Insights on the Hubble Tension from JWST

NGC 1380 (GO-3055)

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with the SH0ES and TRGB-SBF Project teams

Hubble Tension

- In the last 5-10 years, it has become clear that there is a likely mismatch between the predicted value of H_0 and what is directly measured.
  - “Indirect” path, assume ΛCDM cosmology and use measurements of the Cosmic Microwave Background (e.g. Planck) -> ~67 +/- ~0.5 km/s/Mpc
  - “Direct” path, measure distances and recessional velocities of galaxies -> ~73 +/- ~1 km/s/Mpc

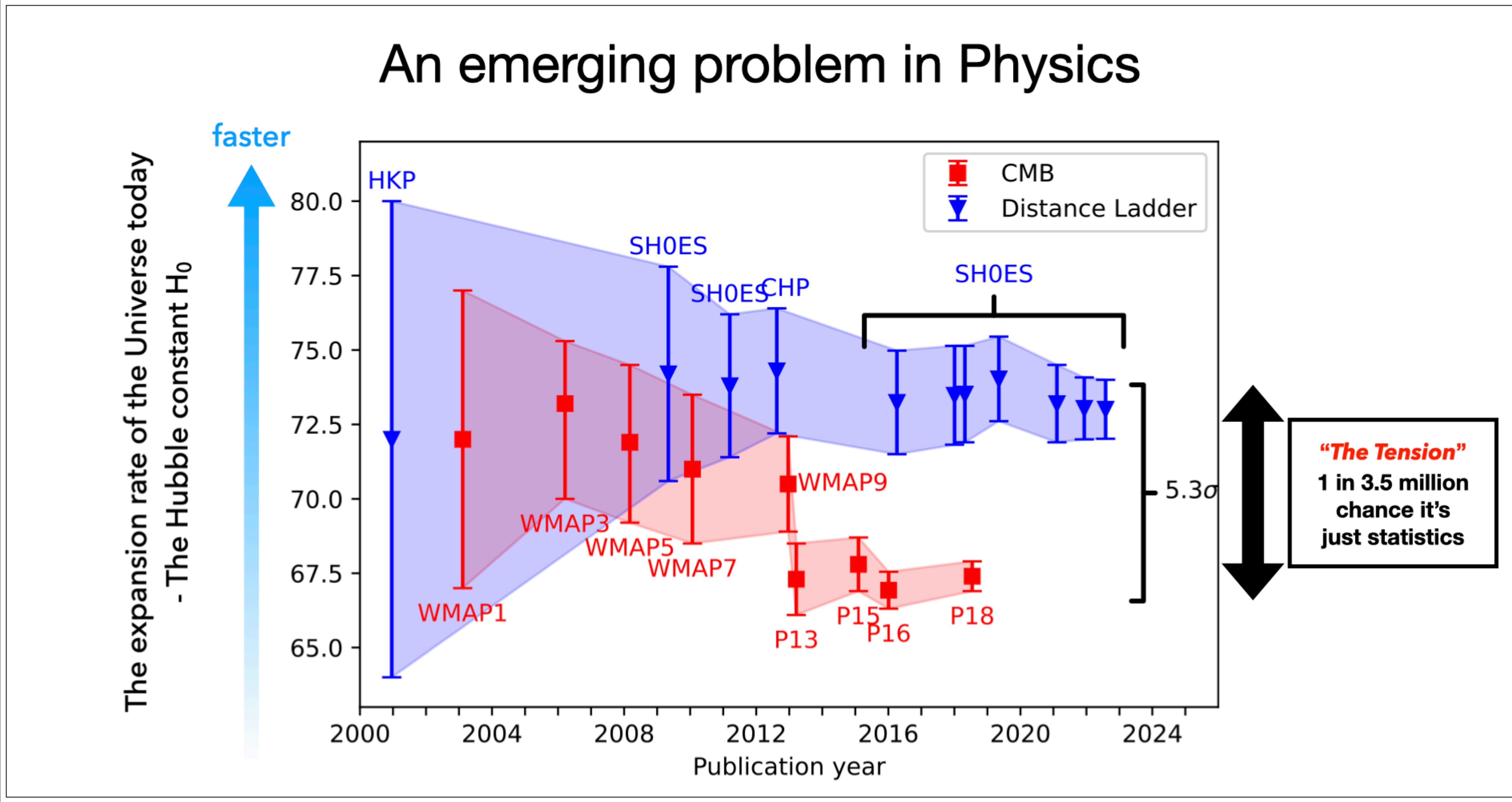
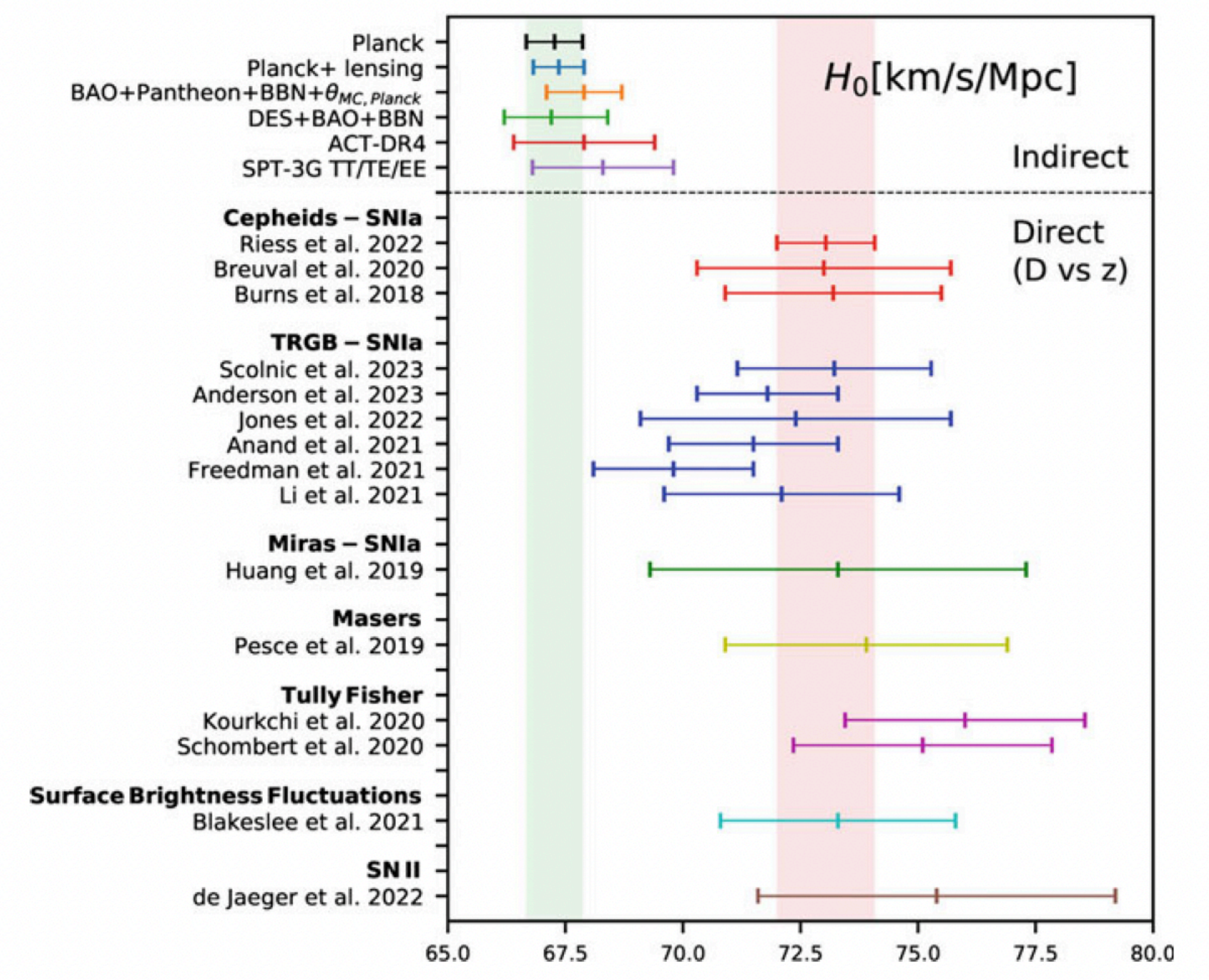


Image Credit: D’arcy Kenworthy

Hubble Tension

- Not just a SH_0ES issue either!
- Work by many groups settle on a higher value for H_0 than what is found by Planck.
  - If Planck and ΛCDM's prediction of H_0 is correct, then shouldn't local distance ladder methods scatter about the Planck value?
- What is going on with all of our distance indicators?
- Or, perhaps more tantalizing, is there an issue with ΛCDM?



Di Valentino 21

SH_0ES

SH_0ES Team and Collaborators: see 4 ApJ papers, 2 arxiv preprints

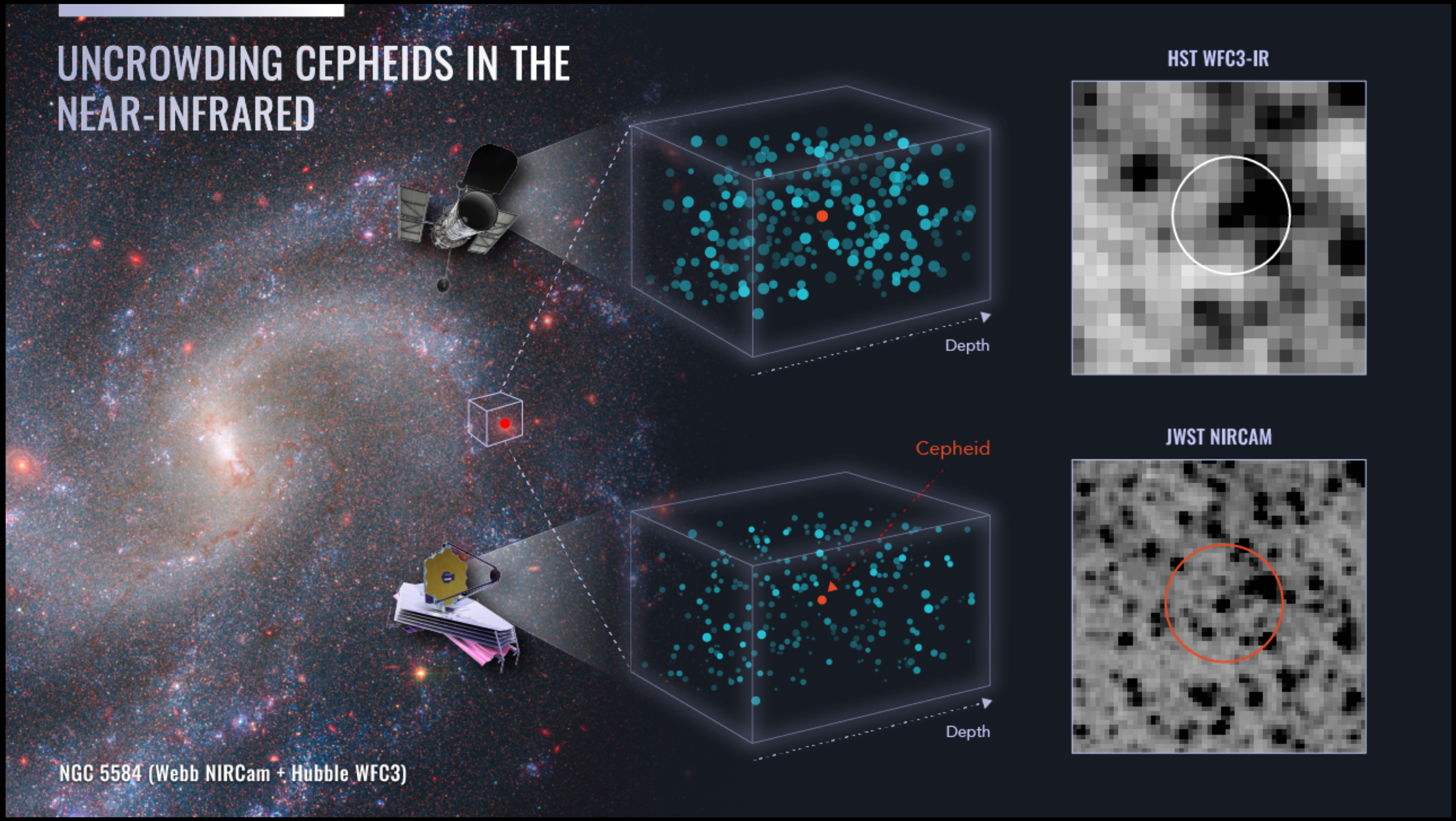
Riess, Anand, Yuan, Macri, Casertano, Scolnic, Breuval, Li, Murakami, et al.

arxiv 24081177: SH_0ES + CCHP Samples, 3 methods

A. Riess et al., ApJL, 2023, 956, L18: JWST Cepheids
A. Riess et al., ApJL, 2024, 962, L17: JWST Cepheids
G. Anand et al., ApJ, 2024, 966, 89: JWST TRGB
S. Li et al., ApJ, 2024, 966, 20: JWST JAGB
S. Li et al., arxiv 2408.00065: JWST TRGB

Cepheid Distance Scale

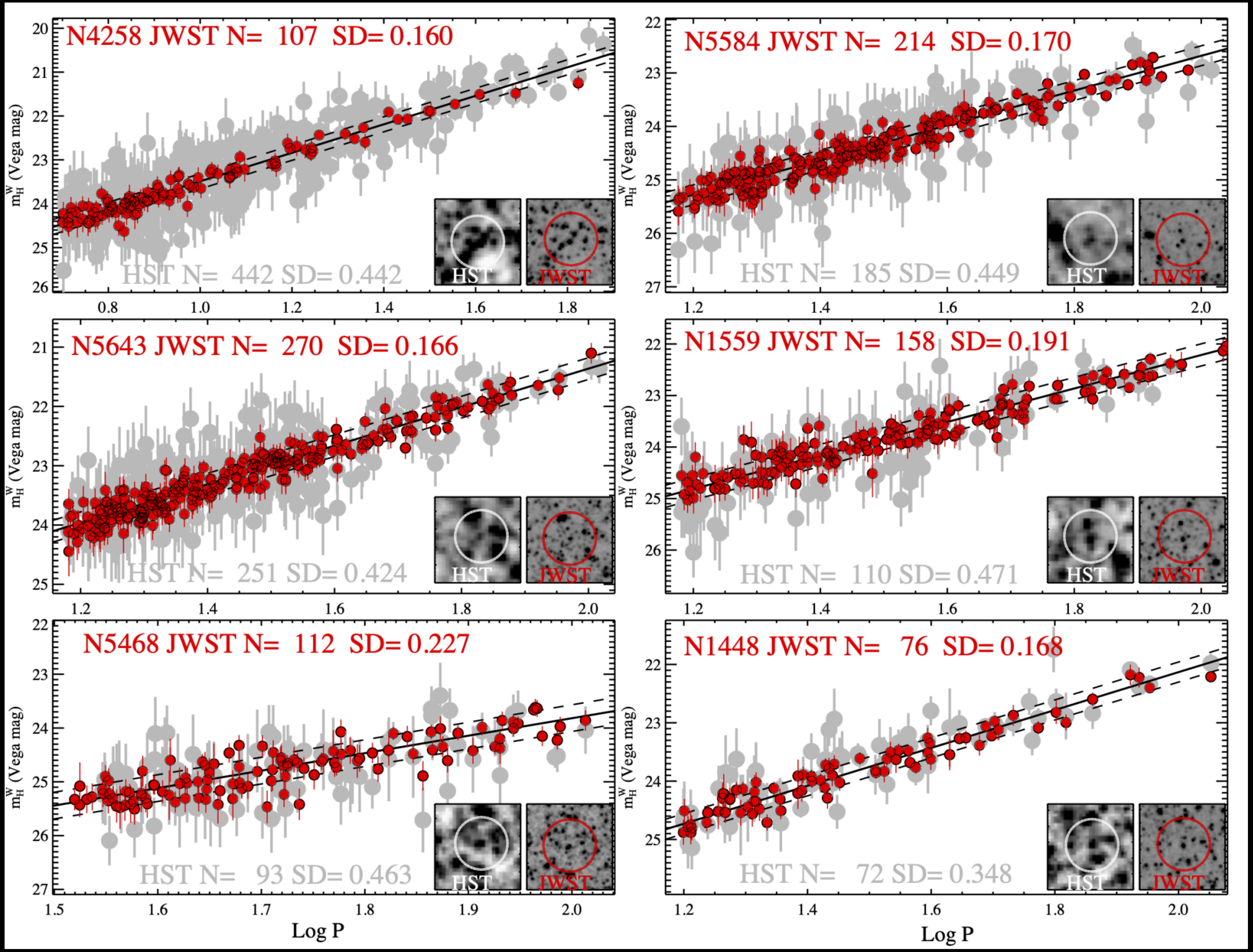
- Cepheids have been the gold-standard of extragalactic distances.
- Cepheid period-luminosity relations best constructed at near-infrared wavelengths, due to low intrinsic scatter and low dust extinction.
- Largest concern with HST Cepheid distance scale was the size of the crowding corrections needed in near-infrared with WFC3/IR.
- JWST provides much sharper images at NIR wavelengths, allows us to “uncrowd” the Cepheids.



Riess, Anand, Yuan+ 23
Riess, Anand, Yuan+ 24

Cepheid Distance Scale

- Cycle 1 JWST Program (GO–1685, PI A. Riess)
    - Observed >1000 Cepheids in 5 hosts of 8 Type Ia supernovae, plus maser-host NGC 4258 (geometric anchor).
- Factor of 2-3x lower scatter in Cepheid PLR with JWST/NIRCam!
- The Cepheid distance measurements (calibrated to NGC 4258) agree very well for HST and JWST (to within ~0.5%, size of Hubble tension ~9%)



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- The Cepheid distance measurements (calibrated to NGC 4258) agree very well for HST and JWST (to within ~0.5%, size of Hubble tension ~9%)
- No evidence for any distance-dependent crowding bias (ruled out at >8σ level)
  - Ongoing Cycle 2 program to measure Cepheids in the most crowded hosts (preview: not finding an offset here either!)

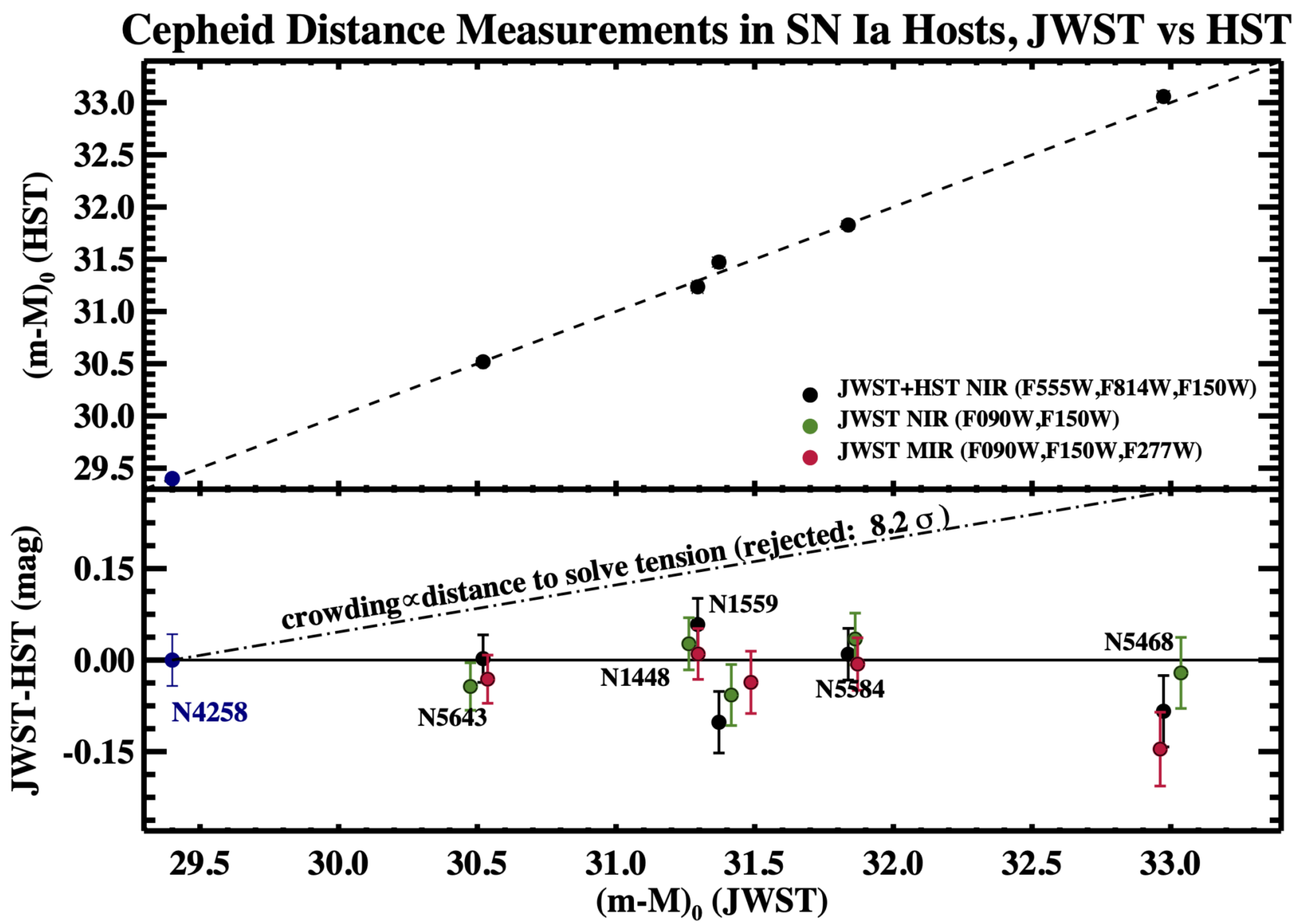
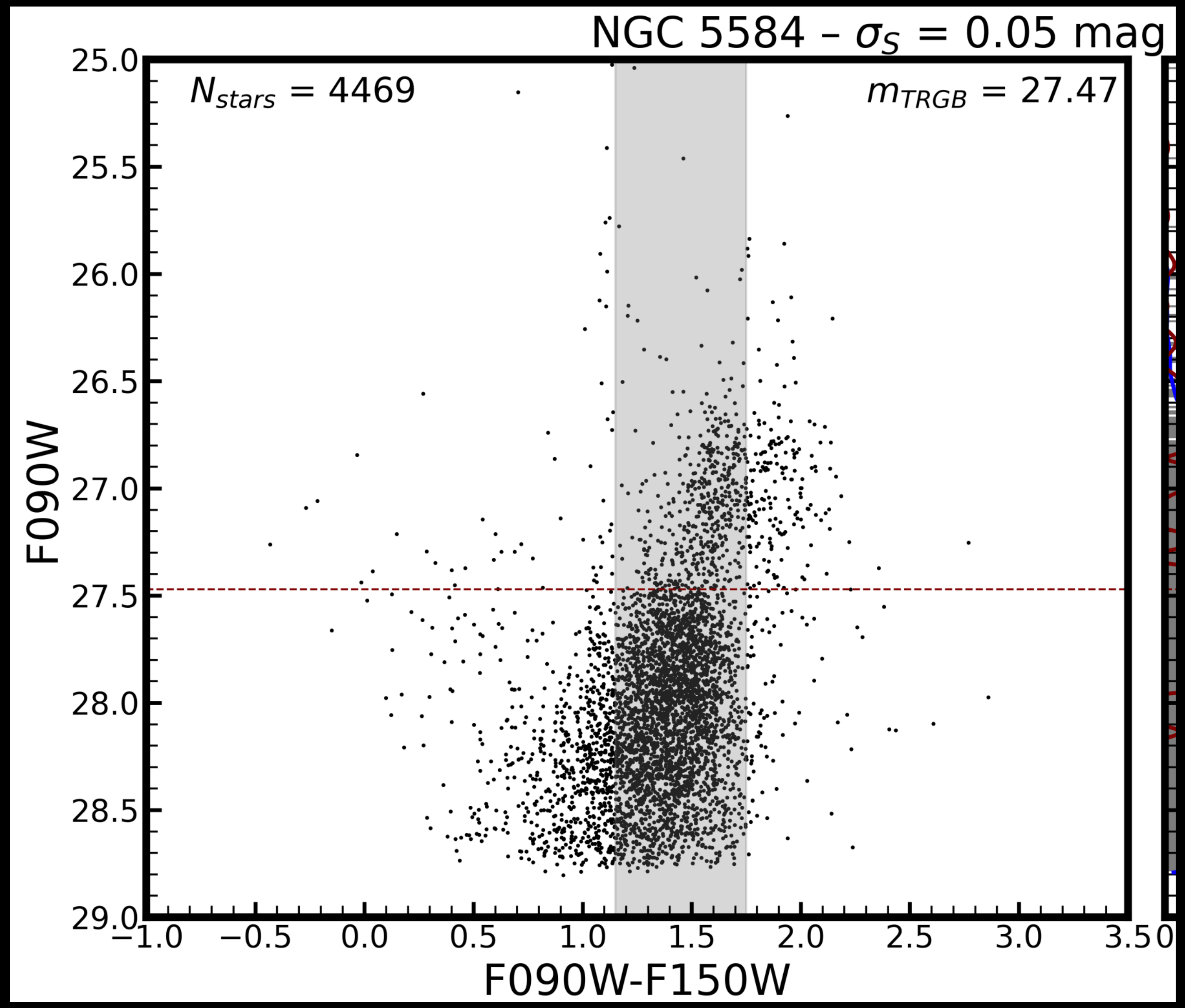


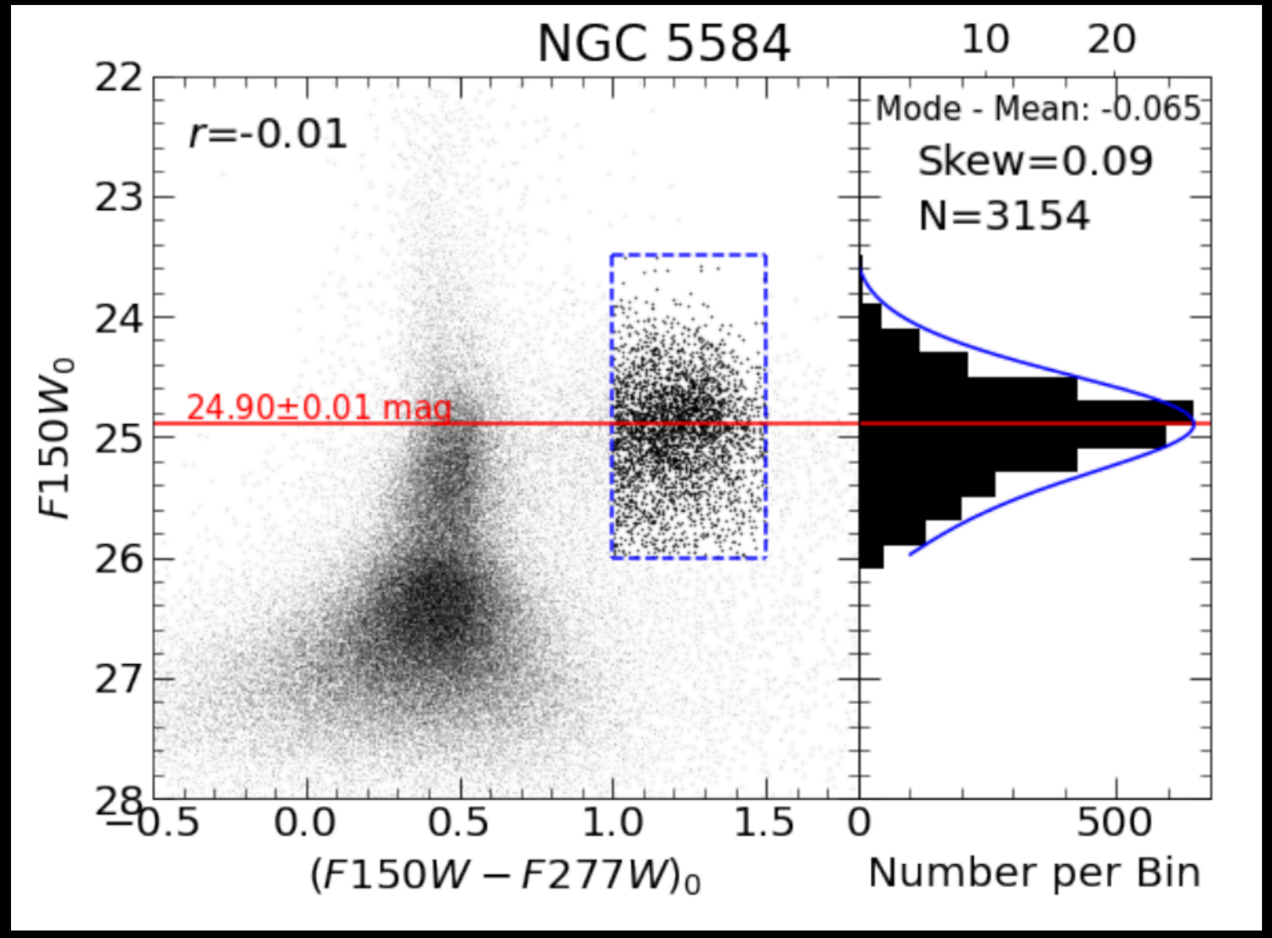
Figure 8. Comparison of distances to the five SN Ia hosts measured with *HST* and *JWST* anchored by the same geometric distance reference, NGC 4258. The lower plot shows the differences in the measurements from the two telescopes. Black shows the comparison for the baseline system used to measure H_0, $W^H_{V,I}$ and is the only system plotted on the top panel. Green and red shows comparisons with two JWST-only magnitude systems. The bottom plot shows a hypothetical, linear model of unrecognized crowding tuned to match the Hubble Tension, 5log(73/67.5)=0.17 mag at the mean distance of the SH0ES sample, $\mu = 31.7$, a trend of 0.07 mag per magnitude of distance modulus beyond NGC 4258. This model is ruled out at 8.2σ.

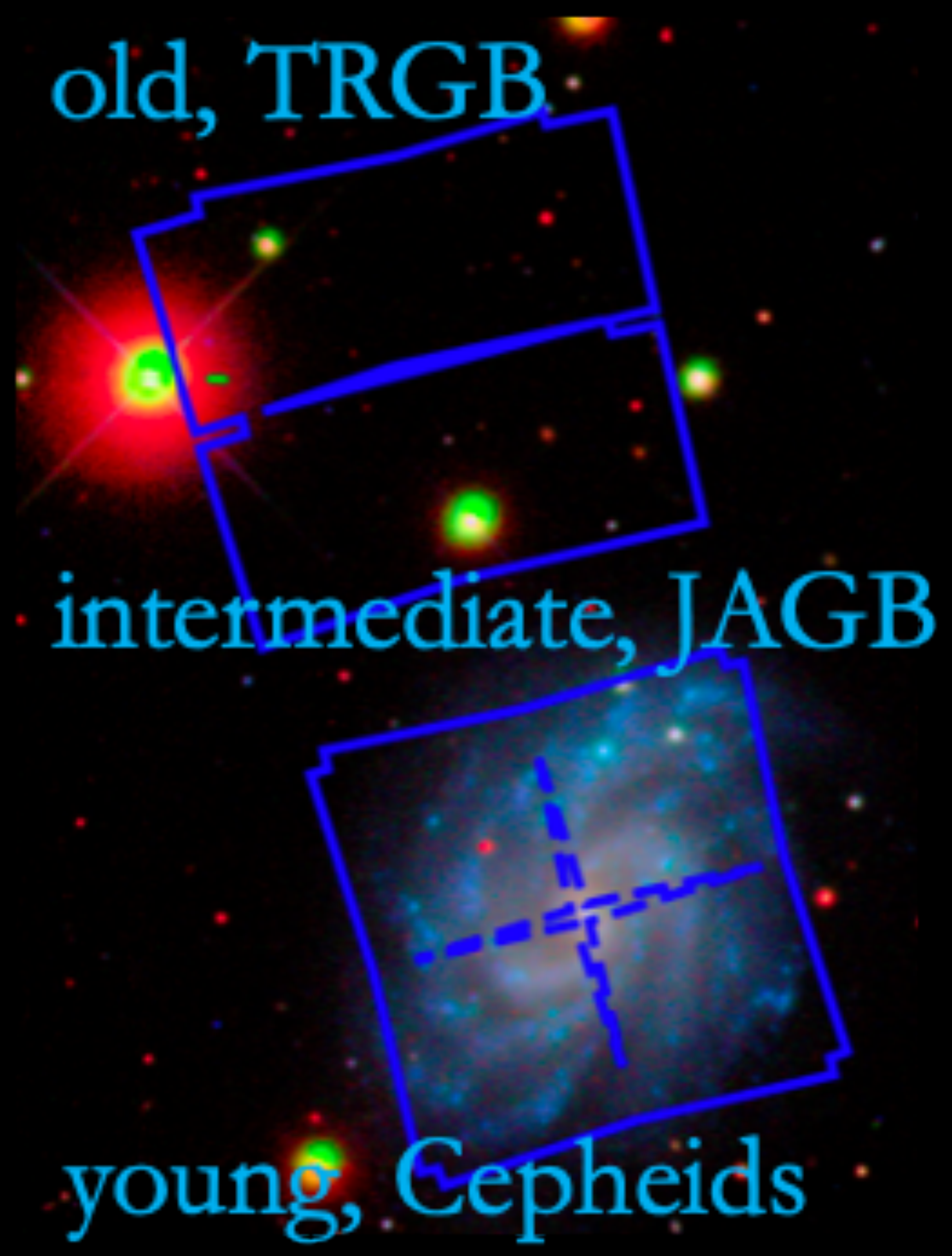
Riess, Anand, Yuan+ 23
Riess, Anand, Yuan+ 24

TRGB, JAGB Distance Scales

- What about Tip of the Red Giant Branch (TRGB) and Carbon Star distances (JAGB)?
  - TRGB: brightest ascent of red giant stars before they undergo the helium flash, present as sharp discontinuity in color-magnitude diagram.
  - JAGB: mean/median/mode of the luminosity of carbon-rich AGB stars.
- Different regions of the same JWST fields can be used for these measurements.







NGC 5584
(22 Mpc)

Anand+24a
Li+24a
Li+24b

Second-Rung Distance Indicators Agree

- Excellent agreement between all nine groups of distance measures, from two different groups (SH_0ES and CCHP).
- All comparisons against HST Cepheids of the other eight distance measures agree to within 1σ.
- We see no cause for concern at this juncture.

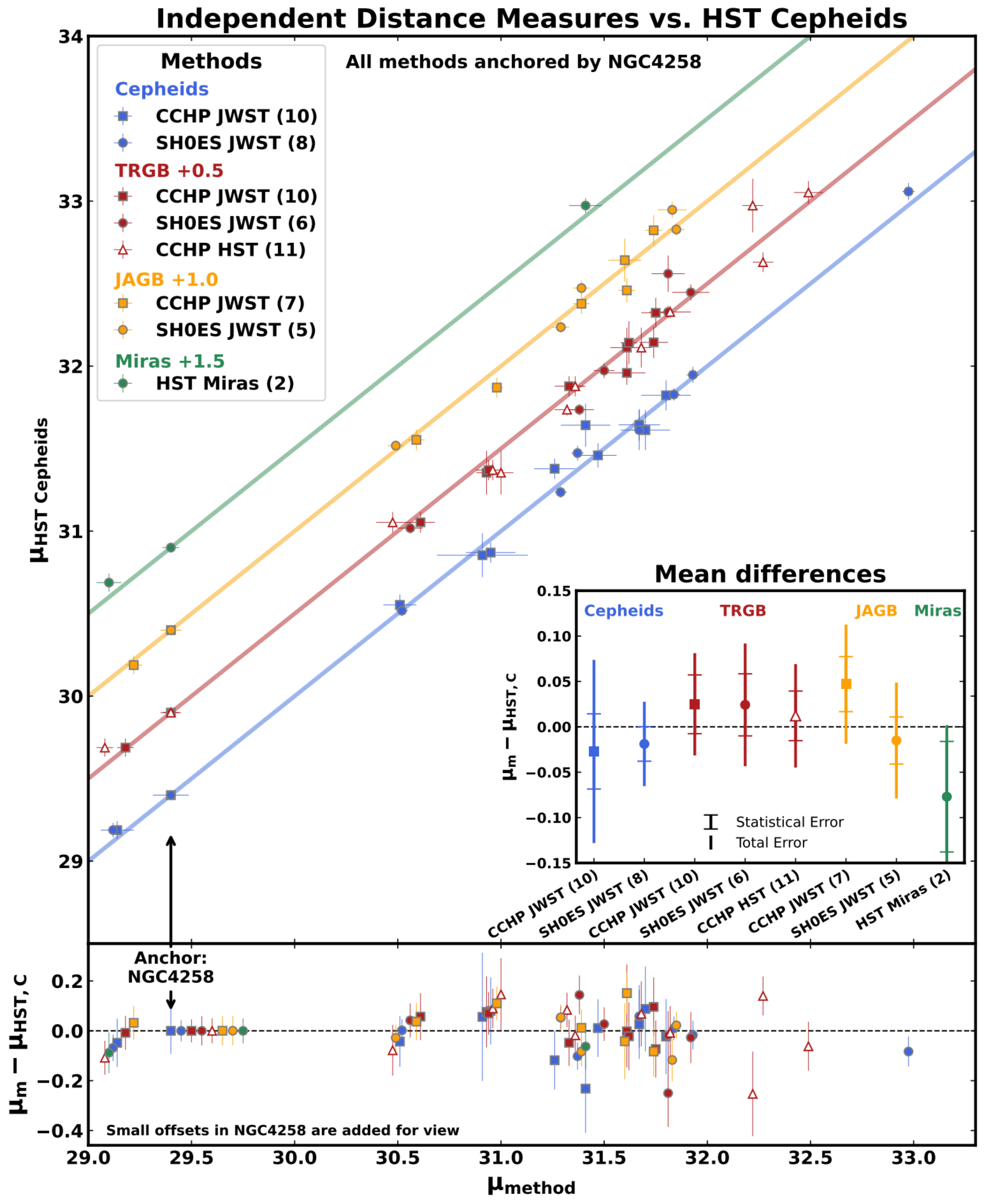


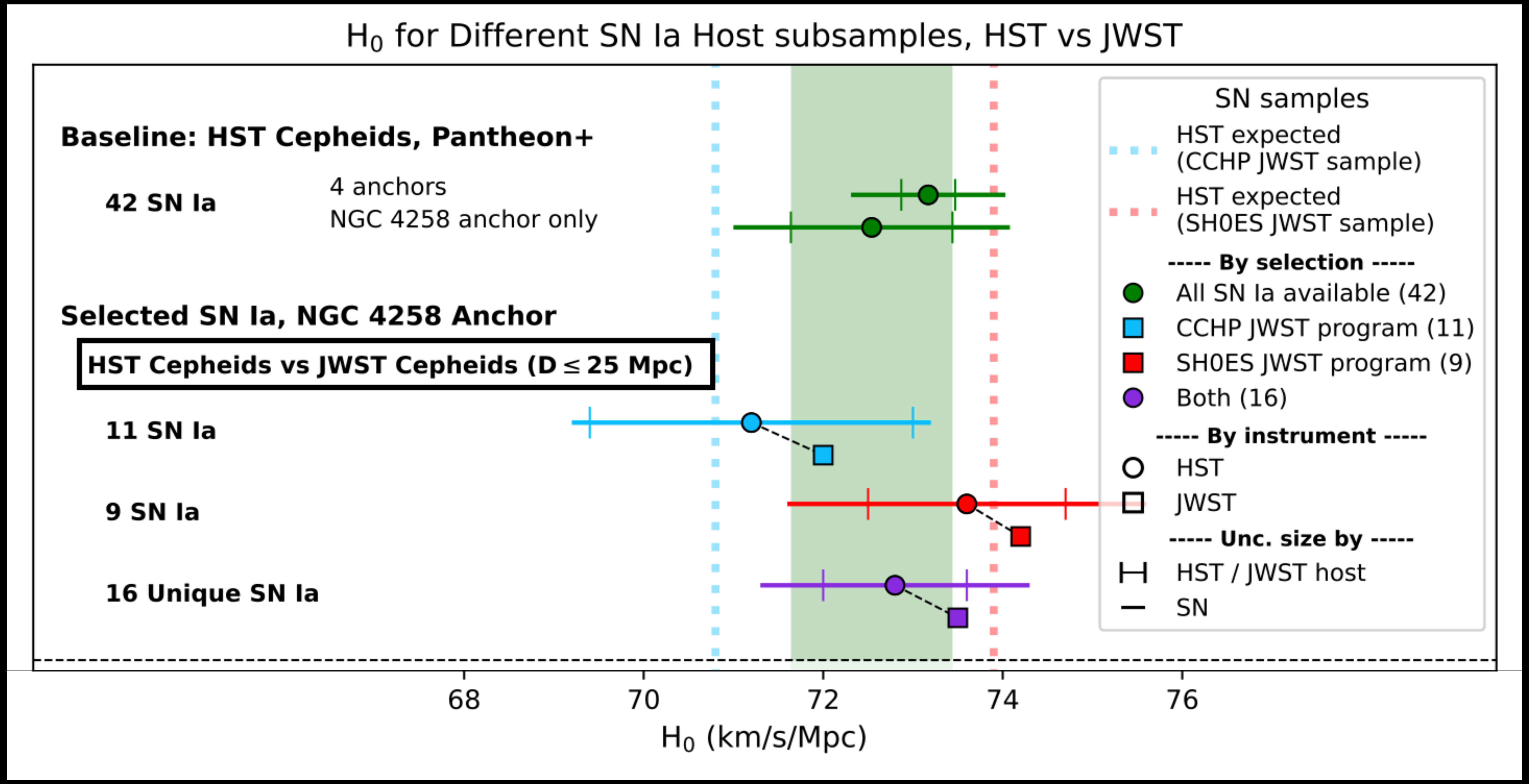
Figure 2. Mean differences of SN Ia host distance moduli calibrated by NGC 4258 as measured with different telescopes or methods. *HST* Cepheids are all observed by *HST* and analyzed by R22 and Riess et al. (2024); see Table A1 with the mean results given in Table 2. *JWST* (and specific *HST*) results can be found either in R24 (corresponding to SH0ES-selected) or F24 (corresponding to CCHP-selected) and computed here from the distances table, Table A2. All measures are in good, $\sim 1\sigma$ agreement. The largest uncertainties in these comparisons arise from the individual measurements in NGC 4258 and the mean measures of the SN Ia hosts as given in Table 1.

Riess+24b

CCHP Results- Subsample Selection

- Chicago Carnegie Hubble Program (CCHP; Freedman+24, Lee+24, more in prep.) report no substantial Hubble tension with JWST data?

- Selection of CCHP subsample explains their lower H_0 measurement.

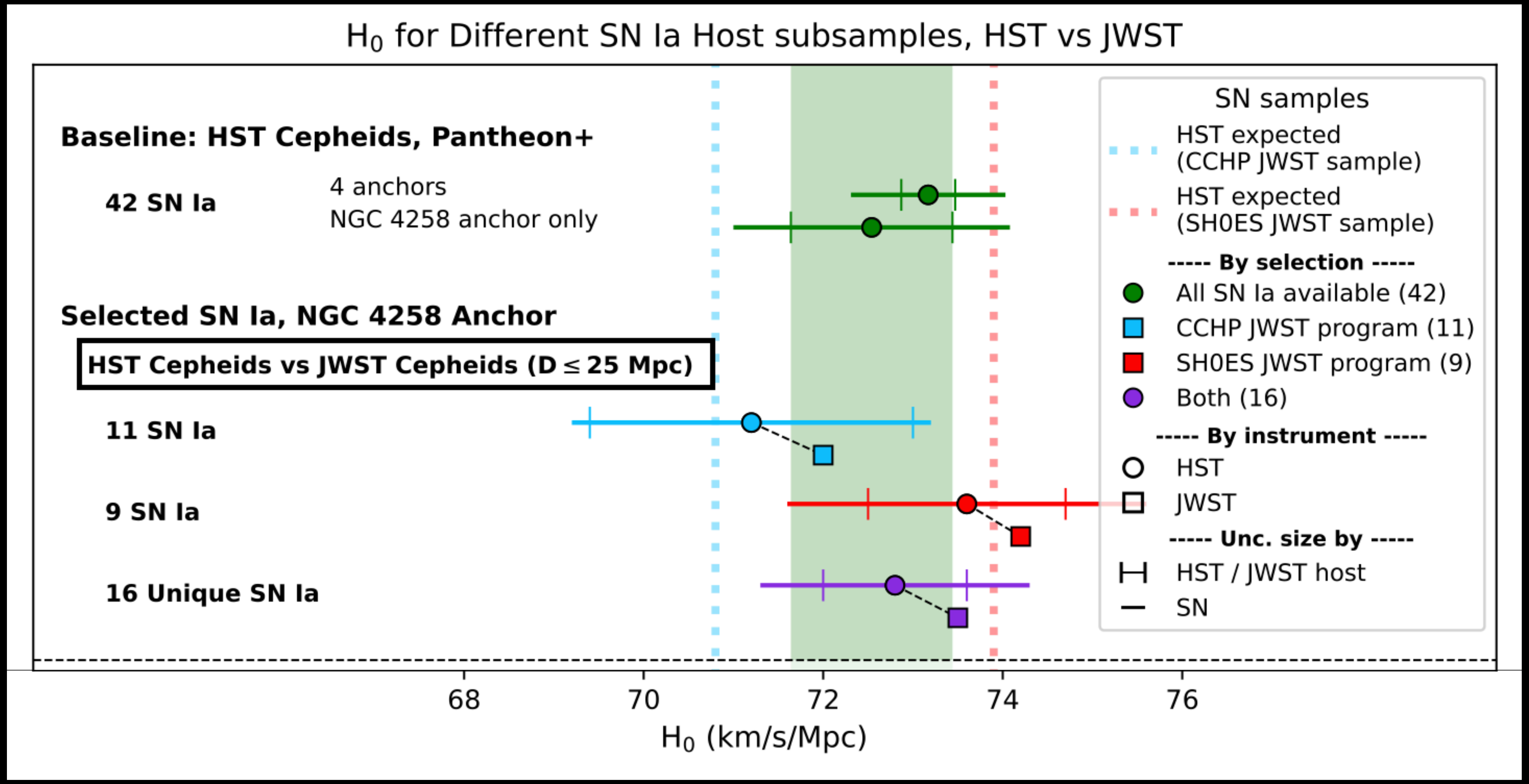


Freedman+24
Riess+24b


Anchors
SN Ia hosts
HST
JWST
+0.5
LMC
-0.2
Milky Way
-0.7 -0.7
NGC 4258
+0.9
SMC
(ΔH0)
+8.1 -8.5
N1448
-3.2
N4639
+4.7
N3254
-1.1
N3583
+5.6
N7678
-2.3
N1309
-3.1 -1.7
-3.1 -1.7
N5643
-3.1
N1559
+2.7
N3370
-3.1
N3021
+0.9 +4.8
N5468
-2.5
N7250
-3.3 *
N4424
-0.7
N5861
-5.4
N4680
+0.8
N7329
+10.6
N5584
+6.3
N7541
+5.5
+1.2 +2.2
N3147
-0.7
N4536
+5.9 *
N3972
-4.8
-4.8
M101
+1.5
N2442
+2.7
N2608
-10.4
N5728
-0.5
N0105
-2.4
N2525
-6.5
N3982
1.6
N1015
-1.9
U9391
-6.4
N0976
-6.8
N1365
+2.2
N3447
+0.7
N0691
+0.0
M1337
+2.0 *
+2.0
N4038
-0.6
N5917
10
20
30
40
50
60
Distance (Mpc)
- 4 anchors + 42 SNIa: ~73.2
- CCHP Selected: ~71
* JAGB excluded: ~70
- SH0ES Selected: ~74
(D < 25 Mpc)
- Both Selected: ~72.8
(D < 25 Mpc)
- SH0ES (D > 25 Mpc)

CCHP Results- Subsample Selection

- Chicago Carnegie Hubble Program (CCHP; Freedman+24, Lee+24, more in prep.) report no substantial Hubble tension with JWST data?
- Selection of CCHP subsample explains their lower H_0 measurement.
- Combining SH_0ES+CCHP reduces sampling differences, gives ~complete sample (<25 Mpc)
    - Combination of samples results in "reversion to the mean"
    - HST Cepheids predict H_0=72.8 km/s/Mpc for the D<25 Mpc sample (and using NGC 4258 as sole anchor)
    - JWST result from the D<25 Mpc sample is H_0=72.6 +/- 2.0 km/s/Mpc
    - Excellent agreement between HST and JWST!



Freedman+24
Riess+24b

TRGB–SBF Project

TRGB–SBF Team and Collaborators: see 1 ApJ paper, 1 arXiv preprint, more in prep.

Tully, Jensen, Blakeslee, Anand, Cantiello, Kourkchi, Raimondo, et al.

G. Anand et al., ApJ, in press (arXiv:2405.03743): Fornax Cluster TRGB
G. Anand et al., submitted, (arXiv 2408.16810): Virgo Cluster TRGB

Direct Measurements- A Distance Ladder

- Type Ia supernovae are excellent standard candles out into the Hubble flow.
    - Their calibration is based on observations of Cepheid variables in 42 host galaxies (Riess+22).
- Remaining concerns about SN Ia (nature of dust in other galaxies compared to Milky Way, Cepheid calibration limited to late-type galaxies, etc.).
- And what about “unknown unknowns”?
- We need a new distance ladder!
    - TRGB–SBF Project

A Comprehensive Measurement of H_0 from SH0ES 31

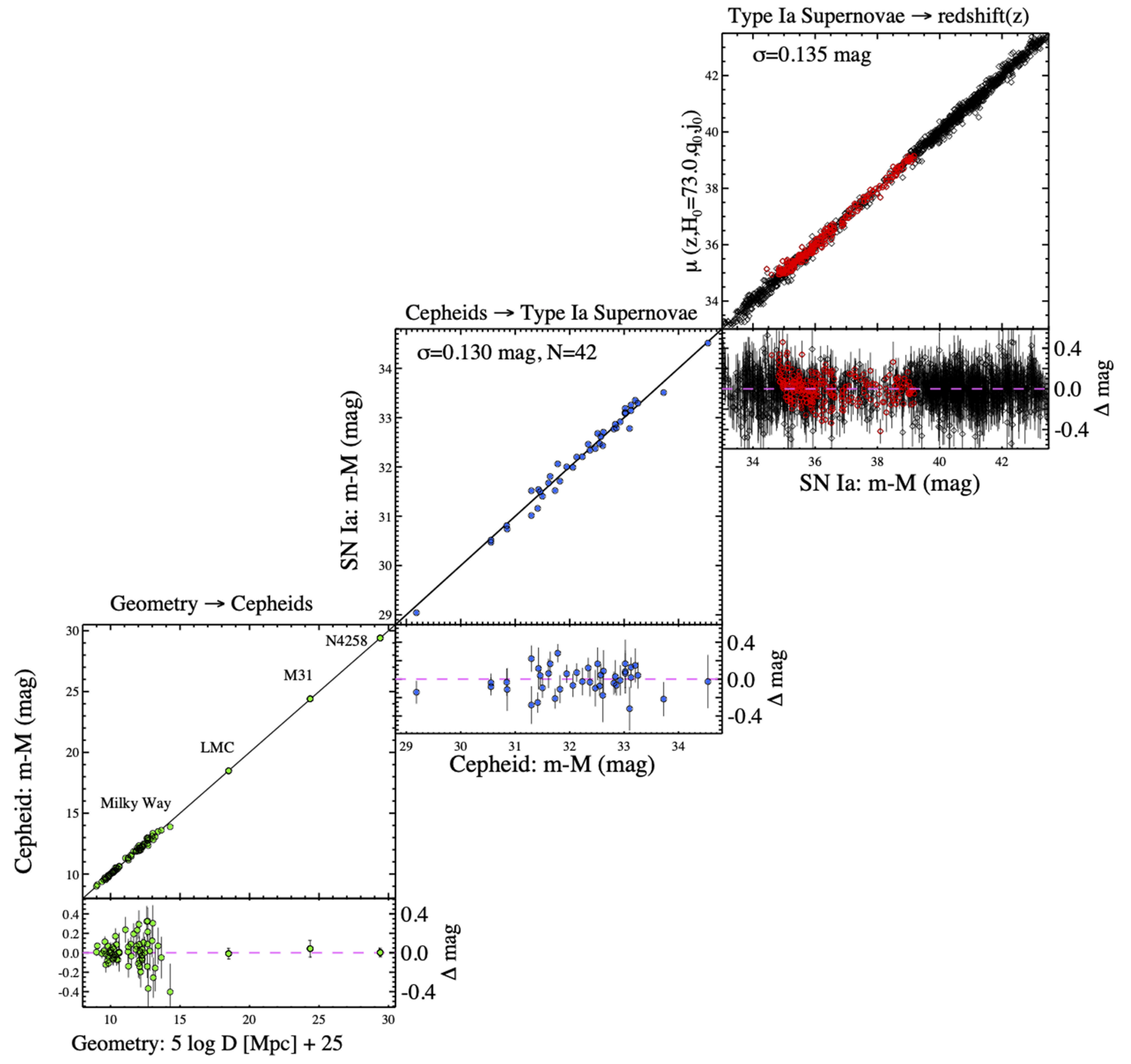
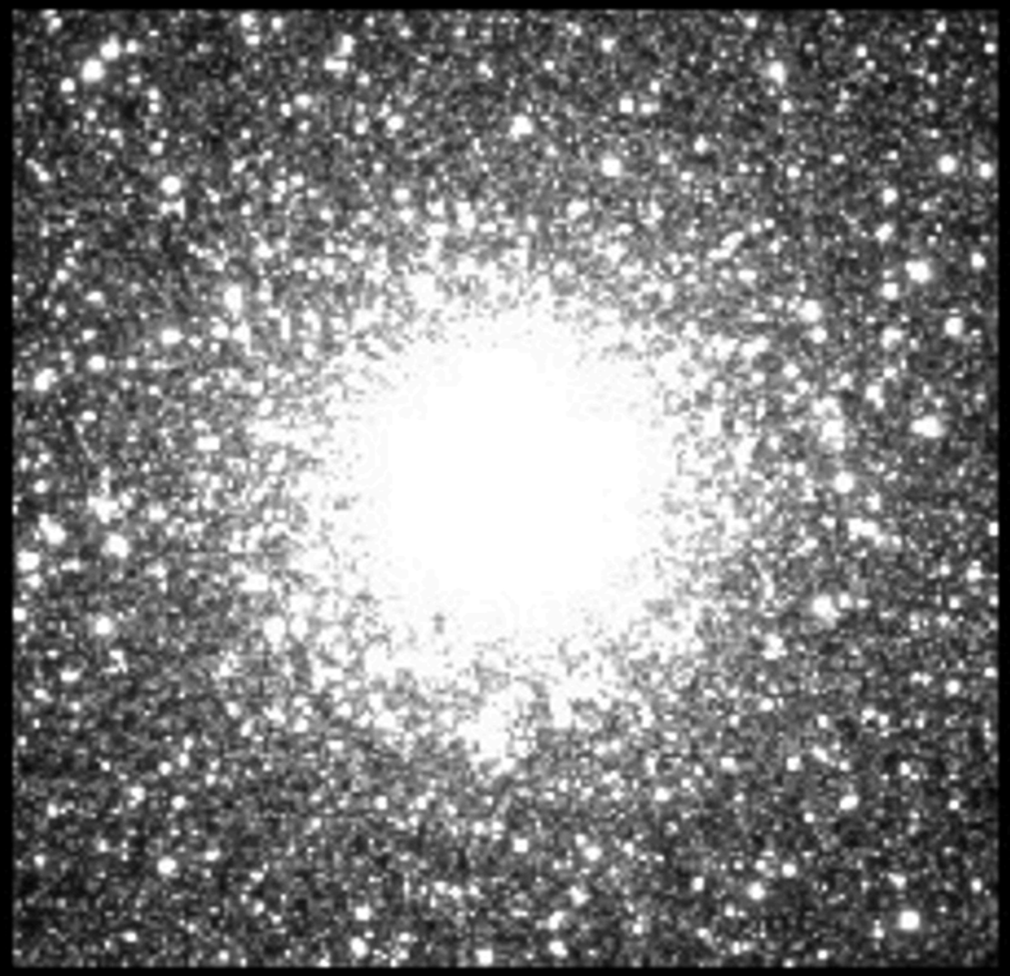


Figure 12. Complete distance ladder. The simultaneous agreement of distance pairs: geometric and Cepheid-based (lower left), Cepheid- and SN-based (middle), and SN- and redshift-based (top right) provides the measurement of H_0. For each step, geometric or calibrated distances on the abscissa serve to calibrate a relative distance indicator on the ordinate through the determination of M_B or H_0. Results shown are an approximation to the global fit as discussed in the text. Red SN points are at $0.0233 < z < 0.15$, with the lower-redshift bound producing the *appearance* of asymmetric residuals when plotted against distance.

Riess+22

Surface Brightness Fluctuations

- Number of stars/pixel varies with galaxy distance, more distant galaxies look smoother.
- Observed “mottling” is directly related to the target’s distance (Tonry & Schneider 1998).
- Relies on RGB stars (same as TRGB).
- Compare SBF to Type Ia supernovae
    - No shortage of targets.
    - Only need single epoch of data.
    - ~4% precision per target.

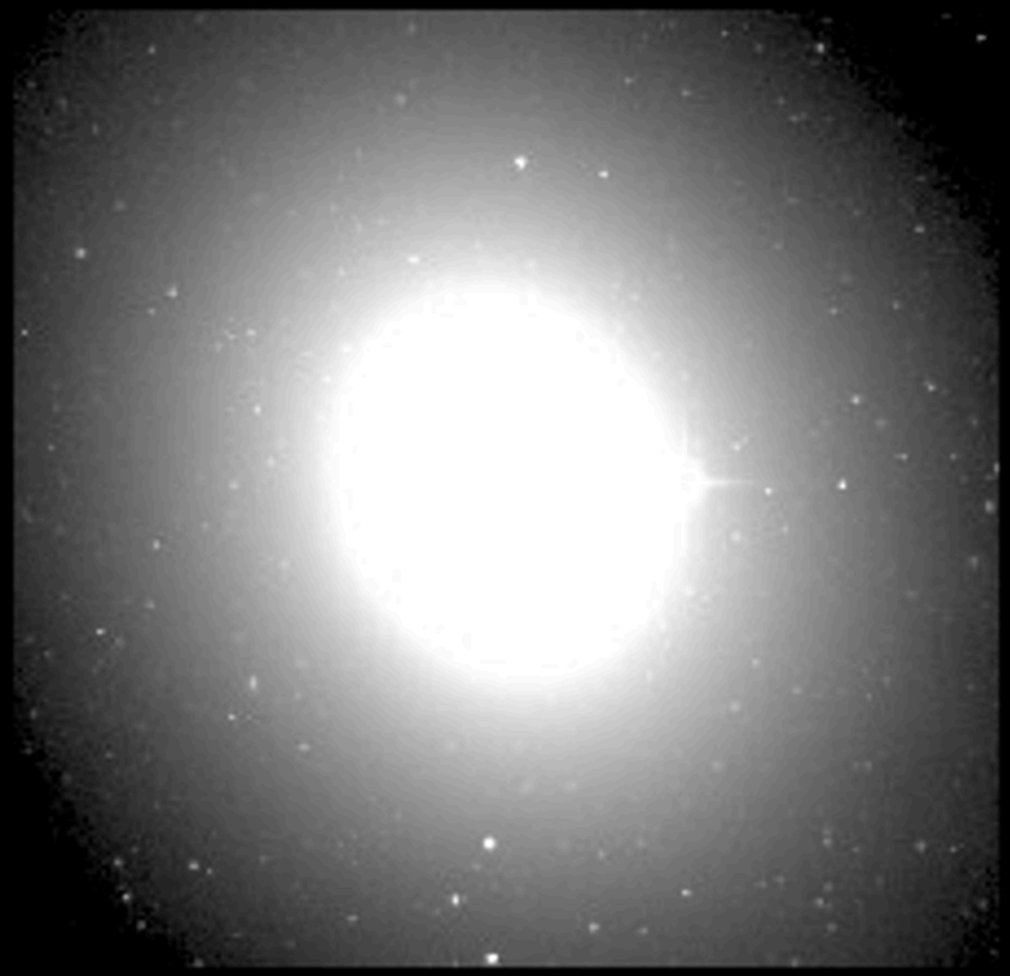


globular cluster

~10 kpc

Messier 32 (Andromeda Satellite)

~770 kpc



M49 (Virgo Cluster)

~16 Mpc

Slide Basics: R. Kudritzki
Images: J. Blakeslee

Surface Brightness Fluctuations

- IR SBF has been used to measure the Hubble constant: H0 = 73.3 +/- 0.7 +/- 2.4 km/s/Mpc (Blakeslee+21).
- Limitations of prior HST SBF work
  - Limited number of second-rung calibrator galaxies (six Cepheid, two TRGB).
  - Peculiar velocities non-negligible (corrected with either group-averaged velocities or flow model).
  - Both limitations can be dealt with using JWST!

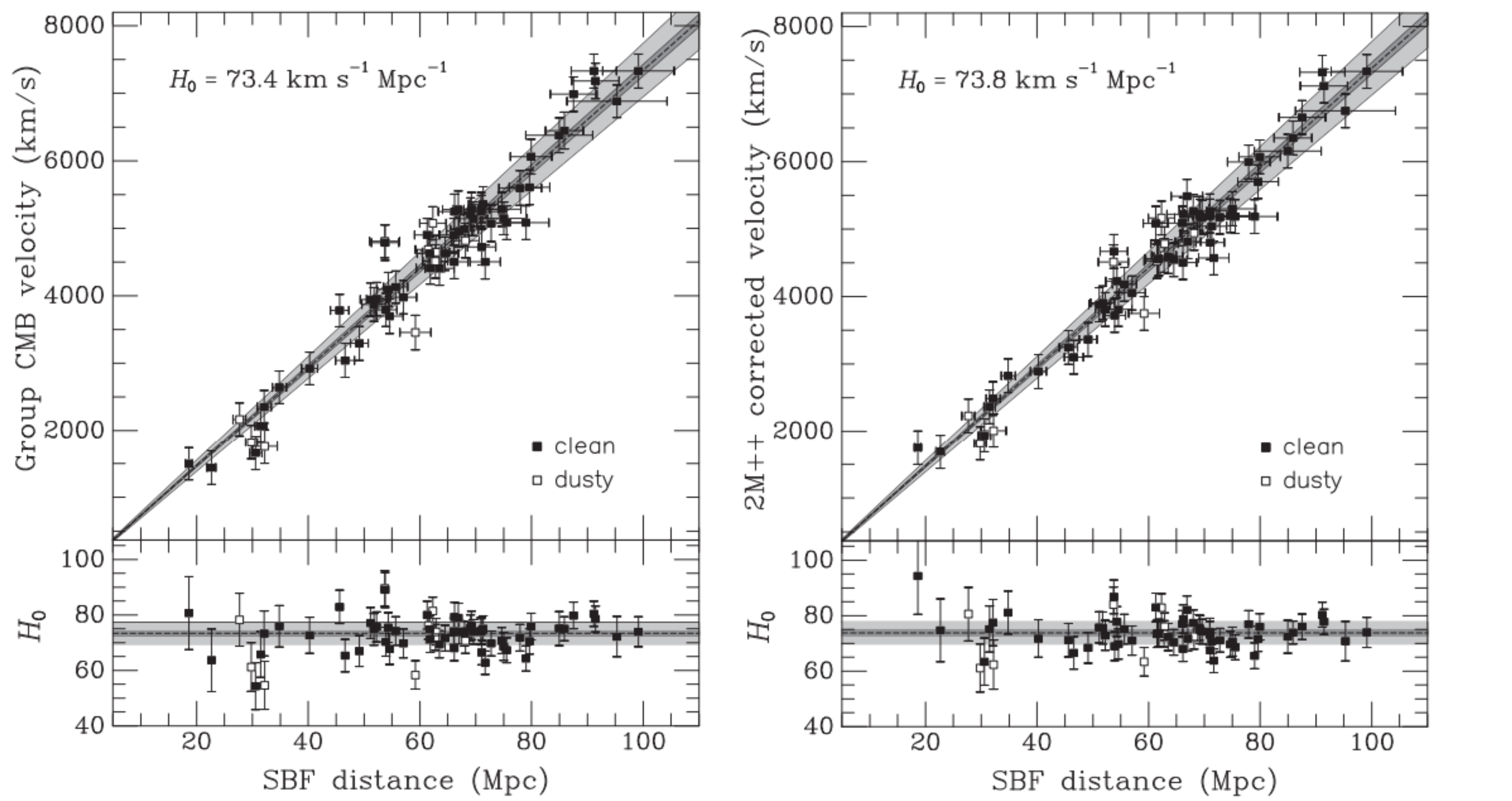
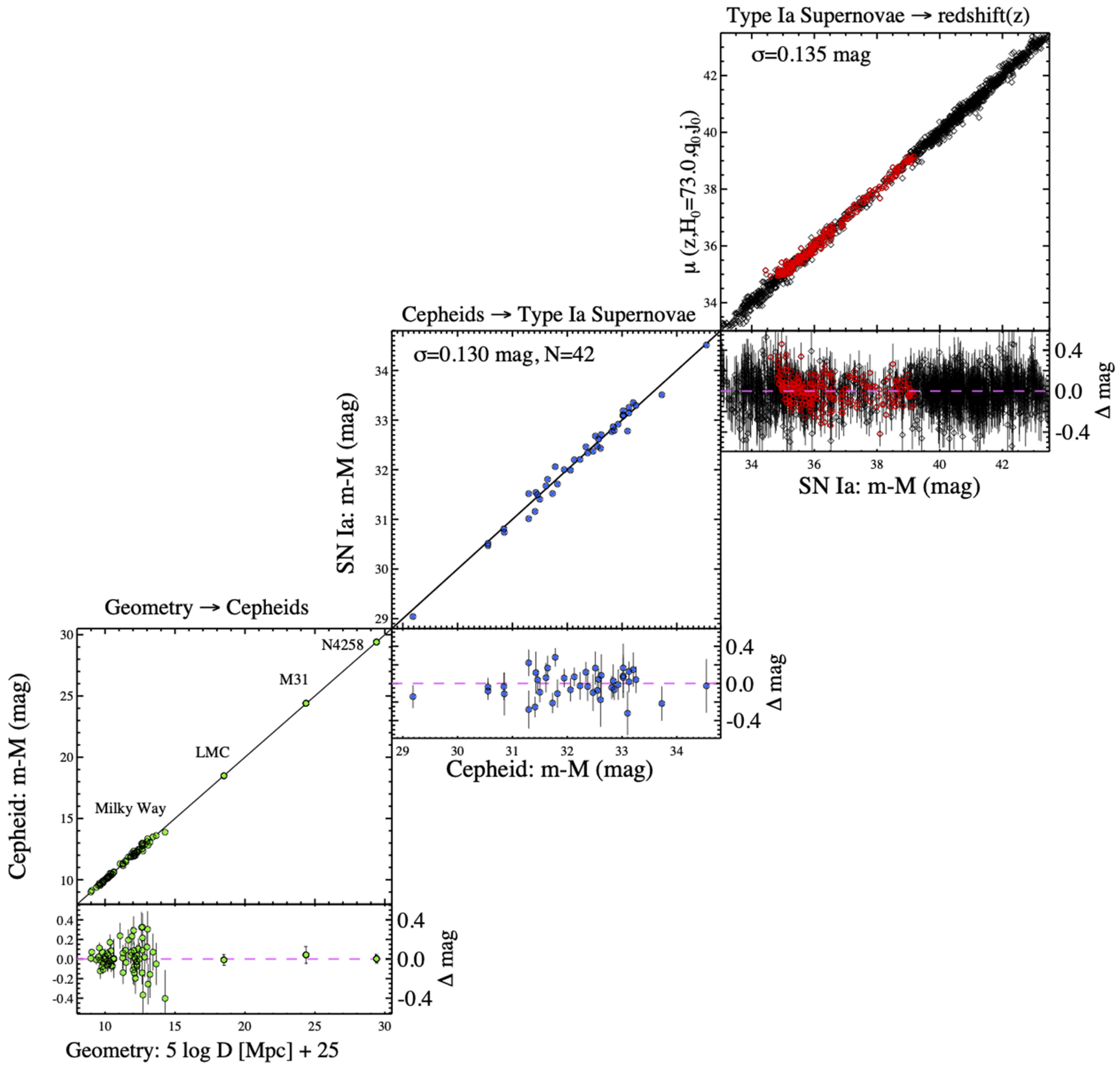


Figure 1. Left: Hubble diagram (top) and individual H_0 values (bottom) for the Cepheid-calibrated WFC3/IR SBF distances and the galaxy group-averaged velocities in the CMB rest frame. Solid symbols indicate "clean" galaxies, for which no dust or spiral structure is evident. The open symbols indicate 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).

Blakeslee+21



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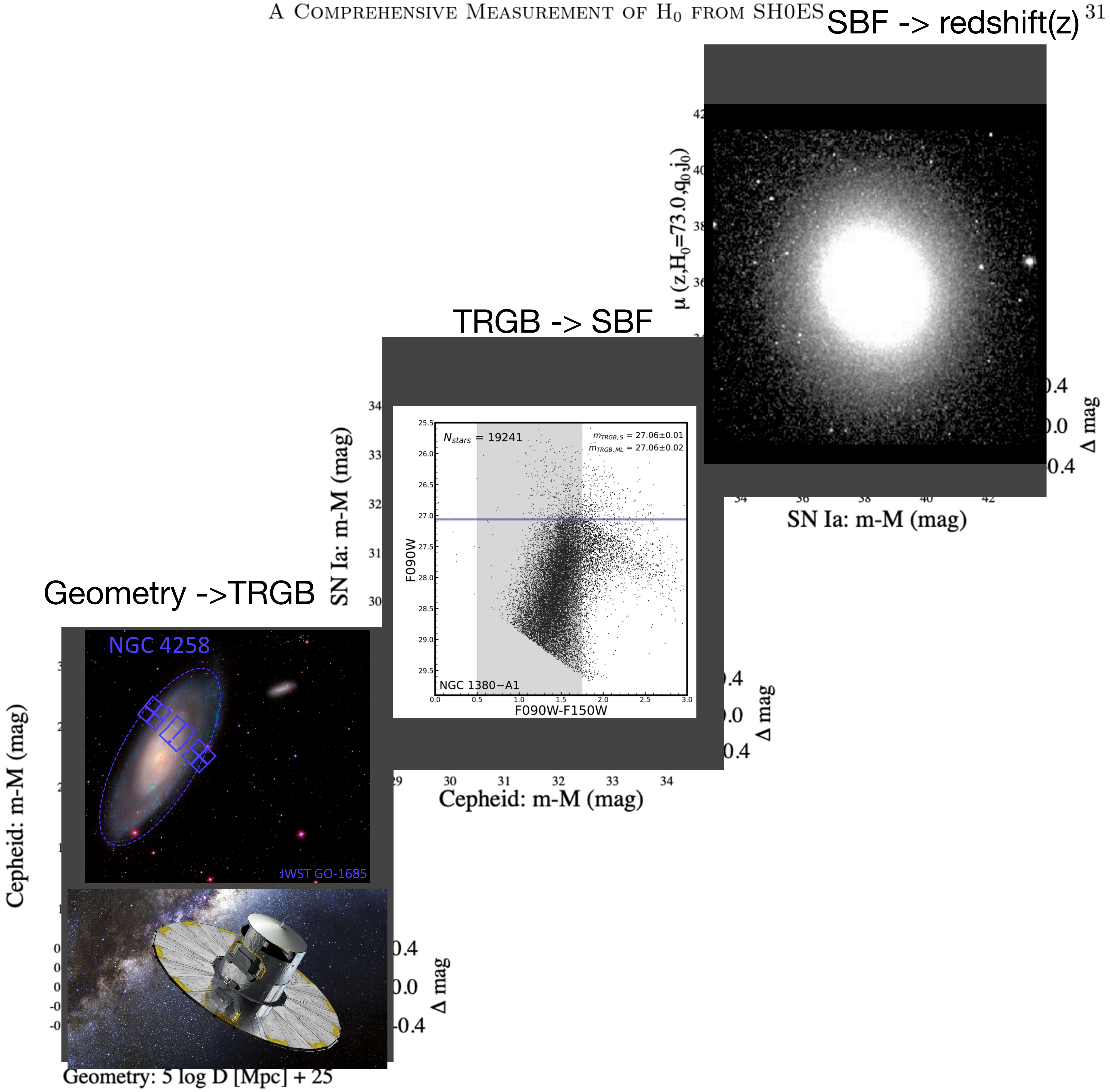

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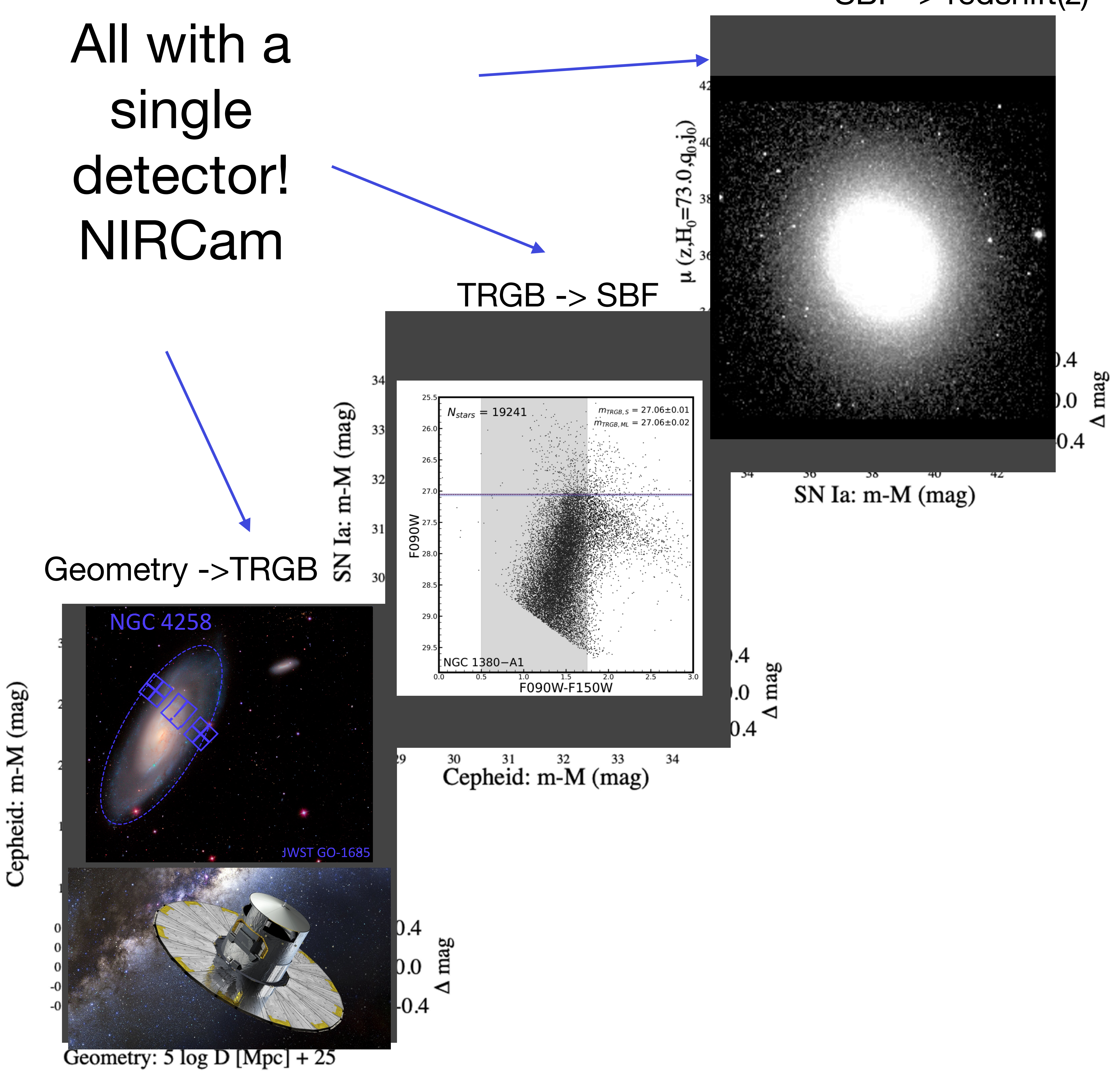

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The TRGB–SBF Project

- Need a completely separate distance ladder to definitively confirm a Hubble tension, and the need for new physics beyond ΛCDM.
- Awarded JWST Time:
  - 47 hour Cycle 2 program (GO–3055, PI R. Tully), 14 early-type galaxies within 20 Mpc, calibrate SBF zero-point with TRGB distances
  - 30 hour Cycle 3 program (GO–5989, PI J. Jensen), 40 fields in Coma cluster to fully calibrate color dependence of SBF magnitudes
- Absolute scaling of TRGB zero-point will come from Gaia and NGC 4258 (geometrical distances)

3055 - A TRGB calibration of Surface Brightness Fluctuations

Cycle: 2, Proposal Category: GO

ABSTRACT

If the holy grail of a 1% measurement of the Hubble constant from measurements of galaxy distances and velocities is to be achieved, it will be essential to complement the current effort based on Population I star Cepheid and Type Ia supernova measurements. An alternate path that promises comparable accuracy involves the Population II route through tip of the red giant branch (TRGB) and surface brightness fluctuation (SBF) distances. This path requires implementation of 4 steps: (1) parallax zero-point calibration of TRGB, (2) transfer of the TRGB calibration to SBF, (3) full vetting of the SBF methodology, and (4) exploitation of SBF to a large sample at large distances.

The current program addresses the second step: the connection between TRGB and SBF distance scales. These two methodologies are physically connected; the constancy of energy release from the brightest stars on the red giant branch when degenerate helium cores commence burning to carbon. With TRGB, the individual brightest RGB stars are observed; with SBF, the unresolved mottling caused by these stars is recorded. In detail, metallicity-age effects are such that optimal passbands and positioning of targets are different for TRGB and SBF measurements. In the case of TRGB, there is relative constancy at low metallicities in F090W and fields in halos are favored where low metallicity stars are dominant. With SBF, there is relative constancy at high metallicities in the F150W passband and such stars are dominant in the centers of the E-S0 systems to be given attention. With the extended spatial coverage of NIRCam, the observations required for TRGB and SBF studies can be acquired simultaneously.

5989 - The JWST SBF Coma Cluster Survey: Building an Alternative Precision Distance Ladder for Cosmology

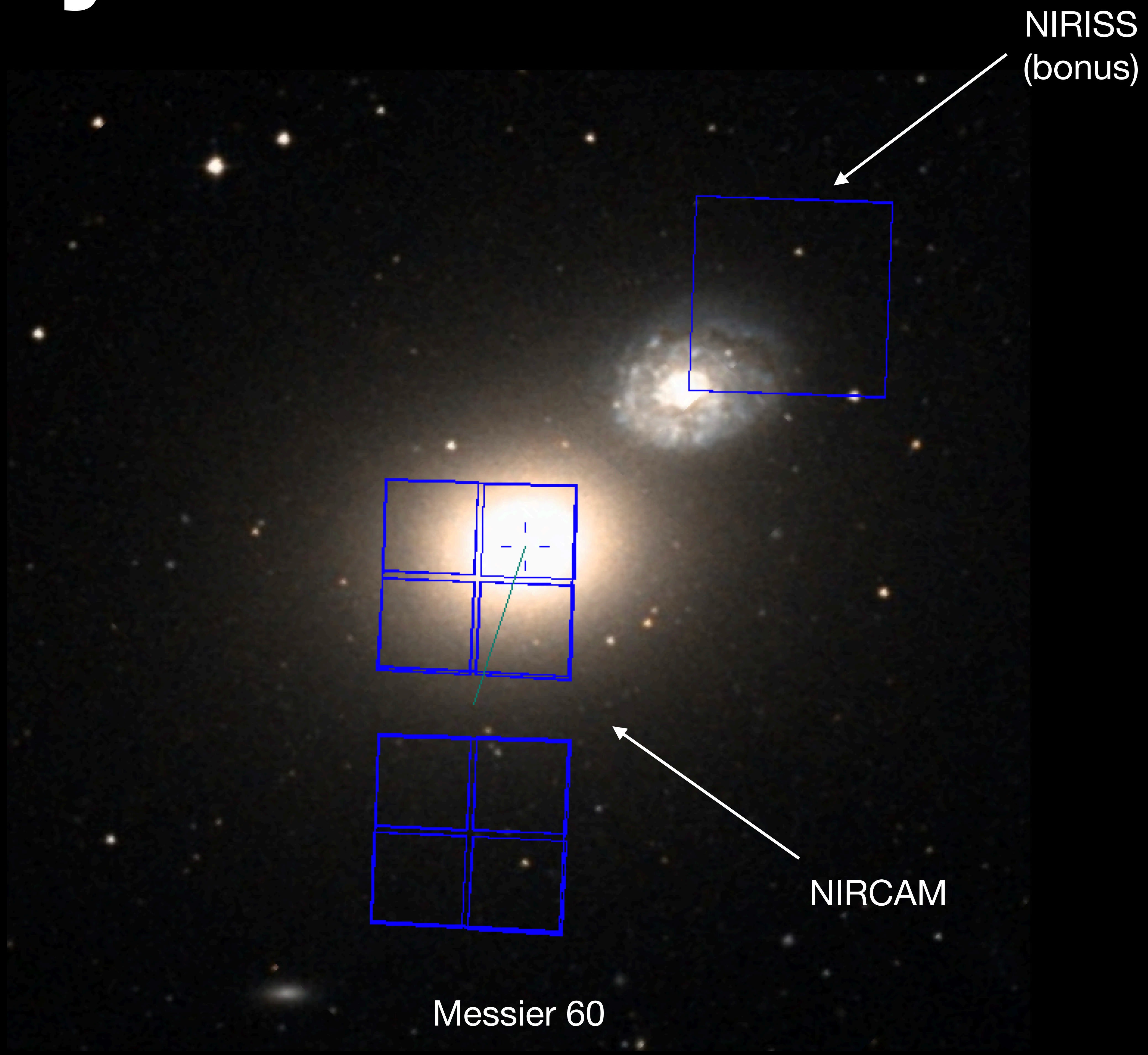
Cycle: 3, Proposal Category: GO

ABSTRACT

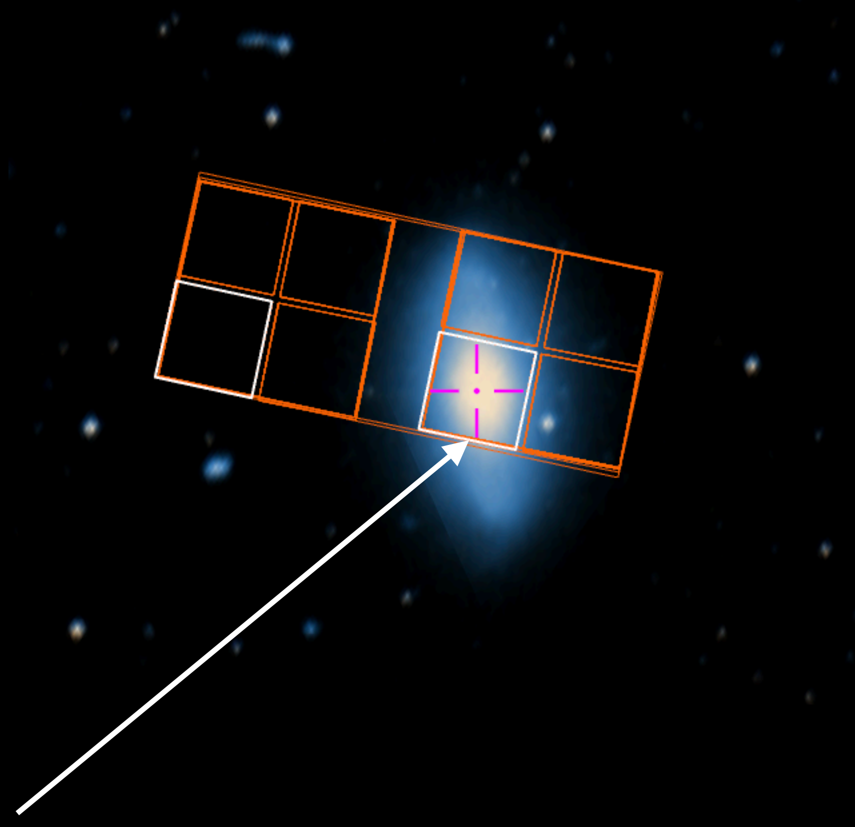
The Coma cluster is the nearest rich cluster in the universe and a key touchstone for the extragalactic distance scale. Precise extragalactic distances are at the heart of the "Hubble tension" controversy, the most important problem in cosmology today. To address this problem, we will image more than 100 fields centered on 39 of the largest elliptical galaxies in the Coma cluster. We will measure surface brightness fluctuations (SBF) for more than 40 galaxies (depending somewhat on the field orientations), calibrate the color dependence of SBF magnitudes, and study the galaxy and globular cluster population properties in Coma. The SBF distance scale zero point will be set by scheduled JWST observations of the tip of the red giant branch in local elliptical galaxies. The Coma cluster observations are required to establish the SBF calibration as a function of galaxy age and metallicity in rich clusters, where future JWST observations will yield distances out to several hundred Mpc. The resulting calibration will enable an independent, high-precision determination of the cosmological distance scale in the local universe using a technique with precision comparable to that of Type Ia supernovae, but requiring only a single observation per measurement. The ability to measure precision distances efficiently will be an important step towards the ultimate goal of measuring H0 to 1% and resolving the Hubble constant controversy.

JWST TRGB+SBF Efficiency

- With JWST/NIRCAM's two modules, we can get the required measurements for TRGB+SBF *simultaneously.*
  - SBF signal much higher than needed, given that exposures are designed for TRGB.
- Observe 14 nearby (< 20 Mpc) elliptical galaxies with our Cycle 2 program, provide a better than 2% calibration for the TRGB + SBF distance scale.
- SBF -> Hubble Flow will require observations of ellipticals in the Hubble Flow with JWST/Roman/ELTs/Rubin.
  - JWST capable of SBF measurements out to ~300 Mpc (into Hubble flow).

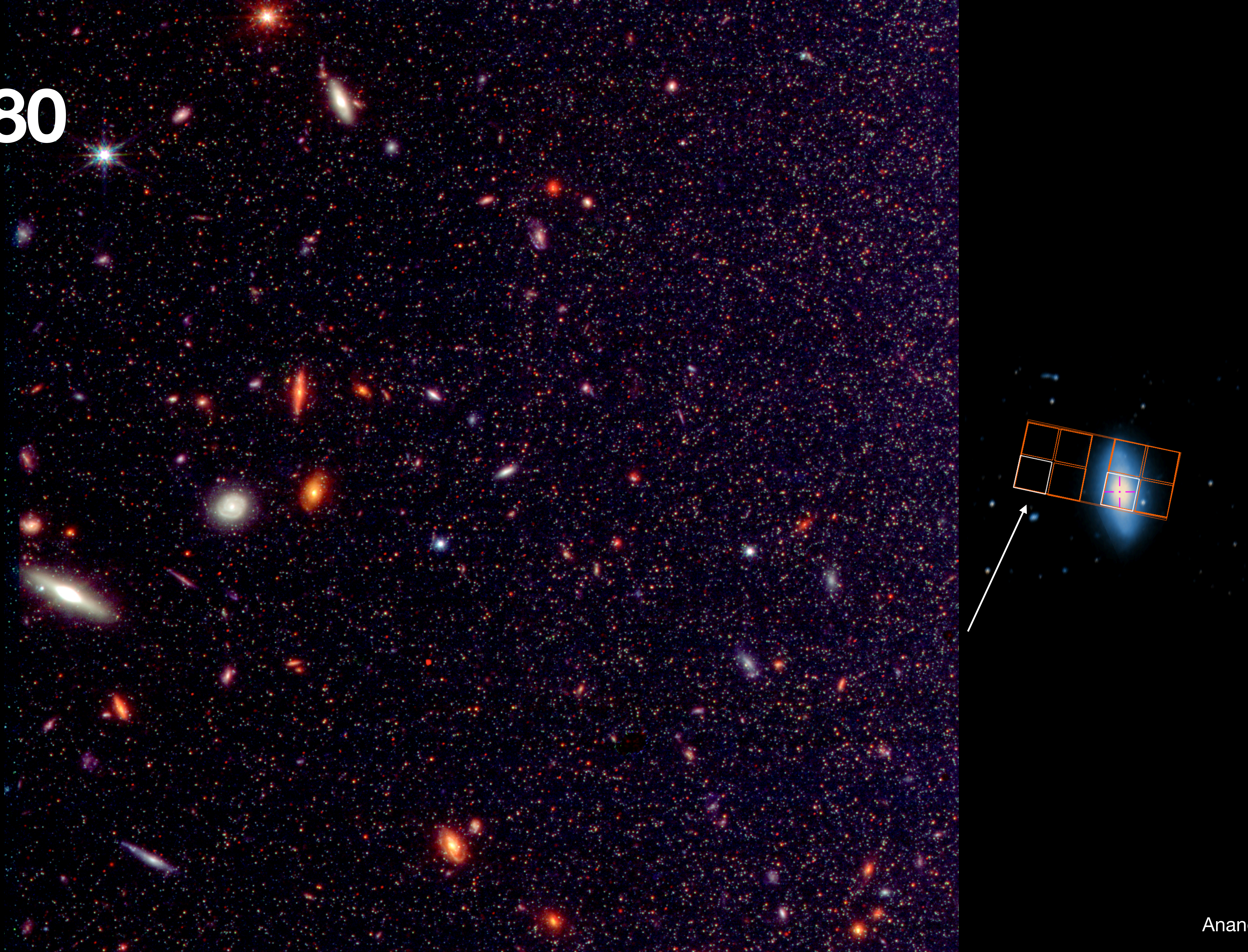


NGC 1380



Anand+24b

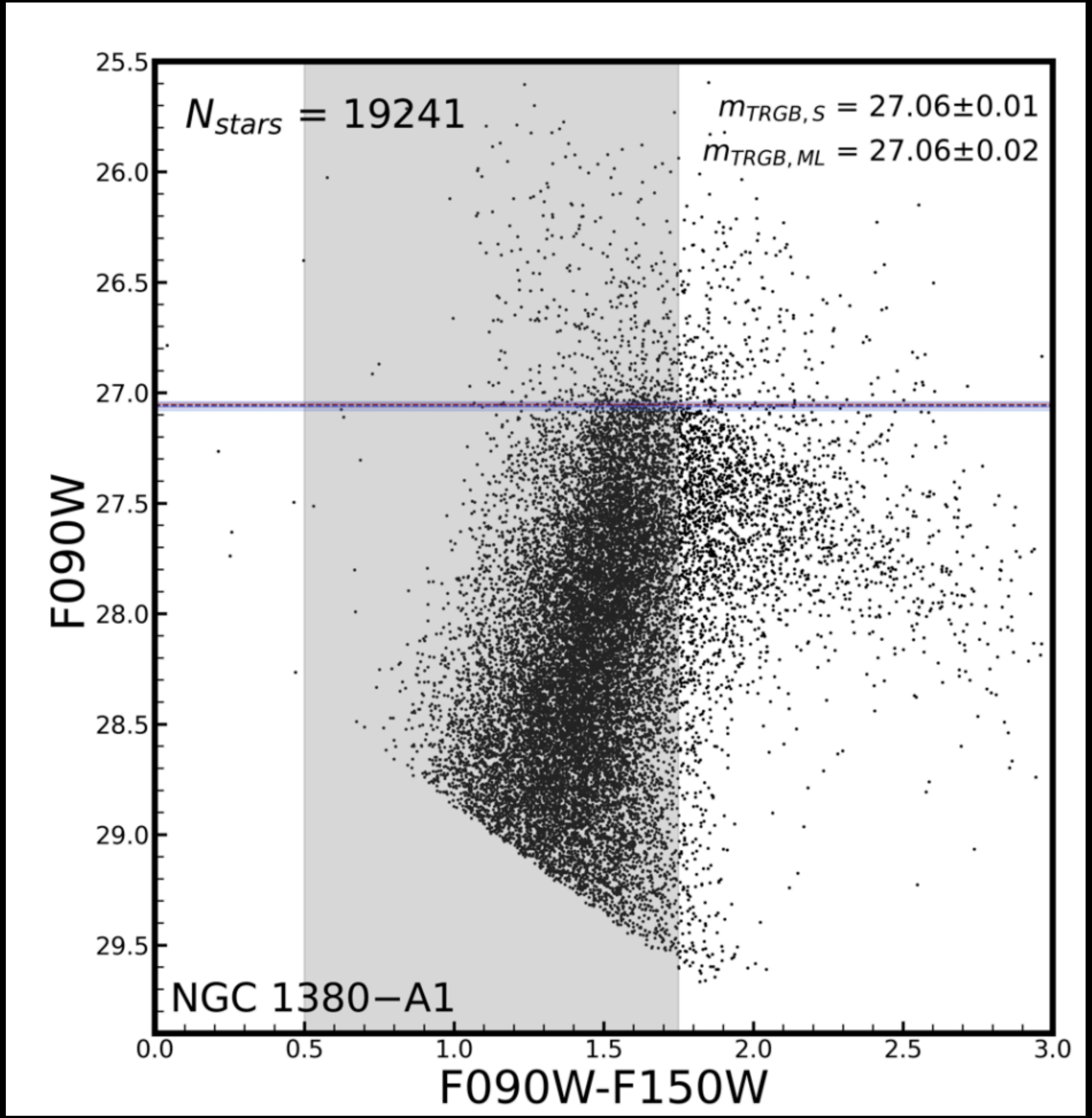
NGC 1380



Anand+24b

First Results of the TRGB-SBF Project

- First results provide TRGB distances to 13/14 galaxies from our program.
  - 3 galaxies within Fornax
  - 10 galaxies in and around Virgo
- Extremely high-fidelity color-magnitude diagrams, JWST is an absolute powerhouse for distance measurements.
- Measurements performed two ways (edge detection, and maximum-likelihood model fitting), good general agreement.



Anand+24b (Fornax)
Anand+24c (Virgo)

Next Steps of TRGB–SBF Project

- Recalibration of HST SBF with JWST TRGB, leading to revised H0 value.
    - Coming later this year… will only strengthen the Hubble tension!
- Measurements of JWST SBF with same data as JWST TRGB.
    - Will set the JWST SBF zero-point, extremely high S/N data (S/N~ 250)
- Cycle 3 program in 40 fields within the Coma cluster (D~100 Mpc), Spring 2025, calibrate SBF metallicity/age effects in JWST filters.
- Need SBF measurements into Hubble flow (JWST/NIRCam, Roman/WFI, ELTs).

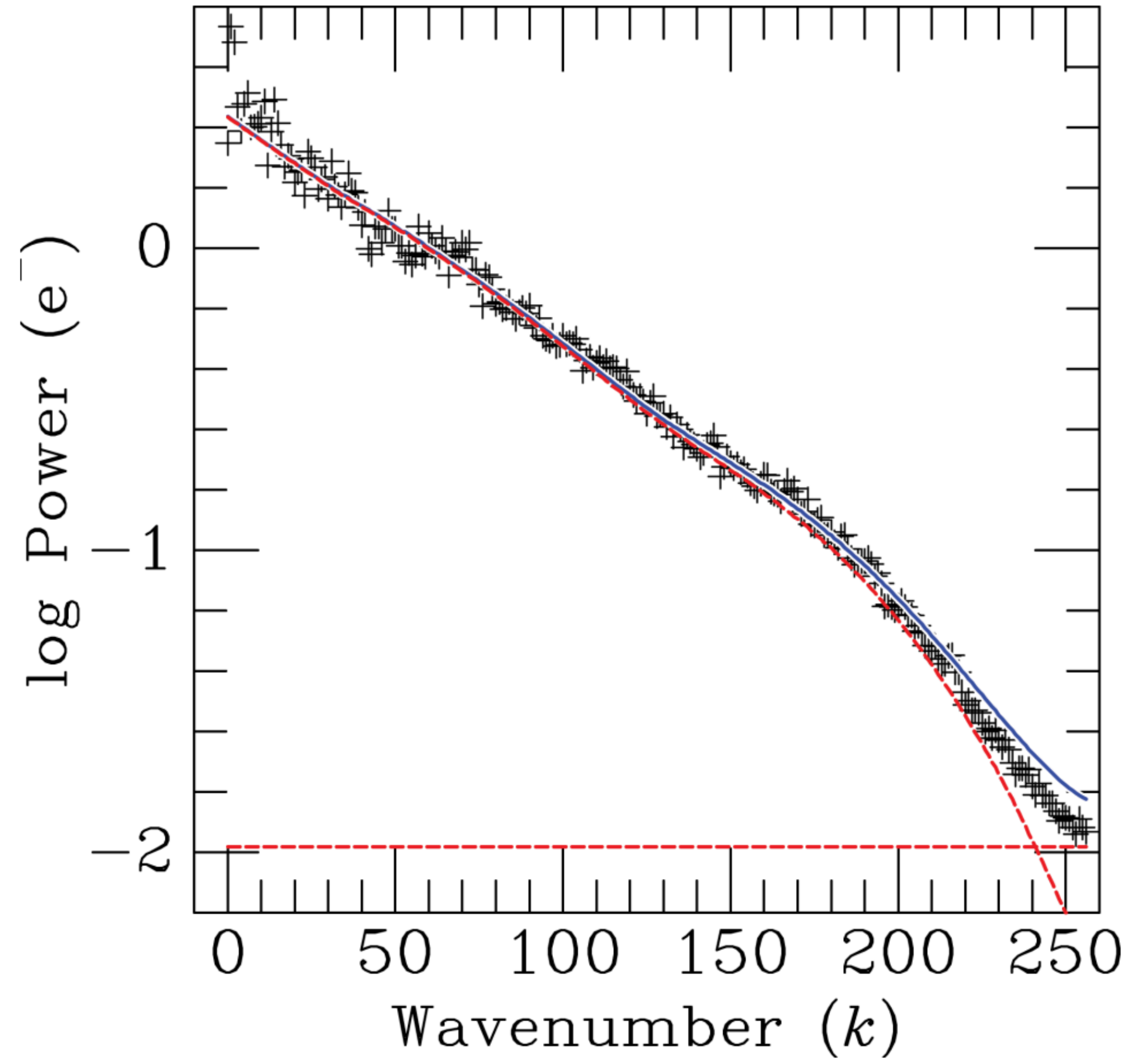


Figure 9. Spatial power spectra for NGC 1399 for the center of the galaxy (B3) in the $F150W$ band and near the peak of the SBF luminosity. The power spectra shows a fit to the PSF power spectrum scaled to match the data and fit in two dimensions, and the constant noise floor (shown with red dotted lines). The blue line shows the excellent fit to the power spectrum over a large range in wavenumber k (x-axis).

Anand+24b

Summary

- Cycle 1+2 JWST data shows good agreement between all second-rung distance indicators and with prior HST Cepheid measurements.
    - Consistency of HST and JWST means increased confidence in the Hubble tension
- No evidence from JWST data that HST Cepheid crowding was not dealt with appropriately, distance-dependent crowding ruled at $>8\sigma$ level.
- A JWST-only measurement of the Hubble constant requires a larger sample of hosts, really worth collecting *all* 37 HST SN hosts.
- At the end of the day, we will need a fully independent pathway to H_0 if we are ever going to get the bottom of this issue.
    - Cepheid+Type Ia supernovae have served as the gold-standard measurement and have held up in the face of scrutiny.
    - TRGB+SBF show incredible promise for a similarly precise local measurement of H_0.

Questions?

NGC 1380 (GO-3055)