

Title: Tension in the Hubble Constant: Is There a Crisis in Cosmology?

Speakers: Wendy Freedman

Series: Colloquium

Date: February 24, 2021 - 2:00 PM

URL: <http://pirsa.org/21020006>

Abstract: An important and unresolved question in cosmology today is whether there is new physics that is missing from our current standard Lambda Cold Dark Matter (LCDM) model. A current discrepancy in the measurement of the Hubble constant could be signaling a new physical property of the universe or, more mundanely, unrecognized measurement uncertainties. I will discuss two of our most precise methods for measuring distances in the local universe: Cepheids and the Tip of the Red Giant Branch (TRGB). I will present new results from the Carnegie-Chicago Hubble Program (CCHP), the goal of which is to independently measure a value of the Hubble constant to a precision and accuracy of 2%. Using the Hubble Space Telescope Advanced Camera for Surveys, we are using the TRGB to calibrate Type Ia supernovae. I will address the uncertainties, discuss the current tension in H_0 , and whether there is need for additional physics beyond the standard LCDM model.

Is There a Crisis in Cosmology?

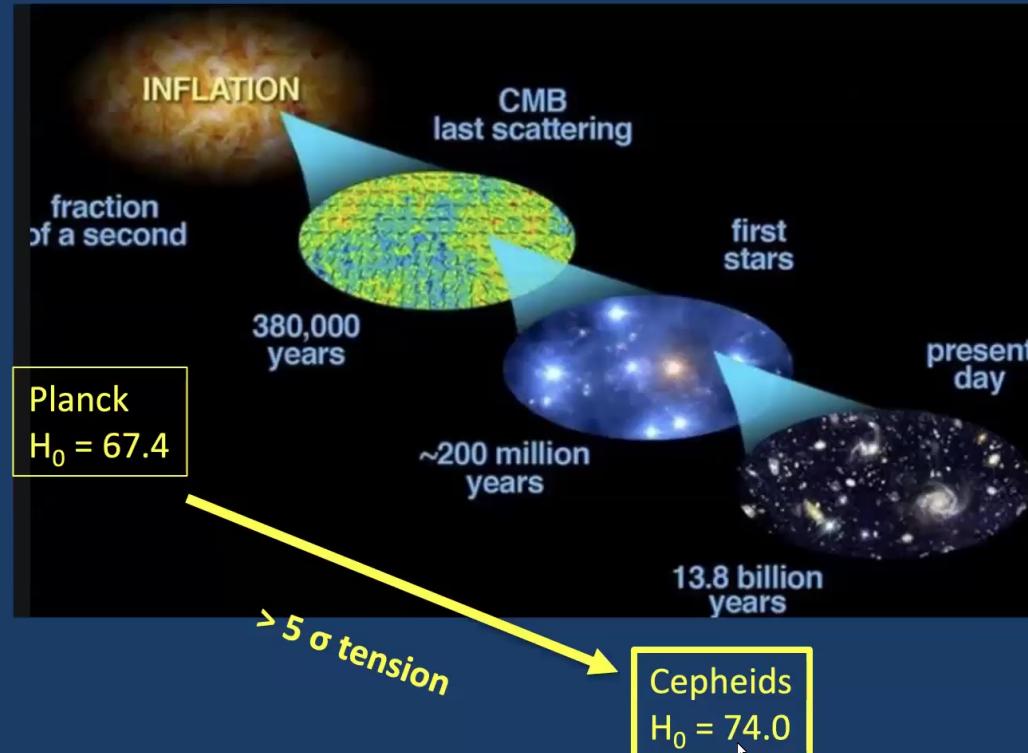
A New Debate Over the Value of the Hubble Constant



Wendy L Freedman
University of Chicago

Perimeter Institute (via Zoom)
February 24, 2021

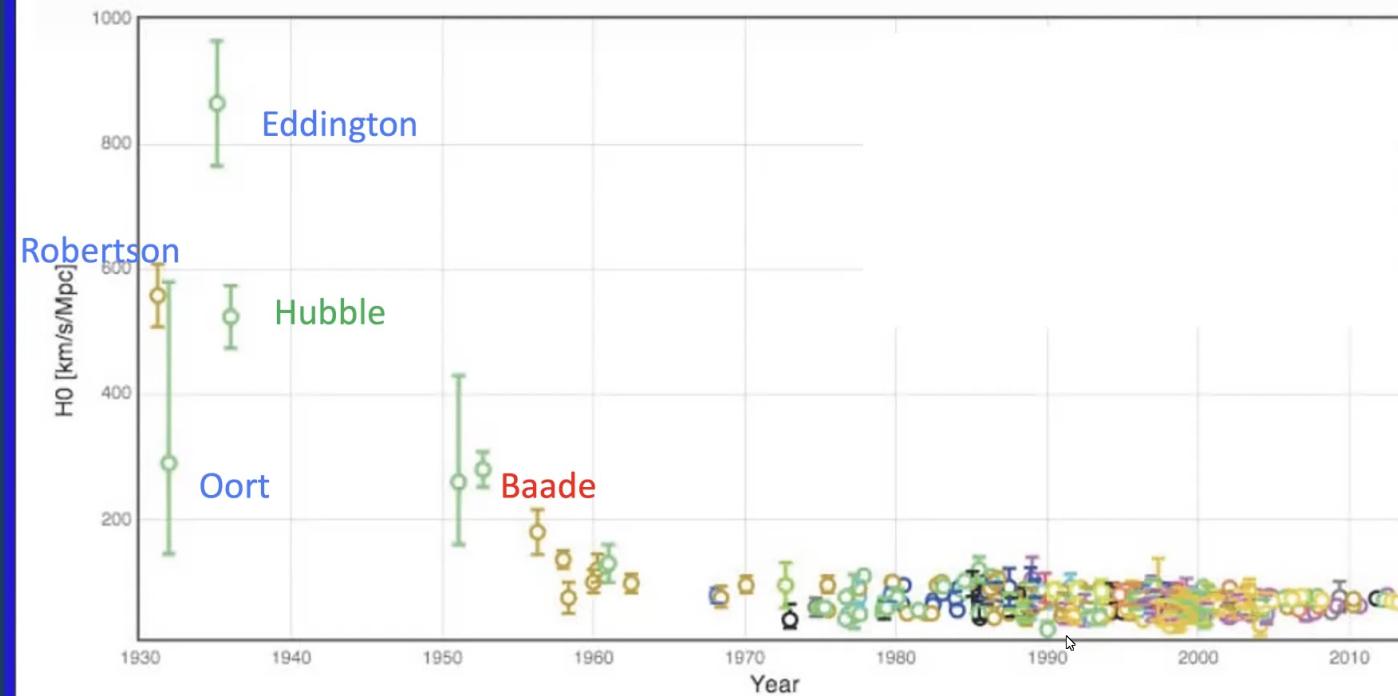
Tension in the Hubble Constant



Forbes.com



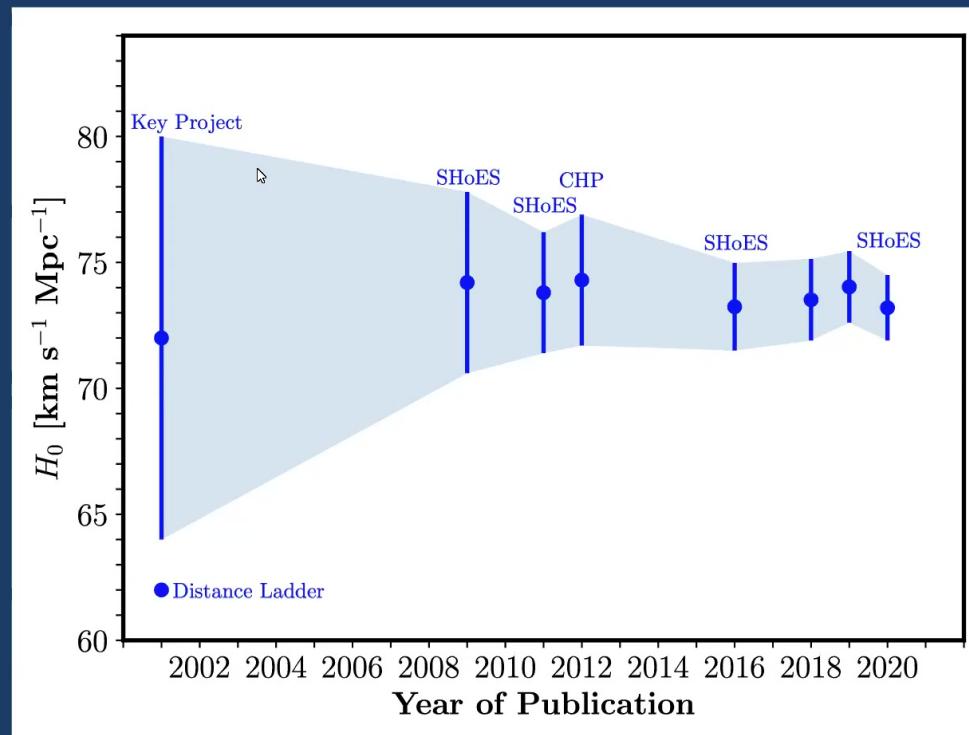
H_0 Over Time



H_0 data compiled by J. Huchra and C. Booth
<http://www.craigmbooth.com/hubble/>



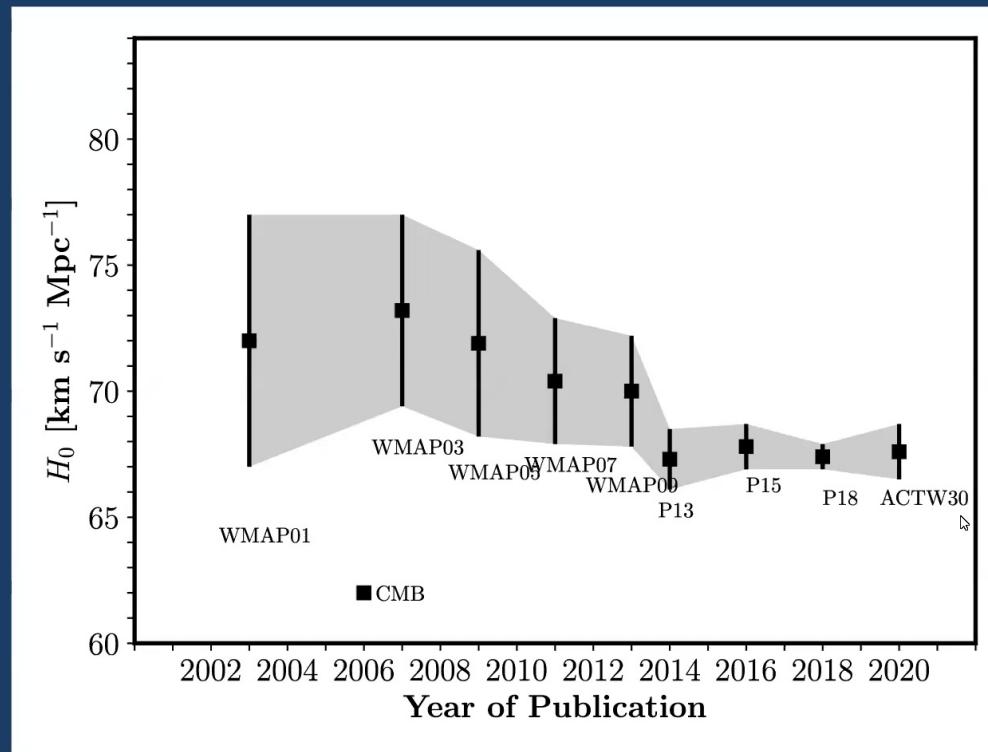
The Current Tension in H_0



Updated from WLF et al., 2017



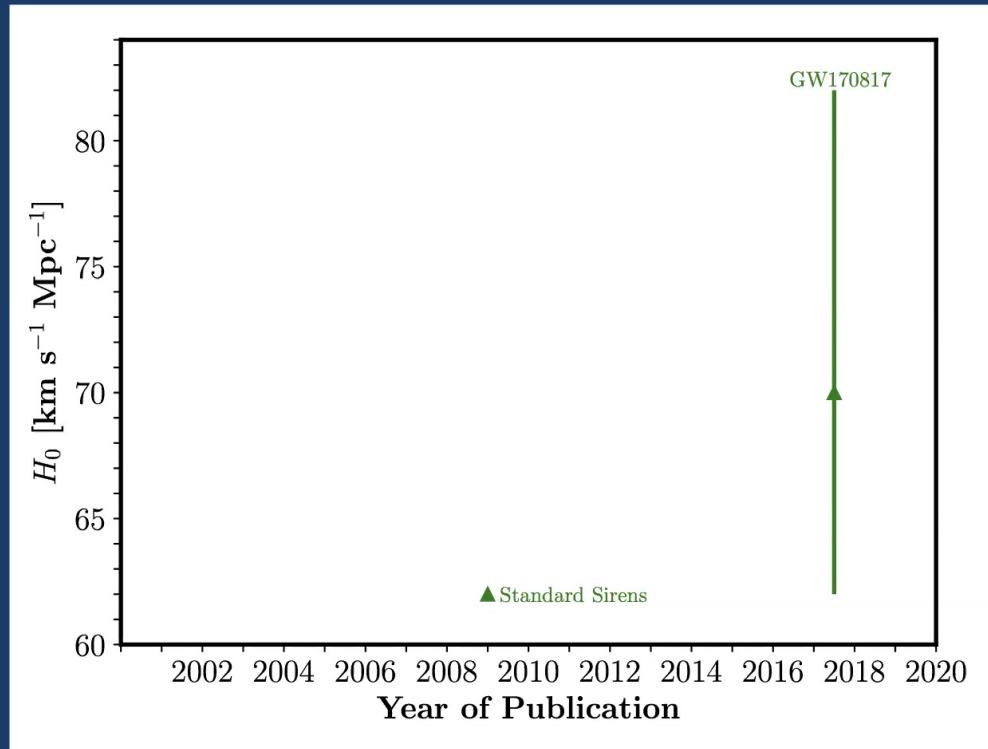
The Current Tension in H_0



Updated from WLF et al., 2017



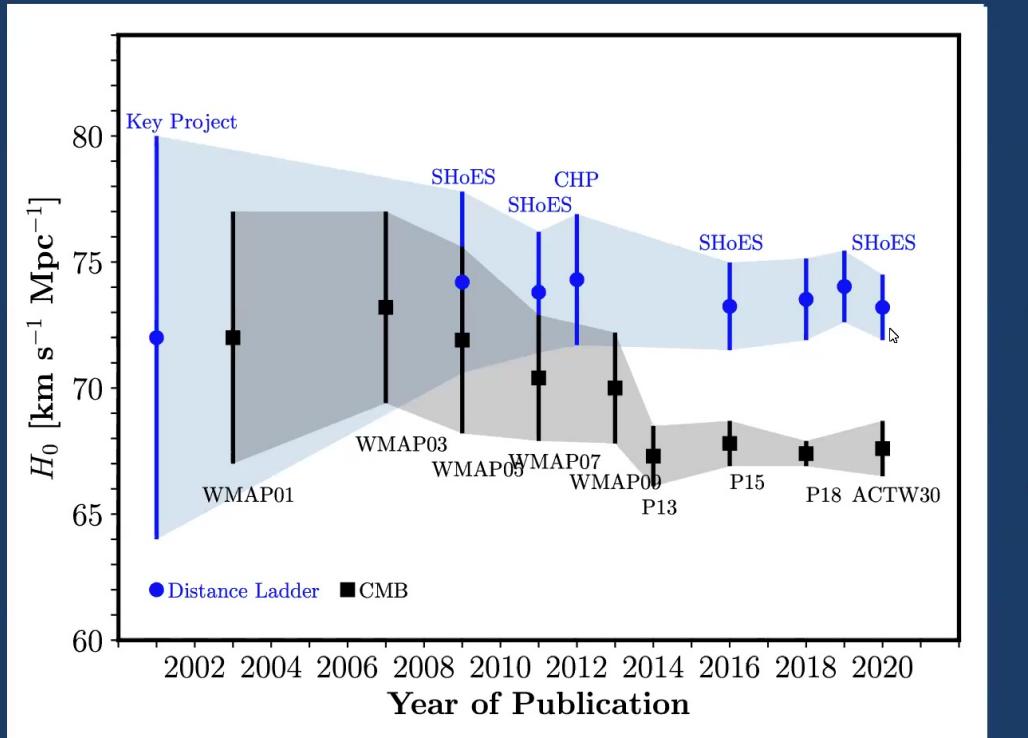
The Current Tension in H_0



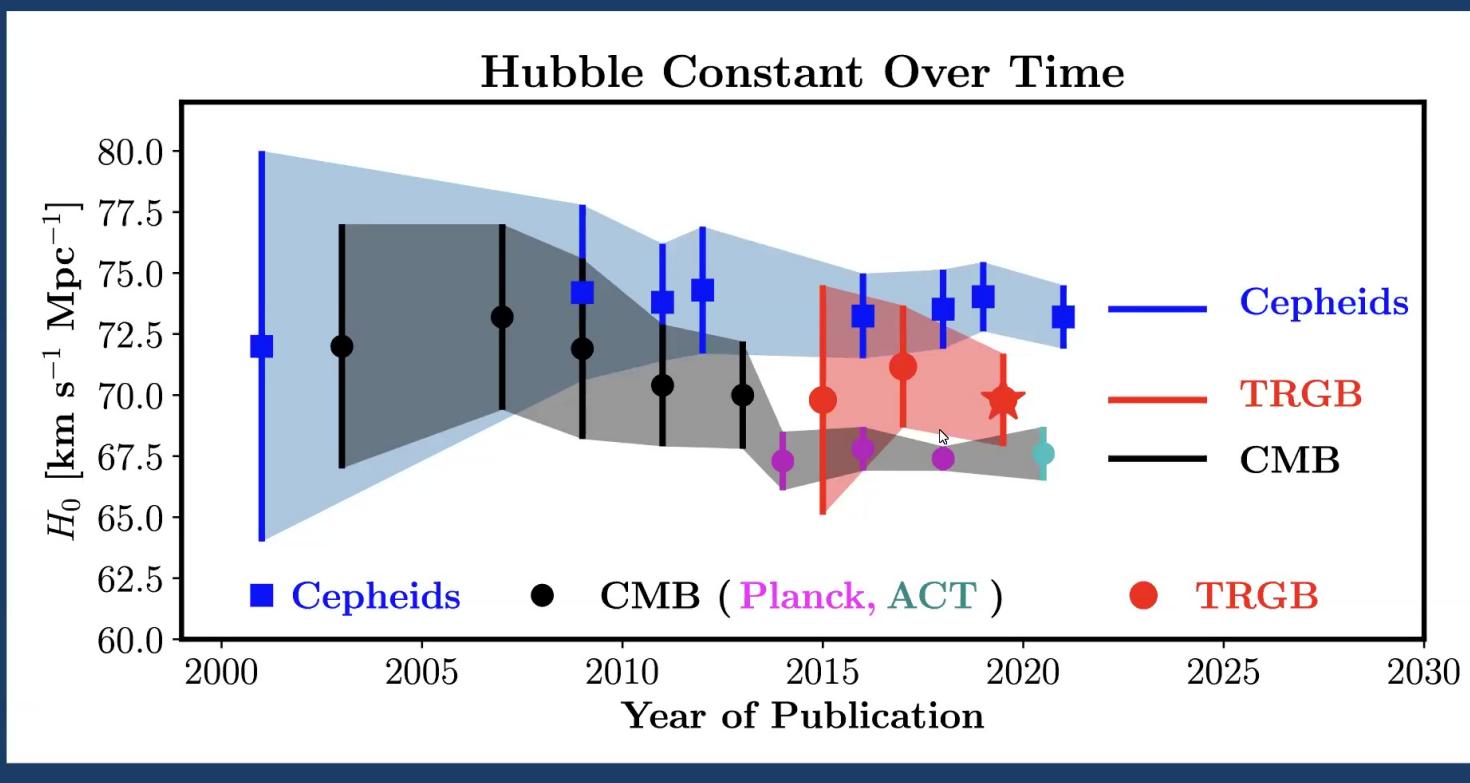
Updated from WLF et al., 2017



The New Controversy Over the Hubble Constant



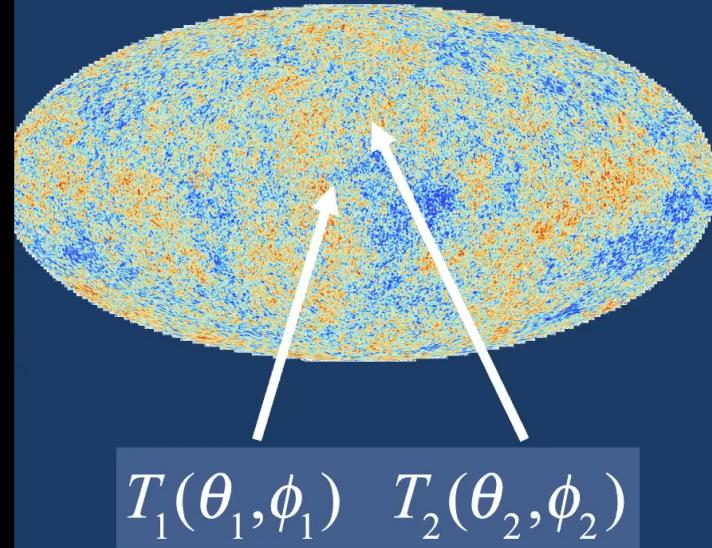
H_0 Values With Time



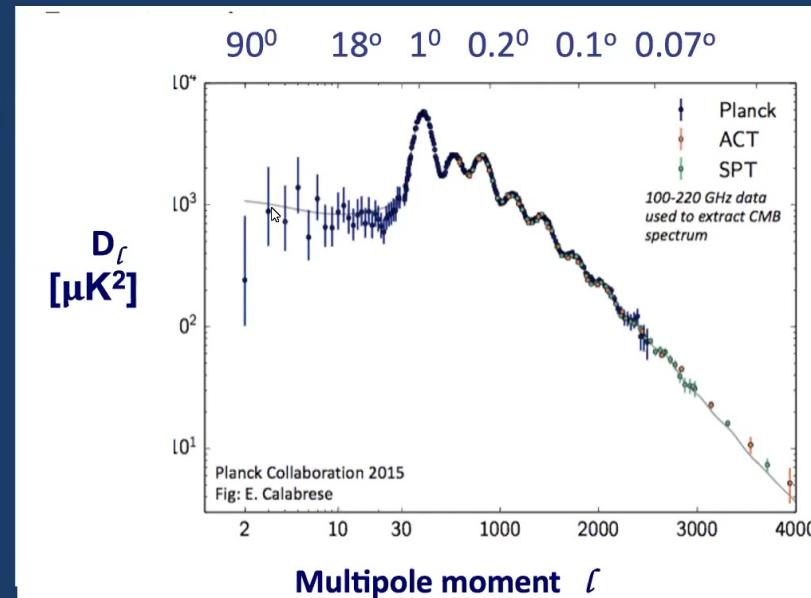
WLF (2021)



Cosmic Microwave Background (CMB) Anisotropies

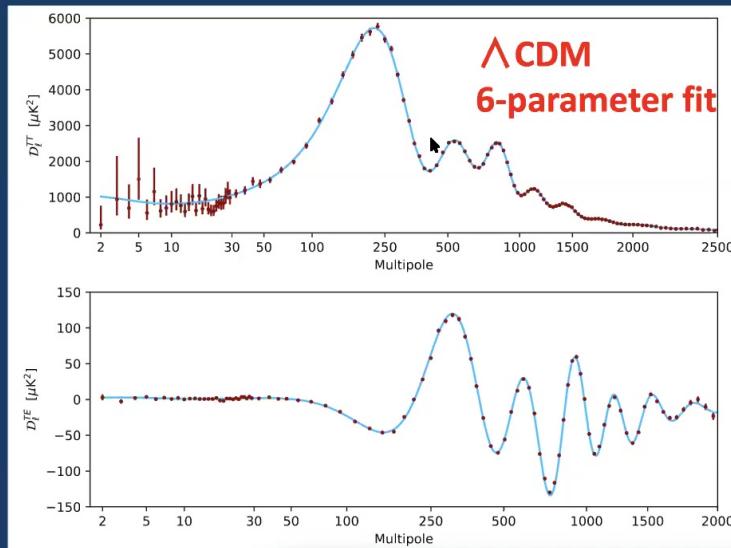
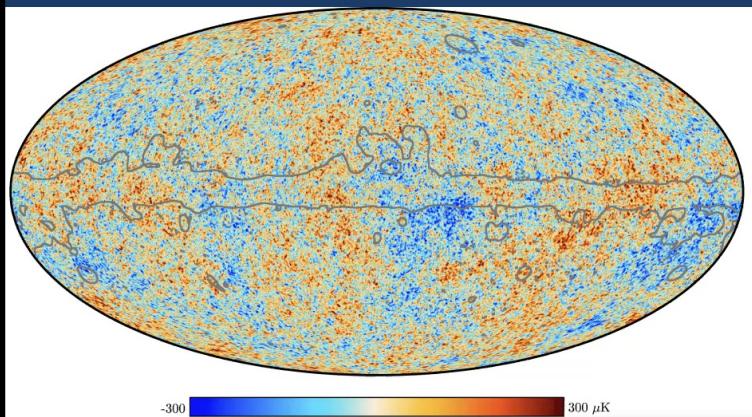


$$\langle T_1 T_2 \rangle = \sum a_{lm} Y_{lm}(\theta, \phi)$$
$$\left\langle |a_{lm}|^2 \right\rangle^{1/2} \equiv C_l$$



Planck 2015
E. Calabrese

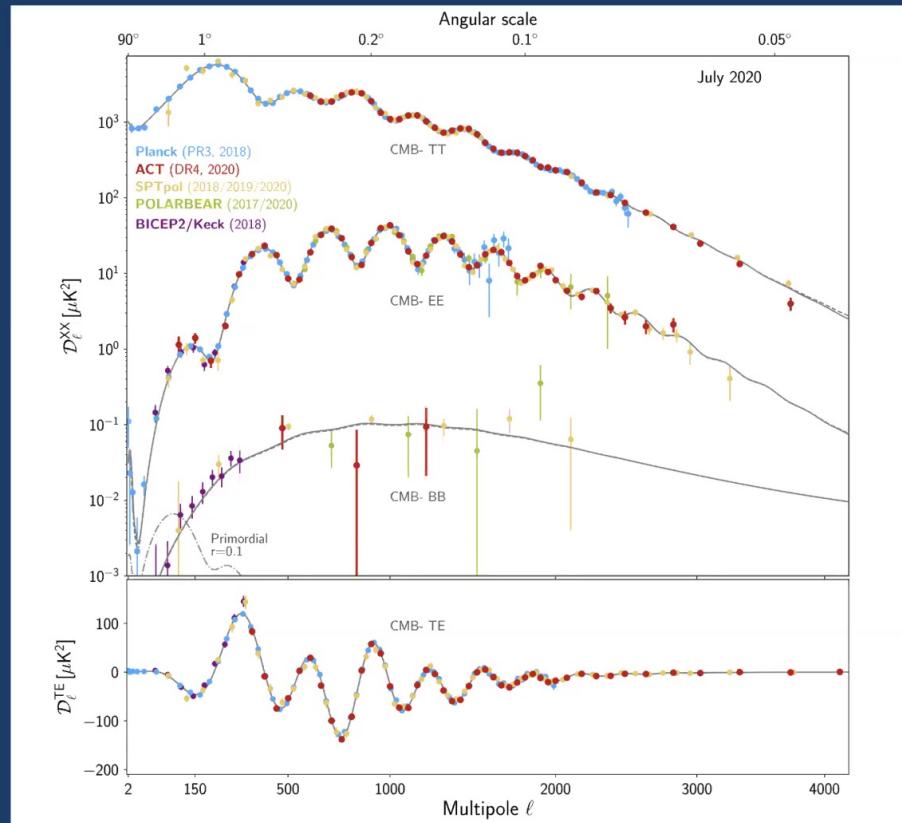
CMB Anisotropies 2018



Planck 2018



CMB Anisotropies: ACT Results 2020



ACT Choi et al. 2020



Summary of Recent H_0 Values

Λ CDM:	67.8 ± 0.9 (1.3%)	[Planck 2015]
+ polarization	66.93 ± 0.62 (0.9%)	[Planck 2016]
	67.4 ± 0.5 (0.7%)	[Planck 2018]
	67.6 ± 1.1 (1.6%)	[ACT/WMAP 2020]

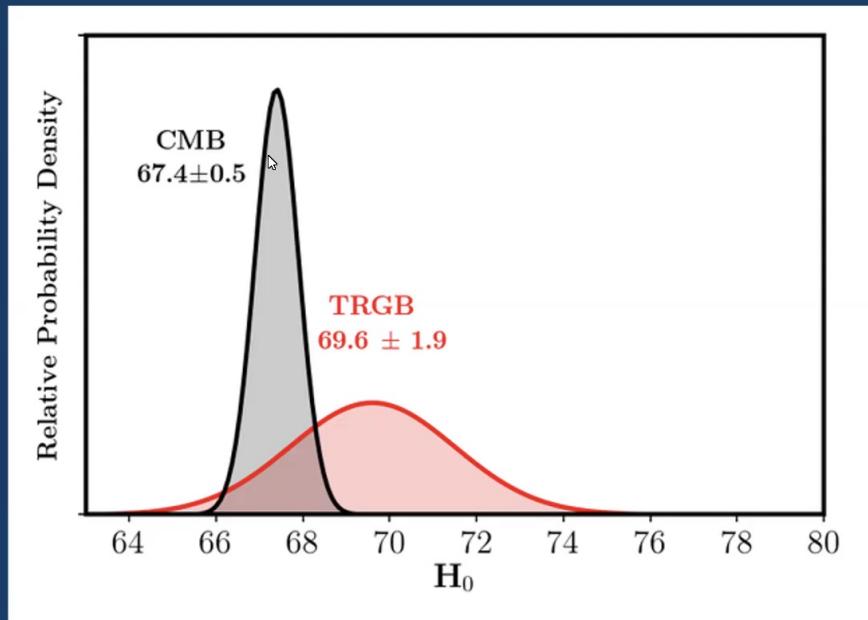
Cepheids	74.3 ± 2.1 (2.8%)	[WLF+ 2012]
+ SNIa :	73.24 ± 1.74 (2.4%)	[Riess+ 2016]
	74.03 ± 1.42 (1.9%)	[Riess+ 2019]
	73.2 ± 1.3 (1.8%)	[Riess+ 2020]

TRGB	69.8 ± 1.9 (2.7%)	[WLF+ 2019]
	69.6 ± 1.9 (2.7%)	[WLF+ 2020]

GL	73.3 ± 1.8 (2.5%)	[Wong+ 2019]
	$67.4_{(+4.1,-3.2)}$ (5.5%)	[Birrer+ 2020]



TRGB Compared to CMB



1.1 sigma tension with Planck

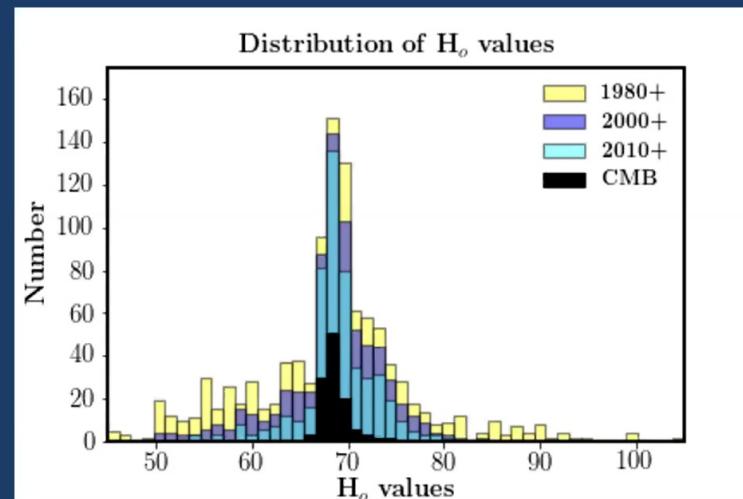
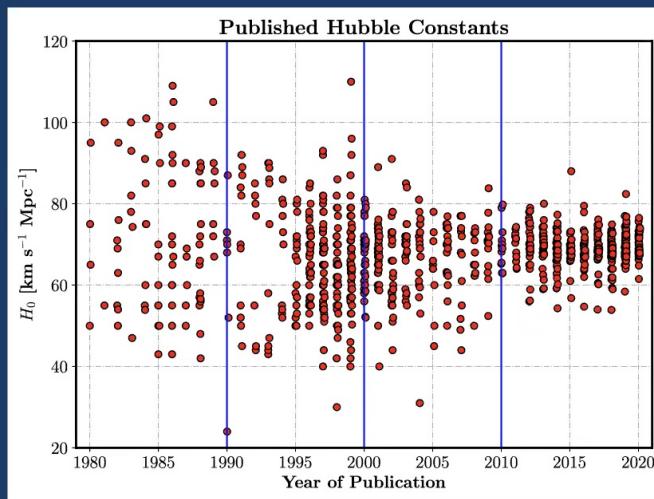
WLF et al. (2019, ApJ)
WLF et al. (2020), ApJ



Potential New Physics Beyond Λ CDM, 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
- Modified gravity
- Non-zero spatial curvature
- Additional early-universe physics (prior to recombination)
- Non-Gaussian primordial fluctuations

Published Values of the Hubble Constant (1980 – 2020)

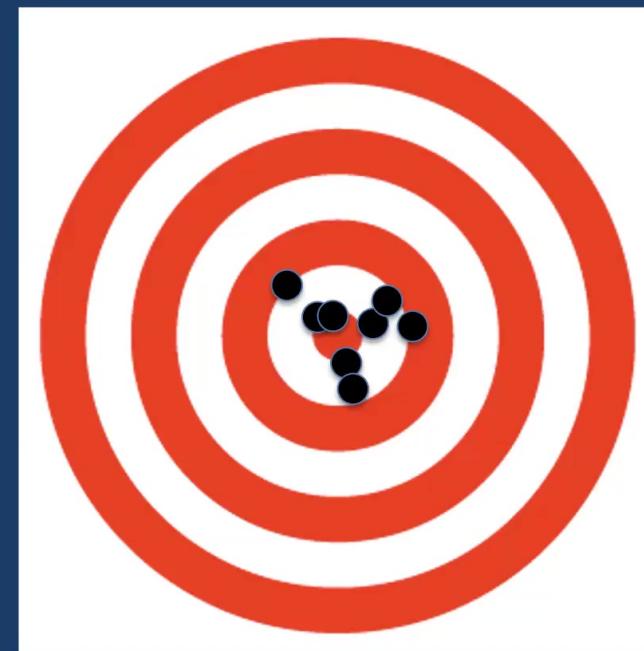


WLF (2021)
Database from Huchra, updated by Steer

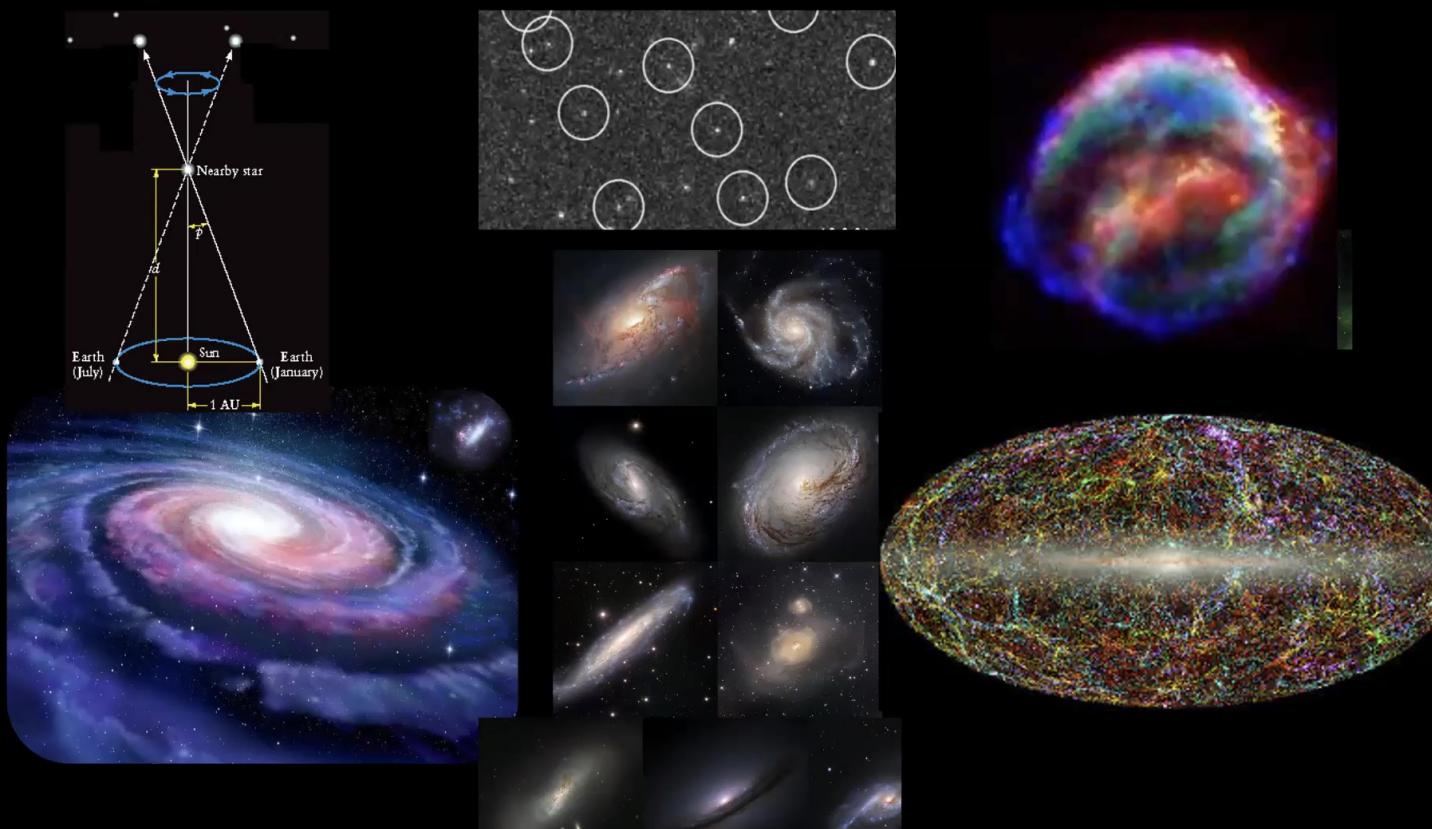
Precision vs Accuracy



Precision



Accuracy



Distances from geometry

Geometric Anchors
1-50 kpc, 7.6 Mpc

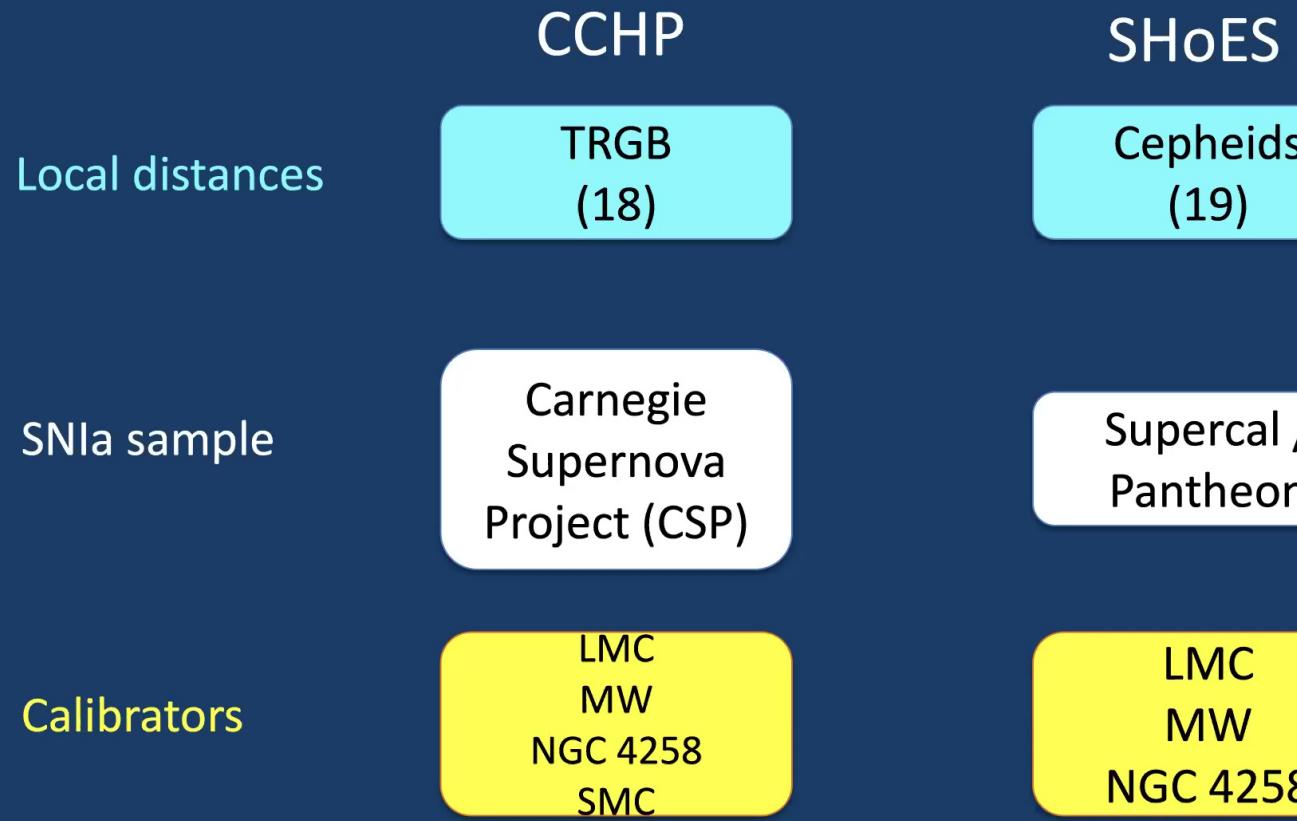
Nearby Galaxies Hubble
Space Telescope

SNe Ia Calibration
7-30 Mpc

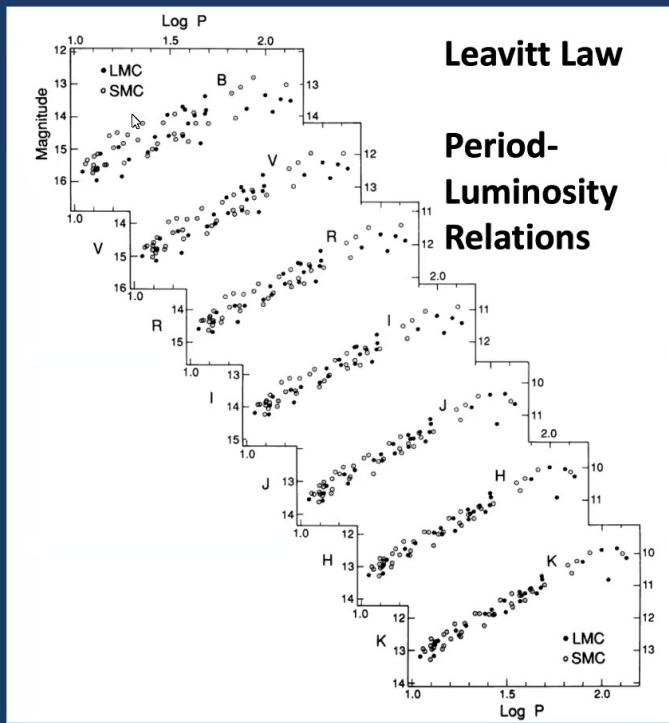
Distant Galaxies: supernovae

SNe Ia Hubble Diagram
100-500 Mpc

Independent Paths to H_0



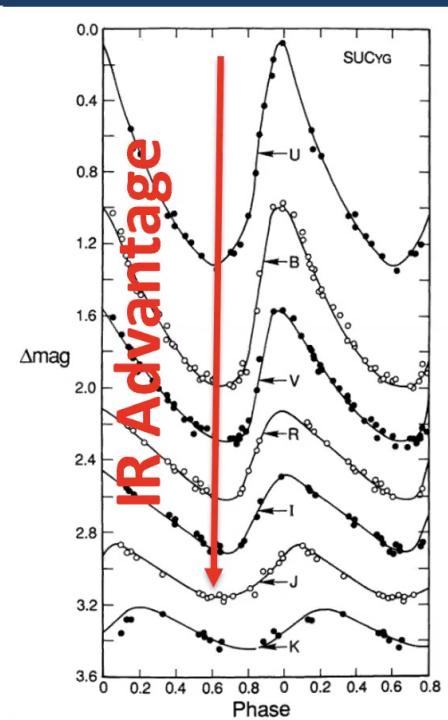
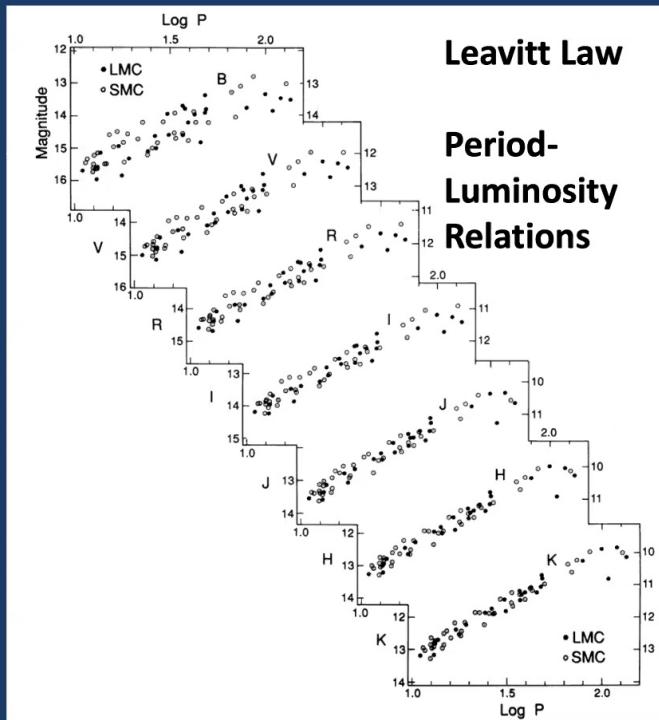
Stellar Astrophysical Distance Methods: Cepheids



WLF et al. 1990, 1991
Madore & WLF 1991



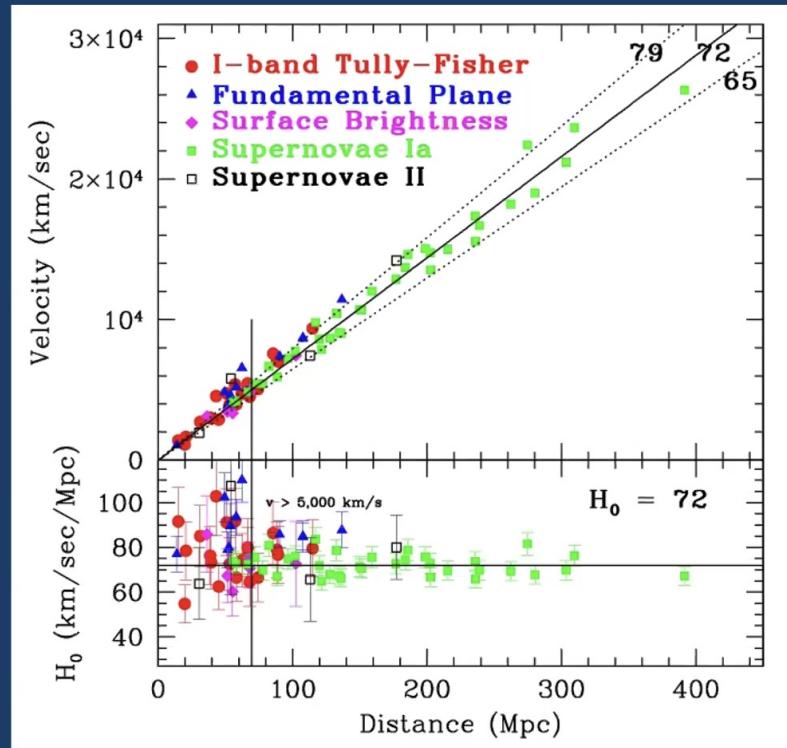
Stellar Astrophysical Distance Methods: Cepheids



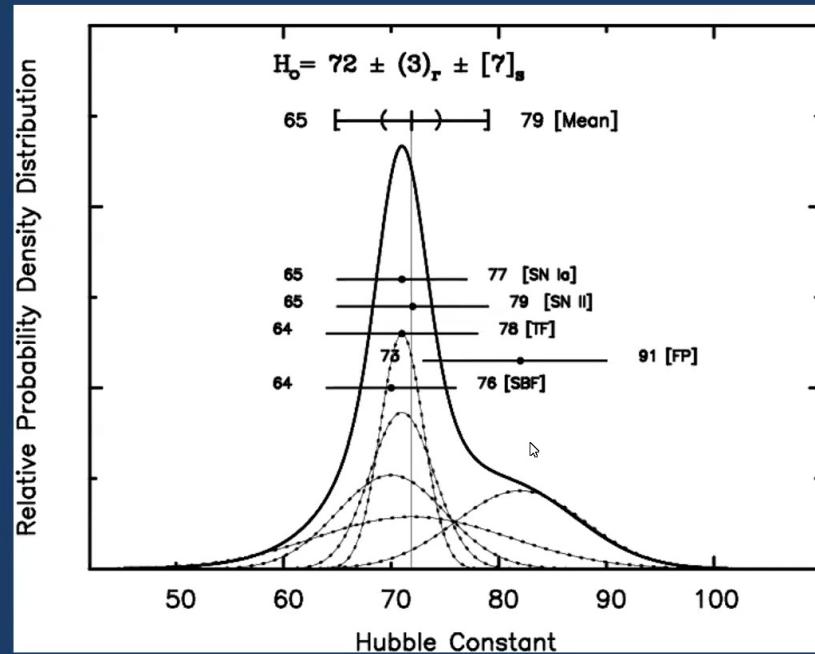
WLF et al. 1990, 1991
Madore & WLF 1991



Final Key Project Combined Results



Final Key Project Combined Results



$$H_0 = 72 \pm 3 \text{ (stat.)} \\ \pm 7 \text{ (sys.)}$$

km/sec/Mpc

WLF et al. 2001

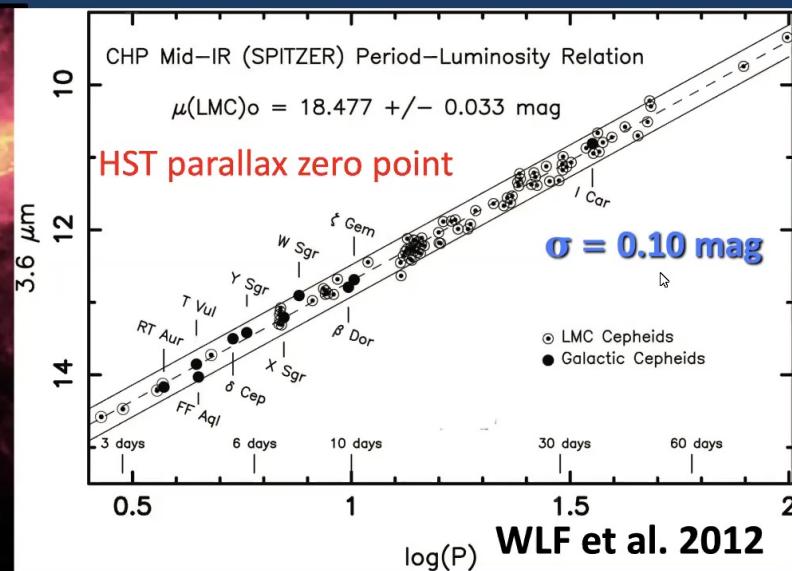


Cepheids: Recent Progress

Cepheids: Milky Way and LMC



Spitzer Infrared Telescope

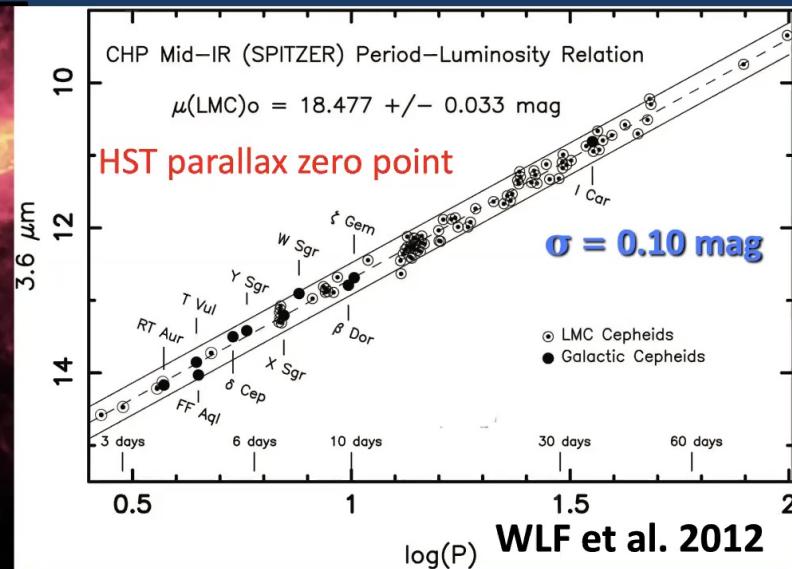


Cepheids: Recent Progress



Spitzer Infrared Telescope

Cepheids: Milky Way and LMC



Pietrzynski et al. (2019)

1% Distance to LMC from DEBs

$$\mu_{\text{LMC}} = 18.477 \pm 0.004 \text{ (stat)} \pm 0.26 \text{ (sys)}$$

Agreement to <1%

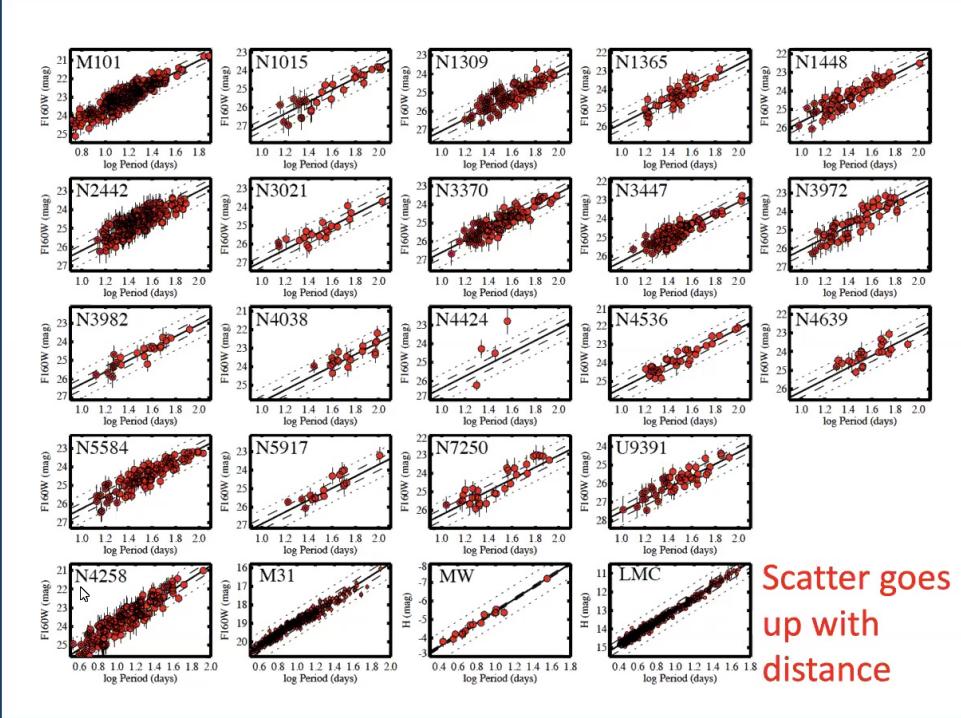
$$\mu_{\text{LMC}} = 18.48 \pm 0.01 \text{ (stat)} \pm 0.03 \text{ (sys)}$$

$$d = 49.6 \pm 0.8 \text{ kpc}$$

$$H_0 = 74.3 \pm 2.1 \text{ (stat)} \text{ km/sec/Mpc}$$



Cepheids: Recent Progress



SHoES program

- > 1000 HST orbits
- 19 Cepheid galaxies
- Milky Way parallaxes



Riess et al. 2016

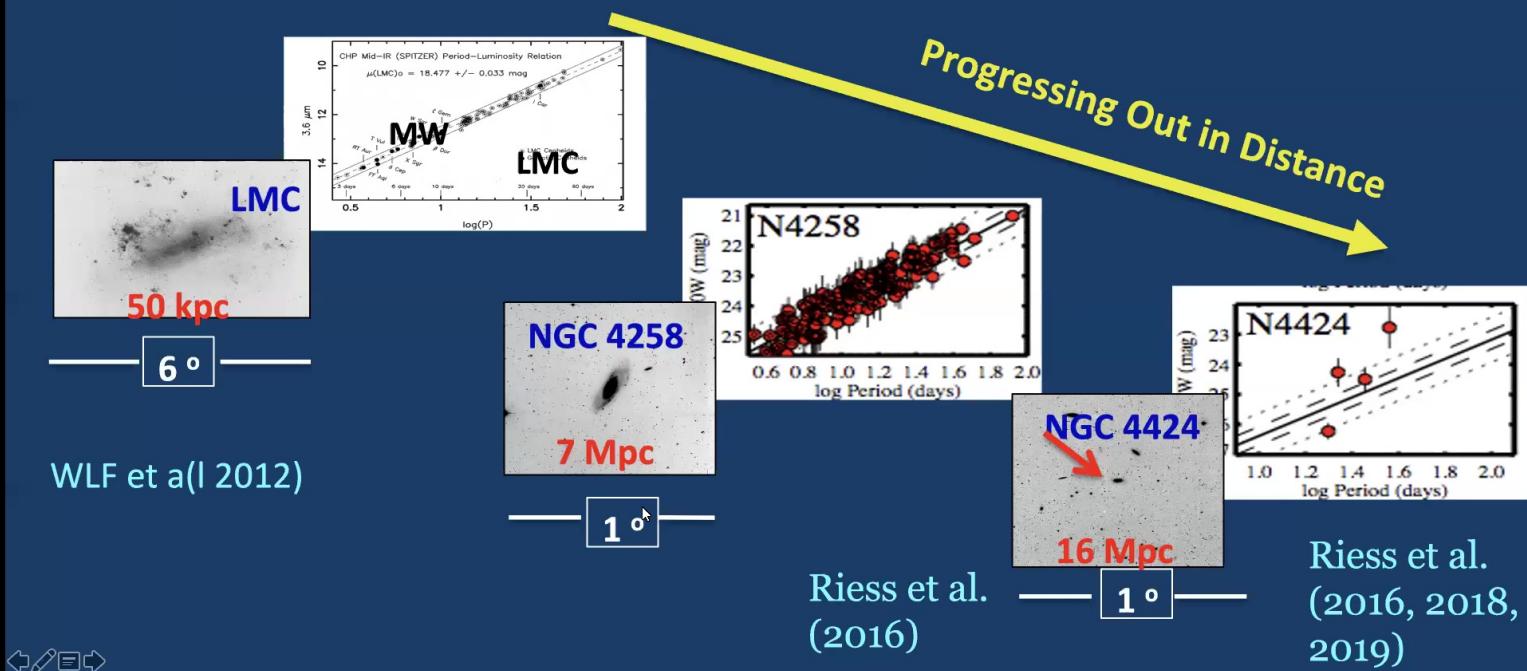
Cepheids: Challenges

- Metallicity effects (at what level?)
- Stellar evolutionary effects: multiple crossings of instability strip
- Small numbers of galaxies for which both SNe Ia and Cepheids
- Crowding and blending effects **

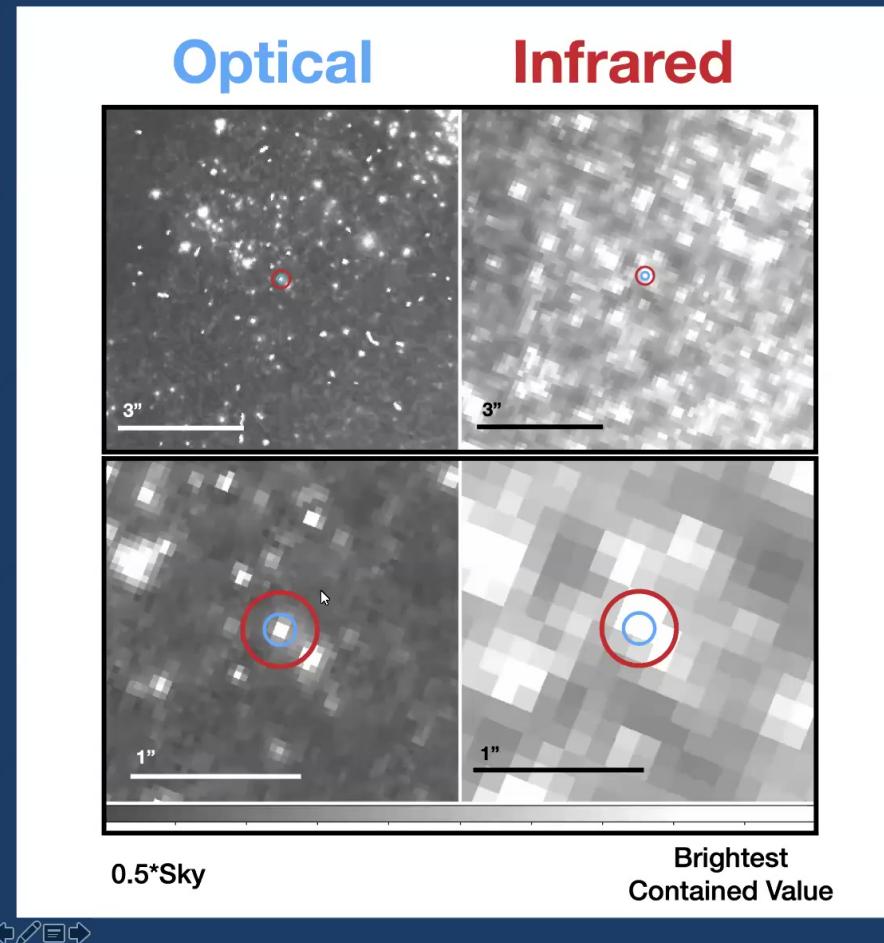


Cepheids: Challenges

- Metallicity effects (at what level?)
- Stellar evolutionary effects: multiple crossings of instability strip
- Small numbers of galaxies for which both SNe Ia and Cepheids
- Crowding and blending effects **



Cepheids: NGC 4258



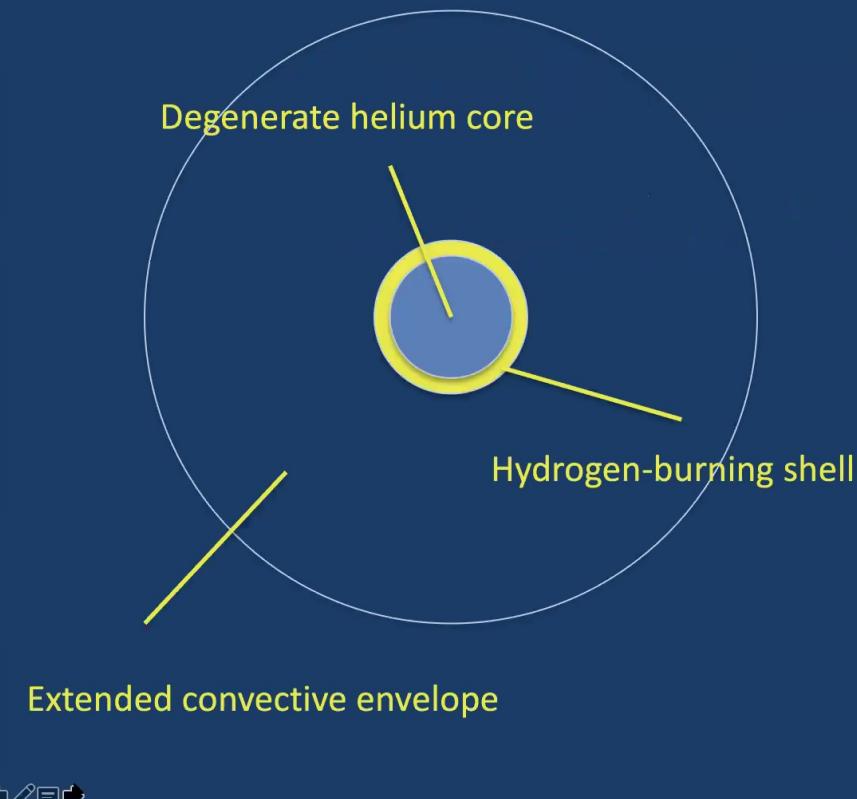
- These are crowded fields, rendering accurate photometry a challenge

2nd nearest galaxy in the sample! D = 7.6 Mpc

It is also one of three anchor galaxies that sets the overall calibration of Cepheid luminosities.

Data from Riess et al. 2011

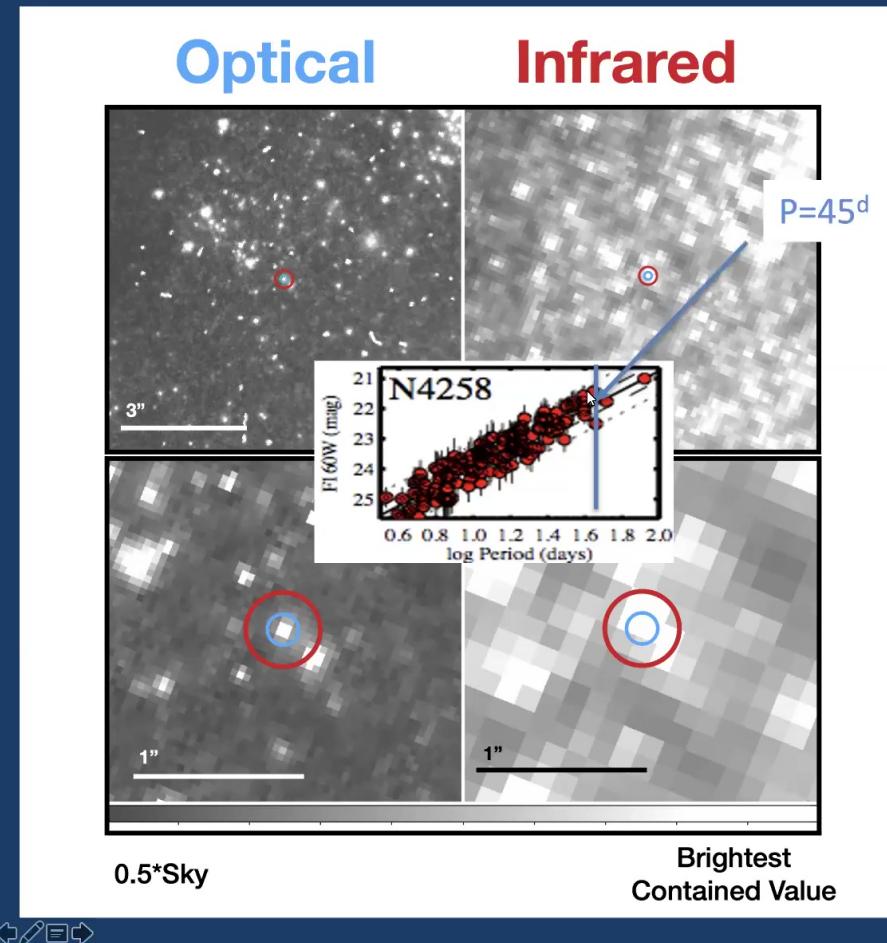
Stellar Astrophysical Distance Methods: Lifting Degeneracy in Helium Core for Low-mass Stars (TRGB)



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

*

Cepheids: NGC 4258



- These are crowded fields, rendering accurate photometry a challenge

2nd nearest galaxy in the sample! D = 7.6 Mpc

It is also one of three anchor galaxies that sets the overall calibration of Cepheid luminosities.

Data from Riess et al. 2011

Tip of the Red Giant Branch (TRGB)



The Chicago Carnegie Hubble Program (CCHP)

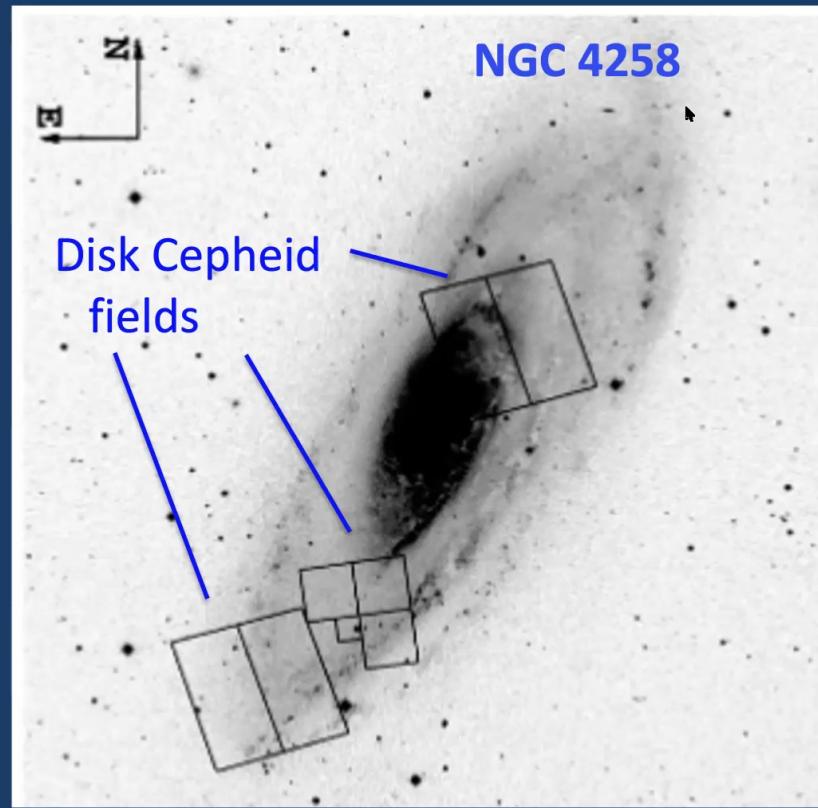
Stellar Astrophysical Distance Methods



Goal: H_0 to 2% (statistical +systematic)



Cepheids / The Tip of the Red Giant Branch



Cepheid HST ACS + WFPC2 fields

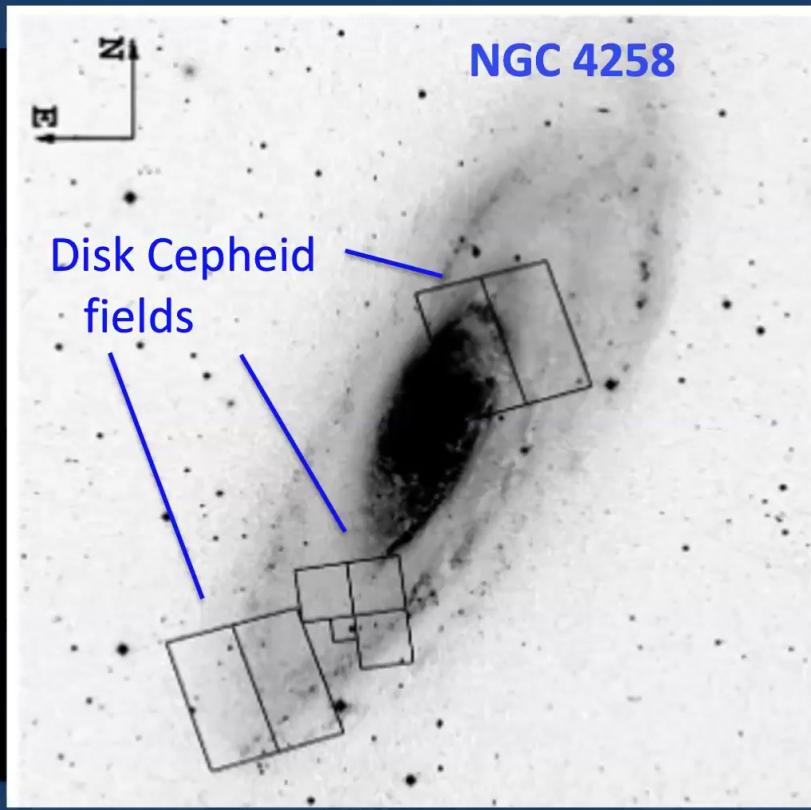
Macri + Riess et al. (2006)



Cepheids / The Tip of the Red Giant Branch



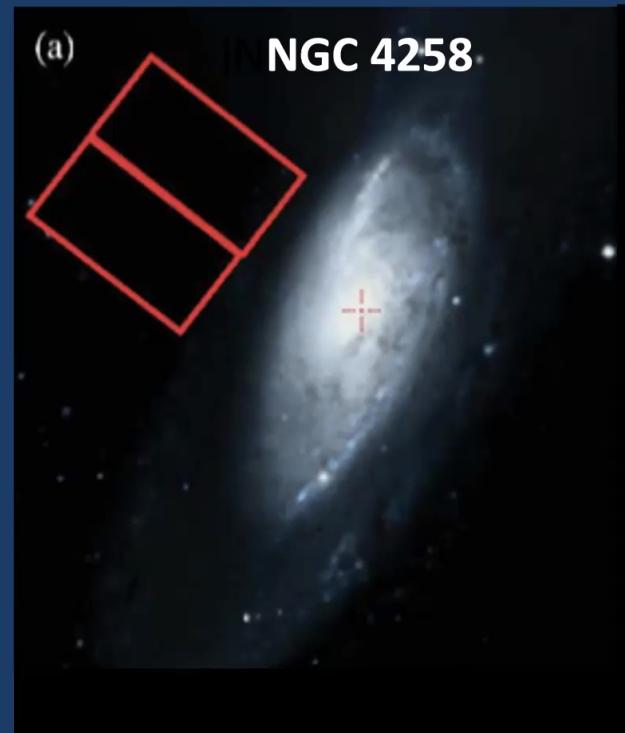
TRGB HST ACS field
Mager, Madore & WLF (2008)



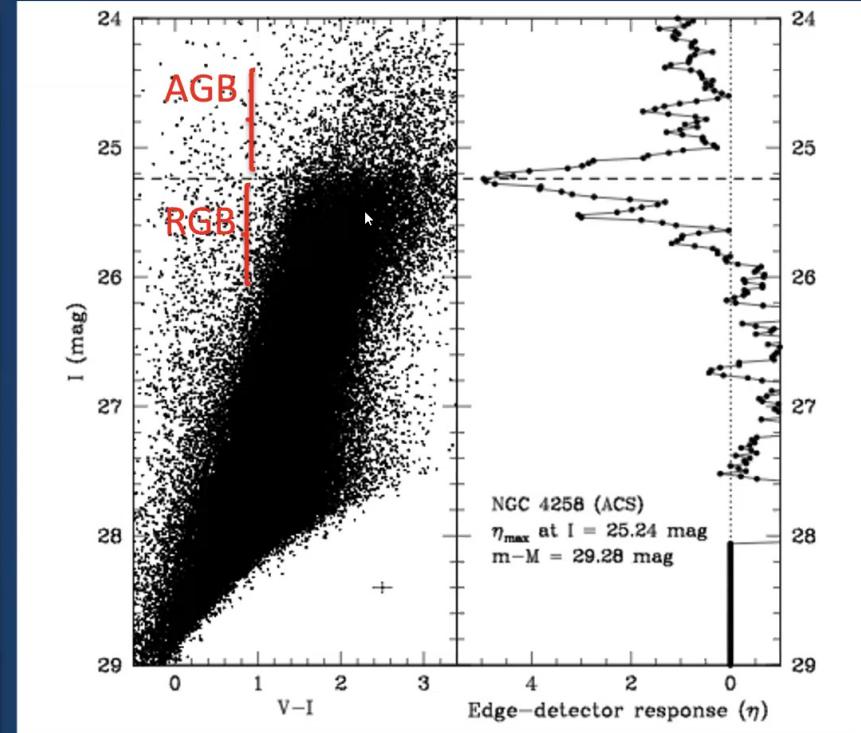
Cepheid HST ACS + WFPC2 fields
Macri + Riess et al. (2006)



The Tip of the Red Giant Branch



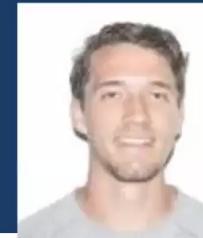
Measure 1st derivative
of luminosity function



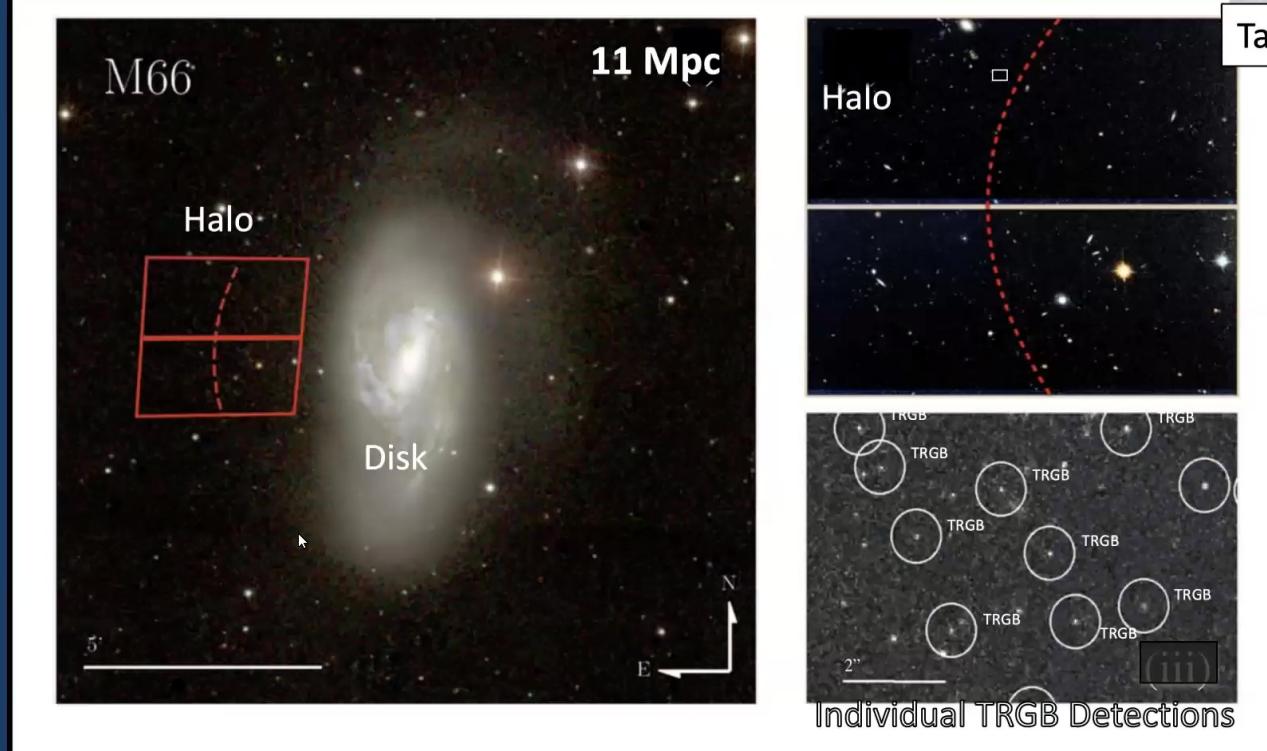
Mager, Madore & WLF (2008)



TRGB Halo Fields No Dust, Minimal Crowding

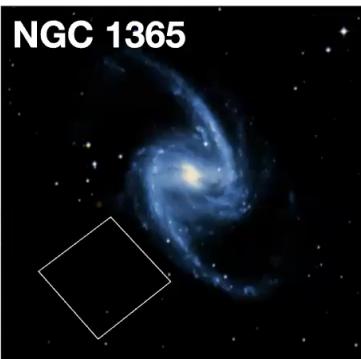
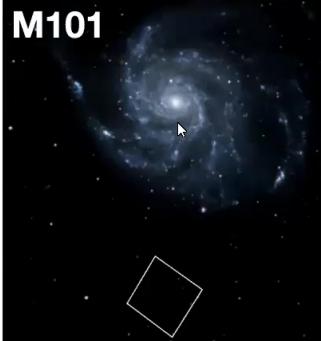


Taylor Hoyt



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



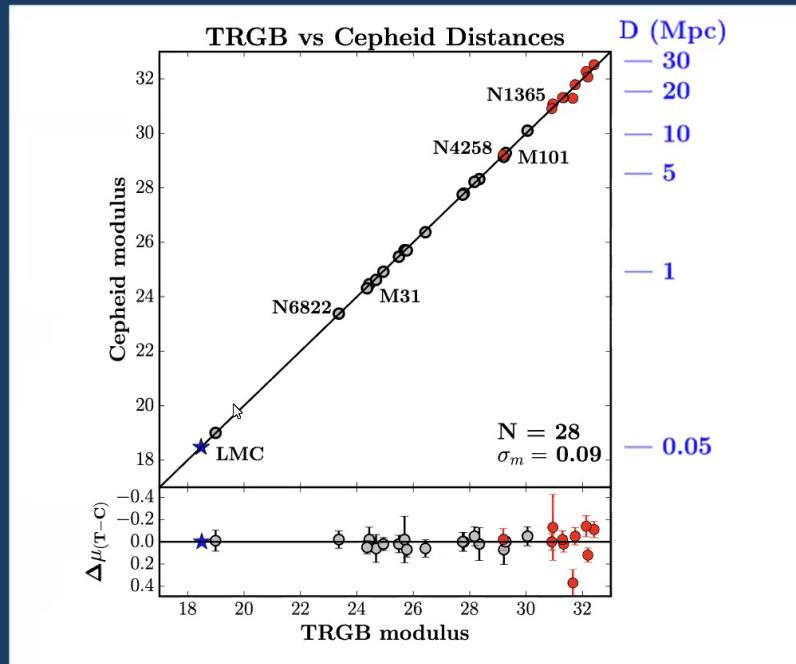


HST Program:

- Advanced Camera for Surveys (ACS)
- VI data for 9 galaxies host to 11 SNe Ia
- Archival data for 5 galaxies
- 2 additional Fornax galaxies

18 TRGB calibrators

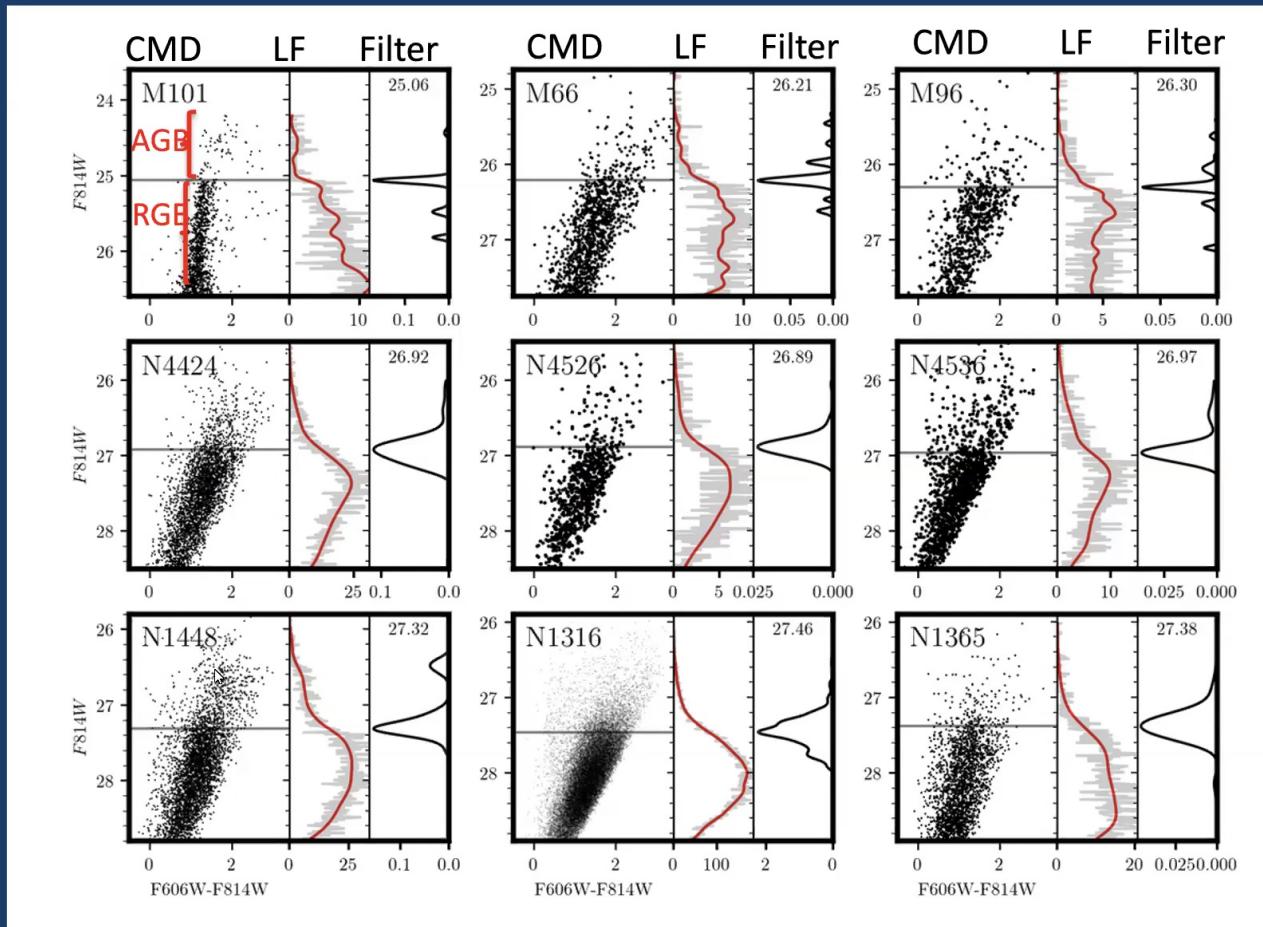
Comparison of Published TRGB and Cepheid Distances



WLF et al. (2019)



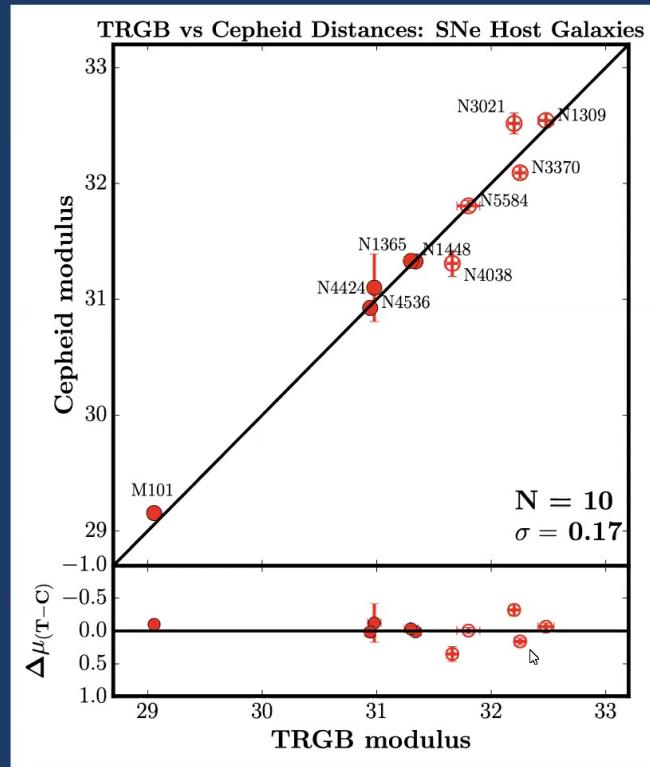
Taylor
Hoyt



Independent subgroups “blinded” / separate analyses / artificial star tests
Photometric reductions, photometric calibration, TRGB measurements



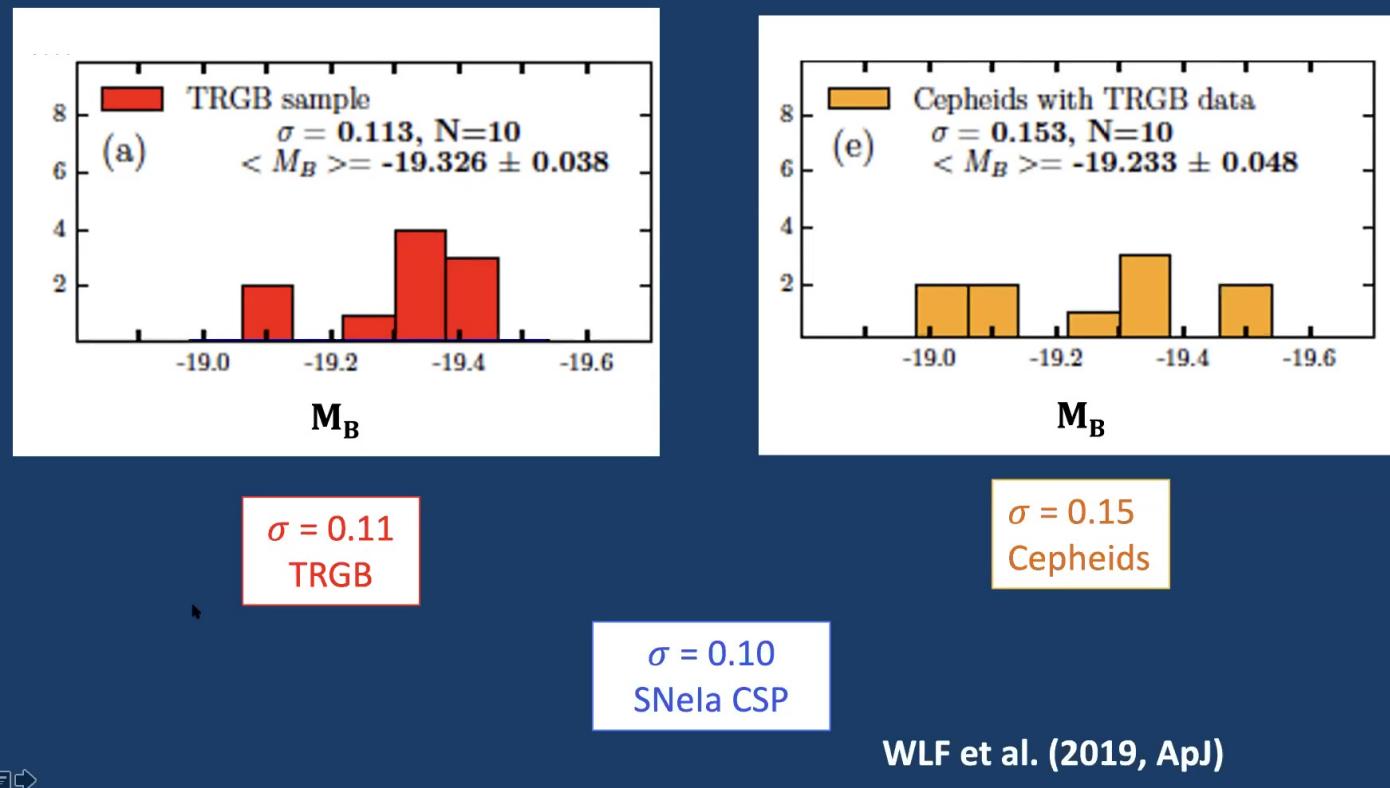
Comparison of TRGB and Cepheid Distances to SNeIa Hosts in Common



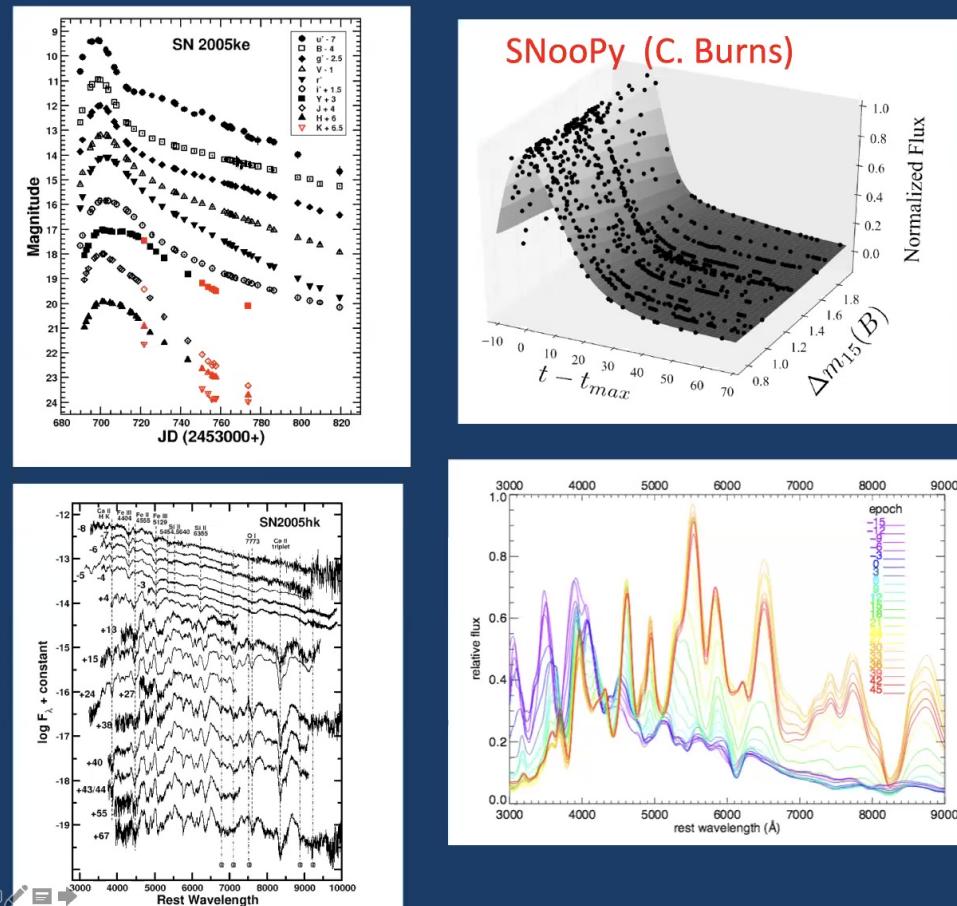
WLF et al. (2019)



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



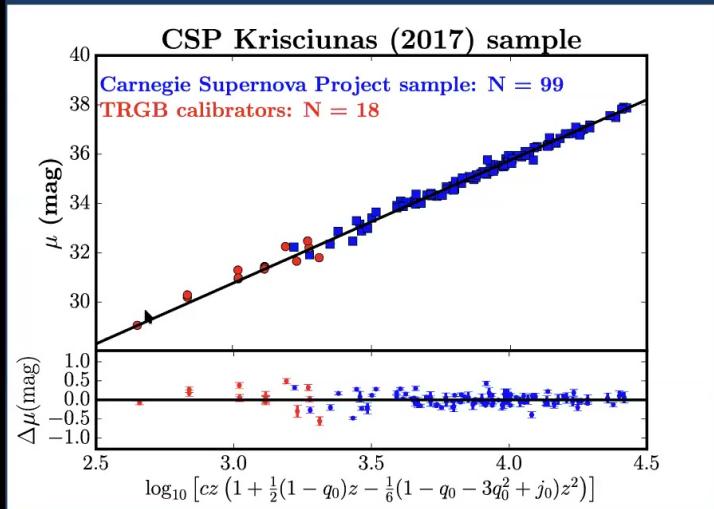
CSP: Dealing With Systematics



Well-sampled:

- Photometry
- Spectra
- Reddening
- K-corrections
- Evolution
- **Most extensive, self-consistent data set for dealing with systematics**

CCHP TRGB Calibration of H_0



Fit light-curve parameters:

time of maximum

light-curve shape

magnitude at maximum for each filter (9 filters)

Use as inputs for MCMC analysis: simultaneously solve for

slope of color correction

K-corrected peak magnitudes

slope of correlation between peak luminosity and host galaxy mass

H_0

Full covariance matrix

$$q_0 = \frac{-\ddot{a}a}{\dot{a}^2}$$

$$j_0 = \frac{-\ddot{\dot{a}}a^2}{\dot{a}^3}$$

$$H_0 = 69.8 \pm 1.1 \text{ (stat)} \pm 1.7 \text{ (sys)} [2.7\%] \text{ km s}^{-1} \text{ Mpc}^{-1}$$

WLF et al. (2019)

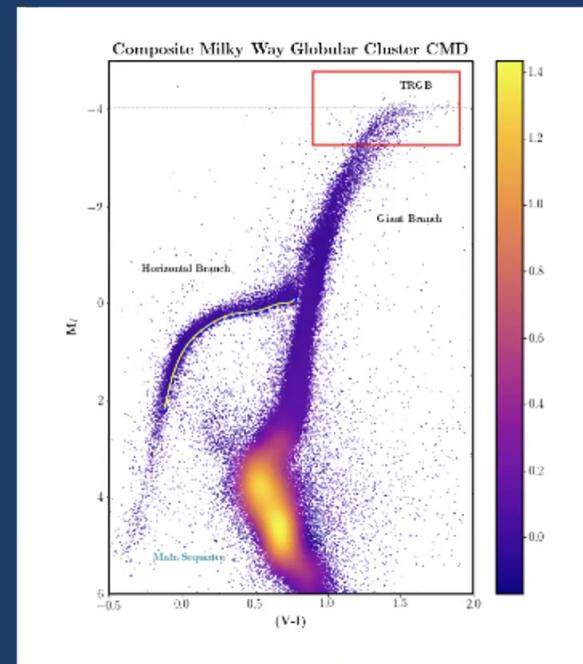
$$H_0 = 69.6 \pm 1.1 \text{ (stat)} \pm 1.7 \text{ (sys)} [2.7\%] \text{ km s}^{-1} \text{ Mpc}^{-1}$$

WLF et al. (2020)



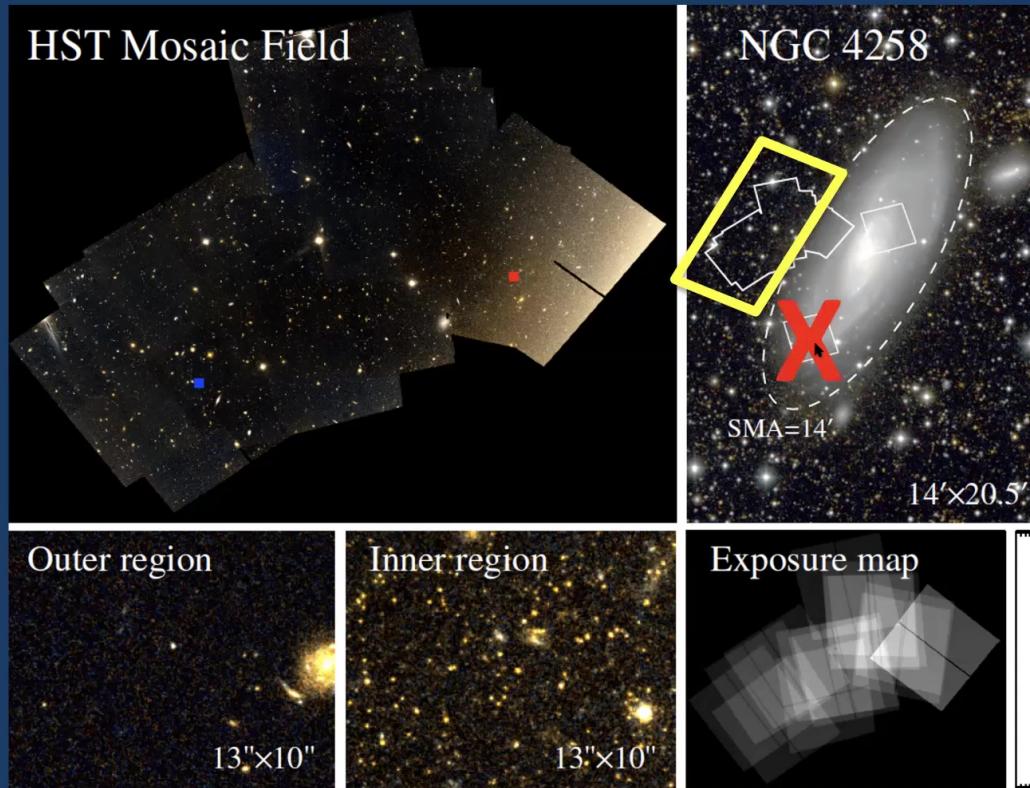
More Tests of the TRGB Calibration: Milky Way Globular Clusters

- 46 Milky Way clusters
- Gaia proper motion sample
- Stetson uniform photometry
- -2.2 to -0.7 dex
- Agree with Freedman et al. (2019).



47

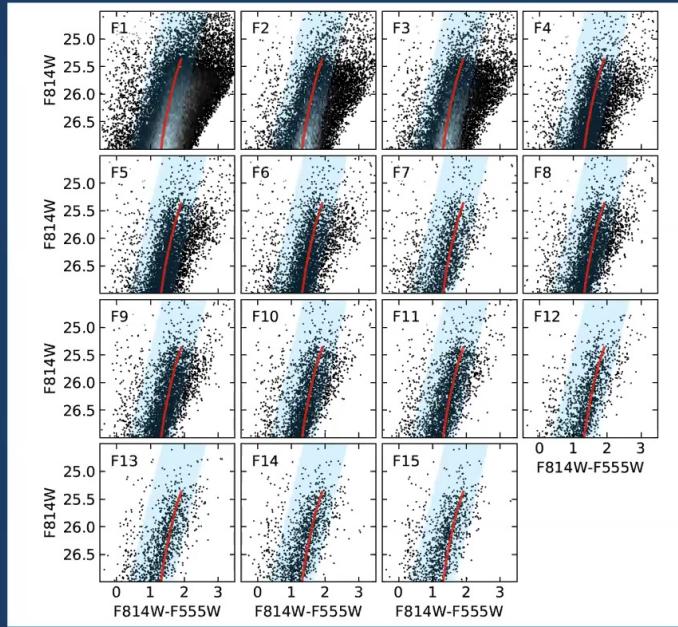
NGC 4258 TRGB ***NEW



Jang et al, ApJ, 2020



NGC 4258 TRGB ***NEW



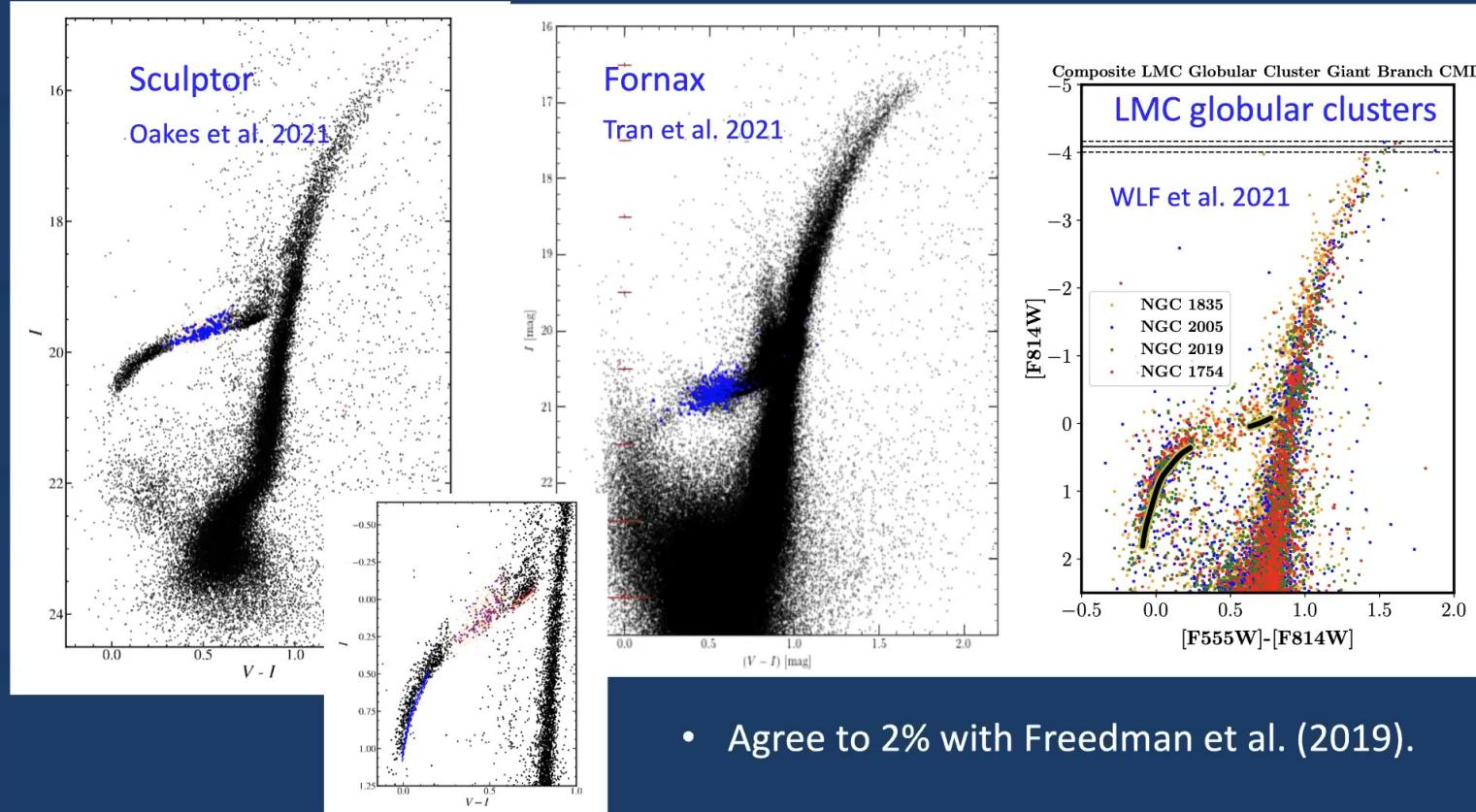
Jang et al. 2020:
 M_{814} (TRGB)
 $= -4.050 \pm 0.027 \text{ (stat)} \pm 0.045 \text{ (sys)}$

Compare with WLF 2020:
 M_{814} (TRGB)
 $= -4.054 \pm 0.022 \text{ (stat)} \pm 0.039 \text{ (sys)}$

Jang et al, ApJ, 2020



More Tests of the TRGB Calibration: Milky Way Dwarf Spheroidals and LMC Globular Clusters



Gaia – Early Data Release 3



- December 3, 2020
- 34 months of data
(22 months for DR2)
- Parallaxes, proper motions
- 1.5 billion stars
- DR3 Parallax uncertainty:
 - ~ 0.02-0.03 mas G < 15 mag
 - ~ 0.07 mas @ 17 mag
 - ~ 0.5 mas @ 20 mag

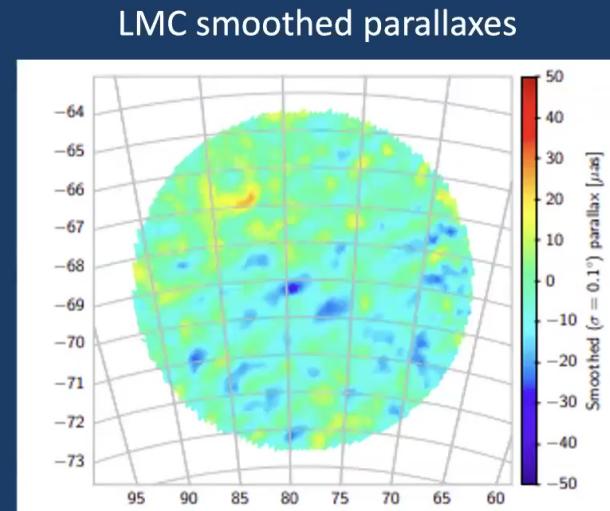
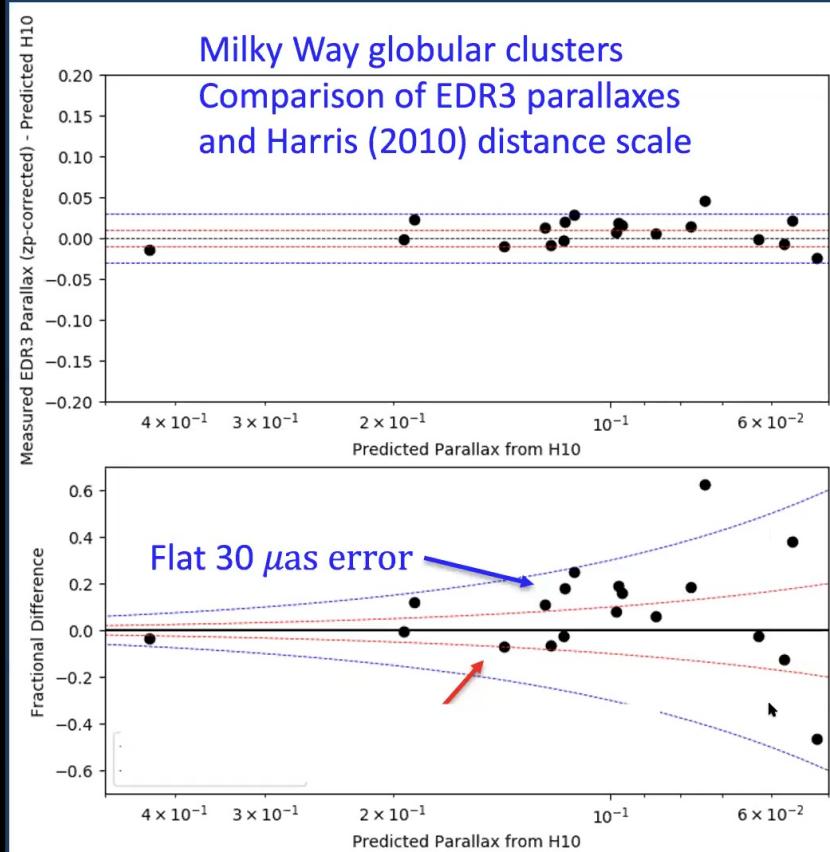
Gaia DR2 (2018): parallax zero-point offset of -29 μ as.

EDR3: parallax improvement 20% wrt Gaia DR2

parallax zero-point offset of -17 μ as

proper motions a factor of two better

EDR3 Systematic Uncertainties

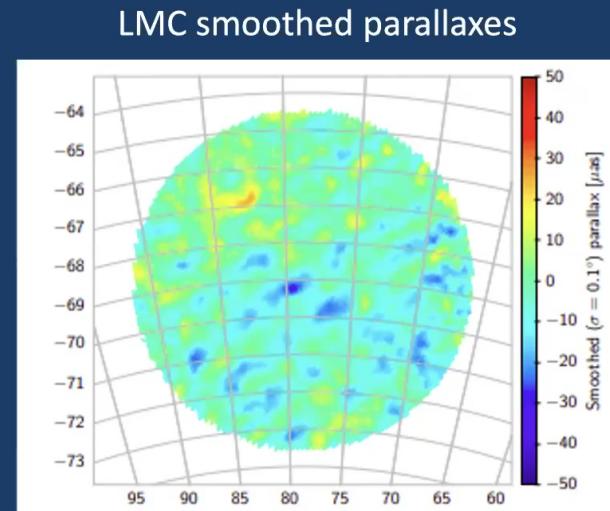
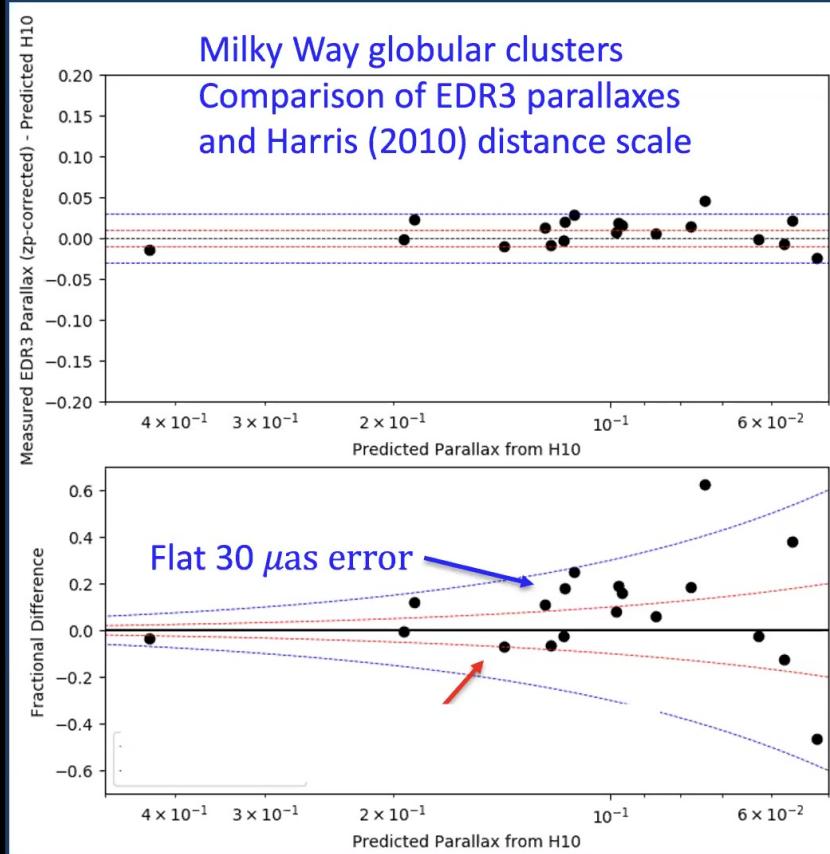


Lindgren et al. 2020
Figure 14

Cerny et al 2021, in prep.



EDR3 Systematic Uncertainties

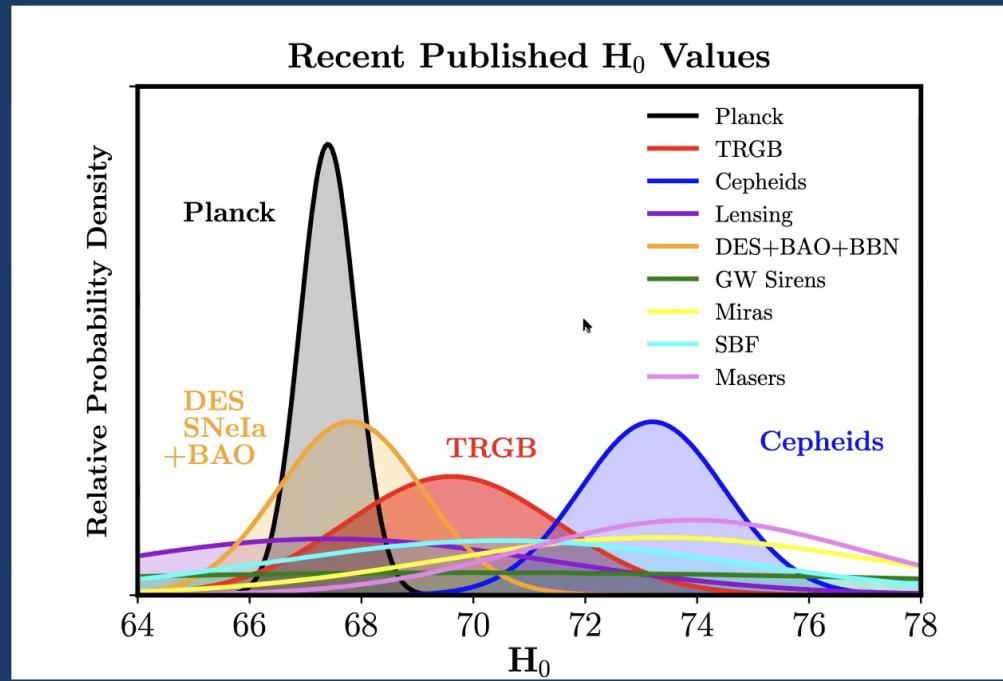


Lindgren et al. 2020
Figure 14

Cerny et al 2021, in prep.

Thus, we are not using EDR3 data for our calibration.

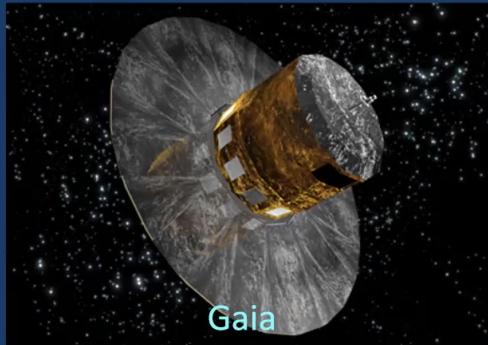
Recent Published Values of the Hubble Constant



WLF (2021)



TRGB Increasing Precision and Accuracy for Future



H_0 zero-point to
<1%



Hubble Space Telescope (HST)

Improved LMC &
N4258 calibration
(<1%)

Survey larger
volume; increase
statistical precision
to 1%



James Webb Space Telescope (JWST)

Launch date: Oct. 31, 2021

Concluding Remarks

- The Hubble tension remains unresolved.
- There is the exciting possibility of new physics beyond the standard model supported by Cepheid data from Spitzer (WLF et al. 2001, 2012) and the SHoES team (Riess et al. 2020). And some evidence from less accurate methods.
- There are indications that there may still be systematic errors that could be affecting the local distance scale at the 2-3% level. The TRGB results do not require new physics.
- Discriminating between new physics and systematic errors will take a few more years, but is entirely feasible with longer-baseline Gaia data, the James Webb Space Telescope, and longer term with other techniques (e.g., LIGO).