Astronomy from 4 Perspectives

Bi-national Heraeus Sumer School Series for Teacher Students and Teachers

I. Cosmology

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Cosmic Distances

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KTS
Klaus Tschira Stiftung gemeinnützige GmbH

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Cosmic Distances

- **Distance determinations: a fundamental, omnipresent problem in astronomy**
- **Local universe**
  - Distance ladder
    - Methods/objects/calibration
    - Hubble constant and galaxy distribution
- **expanding curved space**
  - Distance and redshift
    - Luminosity, surface brightness, sizes
    - Cornerstone observations

Units

Units

- Length: $1 parsec = 1 pc = 648,000 AU/\pi$

  $= 206,265 AU = 3.26 ly = 3.086 \cdot 10^{18} cm$
- Time: $1 year = 1 yr = 3.156 \cdot 10^7 s$
- Velocity: $1 km/s \approx 1 pc/Myr$
- Mass: $1 M_\odot \approx 2 \cdot 10^{33} g$
- Gravitational constant:

$$G = 4.3 \cdot 10^{-3} \frac{pc}{M_\odot} \frac{km^2}{s^2} = 4.5 \cdot 10^{-15} \frac{pc^3}{M_\odot yr^2}$$

Units

- **the astronomical unit AU**
  - physical definition from light running time

$$A = 499.004782s * c = 149,597,870km$$

  - Attention: semi-major axis of the orbit

$$a_{Earth} = 1.000000031A$$

  - therefore rounded value:

$$1AU = 149.6 \cdot 10^6 km$$

  - maximum diameter D (e=0.017, b=minor axis):

$$D = 2a = 1.00014 \cdot 2b$$

Basic principle

- Compare an **absolute** and an **apparent** property with known dependence on distance
  - Trigonometric parallax
    - orbital motion of Earth - angular motion of star at sky
  - Distance modulus
    - Absolute luminosity - apparent brightness
    - Classification of objects and calibration
      - Period-luminosity relation (variable stars)
      - Tully-Fisher relation (spiral galaxies)
  - Kinematic distances
    - Binary stars: Radial velocities (+ Kepler laws)
    - Radial velocities – proper motion (+spherical expansion)
    - Radial velocities – Galactic rotation (+ rotation curve)
  - Hubble flow
    - Hubble constant and redshift

Methods

- direct: light running time
  - radar, satellite signals
  - Planetary system (Kepler laws)
- trigonometric parallaxes: motion of observer projected at sky
  - Nearby stars
- proper motions
  - Binary orbits, streaming parallaxes, shell expansion
- apparent sizes
- photometric parallaxes: distance modulus
  - Variable stars, supernovae
  - Galaxies
    - Tully-Fisher-relation, fundamental plane, brightest cluster members
- Hubble flow/expansion
  - Redshift and Hubble constant
- Miscellaneous methods
  - Surface brightness fluctuations
  - Sunyaev-Zel'dovich-effect
  - Acoustic waves/baryonic oscillations

The distance ladder

step	range	methods/objects
1.	10 light-min	light traveling time/ Earth diameter, distance to Moon, **Mars**, and Venus
2.	5 light-hours; Solar system	light traveling time, **Kepler laws**/ satellite positions, other planets
3.	100 pc; Solar neighbourhood	**trigonometric parallaxes**, streaming parallaxes/ nearby stars, **Hyades**
4.	20 kpc; Milky Way	rotational distances/gas, OB-stars in the Galaxy
5.	1 Mpc; Local Group	photometry; HR-diagram; main sequence fitting: star cluster/nearby galaxies
6.	20 Mpc	photometry; variable stars: **cepheids**, **RR-Lyrae**;/local universe
7.	1 Gpc	**supernova luminosity**; **Hubble flow**; galaxy cluster luminosities; Tully-Fisher-relation (up to redshift $z \approx 0.3$)
8.	>1 Gpc	Redshifts: galaxies, quasars, gas; CMB (world model dependent)

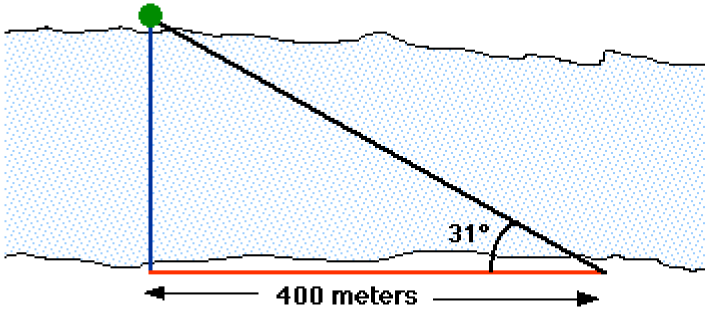
Distance determination

direct methods

- Size of the Earth
  - historically by triangulation and the solar altitude at culmination (Erastothenes 200 B.C.; Picard 1671)
  - definition of the 'meter': 1m=1/40,000,000 of the meridian through Paris: R=6366.2km
  - R(pole)=6357km, R(equator)=6378km
  - light traveling times by satellites (GPS)
- Distance to Moon
  - historically by triangulation and duration of lunar eclipses, orbital time of the Moon: $D_{Moon}=60.3R_{Earth}=384{,}400$km
  - Lunar laser ranging experiment (Apollo 11: July 21, 1969): $D_{Moon}=384{,}467$ km (mean value)
- Planetary system
  - radar, light traveling time (satellite orbits); Kepler laws

(annual) trigonometric parallaxes

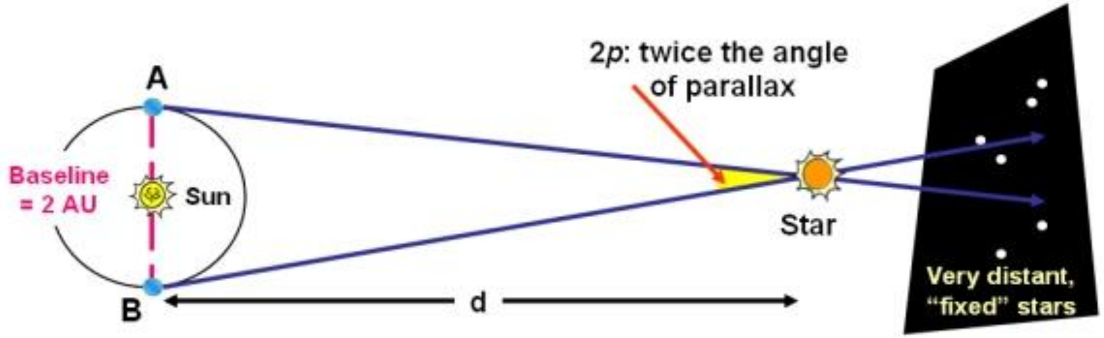
- Changing direction of a nearby object due to the motion of the observer
- On Earth
  - Measuring the width of a river by the relative angles from two points

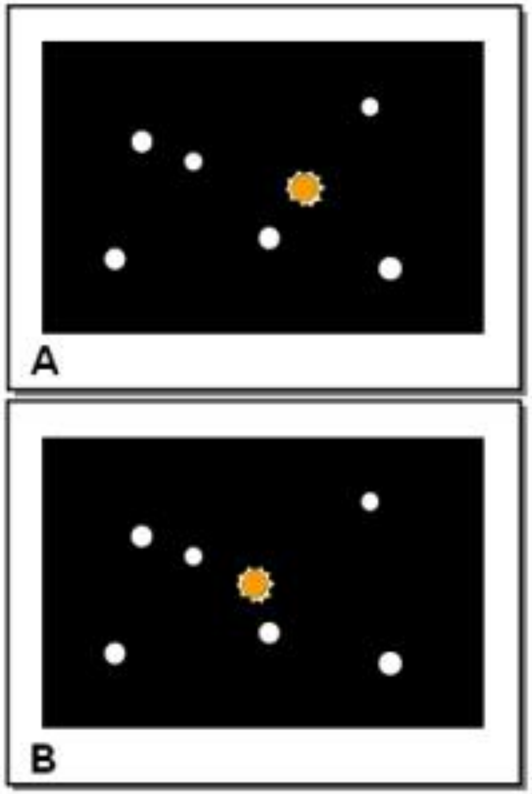


- Celestial objects
  - Relative positions with respect to distant stars from different points at the Earth or in different seasons (annual)

(annual) trigonometric parallaxes

in the sky





from measuring the shift in position of a star against fixed background sources, we can derive its distance

Nearby star moves on an ellipse with angular size in arc seconds: semi-major axis = projection of 1AU

Distance determination

(annual) trigonometric parallaxes

- The parallax p (in arcsec) is the inverse distance r (in parsec) given by

$$p['']=\frac{1}{r\,[pc]}$$

- precision and range
  - p=0.05'' from ground (statistics of many data points)
  - HIPPARCOS satellite: 1mas (=10% error at p=10mas, r=100pc); 20,000 stars at r<100pc
  - Gaia project (launch: Nov. 2013): 10^{-5}''=10µas, r=10kpc

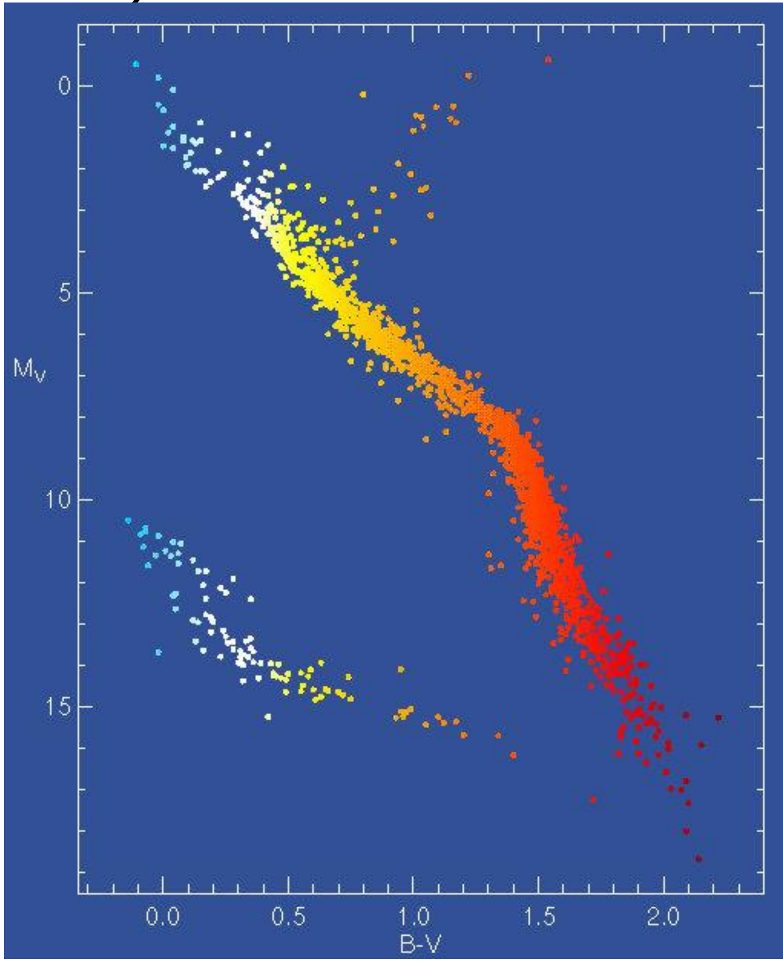
    ---> will provide position and velocity information of ~ one billion (<m_V=20mag) stars in the Milky Way

Distance determination

- next system
  - binary star: α Cen; p = 0.″75 - Proxima Cen. p = 0.″76 (r = 1.3 pc)
  - separation at sky: 3 (=0.1pc in space)
- 2003: new brown dwarf companion of ε Indi discovered
  - r=3.7pc
- 2003: new nearby star discovered
  - p = 0.″257 (r = 3.9pc)
  - proper motion μ=5.2mas/yr (8th fast; v_t≈0.1km/s)
  - m_V=15.4mag (red dwarf)

Distance determination

- Colour-magnitude diagram CMD (Hertzsprung-Russell diagram HRD) of nearby stars (r<25pc; Catalogue of Nearby Stars CNS 4)
  - ~6000 stars
  - main sequence widened by
    - unresolved binary stars
    - age spread of the stars
    - metallicity spread
  - **Basis for photometric Distances of stars**



Jahreiss, ARI

Distance determination

dynamical parallaxes

- visual binaries
  - comparison of semi-major axis 'a' from radial velocities or from the orbital period (3. Kepler law: $P^2 \sim a^3$) and the apparent orbit in arcsec
  - sum of the masses must be known roughly
  - with period in years and mass in solar units:

$$p[''] = \frac{a['']}{(P^2(M_1 + M_2))^{1/3}}$$

  - Distances to binaries are important to calibrate the absolute magnitudes of main sequence stars

Distance determination

photometric parallaxes

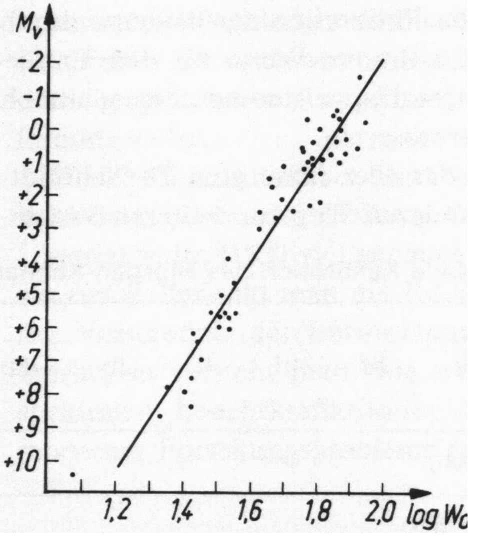
- comparison: apparent – absolute magnitude: m-M
  - basic principle $I = \frac{L}{4\pi r^2}$
  - the definition $m = -2.5 \lg I + const.$
    leads to $m = 5 \lg r - 2.5 \lg L + const.$
  - the definition $M = m(r = 10pc)$
    yields $M = 5 - 2.5 \lg L + const.$
  - **distance modulus**: $m - M = 5 \lg r - 5$
  - with absorption $A[mag]$ $m = M + 5 \lg r - 5 + A$
  - abbreviations: $m_B = B$ $m_V = V$

Distance determination

photometric/spectroscopic parallaxes

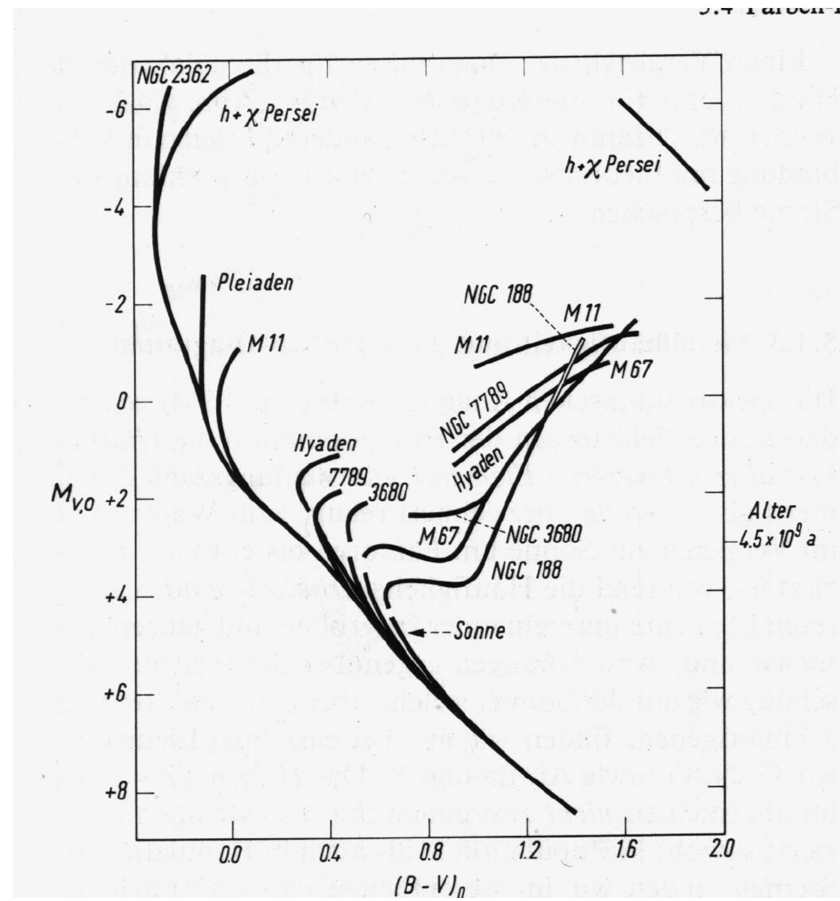
- spectral classification of stars
  - giants and dwarfs distinguished by high resolution spectroscopy only
  - correction of extinction and reddening
  - intrinsic scatter of main sequence by
    - metallicity
    - unresolved binary stars
  - main sequence very steep at the bright and at the faint end -> sensitive to colour errors
- spectroscopy
  - observationally high effort
  - individual corrections as above
  - application: equivalent width of Ca K-line

Src.: Voigt



Star clusters

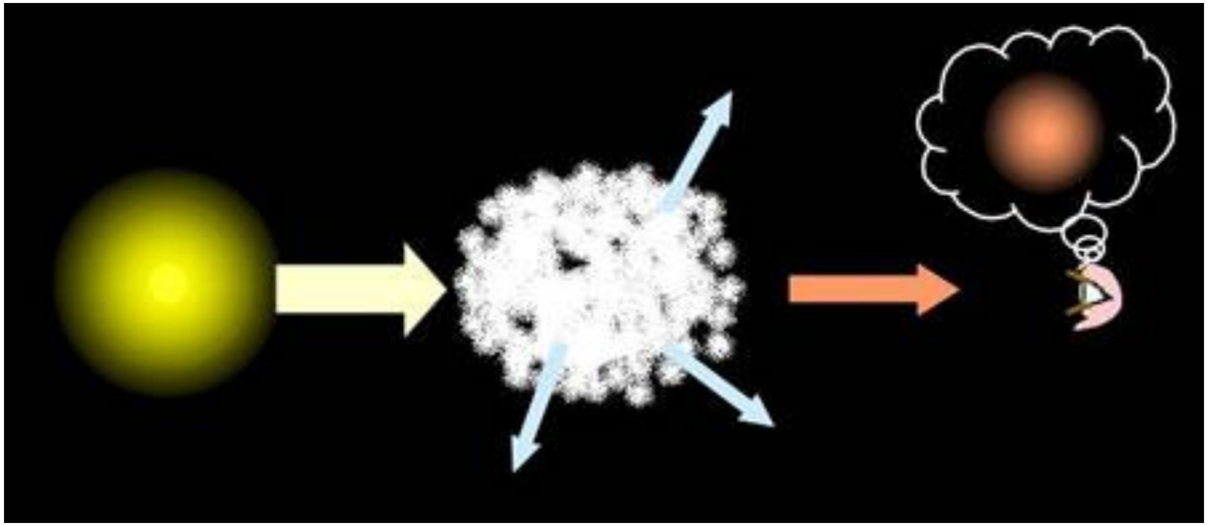
- main sequence fitting:
  - star clusters
    - uniform metallicity, age
    - same extinction
    - same distance
  - Zero-Age-Main-Sequence (ZAMS) in CMD
    - main sequence of age=0
    - superposition of all main sequences at the lower end; bright end evolved
    - calibration with Hyades
    - metallicity dependence neglected
  - Dust extinction and reddening corrections



Src.: New Cosmos

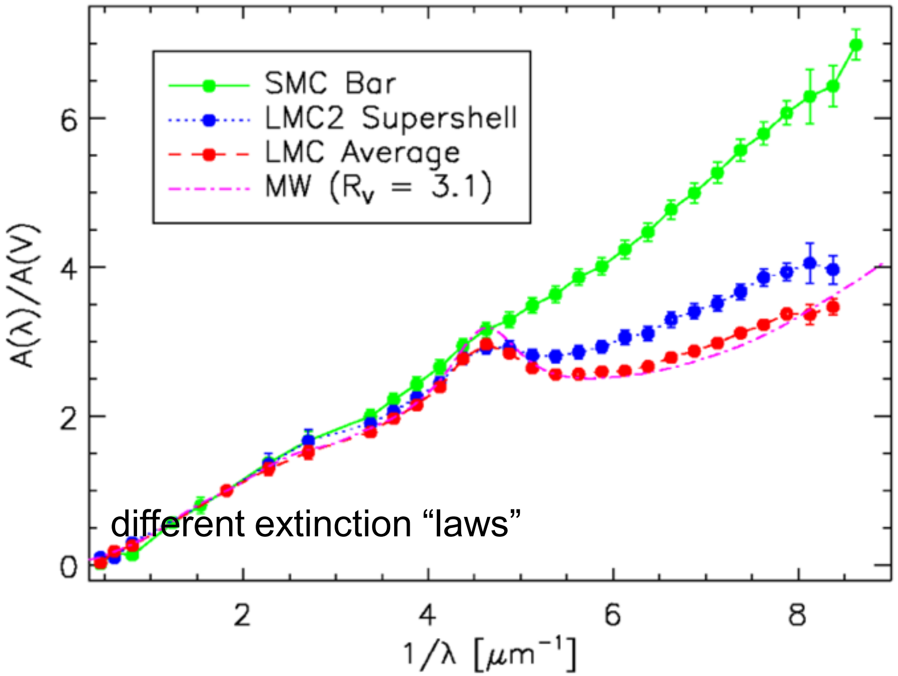
Distance determination

- dust correction
  - interstellar dust between star and observer leads to
    - a change in magnitude (extinction)
    - and a change in color (reddening), because the extinction is stronger at shorter wave lengths



Distance determination

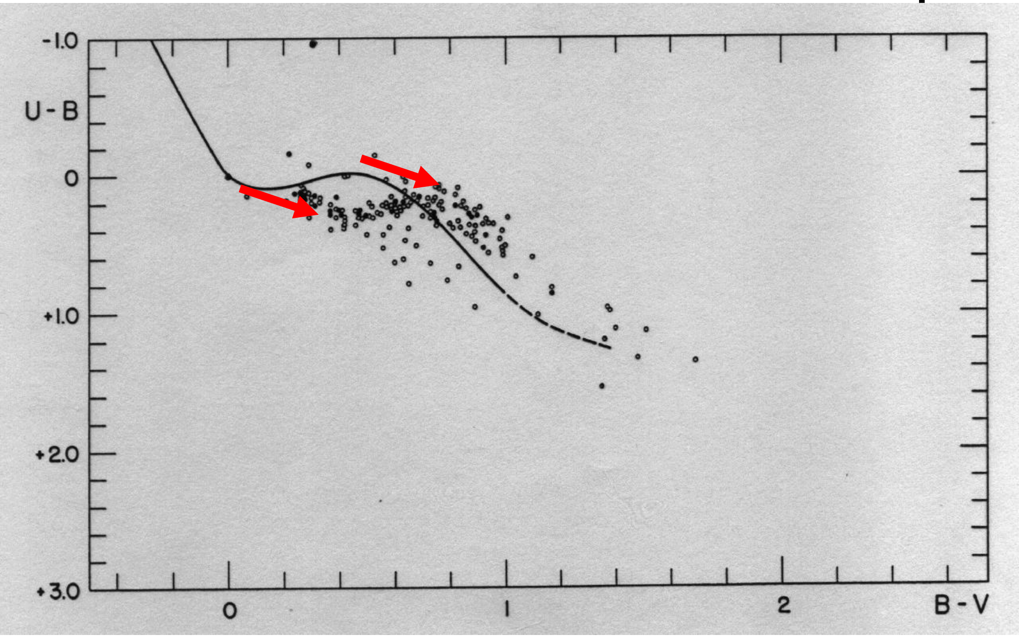
- dust correction
  - in magnitude (extinction) and colour (reddening)
    - independent of distance (for same foreground dust)
    - extinction A_V connected to reddening $E_{B-V}=(B-V)-(B-V)_0$: $A_V=3.1E_{B-V}=3.1[A_B-A_V]=4.8E_{U-B}$

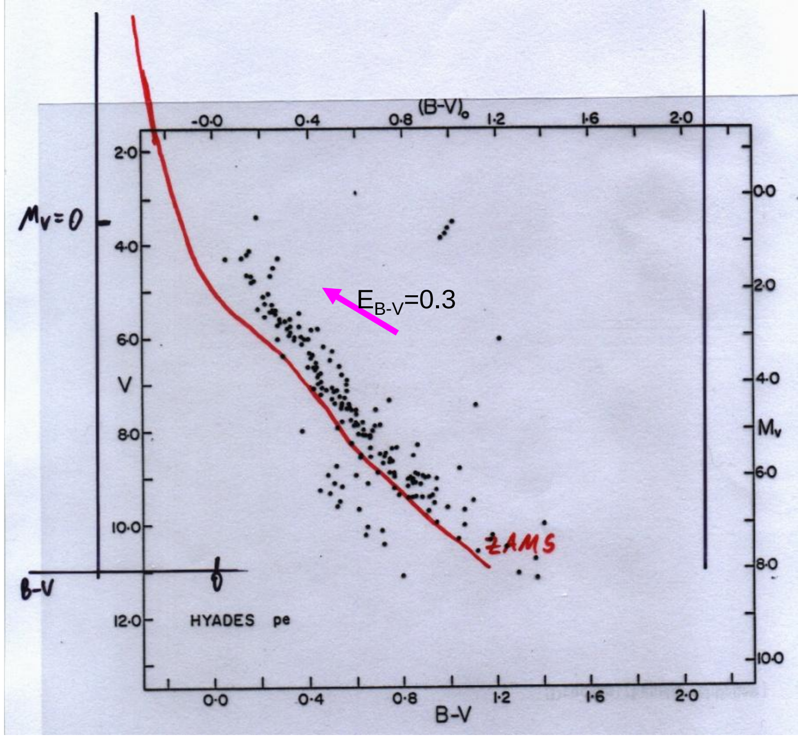


Distance determination

- dust correction
  - Reddening E_{B-V} from shift in 2-colour diagram
  - Extinction $A_V=3.1E_{B-V}$ from reddening law
  - (E_{B-V},A_V)-shift in CMD to get dereddened data
  - vertical shift for distance modulus $m_V - M_V$
  - distance $r=10^{1+0.2(m-M)}$pc

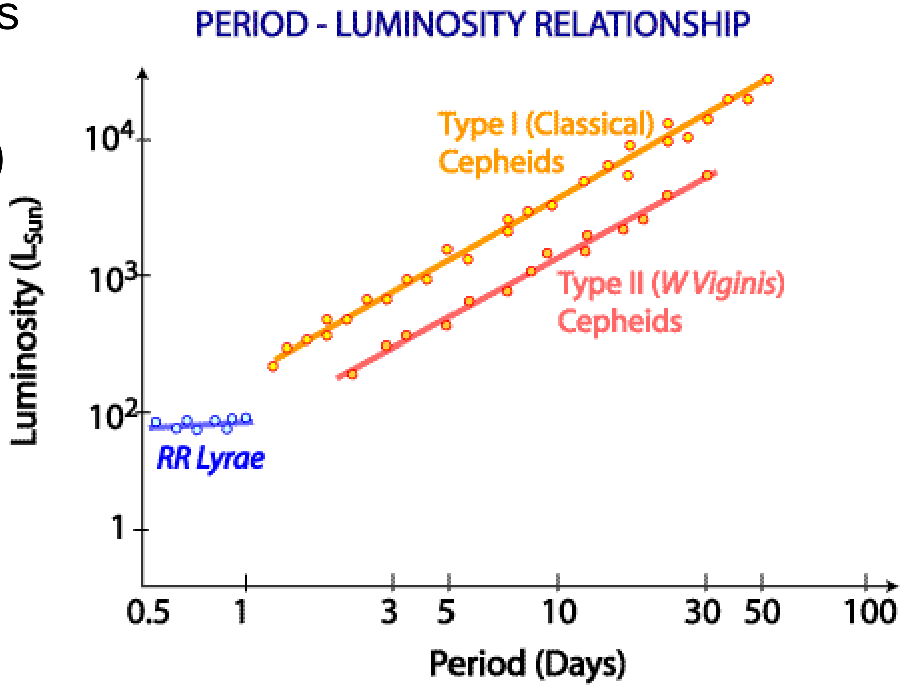
Src.: Fuchs (ARI)





Variable stars

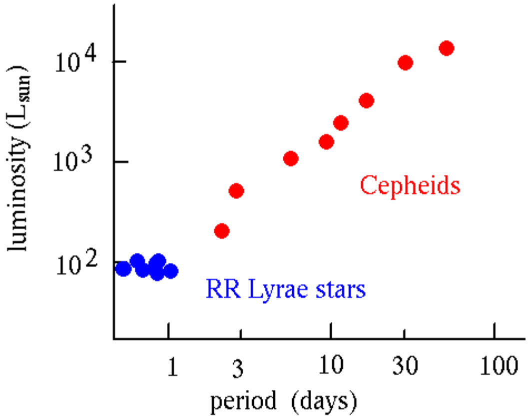
- types and periods
  - **RR Lyrae** (P < 1 d)
    - old, metal poor, low mass stars
    - Halo and globular clusters
  - **Type I Cepheids** (P = 1-50 d)
    - high-mass stars
    - late evolutionary phase
    - Pop I-stars (disc)
  - Type II Cepheids (P = 1-50 d)
    - 1.5 mag fainter
    - Low mass, after helium flash
  - Historical remark
    - δ Cephei in Andromeda galaxy mixed-up with W Virgines in globular clusters
    - Distance too small by factor 2
    - Resolved ~1940 by Baade



http://outreach.atnf.csiro.au/education/senior/astrophysics/variable_cepheids.html

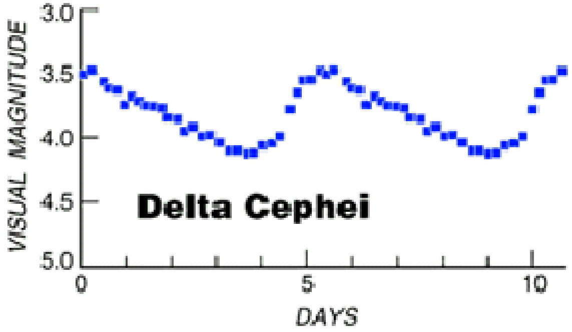
Period-Luminosity relation

- **RR-Lyrae**
  - constant absolute luminosity
- **Cepheids**
  - Characteristic light curve
  - period-luminosity relation
  - colour dependent



http://casswww.ucsd.edu/archive/public/tutorial/Distances.html

$$\langle M_V \rangle = -3.53 \lg P + 2.13 \langle (B-V)_0 \rangle - 2.13$$



Distances and redshift: Hubble flow

- Milestones of Classical Cosmology
  - ~ 1920's: "spiral nebulae" are galaxies similar to the Milky Way (universe ≠ Milky Way)
  - Expansion of the universe
    - Hubble diagram (1929): $H_0 \approx 500$ km/s/Mpc

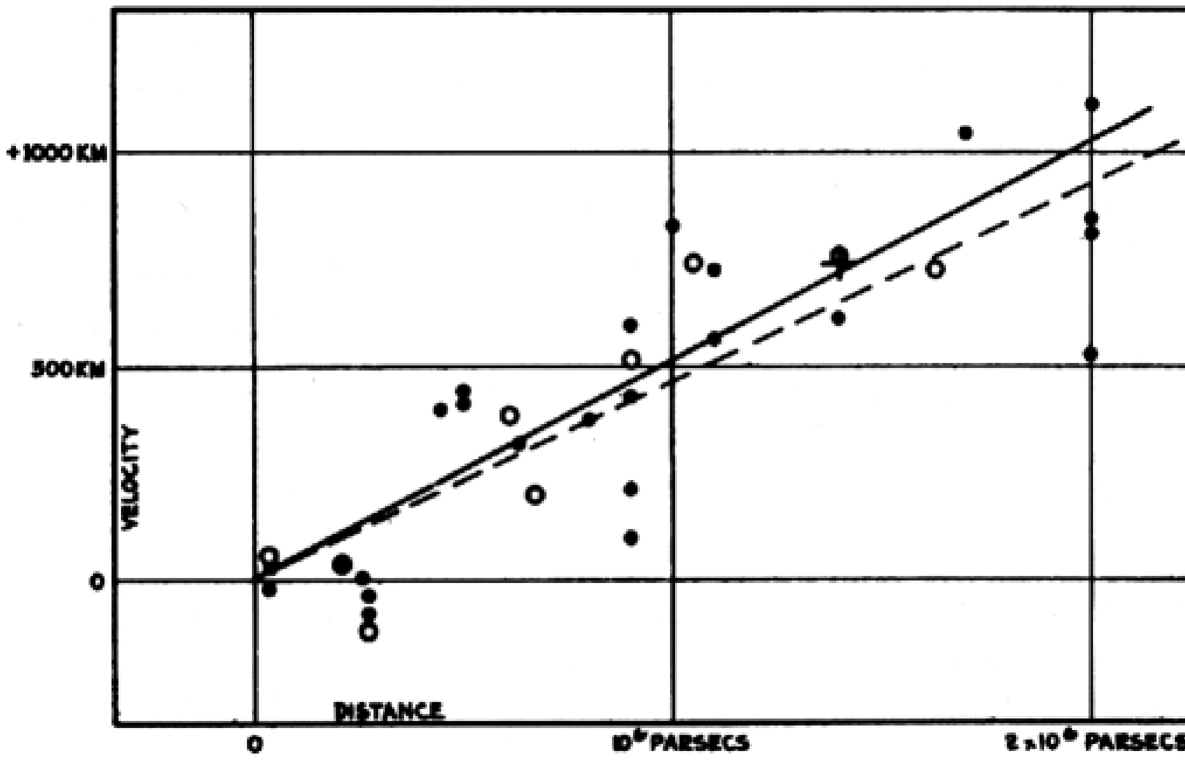
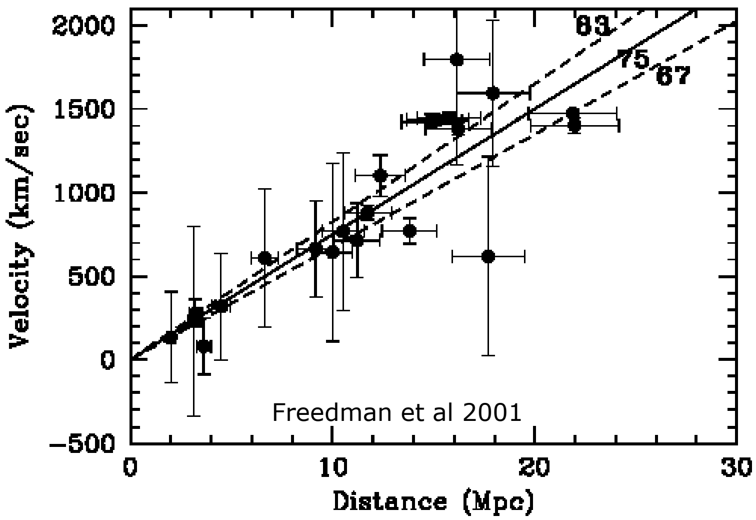


FIGURE 1

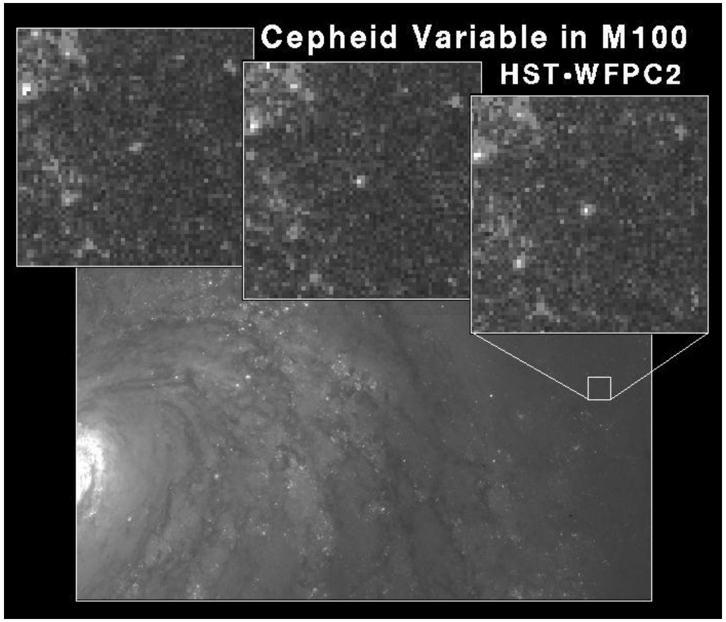
Velocity-Distance Relation among Extra-Galactic Nebulae.

Application to more distant galaxies

- Cepheid stars
  - Identify Cepheids in galaxies far enough away that their redshift reflects the expansion of the universe



$$H_0 = 71 \pm 2 \text{ (random)} \pm 6 \text{ (systematic)}$$



Freedman 2001

The local universe

- outer boundary of 'present day (local) universe'
  - look-back time $t \sim 1$ Gyr
  - distance $D \sim 300$ Mpc
  - Hubble flow: $v \sim 21{,}000$ km/s
  - redshift $z \sim 0.07$
  - distance modulus $m-M \sim 37.5$ mag
  - appearance of Milky Way at distance D~ 300 Mpc
    - absolute mag $M_V=-20$ $m_V=17.5$
    - disc scale length L=3kpc   l = 2''
    - cosmol. redshift $\lambda=550$nm $\lambda_{obs} = 589$nm
      - still in V band, but colour corrections already relevant

Hubble expansion

- Our personal view
  - Normalize to present time
    - $H_0 \approx 70$km/s/Mpc, $a_0=1$, critical density, Hubble time and length

$$\rho_{c0} = \frac{3H_0^2}{8\pi G}, \quad t_H = \frac{1}{H_0} \approx 14 Gyr, \quad r_H = \frac{c}{H_0} \approx 4.2 Gpc$$

  - Redshift instead of scale factor

$$a = \frac{1}{1+z}, \quad \mathrm{d}z = -\frac{\mathrm{d}a}{a^2}$$

  - Friedman equation for expansion history

$$H(z) = \frac{\dot{a}(z)}{a(z)} = H_0\, E(z)$$

$$E(z) = \sqrt{(1+z)^4\Omega_R + (1+z)^3\Omega_M + (1+z)^2\Omega_K + \Omega_\Lambda}$$

Hubble expansion

- Distances
  - Comoving (coordinate) distance is the only 'real' (but unobservable) distance = distance at present time

$$D_{com} = \int \mathrm{d}x = \int \frac{c}{a}\mathrm{d}t = \int_a^1 \frac{c}{a\dot{a}}\mathrm{d}a = r_h \int_0^z \frac{\mathrm{d}z'}{E(z')}$$

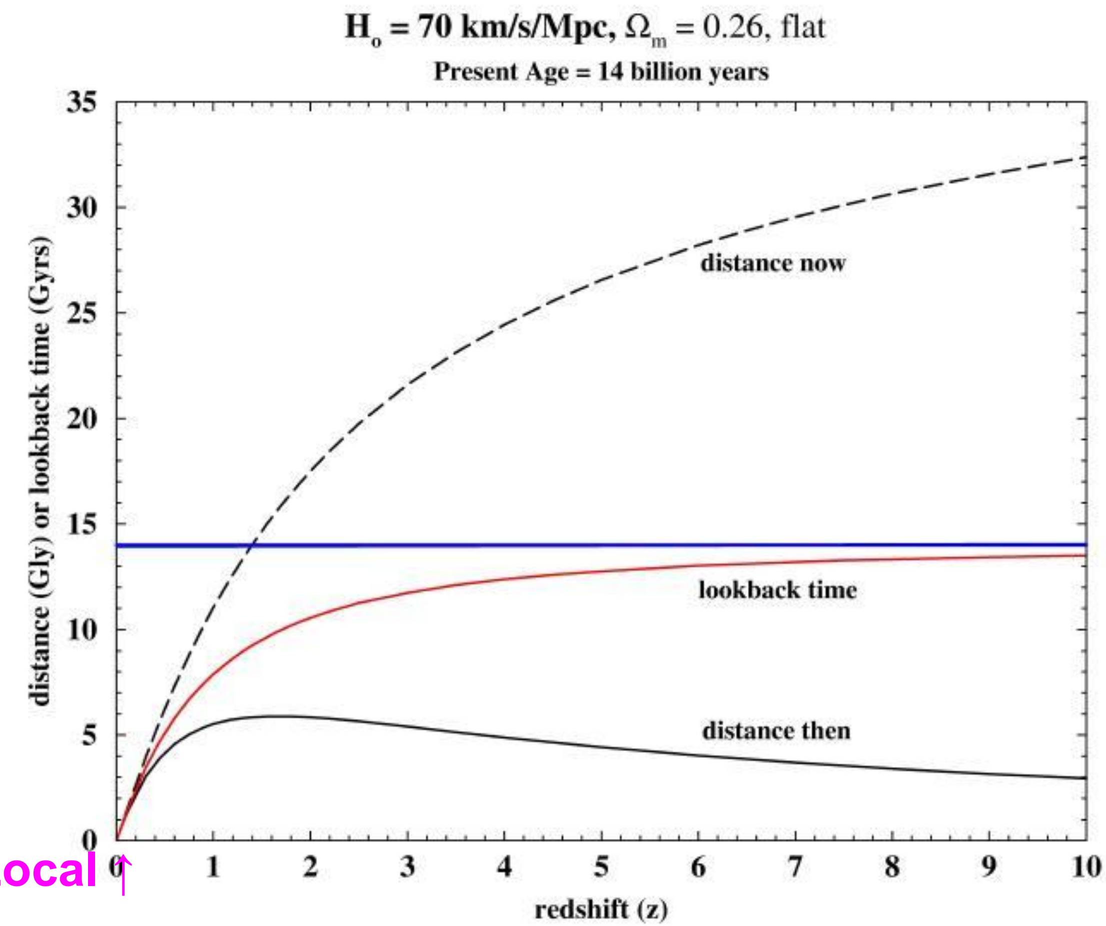
  - Comoving distance at time of emission factor (1+z) smaller
- Local Hubble expansion
  - $H(z)=H_0=\mathrm{const}$

$$D_{com} \approx r_H \cdot z = \frac{v_{Doppler}}{H_0}$$

$$H_0 = \frac{v_{Doppler}}{D_{com}}, \quad v_{Doppler} = cz$$

  - The measured redshift is often mis-interpreted as "recession velocity" of an object

Lookback time and distances



Local ↑

D_{com} (comoving)

r_H (Hubble length)

D_{prop} (proper)

$D_{com}(t_e)$
(at emission time)

Galaxy distribution

$$D_{com} = \frac{v_{Doppler}}{H_0} = \frac{cz}{H_0}$$

- Redshift surveys: **foam structure**

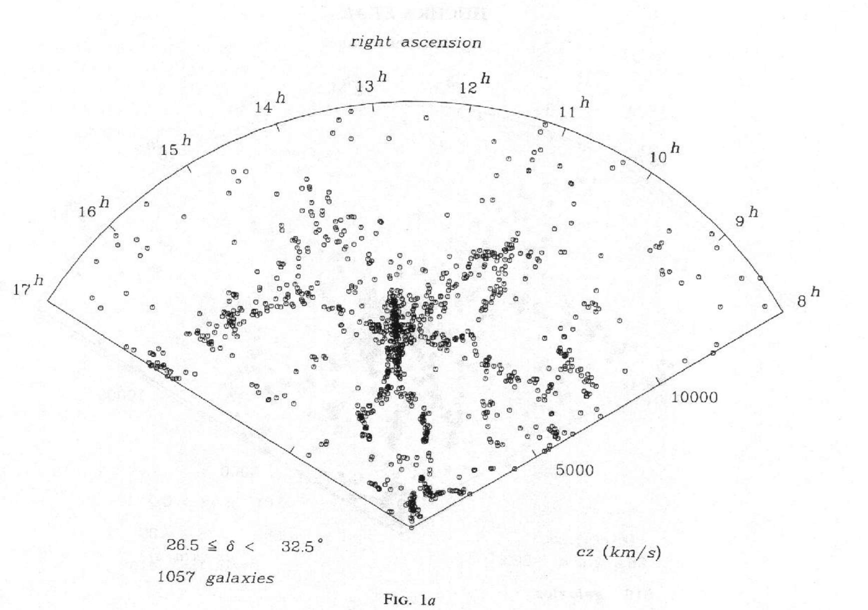
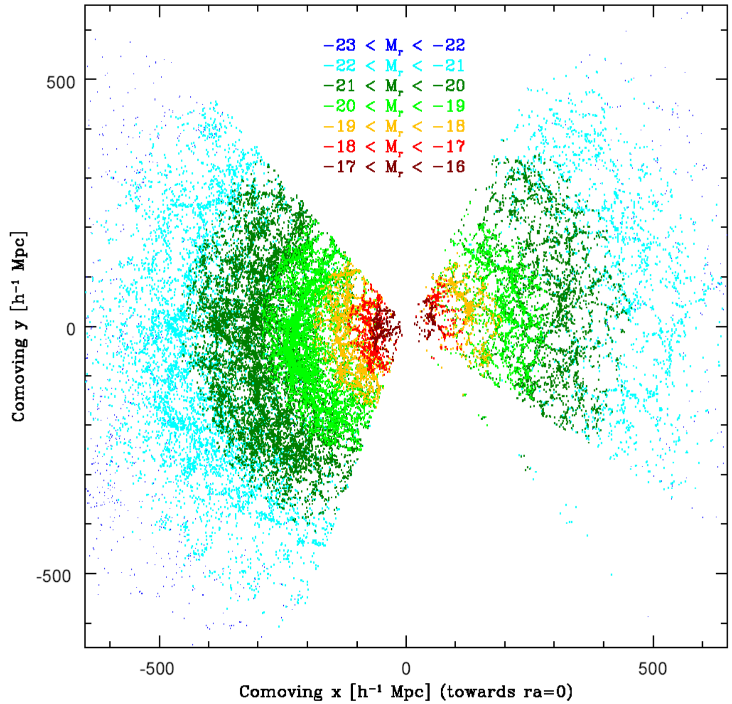


FIG. 1a

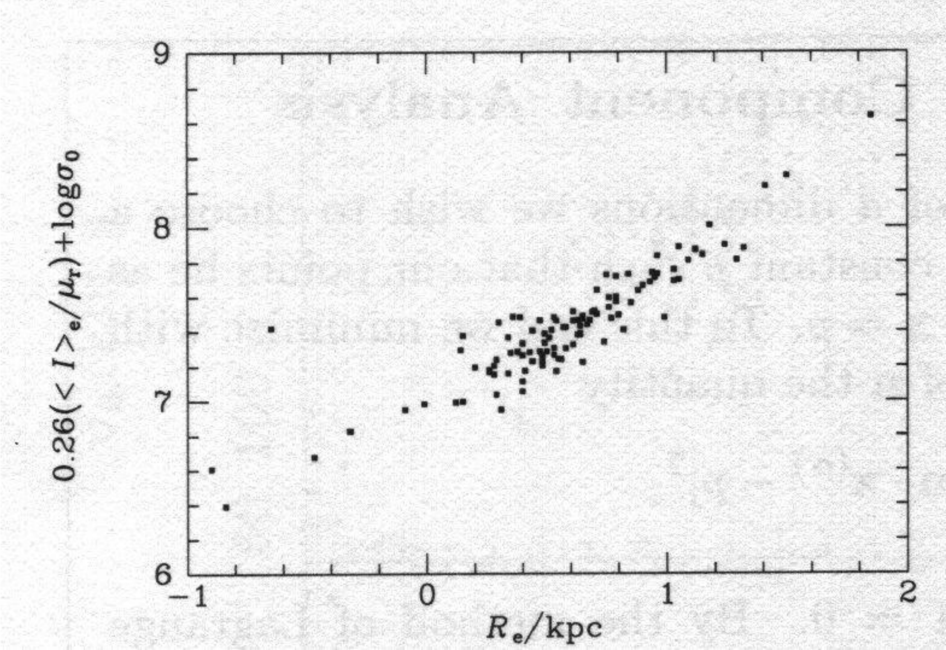


- calibration uncertain due to peculiar velocities of v~1000km/s
- deviations from linear law at z>0.3 => dependence on world model
- Solved by a combination of (up to z~1)
  - **cepheids** and **SN1a**

Galaxy distribution

- Faber-Jackson relation
  - for elliptical galaxies
  - correlation: $L_e \approx C\sigma_0^4$
  - generalized to (L_e,σ_0,μ_0) relation **fundamental plane**

Src.: Galactic Astronomy



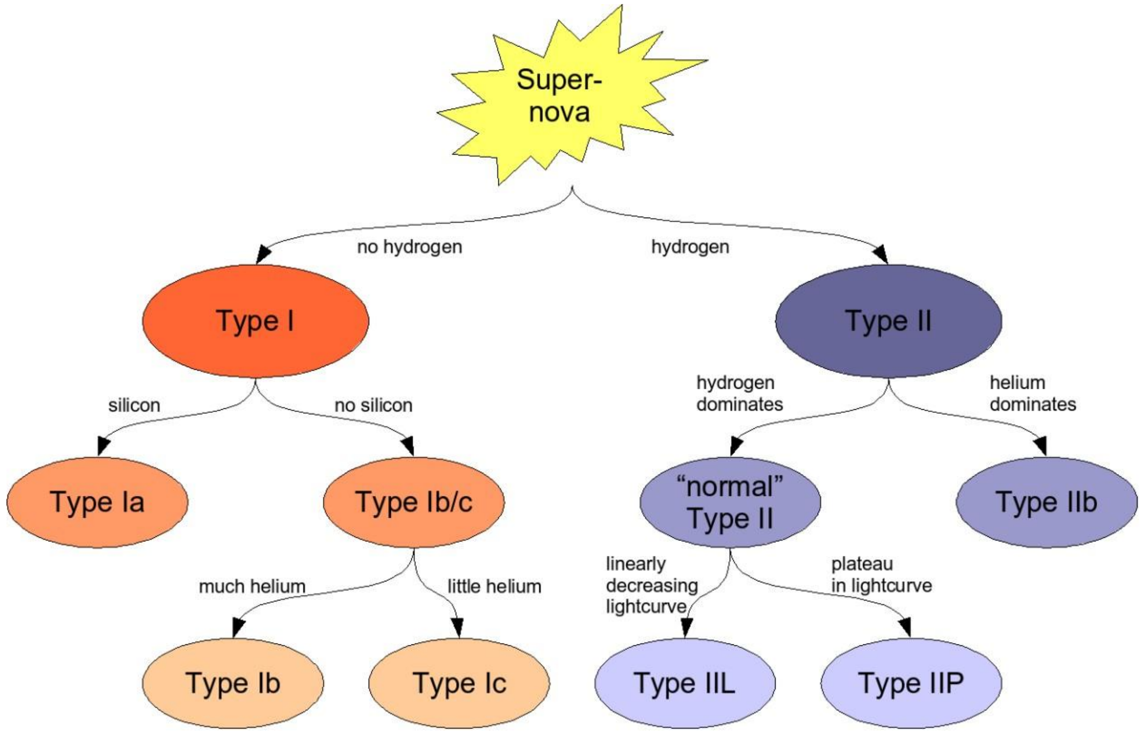
- Tully-Fisher relation
  - spiral galaxies
  - M_V-v_{rot} relation
  - maximal rotation velocity from 21cm line width

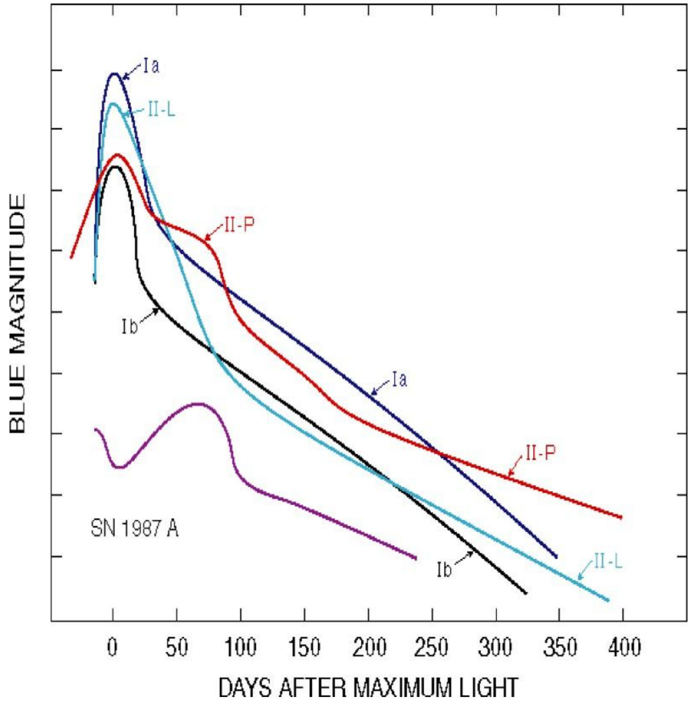
‘The’ cosmological standard candle

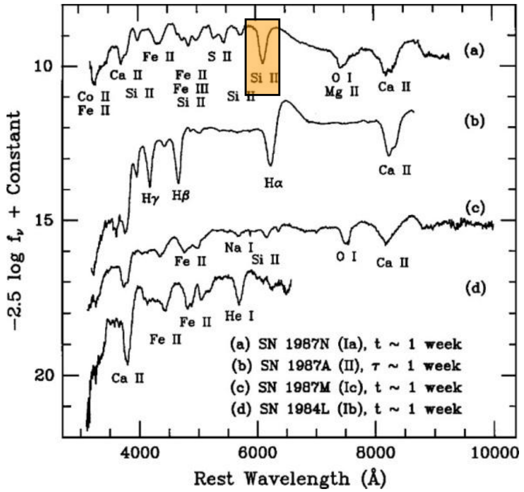
- Supernovae type 1a (SN1a):
  - identification by spectrum
  - very bright: range >100Mpc
  - Maximum brightness depends on width of light curve -> **correct to standard light curve** -> distance modulus
  - Absolute calibration complicated: few nearby SNs; distance to nearby galaxies with large uncertainties

Supernovae Typ 1a

- Classification
  - Lightcurves
  - Spectra

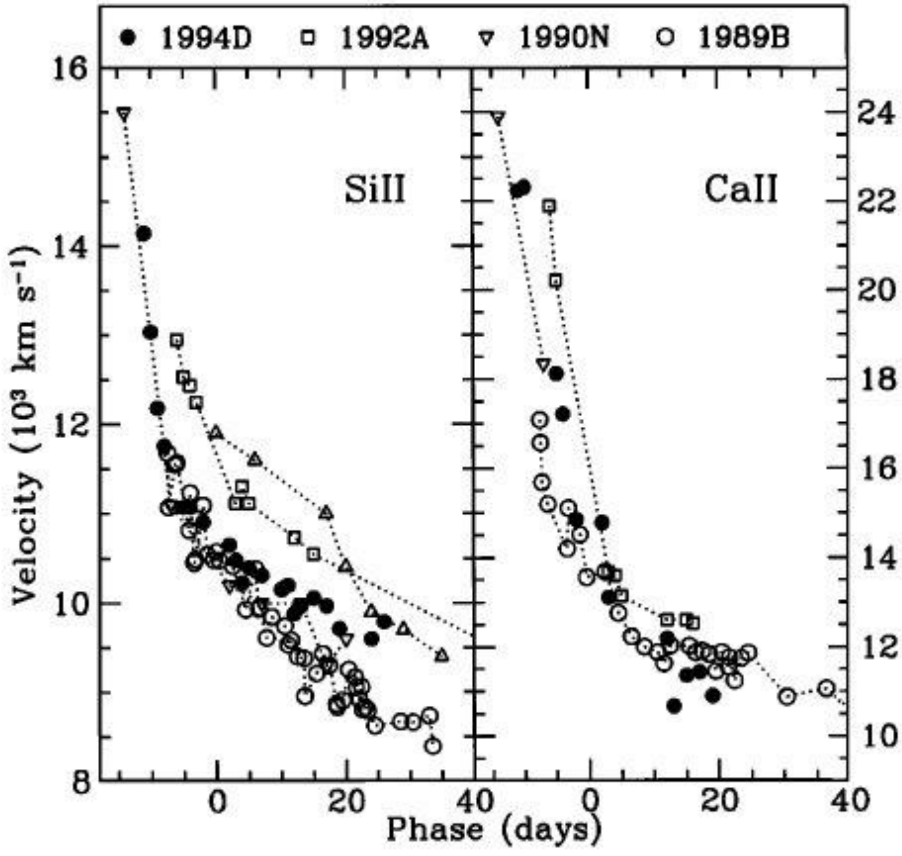






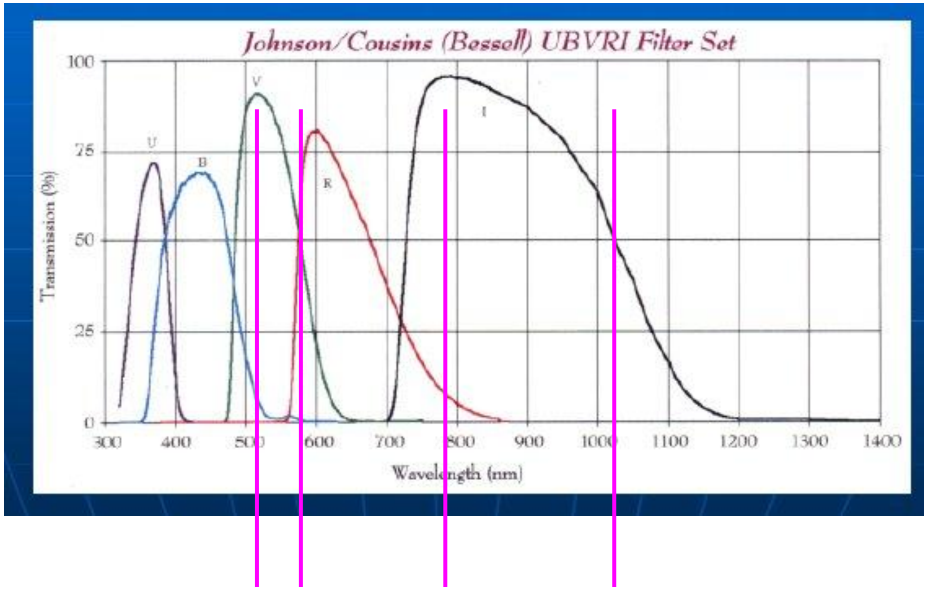
Supernovae Typ 1a

- Doppler shift
  - Hubble expansion + explosion speed
  - Expansion of outer shells: v = 10000-15000 km/s

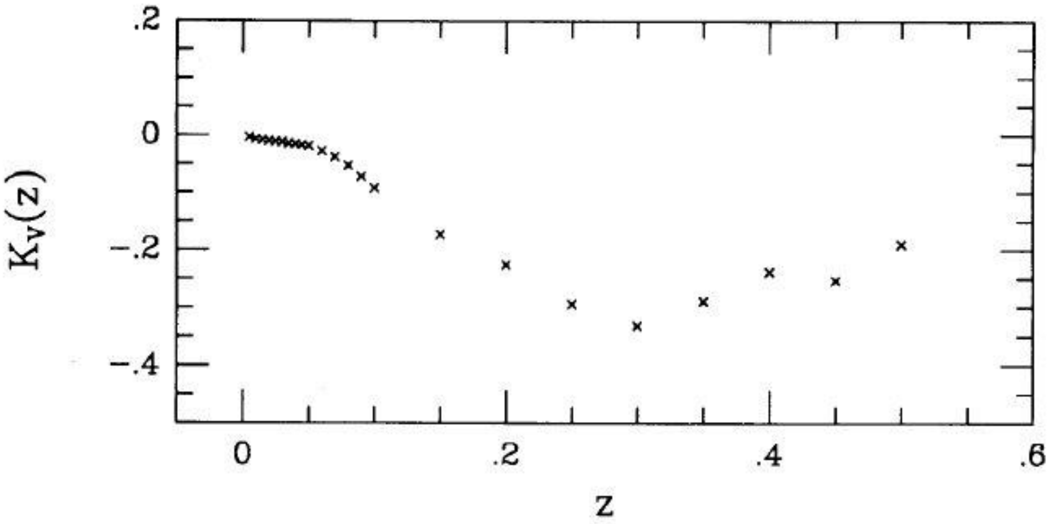


Supernovae Typ 1a

- Luminosity corrections
  - K-correction
  - Extinction + reddening

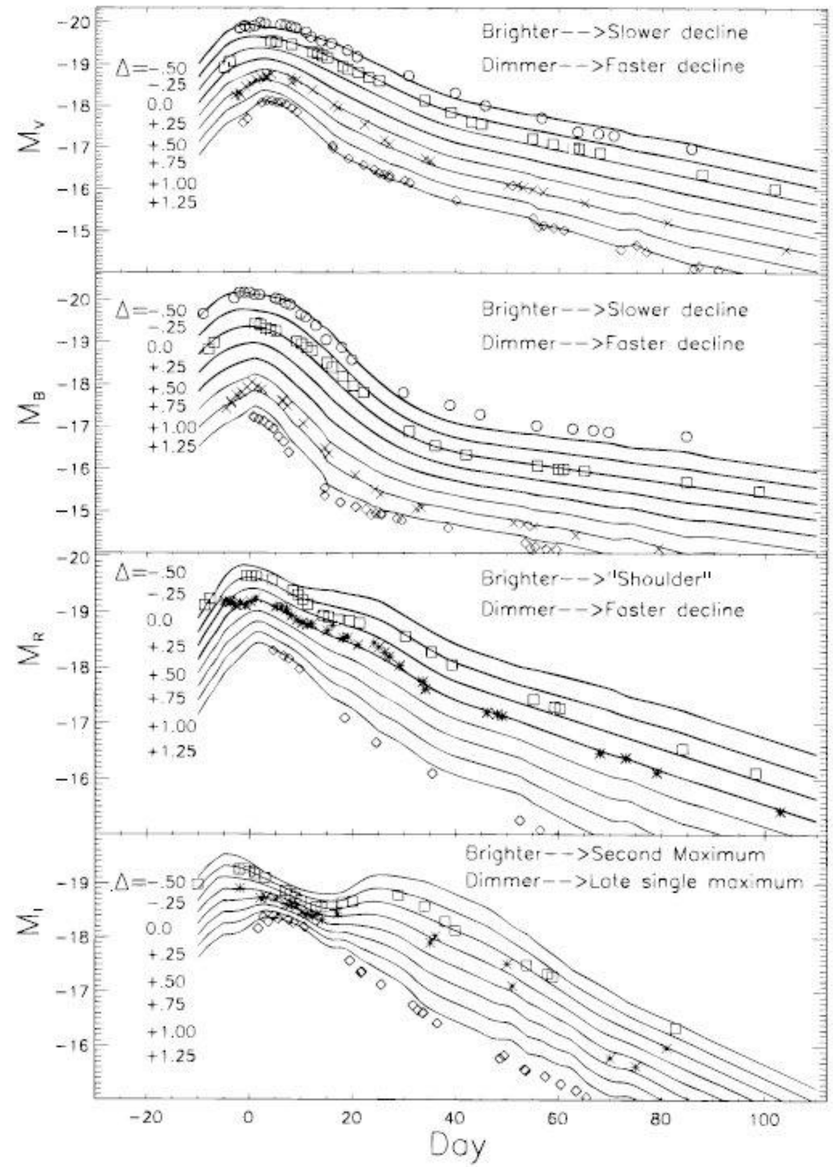


0, 0.1, 0.5, 1.0 =z



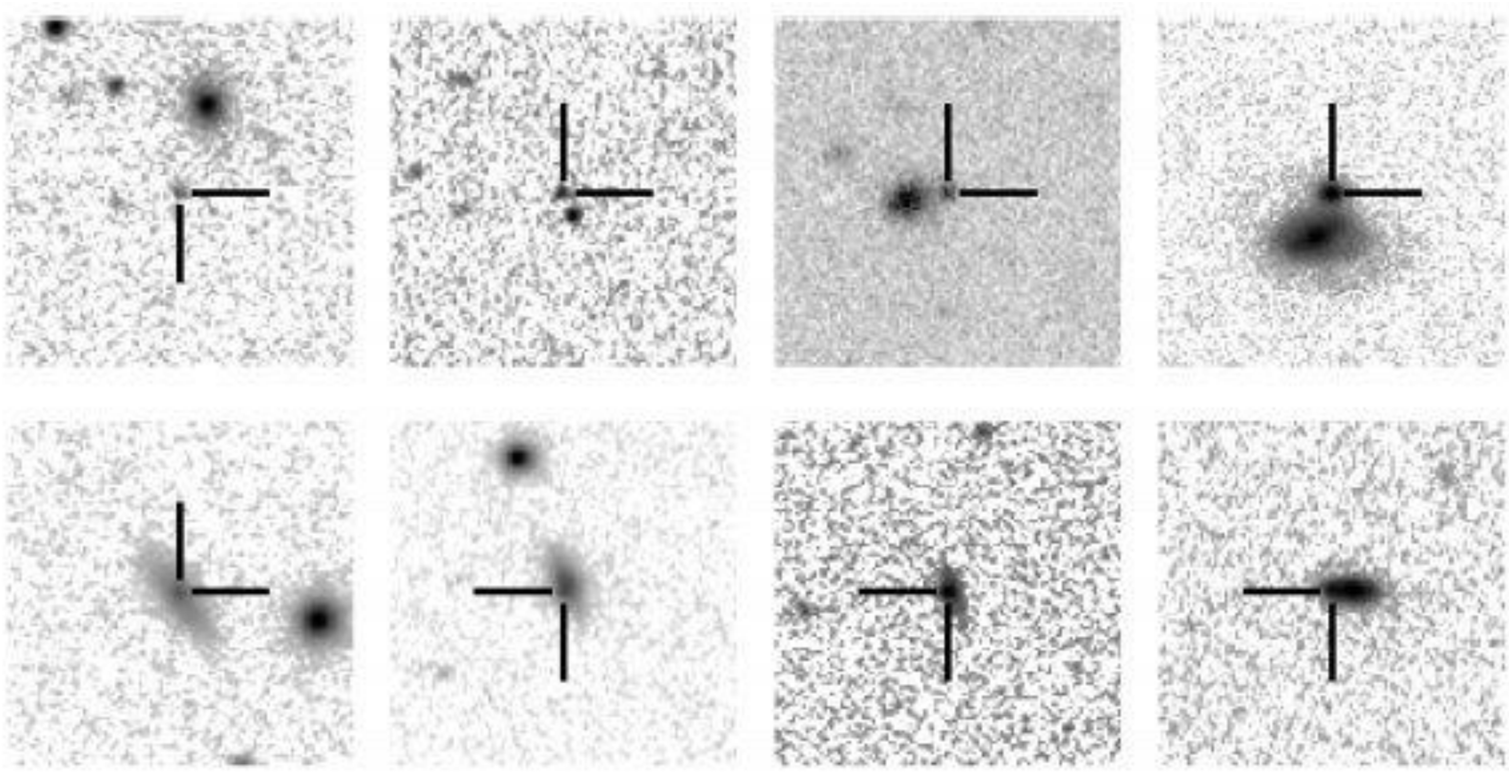
Supernovae Typ 1a

- Max. luminosity **not** the same
  - Correlation
    - Duration – max. luminosity
  - corrections
    - Time dilatation
    - K-correction
    - Extinction
    - Correct for host galaxy light
  - **calibration** with observed SN1a with known distance



Supernovae Typ 1a

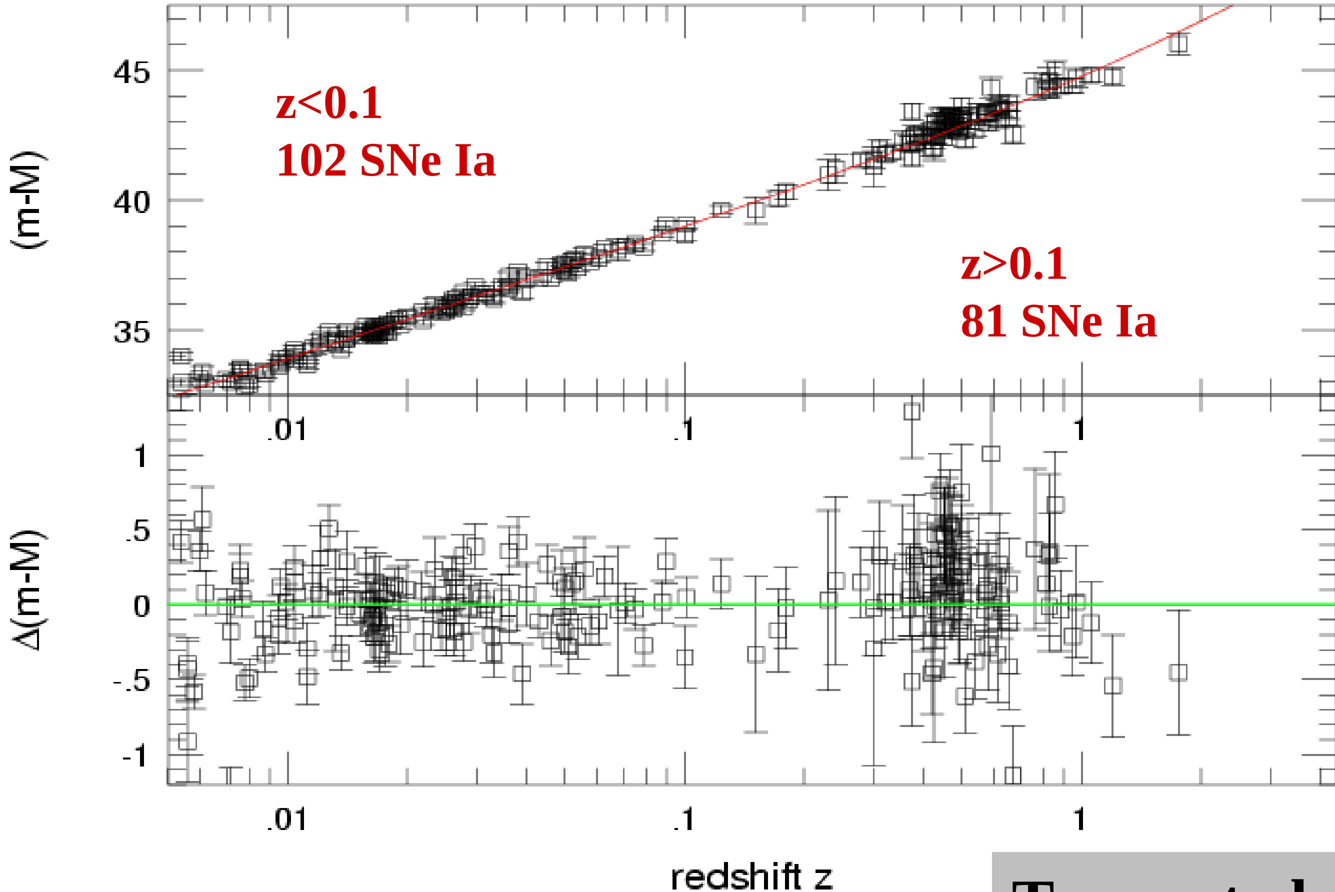
- SDSS II: Supernova Survey: examples



Src.: Zheng et al. 2008 AJ 135, 1766

Distances and Redshift: Standard candles

- Slope at z<0.1 determines Hubble constant
- Slope at high redshift constrains the world model



Tonry et al. 2003

Expanding curved space

- Observable quantities in cosmology
  - observables independent on the expansion history
    - Redshift – scale factor $a=1/(1+z)$
  - in expanding curved space
    - luminosity ≠ $(\text{distance})^{-2}$
    - apparent size ≠ $(\text{distance})^{-1}$
    - surface brightness ≠ constant
  - Virtual distances to stick on traditional observables
    - Doppler distance

$$D_{Doppler} = \frac{v_{Doppler}}{H_0} = \frac{cz}{H_0} = r_H \cdot z$$

Distance measures in cosmology

- Transversal sizes
  - Comoving size D_M (today) and angular size D_{ang} (at emission time)

$$D_M = \begin{cases} \frac{r_H}{\sqrt{\Omega_k}} \sinh\left(\sqrt{\Omega_k} D_{com}/r_H\right) & \Omega_k > 0 \\ D_{com} & \Omega_k = 0 \\ \frac{r_H}{\sqrt{|\Omega_k|}} \sin\left(\sqrt{|\Omega_k|} D_{com}/r_H\right) & \Omega_k < 0 \end{cases}$$

$$D_{ang} = a(z) D_M = \frac{D_M}{1+z}$$

  - Acoustic waves (D_M in CMB at z=1200: Ω_K=0)

- Luminosity distance D_{lum} and distance modulus DM
  - bolometric flux diluted with $a(z)^4$

$$S = \frac{L_{bol}}{4\pi D_{lum}^2}$$

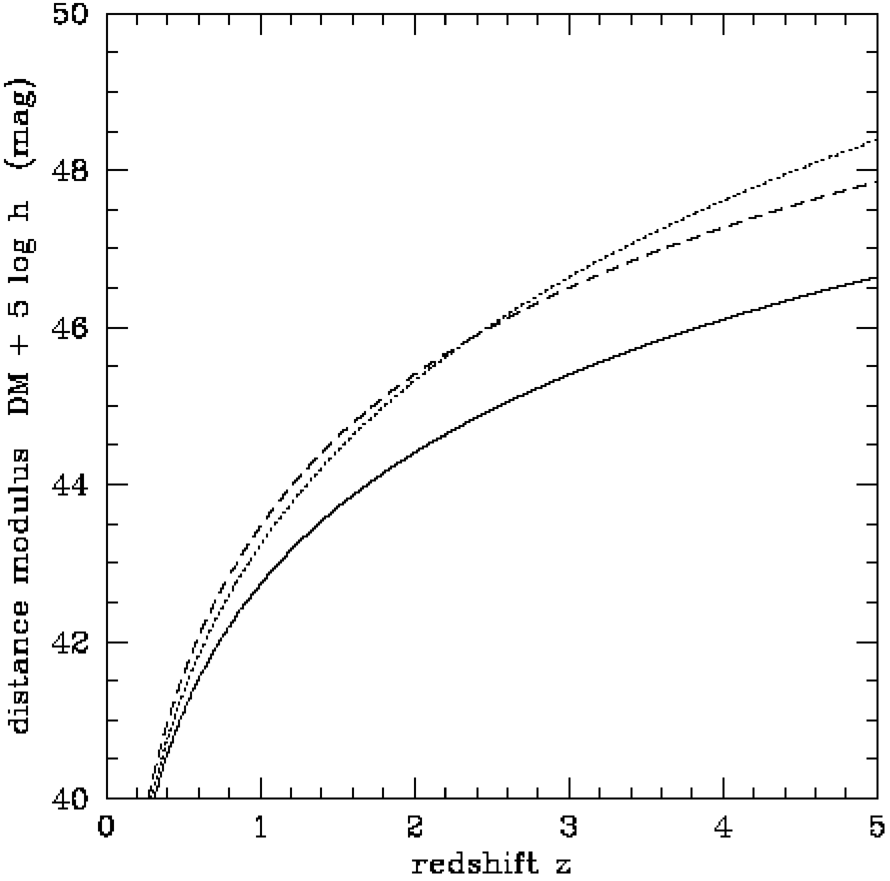
$$D_{lum} = (1+z)^2 D_{ang} = (1+z) D_M$$

  - with K-correction in filters

$$DM = m - M - K = 5\lg\left(\frac{D_{lum}}{10pc}\right) - K$$

Distance measures in cosmology

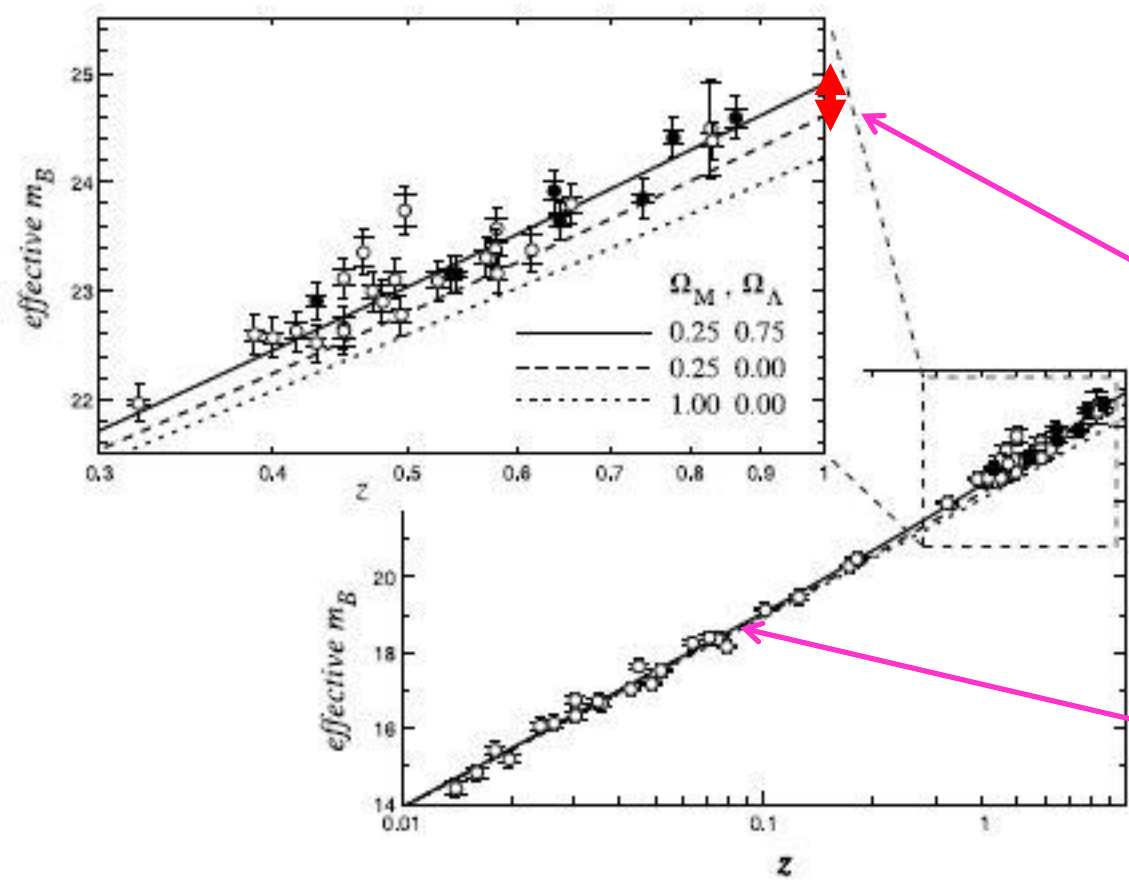
- distance modulus DM(z) from D_{lum}

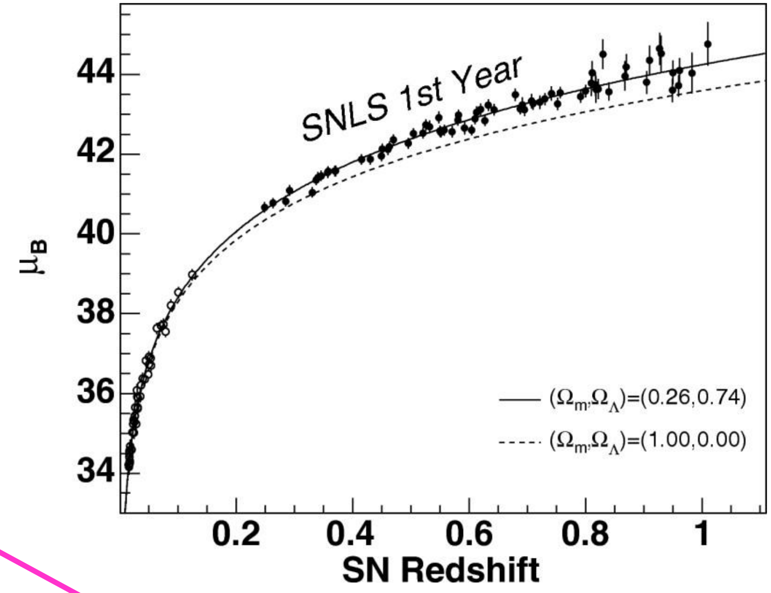


Closed/flat/open universe = full/dotted/dashed lines

Cosmological redshift

- Distance module of SN 1a
  - In B-band $(m_B - M_B)(z)$
    - Dependent on world model



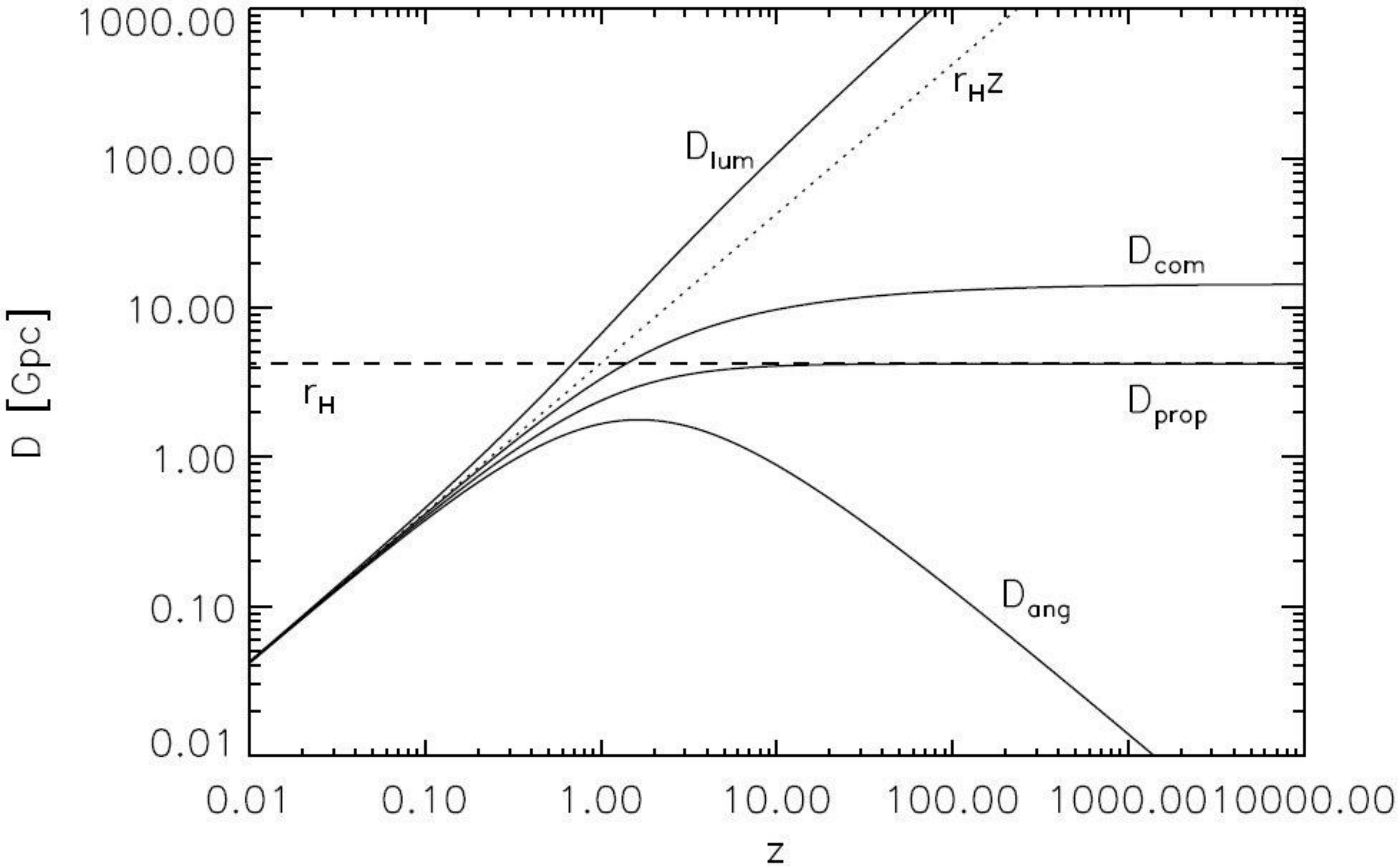


Accelerated expansion (**Physics Nobelprice 2011**)

Slope at small redshift z provides Hubblekonstante H_0=71km/s/Mpc

Distance measures in cosmology

- Overview (in standard, flat cosmology)



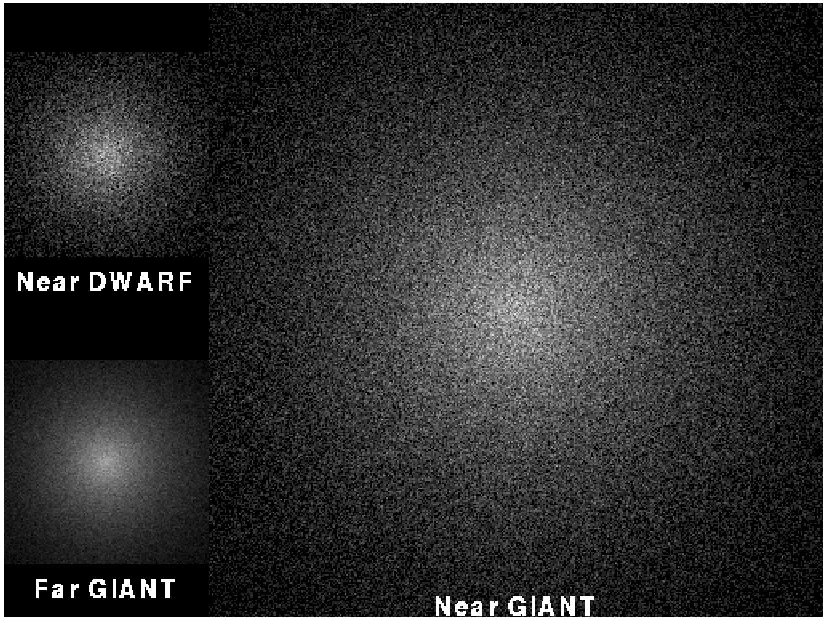
Dullemond, cosmology lecture WS11/12

Further methods

- 11th-brightest galaxy in galaxy clusters
  - compromise of using bright galaxies and reducing statistical small number noise at bright end of luminosity function
- scintillation measurements at galaxies
  - Relative noise

$$\sigma \propto \sqrt{1/N}$$

  - N=number of stars per pixel



http://www.astro.ucla.edu/~wright/distance.htm

Further methods

- Sunyaev-Zeldovich-effect
  - inverse-Compton scattering of CMB-photons at hot electrons of intra-cluster gas
  - cooling of CMB at low frequencies
  - additional radiation in UV-range
  - column density of electrons from X-ray observations and diameter
  - method independent of Hubble expansion