The Hubble Tension: New Results from JWST

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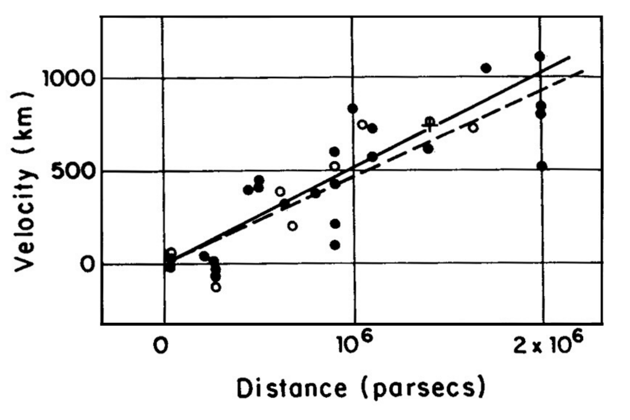
University of Chicago

June 18, 2024
Lemaître Conference 2024
Vatican Observatory

Georges Lemaître

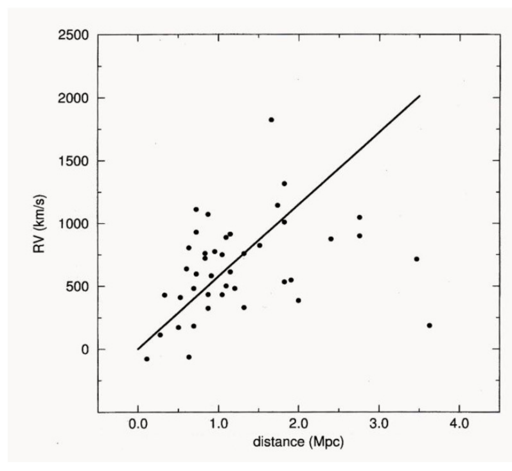
First to make a connection between observations and theory of the expanding universe (Lemaître 1927).



Hubble (1929)

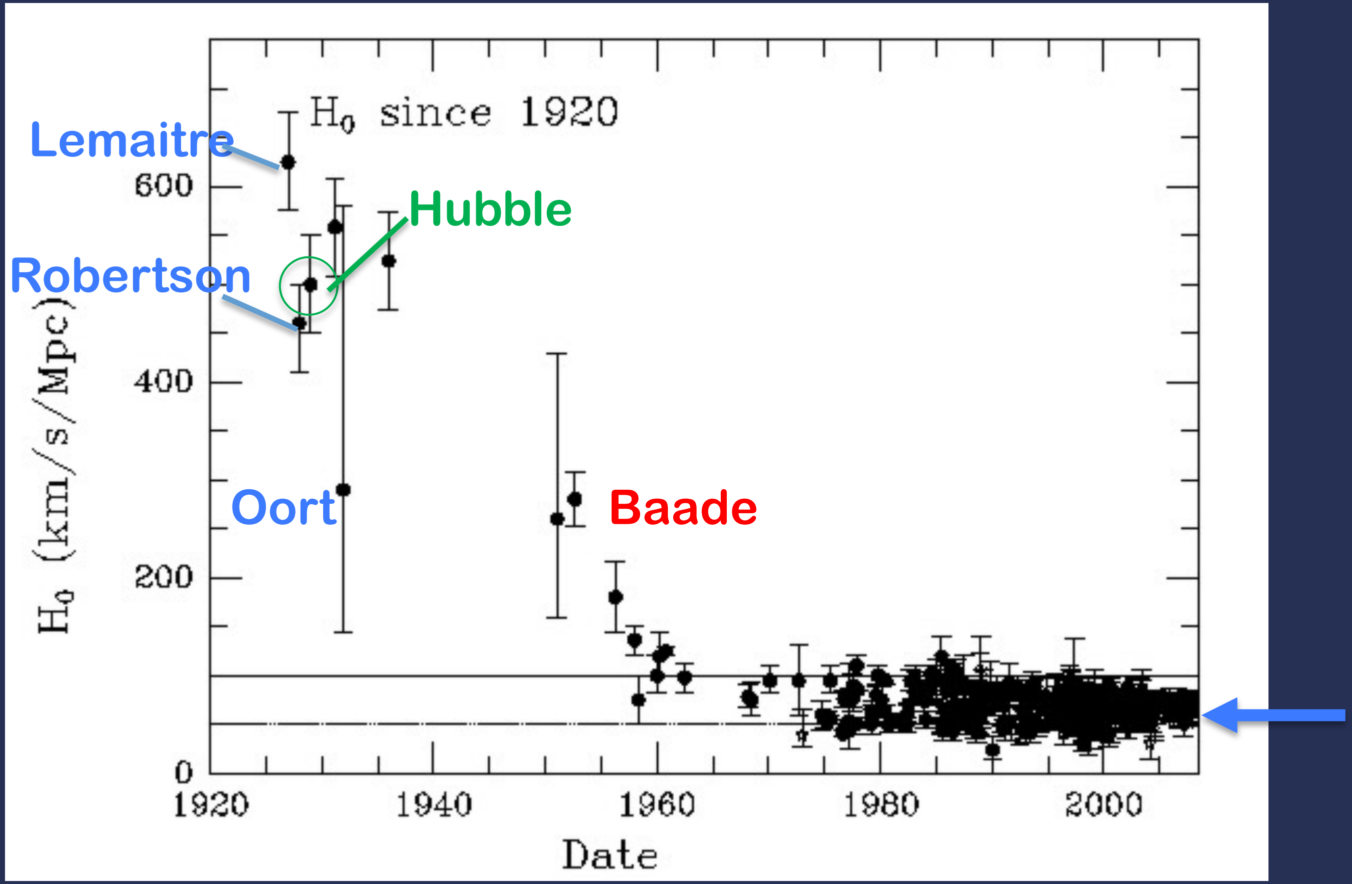
H_0 = 500 km s^{-1} Mpc^{-1}

Hubble-Lemaître law

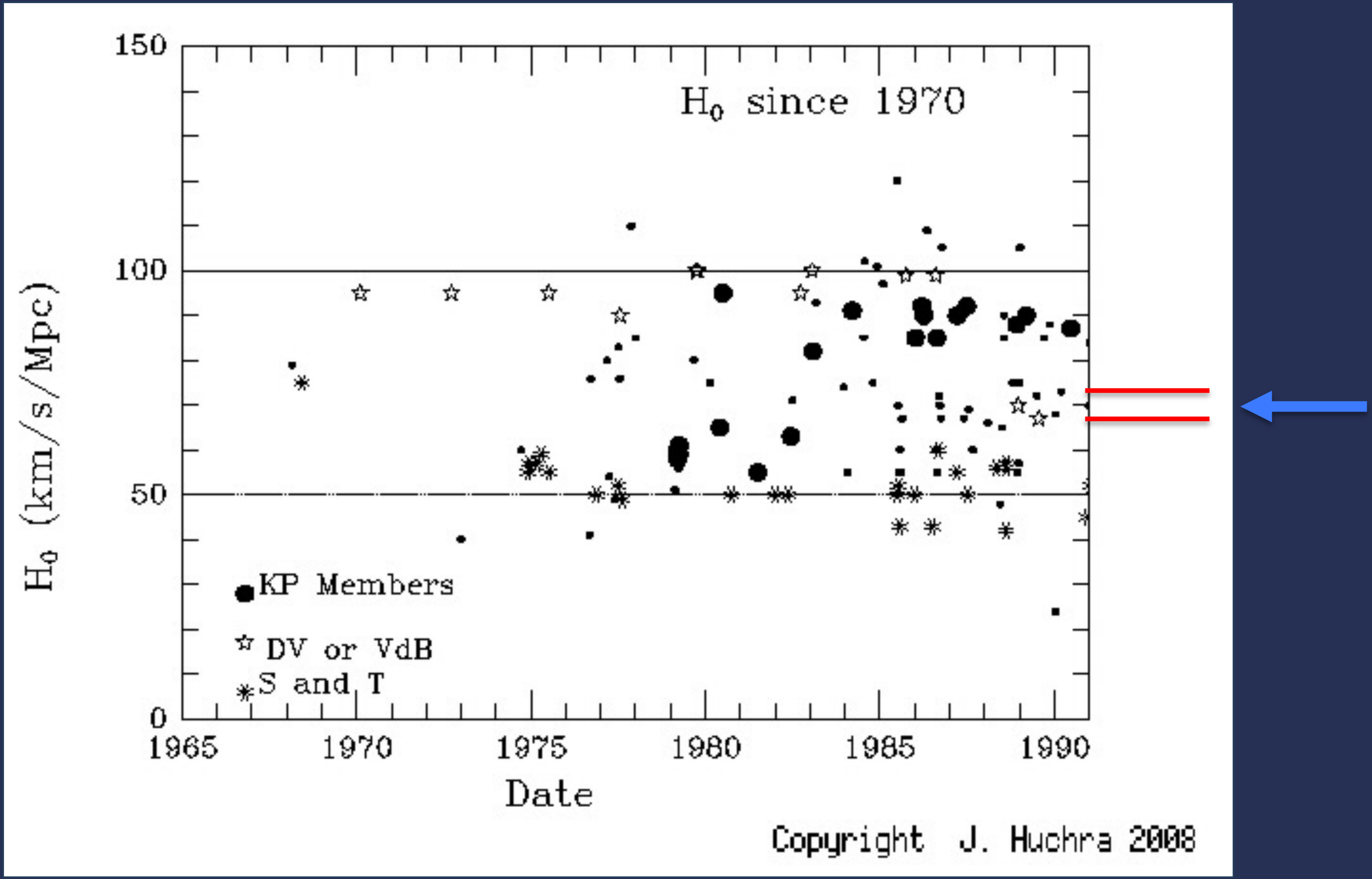


H_0 = 625 km s^{-1} Mpc^{-1}
Credit H. Duerbeck

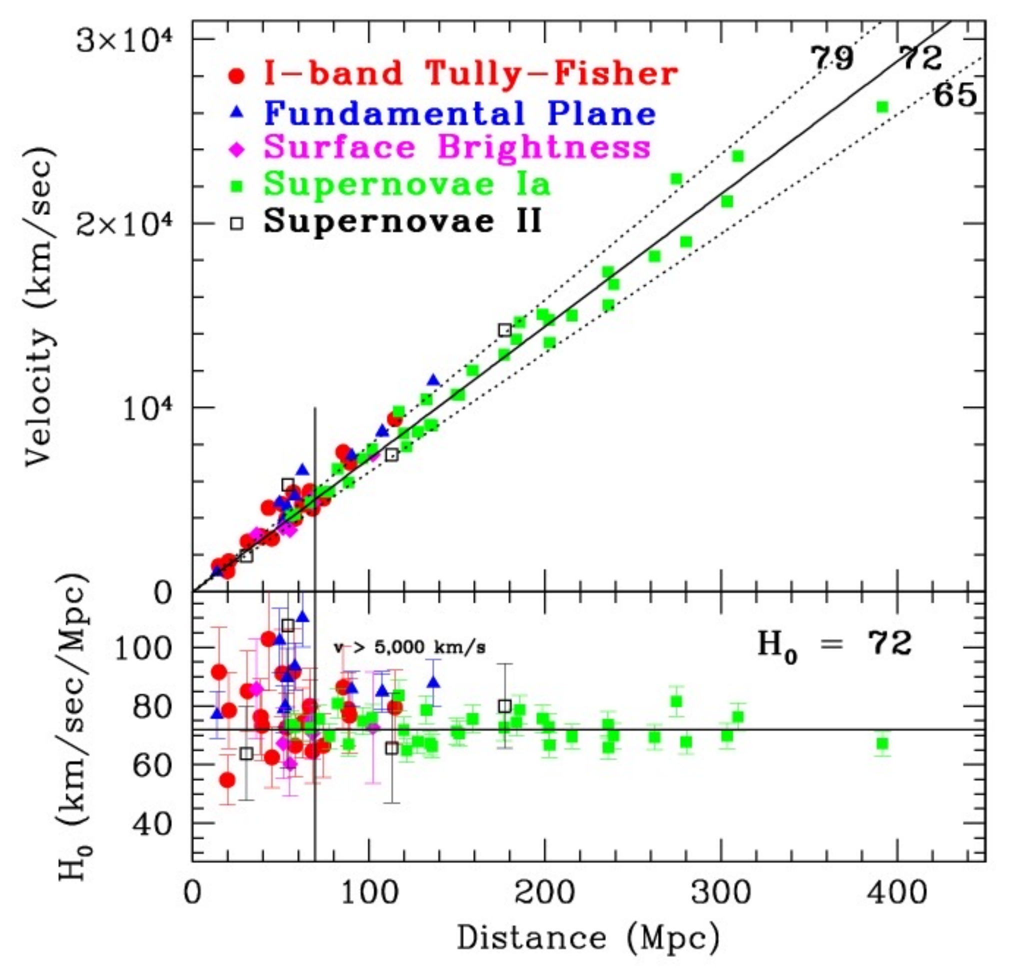
History of H_0 Measurements



History of H_0 Measurements



Final HST Key Project Combined Results

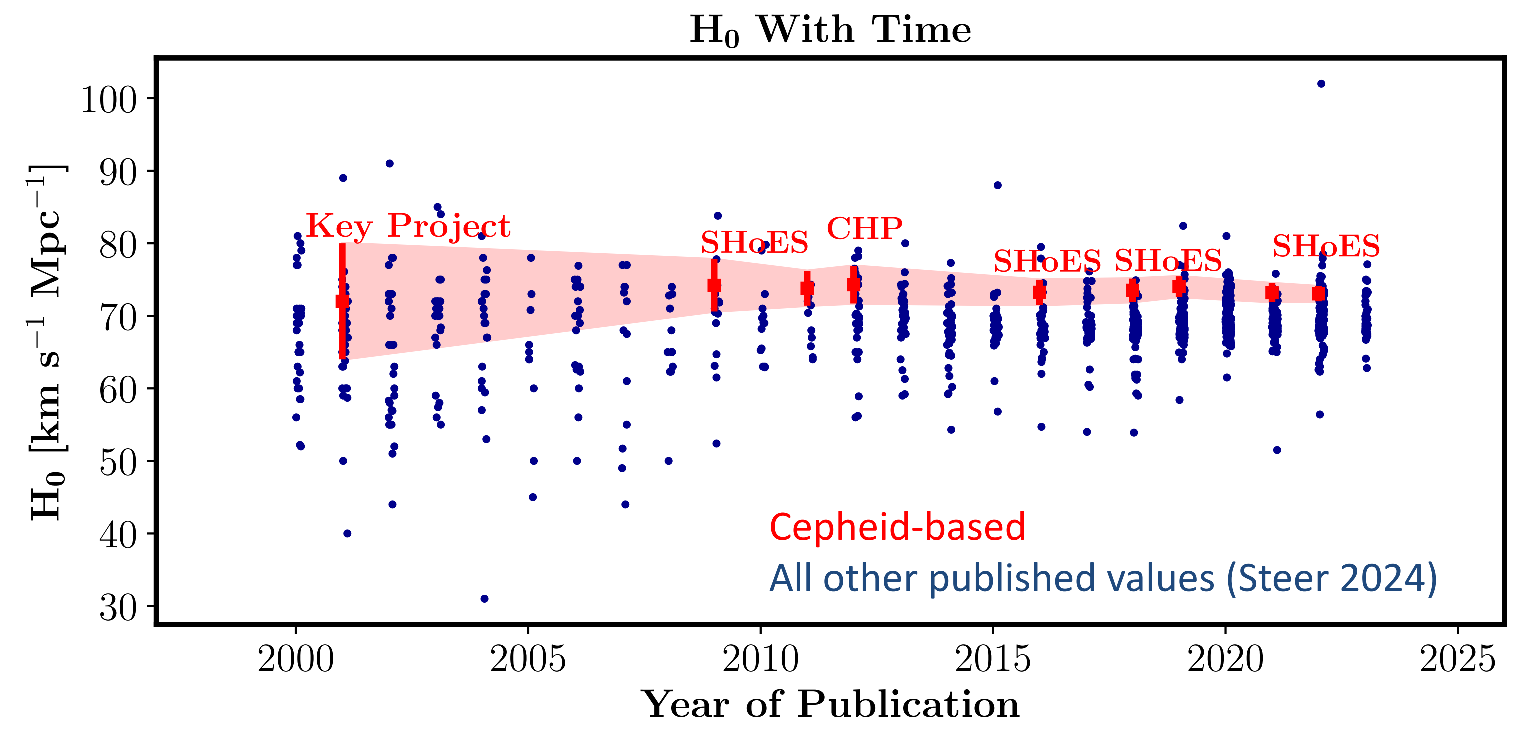


HST Key Project resolved "factor of two" debate

$H_0 = 72 \pm 3$ (stat.) $\pm$ 7 (sys.) km/sec/Mpc

Freedman et al. 2001

Recent Measurements of the Hubble Constant



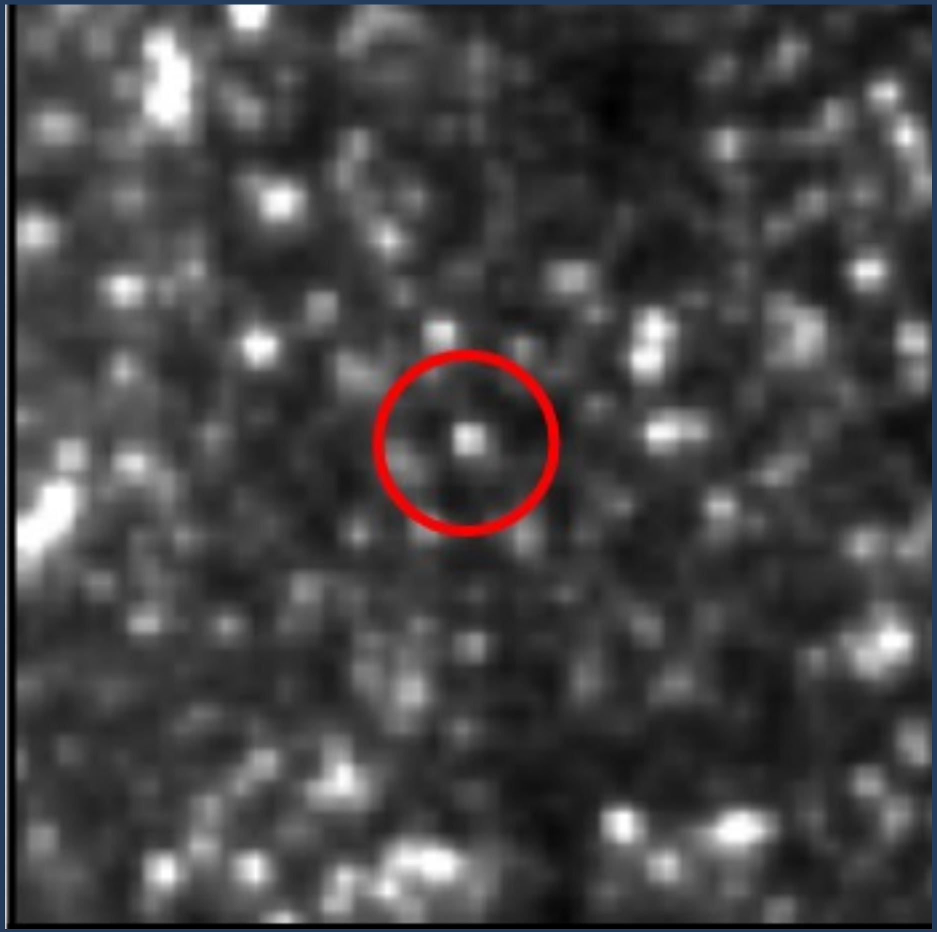
The Route to Higher Accuracy in H_0

What are the challenges in measuring an accurate local value of H_0?

HST Near-IR Data

Cepheid in
NGC 7250 at a
distance of 20 Mpc.

New JWST Near-IR Data



Cepheid in
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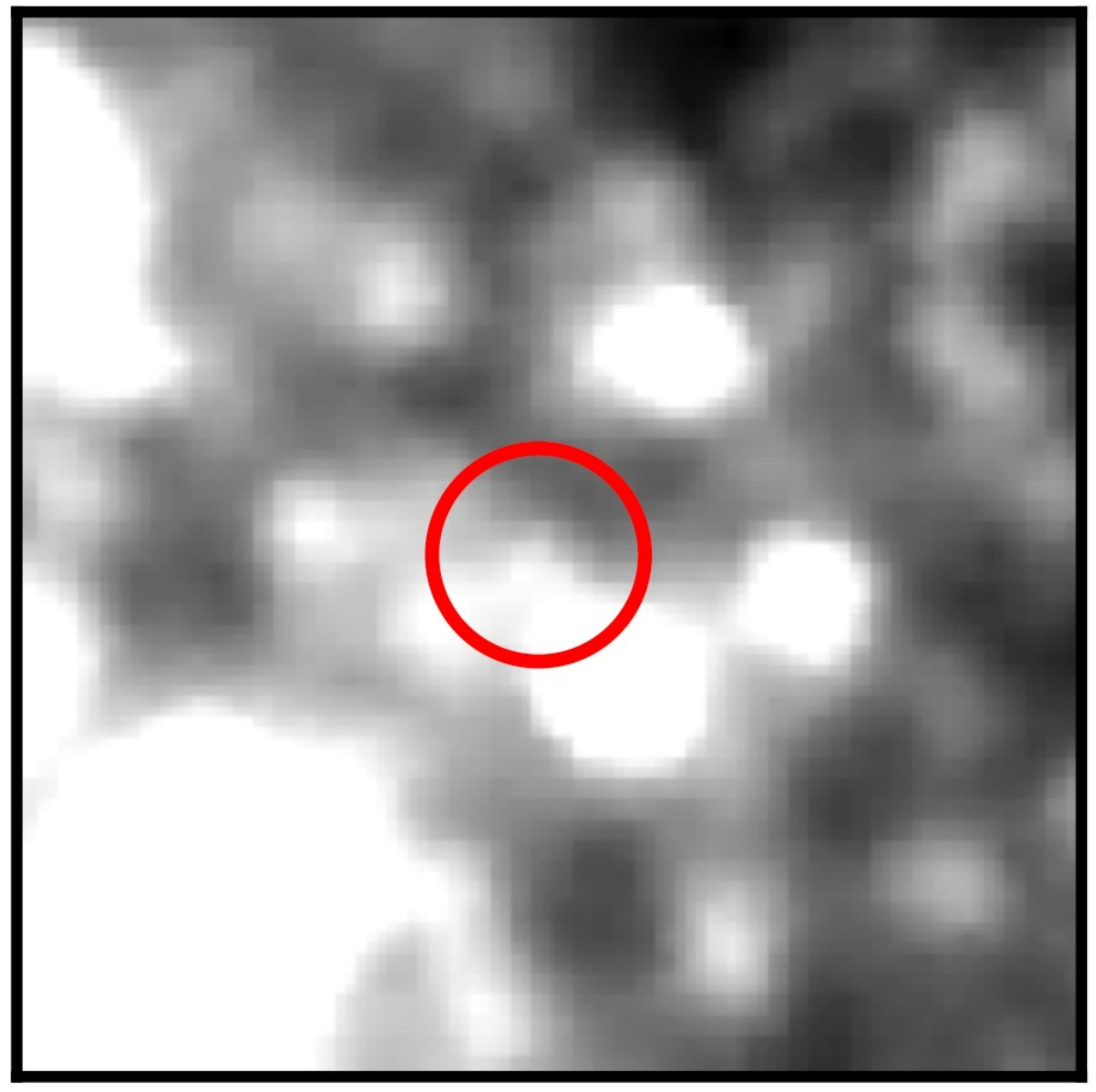
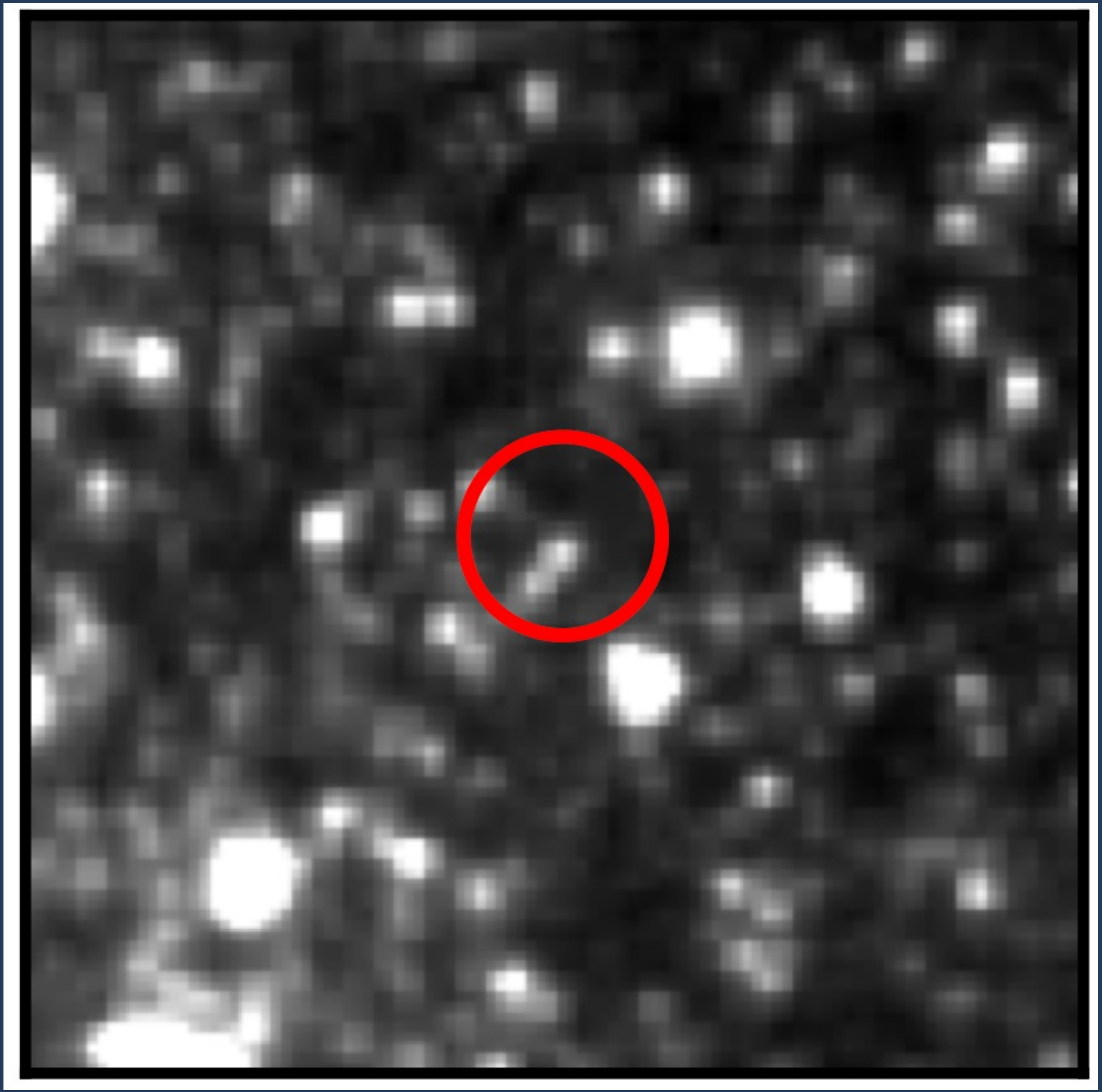
HST



HST: SNR 1-23
JWST : SNR 35-120

JWST



HST: SNR 1-23
JWST : SNR 35-120

New JWST Results To Date

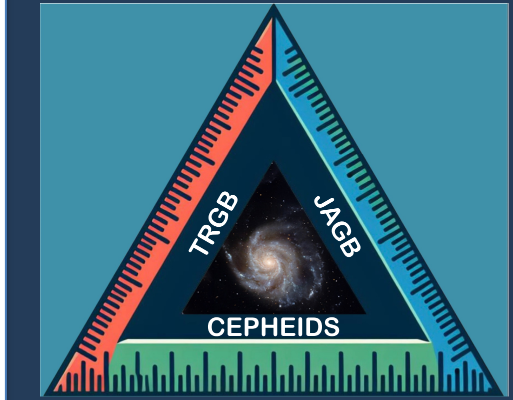
- Tip of the Red Giant Branch (TRGB) -- JWST alone
- JAGB / Carbon stars -- JWST alone
- Cepheid PL-Color-Metallicity Relation -- JWST + HST

- L2 orbit
- 1.5 x 10^6 km from Earth
- 6.5 meter primary mirror
- Infrared optimized
- 18 gold-coated beryllium segments

James Webb Space Telescope

The CCHP JWST Program

- JWST has
    - almost 10x the sensitivity of HST at NIR wavelengths
    - >3x the resolution.
- Program: measure distances using three independent methods applied to the same SNIa host galaxies
- BLIND analysis



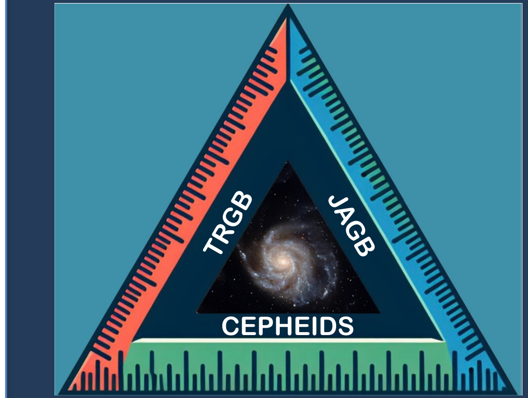
Our Blinding Procedure

- Random numbers applied to each of our photometry catalogs

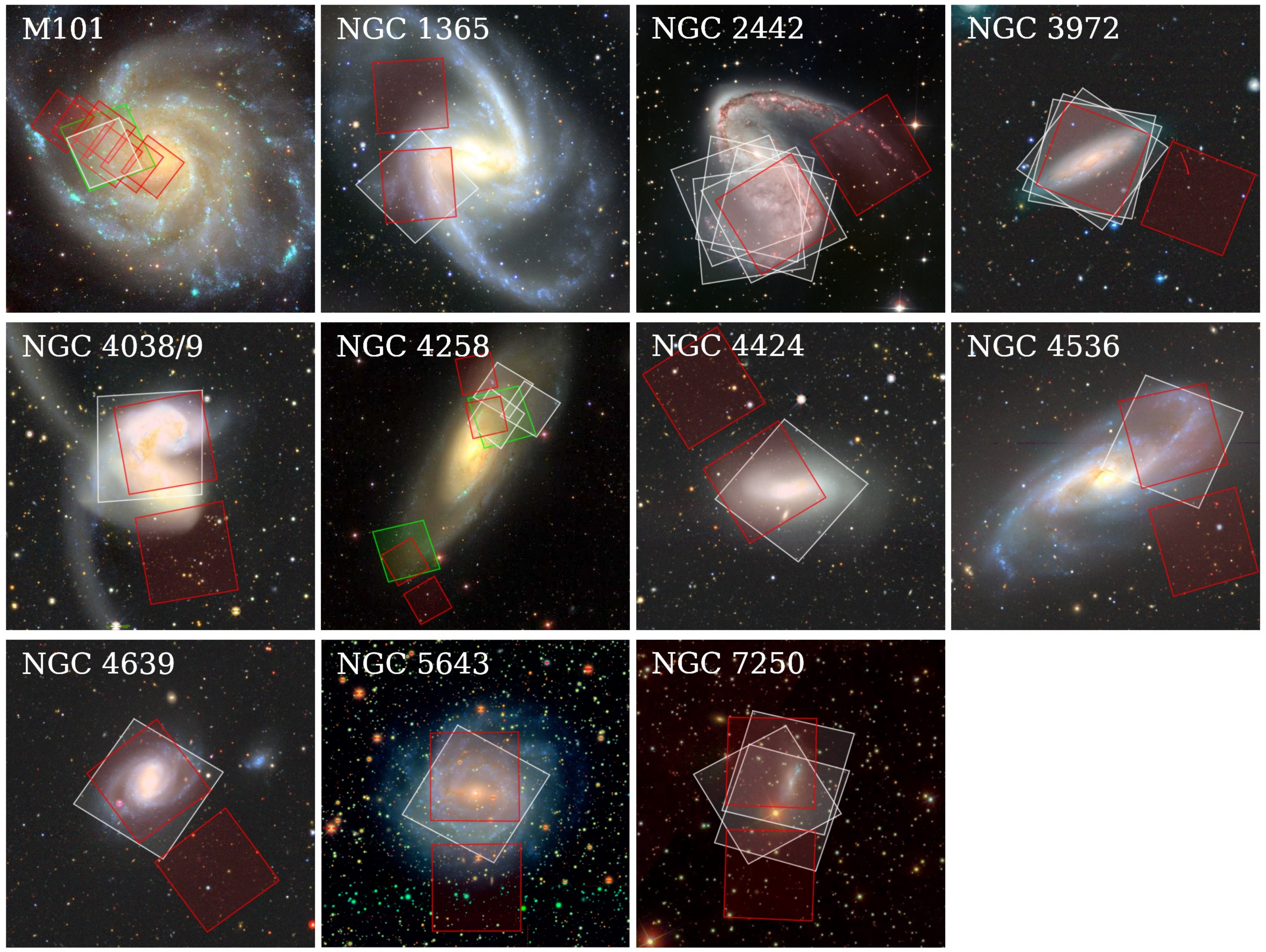
- All analysis carried out with arbitrary zero points and no knowledge of distances or H_0

  (PL relations for Cepheids; Luminosity functions for TRGB and JAGB; artificial star tests)

- Only once all of the analysis complete were the data unblinded



The CCHP JWST Program



CCHP JWST Program

Three Independent Methods in the Same SN Ia Galaxies

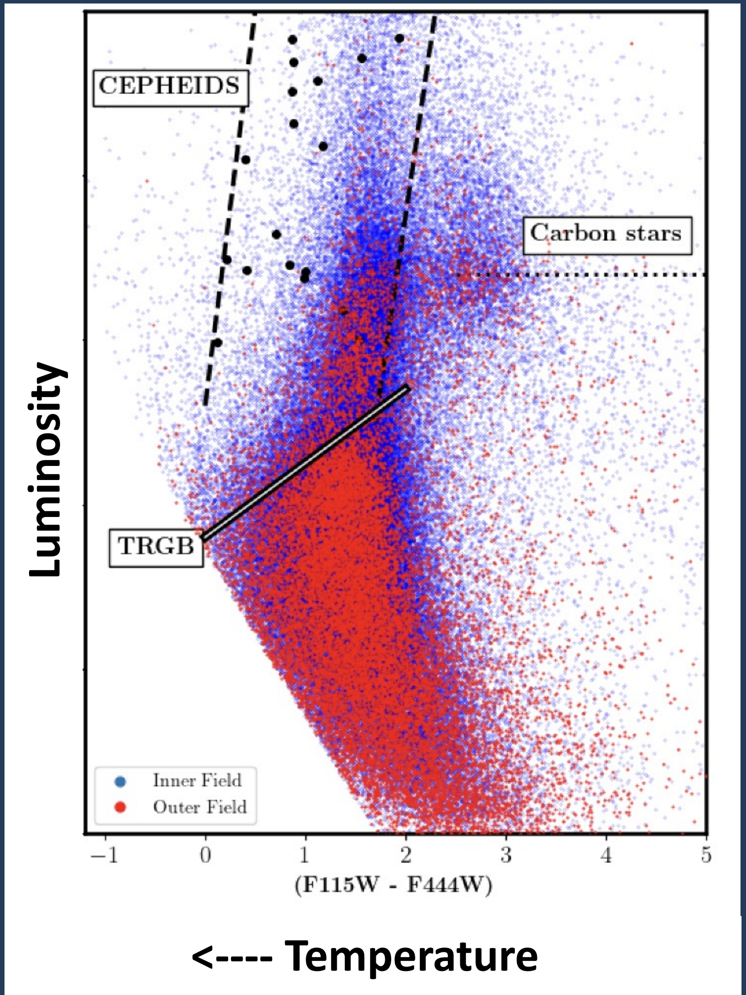
1. Tip of the Red Giant Branch (TRGB)
2. JAGB/carbon stars
3. Cepheids

a. Independent techniques

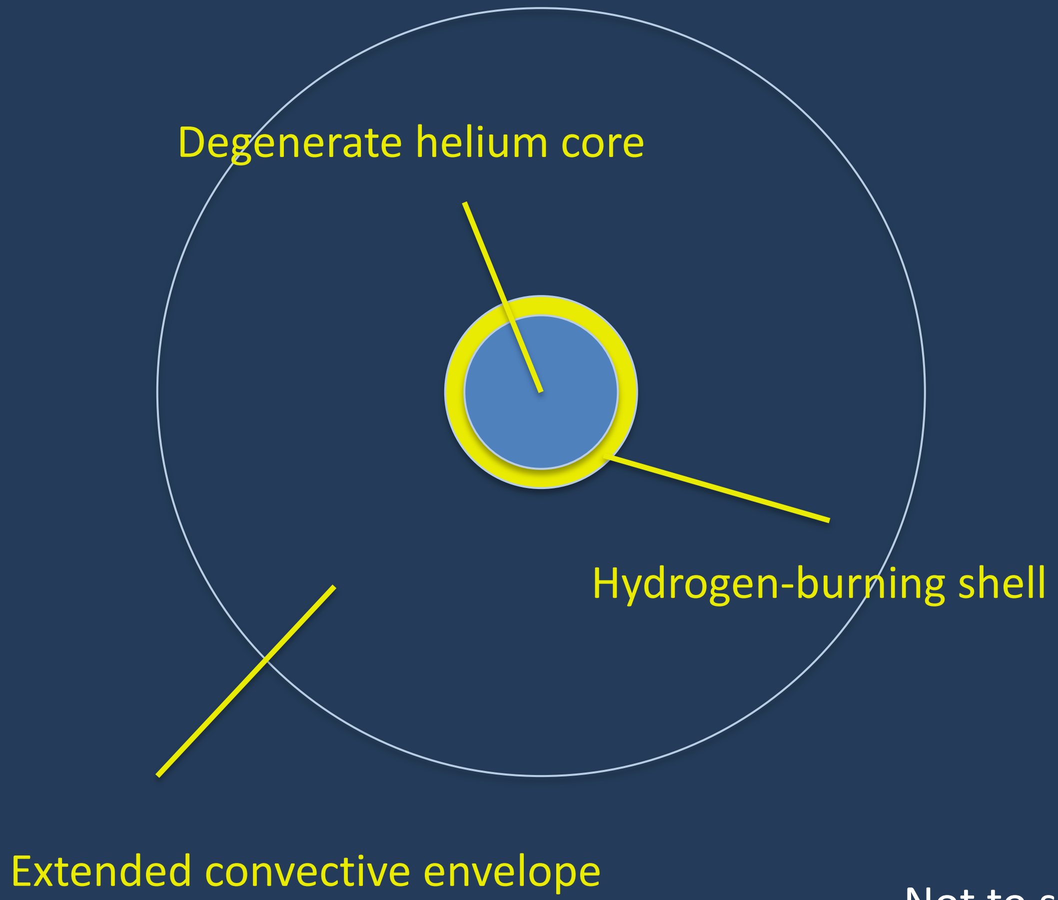
b. Different environments - crowding, dust, chemistry

c. Different evolutionary stages (masses)

d. Advantage of same detectors, filters, PSFs, software, absolute calibration



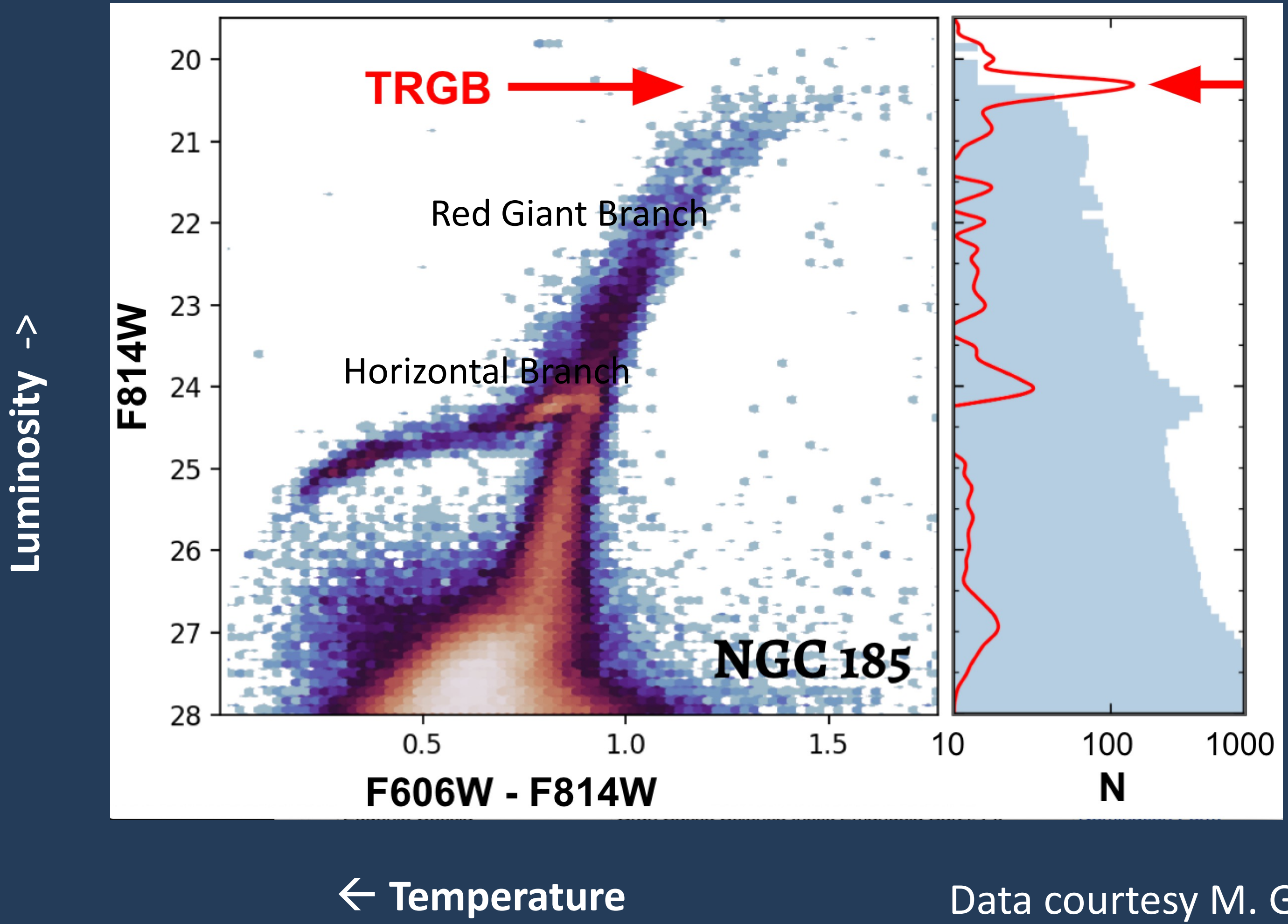
Method 1. Lifting the Degeneracy in the Helium Core for Low-mass Stars (TRGB)



Not to scale

- Well-understood nuclear physics determines the temperature at which the electron degeneracy in the core is lifted, followed by helium core ignition
- $T_c \sim 10^8$ K, $M_c = 0.47\ M_\odot$
- Because of the degeneracy, the helium ignition happens at almost constant core mass. Thus the ignition occurs at a predictable luminosity.

Observing the TRGB



Data courtesy M. Geha,
Plot by I. Jang

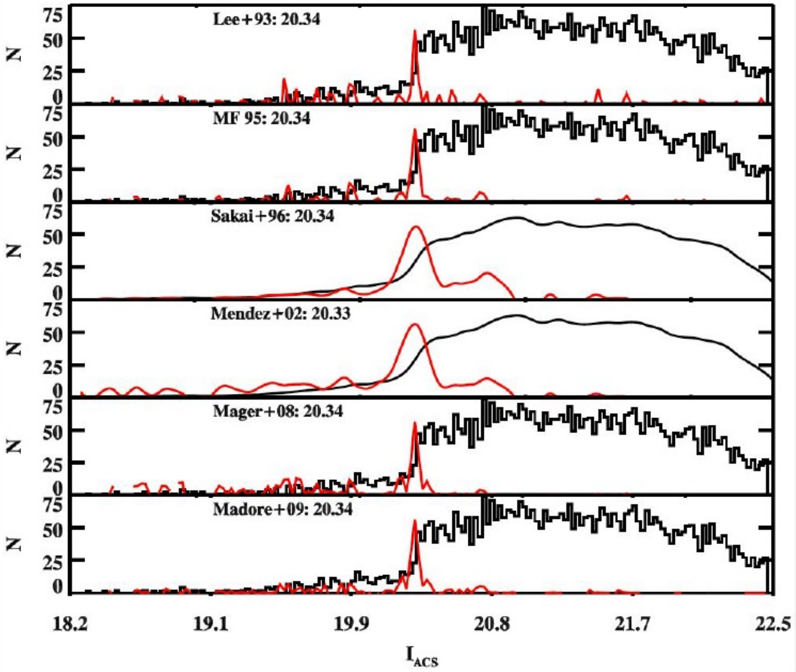
Measuring the TRGB

Two approaches

Sobel kernels

- e.g., [-1, 0, 1] (Lee+93)

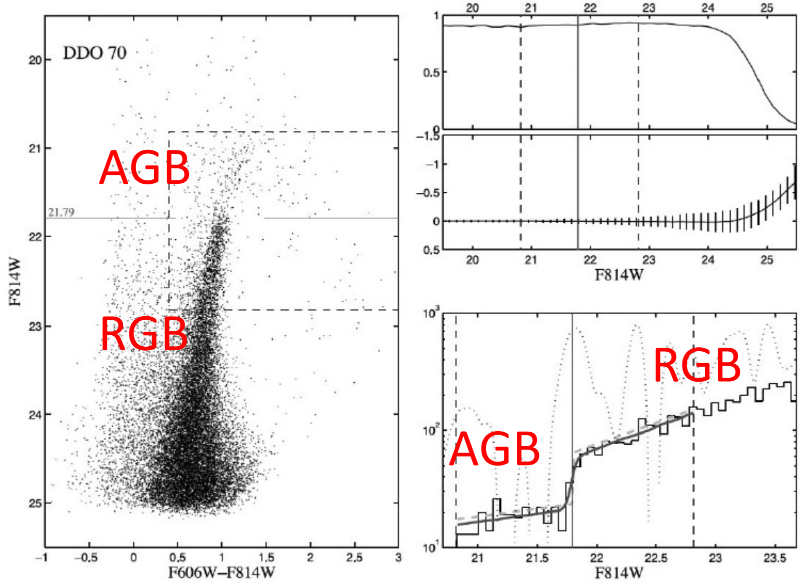
IC 1613 (Hatt+17)



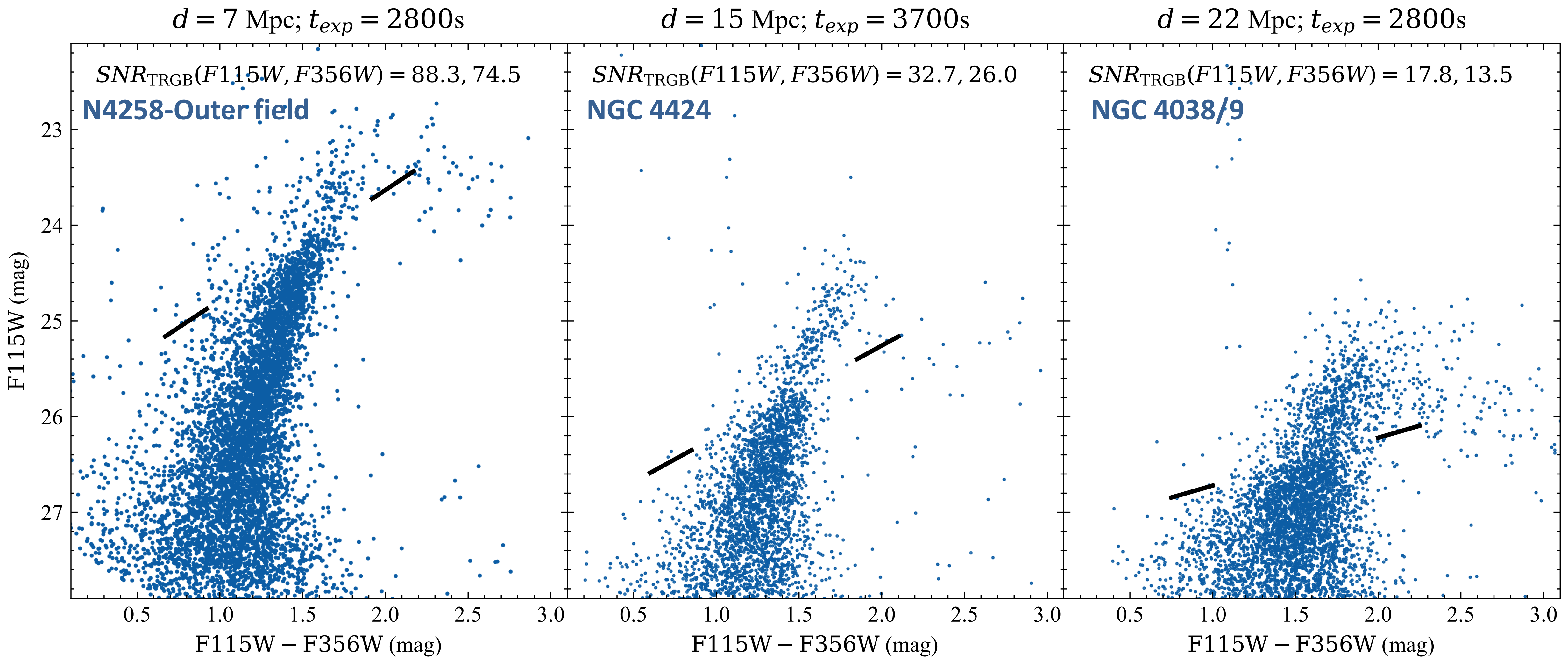
Maximum likelihood

$$\mathcal{L} = -\sum_{i=1}^{N} \ln \varphi(m_i|\boldsymbol{x}) + N \ln \int_{m_{\min}}^{m_{\max}} \varphi(m|\boldsymbol{x})\, dm.$$

(Mendez+02, Makarov+06)

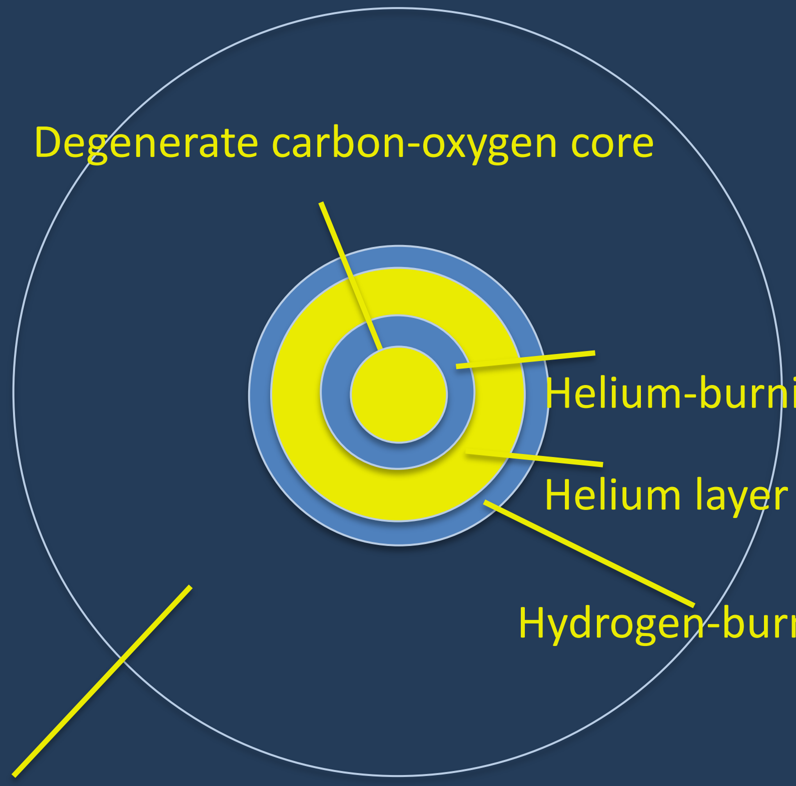


TRGB Results from JWST



Hoyt et al., in prep.

Method 2. Carbon/J-band Asymptotic Giant Branch (JAGB) Stars



Degenerate carbon-oxygen core

Helium-burning shell

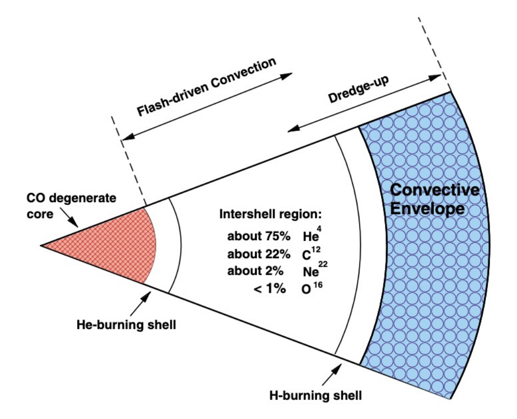
Helium layer

Hydrogen-burning shell

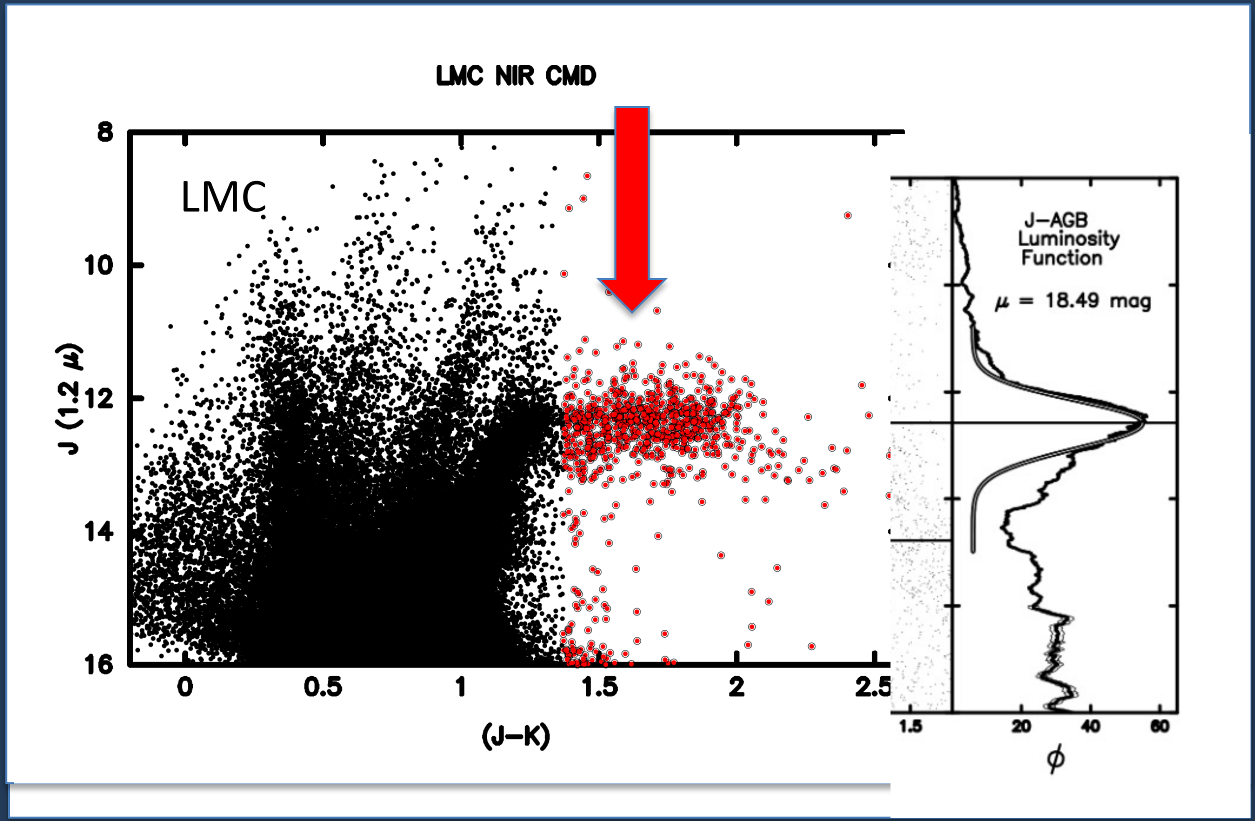
Convective envelope

Not to scale

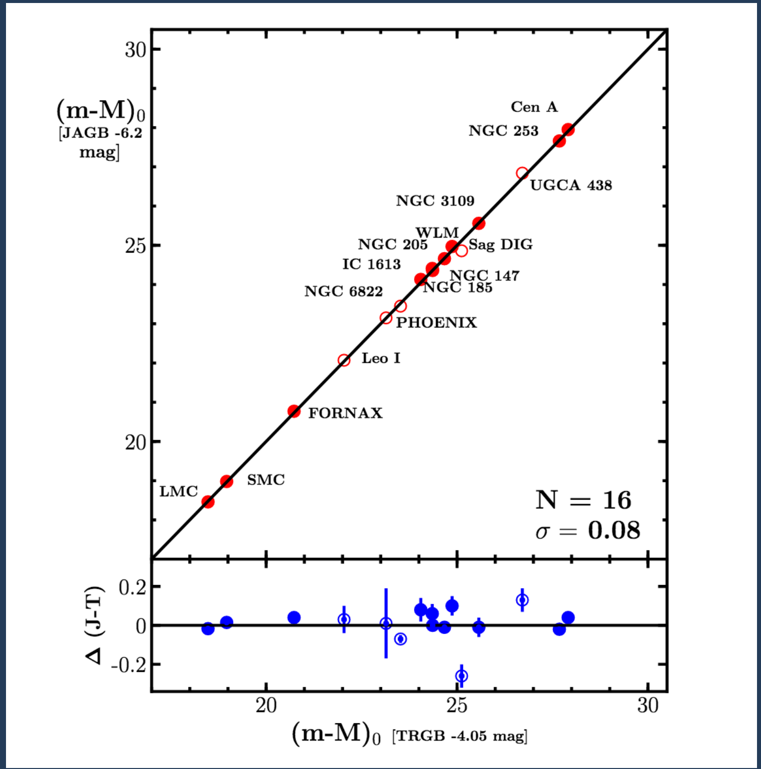
- Class of luminous red carbon AGB stars
- Small intrinsic dispersion in near-IR (0.2 mag)
- Carbon mixed up to surface (why appear red)
  - For massive stars carbon is burned before it reaches the surface
  - For lower masses, the carbon never reaches the surface



JAGB (Carbon) Stars

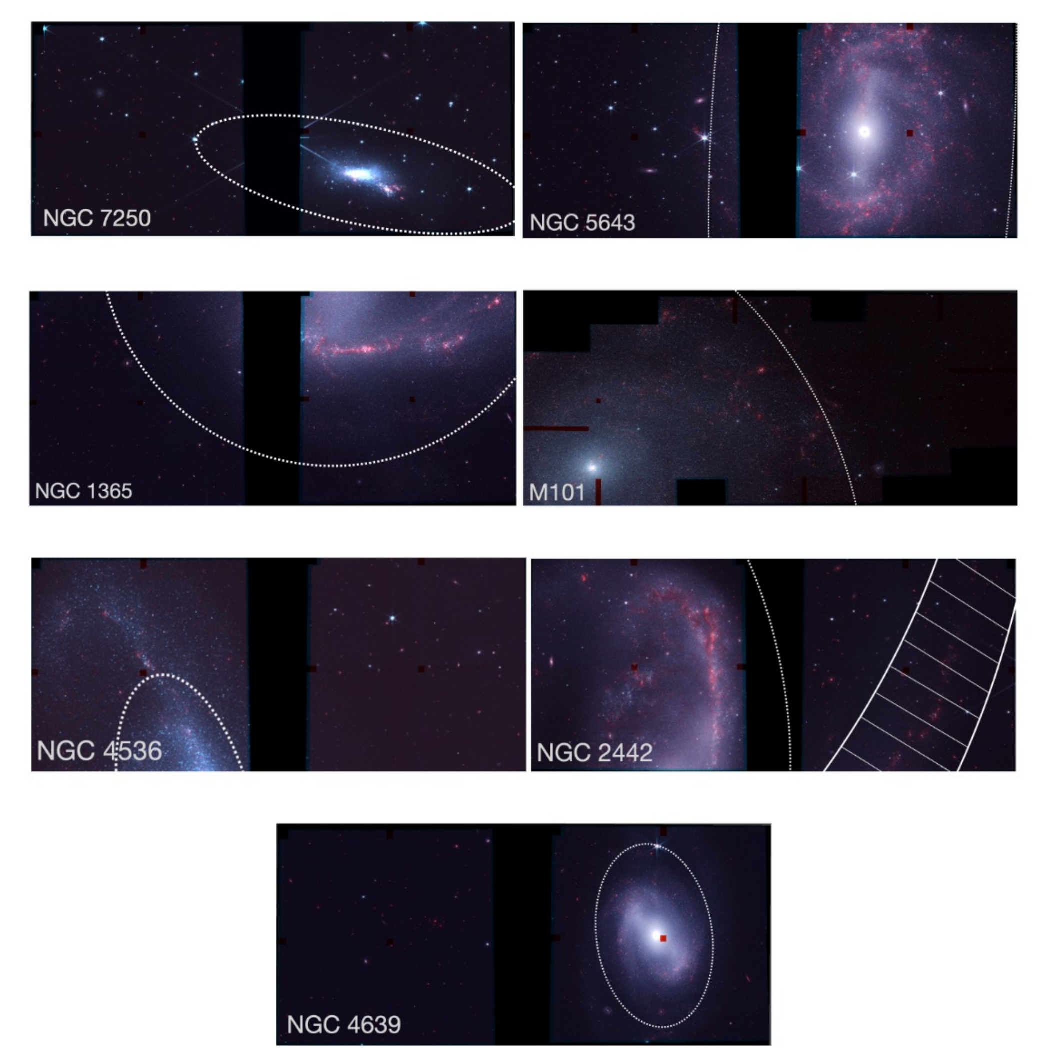


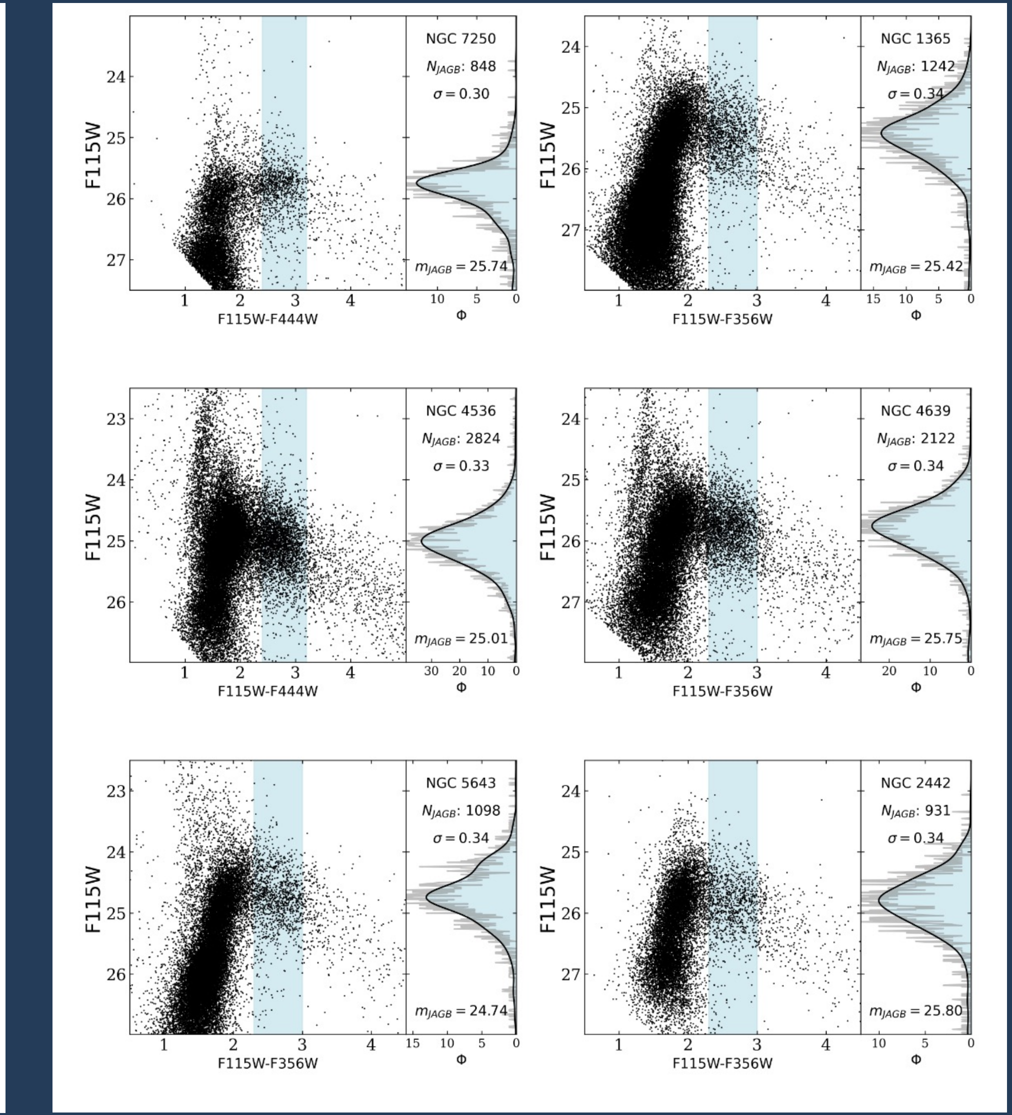
Madore + WLF, ApJ 2020



WLF + Madore, ApJ 2020

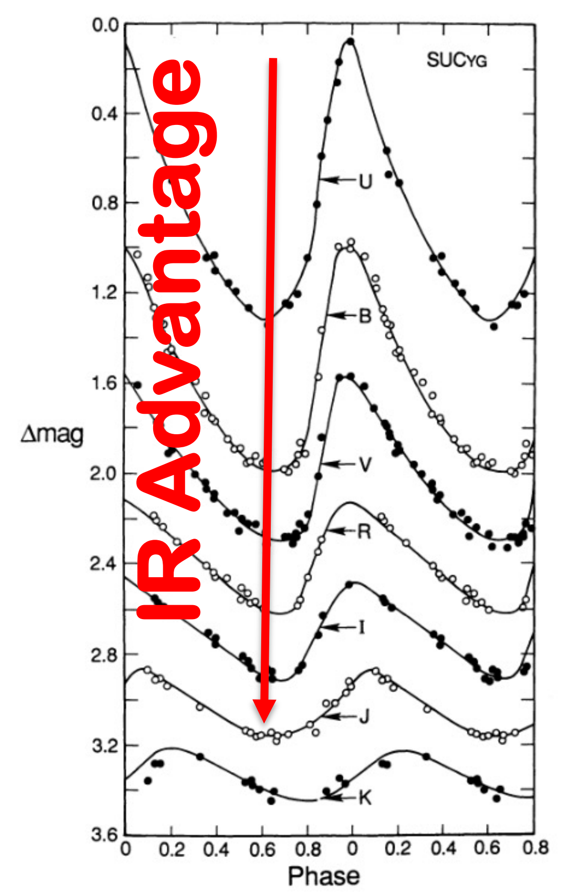
JWST: JAGB Distances





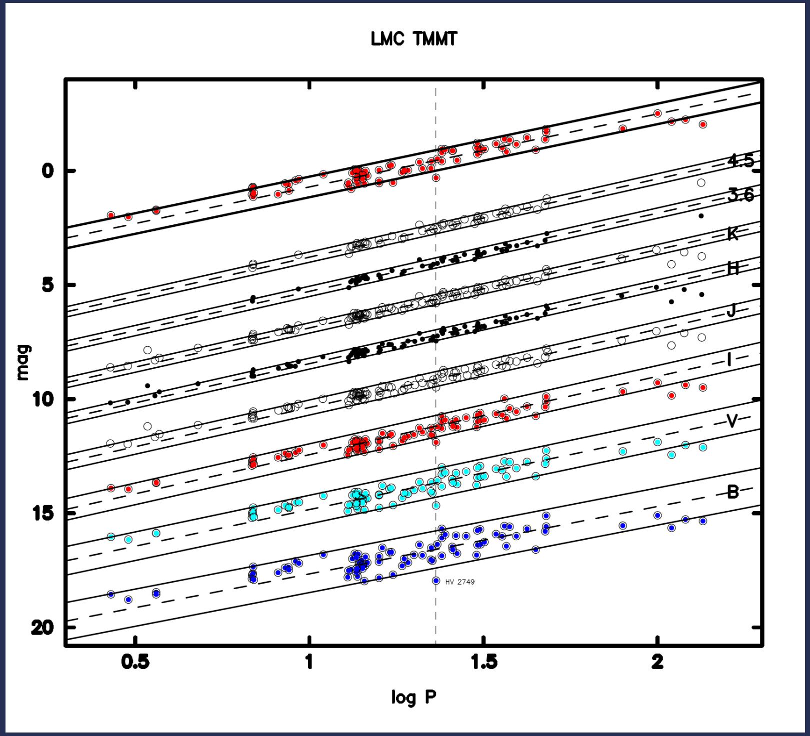
Lee et al., in prep

Method 3. Cepheids: Historical Standard For the Extragalactic Distance Scale



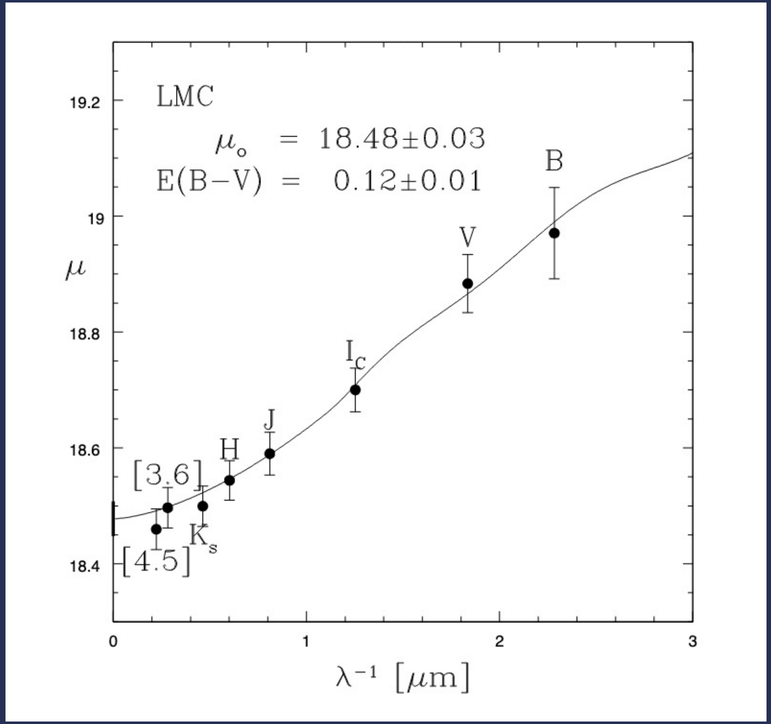
WLF et al. (1990, 1991)
Madore & WLF (1991)

Multiwavelength Cepheid PLs



Monson + WLF et al (2012)
Monson + WLF et al. (2024, in prep.)

Fit to Galactic `Extinction Curve'



Monson + WLF et al. (2012)

Why is 1% so hard?

Requires a slight digression…

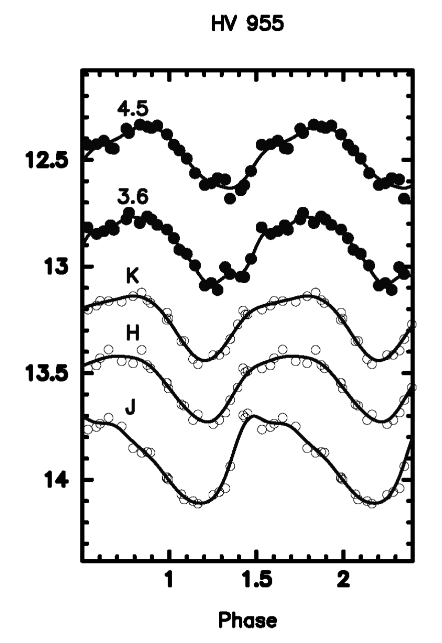
New JWST, Reanalysis of HST, Multiple Cross-checks

- New, updated STScI pipeline analysis (Feb. 2024)
- Re-analysis of V,I archival HST data for Cepheids
- We have not included the (crowded) HST H-band data
- New JWST J-band data
- Artificial star experiments – 1000 stars for each Cepheid
- VIJ extinction (dust-correction) plots
- 2 independent PSF-fitting packages for internal check
- Independent STScI aperture photometry external check
- Completely blind analysis
- 2 Supernova samples (Pantheon+ and CSP)
- Maser galaxy NGC 4258 geometric distance calibration

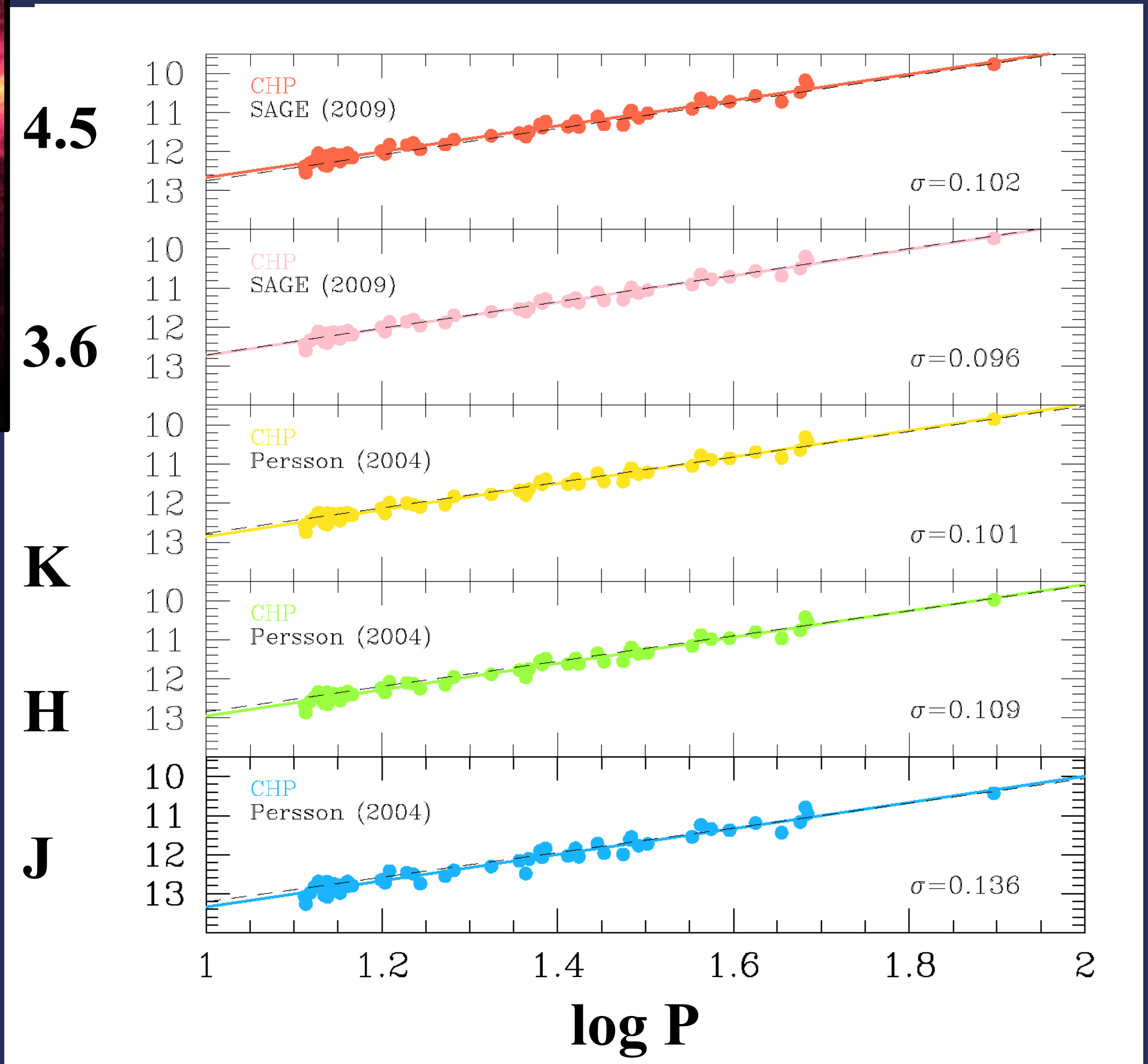
WLF et al., in prep

Improvement in the Near-IR

Cepheids: Near-Infrared



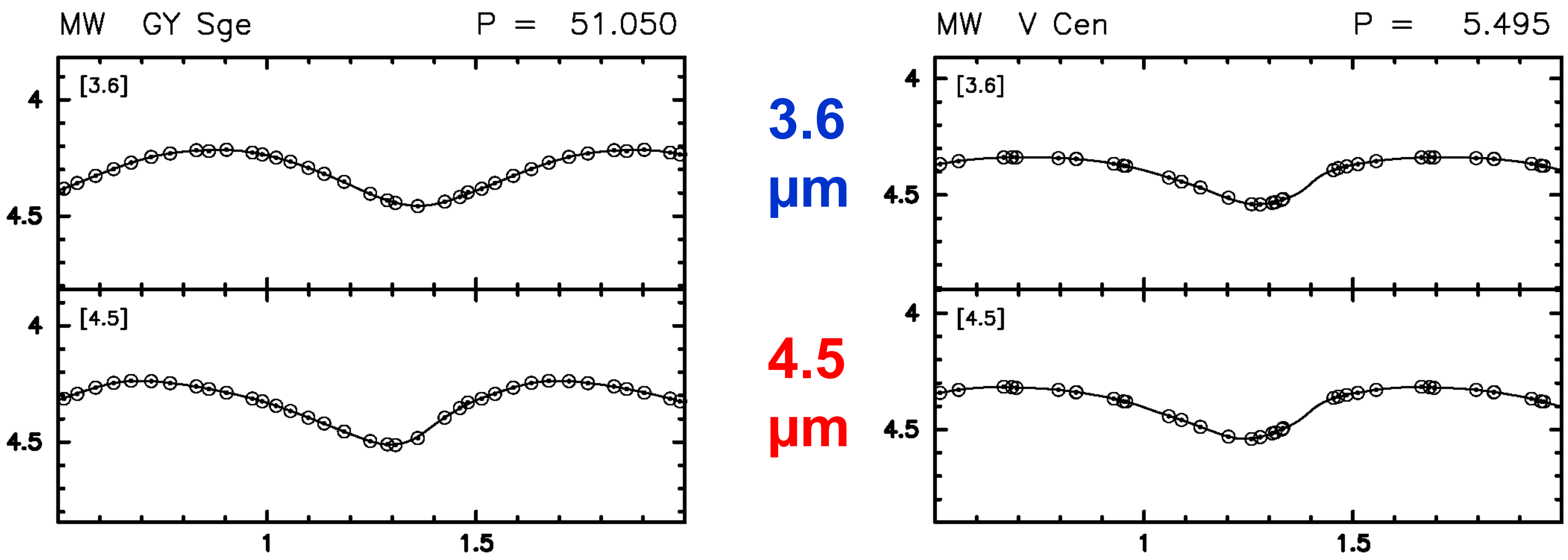
Near- and Mid-IR LMC PL (Leavitt) Relations



Carnegie Hubble Project (CSP) Spitzer mid-IR (2012)

Las Campanas Swope1-m Telescope JHK (Persson et al. (2004)

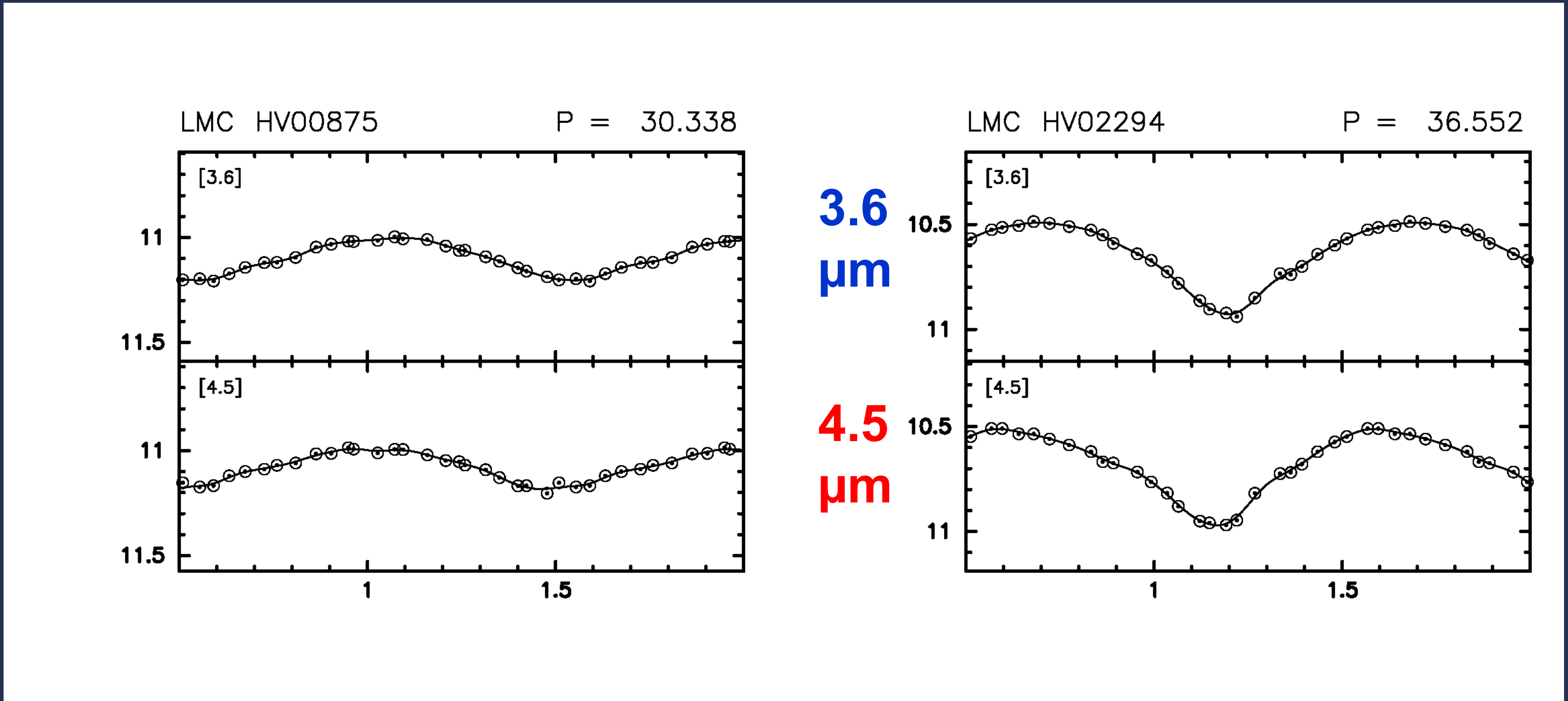
Spitzer 3.6 and 4.5 µm Milky Way light curves



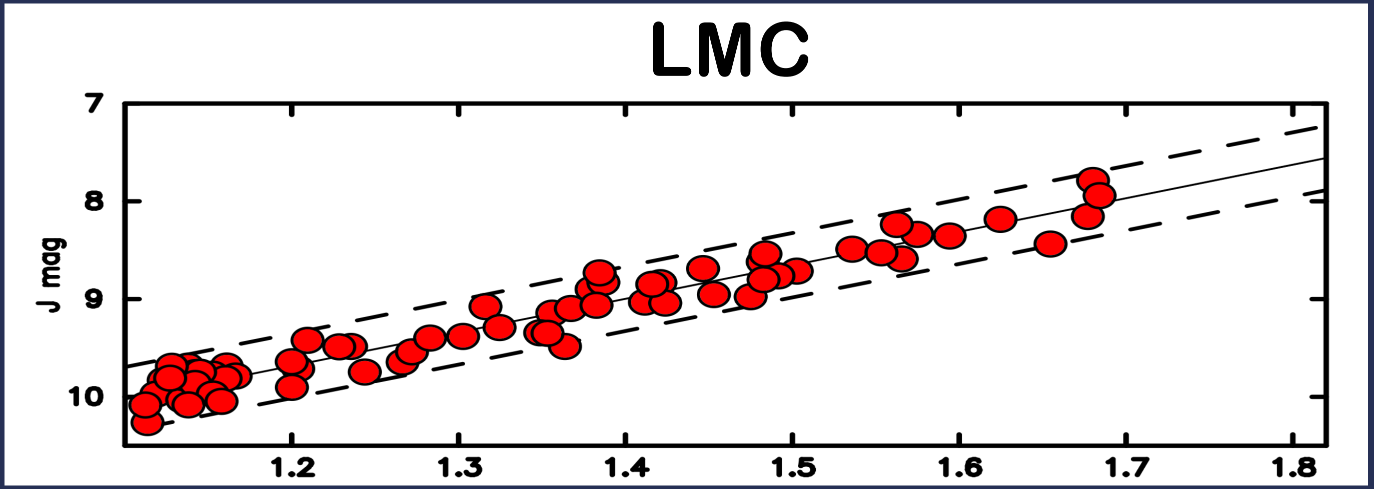
3.6 µm

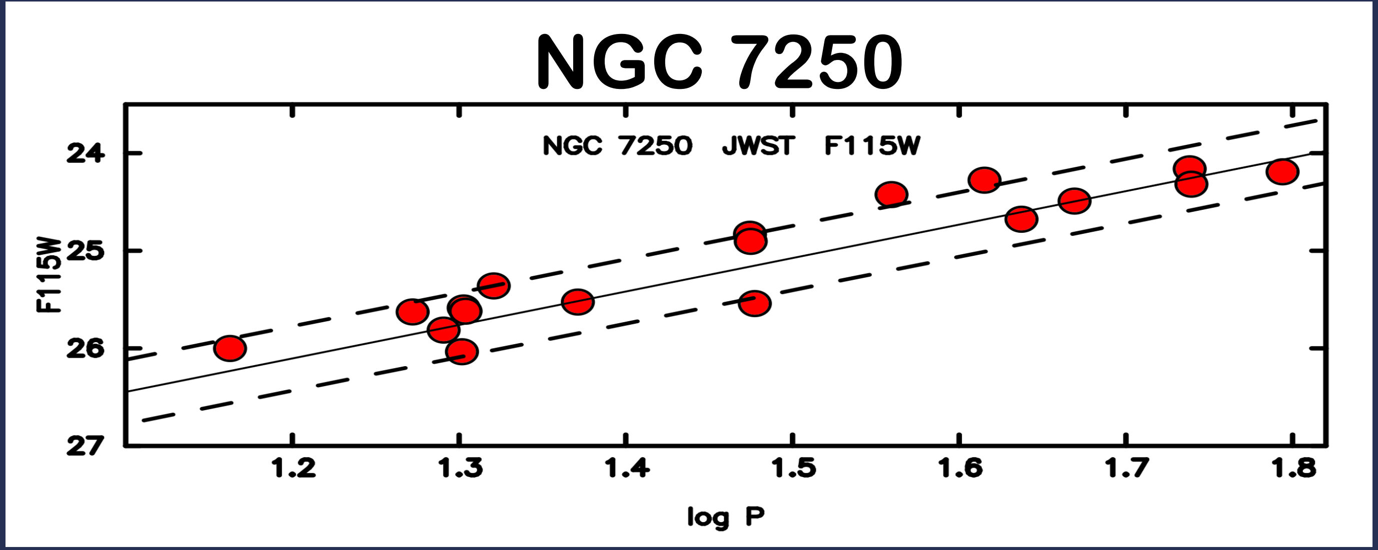
4.5 µm

Spitzer 3.6 and 4.5 µm LMC light curves



Near-infrared JWST Compared to Ground





- A factor of 400 in distance
- Comparable scatter in the period-luminosity relations!

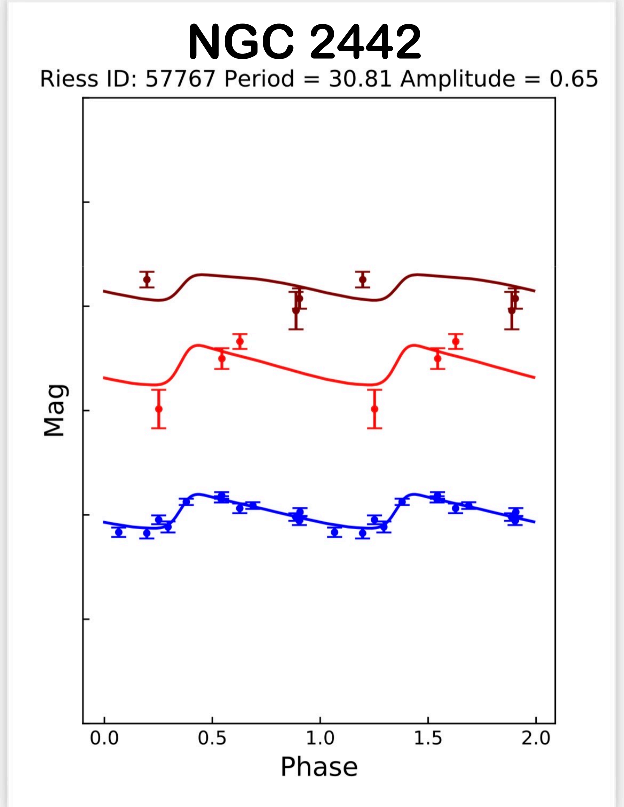
NOTE: We do not yet have a JWST-only Cepheid distance scale!!

Challenges as the distances increase…

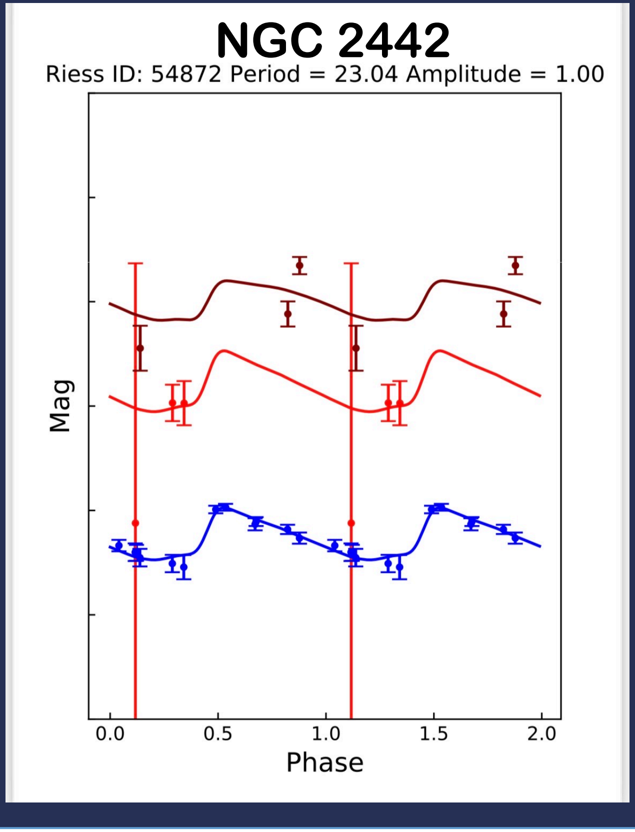
And you need optical HST data for the extinction corrections…

and the precision and accuracy decrease…

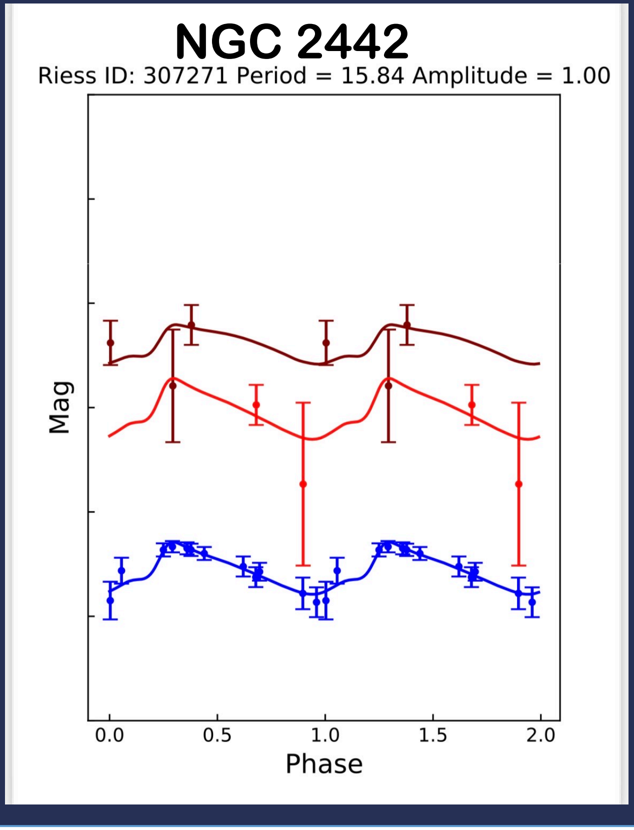
SH$_0$ES V and I Data / Cepheid Light Curves



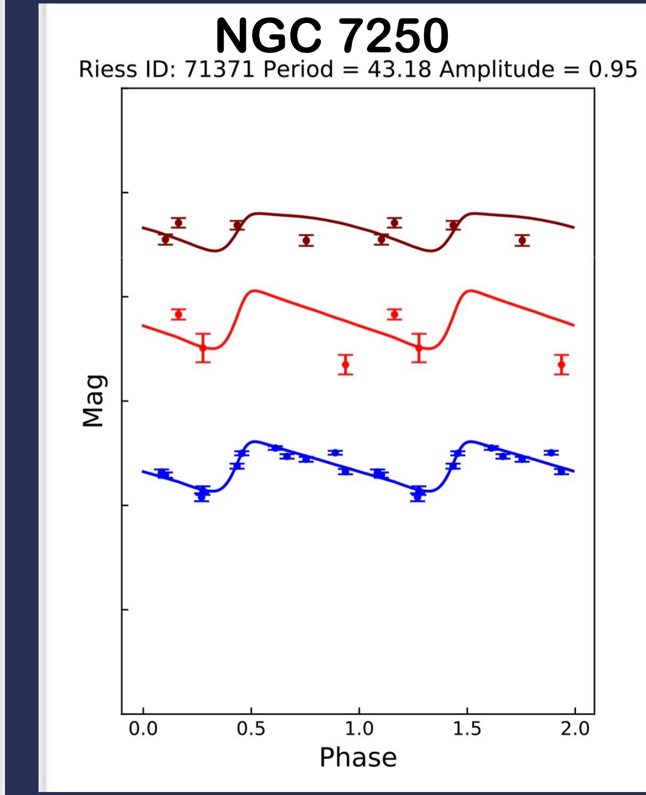
NGC 2442
Riess ID: 57767 Period = 30.81 Amplitude = 0.65



NGC 2442
Riess ID: 54872 Period = 23.04 Amplitude = 1.00



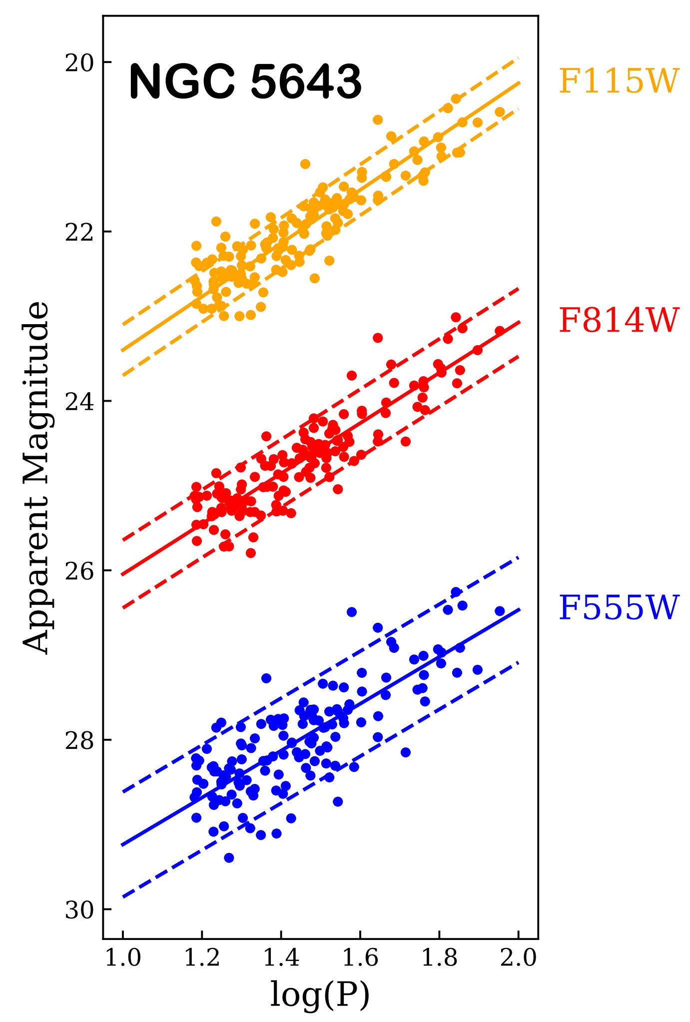
NGC 2442
Riess ID: 307271 Period = 15.84 Amplitude = 1.00

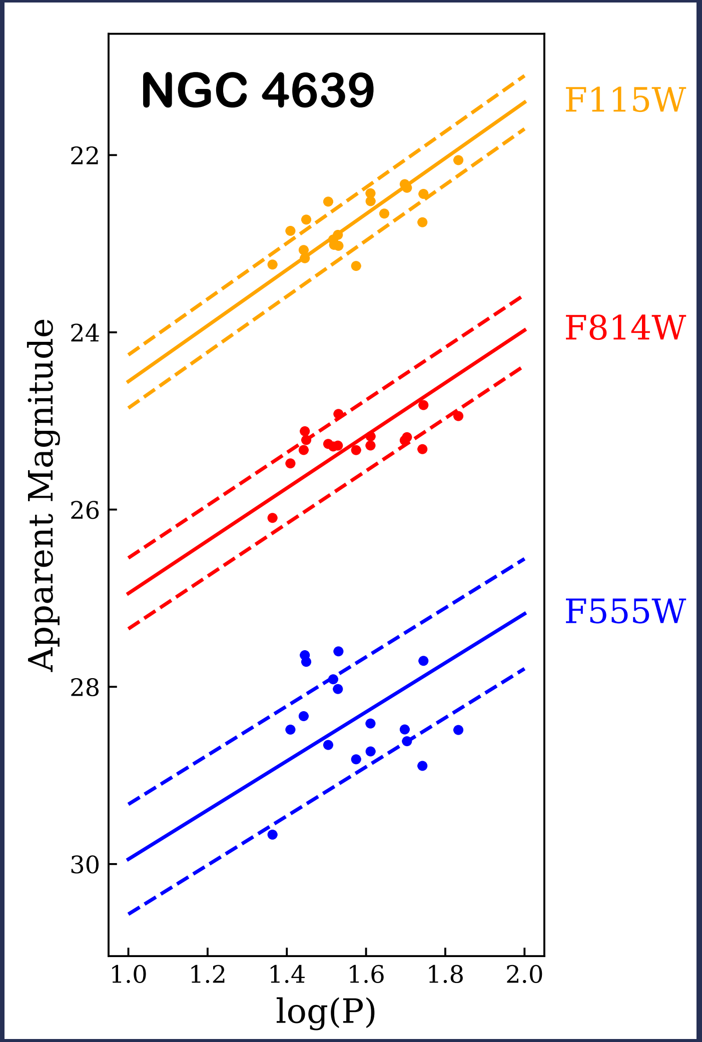


NGC 7250
Riess ID: 71371 Period = 43.18 Amplitude = 0.95

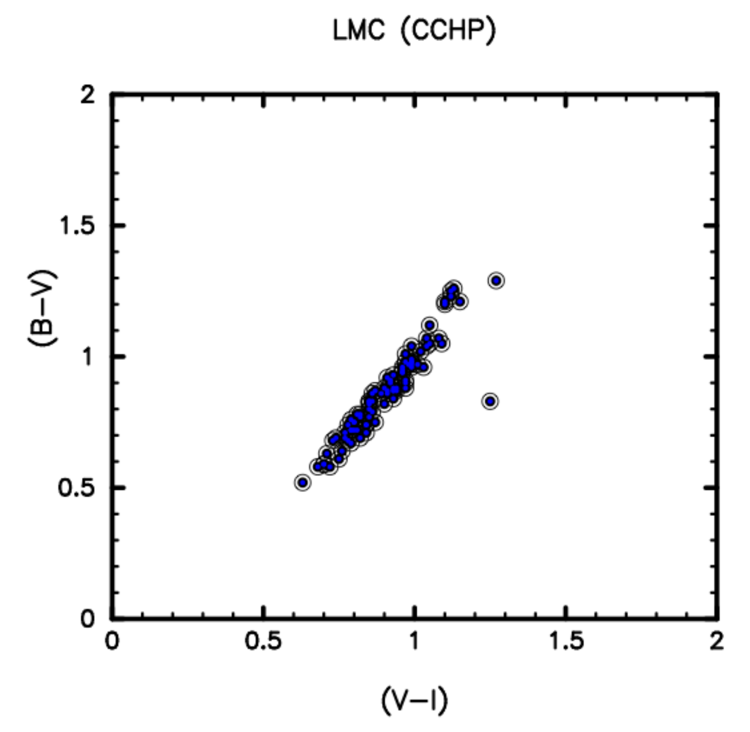
White light (F350LP)   V-band (F555 W)   I-band (F814W)   SH$_o$ES: $W = H - R\,(V\text{-}I)$; $R \equiv A_H / (A_V - A_I)$

SH$_0$ES HST V and I Data
JWST CCHP J Data / Cepheid Light Curves



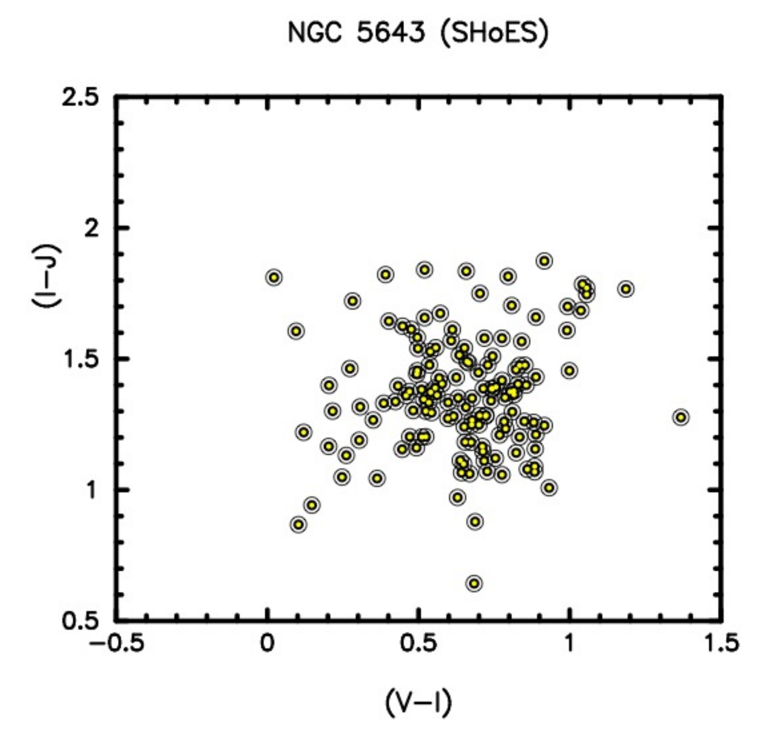


Challenges / Accurate Cepheid Colors



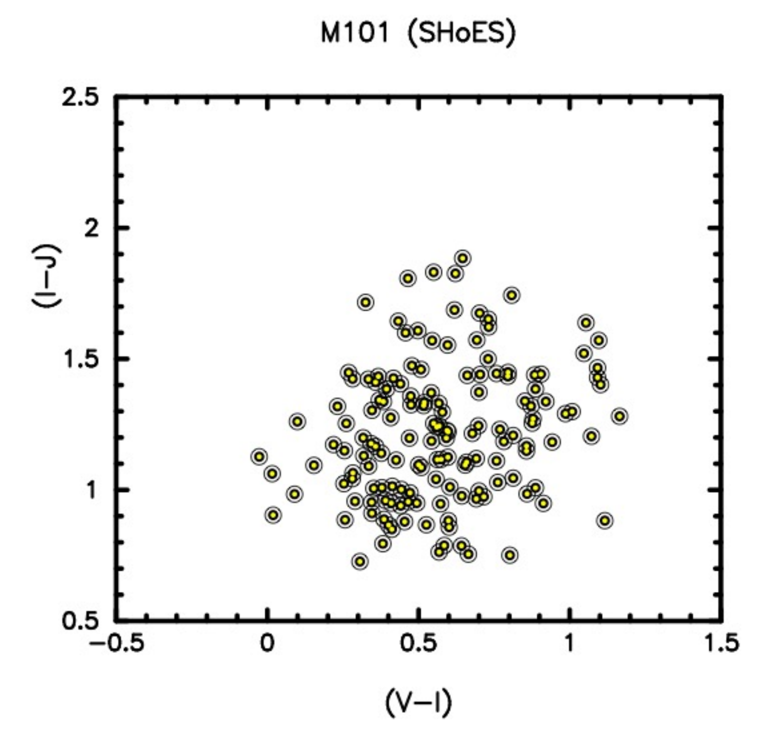
LMC – 50 kpc

Challenges



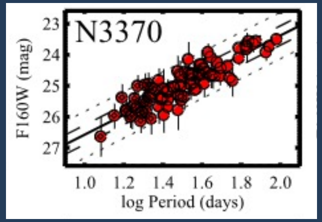
NGC 5643 – HST/JWST 13 Mpc

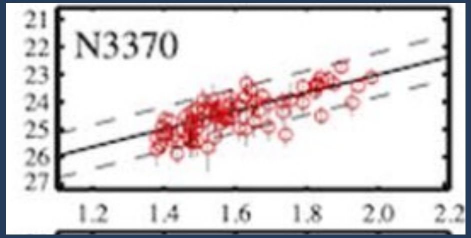
Challenges

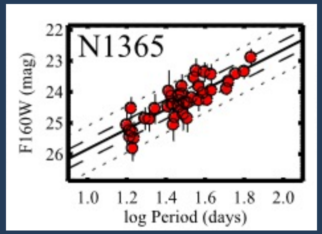


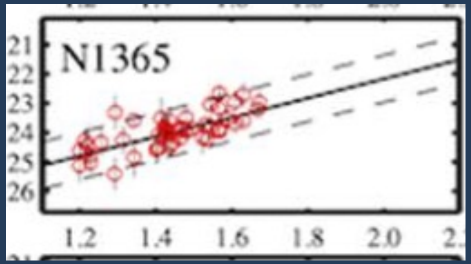
M101– HST/JWST 6.9 Mpc

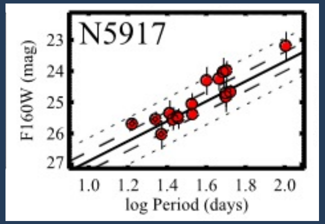
Period Cuts Matter

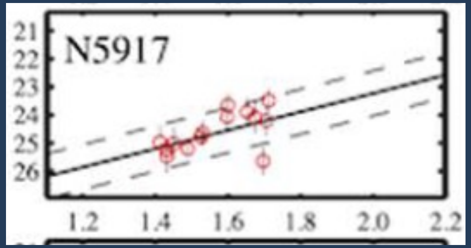


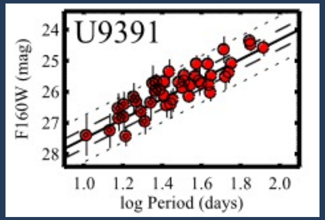


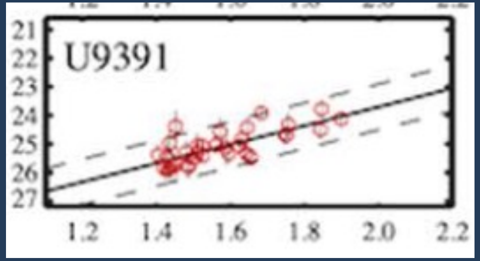




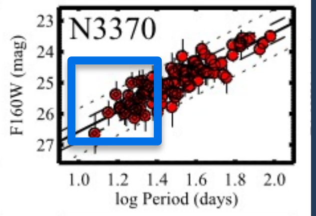


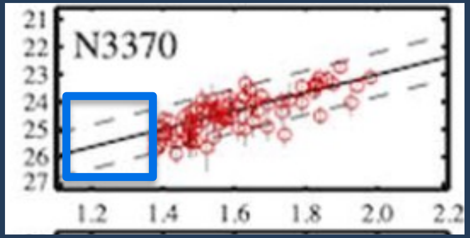


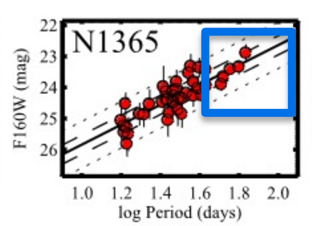


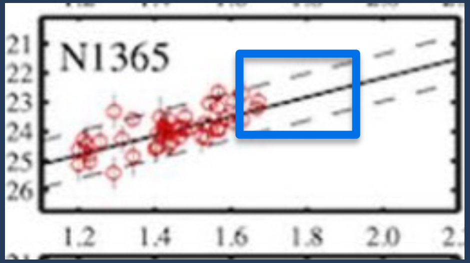


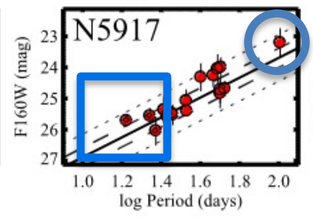
Period Cuts Matter

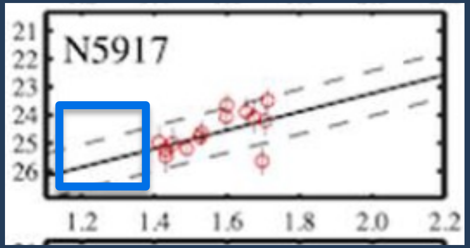


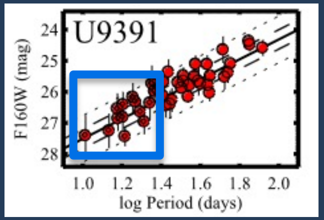


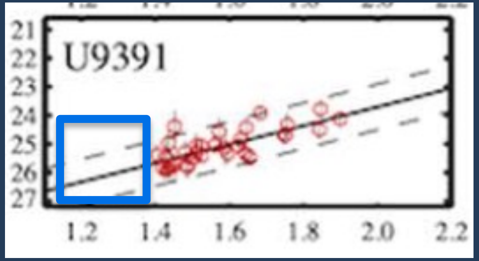












Metallicity

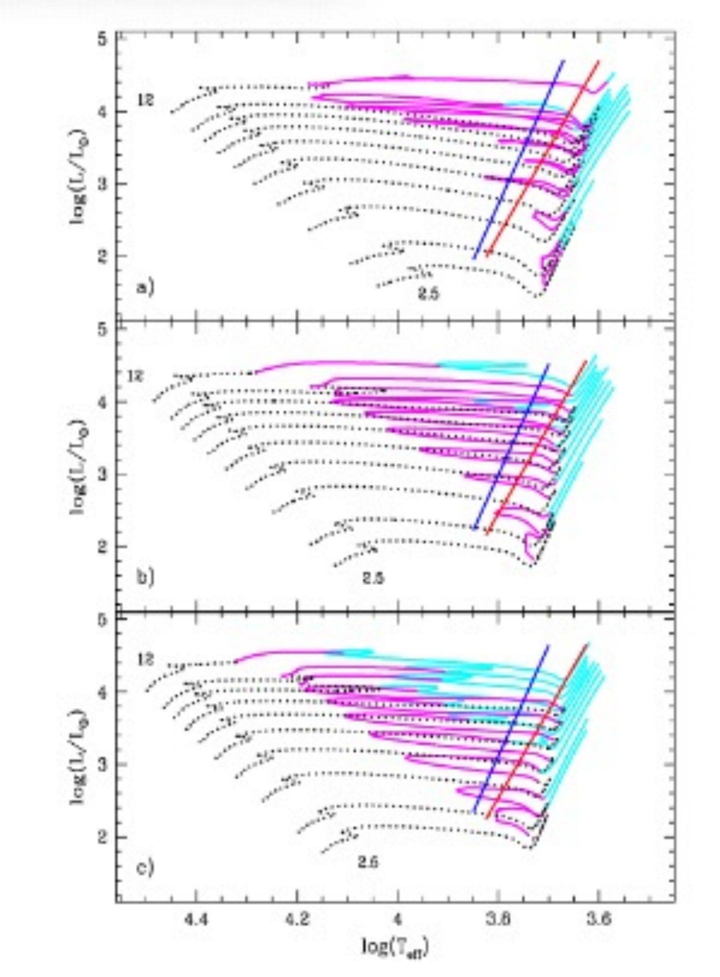
The Cepheid **Period-Luminosity-Color-Metallicity** Relation (Leavitt Law)

$$M_{\lambda_1} = \alpha\, logP + \beta(m_{\lambda_1} - m_{\lambda_2})_o + \gamma[O/H] + \delta$$

Luminosity	**Period**	**Color term**	**‘Metallicity’**	**Zero point**

Effects of Metallicity on Cepheid Evolution

Metallicity



Z = 0.02

Z = 0.01

Z = 0.001

De Somma et al. 2021

Metallicity coefficient γ (mag / dex)

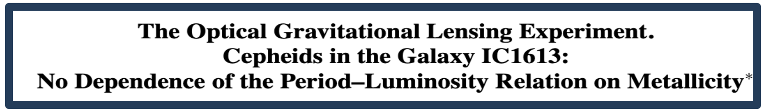
Ripepi et al. 2021
Best estimates:
$-0.366 < \gamma < -0.465$

Gaia EDR3 measurements:
New spectroscopy

Breuval + Riess et al. 2021
$-0.048 < \gamma < -0.251$

Gaia EDR3 parallax measurements:
Effect in near-infrared as large as in optical, contrary to previous studies.

Udalski et al. 2001
$\gamma = 0$


The Optical Gravitational Lensing Experiment.
Cepheids in the Galaxy IC1613:
No Dependence of the Period–Luminosity Relation on Metallicity*

Ripepi et al. 2022
$-0.520 < \gamma < -0.725$

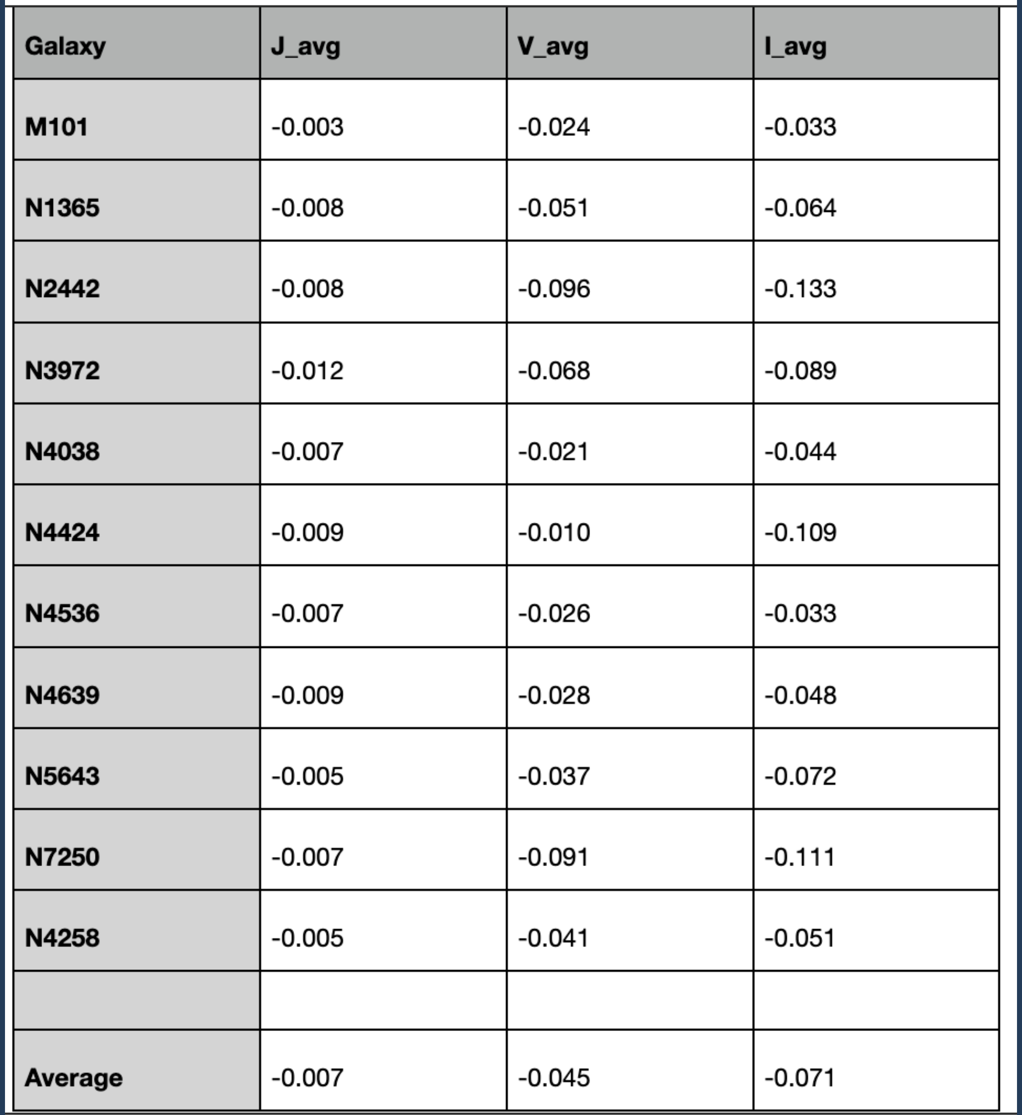
Gieren et al. 2021
$-0.221 < \gamma < -0.335$

Riess et al. 2016
$\gamma = -0.13 \pm 0.07$

Riess et al. 2021
$\gamma = -0.217 \pm 0.046$

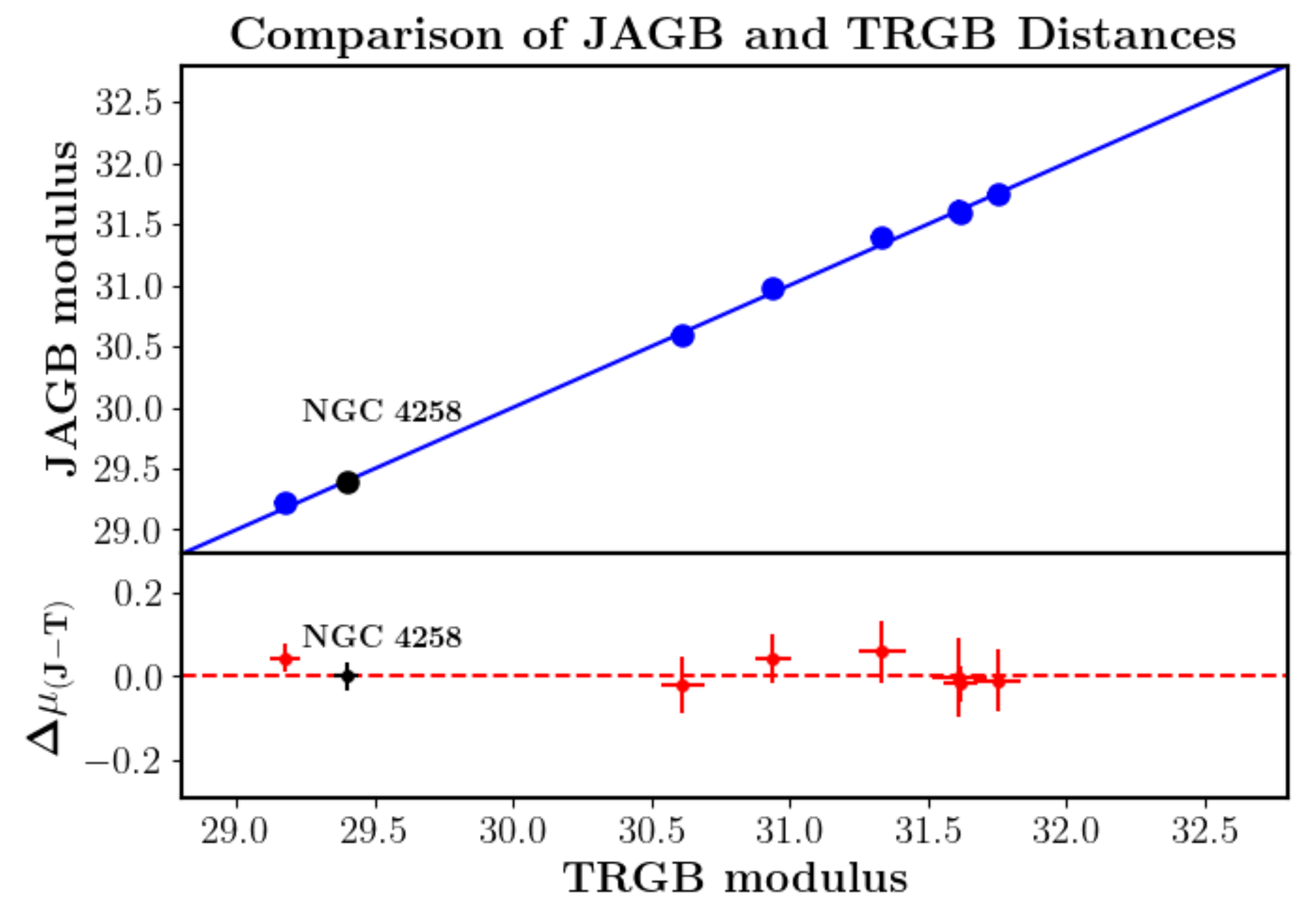
$-0.5 < \gamma < 0$

Artificial Star Corrections



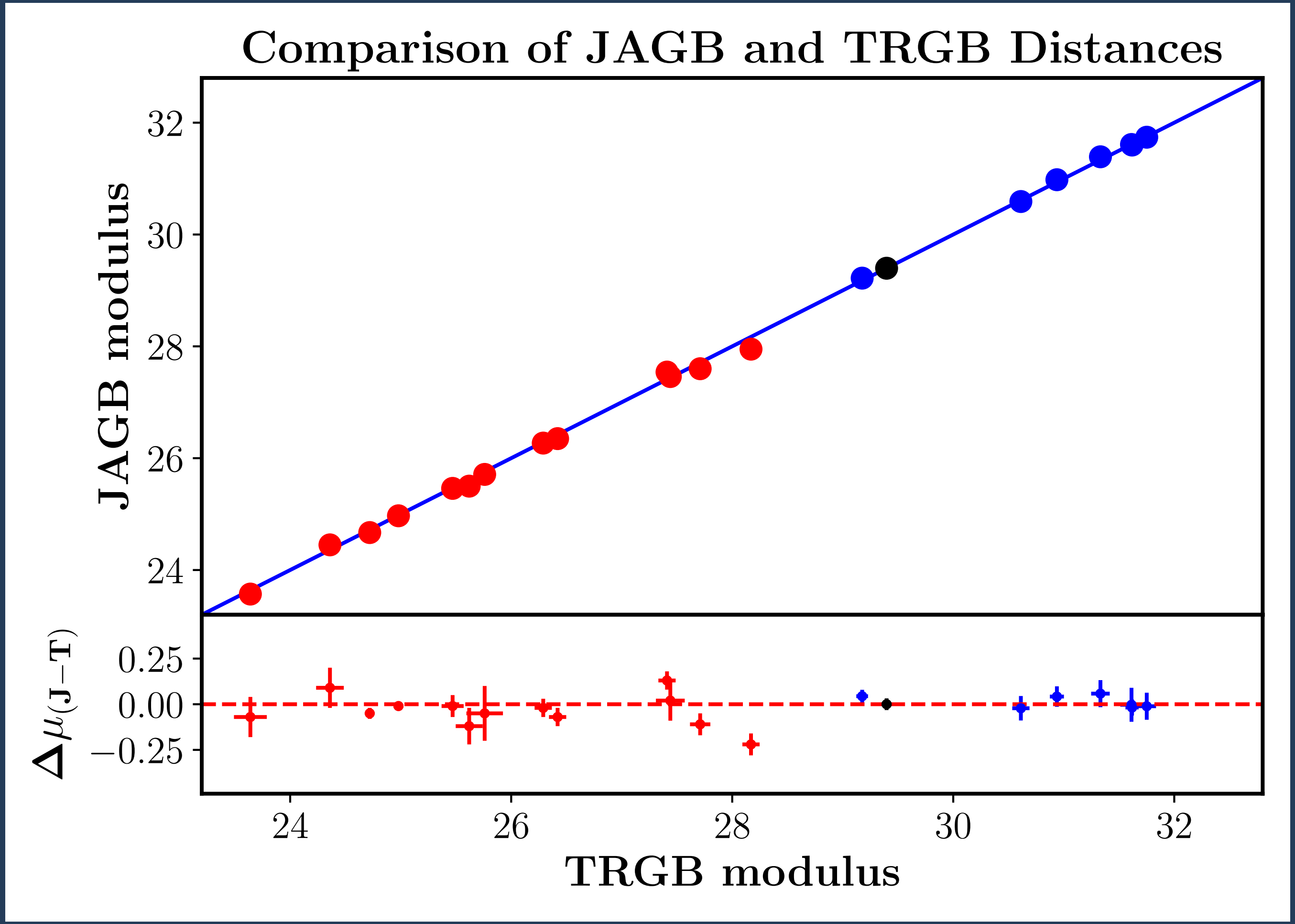
Galaxy	J_avg	V_avg	I_avg
M101	-0.003	-0.024	-0.033
N1365	-0.008	-0.051	-0.064
N2442	-0.008	-0.096	-0.133
N3972	-0.012	-0.068	-0.089
N4038	-0.007	-0.021	-0.044
N4424	-0.009	-0.010	-0.109
N4536	-0.007	-0.026	-0.033
N4639	-0.009	-0.028	-0.048
N5643	-0.005	-0.037	-0.072
N7250	-0.007	-0.091	-0.111
N4258	-0.005	-0.041	-0.051
Average	-0.007	-0.045	-0.071

Comparison of the Blinded TRGB and JAGB Distances



WLF et al. 2024

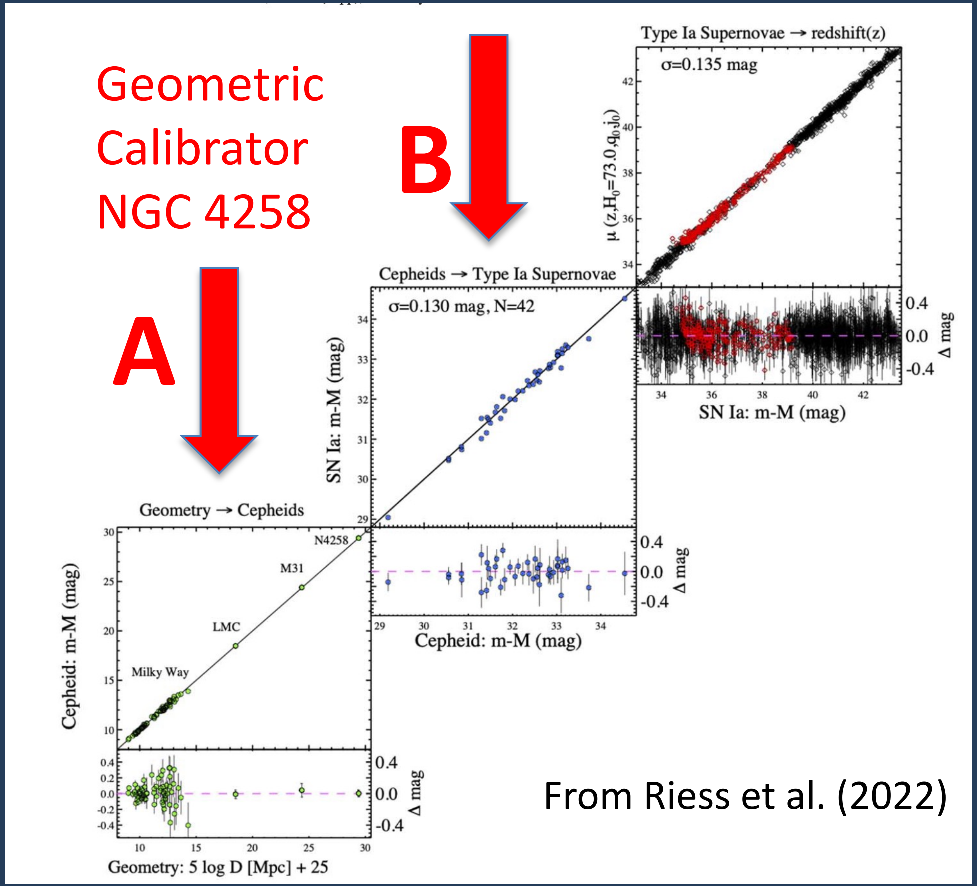
Comparison of Previously Published (Ground-Based + JWST) TRGB and JAGB Distances



WLF et al. 2024

SH$_0$ES / Pantheon+ Supernovae

CCHP JWST distances



From Riess et al. (2022)

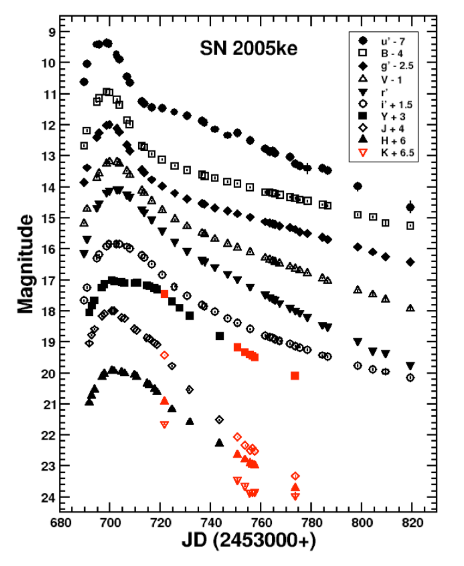
- **Composite sample of SNe from 18 surveys (Riess et al. 2022; Scolnic et al. 2023)**

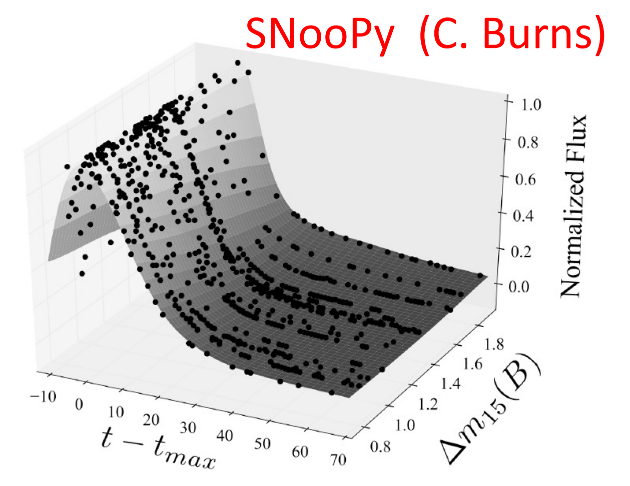
A) Nearby anchor NGC 4258 (same chemical composition as our JWST target galaxies (mean).

B) CCHP JWST calibration for galaxies in middle rung

- **All three methods (Cepheids,TRGB,JAGB)**
- **NGC 4258 distance largest systematic: 1.5%**

Carnegie Supernova Project (CSP)
Dealing With Systematics



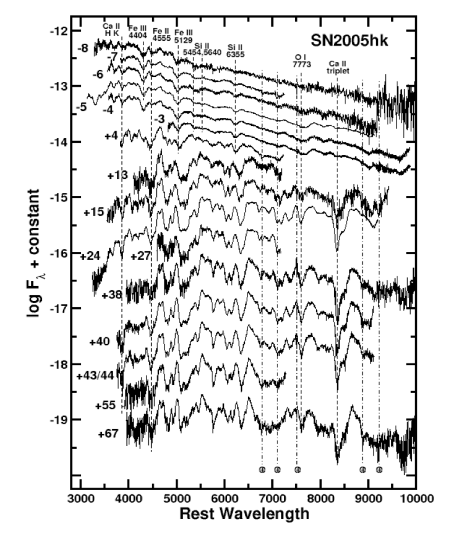

SNooPy (C. Burns)

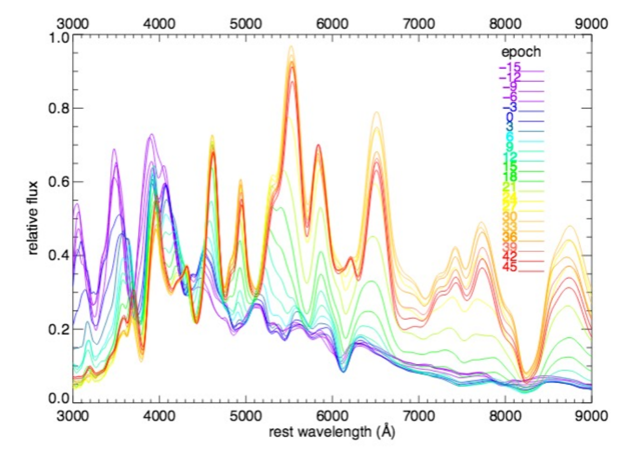
M. Phillips, W. Freedman, co-PIs

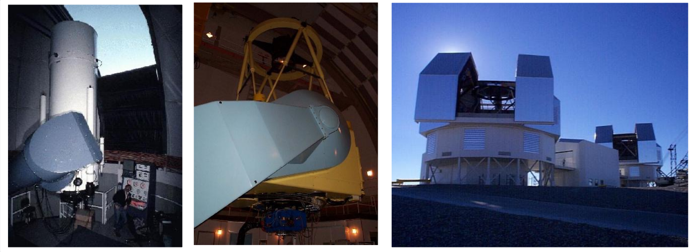
Well-sampled photometry and spectra

Most extensive, self-consistent data set for dealing with systematics

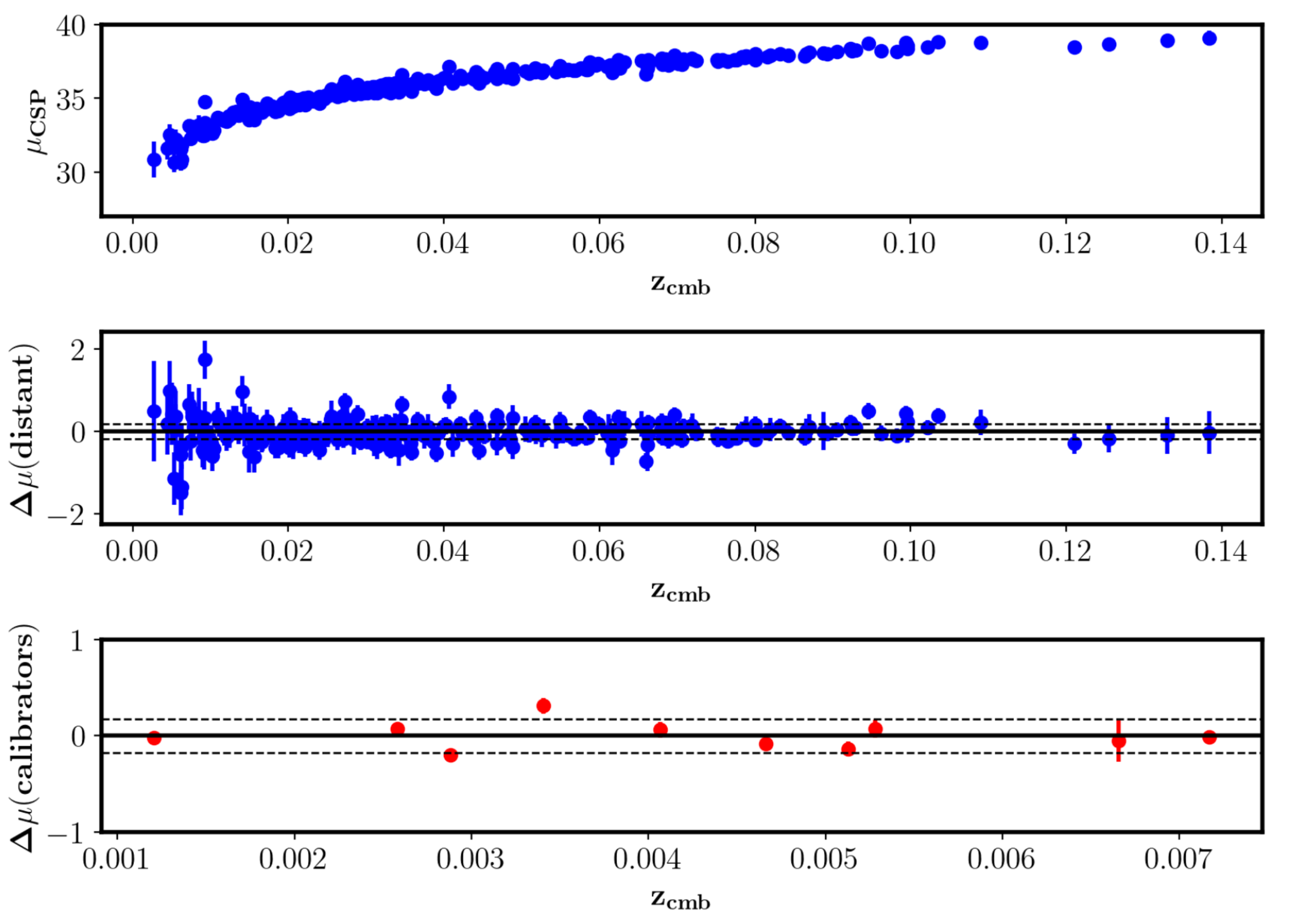
Input to MCMC analysis





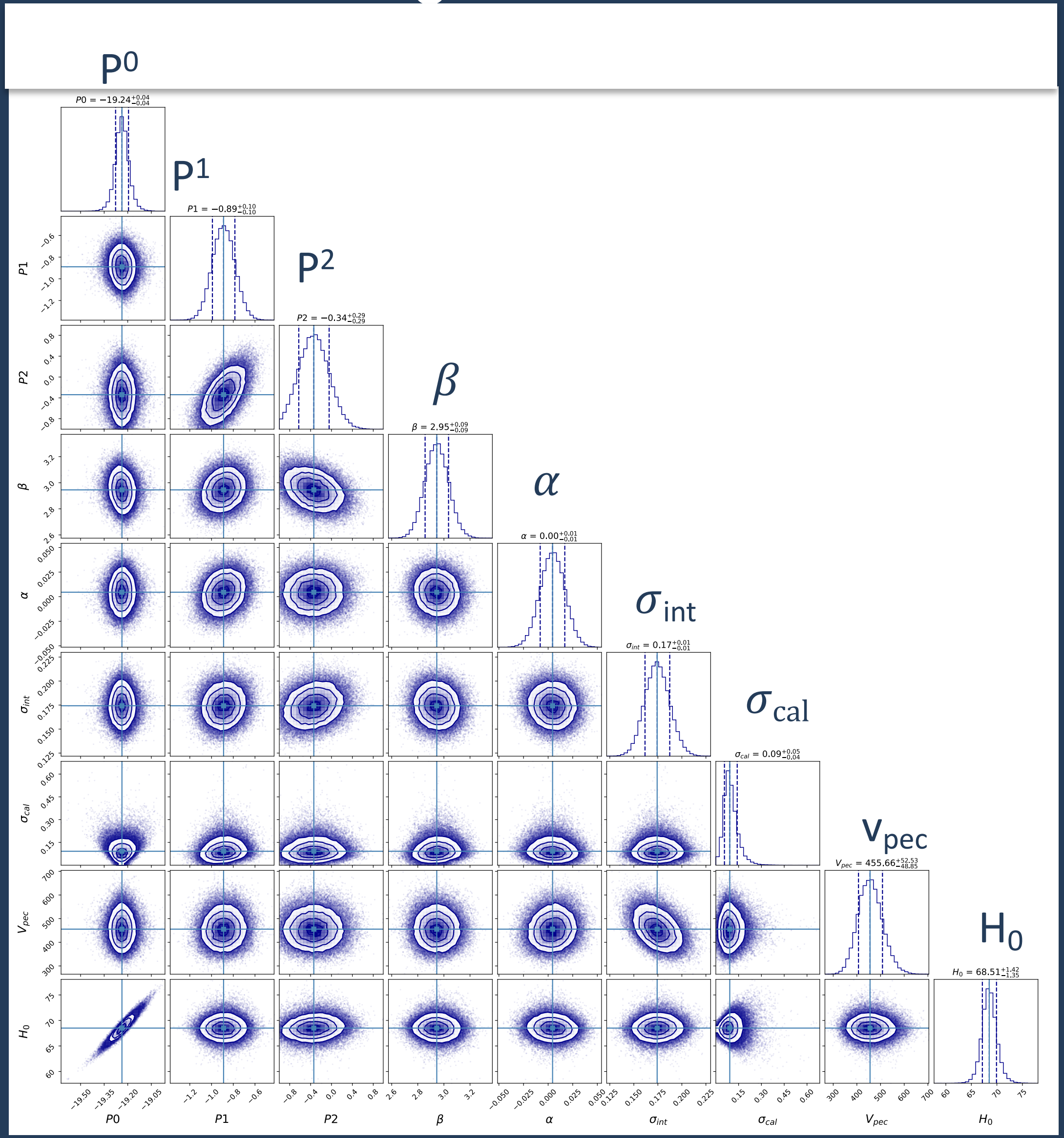


Carnegie Supernova Project (CSP)



WLF et al. 2024

H_0 Results : CSP / (JAGB + TRGB)



EMCEE + pymc analyses

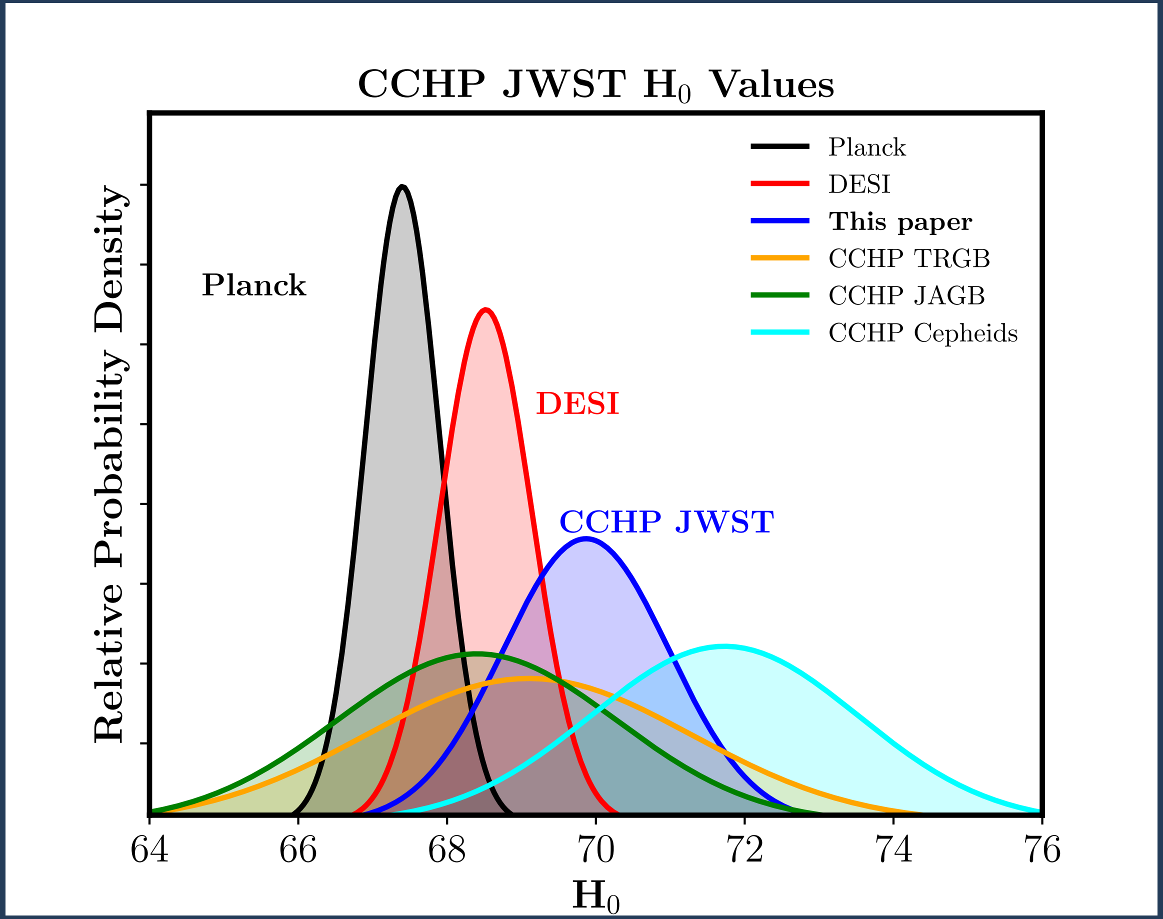
$$B_{corr} = P^0 - P^1(s_{BV}-1) - P^2(s_{BV}-1)^2 - \beta(B-V) - \alpha_M(\log_{10} M_*/M_\odot - M_0),$$

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

- **9 dimensions, 20,000 steps, 1000 step burn-in**
- **TRGB, JAGB combined**
- **$H_0 = 69.4 \pm 1.7$ km s^{-1} Mpc^{-1}**
- **corrected for peculiar velocities based on Carrick et al. (2015) flow model**

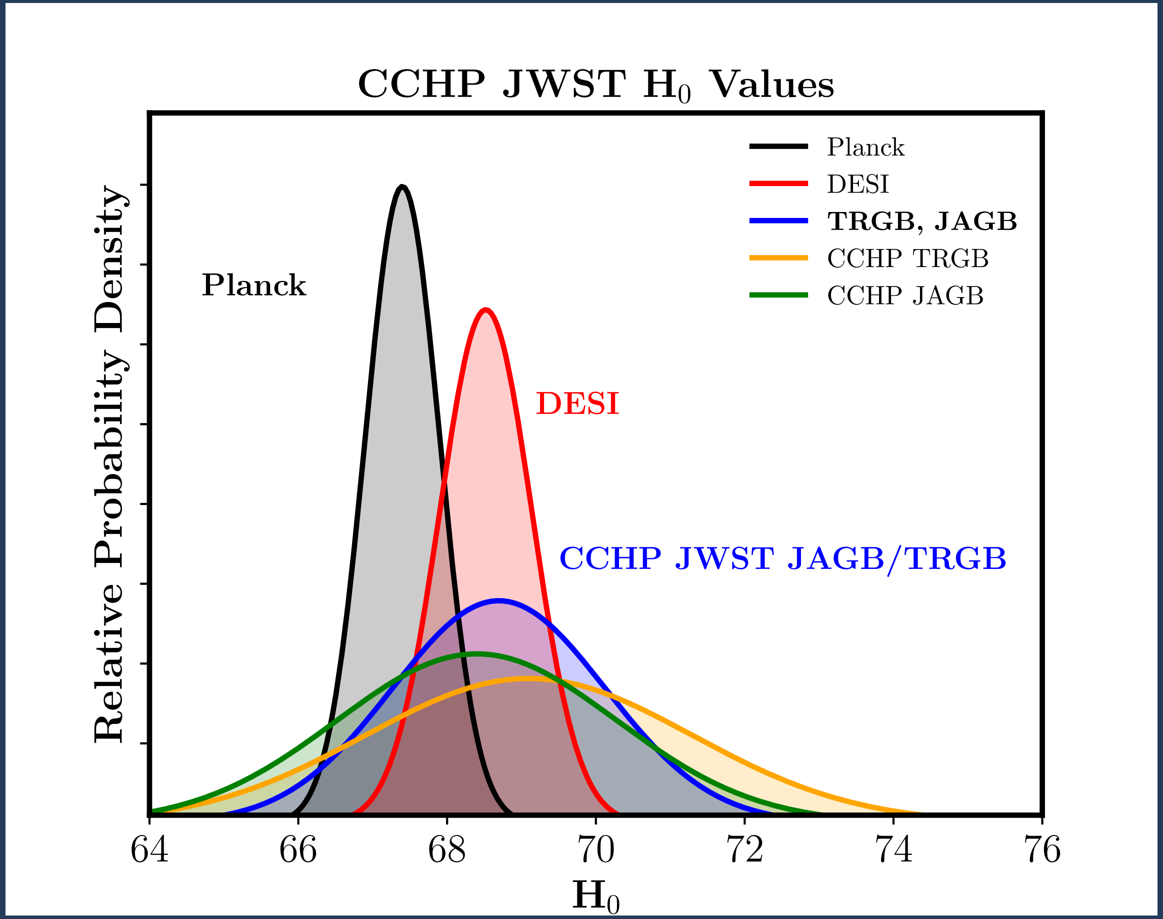
WLF et al. 2024

Results



CCHP: 3 independent methods

Results

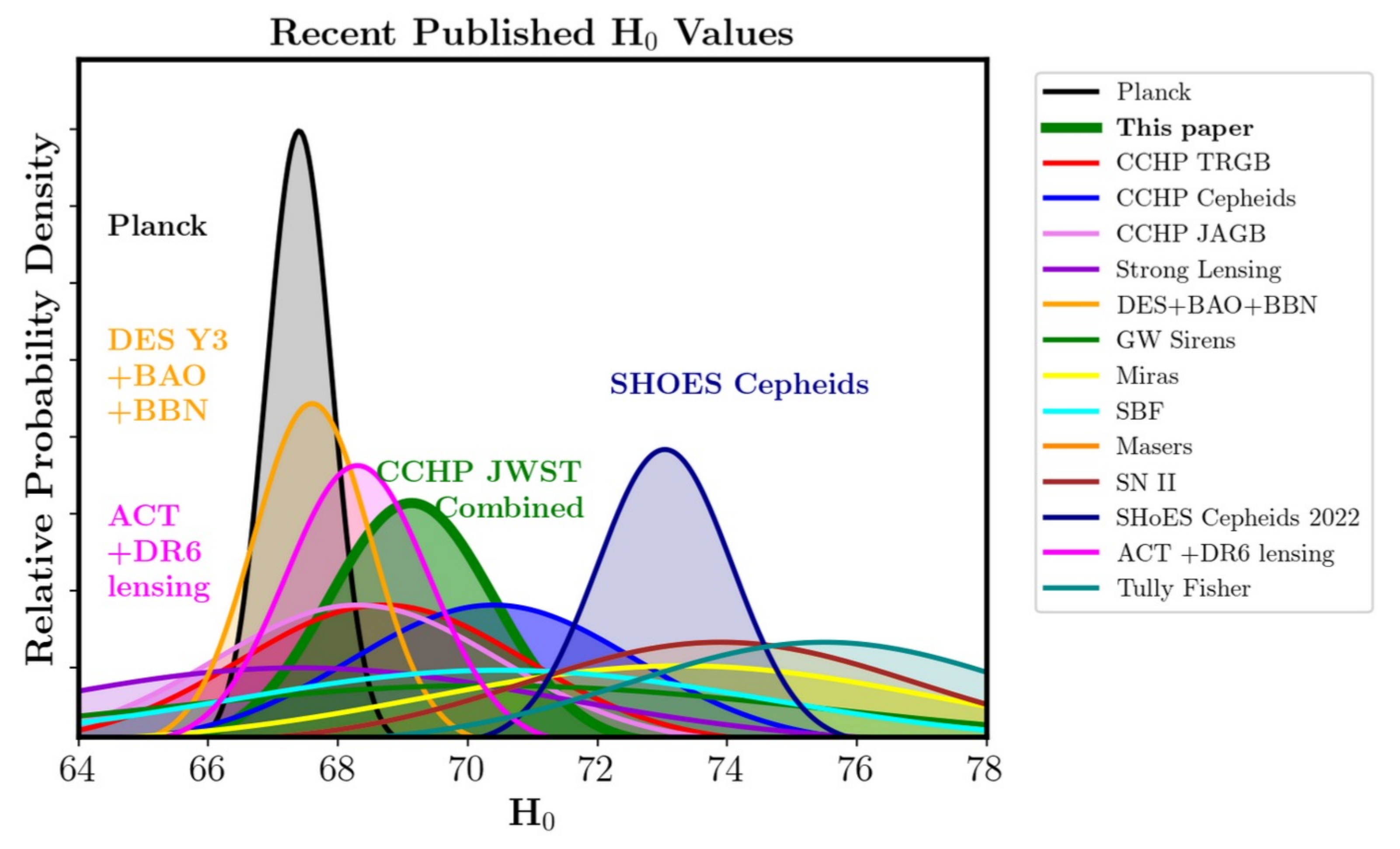


JAGB + TRGB (JWST data alone)

Concluding Remarks

- JWST has ushered in a new era of accuracy in our measurement of H_0, similar to what HST did three decades ago.
- Independent distances from the TRGB and JAGB/carbon stars agree at the percent level. **These distances are based on JWST data alone.**
- A combined analysis for these two methods gives $H_0 = 69.4 \pm 1.7$ km s^{-1} Mpc^{-1}
- These new JWST H_0 results do not require adding new physics to ΛCDM.
- The distances based on Cepheids are not based on JWST alone. They also require optical data to correct for the presence of dust. Different approaches / choice of sample lead to values of H_0 ranging from 69-73 km s^{-1} Mpc^{-1} .
- More JWST data at higher resolution will be required to measure H_0 at a 1% level from Cepheids alone. The HST data are currently the limiting factor.

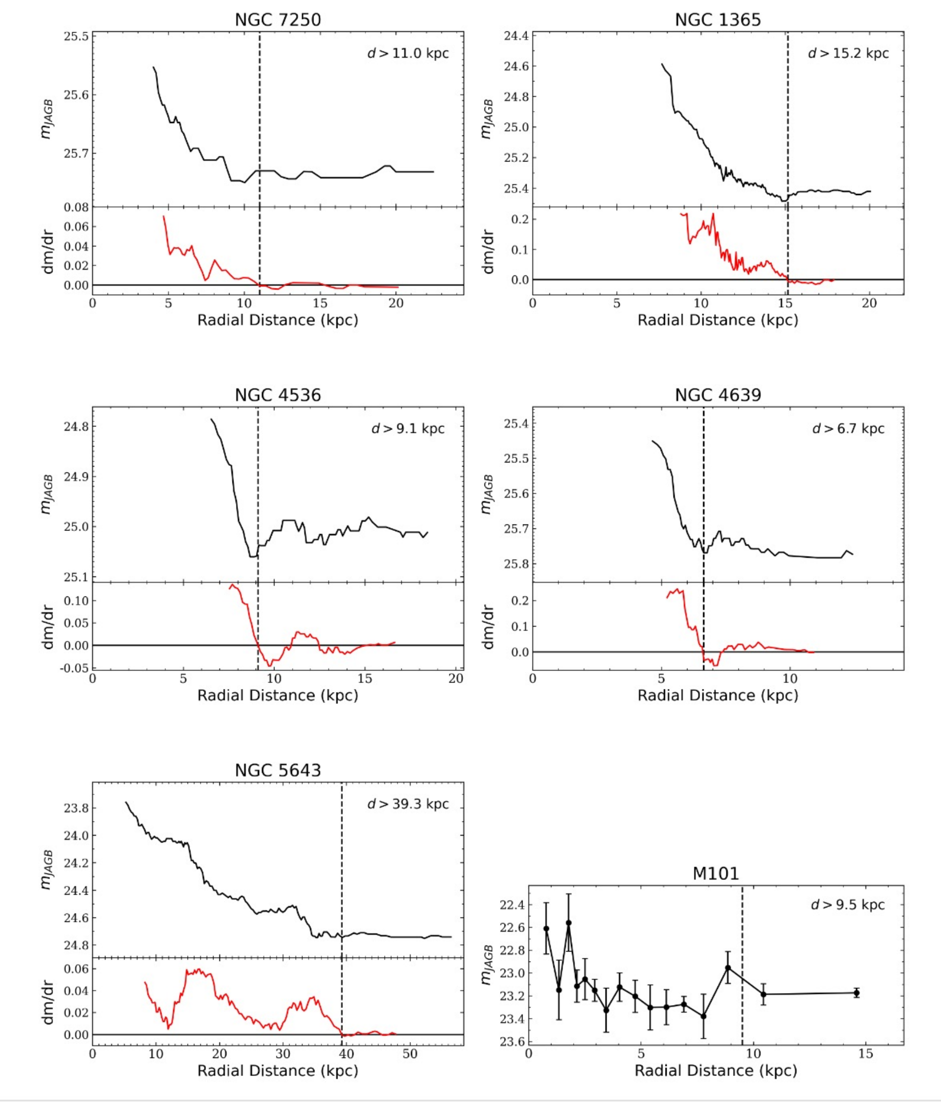
Results

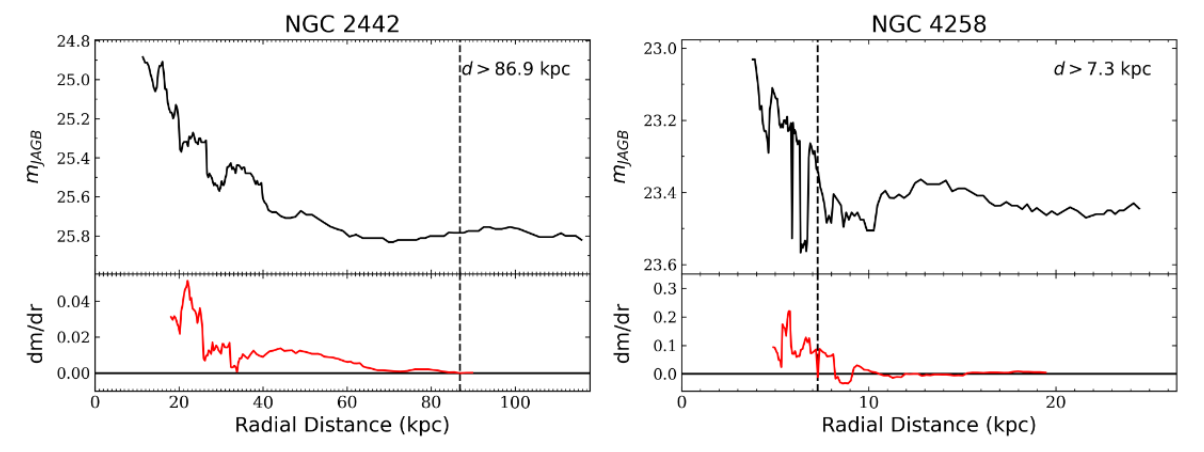


WLF et al., in prep.

JAGB Distances

Abby Lee





Lee et al., in prep