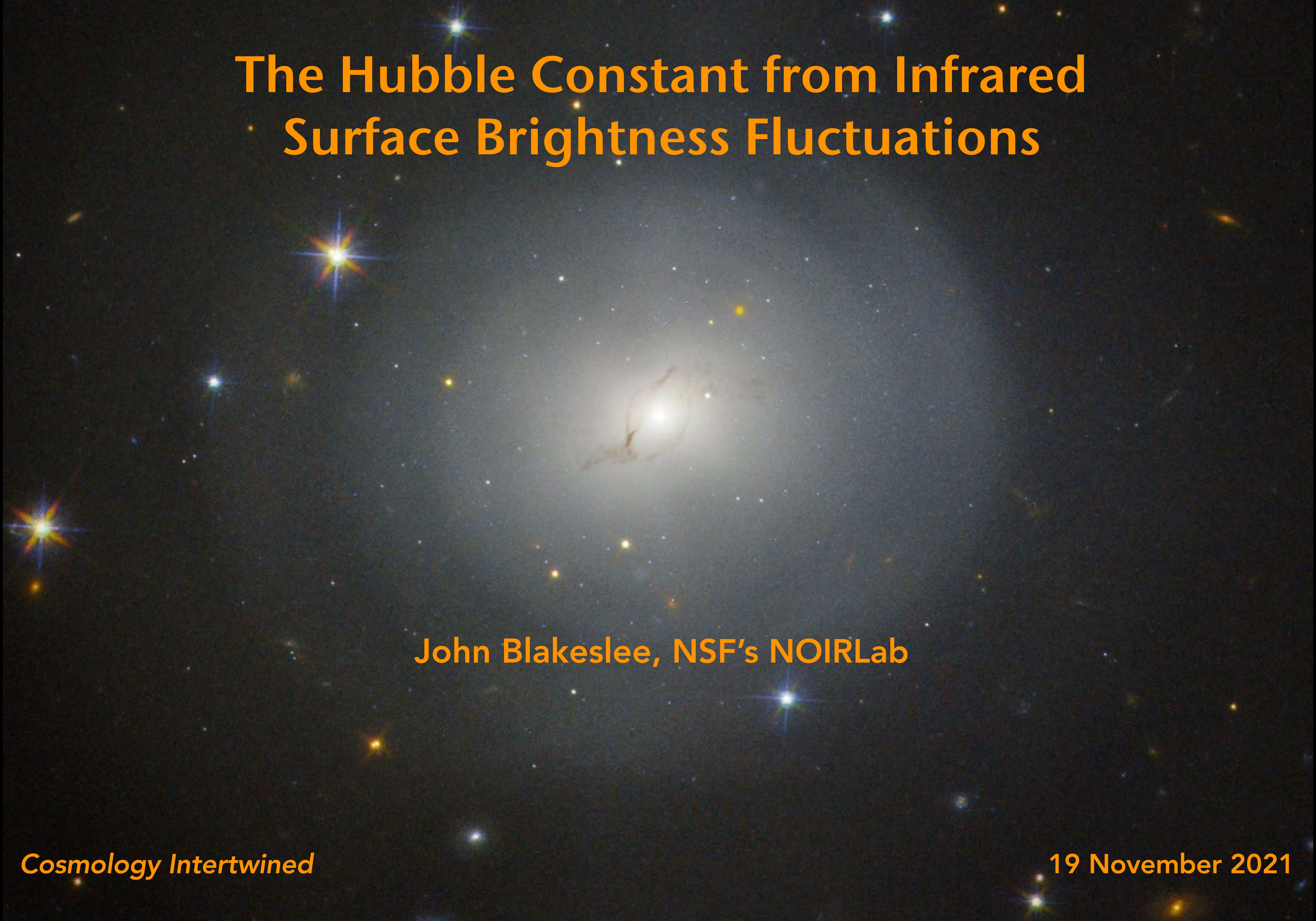
The Hubble Constant from Infrared Surface Brightness Fluctuations

John Blakeslee, NSF's NOIRLab



GW170817
host NGC4339

Cosmology Intertwined

19 November 2021

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Measuring Distances to Low-luminosity Galaxies Using Surface Brightness Fluctuations

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Abstract

We present an in-depth study of surface brightness fluctuations (SBFs) in low-luminosity stellar systems. Using the MIST models, we compute theoretical predictions for absolute SBF magnitudes in the LSST, HST ACS/WFC, and proposed Roman Space Telescope filter systems. We compare our calculations to observed SBF–color relations of systems that span a wide range of age and metallicity. Consistent with previous studies, we find that single-age population models show excellent agreement with observations of low-mass galaxies with $0.5 \lesssim g - i \lesssim 0.9$. For bluer galaxies, the observed relation is better fit by models with composite stellar populations. To study SBF recovery from low-luminosity systems, we perform detailed image simulations in which we inject fully populated model galaxies into deep ground-based images from real observations. Our simulations show that LSST will provide data of sufficient quality and depth to measure SBF magnitudes with precisions of ∼0.2–0.5 mag in ultra-faint ($10^4 \leqslant M_\star/M_\odot \leqslant 10^5$) and low-mass classical ($M_\star \leqslant 10^7\ M_\odot$) dwarf galaxies out to ∼4 Mpc and ∼25 Mpc, respectively, within the first few years of its deep-wide-fast survey. Many significant practical challenges and systematic uncertainties remain, including an irreducible "sampling scatter" in the SBFs of ultra-faint dwarfs due to their undersampled stellar mass functions. We nonetheless conclude that SBFs in the new generation of wide-field imaging surveys have the potential to play a critical role in the efficient confirmation and characterization of dwarf galaxies in the nearby universe.

Unified Astronomy Thesaurus concepts: Dwarf galaxies (416); Distance indicators (394); Stellar populations (1622); Low surface brightness galaxies (940)

1. Introduction

Current and future generations of imaging surveys—which are simultaneously wide, deep, and sharp—will uncover thousands of diffuse dwarf galaxy candidates beyond the Local Group (e.g., Bennet et al. 2017; Müller et al. 2017; Greco et al. 2018; Prole

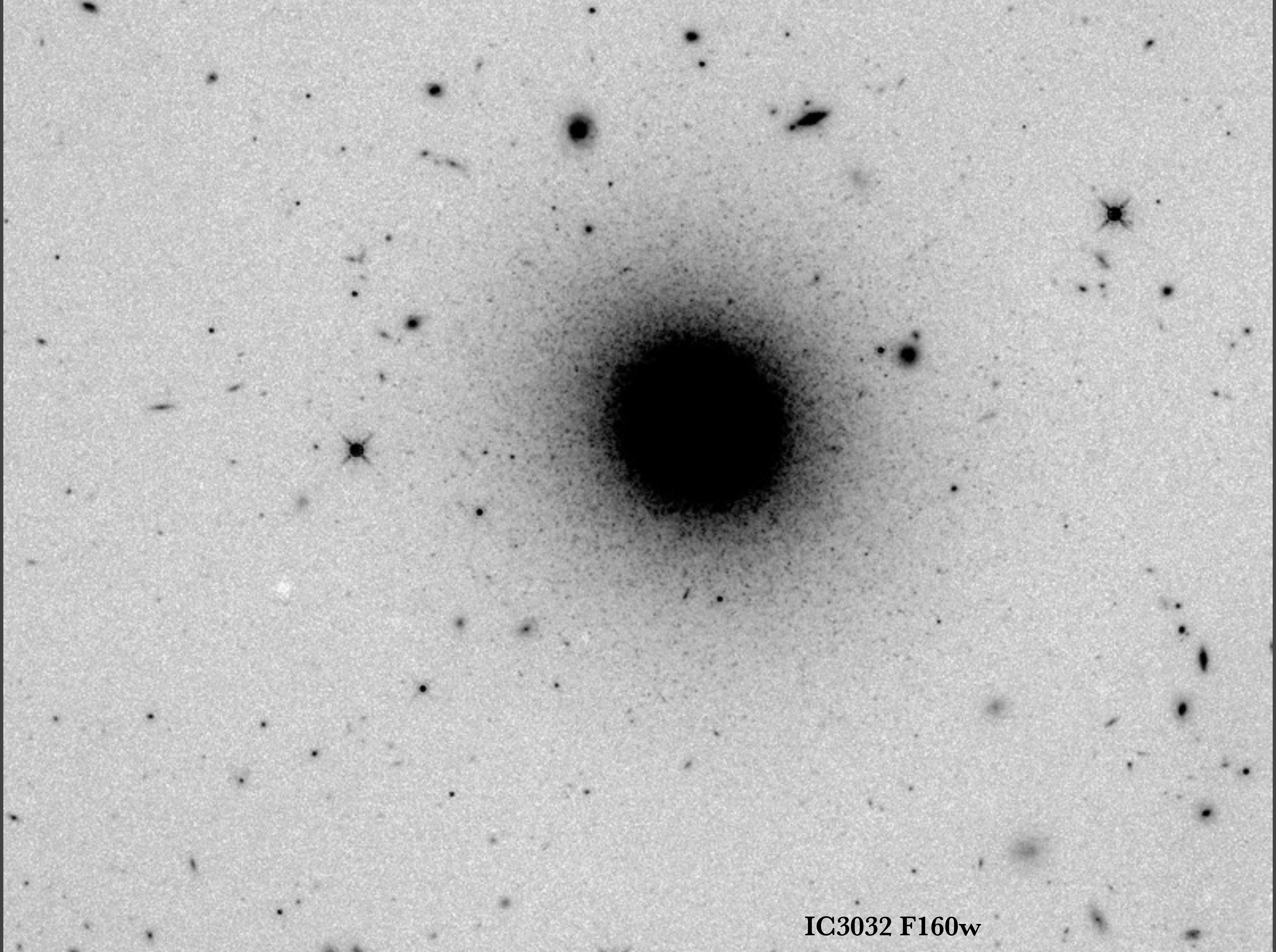
cosmic distance ladder, they require the detection of individual stars, which significantly limits the range of distances that they can probe from the ground.

Surface brightness fluctuations (SBFs) provide a method for measuring distances to semiresolved galaxies using imaging data alone, making it one of the most promising tools for

SBF Models at 3 distances

(Greco, van Dokkum, Danieli, Carlsten, Conry 2021, ApJ)

Simulated ground-based data, Rubin/LSST-like 0.6” seeing.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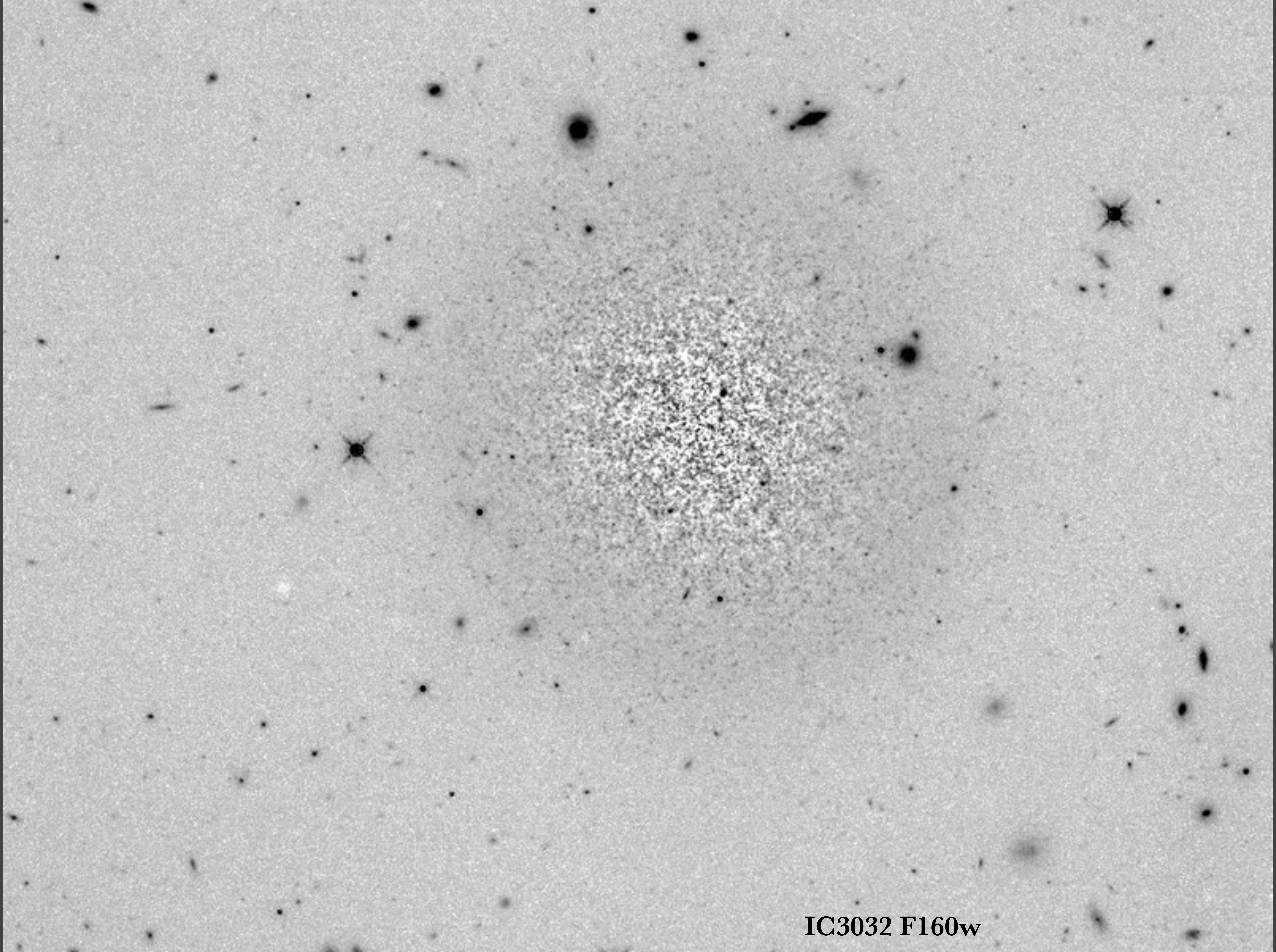
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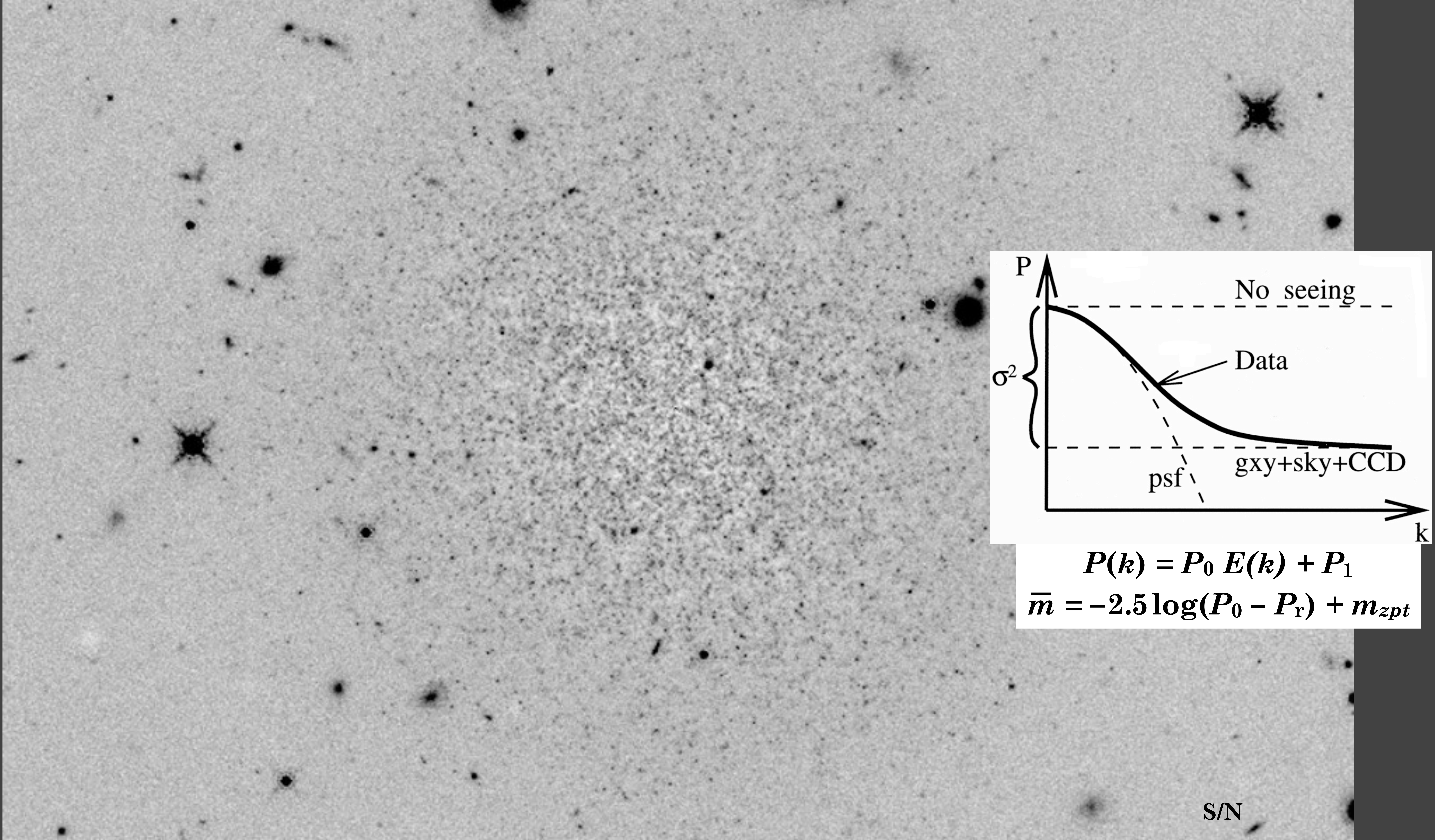

$$P(k) = P_0\, E(k) + P_1$$

$$\overline{m} = -2.5 \log(P_0 - P_r) + m_{zpt}$$

S/N

The Astrophysical Journal Supplement Series, 255:21 (17pp), 2021 August https://doi.org/10.3847/1538-4365/ac01e7

Infrared Surface Brightness Fluctuation Distances for MASSIVE and Type Ia Supernova Host Galaxies*

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Abstract

We measured high-quality surface brightness fluctuation (SBF) distances for a sample of 63 massive early-type galaxies using the WFC3/IR camera on the Hubble Space Telescope. The median uncertainty on the SBF distance measurements is 0.085 mag, or 3.9% in distance. Achieving this precision at distances of 50–100 Mpc required significant improvements to the SBF calibration and data analysis procedures for WFC3/IR data. Forty-two of the galaxies are from the MASSIVE Galaxy Survey, a complete sample of massive galaxies within ∼100 Mpc; the SBF distances for these will be used to improve the estimates of the stellar and central supermassive black hole masses in these galaxies. Twenty-four of the galaxies are Type Ia supernova hosts, useful for calibrating SN Ia distances for early-type galaxies and exploring possible systematic trends in the peak luminosities. Our results demonstrate that the SBF method is a powerful and versatile technique for measuring distances to galaxies with evolved stellar populations out to 100 Mpc and constraining the local value of the Hubble constant.

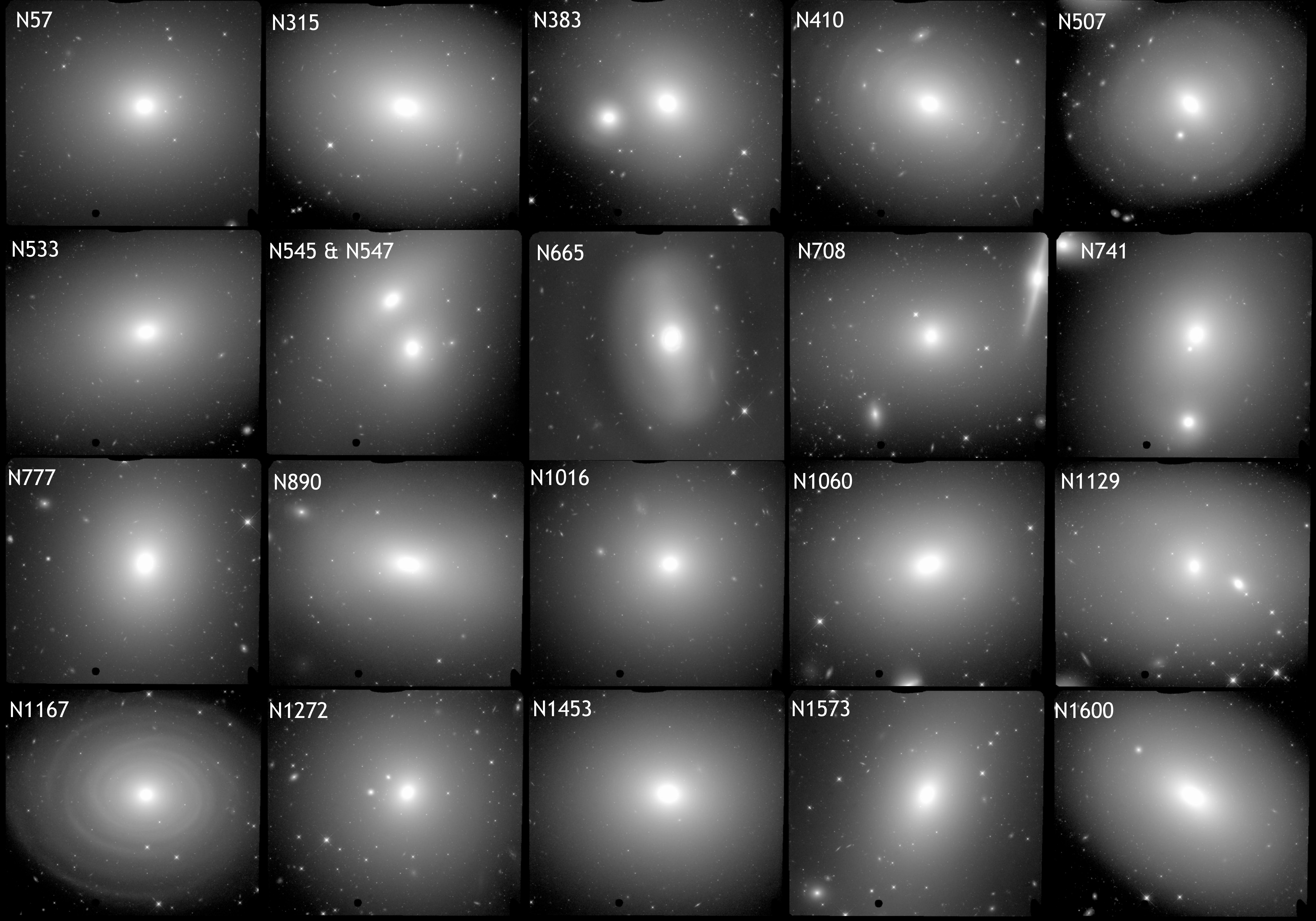
Unified Astronomy Thesaurus concepts: Galaxy distances (590); Distance indicators (394); Distance measure (395); Elliptical galaxies (456); Giant elliptical galaxies (651); Lenticular galaxies (915)

Supporting material: figure set

1. Introduction

To understand the expansion history and contents of the universe, we must be able to measure accurate extragalactic distances with high precision and low systematic uncertainty well out into the Hubble flow. We have measured high-precision surface brightness fluctuation (SBF; Tonry & Schneider 1988) distances to 63 galaxies out to 100 Mpc to answer specific questions related to the most important issues in the extragalactic distance scale (e.g., Cantiello et al. 2018; Verde et al. 2019; Blakeslee et al. 2021). The SBF technique uses the Poisson statistics of discrete stars to determine the mean brightness of red giant branch (RGB) stars in a distant methods (Jensen et al. 2003; Blakeslee et al. 2009). It does not require the serendipitous discovery of a supernova (SN) explosion or assumptions about the relative velocities and distances of elliptical and spiral galaxies in a given group or galaxy cluster (Riess et al. 2021, for example). SBF reaches distances far greater than Cepheid variable stars or other techniques that depend on resolving individual stars such as the tip of the RGB (Freedman et al. 2020, and references therein). It is also independent of the dynamics or mass of the target galaxy.

By measuring the power in the spatial Fourier power spectrum of an early-type galaxy (ETG) with globular clusters (GCs) and background galaxies removed, we can determine the mean


N57
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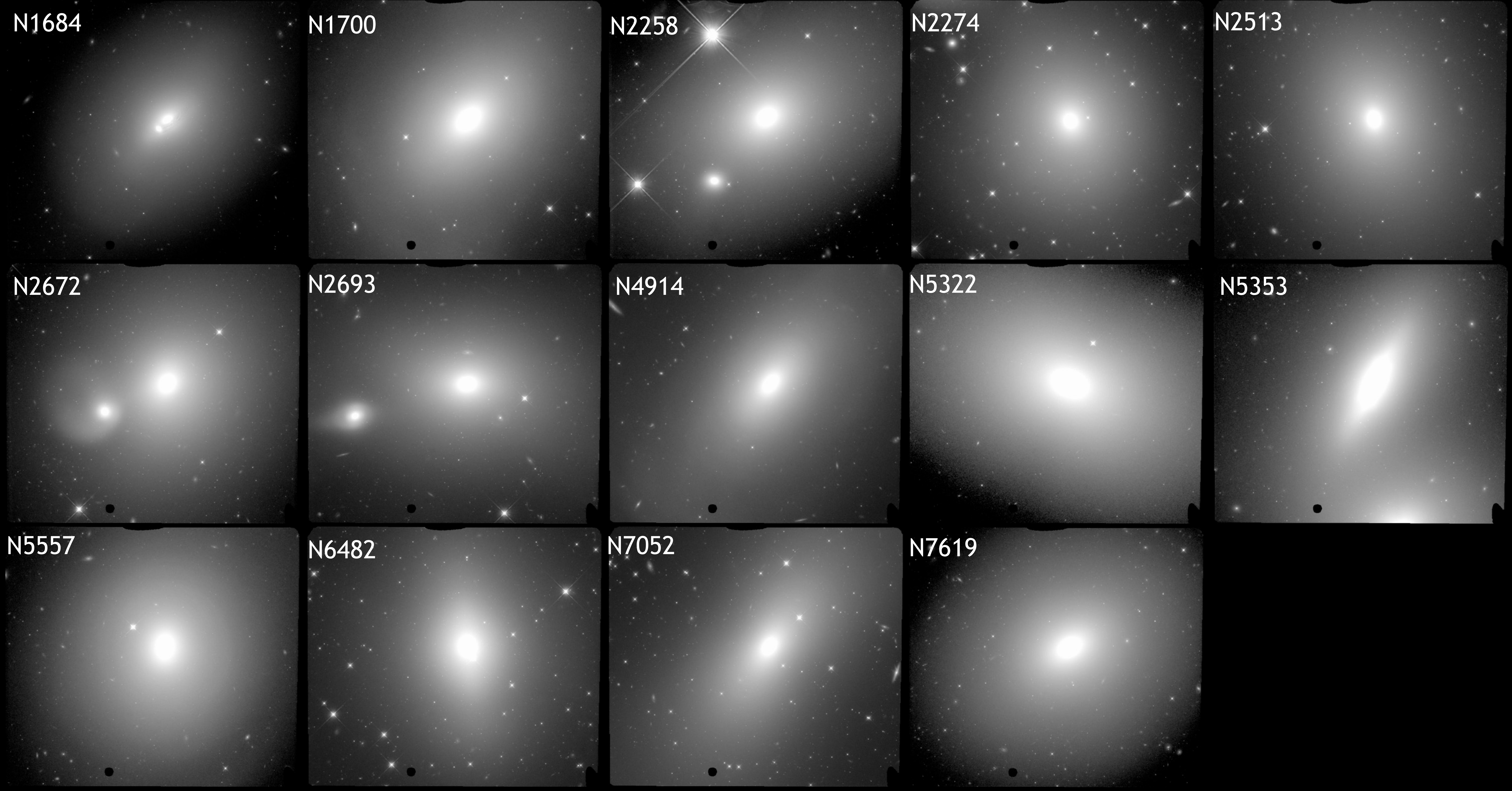
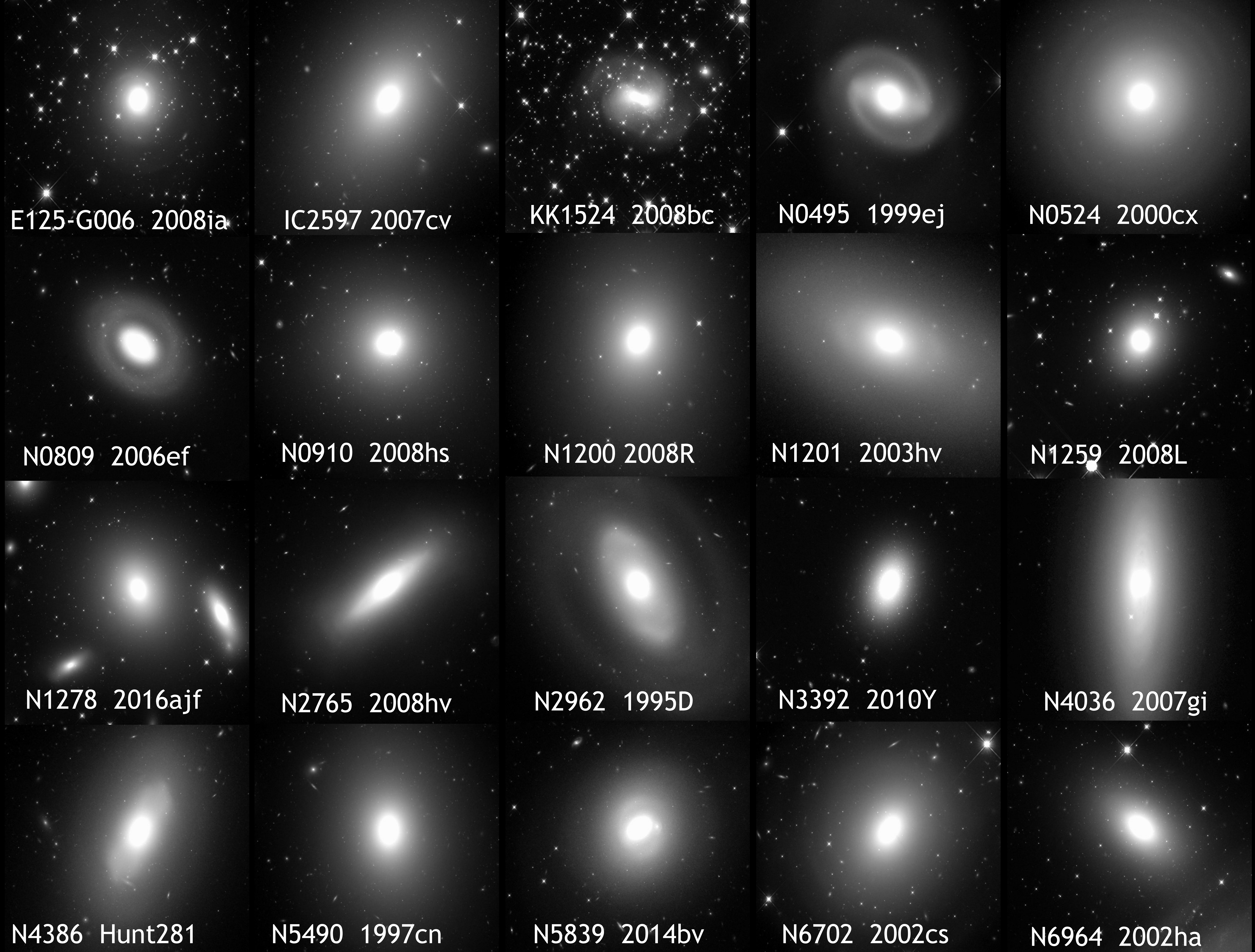
N1453
N1573
N1600



A complete sample of the most massive galaxies ($M_K < -25.5$) in all environments within ~75 Mpc; plus another six out to ~100 Mpc, and …



20 hosts of SNe Ia.

Example WFC3/IR
SBF reduction

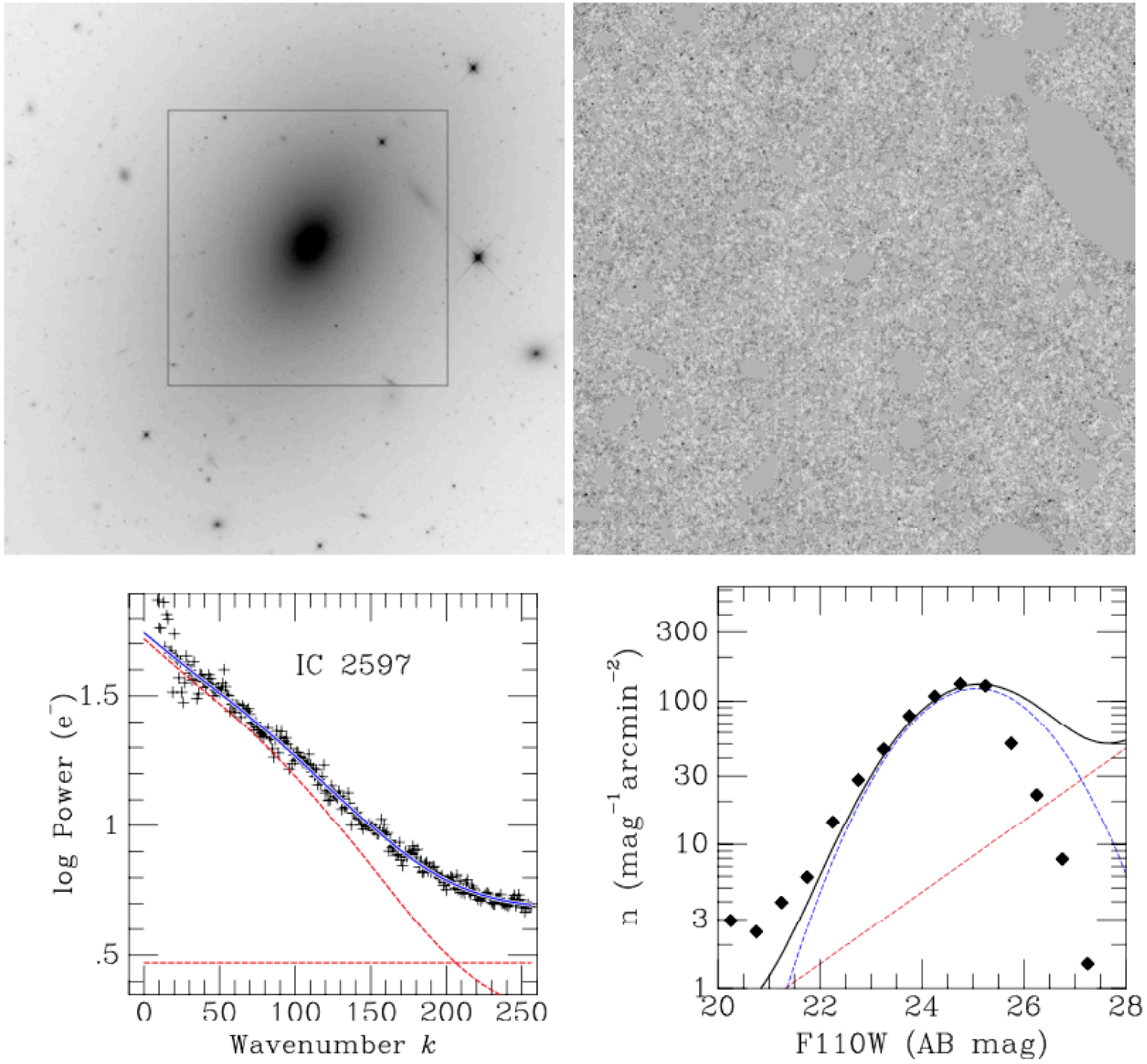


Figure 8. Combined figure for IC 2597.

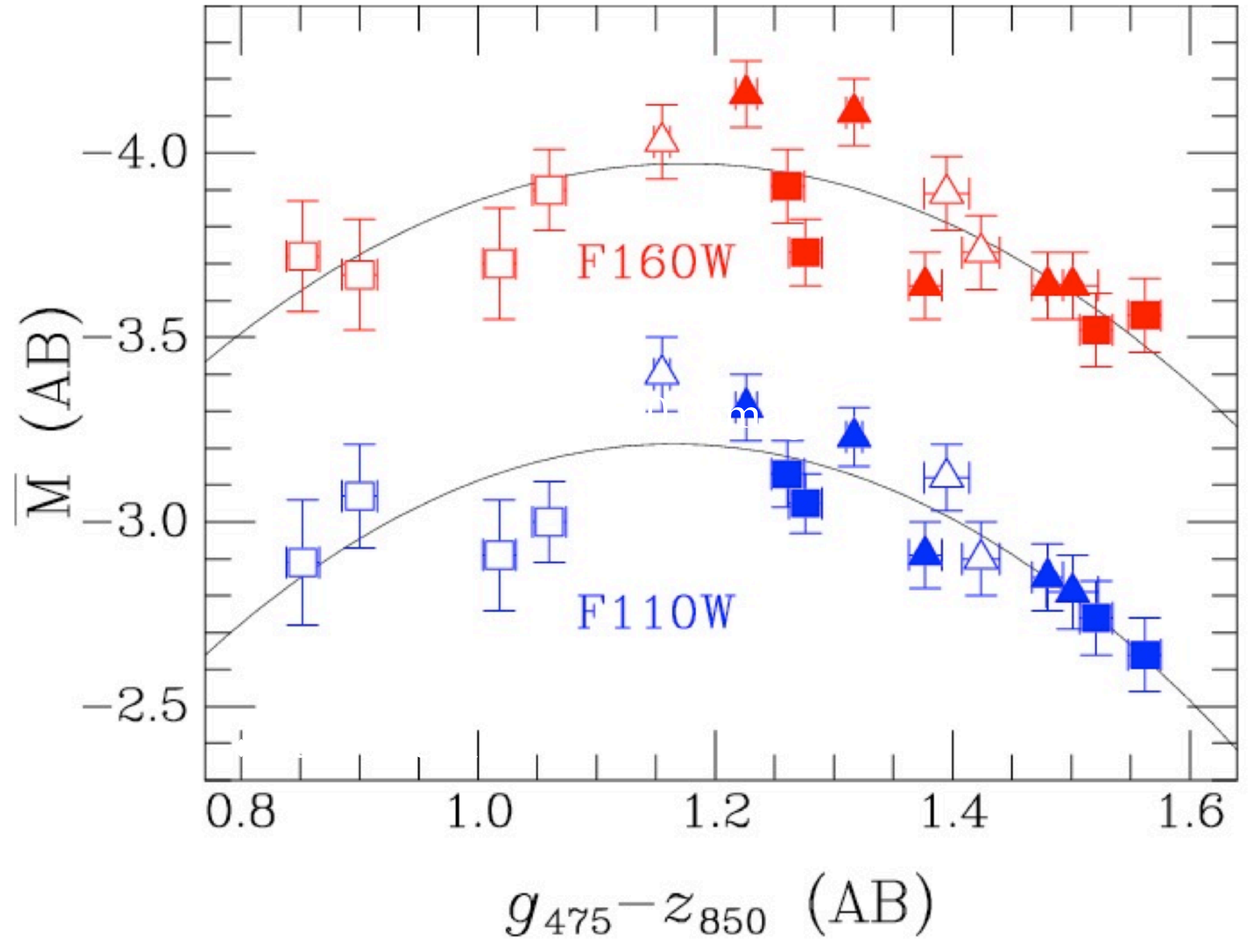
Jensen, Blakeslee et al. 2021

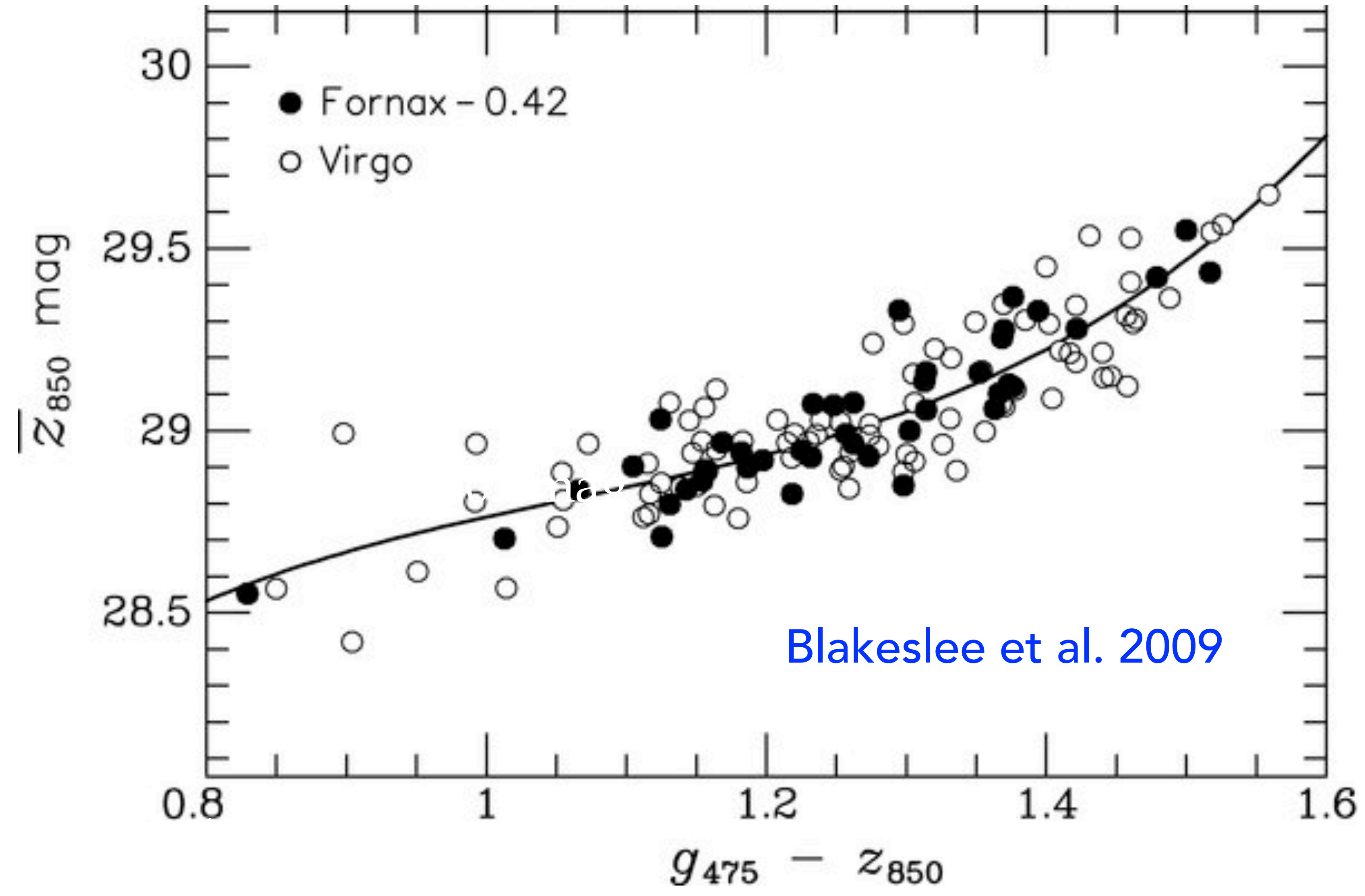
Typical WFC3/IR F110W SBF Error Budget

Source	(m−M) sigma
PSF normalization	0.02 mag
Sky background	0.02 mag
External sources fit (GC+gal)	0.03 mag
Total SBF power spectrum fit	0.03 mag
(g-z) color from PanSTARRS + extinction uncertainty	0.03 mag
Calibration rms scatter, for red galaxies	0.06 mag
Total distance uncertainty (random)	~ 0.084 mag (4% in distance)

Cepheid-based zero-point uncertainty ~ 4.2%.

Jensen et al. 2015





Blakeslee et al. 2009

Jensen, Blakeslee et al. 2021

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The Hubble Constant from Infrared Surface Brightness Fluctuation Distances*

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Abstract

We present a measurement of the Hubble constant H_0 from surface brightness fluctuation (SBF) distances for 63 bright, mainly early-type galaxies out to 100 Mpc observed with the WFC3/IR on the Hubble Space Telescope (HST). The sample is drawn from several independent HST imaging programs using the F110W bandpass, with the majority of the galaxies being selected from the MASSIVE survey. The distances reach the Hubble flow with a median statistical uncertainty per measurement of 4%. We construct the Hubble diagram with these IR SBF distances and constrain H_0 using four different treatments of the galaxy velocities. For the SBF zero-point calibration, we use both the existing tie to Cepheid variables, updated for consistency with the latest determination of the distance to the Large Magellanic Cloud from detached eclipsing binaries, and a new tie to the tip of the red giant branch (TRGB) calibrated from the maser distance to NGC 4258. These two SBF calibrations are consistent with each other and with theoretical predictions from stellar population models. From a weighted average of the Cepheid and TRGB calibrations, we derive $H_0 = 73.3 \pm 0.7 \pm 2.4$ km s^{-1} Mpc^{-1}, where the error bars reflect the statistical and systematic uncertainties. This result accords well with recent measurements of H_0 from Type Ia supernovae, time delays in multiply lensed quasars, and water masers. The systematic uncertainty could be reduced to below 2% by calibrating the SBF method with precision TRGB distances for a statistical sample of massive early-type galaxies out to the Virgo cluster measured with the James Webb Space Telescope.

Unified Astronomy Thesaurus concepts: Galaxy distances (590); Distance indicators (394); Cosmological parameters (339); Early-type galaxies (429); Observational cosmology (1146)

1. Introduction

Ever since Cook's first expedition to Tahiti to observe the transit of Venus in 1769 (Cook & Mohr 1771), astronomers have been going to great lengths to measure accurate distances and to corroborate their results through multiple independent routes (see Sawyer Hogg 1947). Distances enable us to convert the observed properties of planets, stars, galaxies, black holes, and cosmic explosions into physical quantities. They reveal the structure of the Local Supercluster, map the peculiar motions, and constrain the present-day expansion rate, parameterized by the Hubble constant H_0. The successful gauging of distances beyond our planet has been the key to understanding the universe.

uncertainties on the local expansion rate. For instance, using Type Ia supernovae (SNe Ia) tied to Cepheids, in turn calibrated by a combination of Galactic parallaxes, DEBs in the LMC, and the maser distance to NGC 4258, Riess et al. (2019) find $H_0 = 74.03 \pm 1.42$ km s^{-1} Mpc^{-1}. However, Freedman et al. (2020) conclude $H_0 = 69.6 \pm 0.8 \pm 1.7$ km s^{-1} Mpc^{-1} from a calibration of SNe Ia via the tip of the red giant branch (TRGB), assuming the DEB distance to the LMC. These two studies, which report precise values of H_0 that differ by nearly 2σ, use the same first and third rungs in their distance ladders but differ in the intermediate step (Cepheids versus TRGB).

Also using the LMC-based TRGB method to calibrate SNe Ia but with a different treatment of the extinction for the

$$H_0 = 73.4 \pm 0.7 \pm 3.1$$

(stat) (sys)

Cepheid-based SBF calibration

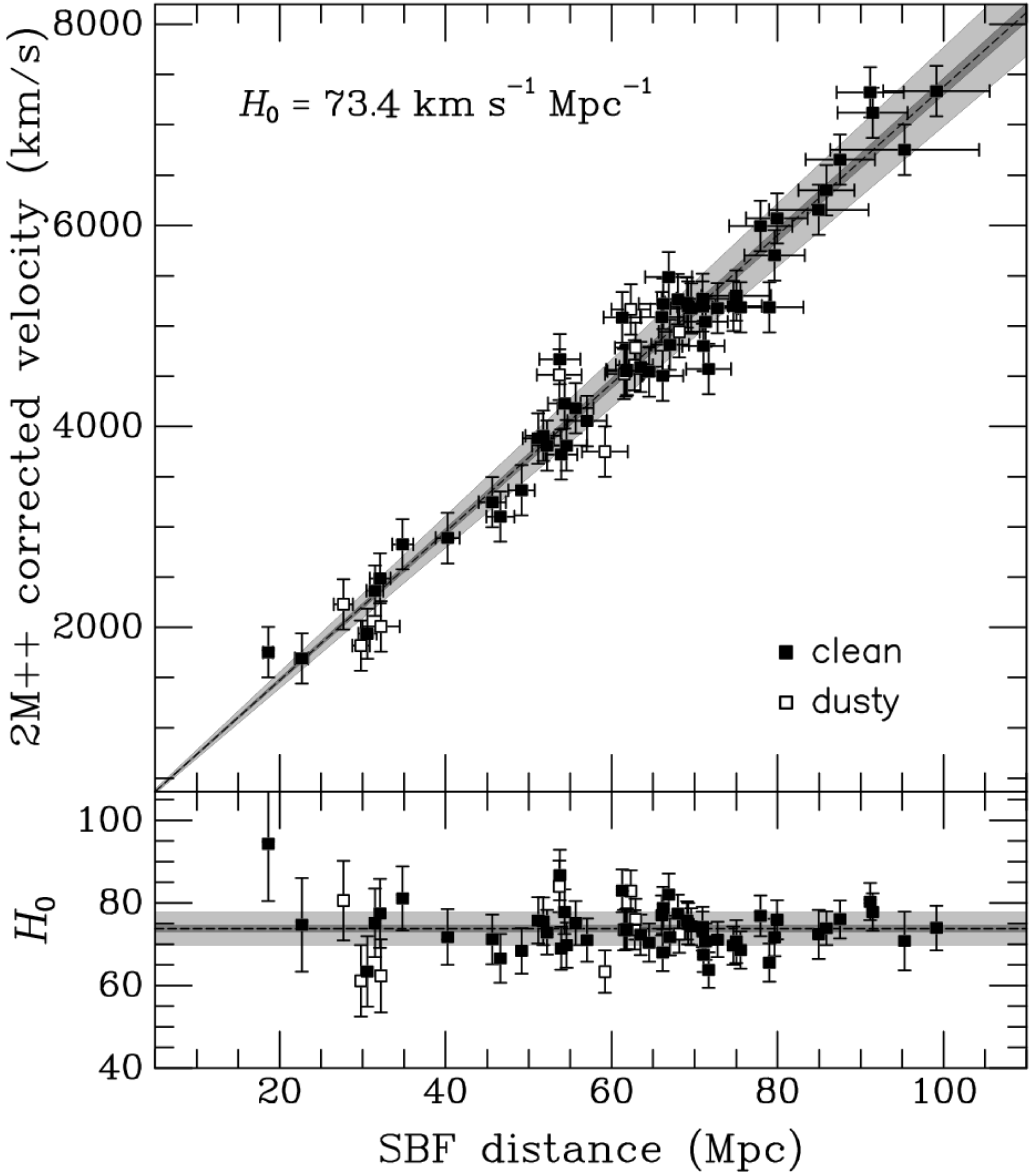


Table 1
Hubble Constants for Various Selections

Selected Sample[a]	v[b]	N_{gxy}	χ^2_ν	H_0
All galaxies	grp	63	1.19	73.53 ± 0.66
Ellipticals	grp	45	1.02	73.52 ± 0.74
All clean	grp	53	0.97	73.44 ± 0.71
MASSIVE, clean	grp	37	1.16	73.86 ± 0.82
$d > 60$, clean	grp	34	0.88	73.33 ± 0.82
$d < 70$, clean	grp	33	0.88	74.08 ± 0.96
$d < 80$, clean	grp	46	0.96	72.78 ± 0.77
SN Ia hosts, clean	grp	20	0.68	73.31 ± 1.26
All galaxies	ind	63	1.53	73.31 ± 0.67
All clean	ind	53	0.95	73.27 ± 0.73
MASSIVE, clean	ind	37	0.86	73.79 ± 0.85
$d < 80$, clean	ind	46	1.02	72.96 ± 0.76
All galaxies	cf3	63	1.14	73.32 ± 0.71
All clean	cf3	53	1.05	73.30 ± 0.76
MASSIVE, clean	cf3	37	1.16	73.62 ± 0.88
$d < 80$, clean	cf3	46	1.07	72.67 ± 0.83
All clean, −1%[c]	cf3	53	1.03	72.54 ± 0.76
All clean, +1%[c]	cf3	53	1.06	74.07 ± 0.77
All galaxies	2M++	63	0.99	73.90 ± 0.65
All clean	2M++	53	0.89	73.78 ± 0.69
Massive, clean	2M++	37	1.02	74.09 ± 0.80
$d < 80$, clean	2M++	46	0.94	73.42 ± 0.75

Explored many sample cuts and 4 different approaches for the galaxy velocities.

Generally, H_0 values scatter within errors (Table 1), but caution required w/velocities…

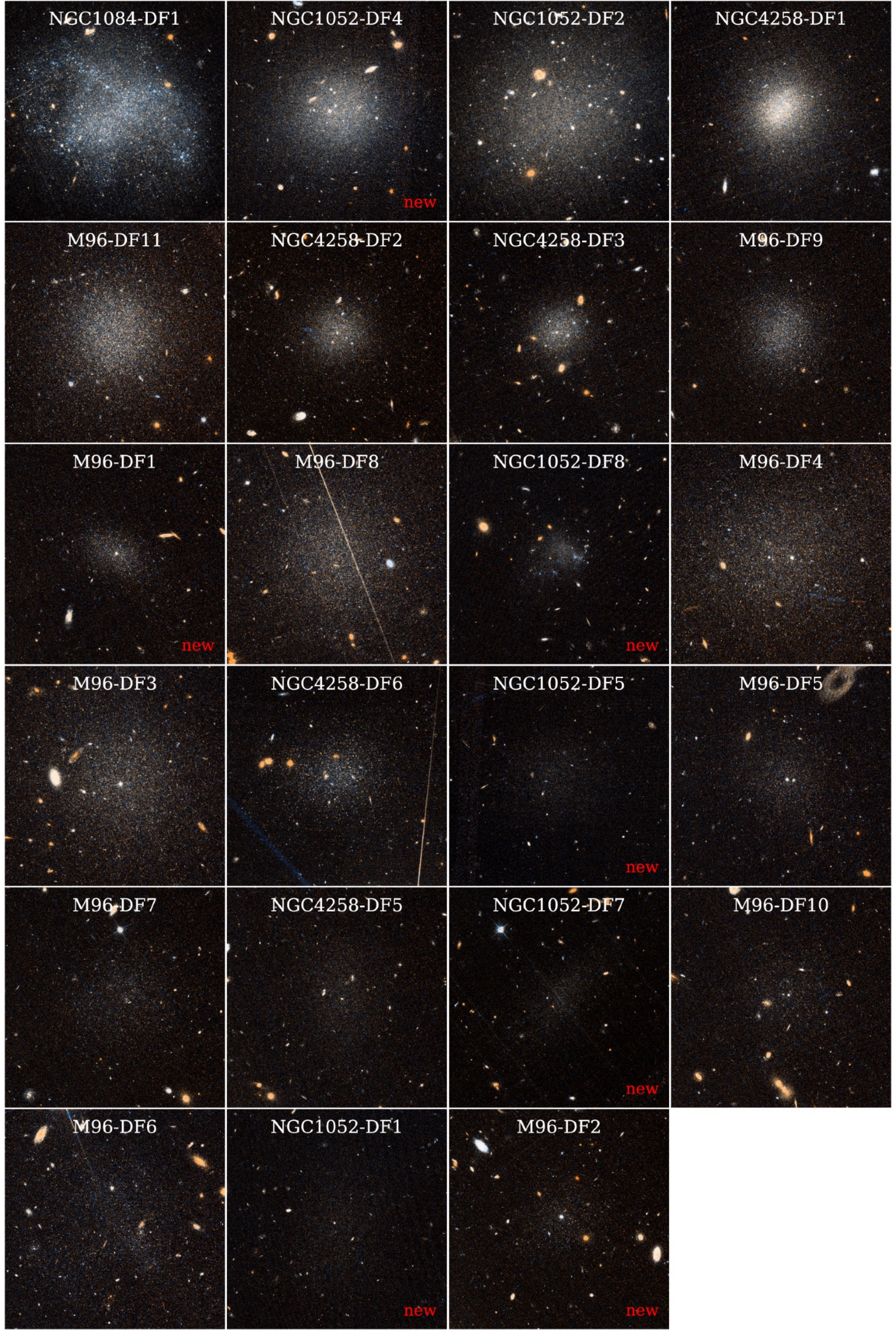
Notes.
[a] "Ellipticals" refers to morphological type $T \leqslant -3$; "clean" indicates galaxies with no discernible dust or spiral structure; "MASSIVE" means limited to MASSIVE Survey galaxies.
[b] Velocities used for the fit: grp for group-averaged; ind for individual galaxy; cf3 for the flow model of Graziani et al. (2019); 2M++ for the flow model of Carrick et al. (2015).
[c] Velocities from the CF3 linear flow model rescaled by ±1%

Cautionary note about velocities

Velocity treatment	SBF H_0, N=60 (JPB+ 2021)	Maser H_0, N=6 (Pesce+ 2020)	χ^2_n SBF / Maser
CMB frame velocities (group or individual), no corrections	73.4	73.9	0.97 / 0.60
CF3 model (Graziani+ 2019)	73.3	71.8	1.05 / 0.75
2M++ model (Carrick+ 2015)	73.8	71.8	0.89 / 0.55
Mould+ 2000 model	76.5	76.9	~1.05 / 0.75

H_0 higher by ~4% using old flow model.

Calibrating SBF via TRGB?

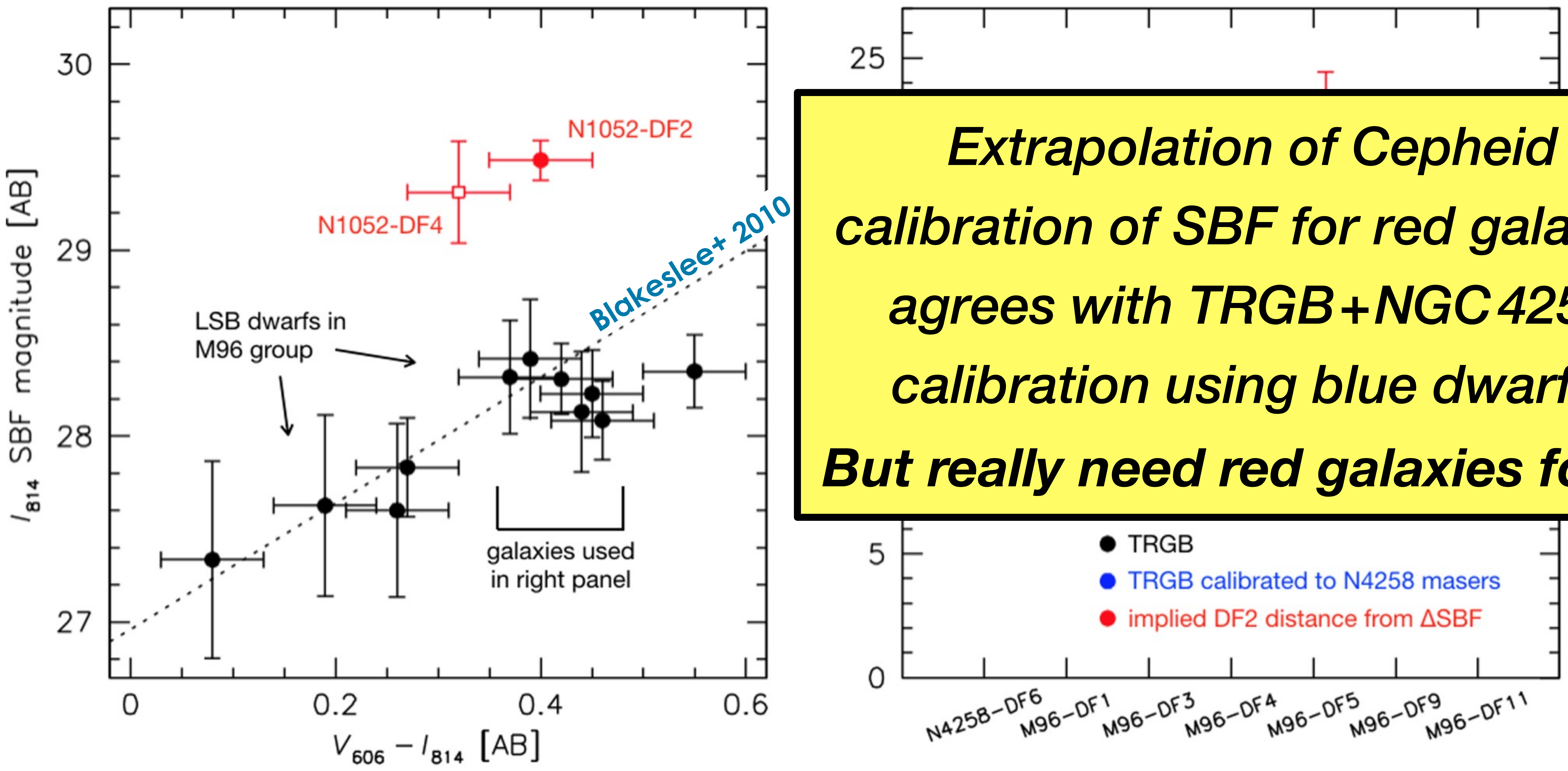


23 dwarfs w/SBF;
12 also with TRGB

23 diffuse dwarfs studied by

Cohen, van Dokkum et al. 2018

SBF calibration via TRGB anchored to maser galaxy



Extrapolation of Cepheid calibration of SBF for red galaxies agrees with TRGB+NGC 4258 calibration using blue dwarfs.

But really need red galaxies for H_0

van Dokkum et al. 2018

Finally…

Table 2
Final Hubble Constant and Errors

SBF Calibration	H_0[a]	σ_{stat}[b]	$\sigma_{sys}(d)$[c]	$\sigma_{sys}(v)$[d]
Cepheid	73.44	1.0%	4.1%	1.0%
TRGB	73.20	1.0%	4.7%	1.0%
Average	73.33	1.0%	3.1%	1.0%
Final: $H_0 = 73.3 \pm 0.7 \pm 2.4$ km s^{-1} Mpc^{-1}				

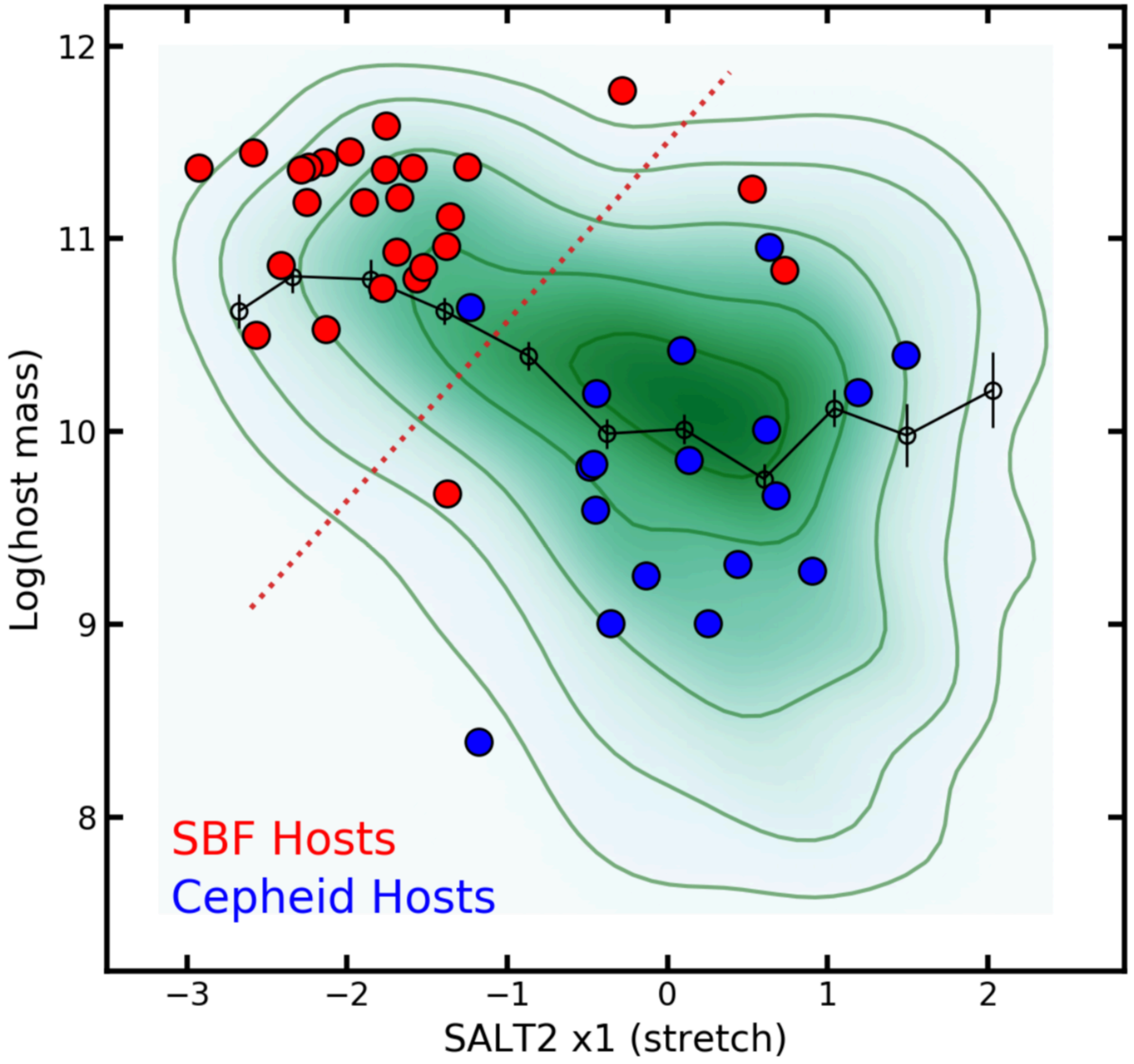
Notes.
[a] H_0 for "clean" galaxy sample with group velocities. **(CMB frame, no model correction)**
[b] Statistical error from the H_0 fit.
[c] Systematic uncertainty in distance calibration.
[d] Systematic uncertainty in velocity scaling.

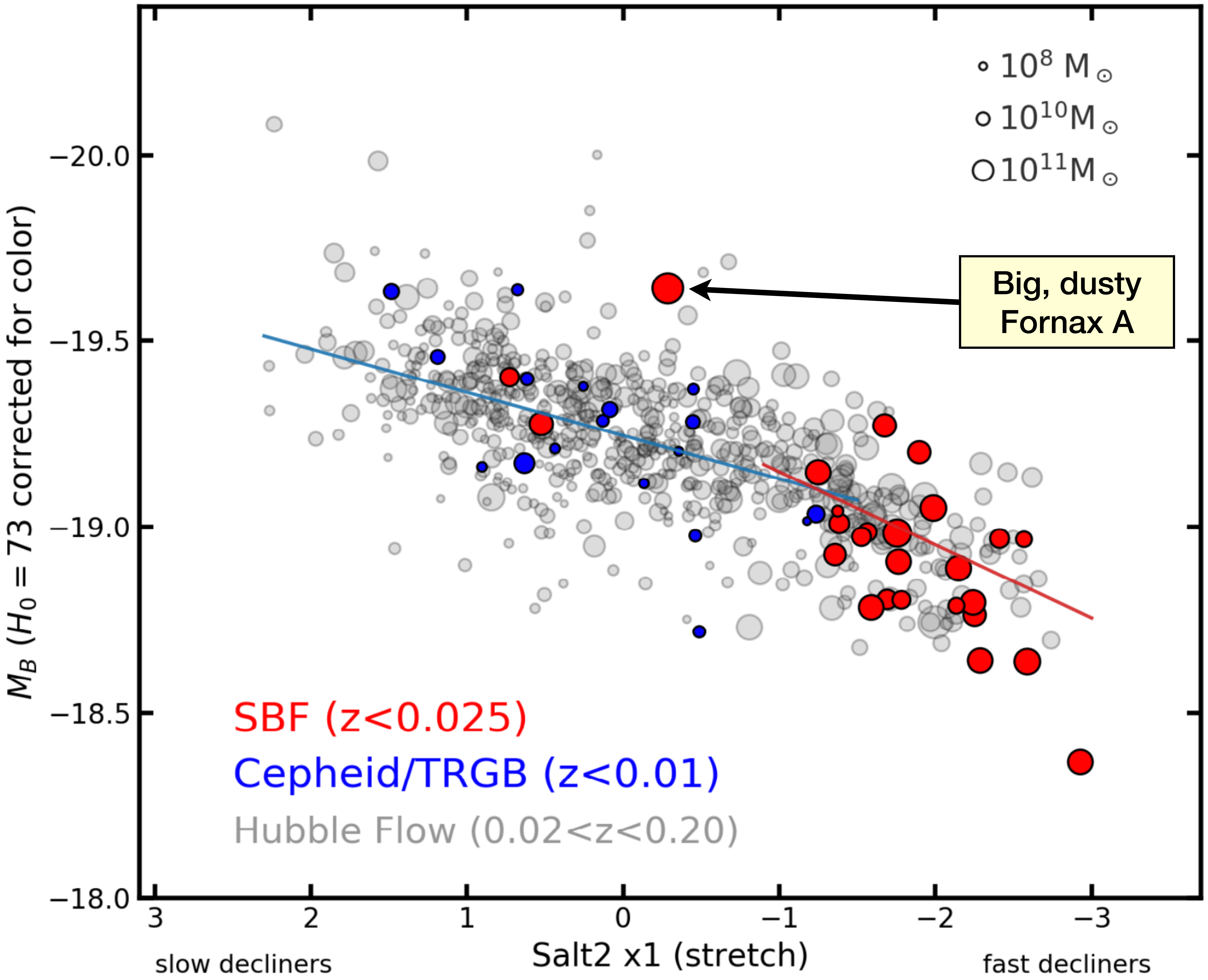
See Appendix of paper for details of TRGB-SBF calibration for giant ellipticals

Blakeslee et al. 2021

SBF+TRGB and Cepheid calibrations of SNeIa are quite complementary…

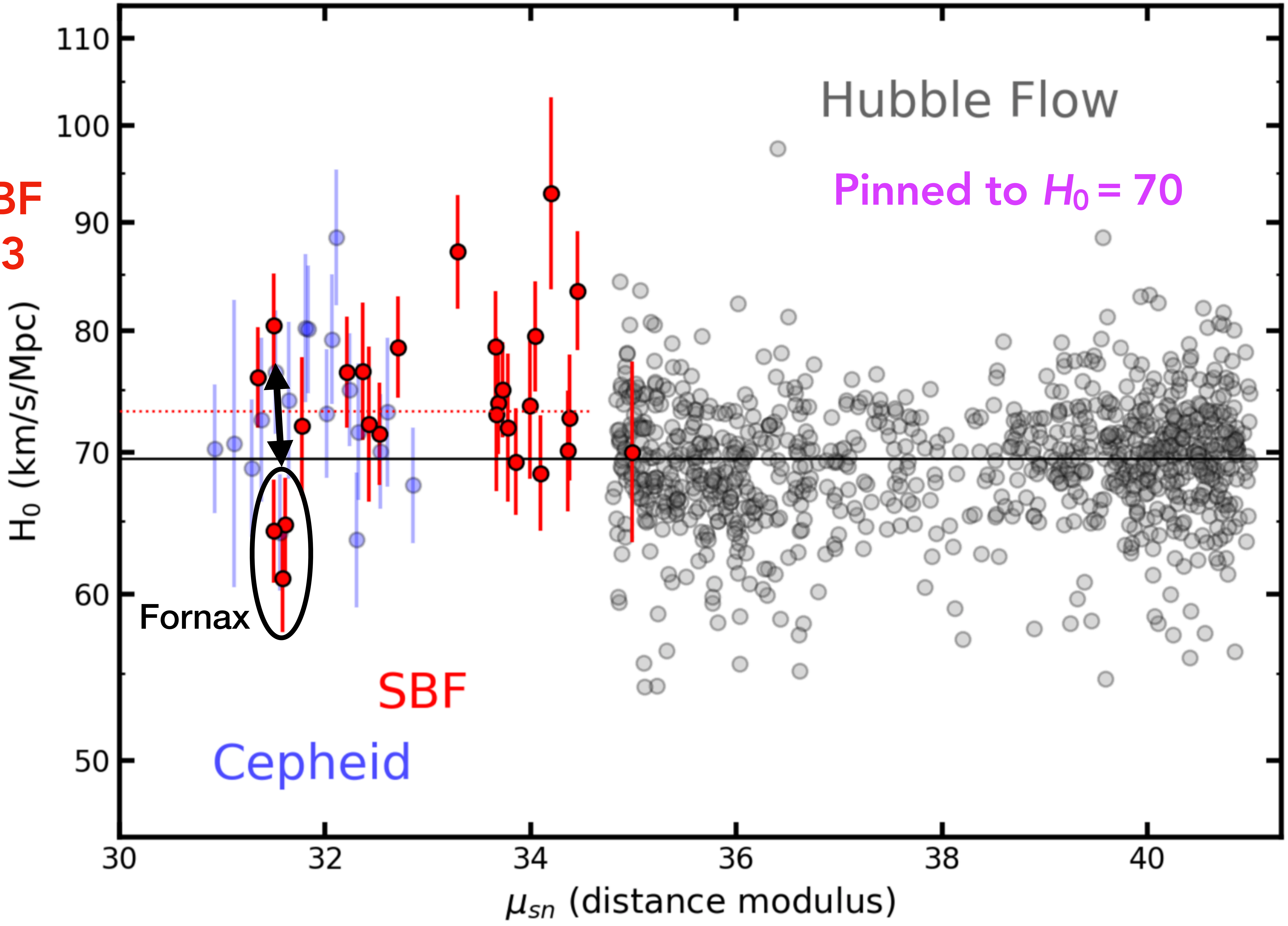
Work in progress…

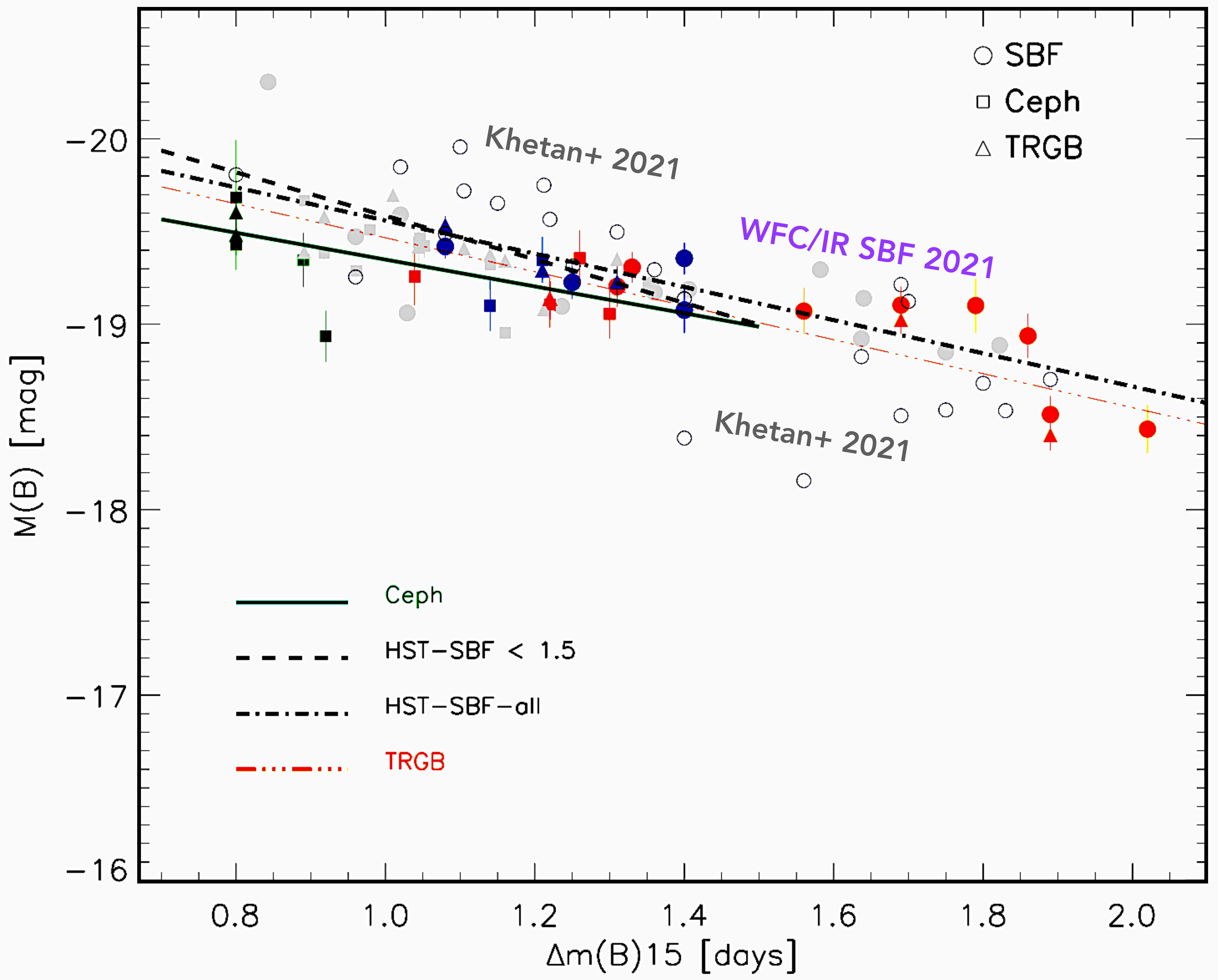




P. Garnavich et al., in prep.

Cepheid & SBF imply $H_0 \sim 73$



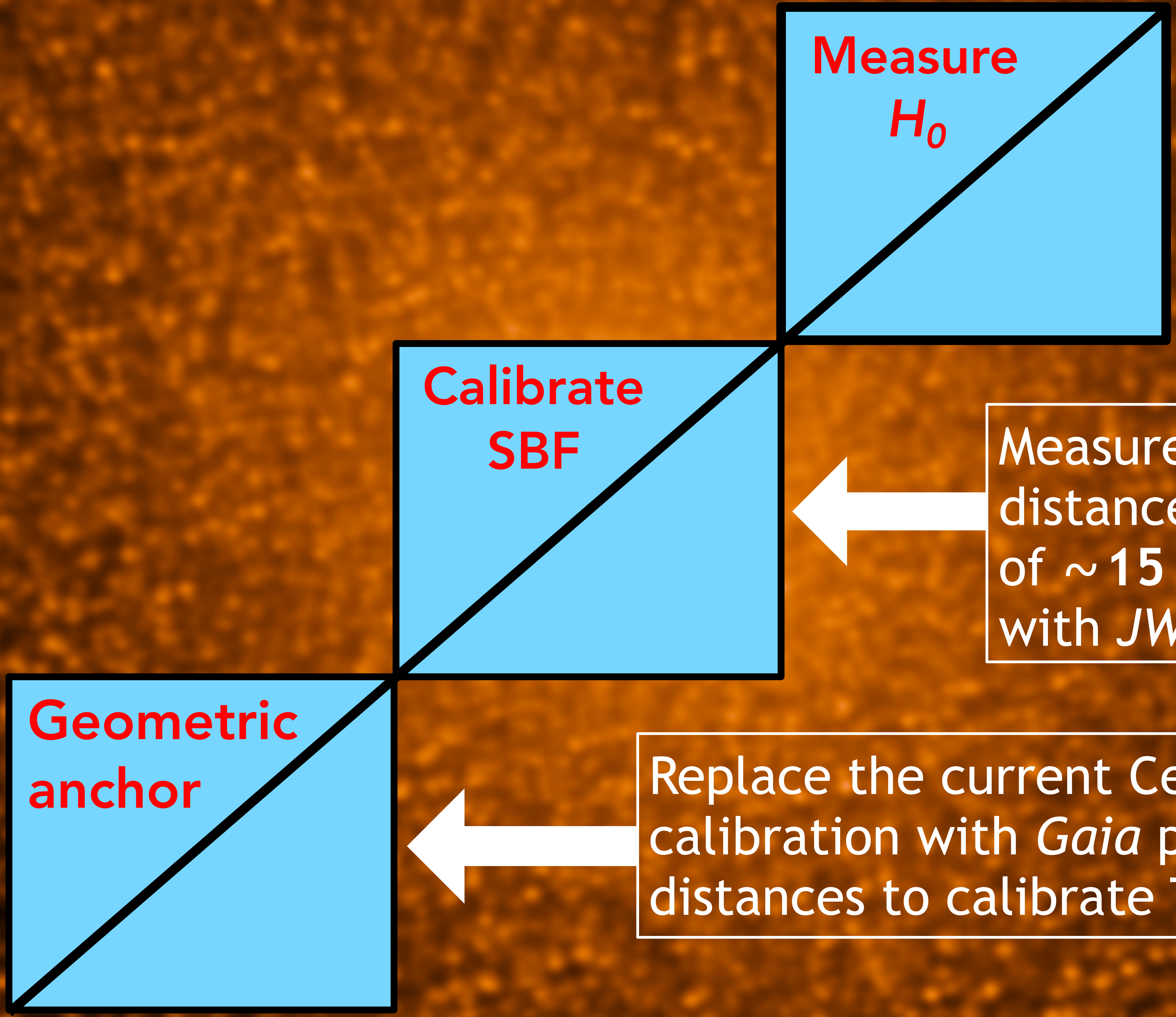


Work in progress...

SN Ia calibration via Cepheids, TRGB, heterogenous SBF & WFC3/IR SBF

P. Milne et al., in prep.

Towards < 2% H_0 from SBF…



With *JWST*, extend current limit from 100 to ~200 Mpc.

Measure TRGB and SBF distances to common set of ~**15** giant ellipticals with *JWST* or *HST*.

Replace the current Cepheid calibration with *Gaia* parallax distances to calibrate TRGB.

In parallel, use realistic galaxy models to predict SBF zero points.