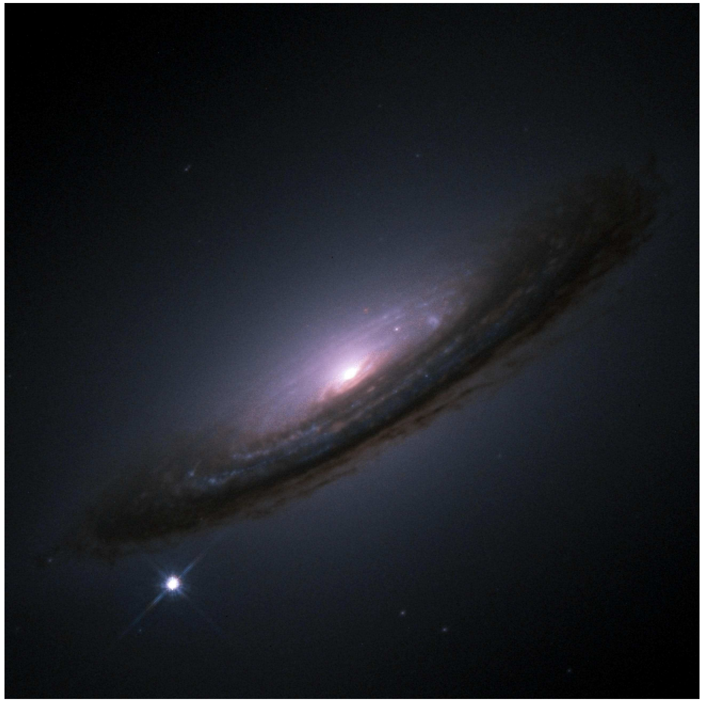
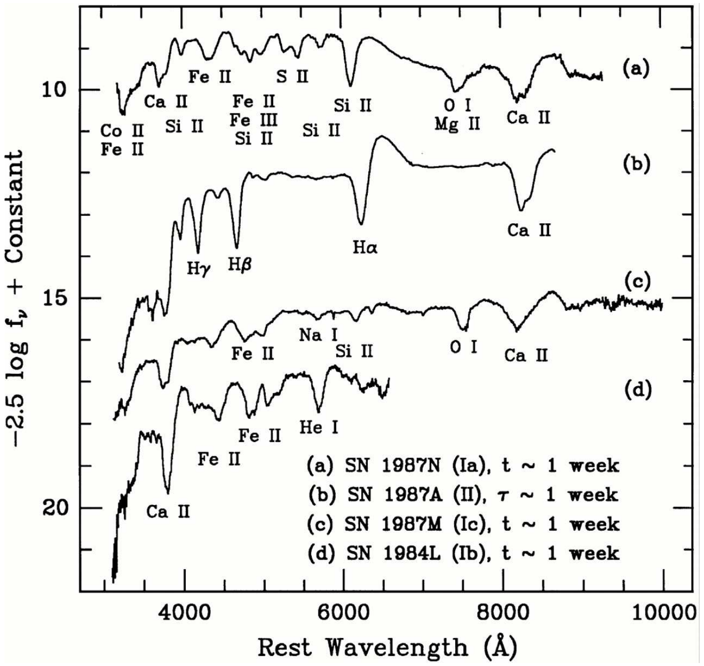


Supernovae have luminosities comparable to whole galaxies:
$\sim 10^{51}\,\mathrm{erg\,s^{-1}}$ in light,
100× more in neutrinos.

SN1994d (HST WFPC)



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

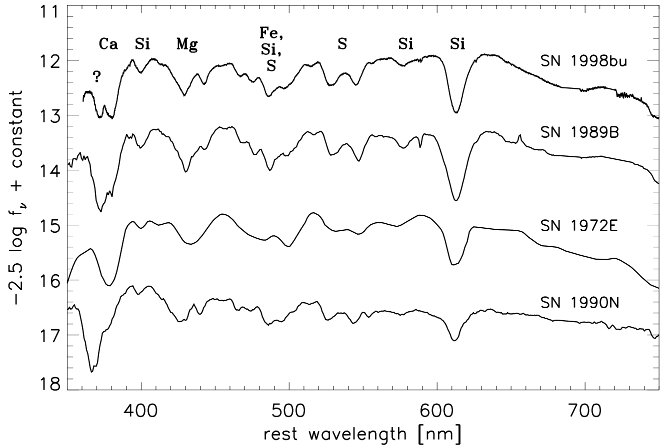
Rough classification (Minkowski, 1941):

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 ⟹ beware when reading older texts.

Type Ia Supernovae, II

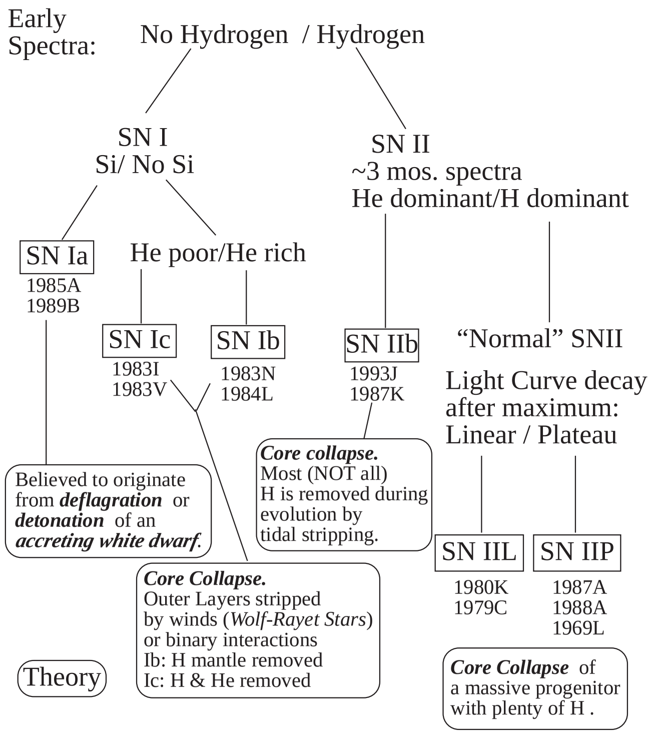


(Spectra of several SNe at maximum light Jha et al., 1999, Fig. 6)

Different supernovae can have very similar spectra.

⟹

Allows their classification.



Early Spectra:

No Hydrogen / Hydrogen

SN I
Si/ No Si

SN II
~3 mos. spectra
He dominant/H dominant

SN Ia
1985A
1989B

He poor/He rich

SN Ic
1983I
1983V

SN Ib
1983N
1984L

SN IIb
1993J
1987K

“Normal” SNII

Light Curve decay after maximum:
Linear / Plateau

SN IIL
1980K
1979C

SN IIP
1987A
1988A
1969L

Believed to originate from ***deflagration*** or ***detonation*** of an ***accreting white dwarf.***

Core collapse.
Most (NOT all)
H is removed during evolution by tidal stripping.

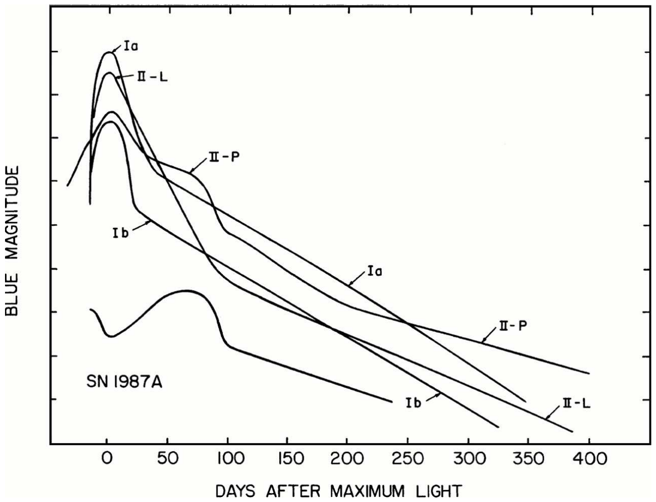
Core Collapse.
Outer Layers stripped by winds (*Wolf-Rayet Stars*) or binary interactions
Ib: H mantle removed
Ic: H & He removed

Core Collapse of a massive progenitor with plenty of H .

Theory

courtesy M.J. Montes

Type Ia Supernovae, V

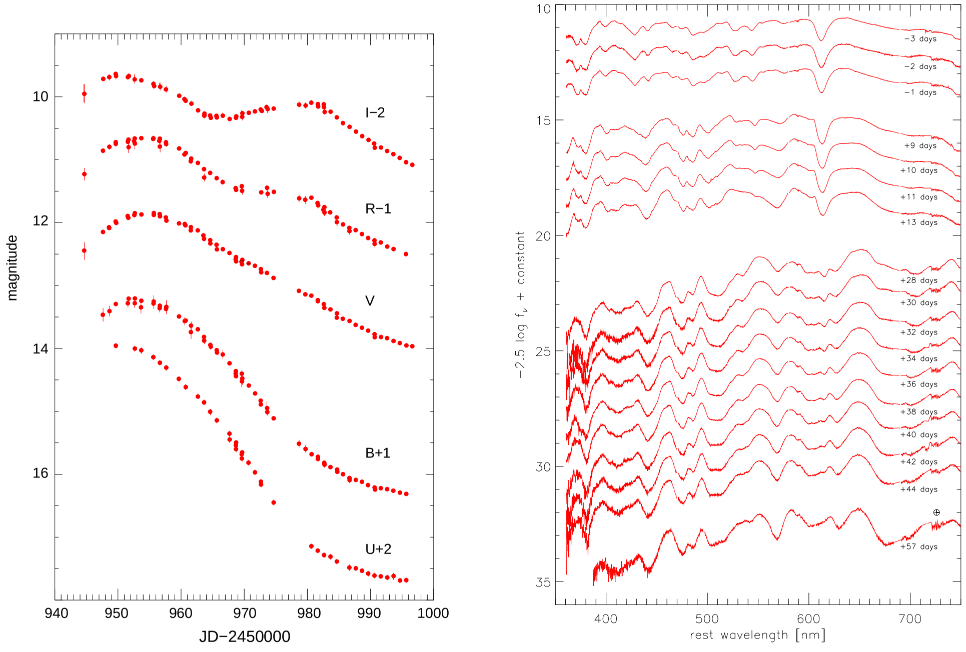


(Filippenko, 1997, Fig. 3)

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)

Type Ia Supernovae, VII

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.

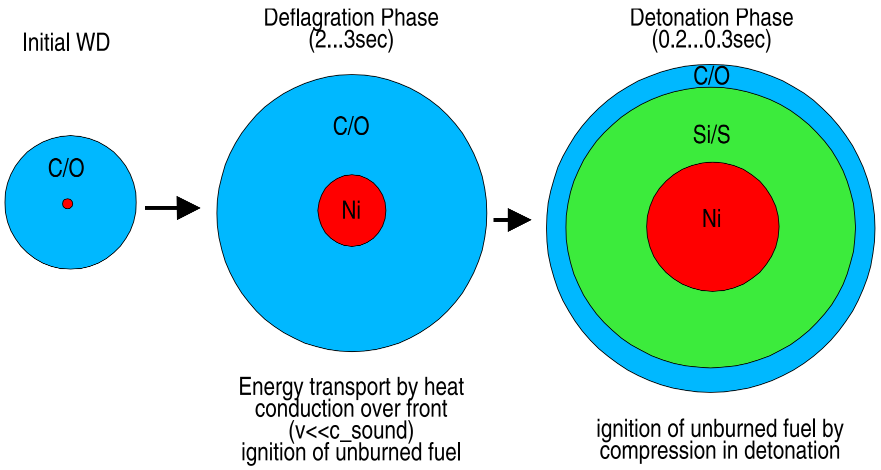
$\Longrightarrow$ *progenitor of SNe II, Ib, Ic:* massive stars ($\gtrsim 8\,M_\odot$) $\Longrightarrow$ core collapse

- SNe Ia: all types of galaxies, no preference for arms, almost no scatter in lightcurves

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

Rule of thumb: 1…3 SNe per galaxy and per century

Type Ia Supernovae, VIII



after P. Höflich

Type Ia Supernovae, IX

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 ("FRED") 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).

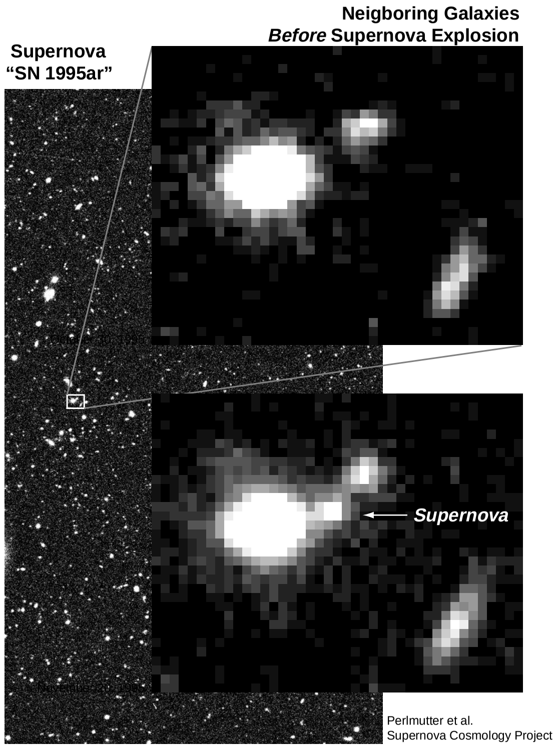
Calibration: SNe Ia in nearby galaxies where Cepheid distances known.

At maximum light:

$$M_{\mathrm{B}} = -18.33 \pm 0.11 + 5 \log h_{100} \quad (L \sim 10^{9\ldots10}\,L_\odot) \tag{5.33}$$

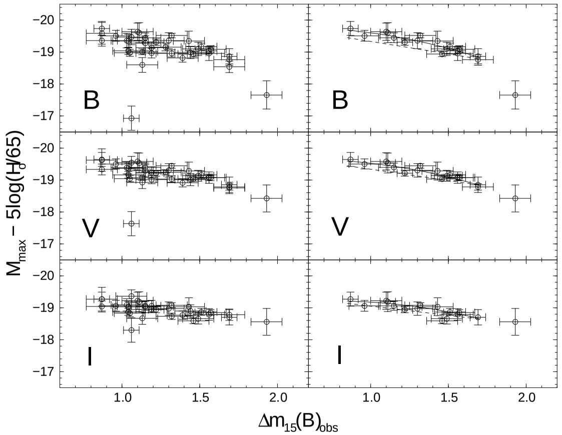
Intrinsic dispersion: $\lesssim$0.25 mag (possibly due to size of clusters analyzed?!?)

Observable out to 1000 Mpc



Perlmutter et al.
Supernova Cosmology Project

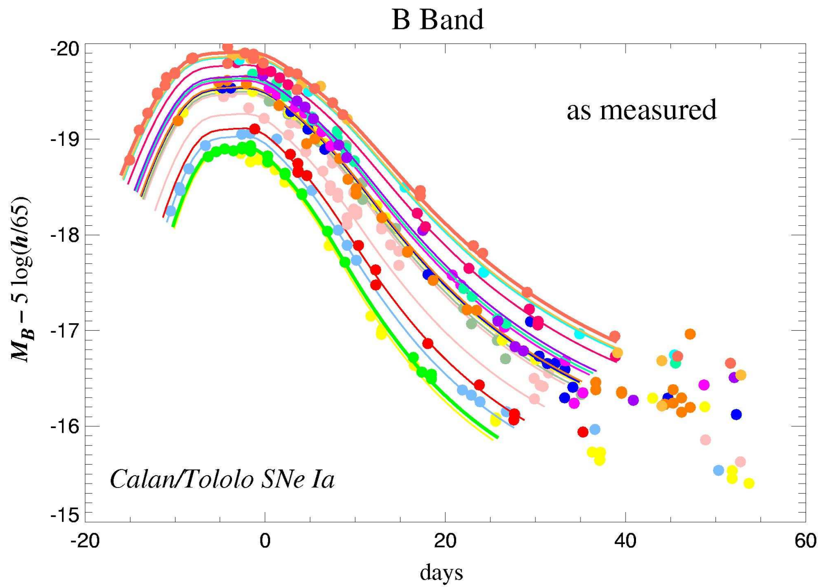
Type Ia Supernovae, XI



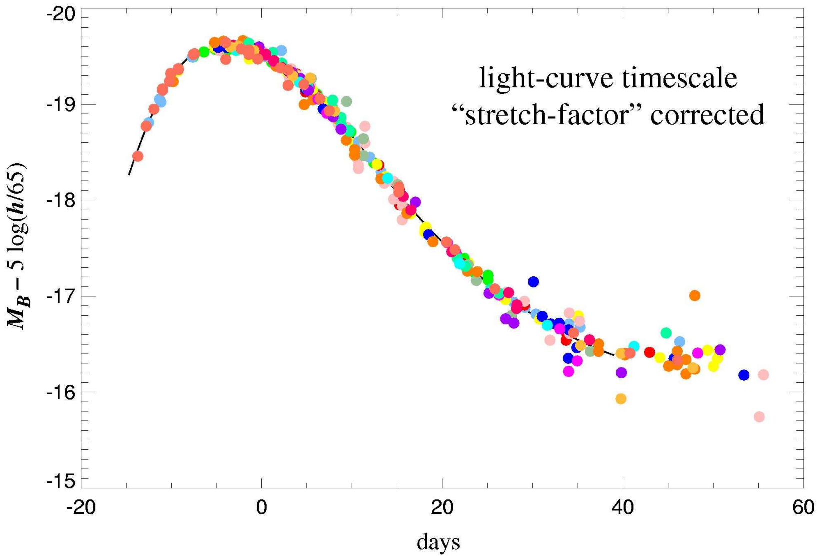
(Phillips et al., 1999, Fig. 8)

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. (5.33) 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).



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., $z < 0.1$)



Kim, *et al.* (1997)

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, XIV

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

$$\begin{aligned}\log H_0 = 0.2\Big\{ M_{\mathrm{B}}^{\max} &- 0.720(\pm 0.459) \\ &\cdot [\Delta m_{\mathrm{B},15,t} - 1.1] - 1.010(\pm 0.934) \\ &\cdot [\Delta m_{\mathrm{B},15,t} - 1.1]^2 + 28.653(\pm 0.042) \Big\} \quad (5.34)\end{aligned}$$

where

$$\Delta m_{\mathrm{B},15,t} = \Delta m_{\mathrm{B},15} + 0.1 E(\mathrm{B}-\mathrm{V}) \quad (5.35)$$

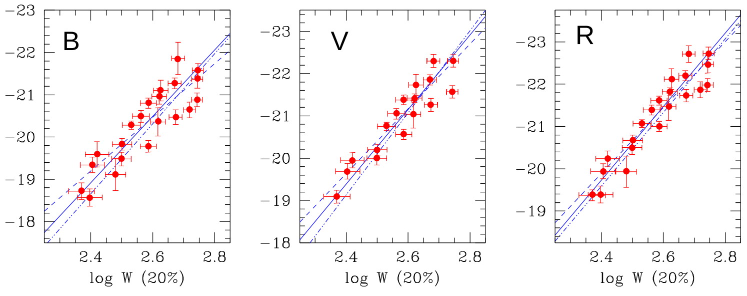
where

$\Delta m_{\mathrm{B},15}$: observed 15 d decline rate,
$E(\mathrm{B}-\mathrm{V})$: total extinction (galactic+intrinsic).

Eq. (5.34) 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



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

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

$$M = -a \log\left(\frac{W_{20}}{\sin i}\right) - b \quad (5.36)$$

where W_{20}: 20% line width ($\mathrm{km\,s^{-1}}$; typically $W_{20} \sim 300\,\mathrm{km\,s^{-1}}$), 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

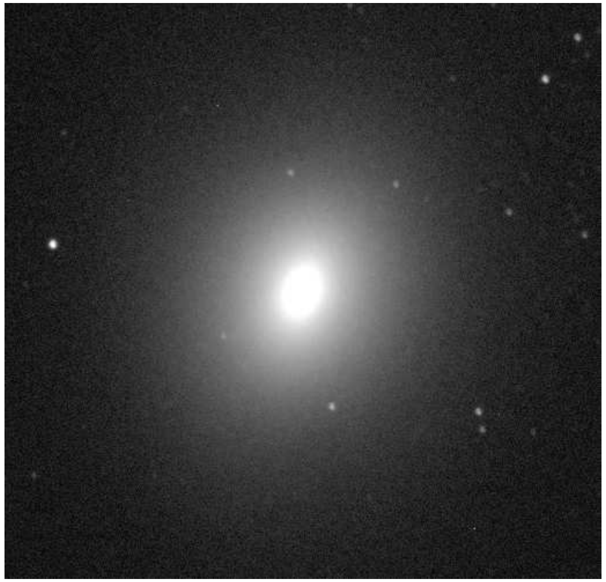
Qualitative Physics: Line width related to mass of galaxy: $W/2 \sim V_{\max}$, where $V_{\max}$ max. velocity of rotation curve
$\Longrightarrow$ Assume $M/L = $ const. (good assumption)
$\Longrightarrow$ width related to luminosity.

Detailed physical basis unknown. Might be related to galaxy formation (“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 ∼2).
4. Optical extinction.
5. Intrinsic dispersion ∼0.2 mag.
6. Barred Galaxies problematic.



“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.

M32 (companion of Andromeda), courtesy W. Keel

Ellipticals: $M_\mathrm{B} = -19.38 \pm 0.07 - (9.0 \pm 0.7)(\log\sigma - 2.3)$ (5.37)

Lenticulars (Type S0): $M_\mathrm{B} = -19.65 \pm 0.08 - (8.4 \pm 0.8)(\log\sigma - 2.3)$ (5.38)

D_n-σ

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:

$$I(r) = I_0 \exp\left(-(r/r_0)^{1/4}\right) \quad\Longrightarrow\quad L = \int I \propto I_0 r_0^2 \tag{5.39}$$

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

$$\frac{1}{2}m\sigma^2 = G\frac{mM}{r_0} \quad\Longleftrightarrow\quad \sigma^2 \propto \frac{M}{r_0} \tag{5.40}$$

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

$$M/L \propto M^\alpha \tag{5.41}$$

($\alpha \sim 0.25$). and use r_0 from Eq. (5.39) to obtain

$$L^{1+\alpha} \propto \sigma^{4-4\alpha} I_0^{\alpha-1} \tag{5.42}$$

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

D_n-σ

Observational version of the fundamental plane relationship: Instead of inserting r_0 and 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).

Path to H_0

To obtain H_0, we need distances, and redshifts.

Redshifts: Trivial

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 candles: 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.

Velocity Field, I

Before determining H_0: correct for **influence of velocity field** (cluster motion with respect to comoving coordinates).

The observed redshift is given by

$$1 + z = (1 + z_{\mathrm{R}}) \left(1 - \frac{v_0}{c} + \frac{v_{\mathrm{G}}}{c}\right) \tag{5.43}$$

where

v_0: observer's radial velocity in direction of galaxy

v_{G}: radial velocity of the galaxy, difficult to find

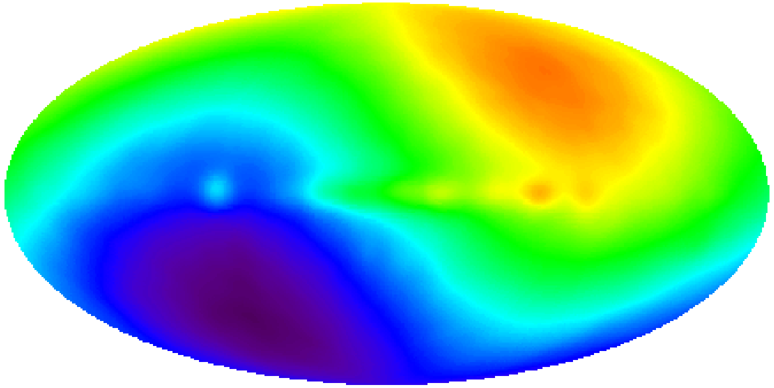
z_{R}: cosmological redshift

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

$$1 + z = (1 + z_{\mathrm{R}}) \left(1 + \frac{v_0}{c}\right) \sim 1 + z_{\mathrm{R}} - \frac{v_0}{c} \implies z_{\mathrm{R}} \sim z + \frac{v_0}{c} \tag{5.44}$$

since v_0 was not well known before COBE $\Longrightarrow$ introduces unnecessary problems

$\Longrightarrow$ correction not used in recent redshift surveys! (see Harrison & Noonan, 1979, for details)



(COBE DMR; Bennett et al., 1996)

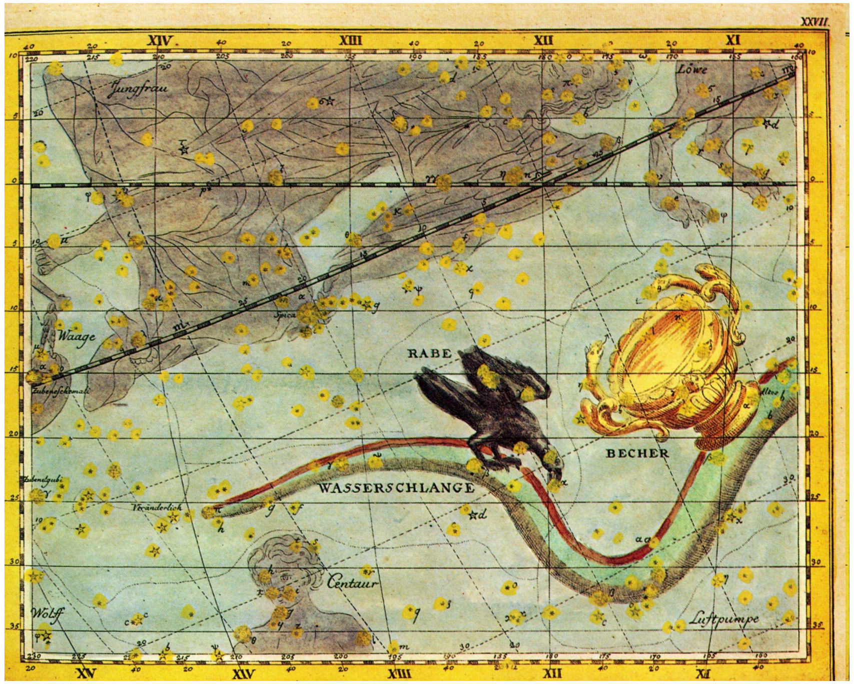
v_0 is easy to find $\Longrightarrow$ Measure velocity of Earth with respect to 3 K radiation. COBE finds $\Delta T = 3.353 \pm 0.024$ mK of 3K black-body spectrum of $T = 2.725 \pm 0.020$ K, using $\Delta T/T = v/c$.

$$v_0 = (369.1 \pm 2.6)\,\mathrm{km\,s^{-1}} \cdot \cos\theta_{\mathrm{CMB}} \tag{5.45}$$

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

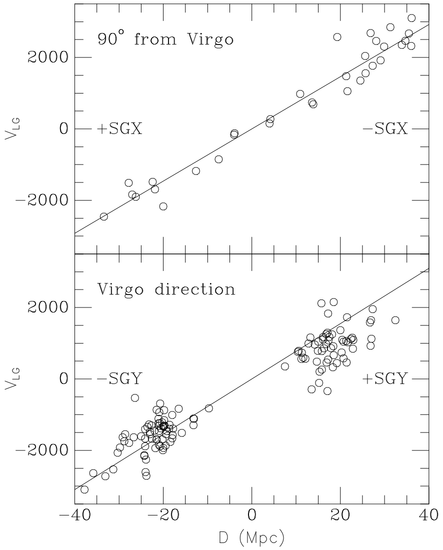
$$(l, b) = (264^\circ\!.26 \pm 0^\circ\!.33, 48^\circ\!.22 \pm 0^\circ\!.13)$$
$$(\alpha, \delta)_{\mathrm{J2000.0}} = (11^{\mathrm{h}}12^{\mathrm{m}}\!.2 \pm 0^{\mathrm{m}}\!.8, -7^\circ\!.06 \pm 0^\circ\!.16)$$

in constellation Crater.



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.

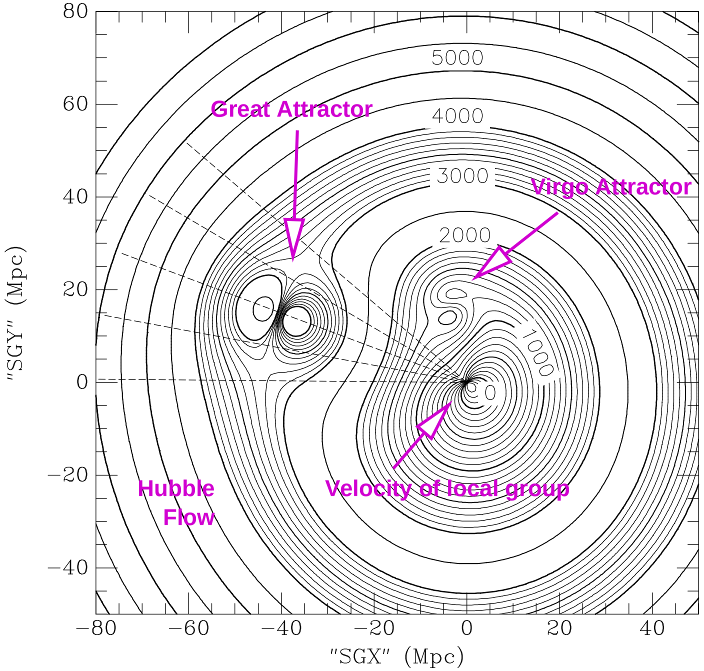
Two major velocity components:

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.

Galaxy moves within local group with $v \sim 630\,\mathrm{km\,s^{-1}}$



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

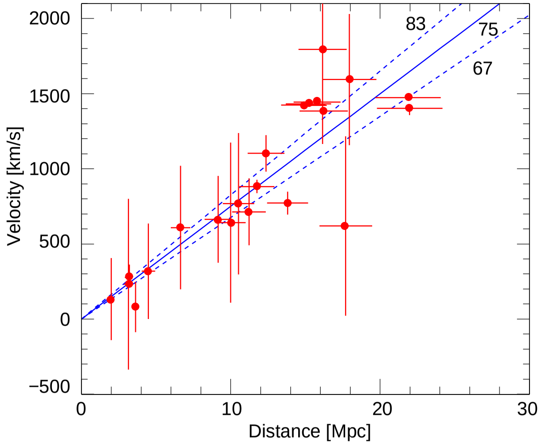
	$\alpha_{1950.0}$	$\delta_{1950.0}$
Virgo	12^h28^m	$+12°40'$
GA	13^h20^m	$+44°00'$
Shapley	13^h30^m	$+31°00'$

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

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

H from HST

Hubble Diagram for Cepheids (flow−corrected)



Freedman et al. (2001, Fig. 1)

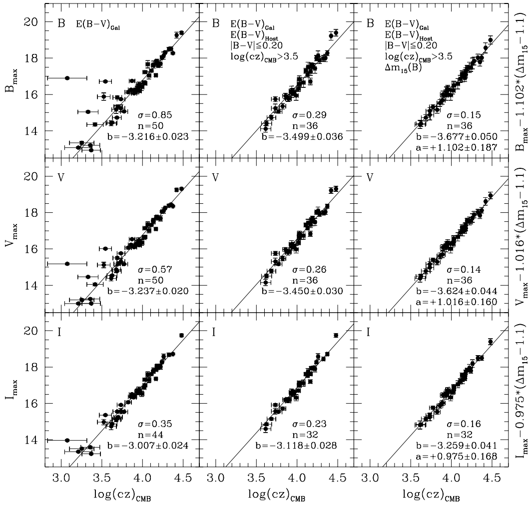
To obtain H_0:

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:

$$H_0 = 75 \pm 10\,\mathrm{km\,s^{-1}\,Mpc^{-1}} \tag{5.46}$$

H from HST



Cepheids alone: nearby

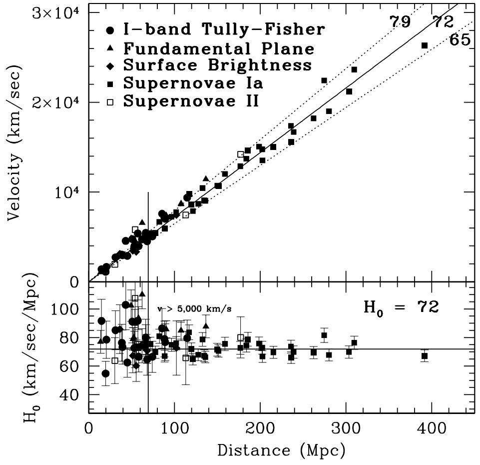
$\Longrightarrow$ systematic uncertainties due to local flow correction and small overall v

$\Longrightarrow$ use secondary candles to get to larger distances.

Example: 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 $\Longrightarrow m \propto \log cz$).

(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)

H from HST

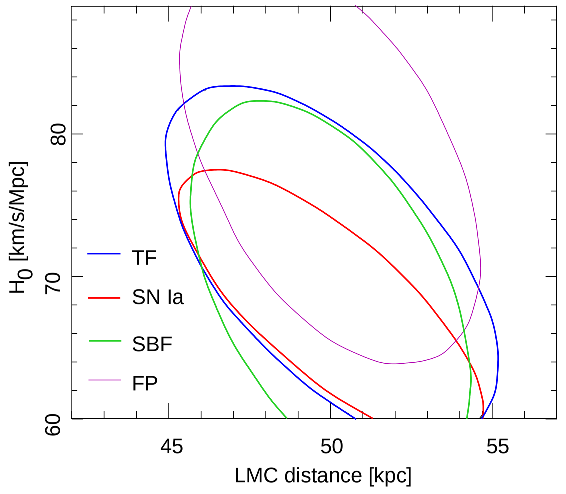


Freedman et al. (2001, Fig. 4)

Combining all secondary methods, best value found:

$$H_0 = 72 \pm 8\,\mathrm{km\,s^{-1}\,Mpc^{-1}} \tag{5.47}$$

H from HST



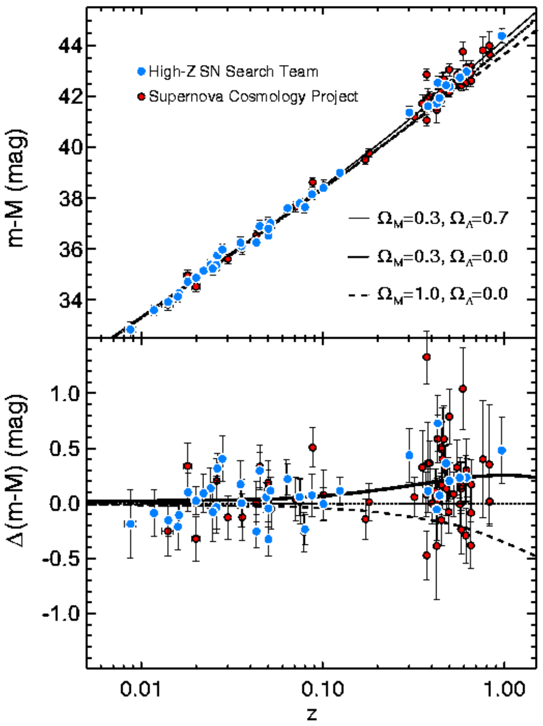
(after Mould et al., 2000, Fig. 5)

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

H_0 controversy is over



For larger distances: There are deviations from Hubble-Relation! Before we understand why: Need to understand the Big-Bang itself!

Abraham, R. G., & van den Bergh, S., 1995, ApJ, 438, 218

Ajhar, E. A., Lauer, T. R., Tonry, J. L., Blakeslee, J. P., Dressler, A., Holtzman, J. A., & Postman, M., 1997, Astron. J., 114, 626

Arp, H. C., 1956, Astron. J., 61, 15

Bennett, C. L., et al., 1996, ApJ, 464, L1

Blakeslee, J., Ajhar, E. A., & Tonry, J. L., 1999, in Post-Hipparcos Cosmic Candles, ed. A. H. . F. Caputo, (Dordrecht: Kluwer), 181, astro-ph/9807124

Ciardullo, R., Jacoby, G. H., Ford, H. C., & Neill, J. D., 1989, ApJ, 339, 53

Feast, M., 1999, PASP, 111, 775

Fenkart, R. F., & Binggeli, B., 1979, ApJS, 35, 271

Ferrarese, L., et al., 2000, ApJ, 529, 745

Filippenko, A. V., 1997, ARA&A, 35, 309

Freedman, W. L., et al., 2001, ApJ, 553, 47

Gibson, B. K., et al., 2000, ApJ, 529, 723

Gieren, W. P., Gómez, M., Storm, J., Moffett, T. J., Infante, L., Barnes, III, T. G., Geisler, D., & Fouqué, P., 2000, ApJS, 129, 111

Hanson, R. B., 1980, in Star Formation, ed. J. E. Hesser, Vol. 85, 71

Harrison, E. R., & Noonan, T. W., 1979, ApJ, 232, 18

Jacoby, G. H., et al., 1992, PASP, 104, 599

Jha, S., et al., 1999, Astrophys. J., Suppl. Ser., 125, 73

Kelson, D. D., et al., 2000, ApJ, 529, 768

Kim, A. G., et al., 1997, ApJ, 476, L63

Lee, J.-W., & Carney, B. W., 1999, ApJ, 117, 2868

Mould, J., Kennicutt, Jr., R. C., & Freedman, W., 2000, Rep. Prog. Phys., 63, 763

Mould, J. R., et al., 2000, ApJ, 529, 786

Phillips, M. M., Lira, P., Suntzeff, N. B., Schommer, R. A., Hamuy, M., & Maza, J., 1999, Astron. J., 118, 1766

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

Sakai, S., et al., 2000, ApJ, 529, 698

Seidelmann, P. K., (eds.) 1992, Explanatory Supplement to the Astronomical Almanac, (Mill Valley, CA: University Science Books)

Straniero, O., Chieffi, A., & Limongi, M., 1997, ApJ, 490, 425

Tonry, J. L., Blakeslee, J. P., Ajhar, E. A., & Dressler, A., 2000, ApJ, 530, 625

van den Bergh, S., & Pritchet, C. J., 1986, PASP, 98, 110

van Leeuwen, F., 2007, A&A, 474, 653