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Clustering of Local Group Distances: Publication Bias or Correlated Measurements? VII. A Distance Framework out to 100 Mpc

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Abstract

We consider the body of published distance moduli to the Fornax and Coma galaxy clusters, with specific emphasis on the period since 1990. We have carefully homogenized our final catalogs of distance moduli onto the distance scale established in the previous papers in this series. We assessed systematic differences associated with the use of specific tracers and consequently discarded results based on application of the Tully–Fisher relation and of globular cluster and planetary nebula luminosity functions. We recommend "best" weighted relative distance moduli for the Fornax and Coma clusters with respect to the Virgo cluster benchmark of $\Delta(m-M)_0^{\rm Fornax-Virgo} = 0.18 \pm 0.28$ mag and $\Delta(m-M)_0^{\rm Coma-Virgo} = 3.75 \pm 0.23$ mag. The set of weighted mean distance moduli (distances) we derived as most representative of the clusters' distances is

$$\begin{aligned} (m-M)_0^{\rm Fornax} &= 31.41 \pm 0.15 \text{ mag } (D = 19.1^{+1.4}_{-1.2} \text{ Mpc}) \text{ and} \\ &= 31.21 \pm 0.28 \text{ mag } (D = 17.5^{+2.4}_{-2.2} \text{ Mpc}), \\ (m-M)_0^{\rm Coma} &= 34.99 \pm 0.38 \text{ mag } (D = 99.5^{+19.0}_{-15.9} \text{ Mpc}) \text{ and} \\ &= 34.78 \pm 0.27 \text{ mag } (D = 90.4^{+11.9}_{-10.6} \text{ Mpc}), \end{aligned}$$

where the first distance modulus for each cluster is the result of our analysis of the direct, absolute distance moduli, while the second modulus is based on distance moduli relative to the Virgo cluster. While the absolute and relative distance moduli for both clusters are mutually consistent within the uncertainties, the relative distance moduli yield shorter absolute distances by $\sim 1\sigma$. It is unclear what may have caused this small difference for both clusters; lingering uncertainties in the underlying absolute distance scale appear to have given rise to a systematic uncertainty of the order of 0.20 mag.

Unified Astronomy Thesaurus concepts: Astronomical reference materials (90); Astronomy databases (83); Distance measure (395); Galaxy distances (590); Coma Cluster (270)

1. A Robust Framework of Extragalactic Distances

Over the course of the past decade, we have established a robust distance framework to galaxies in the Local Group and beyond, based on a set of mutually and internally consistent distance moduli that were validated on a robust statistical basis. In de Grijs et al. (2014, henceforth Paper I), we explored the presence of "publication bias" in the body of published distance determinations for the Large Magellanic Cloud (LMC), as suggested by Schaefer (2008). While we did not find any evidence of authors having jumped on this proverbial bandwagon, we put Freedman et al.'s (2001) canonical LMC distance modulus of $(m-M)_0^{\rm LMC} = 18.50 \pm 0.10$ mag on a well-established statistical footing, recommending $(m-M)_0^{\rm LMC} = 18.49 \pm 0.09$ mag (see also Crandall & Ratra 2015).

This was followed by a series of papers aimed at both exploring the reality and/or the presence of publication bias among published distance measurements and establishing a robust local distance framework. In order of increasing distance, we applied the same analysis as developed in Paper I to the Galactic Center (de Grijs & Bono 2016, Paper IV) and the Galactic rotation constants (de Grijs & Bono 2017, Paper V), the Small Magellanic Cloud (Crandall & Ratra 2015, Paper III; see also de Grijs & Bono 2015), the M31 group (de Grijs & Bono 2014, Paper II), and the Virgo cluster (de Grijs & Bono 2020, Paper VI). In addition, we strongly recommend the independent, geometric distance measurement to the maser host galaxy NGC 4258 published by Herrnstein et al. (1999) as additional, intermediate-distance stepping stone. Our full, internally consistent distance framework thus far established is summarized in Table 3 of Paper VI.

In this paper, we expand our previous analyses by focusing on two additional, rich benchmark galaxy clusters. These include the Fornax cluster as a Southern-Hemisphere benchmark counterpart to the Virgo cluster in the Northern Hemisphere, as well as the Coma cluster. This takes our internally consistent "local" distance framework out to distances of the order of 100 Mpc. At those distances, a significant fraction (although still a large minority) of articles citing distance estimates refer to redshifts rather than linear scales. This will therefore conclude our efforts to establish a benchmark set of statistically validated distance estimates in the local universe.

We have organized this paper as follows. In Section 2, we briefly summarize our data-mining approach and describe the resulting catalogs containing Fornax and Coma distances. We examine trends in distance determinations for both clusters in Section 4. Then, in Section 3, we analyze the systematic differences, if any, among tracer populations for both clusters. This eventually results in a set of recommended benchmark distances, which we summarize in Section 5. These should be combined with the distance moduli summarized in Paper VI (see that paper's Table 3) to gain a full overview of our extragalactic distance framework.

2. Our Database

Similarly to the previous papers in this series, we mined the NASA/Astrophysics Data System (ADS) for newly derived or recalibrated/updated distance measures to the Fornax and Coma clusters. We used as search terms "Fornax Cluster" and "Coma Cluster." We adopted the same criteria as in our previous papers for inclusion of any new values in our final database (for a detailed description, see, e.g., Paper I). We included both measurements to the galaxy clusters as a whole, as well as to individual galaxies in the cluster cores (indicated separately in our final catalogs). For the Fornax cluster, we hence included distance measures to NGC 1316, NGC 1326A, NGC 1365, and NGC 1399 (as well as NGC 1404). The relevant galaxies in the Coma cluster for which distance moduli are included in our final database are NGC 4874, NGC 4881, NGC 4889, NGC 4921, NGC 4923, and IC 4051.

For the "modern" period, from 1990 onward, we carefully perused all articles resulting from our NASA/ADS queries; prior to 1990, we followed the reference trail. As of 2019 December 19, when we completed our data mining, the numbers of hits in the NASA/ADS for the Fornax and Coma clusters were 1849 and 5357, respectively. The resulting numbers of absolute/relative distance measures included in our final catalogs are 140/62 and 95/56 for the Fornax and Coma clusters, respectively. For the Fornax cluster, we retrieved distance moduli relative to that of the Virgo cluster; for the Coma cluster, we retrieved relative distance measures with respect to the Virgo (53), Leo I (2 direct, 10 indirect; see Section 4.4), and Fornax (1) clusters.

Our final database, sorted by year and by tracer for both galaxy clusters separately, is available online through http://astro-expat.info/Data/pubbias.html.[6] For graphical depictions of the clusters' distance moduli as a function of year of publication, see Figures 1 and 2. We will discuss the trends and any evidence of publication bias versus correlated measures in Section 3.

3. Trends in Fornax and Coma Cluster Distance Determinations

Figures 1 and 2 show both the overall distribution of distance moduli and the distance measures for selected individual tracers for the Fornax and Coma clusters, respectively. The bottom panels in both figures show the sets of published relative distance moduli of our target clusters with respect to the Virgo cluster.

Since we have focused our detailed data mining on the "modern" period from 1990 onward, we will concentrate on those measures in our analysis of the distances implied by the individual tracers. However, careful assessment of both figures shows that hidden trends in the distance moduli may be present for Fornax distance measures based on application of the Tully–Fisher relation (TFR), surface brightness fluctuations (SBF), and the planetary nebula luminosity function (PNLF). Hence, for the Fornax distances based on the TFR and SBF, we analyzed the period from 2000 onward, while for PNLF-based measures, we used the time frame since 1995. For the Coma cluster, we restricted our analysis of its TFR-based distances to the period from 2000 given the large scatter of the individual data points prior to 2000, which may imply the presence of unaccounted-for biases and measurement errors. Note that all data points included in Figures 1 and 2 reflect the assumptions made by their original authors. In Section 4, we will first homogenize the data points used for further analysis before drawing our conclusions.

Although we retain the Fornax distance modulus suggested by Drinkwater et al. (2001) in our online catalog (http://astro-expat.info/Data/pubbias.html), we did not include this measurement in our analysis. It is based on the mean distance modulus resulting from three Cepheid-based measurements available at the time of publication for NGC 1365, NGC 1326A, and NGC 1425. These authors suggest that neither NGC 1326A nor NGC 1425 may be representative of the cluster core (but note that our final catalog retains the Cepheid distance to NGC 1326A, since it does not appear out of place with respect to the overall body of measurements), thus only leaving the Cepheid distance of NGC 1365 (Madore et al. 1999). The latter is already included in our Fornax catalog, thus rendering the Drinkwater et al. (2001) result superfluous.

Similarly, we retain two distances based on globular cluster luminosity functions (GCLFs) in our final catalog of Fornax cluster distance measures, which we do not use in our analysis. This relates to the distance moduli of Whitmore (1997) and Dirsch et al. (2003). The former reference does not provide sufficient information for us to include its distance determination in our analysis; the latter distance determination is, in essence, based on an assessment of the measured peak of the GCLF as being "consistent" with the SBF-based distance measurements of Tonry et al. (2001) and Liu et al. (2002). As such, it is not a firm determination.

4. Statistically Validated Distances

4.1. Systematic Differences Affecting Individual Tracers

In the previous section, we identified a number of individual distance tracers for both galaxy clusters for which we had collected a sufficient number of measurements to analyze their distance distributions separately. We show their distance measures separately in panels (b)–(e) in both Figures 1 and 2. Table 1 includes the weighted means for each tracer and for the relevant period of interest, as well as the relevant 1σ uncertainties.

However, before compiling Table 1, we ensured that all distance moduli contributing to the weighted means were carefully homogenized onto our overall distance framework as determined in this series of papers. Tables 2 and 3 include the numerical basis of this homogenization, showing both the zero-point calibrations used by the original authors and our adjustments of their distance moduli to match our distance framework thus far established (see footnote a to Table 2 for a quick overview). The homogenized distance moduli (as well as the original values) are displayed as a function of the publication date and for each of the main tracers separately in Figure 3.

[6] A permanent link to this page can be found at http://web.archive.org/web/20200331174040/http://astro-expat.info/Data/pubbias.html; members of the community are encouraged to send us updates or missing information.

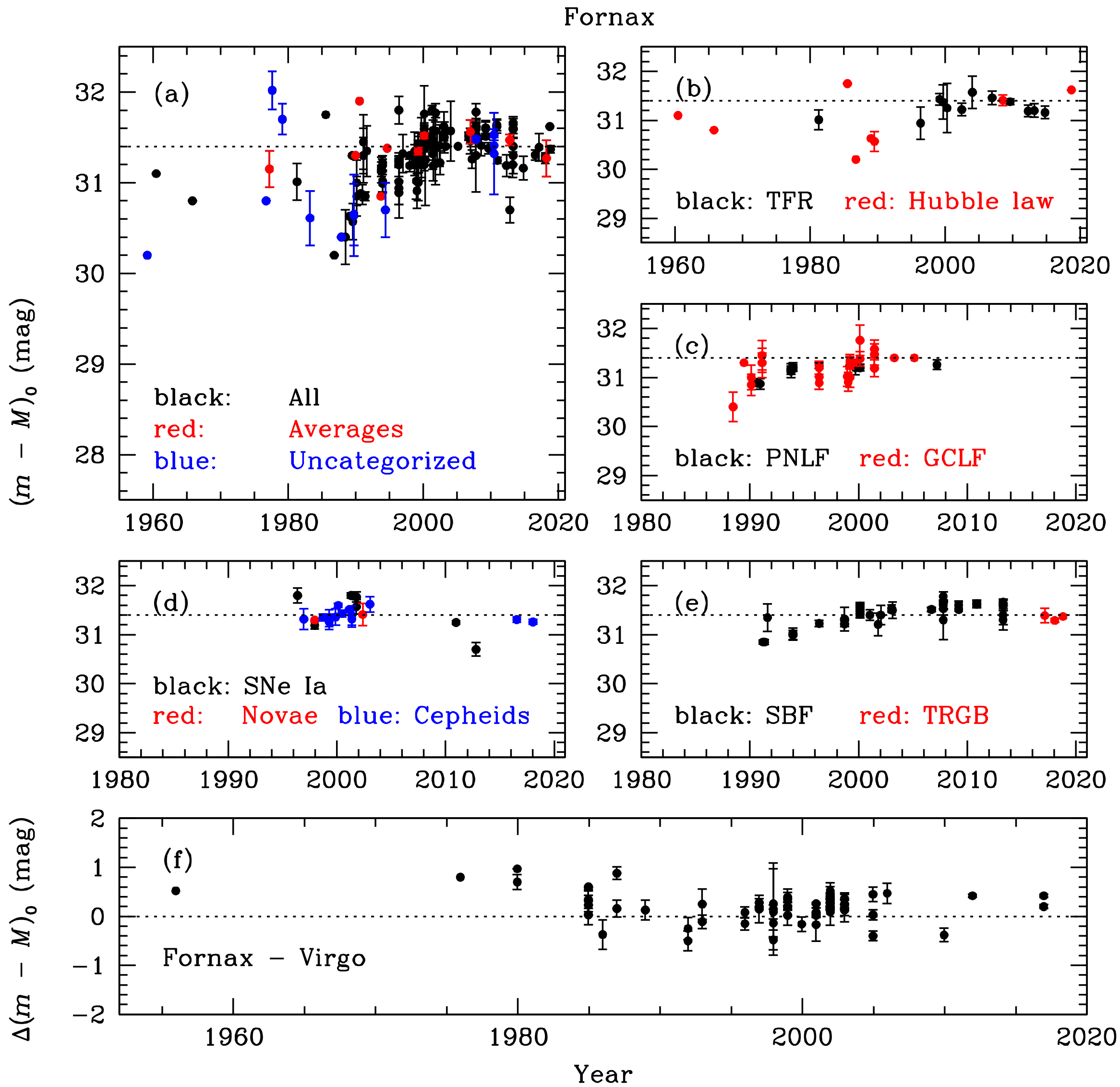

Figure 1. Published distance moduli (original values and original error bars, where available) to the Fornax cluster and its central galaxies, NGC 1316, NGC 1326A, NGC 1365, and NGC 1399 (as well as NGC 1404). The horizontal dotted lines in panels (a)–(e) represent $(m-M)_0 = 31.4$ mag and are meant to guide the eye. GCLF: globular cluster luminosity function, PNLF: planetary nebula luminosity function, TFR: Tully–Fisher relation, TRGB: tip of the red-giant branch, SBF: surface brightness fluctuations, and SNe Ia: Type Ia supernovae. "Averages" in panel (a) include weighted and unweighted means of different methods of distance determination, as well as mean values of the distance moduli to samples of central Fornax cluster galaxies, as published by the original authors (see Section 10 in our externally linked data table); "Uncategorized" distance moduli include any measurements that are not already included in the other panels, mostly because of the scarcity of data points for a particular measurement approach (see Section 11 of the same table). Panel (f) shows the set of published relative Fornax–Virgo Cluster distance moduli (any tracer), where positive values reflect a greater distance to the Fornax cluster compared with Virgo.

From a sociological perspective, we note that distance measures using a specific tracer are often dominated by articles published by the same group and their junior team members. This is not unexpected, of course, since this practice reflects the central expertise of the different groups of authors. Nevertheless, we considered the effects of including series of results from the same group on the overall value of the resulting distance modulus.

4.2. Fornax

First, we considered the post-1990 Cepheid-based distance moduli for the Fornax cluster. Comparing author lists, combined with a careful perusal of the papers in question, it is clear that among our set of 13 Cepheid distances to the Fornax cluster, the only truly independent measurement was provided by Riess et al. (2016), i.e., $(m-M)_0 = 31.21 \pm 0.06$ mag (after adjustment of its zero-point calibration). Their value falls within the mutual 1σ uncertainties of the Cepheid-based distance included in Table 1; one should, of course, keep in mind that all other measurements contributing to that distance are correlated and not independent.

Among the eight post-2000 TFR-based distances to the Fornax cluster, five were published by the same group. The weighted average of those five determinations is $(m-M)_0 = 31.22 \pm 0.25$ mag. Of the remaining three values, two fall comfortably within the 1σ uncertainties following homogenization: $(m-M)_0 = 31.21 \pm 0.13$ mag (Bernardi et al. 2002) and $(m-M)_0 = 31.20 \pm 0.33$ mag (Allen & Shanks 2004). The third value, $(m-M)_0 = 31.45 \pm 0.14$ mag (Masters et al. 2006), is larger although still consistent with the bulk of our values.

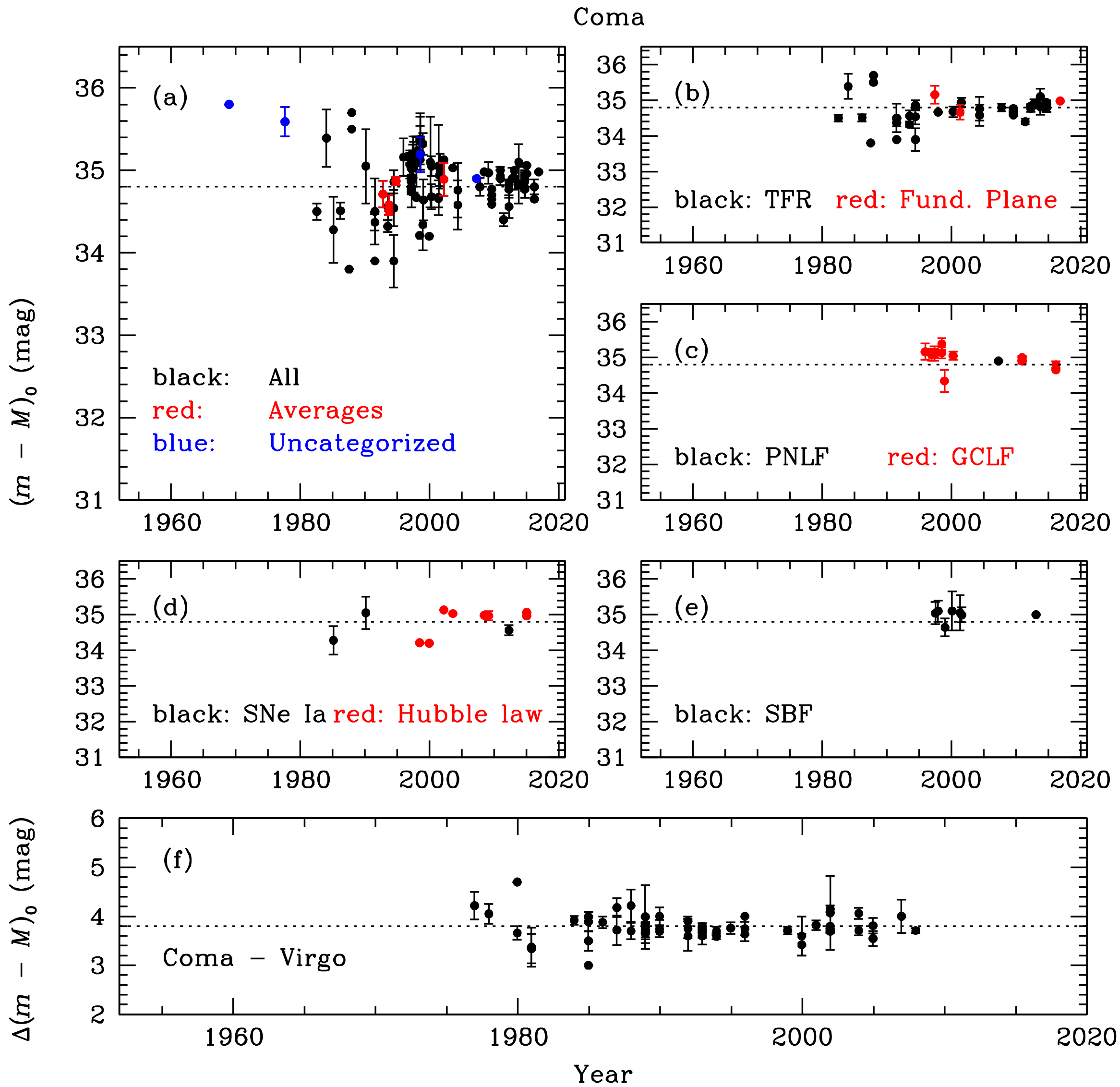

Figure 2. As Figure 1 but for the Coma cluster and its central galaxies, NGC 4874, NGC 4881, NGC 4889, NGC 4921, NGC 4923, and IC 4051. Fund. Plane: Fundamental Plane. Panel (f) shows the relative Coma–Virgo cluster distance moduli (as in Figure 1(f)).

Nevertheless, inspection of Table 1 shows that the TFR-based weighted mean distance to the Fornax cluster is significantly shorter than the equivalent distance estimates based on most other tracers (with the notable exception of GCLF-based distance moduli; see below). A combination of effects may have given rise to this difference. First, Allen & Shanks (2004) concluded that for their sample of 18 galaxies at distances of $(m - M)_0 > 29.5$ mag hosting Cepheid variables, which were observed with the Hubble Space Telescope, and the TFR-based distance moduli yield distances that are shorter by $\Delta(m - M)_0 = -0.44 \pm 0.09$ mag (see also Shanks 1997). They suggested that at least some of this effect may be due to unaccounted-for metallicity differences (e.g., Kennicutt et al. 1998) and sample incompleteness, leading to a significant scale error in TFR-based distances. We note, however, that addition of the offset in distance modulus suggested by Shanks (1997) and Allen & Shanks (2004) would lead to overestimated TFR distances compared with Fornax distance moduli based on other tracers. This situation is exacerbated by the often convoluted calibration approaches, often involving at least some iterative means to tie Cepheid, Type Ia supernovae (SNe Ia), and TFR distances to the same scale.

In addition, TFR distances tend to differ depending on the operating wavelength. Tully & Pierce (2000) found for the Ursa Major galaxy cluster that although the overall agreement among the distance moduli resulting from an analysis of different passbands is good, their *I*-band analysis yielded shorter distance moduli than the weighted mean by 0.02 mag, while in the *B* band, their moduli were overestimated by 0.04 mag. In the *R* and K' bands, their estimates were 0.03 mag larger and 0.05 mag smaller, respectively, than the mean. Finally, a degree of publication bias could have crept into our sample of TFR-based Fornax cluster distance measures, given that some authors confidently state that their derived TFR-based distance moduli comfortably agree with previously published measures but without comparing the underlying calibrations applied (e.g., Bureau et al. 1996).

Our SBF-based distance measures to Fornax represent the largest subsample. Although they do exhibit some spread about the weighted mean, the distribution's standard deviation is small, 0.14 mag, and therefore is not indicative of statistical

Table 1
Mean, Post-1990 Published Distance Measures to the Centers of the Fornax and Coma Clusters as a Function of Tracer Population

Fornax				Coma			
Tracer	Period	N	$(m-M)_0$ (mag)	Tracer	Period	N	$(m-M)_0$ (mag)
Cepheids[b]	1990–2019	13	31.38 ± 0.14	Hubble law[a]	1990–2019	8	35.02 ± 0.06
TFR	2000–2019	8	31.25 ± 0.24	TFR[b]	2000–2019	33	34.72 ± 0.18
SBF	2000–2019	28	31.44 ± 0.19	SBF[b]	1990–2019	7	34.98 ± 0.37
TRGB	1990–2019	3	31.41 ± 0.09	GCLF[b]	1990–2019	15	34.90 ± 0.17
GCLF[b]	1990–2019	19	31.22 ± 0.21				
PNLF	1995–2019	5	31.36 ± 0.09				

Notes.
[a] Adopting $H_0 = 70$ km s^{-1} Mpc^{-1}; a reduction (increase) to $H_0 = 67.3$ (72) km s^{-1} Mpc^{-1} (spanning the range implied by the current "Hubble tension") would result in an increase (decrease) in the Coma distance modulus by 0.09 (0.06) mag. The uncertainty represents the Gaussian width (σ) of the distribution, given that none of the published Coma distances based on application of the Hubble law included estimates of the associated uncertainties.
[b] Since a number of published distance measures did not include associated uncertainties, the central values are based on the full set of published measurements, while the uncertainties only include those values that were published with their associated uncertainties. This affects the following numbers of measurements: (1) Fornax—Cepheids: 1 and GCLF: 3, (2) Coma—GCLF: 3, SBF: 1, and TFR: 8.

anomalies. Nevertheless, 21 of the 28 post-2000 values considered here were published by the same team (and are, hence, likely correlated). However, the remaining seven values (Ferrarese et al. 2000; Liu et al. 2002; Jerjen 2003; Dunn & Jerjen 2006) are all fully consistent with the overall weighted mean and its 1σ uncertainty. Both data sets are statistically indistinguishable. We note that our three TRGB-based Fornax distances were all published by the same team, but we included them in our analysis because they provide an independent stellar population tracer. Both the SBF technique and the TRGB-based distances rely on red-giant stars; it is therefore comforting to see that the distance moduli resulting from independent application of these techniques are indeed very close to one another.

The GCLF-based data set comprises 19 distance moduli. The author lists of the contributing papers are more diverse than for the previously discussed tracers. The largest single group of collaborators contributed to nine of the measures included in our catalog. Overall, assuming a Gaussian distribution of distance measures, the 1σ spread is 0.19 mag, similar to the uncertainty on the mean. This indicates that the intrinsic spread among the contributing values is more significant than the equivalent spreads resulting from the other tracers used here. Some of the most significantly deviating values result from calibrations using nonstandard calibrators, specifically the poorly defined *B*- or *I*-band GCLFs pertaining to the Milky Way or M31 (e.g., Kohle et al. 1996; Ferrarese et al. 2000; Gómez et al. 2001). In addition, calibration of the (*V*-band) GCLF in the Milky Way relies on accurate distance determinations to the contributing globular clusters (and, in fact, a reliable distance determination to the Galactic Center; see Paper IV). Moreover, one must make assumptions regarding the shape (width) of the GCLF, which may differ among different galaxy types (e.g., Jordán et al. 2006).

Finally, as we discussed in the context of the distance to the Galactic Center (Paper IV), distances based on GCLFs tend to be systematically smaller than most other distance measurements (for the Fornax cluster, see also Villegas et al. 2010). This could be caused by incomplete corrections for internal or foreground extinction or because of incomplete samples of objects, in the sense that our observational data may be biased toward objects in the foreground of the host galaxy. In view of these lingering uncertainties, we will refrain from further consideration of the GCLF-based distances.

The five articles yielding PNLF-based distances to Fornax were published by four different groups, yet following homogenization, the weighted mean is well-defined with a small uncertainty (0.09 mag). Nevertheless, we are reluctant to place too much emphasis on this result, given that—like the GCLF—planetary nebulae samples are often dominated by objects located predominantly in the foreground of their host galaxies, thus resulting in underestimated distances (for a discussion, see Paper VI).

In summary, we argue that the most reliable Fornax distance moduli among the values in our database are those resulting from analyses of Cepheid distances, SBF, and the TRGB. Their weighted mean results in

$$(m-M)_0^{\rm Fornax} = 31.41 \pm 0.15 \text{ mag}$$
$$\text{or } D = 19.1^{+1.4}_{-1.2} \text{ Mpc}.$$

For completeness, we also considered the post-1990 distance moduli that were not included in our analysis, including those based on SNe Ia, novae, application of the Hubble law, and other, less commonly used tracers (see the online table at http://astro-expat.info/Data/pubbias.html). With few exceptions, the vast majority of these post-1990 measures were comfortably consistent with the weighted mean distance modulus derived above.

4.3. Coma

We will now briefly review the published Coma cluster distance moduli along the same lines as we just did for the Fornax cluster. Table 1 includes four different distance measures. As we argued above for the Fornax cluster, use of GCLF-based distances is fraught with lingering uncertainties, and so we will not consider those measurements here. Of the remaining three tracers, use of the Hubble law requires a somewhat different analysis. The Coma cluster distance coincides with the distance where the "smooth" Hubble flow starts, i.e., where redshifts of field galaxies become reasonably reliable proxies of their distances. Riess et al. (2009) suggested a minimum redshift of z=0.023 ($D \sim 100$ Mpc) for the smooth Hubble flow. At $D = 100$ Mpc, the Hubble-flow velocity is

Table 2
Corrections to Published Fornax Cluster Distance Moduli

Date (year month)	$(m-M)_0^{\rm orig}$ (mag)	Orig. Calibration	Correction[a] (mag)	$(m-M)_0^{\rm scaled}$ (mag)	Target	Notes	Reference
			Cepheids				
1996 Dec	31.32 ± 0.21	$(m-M)_0^{\rm LMC}=18.50$ mag	−0.01	31.31	NGC 1365		Madore et al. (1996)
1998 Sep	31.35 ± 0.07	$(m-M)_0^{\rm LMC}=18.50$ mag	−0.01	31.34	NGC 1365		Madore et al. (1998)
1999 Apr	31.35 ± 0.07	$(m-M)_0^{\rm LMC}=18.50$ mag	−0.01	31.34	NGC 1365		Madore et al. (1999)
1999 Apr	31.31 ± 0.20	$(m-M)_0^{\rm LMC}=18.50$ mag	−0.01	31.30	NGC 1365		Silbermann et al. (1999)
1999 Apr	31.26 ± 0.10	$(m-M)_0^{\rm LMC}=18.50$ mag	−0.01	31.25	NGC 1365		Silbermann et al. (1999)
1999 Nov	31.36 ± 0.17	$(m-M)_0^{\rm LMC}=18.50$ mag	−0.01	31.35	NGC 1326A		Prosser et al. (1999)
2000 Feb	31.60 ± 0.04	$(m-M)_0^{\rm LMC}=18.50$ mag	−0.01	31.59	Fornax		Ferrarese et al. (2000)
2000 Jun	31.43 ± 0.07	$(m-M)_0^{\rm LMC}=18.50$ mag	−0.01	31.42	NGC 1365		Ferrarese et al. (2000)
2001 May	31.32 ± 0.17	$(m-M)_0^{\rm LMC}=18.50$ mag	−0.01	31.31	Fornax		Freedman et al. (2001)
2001 May	31.39 ± 0.20	$(m-M)_0^{\rm LMC}=18.50$ mag	−0.01	31.38	Fornax	Corr. for metallicity	Freedman et al. (2001)
2003 Jan	31.62 ± 0.16	$M_I^{\rm TRGB}=-4.05$ mag	0.00	31.62	Fornax		Jerjen (2003)
2016 Jul	31.307 ± 0.057	$(m-M)_0^{\rm N4258}=29.387$ mag	−0.10	31.21	NGC 1365		Riess et al. (2016)
2018 Jan	31.26 ± 0.05	$(m-M)_0^{\rm LMC}=18.49$ mag	0.00	31.26	NGC 1365		Jang et al. (2018)
			SBF				
1991 Mar	30.85 ± 0.04	$(m-M)_0^{\rm M31}=24.43$ mag	+0.03	30.88	Fornax		Tonry (1991a)
1991 May	30.85 ± 0.05	$(m-M)_0^{\rm M31}=24.43$ mag	+0.03	30.88	Fornax		Tonry (1991b)
1991 Aug	31.35 ± 0.28	$(m-M)_0^{\rm M31}=24.43$ mag	+0.03	31.38	Fornax		Bothun et al. (1991)
1993 Dec	31.02 ± 0.12	$(m-M)_0^{\rm M31}=24.43$ mag	+0.03	31.05	NGC 1316		Ciardullo et al. (1993)
1993 Dec	30.99 ± 0.10	$(m-M)_0^{\rm M31}=24.43$ mag	+0.03	31.02	NGC 1399		Ciardullo et al. (1993)
1996 May	31.23 ± 0.06	$(m-M)_0^{\rm M31}=24.43$ mag	+0.03	31.26	Fornax		Tonry (1997)
1998 Sep	31.22 ± 0.06	$(m-M)_0^{\rm Virgo}=31.00$ mag	+0.03	31.25	Fornax	I	Jensen et al. (1998)
1998 Sep	31.32 ± 0.24	$(m-M)_0^{\rm Virgo}=31.00$ mag	+0.03	31.35	Fornax	K'	Jensen et al. (1998)
2000 Feb	31.41 ± 0.06	[b]	+0.01	31.42	Fornax	I	Tonry et al. (2000)
2000 Feb	31.50 ± 0.16	[b]	+0.01	31.51	NGC 1399	I	Tonry et al. (2000)
2000 Feb	31.59 ± 0.04	+0.05 mag w.r.t. Tonry et al. (2001)	−0.04	31.55	Fornax	I	Ferrarese et al. (2000)
2000 Feb	31.51 ± 0.08	+0.05 mag w.r.t. Tonry et al. (2001)	−0.04	31.47	Fornax	K'	Ferrarese et al. (2000)
2001 Jan	31.40 ± 0.11	$(m-M)_0^{\rm Virgo}=31.03$ mag	0.00	31.40	Fornax	I	Blakeslee et al. (2001)
2001 Oct	31.21 ± 0.23	based on Ferrarese et al. (2000)	−0.04	31.17	NGC 1316		Ajhar et al. (2001)
2002 Jan	31.4 ± 0.2	Tonry et al. (2000) calibration	+0.01	31.41	NGC 1399		Liu et al. (2002)
2003 Jan	31.54 ± 0.07	$M_I^{\rm TRGB}=-4.05$ mag	0.00	31.54	Fornax	Dwarf galaxies	Jerjen (2003)
2003 Jan	31.50 ± 0.04	$M_I^{\rm TRGB}=-4.05$ mag	0.00	31.50	Fornax	Early-type galaxies	Jerjen (2003)
2003 Feb	31.50 ± 0.17	$(m-M)_0^{\rm LMC}=18.50$ mag	−0.01	31.49	NGC 1316		Jensen et al. (2003)
2006 Sep	31.51 ± 0.04	$M_I^{\rm TRGB}=-4.05$ mag	0.00	31.51	Fornax		Dunn & Jerjen (2006)
2006 Sep	31.52 ± 0.04	$M_I^{\rm TRGB}=-4.05$ mag	0.00	31.52	NGC 1399		Dunn & Jerjen (2006)
2007 Oct	31.78 ± 0.09	−0.21 mag w.r.t. Ferrarese et al. (2000)	−0.25	31.53	NGC 1316		Cantiello et al. (2007)
2007 Oct	31.62 ± 0.09	−0.21 mag w.r.t. Ferrarese et al. (2000)	−0.25	31.37	NGC 1316		Cantiello et al. (2007)
2007 Oct	31.62 ± 0.09	−0.21 mag w.r.t. Ferrarese et al. (2000)	−0.25	31.37	NGC 1316		Cantiello et al. (2007)
2007 Oct	31.53 ± 0.13	−0.21 mag w.r.t. Ferrarese et al. (2000)	−0.25	31.28	NGC 1316		Cantiello et al. (2007)
2007 Oct	31.59 ± 0.08	−0.21 mag w.r.t. Ferrarese et al. (2000)	−0.25	31.34	NGC 1316		Cantiello et al. (2007)
2007 Oct	31.3 ± 0.4	−0.21 mag w.r.t. Ferrarese et al. (2000)	−0.25	31.05	Fornax		Cantiello et al. (2007)
2009 Mar	31.51 ± 0.03	$(m-M)_0^{\rm Virgo}=31.09$ mag	−0.06	31.45	Fornax	z	Blakeslee et al. (2009)

Table 2
(Continued)

Date (year month)	$(m-M)_0^{\rm orig}$ (mag)	Orig. Calibration	Correction[a] (mag)	$(m-M)_0^{\rm scaled}$ (mag)	Target	Notes	Reference
2009 Mar	31.606 ± 0.065	$(m-M)_0^{\rm Virgo} = 31.09$ mag	−0.06	31.55	NGC 1316	*z*	Blakeslee et al. (2009)
2009 Mar	31.596 ± 0.091	$(m-M)_0^{\rm Virgo} = 31.09$ mag	−0.06	31.54	NGC 1399	*z*	Blakeslee et al. (2009)
2010 Nov	31.620 ± 0.071	+0.06 mag w.r.t. Tonry et al. (2001)	−0.05	31.57	NGC 1399	F814W	Blakeslee et al. (2010)
2010 Nov	31.638 ± 0.066	+0.06 mag w.r.t. Tonry et al. (2001)	−0.05	31.59	NGC 1316	F814W	Blakeslee et al. (2010)
2013 Apr	31.59 ± 0.05	+0.06 mag w.r.t. Tonry et al. (2001)	−0.05	31.54	NGC 1316		Cantiello et al. (2013)
2013 Apr	31.60 ± 0.11	+0.06 mag w.r.t. Tonry et al. (2001)	−0.05	31.55	NGC 1316		Cantiello et al. (2013)
2013 Apr	31.66 ± 0.07	+0.06 mag w.r.t. Tonry et al. (2001)	−0.05	31.61	NGC 1316	*z*	Cantiello et al. (2013)
2013 Apr	31.3 ± 0.2	+0.06 mag w.r.t. Tonry et al. (2001)	−0.05	31.25	NGC 1316	*z*	Cantiello et al. (2013)
2013 Apr	31.4 ± 0.2	+0.06 mag w.r.t. Tonry et al. (2001)	−0.05	31.35	NGC 1316	*z*	Cantiello et al. (2013)
			GCLF				
1990 Feb	31.0 ± 0.25	$R_0 = 8.0$ kpc	+0.08	31.08	Fornax		Geisler & Forte (1990)
1990 Feb	30.85 ± 0.22	$R_0 = 8.0$ kpc	+0.08	30.93	NGC 1399		Geisler & Forte (1990)
1991 Feb	31.3 ± 0.2	$M_{V,{\rm TO}}^{\rm MW} = -7.36$ mag	−0.14	31.16	NGC 1399		Bridges et al. (1991)
1991 Feb	31.45 ± 0.30	$M_{V,{\rm TO}}^{\rm MW} = -7.36$ mag	−0.14	31.31	Fornax		Bridges et al. (1991)
1991 Feb	31.3 ± 0.3	$M_{V,{\rm TO}}^{\rm MW} = -7.36$ mag	−0.14	31.16	Fornax		Bridges et al. (1991)
1996 May	31.20 ± 0.13	$M_{V,{\rm TO}}^{\rm MW} = -7.40$ mag	+0.10	31.30	Fornax	*V*	Kohle et al. (1996)
1996 May	30.89 ± 0.13	$M_{V,{\rm TO}}^{\rm MW} = -7.40$ mag	+0.10	30.99	Fornax	*I*	Kohle et al. (1996)
1998 Dec	31.02 ± 0.2	$M_{V,{\rm TO}}^{\rm MW} = -7.40$ mag	+0.10	31.12	NGC 1399		Ostrov et al. (1998)
1999 Jan	30.91 ± 0.19	$(m-M)_0^{\rm M31} = 24.43$ mag	+0.03	30.94	NGC 1399		Grillmair et al. (1999)
1999 Mar	31.30 ± 0.13	$M_{V,{\rm TO}}^{\rm MW} = -7.61$ mag	−0.11	31.19	Fornax		Richtler et al. (2000)
1999 Mar	31.32 ± 0.15	$M_{V,{\rm TO}}^{\rm MW} = -7.61$ mag	−0.11	31.21	NGC 1316		Richtler et al. (2000)
1999 Mar	31.0 ± 0.2	$M_{V,{\rm TO}}^{\rm MW} = -7.4$ mag	+0.10	31.10	Fornax		Kissler-Patig et al. (1997)
1999 Jul	31.3	$M_{V,{\rm TO}}^{\rm MW} = -7.4$ mag	+0.10	31.40	Fornax		Hilker et al. (1999)
2000 Feb	31.38 ± 0.15	$M_{V,{\rm TO}}^{\rm MW} = -7.60$ mag	−0.10	31.28	Fornax	*V*	Ferrarese et al. (2000)
2000 Feb	31.76 ± 0.31	$M_{V,{\rm TO}}^{\rm MW} = -7.60$ mag	−0.10	31.66	Fornax	*B*	Ferrarese et al. (2000)
2001 Jun	31.58 ± 0.18	$M_{V,{\rm TO}}^{\rm MW} = -7.60$ mag	−0.10	31.48	NGC 1316	*B*	Gómez et al. (2001)
2001 Jun	31.47 ± 0.22	$M_{V,{\rm TO}}^{\rm MW} = -7.60$ mag	−0.10	31.37	NGC 1316	*V*	Gómez et al. (2001)
2001 Jun	31.19 ± 0.17	$M_{V,{\rm TO}}^{\rm MW} = -7.60$ mag	−0.10	31.09	NGC 1316	*I*	Gómez et al. (2001)
2005 Jan	31.4	$M_{V,{\rm TO}}^{\rm MW} = -7.50$ mag	0.00	31.4	NGC 1399		Forte et al. (2005)
			PNLF				
1990 Sep	30.88	$(m-M)_0^{\rm M31} = 24.27$ mag	+0.19	31.07	Fornax		Ciardullo et al. (1990)
1991	30.87 ± 0.11	$(m-M)_0^{\rm M31} = 24.27$ mag	+0.19	31.06	Fornax		cited by de Vaucouleurs (1993)
1993 Oct	31.14 ± 0.14	$(m-M)_0^{\rm M31} = 24.27$ mag	+0.19	31.33	Fornax		McMillan et al. (1993)
1993 Oct	31.13 ± 0.06	$(m-M)_0^{\rm M31} = 24.27$ mag	+0.19	31.32	NGC 1316		McMillan et al. (1993)
1993 Oct	31.17 ± 0.06	$(m-M)_0^{\rm M31} = 24.27$ mag	+0.19	31.36	NGC 1399		McMillan et al. (1993)
1993 Dec	31.19 ± 0.07	$(m-M)_0^{\rm M31} = 24.32$ mag	+0.14	31.33	NGC 1316		Ciardullo et al. (1993)
1993 Dec	31.22 ± 0.08	$(m-M)_0^{\rm M31} = 24.32$ mag	+0.14	31.36	NGC 1399		Ciardullo et al. (1993)
1996 May	31.24 ± 0.06	$(m-M)_0^{\rm M31} = 24.24$ mag	+0.19	31.43	Fornax		Jacoby (1997)
1999 Mar	31.33 ± 0.08	$(m-M)_0^{\rm M31} = 24.44$ mag	+0.02	31.35	Fornax		Richtler et al. (2000)
1999 Sep	31.20 ± 0.14	+0.06 mag w.r.t. McMillan et al. (1993)	+0.13	31.33	Fornax		Lindblad (1999)

Table 2
(Continued)

Date (year month)	$(m-M)_0^{\rm orig}$ (mag)	Orig. Calibration	Correction[a] (mag)	$(m-M)_0^{\rm scaled}$ (mag)	Target	Notes	Reference
2000 Feb	31.20 ± 0.07	$M^* = -4.58$ mag	−0.10	31.10	Fornax		Ferrarese et al. (2000)
2007 Mar	31.26 ± 0.10	$M^* = -4.47$ mag	+0.01	31.27	NGC 1316		Feldmeier et al. (2007)
			TFR				
1996 May	30.94 ± 0.33	$(m-M)_0^{\rm Virgo} = 31.00$ mag	+0.03	30.97	Fornax		Bureau et al. (1996)
1999 Mar	31.43 ± 0.12	$(m-M)_0^{\rm Virgo} = 31.58$ mag	−0.55	30.88	Fornax		Richtler et al. (2000)
1999 Sep	31.37 ± 0.35	$(m-M)_0^{\rm Virgo} = 31.39$ mag	−0.36	31.01	Fornax		Lindblad (1999)
2000 Apr	31.25 ± 0.50	$(m-M)_0^{\rm LMC} = 18.50$ mag	−0.01	31.24	Fornax		Tully & Pierce (2000)
2002 Jun	31.22 ± 0.13	$(m-M)_0^{\rm LMC} = 18.50$ mag	−0.01	31.21	Fornax		Bernardi et al. (2002)
2004 Jan	31.57 ± 0.33	$(m-M)_0^{\rm Virgo} = 31.40$ mag	−0.37	31.20	Fornax		Allen & Shanks (2004)
2006 Dec	31.46 ± 0.14	$(m-M)_0^{\rm LMC} = 18.50$ mag	−0.01	31.45	Fornax		Masters et al. (2006)
2009 Aug	31.38 ± 0.06	$(m-M)_0^{\rm LMC} = 18.50$ mag	−0.01	31.37	NGC 1365		Tully et al. (2009)
2012 Apr	31.19 ± 0.12	$(m-M)_0^{\rm LMC} = 18.50$ mag	−0.01	31.18	Fornax		Tully & Courtois (2012)
2013 Mar	31.20 ± 0.14	$(m-M)_0^{\rm LMC} = 18.48$ mag	+0.01	31.21	Fornax	3.6 μ m	Sorce et al. (2013)
2014 Oct	31.16 ± 0.13	$(m-M)_0^{\rm LMC} = 18.48$ mag	+0.01	31.17	Fornax		Sorce et al. (2014)

Notes.
[a] The calibration of our distance framework is based on distance moduli to the LMC, M31, NGC 4258, and the Virgo cluster of $(m-M)_0^{\rm LMC} = 18.49$ mag (Paper I), $(m-M)_0^{\rm M31} = 24.46$ mag (Paper II), $(m-M)_0^{\rm Virgo} = 31.06$ mag (Paper VI), and $(m-M)_0^{\rm N4258} = 29.29$ mag (Herrnstein et al. 1999). In addition, we have adopted $M_I^{\rm TRGB} = -4.05$ mag (TRGB magnitude in the I band; Bellazzini et al. 2004), $M^* = -4.67$ mag (PNLF cut-off magnitude at 5007 Å; Ciardullo et al. 1989), $M_{V,{\rm TO}}^{\rm MW} = -7.50$ mag (GCLF turnover magnitude in the Milky Way; Harris 1996), and a Galactic Center distance of $R_0 = 8.3$ kpc (paper IV).
[b] This calibration corresponds to $(m-M)_0^{\rm Virgo} = 31.03$ mag (based on group membership) and $(m-M)_0^{\rm M31} = 24.44$ mag. We adopted a mean adjustment of +0.01 mag to reconcile these calibration choices with our distance framework.

Table 3
Corrections to Published Coma Cluster Distance Moduli

Date (year month)	$(m-M)_0^{\rm orig}$ (mag)	Orig. Calibration	Correction (mag)	$(m-M)_0^{\rm scaled}$ (mag)	Target	Notes	Reference
			SBF				
1997 Jul	35.04 ± 0.31	$(m-M)_0^{\rm M31} = 24.43$ mag	+0.03	35.07	NGC 4881		Thomsen et al. (1997)
1998	35.1 ± 0.3	$(m-M)_0^{\rm M31} = 24.43$ mag	+0.03	35.13	NGC 4881		Brocato et al. (1998)
1999 Jan	34.64 ± 0.25	$(m-M)_0^{\rm Virgo} = 31.06$ mag	−0.03	34.61	NGC 4889		Jensen et al. (1999)
2000 Feb	35.10 ± 0.55	+0.05 mag w.r.t. Tonry et al. (1997)	−0.02	35.08	Coma		Ferrarese et al. (2000)
2001 May	35.05 ± 0.50	+0.05 mag w.r.t. Tonry et al. (1997)	−0.02	35.03	NGC 4881		Freedman et al. (2001)
2001 Aug	34.99 ± 0.21	+0.05 mag w.r.t. Tonry et al. (1997)	−0.02	34.97	Coma	*K*	Liu & Graham (2001)
2013 Feb	35.	$(m-M)_0^{\rm Virgo} = 31.09$ mag	−0.06	34.94	Coma		Blakeslee (2013)
			GCLF				
1995 Dec	35.16 ± 0.23	$(m-M)_0^{\rm M31} = 24.6$ mag	−0.14	35.02	NGC 4881	Lower limit	Baum et al. (1995)
1996 Dec	35.15 ± 0.06	$(m-M)_0^{\rm M31} = 24.6$ mag	−0.14	35.01	IC 4051		Baum et al. (1996)
1996 Dec	35.07 ± 0.17	$(m-M)_0^{\rm M31} = 24.6$ mag	−0.14	34.93	IC 4051		Baum et al. (1996)
1997 May	35.15 ± 0.16	$(m-M)_0^{\rm M31} = 24.6$ mag	−0.14	35.01	IC 4051		Baum et al. (1997)
1997 May	35.07 ± 0.17	$(m-M)_0^{\rm M31} = 24.6$ mag	−0.14	34.93	IC 4051		Baum et al. (1997)
1997 May	35.11 ± 0.12	$(m-M)_0^{\rm M31} = 24.6$ mag	−0.14	34.97	IC 4051		Baum et al. (1997)
1998 Jul	35.13 ± 0.15	$(m-M)_0^{\rm M31} = 24.6$ mag	−0.14	34.99	IC 4051		Baum (1998)
1998 Jul	35.38 ± 0.16	$(m-M)_0^{\rm M31} = 24.6$ mag	−0.14	35.24	IC 4051		Baum (1998)
1999	34.34 ± 0.31	$M_{V,{\rm TO}}^{\rm MW} = -7.62$ mag	−0.12	34.22	Coma		Tammann & Sandage (1999)
2000 Apr	35.05 ± 0.12	$M_{V,{\rm TO}}^{\rm MW} = -7.26$ mag	+0.14	35.19	Coma		Kavelaars et al. (2000)
2011	34.9	$M_{V,{\rm TO}}^{\rm MW} = -7.5$ mag	0.00	34.9	NGC 4921		Tikhonov & Galazutdinova (2011)
2011	35.0	$M_{V,{\rm TO}}^{\rm MW} = -7.5$ mag	0.00	35.0	NGC 4923		Tikhonov & Galazutdinova (2011)
2011	34.93 ± 0.11	$M_{V,{\rm TO}}^{\rm MW} = -7.5$ mag	0.00	34.93	Coma		Tikhonov & Galazutdinova (2011)
2016 Mar	34.80 ± 0.09	$M_{V,{\rm TO}}^{\rm MW} = -7.66$ mag	−0.16	34.64	Coma		Lee & Jang (2016)
2016 Mar	34.65	$M_{V,{\rm TO}}^{\rm MW} = -7.66$ mag	−0.16	34.49	Coma		Lee & Jang (2016)
			TFR				
1991 Jul	34.5 ± 0.4	$(m-M)_0^{\rm M31} = 24.2$ mag	+0.26	34.76	Coma	*B*	Fukugita et al. (1991)
1991 Jul	34.37 ± 0.1	$(m-M)_0^{\rm M31} = 24.2$ mag	+0.26	34.63	Coma	*B*	Fukugita et al. (1991)
1991 Jul	33.9	$(m-M)_0^{\rm M31} = 24.2$ mag	+0.26	34.16	Coma	*B*	Fukugita et al. (1991)
1991 Jul	34.5	$(m-M)_0^{\rm M31} = 24.2$ mag	+0.26	34.76	Coma	*B*	Fukugita et al. (1991)
1993 Jul	34.32 ± 0.07	$(m-M)_0^{\rm M31} = 24.37$ mag	+0.09	34.41	Coma	*B*	Rood & Williams (1993)
1993 Jul	34.56 ± 0.16	$(m-M)_0^{\rm M31} = 24.37$ mag	+0.09	34.65	Coma	*H*	Rood & Williams (1993)
1994 Jun	34.86 ± 0.14	$(m-M)_0^{\rm M31} = 24.43$ mag	+0.03	34.89	Coma		Bernstein et al. (1994)
1994 Jun	34.54 ± 0.22	$(m-M)_0^{\rm M31} = 24.43$ mag	+0.03	34.57	Coma		Bernstein et al. (1994)
1994 Jun	33.90 ± 0.32	$(m-M)_0^{\rm M31} = 24.43$ mag	+0.03	33.93	Coma		Bernstein et al. (1994)
1998	34.67	$(m-M)_0^{\rm LMC} = 18.50$ mag	−0.01	34.66	Coma	*BRI*	Tully (1998)
2000 Apr	34.68 ± 0.15	$(m-M)_0^{\rm LMC} = 18.50$ mag	−0.01	34.67	Coma	*I*	Tully & Pierce (2000)
2001 May	34.66	$(m-M)_0^{\rm LMC} = 18.50$ mag	−0.01	34.65	Coma	*I*	Freedman et al. (2001)
2001 Jul	34.94 ± 0.13	$(m-M)_0^{\rm M31} = 24.44$ mag	+0.02	34.96	Coma	IR	Watanabe et al. (2001)
2004 May	34.58 ± 0.30	$(m-M)_0^{\rm M31} = 24.48$ mag	−0.02	34.56	Coma		Russell (2004)
2004 May	34.76 ± 0.33	$(m-M)_0^{\rm M31} = 24.48$ mag	−0.02	34.74	Coma		Russell (2004)
2007 Oct	34.80 ± 0.11	$(m-M)_0^{\rm LMC} = 18.50$ mag	−0.01	34.79	Coma		Springob et al. (2007)
2009 Aug	34.65	$(m-M)_0^{\rm LMC} = 18.39$ mag	+0.11	34.76	NGC 4881	*K*	Russell (2009)
2009 Aug	34.59	$(m-M)_0^{\rm LMC} = 18.39$ mag	+0.11	34.70	NGC 4881	*K*	Russell (2009)
2009 Aug	34.70	$(m-M)_0^{\rm LMC} = 18.39$ mag	+0.11	34.81	Coma	*K*	Russell (2009)
2009 Aug	34.77	$(m-M)_0^{\rm LMC} = 18.39$ mag	+0.11	34.88	Coma	*K*	Russell (2009)

Table 3
(Continued)

Date (year month)	$(m-M)_0^{\rm orig}$ (mag)	Orig. Calibration	Correction (mag)	$(m-M)_0^{\rm scaled}$ (mag)	Target	Notes	Reference
2011 Jun	34.40 ± 0.08	$M_I^{\rm TRGB} = -4.05$ mag	0.00	34.40	Coma		Hislop et al. (2011)
2012 Apr	34.77 ± 0.10	$(m-M)_0^{\rm LMC} = 18.50$ mag	−0.01	34.76	Coma	*I*	Tully & Courtois (2012)
2012 Apr	34.83 ± 0.06	$(m-M)_0^{\rm LMC} = 18.50$ mag	−0.01	34.82	Coma		Courtois & Tully (2012)
2012 Oct	34.90 ± 0.13	$(m-M)_0^{\rm LMC} = 18.48$ mag	+0.01	34.91	Coma	3.6 μm	Sorce et al. (2012)
2013 Mar	34.90 ± 0.13	$(m-M)_0^{\rm LMC} = 18.48$ mag	+0.01	34.91	Coma	Mid-IR	Sorce et al. (2013)
2013 Oct	35.10 ± 0.22	$(m-M)_0^{\rm LMC} = 18.48$ mag	+0.01	35.11	NGC 4889	*I*	Tully et al. (2013)
2013 Oct	34.82 ± 0.22	$(m-M)_0^{\rm LMC} = 18.48$ mag	+0.01	34.83	NGC 4874	*I*	Tully et al. (2013)
2014 Sep	34.91 ± 0.06	$(m-M)_0^{\rm LMC} = 18.48$ mag	+0.01	34.92	Coma	*W1*	Neill et al. (2014)
2014 Sep	34.94 ± 0.06	$(m-M)_0^{\rm LMC} = 18.48$ mag	+0.01	34.95	Coma	*W2*	Neill et al. (2014)
2014 Sep	34.86 ± 0.11	$(m-M)_0^{\rm LMC} = 18.48$ mag	+0.01	34.87	Coma	*W1*	Neill et al. (2014)
2014 Sep	34.87 ± 0.11	$(m-M)_0^{\rm LMC} = 18.48$ mag	+0.01	34.88	Coma	*W2*	Neill et al. (2014)
2014 Sep	34.77 ± 0.10	$(m-M)_0^{\rm LMC} = 18.48$ mag	+0.01	34.78	Coma	*I*	Neill et al. (2014)
2014 Oct	34.78 ± 0.11	$(m-M)_0^{\rm LMC} = 18.48$ mag	+0.01	34.79	Coma		Sorce et al. (2014)
			Hubble law				
1998 Jun	34.21	$H_0 = 100$ km s^{-1} Mpc^{-1}	+0.77	34.98	Coma		Kashikawa et al. (1998)
1999 Dec	34.2	$H_0 = 100$ km s^{-1} Mpc^{-1}	+0.77	34.97	Coma		Terlevich et al. (1999)
2002 Mar	35.13	$H_0 = 70$ km s^{-1} Mpc^{-1}	0.00	35.13	Coma		Brighenti & Mathews (2002)
2003 Aug	35.03	$H_0 = 70$ km s^{-1} Mpc^{-1}	0.00	35.03	Coma		Łokas & Mamon (2003)
2008 Jun	34.98	$H_0 = 71$ km s^{-1} Mpc^{-1}	+0.03	35.01	Coma		Carter et al. (2008)
2009 Feb	34.97 ± 0.13	$H_0 = 72$ km s^{-1} Mpc^{-1}	+0.06	35.03	Coma		Harris et al. (2009)
2015 Jan	34.96	$H_0 = 70$ km s^{-1} Mpc^{-1}	0.00	34.96	Coma		van Dokkum et al. (2015)
2015 Jan	35.06	$H_0 = 70$ km s^{-1} Mpc^{-1}	0.00	35.06	Coma		van Dokkum et al. (2015)

around 7000 km s^{-1} and peculiar velocities will typically amount to a 5% contribution.

The main uncertainty in this context relates to the value of the Hubble parameter; radial velocities to individual galaxies, and even to entire galaxy clusters, can be determined to high accuracy and precision. The mean distance modulus to the Coma cluster based on its recession velocity has been homogenized to a Hubble parameter of $H_0 = 70$ km s^{-1} Mpc^{-1}, adopted as a compromise value given the prevailing 1–2σ tension remaining in this field (e.g., Riess et al. 2019, and references therein). A reduction (increase) to $H_0 = 67.3$ (72) km s^{-1} Mpc^{-1} would result in an increase (decrease) in the Coma distance modulus by 0.09 (0.06) mag. The "uncertainty" associated with this method included in the table reflects the Gaussian σ of the distribution (since only one of the measurements included in our final catalog quoted uncertainties). Using the single uncertainty estimate published in this context (Harris et al. 2009), a more realistic uncertainty would require addition in quadrature of this 0.13 mag uncertainty, resulting in a total error of the order of 0.14 mag.

As for the Fornax cluster, the TFR-based distances to the Coma cluster are systematically shorter than our other distances. We will therefore not include TFR-based distance measures in our analysis. This thus leaves the SBF-based Coma cluster distances. Of the seven values, four relate to the SBF distance to NGC 4881, with the remaining three referring to the Coma cluster as a whole. None of the groups contributing to its weighted mean dominate the set of values, so we have no reason to suspect correlated measurements.

In summary, if we adopt the Hubble law- and SBF-based distance moduli (with our updated uncertainty for the Hubble distances), we find a Coma cluster distance modulus of

$$(m-M)_0^{\rm Coma} = 34.99 \pm 0.38 \text{ mag}$$
$$\text{or } D = 99.5^{+19.0}_{-15.9} \text{ Mpc}.$$

For completeness, we again considered the post-1990 distance moduli that were not included in our analysis, including those based on SNe Ia, Fundamental Plane scaling, and other, less commonly used tracers (see the online table at http://astro-expat.info/Data/pubbias.html). All of the latter post-1990 measures were comfortably consistent with the weighted mean distance modulus derived above.

4.4. Relative Distance Moduli

At distances equivalent to or beyond that of the Virgo cluster, it has become relatively common to quote distance measures relative to the Virgo cluster. The main advantage of using relative rather than absolute distances is that the number of assumptions one has to make is significantly reduced, provided that the physical basis on which the distances are compared is similar. For the Fornax cluster, our database includes 43 relative Fornax–Virgo cluster distance moduli published since 1990. A straight weighted mean yields $\Delta(m-M)_0^{\rm Fornax-Virgo} = 0.18 \pm 0.28$ mag. We used all 43 values to determine the central value of this relative distance modulus; since five measurements do not have any uncertainties associated with them, we used the remaining 38 values to determine the uncertainty pertaining to our weighted mean. Both clusters thus appear to be located at very similar distance, with the Fornax placed marginally more distant.

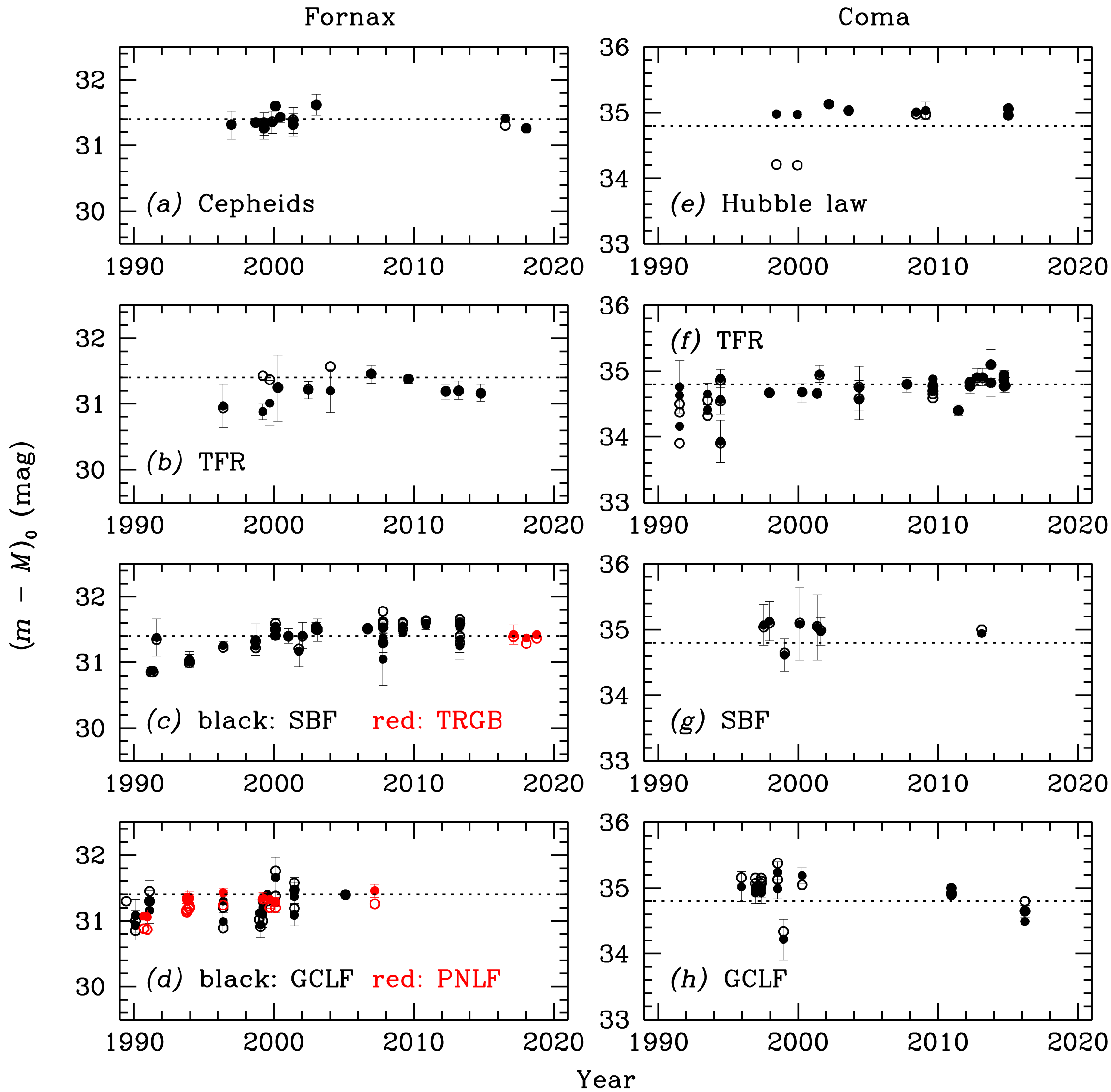

Figure 3. Original and homogenized distance moduli published since 1990 to (left; (a)–(d)) the Fornax and (right; (e)–(h)) the Coma clusters for specific tracers. The horizontal dotted lines, meant to guide the eye, are drawn at $(m - M)_0 = 31.4$ and 34.8 mag for the Fornax and Coma clusters, respectively. Open circles represent original, published values; solid bullets have been corrected to a common distance framework (see the text). Error bars are included where they were provided by the original authors.

To avoid any effects associated with small number statistics, we subdivided our 43 relative distance moduli into three groups of similar tracers, yielding post-1990 weighted mean relative distance moduli of $\Delta(m - M)_0^{\rm Fornax-Virgo} = 0.23 \pm 0.18$ mag for the 11 SBF-based measurements, $\Delta(m - M)_0^{\rm Fornax-Virgo} = 0.10 \pm 0.12$ mag for the 10 values based on luminosity functions (GCLF and PNLF), and $\Delta(m - M)_0^{\rm Fornax-Virgo} = 0.15 \pm 0.15$ mag for the 11 relative distance measures based on kinematic tracers (TFR, the $D_n - \sigma$ relation, and Fundamental Plane scaling). Combined with our recommended Virgo cluster distance modulus of $(m - M)_0^{\rm Virgo} = 31.03 \pm 0.14$ mag (Paper VI), these relative measurements convert to absolute Fornax cluster distance moduli of

1. $(m - M)_0^{\rm Fornax} = 31.21 \pm 0.28$ mag (all values),
2. $(m - M)_0^{\rm Fornax,SBF} = 31.26 \pm 0.23$ mag (SBF-based measures),
3. $(m - M)_0^{\rm Fornax,LFs} = 31.13 \pm 0.12$ mag (luminosity functions), and
4. $(m - M)_0^{\rm Fornax,kin} = 31.18 \pm 0.15$ mag (kinematic tracers).

The weighted mean of the latter three values is

$$(m - M)_0^{\rm Fornax,stat} = 31.18 \pm 0.17 \text{ mag}$$
$$\text{or D} = 17.2^{+1.4}_{-1.3} \text{ Mpc}.$$

As for the Coma cluster, relative distance moduli have been determined with respect to the Virgo and Fornax clusters and the Leo I group. The 23 post-1990 relative Coma–Virgo distance moduli (of which 22 have associated uncertainties) yield a straight weighted mean of $\Delta(m - M)_0^{\rm Coma-Virgo} = 3.75 \pm 0.23$ mag. The subset of six kinematics-based relative distance measures (TFR and Fundamental Plane) result in $\Delta(m - M)_0^{\rm Coma-Virgo} = 3.63 \pm 0.22$ mag. (None of the other possible subsets of

Coma–Virgo relative distance determinations reach the threshold where a statistical analysis becomes meaningful.)

Combining the weighted mean of the full set of measurements with our preferred Virgo cluster distance modulus yields

$$(m - M)_0^{\rm Coma} = 34.78 \pm 0.27 \text{ mag}$$
$$\text{or D} = 90.4^{+11.9}_{-10.6} \text{ Mpc},$$

while the kinematics-based distances yield

$$(m - M)_0^{\rm Coma} = 34.66 \pm 0.26 \text{ mag}$$
$$\text{or D} = 85.5^{+10.9}_{-9.6} \text{ Mpc}.$$

Second, a significant number of relative distance moduli with respect to the Leo I group were published by Gregg (1997), in the form of Coma distance moduli based on a variety of independent calibrations. His unweighted mean distance modulus to the Coma cluster, $(m - M)_0 = 34.90 \pm 0.13$ mag, is based on a mean distance ratio of $D_{\rm Coma}/D_{\rm Leo\ I} = 8.84 \pm 0.23$, corresponding to $\Delta(m - M)_0^{\rm Coma-Leo\ I} = 4.73 \pm 0.06$ mag. However, on closer inspection, the data set underlying these values raises a number of concerns. If one calculates the individual Coma/Leo I distance ratios using the values included in his Table 3, the central value of the resulting ratio is $D_{\rm Coma}/D_{\rm Leo\ I} = 8.84$ for every single, presumably independent calibration method.

In the preamble to his Section 3, Gregg (1997) states that he derived the Leo I distances included in his Table 3 on the basis of four different calibration methods. In addition, he states that the Coma cluster distances included are based on the zero-point calibration of the distance–velocity dispersion relation for Coma. If the Leo I calibration methods applied were indeed independent (which we have no reason to doubt), this very tightly defined central value is statistically highly unlikely. Therefore, we decided to discard Gregg's (1997) measurements, since we cannot ascertain their integrity. This has unintended consequences, however, because a number of subsequently published Coma distance moduli were also based on this result (Cassisi & Salaris 1998; Salaris & Cassisi 1998), and so we were forced to discard them.

Thomsen et al. (1997) provided the only independent relative distance modulus between the Coma cluster and the Leo I group, $\Delta(m - M)_0^{\rm Coma-Leo\ I} = 4.89 \pm 0.30$ mag. Although this measurement is consistent, within the 1σ uncertainties, with the value promoted by Gregg (1997), we will nevertheless refrain from further analysis of the Coma–Leo I distance differential.

Finally, van den Bergh (1994) cited a distance ratio of $D_{\rm Coma}/D_{\rm Fornax} = 5.25 \pm 0.38$, although without providing provenance. This corresponds to a relative distance modulus between the Coma and Fornax clusters of $\Delta(m - M)_0^{\rm Coma-Fornax} = 3.60 \pm 0.15$ mag. Combining this with the Fornax cluster distance moduli obtained above, we obtain

$$(m - M)_0^{\rm Coma} = 34.78 \pm 0.23 \text{ mag},$$
$$= 34.81 \pm 0.32 \text{ mag}, \text{ and}$$
$$= 35.01 \pm 0.21 \text{ mag}$$

for a subset of relative Coma–Virgo distance moduli, the full set of Coma–Virgo measures, and our best direct estimate for the Virgo cluster distance, respectively.

5. A Distance Framework out to 100 Mpc

In this paper, we have considered the body of published distance moduli to the Fornax and Coma clusters, with specific emphasis on the period since 1990. We carefully homogenized our final catalogs of distance moduli onto the distance scale established in Papers I–VI. We assessed systematic differences associated with the use of specific tracers and consequently discarded results based on application of the TFR and of luminosity functions.

We recommend "best" weighted relative distance moduli for the Fornax and Coma clusters with respect to the Virgo cluster benchmark of $\Delta(m - M)_0^{\rm Fornax\ -\ Virgo} = 0.18 \pm 0.28$ mag and $\Delta(m - M)_0^{\rm Coma\ -\ Virgo} = 3.75 \pm 0.23$ mag. On balance, the set of weighted mean distance moduli we derived as most representative of the clusters' distances is as follows:

$$(m - M)_0^{\rm Fornax} = 31.41 \pm 0.15 \text{ mag and}$$
$$= 31.21 \pm 0.28 \text{ mag},$$
$$(m - M)_0^{\rm Coma} = 34.99 \pm 0.38 \text{ mag and}$$
$$= 34.78 \pm 0.27 \text{ mag}.$$

For each cluster, this first distance modulus is the result of our analysis of the direct, absolute distance moduli published since 1990, while the second modulus is based on the relative measures published during the same period.

Interestingly, while the absolute and relative distance moduli for both clusters are mutually consistent within the uncertainties, the relative distance moduli yield absolute distances that are shorter by $\sim$0.20 mag, or about 1σ. It is unclear what may have caused this small difference for both clusters; investigation of the cause is beyond the scope of the present paper since it requires careful examination of the individual distances comprising the tracers commonly used in this field. It is unlikely that line-of-sight depth effects are to blame (e.g., Jerjen 2003; Dunn & Jerjen 2006; Blakeslee et al. 2009), given that most individual galaxies and galaxy samples in both of our clusters comprise the same or similar objects. We speculate that lingering uncertainties in the underlying absolute distance scale appear to have given rise to a systematic uncertainty of order 0.20 mag.

This concludes our series of papers aimed at establishing a robust and internally consistent, statistically validated distance framework out to distances of order 100 Mpc. Our recommended distances to the Fornax and Coma clusters quoted above should be read in tandem with the distance moduli we derived and recommend for the Galactic Center (Paper IV), the Magellanic Clouds (Papers I and III), the M31 group (Paper II), NGC 4258 (Herrnstein et al. 1999), and the Virgo cluster (Paper VI); see Table 3 in Paper VI for the full set of recommended distance moduli.

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References

Ajhar, E. A., Tonry, J. L., Blakeslee, J. P., et al. 2001, ApJ, 559, 584
Allen, P. D., & Shanks, T. 2004, MNRAS, 347, 1011
Baum, W. A. 1998, AJ, 116, 31
Baum, W. A., Hammergren, M., Groth, E. J., et al. 1995, AJ, 110, 2537
Baum, W. A., Hammergren, M., Thomsen, B., et al. 1996, AAS, 189, 12.04

Baum, W. A., Hammergren, M., Thomsen, B., et al. 1997, AJ, 113, 1483
Bellazzini, M., Ferraro, F. R., Sollima, A., et al. 2004, A&A, 424, 199
Bernardi, M., Alonso, M. V., da Costa, L. N., et al. 2002, AJ, 123, 2990
Bernstein, G. M., Guhathakurta, P., Raychaudhury, S., et al. 1994, AJ, 107, 1962
Blakeslee, J. P. 2013, in IAU Symp. 289, Advancing the Physics of Cosmic Distances, ed. R. de Grijs (Cambridge: Cambridge Univ. Press), 304
Blakeslee, J. P., Cantiello, M., Mei, S., et al. 2010, ApJ, 724, 657
Blakeslee, J. P., Jordán, A., Mei, S., et al. 2009, ApJ, 694, 556
Blakeslee, J. P., Vazdekis, A., & Ajhar, E. A. 2001, MNRAS, 320, 193
Bothun, G. D., Impey, C. D., & Malin, D. F. 1991, ApJ, 376, 404
Bridges, T. J., Hanes, D. A., & Harris, W. E. 1991, AJ, 101, 469
Brighenti, F., & Mathews, W. G. 2002, ApJ, 567, 130
Brocato, E., Capaccioli, M., & Condelli, M. 1998, MmSAI, 69, 155
Bureau, M., Mould, J. R., & Staveley-Smith, L. 1996, ApJ, 463, 60
Cantiello, M., Blakeslee, J., Raimondo, G., et al. 2007, ApJ, 668, 130
Cantiello, M., Grado, A., Blakeslee, J. P., et al. 2013, A&A, 552, A106
Carter, D., Goudfrooij, P., Mobasher, B., et al. 2008, ApJS, 176, 424
Cassisi, S., & Salaris, M. 1998, MmSAI, 69, 127
Ciardullo, R., Jacoby, G. H., & Engle, K. A. 1990, BAAS, 22, 1312
Ciardullo, R., Jacoby, G. H., Ford, H. C., et al. 1989, ApJ, 339, 53
Ciardullo, R., Jacoby, G. H., & Tonry, J. L. 1993, ApJ, 419, 479
Courtois, H. M., & Tully, R. B. 2012, ApJ, 749, 174
Crandall, S., & Ratra, B. 2015, ApJ, 815, 87
de Grijs, R., & Bono, G. 2014, AJ, 148, 17, (Paper II)
de Grijs, R., & Bono, G. 2015, AJ, 149, 179, (Paper III)
de Grijs, R., & Bono, G. 2016, ApJS, 227, 5, (Paper IV)
de Grijs, R., & Bono, G. 2017, ApJS, 232, 22, (Paper V)
de Grijs, R., & Bono, G. 2020, ApJS, 246, 3, (Paper VI)
de Grijs, R., Wicker, J. E., & Bono, G. 2014, AJ, 147, 122, (Paper I)
de Vaucouleurs, G. 1993, ApJ, 415, 10
Dirsch, B., Richtler, T., Geisler, D., et al. 2003, AJ, 125, 1908
Drinkwater, M. J., Gregg, M. D., & Colless, M. 2001, ApJL, 548, L139
Dunn, L. P., & Jerjen, H. 2006, AJ, 132, 1384
Feldmeier, J. J., Jacoby, G. H., & Phillips, M. M. 2007, ApJ, 657, 76
Ferrarese, L., Mould, J. R., Kennicutt, R. C., et al. 2000, ApJ, 529, 745
Forte, J. C., Faifer, F., & Geisler, D. 2005, MNRAS, 357, 56
Freedman, W. L., Madore, B. F., Gibson, B. K., et al. 2001, ApJ, 553, 47
Fukugita, M., Okamura, S., Tarusawa, K., et al. 1991, ApJ, 376, 8
Geisler, D., & Forte, J. C. 1990, ApJL, 350, L5
Gómez, M., Richtler, T., Infante, L., et al. 2001, A&A, 371, 875
Gregg, M. D. 1997, NewA, 1, 363
Grillmair, C. J., Forbes, D. A., Brodie, J. P., et al. 1999, AJ, 117, 167
Harris, W. E. 1996, AJ, 112, 1487
Harris, W. E., Kavelaars, J. J., Hanes, D. A., et al. 2009, AJ, 137, 3314
Herrnstein, J. R., Moran, J. M., Greenhill, L. J., et al. 1999, Natur, 400, 539
Hilker, M., Infante, L., & Richtler, T. 1999, A&AS, 138, 55
Hislop, L., Mould, J., Schmidt, B., et al. 2011, ApJ, 733, 75
Jacoby, G. H. 1997, in The Extragalactic Distance Scale, ed. M. Livio, M. Donahue, & N. Panagia (Cambridge: Cambridge Univ. Press), 197
Jang, I. S., Hatt, D., Beaton, R. L., et al. 2018, ApJ, 852, 60
Jensen, J. B., Tonry, J. L., Barris, B. J., et al. 2003, ApJ, 583, 712
Jensen, J. B., Tonry, J. L., & Luppino, G. A. 1998, ApJ, 505, 111
Jensen, J. B., Tonry, J. L., & Luppino, G. A. 1999, ApJ, 510, 71
Jerjen, H. 2003, A&A, 398, 63
Jordán, A., McLaughlin, D. E., Côté, P., et al. 2006, ApJL, 651, L25
Kashikawa, N., Sekiguchi, M., Doi, M., et al. 1998, ApJ, 500, 750
Kavelaars, J. J., Harris, W. E., Hanes, D. A., et al. 2000, ApJ, 533, 125
Kennicutt, R. C., Stetson, P. B., Saha, A., et al. 1998, ApJ, 498, 181
Kissler-Patig, M., Kohle, S., Hilker, M., et al. 1997, A&A, 319, 470
Kohle, S., Kissler-Patig, M., Hilker, M., et al. 1996, A&A, 309, L39
Lee, M. G., & Jang, I. S. 2016, ApJ, 819, 77
Lindblad, P. O. 1999, A&ARv, 9, 221
Liu, M. C., & Graham, J. R. 2001, ApJL, 557, L31
Liu, M. C., Graham, J. R., & Charlot, S. 2002, ApJ, 564, 216
Łokas, E. L., & Mamon, G. A. 2003, MNRAS, 343, 401
Madore, B. F., Freedman, W. L., Kennicutt, R. C., et al. 1996, AAS, 189, 108.04
Madore, B. F., Freedman, W. L., Silbermann, N., et al. 1998, Natur, 395, 47
Madore, B. F., Freedman, W. L., Silbermann, N., et al. 1999, ApJ, 515, 29
Masters, K. L., Springob, C. M., Haynes, M. P., et al. 2006, ApJ, 653, 861
McMillan, R., Ciardullo, R., & Jacoby, G. H. 1993, ApJ, 416, 62
Neill, J. D., Seibert, M., Tully, R. B., et al. 2014, ApJ, 792, 129
Ostrov, P. G., Forte, J. C., & Geisler, D. 1998, AJ, 116, 2854
Prosser, C. F., Kennicutt, R. C., Bresolin, F., et al. 1999, ApJ, 525, 80
Richtler, T., Drenkhahn, G., Gómez, M., et al. 2000, in Proc. ESO Astrophysics Symp., From Extrasolar Planets to Cosmology: VLT Opening Symp., ed. J. Bergeron & A. Renzini (Berlin: Springer), 259
Riess, A. G., Casertano, S., Yuan, W., et al. 2019, ApJ, 876, 85
Riess, A. G., Macri, L., Casertano, S., et al. 2009, ApJ, 699, 539
Riess, A. G., Macri, L. M., Hoffmann, S. L., et al. 2016, ApJ, 826, 56
Rood, H. J., & Williams, B. A. 1993, MNRAS, 263, 211
Russell, D. G. 2004, ApJ, 607, 241
Russell, D. G. 2009, JApA, 30, 93
Salaris, M., & Cassisi, S. 1998, MNRAS, 298, 166
Schaefer, B. E. 2008, AJ, 135, 112
Shanks, T. 1997, MNRAS, 290, L77
Silbermann, N. A., Harding, P., Ferrarese, L., et al. 1999, ApJ, 515, 1
Sorce, J. G., Courtois, H. M., Tully, R. B., et al. 2013, ApJ, 765, 94
Sorce, J. G., Tully, R. B., & Courtois, H. M. 2012, ApJL, 758, L12
Sorce, J. G., Tully, R. B., Courtois, H. M., et al. 2014, MNRAS, 444, 527
Springob, C. M., Masters, K. L., Haynes, M. P., et al. 2007, ApJS, 172, 599
Tammann, G. A., & Sandage, A. 1999, in ASP Conf. Ser. 167, Harmonizing Cosmic Distance Scales in a Post-Hipparcos Era, ed. D. Egret & A. Heck (San Francisco, CA: ASP), 204
Terlevich, A. I., Kuntschner, H., Bower, R. G., et al. 1999, MNRAS, 310, 445
Thomsen, B., Baum, W. A., Hammergren, M., et al. 1997, ApJL, 483, L37
Tikhonov, N. A., & Galazutdinova, O. A. 2011, AstL, 37, 766
Tonry, J. L. 1991a, BAAS, 23, 956
Tonry, J. L. 1991b, ApJL, 373, L1
Tonry, J. L. 1997, in The Extragalactic Distance Scale, ed. M. Livio, M. Donahue, & N. Panagia (Cambridge: Cambridge Univ. Press), 297
Tonry, J. L., Blakeslee, J. P., Ajhar, E. A., et al. 1997, ApJ, 475, 399
Tonry, J. L., Blakeslee, J. P., Ajhar, E. A., et al. 2000, ApJ, 530, 625
Tonry, J. L., Dressler, A., Blakeslee, J. P., et al. 2001, ApJ, 546, 681
Tully, R. B. 1998, MmSAI, 69, 237
Tully, R. B., & Courtois, H. M. 2012, ApJ, 749, 78
Tully, R. B., Courtois, H. M., Dolphin, A. E., et al. 2013, AJ, 146, 86
Tully, R. B., & Pierce, M. J. 2000, ApJ, 533, 744
Tully, R. B., Rizzi, L., Shaya, E. J., et al. 2009, AJ, 138, 323
van den Bergh, S. 1994, PASP, 106, 1113
van Dokkum, P. G., Abraham, R., Merritt, A., et al. 2015, ApJL, 798, L45
Villegas, D., Jordán, A., Peng, E. W., et al. 2010, ApJ, 717, 603
Watanabe, M., Yasuda, N., Itoh, N., et al. 2001, ApJ, 555, 215
Whitmore, B. C. 1997, in The Extragalactic Distance Scale, ed. M. Livio, M. Donahue, & N. Panagia (Cambridge: Cambridge Univ. Press), 254