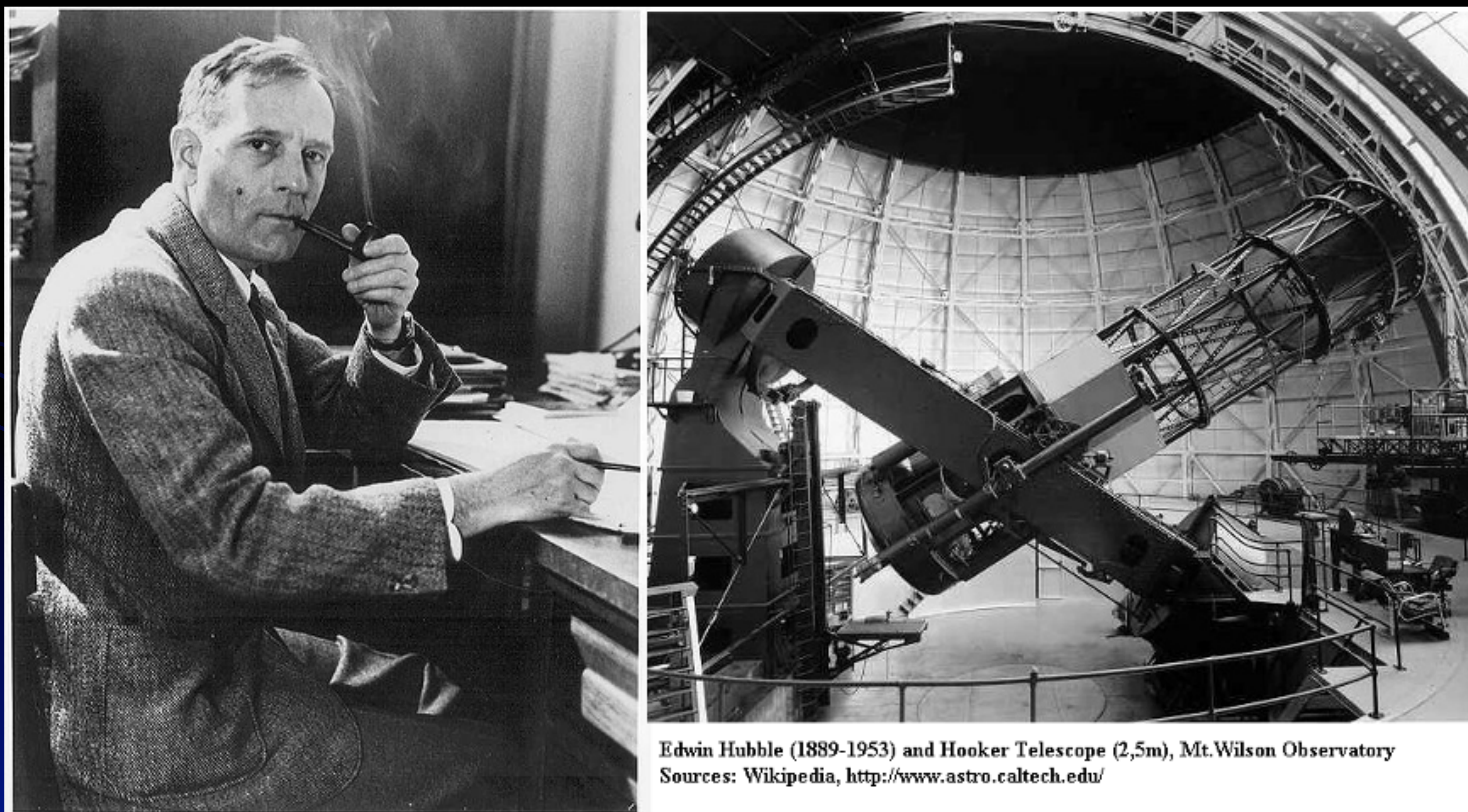
The Distance to M31

Krzysztof (Kris) Stanek
The Ohio State University

Quote of the Talk:

"The history of astronomy is a history of receding horizons." **Edwin Powell Hubble (1889 - 1953)**



Edwin Hubble (1889-1953) and Hooker Telescope (2,5m), Mt.Wilson Observatory
Sources: Wikipedia, http://www.astro.caltech.edu/

Outline

- Why do we care about measuring distances;
- A brief history of the distance to M31;
- Different ways that we measure the distance to M31;
- Future improvements?

Why Do We Measure Distances

- Obvious reason #1: distances;
- Obvious reason #2: luminosities;
- Obvious reason #3: Hubble Constant;
- Other reasons;

Measuring Distances in the Universe: the Master Plan

- Use **geometry** when possible;
- Start with measuring the size of **Earth**;
- Measure the size of the **Solar System**;
- Measure distances to **nearby stars**;
- Measure the size of **our Galaxy**;
- Measure distances to **nearby galaxies**;
- Measure distances to **galaxies in the Hubble flow**;
- Measure the size of the **Universe**.

This procedure is called a "**cosmological distance ladder.**"

Cosmological Distance Ladder

Plan

Reality

The Distance to M31: History

Astrophysical Journal, 55, 406-410 (1922)

AN ESTIMATE OF THE DISTANCE OF THE ANDROMEDA NEBULA

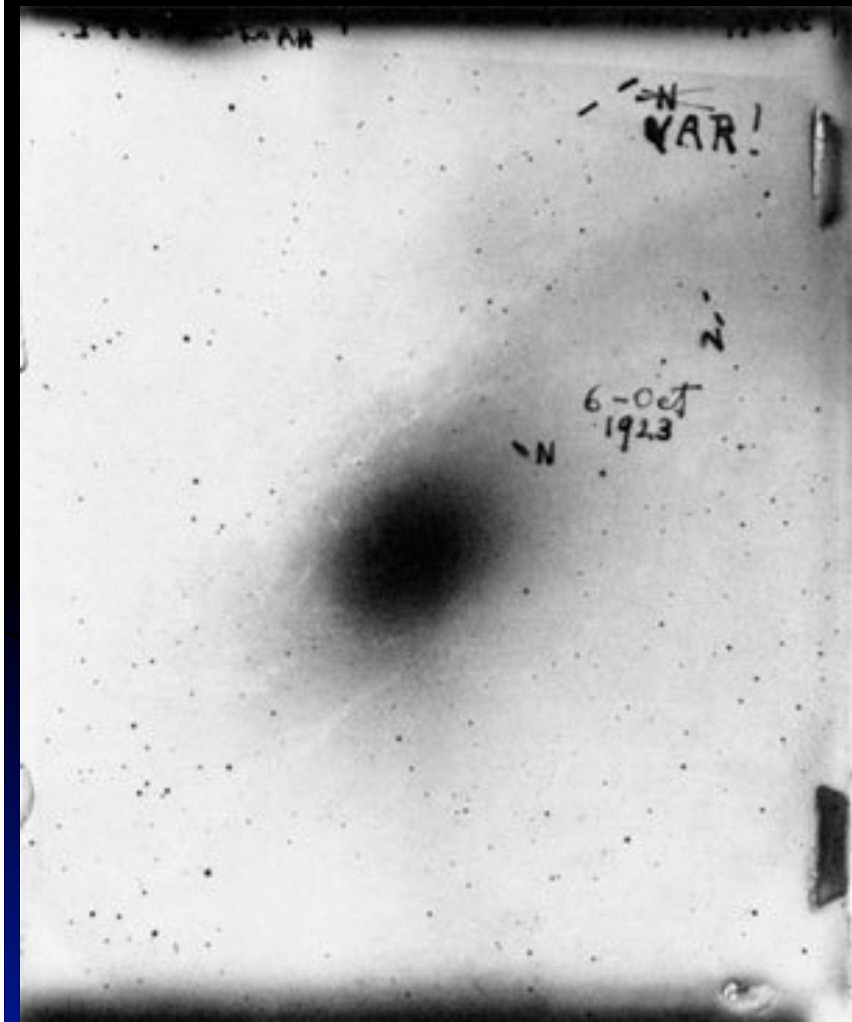
By E. OEPIK

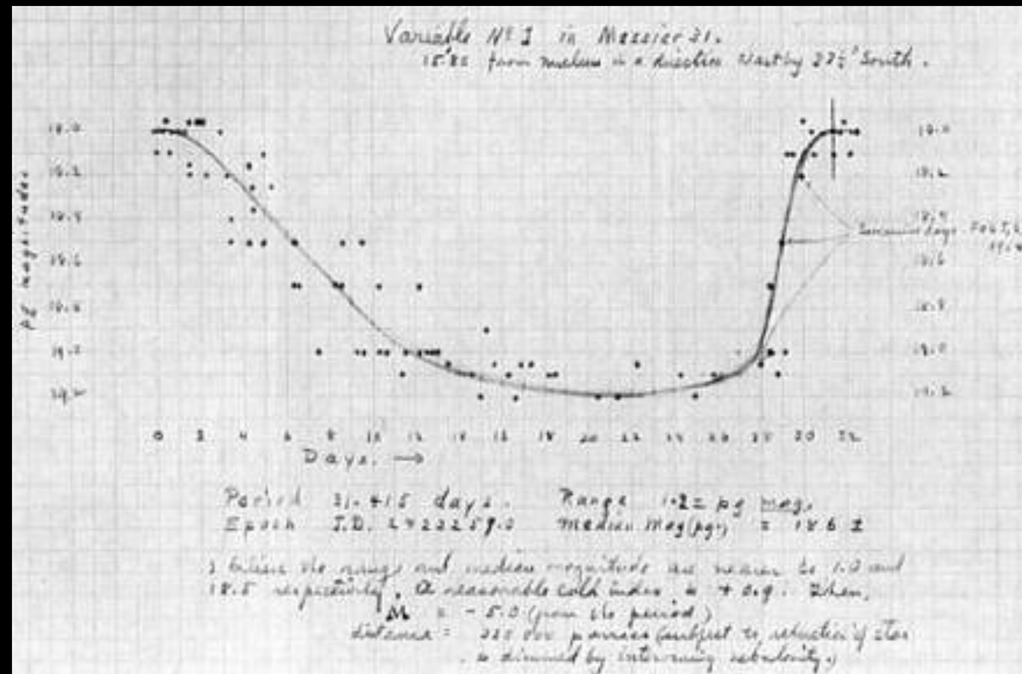
ABSTRACT

Andromeda Nebula.—Assuming the centripetal acceleration at a distance r from the center is equal to the gravitational acceleration due to the mass inside the sphere of radius r, an expression is derived for the *absolute distance* in terms of the linear speed v_o at an angular distance ρ from the center, the apparent luminosity i, and E, the energy radiated per unit mass. From observations, v_o comes out 157 km/sec. for $\rho = 150''$; and giving i a value corresponding to magnitude 6.1, and assuming E the same as for our Galaxy, the distance is computed to be 450,000 parsecs. This result is in agreement with that obtained by several independent methods. If it is correct, the *mass* within 150″ of the center is about 4.5×10^9 times the sun's mass, and the nebula is a stellar universe comparable with our Galaxy. *The ratio of the axes of the central ellipsoid*, whose shape is supposed to be due to rotation, was determined from photographs to be about 0.79.

Various estimates of the distance of the Andromeda Nebula have been made hitherto by H. Shapley,[1] H. D. Curtis,[2] K. Lundmark,[3] Luplau-Janssen and Haarh[4] and others; these estimates, based on the hypothesis that the Nebula consists of stellar matter similar to the matter of our Galaxy, lead to a distance of about 10^5 to 10^6 parsecs. Here we shall propose a method based on observed rotational movement, a method which may be applied to any nebula or cosmic system provided sufficient data are available. The principle is the same as that used by Campbell and Moore[5]

The Distance to M31: History





Hubble (1923?)

A SPIRAL NEBULA AS A STELLAR SYSTEM, MESSIER 31[1]

By EDWIN HUBBLE (1929)

Distance of M 31 derived from Cepheid criteria.—Comparisons of period-luminosity diagrams indicate that M 31 is about 0.1 mag. or 5 per cent more distant than M 33, and about 8.5 times more distant than the Small Magellanic Cloud. Using Shapley's value for the Cloud, we find the *distance of M 31* to be *275,000 parsecs.*

The accuracy of the relative distances is very satisfactory. In the case of the two spirals, the probable error is of the order of 2.5 per cent; for the spirals and the Cloud, it is of the order of 5 per cent. The accuracy of the distances in parsecs or light-years, however, depends largely upon the accuracy of the zero point of the period-luminosity curve. Accumulating evidence indicates that Shapley's value is certainly of the right general order of magnitude, but there still remains the possibility of a considerable correction when more data on galactic Cepheids become available.

of M 31 by adding 4.65 to those in the Small Magellanic Cloud, 0.1 to those in M 33, and 0.55 to those in N.G.C. 6822. The absolute photographic magnitudes at the top of the diagram are based upon Shapley's zero point ($m-M=17.55$ for the Small Magellanic Cloud).

M31 Strikes Again

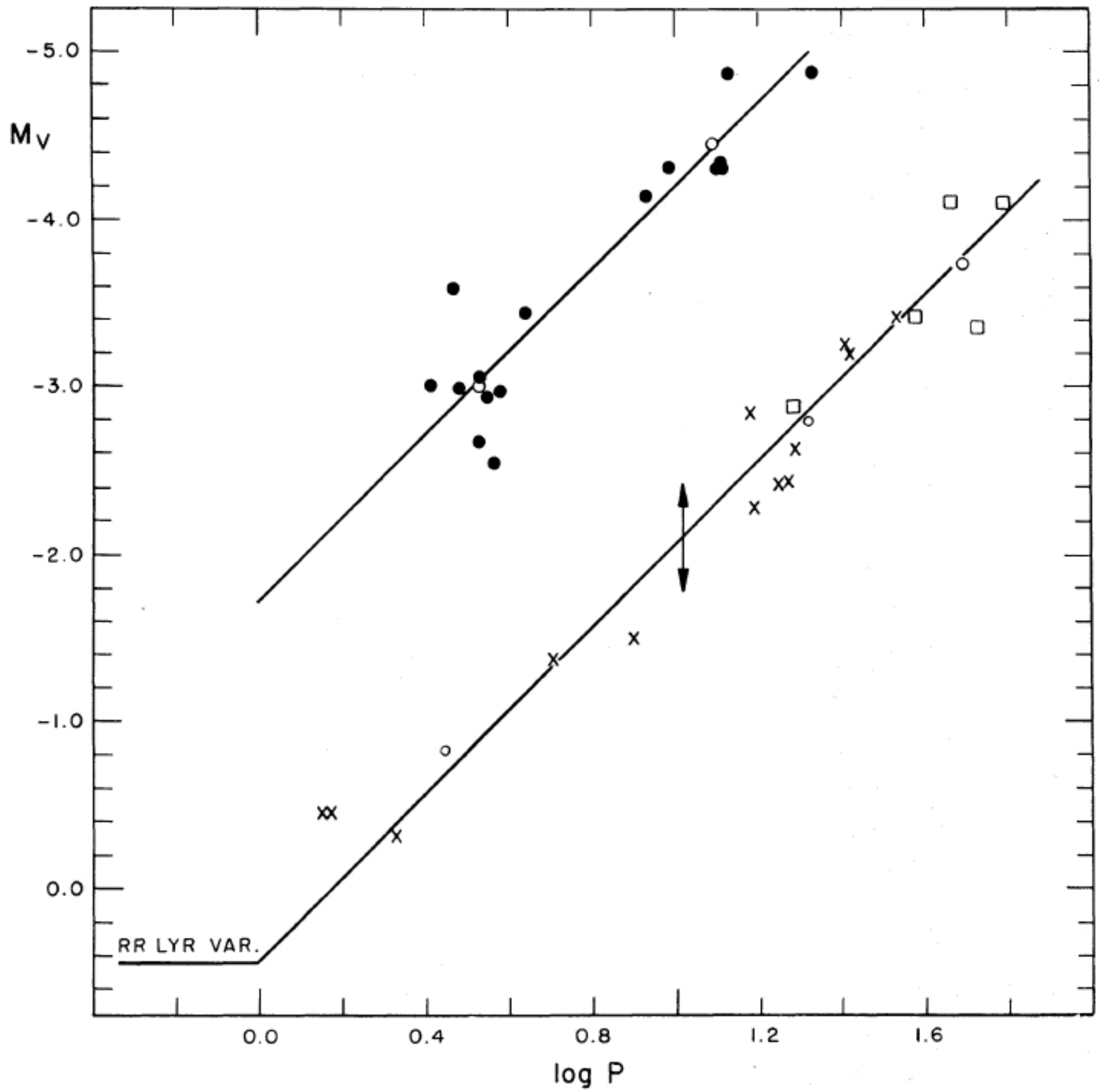
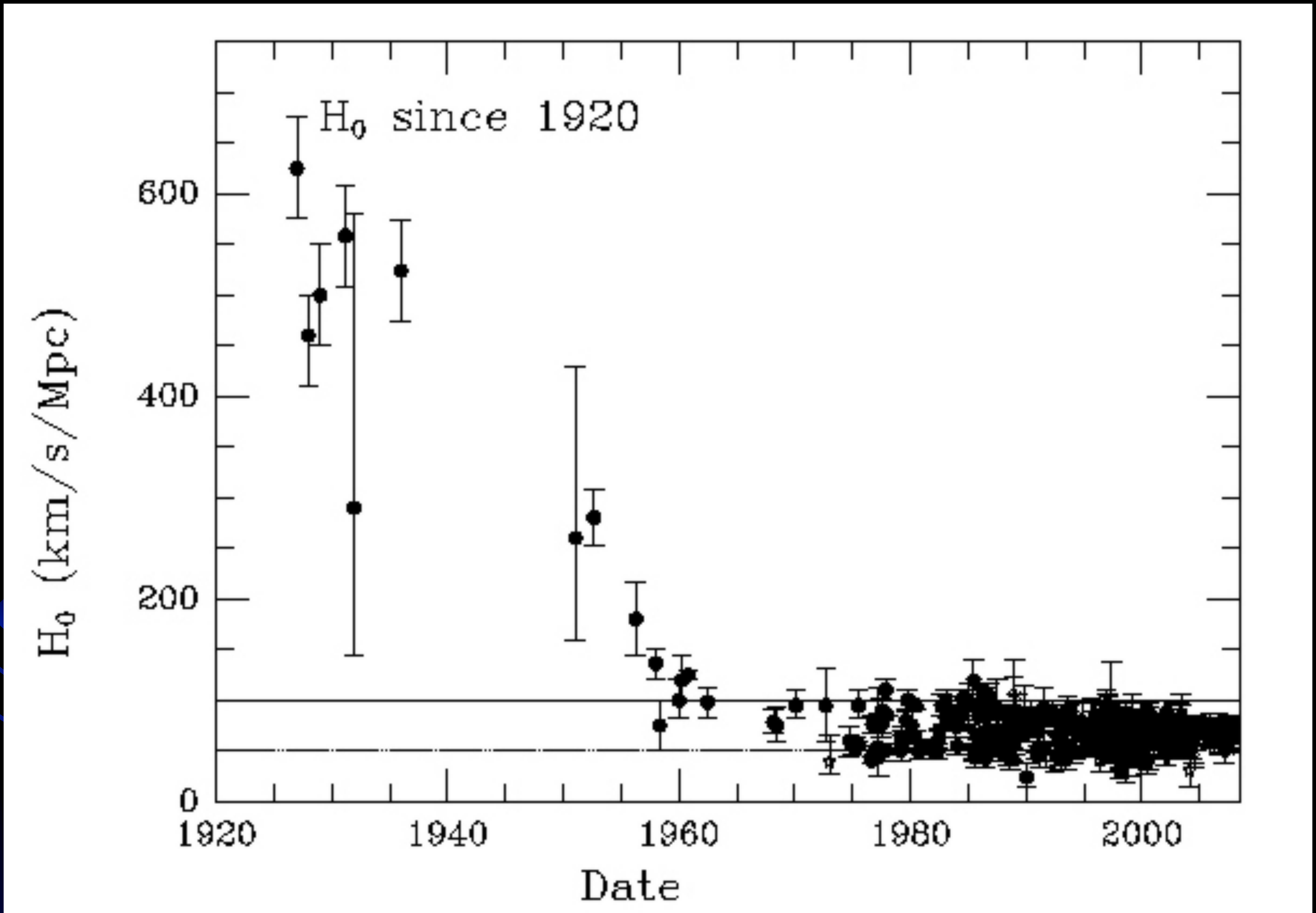


FIG. 15. Period–luminosity relation. Dots and open squares, Cepheids and Population II variables in M31, respectively; crosses, variables with $P>1$ day in Milky Way globular clusters; small open circles are mean values. Coordinates are visual absolute magnitude M_V and $\log P$. Upper line is $M_V = -1.70 - 2.50 \log P$; lower line is $M_V = +0.45 - 2.50 \log P$.

History of Hubble's Constant



Compilation by J. Huchra

The Distance to M31 With:

- Red clump;
- TRGB;
- Cepheids;
- Eclipsing binaries;

Red Clump

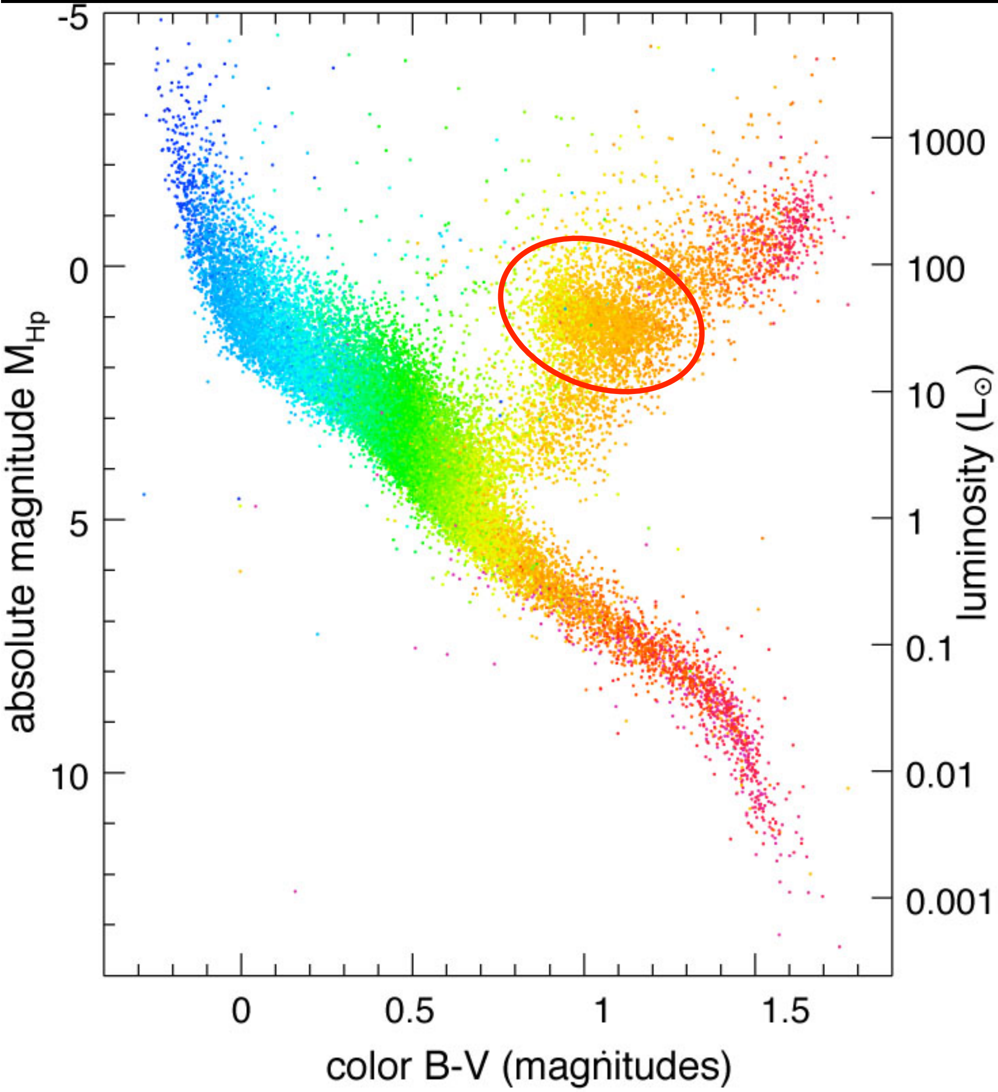
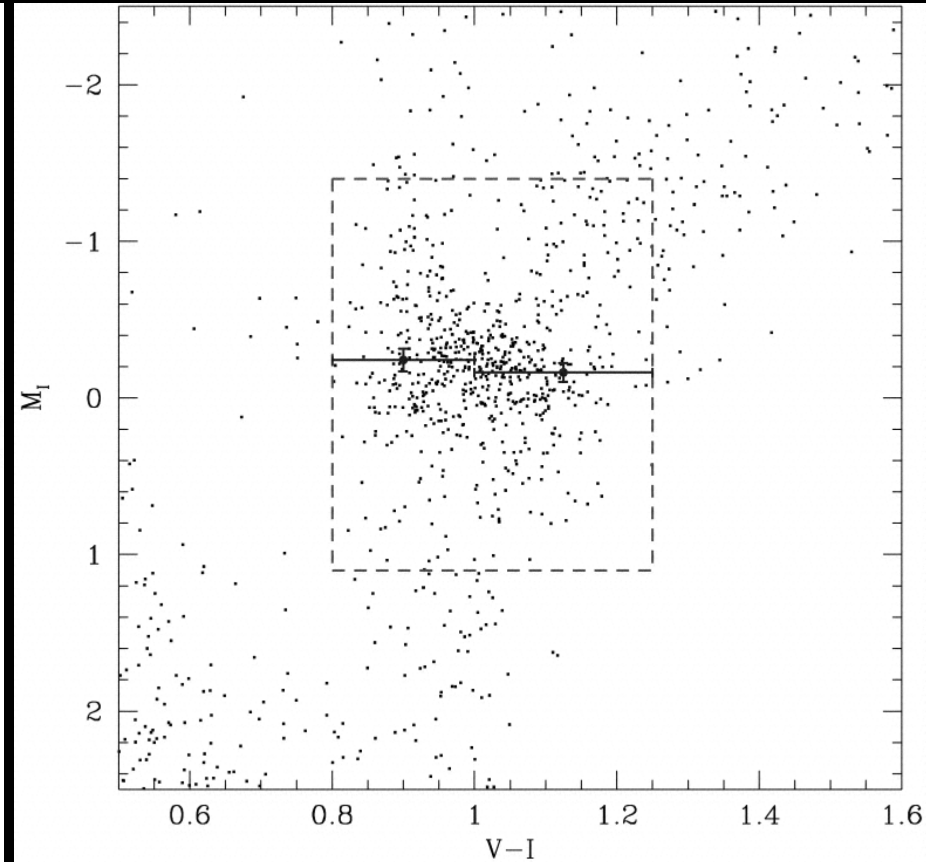
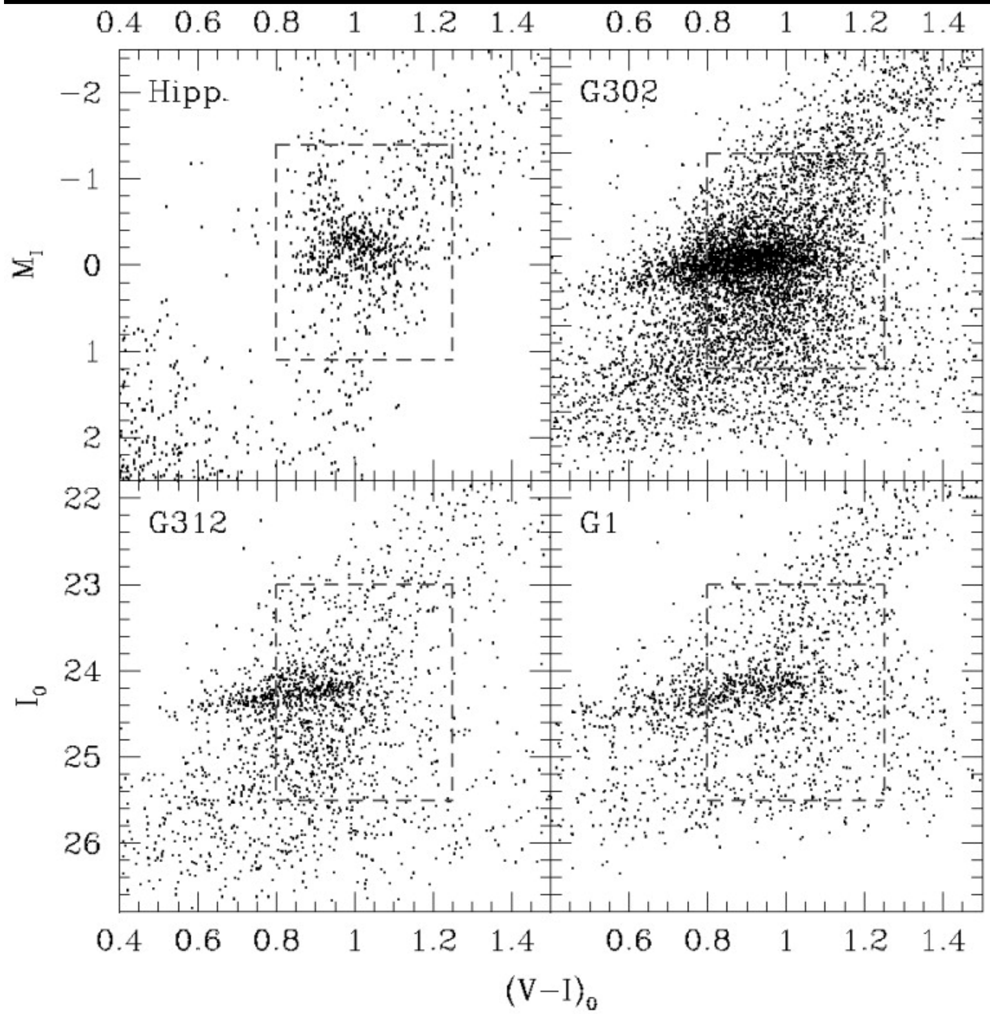


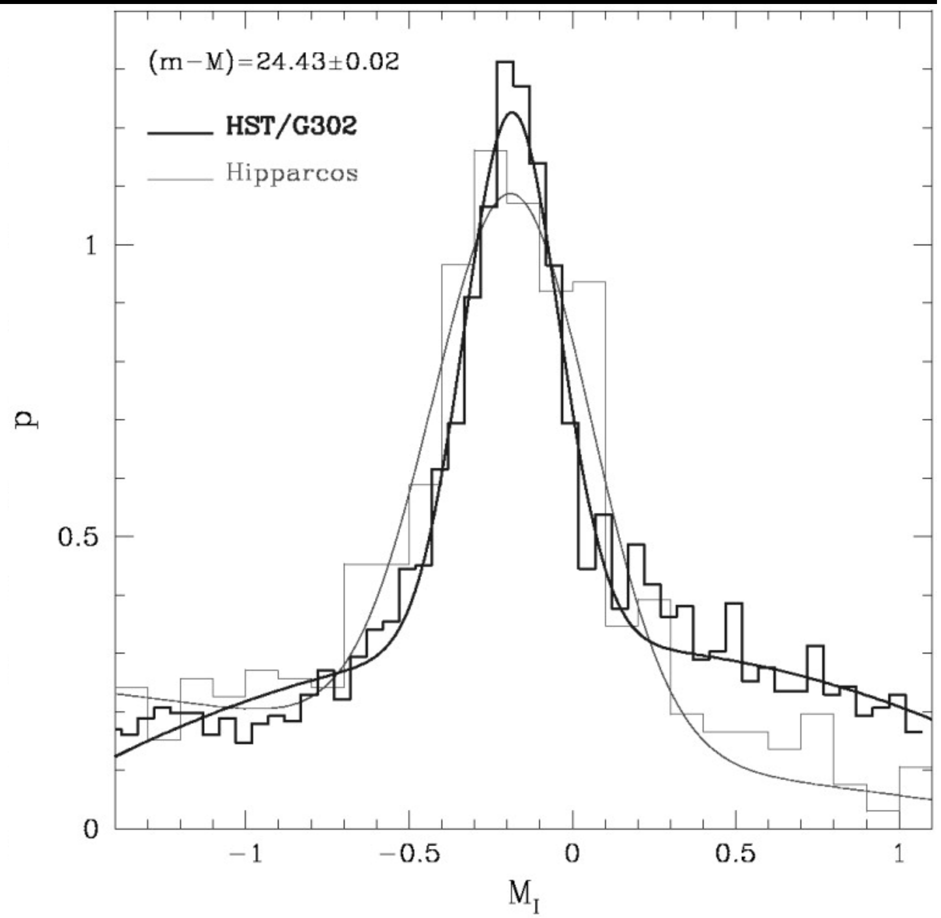
Fig 2.2 (F. van Leeuwen) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007



Paczynski & Stanek (1998)

Red Clump



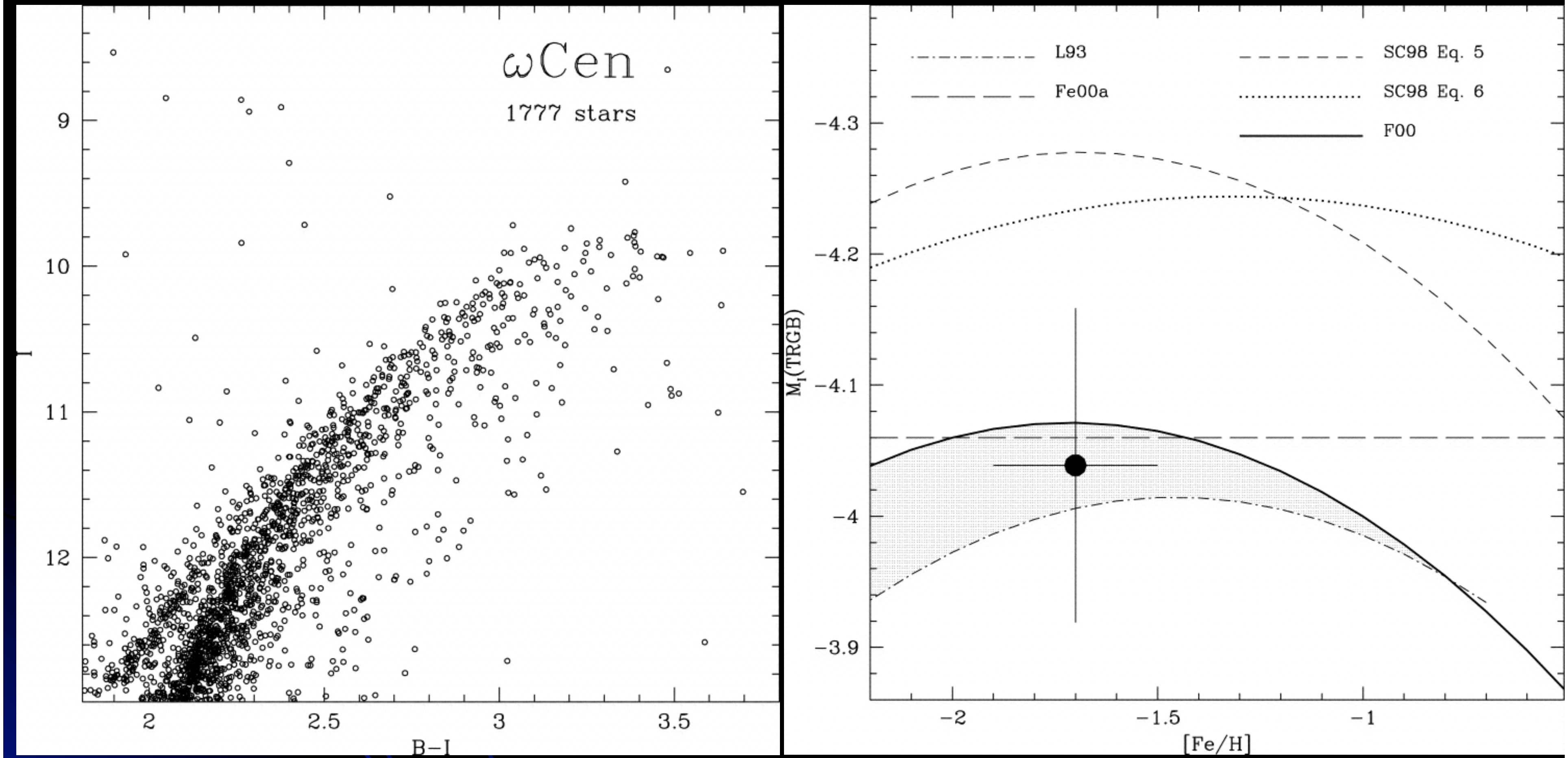


Stanek & Garnavich (1998)

m-M=24.47 ± 0.035 ± 0.045 mag

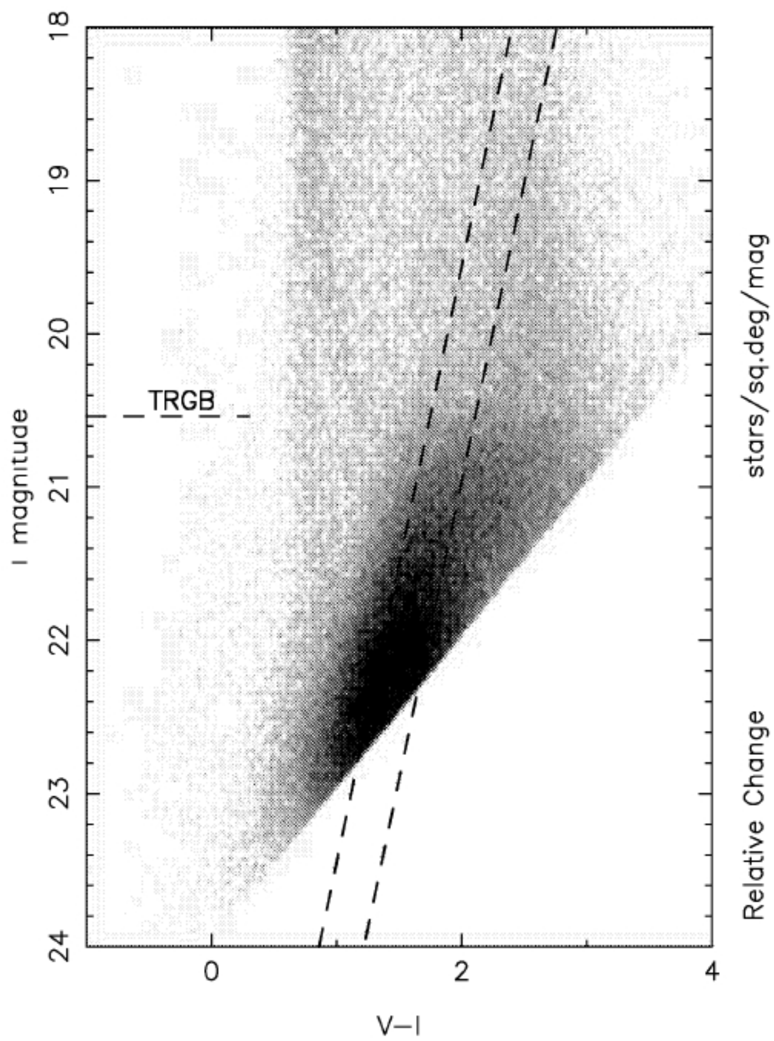
R=784 ± 13 ± 17 kpc

Tip of the Red Giant Branch



Bellazzini et al. (2001)

Tip of the Red Giant Branch



McConnachie et al. (2005)

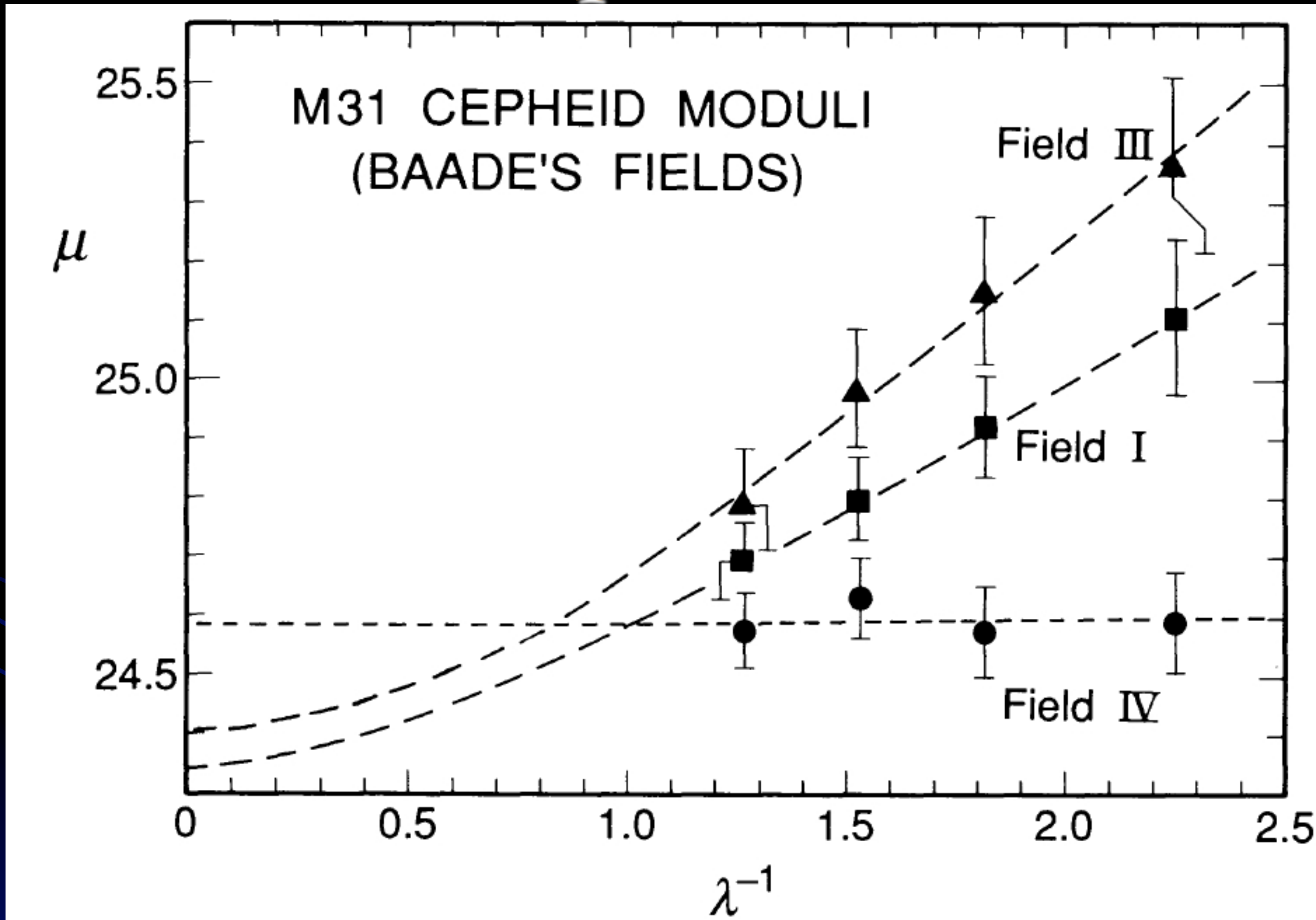
M31:

$$I_{\rm TRGB} = 20.54 \pm 0.03\,{\rm mag}$$
$$E(B-V) = 0.06\,{\rm mag}$$
$$[{\rm M/H}]_{\alpha=0.0} = -0.6$$
$$[{\rm M/H}]_{\alpha=0.3} = -0.5$$
$$M_I^{\rm TRGB} = -4.05\,{\rm mag}$$
$$(m-M)_{\rm o} = 24.47 \pm 0.07\,{\rm mag}$$
$$D_{\rm M31} = 785 \pm 25\,{\rm kpc}$$

M31 error budget:

Photometry – rms	:	±0.03 mag
– zero-point	:	±0.02 mag
Reddening	:	±0.02 mag
$M_I^{\rm TRGB}$	:	±0.05 mag
Algorithm	:	±0.03 mag
Total	:	±0.07 mag

Cepheids



Freedman & Madore (1990)

Cepheids

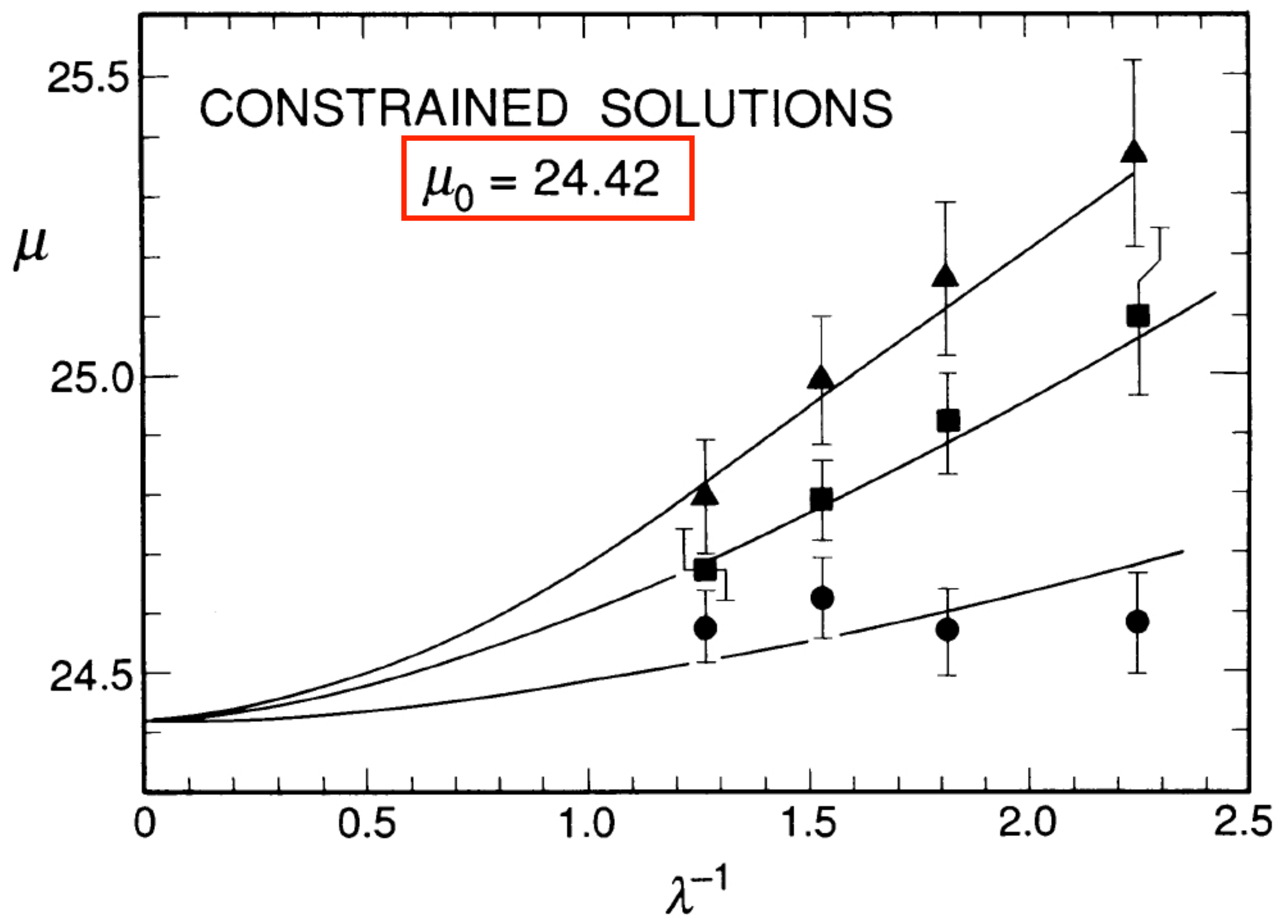


FIG. 5.—The same as Fig. 4 except that the multi-wavelength fitting solutions given here have all been constrained to pass through the average true distance modulus of 24.42 mag.

Freedman & Madore (1990)

Cepheids

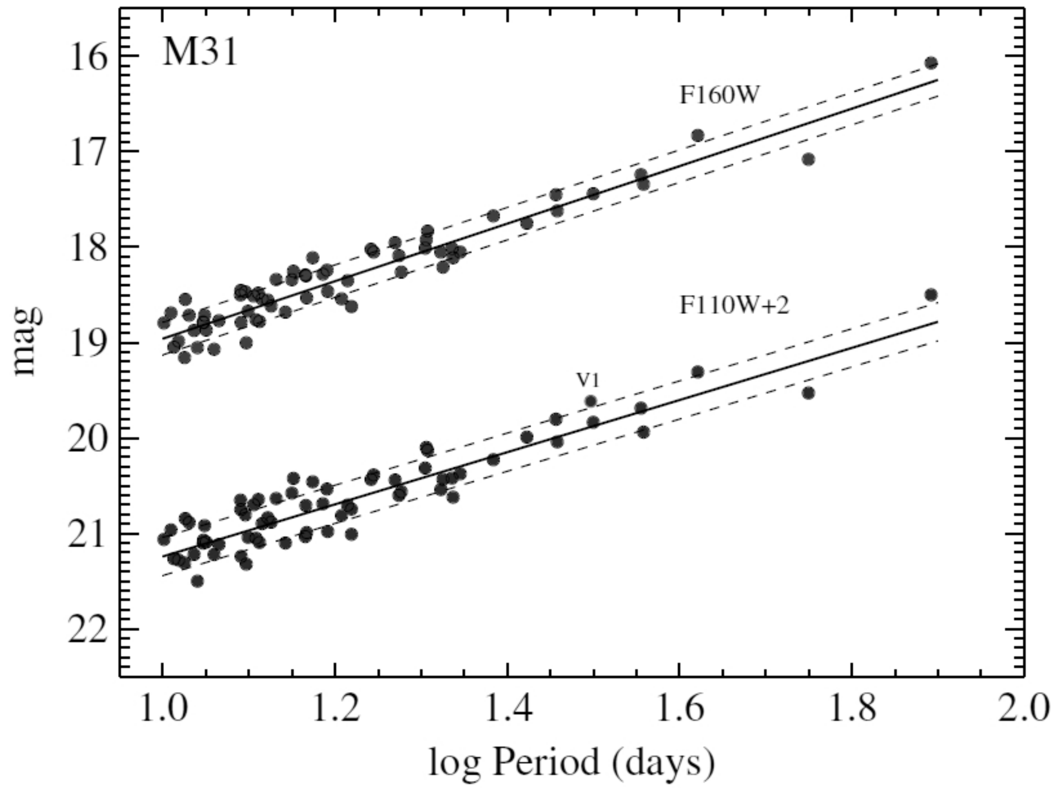


Figure 2. Near-IR *P*–*L* relations for 69 Cepheids in M31 with log $P > 1$ (Table 1). The single slope fitted to the relations is given in Table 2 and is shown as the solid lines. Dashed lines indicate the average dispersion of 0.17 mag ($F160W$), a factor 3.5 smaller than previous ground-based optical *P*–*L* relations, and 0.20 mag ($F110W$).

Riess et al. (2012)

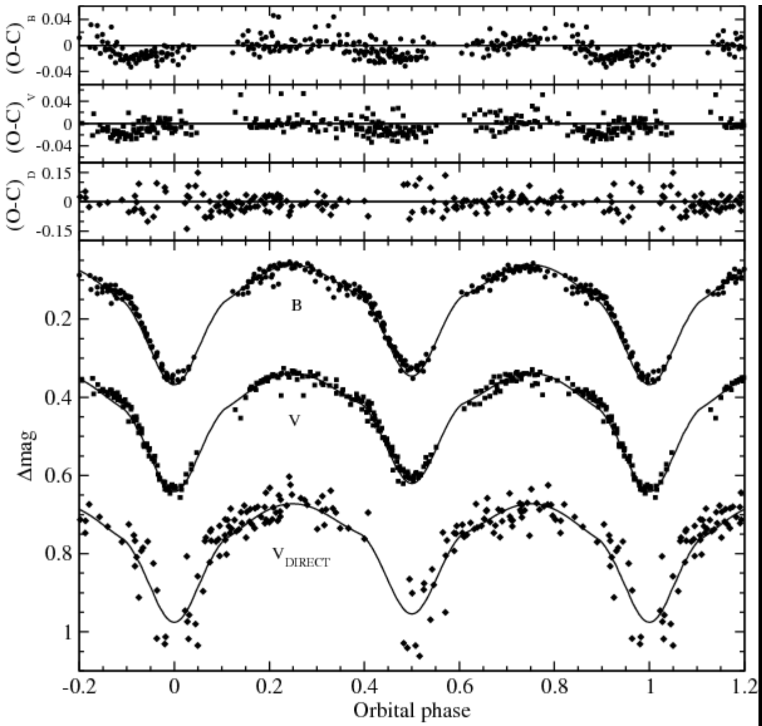
$\mu_0 = 24.38 \pm 0.06$(statistical) $\pm\ 0.03$(systematic), 752 ± 27 kpc

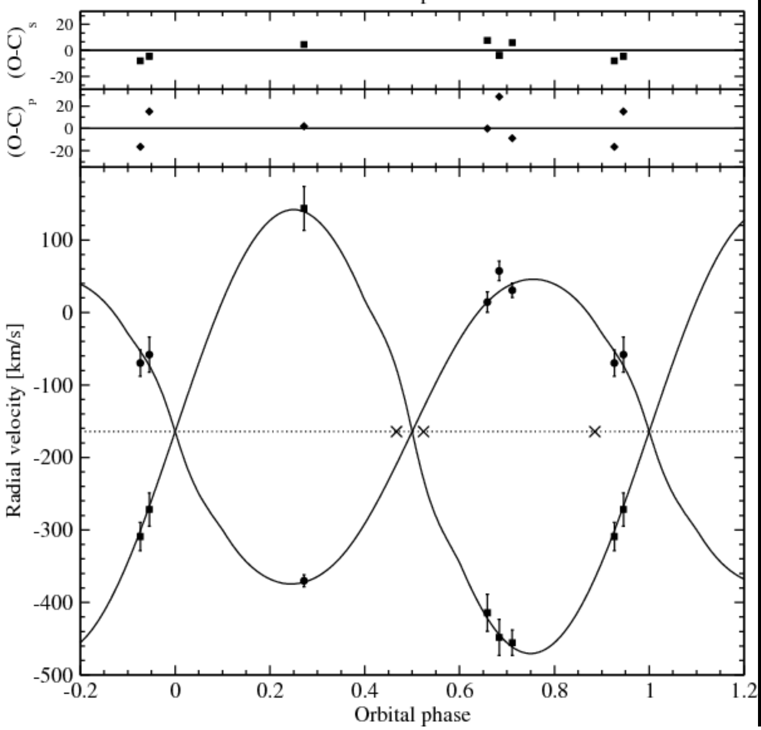
a ($R_\odot$)	33.0 ± 0.7	
$q \equiv M_2/M_1$	0.65 ± 0.03	
$T_{\rm eff2}/T_{\rm eff1}$	0.817 ± 0.015	
$F_2/F_1\|_B$ [a]	0.487 ± 0.023	
$F_2/F_1\|_V$ [a]	0.501 ± 0.022	
	Primary	**Secondary**
K [b] (km s^{-1})	185 ± 6	285 ± 6
$r_v \equiv R/a$	0.397 ± 0.005	0.342 ± 0.005
M ($M_\odot$)	23.1 ± 1.3	15.0 ± 1.1
R ($R_\odot$)	13.1 ± 0.3	11.3 ± 0.3
log g (cgs)	3.57 ± 0.03	3.51 ± 0.04
$T_{\rm eff}$ (K)	33,900 ± 500	27,700 ± 500
$v \sin i$ (km s^{-1})	230 ± 10	145 ± 8
M_V (mag)	−5.29 ± 0.07	−4.66 ± 0.07
$(B - V)_0$	−0.28 ± 0.01	−0.27 ± 0.01
	System	
B [a] (mag)	19.19 ± 0.02	
V [a] (mag)	19.27 ± 0.02	
[m/H]	−0.01 ± 0.06	
$E(B - V)$ (mag)	0.19 ± 0.03	
A_V (mag)	0.60 ± 0.10	
M_V (mag)	−5.77 ± 0.06	
$(m - M)_0$ (mag)	24.44 ± 0.12	

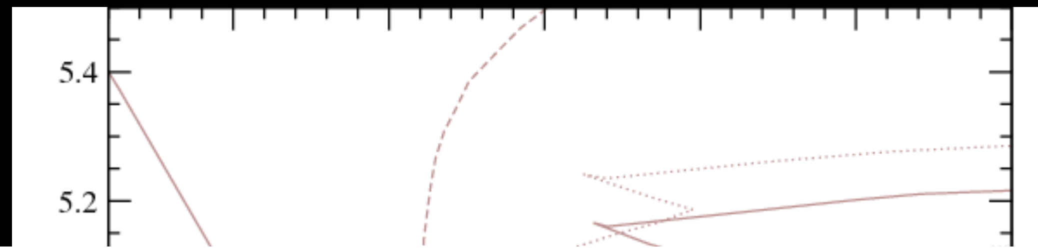
[a] Out-of-eclipse average: $\Delta\phi = [0.14 - 0.36] + [0.64 - 0.86]$.

[b] Including non-Keplerian corrections.

Eclipsing Binaries



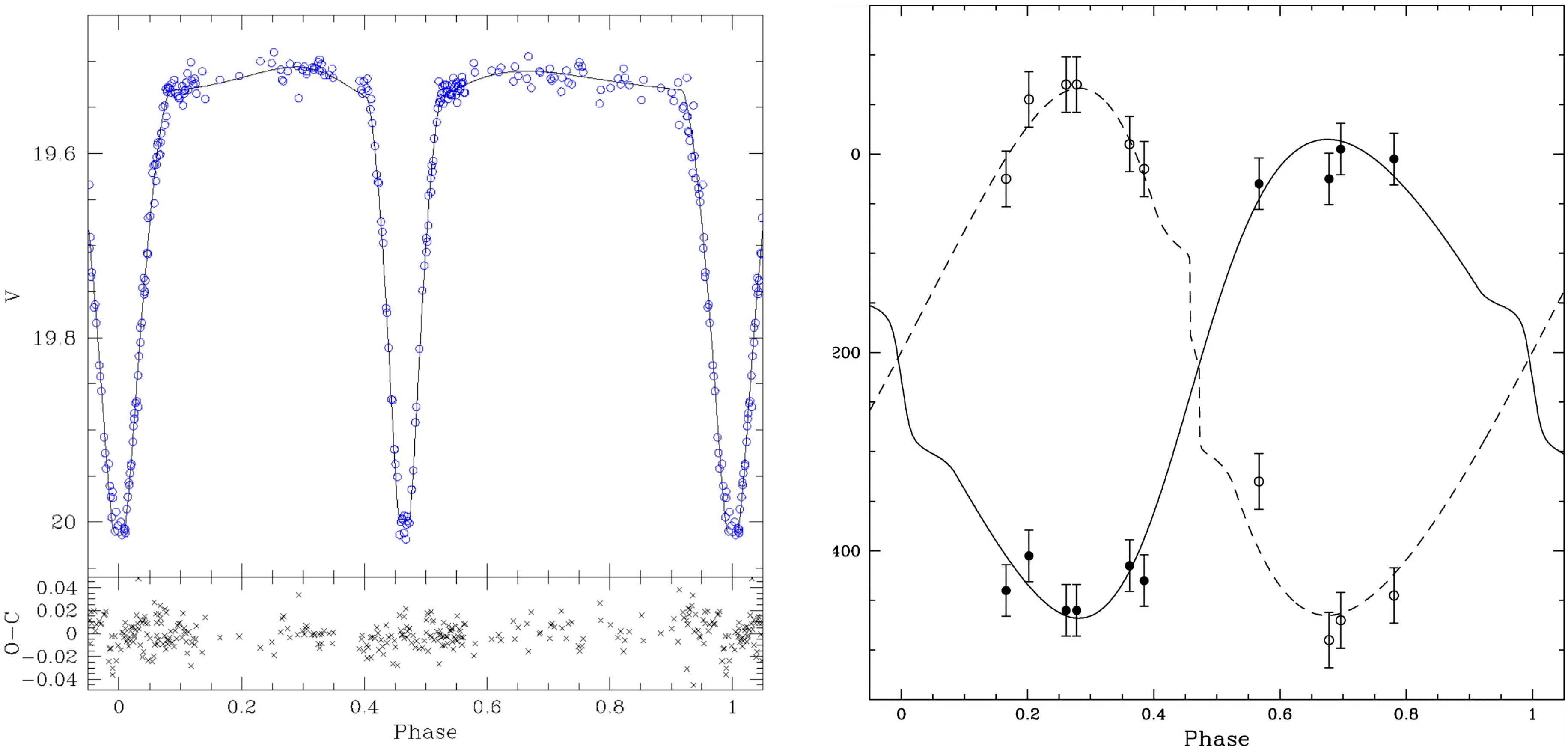




System properties		
M_V (mag)	-4.90 ± 0.08	
$E(B-V)$ (mag)	0.18 ± 0.02	
A_V (mag)	0.55 ± 0.08	
$(m-M)_0$ (mag)	24.30 ± 0.11	
Component properties	**Primary**	**Secondary**
$T_{\rm eff}$ (K)	$33\,600 \pm 600$	$30\,100 \pm 900$
$\log g$ (cgs)	3.86 ± 0.12	...
$v_{\rm rot} \sin i$ (km s^{-1})	189 ± 12	...
M_V (mag)	-4.59 ± 0.07	-3.38 ± 0.12
$(B-V)_0$ (mag)	-0.295 ± 0.002	-0.286 ± 0.004

Villardelli et al. (2010)

Eclipsing Binaries: M33



Bonanos, Stanek et al. (2006)

Eclipsing Binaries: M33

TABLE 7

Recent Distance Determinations to M33

Study	Method[a]	Distance Modulus	Reddening
This work	DEB	24.92 ± 0.12	$E(B-V) = 0.09 \pm 0.01$
Sarajedini et al. (2006)	RR Lyrae	24.67 ± 0.08	$\sigma_{E(V-I)} = 0.30$
Brunthaler et al. (2005)	Water masers	24.32 ± 0.45	...
Ciardullo et al. (2004)	PNe	$24.86^{+0.07}_{-0.11}$	$E(B-V) = 0.04$
Galleti et al. (2004)	TRGB	24.64 ± 0.15	$E(B-V) = 0.04$
McConnachie et al. (2004)	TRGB	24.50 ± 0.06	$E(B-V) = 0.042$
Tiede et al. (2004)	TRGB	24.69 ± 0.07	$E(B-V) = 0.06 \pm 0.02$
Kim et al. (2002)	TRGB	$24.81 \pm 0.04(r)^{+0.15}_{-0.11}(s)$	$E(B-V) = 0.04$
	RC	$24.80 \pm 0.04(r) \pm 0.05(s)$	$E(B-V) = 0.04$
Lee et al. (2002)	Cepheids	$24.52 \pm 0.14(r) \pm 0.13(s)$	$E(B-V) = 0.20 \pm 0.04$
Freedman et al. (2001)	Cepheids	24.62 ± 0.15	$E(V-I) = 0.27$
Pierce et al. (2000)	LPVs	24.85 ± 0.13	$E(B-V) = 0.10$
Sarajedini et al. (2000)	HB	24.84 ± 0.16	$\langle E(V-I) \rangle = 0.06 \pm 0.02$

[a] DEB: detached eclipsing binary; TRGB: tip of the red giant branch; PNe: planetary nebulae; RC: the red clump; LPVs: long-period variables; HB: horizontal-branch stars.

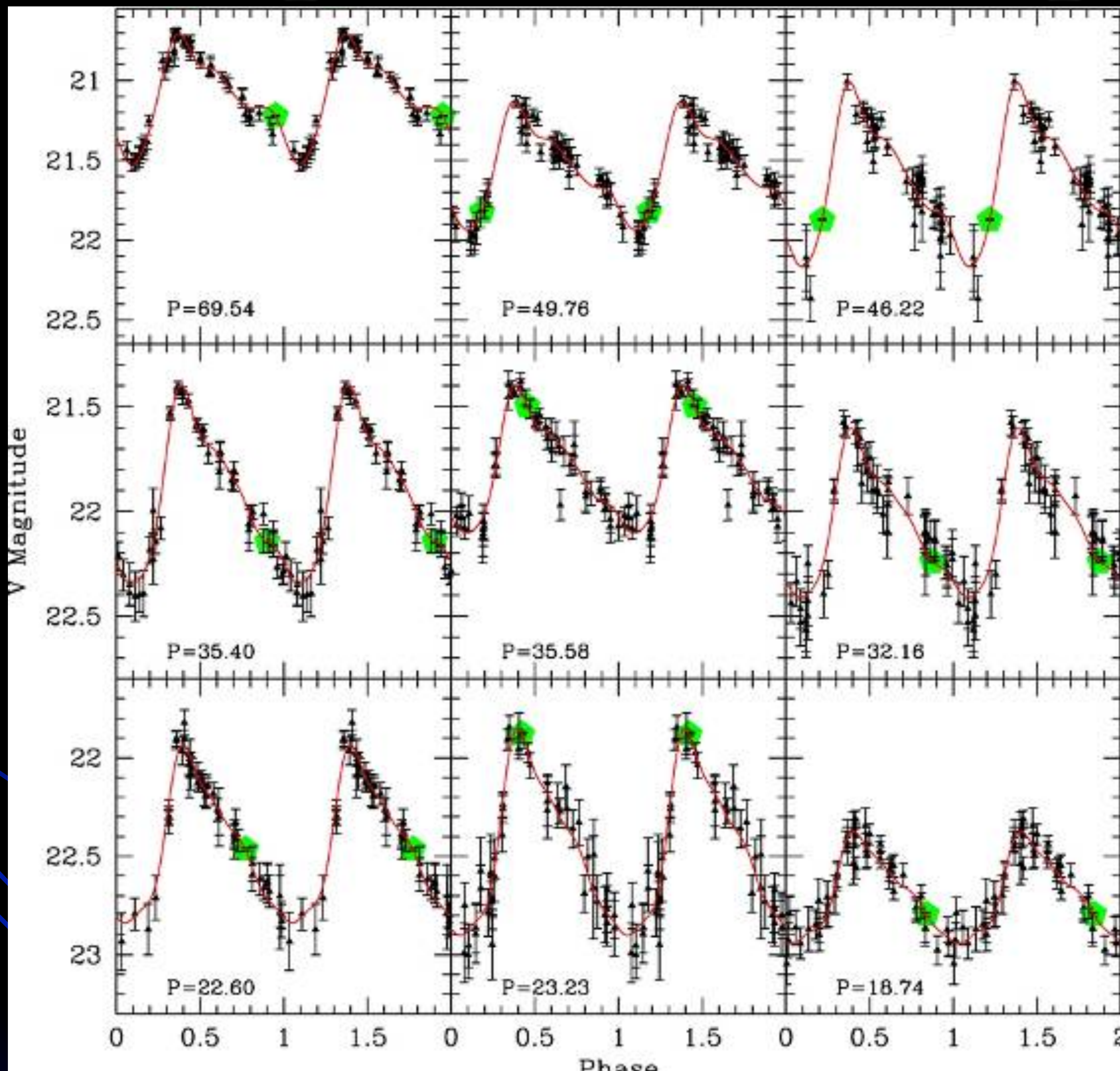
Bonanos, Stanek et al. (2006)

The Distance to M31: Summary

- Red clump: 24.47 ± 0.06
- TRGB: 24.47 ± 0.07
- Cepheids: 24.38 ± 0.07
- Eclipsing binaries: 24.36 ± 0.08

(m-M)_0 = 24.42 ± 0.06
D_M31 = 766 ± 21 kpc

Future Improvements: Cepheids



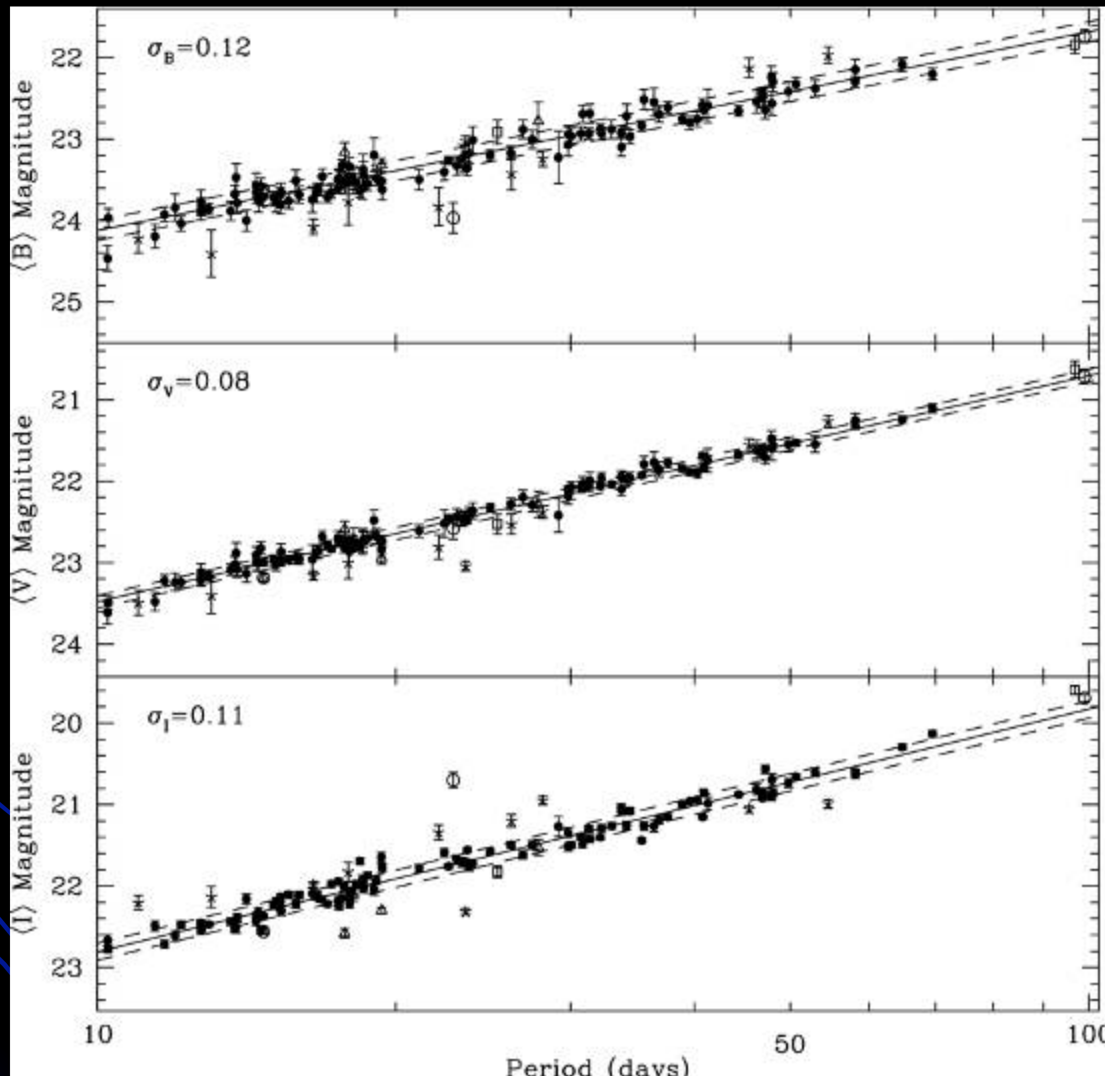
M81:

LBT +

HST

Gerke et al. (2011)

Cepheids: Ground/HST Hybrid



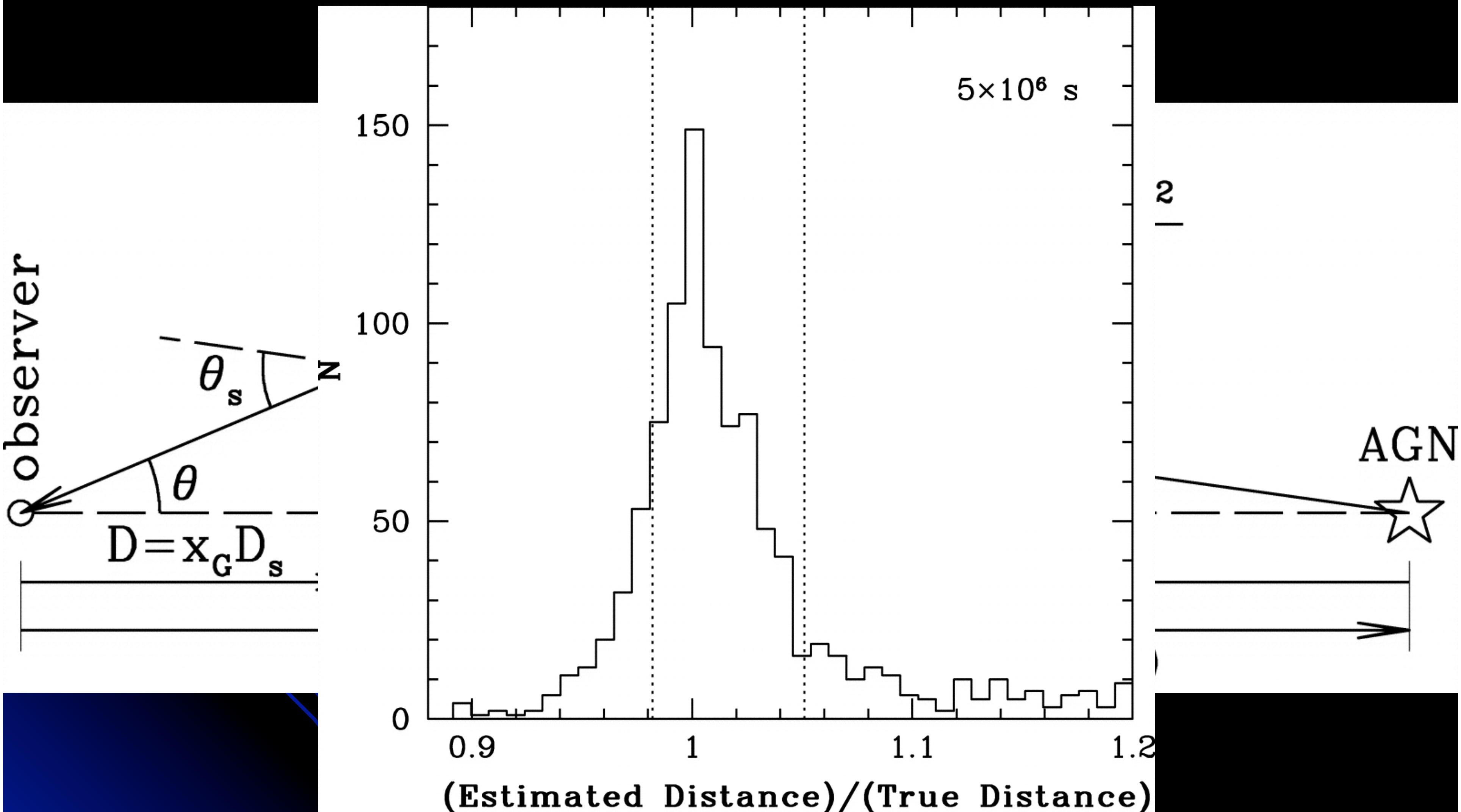
M81:

LBT +

HST

Gerke et al. (2011)

Future Improvements: X-rays?



Draine & Bond (2004)

Future Improvements: Rotational Parallax?

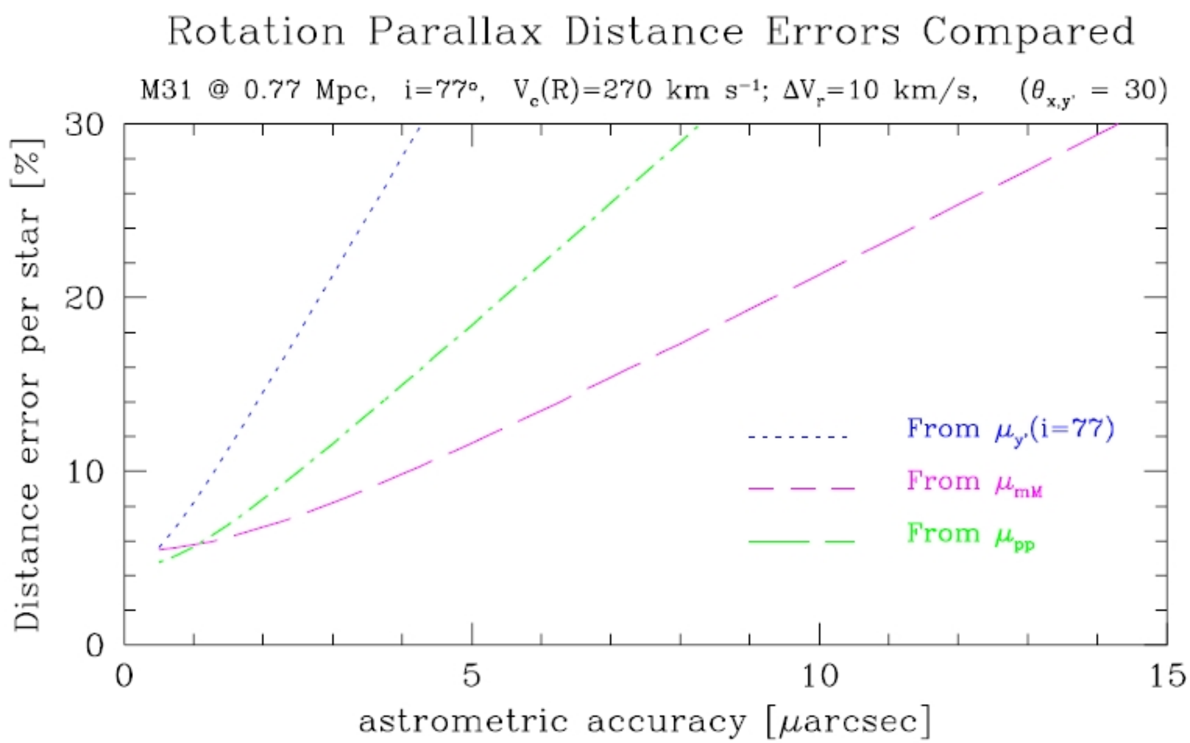


Fig. 5.— Inferred distance errors for M31 as a function of measurement errors. For three different estimates of D. The magnitude of the smallest distance error, at $\Delta\mu = 0.5\ \mu\mathrm{as\,yr}^{-1}$, is set by the assumed radial velocity error.

Olling & Peterson (2000)

Questions?
Comments?

Angry e-mails?

stanek.32@osu.edu