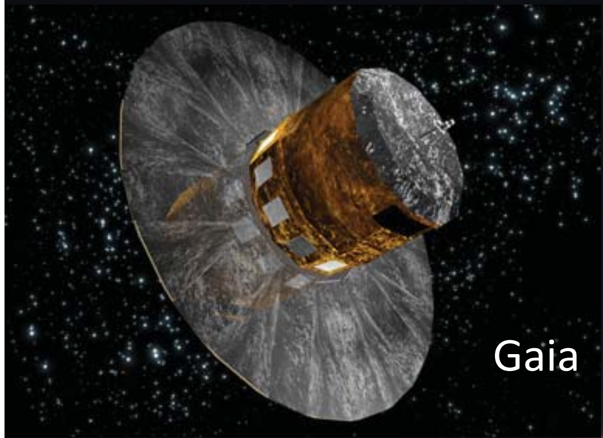
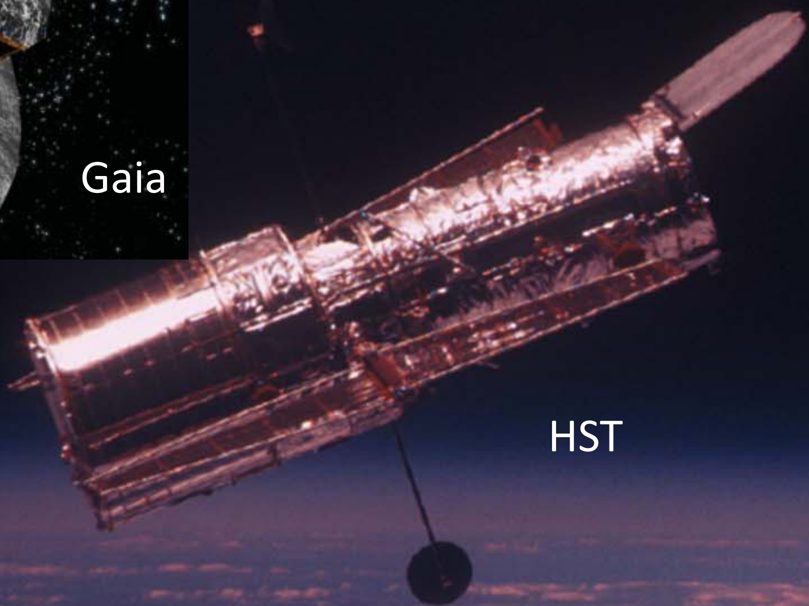
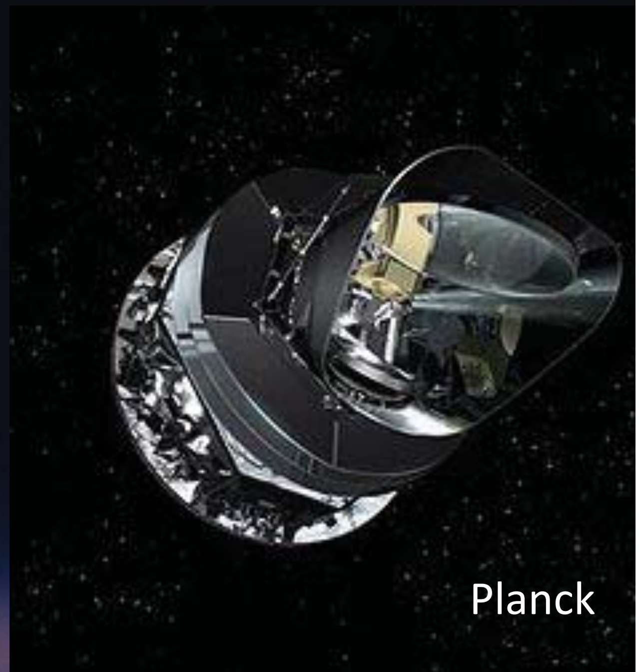
Cosmological Controversy: Resolving the Tension in the Hubble Constant



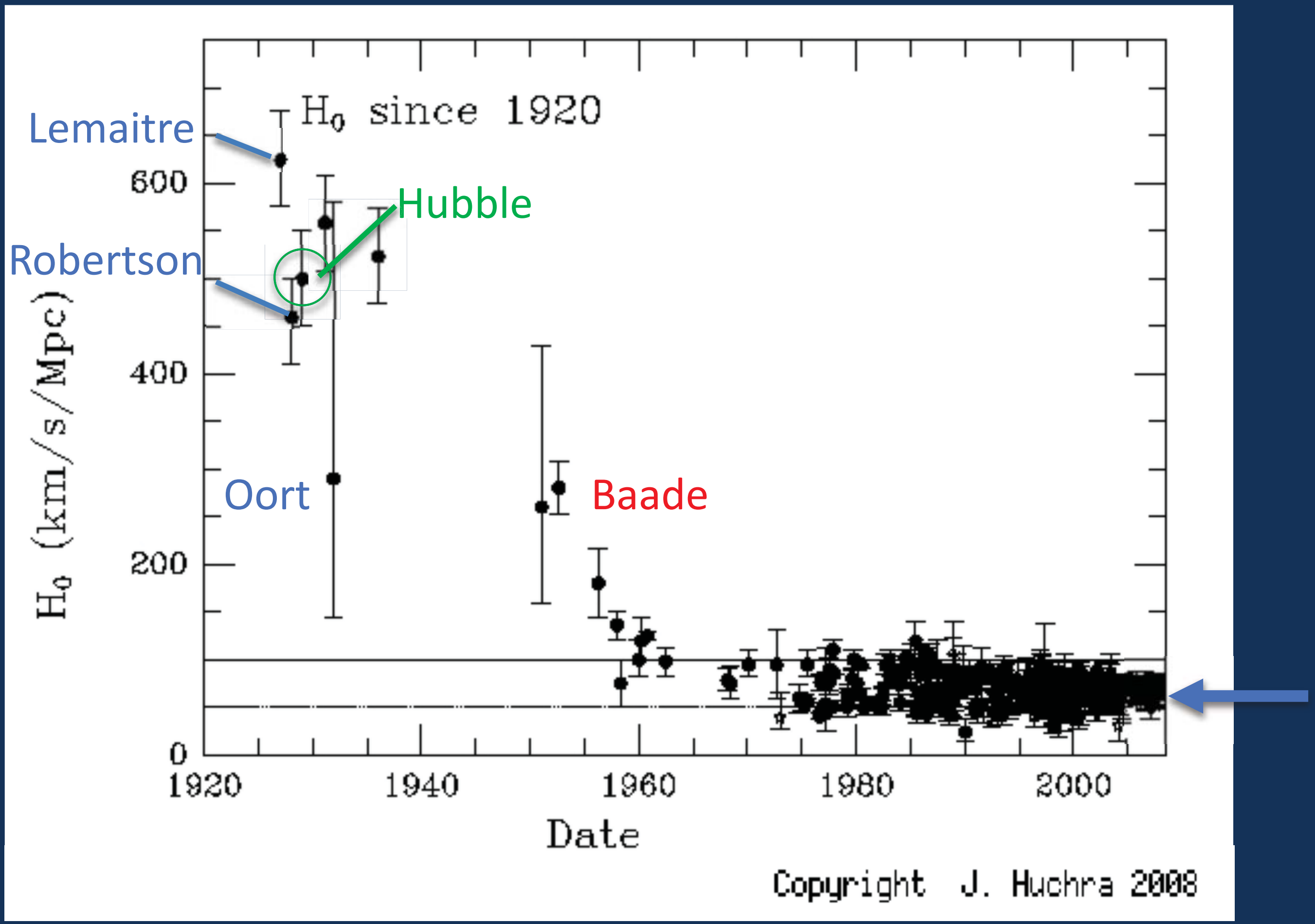




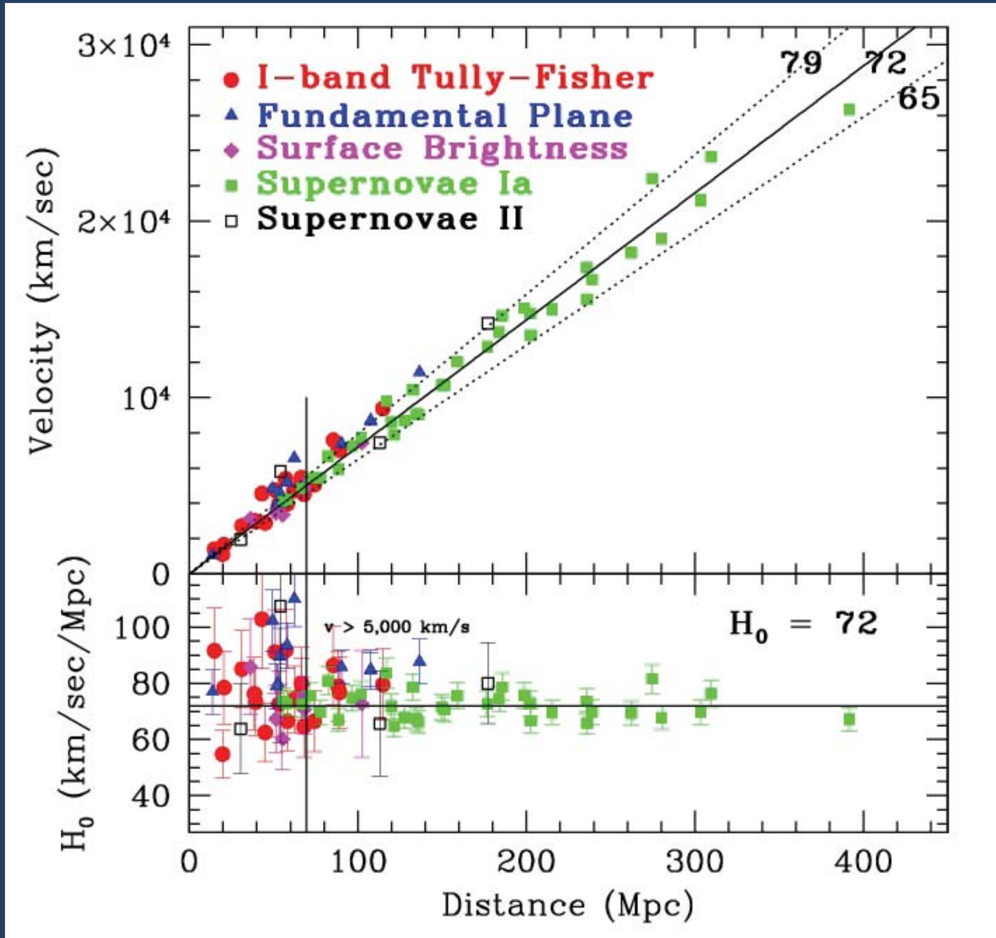
Wendy L Freedman
University of Chicago

"The Hubble constant controversy: status, implications and solutions"
Berlin, November 9, 2018

History of the Hubble Constant



Final Hubble Space Telescope Key Project Combined Results

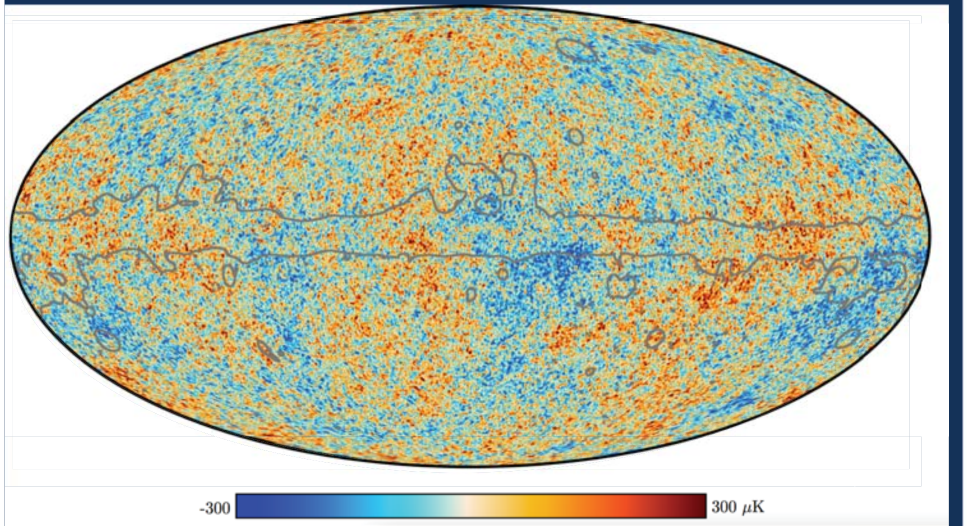


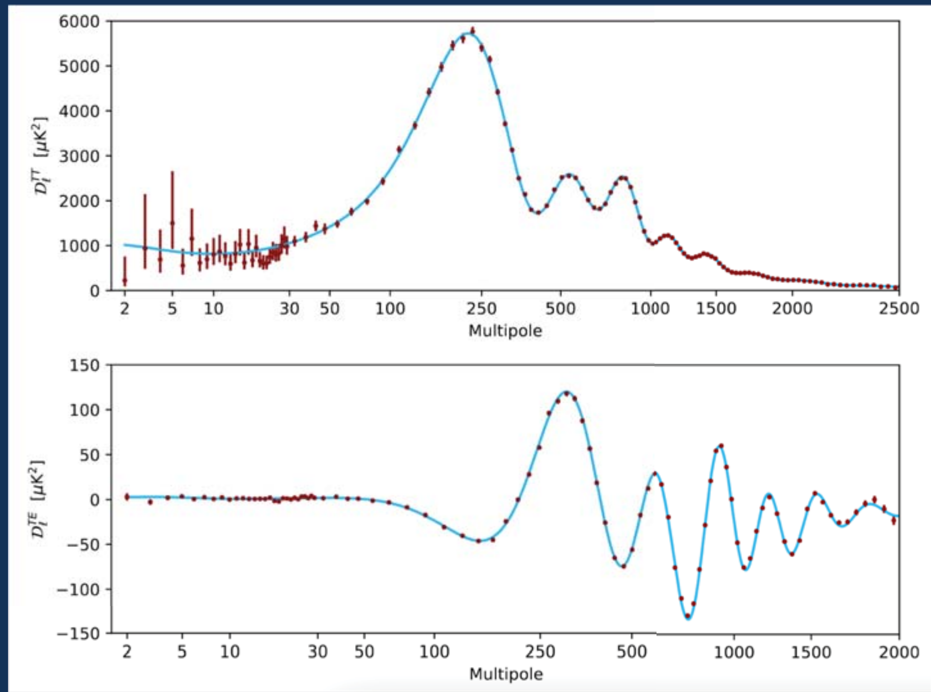
HST Key Project:

Discovery of Cepheid variables and a measurement of H_o to an accuracy of 10%.

Freedman et al. 2001

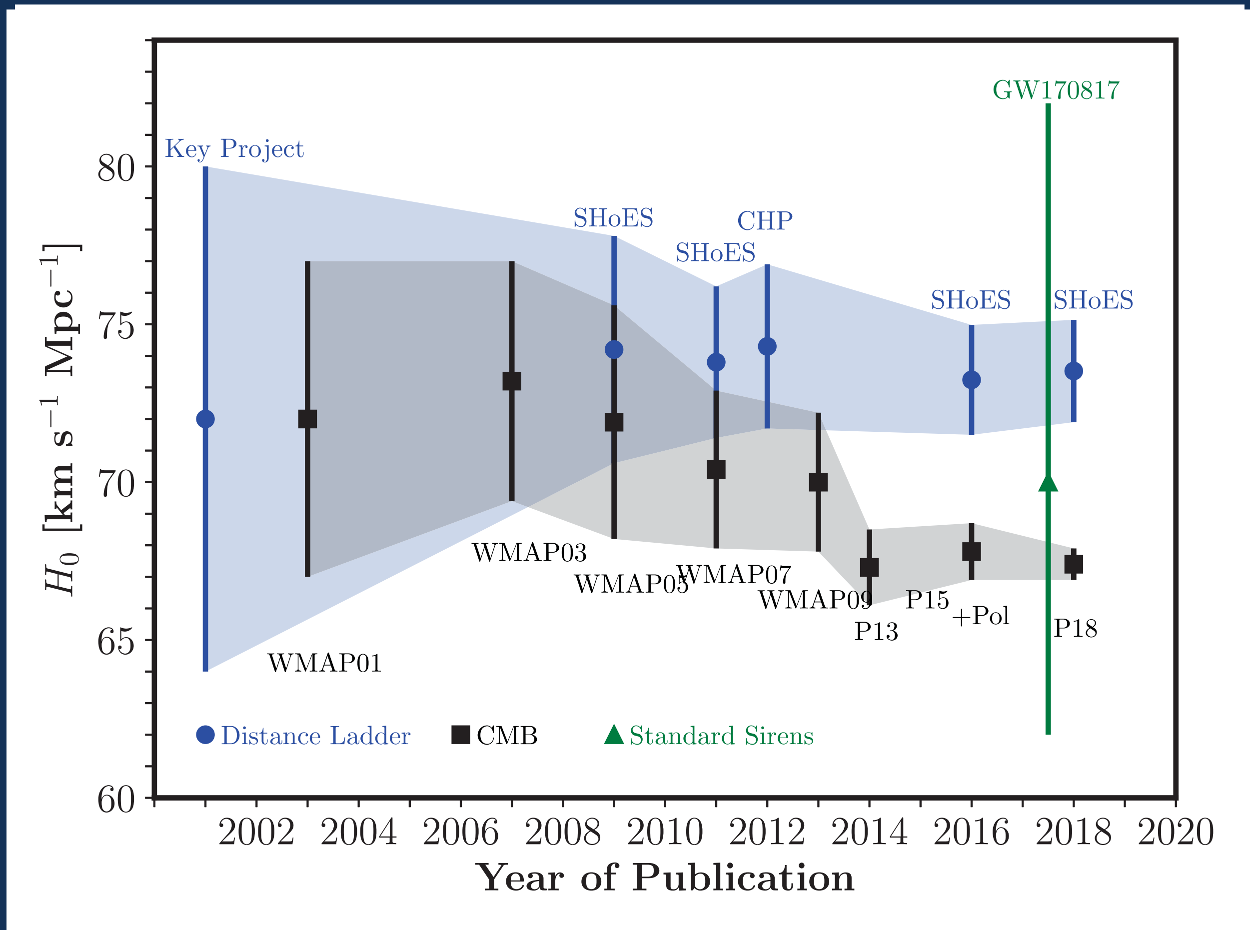
CMB Anisotropies





Planck 2018

The Current Tension in H_0



3.8 σ

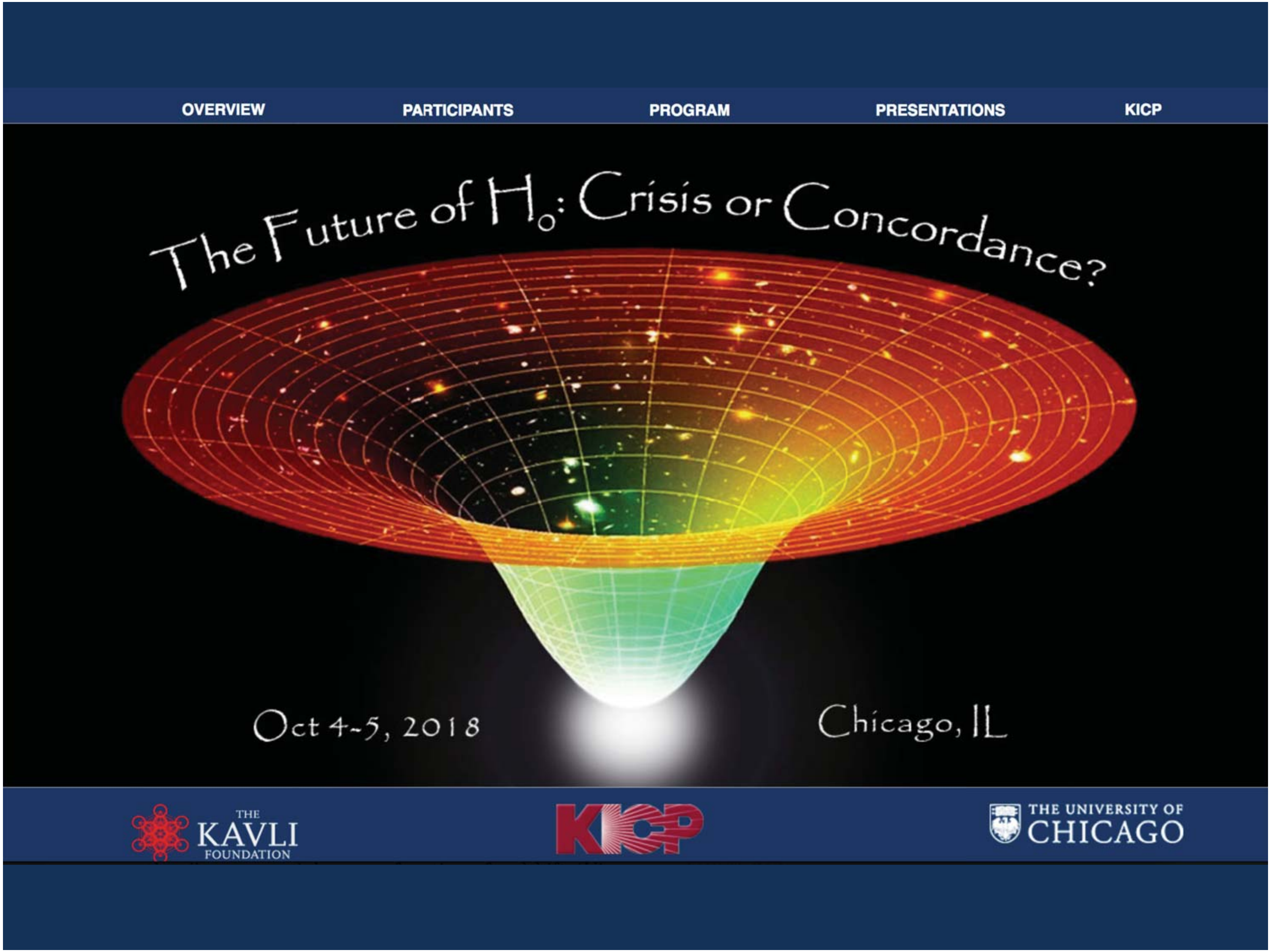
Summary of Recent H_o Values

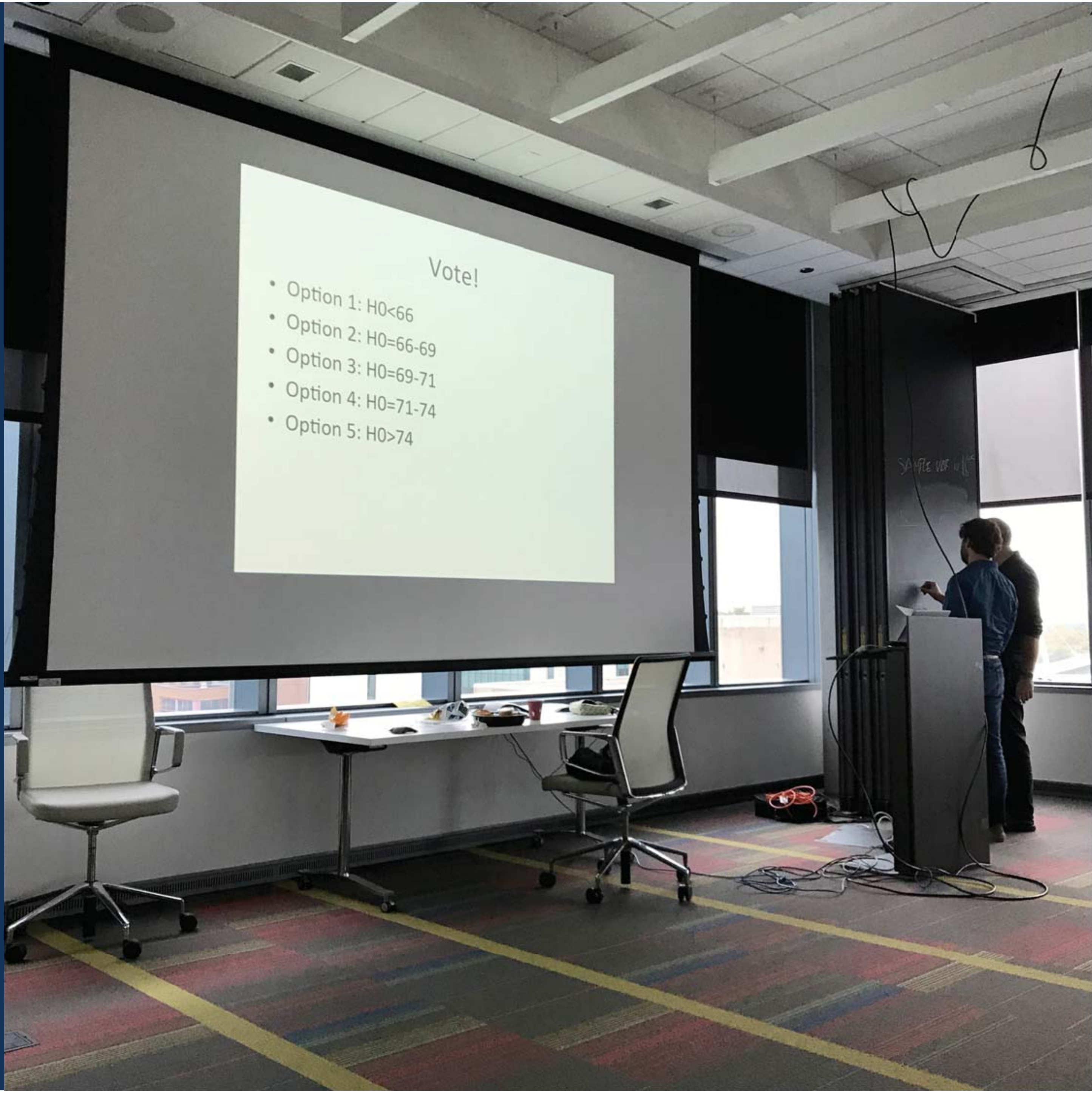
ΛCDM:	67.8 ± 0.9	(1.3%)	[Planck 2015]
+ polarization	66.93±0.62	(0.9%)	[Planck 2016]
	67.4 ± 0.5	(0.7%)	[Planck 2018]

Cepheids	74.3 ± 2.1	(2.8%)	[WLF+ 2012]
+ SNIa :	73.24 ± 1.74	(2.4%)	[Riess+ 2016]
	73.52 ± 1.62	(2.2%)	[Riess+ 2016]

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
- Modified gravity (LIGO has already killed many models…)
- Non-zero spatial curvature


OVERVIEW
PARTICIPANTS
PROGRAM
PRESENTATIONS
KICP
The Future of H0: Crisis or Concordance?
Oct 4-5, 2018
Chicago, IL
THE KAVLI FOUNDATION
KICP
THE UNIVERSITY OF CHICAGO


Vote!
• Option 1: H0<66
• Option 2: H0=66-69
• Option 3: H0=69-71
• Option 4: H0=71-74
• Option 5: H0>74


Dan Holz
Josh Frieman

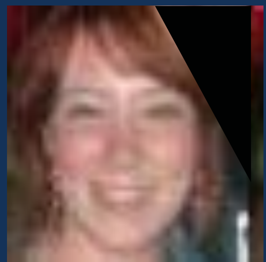
Carnegie-Chicago Hubble Project (CCHP) Team

Myung Gyoon Lee

Taylor Hoyt

Dylan Hatt

Jane Rigby



Vicky Scowcroft

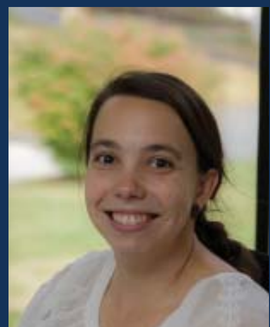
Barry Madore

Wendy Freedman, PI

In Sung Jang

Eric Persson

Andy Monson



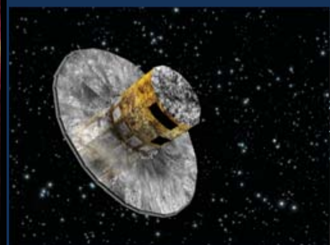
Rachael Beaton

Mark Seibert

The Carnegie Chicago Hubble Program (CCHP) : Overview

1. Cepheids	Magellan, HST, Spitzer, Gaia
2. RR Lyrae	TMMT, HST, Spitzer, Gaia
3. TRGB	TMMT, Magellan, Gaia, JWST



H_0 to 2% (statistical +systematic)

Carnegie Chicago Hubble Project II : TMMT***

*** Three hundred Millimeter Telescope at Las Campanas

Tip of the Red Giant Branch (TRGB)

Lee, Freedman & Madore (1993); Madore & Freedman (1999)

Advantages : Simplicity of the method

- Found in outer (largely metal-poor) halos of galaxies
  - reddening negligible, especially in IR
  - stellar density significantly lower than disk (minimizing crowding issues)
- Metallicity effects small and *directly calibrated*, unlike for Cepheids
- No long-term variability follow-up needed
- Can be applied to galaxies of all inclinations and Hubble types
- AGB stars minimal contamination compared to disk

Disadvantages

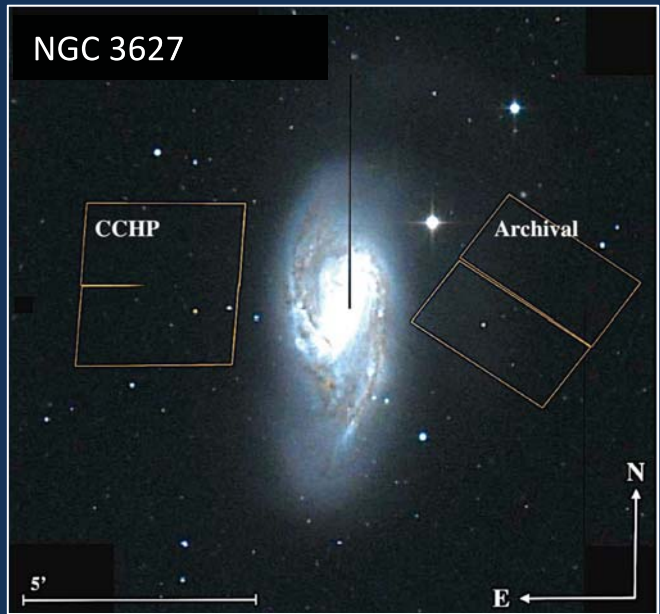
- M_I ~ -4 mag (Cepheids: $-4 < M_I < -1$) **

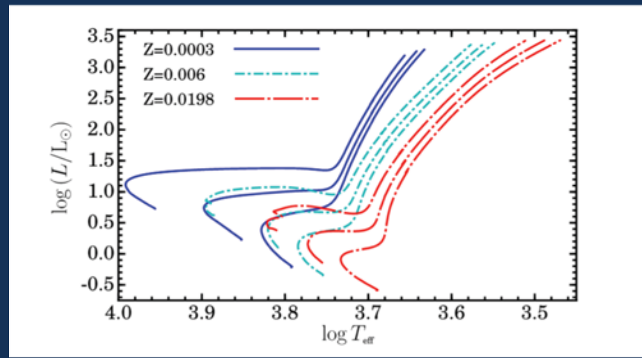
The Carnegie Chicago Hubble Program (CCHP) : Overview

Tip of the Red Giant Branch

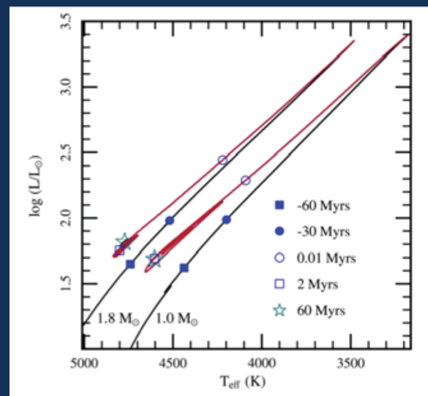
1. Spitzer
2. HST
3. TMMT
4. LCO

TRGB Halos in Nearby Galaxies





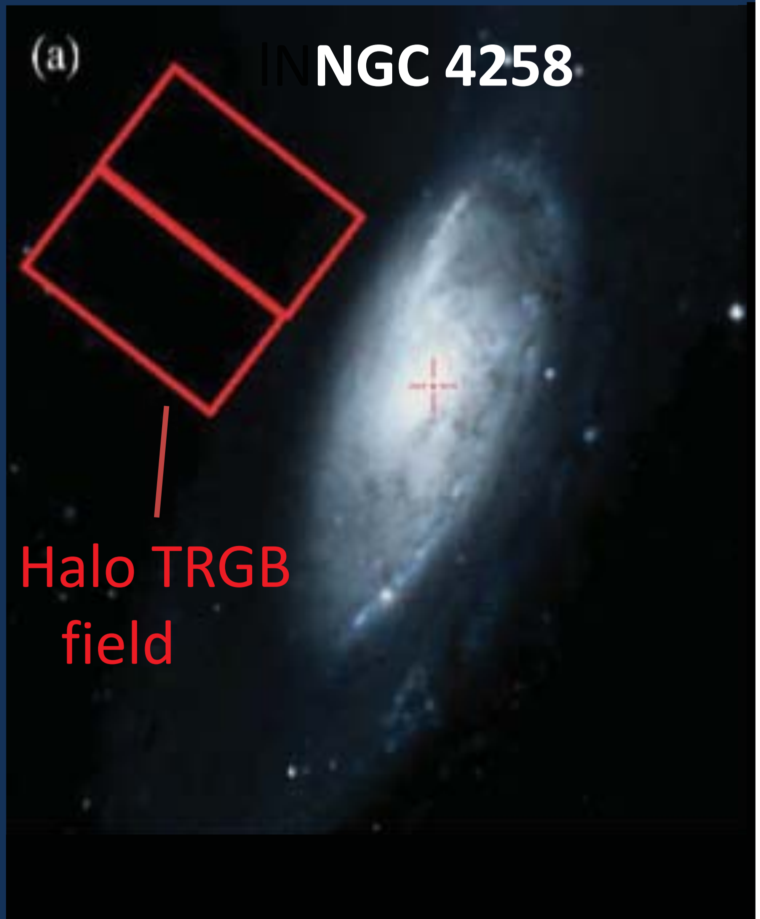
Serenelli et al. (2017)



He flash

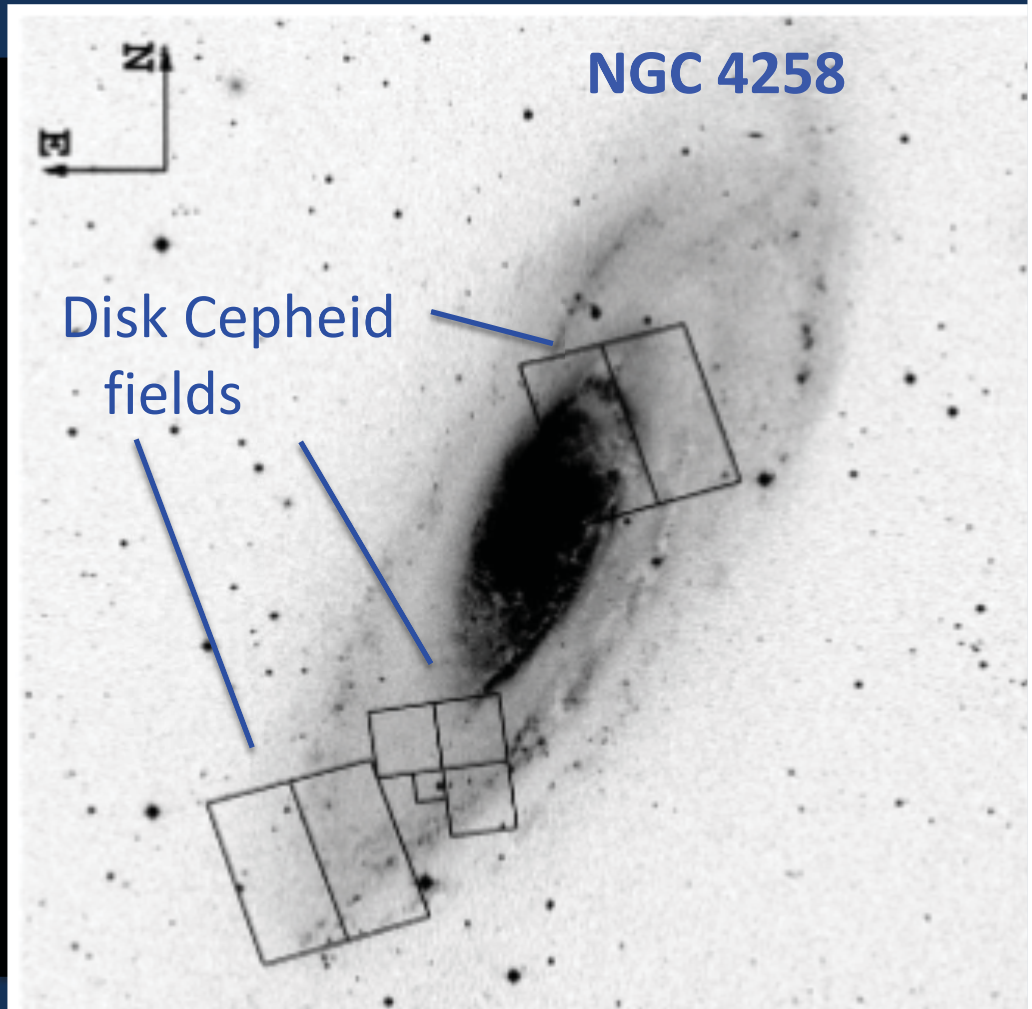
Bildsten et al. 2012 (MESA)

Cepheids / The Tip of the Red Giant Branch



TRGB HST ACS field

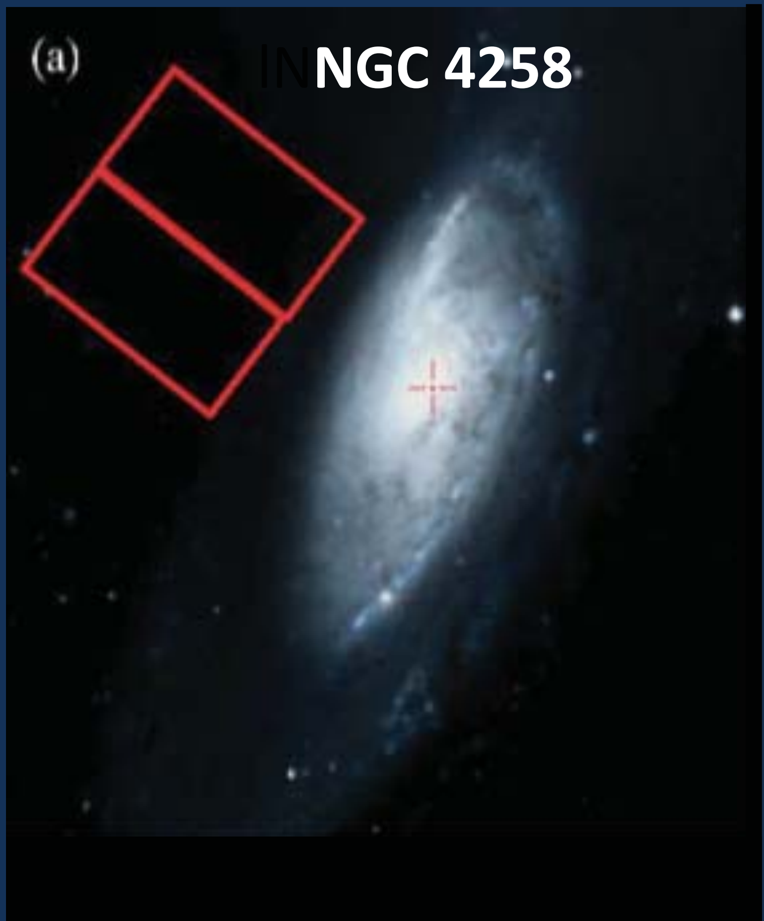
Mager, Madore & WLF (2008)

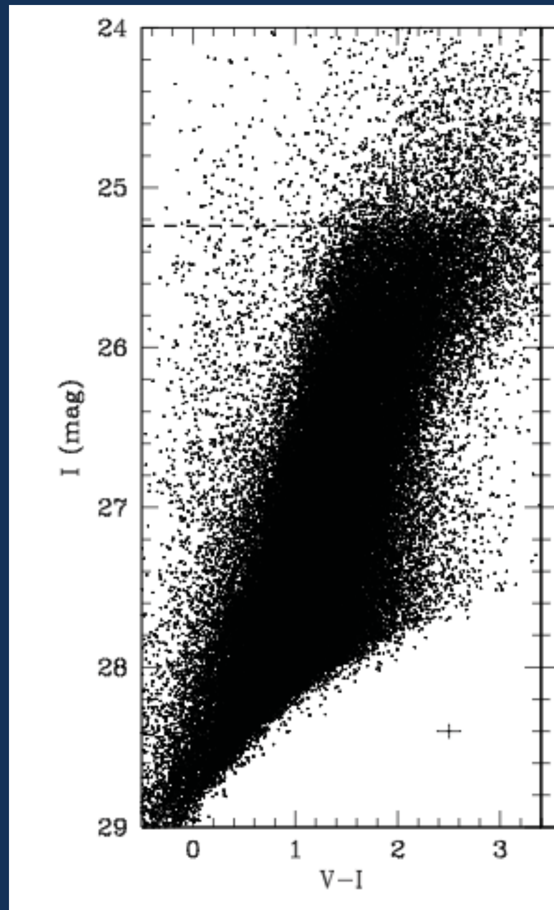


Cepheid HST ACS + WFPC2 fields

Macri + Riess et al. (2006)

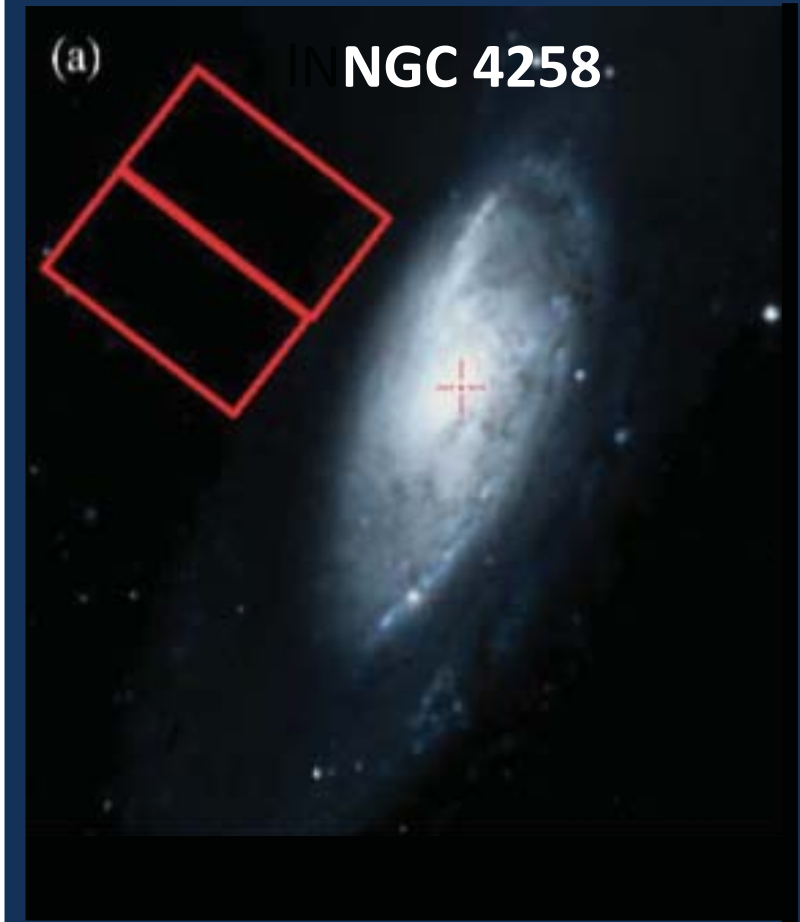
The Tip of the Red Giant Branch

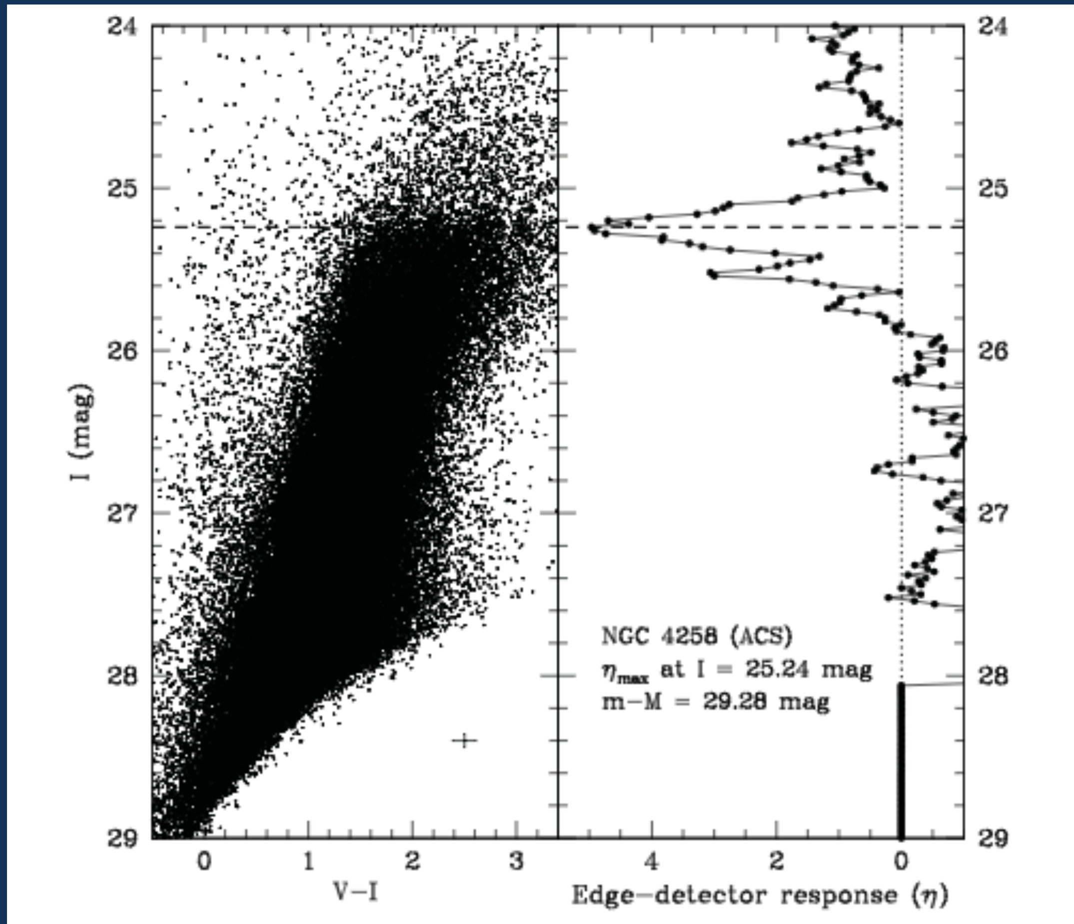




Mager, Madore & WLF (2008)

The Tip of the Red Giant Branch

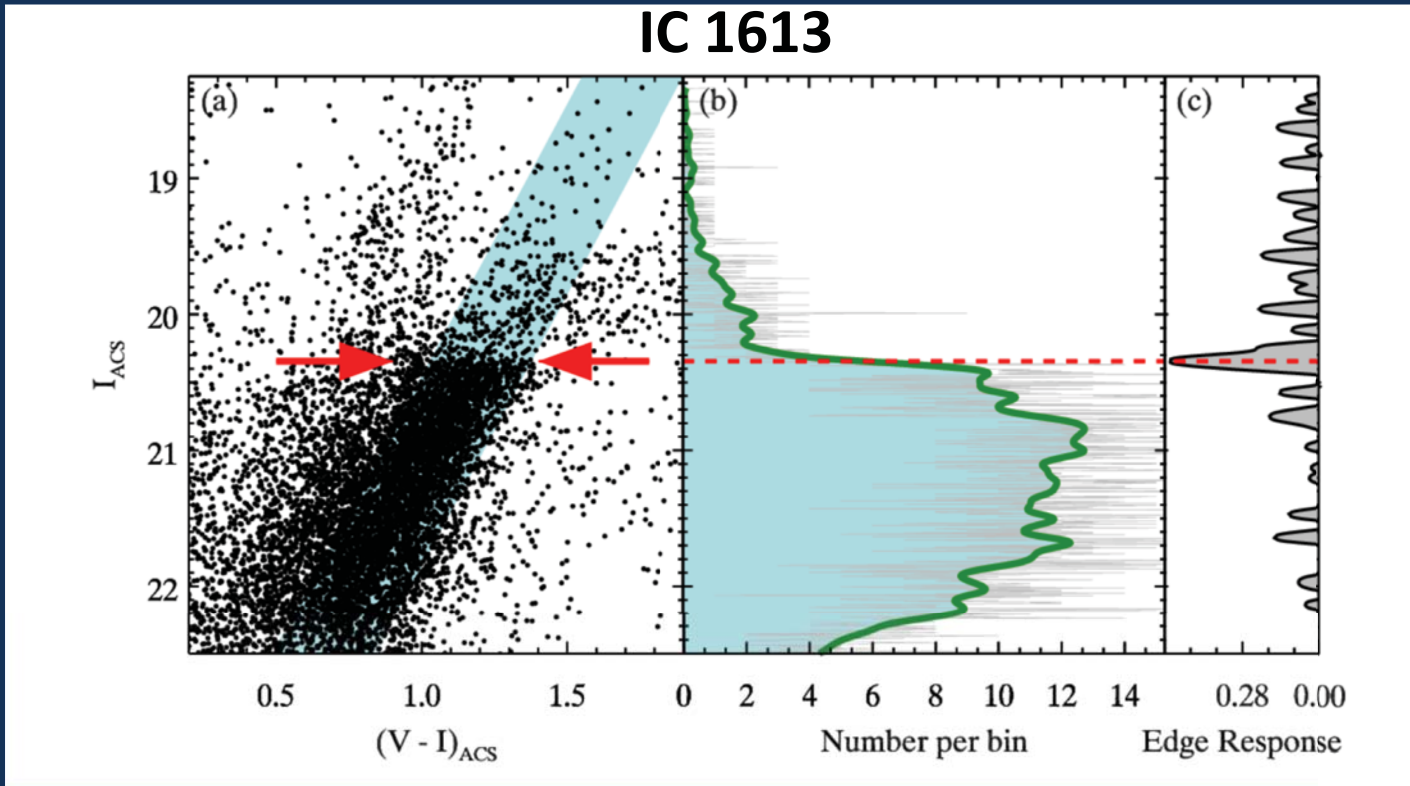




Measure 1st derivative of luminosity function

Mager, Madore & WLF (2008)

The Tip of the Red Giant Branch

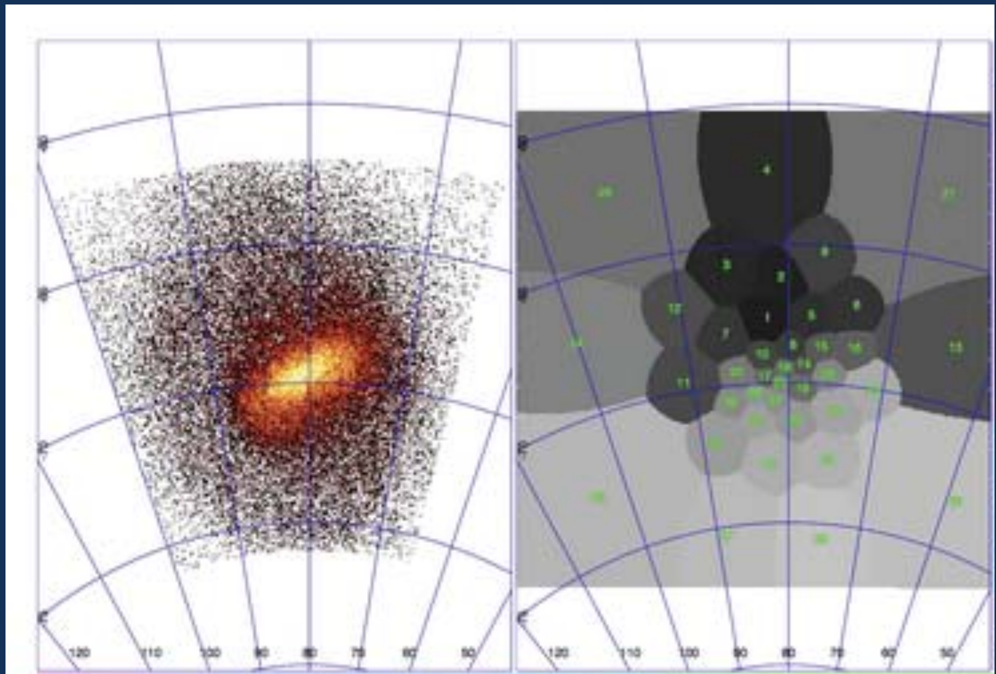


Hatt et al (2017)

Calibration of the Tip of the Red Giant Branch: II. LMC

Geometry of the LMC seen in the LMC red giant branch stars

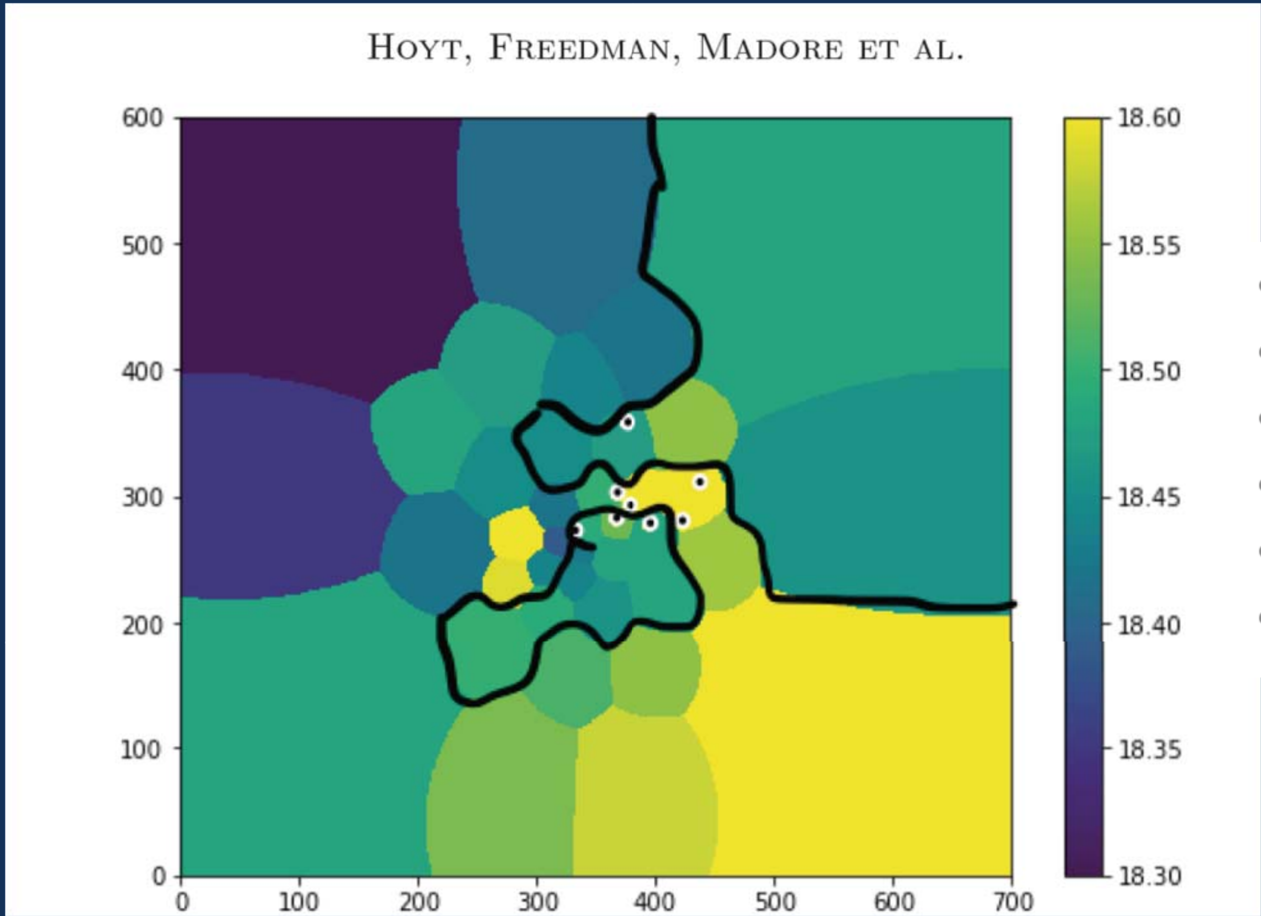
Taylor Hoyt

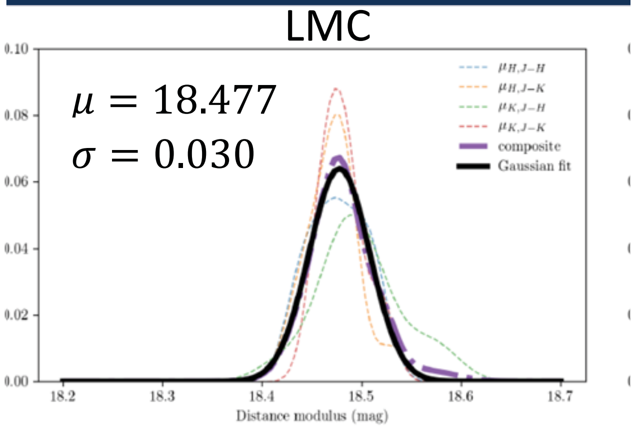


Hoyt, WLF et al. (2019)
Based on JHK LMC data from Macri et al (3.5 million sources; 860,000 RGB stars)

Comparison: 2MASS catalog
2 million sources

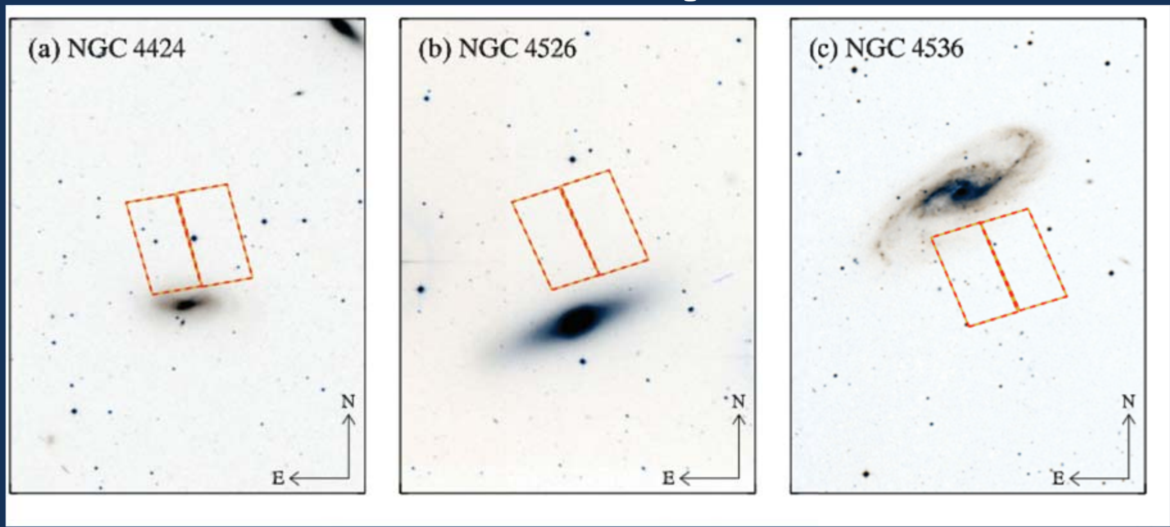
Calibration of the Tip of the Red Giant Branch: II. LMC

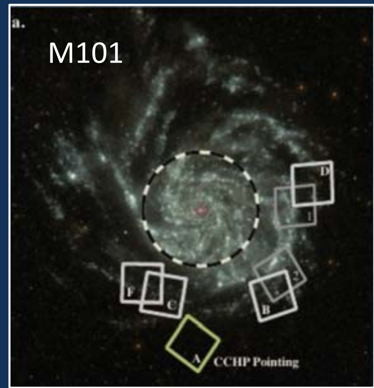


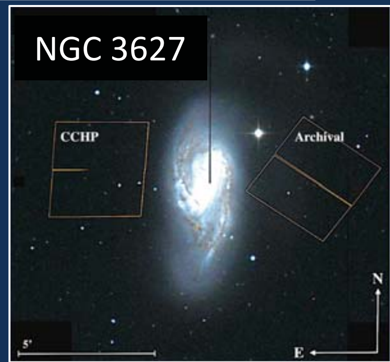


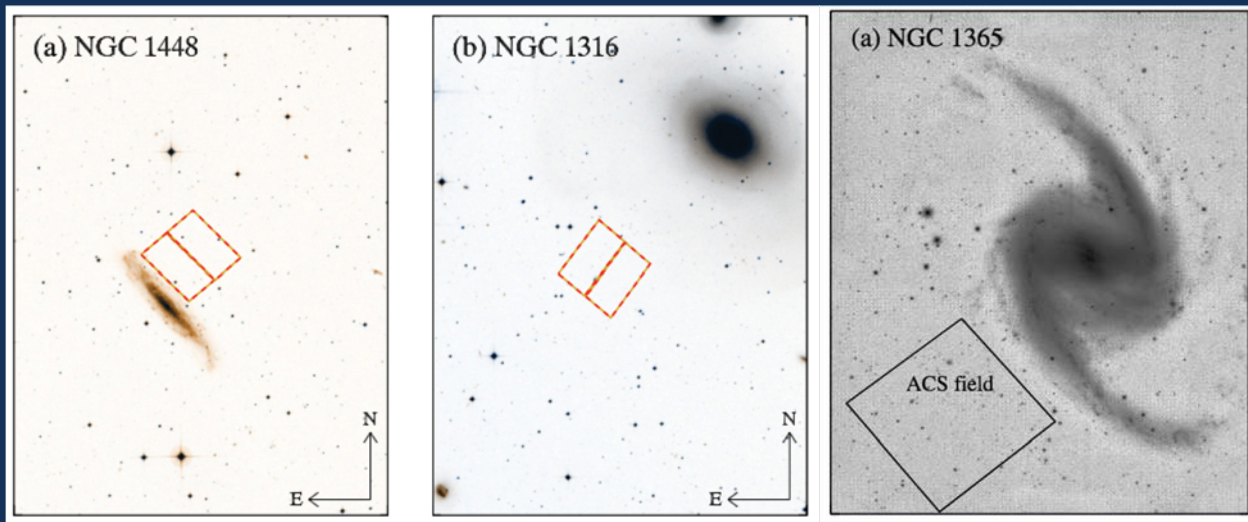
Hoyt, WLF et al. (2018)

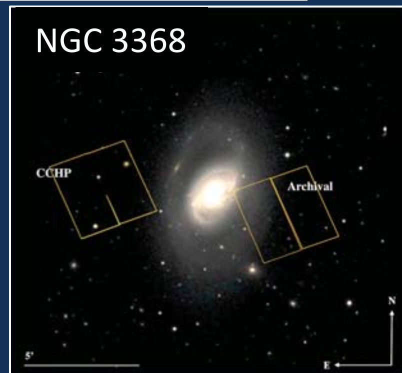
TRGB Distances to SN Ia Galaxy Hosts
HST ACS/WFC Observations



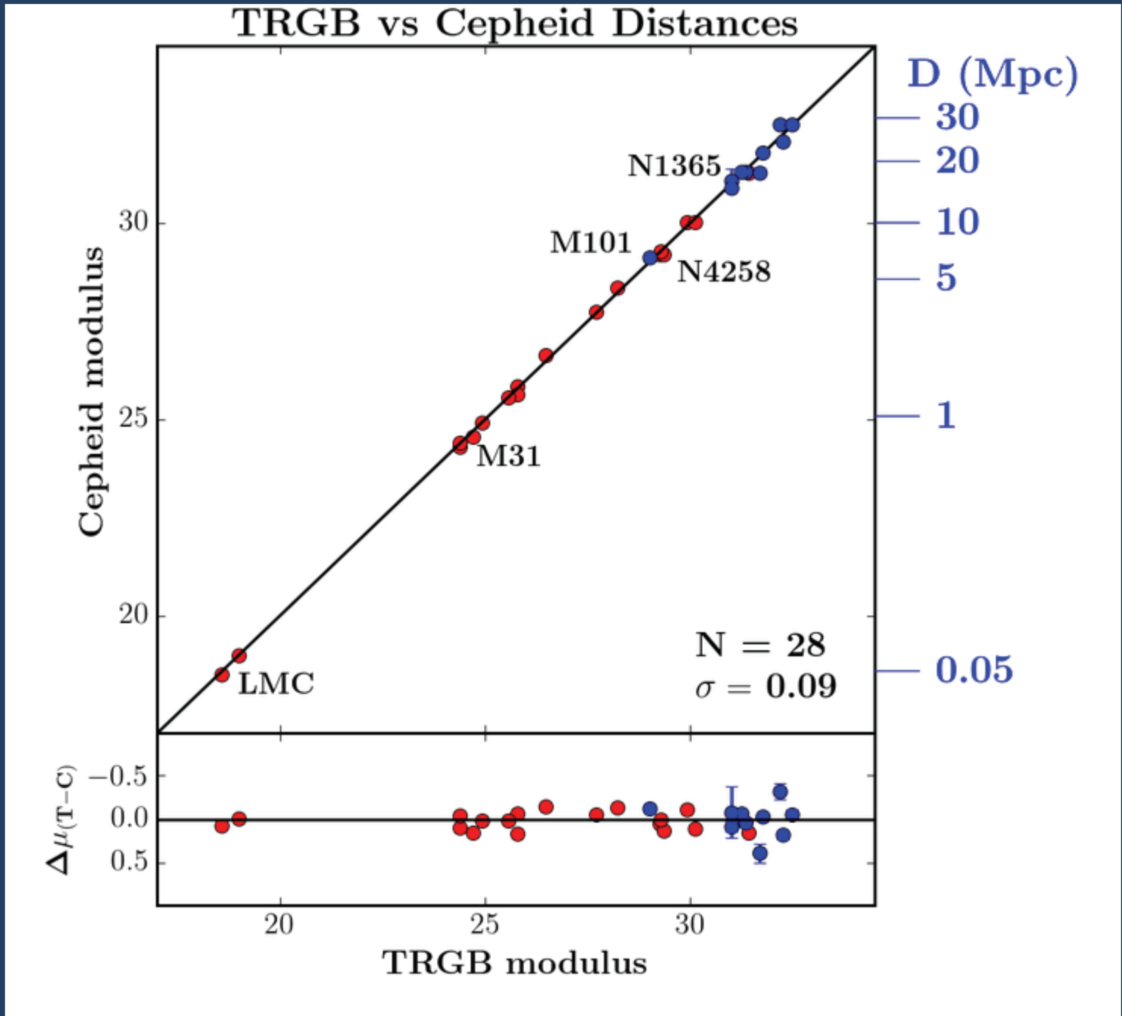






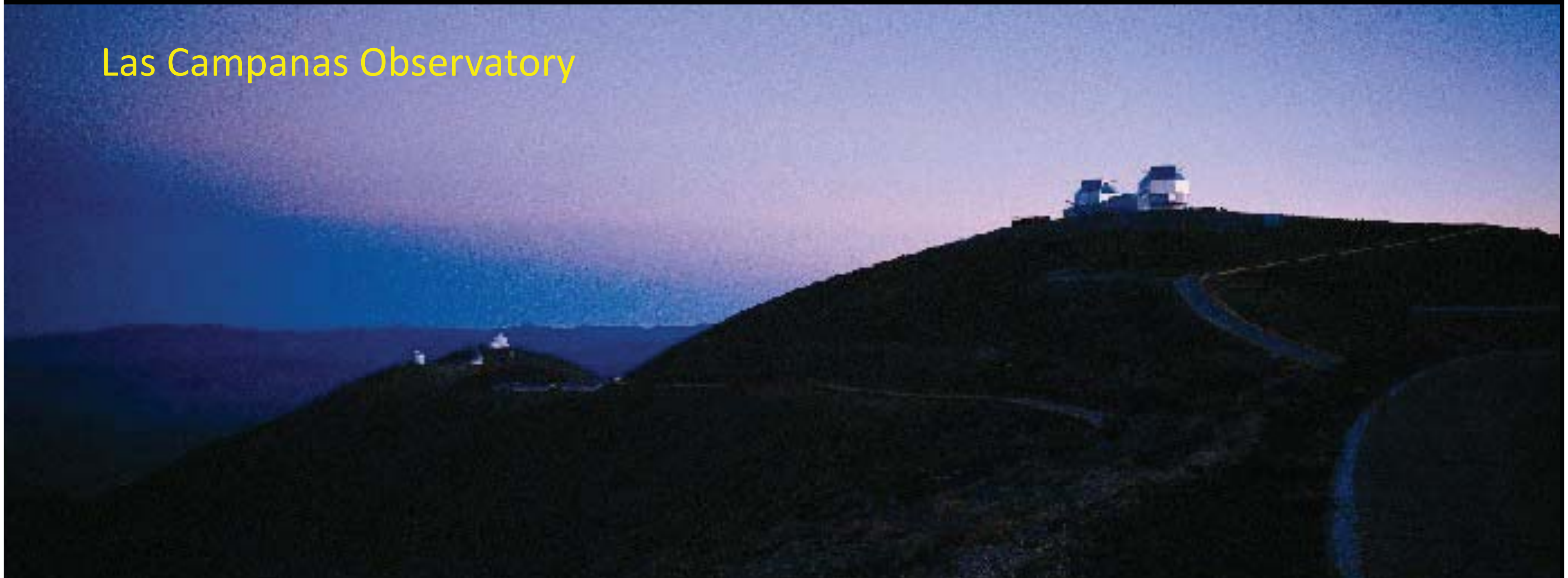


Comparison of TRGB & Cepheid Distances *Preliminary*



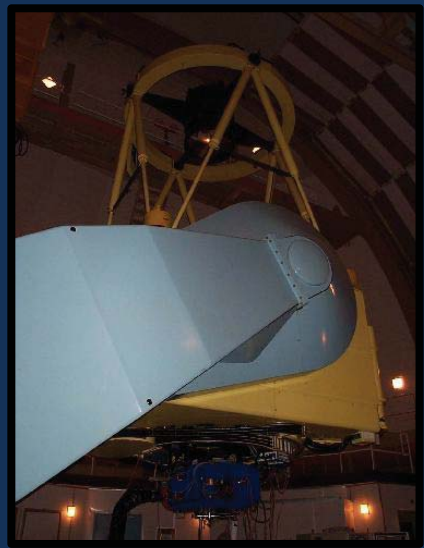
WLF et al. (2018)

The Carnegie Supernova Project (CSP)



Carnegie Supernova Project (CSP)

Swope 1-meter



du Pont 2.5-meter

Magellan 6.5-meter

M. Phillips, PI

- u'BVg'r'i'YJHK photometry 123 SNe Ia
- 2.5-meter, 6.5-meter optical spectroscopy

CSPII :

- BVg'r'i'YJHK photometry 116 SNe Ia
- Magellan FIRE 6.5-meter spectroscopy

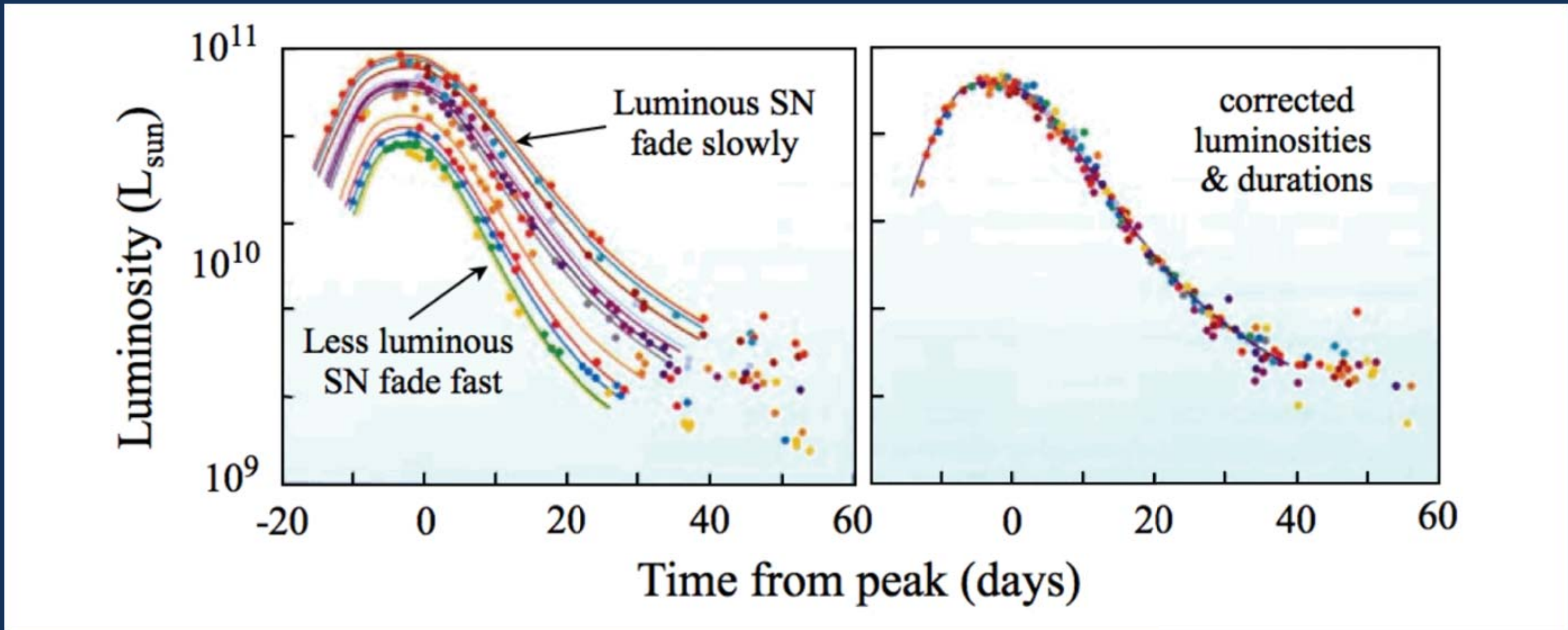
W. Freedman, PI

$0.2 < z < 0.8$ 55 SNe Ia

Multi-wavelength Light curves

$0.03 < z < 0.1$

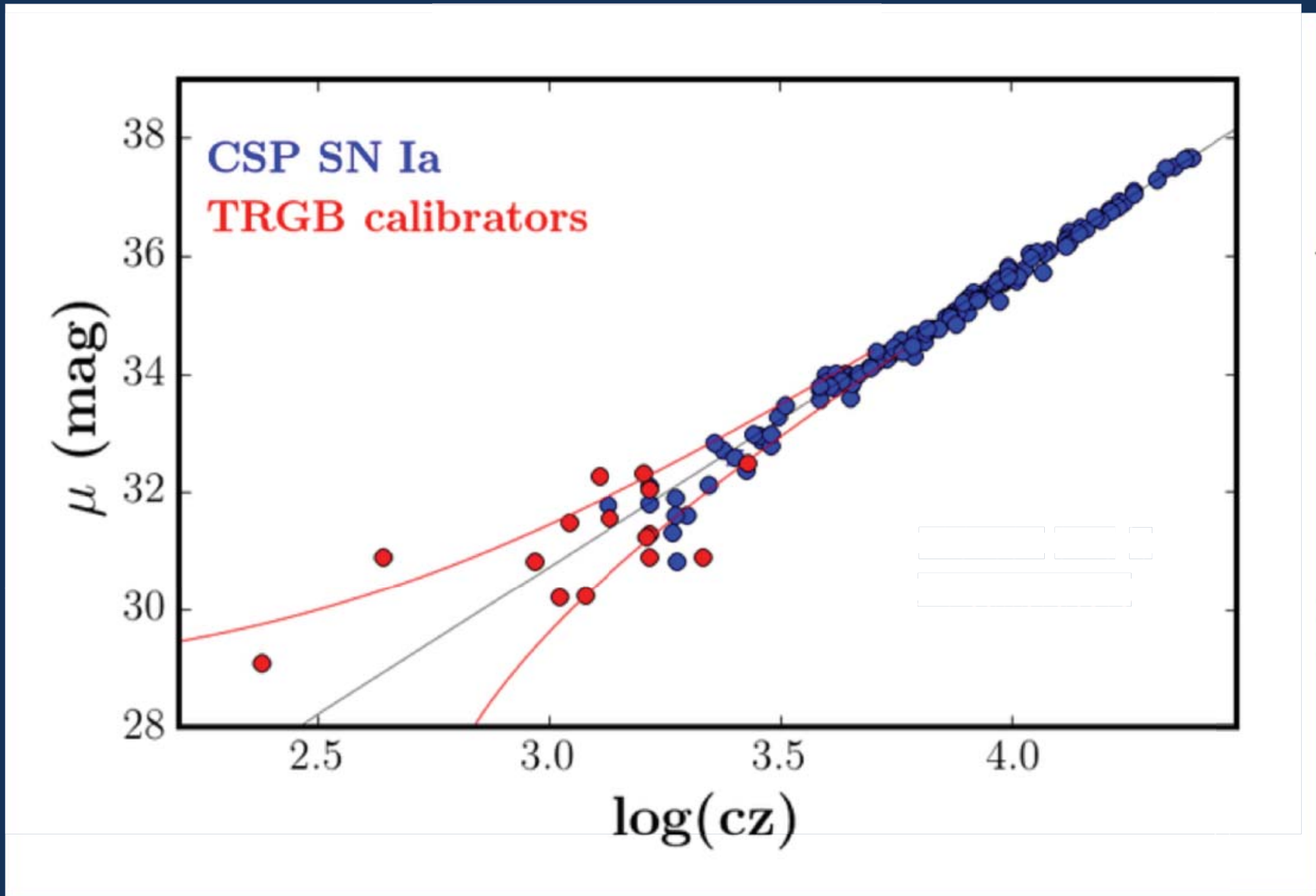
Supernovae ("Standardizable" Candles)



Supernova Cosmology Project

CCHP TRGB Calibration of H_o

(Preliminary)

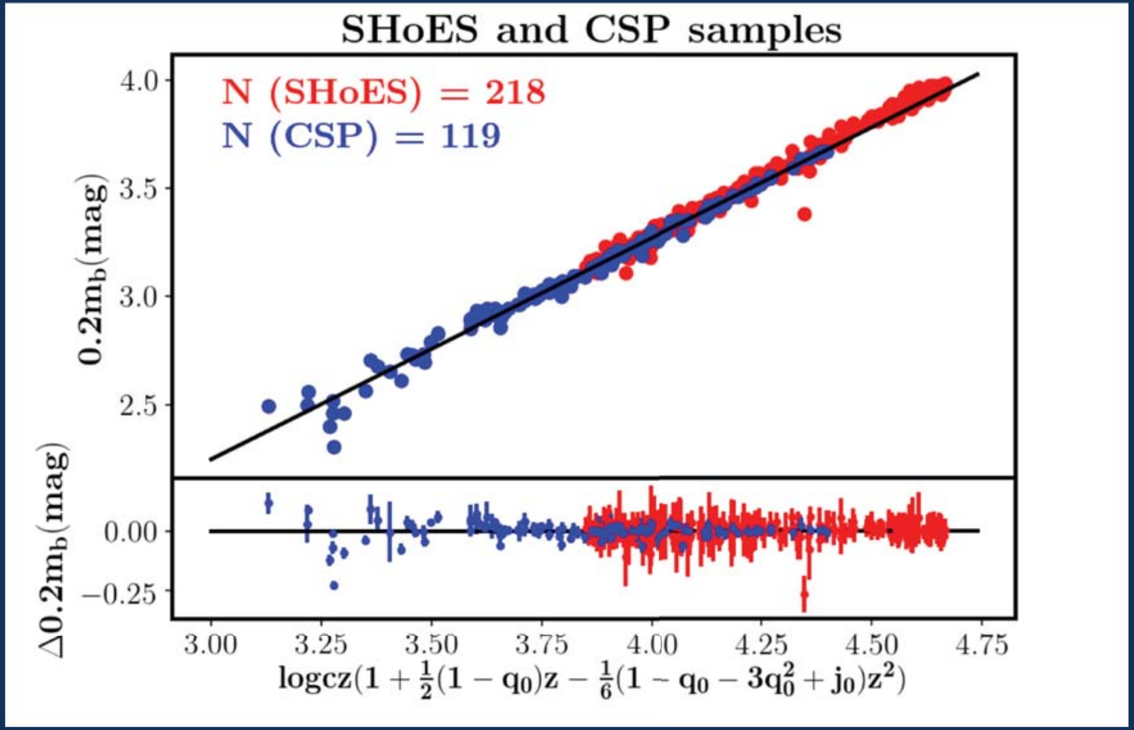


Burns et al. 2018

WLF et al. 2018

CSP and SHoES comparison

(Preliminary)



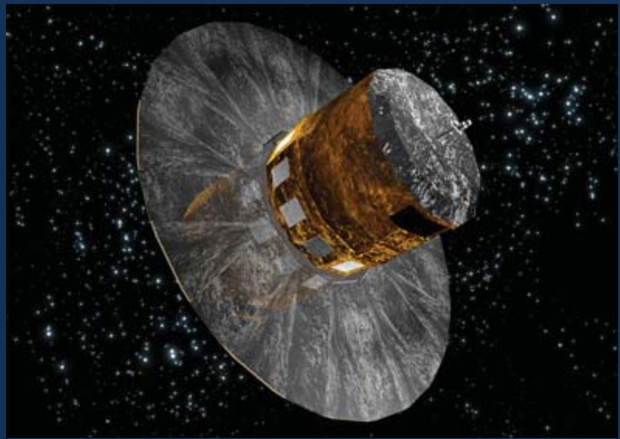
Gaia – Data Release 2

- April 25, 2018
- 22 months of data
- Gaia data alone
- 1.3 billion stars
- Parallax uncertainty:
  - ~ 0.04 mas G < 15 mag
  - ~ 0.1 mas @ 17 mag
  - ~ 0.7 mas @ 20 mag

Note:
"There is a significant parallax zero-point offset of about -30 µas."

DR3: delayed until mid- to late 2020.

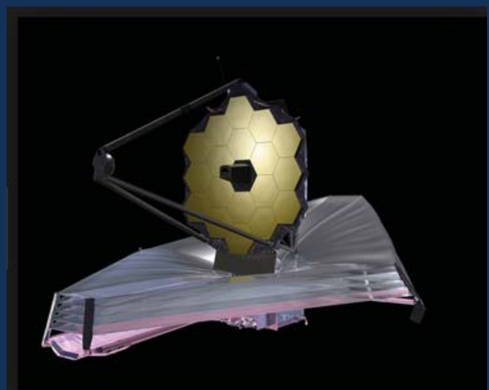
TRGB Increasing Precision and Accuracy for Future



Gaia parallaxes

H_o to 1%

Hubble Space Telescope (HST)



James Webb Space Telescope (JWST)
Launch date: March 30, 2021

Concluding Remarks

There is no single, obvious systematic effect that has emerged at the 0.2 mag level, which would be required to reconcile the value of H_o if the true, local H_o were equal to that inferred from Planck + ΛCDM.

[For reference, recall that the evidence for acceleration from SNeIa is comparable in size.]

The Future

1. Future results from Gaia will provide a calibration with <<1% uncertainty (for Cepheids, TRGB, RR Lyrae stars)

2. JWST and 1% *statistical* precision for calibration of total sample of 25 SNe Ia using TRGB method

3. LIGO sirens

The potential for a robust measurement of the local H_o value to both a precision and accuracy at the percent level is real, and with multiple routes (to ascertain systematic uncertainties), could be achieved within a decade.