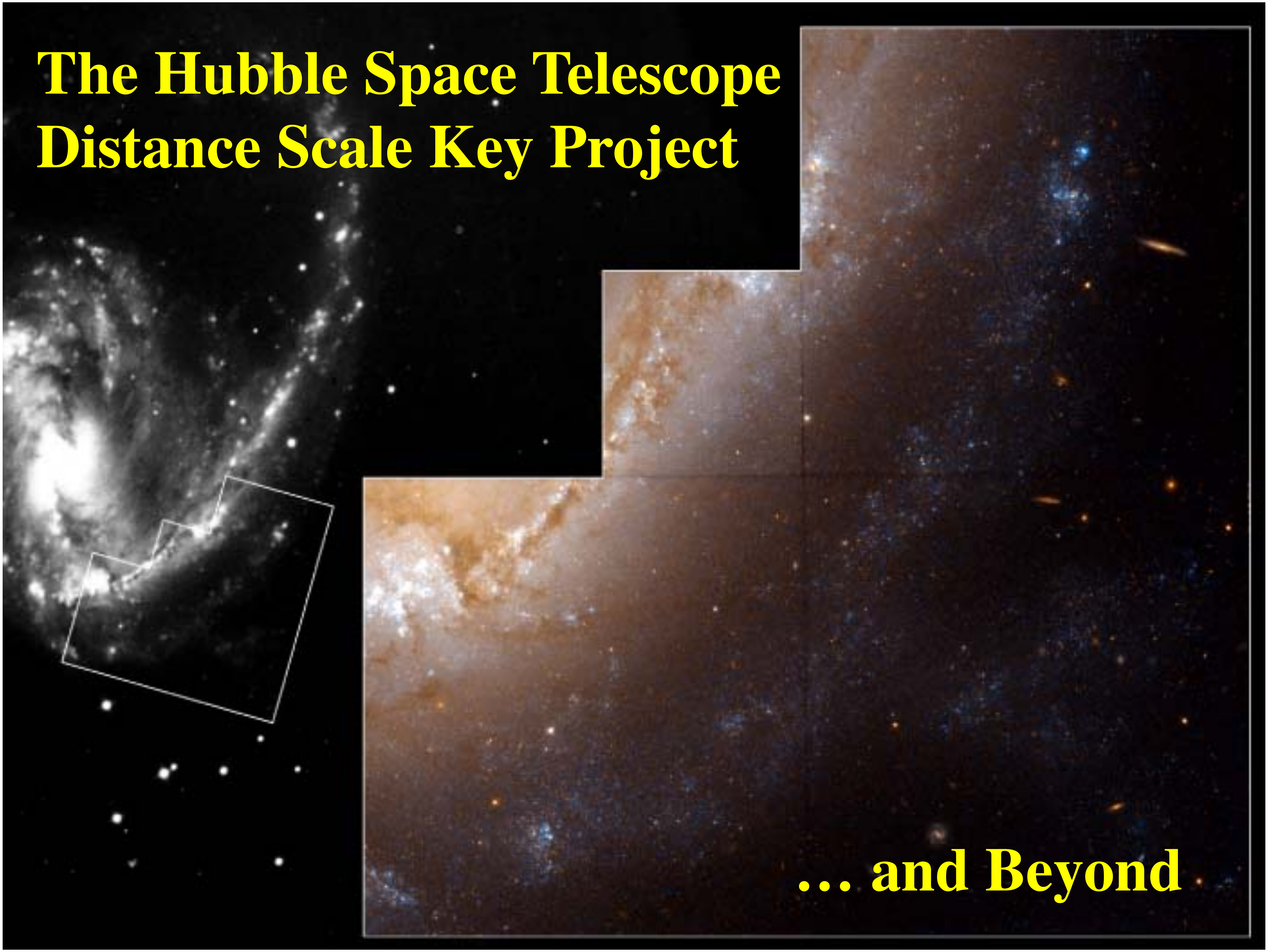

The Hubble Space Telescope
Distance Scale Key Project
… and Beyond

The HST H_0 Key Project

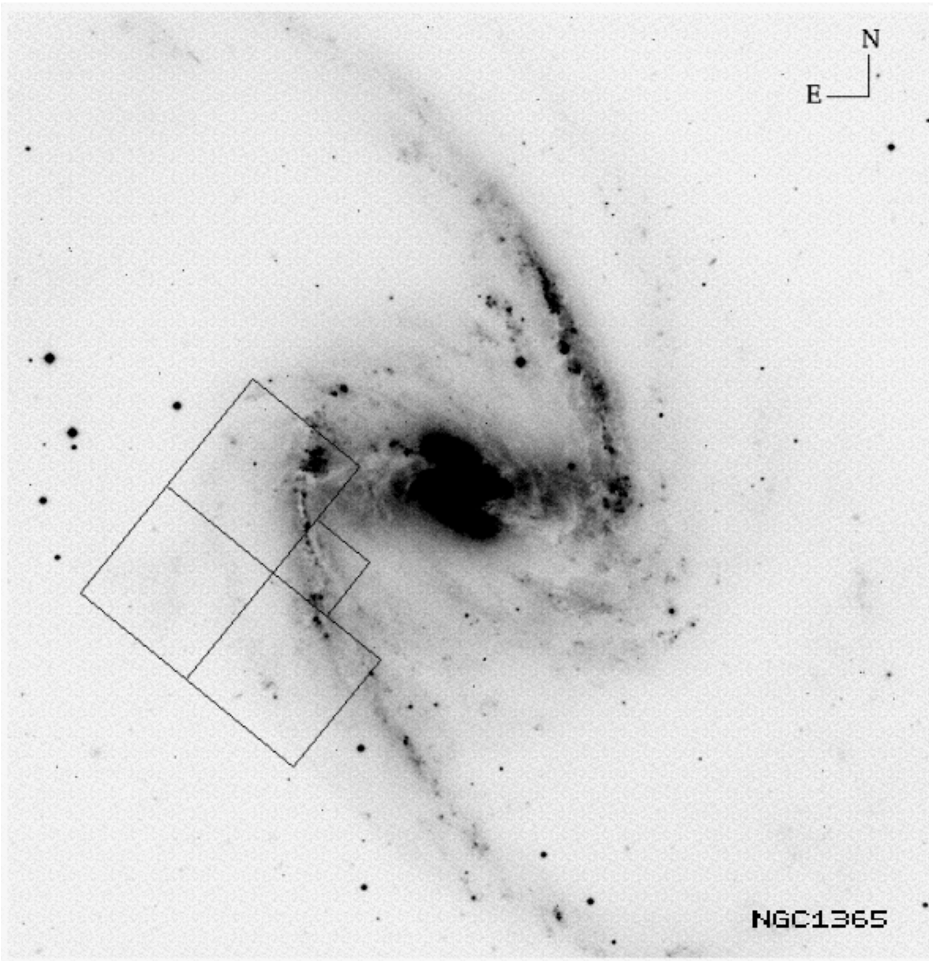
- Started in 1990, final results in 2001! Leaders include W. Freedman, R. Kennicutt, J. Mould, J. Huchra, and many others (reference: Freedman *et al*. 2001, ApJ, 553, 47)
- Observe Cepheids in ~18 spirals to test the universality of the Cepheid P-L relation and greatly improve calibration of other distance indicators
- Their Cepheid P-L relation zeropoint is tied directly to the distance to the LMC (largest source of error for the H_0!)
- Combining different estimators, they find:

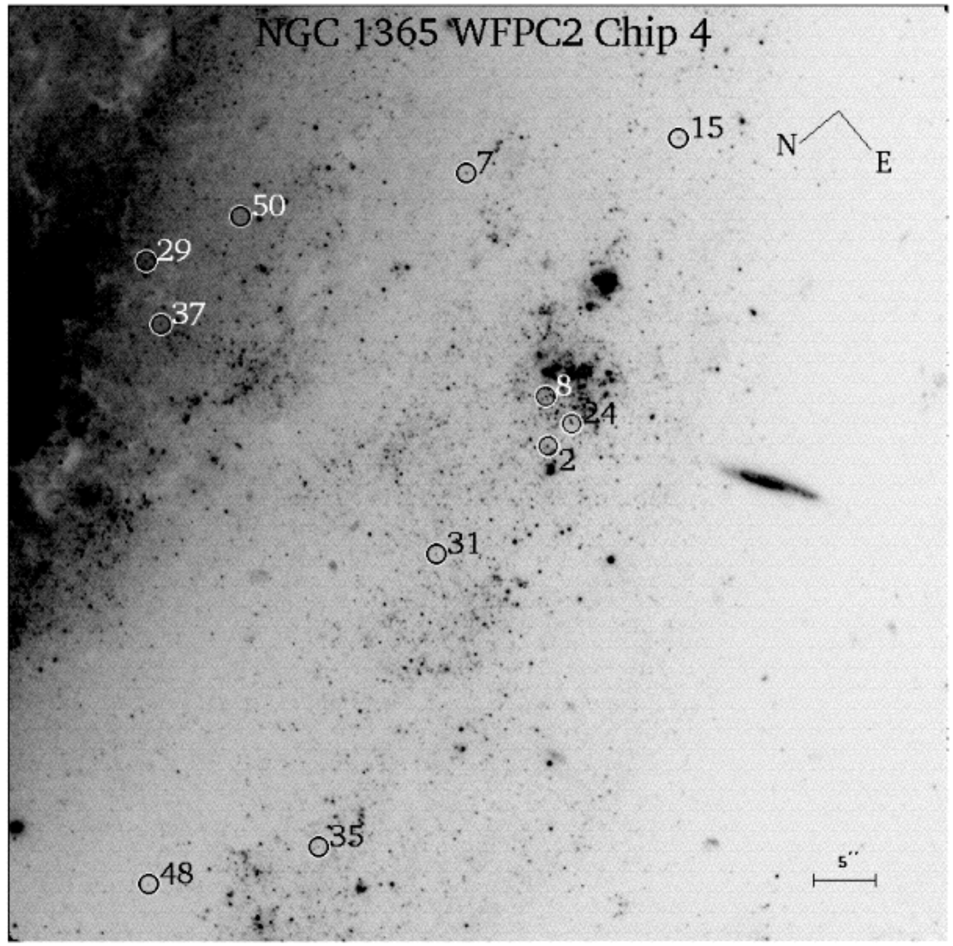
$$H_0 = 72 \pm 3 \text{ (random) } \pm 7 \text{ (systematic) km/s/Mpc}$$

- Some people disagree with their adopted value for the distance to the LMC … and some other methods give different answers … but most are converging to this value

The HST H_0 Key Project

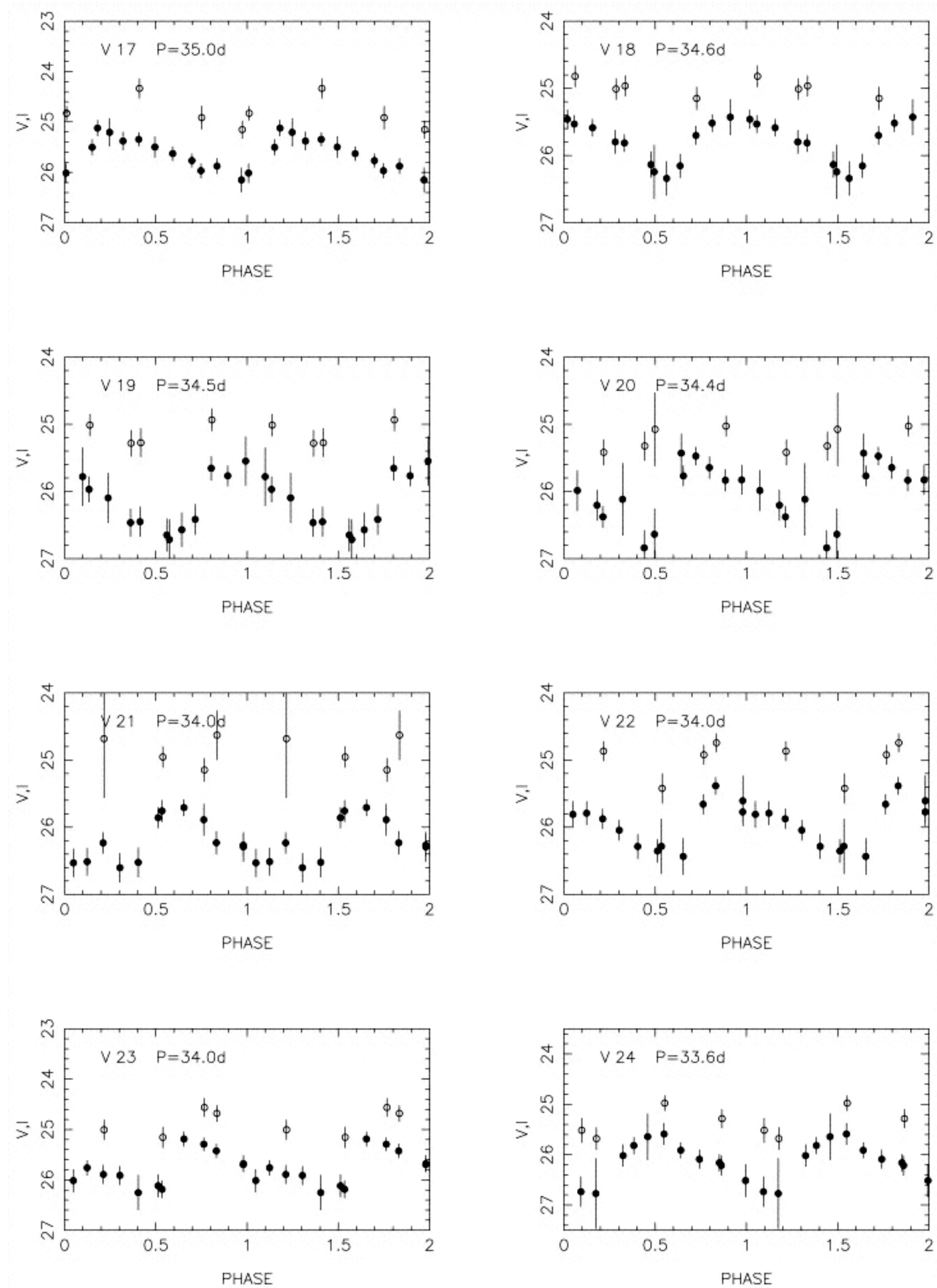
Sample images for discovery of Cepheids





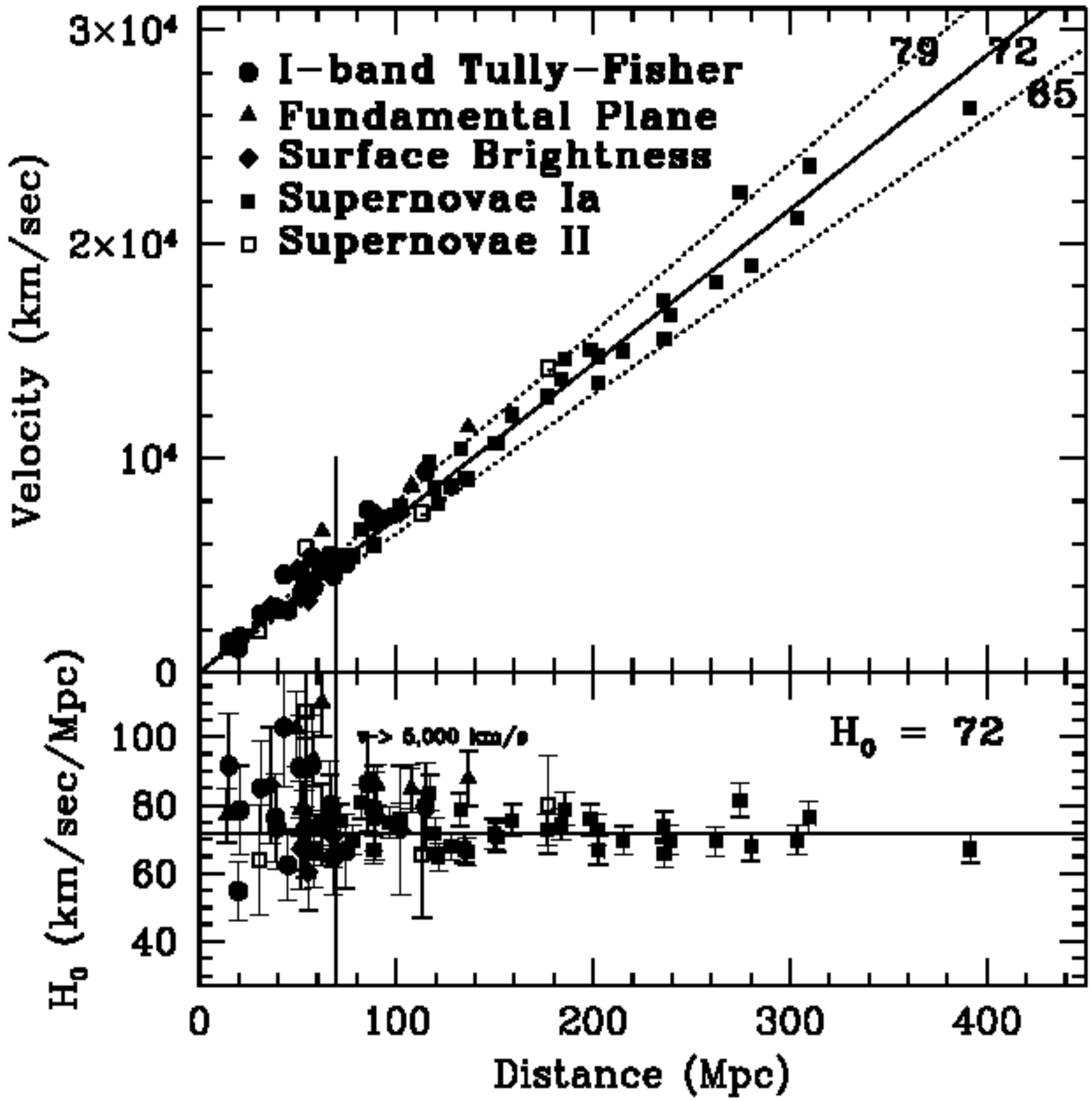
The HST H_0 Key Project

Sample Cepheid light curves for NGC 1365

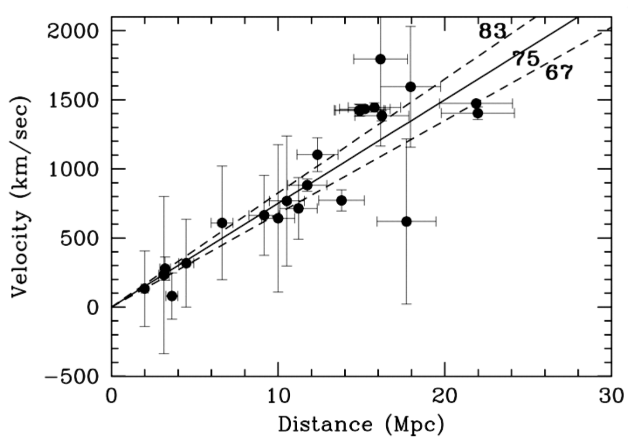


The HST H_0 Key Project Results

Overall Hubble diagram, from all types of distance indicators ➞



From Cepheid distances alone ➘



The H_0 Key Project: Uncertainties

Uncertainties in H_0 for Secondary Methods

Method	H_0	Error (random, systematic (%)
36 Type Ia SN, $4000 < cz < 30{,}000$ km s^{-1}	71	$\pm\ 2 \pm 6$
21 TF clusters, $1000 < cz < 9000$ km s^{-1}	71	$\pm\ 3 \pm 7$
11 FP clusters, $1000 < cz < 11{,}000$ km s^{-1}	82	$\pm\ 6 \pm 9$
SBF for 6 clusters, $3800 < cz < 5800$ km s^{-1}	70	$\pm\ 5 \pm 6$
4 Type II SN, $1900 < cz < 14{,}200$ km s^{-1}	72	$\pm\ 9 \pm 7$

Overall Systematic Errors Affecting All Methods

Source of Uncertainty	Description	Error (%)
LMC zero point	Error on mean from Cepheids, TRGB, SN 1987A, red clump, eclipsing binaries	± 5
WFPC2 zero point	Tie-in to Galactic star clusters	± 3.5
Reddening	Limits from NICMOS photometry	± 1
Metallicity	Optical, NICMOS, theoretical constraints	± 4
Bias in Cepheid PL	Short-end period cutoff	± 1
Crowding	Artificial star experiments	$+5, -0$
Bulk flows on scales $>10{,}000$ km s^{-1}	Limits from SN Ia, CMB	± 5

Note.—Adopted final value of H_0: $H_0 = 72 \pm 3$ (random) $\pm$ 7 (systematic) km s^{-1} Mpc^{-1}.

The HST H_0 Key Project Results

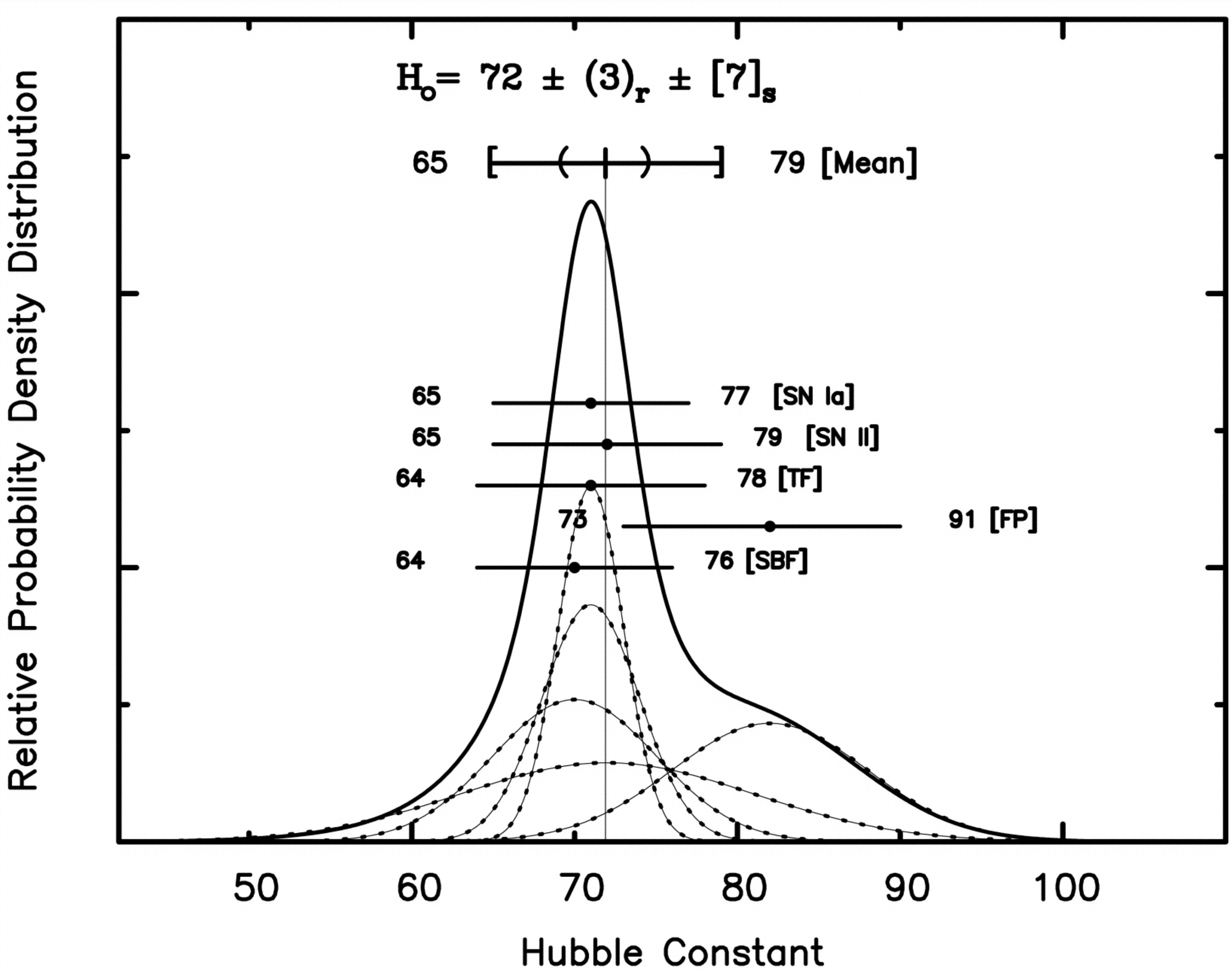


Table 1.1. *A Few Recently Published Hubble Constant Measurements*

Technique	H_0 (km s^{-1} Mpc^{-1})	Cepheid calibration	Reference
Key Project summary	72 ± 8	New PL+Z	Freedman et al. 2001
Cepheids+IRAS flows	85 ± 5	New PL	Willick & Batra 2001
Type Ia Supernovae	59 ± 6	Sandage team	Parodi et al. 2001
	59 ± 6	Sandage team	Saha et al. 2001
	$71 \pm 2 \pm 6$	New PL+Z	Freedman et al. 2001
	74 ± 3	New PL+Z	Tonry et al. 2003, in prep.
	$73 \pm 2 \pm 7$	New PL+Z	Gibson & Stetson 2001
I-band SBFs	$77 \pm 4 \pm 7$	Orig. KP	Tonry et al. 2000
	$70 \pm 5 \pm 6$	New PL+Z	Freedman et al. 2001
	75	New PL+Z	Ajhar et al. 2001
H-band SBFs	$72 \pm 2 \pm 6$	Orig. KP+*I*-SBF	Jensen et al. 2001
	$77 \pm 3 \pm 6$	New PL+Z	Jensen et al. 2003, in prep.
K-band SBFs	71 ± 8	Orig. KP+*I*-SBF	Liu & Graham 2001
Tully-Fisher	$71 \pm 3 \pm 7$	New PL+Z	Freedman et al. 2001
Fundamental Plane	$82 \pm 6 \pm 9$	New PL+Z	Freedman et al. 2001
	$73 \pm 4 \pm 11$	New PL+Z	Blakeslee et al. 2002
Type II Supernovae	$72 \pm 9 \pm 7$	New PL+Z	Freedman et al. 2001
	75 ± 7	New PL+Z	M. Hamuy, private comm.
Globular Custer LF	~ 70	similar to Orig. KP	Okon & Harris 2002
Sunyaev-Zel'dovich	$60 \pm 3 \pm 30\%$	...	Carlstrom et al. 2002
Gravitational lenses	61 to 65	...	Fassnacht et al. 2002
	$59 \pm 12 \pm 3$	...	Treu & Koopmans 2002
Type Ia SNe (theory)	67 ± 9	...	Höflich & Khokhlov, 1996
Type II SNe (theory)	67 ± 9	...	Hamuy 2001

How Well Do the Different Distance Indicators Agree?

The best check on their reliability …

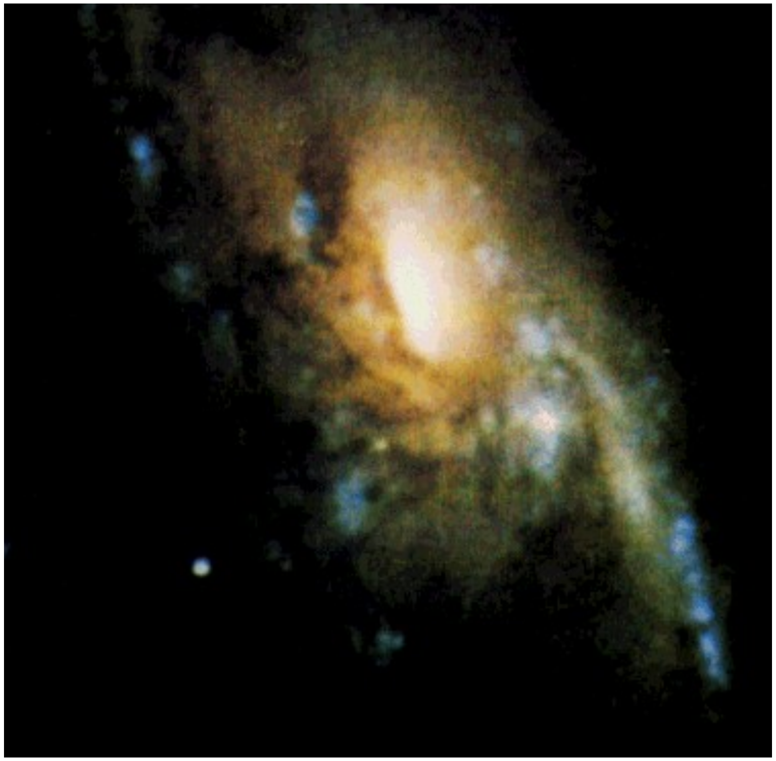
Lets look at the modern distance measurements to the Large Magellanic Cloud (LMC), one of the first stepping stones in the distance scale.

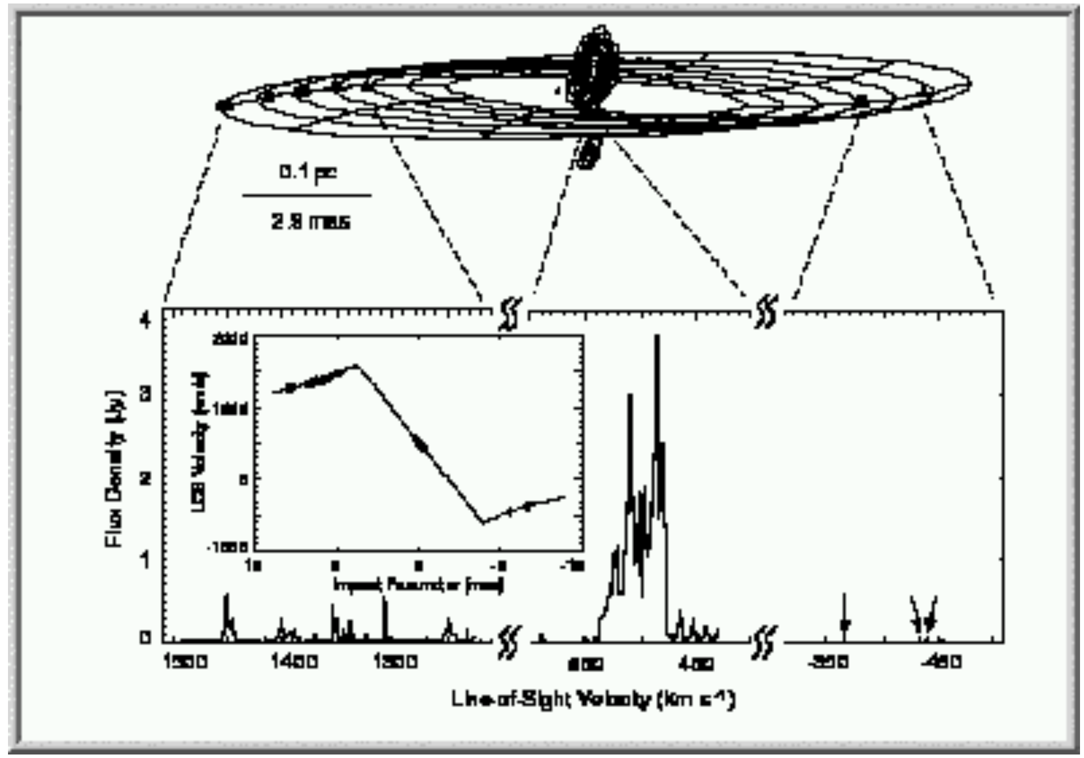
Different techniques give distance moduli $(m\text{-}M) = 5 \, log \, [D/\mathrm{pc}] - 5$, in the range of 18.07 to 18.70 mag, corresponding to a range in distances of 41 to 55 kpc, with typical quoted errors of ~ 5 –10%

How far is the LMC?

Indicator	$(m-M)_{0,LMC}$	Authors
Subdwarf fitting	18.54 ± 0.12	Carretta et al. 1998
Cepheids	18.70 ± 0.10	Feast & Catchpole 1997
	18.50 ± 0.07	Madore & Freedman 1998
Miras	18.54 ± 0.18	van Leeuwen et al. 1997
SN1987a ring	18.37 ± 0.04	Gould & Uza 1998 (circular)
	18.44	Gould & Uza 1998 (elliptical)
	18.59 ± 0.03	Panagia et al. 1997
	18.67 ± 0.08	Lundqvist & Sonneborn 1997
Eclipsing binaries	18.6 ± 0.2	Guinan et al. 1995
HB clump	18.07 ± 0.12	Udalski 1998
	18.31 ± 0.12	revised by Girardi et al. 1998
	18.43 ± 0.12	E(B−V)=0.10
HB trig. parallax	18.37 ± 0.10	Gratton 1998
	18.42 ± 0.12	eliminating HD17072
Stat. parallax	18.29 ± 0.12	Layden et al. 1996
	18.26 ± 0.15	Fernley et al. 1998a
Baade-Wesselink	18.26 ± 0.04	Clementini et al. 1995
	18.34 ± 0.04	Clementini et al. 1995 (p=1.38)
	18.53 ± 0.05	McNamara 1997
GC Dynamical models	18.44 ± 0.11	Rees 1996, revised by Chaboyer

Another Test: Nuclear Masers in NGC 4258





Herrnstein *et al.* (1999) have analyzed the proper motions and radial velocities of NGC 4258's nuclear masers. The orbits are Keplerian and yield a distance of 7.2 ± 0.3 Mpc, or $(m\text{-}M)_0 = 29.29 \pm 0.09$. This is inconsistent with the Cepheid distance modulus of 29.44 ± 0.12 at the ~1.2σ level.

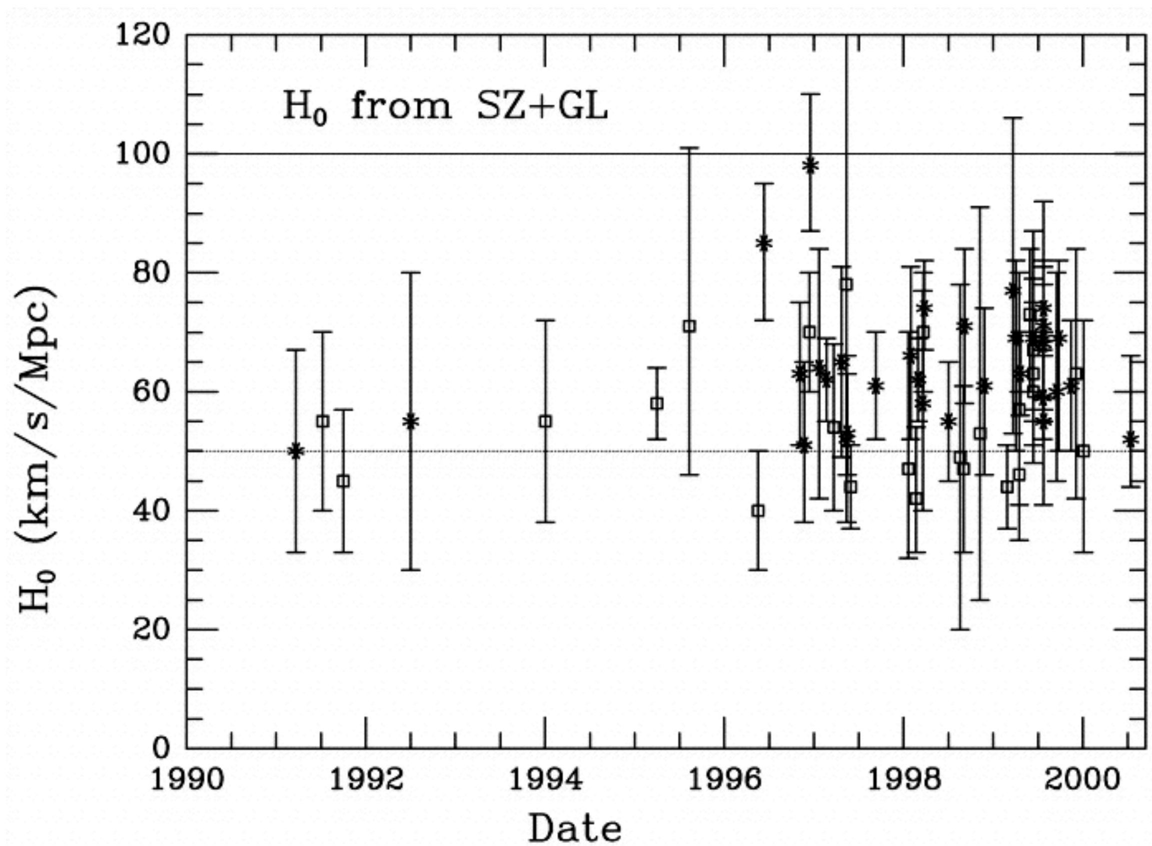
Bypassing the Distance Ladder

There are a two methods which can be used to large distances, which don't depend on local calibrations:

1. **Gravitational lens time delays**
2. **Synyaev-Zeldovich (SZ) effect for clusters of galaxies**

Both are very ***model-dependent!***

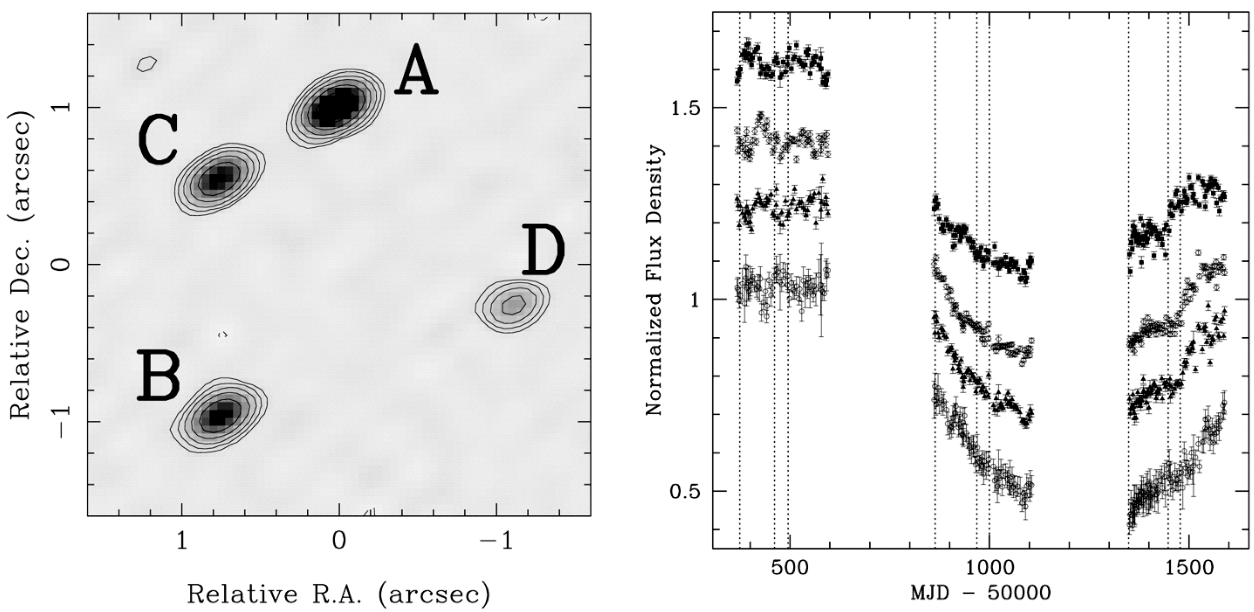
Both tend to produce values of H_0 that are somewhat lower than the Key Project, but within the errors, and possibly explained by systematic effects



Gravitational Lens Time Delays

- Assuming the mass model for the lensing galaxy of a gravitationally lensed quasar is well-known (!?), the different light paths taken by various images of the quasar will lead to time delays in the arrival time of the light to us. This be can be traced by the quasar variability
- If the lensing galaxy is in a cluster, we also need to know the mass distribution of the cluster and any other mass distribution along the line of sight. The modeling is complex!

Images and lightcurves for the lens B1608+656 (from Fassnacht *et al.* 2000)

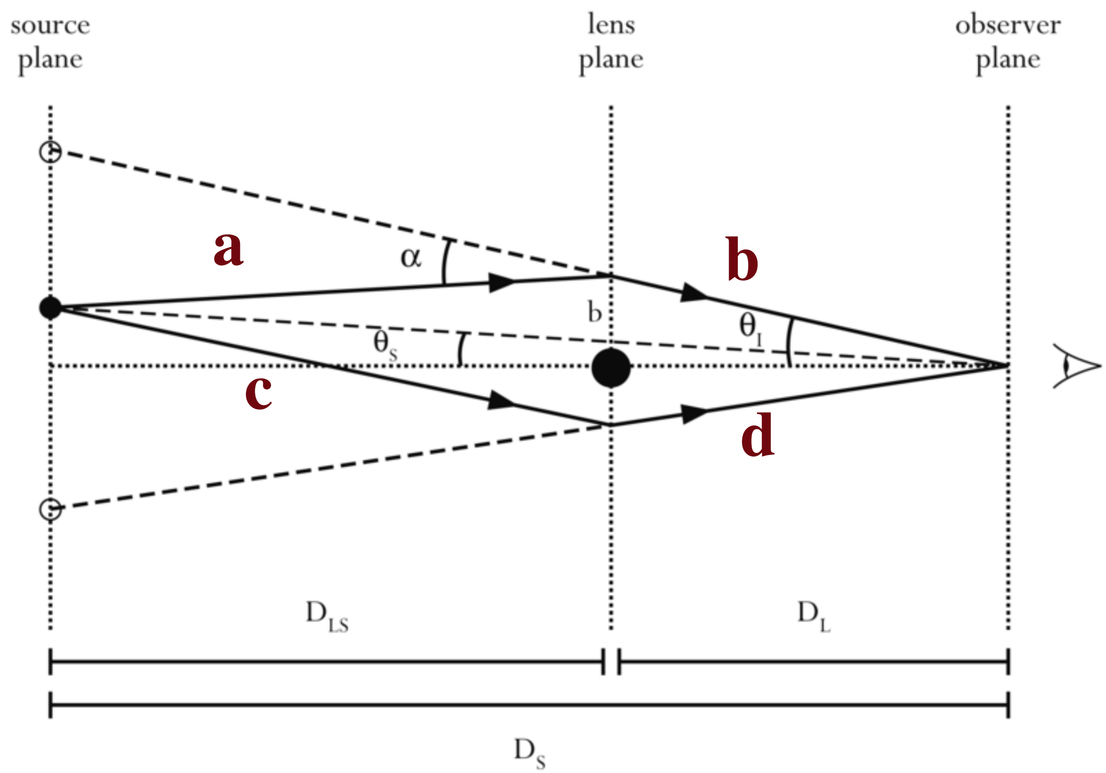


How Does It Work?

Apparent source position 1

Actual source position

Apparent source position 2

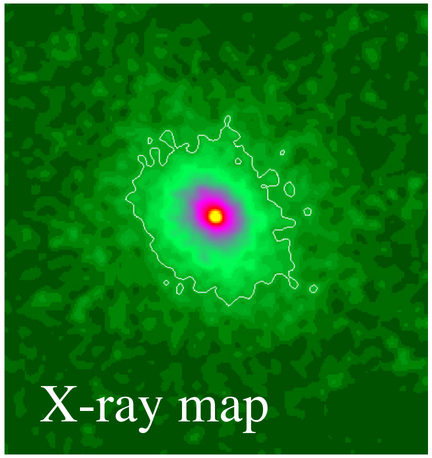


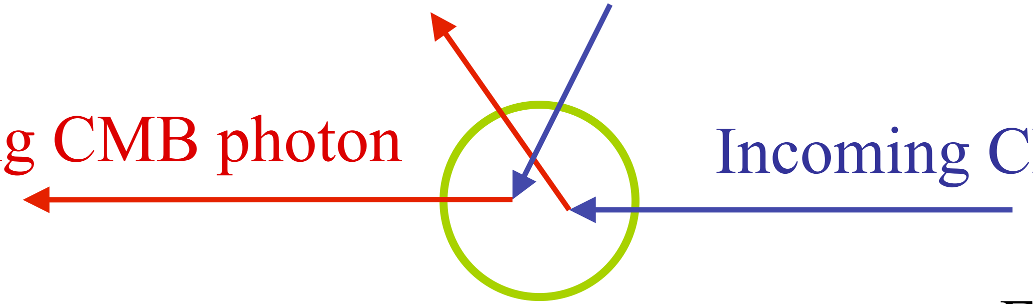
The difference in the light paths is (a+b) – (c+d) = ΔS = c Δt
where Δt is the measured time delay

For a fixed lensing geometry, $\Delta S \sim D_L$ or D_S
and the ratio $\Delta S/D_L$ or $\Delta S/D_S$ is also given by the geometry
Assuming that, measuring Δt gives ΔS, and thus D_L or D_S

Synyaev-Zeldovich Effect

- Clusters of galaxies are filled with hot X-ray gas
- The electrons in the intracluster gas will scatter the background photons from the CMBR to higher energies (frequencies) and distort the blackbody spectrum





Outgoing CMB photon

Incoming CMB photon

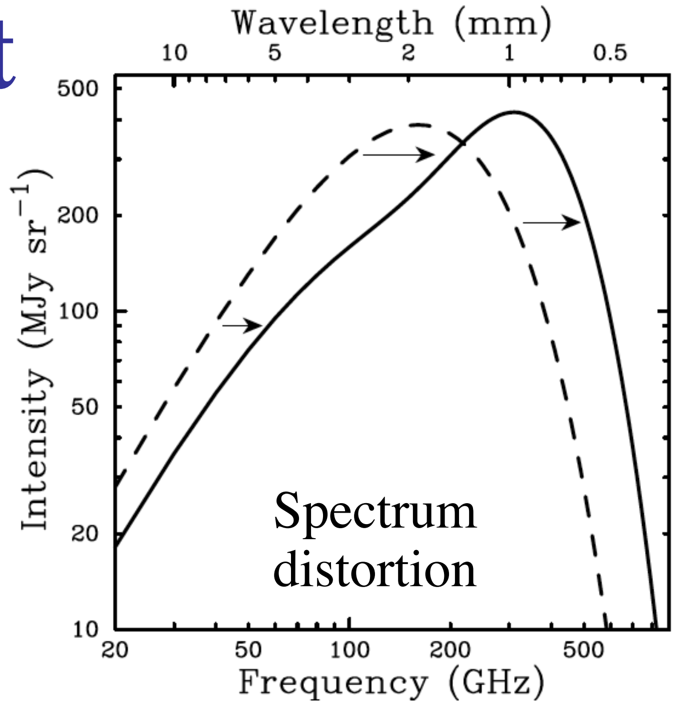
Galaxy Cluster with hot gas

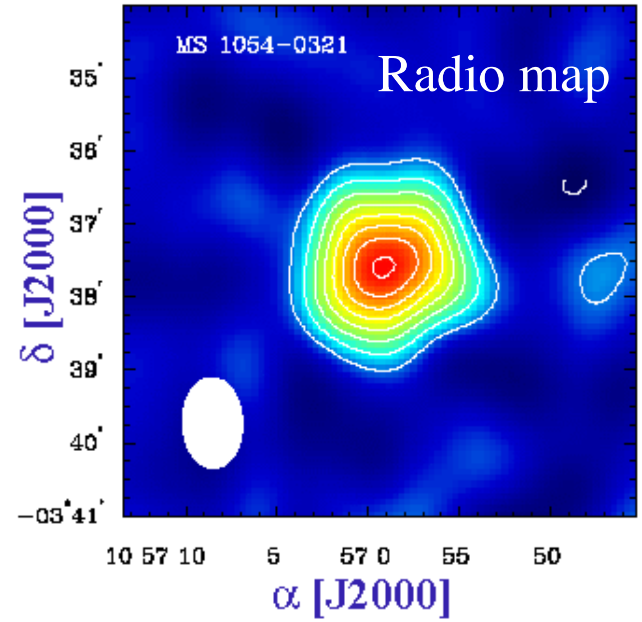
This is detectable as a slight temperature dip or bump (depending on the frequency) in the radio map of the cluster, against the uniform CMBR background

For every photon scattered away from the observer, there is another scattered towards.

Synyaev-Zeldovich Effect

- If we can measure the electron density and temperature of the X-ray emitting gas along the line of sight from X-ray measurements, we can estimate the path length (~ cluster diameter) along the line of sight
- If we assume the cluster is spherical (??), from its angular diameter (projected on the sky) we can determine the distance to the cluster
- Potential uncertainties include cluster substructure or shape (e.g., non-spherical). It is also non-trivial to measure the X-ray temperature to derive the density at high redshifts.





Next:
Estimating the Age of the Universe