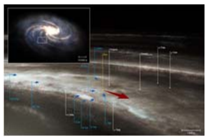
Cosmology

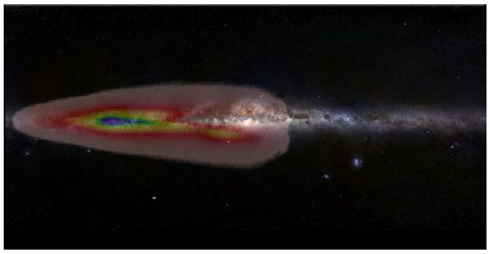
TUM WS 2019/2020
Lecture 4
Wolfgang Hillebrandt and Bruno Leibundgut
(http://www.eso.org/~bleibund/Cosmology)

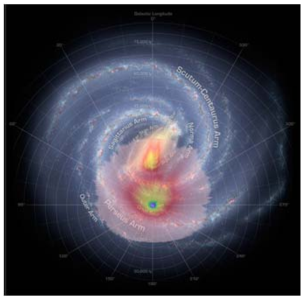
The reach of Gaia

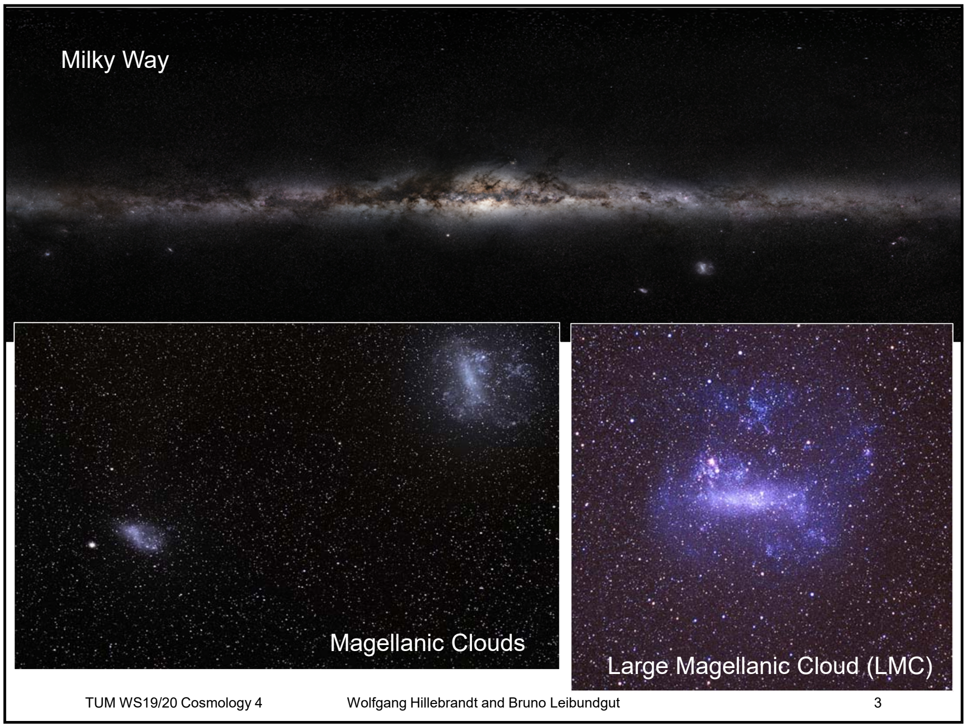
Parallaxes to a fair fraction of the Milky Way

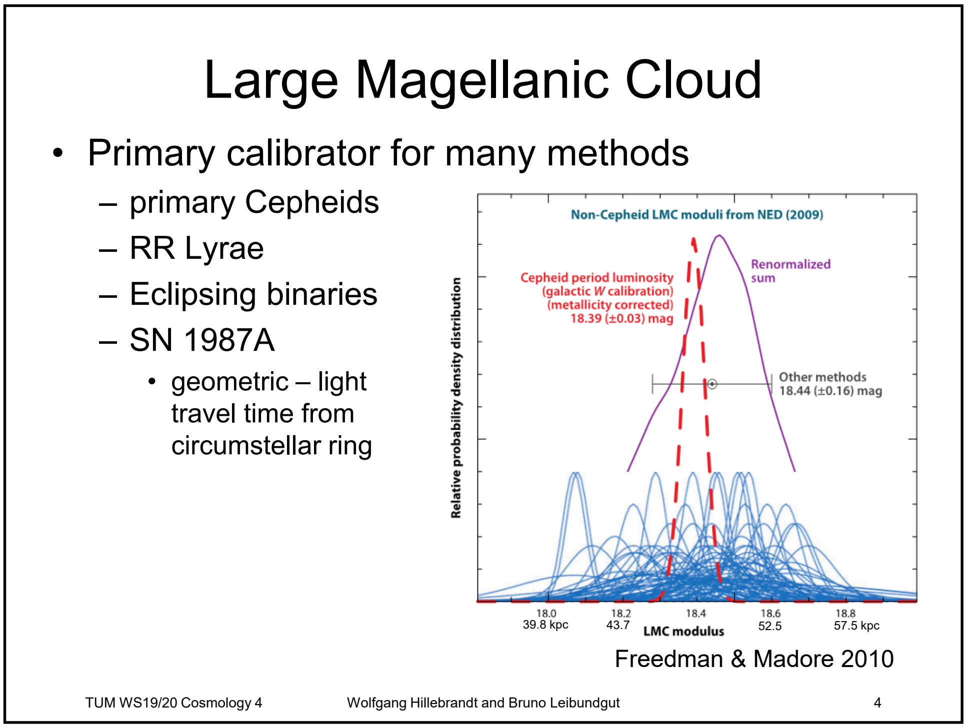
- galaxy structure
  - spiral arms, disk, bulge, halo
- galaxy dynamics
- average distance to the LMC











Large Magellanic Cloud

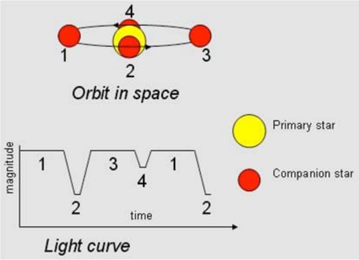
- Primary calibrator for many methods
  - – primary Cepheids
  - – RR Lyrae
  - – Eclipsing binaries
  - – SN 1987A
    - geometric – light travel time from circumstellar ring

Freedman & Madore 2010

Eclipsing binaries

- Binary star with the orbital axis perpendicular to the line of sight

compare the size of the star
(from the duration of the eclipses)
to its apparent angle on the sky
(from the surface brightness of the star; uses Stefan-Boltzmann law)
→ angular size distance

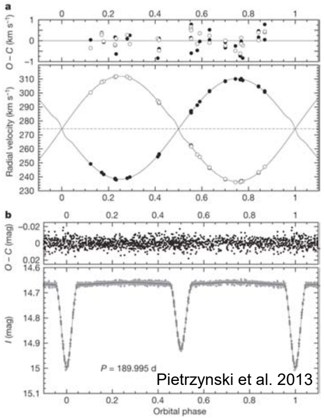


$$d(pc) = 1.337 \cdot 10^{-5} \times \frac{r(km)}{\varphi(mas)}$$

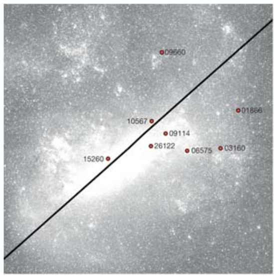
Eclipsing binaries

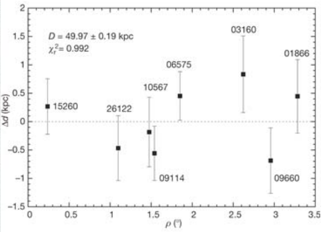
- Binary star with the orbital axis perpendicular to the line of sight

excellent distance to the Large Magellanic Cloud



Pietrzynski et al. 2013

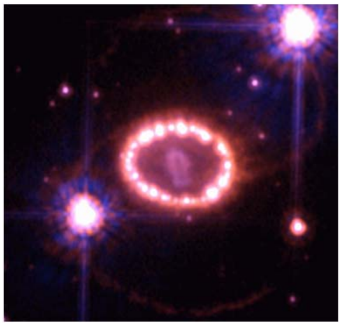




(e.g., Pietrzynski et al. 2013)

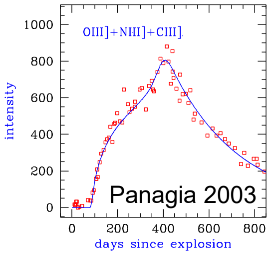
SN 1987A as geometric distance indicator

- Illumination of the circumstellar ring
  - – light travel time and ring size give a distance (need to know the inclination angle)



SN 1987 - Geometric Distance

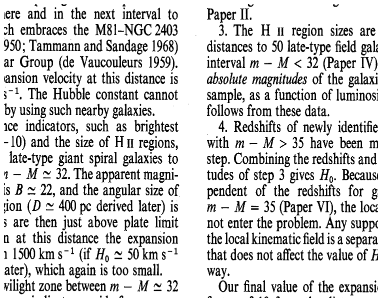
- Distance due to illumination of circumstellar ring from the supernova flash
  - – require speed of light and inclination angle



Panagia 2003

Stepping into the Hubble flow

- Beyond the Large Magellanic Cloud distance indicators typically bridge towards the Hubble flow
  - – Planetary Nebulae Luminosity Function
  - – Globular Clusters
  - – Blue Supergiant stars
  - – **Cepheid stars**
  - – **Masers (geometric)**



ıere and in the next interval to
ch embraces the M81–NGC 2403
950; Tammann and Sandage 1968)
ar Group (de Vaucouleurs 1959).
ansion velocity at this distance is
s^{-1}. The Hubble constant cannot
by using such nearby galaxies.
ıce indicators, such as brightest
-10) and the size of H II regions,
late-type giant spiral galaxies to
ı $- M \simeq 32$. The apparent magni-
is $B \simeq 22$, and the angular size of
ion ($D \simeq 400$ pc derived later) is
s are then just above plate limit
n at this distance the expansion
ı 1500 km s^{-1} (if $H_0 \simeq 50$ km s^{-1}
ater), which again is too small.
wilight zone between $m - M \simeq 32$

Paper II.
3. The H II region sizes are
distances to 50 late-type field gal
interval $m - M < 32$ (Paper IV)
absolute magnitudes of the galaxi
sample, as a function of luminosi
follows from these data.
4. Redshifts of newly identifie
with $m - M > 35$ have been m
step. Combining the redshifts and
tudes of step 3 gives H_0. Becaus
pendent of the redshifts for g
$m - M = 35$ (Paper VI), the loc
not enter the problem. Any supp
the local kinematic field is a separa
that does not affect the value of
way.
Our final value of the expansi

Sandage & Tammann 1974

Into the Hubble Flow

- Typically galaxy properties
  - – **Tully-Fisher relation**
  - – Faber-Jackson relation
  - – Fundamental plane of galaxies
- Other indicators
  - – **Surface Brightness Fluctuations**
  - – **Type Ia Supernovae**

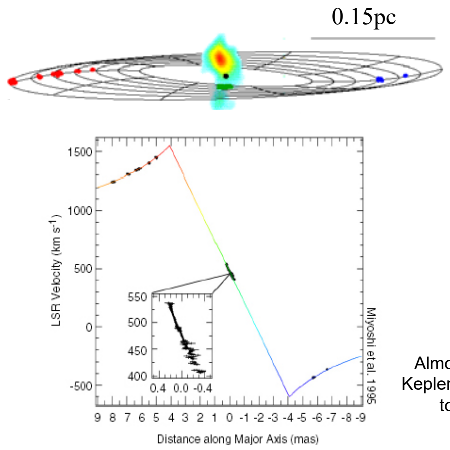
Independent anchor
NGC 4258 (Messier 106)

- Nearby active galactic nucleus

NASA, ESA, the Hubble Heritage Team (STScI/AURA), and R. Gendler (for the Hubble Heritage Team).

Water masers in the inner disk of NGC 4258

- Nearly perfect Keplerian rotation



Humphreys et al. 2013
(plots from
Miyoshi et al. 1995
and Herrnstein et al. 1999)

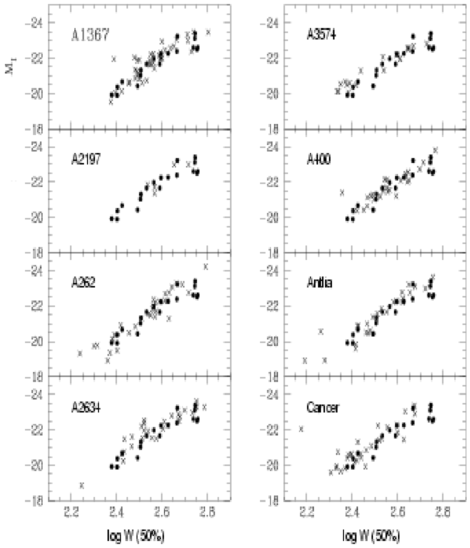
Almost perfect
Keplerian rotation
to ~ 1%

Distance to NGC 4258 and H_0

- From the maser geometry
  7.60±0.23 Mpc (Humphreys et al. 2013)
- Use this to calibrate Cepheids in this galaxy
- with the calibrated Cepheids measure galaxies, which had a SN Ia (Riess et al. 2011
- calibrate SNe Ia
- measure SNe Ia in the Hubble flow

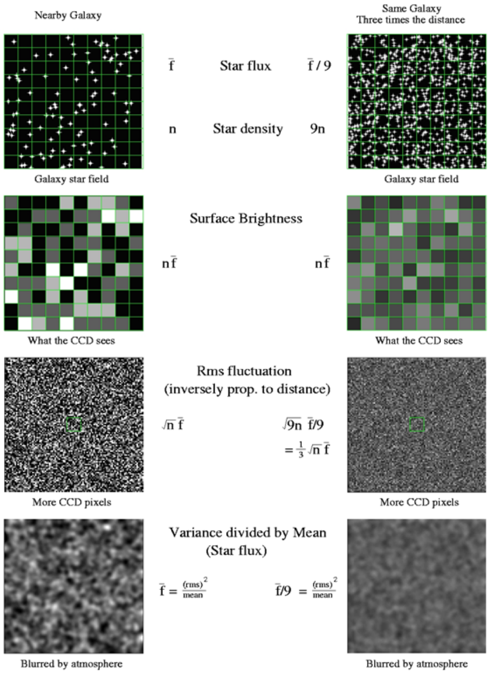
Tully-Fisher method

- Correlate the rotation velocity of a spiral galaxy with its mass and hence luminosity



Surface brightness fluctuations

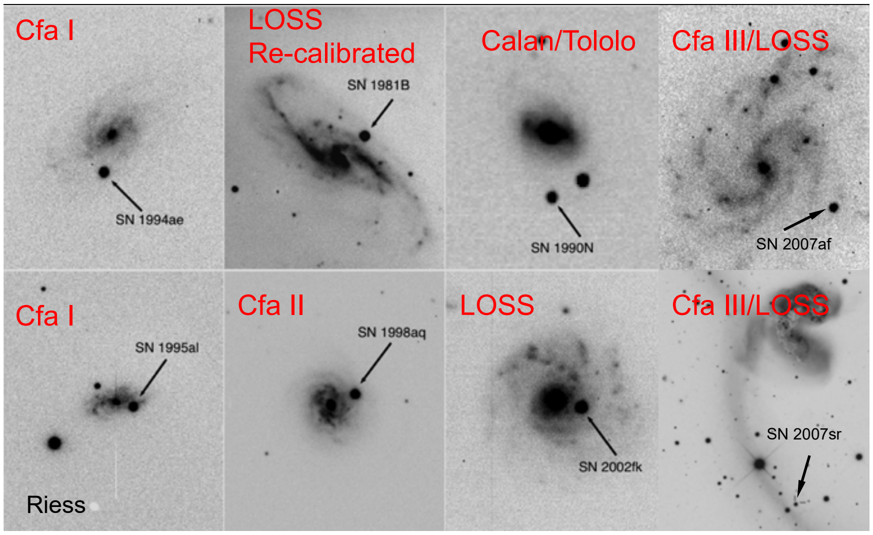
- Distant objects appear smaller
- More stars per pixel in a galaxy far, far away
- Smoother light distribution, less variation from pixel to pixel
- Amplitude of fluctuations proportional to distance
- Good to ~100 Mpc, z~0.01



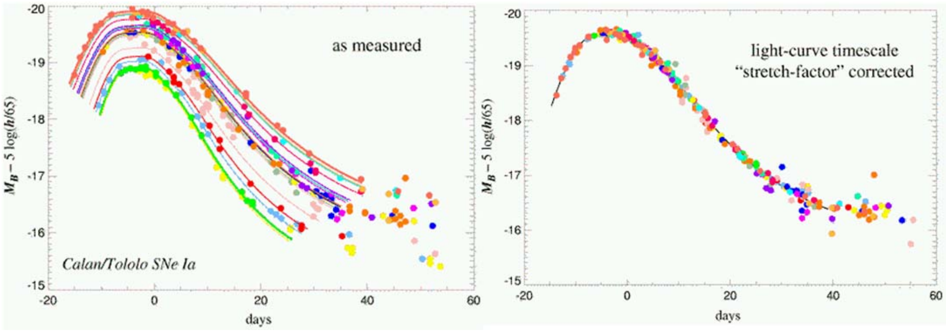
Type Ia Supernovae

- Very luminous: -19 magnitude at maximum
- Variable, easy to identify, when found
- Rare: only about one SN Ia in a typical galaxy every 100 years
- Can be calibrated by light curve shapes to very good accuracy
- Absorption is an issue, unclear absorption law in distant galaxies, possibly local absorption
- Fairly well understood physical processes, although complicated physics (nuclear burning and hydrodynamics)
- Found now frequently and used extensively in large surveys

Type Ia Supernovae



SN Ia: “standardizable” candles

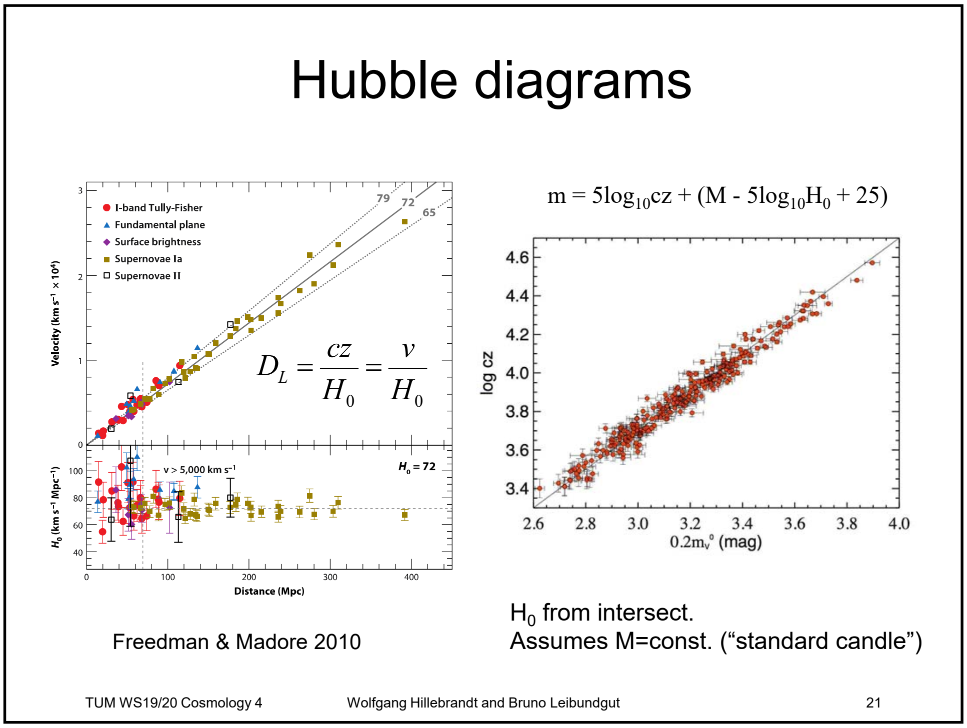


(B-band light curves; Calan/Tololo sample, Kim et al. 1997)

After calibration: SN Ia are good “standard candles”!

Hubble diagrams

- Work mostly with luminosity distances
- Two types
  - velocity/redshift vs. distance
    - linear in distance
    - Hubble constant = slope
  - redshift vs. distance modulus
    - logarithmic in distance
    - Hubble constant = y-axis intercept



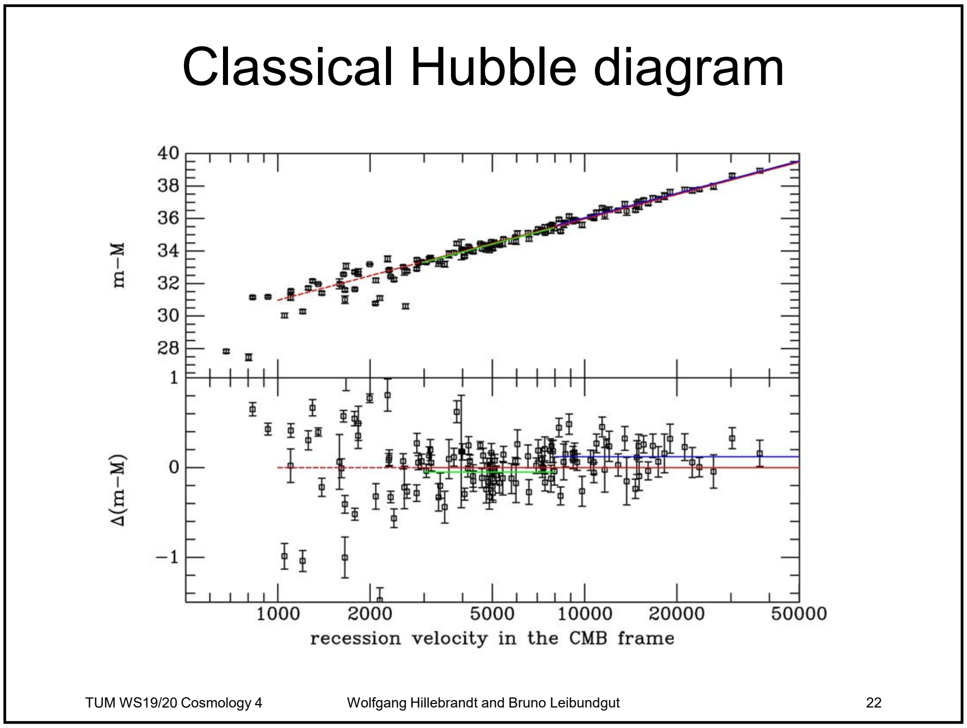
Hubble diagrams

$$D_L = \frac{cz}{H_0} = \frac{v}{H_0}$$

$$m = 5\log_{10}cz + (M - 5\log_{10}H_0 + 25)$$

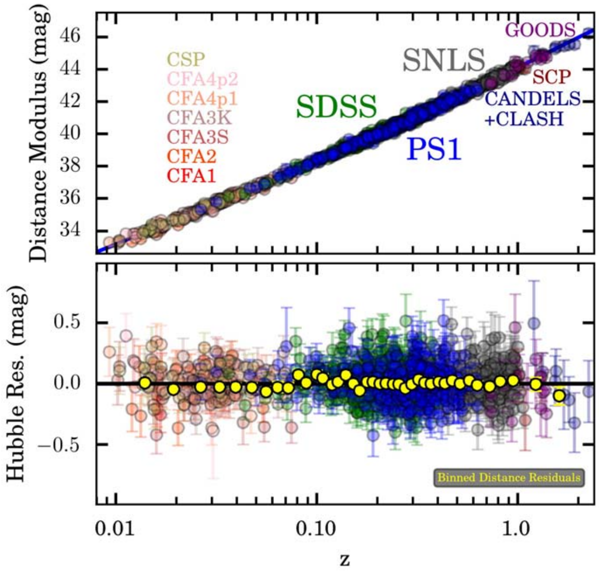
Freedman & Madore 2010

H_0 from intersect.
Assumes M=const. (“standard candle”)



Classical Hubble diagram

More recent SN Ia Hubble diagram



(Scolnic et al., 2018)

≈ 1000 spectroscop. confirmed type SNe Ia!

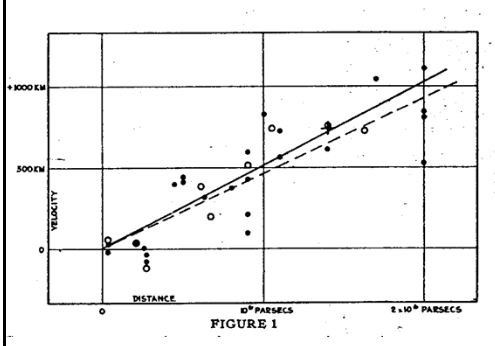
Ω_m = 0.307±0.012

w = -1.026±0.041

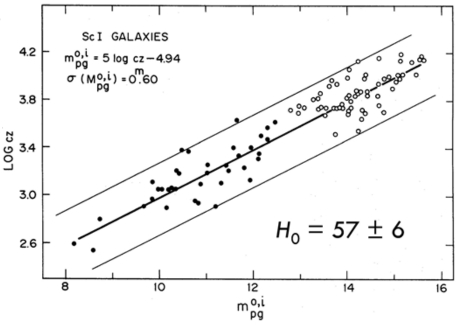
(H_0 = 68.0±0.86)

Early Hubble diagrams

- Attempts of the Hubble diagrams

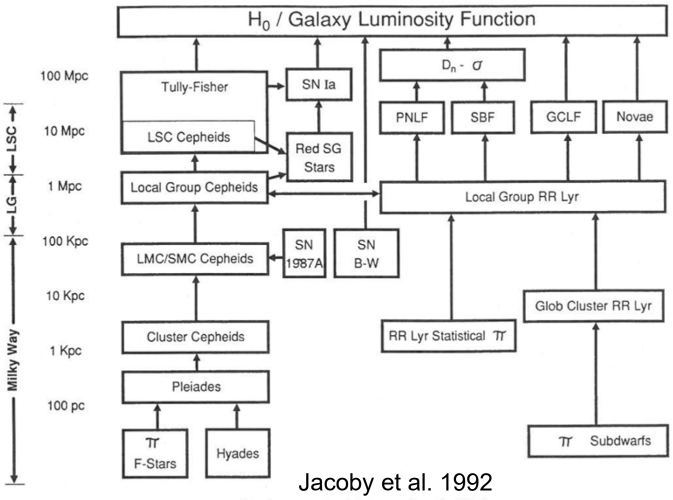


Hubble (1929)



Sandage (1967)

Distance Ladder

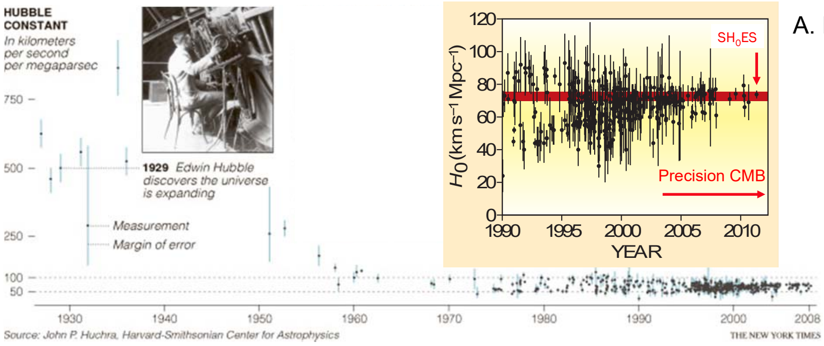


Jacoby et al. 1992

Pathways to Extragalactic Distances

History of the Hubble Constant measurements

- Difficult measurement, depends on many steps in the distance ladder and hence was improved dramatically with time.



A. Riess

Intermezzo
Age of the Universe

- Matter-dominated universe has the following age

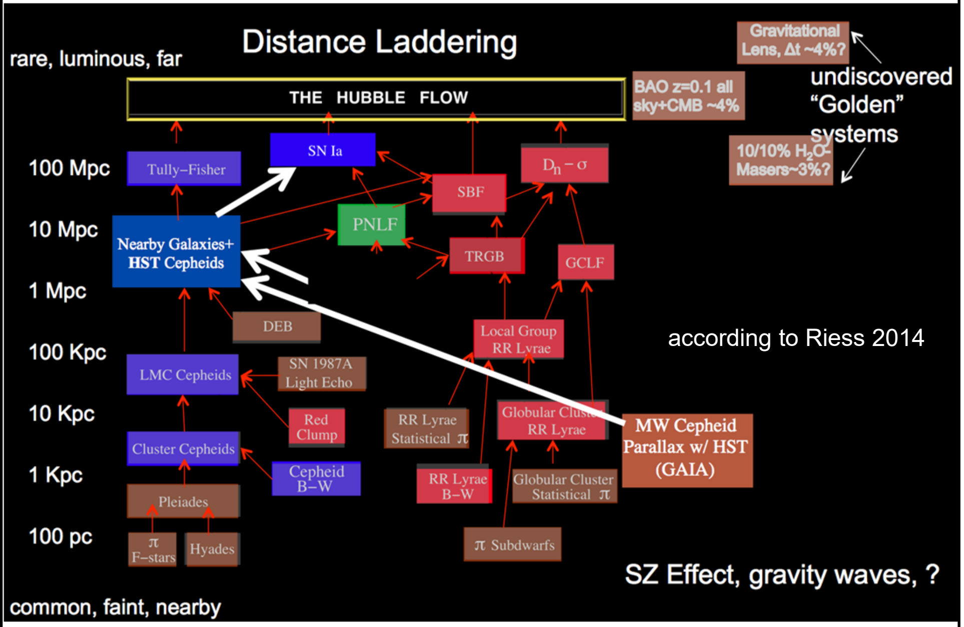
$$t_0 = \frac{2}{3H_0}$$

H_0 (km/s/Mpc)	**t_0 (yr)**
500	$1.30 \cdot 10^{9}$
250	$2.61 \cdot 10^{9}$
100	$6.52 \cdot 10^{9}$
80	$8.15 \cdot 10^{9}$
70	$9.32 \cdot 10^{9}$
60	$1.09 \cdot 10^{10}$
50	$1.30 \cdot 10^{10}$
30	$2.17 \cdot 10^{10}$

age of the Earth: $4.5 \cdot 10^{9}$ years
oldest stars: $\sim 1.2 \cdot 10^{10}$ years

Distance ladder

- Minimise number of “rungs” on the ladder (“steps” into the universe)
- Ideally find objects in the Hubble flow for which the luminosity can be determined through physics
    - theory of Type Ia supernovae
    - Expanding photosphere method of supernovae
    - Sunyaev-Zeldovich effect in galaxy clusters
    - Baryonic Acoustic Oscillations



Distance Laddering

rare, luminous, far

THE HUBBLE FLOW

100 Mpc

10 Mpc

1 Mpc

100 Kpc

10 Kpc

1 Kpc

100 pc

common, faint, nearby

Tully–Fisher

SN Ia

$D_n - \sigma$

SBF

PNLF

TRGB

GCLF

Nearby Galaxies+ **HST Cepheids**

DEB

Local Group RR Lyrae

LMC Cepheids

SN 1987A Light Echo

Red Clump

RR Lyrae Statistical π

Globular Cluster RR Lyrae

MW Cepheid Parallax w/ HST (GAIA)

Cluster Cepheids

Cepheid B–W

RR Lyrae B–W

Globular Cluster Statistical π

Pleiades

π F–stars

Hyades

π Subdwarfs

Gravitational Lens, Δt ~4%?

BAO z=0.1 all sky+CMB ~4%

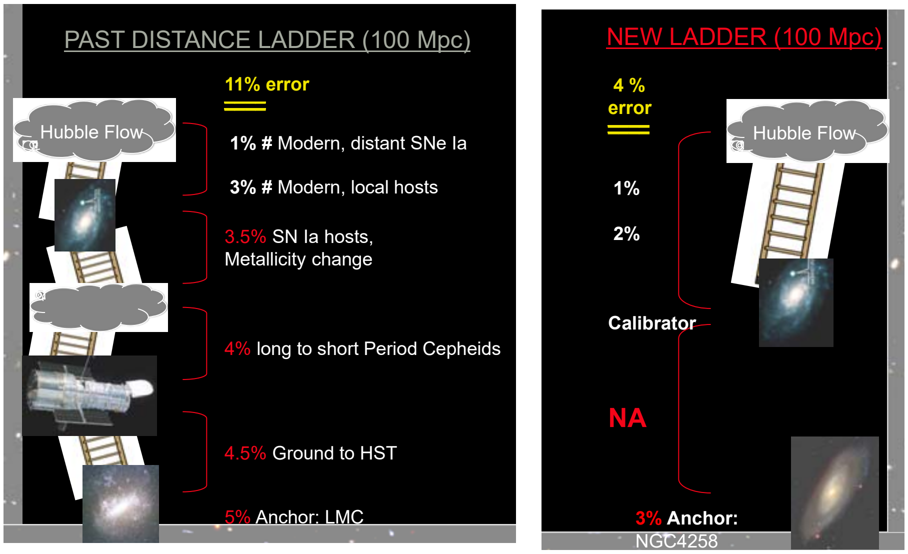
10/10% H_2O-Masers~3%?

undiscovered “Golden” systems

according to Riess 2014

SZ Effect, gravity waves, ?

Distance ladder



PAST DISTANCE LADDER (100 Mpc)

11% error

Hubble Flow

1% # Modern, distant SNe Ia

3% # Modern, local hosts

3.5% SN Ia hosts, Metallicity change

4% long to short Period Cepheids

4.5% Ground to HST

5% Anchor: LMC

NEW LADDER (100 Mpc)

4 % error

Hubble Flow

1%

2%

Calibrator

NA

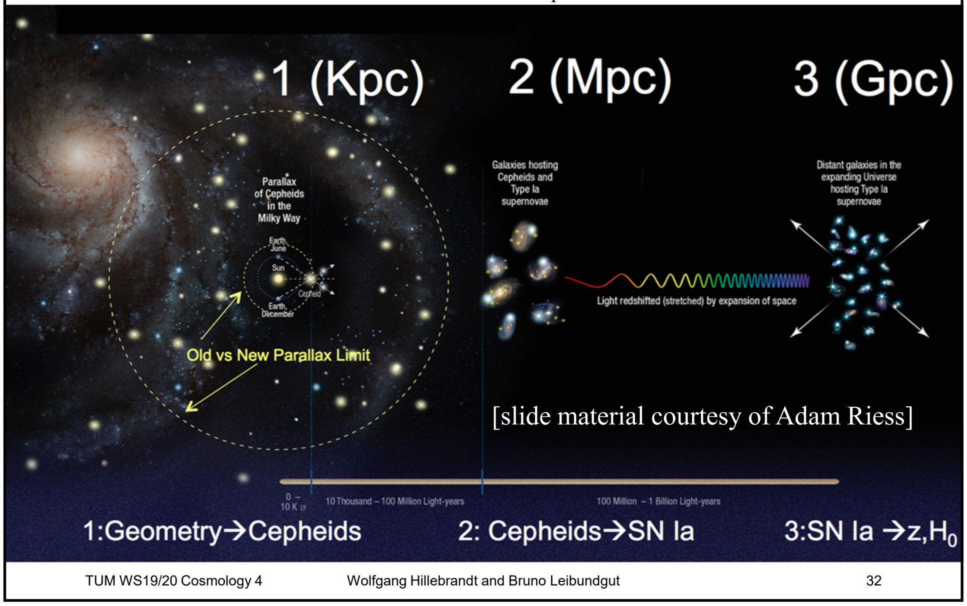
3% Anchor: NGC4258

Distance Ladder measurements

- Hubble Space Telescope Key Project [Freedman et al. 2001]
  - $H_0 = 72 \pm 8$ km s^{-1} Mpc^{-1} (10% uncertainty)
  - resolving multi-decade “factor-of-two” controversy
- Carnegie Hubble Program [Freedman et al. 2012]
  - $H_0 = 74.3 \pm 2.1$ km s^{-1} Mpc^{-1} (2.8% uncertainty)
- Carnegie-Chicago Hubble Program [Beaton et al. 2016]
  - aim 3% precision in H_0 via independent route with RR Lyrae, the tip of red giant branch, SN Ia
- Supernovae, H_0 for the dark energy Equation of State (“SH0ES”) project [Riess et al. 2016]

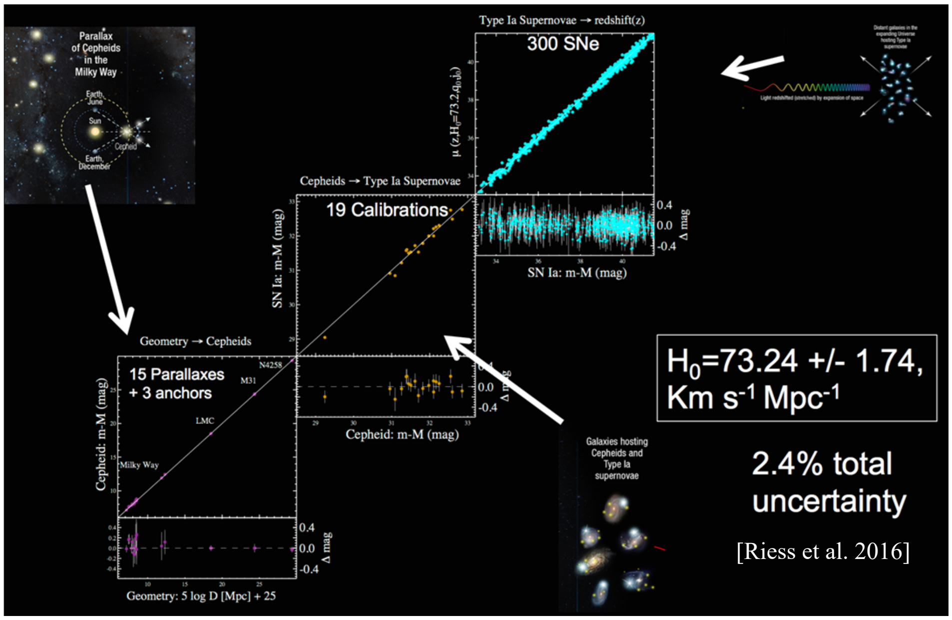
The SH0ES Distance Ladder

ladder to reach objects in Hubble flow ($v_{peculiar} << v_{Hubble} = H_0$ d)



[slide material courtesy of Adam Riess]

H_0 from SH0ES

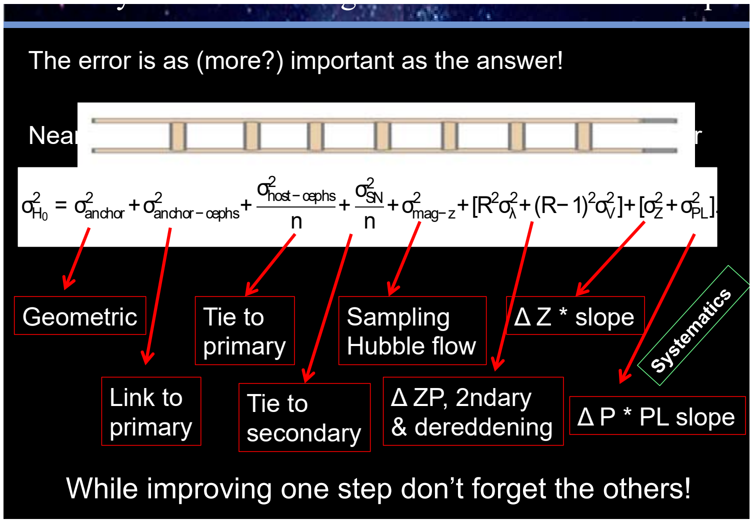


H_0=73.24 +/- 1.74, Km s^{-1} Mpc^{-1}

2.4% total uncertainty

[Riess et al. 2016]

Error propagation in the distance ladder (according to Adam Riess)



The error is as (more?) important as the answer!

$$\sigma^2_{H_0} = \sigma^2_{anchor} + \sigma^2_{anchor-cephs} + \frac{\sigma^2_{host-cephs}}{n} + \frac{\sigma^2_{SN}}{n} + \sigma^2_{mag-z} + [R^2\sigma^2_{\lambda} + (R-1)^2\sigma^2_{V}] + [\sigma^2_{Z} + \sigma^2_{PL}]$$

Geometric

Link to primary

Tie to primary

Tie to secondary

Sampling Hubble flow

Δ ZP, 2ndary & dereddening

Δ Z * slope

Δ P * PL slope

Systematics

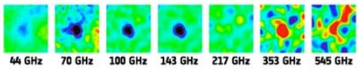
While improving one step don't forget the others!

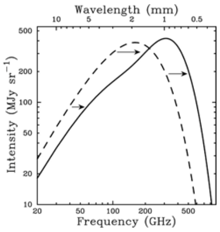
H_0: Physical methods

- **Sunyaev-Zeldovich effect in galaxy clusters**
- Supernovae
  - **Expanding photosphere method**
  - Physical calibration of thermonuclear supernovae
- geometric methods
  - Baryonic acoustic oscillations
  - Masers
  - **Gravitational lenses**

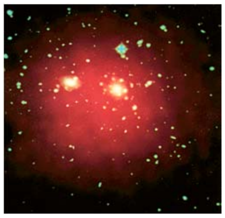
Sunyaev-Zeldovich effect

- Compton scattering of CMB photons in the hot gas of a galaxy cluster
  - temperature dependence $\frac{\Delta T}{T} \propto \int n_e \, dl$



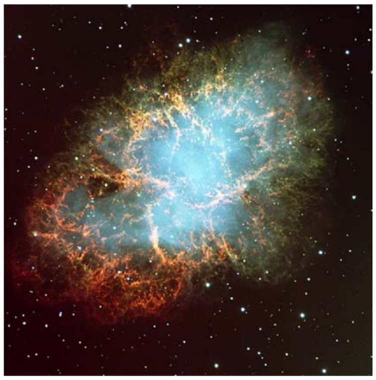


  - X-ray Bremsstrahlung surface brightness $I_\nu = \int n_e^2 \, dl$
  - depth of cluster can be found by eliminating n_e
  - assume that cluster is spherical yields D_A



Type IIP (“core collapse”) supernovae

- High mass stars ($>8M_\odot$)
- Extended envelopes (still burning)
- Single stars
- Collapse to neutron star or black hole



Crab nebula with pulsar
(constellation Orion)
Remnant of a supernova
observed in 1054

A few observational facts

> Very bright events: $L \sim 10^{10}\ L_{sun}$

> Fast expanding ejecta: $v \sim 10^4$ km/s

> Energies: electromagnetic $\sim 10^{42}$ J
kinetic: $\sim 10^{44}$ J
neutrinos (SN1987A): $\sim 3{\cdot}10^{46}$ J

> Progenitor star distroyed (SN 1987A, SN 1993J)

> Compact remnant (as far as we know)

Expanding photosphere method

- Measure the increase in size of a (type IIP) supernova

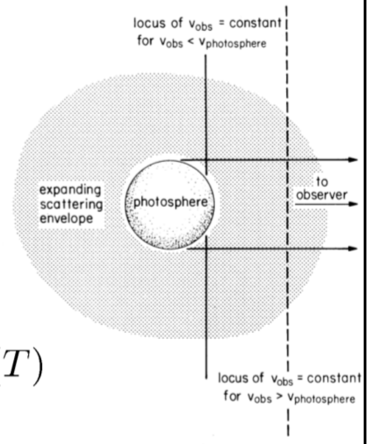
$$R_{\mathrm{ph}} = \xcancel{R_0} + v_{\mathrm{ph}}(t)(t - t_0)$$

- Observed flux depends on the surface area
  - assume blackbody radiation

$$f_\lambda = \left(\frac{R_{\mathrm{ph}}}{D}\right)^2 \pi B_\lambda(T) = \theta^2 \pi B_\lambda(T)$$

(D: distance; B_λ: Planck function)

Image: Kirshner & Kwan 1974



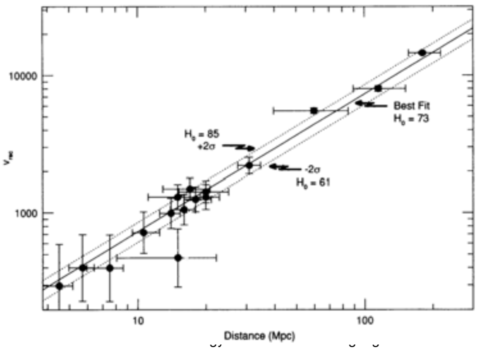
Expanding photosphere method

- Solve for t_0 and D

$$t = D\left(\frac{\theta}{v_{\mathrm{ph}}}\right) + t_0$$

- together with redshift: H_0

Images: Schmidt et al. 1994b



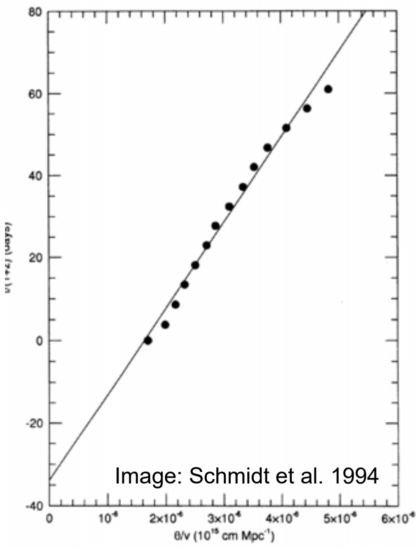
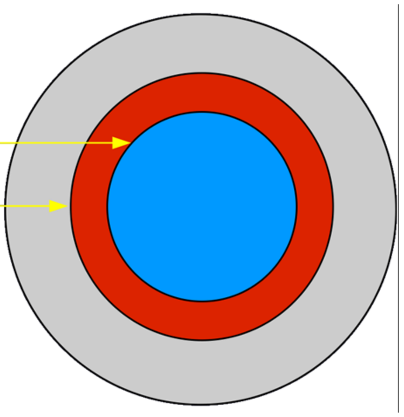


Image: Schmidt et al. 1994

Expanding photosphere method

Main problem: supernova radiation is not a black body!



Origin of BB photons: thermalisation radius R_{th}

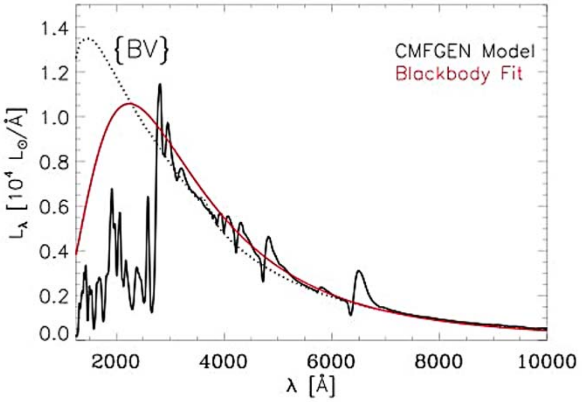
Photosphere: surface of last scattering ($R_{ph} > R_{th}$)

Expanding photosphere method

Main problem: supernova radiation is not black body!

Radiation is "diluted" in the blue and UV bands!

Corrected for by means of a "dilution factor" ς.

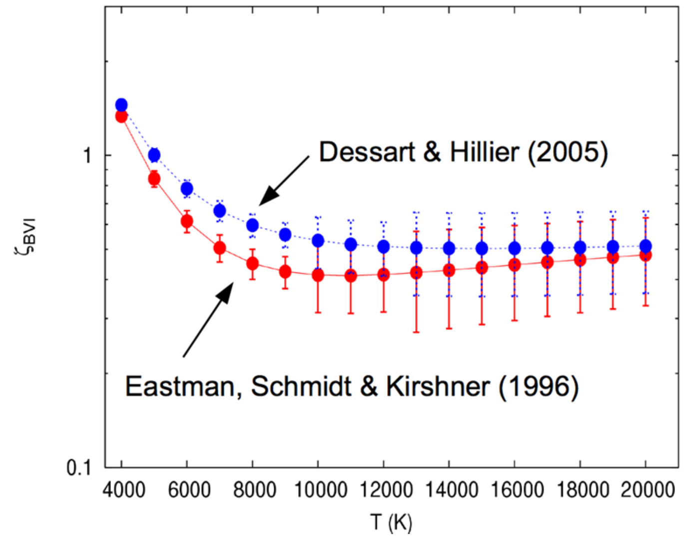


$$f_\lambda = \theta^2 \zeta^2 \pi B_\lambda(T) \qquad \zeta = \frac{R_{\rm th}}{R_{\rm ph}}$$

Dessart & Hillier 2005

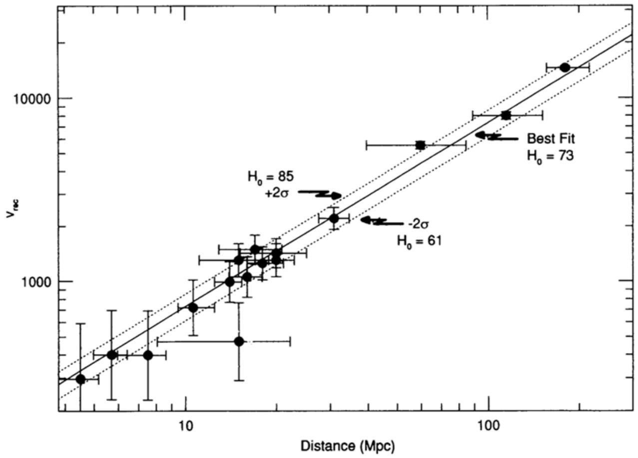
Expanding photosphere method

From fits to models:



Expanding photosphere method

An early EPM Hubble diagram (16 SNe, dilution as in Eastman et al.)

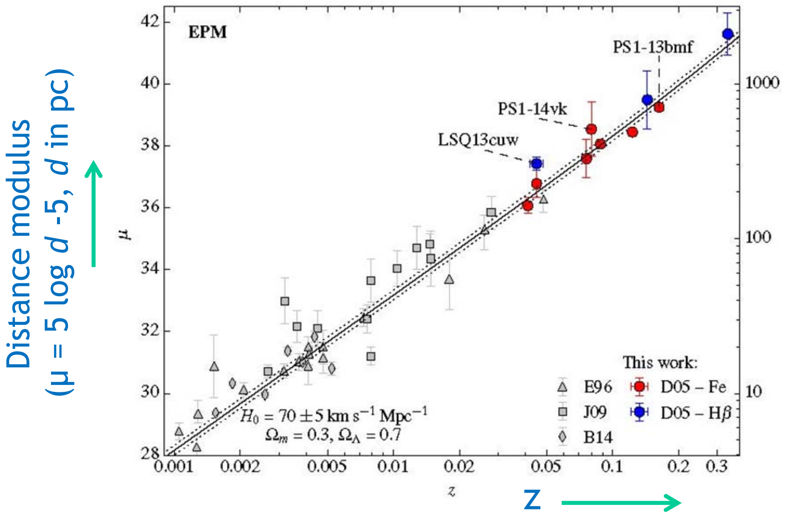


Schmidt et al. 1994

H_0 = 73 ± 6 (stat.) ± 7 (syst.) [km/s/Mpc]

Expanding photosphere method

A more recent EPM Hubble diagram (Gall et al. 2018):



Determining H_0 from models of thermonuclear supernovae (SNe Ia)

- Hubble's law

$$D = \frac{v}{H_0} = \frac{cz}{H_0}$$

- Luminosity distance

$$D_L = \sqrt{\frac{L}{4\pi F}}$$

- Ni-Co decay

$$E_{Ni} = \frac{\lambda_{Ni}\lambda_{Co}}{\lambda_{Ni} - \lambda_{Co}} \left\{ \left[Q_{Ni}\left(\frac{\lambda_{Ni}}{\lambda_{Co}} - 1 \right) - Q_{Co} \right] e^{-\lambda_{Ni}t} + Q_{Co} e^{-\lambda_{Co}t} \right\} N_{Ni,0}$$

H_0 from the nickel mass

$$H_0 = \frac{cz}{D} = cz\sqrt{\frac{4\pi F}{L}} = cz\sqrt{\frac{4\pi F}{\alpha E_{Ni}}} = cz\sqrt{\frac{4\pi F}{\alpha \varepsilon(t) M_{Ni}}}$$

Hubble law

Luminosity distance

'Arnett's rule'

Ni-Co decay and rise time

α: conversion of nickel energy into radiation ($L=\alpha E_{Ni}$)
$\varepsilon(t)$: energy deposited in the supernova ejecta

Need bolometric flux at maximum F and the redshift *z* as observables

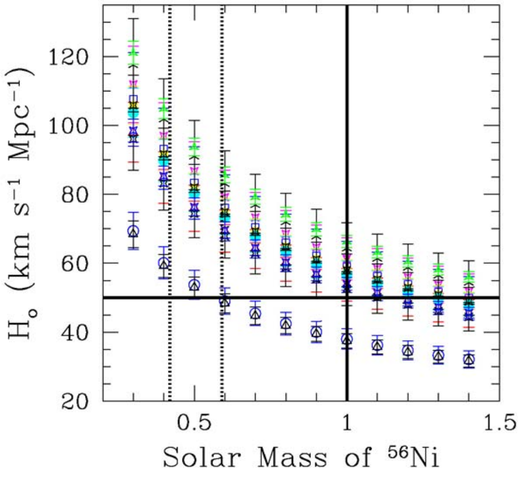
Stritzinger & Leibundgut (2005)

Assumptions

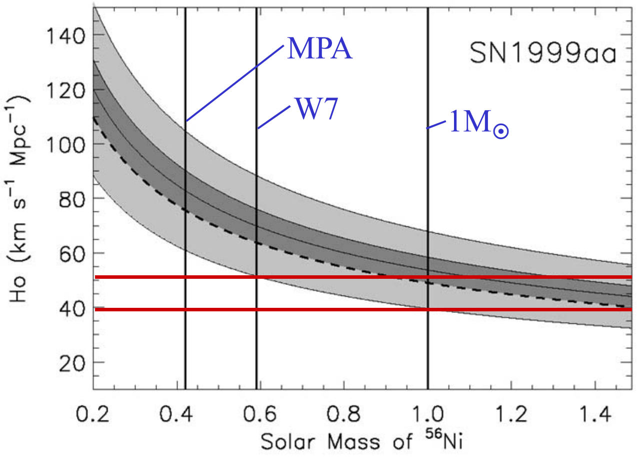
- Rise time (15-25 days) → about 10% uncertainty
- Arnett's rule
  - energy input at maximum equals radiated energy (i.e. $\alpha \approx 1$, $\varepsilon(t_{max}) \approx 1$)
- Nickel mass from models
- → uniquely defines the bolometric peak luminosity

H_0 and the Ni mass

- Individual SNe follow the $M^{-1/2}$
- dependency.
- Problem:
- Since they have individual Ni masses it is not clear which one to apply!



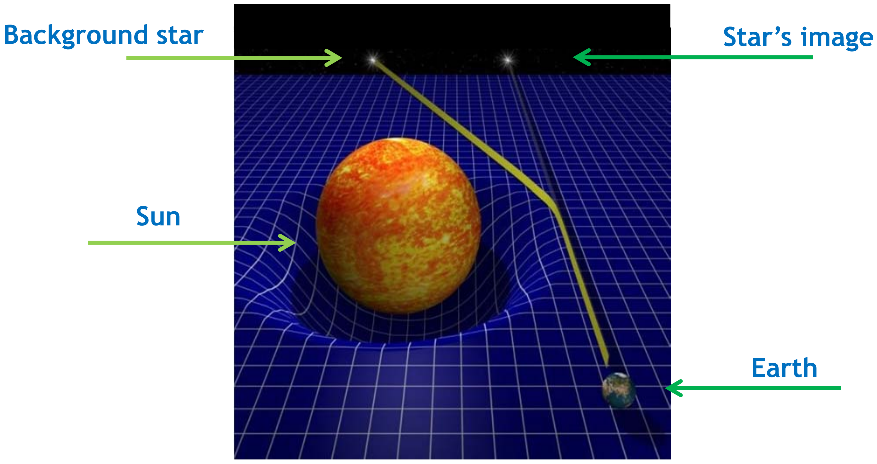
Determine a lower limit for H_0



Gravitationally lensed supernova

(courtesy Sherry Suyu, MPA)

Gravitational lensing:



Background star

Star's image

Sun

Earth

Strong optical lensing

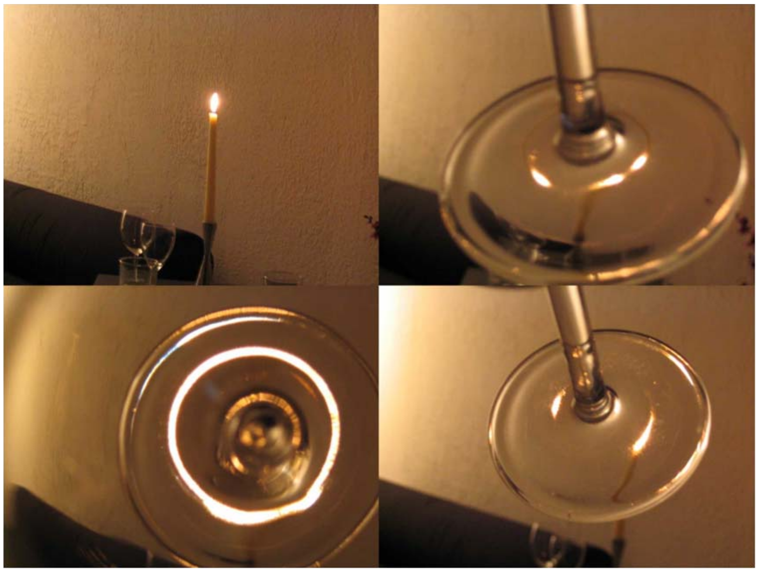
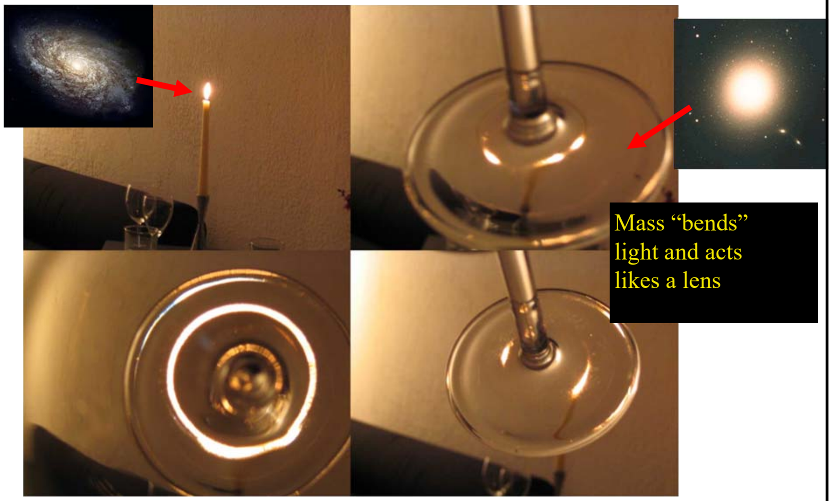


Image credit: P. J. Marshall

Strong gravitational ~~optical~~ lensing



Mass “bends” light and acts likes a lens

Gravitational lens

HST image: SLACSJ0737+3216

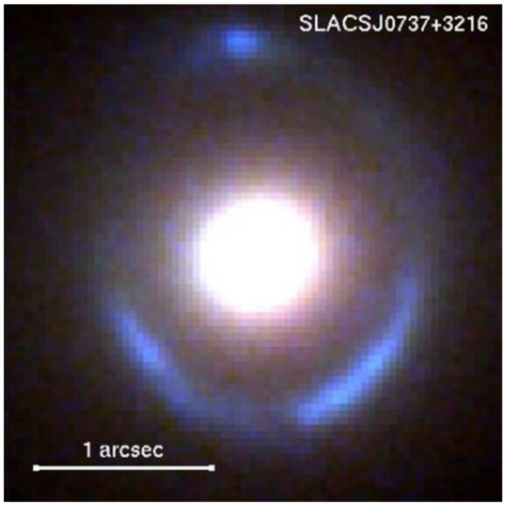


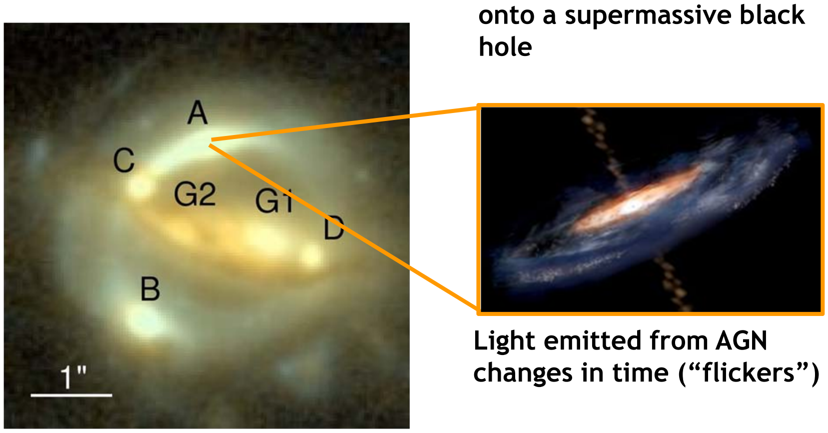
Image credit: P. J. Marshall

Marshall et al. (2007)

Strong gravitational lensing

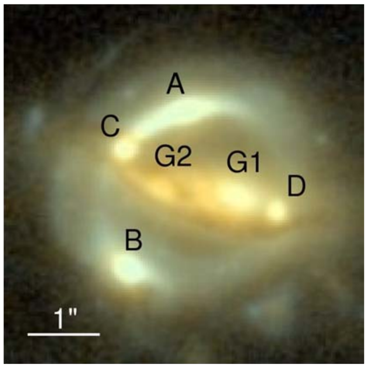
B1608+656

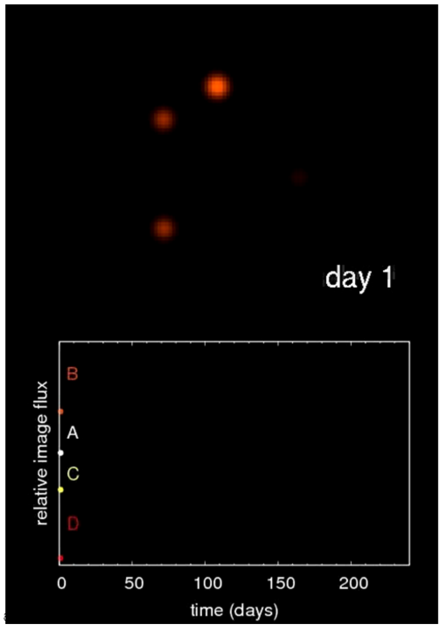
Active galactic nucleus (AGN): accretion of material onto a supermassive black hole



Light emitted from AGN changes in time (“flickers”)

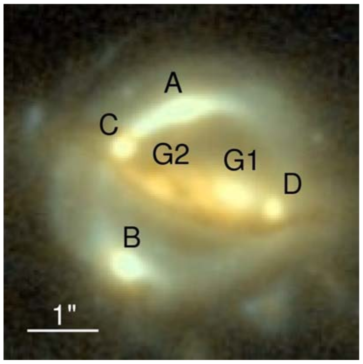
Gravitational lens time delays





[Fassnacht et al. 1999, 2002]
Movie Credits:
S. H. Suyu, C. D. Fassnacht

Gravitational lens time delays



Time delay:

$$t = \frac{1}{c} D_{\Delta t}\, \phi_{\text{lens}}$$

Time-delay distance:

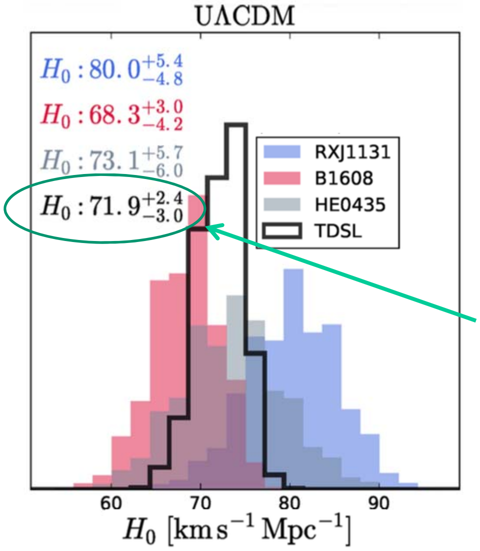
$$D_{\Delta t} \propto \frac{1}{H_0}$$

Obtain from lens mass model

For cosmography, need:
(1) time delays
(2) lens mass model
(3) mass along line of sight

Advantages:
- simple geometry and well-tested physics
- one-step physical measurement of a cosmological distance

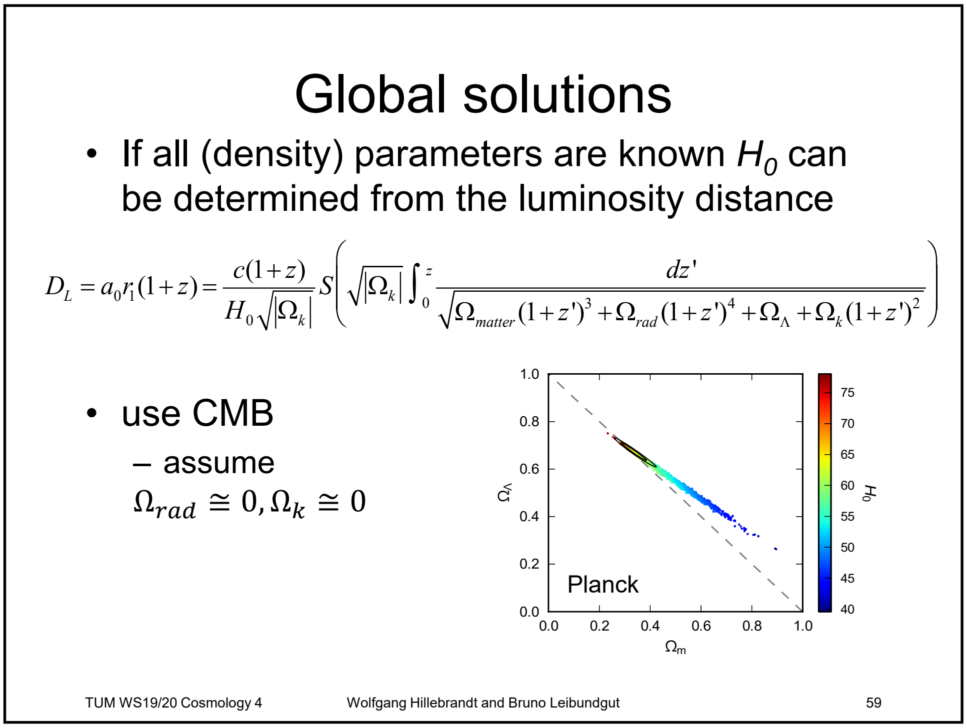
H_0 from 3 strong lenses



H ∈ [0,150] km/s/Mpc
$\Omega_m = 1 - \Omega_\Lambda \in [0,1]$
w = -1

H_0 with 3.8% precision for flat ΛCDM !

[Bonvin, Courbin, Suyu et al. 2017]



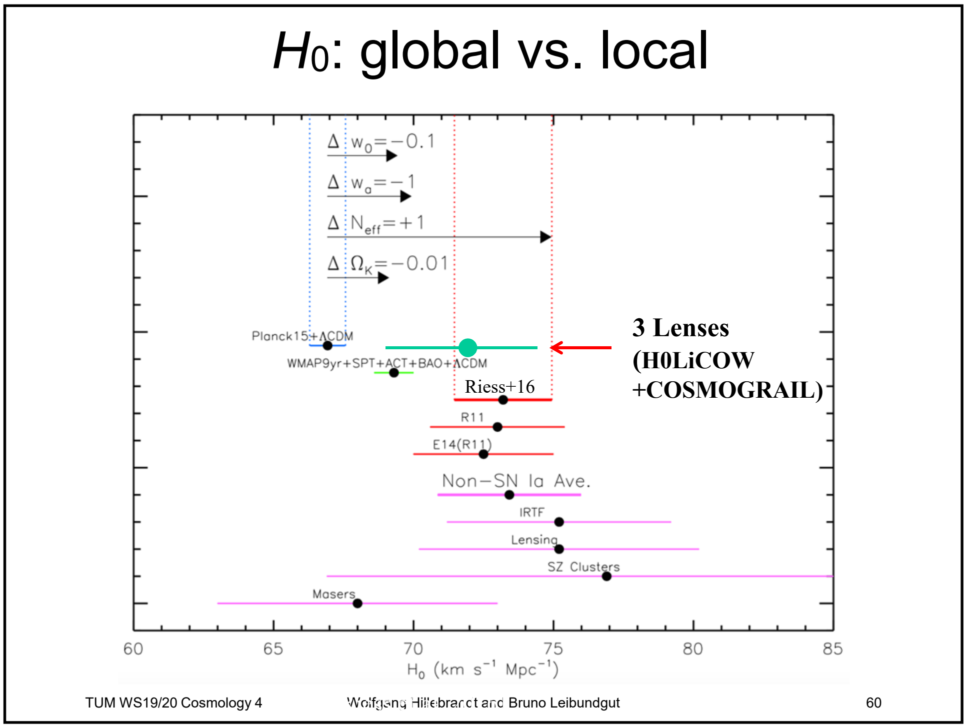
Global solutions

- If all (density) parameters are known H_0 can be determined from the luminosity distance

$$D_L = a_0 r_1 (1+z) = \frac{c(1+z)}{H_0\sqrt{|\Omega_k|}} S\left(\sqrt{|\Omega_k|}\int_0^z \frac{dz'}{\sqrt{\Omega_{matter}(1+z')^3 + \Omega_{rad}(1+z')^4 + \Omega_\Lambda + \Omega_k(1+z')^2}}\right)$$

- use CMB
  - assume $\Omega_{rad} \cong 0, \Omega_k \cong 0$

TUM WS19/20 Cosmology 4 Wolfgang Hillebrandt and Bruno Leibundgut 59

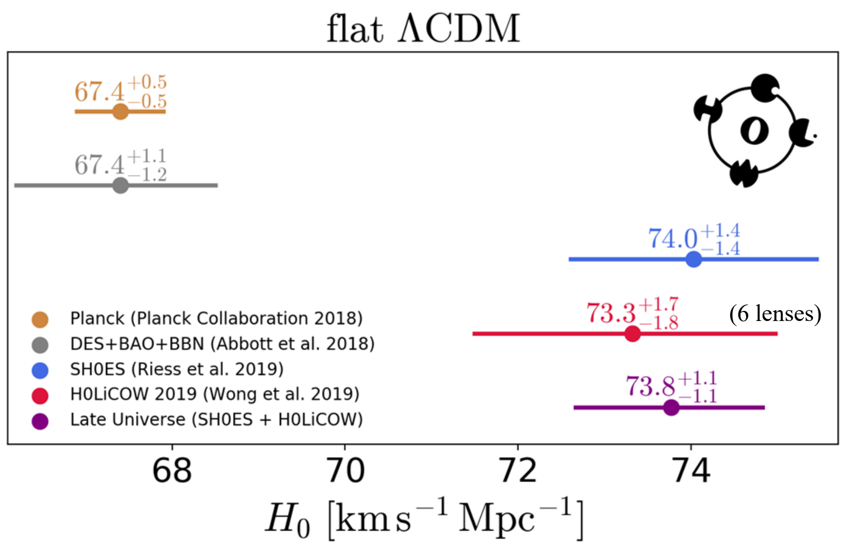


H_0: global vs. local

3 Lenses (H0LiCOW +COSMOGRAIL)

TUM WS19/20 Cosmology 4 Wolfgang Hillebrandt and Bruno Leibundgut 60

H_0: Summary (as of 2019)

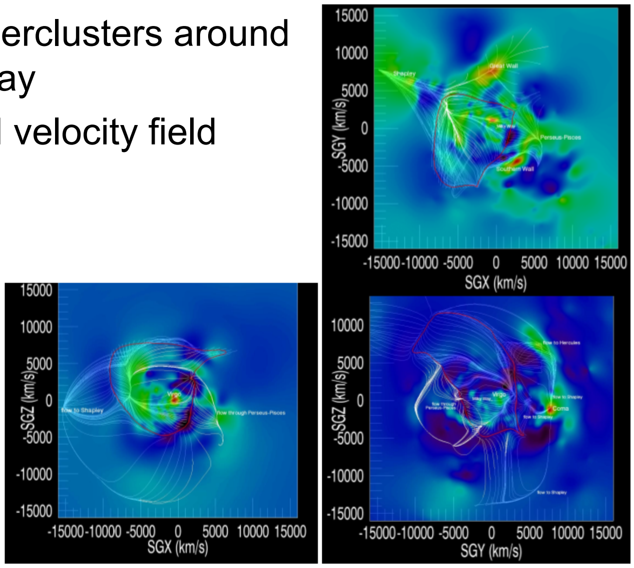


Issues

- Big unresolved issue is dust obscuration
  - correction uncertain for other galaxies
- Evolution of the object
  - e.g. supernovae different in the past
- Sample contamination by other objects
- Subtleties in the geometry
- Disturbance in the pure Hubble flow
  - peculiar velocities

Local galaxy environment

- Several superclusters around the Milky Way
- complicated velocity field



Literature

- Steven Weinberg, Gravitation and cosmology : principles and applications of the general theory of relativity, New York, Wiley 1972 ISBN: 0471925675
- Lars Bergström and Ariel Goobar, Cosmology and Particle Physics, Springer Verlag, 2004, ISBN 3-540-43128-4
- Wendy Freedman and Barry Madore, The Hubble Constant, Annual Reviews of Astronomy and Astrophysics 48, 673 (2010); http://www.annualreviews.org/doi/full/10.1146/annurev-astro-082708-101829
- Michael Rowan-Robinson, The Cosmological Distance Ladder, New York, W.H. Freeman and Company, 1985, ISBN o-7167-1586-4
- Stephen Webb, Measuring the Universe – The Cosmological Distance Ladder, Springer Verlag, 1999, ISBN 1852331062
- Edwin Hubble, The Law of Red-Shifts, 1953, Monthly Notices Royal Astronomical Society 113, 658
- Alan Sandage, The Ability of the 200-inch Telescope to Discriminate between Selected World Models, 1961, Astrophys. J. 133, 355
- Alan Sandage and Gustav Tamman, Series of papers "Steps towards the Hubble Constant" between 1974 and 1995 in the Astrophysical Journal
- Michael Perryman, The Making of History's Greatest Star Map, Heidelberg, Springer Verlag, 2009, ISBN 978-3-642-11601-8, e-ISBN 978-3-642-11602-5
- An Atlas of the Universe, http://www.atlasoftheuniverse.com/index.html
- Talks at the Munich Institute for Astro- and Particle Physics (MIAPP) conference "The Extragalactic Distance Scale", June 2014 and June 2018 (http://www.munich-iapp.de/)

Literature (cont.)

- A. Riess et al.: A 2.4% Determination of the Local Value of the Hubble Constant, Astrophysical Journal, Volume 826, Issue 1, article id. 56, 31 pp. (2016).
- /S. Hoffmann et al.: Optical Identification of Cepheids in 19 Host Galaxies of Type Ia Supernovae and NGC 4258 with the Hubble Space Telescope, Astrophysical Journal, Volume 830, Issue 1, article id. 10, 15 pp. (2016).
- A. Riess et al.: Type Ia Supernova Distances at Redshift >1.5 from the Hubble Space Telescope Multi-cycle Treasury Programs: The Early Expansion Rate, Astrophysical Journal, Volume 853, Issue 2, article id. 126, 15 pp. (2018).
- A. Riess et al.: New Parallaxes of Galactic Cepheids from Spatially Scanning the Hubble Space Telescope: Implications for the Hubble Constant, Astrophysical Journal, Volume 855, Issue 2, article id. 136, 18 pp. (2018).
- A. Riess et al.: Milky Way Cepheid Standards for Measuring Cosmic Distances and Application to Gaia DR2: Implications for the Hubble Constant, Astrophysical Journal, Volume 861, Issue 2, article id. 126, 13 pp. (2018).
- D. Kenworthy et al.: The Local Perspective on the Hubble Tension: Local Structure Does Not Impact Measurement of the Hubble Constant. Astrophysical Journal, Volume 875, Issue 2, article id. 145, 10 pp. (2019).
- A. Riess et al.: Large Magellanic Cloud Cepheid Standards Provide a 1% Foundation for the Determination of the Hubble Constant and Stronger Evidence for Physics beyond ΛCDM, Astrophysical Journal, Volume 876, Issue 1, article id. 85, 13 pp. (2019).

Literature (cont.)

- C. Grillo et al.: Measuring the Value of the Hubble Constant “à la Refsdal” , Astrophysical Journal, Volume 860, Issue 2, article id. 94, 7 pp (2018).
- S. Birrer et al.: H0LiCOW - IX. Cosmographic analysis of the doubly imaged quasar SDSS 1206+4332 and a new measurement of the Hubble constant, Monthly Notices of the Royal Astronomical Society, Volume 484, Issue 4, p.4726-4753 (2019).
- I.Jee et al: A measurement of the Hubble constant from angular diameter distances to two gravitational lenses, Science, Volume 365, Issue 6458, pp. 1134-1138 (2019).
- S. Taubenberger et al.: The Hubble constant determined through an inverse distance ladder including quasar time delays and Type Ia supernovae, Astronomy & Astrophysics, Volume 628, id.L7, 5 pp (2019).
- W. Freedman et al.: The Carnegie-Chicago Hubble Program. VIII. An Independent Determination of the Hubble Constant Based on the Tip of the Red Giant Branch, Astrophysical Journal, Volume 882, Issue 1, article id. 34, 29 pp. (2019).