The Hubble Tension in 2024?

2024.10.28

Myung Gyoon Lee

Seoul National University

The 11th KIAS workshop on Cosmology and Structure Formation, Oct 27-Nov 2, 2024, Gyeongju Korea

Observational Cosmology in 100 years

- **Beginning of Observational Cosmology in 1924**
  - the first extragalactic Cepheids in M31 by Hubble in 1924 showing an island universe

- **Structure and Dynamics of the Universe**
  - Hubble-Lemaitre law in 1927 and 1929: expanding universe
  - SN Ia cosmology in 1998: accelerating universe

- Today, our KIAS workshop (Cosmology and Structure Formation) in 2024!

The Hubble Tension?

Myung Gyoon Lee

Department of Physics & Astronomy

Seoul National University (SNU), Korea

(mglee@astro.snu.ac.kr)

The 9th KIAS workshop on Cosmology and Structure Formation, Nov 2-6, 2020

H_0

(Current expansion rate of the Universe)

The most debated parameter in cosmology today!

Two Ways to Estimate H_0 in 21C

1) $H(t=t_0)$ from local universe (z~0)

- cosmic distance ladder
  - SN Ia etc
- direct methods based on modelling
  - gravitational lenses, water megamasers, gravitational wave sirens, etc

2) H(high z) $H(t_0)$

- inverse distance ladder based on modelling
  - CMBR, BAO, etc

The Hubble Tension in a slide (2020)

1) Cepheid-calibrated SN Ia (SH0ES 2020)

H_0 (SN Ia)= 74.03±1.42 km/s/Mpc (error~2%)

2) CMBR (Planck 2018, 2020)

H_0 (CMBR) = 67.44±0.58 km/s/Mpc (error<1%)

Difference: °H_0 = 6.6 km/s/Mpc ~10%

- a tension at 4.3σ

How to resolve it? That's the question!

The TRGB (Lee+1993) is our answer!

Errors for Candle Cosmography

What we measure directly is a magnitude,
not a distance, of a candle!

Errors in magnitude ⇨ Errors in distance & H_0 (=v/d)

Distance modulus: $(m\text{-}M)_0 = \mu = 5\log d[\mathrm{pc}] - 5$

$\mathrm{err}(d)/d = \mathrm{err}(H_0)/H_0 = 0.2 \ln 10\ \mathrm{err}(m)$
$= 0.46\ \mathrm{err}(m)$

(ex) err(m or M)=0.1 mag-> $\mathrm{err}(H_0)$ ~ 4.6%
~3.2 km/s/Mpc for H_0=70

Empirical relation for SN Ia from the Panteon+ SN sample (Riess+2022)

$$5\log(\mathrm{H}_0/72.5) = M_B^0 - (-19.28)$$

How about in 2024?

- Problems are solved or not?
- The field is getting hotter!

The Hubble Tension in a slide (2024)

1) Cepheid-calibrated SN Ia (SH0ES 2024)

H_0 (SN Ia)= **74.03±1.42 km/s/Mpc (error~2%) (2020)**

(=73.04±1.04 km/s/Mpc Riess+2022)

(=73.2±0.9 km/s/Mpc Riess+2024) (error~1%)

2) CMBR (Planck 2018, 2020)

H_0 (CMBR) = 67.44±0.58 km/s/Mpc (error<1%)

Difference: °H_0 = 5.8 km/s/Mpc - a tension at ~6σ

(-> °(m-M)(candles) = 0.18 mag)

How to resolve it? That's the question!

The TRGB is an answer!

What are new major data recently?

- **JWST since 2022!**
- **DESI 2024 for BAO**

DESI2024 results

- Sample: N>6M galaxies (bright galaxies, LRGs, ELGs, Lya forests, quasars) at 0.1<z<4.2
- Measuring BAO (z) (a standard ruler)

  based on correlation functions of galaxies
- The sound horizon at the drag epoch (z~1060)

$$r_{\rm d} = \int_{z_{\rm d}}^{\infty} \frac{c_{\rm s}(z)}{H(z)} dz \qquad c_{\rm s}(z) = \frac{c}{\sqrt{3\left(1 + \frac{3\rho_{\rm B}(z)}{4\rho_{\gamma}(z)}\right)}}$$

- Today:

$$r_{\rm d} = \frac{147.05}{\rm Mpc} \left(\frac{\omega_{\rm m}}{0.1432}\right)^{-0.23} \left(\frac{N_{\rm eff}}{3.04}\right)^{-0.1} \left(\frac{\omega_{\rm b}}{0.02236}\right)^{-0.13}$$

$$\omega_{\rm m} \equiv \Omega_{\rm m} h^2 \text{ and } \omega_{\rm b} \equiv \Omega_{\rm b} h^2$$

DESI24 results

- **BAO(z) measurements: for seven z bins**
- **For the standard flat LCDM cosmology:**
  - **$_m$= 0.295 0.015**
  - **$r_d h$= 101.8 1.3 Mpc (the photon-drag epoch sound horizon x scaled H_0)**
  - **If the value of r_d is known, we can get the value h!**
  - **Calibration of r_d is: baryon density from BBN, or CMB (angular peak, PS)**

- **H_0 = 68.53 0.80 km/s/Mpc** from DESI BAO + CMB, SN Ia
- **H_0 = 68.52 0.62 km/s/Mpc** from DESI BAO +BBN + CMB (acoustic angular scale, independent of models)
- **H_0 = 67.97 0.38 km/s/Mpc** from DESI BAO + full CMB

An example of **butterfly effect**?
(small offsets leading to big things)

- **DESI2024** presented two cases of DE models:
- 1) **for wCDM models with constant w: w=-0.997 0.025** from DESI BAO+CMB, SN Ia
- **2) for w(z) models: a hint on the presence of evolving DE**:

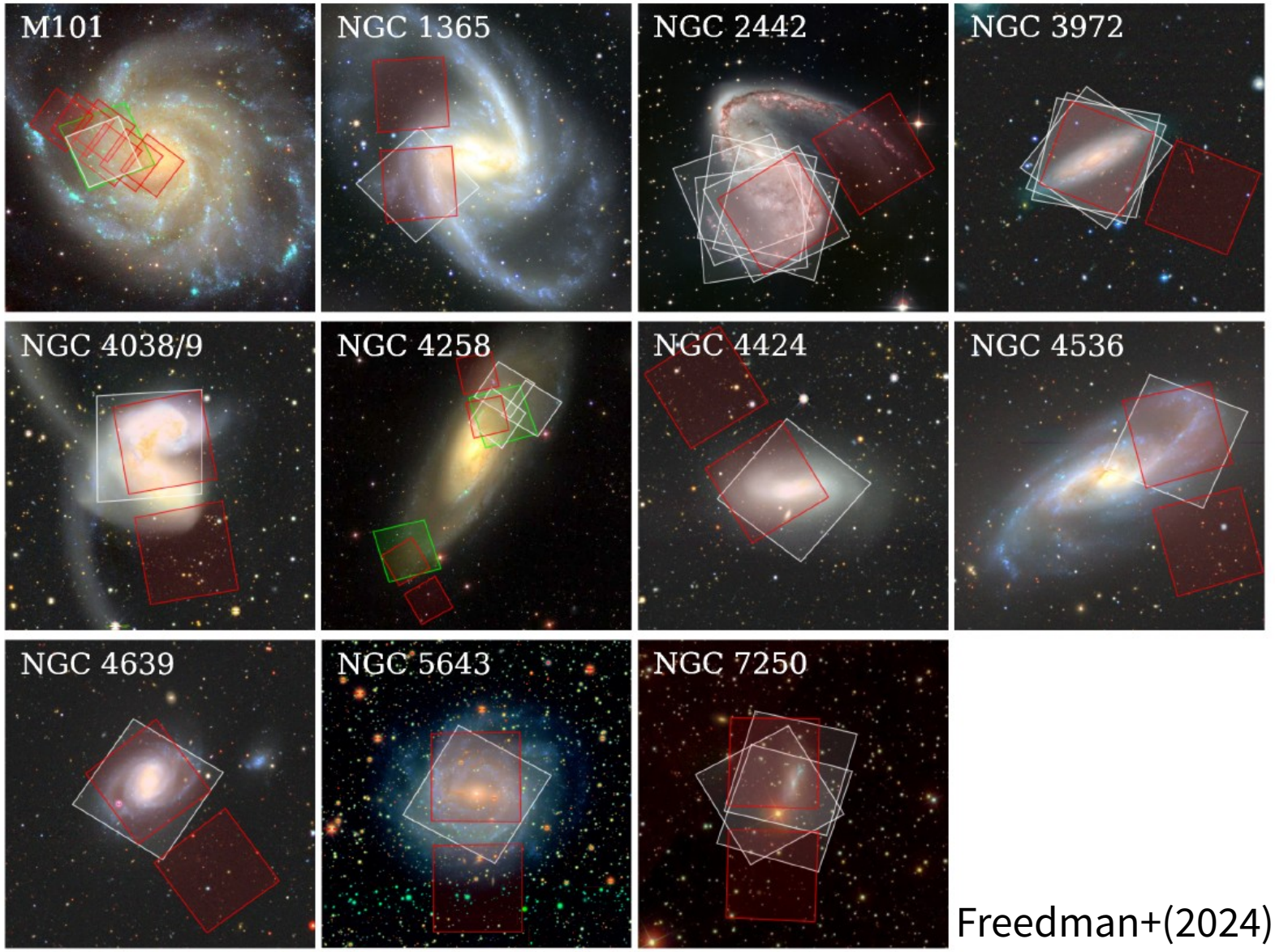
$$w(z)=w_0+w_a(z/(1+z)) \; (w(a)=w_0+w_a(1-a))$$

  - DESI24 BAO+CMB: **$w_0>-1$ and $w_a<0$**
    - **2.2 for the Panteon+ SN sample**
    - **3.5 for the DES5Y SN sample**

- Efstathiou (2024), correcting for **the offset in SN mags, ~0.04 mag, between low and high z SN in the DES5Y SN sample**, find that **DESI results are in good agreement with the PLANCK LCDM cosmology (w=-1)!**

JWST Results of CCHP2024

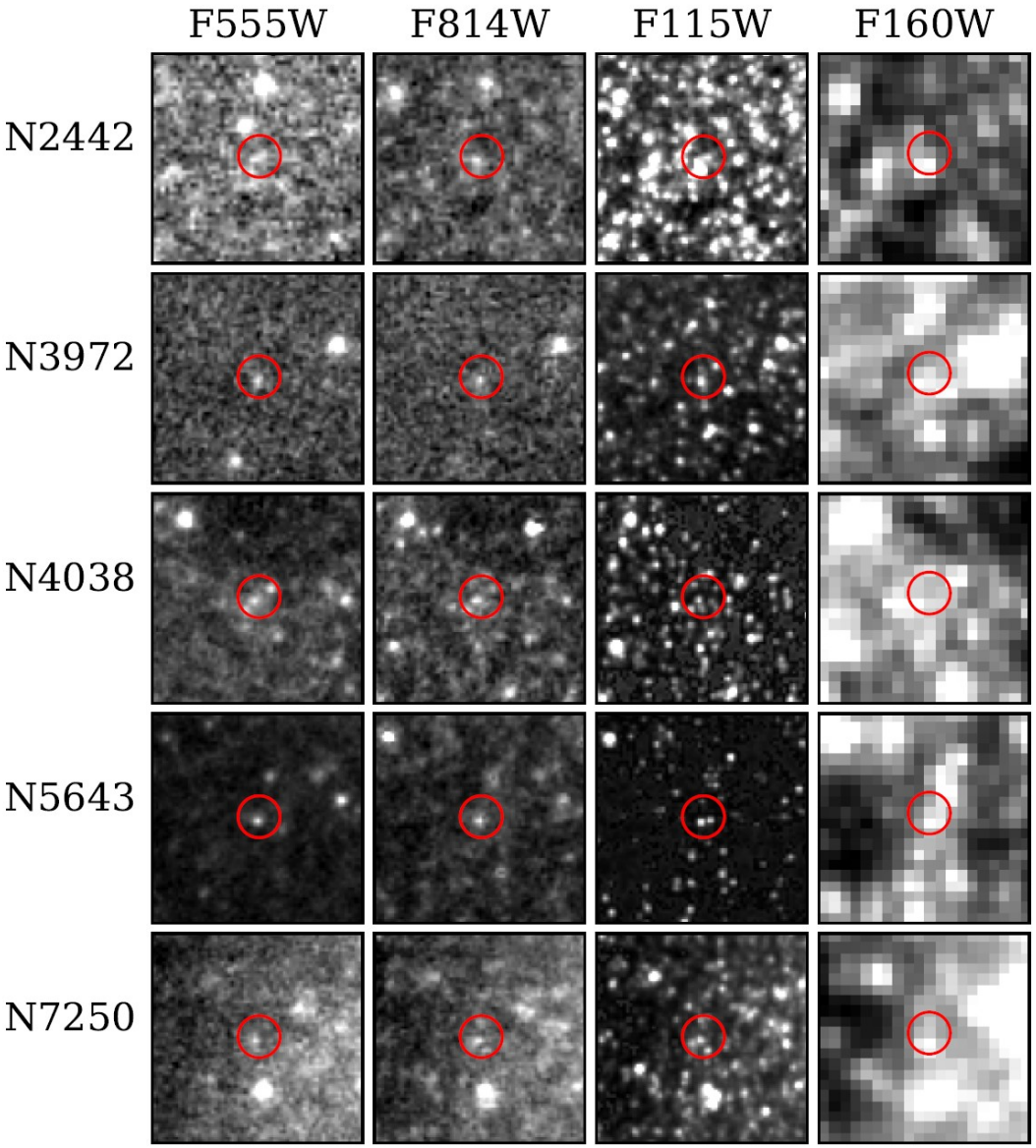
- Freedman+2024(Aug 12)
- 11 galaxies with SN Ia
- JWST/NIRCam(red boxes)
  +HST/WFC3(white boxes)



Freedman+(2024)

Cepheids in JWST/HST Images

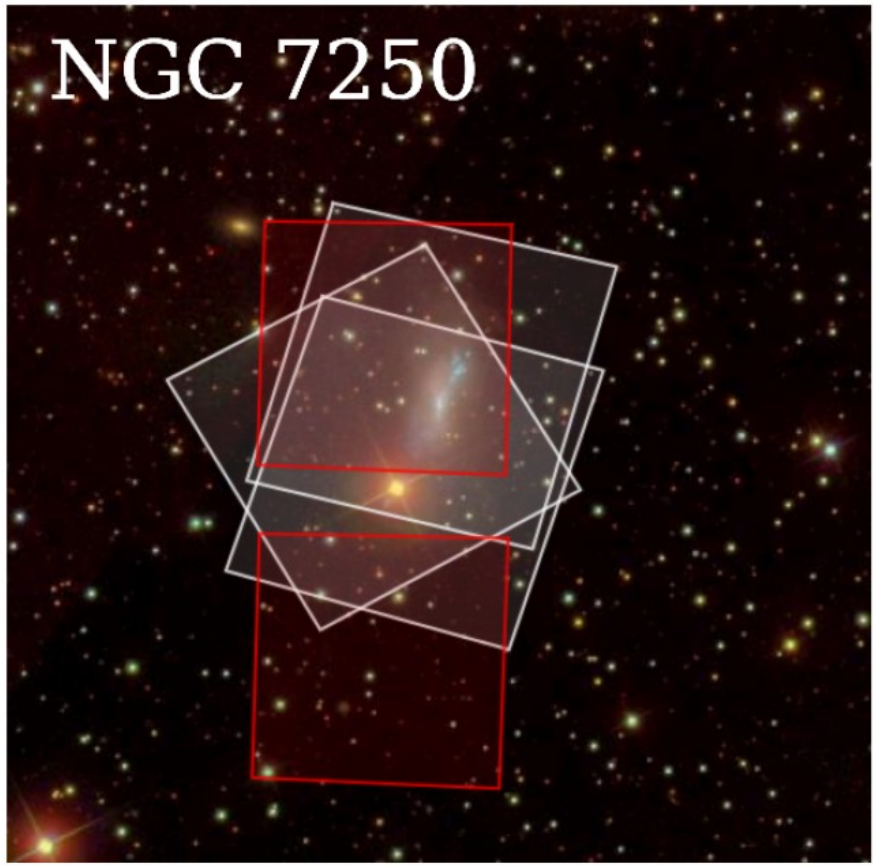
- **HST: F555W, F814W**
- **JWST: F115W (0.035”/px), F160W (0.1”/px)**

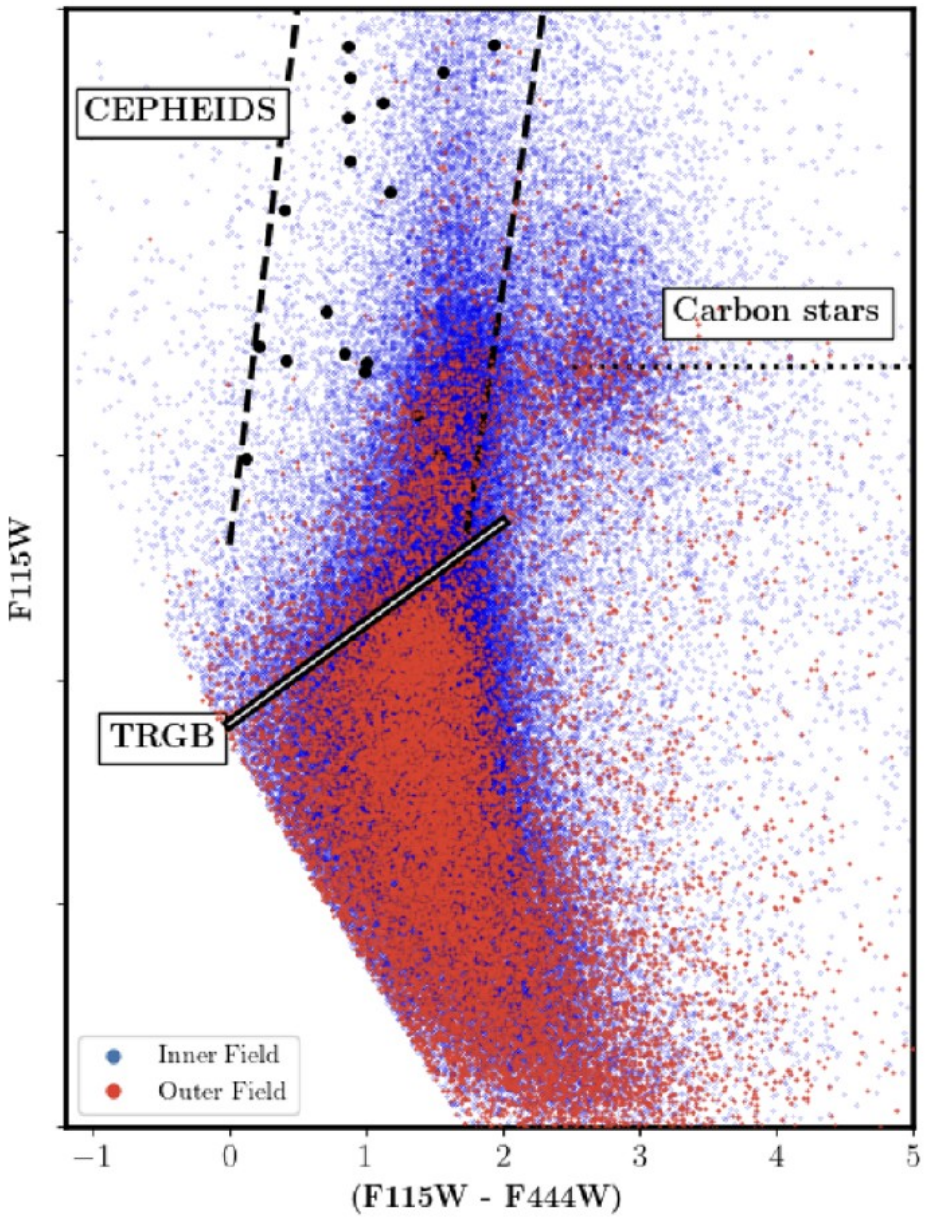


Freedman+(2024)

JWST CMDs of Stars

- JWST/NIRCam CMD of NGC 7250 (Sdm) stars
- Inner (blue) and outer field (red)
- Carbon AGB stars-> JAGB (standard candle)

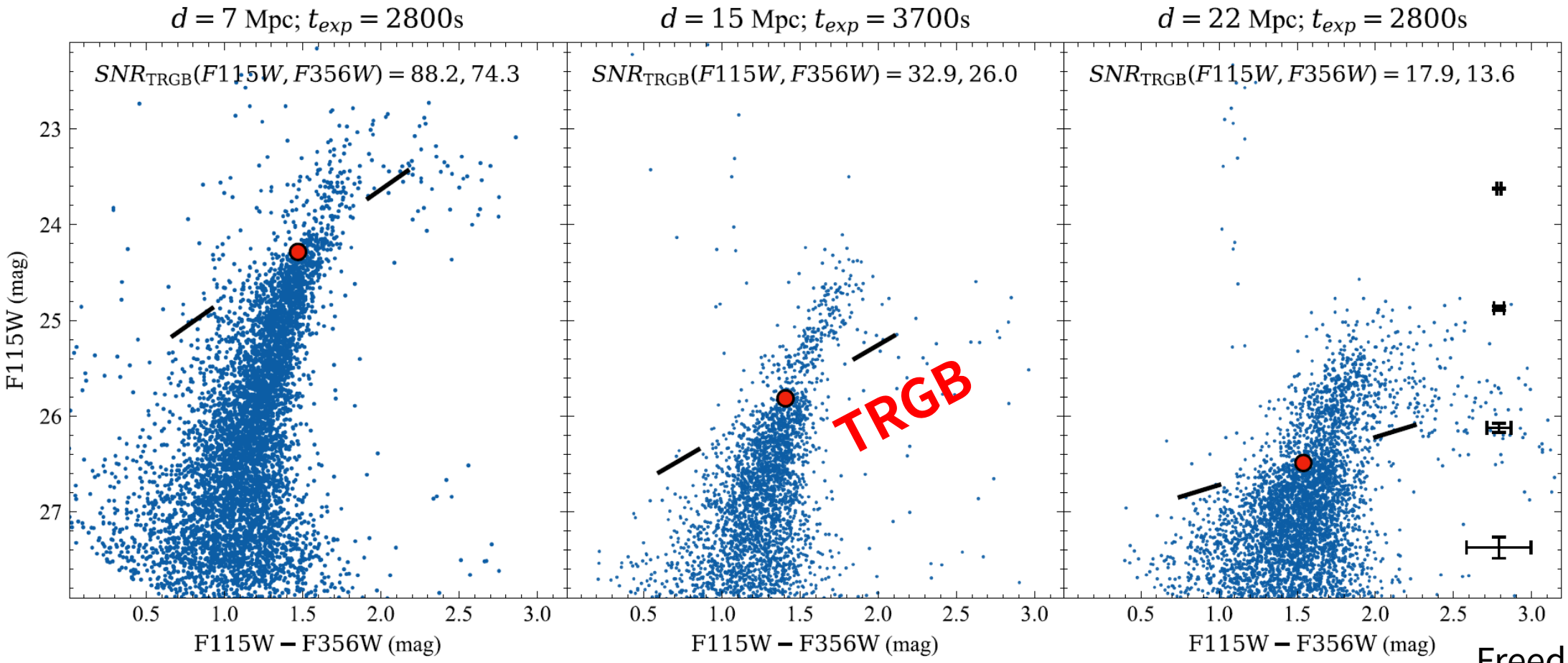




Freedman+(2024)

JWST CMDs for d=7, 15, and 22 Mpc

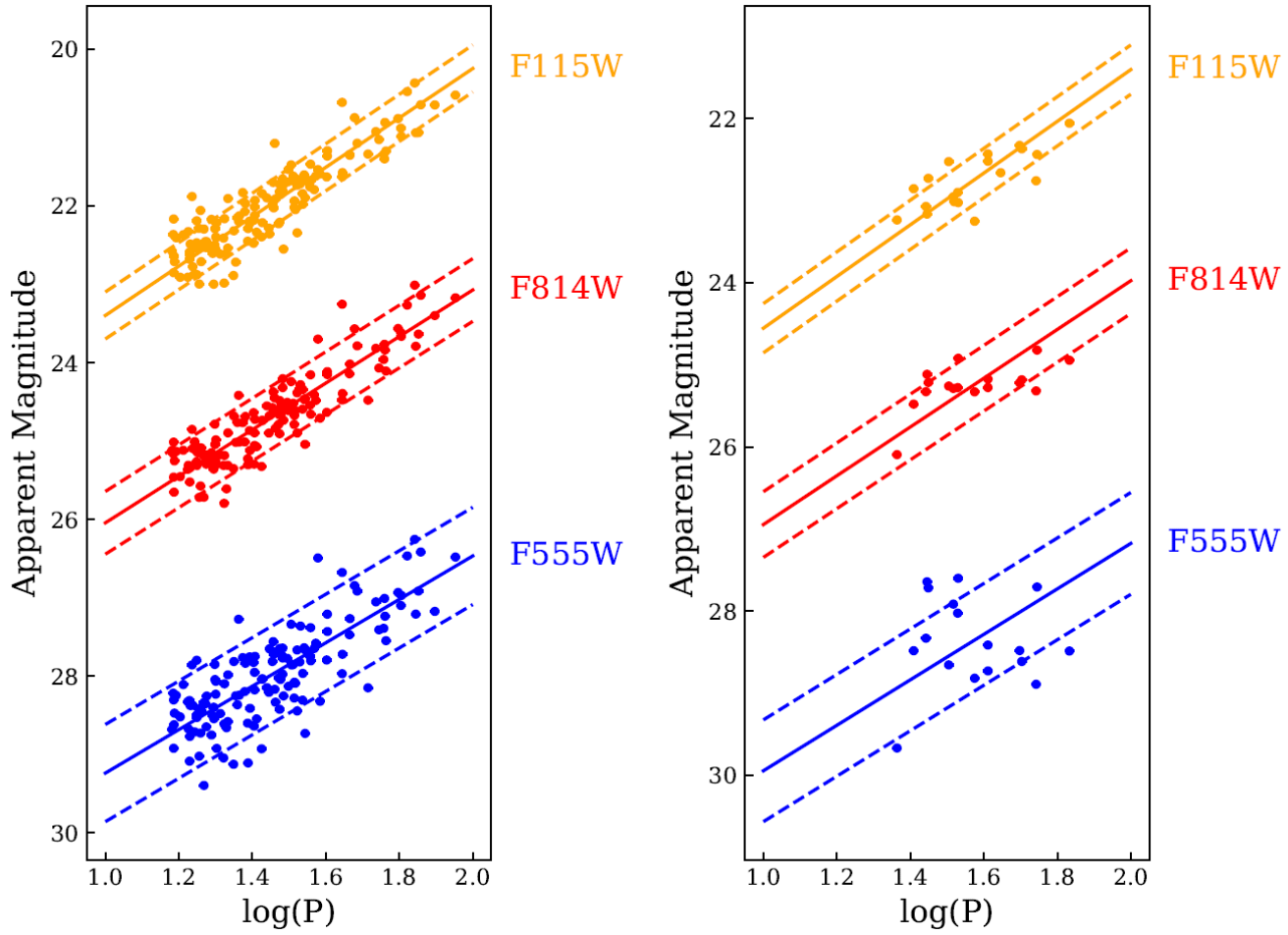
- **NIRCam CMDs of stars**
  in NGC 4258 (d=7Mpc), 4424 (d=15Mpc), and 4039 (d=22Mpc)s



Freedman+(2024)

JWST/HST Cepheids: for d=13 and 22 Mpc

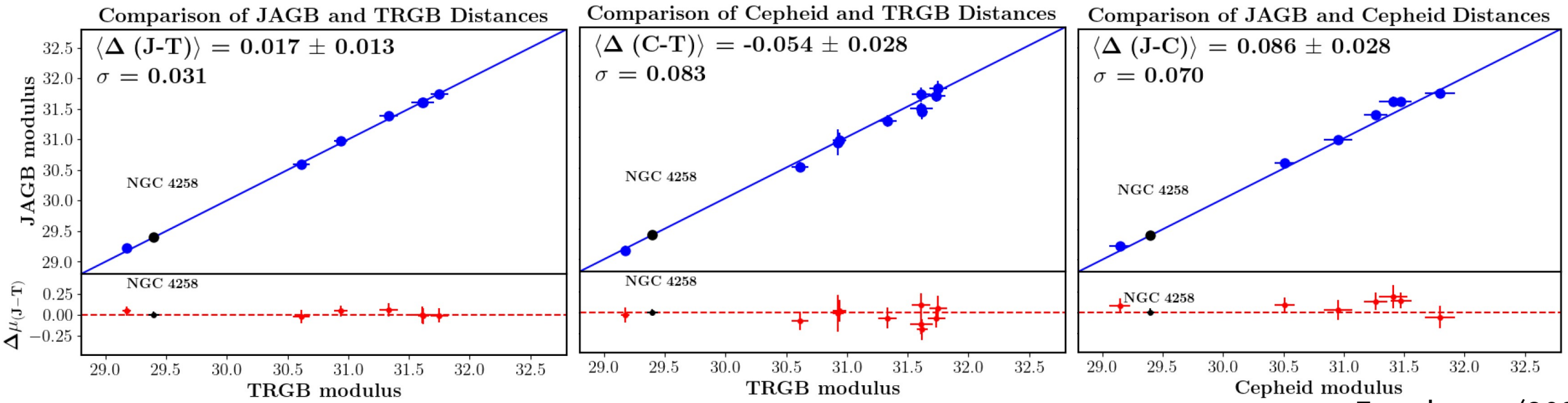
- **P-L Relations of Cepheids: NGC 5643 (d=13Mpc) and 4639 (d=22Mpc)**



Freedman+(2024)

Comparison of TRGB, JAGB, and Cepheids in CCHP

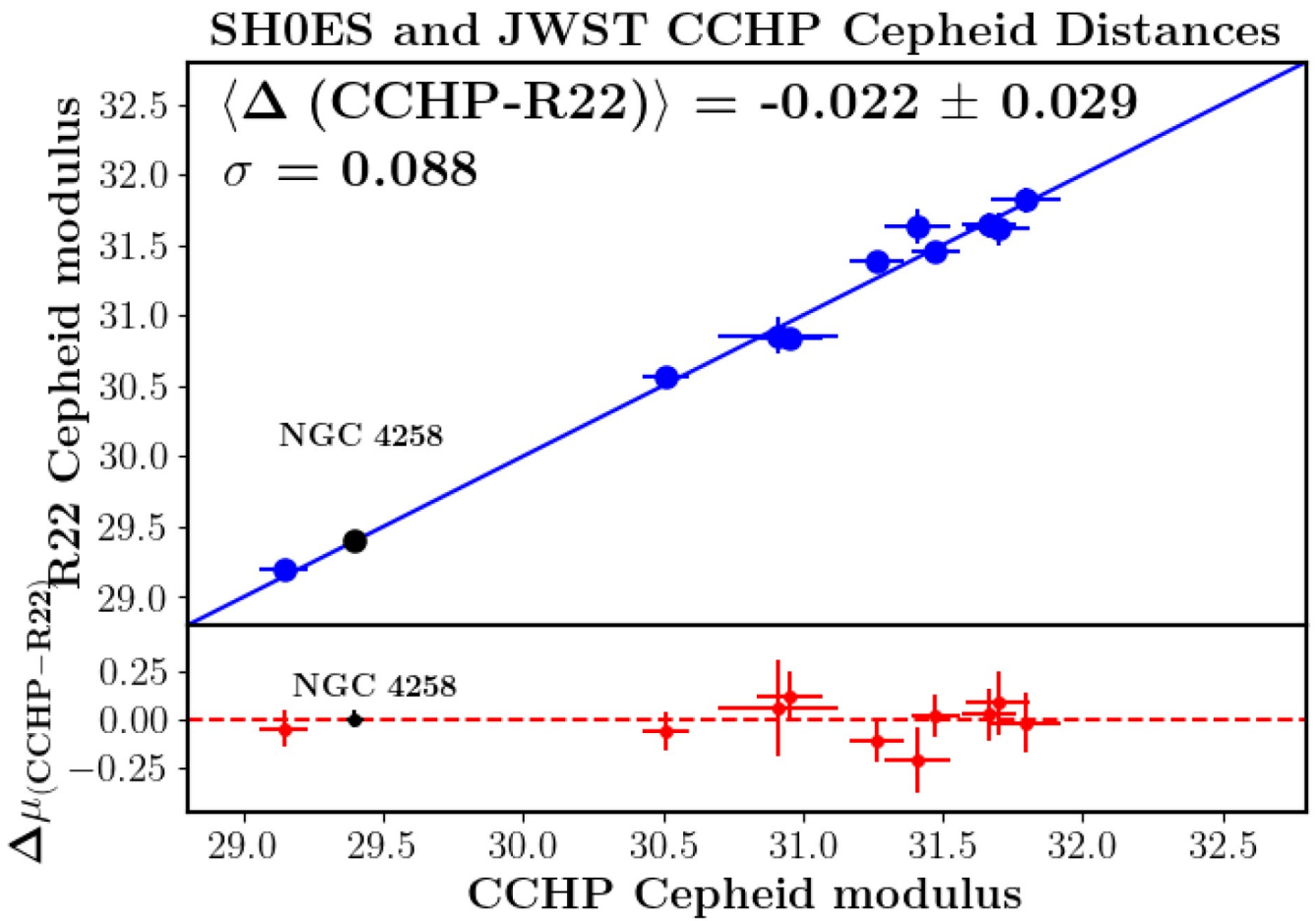
- **TRGB and JAGB distances: excellent agreements**
- **Cepheid distance modulus is 0.05 mag smaller than TRGB!**
- **Cepheid distance modulus is 0.09 mag smaller than JAGB!**



Freedman+(2024)

Comparison of SH0ES and CCHP Cepheids

- **SH0ES HST Cepheid distances (Riess+2022) agree very well with CCHP JWST Cepheid distances!**

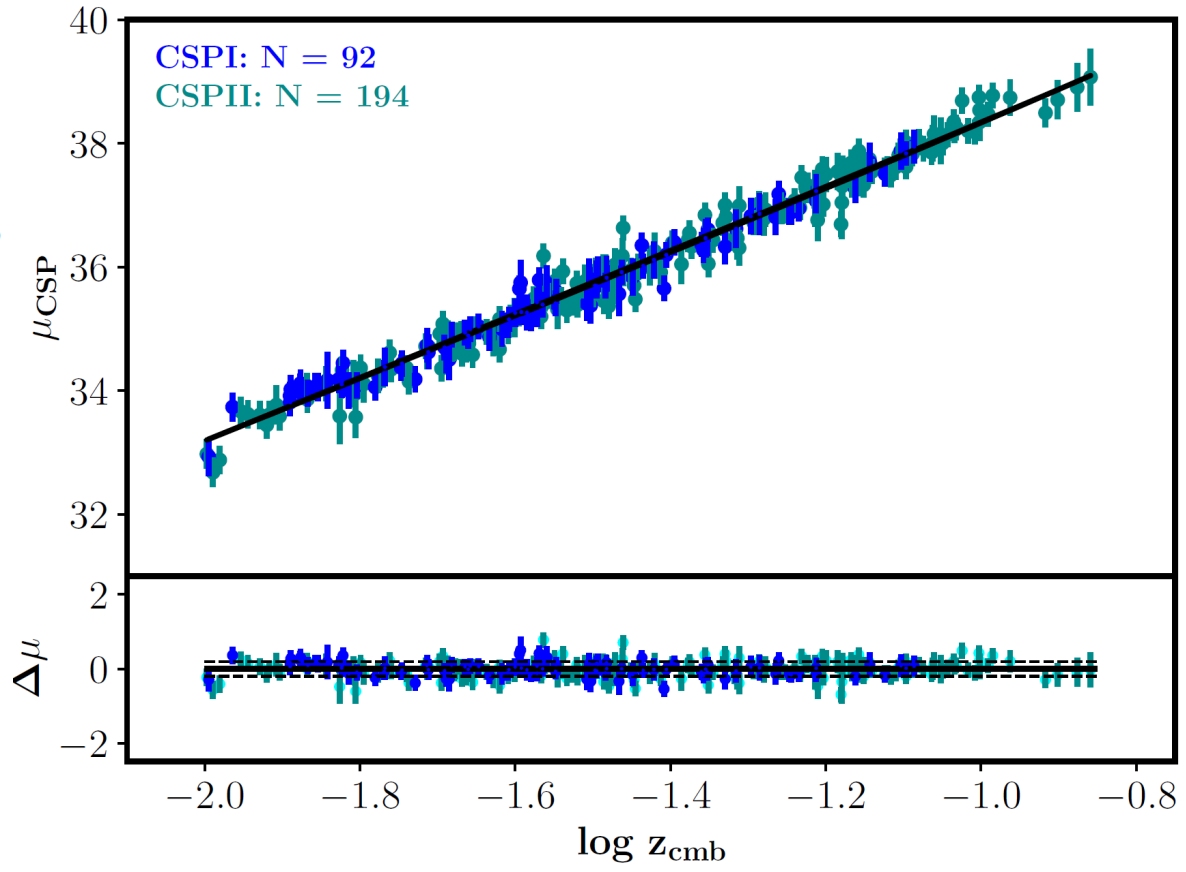


Freedman+(2024)

H_0 from 3 JWST Methods (JAGB, TRGB, Cepheids) in CCHP2024

- **SN Ia sample: CSP I,II: 287 SN Ia (Uddin+2024)**

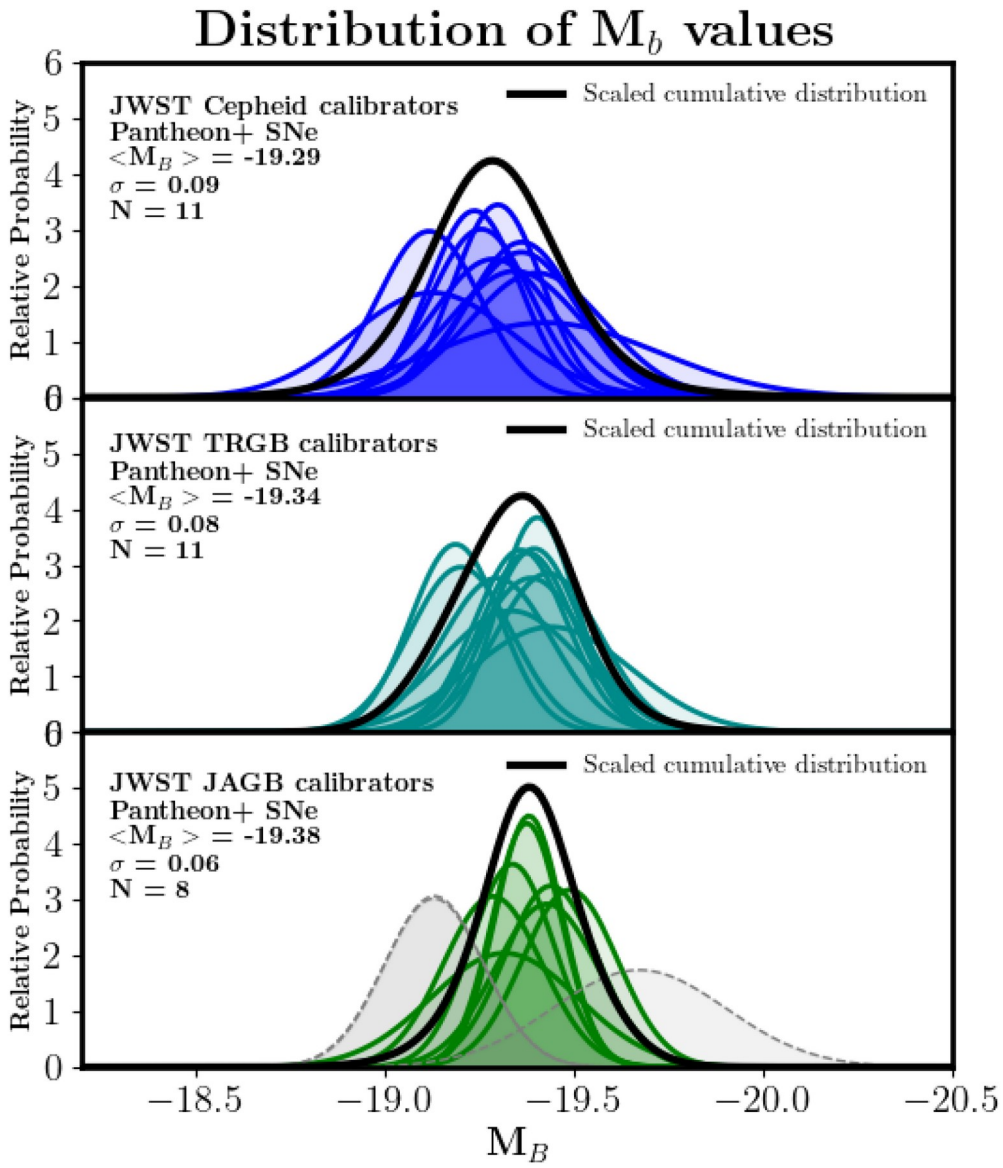
$$\mu(z, H_0, q_0) = 5\ \log_{10}\{\frac{(1+z_{hel})cz}{(1+z)H_0}(1+\frac{1-q_0}{2}z)\} + 25$$



Freedman+(2024)

SN Ia Calibration from CCHP JWST Methods

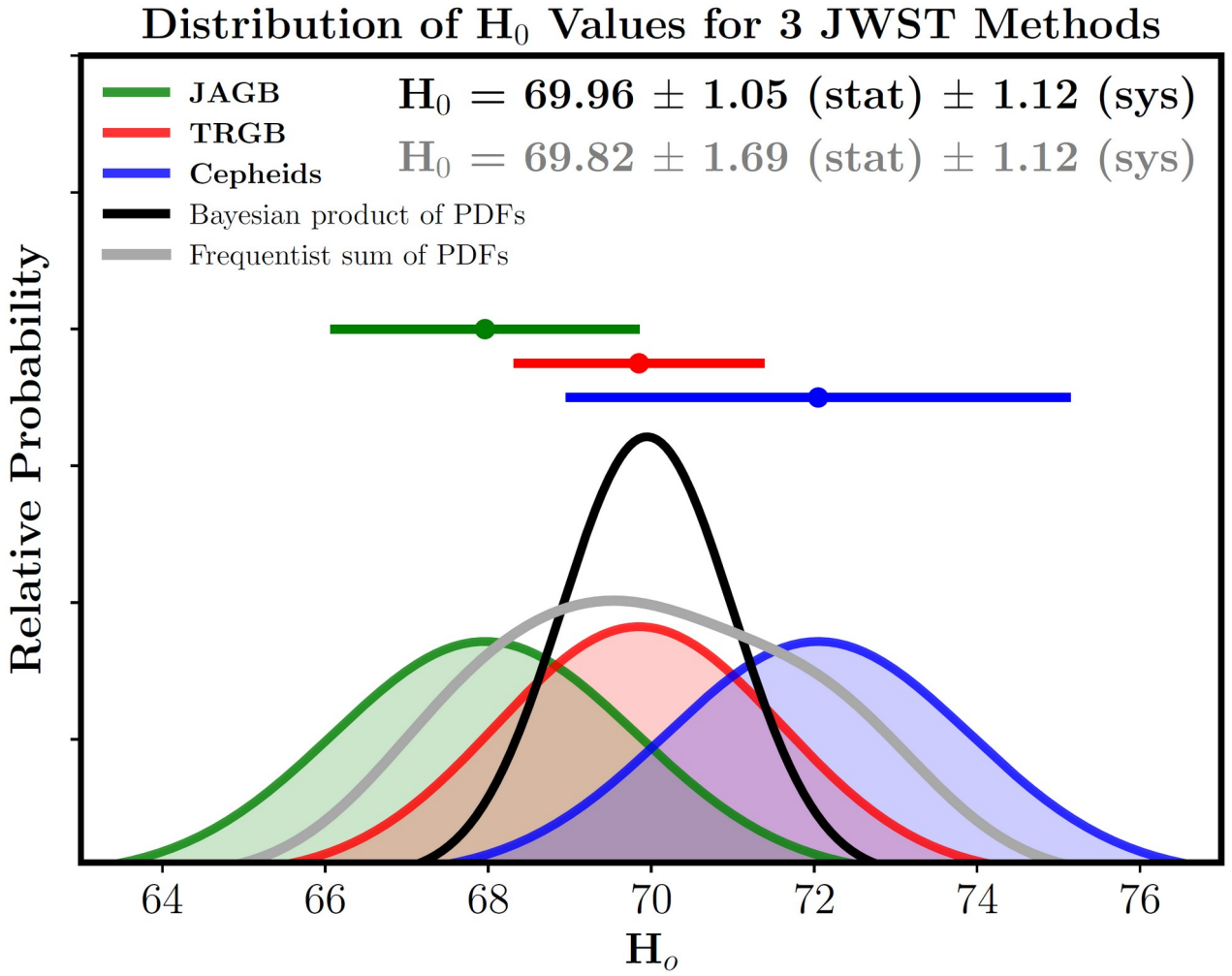
- **TRGB, JAGB, and Cepheids**
- **SN Ia (TRGB) M_B mags are ~0.05 mag brighter than SN Ia (Cepheid)!**

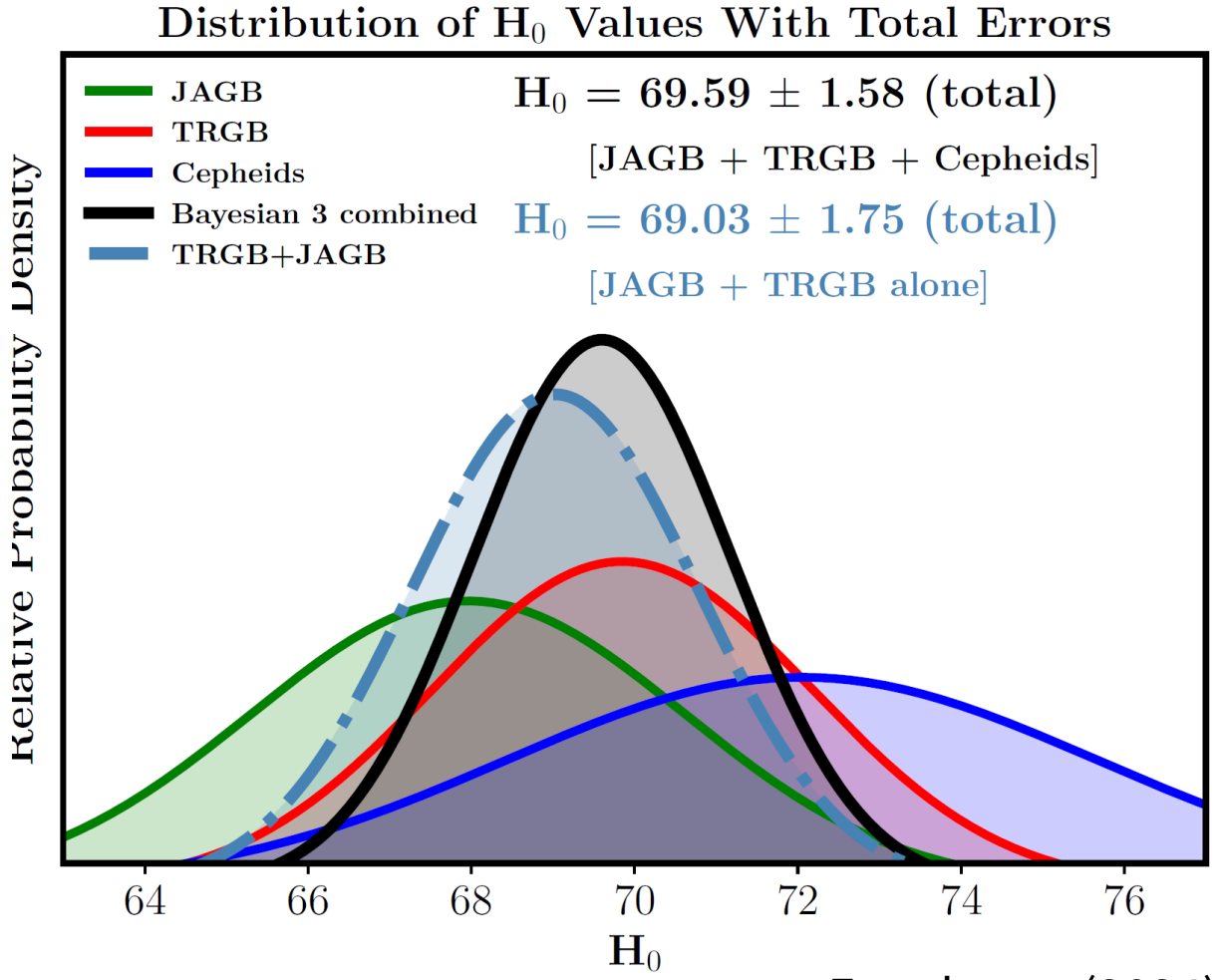


Freedman+(2024)

H_0 from CCHP JWST Methods (JAGB, TRGB, Cepheids)

- SN Ia sample: CSP I,II (287 SN Ia)
- $H_0 = 68.59 \pm 1.58$ km/s/Mpc





Freedman+(2024)

H0 Errors for CCHP JWST Results

- Errors

Table 5. Summary of H_0 Uncertainties

Source of Error	Random Error	Systematic Error	Reference
TRGB zero point	2.5%	2.2% [a]	H24, §9.4
JAGB zero point	2.7%	2.8% [b]	L24, §9.4
Cepheid zero point	2.6%	4.3% [c]	O24, §9.4
Combined methods [d]	1.5%	1.6%	§9.4

(a) Uncertainty of 1.5% in NGC 4258 distance; Reid et al. (2019) and uncertainty in color term, TRGB fitting, extinction, photometry calibration

(b) Uncertainty of 1.5% in NGC 4258 distance; Reid et al. (2019) and uncertainty in the mode, smoothing parameter, convergence error, extinction

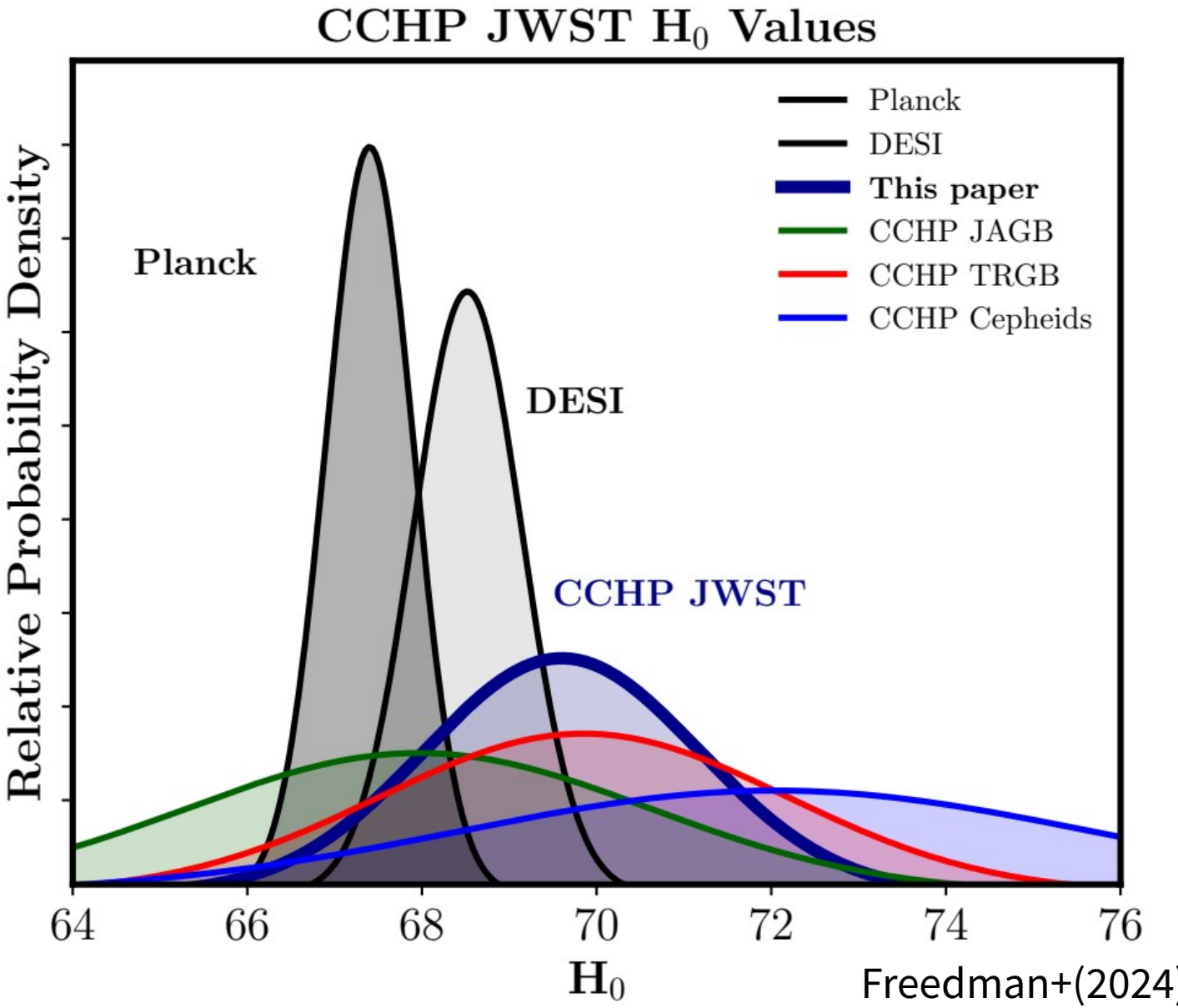
(c) Uncertainty of 1.5% in NGC 4258 distance; Reid et al. (2019) and uncertainty in NGC 4258 reddening law fit zero-point, NGC 4258 PL cutoff, aperture correction uncertainty, including cross matching the *HST* catalogs, photometric zero point uncertainty and metallicity.

(d) Cepheid, TRGB and JAGB combined errors.

Freedman+(2024)

Comparison of CCHP JWST, DESI, and Planck

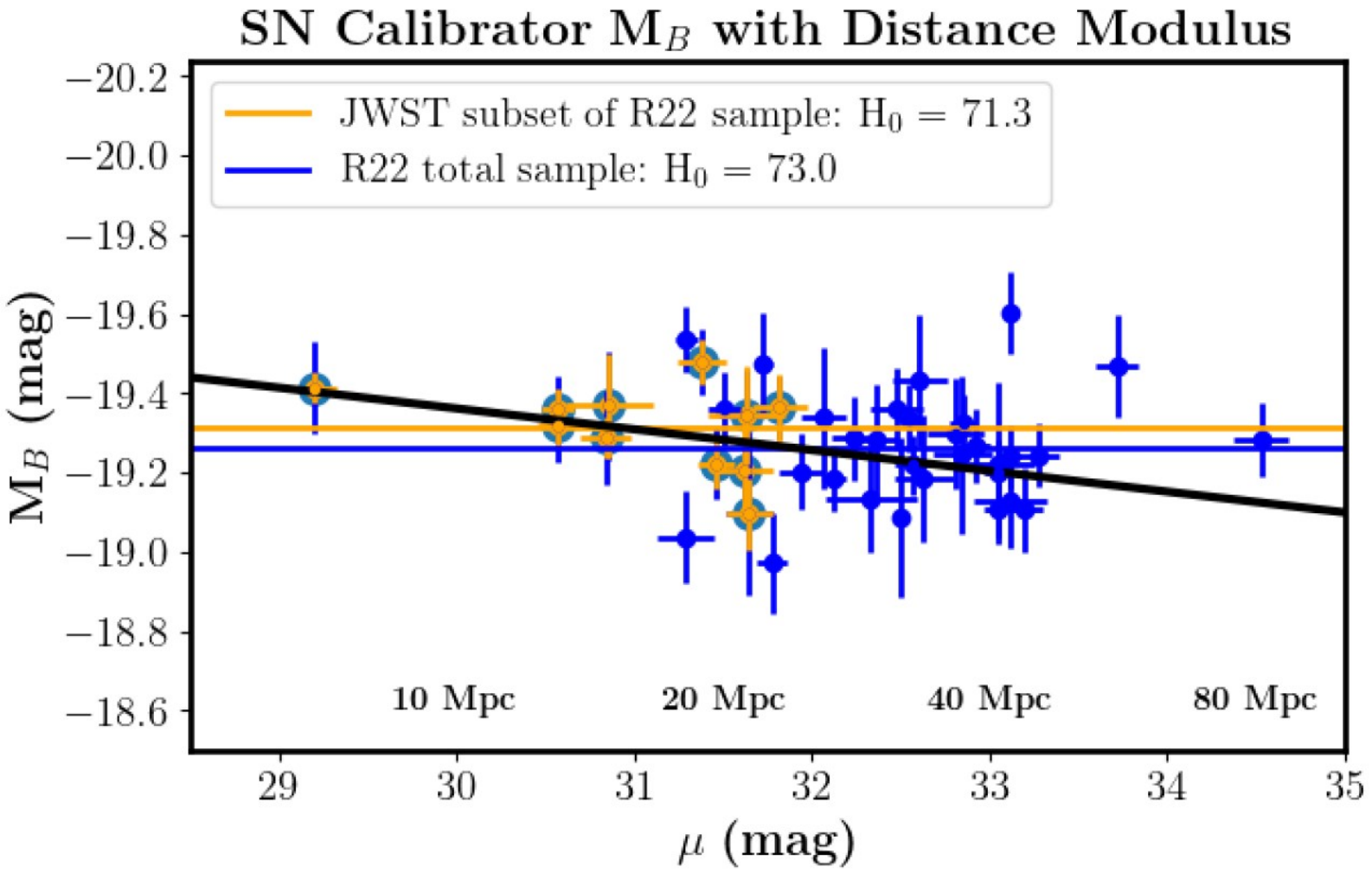
- Any tension?
- CCHP JWST shows little tension with CMB and DESI!



Freedman+(2024)

Comparison of CCHP JWST & SH0ES sample

- JWST subset of R22 sample: yield a slightly smaller value than the R22 value.
- Any dependence on distance?
- Need more JWST galaxies!

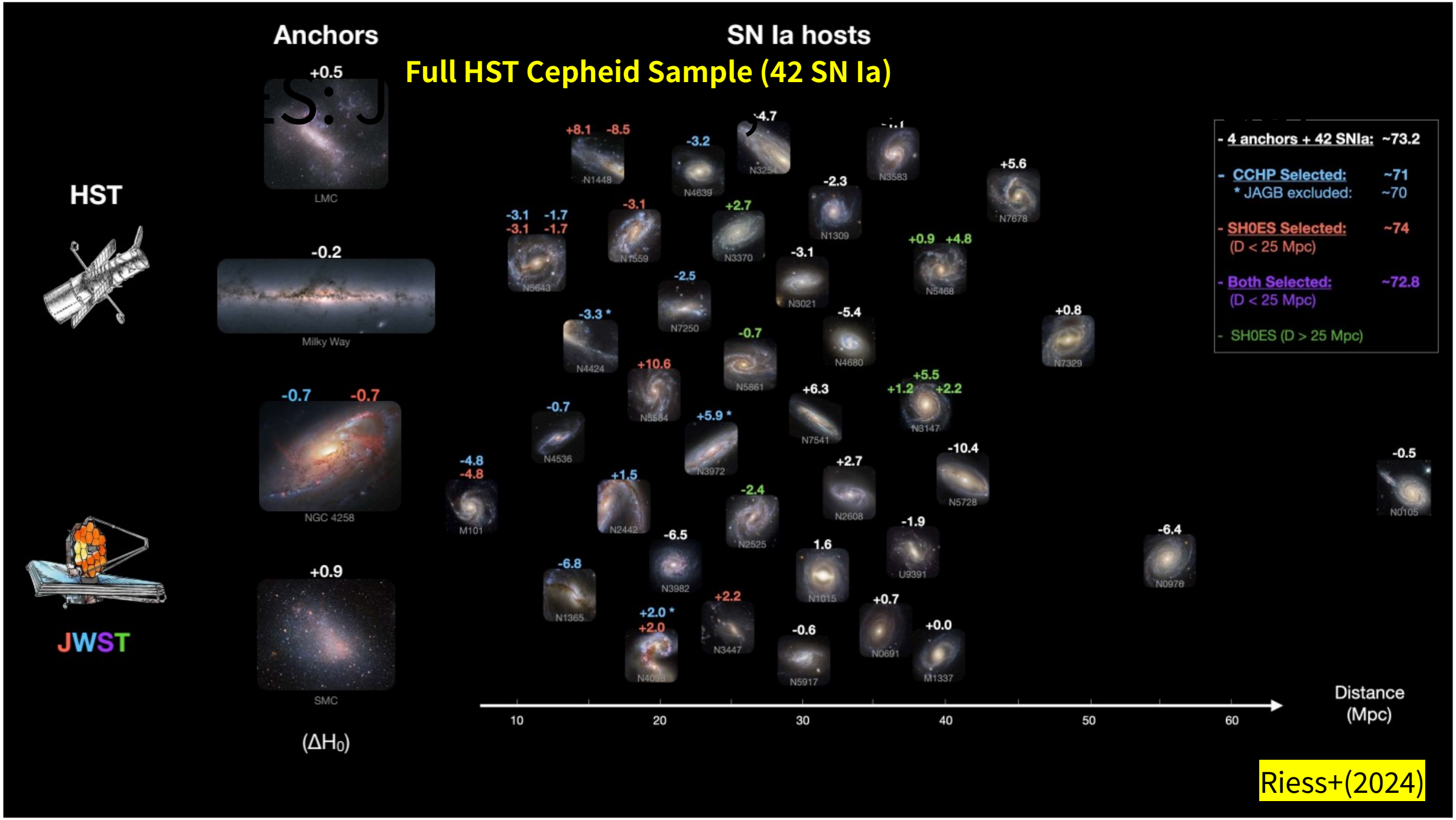


Freedman+(2024)

What about SH0ES in 2024?

- **Riess+2024 (Aug 21),**
  - **SH0ES JWST program:**
  - **Compared the new JWST results to the full HST Cepheid sample (Riess+2022),**
  - **showed a comparison with CCHP JWST 2024**

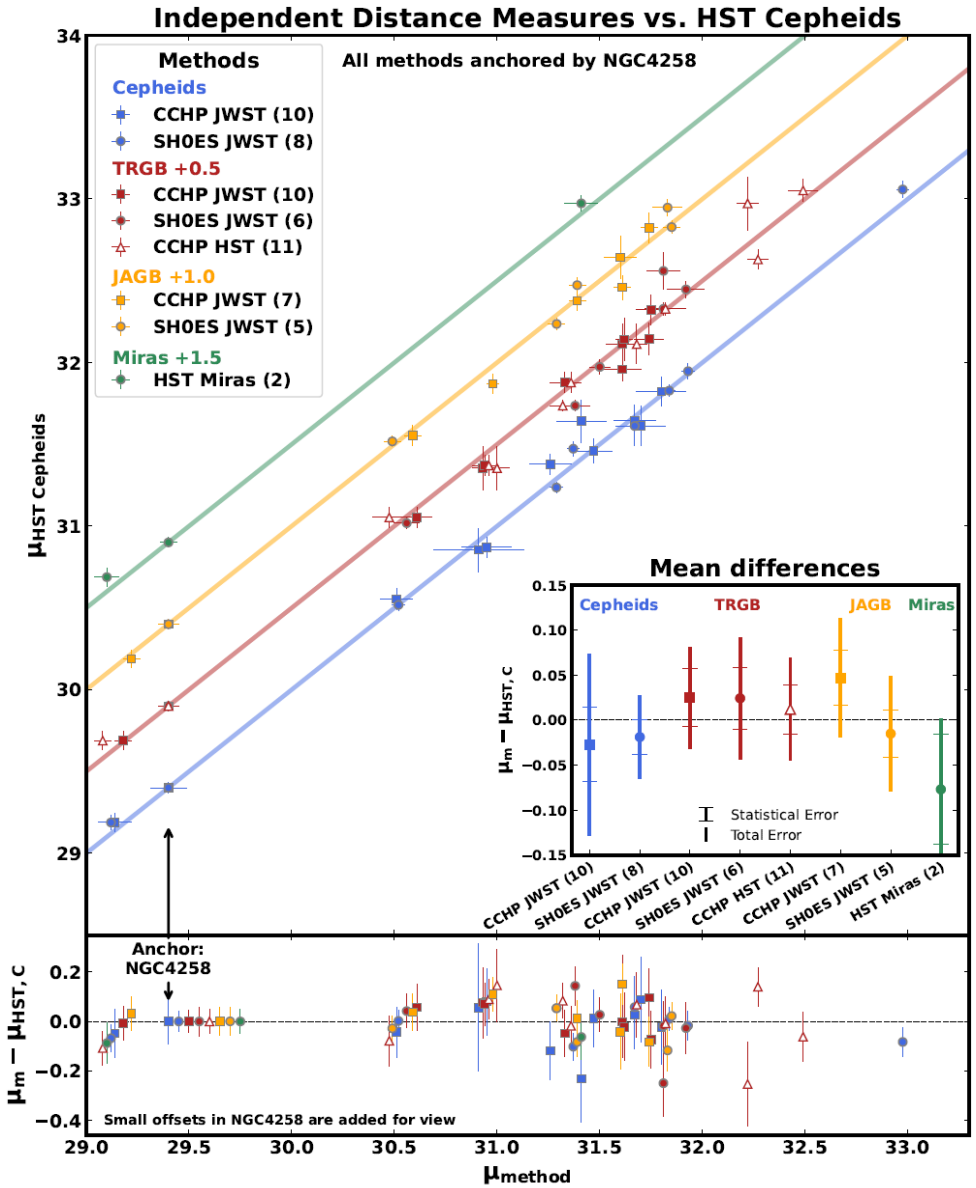
Freedman+(2024)


Anchors
SN Ia hosts
Full HST Cepheid Sample (42 SN Ia)
HST
JWST
+0.5
LMC
-0.2
Milky Way
-0.7
-0.7
NGC 4258
+0.9
SMC
(ΔH0)
- 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)
10
20
30
40
50
60
Distance
(Mpc)
Riess+(2024)

SH0ES 2024: Comparison of distances

- Reference: HST Cepheids (R22)
- JWST/NIRCam: used slightly different filters from CCHP
- Cepheids, TRGB, JAGB, Mira

- SH0ES JWST vs CCHP JWST
  - (anchor: NGC 4258)
- HST vs JWST distances:
  - Cepheid, TRGB, JAGB, and Mira distances derived from JWST (SH0ES, CCHP) observations agree with HST Cepheid distances!



Riess+(2024)

Figure 2. Mean differences of SN Ia host distance moduli calibrated by NGC 4258 as measured with different telescopes or

SH0ES 2024: JWST (Cepheids, TRGB, JAGB)

- **Riess+2022: the full HST Cepheid sample**
  - (42 SN Ia, 4 anchors)

Q1: Are HST Cepheid Measurements Accurate?

- Compare HST vs JWST between NGC 4258 and SN Ia hosts
- Test independent of SNIa, geometric distances, and H_0
- Good $\sim 1\sigma$ agreement between JWST and HST Cepheids.
- Cepheids, JAGB, TRGB all agree within errors
- No evidence against full HST: 42 SN Ia, 4 anchors, H_0 ok

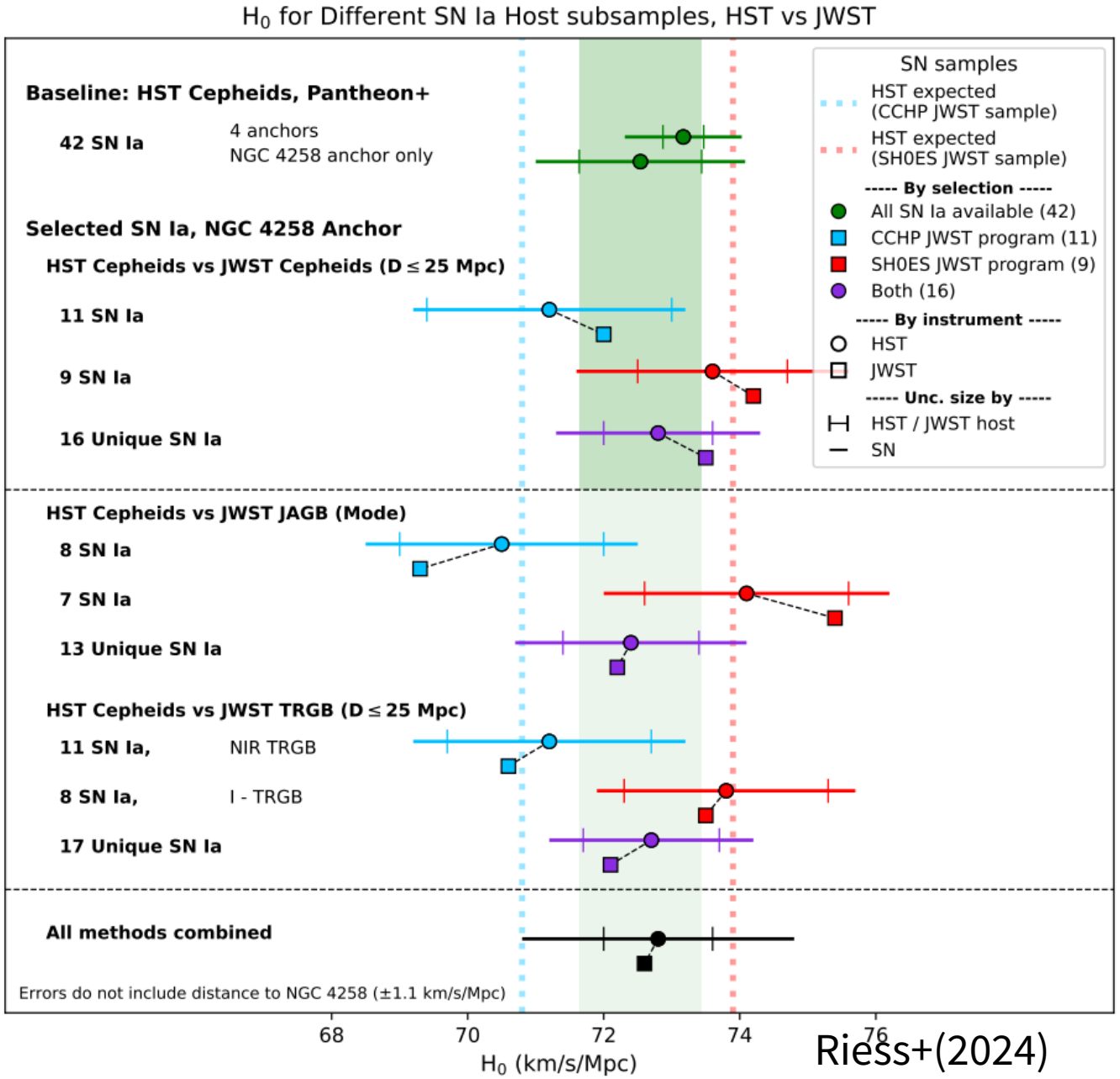
Q2: What H_0 to expect from JWST sub-sample?

- Depends on which (small) SN sub-sample selected!
- SH0ES picked 6/11 above HST mean, expect 74 ± 2
- CCHP picked 8/11 below HST mean, expect $70\text{-}71 \pm 2$
- N4258 as only anchor, all SN: expect 72.5, double errors

Riess+(2024)

Comparison of H_0s in SH0ES and CCHP2024

- Riess+2022: HST Cepheids for 42 SN Ia
  - H_0=73.2±0.9 km/s/Mpc (Riess+2024)
- JWST in SH0ES24 and CCHP24: Cepheids, TRGB, JAGB
- SH0ES24 H_0s are larger than CCHP24 values (sample selection effect), while their mean values are similar to the R22 value.



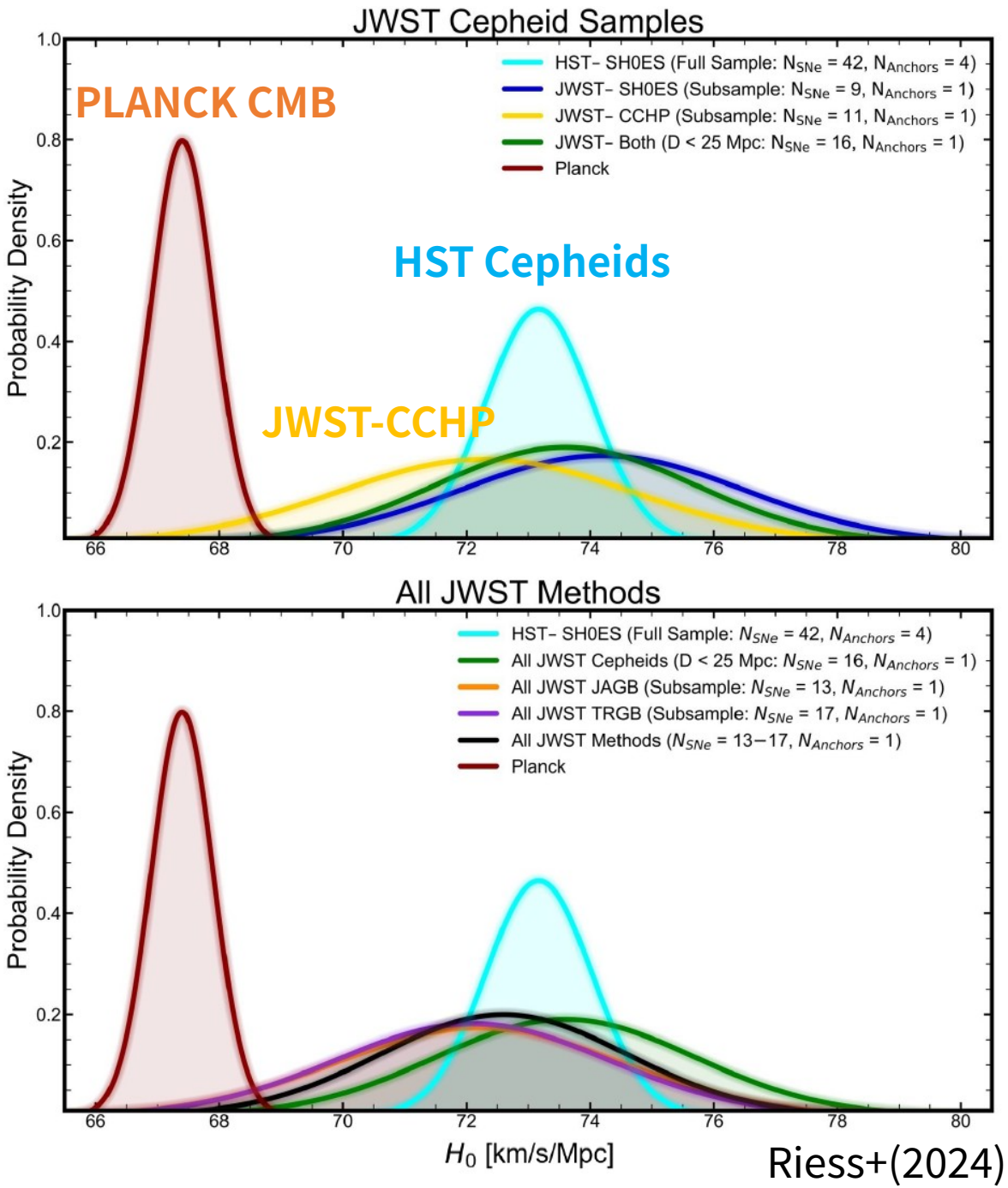
Riess+(2024)

H_0(HST vs. JWST)

- HST Cepheids (R22)
  - H_0=73.2 0.9 km/s/Mpc
  - 6σ tension with CMB
    (H_0 = 67.44±0.58 km/s/Mpc)

- All JWST (SH0ES+CCHP2024)
  - H_0=72.6 2 km/s/Mpc
  - Little tension with CMB

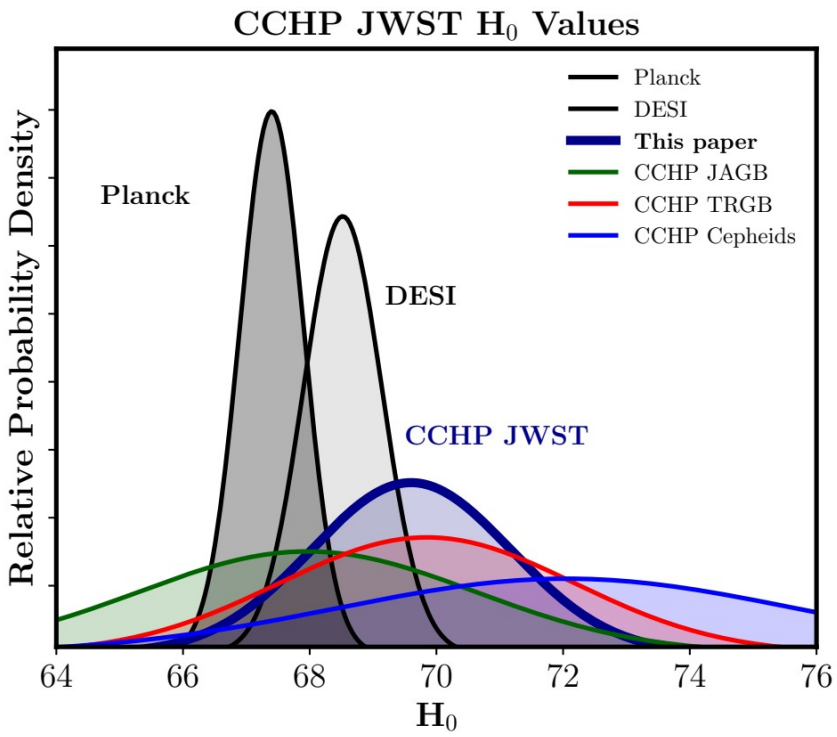
- Errors(JWST 2024)>>Errors(HST Cepheids)



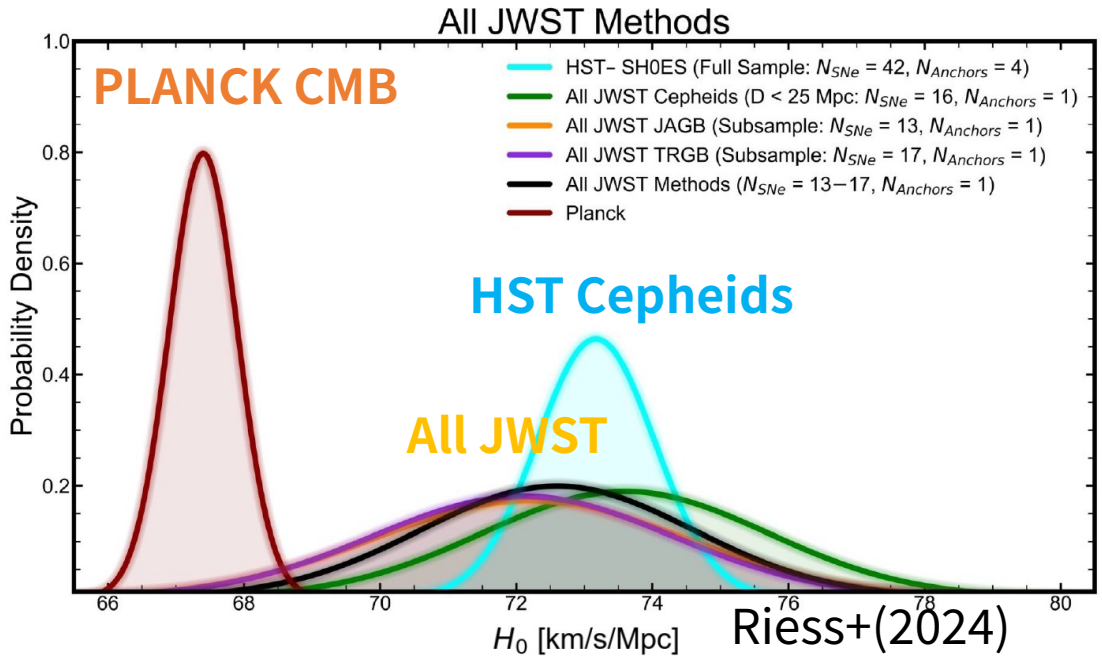
Riess+(2024)

H_0(JWST): CCHP vs SH0ES

- HST Cepheids (R22)
  - H_0=73.2 0.9 km/s/Mpc
- All JWST (SH0ES+CCHP2024 in R24)
  - H_0=72.6 2 km/s/Mpc
- All JWST (CCHP Freedman+24)
  - H_0=68.59 1.58 km/s/Mpc
  - 4 km/s/Mpc smaller than Riess+2024 value!



Freedman+(2024)



Riess+(2024)

H_0 vs time (2000-)

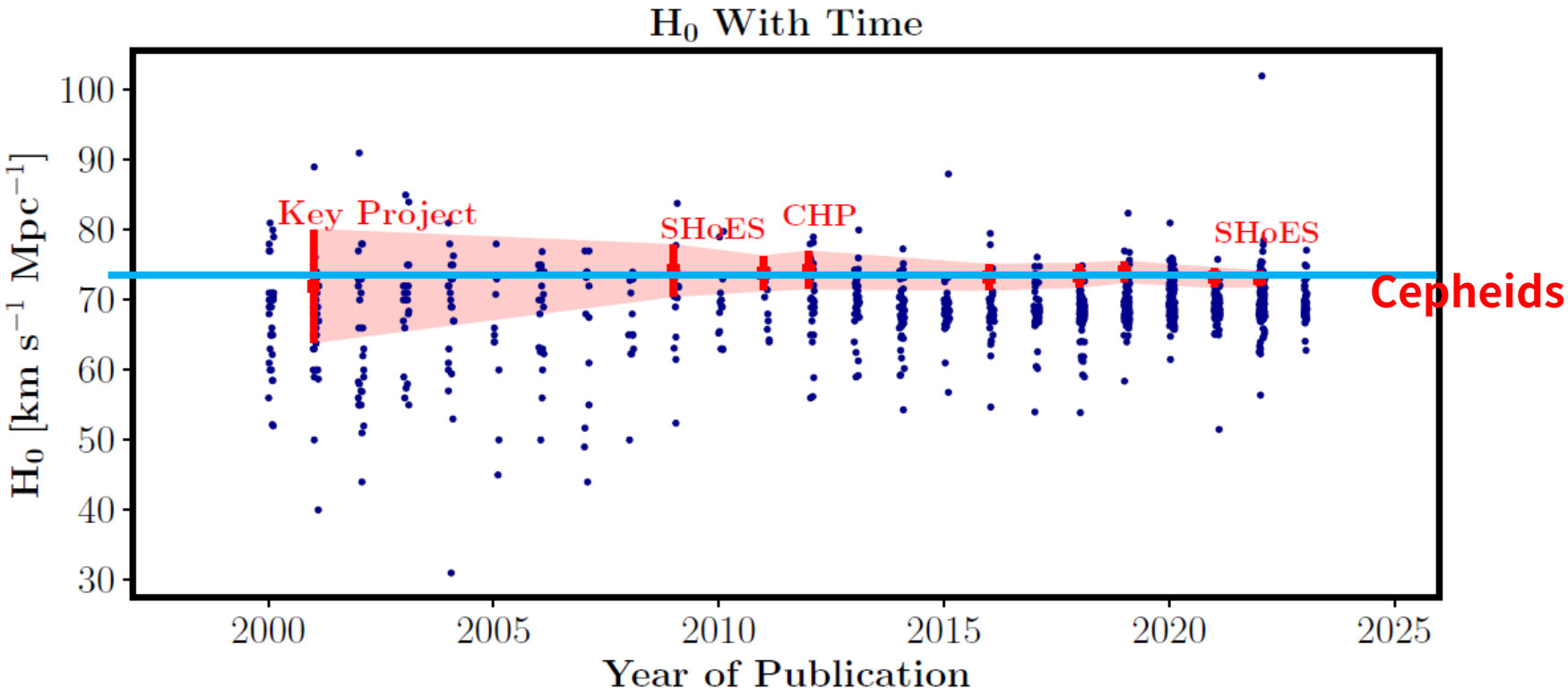
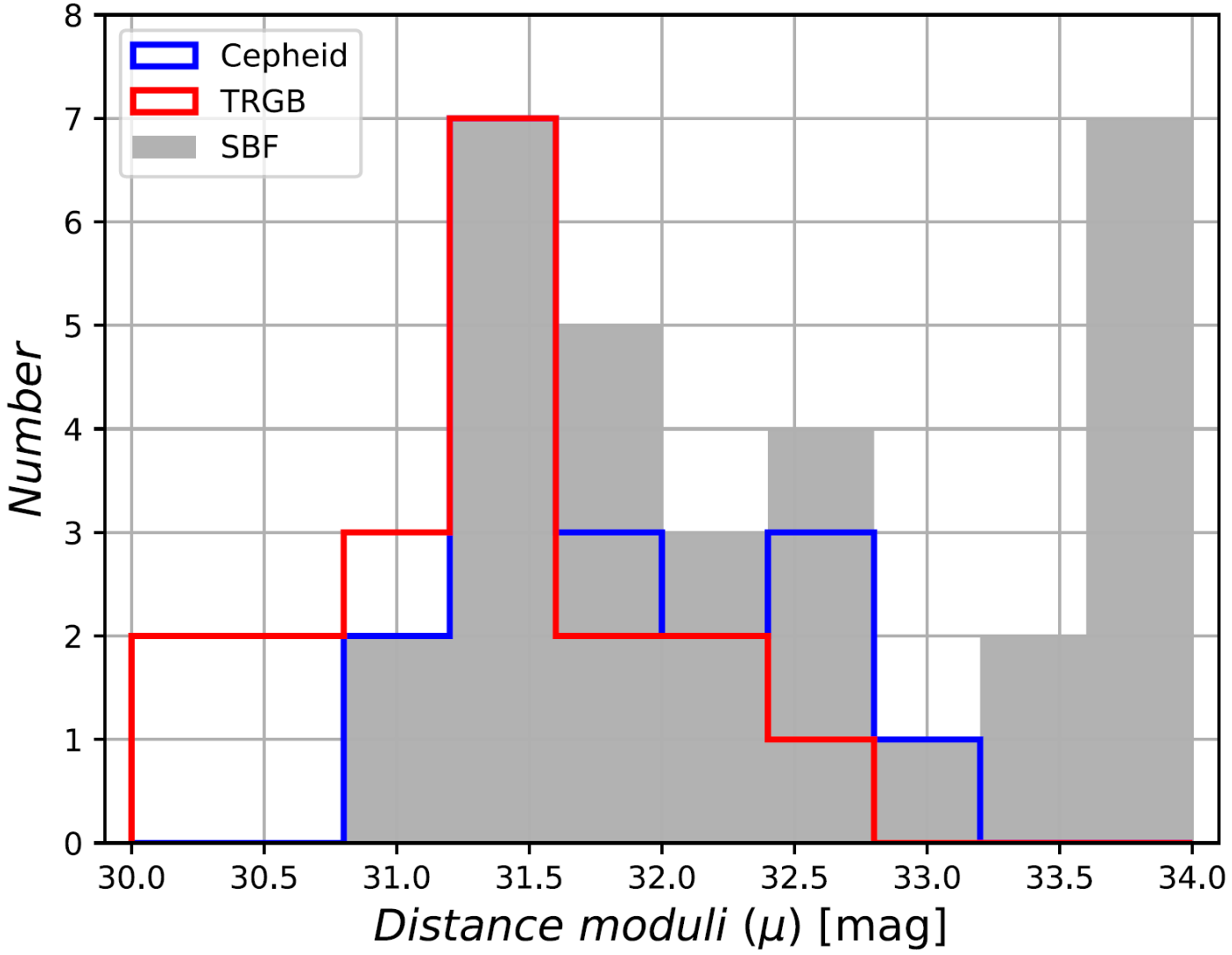


Figure 19. Individual values of H_0 (blue dots) as a function of publication date, using the compilation of Steer (2020), updated by Steer (2024, priv. comm.) shown. The larger red filled circles (with vertical error bars) are H_0 values calibrated using Cepheid distances. The light red shaded region tracks the one-sigma quoted uncertainties of the Cepheid H_0 measurements, which, as can be seen, have decreased significantly over the past 25 years.

Freedman+(2024)

SBF swing in 2024?

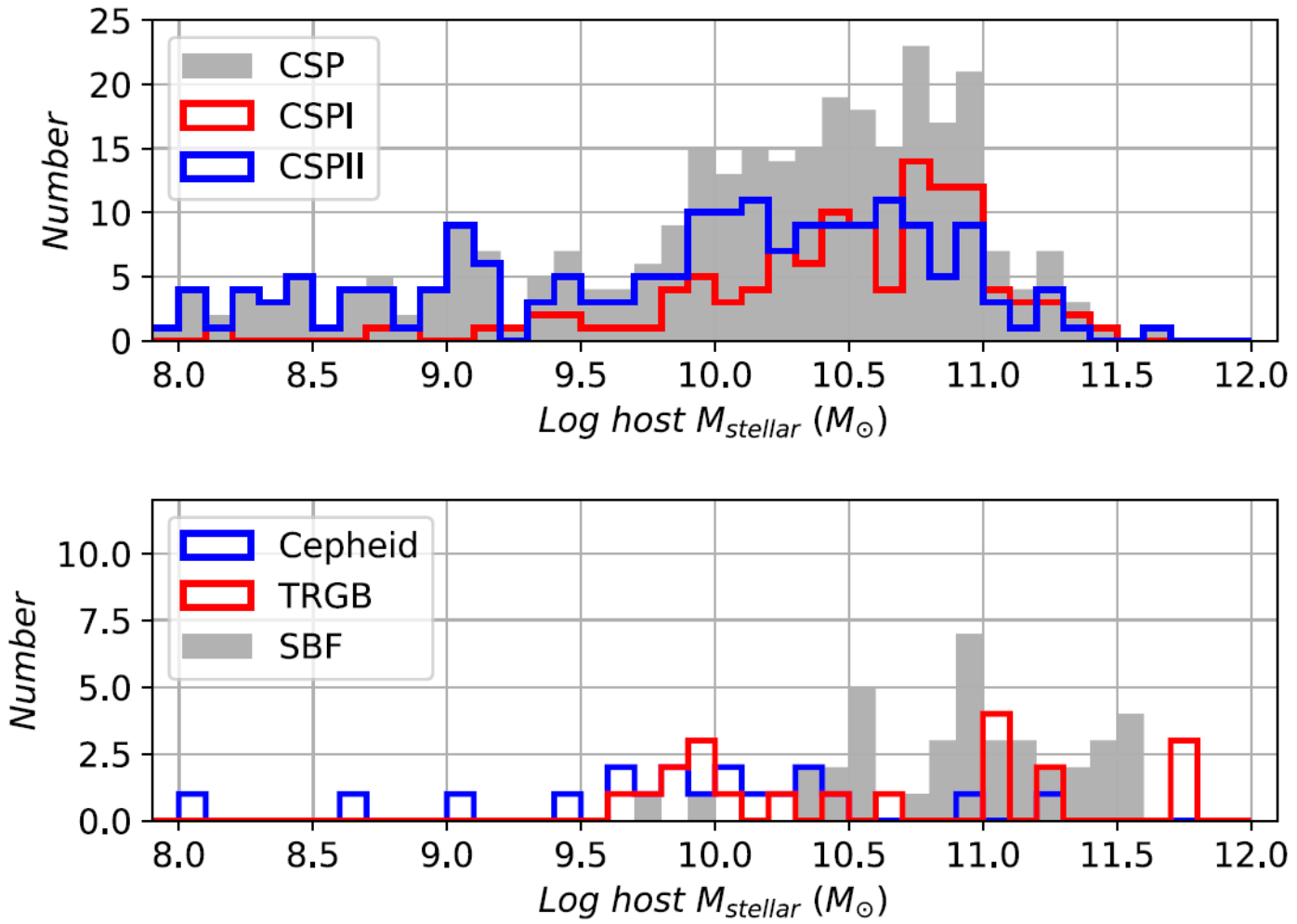
- **SBF to the CSP I,II (Uddin+2024)**
- **SBFs measure unresolved old stellar populations**
- optical to NIR
- **SBFs calibrated by TRGB.**
- **SBF distances extend to higher than Cepheids and TRGB for SN Ia calibration!**



Uddin+(2024)

Host stellar mass distribution of SN Ia

- **SN Ia host galaxy stellar mass in CSP (Uddin+2024)**
- **Distances: Cepheid (Riess+2022), TRGB (Freedman+2019), and SBF (Jensen+2021, Khetan+2021)**
- **SBF galaxies are mostly massive early-type galaxies, while TRGB galaxies show a larger range of mass!**



Uddin+(2024)

Comparison of TRGB, Cepheids, and SBF

- Comparison of H_0

Table 1

Recent H_0 Measurements with Statistical Uncertainties

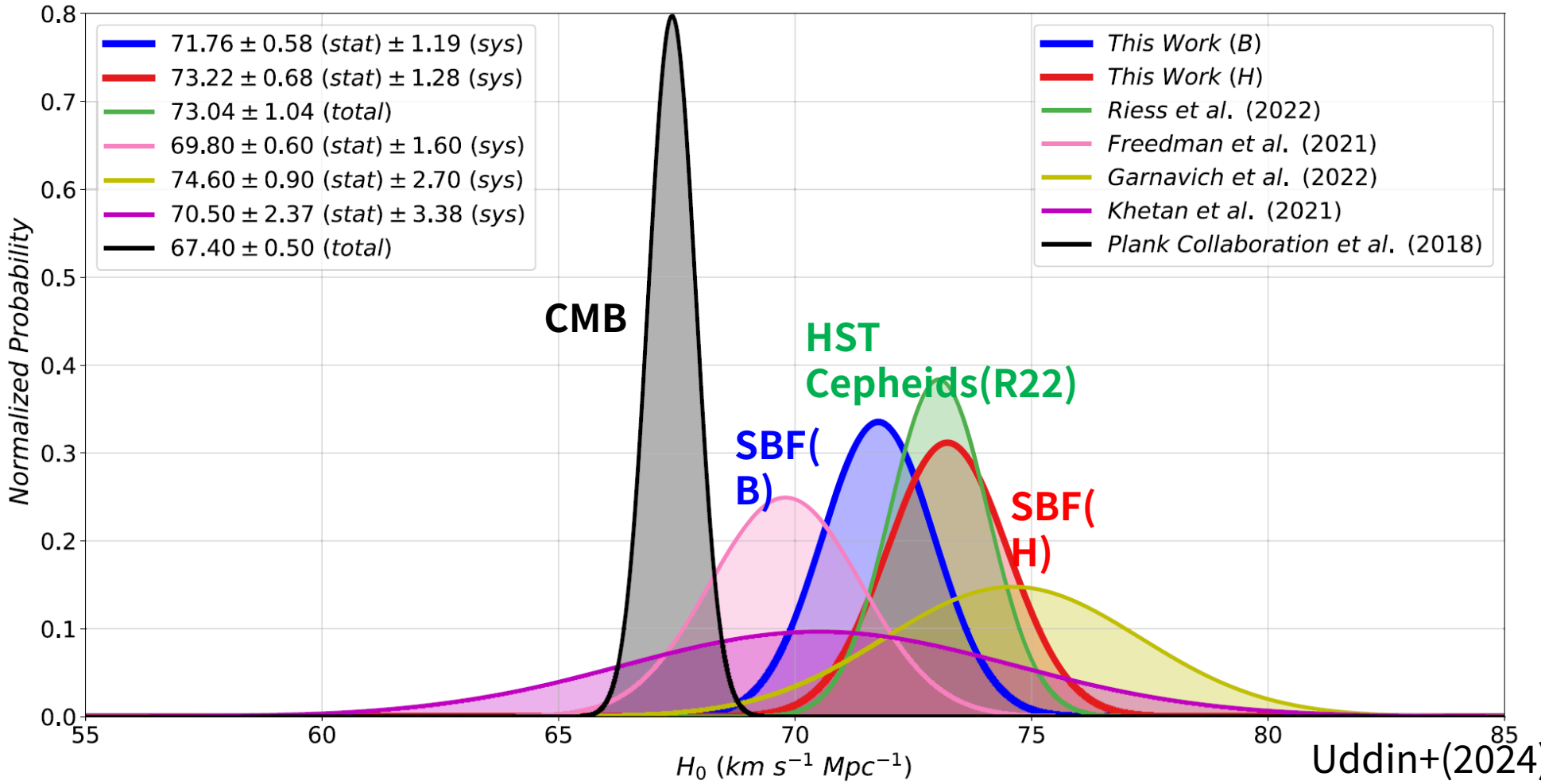
Method	Calibration	H_0 (km s^{-1} Mpc^{-1})	Reference
SN Ia	Cepheid	73.04 ± 1.01	Riess et al. (2022)
SN Ia	TRGB	69.80 ± 0.60	Freedman (2021)
SN Ia	Cepheid	72.70 ± 1.60	Burns et al. (2018)
SN Ia	SBF	70.50 ± 2.40	Khetan et al. (2021)
SN Ia	SBF	74.60 ± 0.90	Garnavich et al. (2022)
SBF	Cepheid	73.30 ± 0.70	Blakeslee et al. (2021)
SN Ia	BAO+CMB	67.80 ± 1.20	Macaulay et al. (2019)
CMB	⋯	67.40 ± 0.50	Planck Collaboration et al. (2018)

Note. Systematic uncertainty in the Cepheid calibration has the least value of 1.04 km s^{-1} Mpc^{-1}, while for TRGB- and SBF-based calibrations, it ranges between 1.6 and 3.4 km s^{-1} Mpc^{-1}.

Uddin+(2024)

SBF swing?

- Combining Cepheids, TRGB, and SBF calibration: systematic errors(H_0): ~1.3 km/s, larger than err(Cep) and err(TRGB)
- **Note the difference between SBF(B) & SBF(H): H_0(H)~ H_0(B)+1.46!**



Uddin+(2024)

Hubble Tension or Distance Ladder Crisis?

- A review of last 4 years results by Perivolaropoulos (2024.Sep)
- One-step measurements are consistent with CMB/BAO values, while distance ladder measurements are not,".

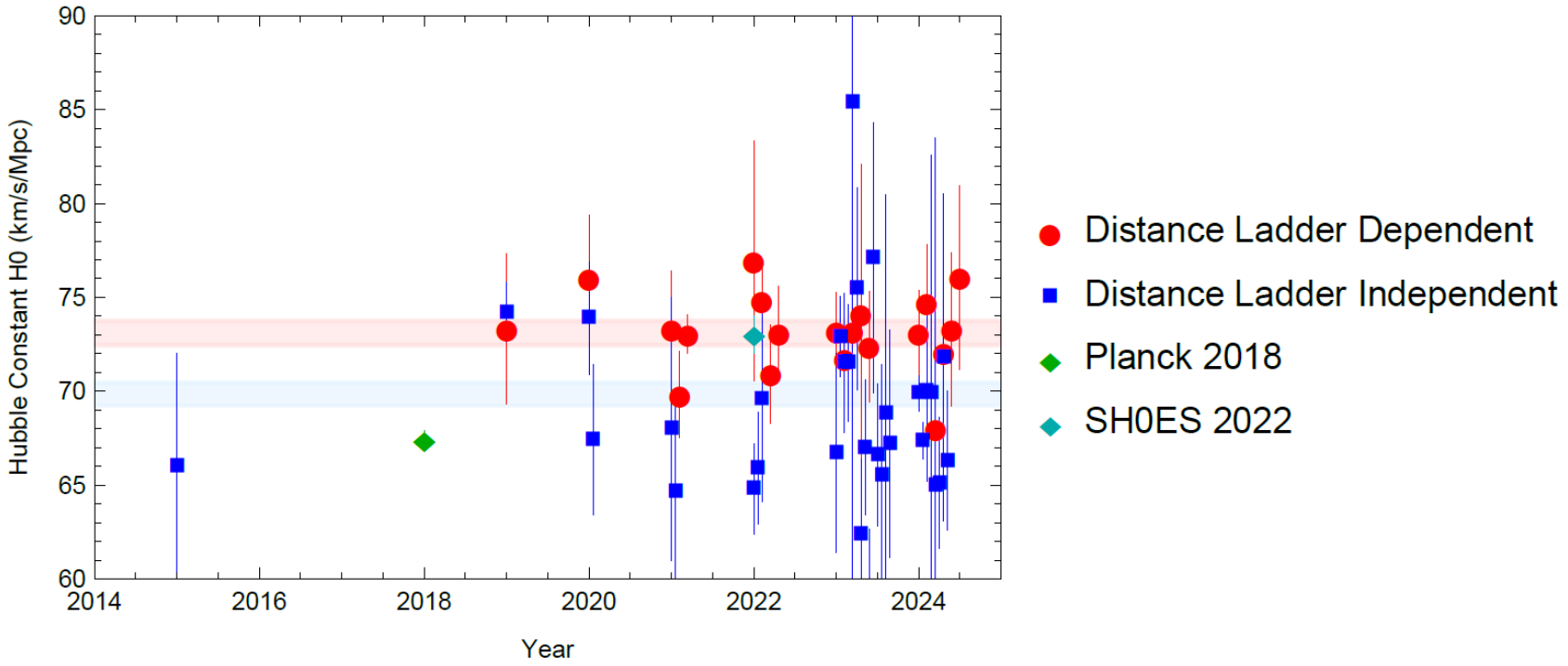
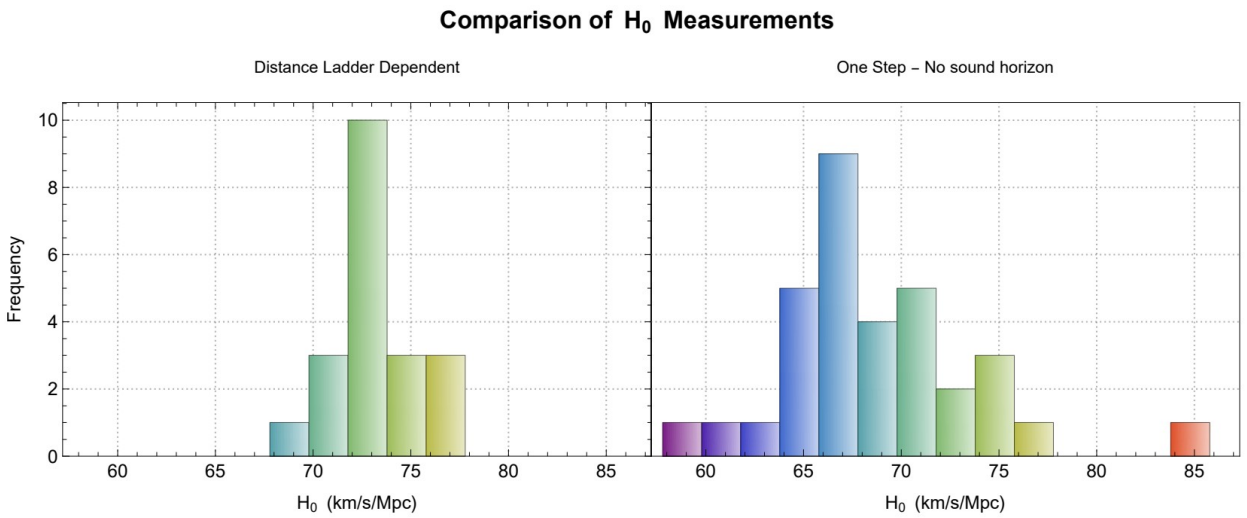


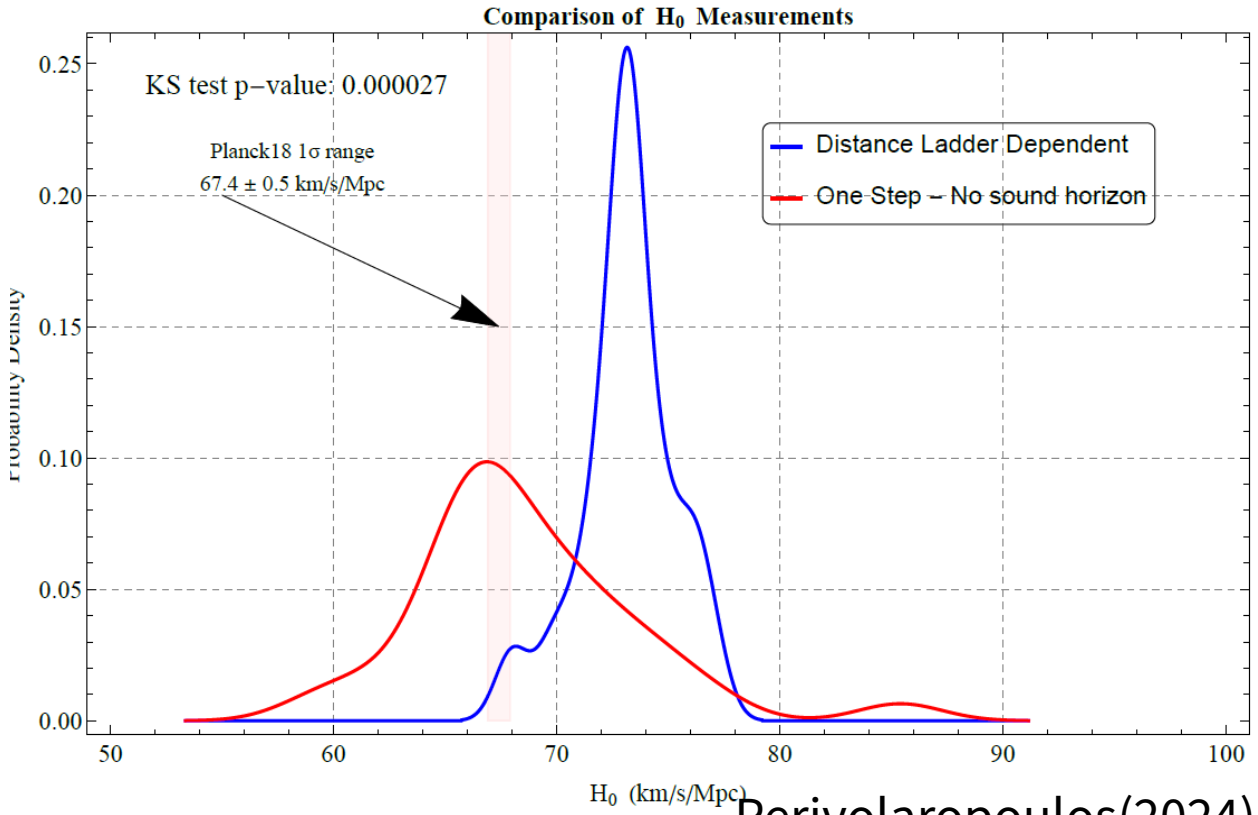
FIG. 1: The measurements of H_0 shown in Tables I (distance ladder dependent-red points) and II (one step distance ladder and sound horizon independent-blue points). The most precise distance ladder dependent measurement (SH0ES 2022[15]) and the most precise sound horizon dependent Planck 18[14] measurements are also shown as green points. The light red and light blue bands denote the combined constraints for distance ladder dependent and one step measurements respectively.

Perivolaropoulos(2024)

Hubble tension or Distance Ladder Crisis?

- Perivolaropoulos(2024) concludes that **“ The core of the Hubble tension lies between distance ladder measurements and all other H_0 determinations”.**
- **However, it is based only on statistics.**





Perivolaropoulos(2024)

Summary

- There is **6σ-level Hubble tension** between Planck CMB (2018) and SH0ES HST Cepheid-SN Ia (2022, 2024).
- There is **little Hubble tension among CMB, DESI BAO, and TRGB-SN Ia.**
- There is **little Hubble tension between TRGB-SN Ia and SH0ES Cepheid-SN Ia.**
- Other distance measurements show a significant scatter, requiring improvements.
- JAGB becomes a promising candle in the JWST era.
- We need more JWST galaxies with SN Ia, checking the full HST Cepheid sample.

Thank You!