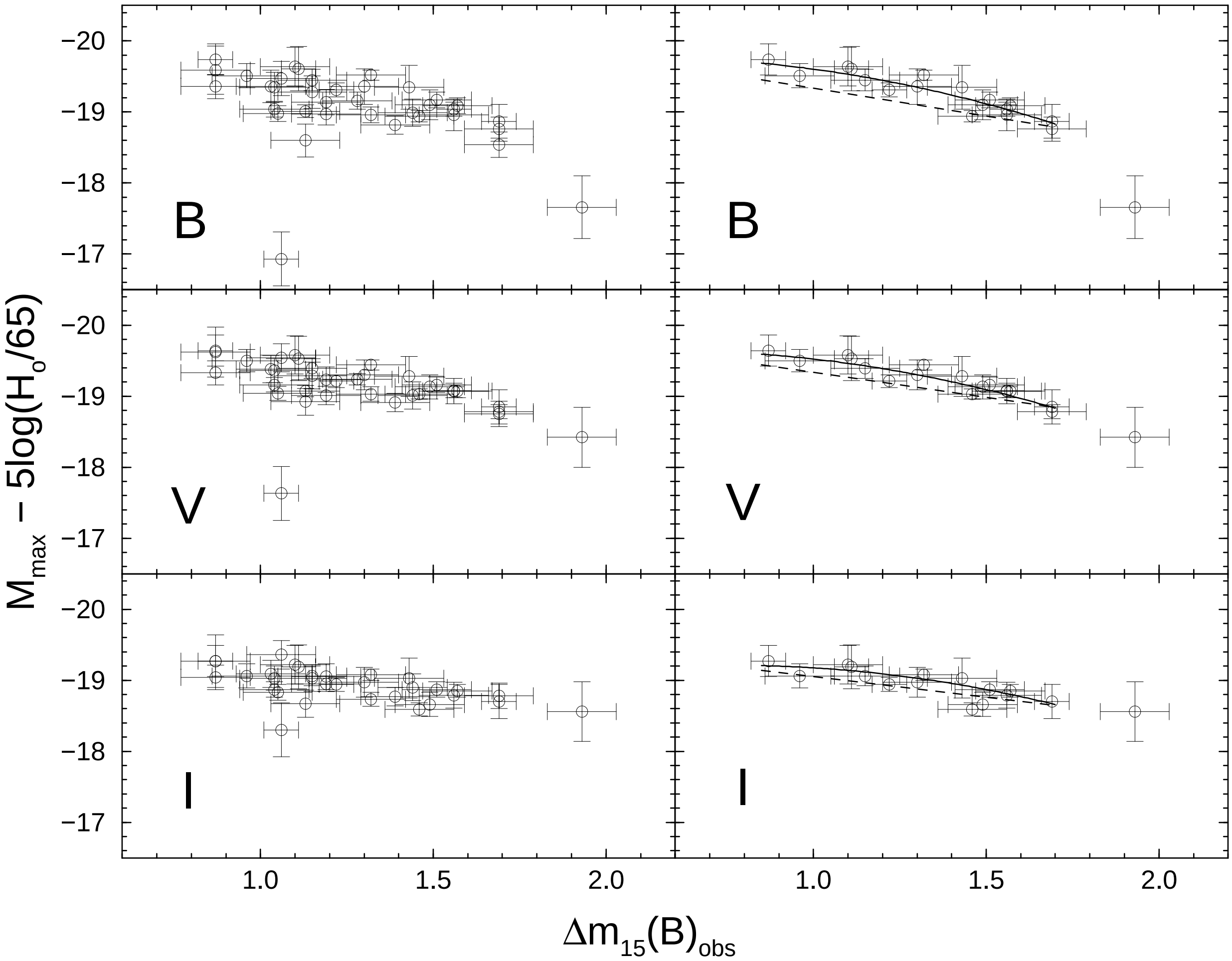
60 d time scale from radioactive decay $\mathrm{Ni}^{56} \rightarrow \mathrm{Co}^{56} \rightarrow \mathrm{Fe}^{56}$ ("self calibration" of lightcurve if same amount of Ni^{56} produced everywhere).

Calibration: SNe Ia in nearby galaxies where Cepheid distances known.
At maximum light:

$$M_\mathrm{B} = -18.33 \pm 0.11 + 5 \log h_{100} \qquad (5.34)$$

($L \sim 10^{9\ldots10}\,L_\odot$).
Intrinsic dispersion: $\lesssim$0.25 mag (possibly due to size of clusters analyzed?!?)
Observable out to 1000 Mpc

Type Ia Supernovae, VIII



(Phillips et al., 1999, Fig. 8)

Caveats:

1. Are they *really* identical? $\Longrightarrow$ history of pre-WD star?
2. Correction for extinction in parent galaxy difficult.
3. Baade-Wesselink for calibration Eq. (5.34) depends crucially on assumed $(\mathrm{B}-\mathrm{V})$-T_{eff} relation.
4. Some SN Iae spectroscopically peculiar $\Longrightarrow$ Do not use these!
5. Decline rate and color vary, but max. brightness and decline rate correlate (see figure).

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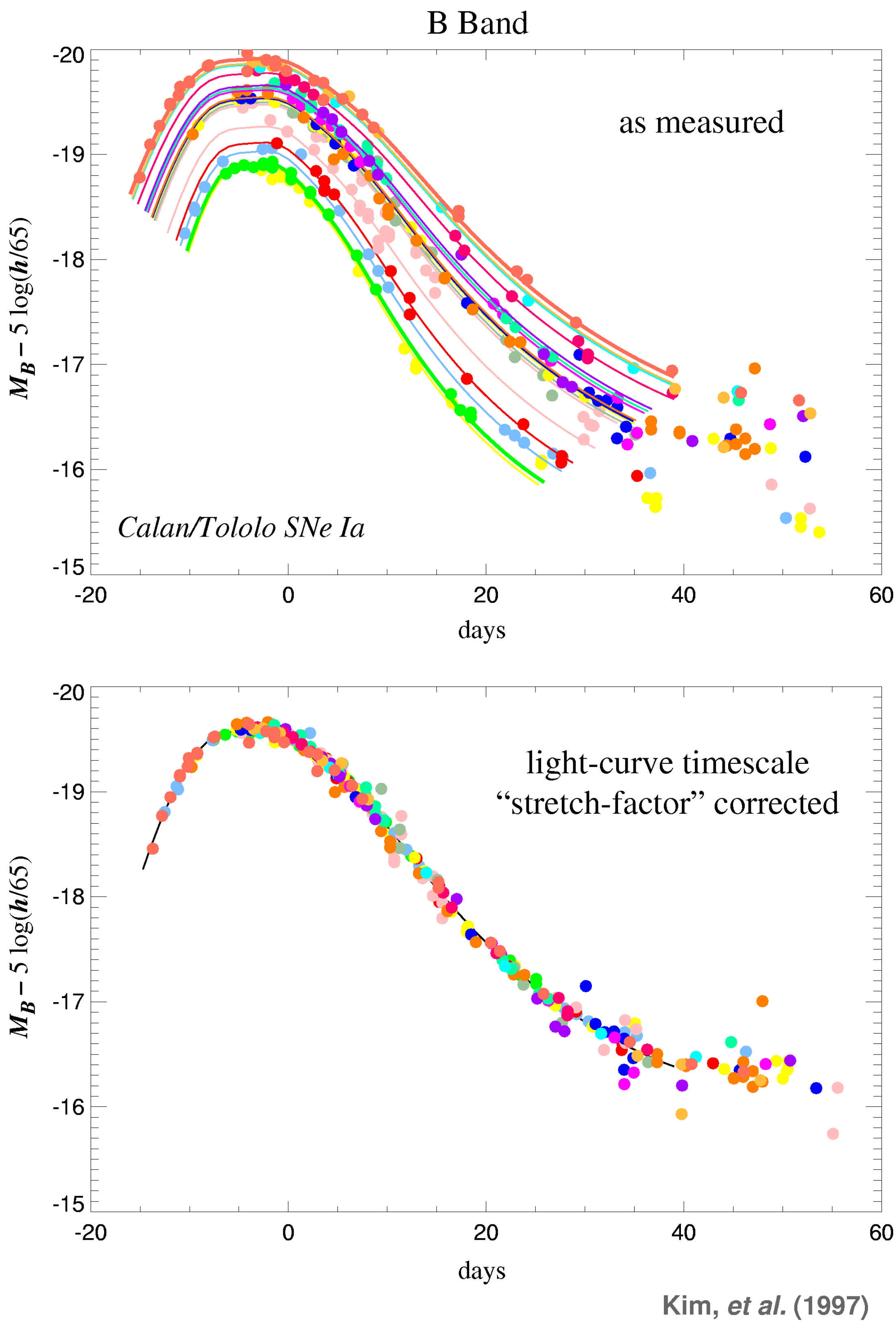


Lightcurves of Hamuy et al. SN Ia sample (18 SNe discovered within 5 d past maximum, with $3.6 < \log cz < 4.5$, i.e., $z < 0.1$, after correction of systematic effects and time dilatation (Kim et al., 1997).

Type Ia Supernovae, X

Recalibration of SN Ia distances with Cepheids gives (Gibson et al., 2000):

$$\log H_0 = 0.2\Big\{M_{\mathrm{B}}^{\max} - 0.720(\pm 0.459) \cdot [\Delta m_{\mathrm{B},15,t} - 1.1] - 1.010(\pm 0.934) \cdot [\Delta m_{\mathrm{B},15,t} - 1.1]^2 + 28.653(\pm 0.042)\Big\} \quad (5.35)$$

where

$$\Delta m_{\mathrm{B},15,t} = \Delta m_{\mathrm{B},15} + 0.1E(\mathrm{B}-\mathrm{V}) \quad (5.36)$$

where

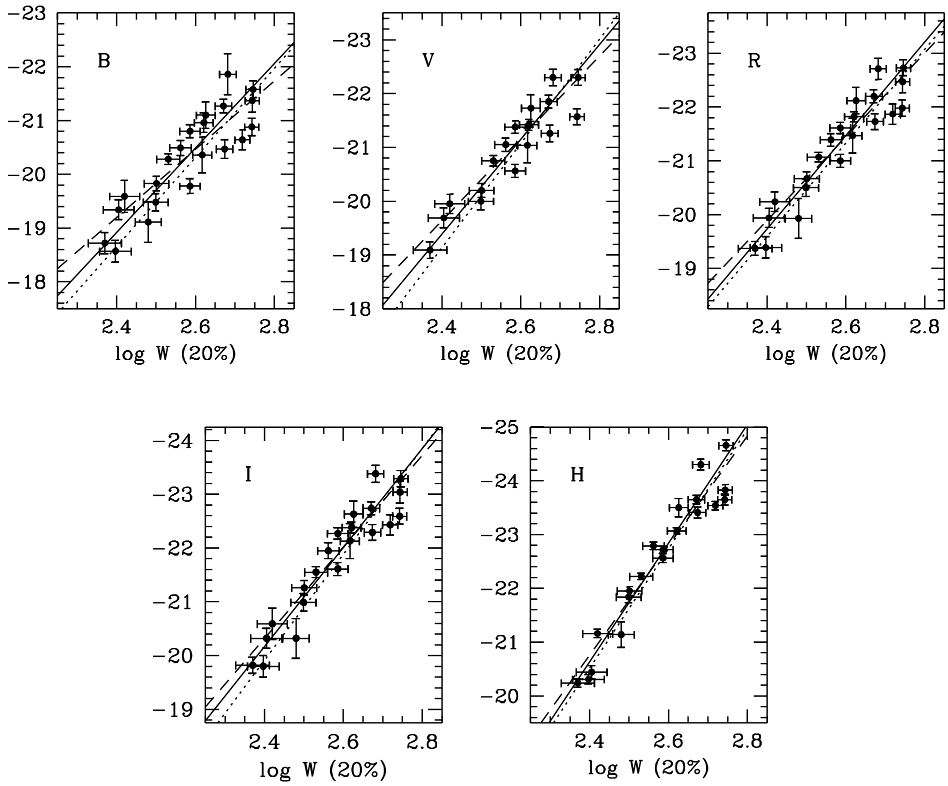
$\Delta m_{\mathrm{B},15}$: observed 15 d decline rate,

$E(\mathrm{B}-\mathrm{V})$: total extinction (galactic+intrinsic).

Eq. (5.35) valid for B-band, equivalent formulae exist for V and I.

Overall, the calibration is good to better than 0.2 mag in B.

Tully-Fisher, I



(Sakai et al., 2000, Fig. 1)

Tully-Fisher relation for spiral galaxies: Width of 21 cm line of H correlated with galaxy luminosity:

$$M = -a \log \left(\frac{W_{20}}{\sin i} \right) - b \quad (5.37)$$

where W_{20}: 20% line width (km/s; typically $W_{20} \sim 300$ km/s), i inclination angle.

For the B- and I-Bands (Sakai et al., 2000):

	B	I
a	7.97± 0.72	9.24± 0.75
b	19.80± 0.11	21.12± 0.12

Tully-Fisher, II

Qualitative Physics: Line width related to mass of galaxy: $W/2 \sim V_{\max}$, where $V_{\max}$ max. velocity of rotation curve

$\Longrightarrow$ Assume $M/L = \text{const.}$ (good assumption)

$\Longrightarrow$ width related to luminosity.

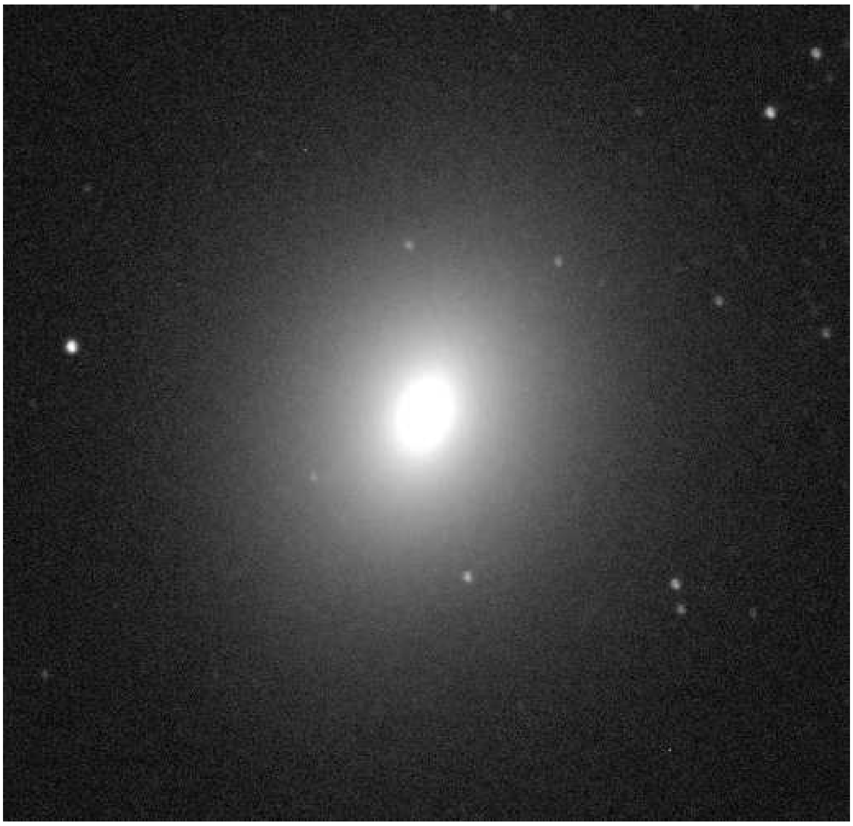
Detailed physical basis unknown. Might be related to galaxy formation in CDM models (“hierarchical clustering”, see later).

I-band is better (less internal extinction).

Caveats:

1. Determination of inclination i.
2. Influence of turbulent motion within galaxy.
3. Constants dependent on galaxy type (Sa and Sb similar, Sc more luminous by factor of $\sim$2).
4. Optical extinction.
5. Intrinsic dispersion $\sim$0.2 mag.
6. Barred Galaxies problematic.

D_n-σ, I



M32 (companion of Andromeda), courtesy W. Keel

"Faber-Jackson" law for elliptical galaxies:

The luminosity L of an elliptical galaxy scales with its intrinsic velocity dispersion, σ, as $L \propto \sigma^4$.

Note that ellipticals have virtually no Hydrogen

$\Longrightarrow$ cannot use 21 cm.

Ellipticals:

$$M_B = -19.38 \pm 0.07 - (9.0 \pm 0.7)(\log \sigma - 2.3) \quad (5.38)$$

Lenticulars:

$$M_B = -19.65 \pm 0.08 - (8.4 \pm 0.8)(\log \sigma - 2.3) \quad (5.39)$$

D_n-σ, II

The Faber-Jackson law is a specialized case of the more general D_n–σ-relation:

The intensity profile of an elliptical galaxy is given by de Vaucouleurs' $r^{1/4}$ law:

$$I(r) = I_0 \exp\left(-(r/r_0)^{1/4}\right) \quad \Longrightarrow \quad L = \int I \propto I_0 r_0^2 \tag{5.40}$$

Because of the virial theorem ($E_{\mathrm{kin}} = -E_{\mathrm{pot}}/2$):

$$\frac{1}{2} m\sigma^2 = G\frac{mM}{r_0} \quad \Longleftrightarrow \quad \sigma^2 \propto \frac{M}{r_0} \tag{5.41}$$

where σ: velocity dispersion.
Assume mass-to-light ratio

$$M/L \propto M^\alpha \tag{5.42}$$

($\alpha \sim 0.25$). and use r_0 from Eq. (5.40) to obtain

$$L^{1+\alpha} \propto \sigma^{4-4\alpha} I_0^{\alpha-1} \tag{5.43}$$

This is called the "fundamental plane" relationship (Dressler et al., 1987).

D_n-σ, III

Observationally easier: Instead of inserting r_0, I_0, measure diameter D_n of aperture to reach some mean surface brightness (typically sky brightness, 20.75 mag arcsec^{-2} in B), and use calibration.

Note: Assumptions are

1. M/L same everywhere.
2. ellipticals have same stellar population everywhere

Calibration paper: Kelson et al. (2000).

Brightest Cluster Galaxies

For very large distances: use brightest cluster galaxies as indicators.

Assumption: Galaxy clusters are similar, brightest galaxy has similar brightness.

Calibration: Close clusters.

10 close galaxy clusters: brightest galaxy has

$$M_{\mathrm{V}} = -22.82 \pm 0.61 \qquad (5.44)$$

Problems:

- Cosmological evolution (e.g., galaxy cannibalism)
- Scatter in brightest galaxy large $\Longrightarrow$ Use 2nd, 3rd brightest, or average brightest N galaxies.

$\Longrightarrow$ The method of brightest cluster galaxies should not be used anymore.

Path to H_0

To obtain H_0: need two things:

1. distances, and
2. redshifts

Distances:

Hubble Space Telescope Key Project on Extragalactic Distance Scale.

Summary paper: Freedman et al. (2001), there are a total of 29 papers on the HST key project!

Strategy:

1. Use high-quality standard candle: Cepheid variables as primary distance calibrator.
2. Calibrate secondary calibrators that work out to $cz = 10000\,\mathrm{km\,s^{-1}}$:
   - Tully-Fisher,
   - Type Ia Supernovae,
   - Surface Brightness Fluctuations,
   - Fundamental-plane for Ellipticals.
3. Combine uncertainties from these methods.

Redshift determination is obviously trivial compared to distance determination. . .

Velocity Field, I

Before determining H_0: correct for influence of velocity field (cluster motion wrt. comoving coordinates).
The observed redshift is given by

$$1 + z = (1 + z_\mathrm{R})\left(1 - \frac{v_0}{c} + \frac{v_\mathrm{G}}{c}\right) \qquad (5.45)$$

where

v_0: observer's radial velocity in direction of galaxy

v_G: radial velocity of the galaxy, difficult to find

z_R: cosmological redshift

Older galaxy catalogues often attempt to correct the measured values of z to produce "corrected redshifts", e.g., by setting $v_\mathrm{G} = 0$ and

$$1 + z = (1 + z_\mathrm{R})\left(1 + \frac{v_0}{c}\right) \sim 1 + z_\mathrm{R} - \frac{v_0}{c} \qquad (5.46)$$

and thus

$$z_\mathrm{R} \sim z + \frac{v_0}{c} \qquad (5.47)$$

since v_0 was up to COBE not well known $\Longrightarrow$ introduces unnecessary problems $\Longrightarrow$ correction not used anymore in recent redshift surveys!

see Harrison & Noonan (1979) for details

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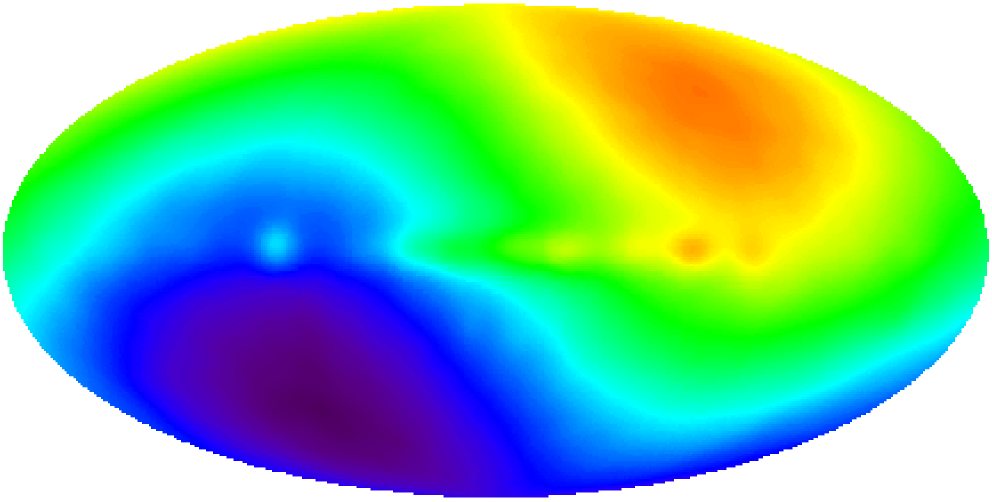
Velocity Field, II



(Bennett et al., 1996, COBE DMR;)

v_0 is easy to find $\Longrightarrow$ Measure velocity of Earth with respect to 3 K radiation. COBE finds speed of (369.1 ± 2.6) km/s, such that

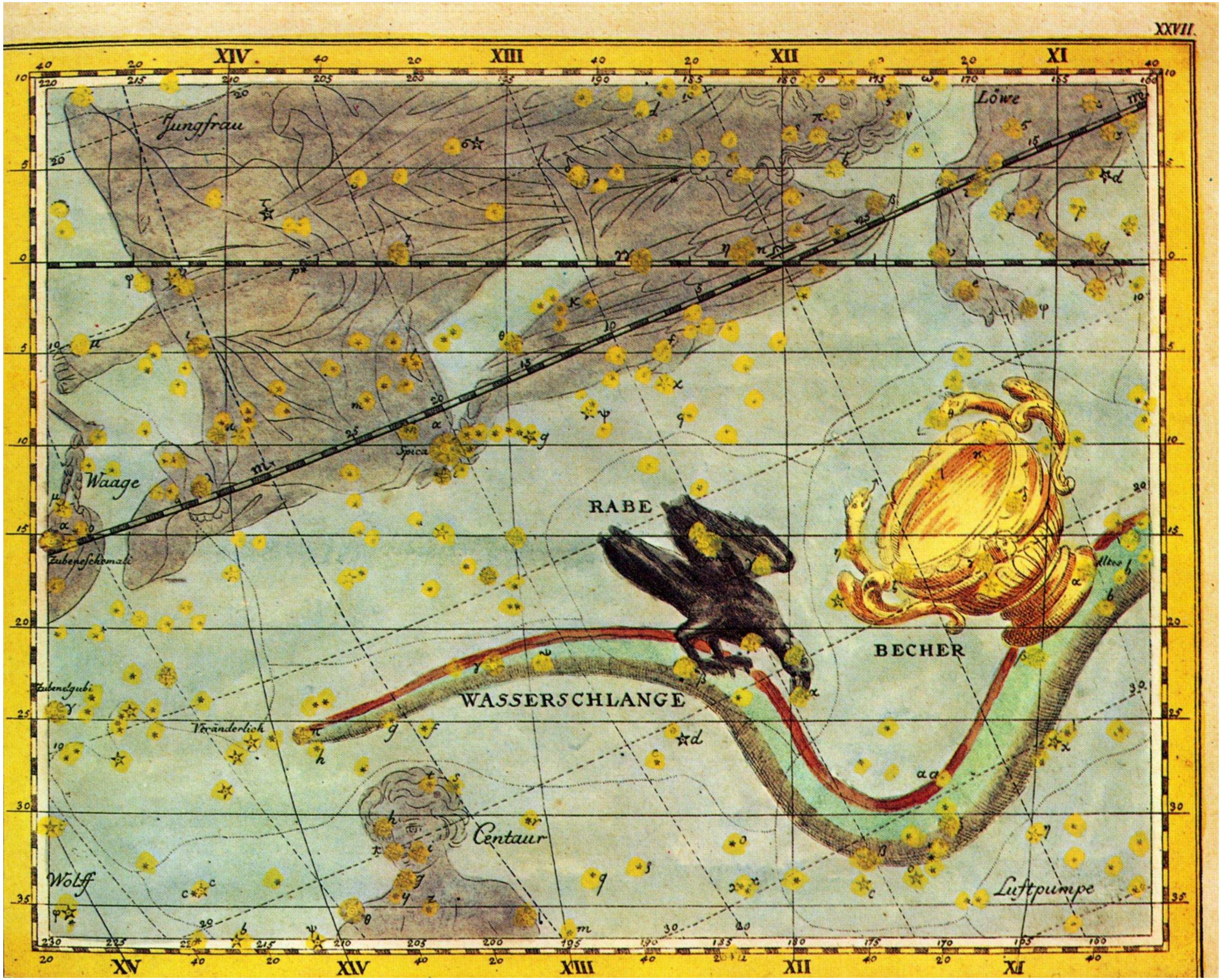
$$v_0 = 370\,\mathrm{km\,s^{-1}} \cdot \cos\theta_{\mathrm{CMB}} \qquad (5.48)$$

where $\theta_{\mathrm{CMB}} = \angle(\mathbf{v}, \mathbf{v}_{\mathrm{CMB}})$, and $\mathbf{v}_{\mathrm{CMR}}$ points towards

$$(l, b) = (264.26^\circ \pm 0.33^\circ, 48.22^\circ \pm 0.13^\circ)$$
$$(\alpha, \delta)_{\mathrm{J2000.0}} = (11^{\mathrm{h}}12.2^{\mathrm{m}} \pm 0.8^{\mathrm{m}}, -7.06^\circ \pm 0.16^\circ)$$

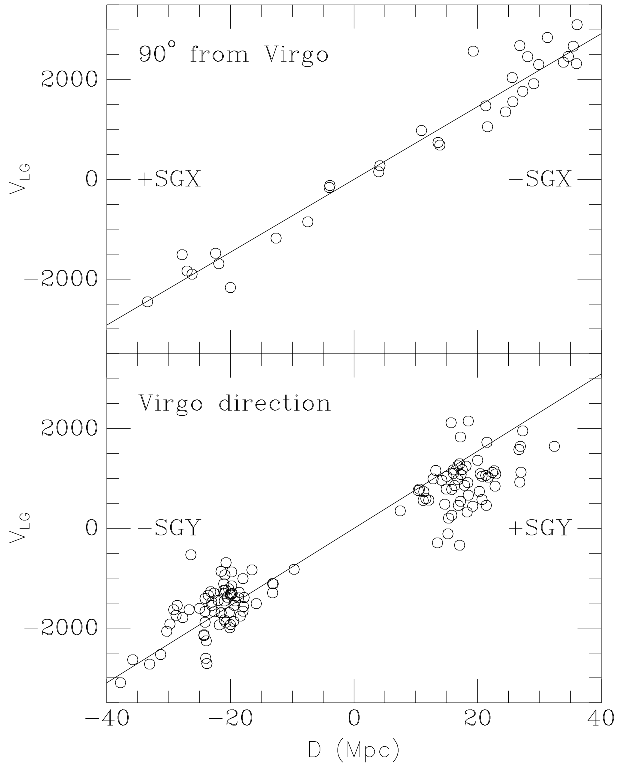
in constellation Crater.

Velocity comes from measured Dipole temperature anisotropy of $\Delta T = 3.353 \pm 0.024$ mK of 3K black-body spectrum of $T = 2.725 \pm 0.020$ K, using $\Delta T/T = v/c$.



The constellation Crater (“Becher”) in Johan Elert Bode’s Sternatlas
(after Slawik/Reichert, Atlas der Sternbilder, Spektrum, 2004)

Velocity Field, IV



To get feeling for v_G out to Virgo, need to study local velocity field surrounding local group and beyond.

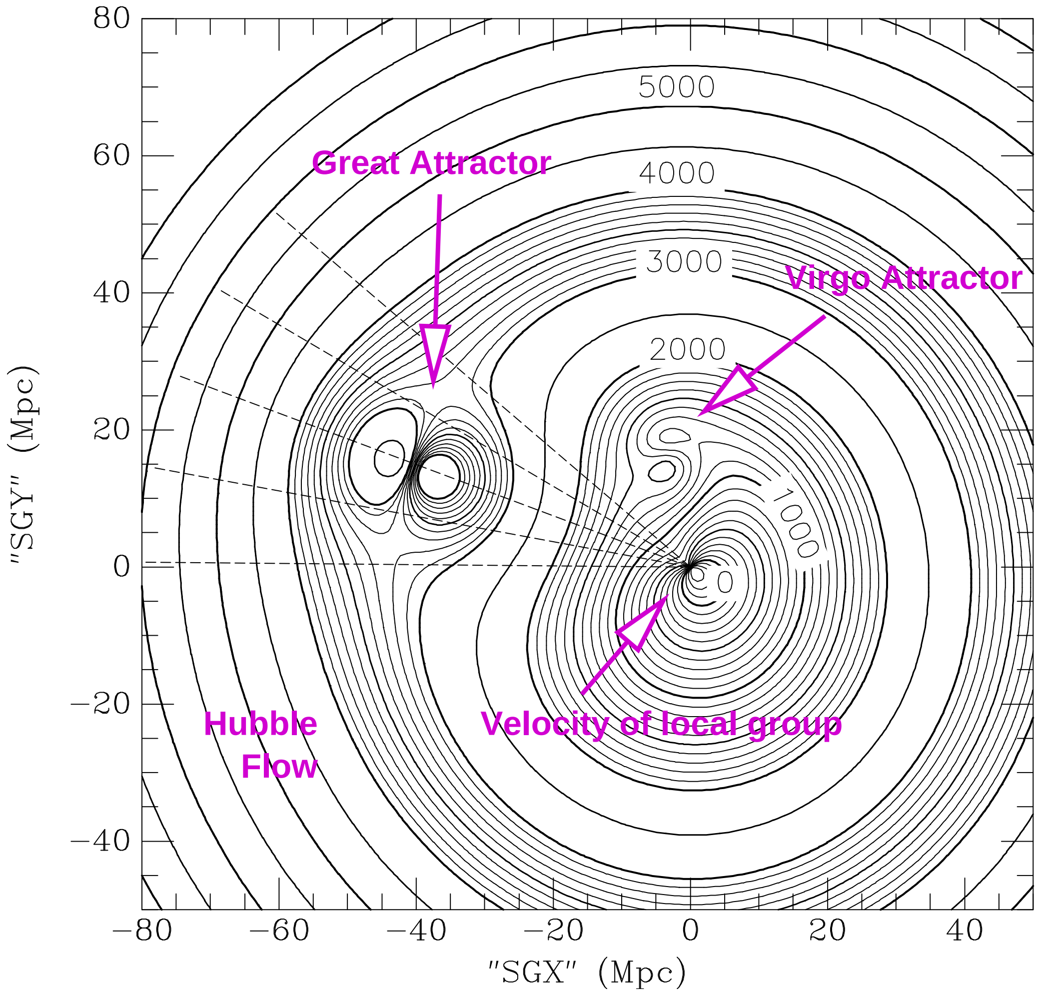
Two major velocity components:

1. Virgocentric infall (known since mid-1970s)
2. Motion towards great attractor ("Seven Samurai", 1980)

plus virialized galaxy motions within clusters.

General analysis: build maximum likelihood model of velocity field including above components *plus* Hubble flow. See Tonry et al. (2000) for details.

Velocity Field, V



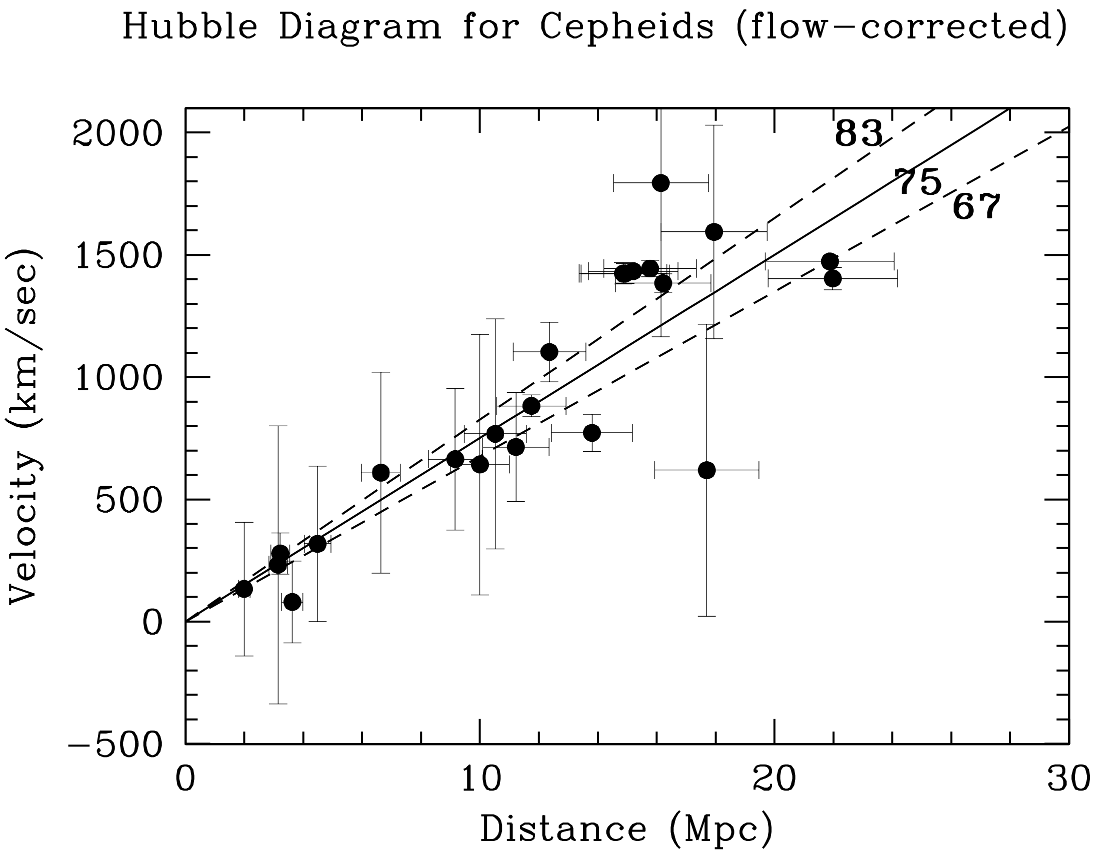
(Tonry et al., 2000, Fig. 20)

Decomposition of velocity field: (Mould et al., 2000, Tab. A1, note that Tonry et al. 2000 find slightly different values)

	$\alpha_{1950.0}$	$\delta_{1950.0}$	v (km s^{-1})
Virgo	$12^{\mathrm{h}}28^{\mathrm{m}}$	$+12^\circ 40'$	957
GA	$13^{\mathrm{h}}20^{\mathrm{m}}$	$+44^\circ 00'$	4380
Shapley	$13^{\mathrm{h}}30^{\mathrm{m}}$	$+31^\circ 00'$	13600

(v wrt. center of local group; *not* taking Hubble flow into account!).

H from HST



Freedman et al. (2001, Fig. 1)

To obtain H_0:

1. Determine d with Cepheids and HST
2. Determine "v", corrected for local velocity field
3. Draw Hubble-diagram
4. Regression Analysis $\Longrightarrow$ H_0

Value from HST Key Project:

$$H_0 = 75 \pm 10\,\mathrm{km/s/Mpc} \tag{5.49}$$

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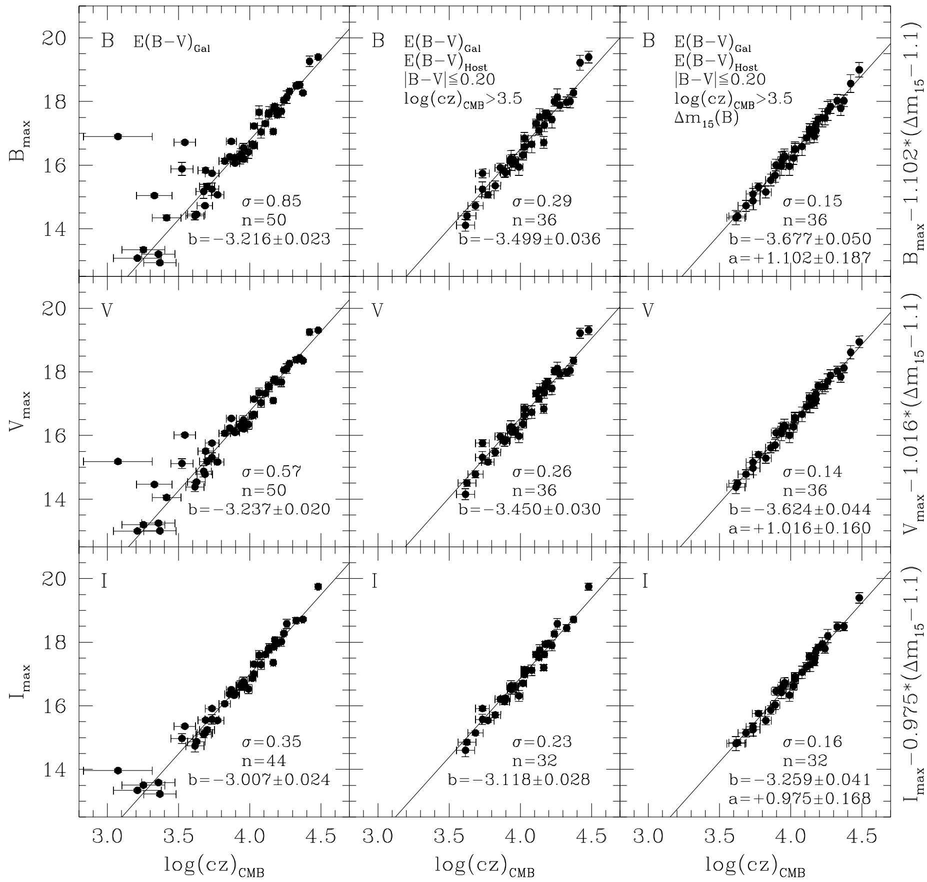
H from HST

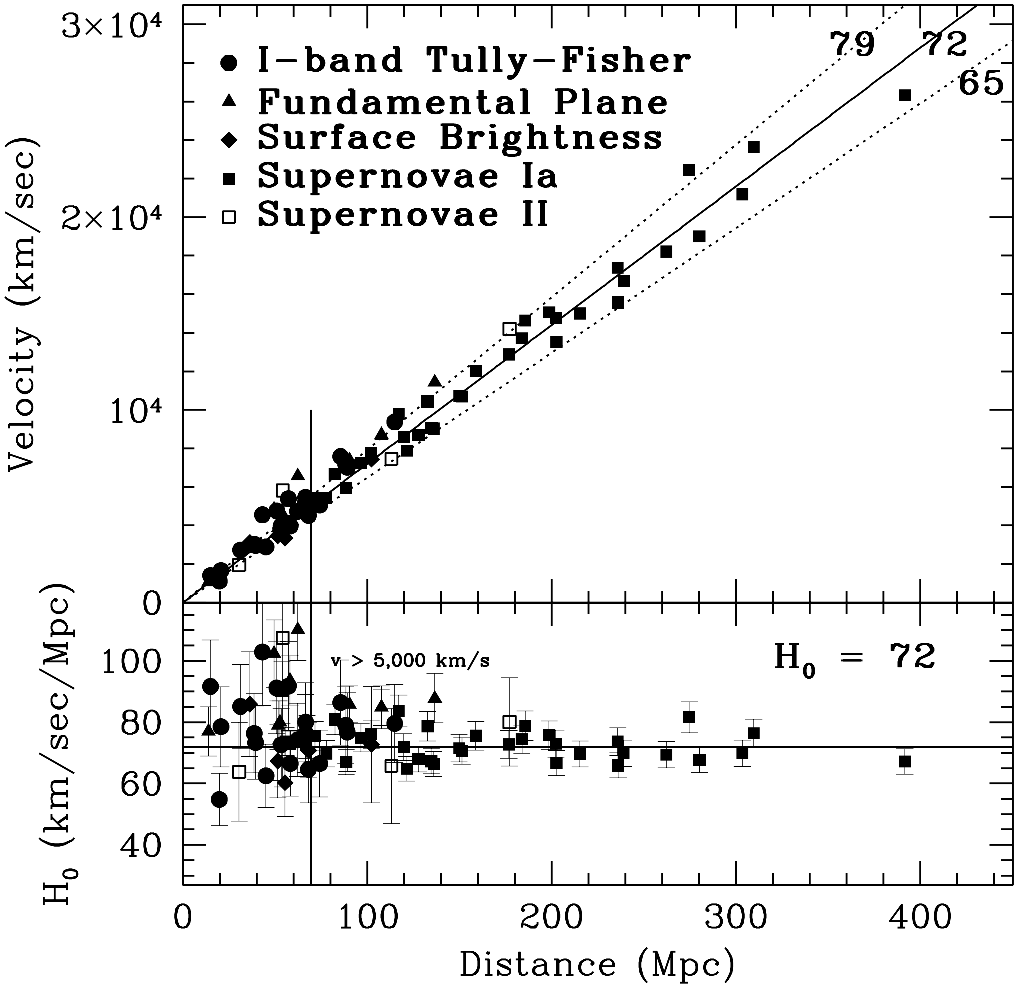


(SN Ia Hubble relations; left: full sample, middle: excluding strongly reddened SN Iae, right: same as middle, correcting for light-curve shape Freedman et al., 2001, Fig. 2)

Cepheids alone: nearby $\Longrightarrow$ systematic uncertainty due to local flow correction and small overall v $\Longrightarrow$ use secondary candles to get to larger distances.

Example above: magnitude-redshift diagram, analoguous to Hubble diagram ($m \propto -5 \log I$, and $I \propto 1/r^2 \propto 1/z^2$ because of Hubble $\Longrightarrow m \propto \log cz$).

H from HST



Freedman et al. (2001, Fig. 4)

Combining all secondary methods, best value found:

$$H_0 = 72 \pm 8\,\mathrm{km\,s^{-1}\,Mpc^{-1}} \qquad (5.50)$$

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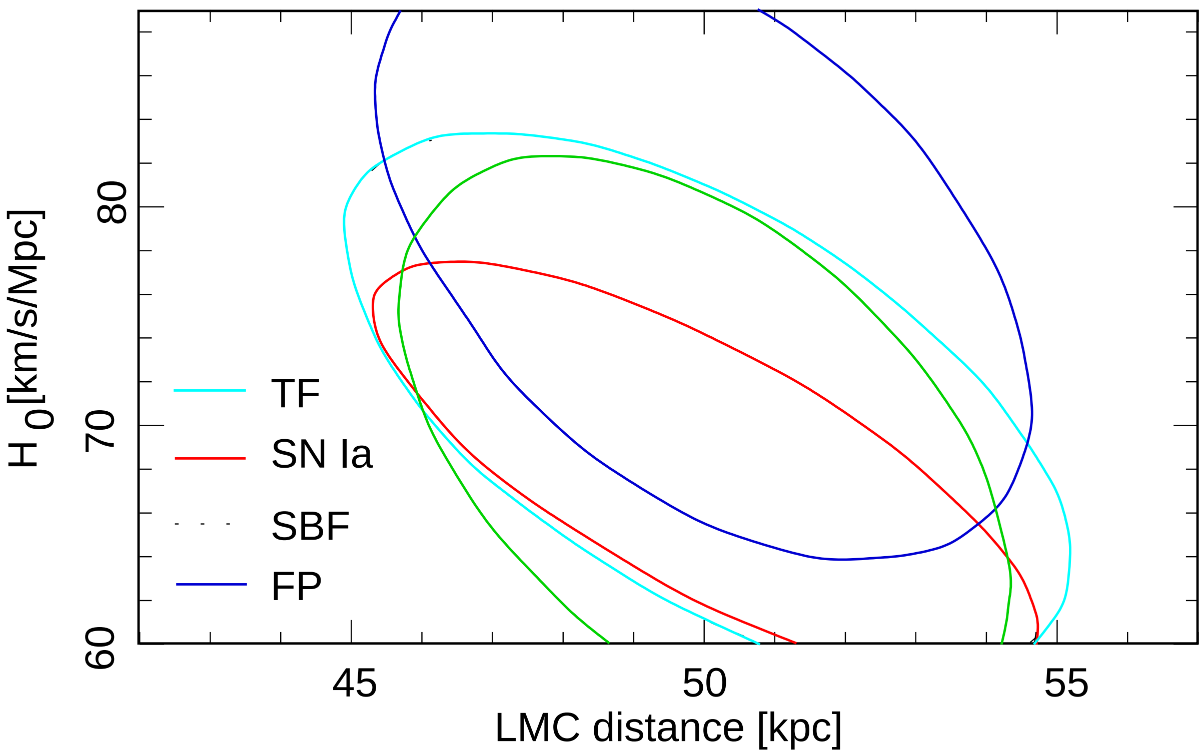
H from HST



(Mould et al., 2000, Fig. 5)

Major systematic uncertainty in current H_0 value: zero-point of Cepheid scale, i.e., distance to Large Magellanic Cloud.

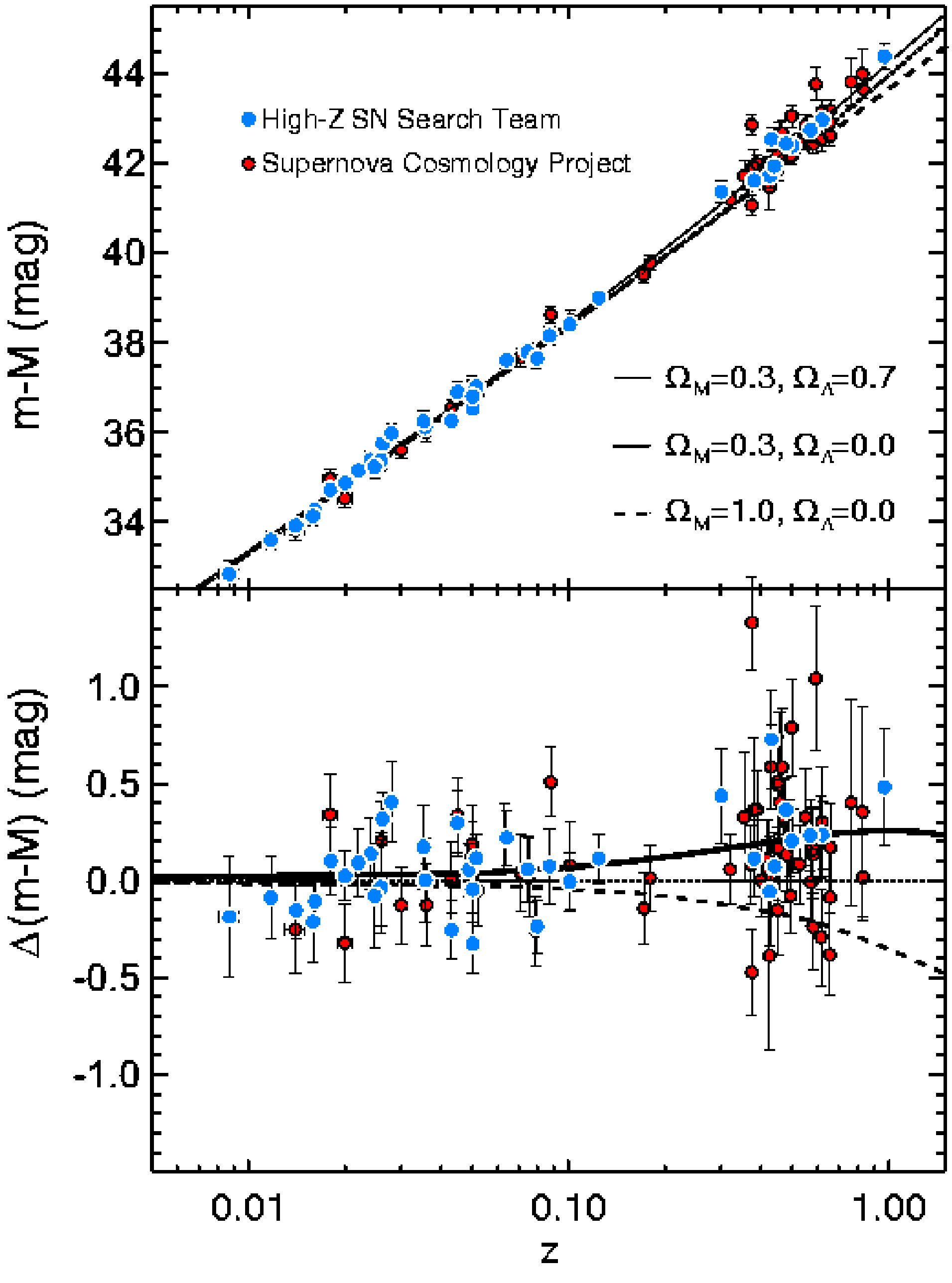
Despite these problems:

$\Longrightarrow$ All current values approach

$\sim 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, with uncertainty $\sim$10%

H_0 controversy is over

H from HST



For larger distances: Deviations from Hubble-Relation!

Before we understand why: Understand Big-Bang itself!

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