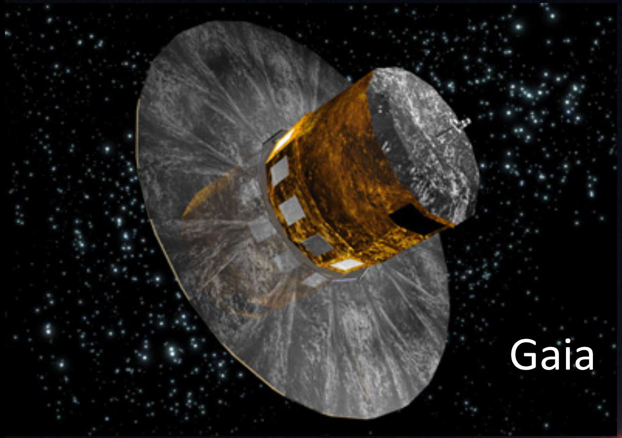
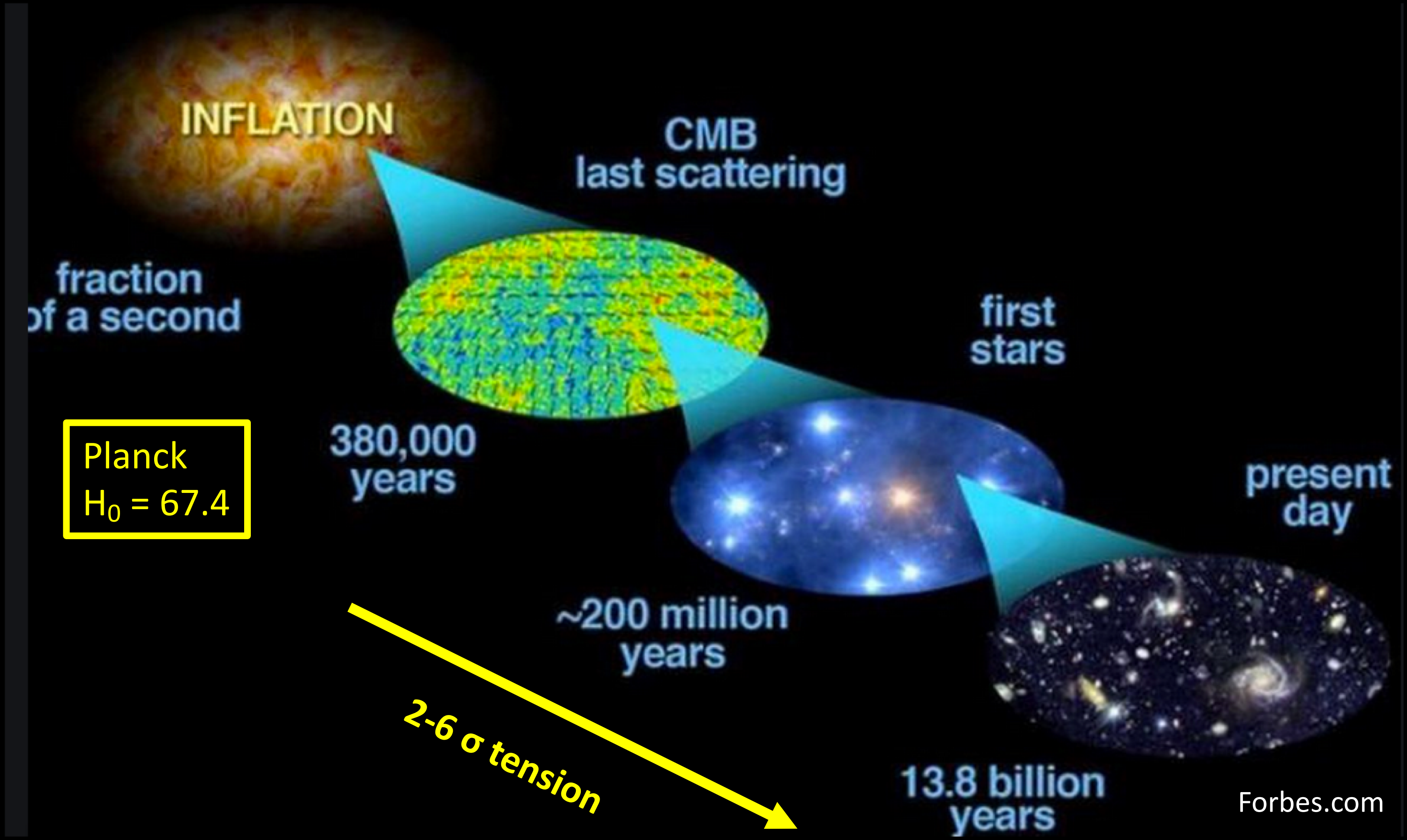
Tension in the Hubble Constant



Wendy L. Freedman
University of Chicago

September 15, 2022
BSCG, Rio de Janeiro

Tension in the Hubble Constant

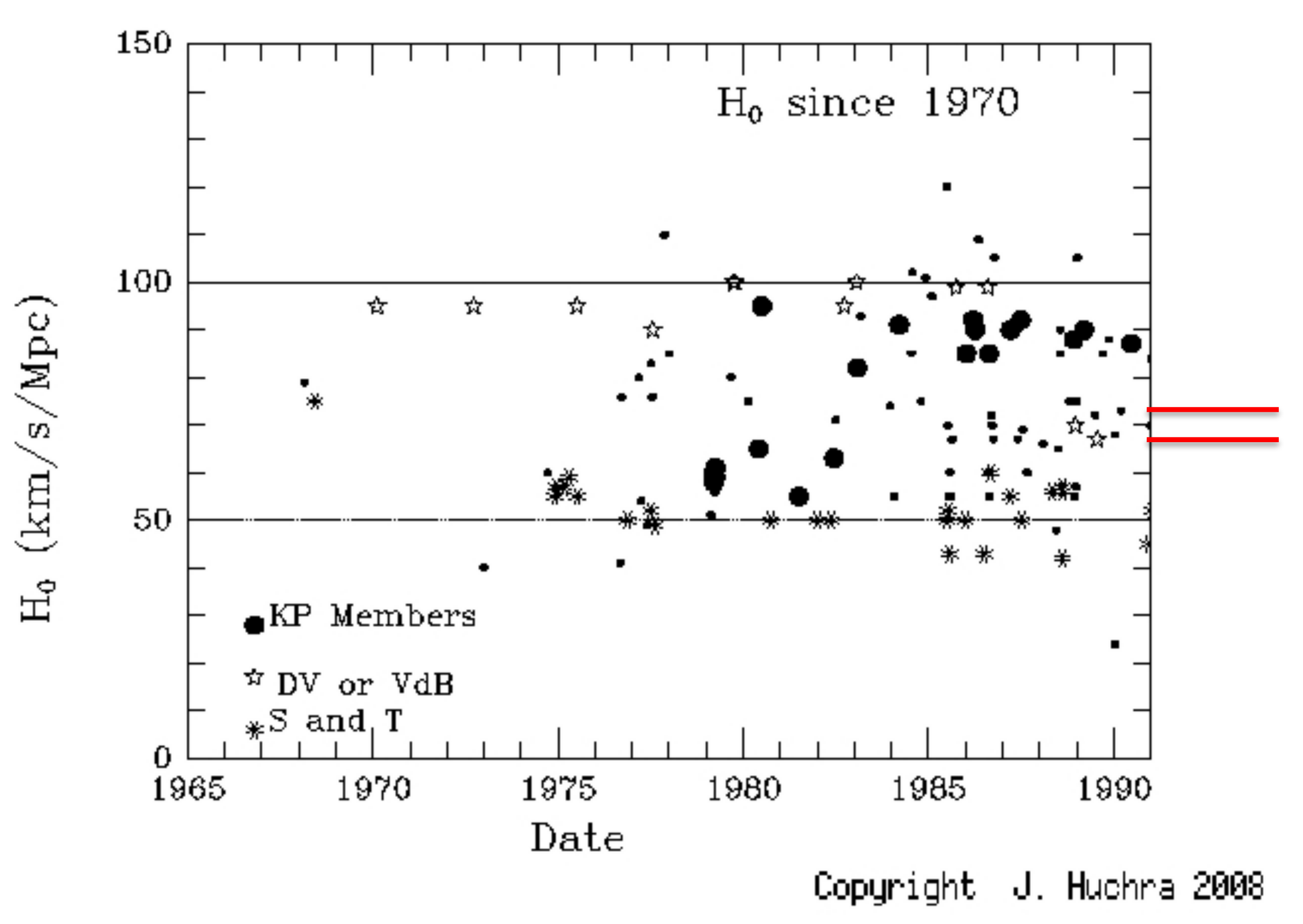


Planck
$H_0 = 67.4$

2-6 σ tension

Cepheids
$H_0 = 73.0$

History of the Hubble Constant…

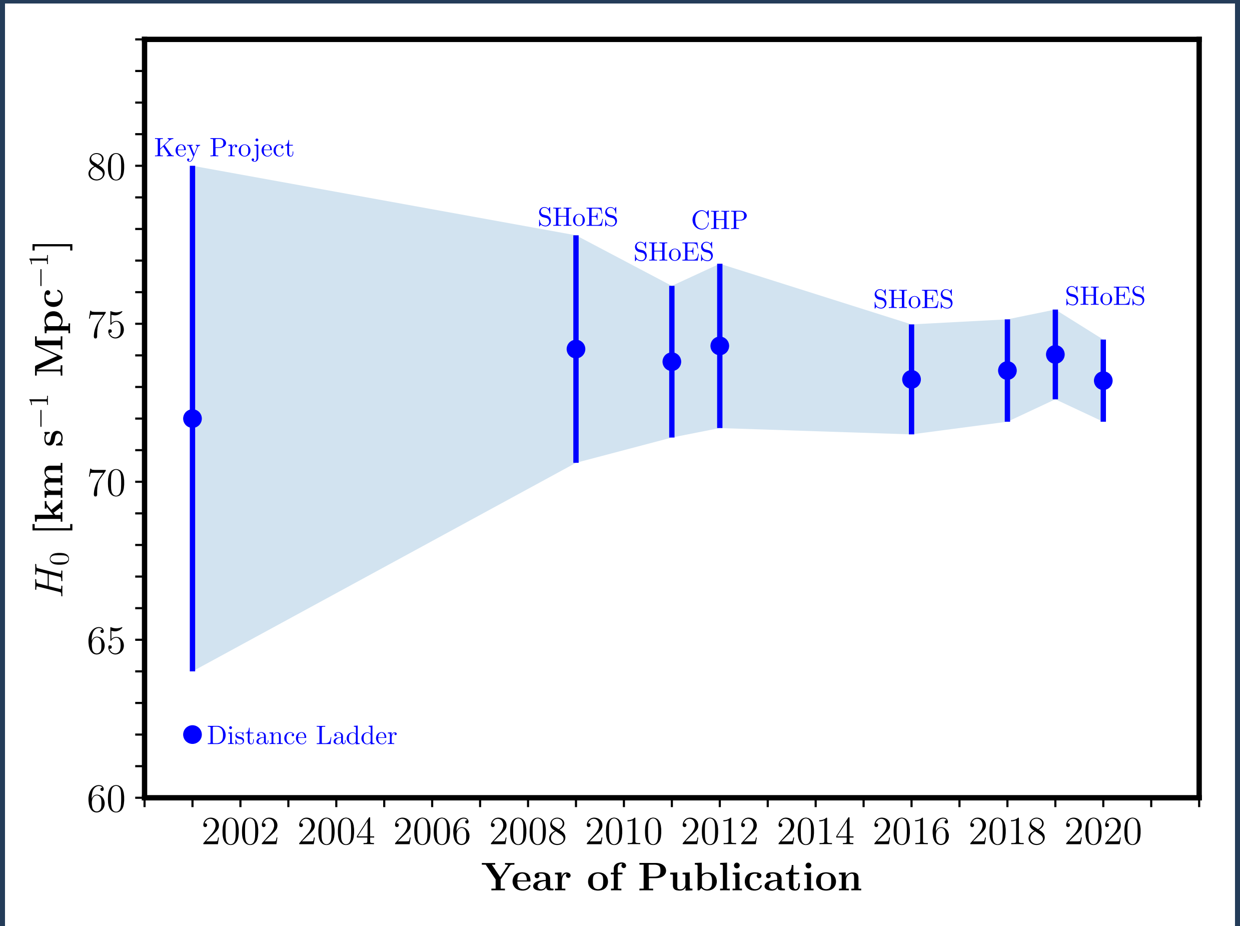


… Is a history of overcoming systematic effects (e.g., factor of 2)

The improvements have been enormous.

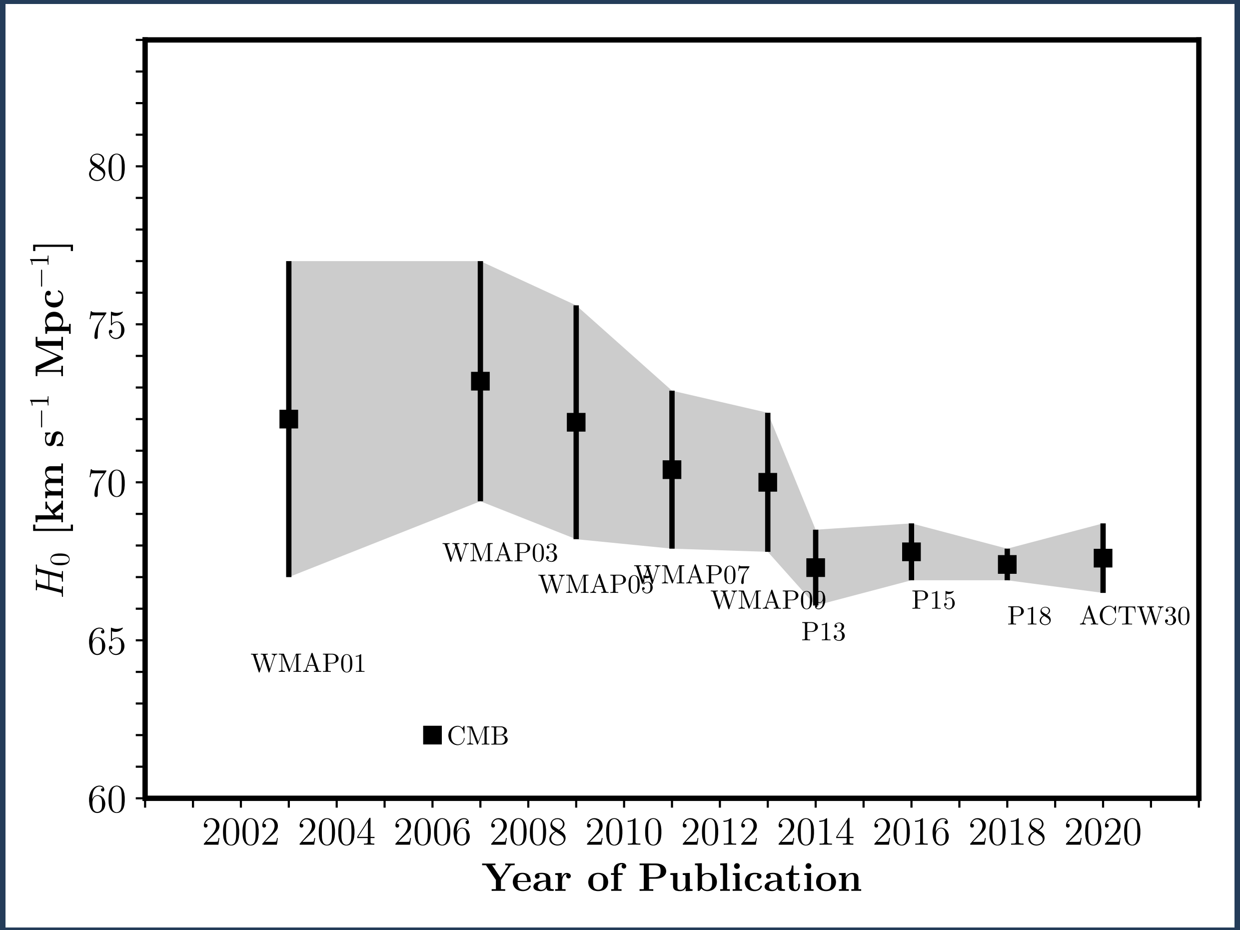
But challenges remain.

The Current Tension in H_0



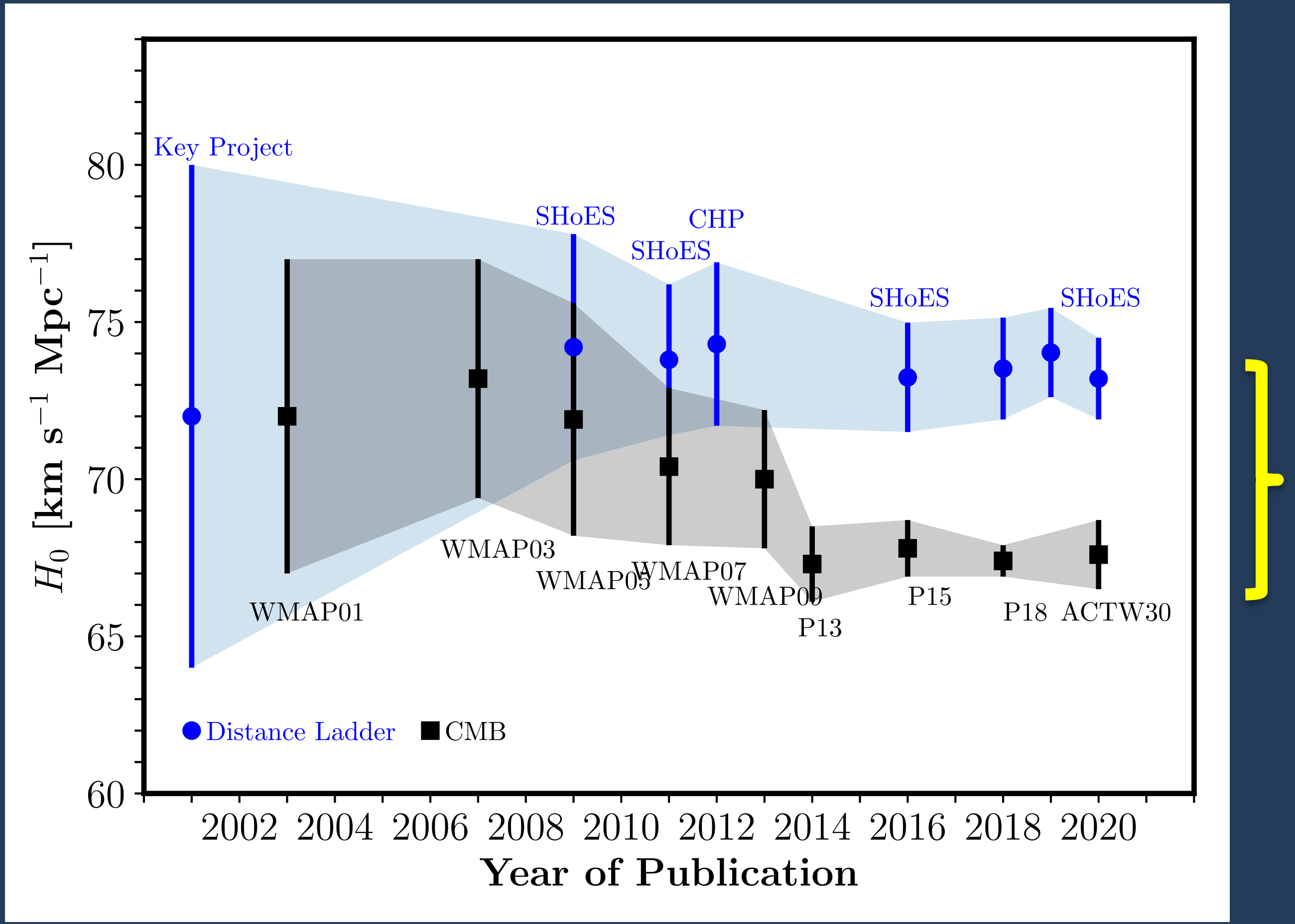
Updated from Freedman et al., 2017

The Current Tension in H_0



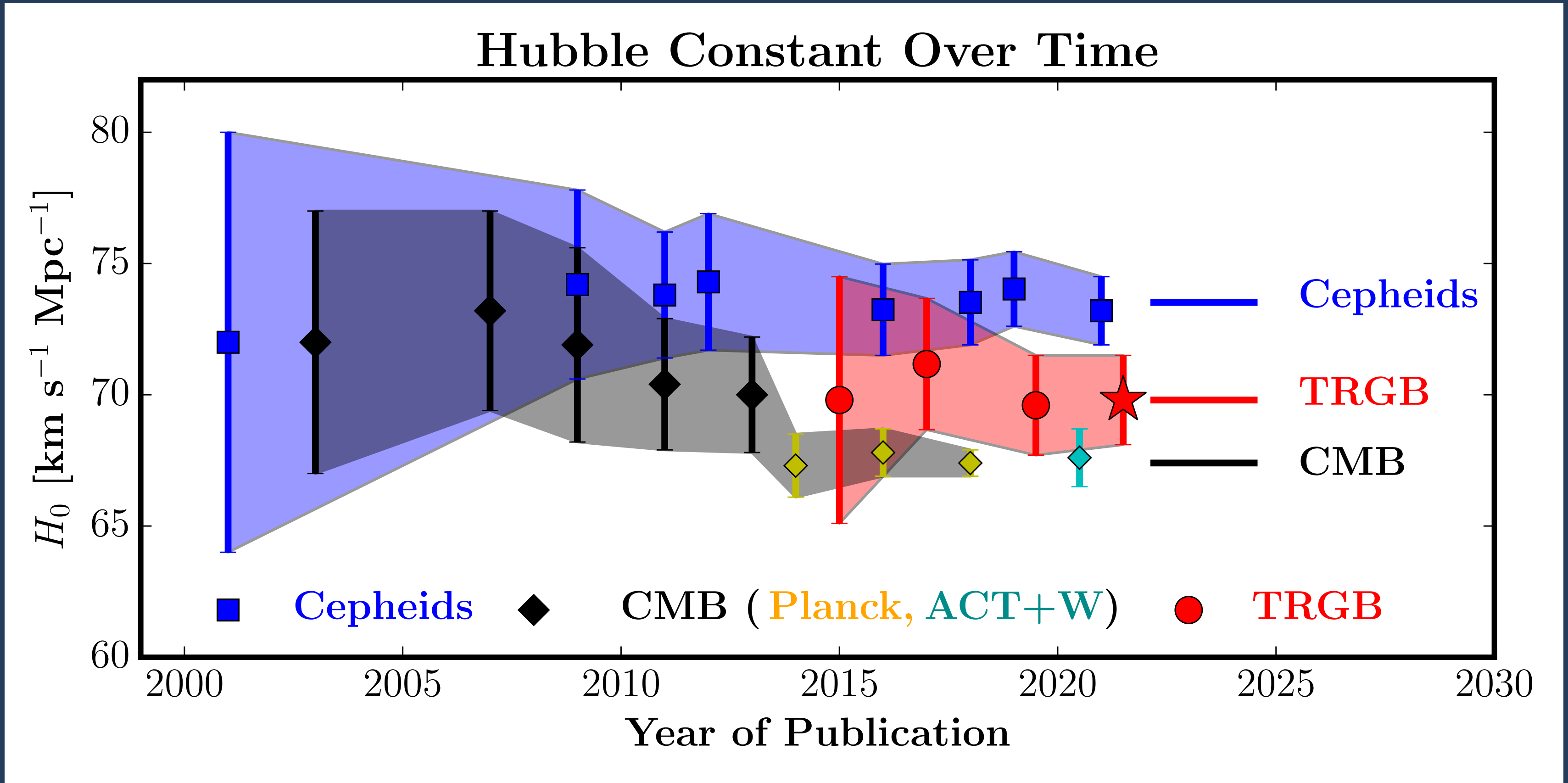
Updated from Freedman et al., 2017

Tension in the Hubble Constant



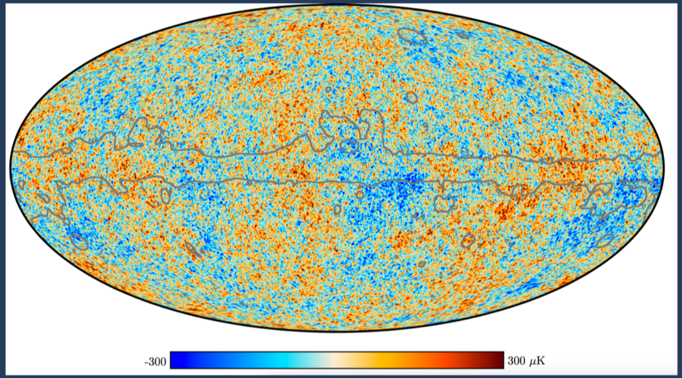
~3-5σ tension

Recent Measurements of the Hubble Constant

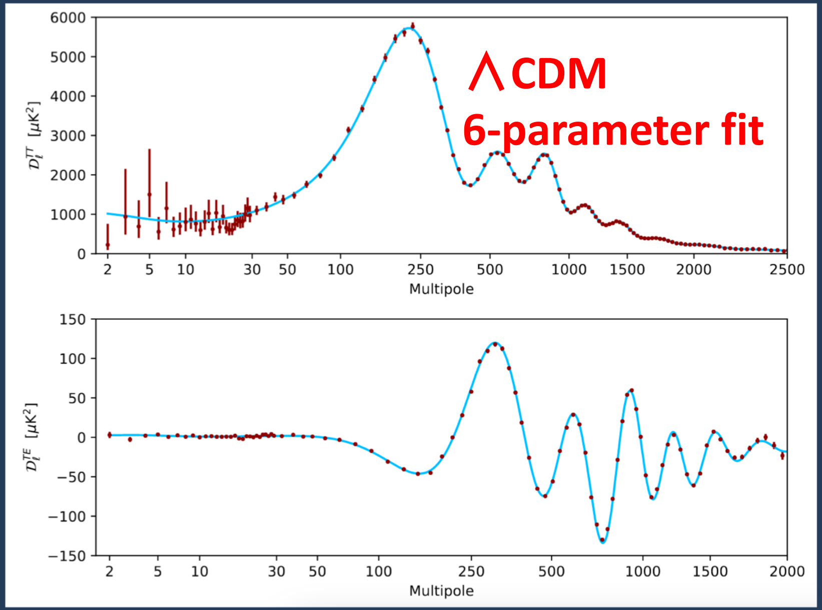


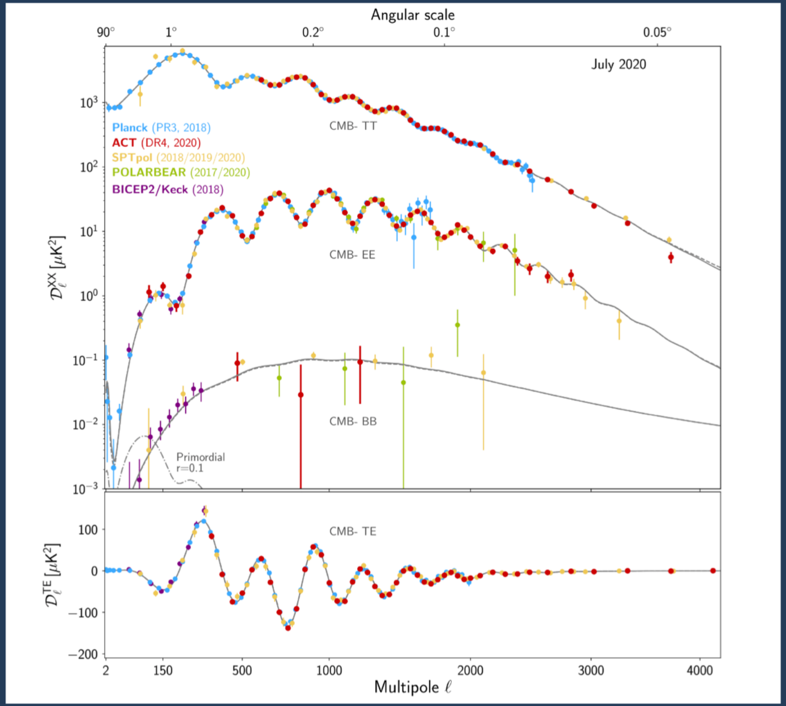
Freedman (2021) ApJ, 919, 16

Recent Measurements of CMB Anisotropies



Planck 2018



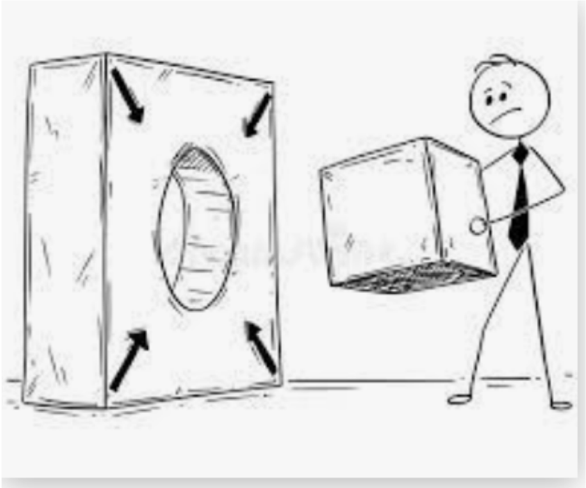


ACT Choi et al. 2020

$$H_0 = 67.4 \pm 0.5 \frac{\text{km}}{\text{sec}} / \text{Mpc}$$

Potential New Physics Beyond ΛCDM, If Real

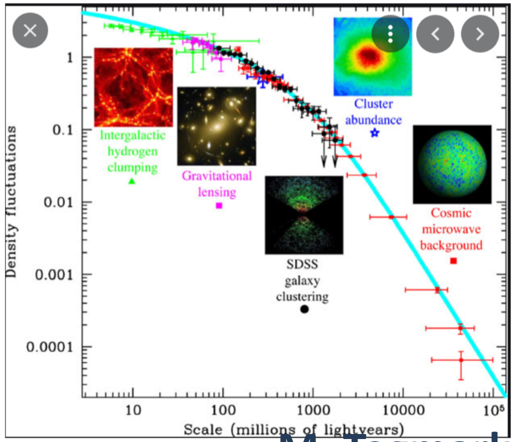
- Another relativistic species (e.g., an additional neutrino or other 'dark radiation')
- A different equation of state for dark energy from w = -1
- A decaying relic massive dark matter particle
- Interacting dark matter and dark energy
- Modified gravity
- Non-zero spatial curvature
- Additional early-universe physics (prior to recombination) **UPCOMING ACTPol



Challenges to Solving the Hubble Tension

Di Valentino (2022):

- **Cosmological models addressing the H0 tension turn out to be extremely difficult to construct!**
- **The flat (6-parameter) ΛCDM model can simultaneously fit a multitude of data sets, in addition to the CMB data, ranging from BBN to BAO, LSS and SNIa data.**
- **Late-time solutions (post-recombination) are thus disfavored.**
- **Early-time solutions (pre-recombination) are currently preferred.**
- **Note: early-time solutions worsen the cosmic shear (S_8) tension.**
- **There is currently no convergence on a new concordance model.**



M. Tegmark

Theoretical Possibilities That Don't Impact the Late-Time Peaks in the CMB Spectrum

This turns out to be very challenging!

Early Dark Energy (EDE)

$H_o > 71$ hard to achieve

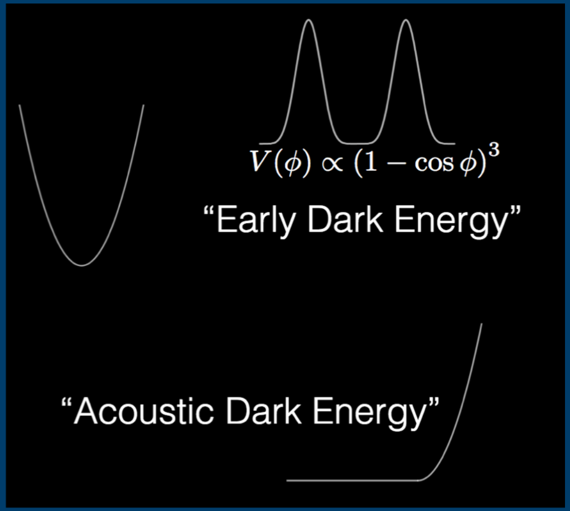
- Scalar field that before recombination, behaves like a cosmological constant, and then falls off as radiation (or faster) at later times.

e.g., Smith, Poulin & Amin (2019)

Acoustic Dark Energy (ADE)

- Scalar field that converts its potential to kinetic energy, is relevant around the time of matter radiation equality and then quickly fades away.

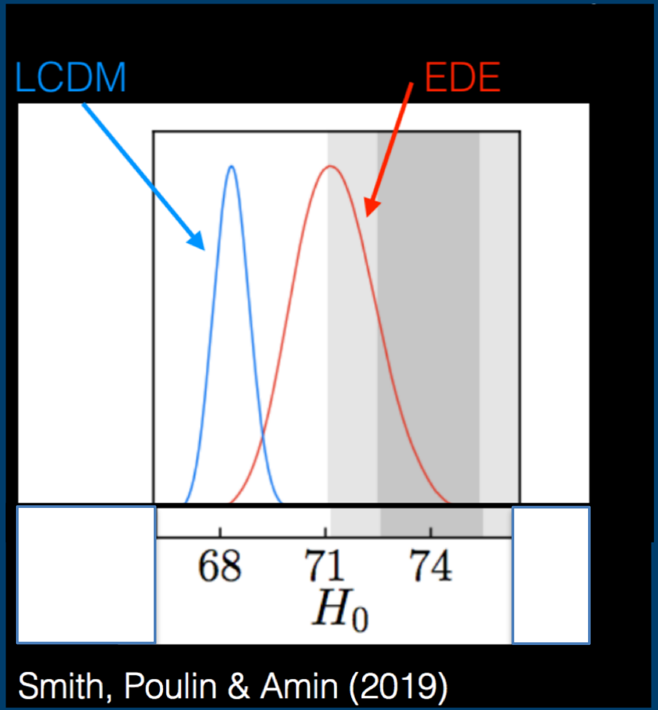
e.g., Lin, Benvenuto, Hu & Raveri (2019)



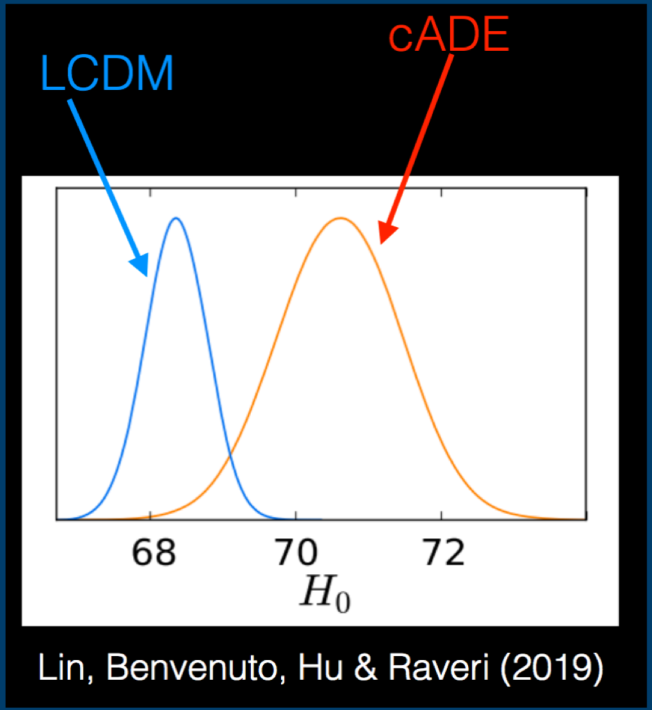
L. Knox

Possible Solutions for Higher H_0

Early Dark Energy (EDE)



Acoustic Dark Energy (ADE)



Adapted from Lloyd Knox; see also Hubble Hunter's Guide.(Knox & Millea, 2019)

N. B. Upcoming E-mode polarization measurements (e.g., ACTPol, SPTPol) can definitively test these models.

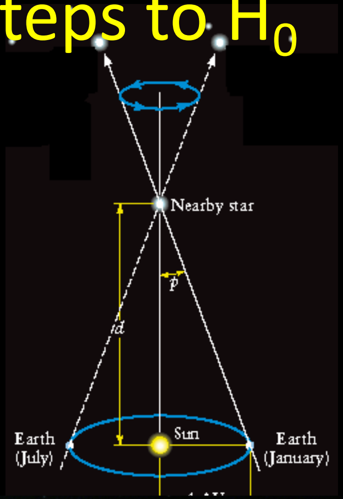
Precision vs Accuracy

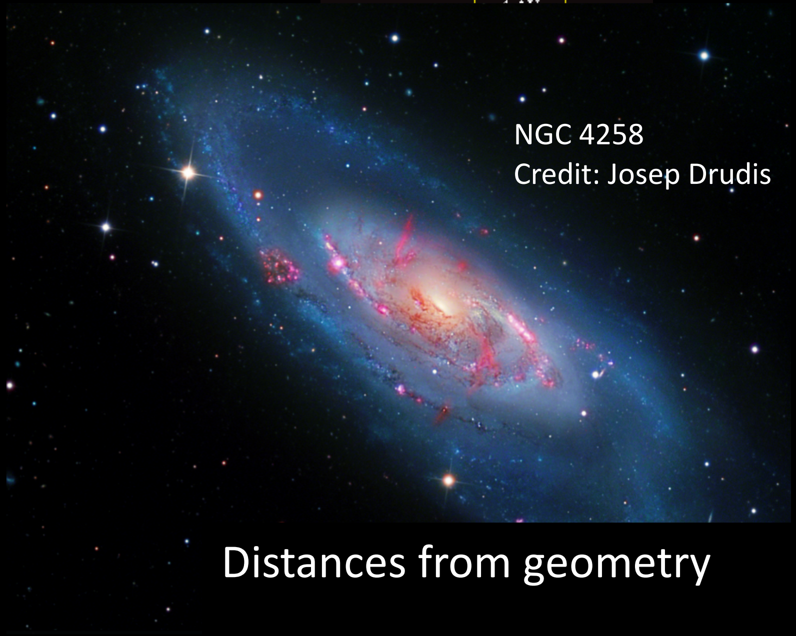
Precision

Accuracy

3 Current Steps to H_0

1.



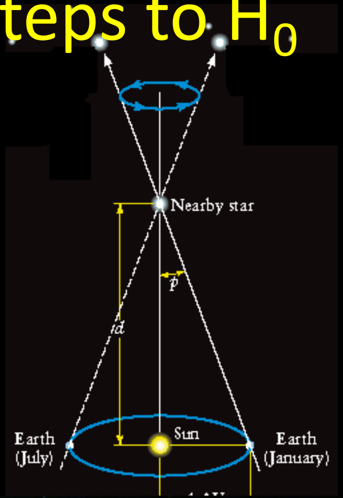


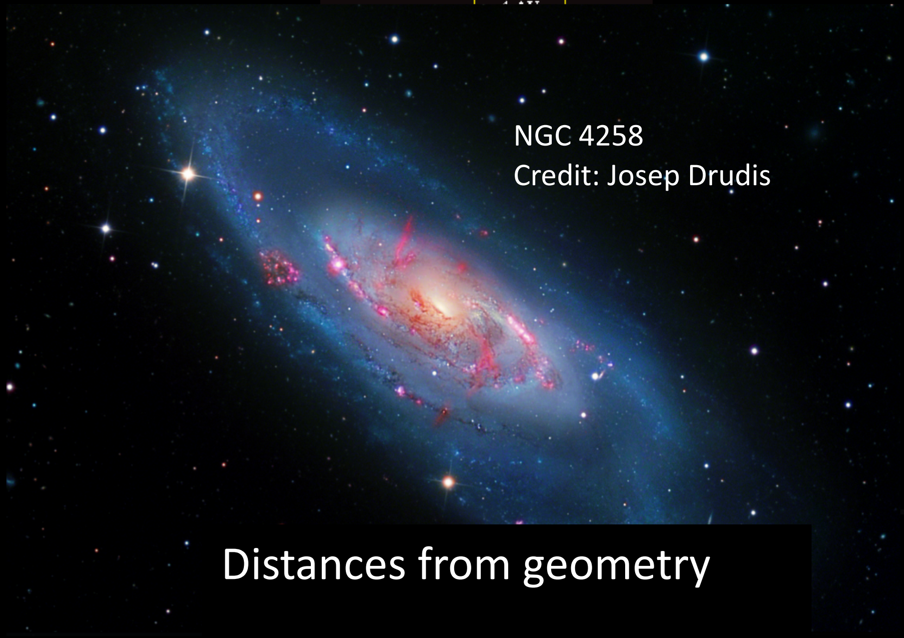
Distances from geometry

Geometric Anchors
1-50 kpc, 7.6 Mpc

3 Current Steps to H_0

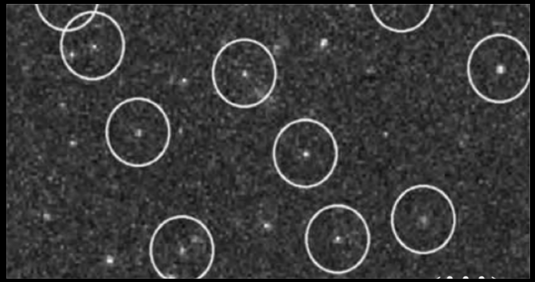
1.





Distances from geometry

2.



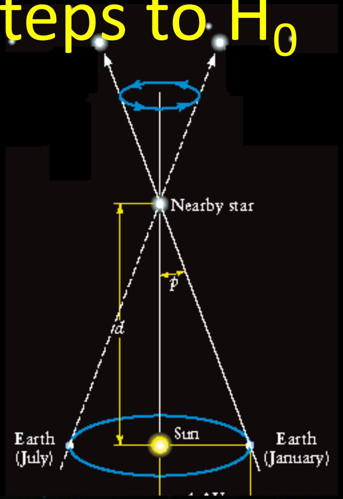
Nearby Galaxies Hubble Space Telescope

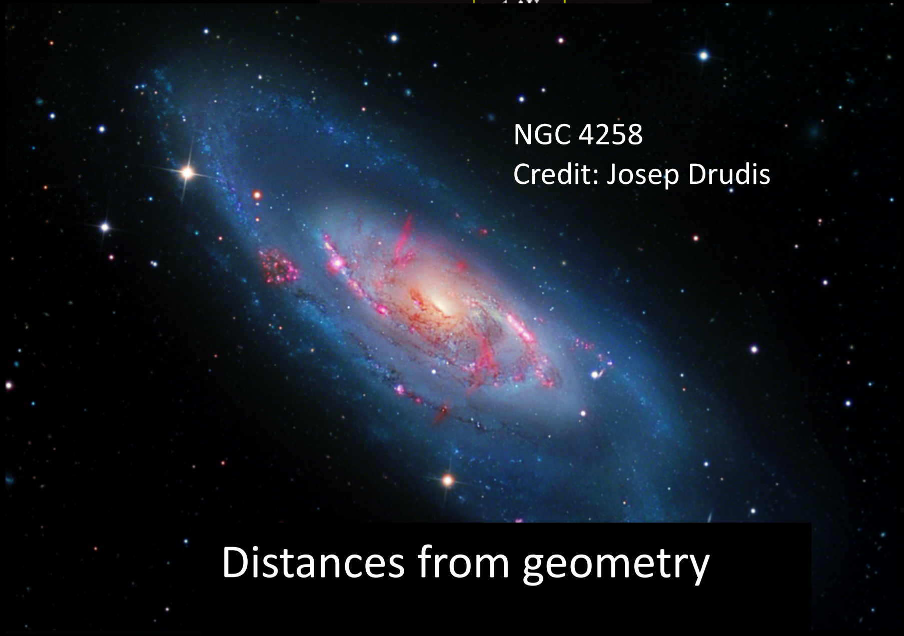
Geometric Anchors
1-50 kpc, 7.6 Mpc

TRGB & Cepheid Supernova Calibration
7-30 Mpc

3 Current Steps to H_0

1.

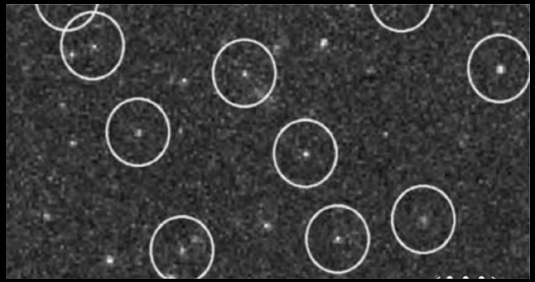




Distances from geometry

Geometric Anchors
1-50 kpc, 7.6 Mpc

2.



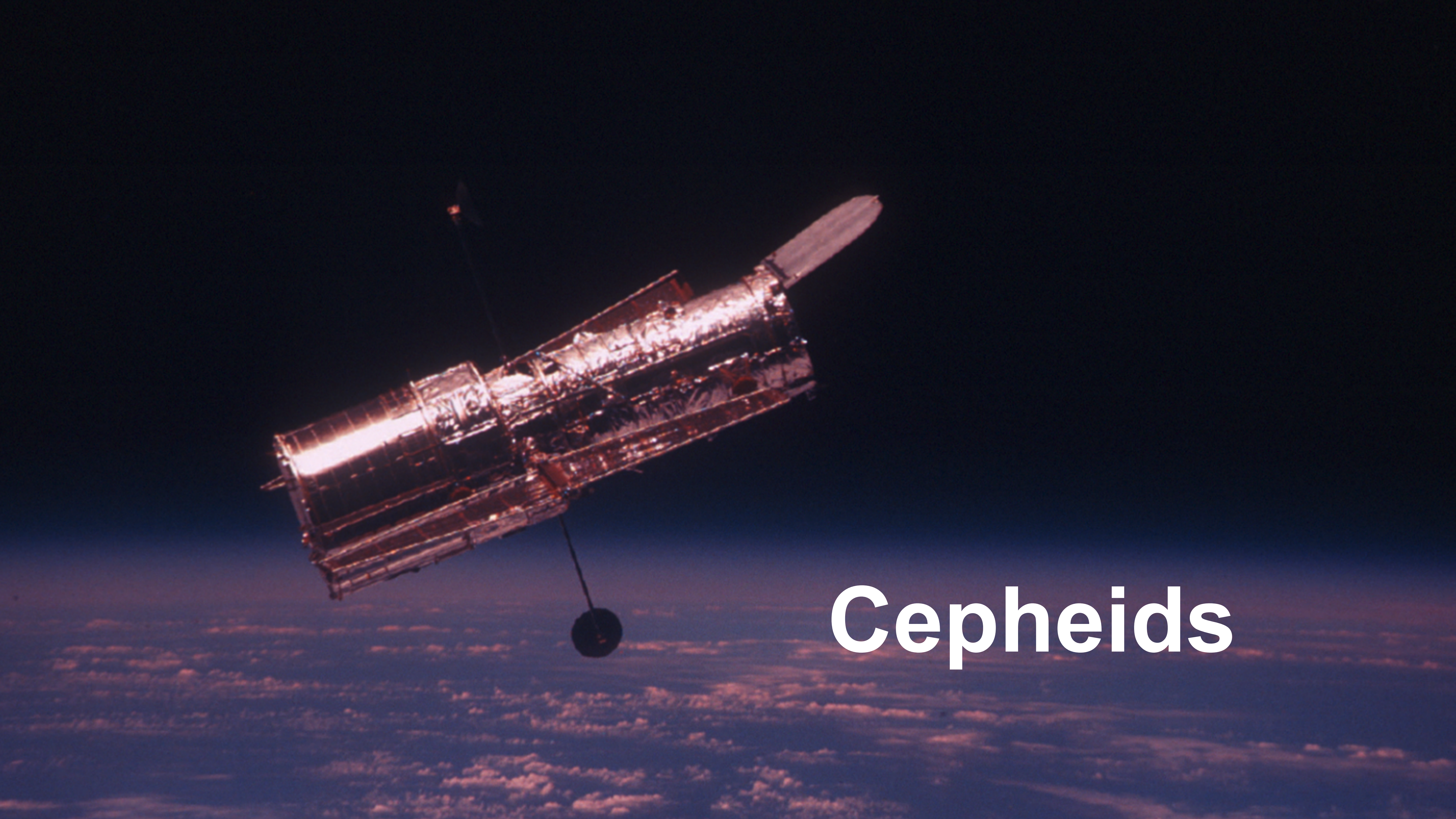
Nearby Galaxies Hubble Space Telescope

TRGB & Cepheid Supernova Calibration
7-30 Mpc

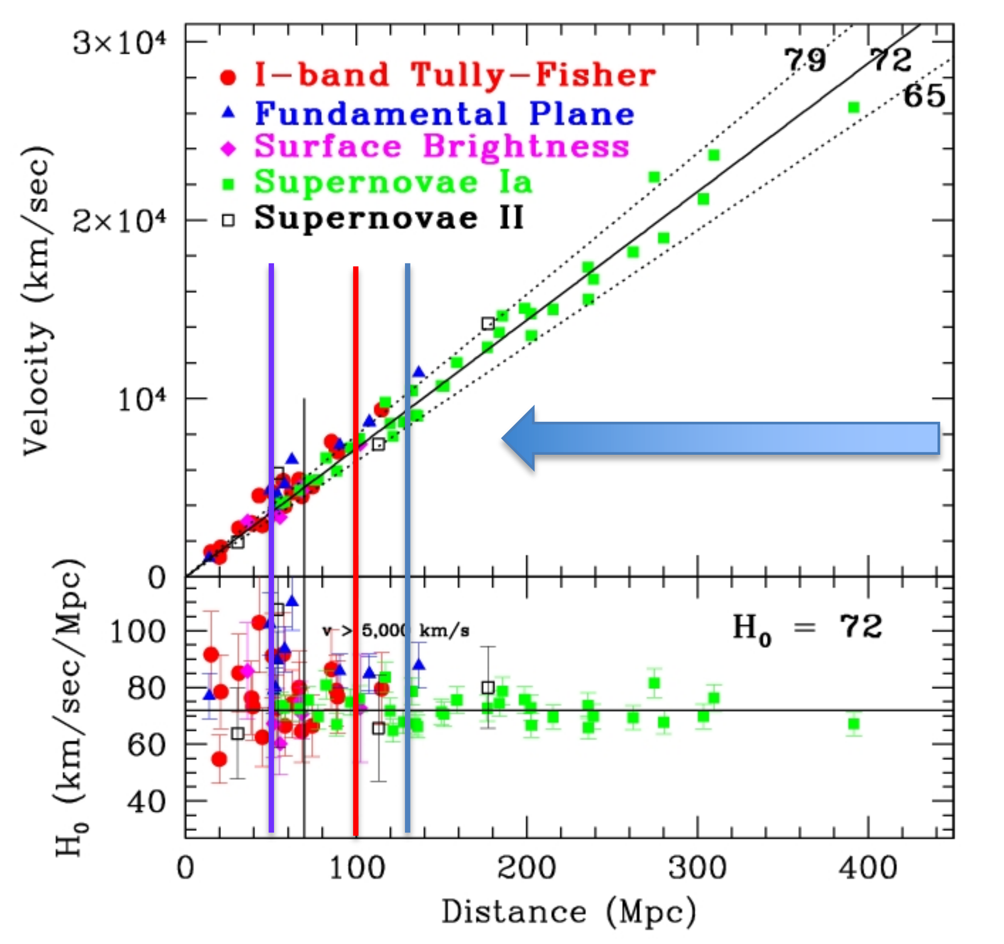
3.

Distant Galaxies: Supernovae

Supernova Hubble Diagram
100-500 Mpc


Cepheids

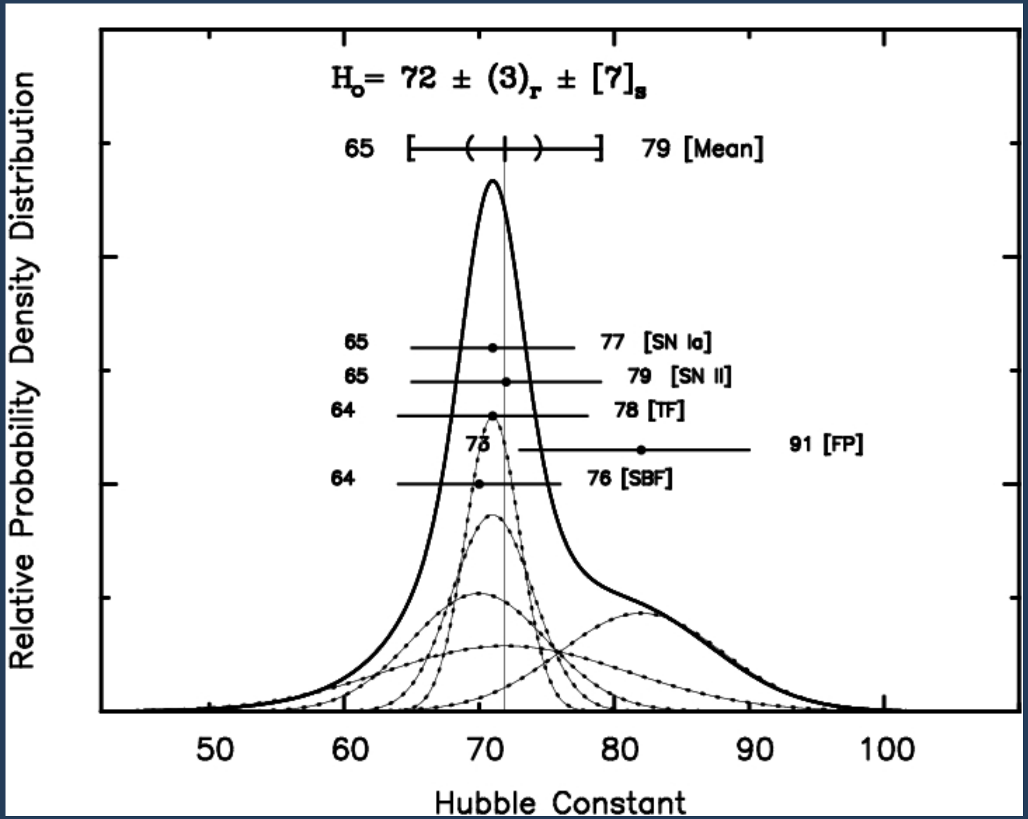
Final HST Key Project Combined Results



Current distance limits of
maser
SBF
GW siren
techniques

Freedman et al. 2001

Final Key Project Combined Results



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

WLF et al. 2001

Advantages & Disadvantages of Cepheids and TRGB for Measuring Distances

Cepheids

Advantages

1 Bright (M_V ~-6 mag)
2 Easily Identifiable
3 Potentially small dispersion in PL

Disadvantages

1 Metallicity dependence
2 Late-type galaxies only
3 Crowding/blending
4 Need many epochs
5 In regions of high extinction

TRGB

Advantages

1 In all types of galaxies
2 In regions of low to no extinction
3 Crowding negligible
4 Non-variable
5 Easily calibrated metallicity
6 Small dispersion in tip luminosity

Disadvantages

1 Fainter (M_I~-4 mag)

Freedman (2021) ApJ, 919, 16

Cepheid Calibration of the Hubble Constant

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

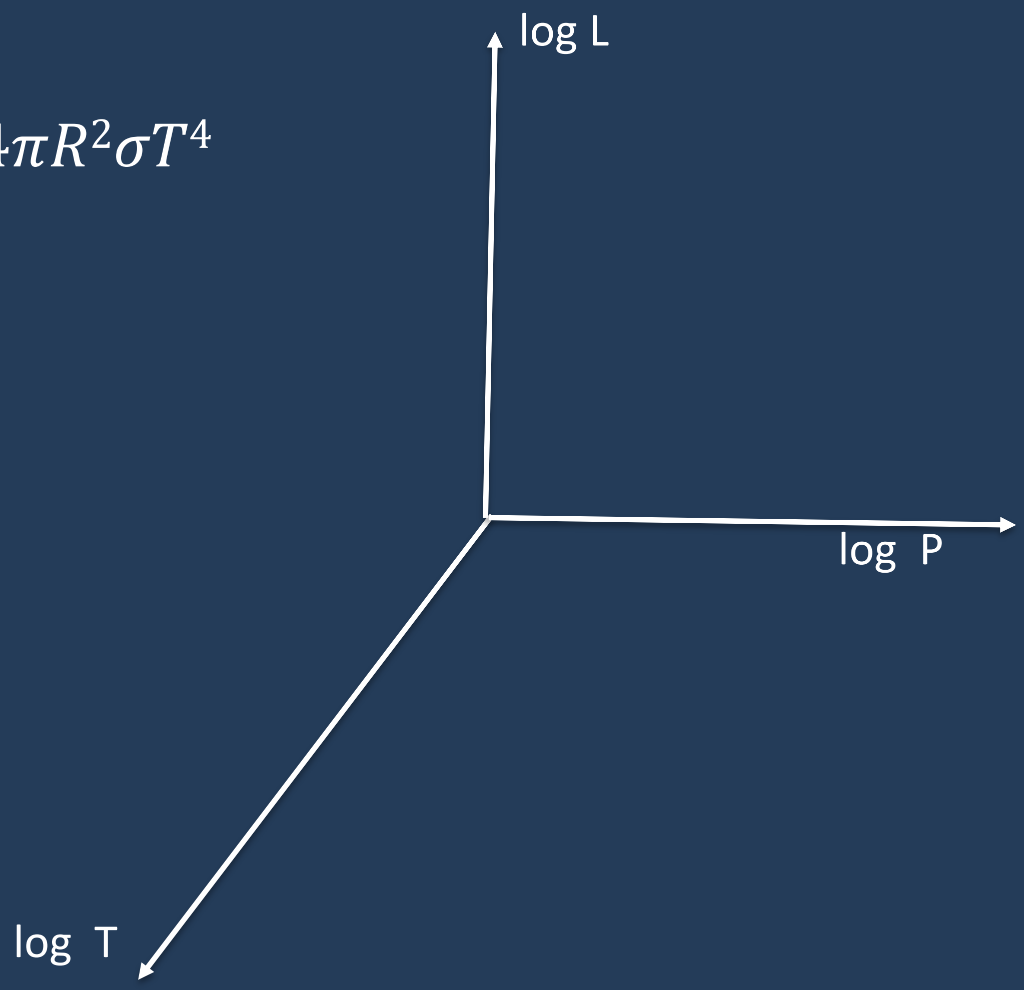
Spitzer: $H_0 = 74.3 \pm 2.1$ (stat.) $\pm$ 4 (sys.) km/sec/Mpc

SHoES: $H_0 = 73.04 \pm 1.04$ (total) km/sec/Mpc

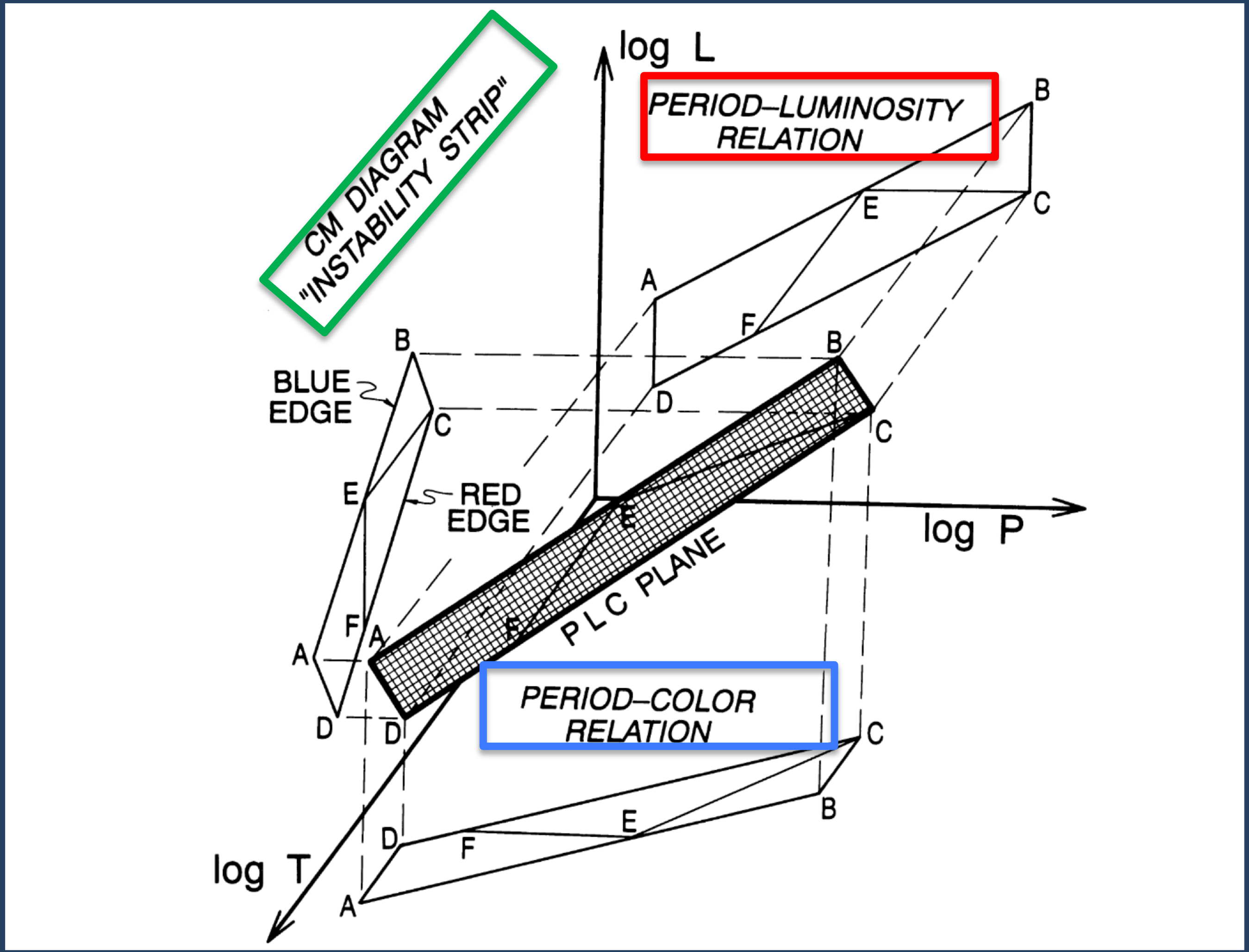
Can we conclude that these Cepheid results are now definitive?

Astrophysical Distance Methods: Cepheids

$$L = 4\pi R^2 \sigma T^4$$



Astrophysical Distance Methods: Cepheids

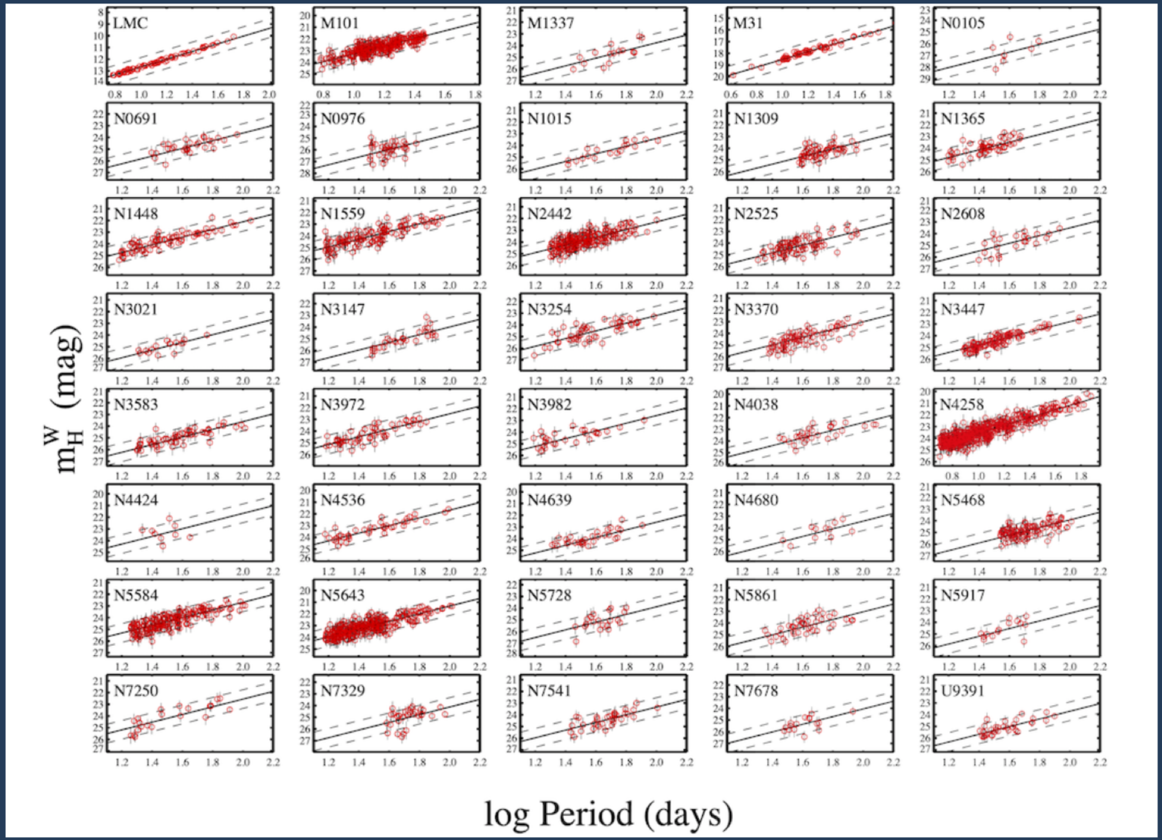


Madore & WLF 1991

Cepheids: Recent Progress

"The difference between H_0 measured locally and the value inferred from Planck CMB and ΛCDM is 6.6±1.5 $kms^{-1}Mpc^{-1}$ or 4.4σ (P=99.999% for Gaussian errors) in significance, raising the discrepancy beyond a plausible level of chance."

Riess et al. 2019



Riess et al. 2021

SHoES program

37 Cepheid galaxies

$H_0 = 73.04 \pm 1.04$ [1.4%]

(Total error)

What Should We Next Understand to Take Cepheid Measurements to Next Level of Accuracy?

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

Important tests of the Cepheids:

1. the metallicity coefficient*
2. image resolution*

* JWST

γ (mag / dex)

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

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

Ripepi et al. 2021
Best estimates:

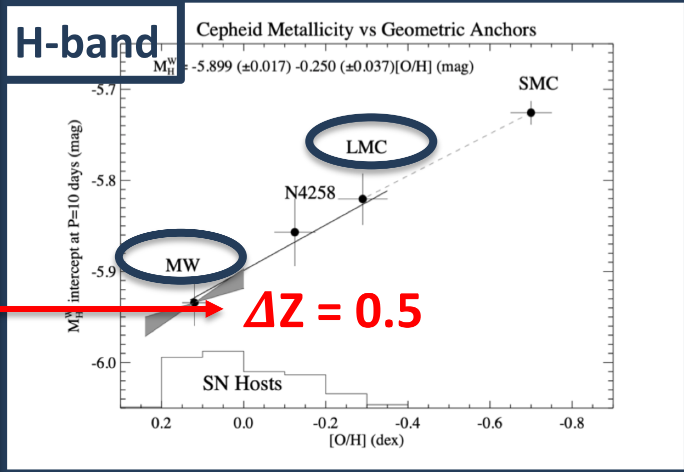
Breuval + Riess et al. 2021
-0.048 < γ < -0.251

Udalski et al. 2001
γ = 0

Implications:

- ΔZ (MW – LMC) = 0.5 dex
- For = -0.2 mag/dex ⇒ 0.1 mag or 5% in distance
- For = -0.4 mag/dex ⇒ 0.2 mag or 10% in distance

Given these uncertainties, it is not yet possible to rule out a systematic effect due to metallicity at the > 1% level.

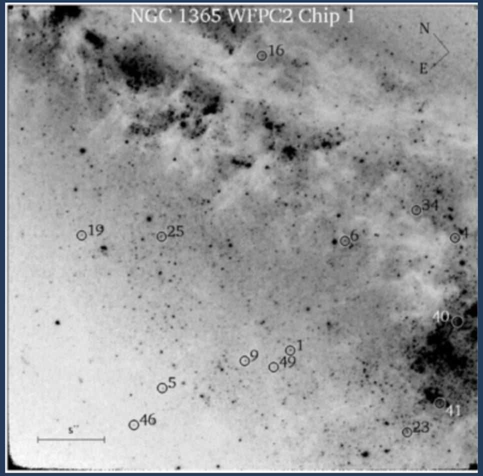


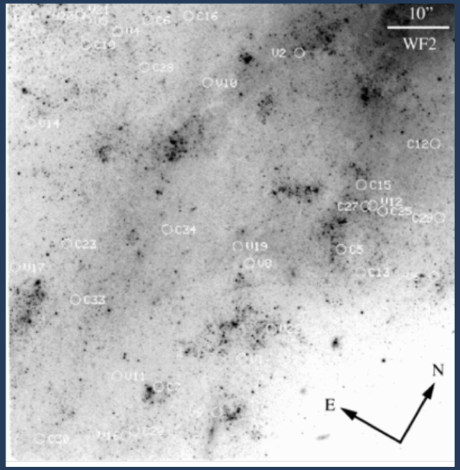
Gieren et al. 2021
-0.221 < γ < -0.335

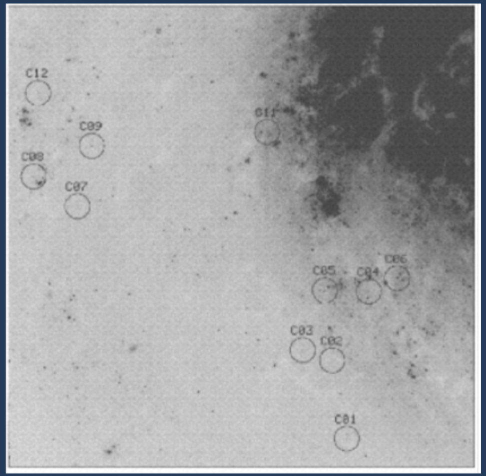
Riess et al. 2016
γ = -0.13 $\pm$ 0.07

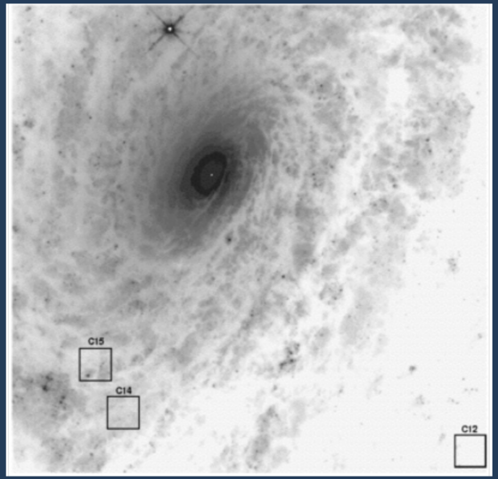
Riess et al. 2021
γ = -0.217 $\pm$ 0.046

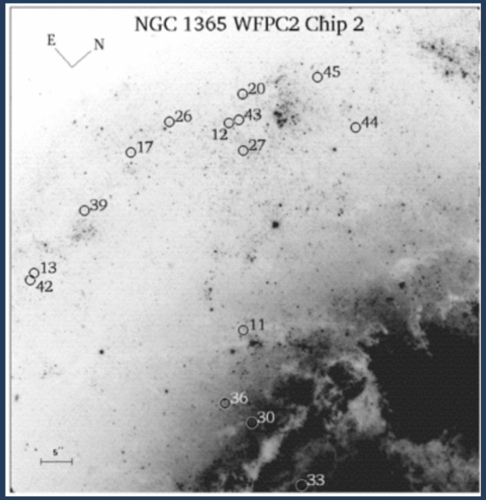
Location of Cepheids: HST Key Project (Nearby Galaxies: D < 15 Mpc)

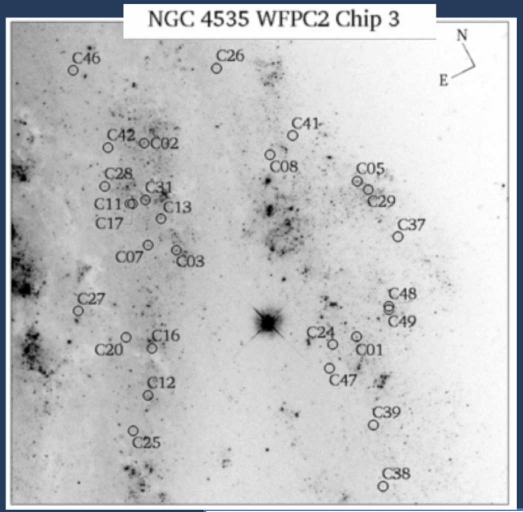


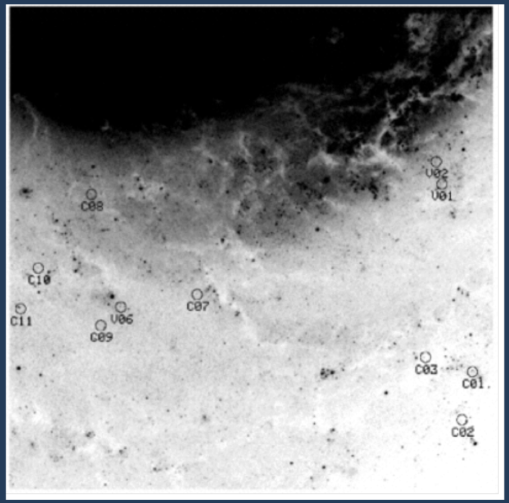


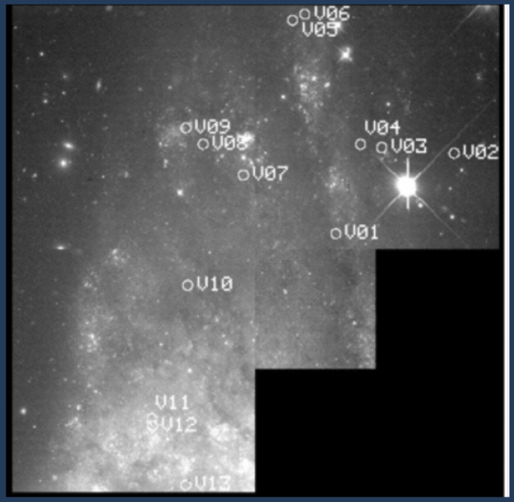












Optical (V-band) images 5550A

The Challenge for H_o Measurements

$$T = \frac{\Delta H}{\sqrt{\sigma_P^2 + \sigma_C^2}}$$

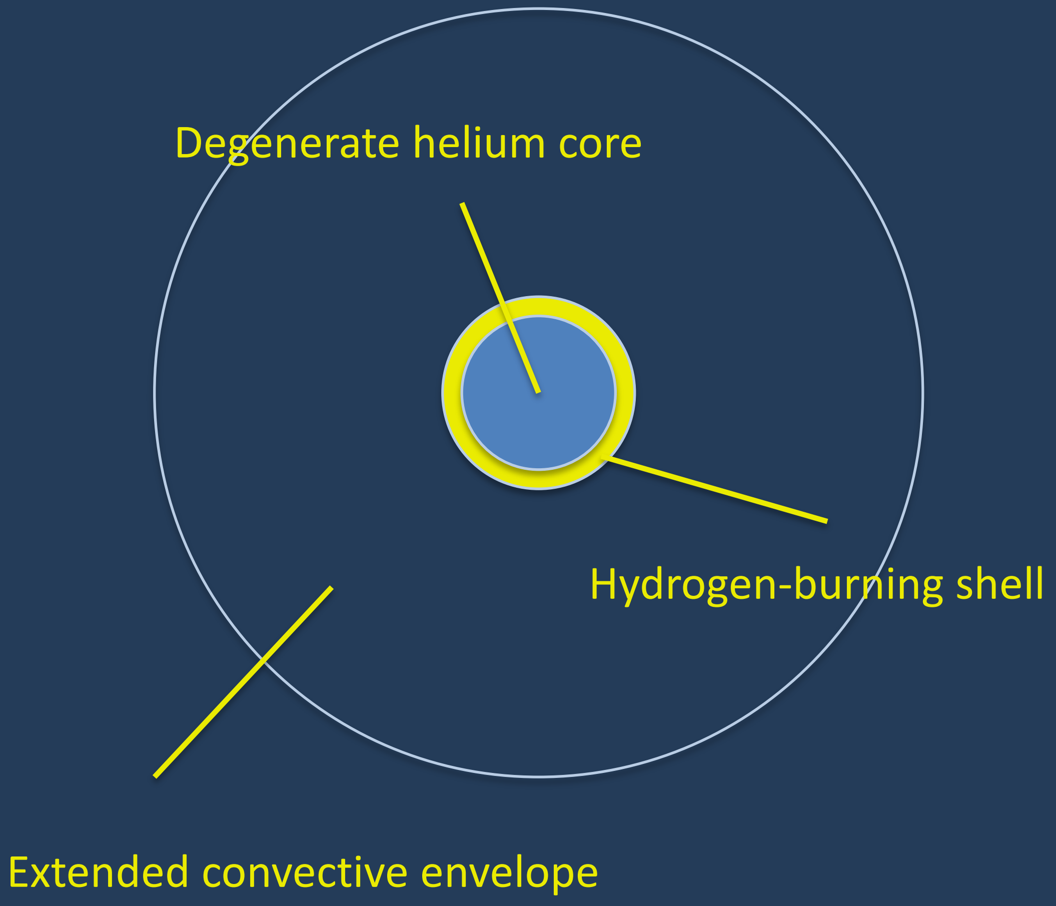
$H_{Planck} = 67.4$
$\sigma_{Planck} = 0.5$

$H_{Ceph} = 73.0$
$\sigma_{Ceph} = ??$

For the tension in H_o to be at a level of 5σ, H_0 has to be measured to a TOTAL (statistical precision + systematic accuracy of) 1.0%

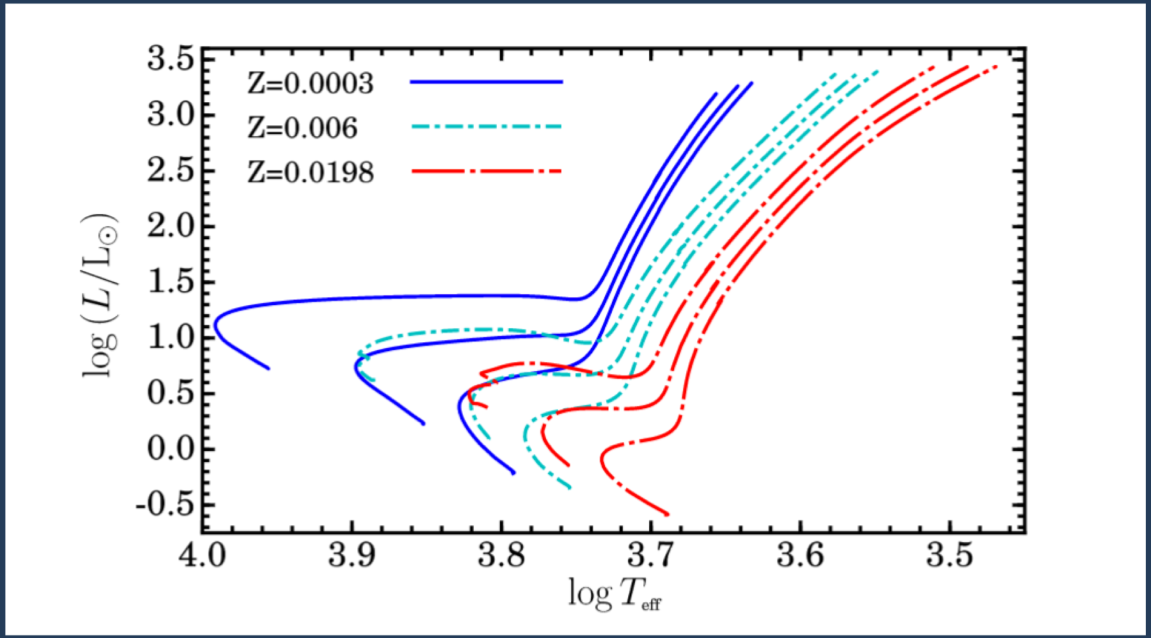
If, say, $H_0 = 72$ and the errors were a factor of 2 (1.5) larger than currently estimated, the tension would be only 1σ (3σ).

Stellar Astrophysical Distance Methods: Lifting Degeneracy in Helium Core for Low-mass Stars (TRGB)

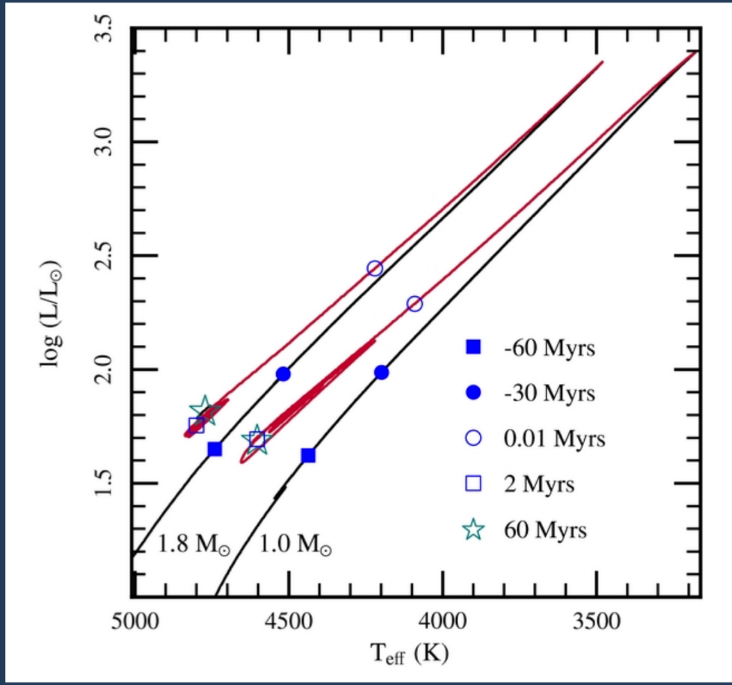


- **Well-understood nuclear physics determines the temperature at which the electron degeneracy in the core is lifted, followed by helium core ignition**
- **T_c~ 10^8 K, M_c=0.47 $M_\odot$**
- **Because of the degeneracy, the helium ignition happens at almost constant core mass. Thus the ignition occurs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

Tip of the Red Giant Branch (TRGB)



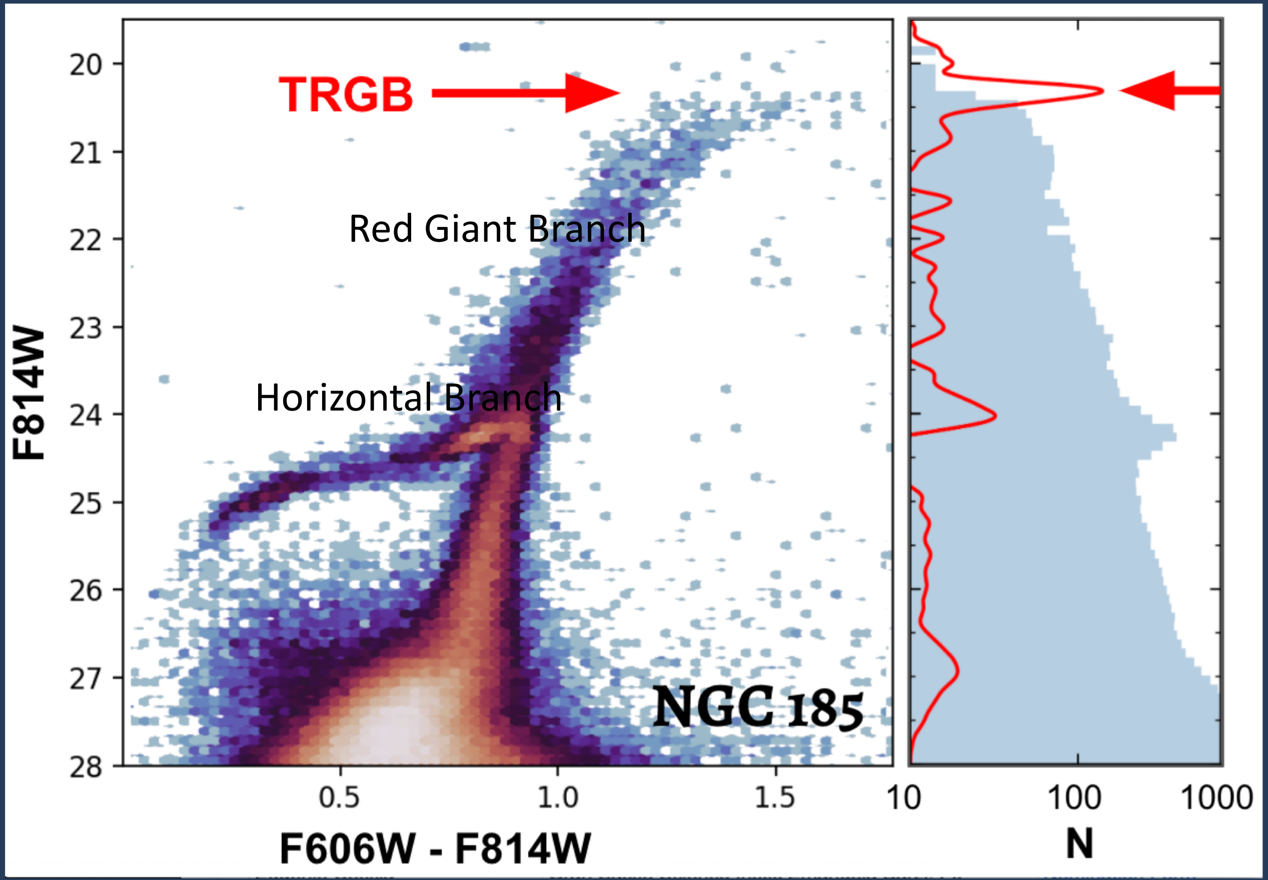
Serenelli et al. (2017)



He flash

Bildsten et al. 2012 (MESA)

Observing the TRGB

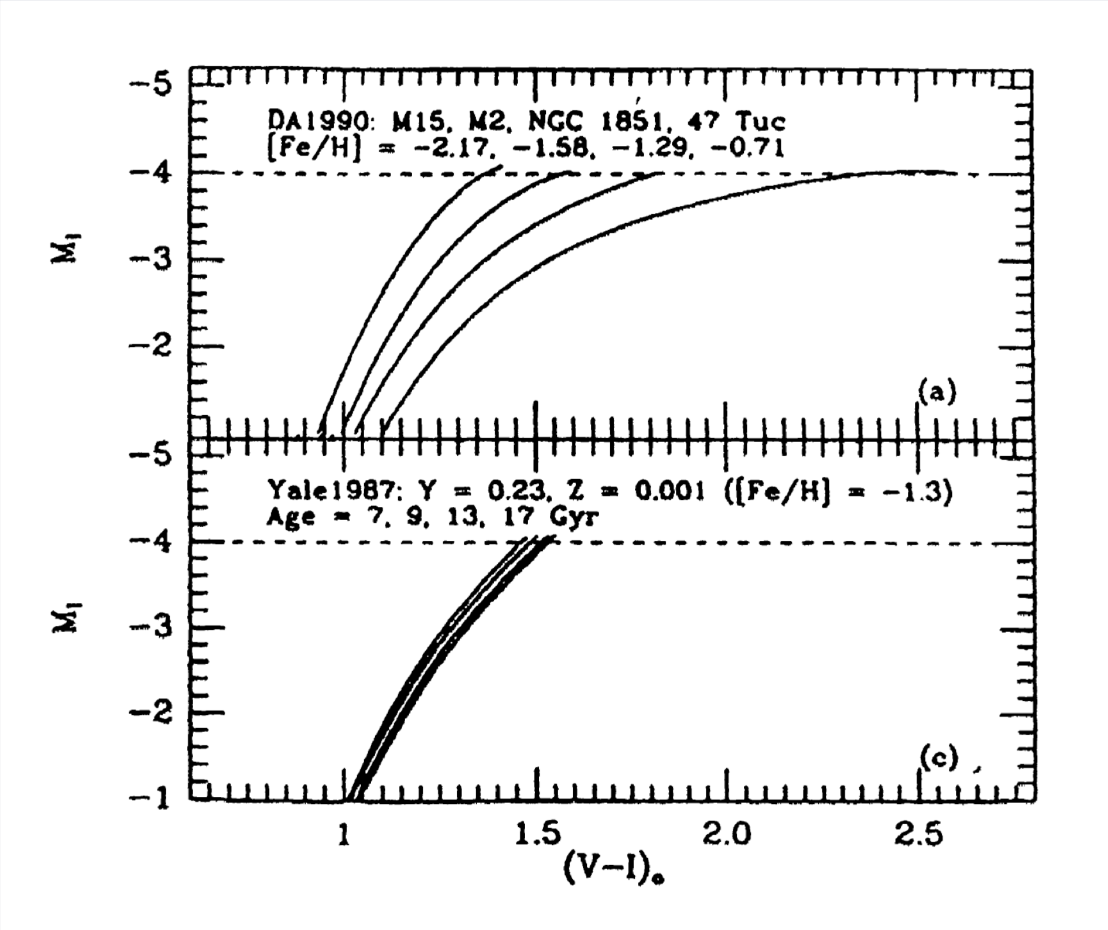


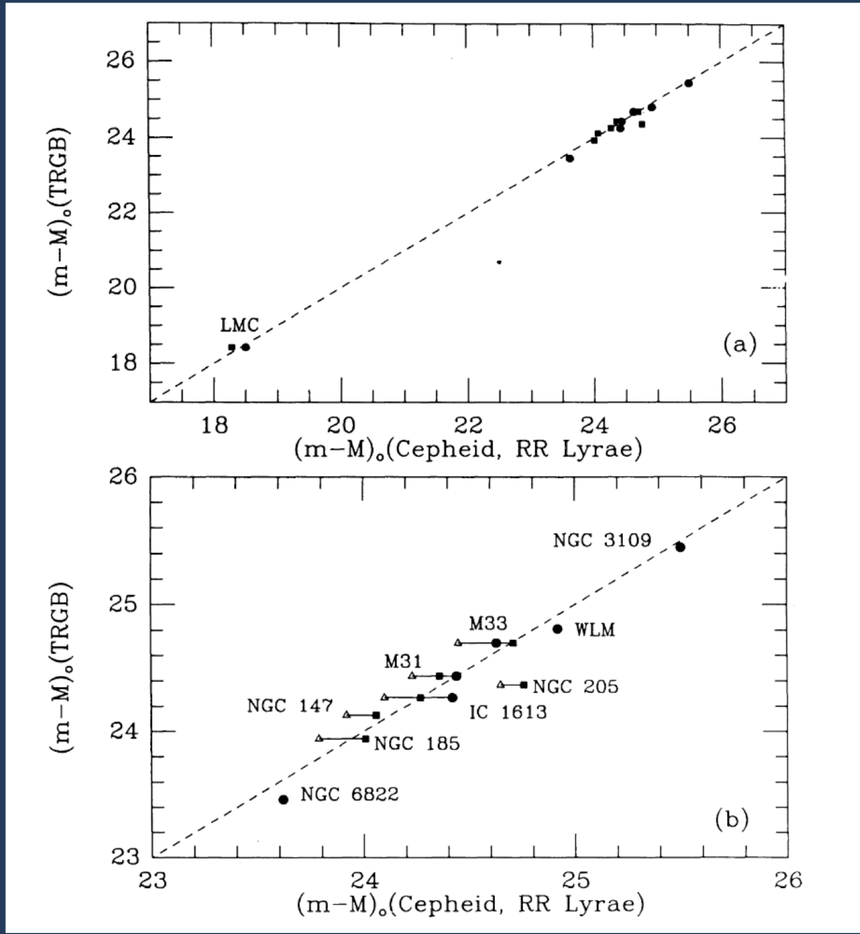
Luminosity ->

← Temperature

Data courtesy M. Geha,
Plot by I. Jang

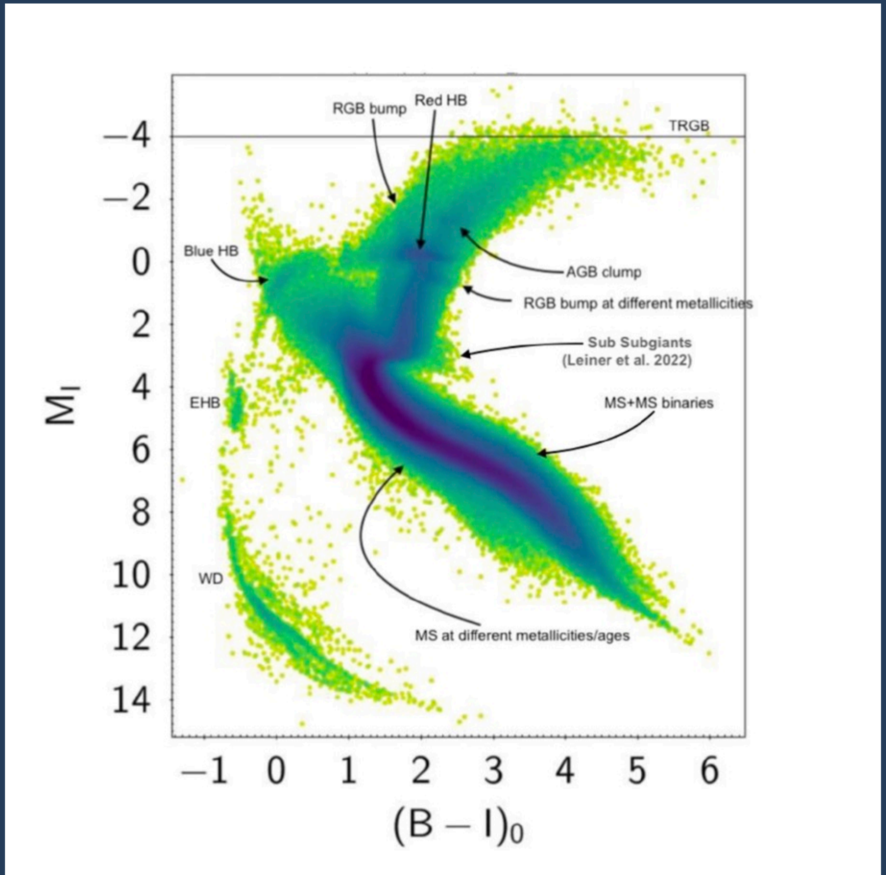
I-band TRGB for Measuring Distances





Lee, WLF, Madore 1990

Milky Way CMD from Gaia

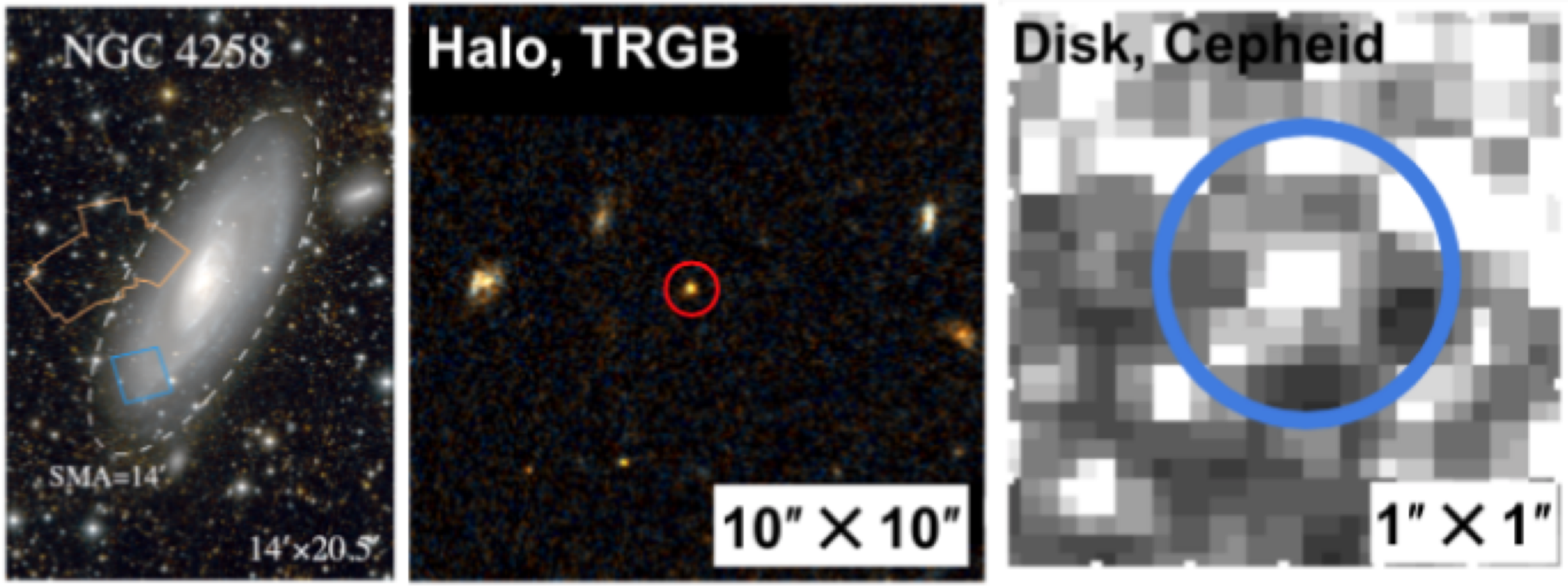


4 million stars |b| > 50º

CMD generated by combining Johnson-Kron-Cousins (B-I) from the Gaia parallax and XP spectra using synthetic photometry

M. Bellazini

Halo (TRGB) vs Disk (Cepheid) fields: NGC 4258



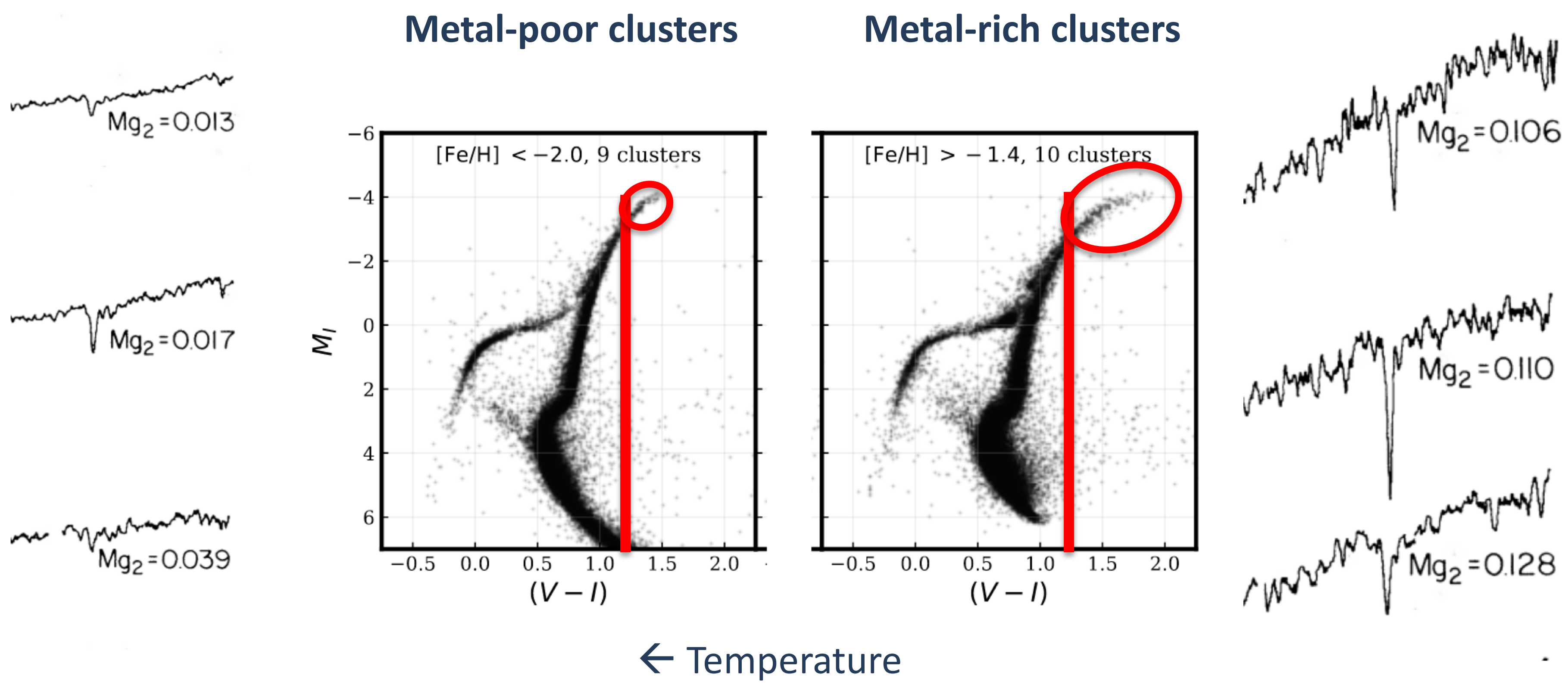
NGC 4258: distance 7.6 Mpc.

Cepheid shown is one of brightest in the sample.

The SN Ia hosts extend to >40 Mpc.

TRGB stars can be found in the outer halos of galaxies where the surface brightness is typically ~5 magnitudes (a factor of 100) fainter that the disk.

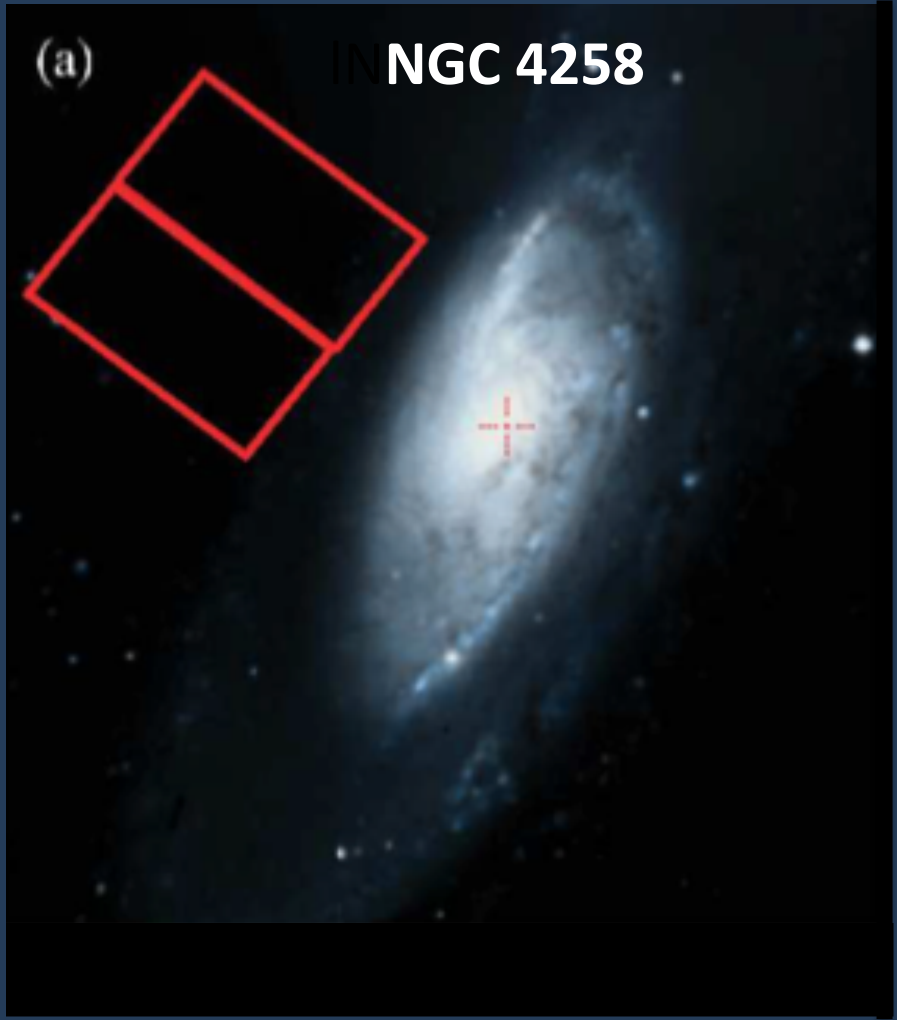
Empirical Calibration of the TRGB: Metallicity Effects

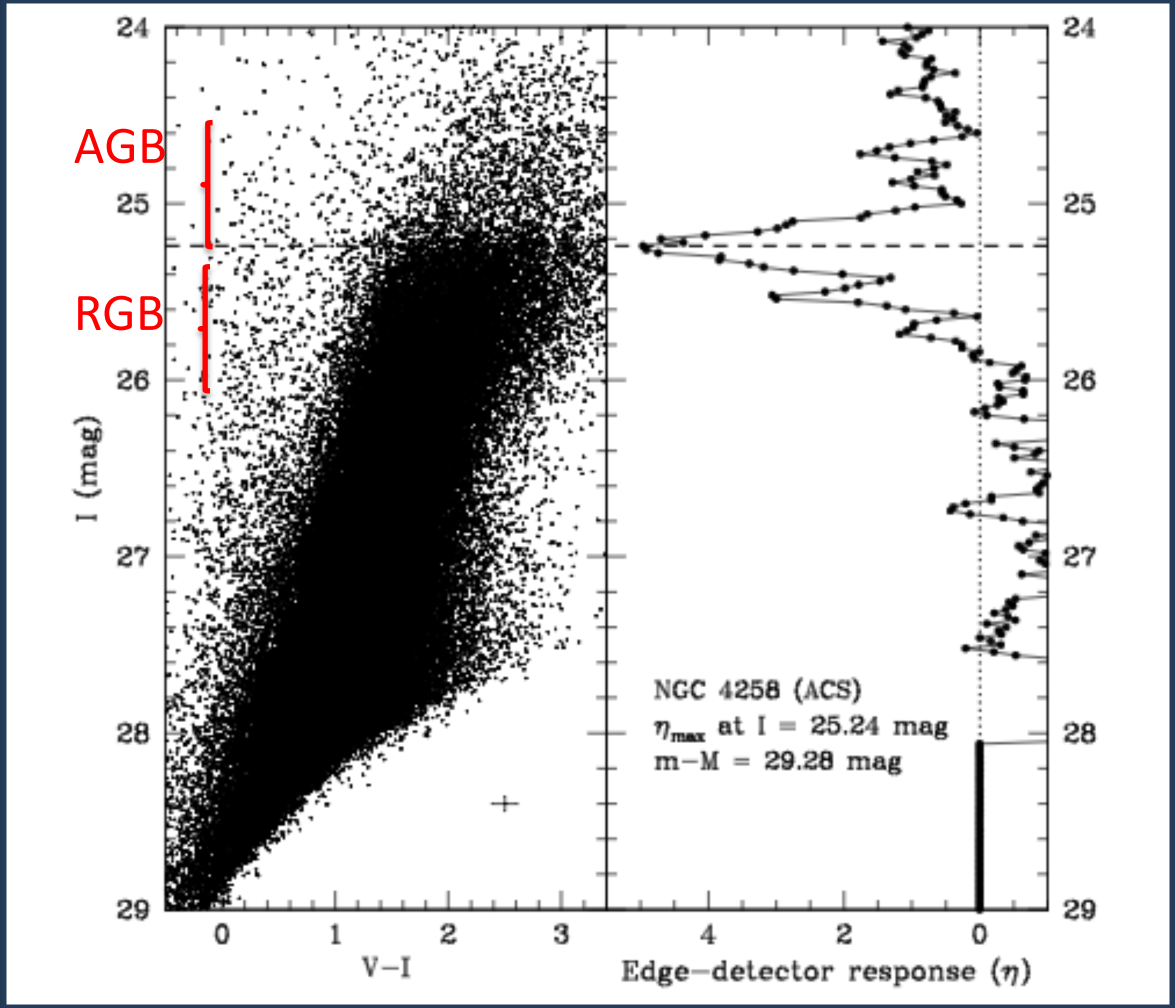


Spectroscopy from Burstein & Faber (1984)

CMDs adapted from Cerny et al. 2020

The Tip of the Red Giant Branch

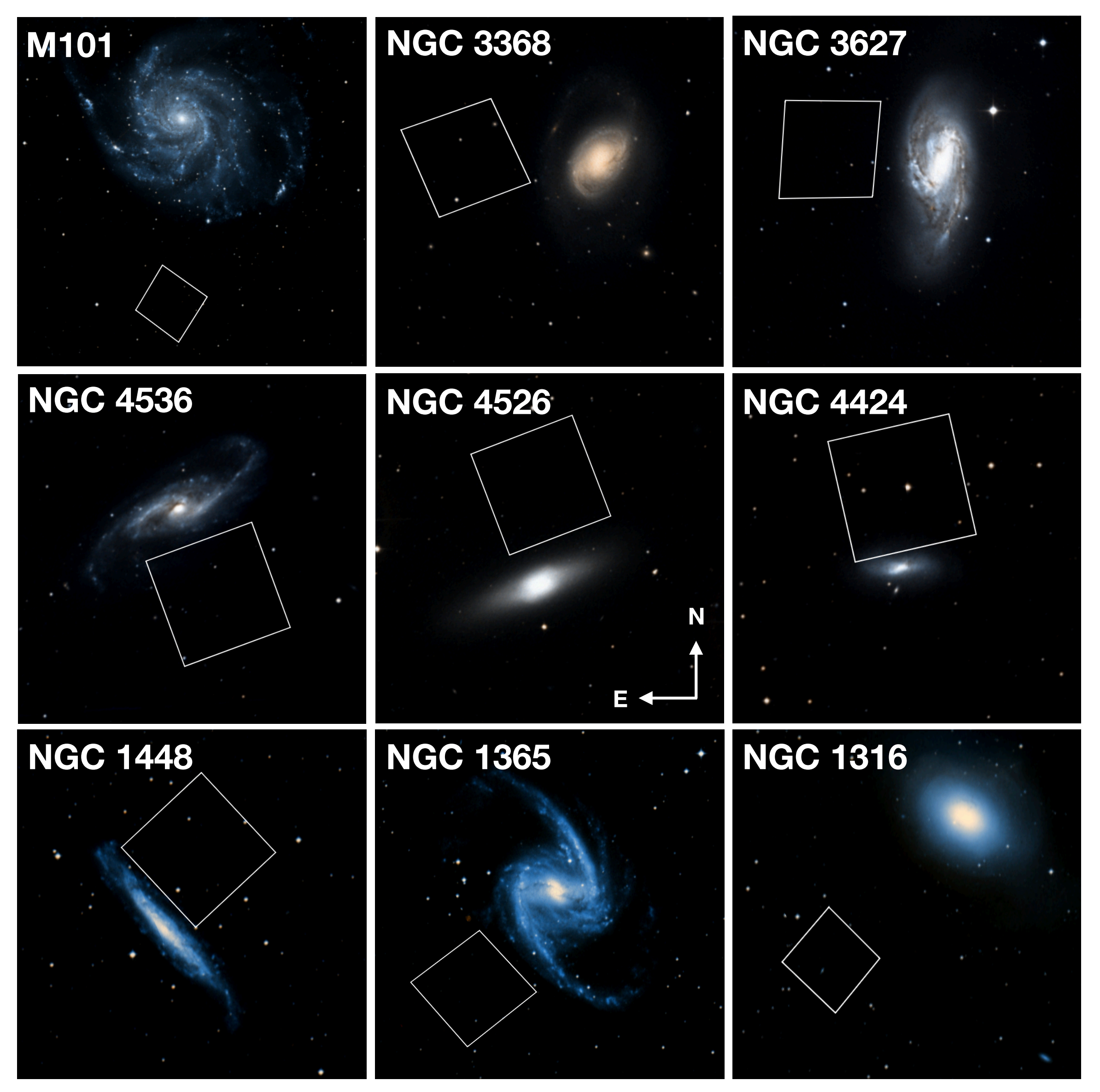




Measure 1st derivative of luminosity function

Mager, Madore & WLF (2008)

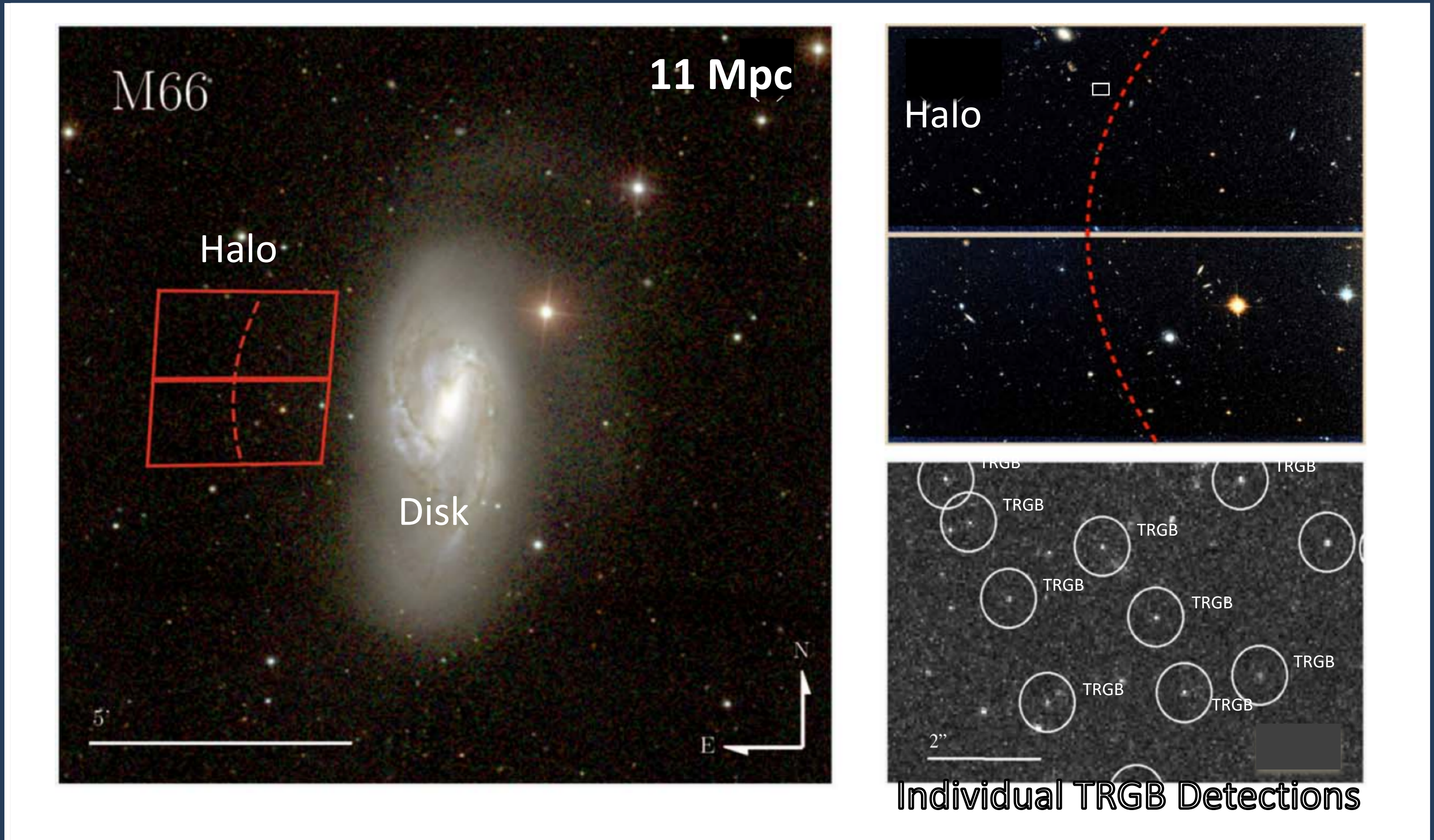
HST Advanced Camera for Surveys (ACS) Observations



TRGB Halo Fields

19 TRGB calibrators

TRGB Halo
No Dust, Crowding



Hoyt, T. et al. 2019, ApJ 882, 150

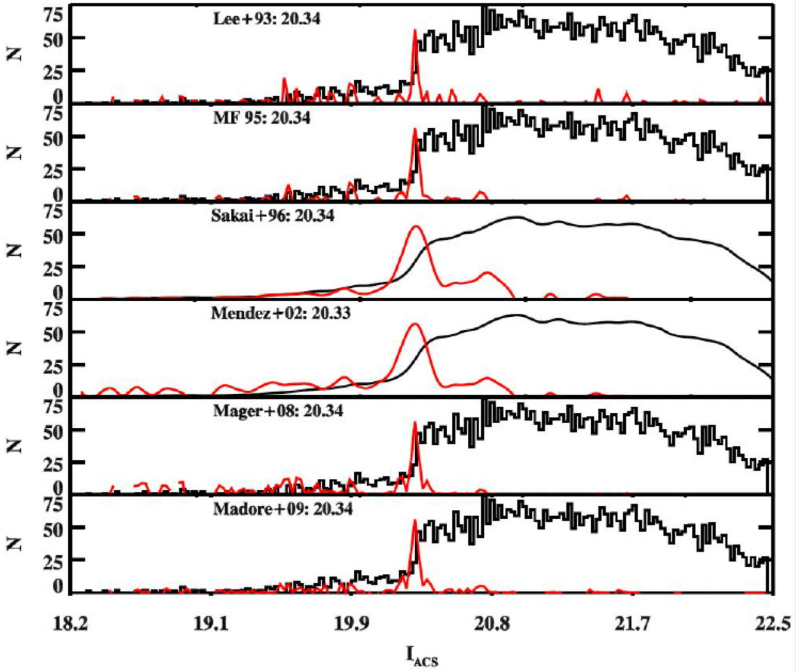
Measuring the TRGB

Two approaches

Sobel kernels

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

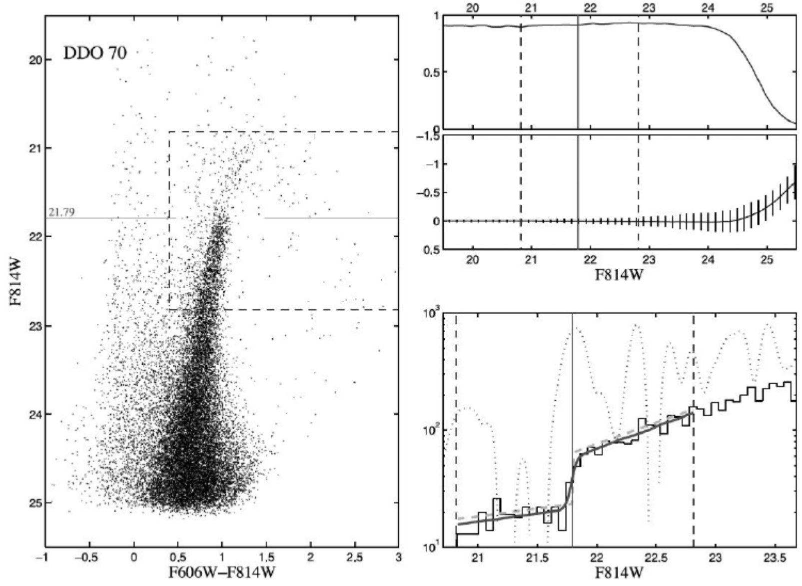
IC 1613 (Hatt+17)



Maximum likelihood

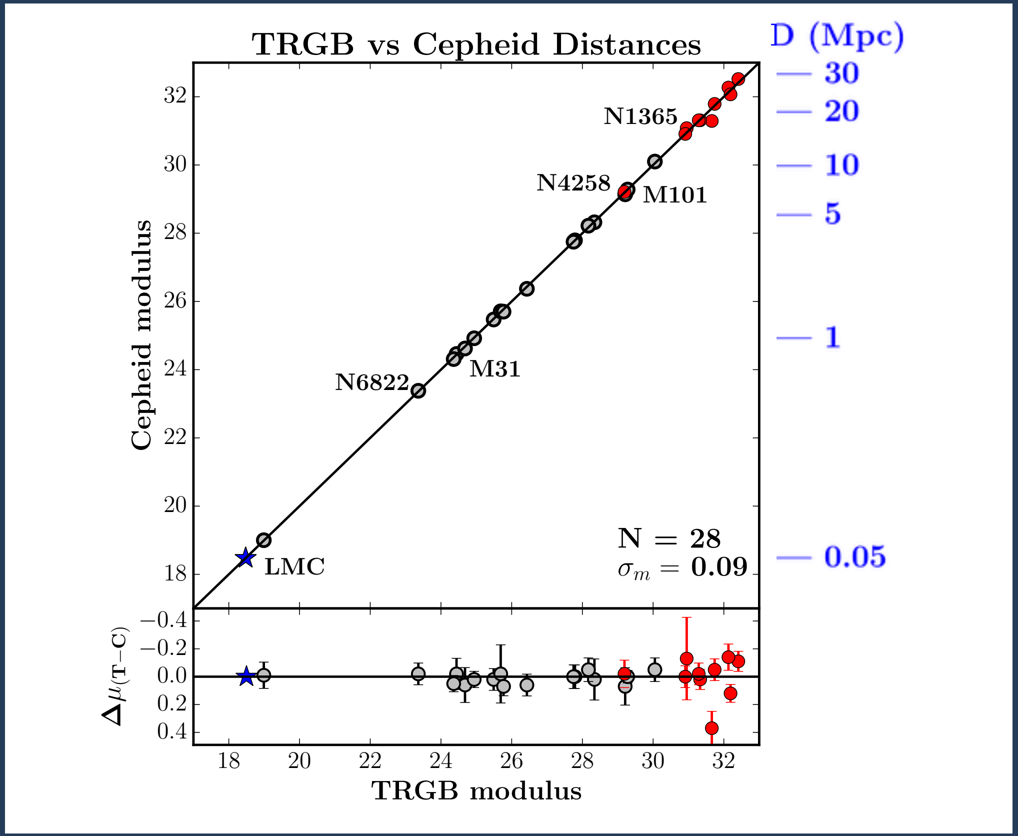
$$\mathcal{L} = -\sum_{i=1}^{N} \ln \varphi(m_i|\boldsymbol{x}) + N \ln \int_{m_{\min}}^{m_{\max}} \varphi(m|\boldsymbol{x})\, dm.$$

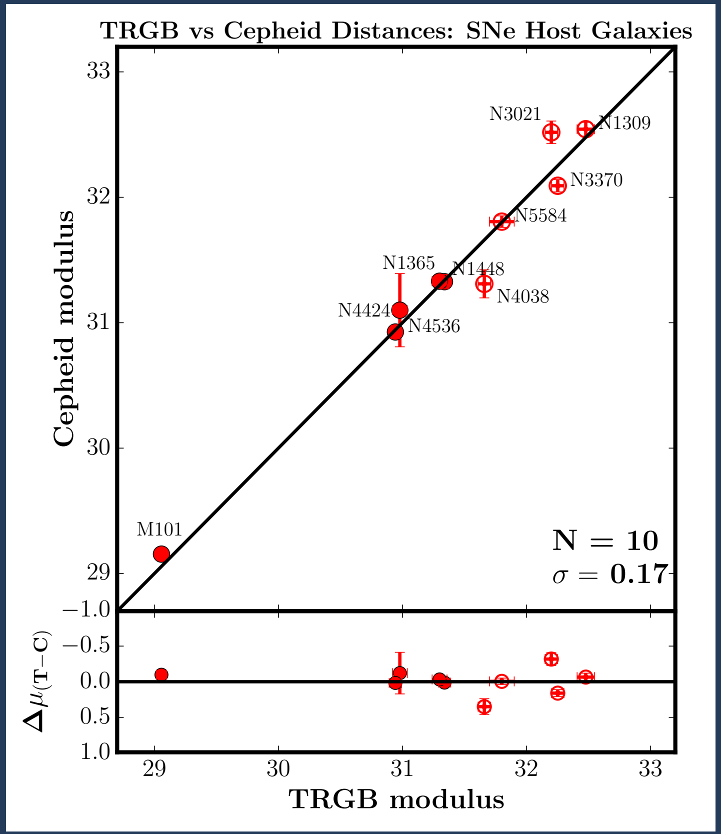
(Mendez+02, Makarov+06)



D. Hatt, I. Jang

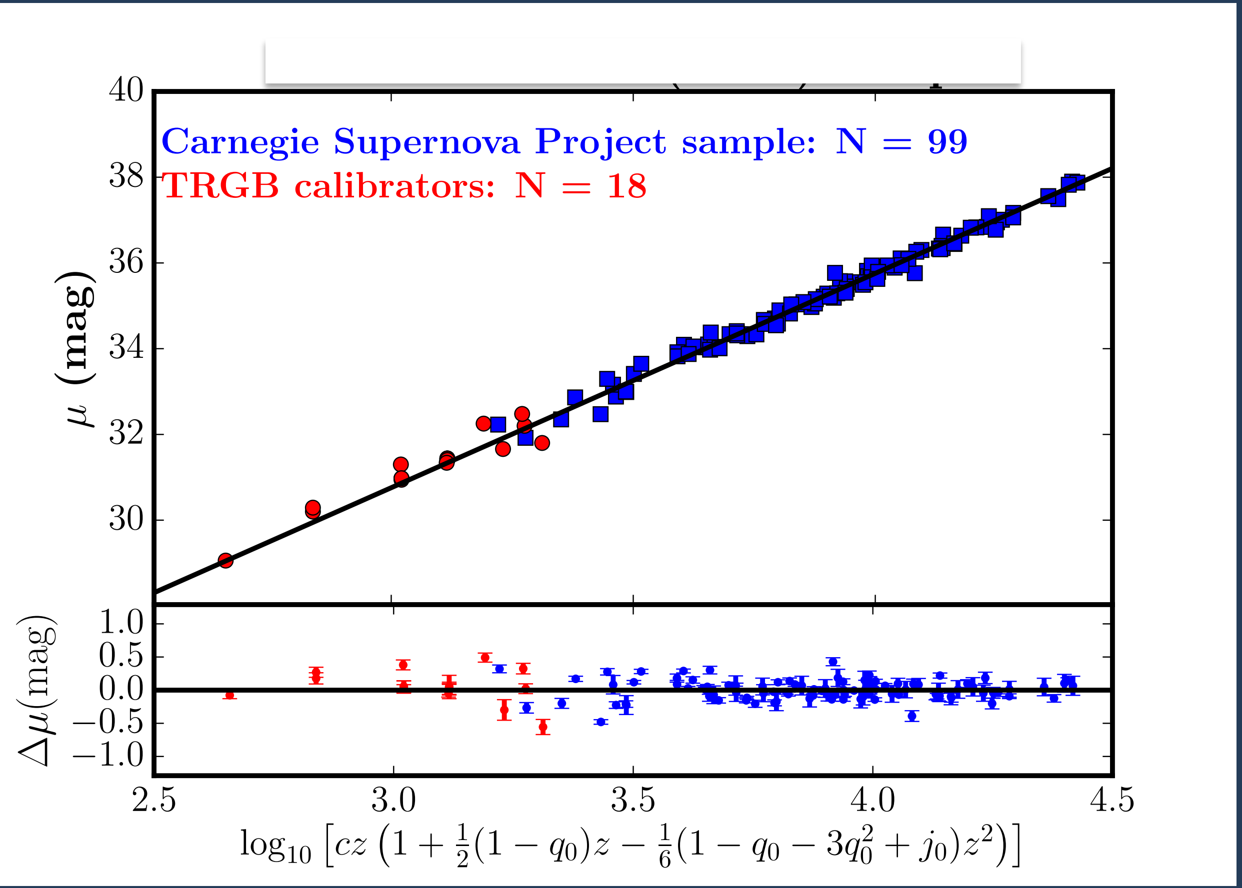
Comparison of Published TRGB and Cepheid Distances





WLF et al. (2019)

CCHP TRGB Calibration of H_o



MCMC analysis:

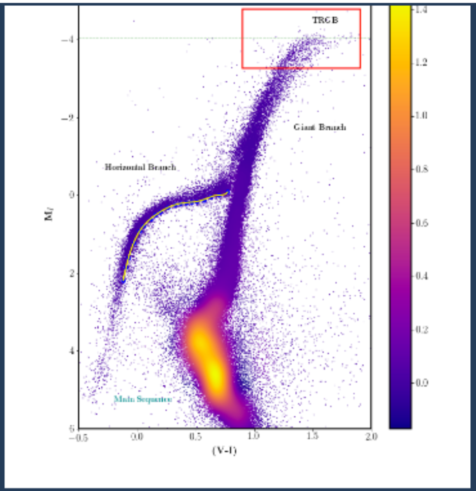
H_0 = 69.6 ± 0.8 (stat) [1.1%]
± 1.7 (sys) [2.4%] km s^{-1} Mpc^{-1}

LMC as the anchor galaxy **

WLF et al. (2019, 2020)

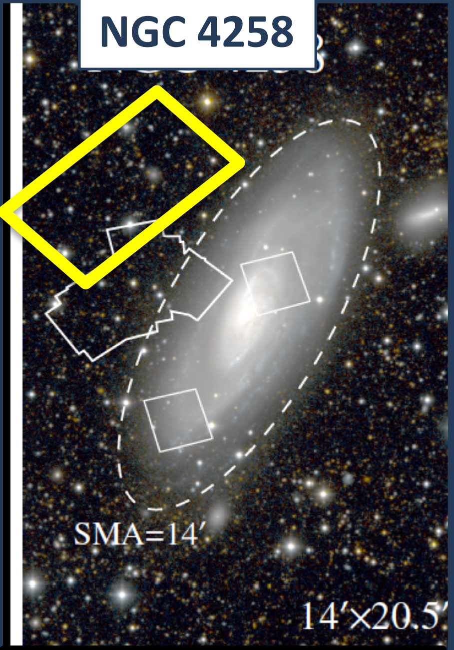
Recent Tests of the TRGB Calibration

Milky Way globular clusters



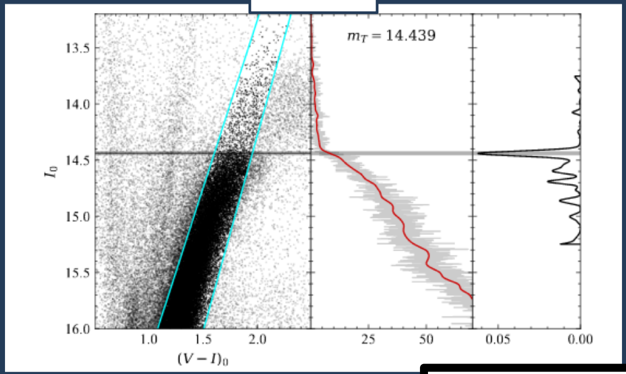
Cerny et al.2021,arXiv:2012.09701

NGC 4258

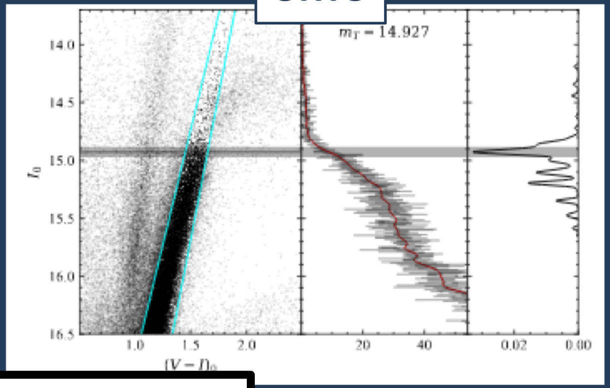


Jang et al. 2021

LMC



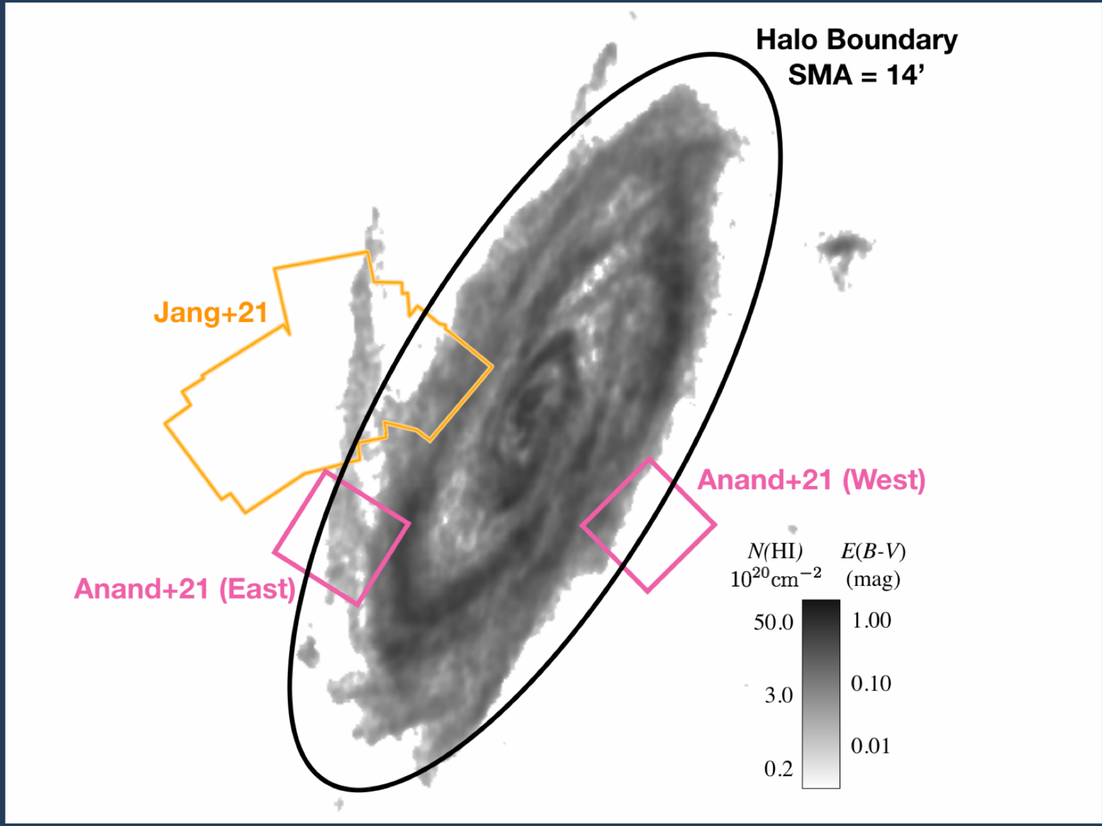
SMC



Hoyt 2021, 2022

Independent zero points in agreement at the $\pm$1% level. [WLF (2021), ApJ, 919, 16]

An Example of Systematic Differences: Recent NGC 4258 TRGB Measurements

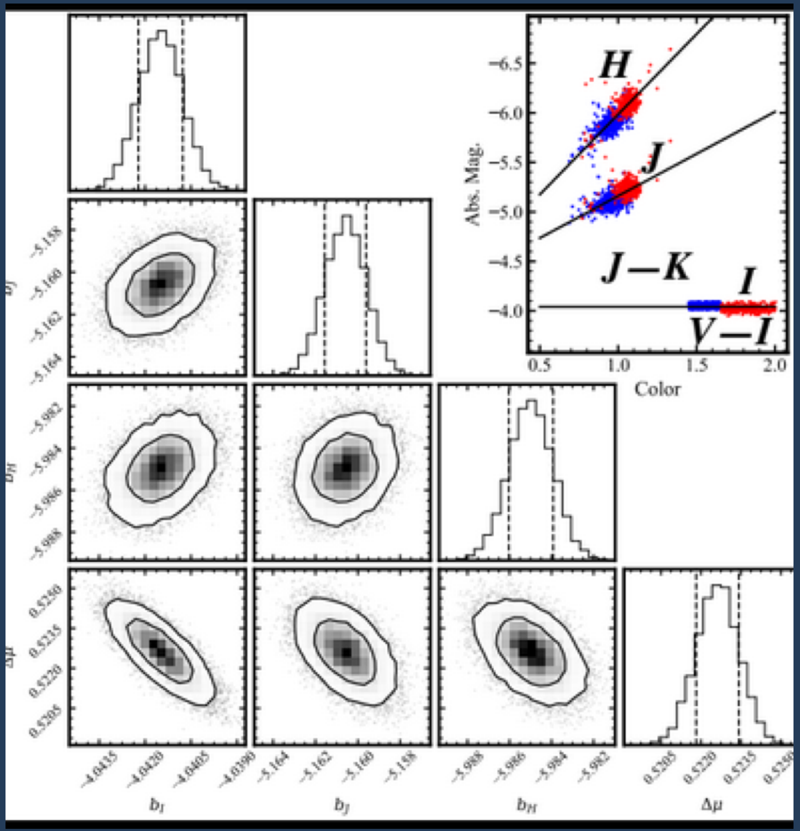


Jang et al, ApJ, 2021

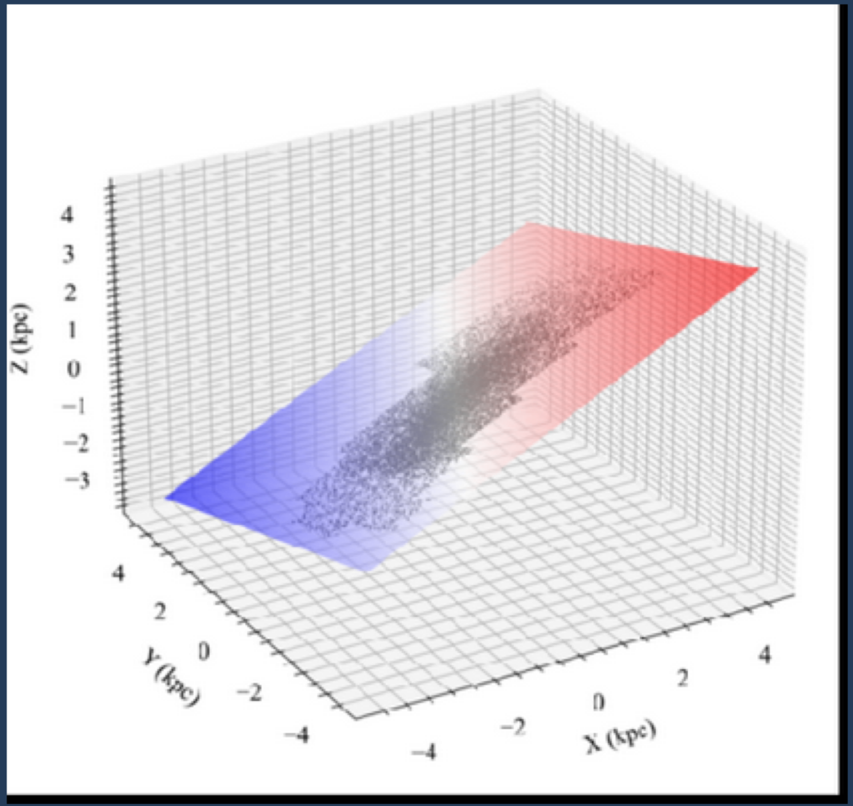
Halo (> 14') differs from Anand et al. (2021) by 0.055 mag or 2.6% in distance.

New deep HST/ACS+WFC3 observations in the halo obtained in December.

Additional Tests of the TRGB: Hoyt (2022) PhD Thesis

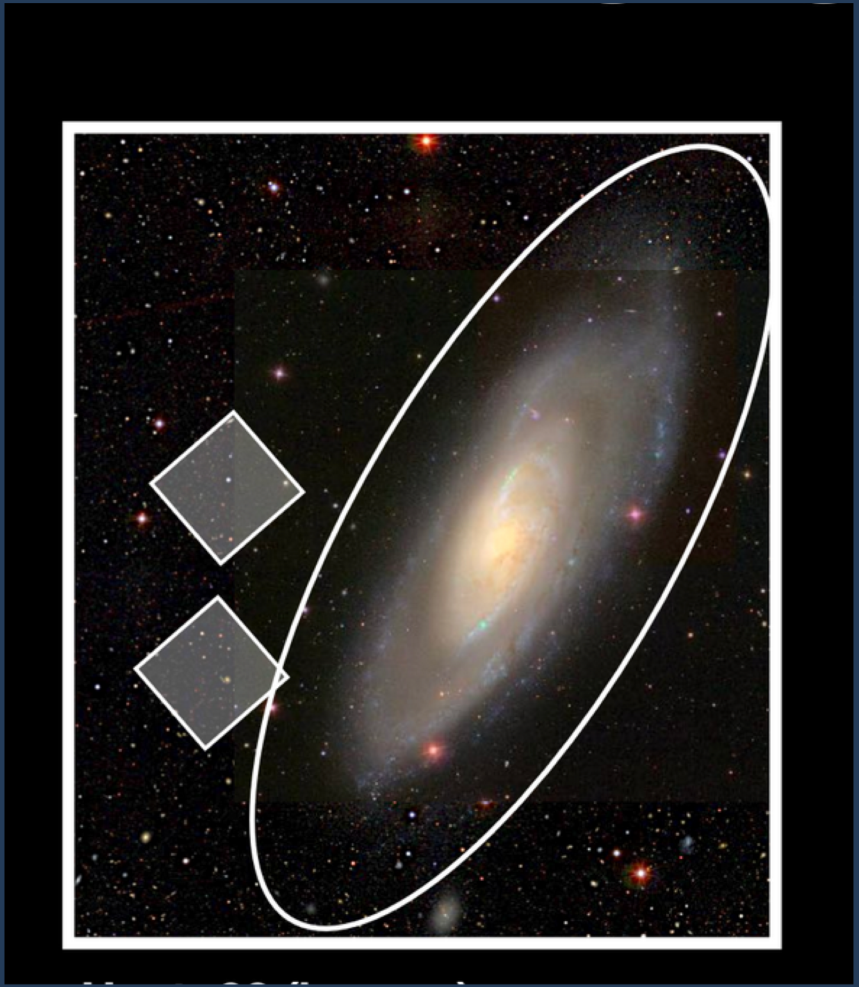


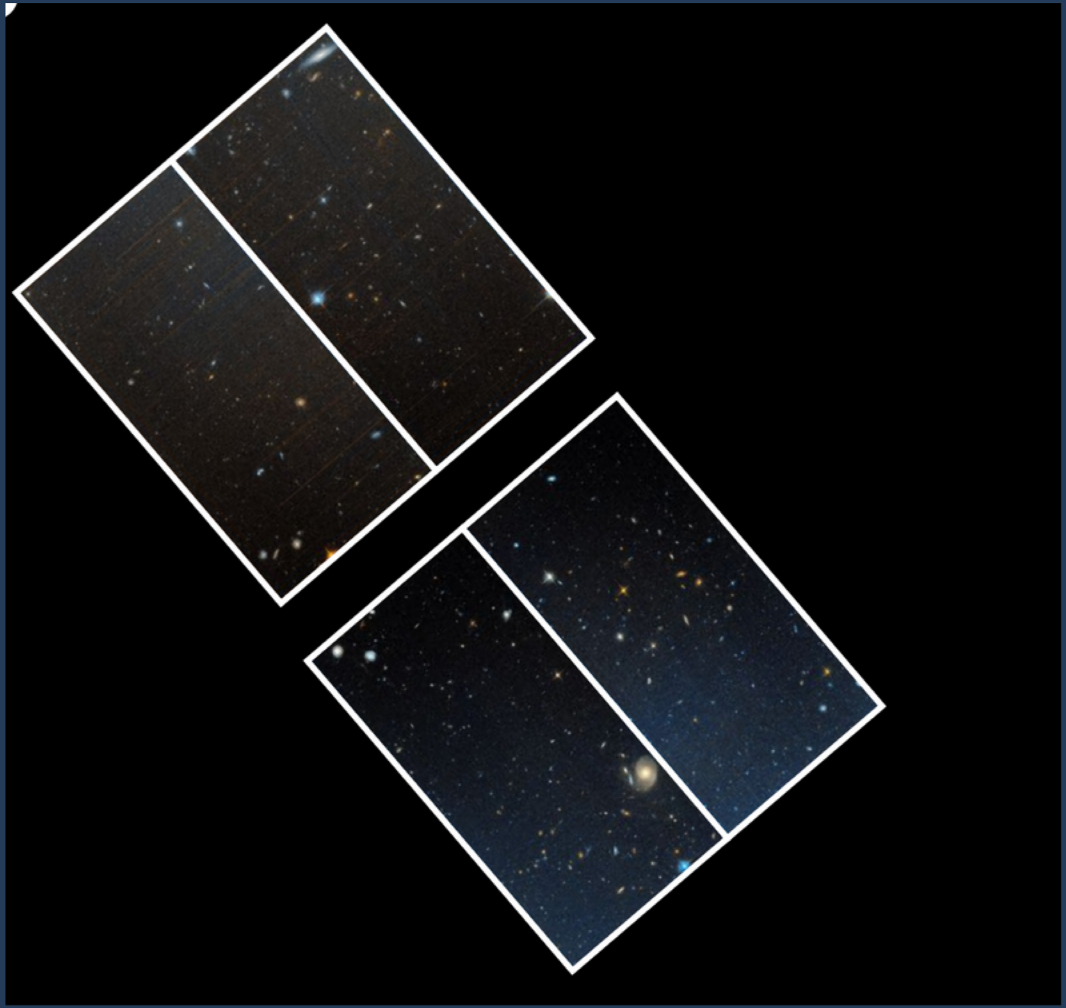
Multiwavelength (VIJHK) measurements of TRGB results in differential LMC/SMC distance modulus consistent with DEBs at 2% level



3D tilt of LMC measured using TRGB, consistent with Cepheid measurements.

Deep Imaging of the Outer Halo of NGC 4258





- 2.5 x deeper than Jang et al (2021)
- Optical and NIR imaging
- Fields chosen to minimize disk contamination

Hoyt et al. (2022, in prep)

Recent Comparison with SHoES + EDD

From Adam Riess
Subject **TRGB vs Cepheid plot**
To Jo Dunkley <jdunkley@princeton.edu>, Jim Peebles, Wendy Freedman, Adam Riess
Reply | Reply All | Forward | Archive | Junk | Delete | More
4/29/22, 9:47 AM

Dear Cepheid-TRGB Comparison enthusiasts,

There was some conversation during the coffee break yesterday and during the talks to produce an up-to-date plot of Cepheids vs TRGB distances to the same SN Ia host galaxies, specifically SH0ES Cepheids vs CCHP TRGB vs EDD TRGB all calibrated by the same anchor, NGC 4258 so we can just compare the second rung.

This table can be passed to a Princeton student who understands magnitudes and can make a plot and generate some stats that we can use in future dialogue to avoid dueling plots and audience confusion.

These are all the SN Ia hosts I am aware of with distances measured by all 3 teams. NGC 4258 is assumed to have mu=29.398 ± 0.032 (Reid et al. 2019) as the calibration for this exercise. The first 7 are straightforward because all 3 groups have entries. The last four are a different category, they are more distant and the EDD team could not identify a TRGB break so take those with a grain of salt.

I filled in the latest SH0ES values (using Table 6 from R22, in press, but using only NGC 4258 as the anchor which makes distances 0.009 mag farther than the 3 anchor version, just like Figure 23–these are the right SH0ES values on pain of death!).

For EDD I used Table 2 and for CCHP I used Table 3 from F19. None of the distance measures include the NGC 4258 distance error so the errors are relatively independent (excepting that the two TRGB groups measure the same data).

I am hoping that Wendy can review or revise the entries for her team's results or confirm I copied them correctly.

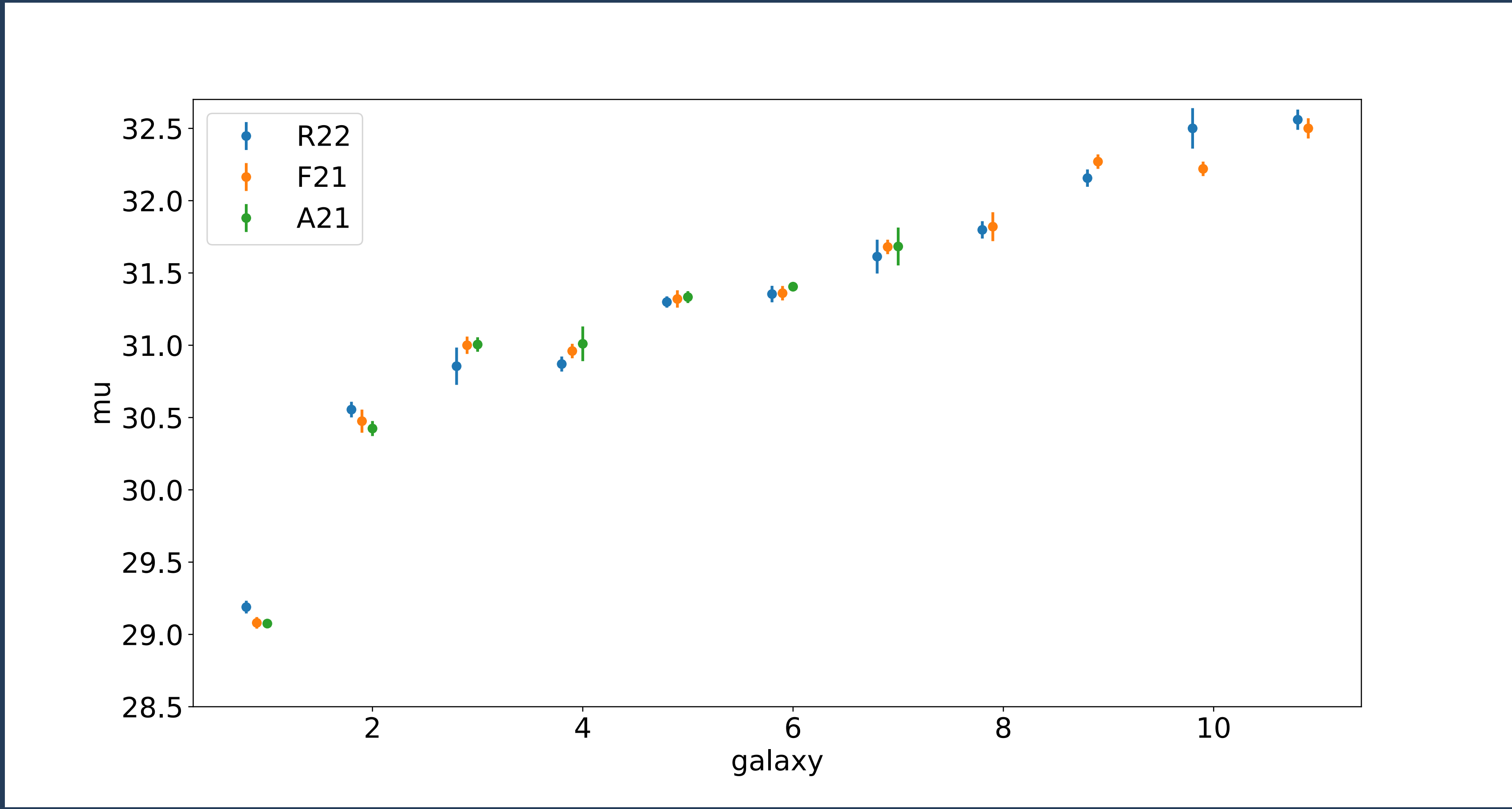
	Host	SH0ES(R22) most	err	CCHP(F19/21) mu	err	EDD(Anand21) mu	err
1	M101	29.189	0.044	29.080	0.040	29.075	0.031
2	N1365	31.354	0.057	31.360	0.050	31.405	0.031
3	N1448	31.299	0.039	31.320	0.060	31.333	0.041
4	N4038	31.613	0.117	31.680	0.050	31.683	0.131
5	N4424	30.855	0.129	31.00	0.060	31.005	0.050
6	N4536	30.870	0.052	30.960	0.050	31.010	0.120
7	N5643	30.555	0.054	30.475	0.080	30.424	0.052
8	N3370	32.156	0.060	32.270	0.050	NA	NA
9	N3021	32.500	0.140	32.220	0.050	NA	NA
10	N1309	32.560	0.070	32.500	0.070	NA	NA
11	N5584	31.798	0.060	31.820	0.100	NA	NA

Best
Adam

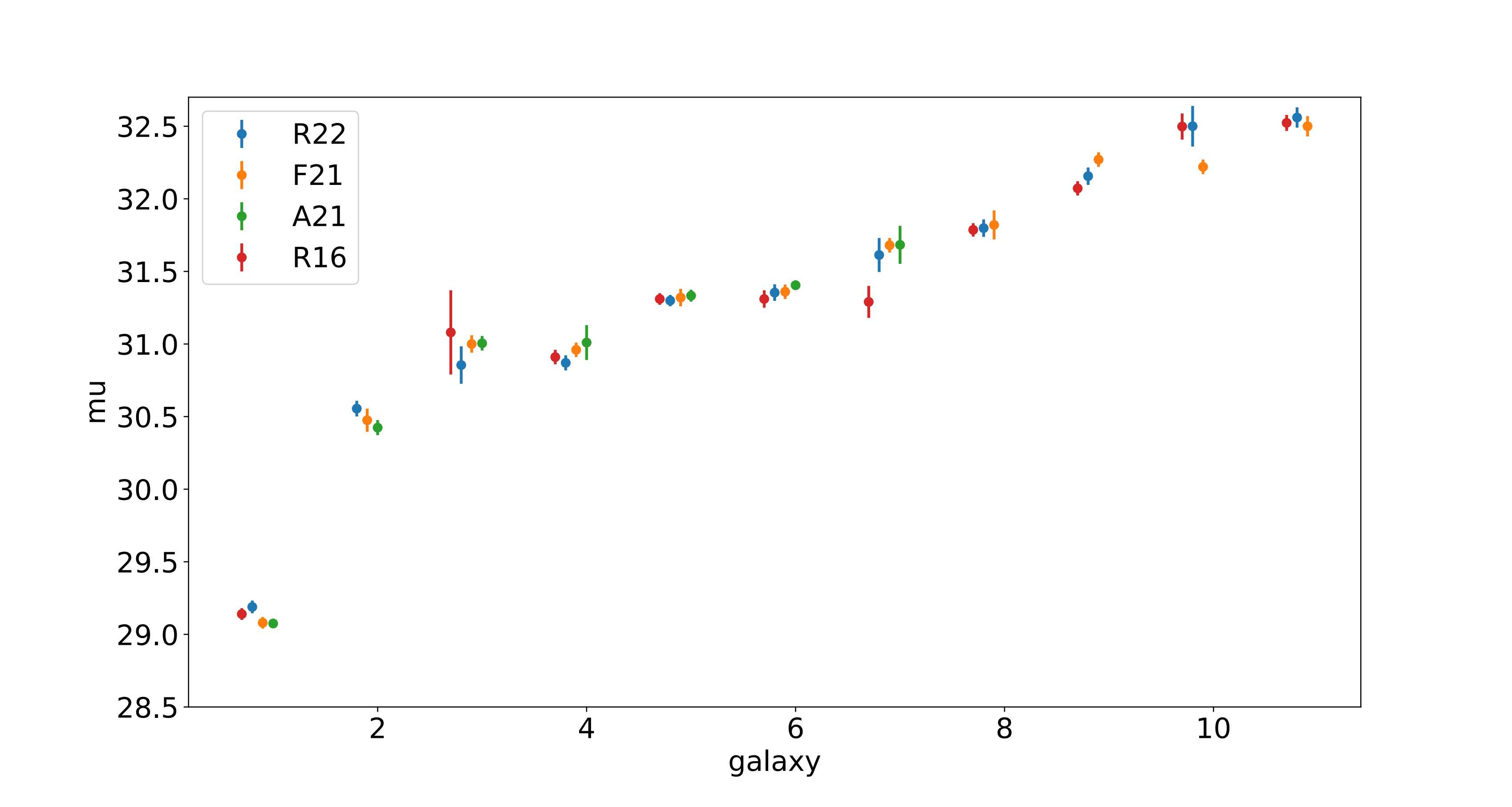
From Adam Riess: "…This table can be passed to a Princeton student who understands magnitudes and can make a plot and generate some stats that we can use in future dialogue… "

"… produce an up-to-date plot of Cepheids vs TRGB distances to the same SN Ia host galaxies, specificially SH0ES Cepheids vs CCHP TRGB vs EDD TRGB all calibrated by the same anchor, NGC 4258 so we can just compare the second rung."

Recent Comparison with SHoES + EDD

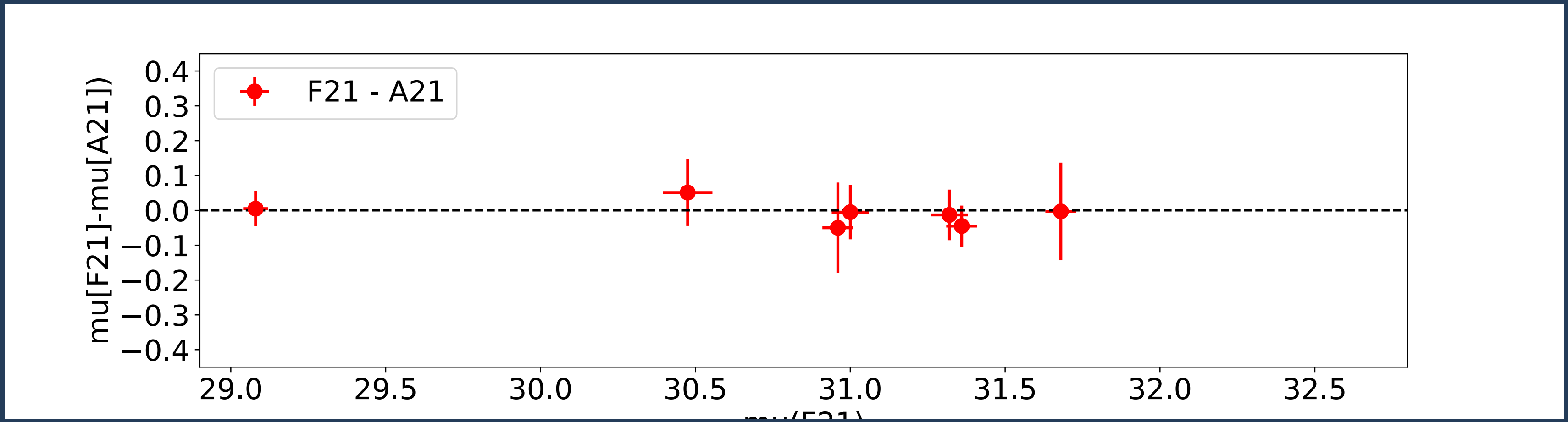


Recent Comparison with SHoES + EDD

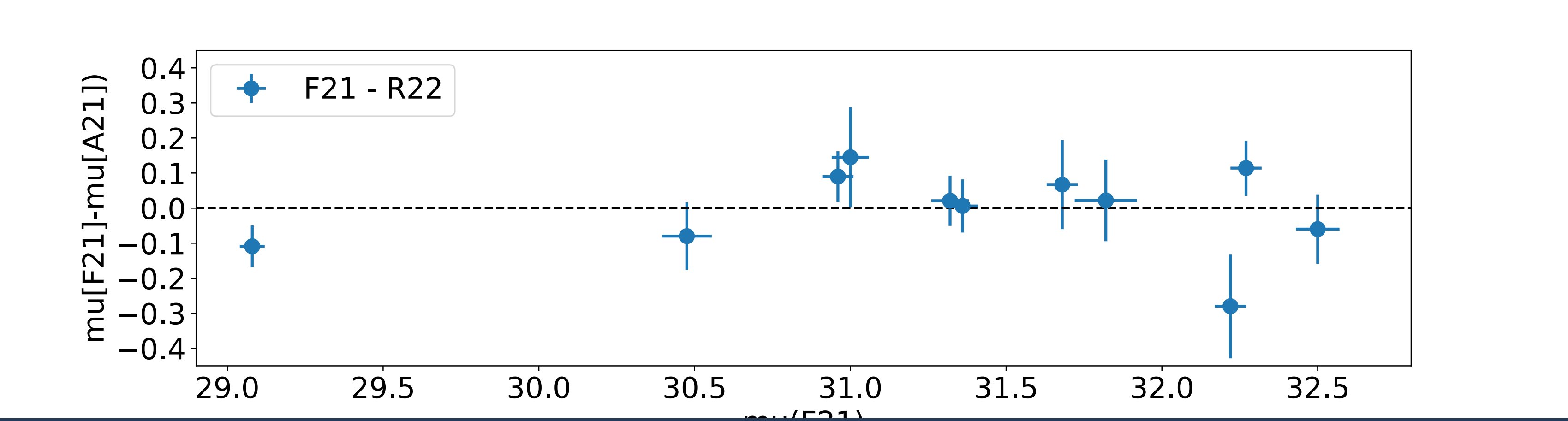


Mean difference 0.006 mag, error weighted 0.003 $\pm$ 0.026 mag

Recent Comparison with SHoES + EDD



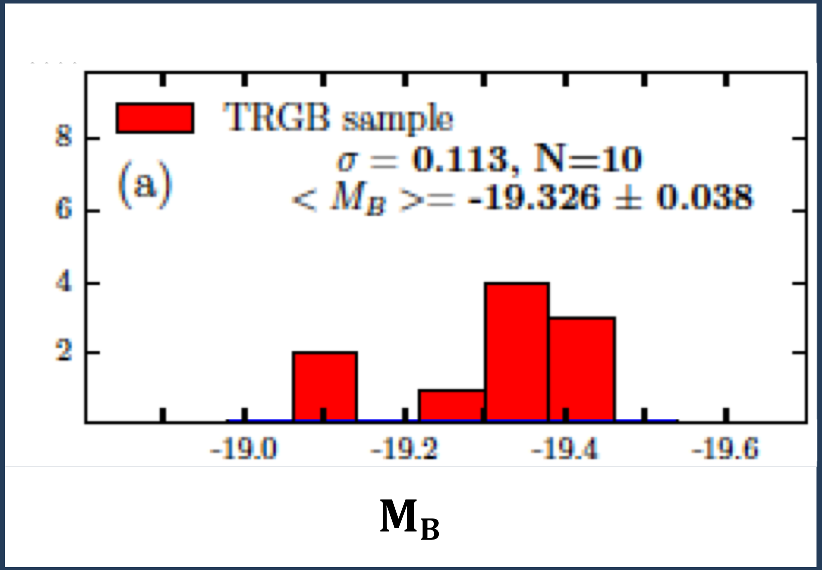
Freedman (2021)
vs
Anand et al.(2021)



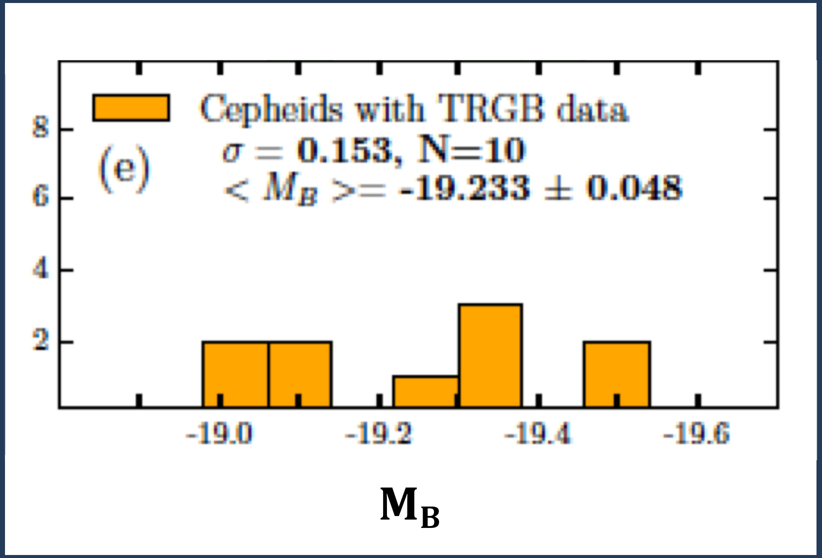
Freedman (2021)
vs
Riess et al.(2022)

Comparison of the 10 TRGB and Cepheid Distances to SNeIa Hosts in Common

TRGB calibration of SNe Ia



Cepheid calibration of SNe Ia



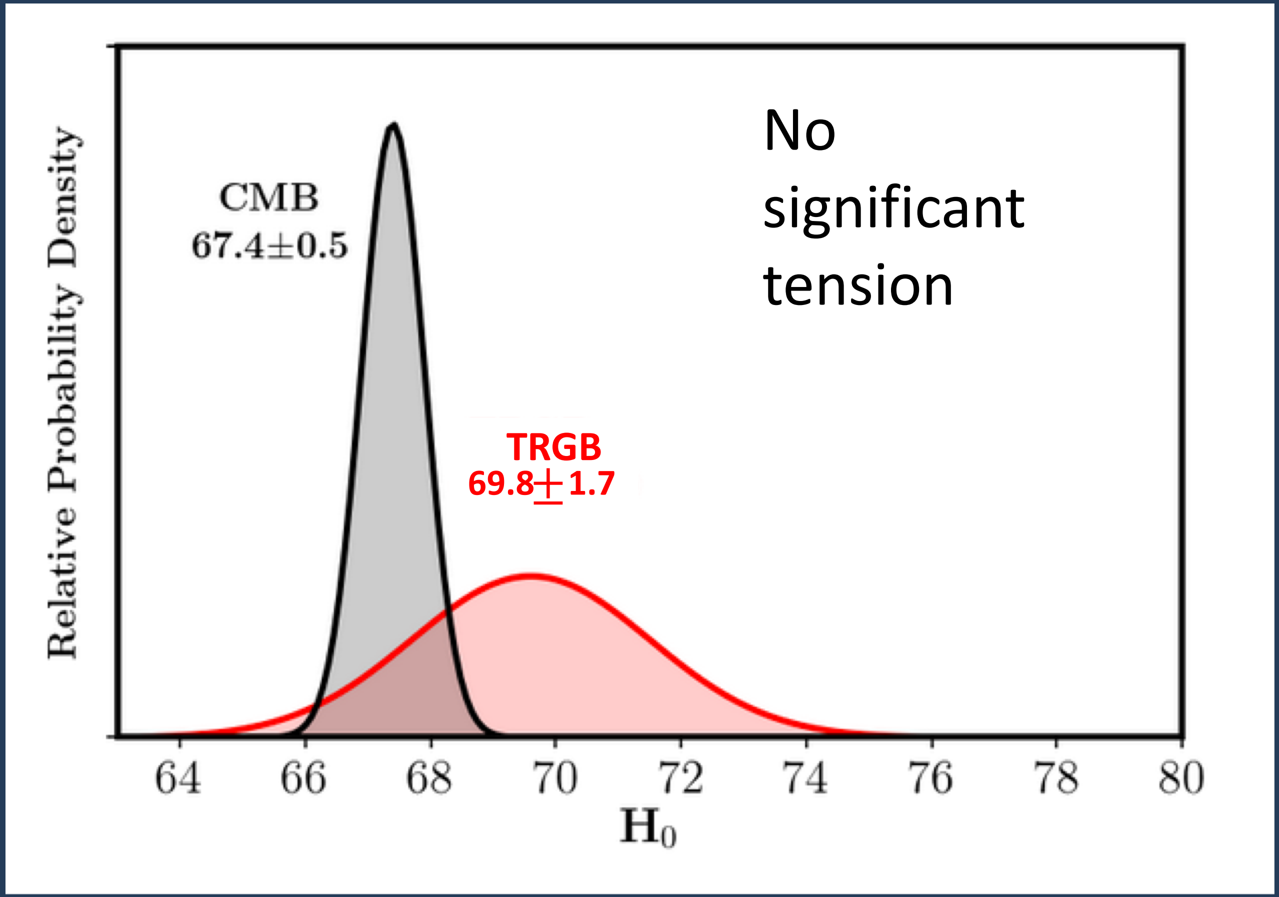
σ = 0.11
TRGB

σ = 0.15
Cepheids

σ = 0.10
SNeIa CSP

WLF et al. (2019, ApJ)

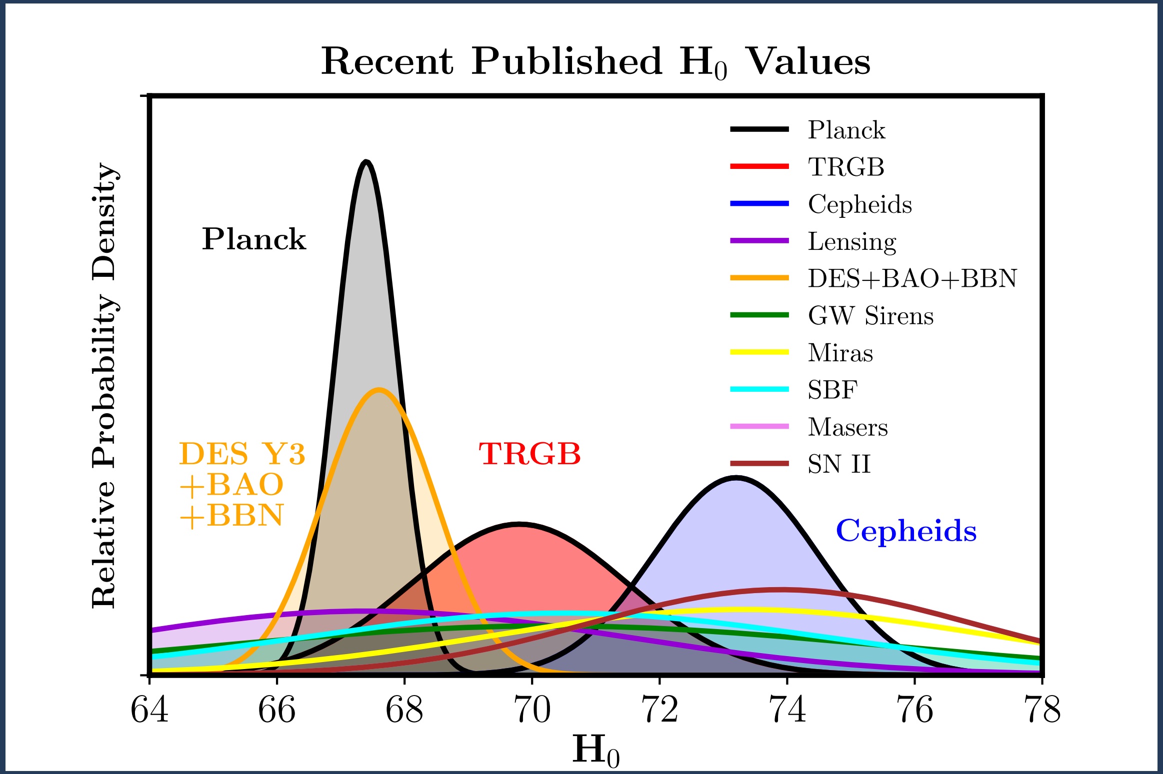
TRGB Compared to CMB



1.3 sigma tension with Planck

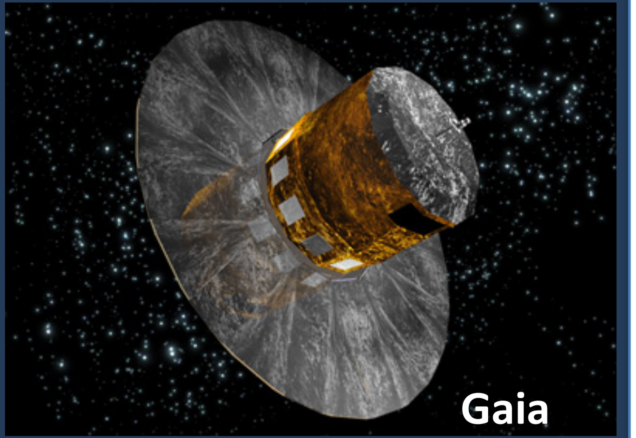
WLF+ (2019); WLF (2021) ApJ, 919, 16

Recent Published Values of the Hubble Constant



WLF (2021)

How to Resolve the Tension: Gaia +HST+ JWST



H_o Milky Way zero-point ~1%

N4258 calibration ~1%

New JWST cosmology program:
Three independent methods applied to the same SNIa host galaxies (PI: Freedman)
JWST has almost 10x the sensitivity of HST at NIR wavelengths and 3x the resolution.

Cepheids

- Increased resolution
- Direct test of metallicity
- Additional wavelength coverage to improve reddenings

TRGB

- Increased resolution
- Extend to greater distances

Carbon stars

- 3rd independent check

James Webb Space Telescope (JWST)

Summary

- Astrophysical Distance Indicators (e.g., the TRGB) provide an increasingly accurate means of measuring distances in the local universe.

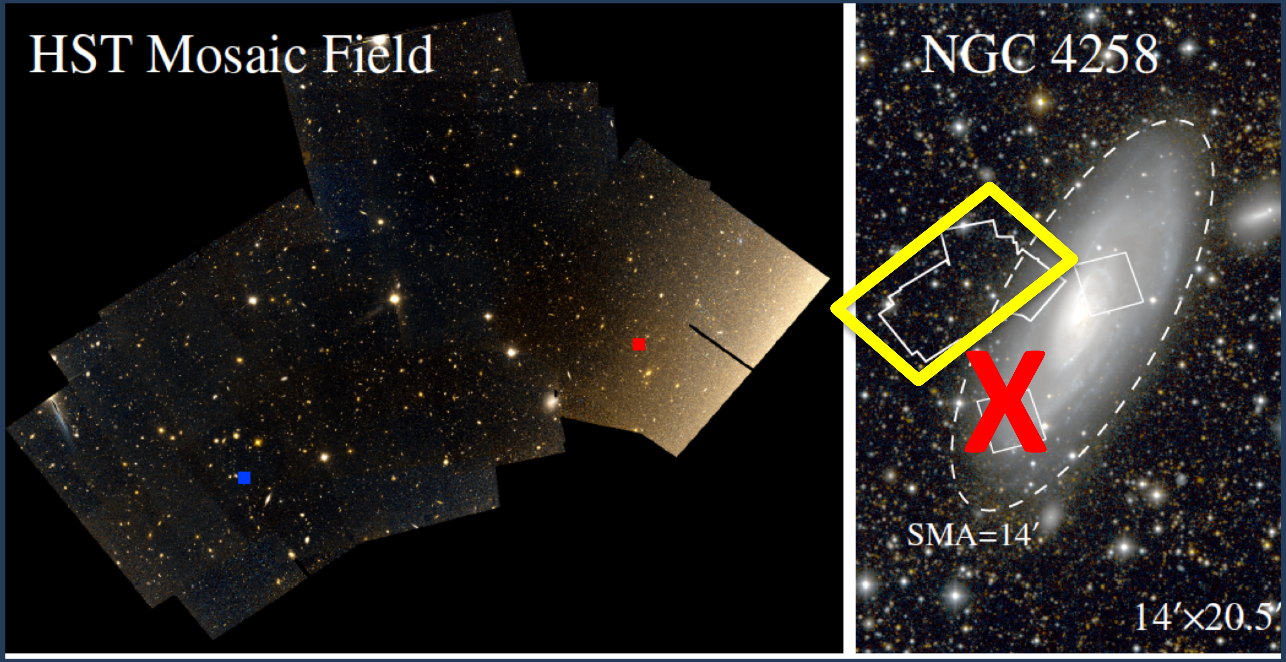
- Three decades ago, the distances to nearby galaxies were not known to better than a factor of two. Including systematic errors, we now have accuracies of

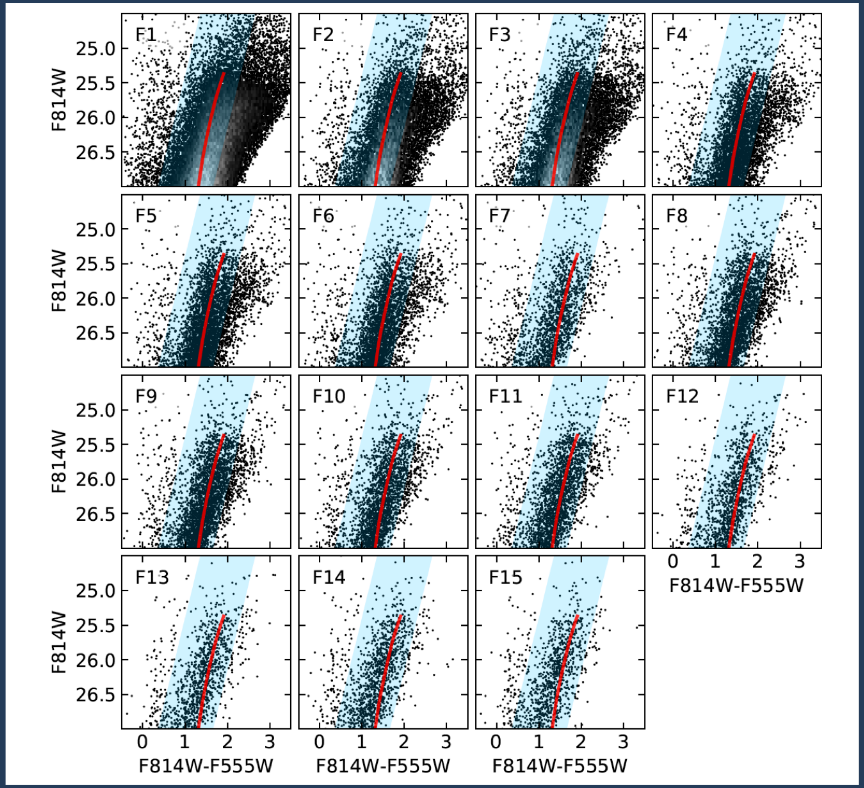
  2% percent for galaxies < 5 Mpc [ground-based observations]

  3% percent for galaxies < 30 Mpc [with HST]

- The TRGB and Cepheid calibrations of SNeIa and H_0 differ by 4.6%

Recent NGC 4258 TRGB Measurements





In Sung Jang

Jang et al, ApJ, 2021