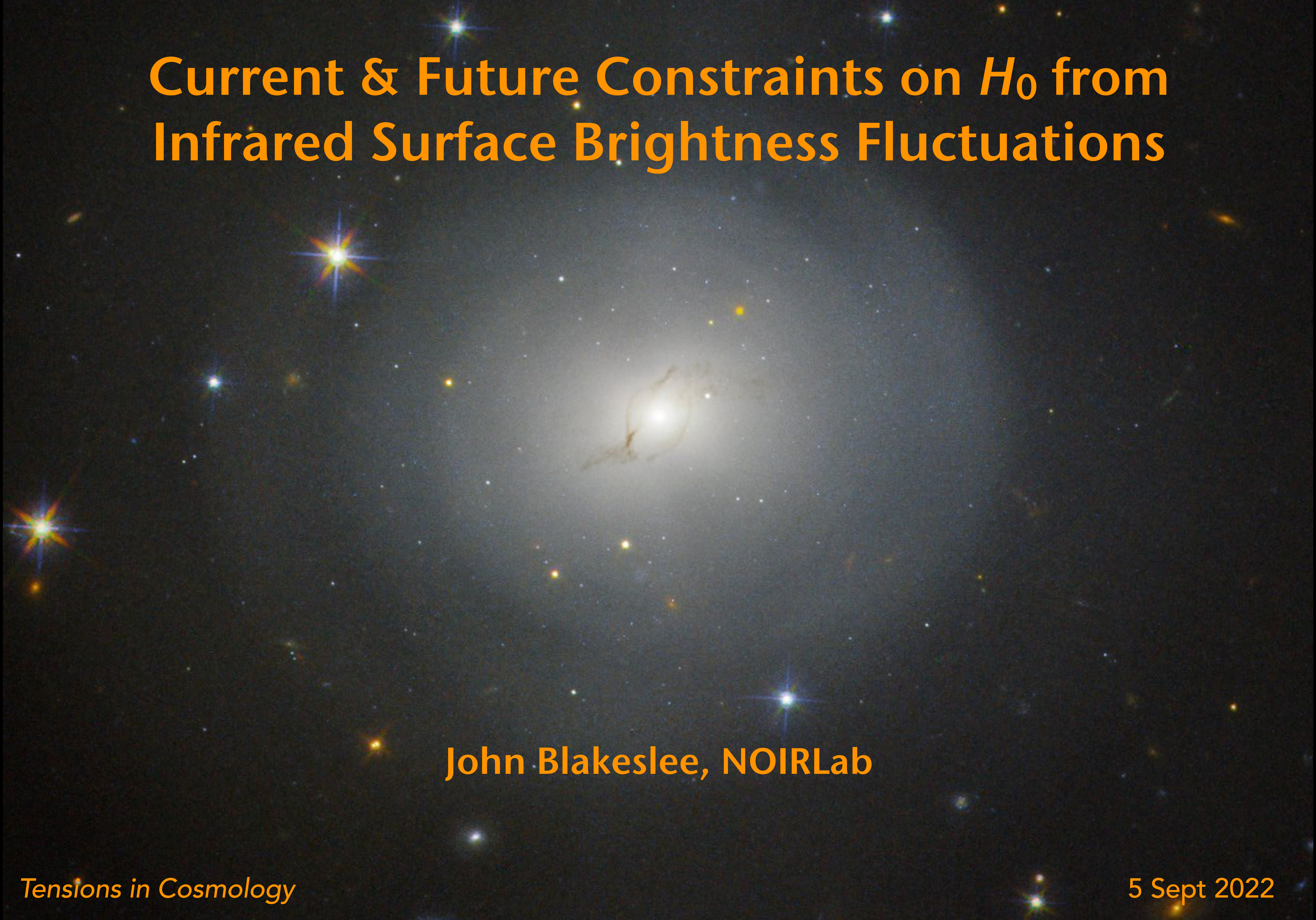
Current & Future Constraints on H_0 from Infrared Surface Brightness Fluctuations



GW170817
host NGC4339

John Blakeslee, NOIRLab

Tensions in Cosmology

5 Sept 2022

Illustration of SBF Models at 3 distances

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

$D = 0.5$ Mpc

$D = 2$ Mpc

$D = 8$ Mpc

Mean i-band surface brightness = 24 mag arcsec^{-2} in all panels

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

Illustration of SBF Models at 3 distances

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

$D \approx 3$ Mpc

$D \approx 12$ Mpc

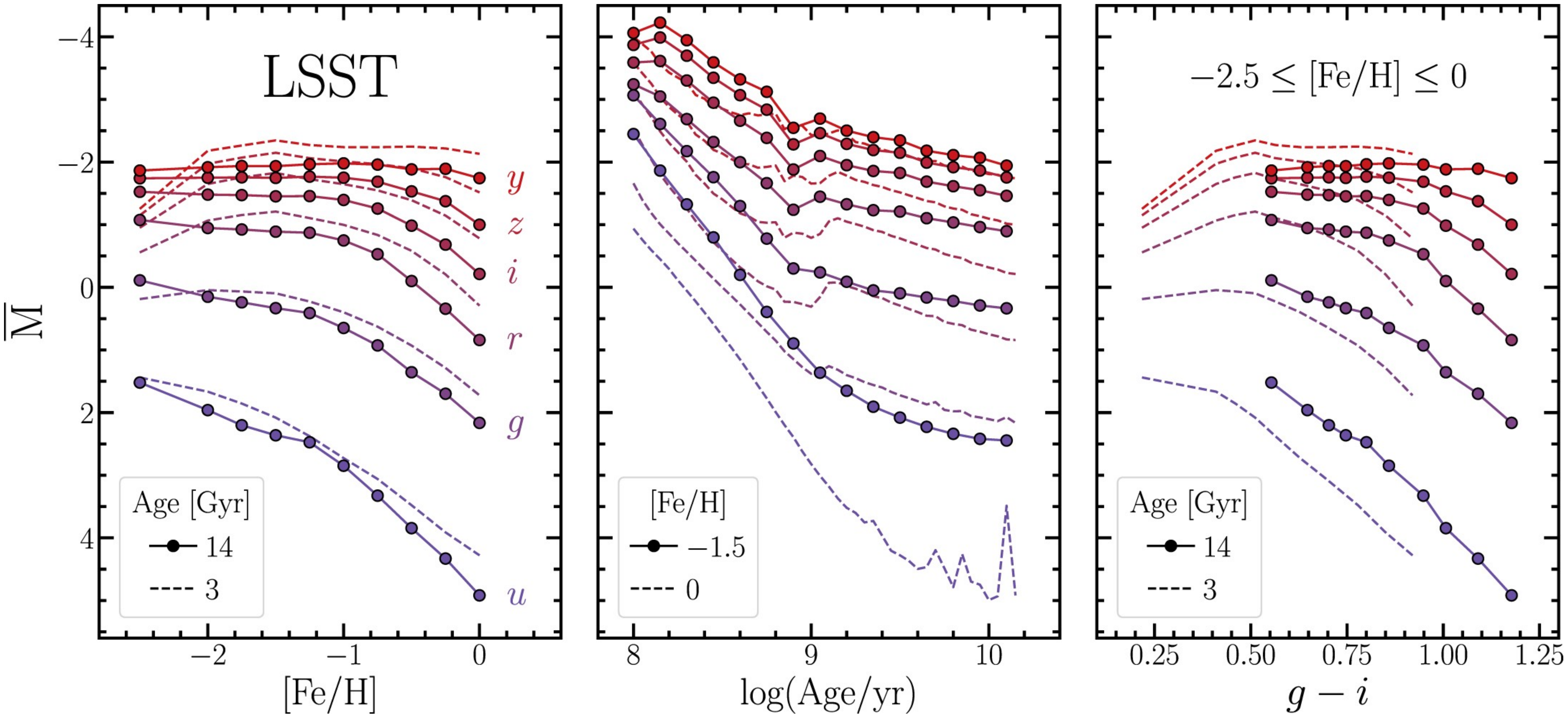
$D \approx 50$ Mpc

Mean i-band surface brightness = 24 mag arcsec^{-2} in all panels

Expected appearance of similar galaxies with Hubble at ~0.1″ in F814W

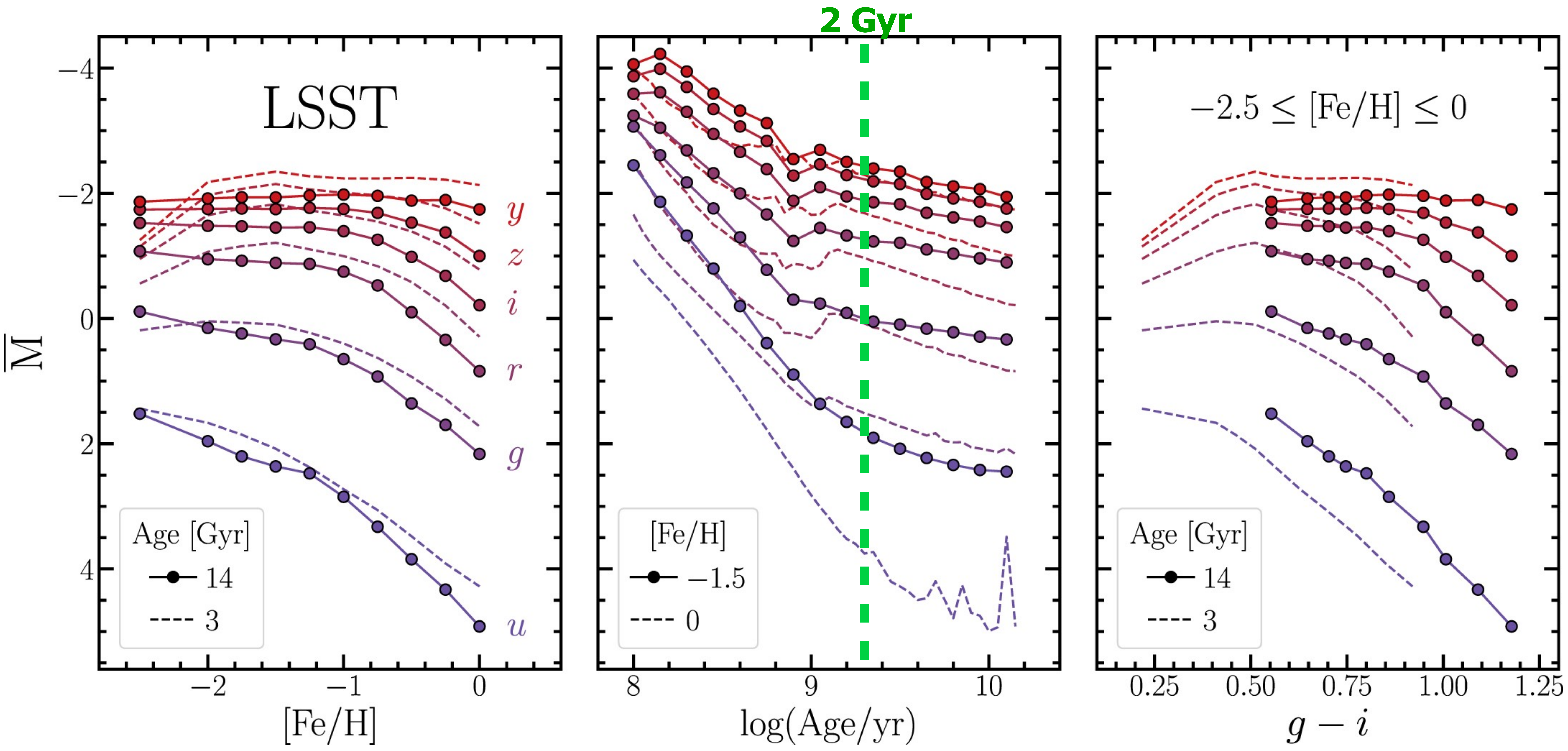
SBF Calibrations from MIST Models

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



SBF Calibrations from MIST Models

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



Need to calibrate using galaxies similar to those used for measuring H_0

For more details on SBF analysis, see…

Unveiling the Universe with Emerging Cosmological Probes,

Moresco et al. 2022
arXiv:2201.07241

Sec. 3.9: ~10 pages on SBF, by M. Cantiello & JPB

(or ask later)

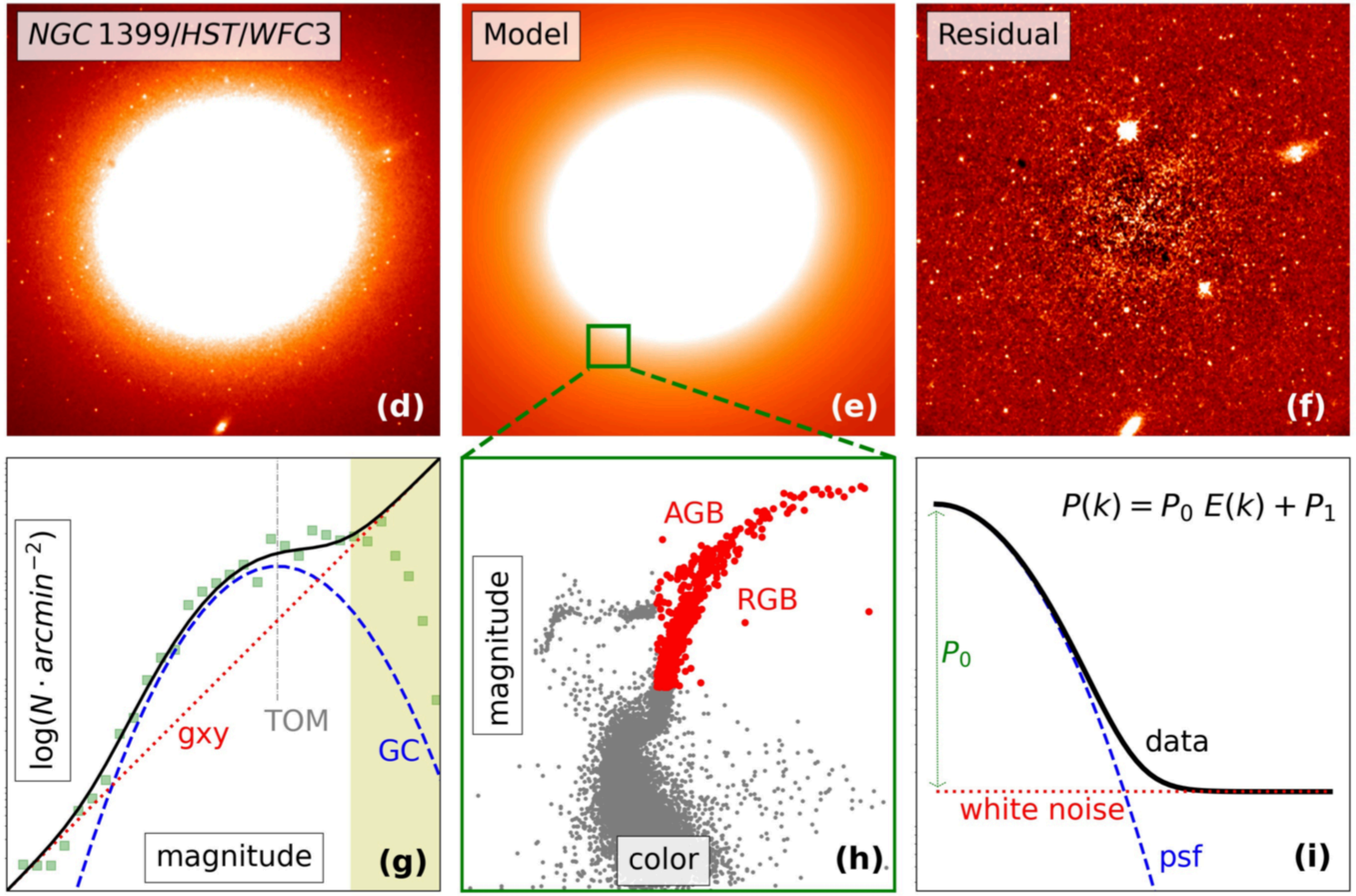
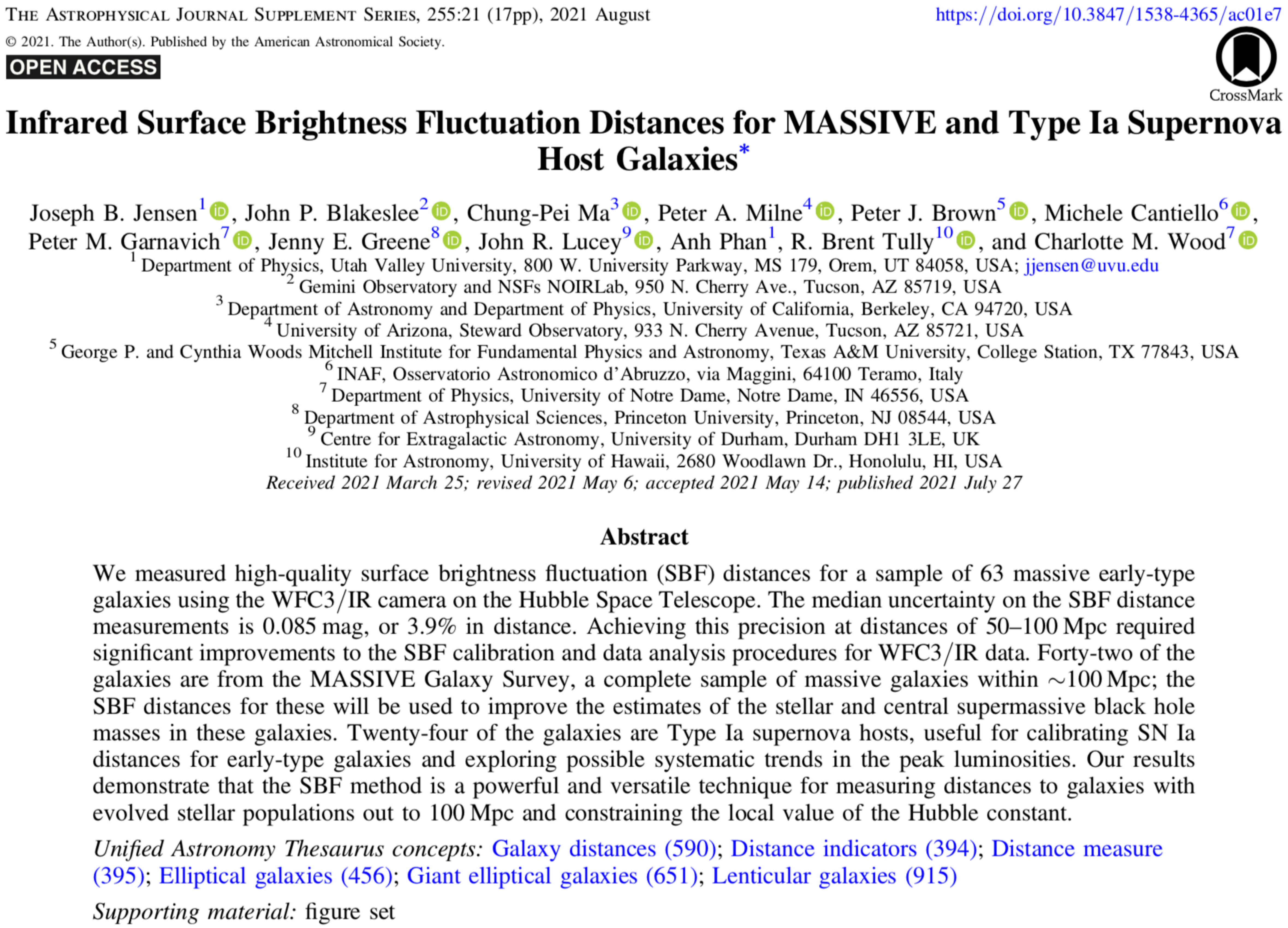


Figure 35: Illustration of SBF observations and measurements. (*a*) Simulation of the stellar population in a spheroidal galaxy at the distance of the Virgo cluster ($D_{Virgo} \simeq 16.5$ Mpc, Blakeslee et al., 2009) as observed with the E-ELT in ~1 hour (Cantiello et al., 2021, in prep.). (*b*) Same as in panel (*a*), but for a galaxy ten times more distant. (*c*) Same as in panel (*a*), but for a galaxy fifty times more distant. Stars, which appear marginally resolved in panel (*a*), blend together into a smooth brightness profile at larger distances. (*d*) Near-infrared image of NGC 1399 from the HST WFC3 camera. (*e*) Model of NGC 1399's surface brightness distribution derived from the WFC3/IR image. (*f*) Residual frame, obtained from the galaxy image (*d*) minus the model (*e*). (*g*) Typical luminosity function analysis for estimating the "residual variance" P_r due to contaminating sources: green squares show the data, the blue curve and red line show the fits to the globular cluster and background galaxy luminosity functions, respectively, and the solid black line is the combined model luminosity funtion (data and fits are from Cantiello et al., 2011). The vertical grey dashed line indicates the GCLF turnover magnitude and the shaded area shows the magnitude interval where the detection is incomplete. (*h*) Color-magnitude diagram of an old stellar population (data for the MW globular cluster NGC 1851 from Piotto et al., 2002); the RGB/AGB population is highlighted with red dots. (*f*) A schematic illustration of the SBF power spectrum analysis (see `https://ned.ipac.caltech.edu/level5/March02/Tonry/frames.html`).



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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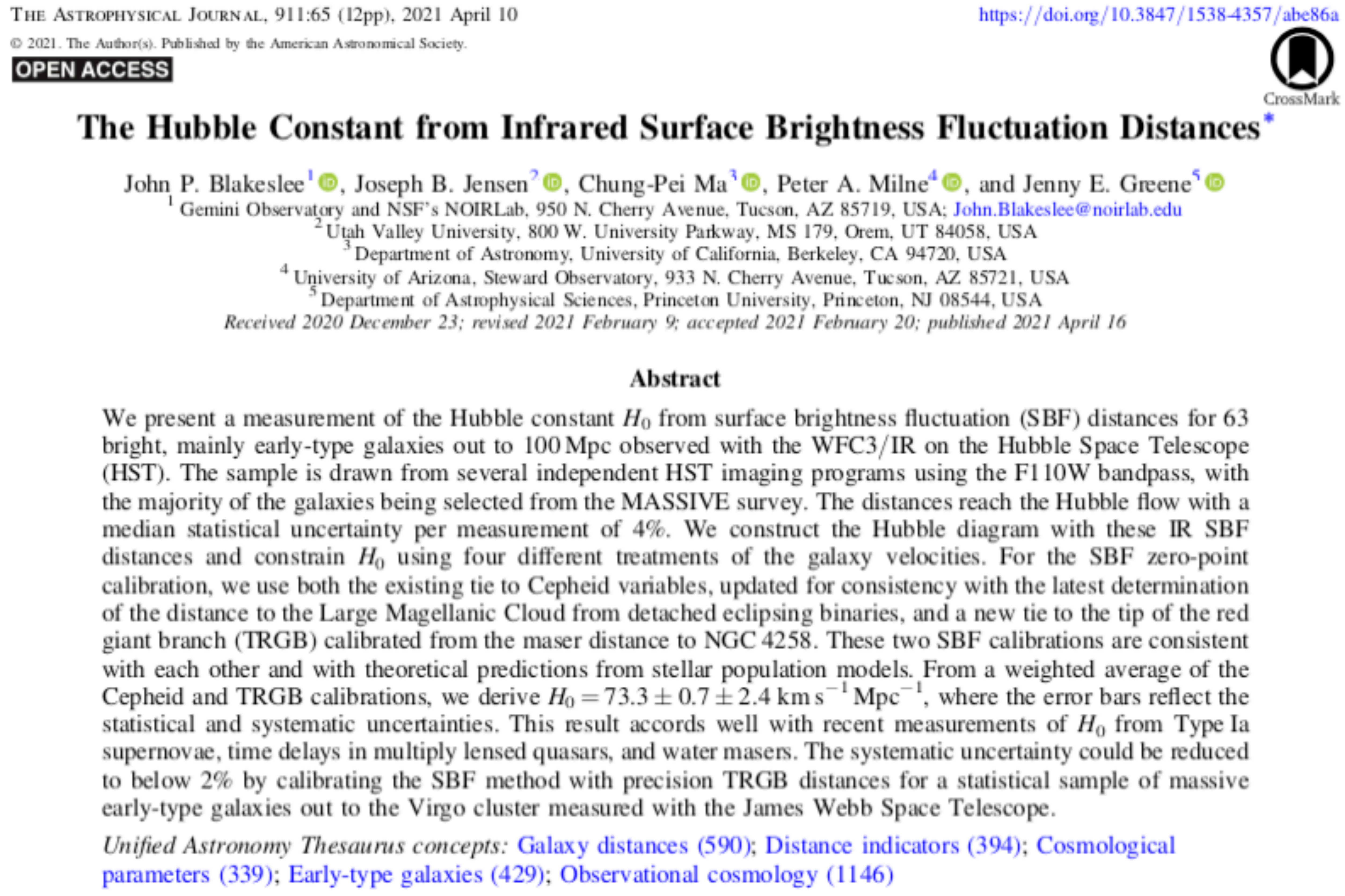
Received 2021 March 25; revised 2021 May 6; accepted 2021 May 14; published 2021 July 27

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



The Astrophysical Journal, 911:65 (12pp), 2021 April 10 https://doi.org/10.3847/1538-4357/abe86a

The Hubble Constant from Infrared Surface Brightness Fluctuation Distances*

John P. Blakeslee[1], Joseph B. Jensen[2], Chung-Pei Ma[3], Peter A. Milne[4], and Jenny E. Greene[5]
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[2] Utah Valley University, 800 W. University Parkway, MS 179, Orem, UT 84058, USA
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Received 2020 December 23; revised 2021 February 9; accepted 2021 February 20; published 2021 April 16

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 $H_0 = 73.3 \pm 0.7 \pm 2.4\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$, 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)

New WFC3/IR SBF distances to a **complete sample of the most massive northern early-type galaxies** ($M_K < -25.5$ mag) with $d \lesssim 75$ Mpc, a sparser sampling to ~100 Mpc, plus **20 early-type hosts of well-observed SNe Ia**. Along with host of GW170817, **total of 63 early-type galaxies, 20 – 100 Mpc**.

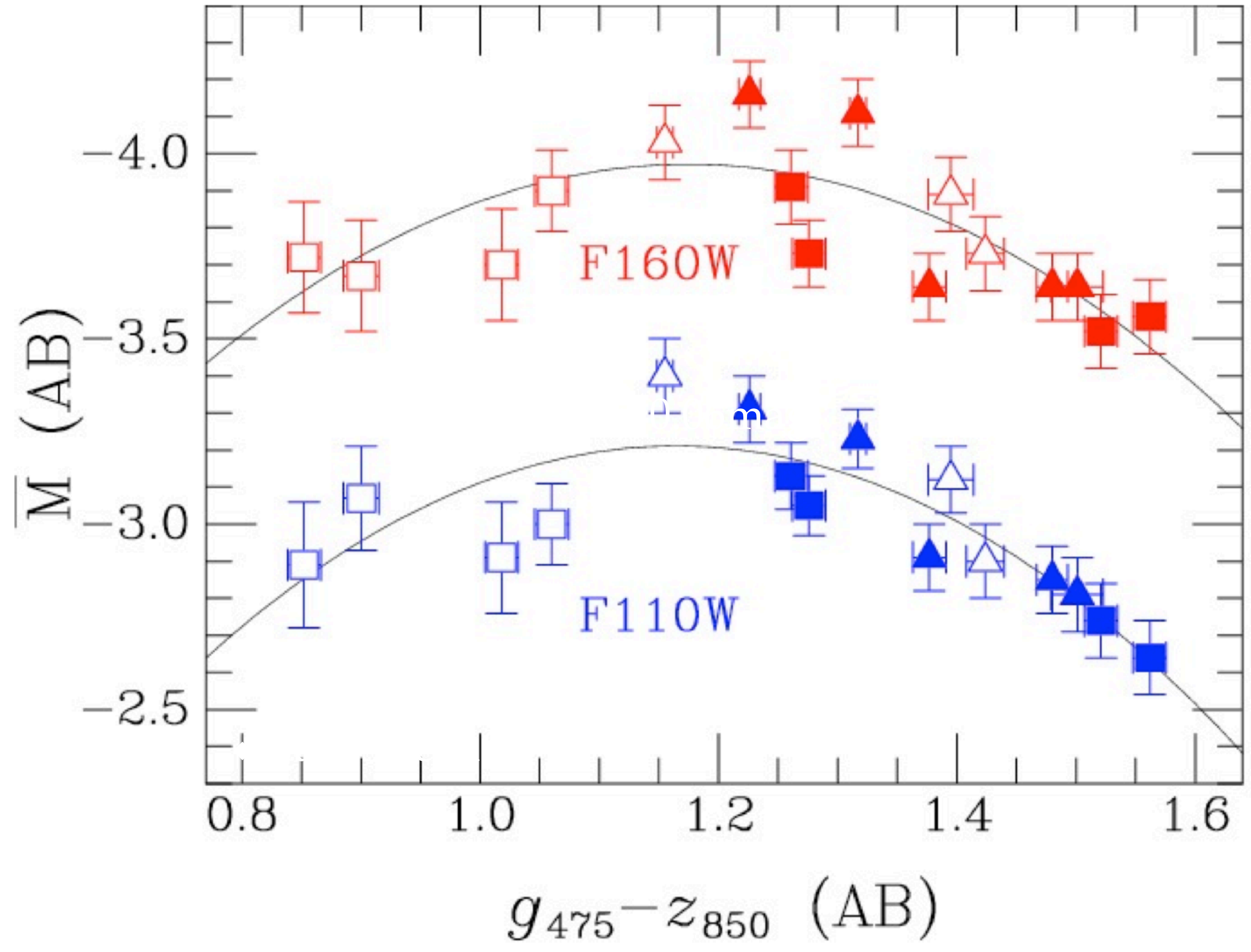
Typical WFC3/IR F110W SBF Error Budget

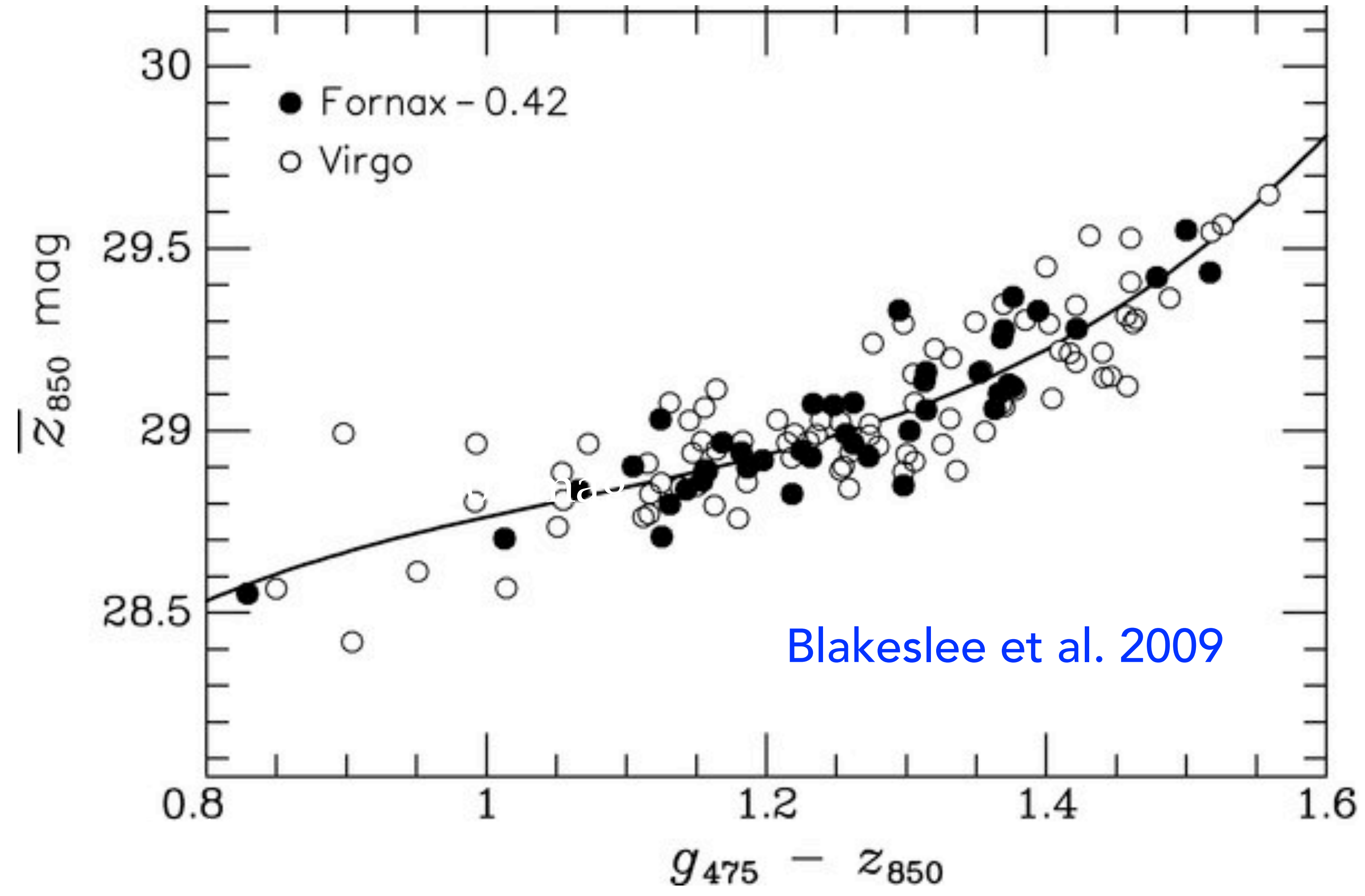
Source	(m-M) sigma
PSF normalization	0.02 mag
Sky background	0.02 mag
External sources fit (GC+gal)	0.03 mag
Total SBF power spectrum fit	0.03 mag
(g-z) color from PanSTARRS + extinction uncertainty	0.03 mag
Calibration intrinsic scatter, for red early-type galaxies	0.06 mag
Total distance uncertainty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

Cepheid-based zero-point uncertainty also ~ 4.2%.

Jensen, Blakeslee et al. 2021

Jensen et al. 2015





Blakeslee et al. 2009

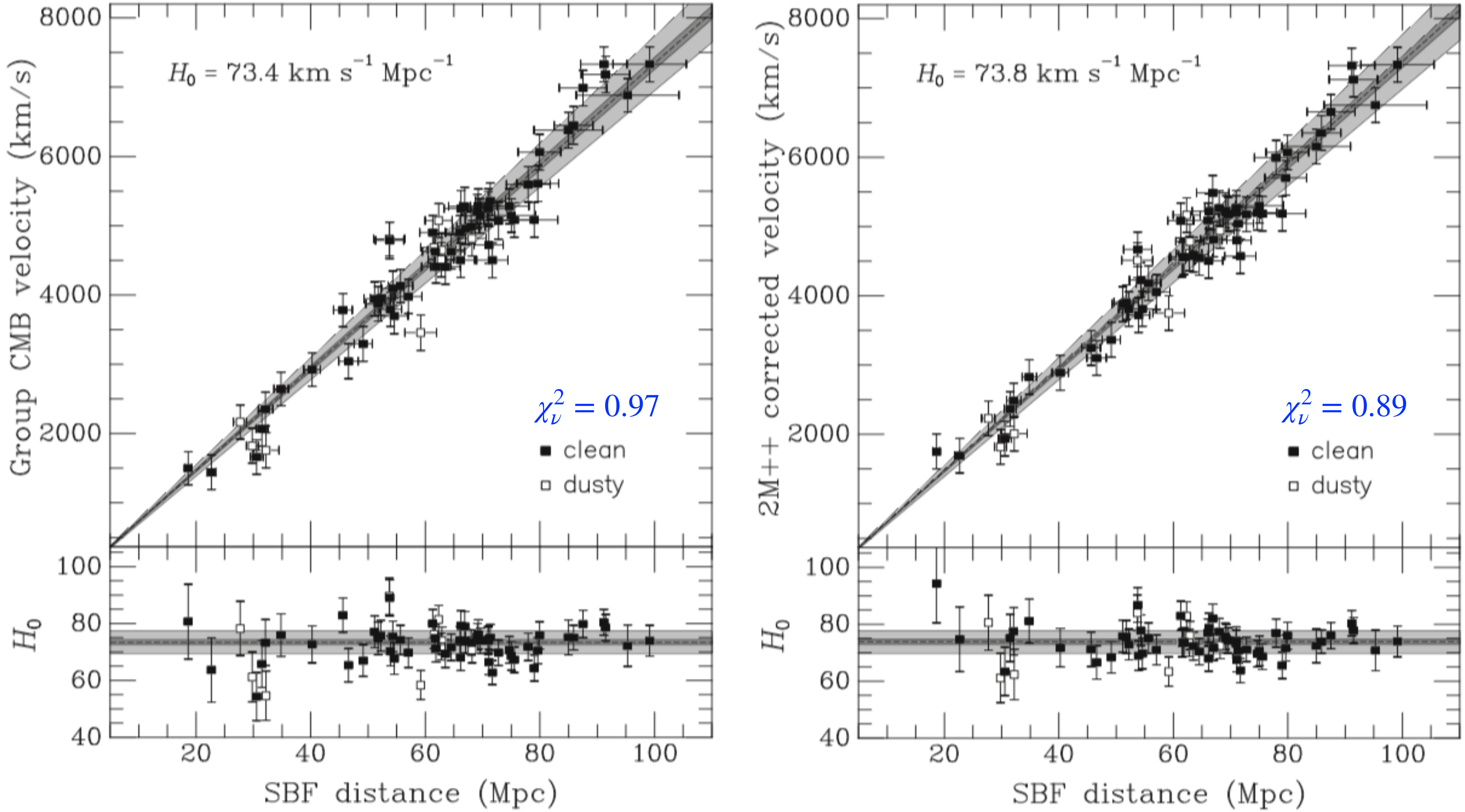
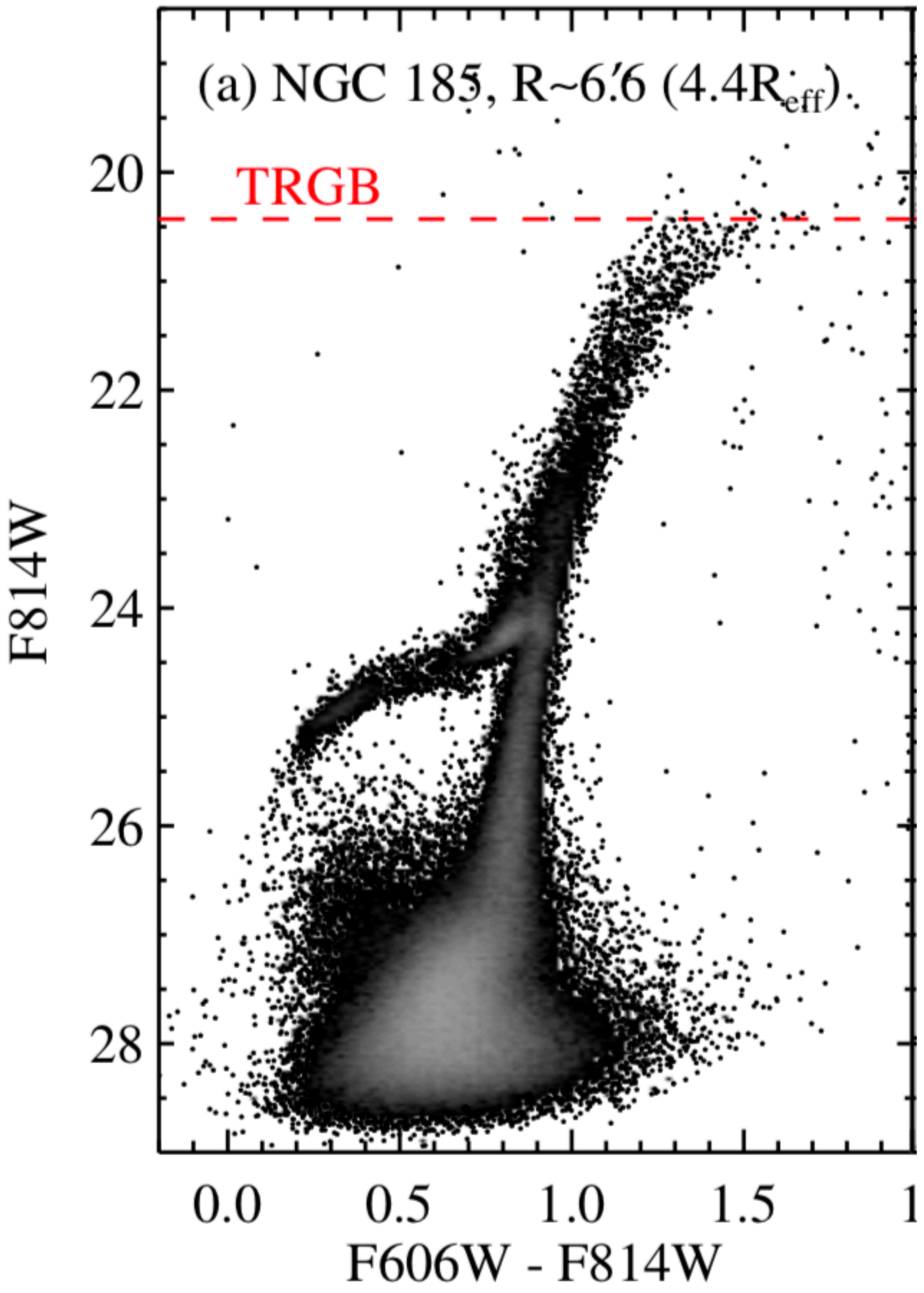


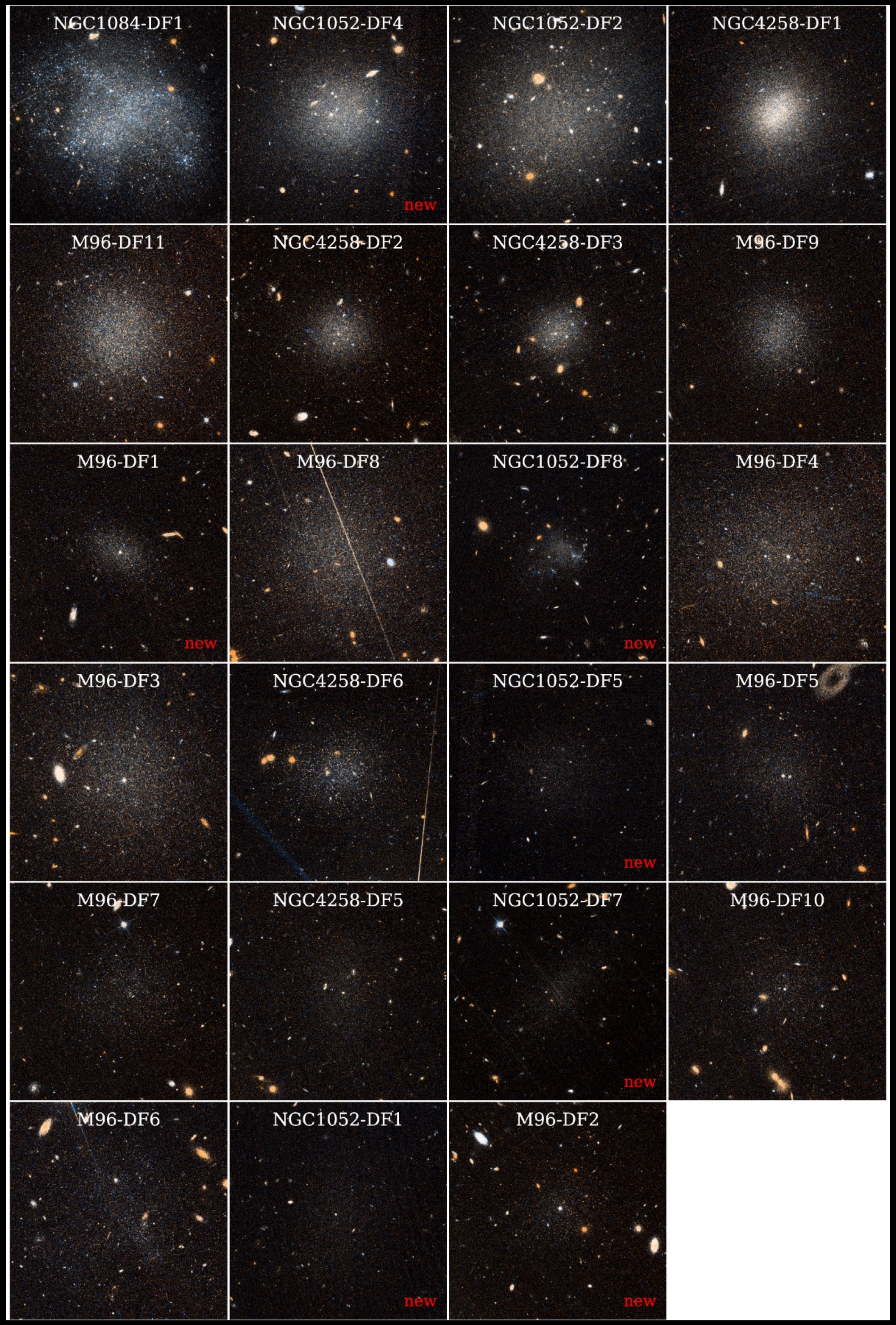
Figure 1. Left: Hubble diagram (top) and individual H_0 values (bottom) for the Cepheid-calibrated WFC3/IR SBF distances and the galaxy group-averaged velocities in the CMB rest frame. Solid symbols indicate "clean" galaxies, for which no dust or spiral structure is evident. The open symbols indicate galaxies with obvious dust and/or spiral structure. The represented Hubble constant is the best-fitting value for the "clean" galaxy sample using these distances and velocities; the statistical and systematic error ranges are shown in dark and light gray, respectively. The plotted H_0 error bars include both velocity and distance errors. Right: same as the plot on the left, except using the flow-corrected recessional velocities derived from the 2M++ density field analysis of Carrick et al. (2015). The scatter is reduced by these flow-corrected velocities. Note that the distances would uniformly increase, and H_0 decrease, by 0.3% for the TRGB-based SBF calibration (see Appendix).

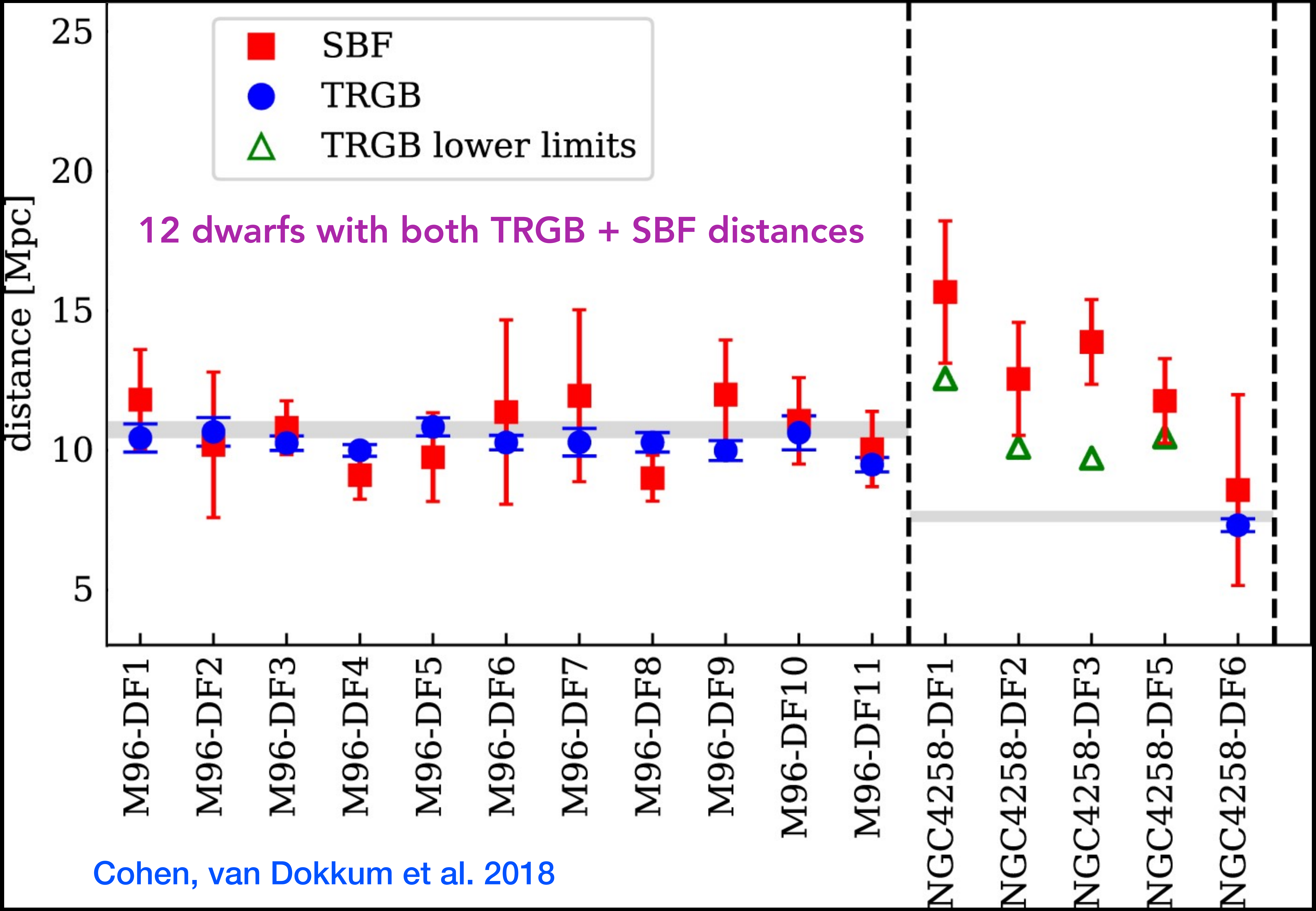
Preceding results are based on the Cepheid calibration of SBF

But, the best calibration of SBF method will come from the Tip of the Red Giant Branch (TRGB) distances.



Calibrating SBF via TRGB in diffuse dwarf galaxies

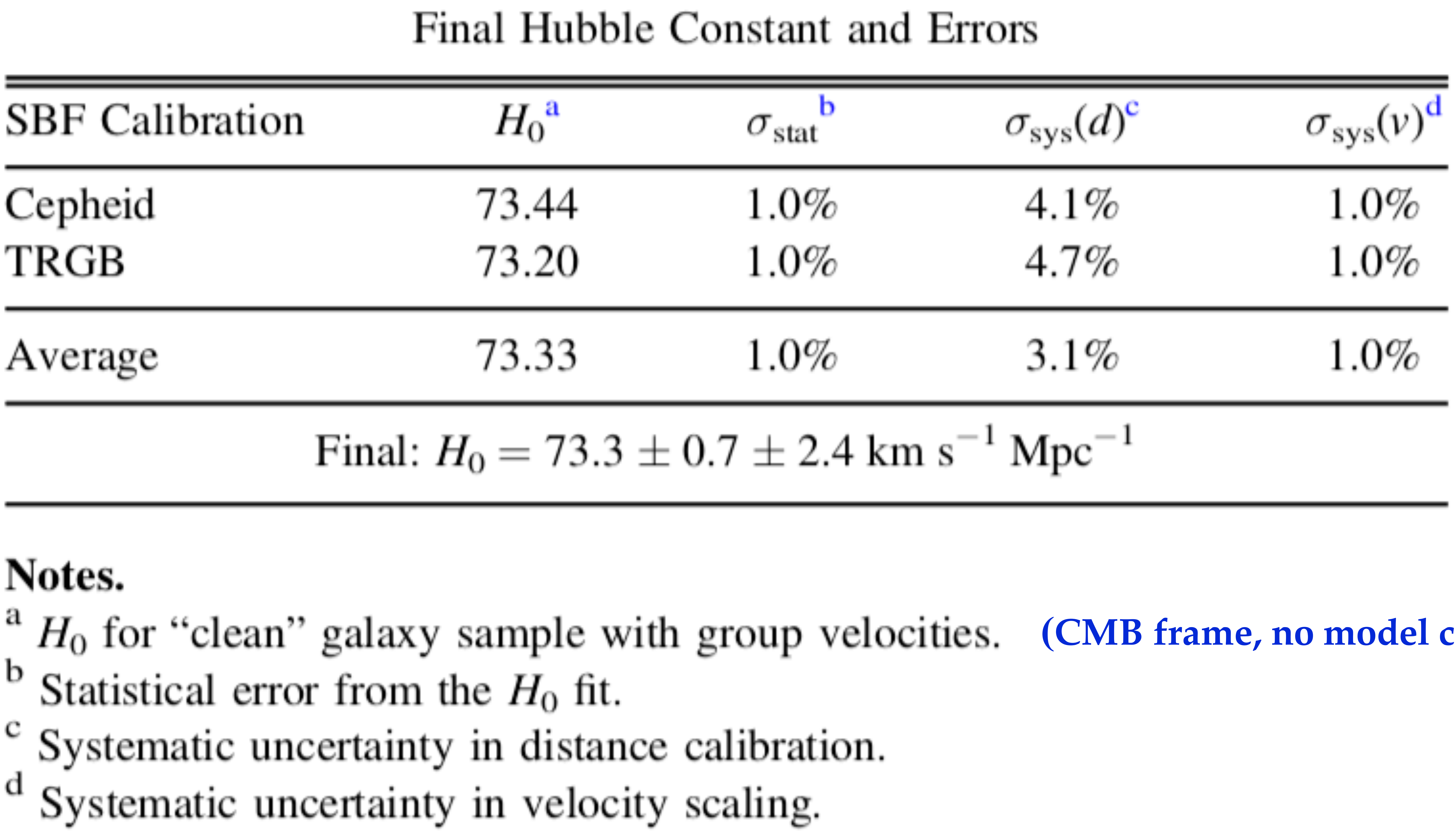




12 dwarfs with both TRGB + SBF distances

Cohen, van Dokkum et al. 2018

Better to calibrate using galaxies similar to those used for measuring H_0



Final Hubble Constant and Errors

SBF Calibration	H_0[a]	$\sigma_{\rm stat}$[b]	$\sigma_{\rm sys}(d)$[c]	$\sigma_{\rm sys}(v)$[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)**

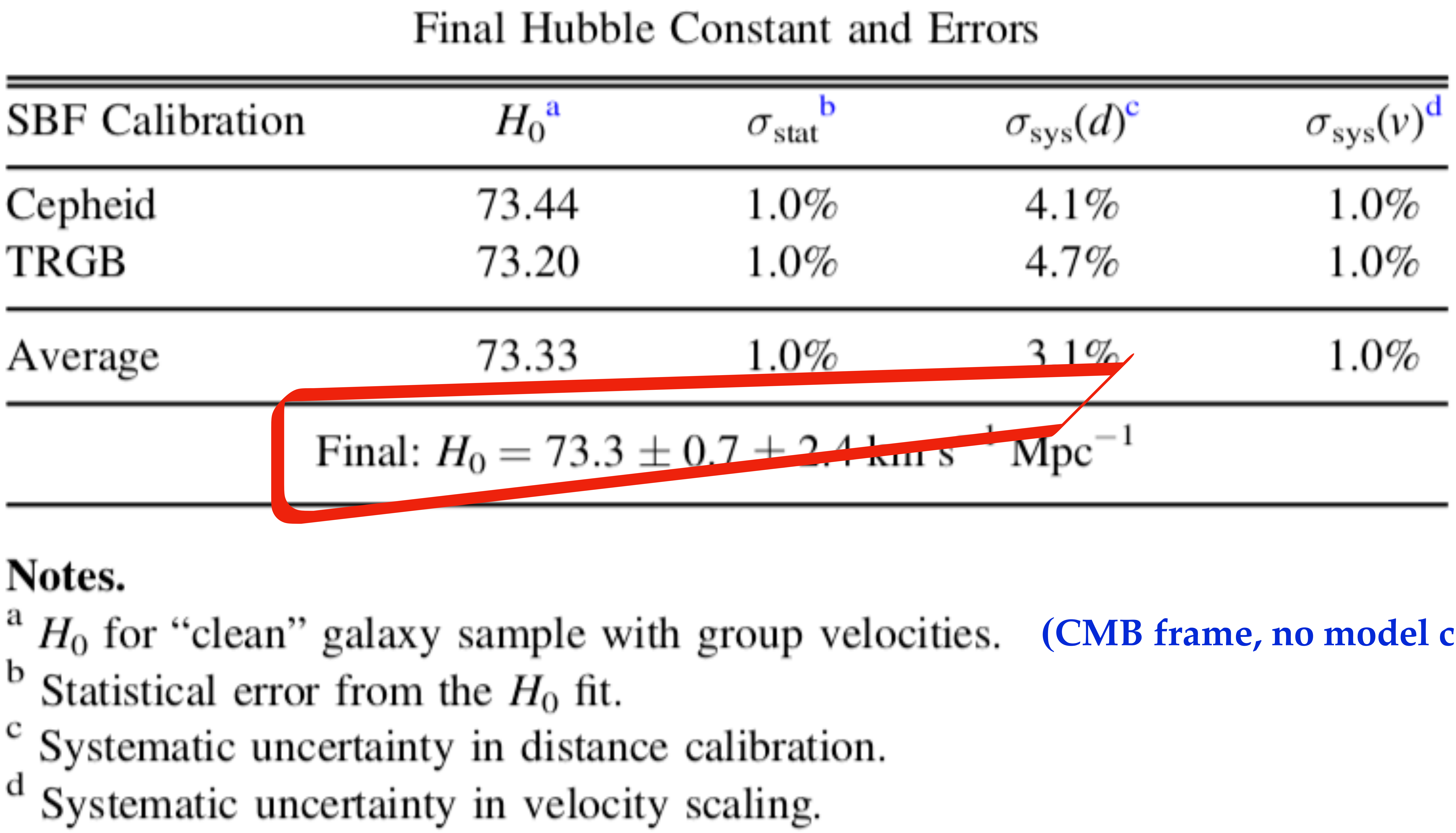
[b] Statistical error from the H_0 fit.

[c] Systematic uncertainty in distance calibration.

[d] Systematic uncertainty in velocity scaling.

Blakeslee et al. 2021

Better to calibrate using galaxies similar to those used for measuring H_0



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[d] Systematic uncertainty in velocity scaling.

Blakeslee et al. 2021

How SBF H_0 compares…

Unveiling the Universe with Emerging Cosmological Probes,

Moresco et al. 2022
arXiv:2201.07241

Section 4: Synergies & complementarities

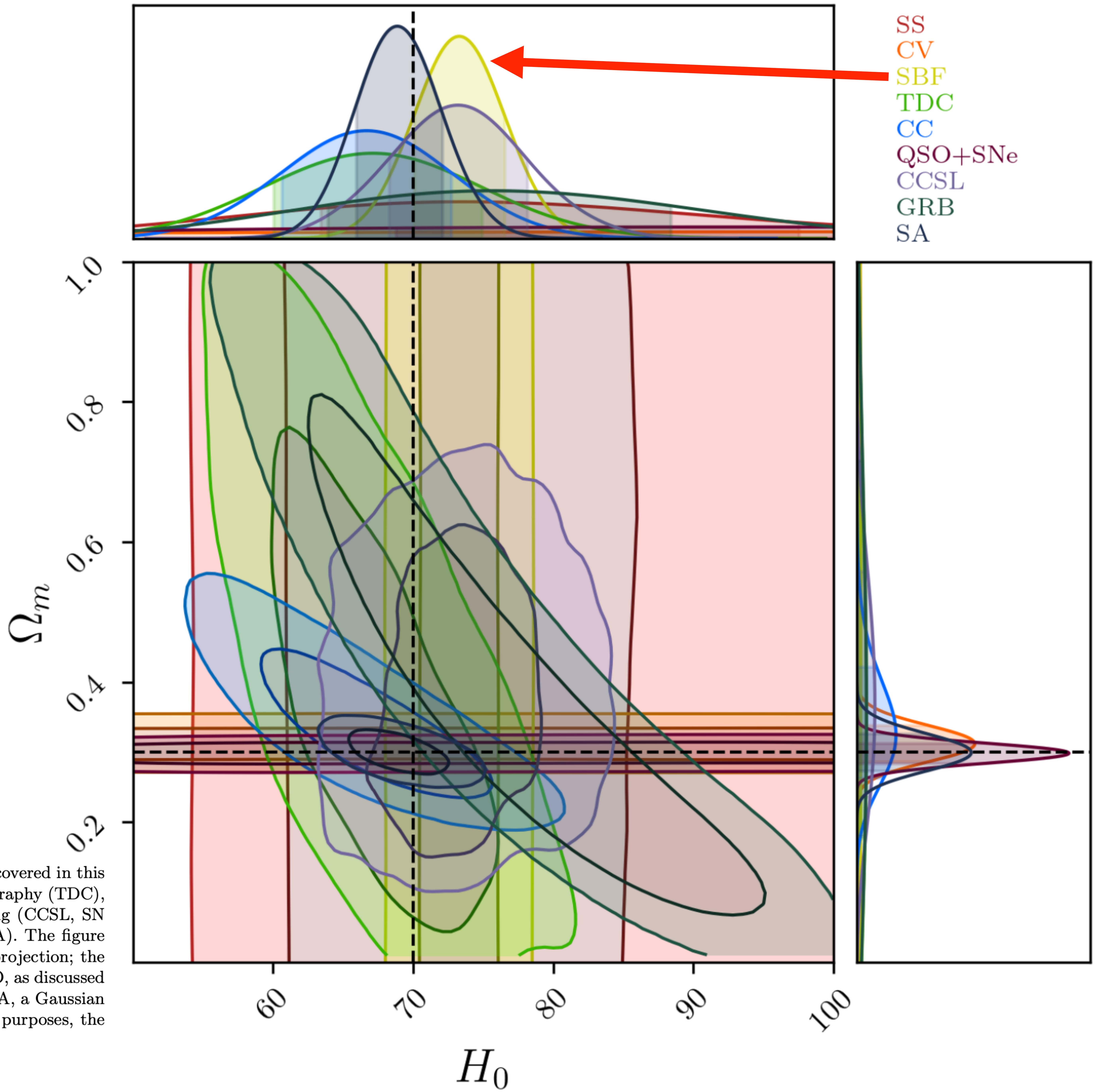


Figure 51: Current constraints on cosmological parameters from the various cosmological probes covered in this review, namely cosmic chronometers (CC), quasars (QSO), standard sirens (SS), time delay cosmography (TDC), surface brightness fluctuations (SBF), cosmic voids (CV), cosmography with cluster strong lensing (CCSL, SN Refsdal case Grillo et al., 2020), gamma-ray bursts (GRB, "Amati" relation), and stellar ages (SA). The figure shows the contour plot in the H_0-Ω_m plane for a flat ΛCDM cosmology, with their marginalized projection; the darker and lighter contours show the 68% and 95% confidence levels, respectively. In the case of QSO, as discussed in Sect. 3.2, also information from SNe Ia have been added to normalize the Hubble diagram; for SA, a Gaussian prior Ω_m=0.3 ± 0.02 is assumed (Jimenez et al., 2019). The dashed lines indicate, for illustrative purposes, the values H_0=70 km $s^{-1}$$Mpc^{-1}$and Ω_m=0.3.

Using SBF to “calibrate” SNe Ia and estimate H_0 ?

Dr Charlotte Wood

- Blakeslee et al. (2021): SBF distances to massive ellipticals in Hubble flow, no supernovae:

$$H_0 = 73.3 \pm 0.7 \pm 2.4$$

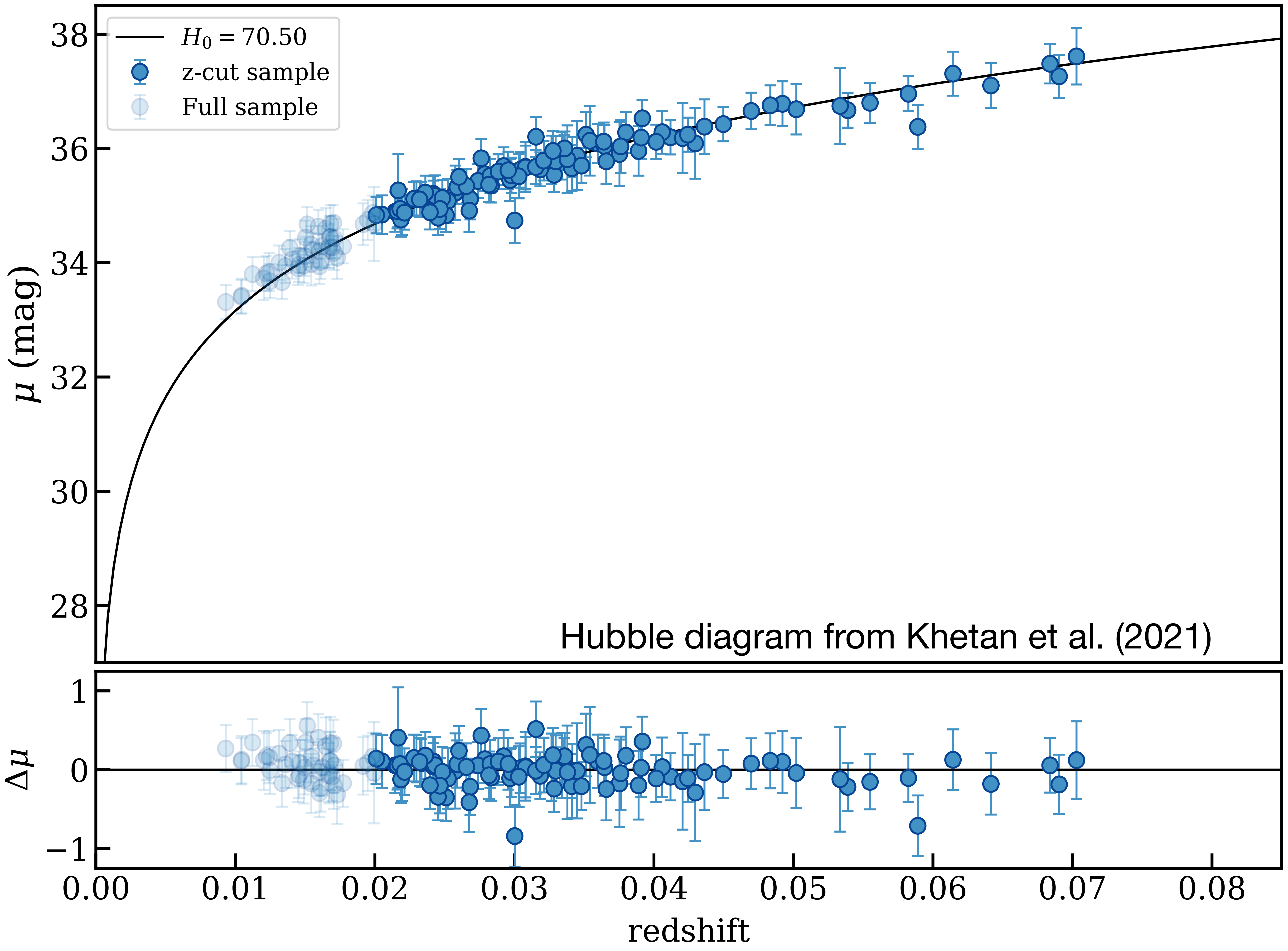
- Khetan et al. (2021): SBF distances from a heterogeneous collection of literature sources cross-matched with SN light curve catalogs:

$$H_0 = 70.5 \pm 2.4 \pm 3.4$$

What's going on with that?

Revised calibration gives $H_0 \approx 71$ for Khetan.

No overlap in samples, so agree to $< 1\sigma$.



Hubble diagram from Khetan et al. (2021)

Phillips/Tripp Relation for SBF vs. Cepheid SNe

Are non-linear corrections needed?

- Modified Tripp relation:

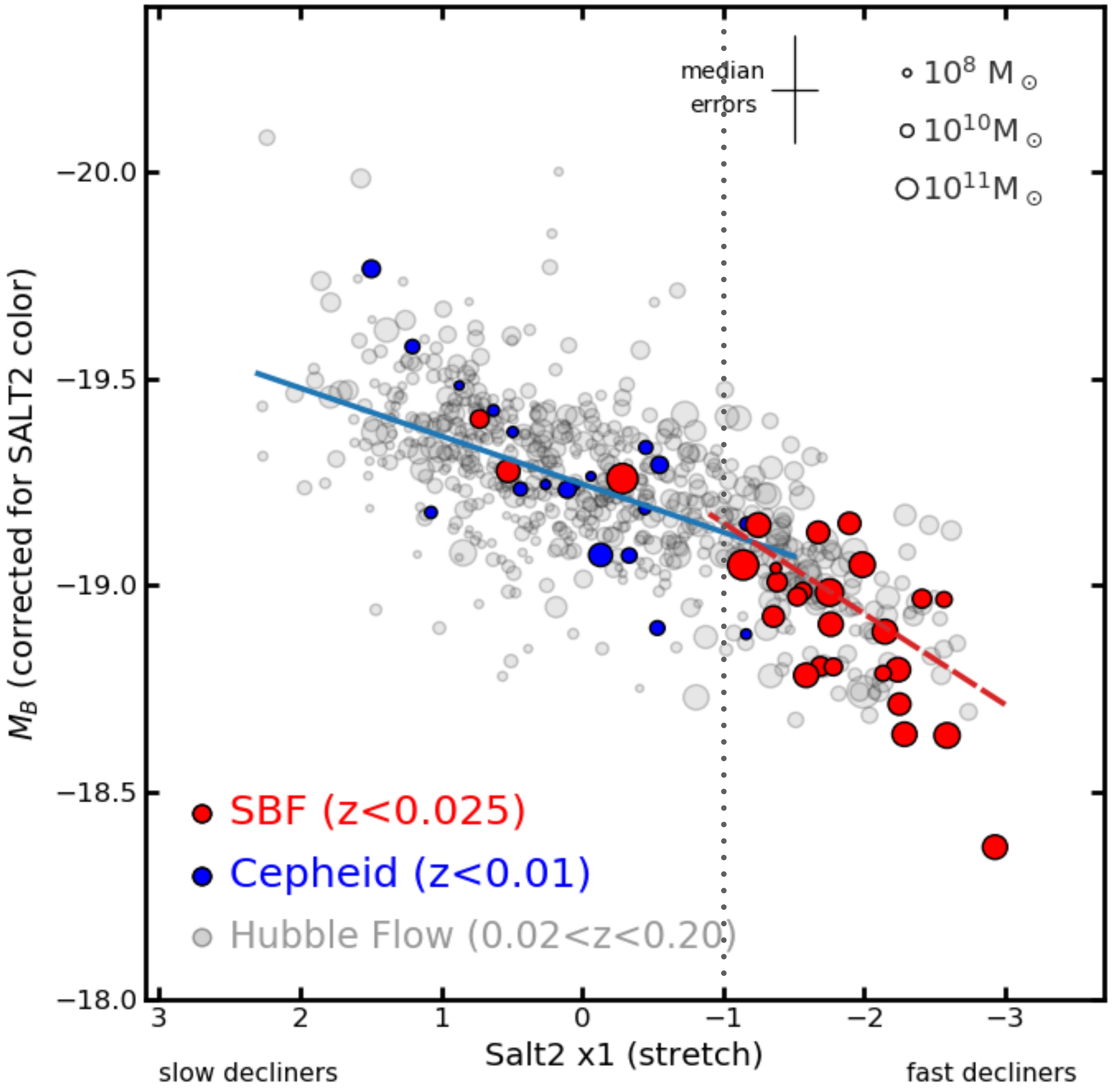
$$\mu = m_B + \alpha x_1 - \beta c - M_B - \delta_{\text{bias}}$$

  correlation between SNIa absolute magnitude, SALT2 stretch & color, with bias corrections.

- 90% of SBF-calibrated SNe have $x_1 < -1$, while 90% of Cepheid-calibrated SNe have $x_1 > -1$.

- Slopes of blue and red line correspond to α, which is twice as steep for SNe with $x_1 < -1$.

Garnavich, Wood, et al. 2022, arXiv:2204.12060



Mag vs. stretch for SBF, Cepheid, & Hubble flow SNe

Phillips/Tripp Relation for SBF vs. Cepheid SNe

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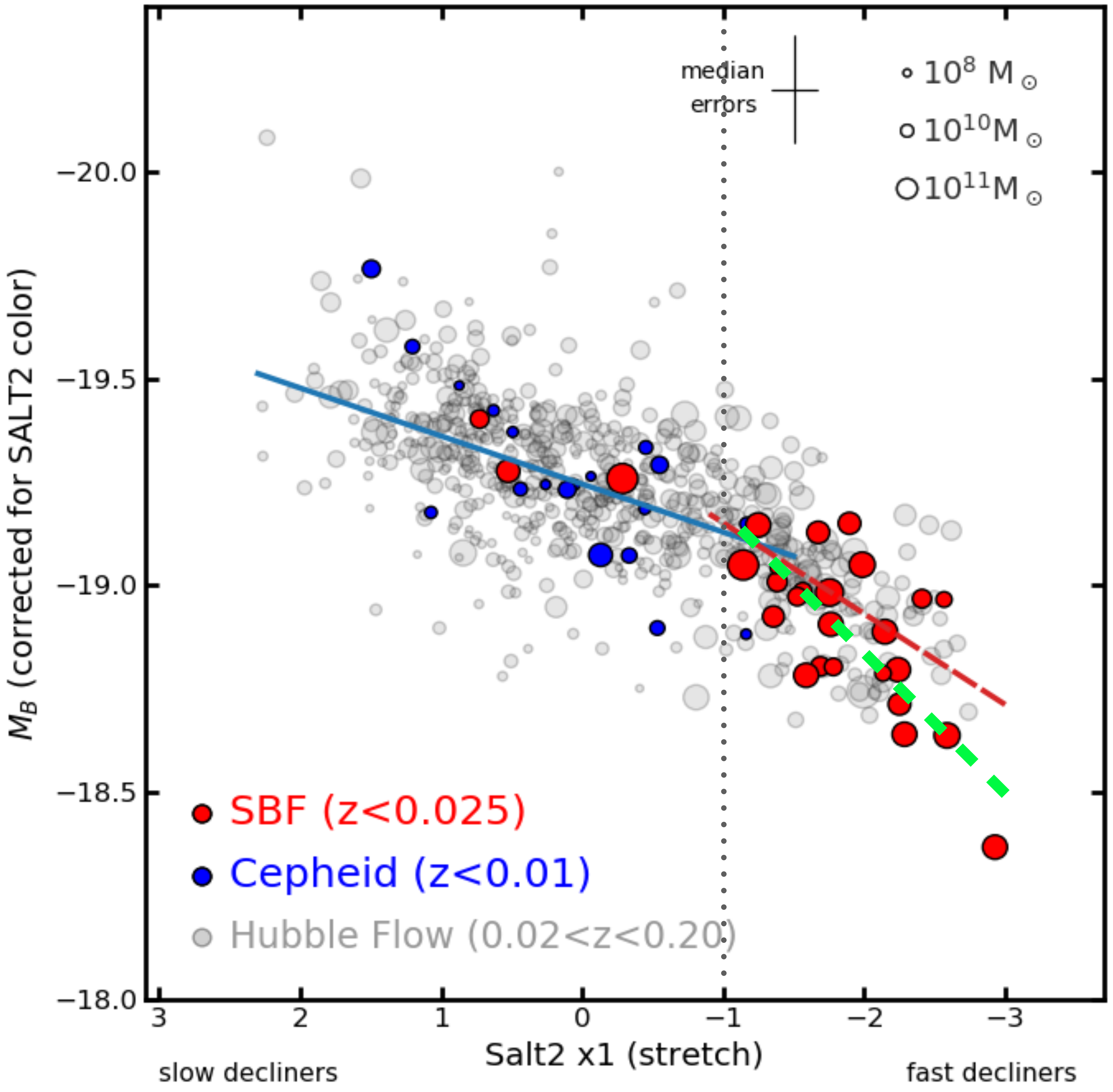
- Slopes of blue and red line correspond to α, which is twice as steep for SNe with $x_1 < -1$.

Tripp relation may be improved by non-linear stretch term **when fast-declining SNe present**.

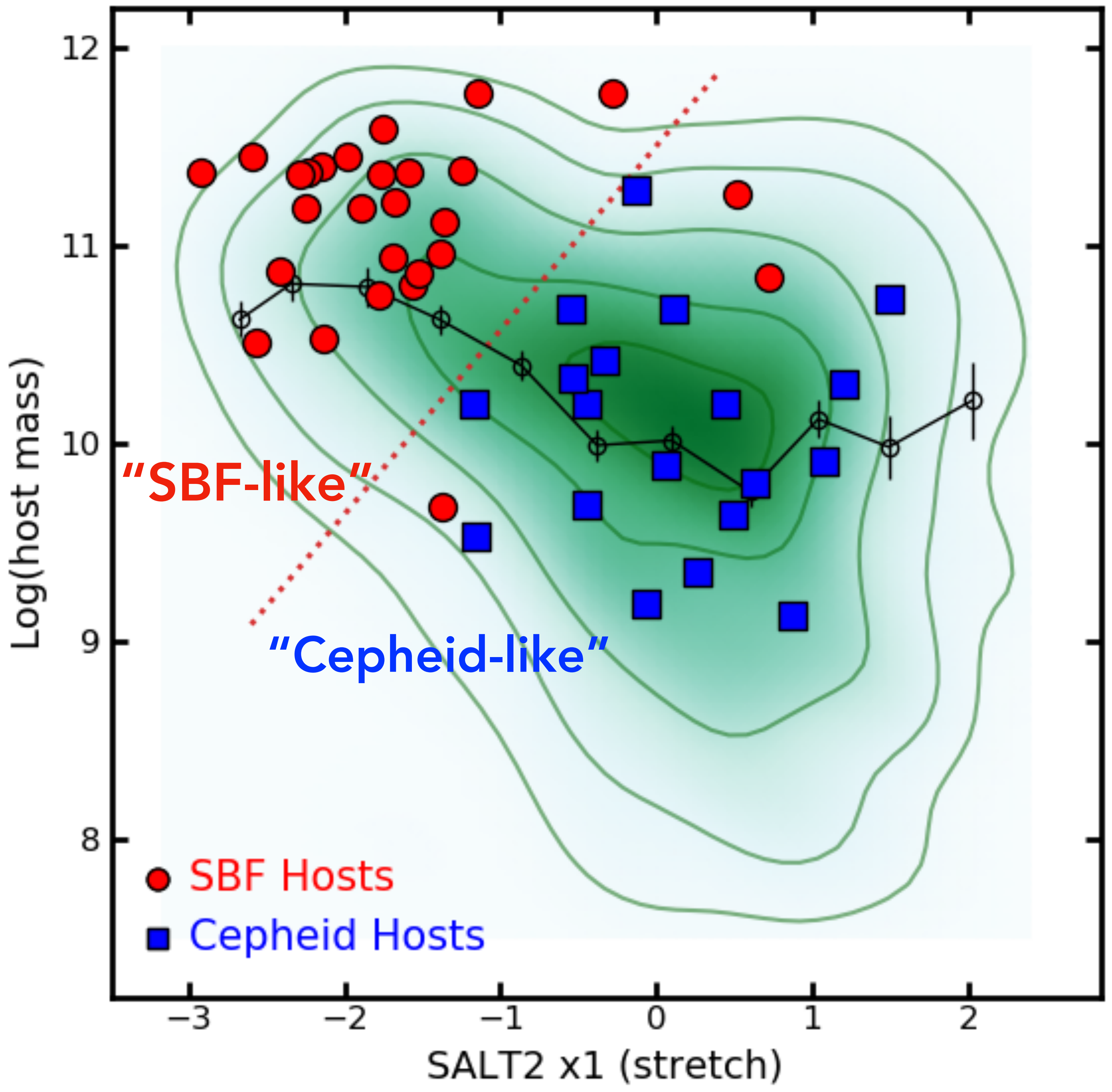
Garnavich, Wood, et al. 2022, arXiv:2204.12060



Mag vs. stretch for SBF, Cepheid, & Hubble flow SNe

Estimations of H_0 — Refitting to SBF-like SNe

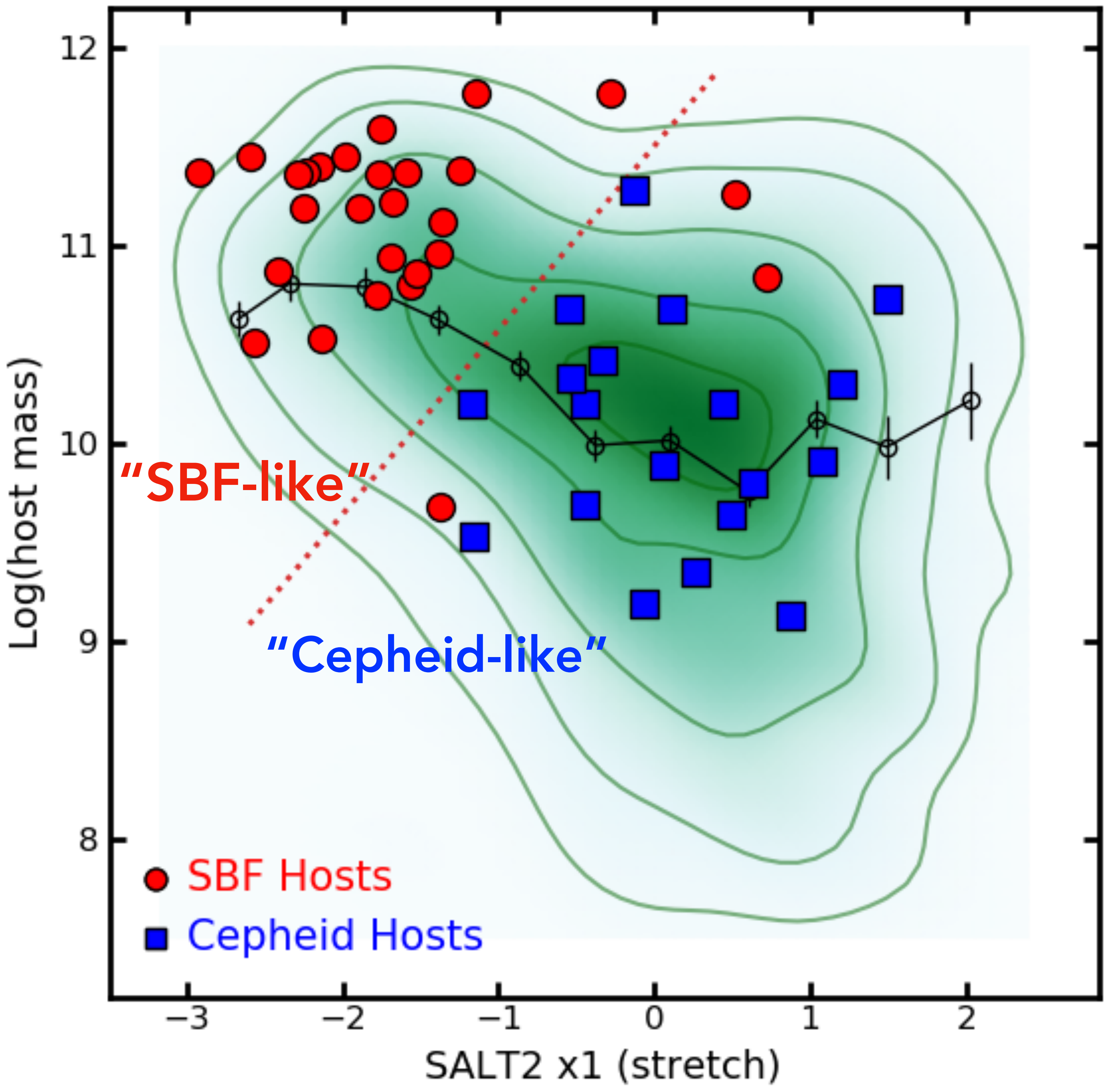
- What if we use a different, optimized set of Tripp-relation coefficients for the fast-declining supernovae?



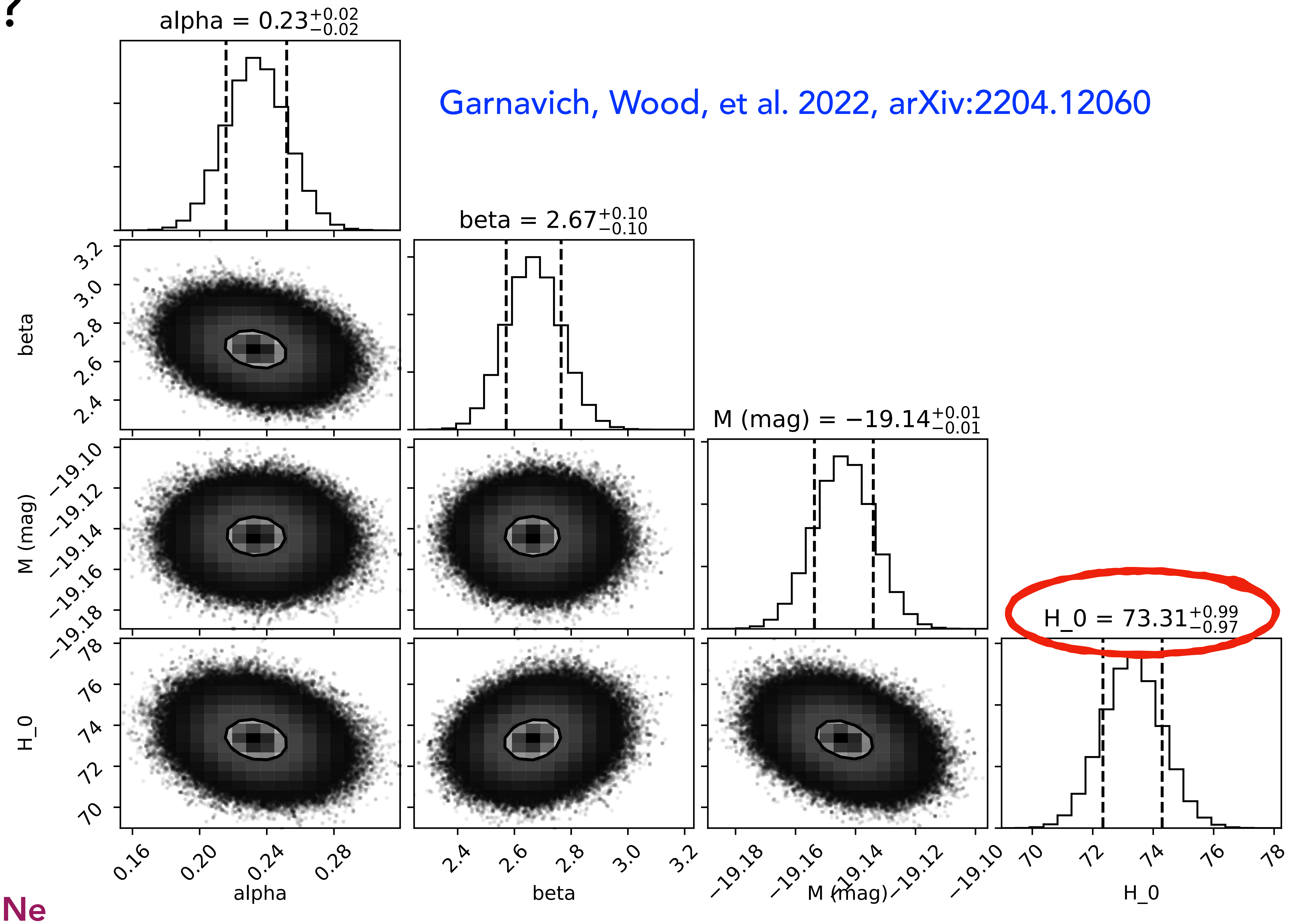
log(host mass) vs stretch for SBF, Cepheid, & Hubble flow SNe

Estimations of H_0 — Refitting to SBF-like SNe

- What if we use a different, optimized set of Tripp-relation coefficients for the fast-declining supernovae?



log(host mass) vs stretch for SBF, Cepheid, & Hubble flow SNe



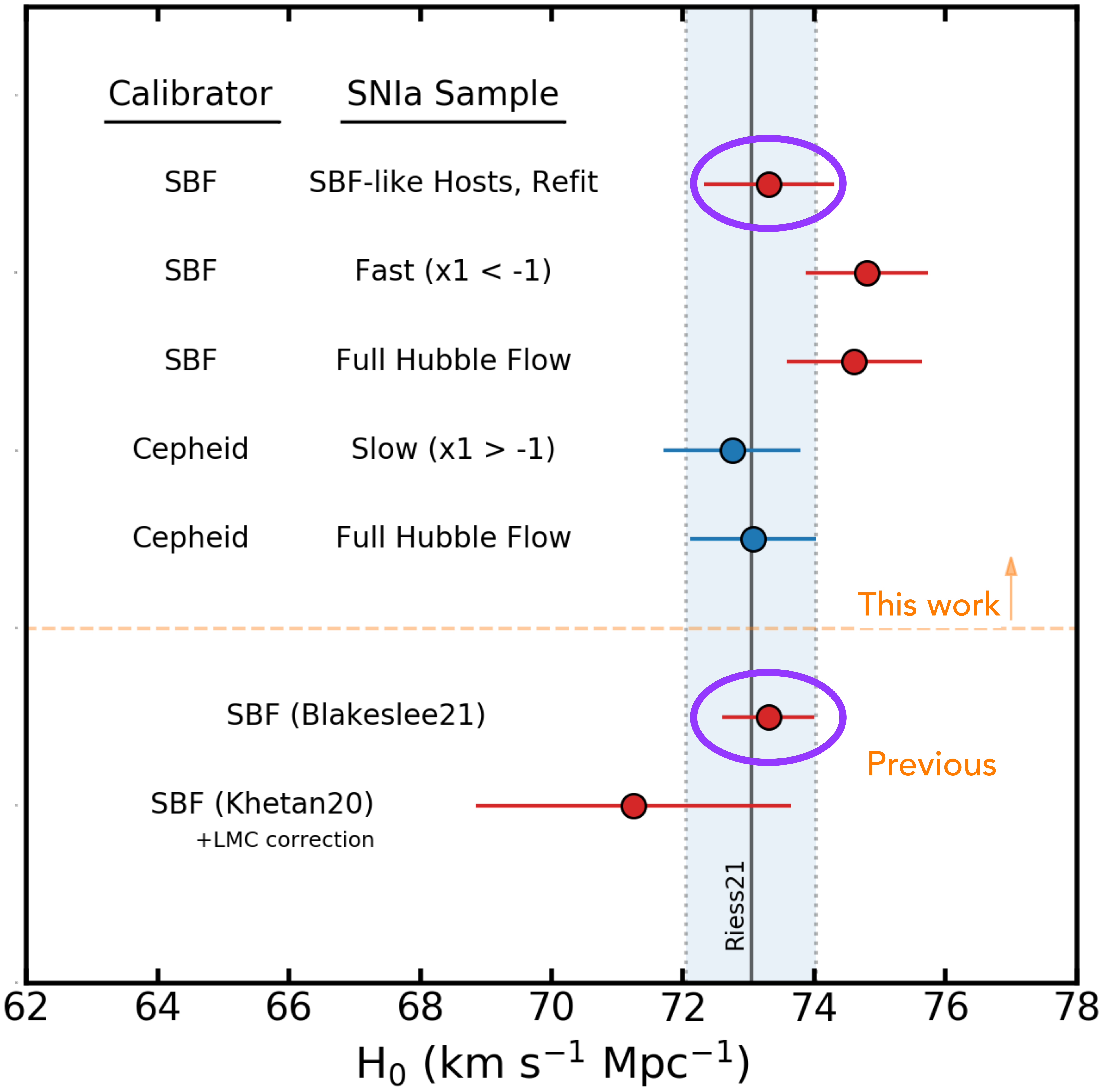
Garnavich, Wood, et al. 2022, arXiv:2204.12060

MCMC refitting of Tripp relation using only the "SBF-like" sample

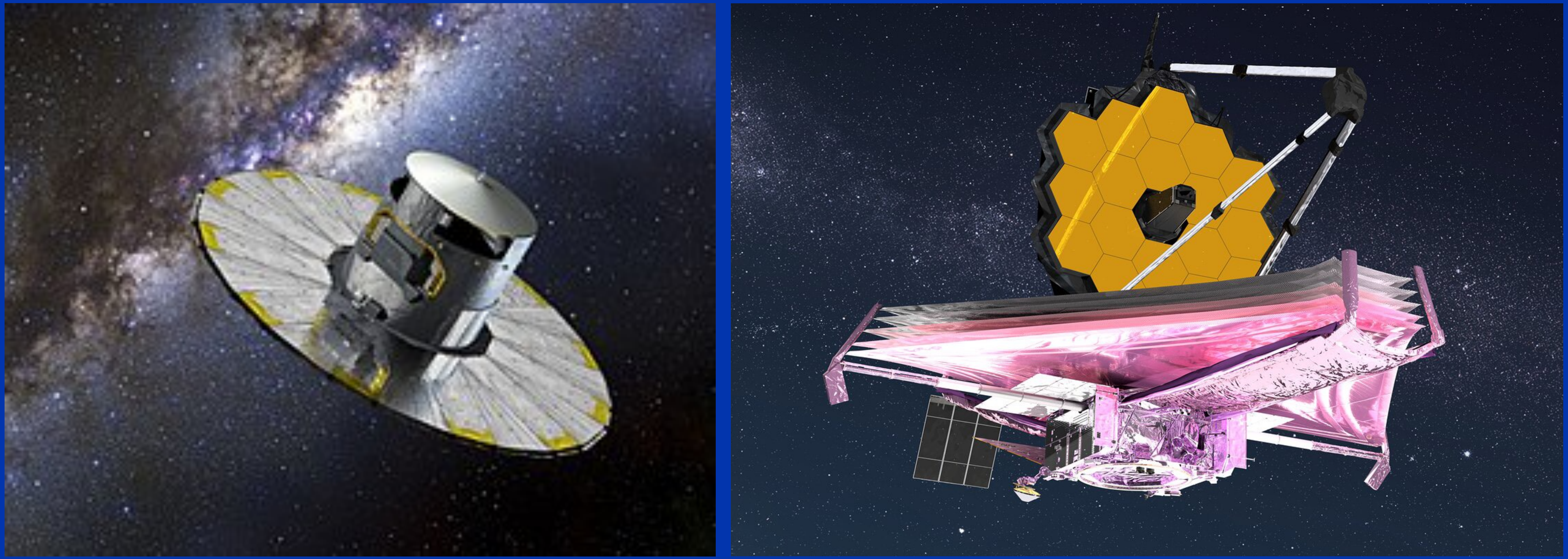
Comparison of Cepheid/TRGB-SBF, Cepheid-SNIa & Cepheid-SBF-SNIa, H_0 results

- Previous SBF-related H_0 results are in line or lower than SH0ES
- SBF-SNIa H_0 results using the Pantheon+ Tripp parameters are higher by $\sim 1\sigma$
- Re-fitting Tripp relation to the "SBF-like" SNIa brings SBF-SNIa H_0 value in line with both SH0ES *and* SBF Hubble flow H_0

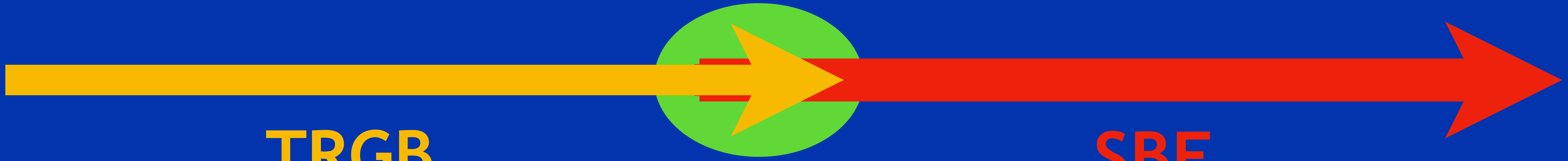
Garnavich, Wood, et al. 2022, arXiv:2204.12060



The way forward: an independent 2-step Pop-II Distance Ladder



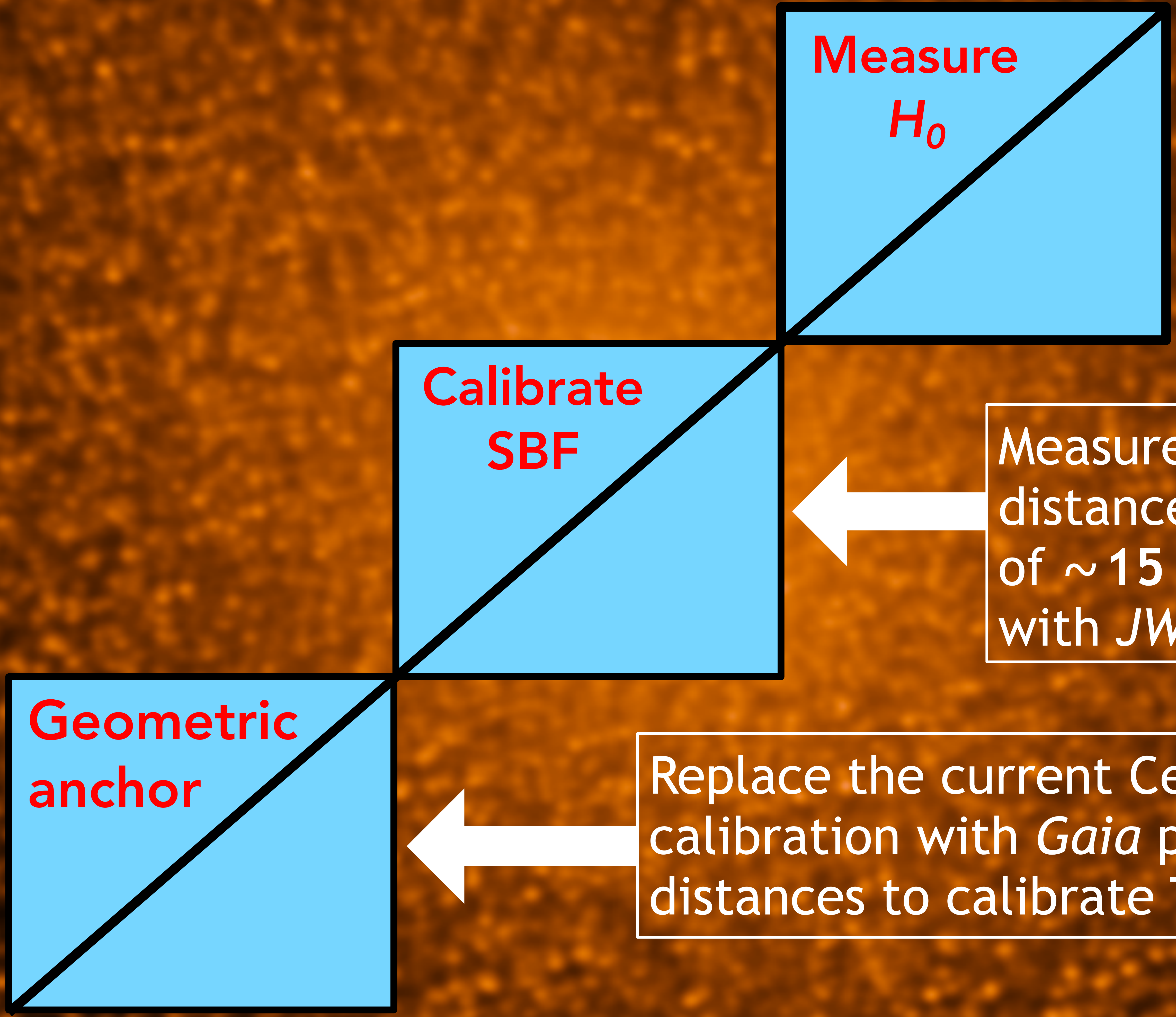
Milky Way Local Group ~Virgo Hubble Flow



TRGB

SBF

Towards < 2% H_0 from SBF…

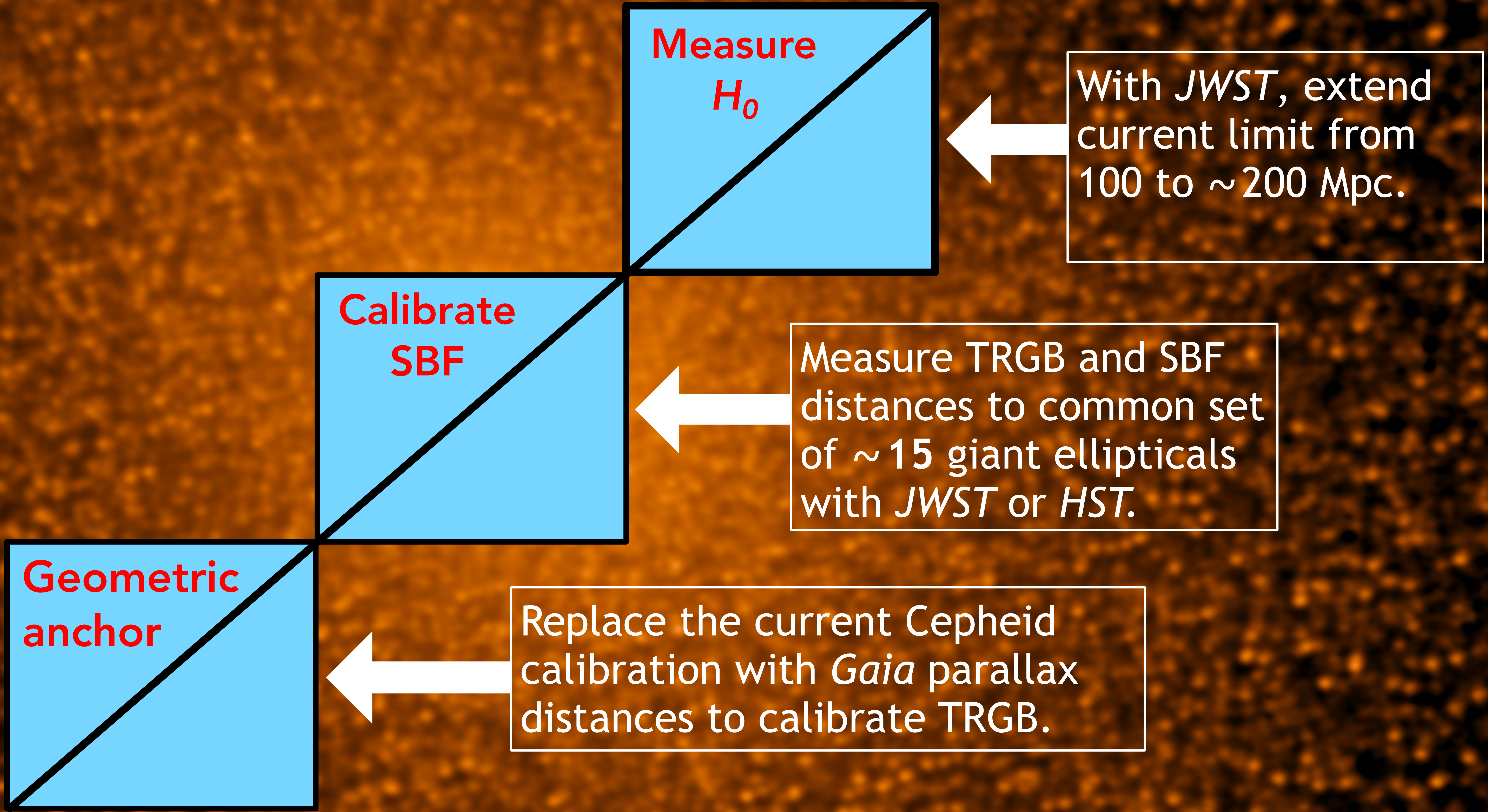


With *JWST*, extend current limit from 100 to ~200 Mpc.

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.

Towards < 2% H_0 from SBF…



Measure
H_0

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

Calibrate
SBF

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

Geometric
anchor

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

In parallel, use realistic galaxy models to check stellar pop effects.

Thanks!

Cautionary note about velocities

Velocity treatment	SBF H_0, N=60 (JPB+ 2021)	Maser H_0, N=6 (Pesce+ 2020)	χ_n^2 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 (as in 2019).

Example WFC3/IR SBF reductions

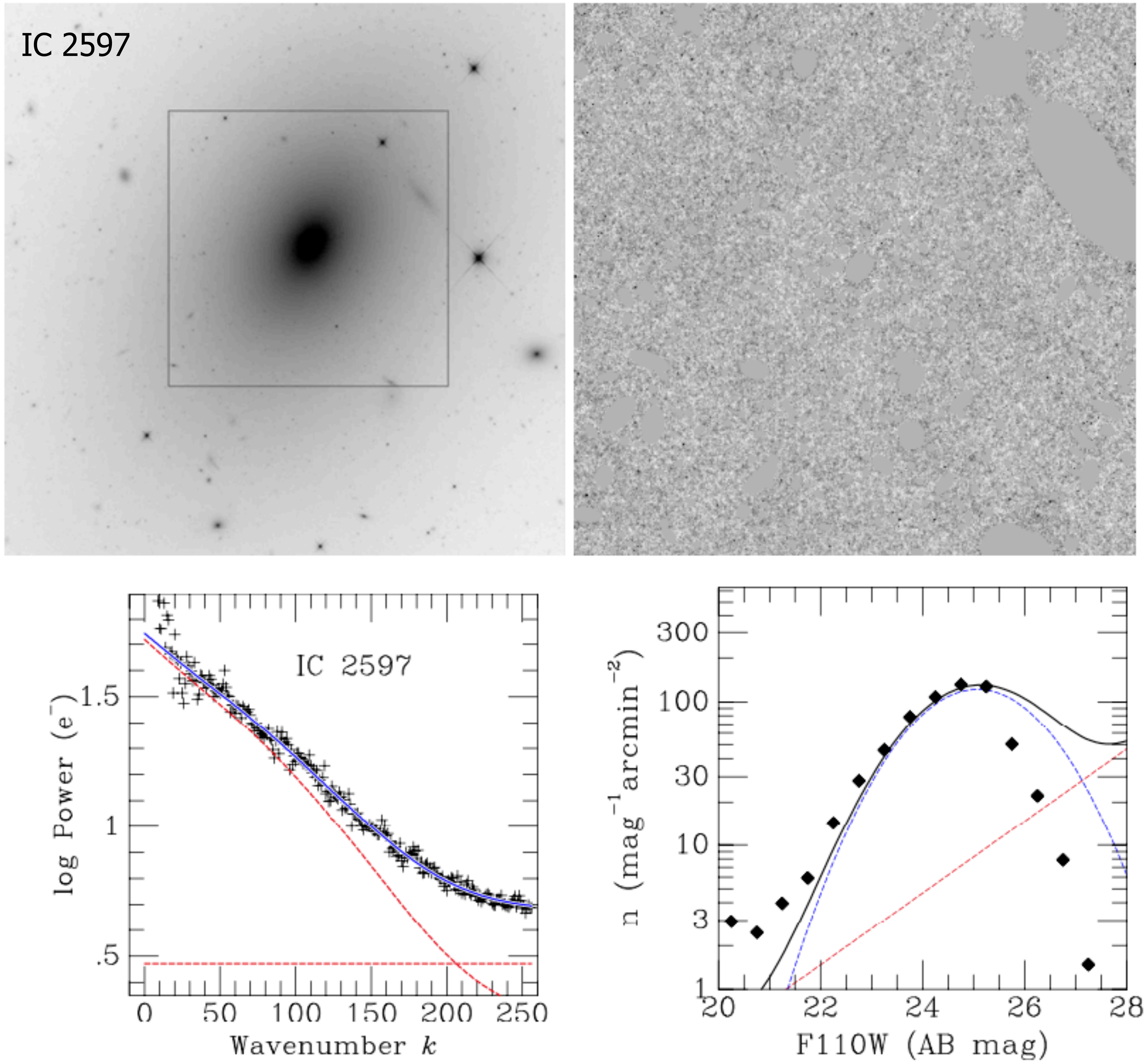


Figure 8. Combined figure for IC 2597.

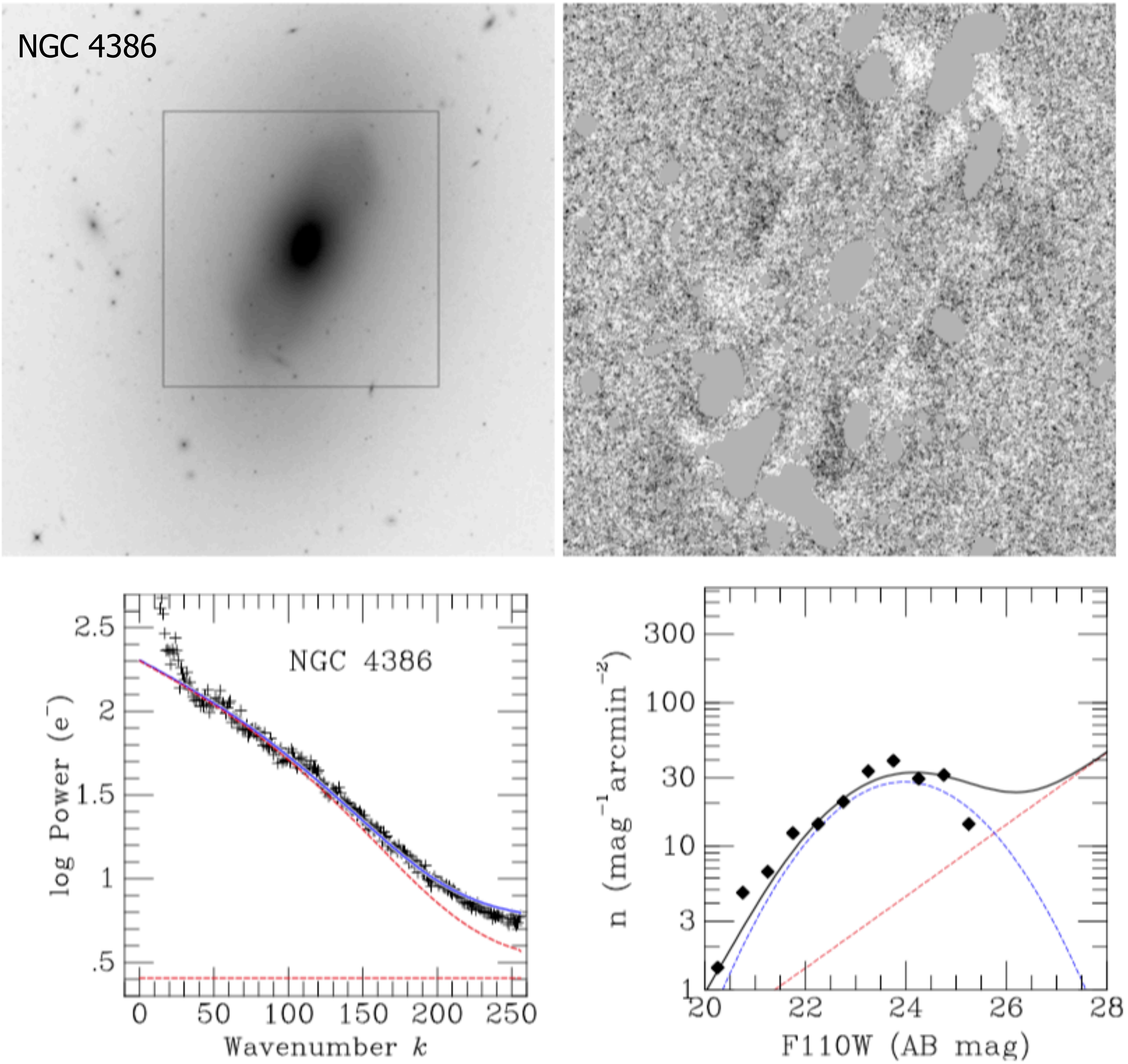
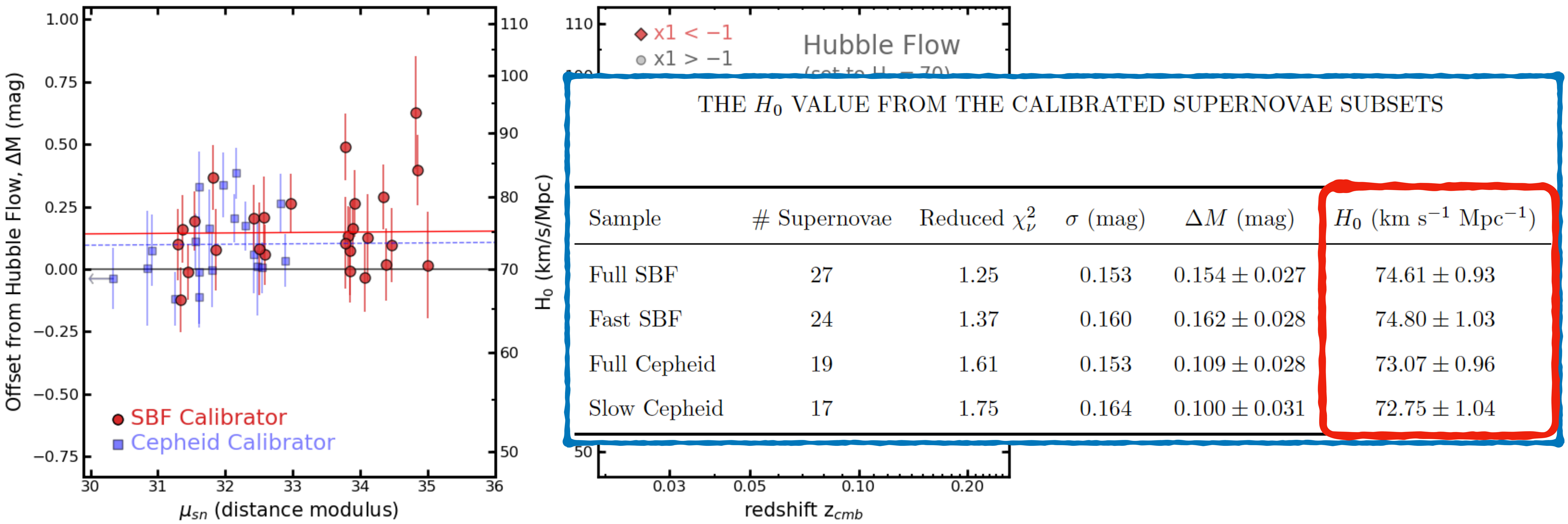


Figure 53. Combined figure for NGC 4386.

Jensen, Blakeslee et al. 2021

Estimations of the Hubble Constant

What happens if we calculate H_0 using different SNe groupings?



THE H_0 VALUE FROM THE CALIBRATED SUPERNOVAE SUBSETS

Sample	# Supernovae	Reduced χ^2_ν	σ (mag)	ΔM (mag)	H_0 (km s^{-1} Mpc^{-1})
Full SBF	27	1.25	0.153	0.154 ± 0.027	74.61 ± 0.93
Fast SBF	24	1.37	0.160	0.162 ± 0.028	74.80 ± 1.03
Full Cepheid	19	1.61	0.153	0.109 ± 0.028	73.07 ± 0.96
Slow Cepheid	17	1.75	0.164	0.100 ± 0.031	72.75 ± 1.04

Figure 25: Estimates of H_0 from individual SBF & Cepheid SNe Ia as compared to the Hubble flow in the Pantheon+ sample

Previous SBF H_0's this century

(ratty data, small samples, and/or shaky calibrations)

Work	H_0 (km s^{-1} Mpc^{-1})	ΔH_0 Statistical	ΔH_0 Systematic	Notes
Tonry et al. (2000)	77	±4	±7	SBF survey, velocity field model, Cepheids ZP
Jensen et al. (2001)	72-76	±2	±9	Near-IR NICMOS/HST data, Cepheids ZP uncertain calibration
Blakeslee et al. (2002)	73	±4	±11	SBF Survey + FP + IRAS Vel. Field model
Biscardi I. et al., (2008)	76	±6	±5	ACS optical Model calibration
Mould & Sakai (2009)	68	±6	±4	SBF survey data, rough TRGB calibration

Courtesy of Michele Cantiello, MIAAP June 2018

Bonus: Appendix on TRGB!

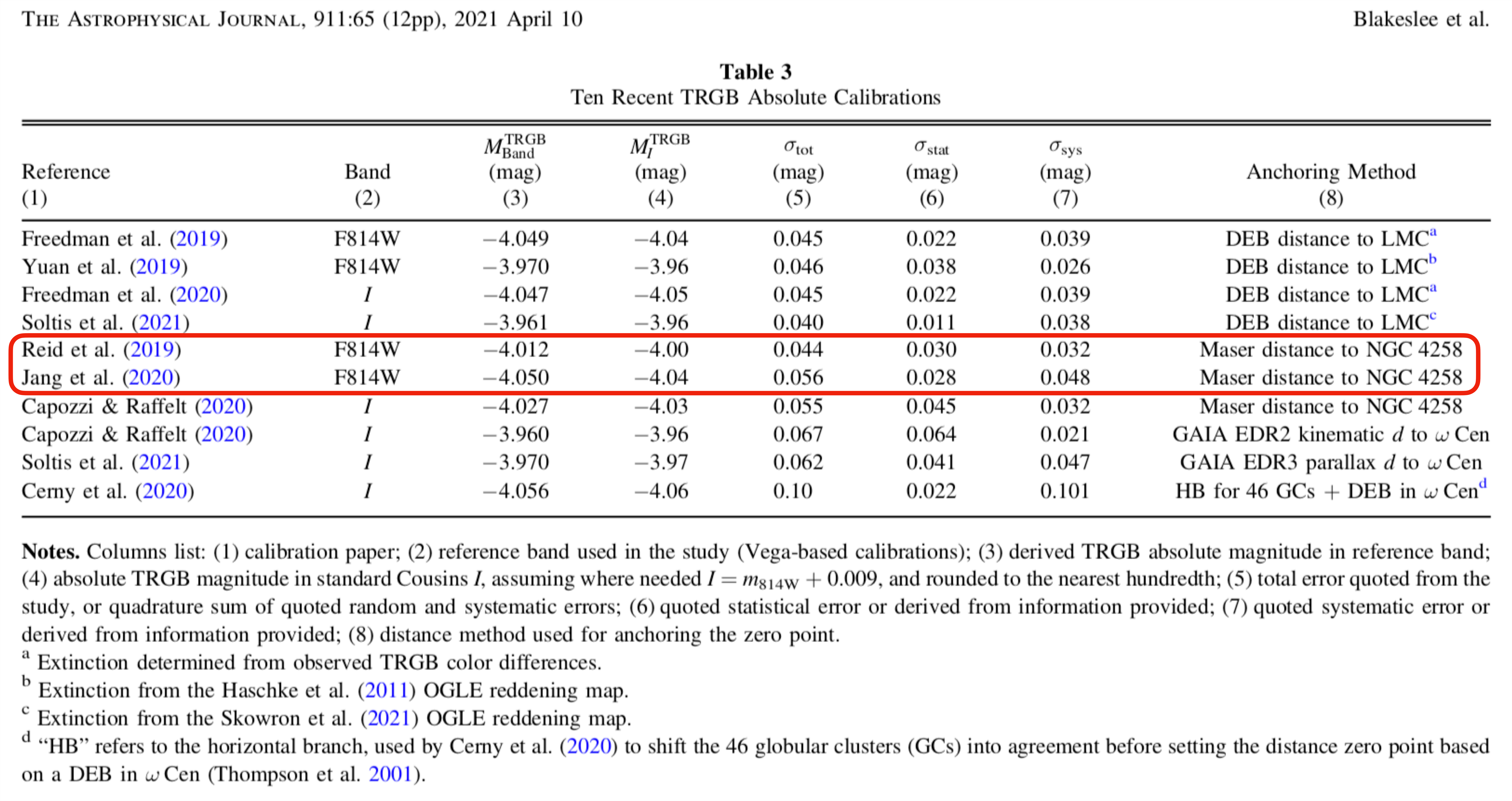


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Table 3
Ten Recent TRGB Absolute Calibrations

Reference (1)	Band (2)	$M_{\rm Band}^{\rm TRGB}$ (mag) (3)	$M_I^{\rm TRGB}$ (mag) (4)	$\sigma_{\rm tot}$ (mag) (5)	$\sigma_{\rm stat}$ (mag) (6)	$\sigma_{\rm sys}$ (mag) (7)	Anchoring Method (8)
Freedman et al. (2019)	F814W	−4.049	−4.04	0.045	0.022	0.039	DEB distance to LMC[a]
Yuan et al. (2019)	F814W	−3.970	−3.96	0.046	0.038	0.026	DEB distance to LMC[b]
Freedman et al. (2020)	*I*	−4.047	−4.05	0.045	0.022	0.039	DEB distance to LMC[a]
Soltis et al. (2021)	*I*	−3.961	−3.96	0.040	0.011	0.038	DEB distance to LMC[c]
Reid et al. (2019)	F814W	−4.012	−4.00	0.044	0.030	0.032	Maser distance to NGC 4258
Jang et al. (2020)	F814W	−4.050	−4.04	0.056	0.028	0.048	Maser distance to NGC 4258
Capozzi & Raffelt (2020)	*I*	−4.027	−4.03	0.055	0.045	0.032	Maser distance to NGC 4258
Capozzi & Raffelt (2020)	*I*	−3.960	−3.96	0.067	0.064	0.021	GAIA EDR2 kinematic *d* to ω Cen
Soltis et al. (2021)	*I*	−3.970	−3.97	0.062	0.041	0.047	GAIA EDR3 parallax *d* to ω Cen
Cerny et al. (2020)	*I*	−4.056	−4.06	0.10	0.022	0.101	HB for 46 GCs + DEB in ω Cen[d]

Notes. Columns list: (1) calibration paper; (2) reference band used in the study (Vega-based calibrations); (3) derived TRGB absolute magnitude in reference band; (4) absolute TRGB magnitude in standard Cousins *I*, assuming where needed $I = m_{814W} + 0.009$, and rounded to the nearest hundredth; (5) total error quoted from the study, or quadrature sum of quoted random and systematic errors; (6) quoted statistical error or derived from information provided; (7) quoted systematic error or derived from information provided; (8) distance method used for anchoring the zero point.

[a] Extinction determined from observed TRGB color differences.

[b] Extinction from the Haschke et al. (2011) OGLE reddening map.

[c] Extinction from the Skowron et al. (2021) OGLE reddening map.

[d] "HB" refers to the horizontal branch, used by Cerny et al. (2020) to shift the 46 globular clusters (GCs) into agreement before setting the distance zero point based on a DEB in ω Cen (Thompson et al. 2001).

Note: Need to calibrate using galaxies similar to those used for measuring H_0

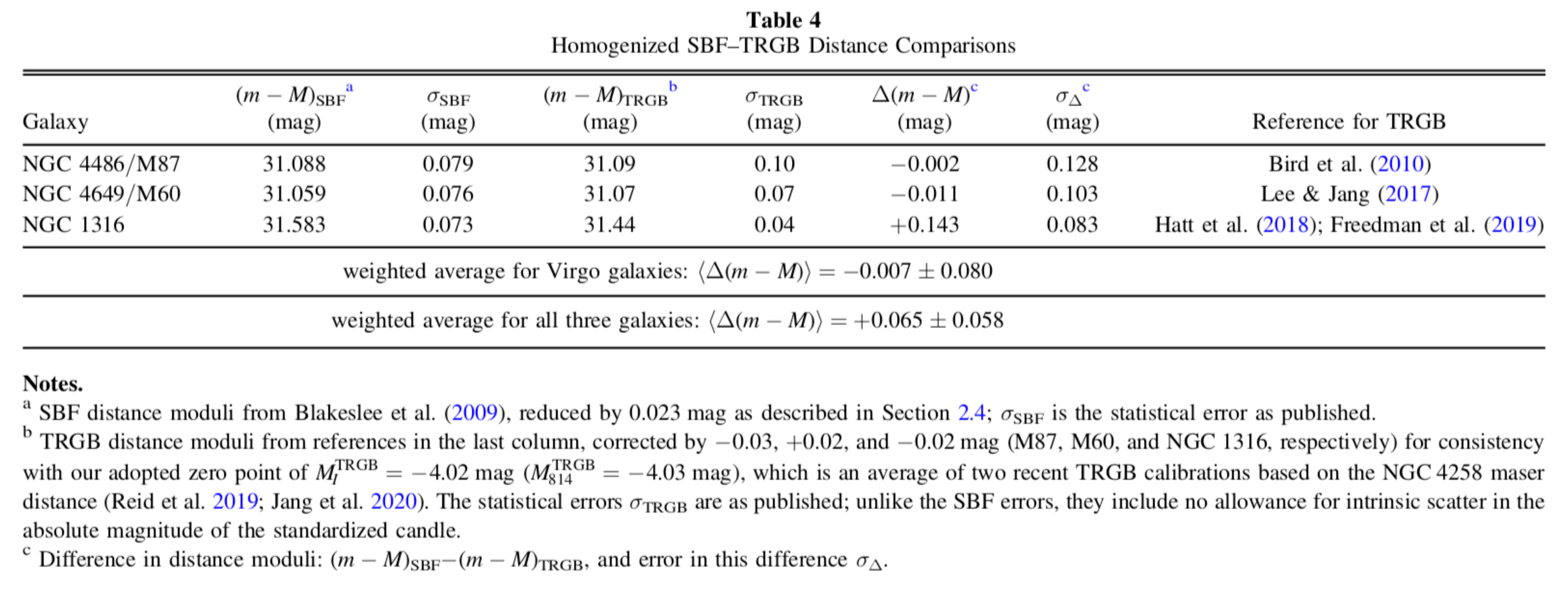

Table 4

Homogenized SBF–TRGB Distance Comparisons

Galaxy	$(m-M)_{\rm SBF}$[a] (mag)	$\sigma_{\rm SBF}$ (mag)	$(m-M)_{\rm TRGB}$[b] (mag)	$\sigma_{\rm TRGB}$ (mag)	$\Delta(m-M)$[c] (mag)	σ_{Δ}[c] (mag)	Reference for TRGB
NGC 4486/M87	31.088	0.079	31.09	0.10	−0.002	0.128	Bird et al. (2010)
NGC 4649/M60	31.059	0.076	31.07	0.07	−0.011	0.103	Lee & Jang (2017)
NGC 1316	31.583	0.073	31.44	0.04	+0.143	0.083	Hatt et al. (2018); Freedman et al. (2019)

weighted average for Virgo galaxies: $\langle\Delta(m-M)\rangle = -0.007 \pm 0.080$

weighted average for all three galaxies: $\langle\Delta(m-M)\rangle = +0.065 \pm 0.058$

Notes.

[a] SBF distance moduli from Blakeslee et al. (2009), reduced by 0.023 mag as described in Section 2.4; $\sigma_{\rm SBF}$ is the statistical error as published.

[b] TRGB distance moduli from references in the last column, corrected by −0.03, +0.02, and −0.02 mag (M87, M60, and NGC 1316, respectively) for consistency with our adopted zero point of $M_I^{\rm TRGB} = -4.02$ mag ($M_{814}^{\rm TRGB} = -4.03$ mag), which is an average of two recent TRGB calibrations based on the NGC 4258 maser distance (Reid et al. 2019; Jang et al. 2020). The statistical errors $\sigma_{\rm TRGB}$ are as published; unlike the SBF errors, they include no allowance for intrinsic scatter in the absolute magnitude of the standardized candle.

[c] Difference in distance moduli: $(m-M)_{\rm SBF}-(m-M)_{\rm TRGB}$, and error in this difference σ_{Δ}.

Takeaway: Cepheid & TRGB calibrations of SBF agree within the errors, but we need more TRGB distances to meaty ellipticals out to Virgo.

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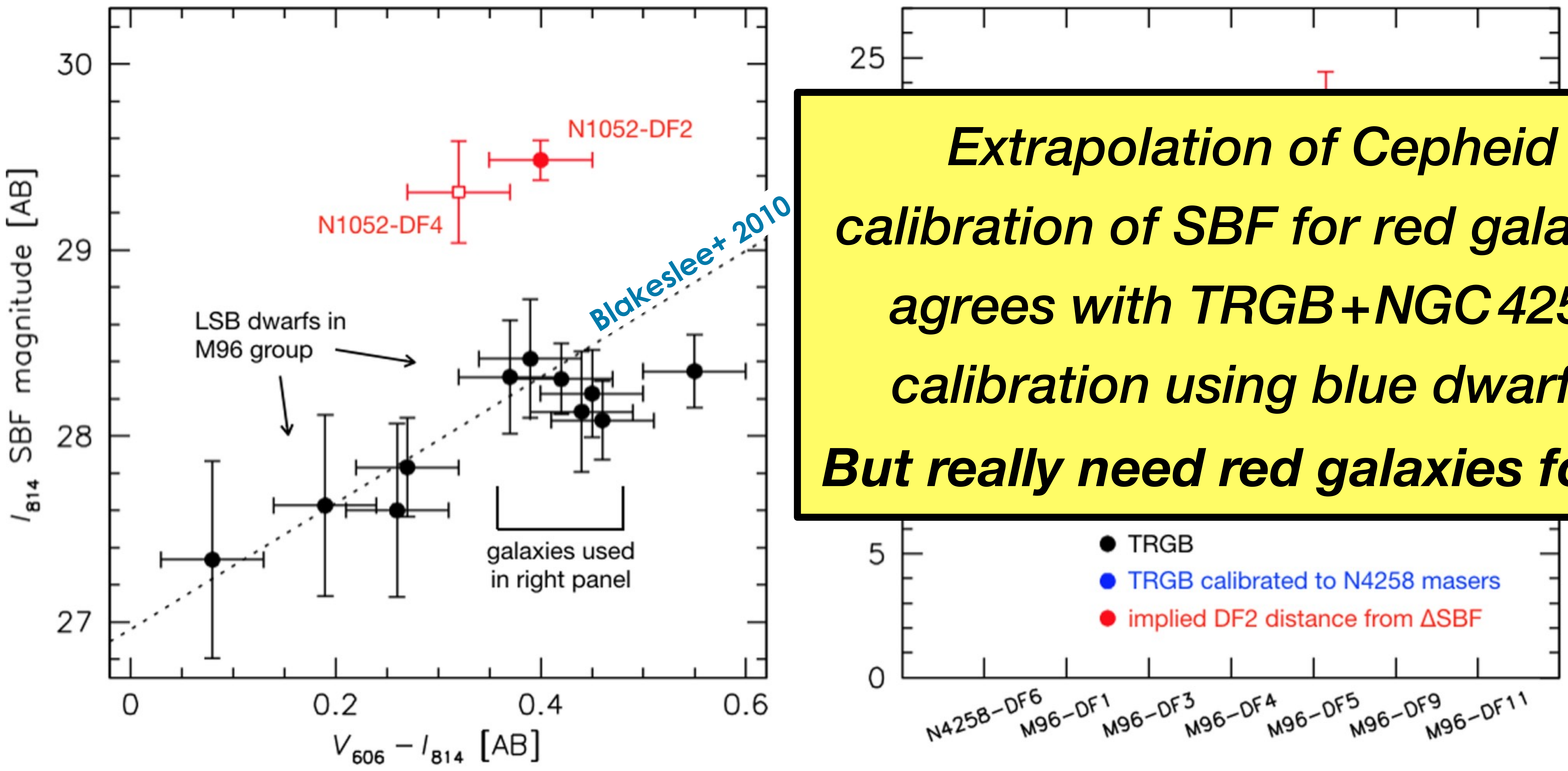
SBF calibration via TRGB anchored to maser galaxy



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