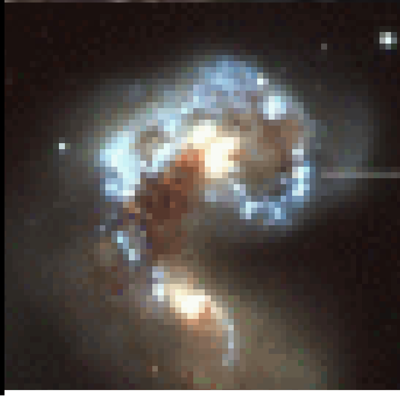
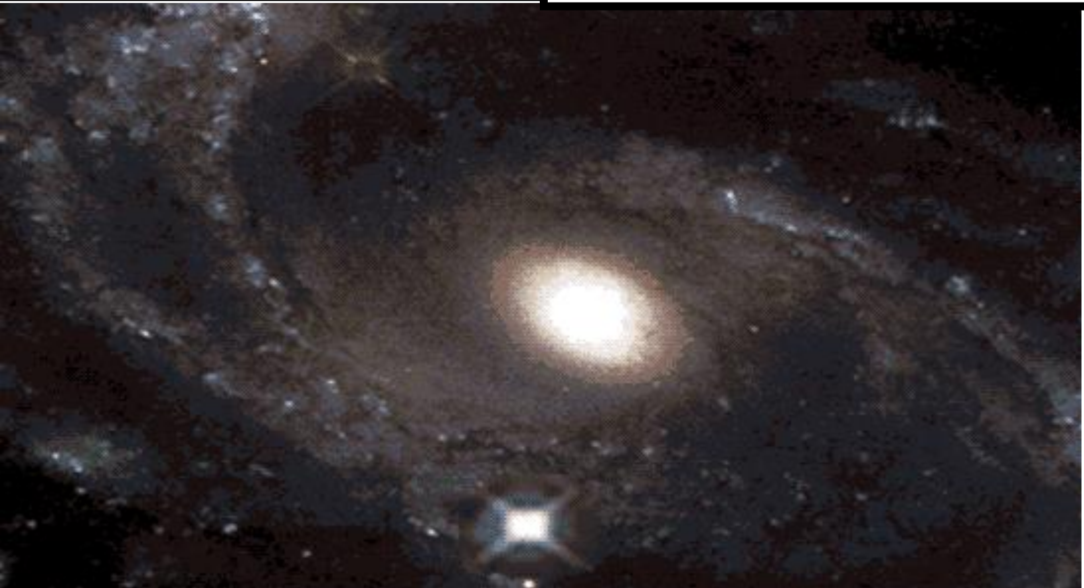
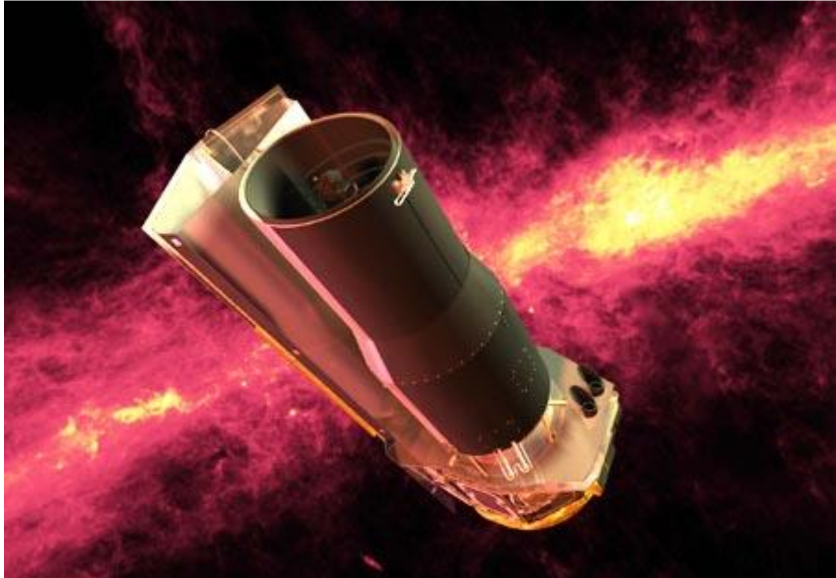
Direct Measurement of H_0: Current Status and Future Prospects

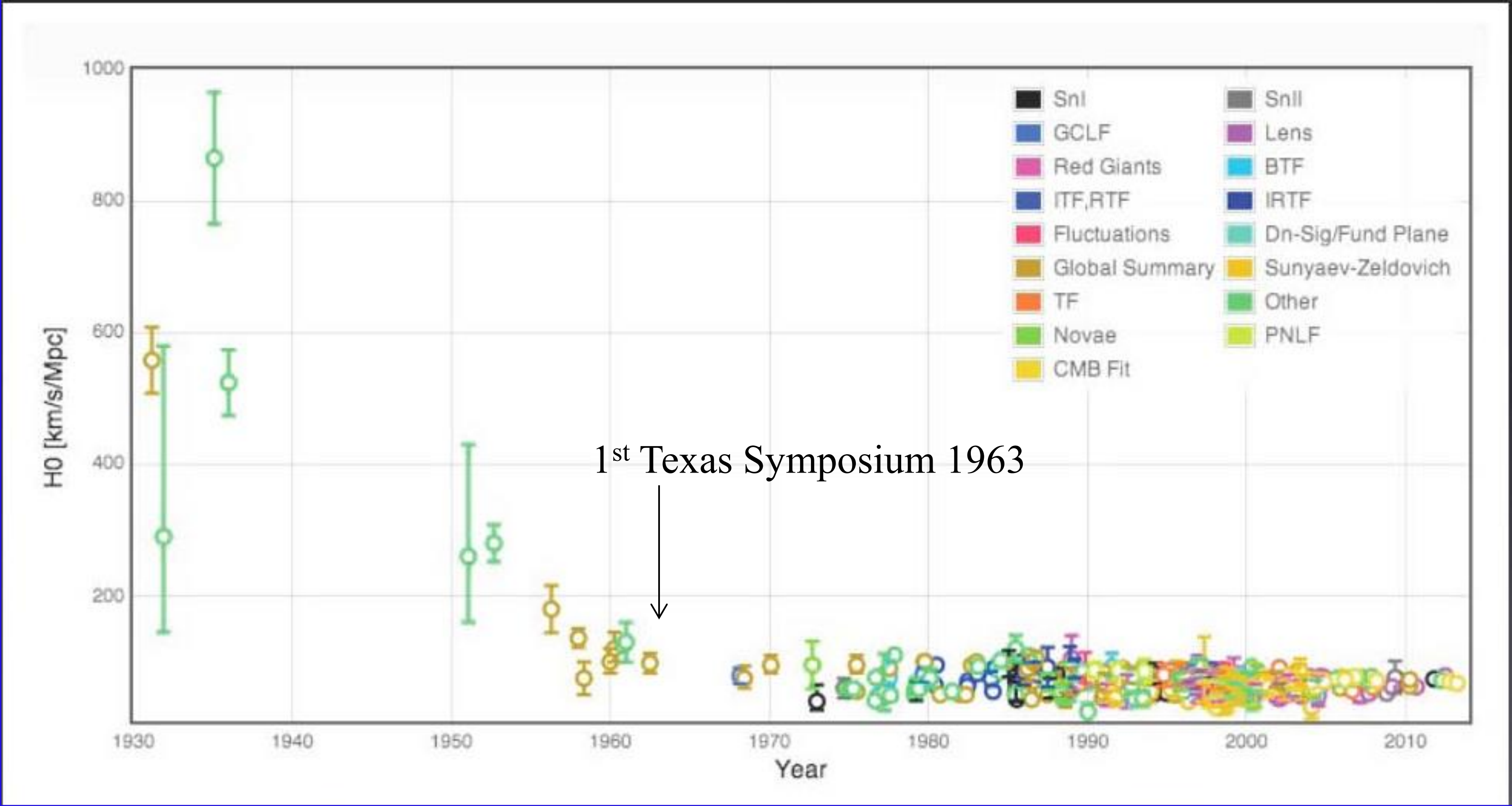
Wendy Freedman
Carnegie Observatories
December 10, 2013
Texas Symposium
Dallas
50 Year Jubilee







H_0 Over Time

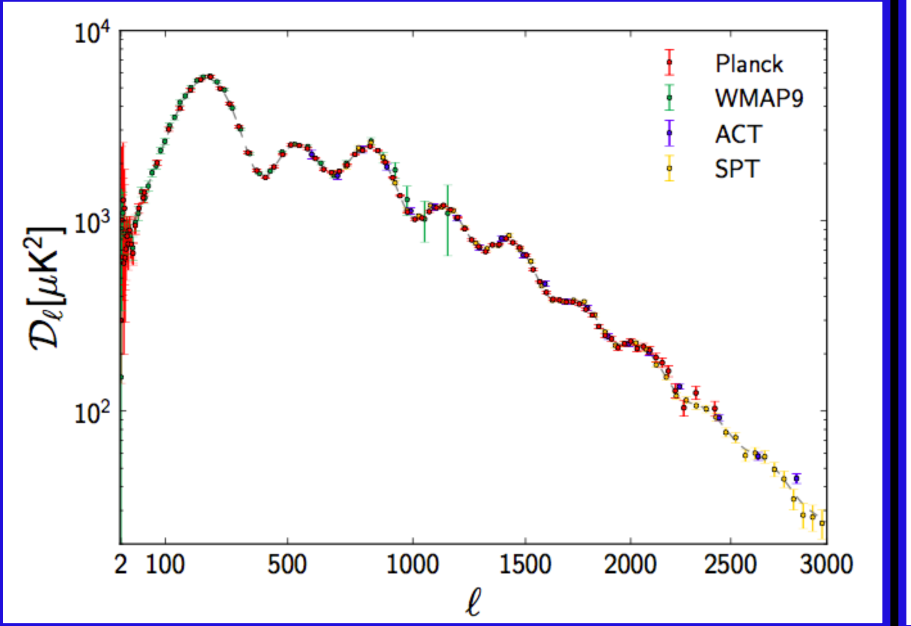


1st Texas Symposium 1963

H0 data compiled by J. Huchra and C. Booth
http:/ www.craigmbooth.com/hubble/

Cosmic Microwave Background Anisotropies

Planck + WMAP9 + ACT + SPT



Cosmological Parameters (Ade et al.)

H_0 = 67.3 ± 1.2 km/s/Mpc**

Ω_M = 0.315 ± 0.017

Ω_{DE} = 0.686 ± 0.020

n_s = 0.9603 ± 0.0074

$w = -1.13_{-0.10}^{+0.13}$

** model-dependent

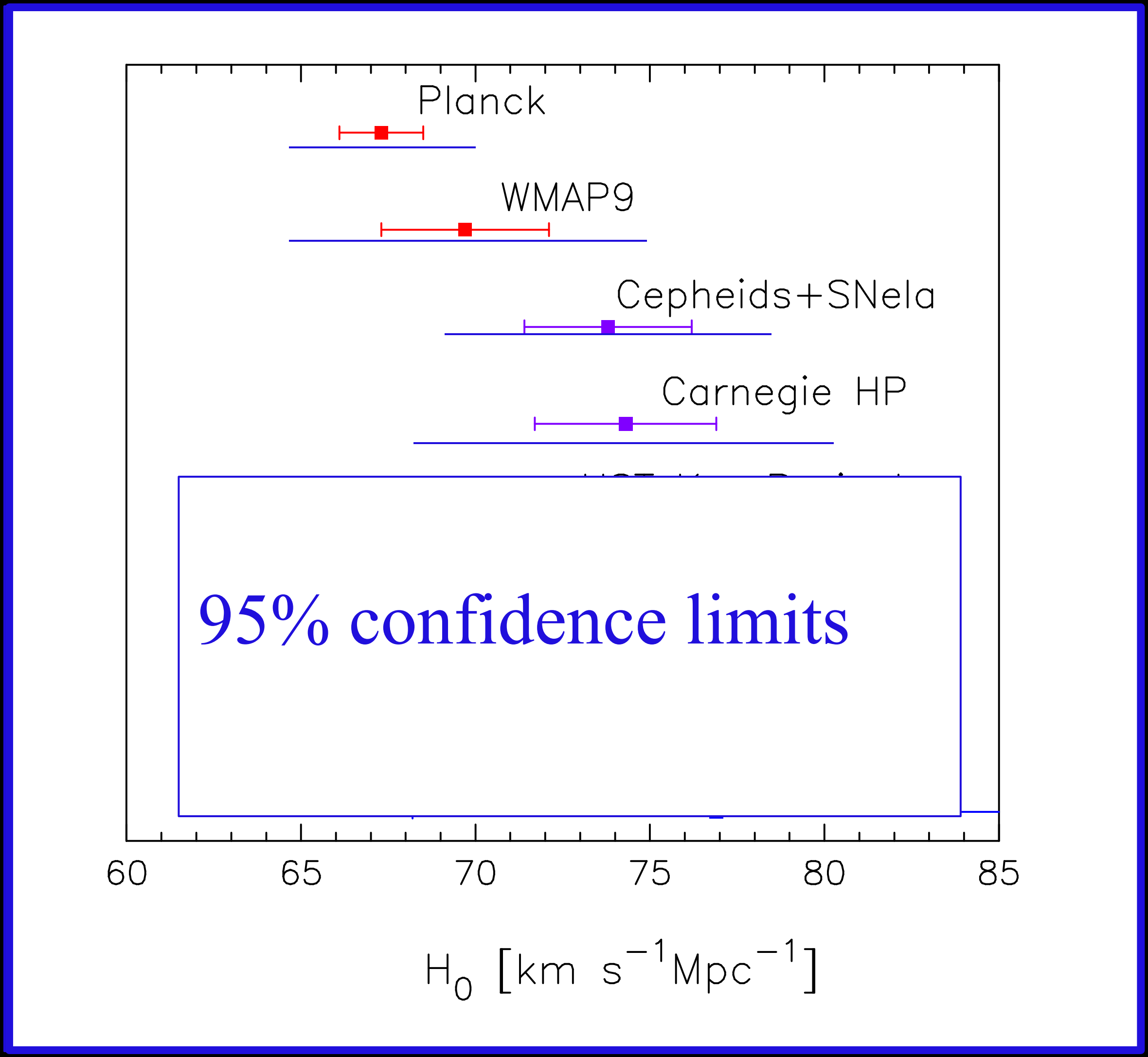
Ade et al (2013); Hinshaw et al (2013)

Implications of Planck Results for H_0

General Remarks:

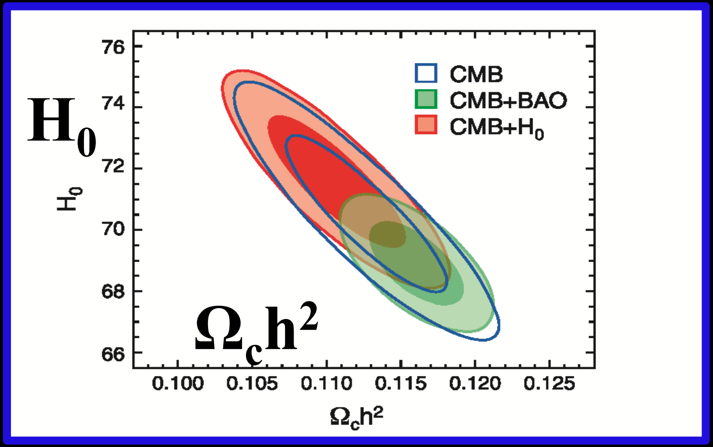
- **A 6-parameter model provides an exquisite fit to the Planck data**
- **However, the value of H_0 must be derived assuming this model**
- **Direct measurements of H_0 are essential to test the model**
- **The key element is understanding the systematics affecting the accuracy of all of these measurements**
- **Given that Planck is measuring the universe at early times, and the direct H_0 measurements are being made at $z \sim 0$ with completely independent techniques, underlying physics, etc. , the 2-2.5-σ agreement is rather remarkable**
- **2-2.5-σ discrepancies are not interesting for claiming new physics**

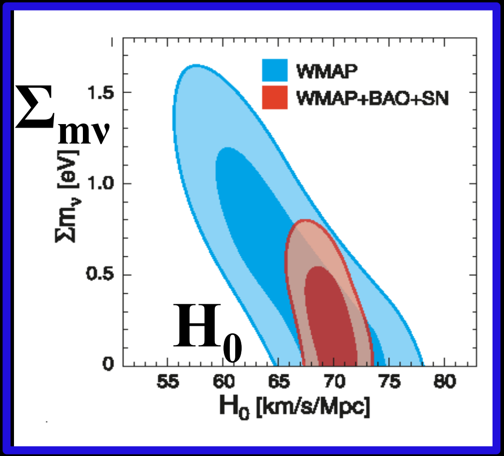
Implications of Planck Results for H_0

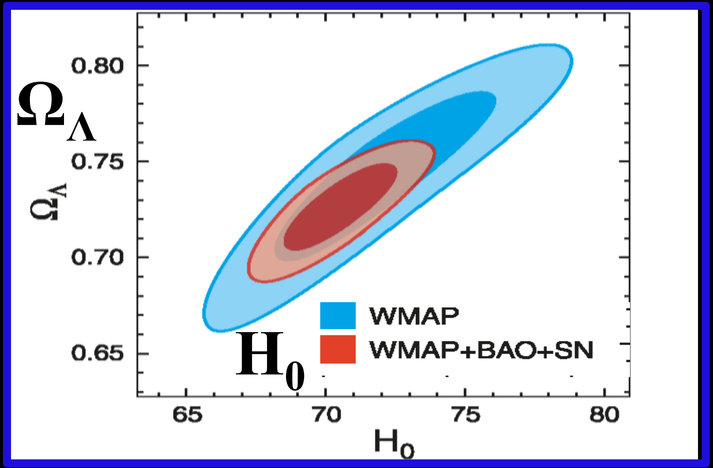


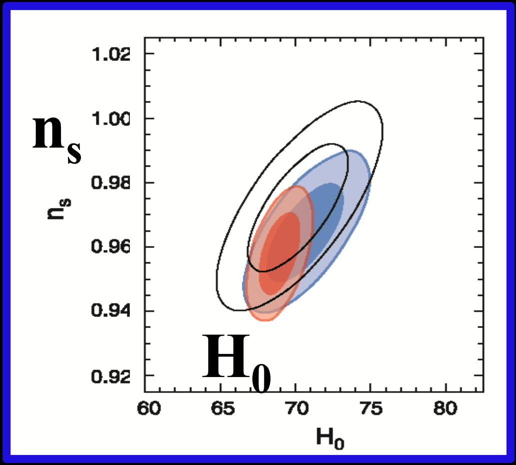
95% confidence limits

Why Do We Need a More Accurate Value of H_0?









Recent Direct Measurements of H_0

- **SH_0ES (Riess et al. 2011) :**
  $H_o = 73.9 \pm 2.4$ km s^{-1} Mpc^{-1}

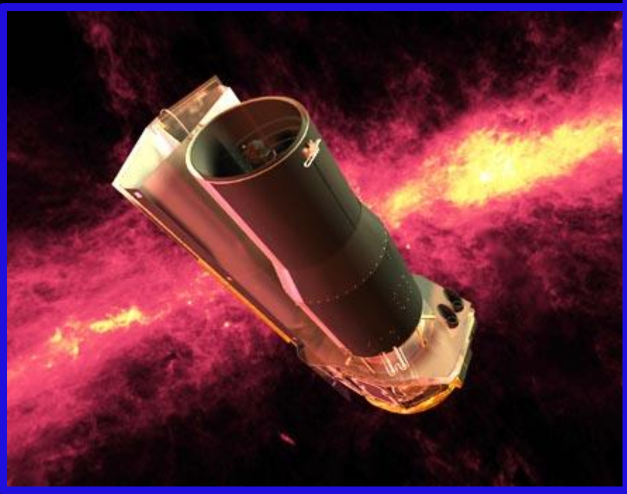
- **Carnegie Hubble Project:**
  $H_o = 74.3 \pm 1.5$ [stat] $\pm$ 2.1 [sys] km s^{-1} Mpc^{-1}
  (WLF et al. 2012)

- **Carnegie supernovae:**
  $H_o = 72.7 \pm 2.0$ [stat] $\pm$ 0.5 [sys] km s^{-1} Mpc^{-1}
  $H_o = 70.4$ (NGC 4258 alone – new maser distance)
  (WLF et al. 2014, in progress)

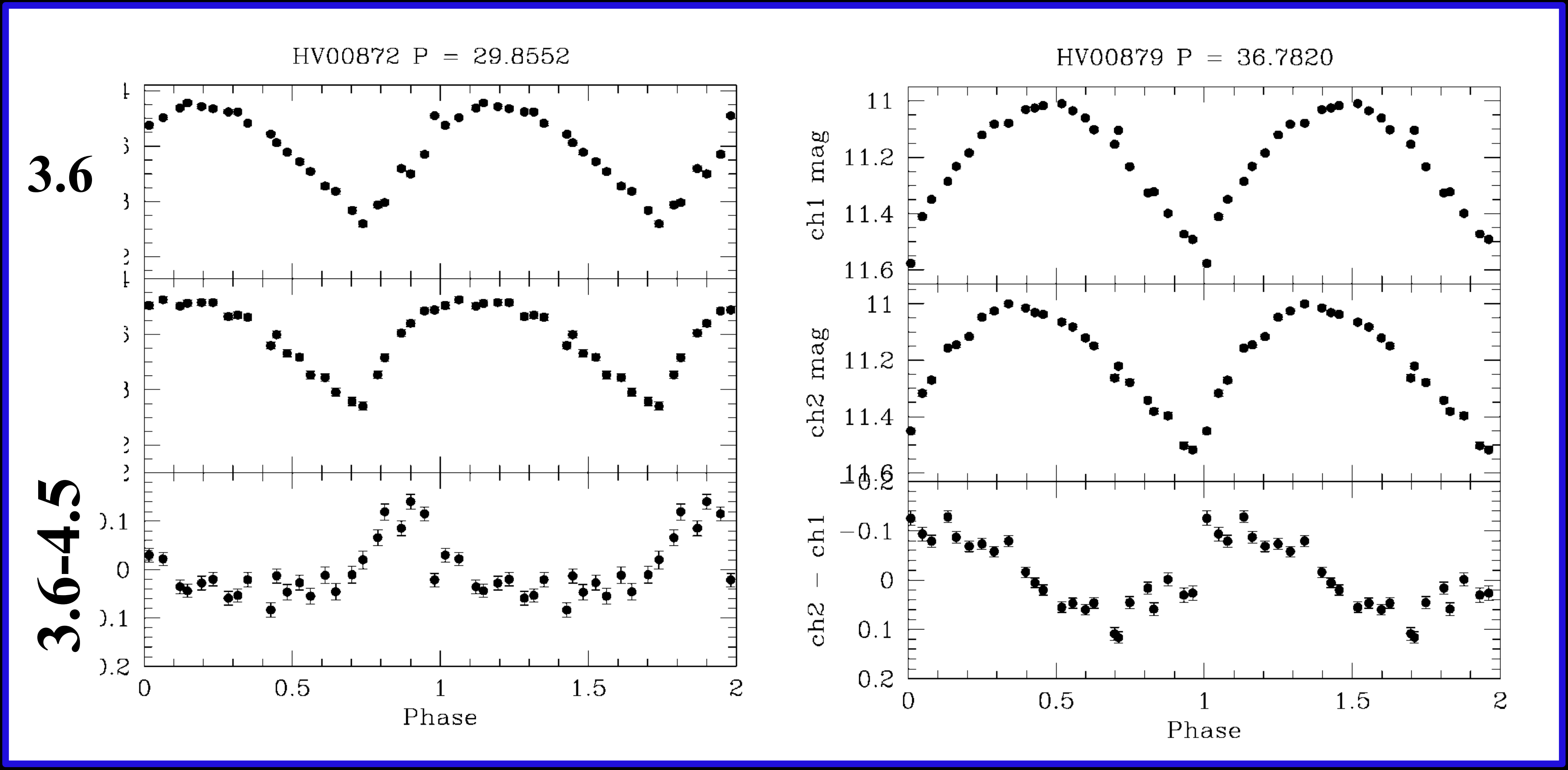
The Carnegie Hubble Program (CHP) ****

The Carnegie Supernova Project (CSP) ***
The Carnegie RR Lyrae Project (CRRP) ***

Barry, Vicky, Andy, Chris, Mark S., Eric, Mark P, Jeff

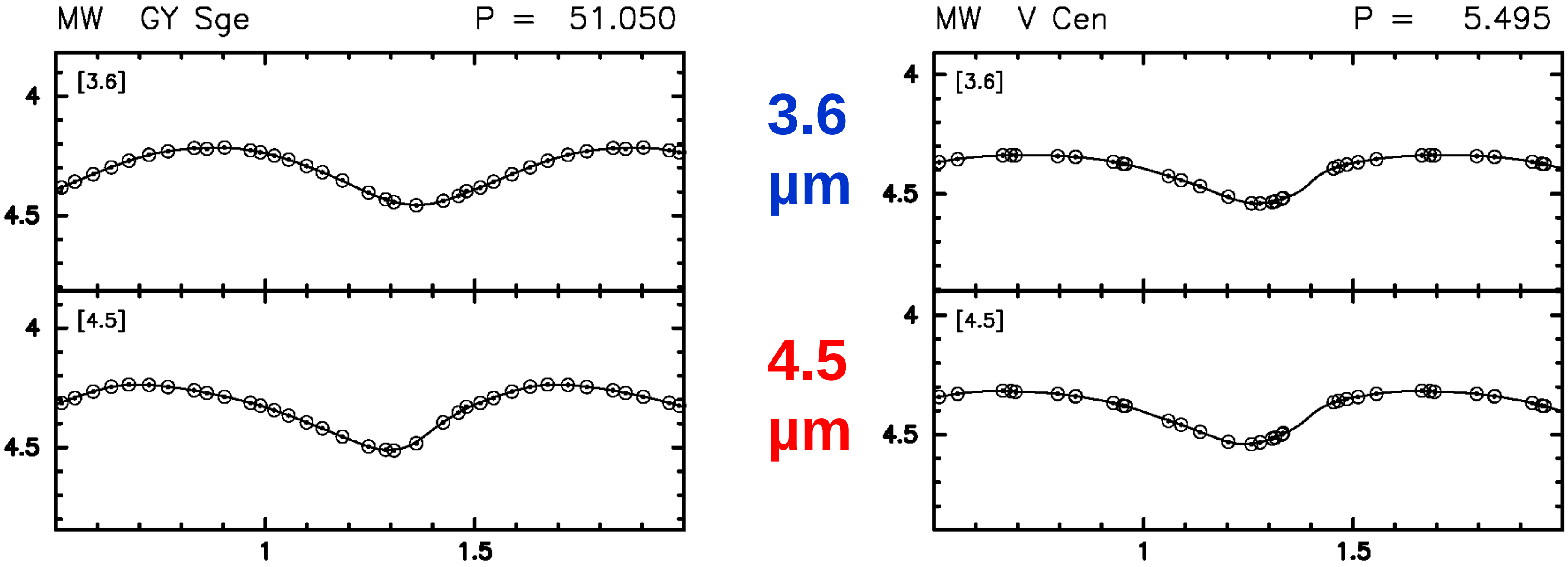


Spitzer LMC Cepheid Data



Scowcroft et al. 2012

Spitzer 3.6 and 4.5 µm Milky Way light curves

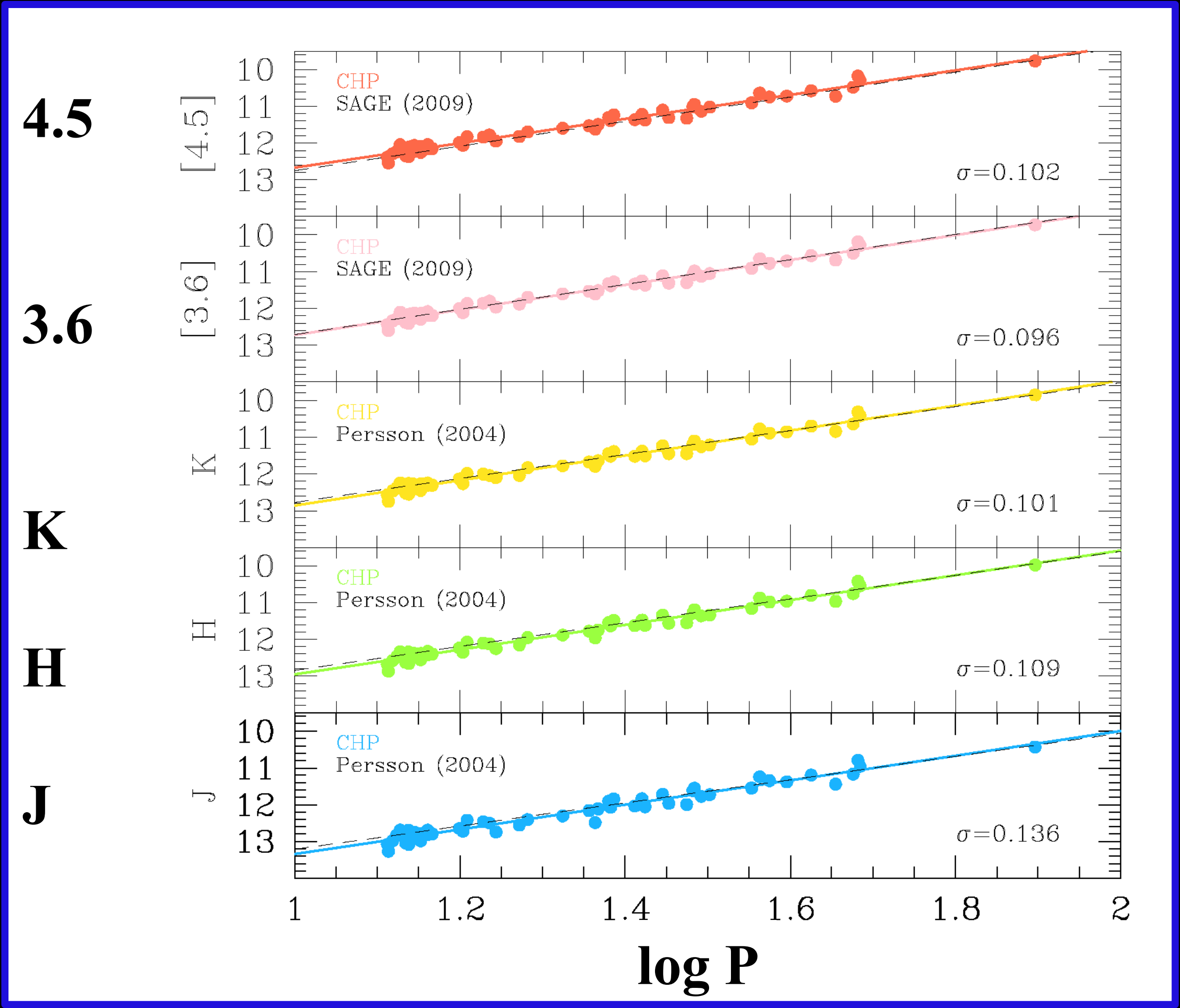


3.6 µm

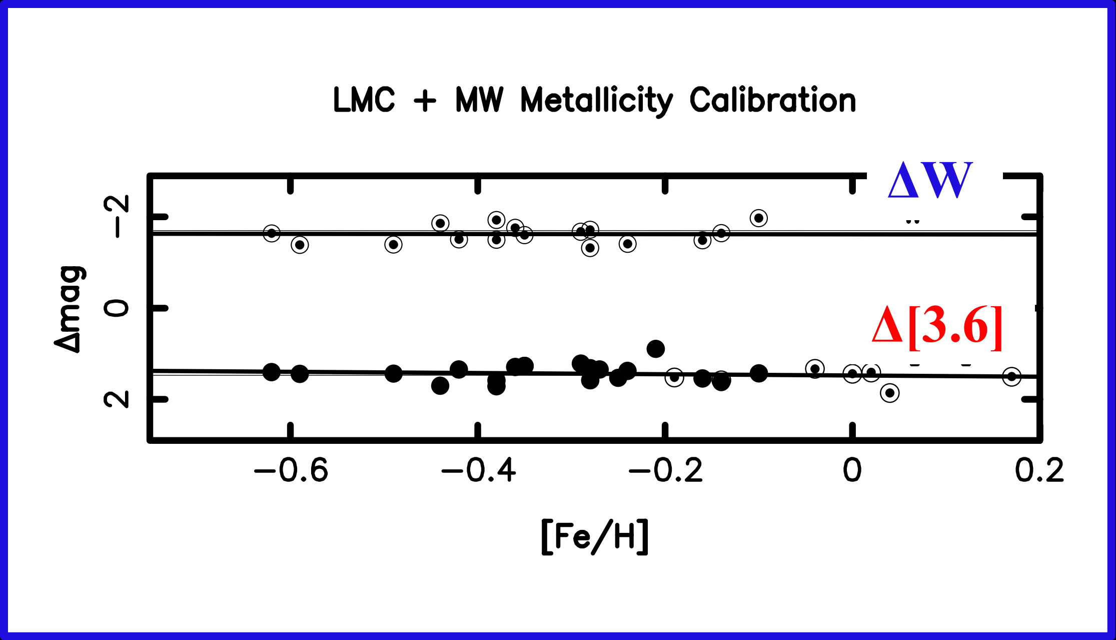
4.5 µm

Monson et al. 2012

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



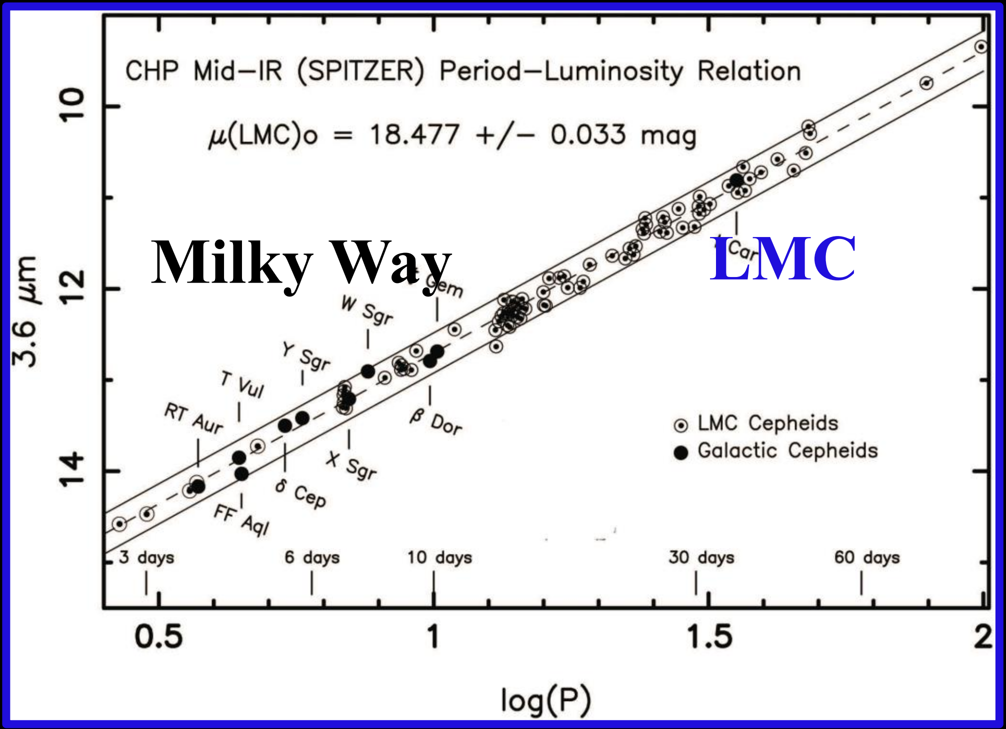
Sensitivity to [Fe/H]

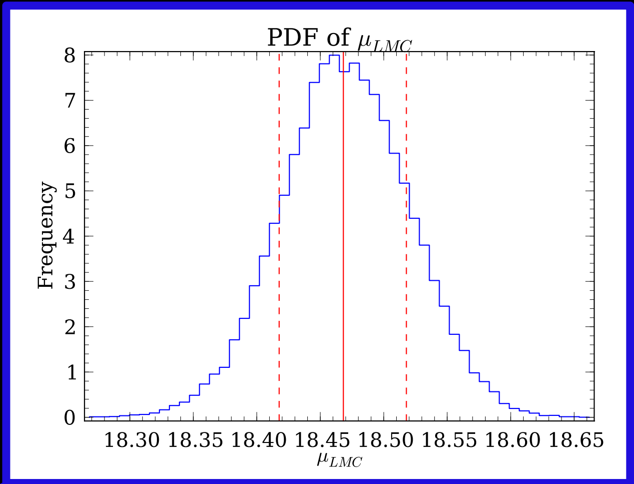


- Spectroscopic [Fe/H] from Romanielli et al. (2008)
- Most sensitive and direct test yet of metallicity effects
- LMC and Milky Way
- Wesenheit function W = V – R (V-I) also very insensitive to metallicity

WLF *et al.* (2012)

Comparison of LMC and Milky Way Leavitt Laws





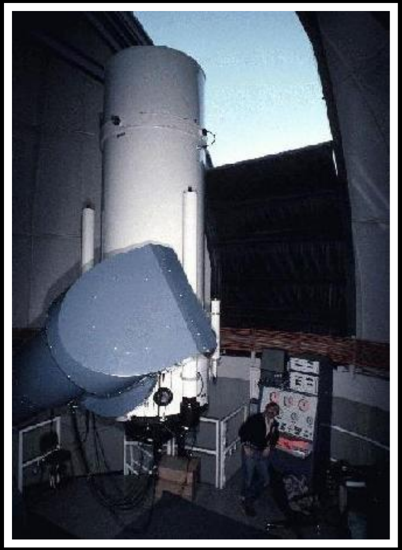
$$\mu_{LMC} = 18.48 \pm 0.01\ (\mathrm{stat}) \pm 0.03(\ \mathrm{sys})$$

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

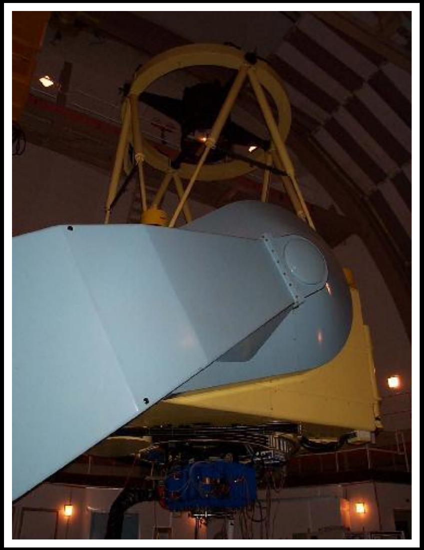
WLF *et al.* (2012)

WLF *et ål.* (2014)

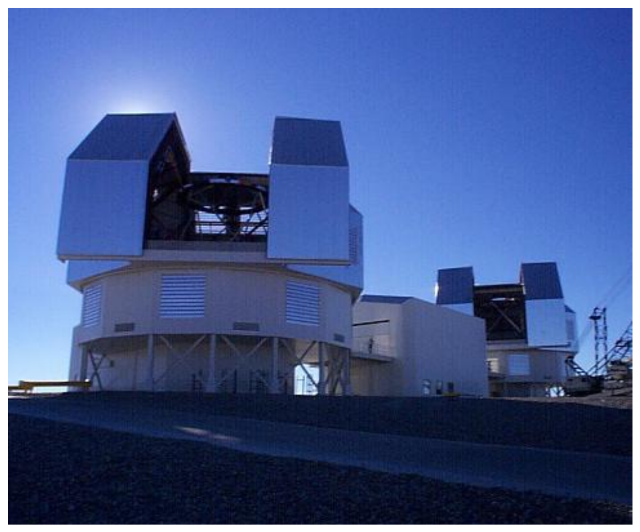
Carnegie Supernova Project (CSP)



Swope 1-meter



Dupont 2.5-meter



Magellan 6.5-meter

Low z:

- u'BVg'r'i'YJHK photometry
- 2.5-meter spectroscopy

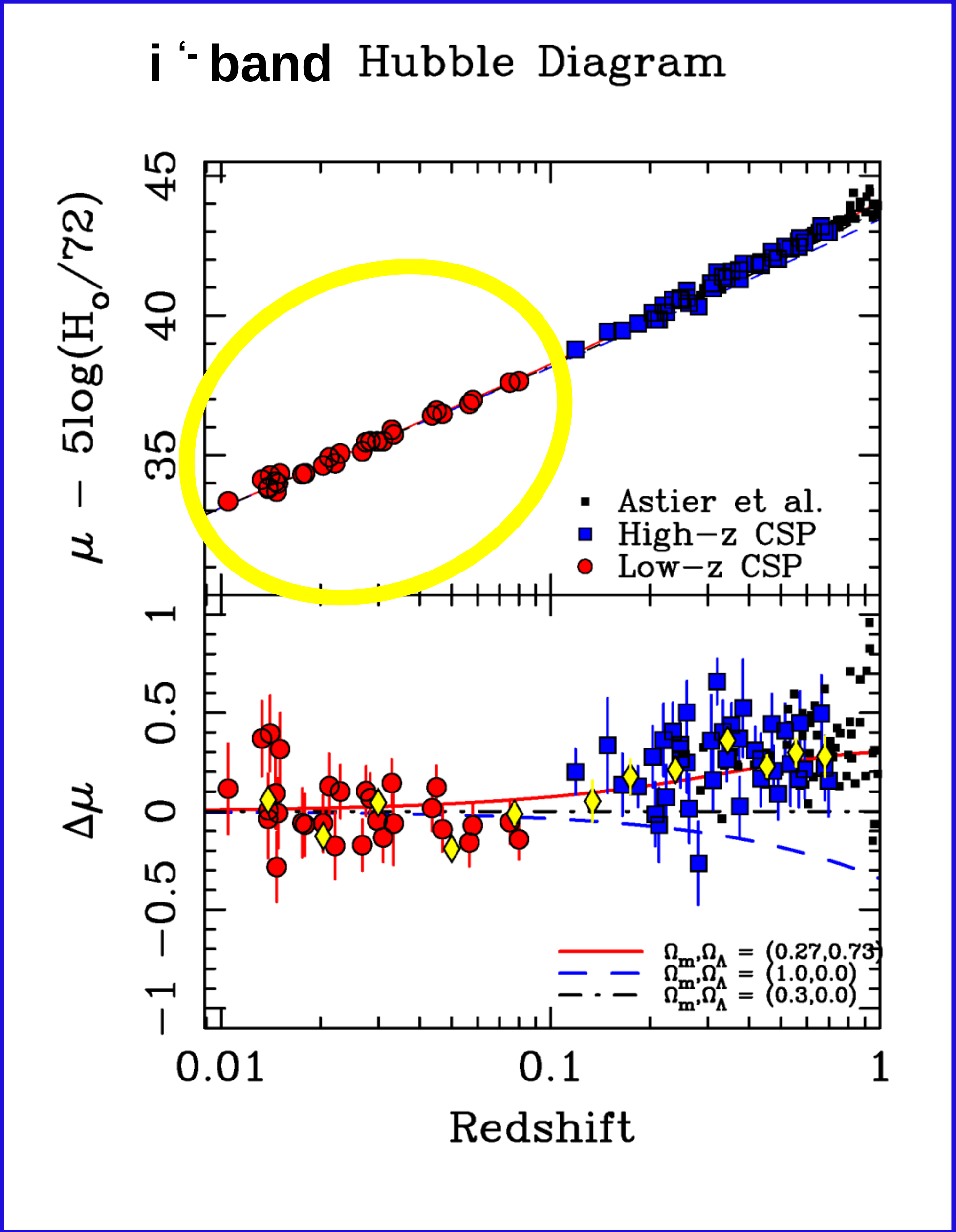
0 < z < 0.1

High z:

- YJ photometry
- Magellan 6.5-meter

0.1 < z < 0.7

i-band Hubble Diagram

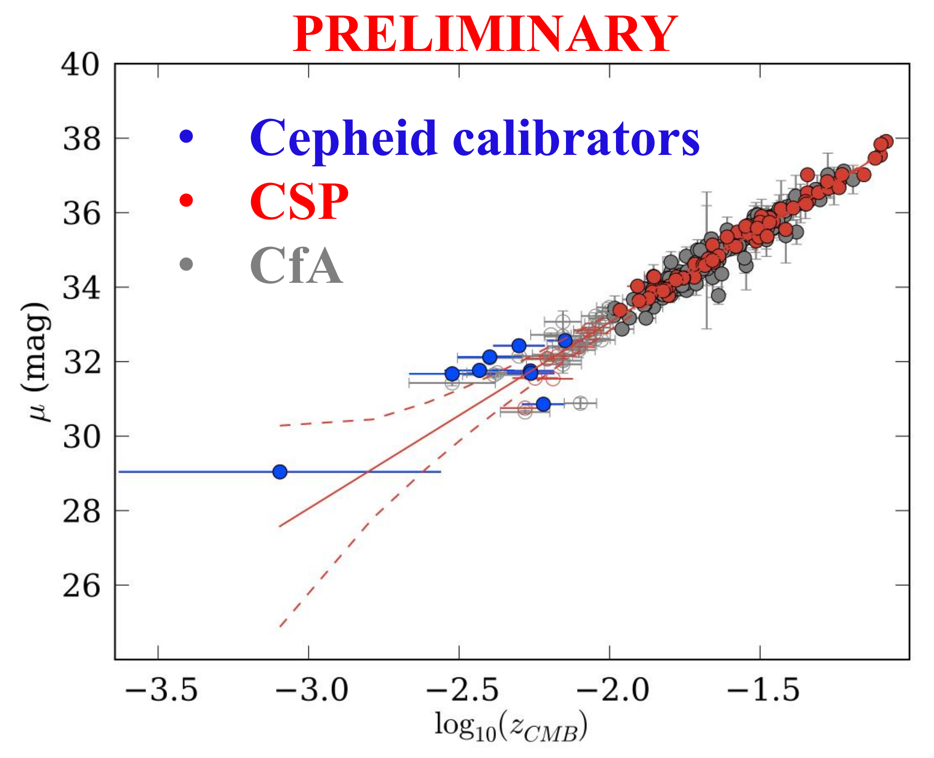


CSP data:

First I-band Hubble Diagram at z > 0.07

WLF et al. (2009)
Folatelli et al. (2010)
Burns et al. (2011)

H_0 From Enlarged Sample of Type Ia Supernovae



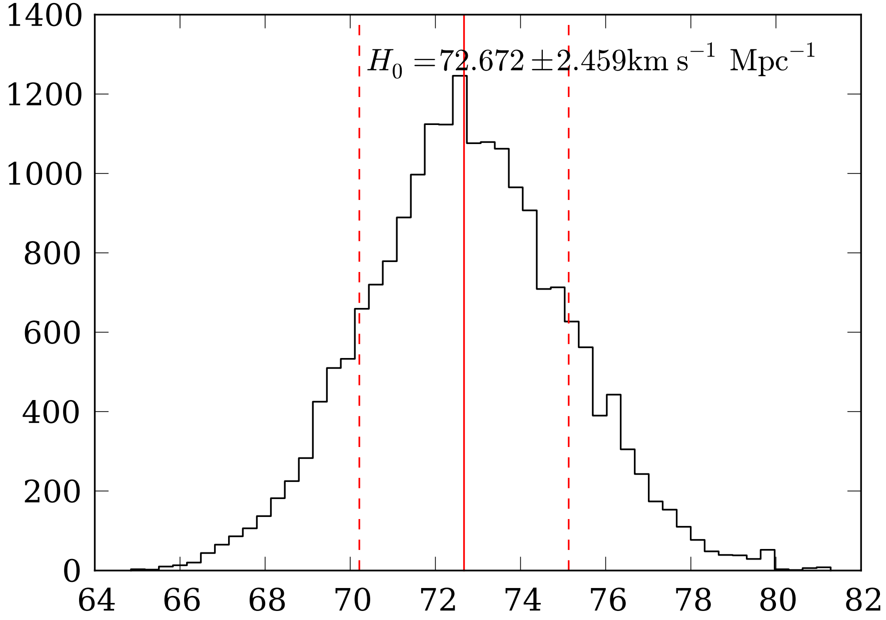
Data for H_0 analysis:

- 9 Cepheid SN Ia hosts *
- 61 CSP SNe Ia *
- 155 CfA + CTIO SNe Ia *
- Total: 215 objects with z>0.01

WLF et al. (2014)

H_0 From Enlarged Sample of Type Ia Supernovae

PRELIMINARY



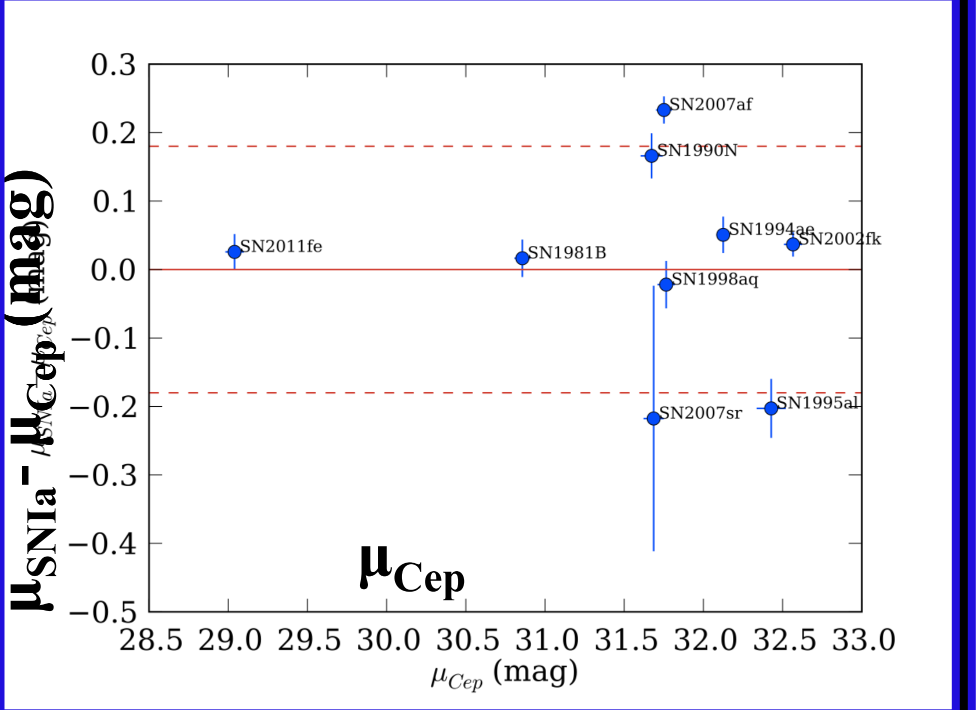
MCMC analysis

Solve for:

H_0, LMC, NGC 4258 distances
Cepheid PL parameters, reddenings,
metallicity dependence
Supernova light curve parameters,
calibrator distances, z_{CMB}

$H_0 = 72.7 \pm 2.0$ [stat] ± 0.5 [sys] km s^{-1} Mpc
($H_0 = 70.4$ based on NGC 4258 alone)

Uncertainty in Type Ia Supernovae Calibrators



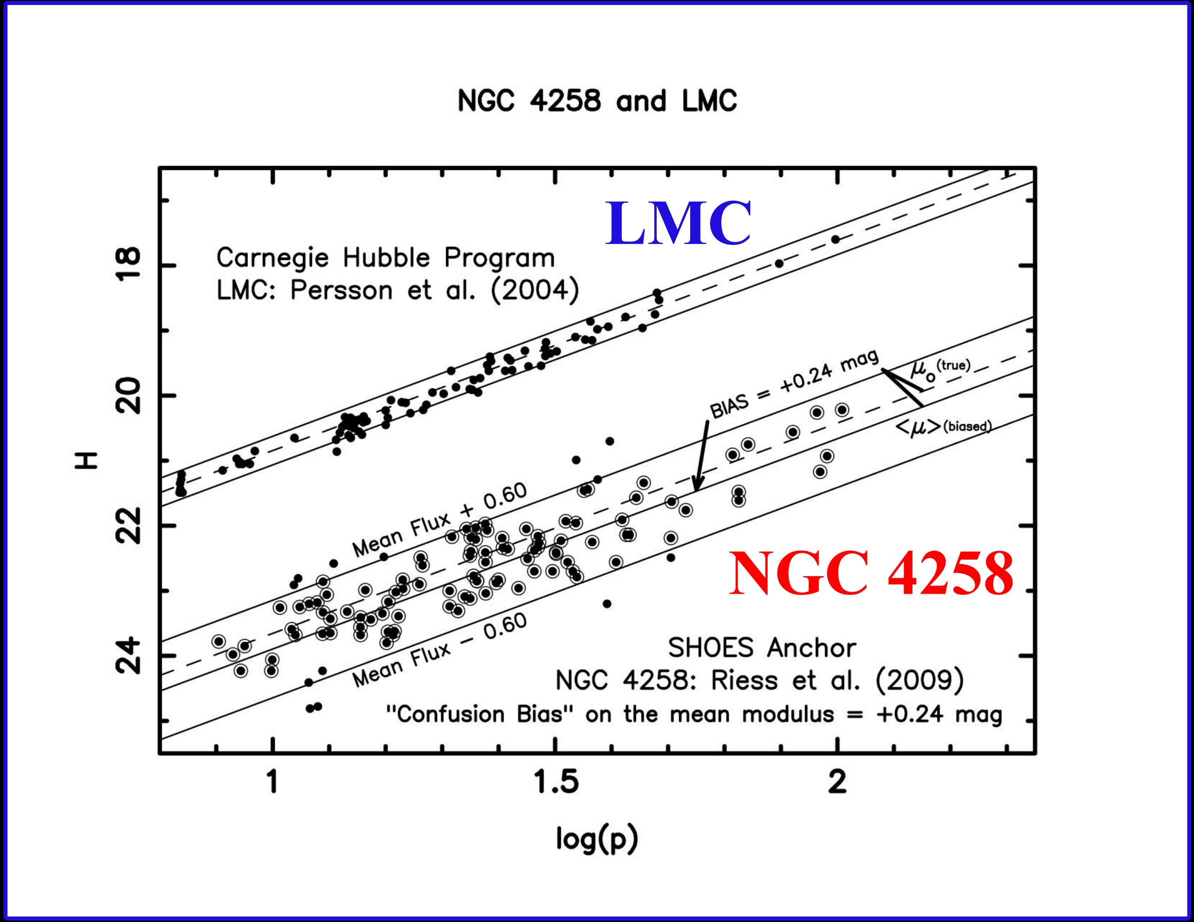
- Largest uncertainty: small number of calibrators

- Dashed lines show ± 0.18 mag, the SNIa dispersion in the far sample.

- For the calibrators, σ ~ 0.14 mag
- Error on mean for the 9 calibrators is 0.046 mag or 2.3% in H_0

- **Challenge for 1%H_0 : only 9 calibrators
- Nature delivers new one only every 2-3 years!

Scatter in the Calibrating Galaxies

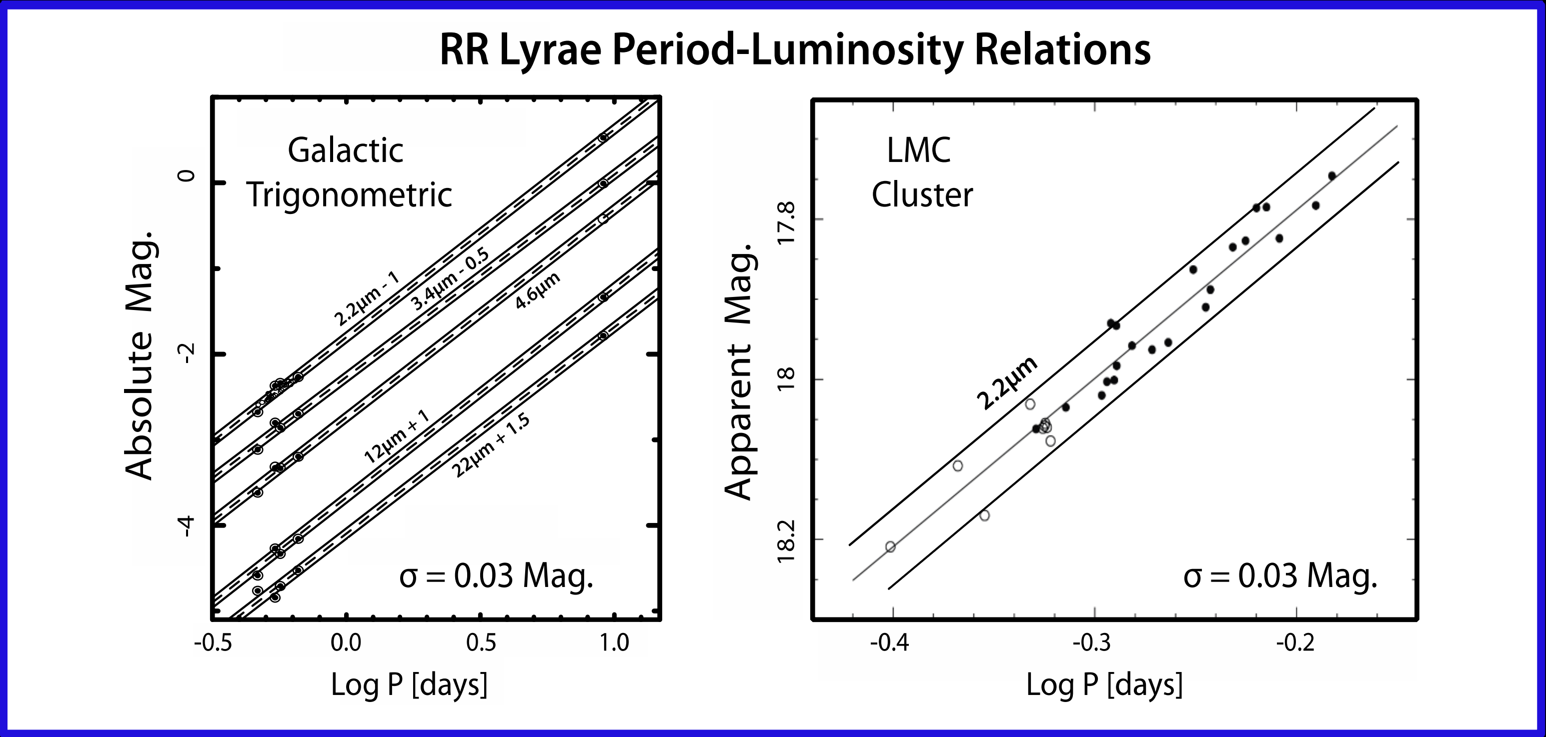


LMC
$\sigma = \pm 0.10$ mag
Scowcroft et al. 2012

NGC 4258
$\sigma = \pm 0.45$ mag
Riess et al. 2011

Upcoming Improvements in H_0 Determinations

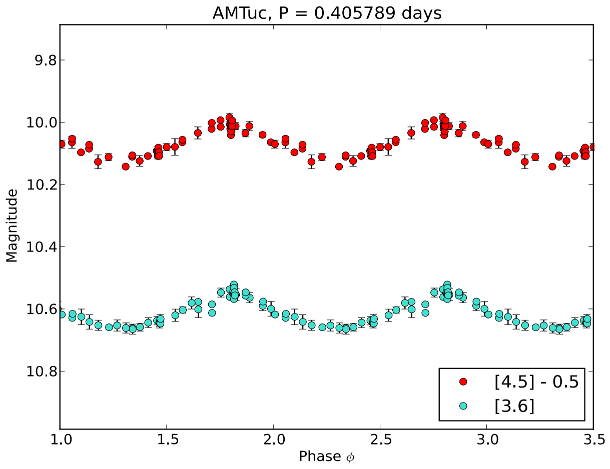
1. RR Lyrae Stars

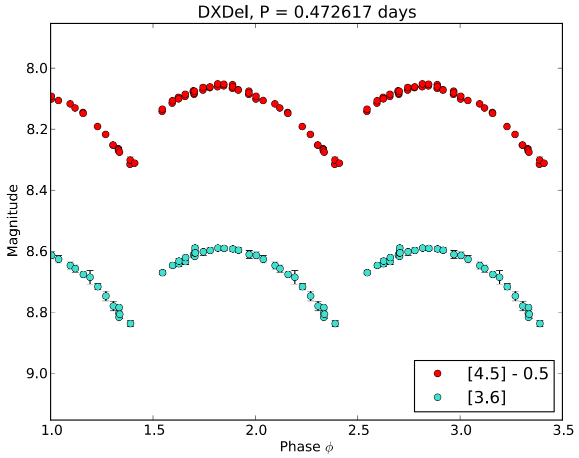


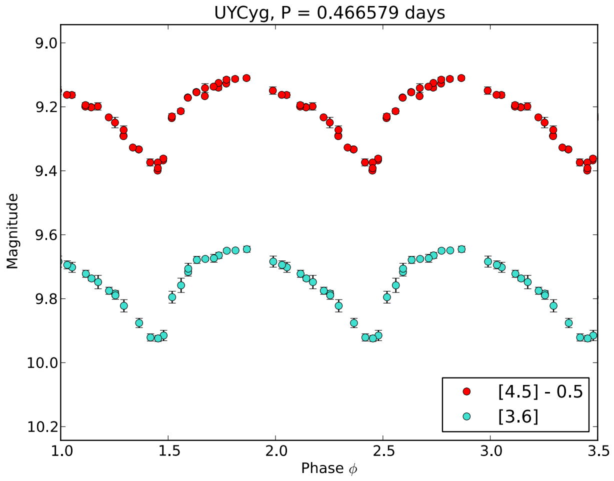
Note σ = 0.03 mag! (1.5% in distance for single star!)

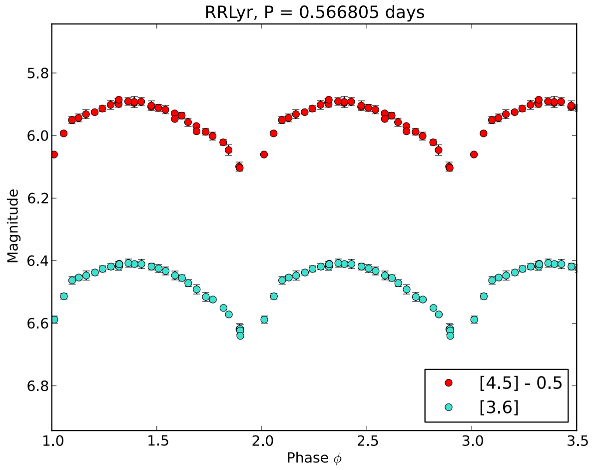
Madore et al. 2013

Spitzer Milky Way RR Lyrae Calibrators









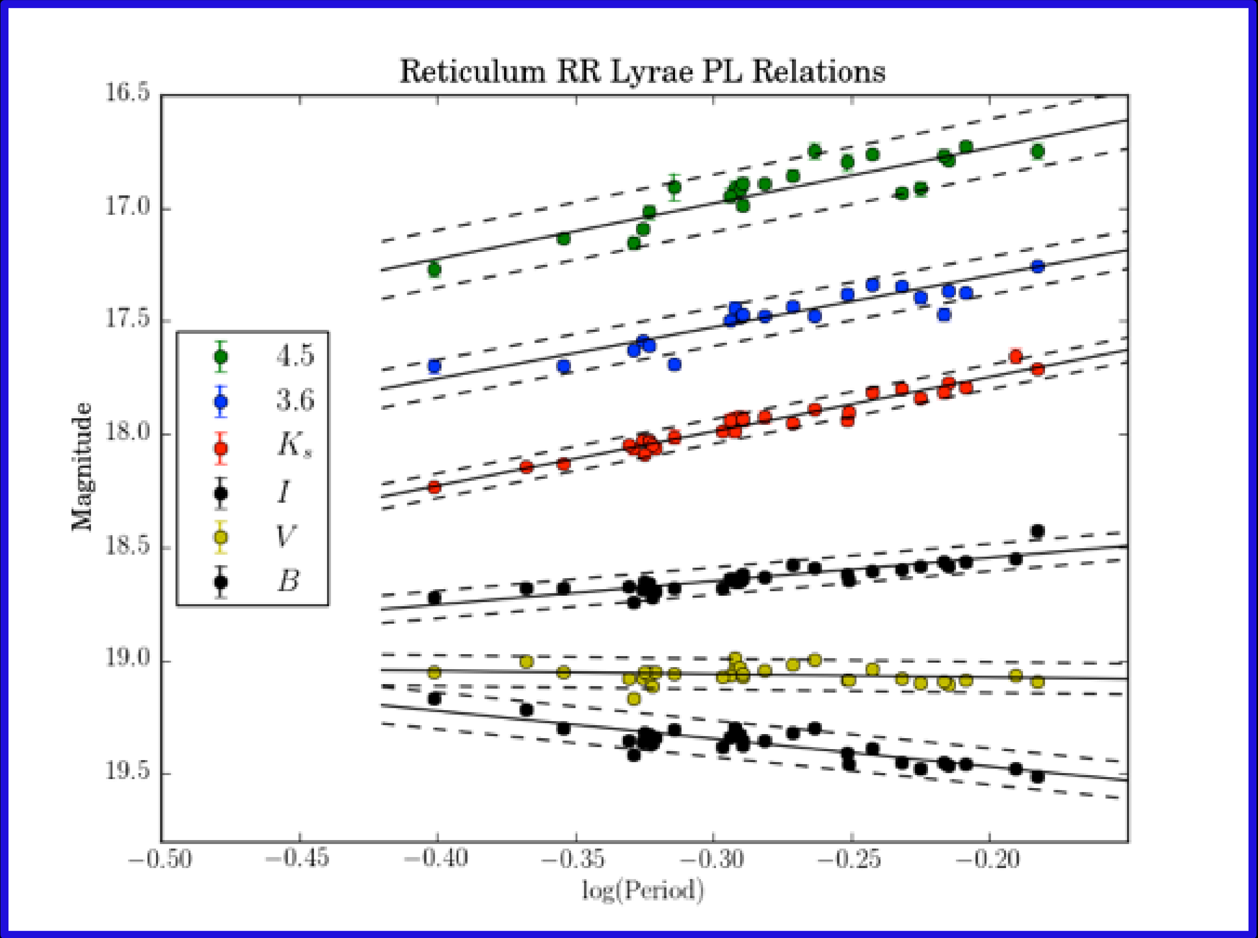
3.6 and 4.5 µm

Scowcroft et al (2013)

+ 10 – inch!

+ Gaia

New Multi-Color RR Lyrae PL Relations



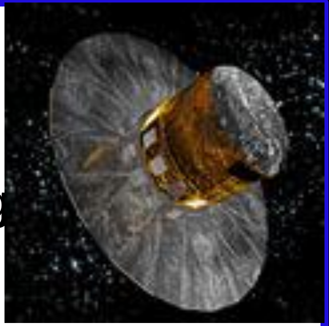
A. Monson et al.

What can you address with accuracies this high?

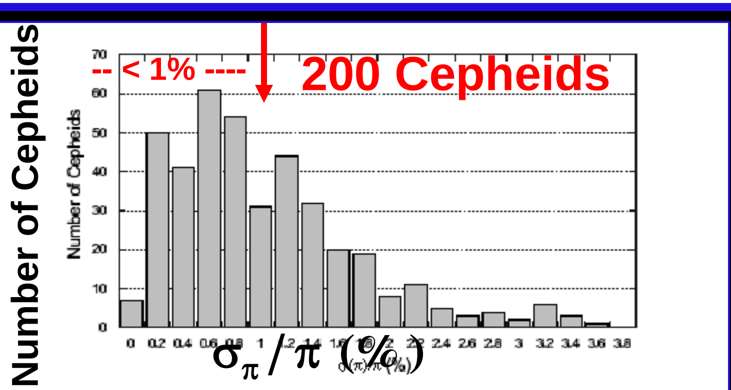
- Structure of the bulge and halo of the Milky Way
- Stellar ages (globular clusters)
- Comparison with Cepheid distances
- Independent calibration of H_0 via TRGB and SNe

2. Future Parallax Measurements

ESA's Global Astrometric Interferometer for Astrophysics (Gaia)



- ❖ Currently planned launch: Dec. 19, 2013
- ❖ A few microsecond accuracy
- ❖ Systematic survey of entire sky to 20 mag
- ❖ $\sigma_\pi / \pi < 1\%$ out to several kiloparsecs
- ❖ Accurate measurements of many Cepheids and RR Lyrae variables (~100's of Cepheids; 1000's of RR Lyraes) [~70 observations per object] + Spitzer
- ❖ Distance to LMC to 0.02-0.04 mag (1-2% in distances)



Expected relative accuracy in the distance of Galactic Cepheids from Gaia.

Decreasing the Uncertainties in H_0

HST Key Project: [±10%]

- Several methods with independent checks
- 5% statistical uncertainties
- Robust tests of 10% final uncertainty ☑
  - Cepheids (RR Lyraes, TRGB, PNLF)
  - SNeIa, TF, SBF, PNLF, SNII

Current H_0 Measurements: [±3-4%]

- Require additional tests to confirm Cepheid and SNeIa distances at the 3-4% level.
- Not yet available, but in progress. ☐

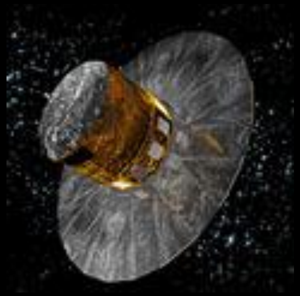
Future H_0 Measurements: [±2-3%]

  - Spitzer RR Lyrae independent distances (2% level)**
  - Gaia parallaxes (<1%) for Cepheids and RR Lyraes.
  - IR measurements of SNeIa
  - Gravitational lensing, masers, Planck SZ clusters

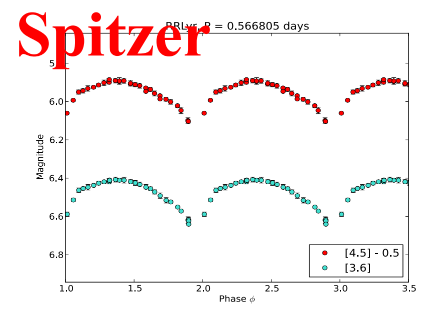
What is needed for H_0 to 1%?

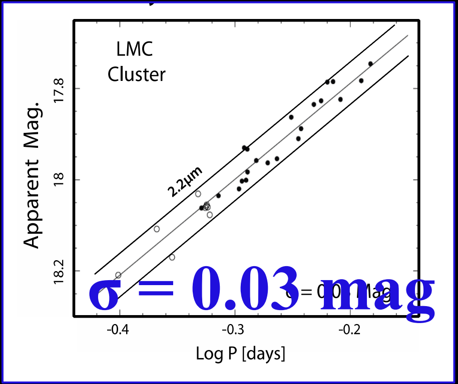
  - Several independent methods capable of 1% ☒

Gaia



Spitzer





σ = 0.03 mag

Advances in Measurements of H_o

Current status:

Freedman et al. (2012, 2013) LMC + Milky Way:

- high spatial resolution
- 0.1-0.2 mag scatter in Leavitt Law
- Spitzer 3.6 μm calibration + optical HST
- Fe/H spectroscopic abundance test

$H_o = 74.3 \pm 1.5 \pm 2.1$ km s^{-1} Mpc^{-1} (recalibration of KP)

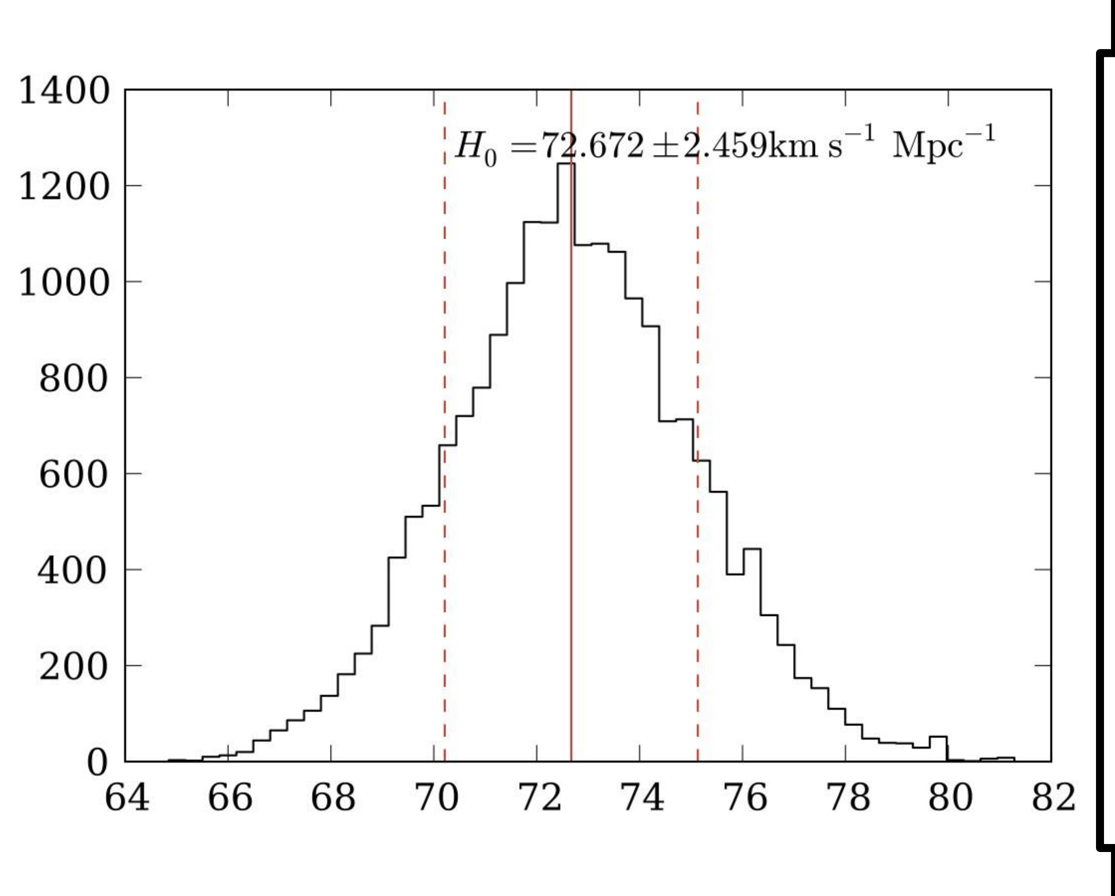
$H_o = 72.7 \pm 2.0$ [stat] ± 0.5 [sys] km s^{-1} Mpc^{-1}
(CSP + CfA + SHOES + 2011fe)
(Cepheids + SNe only)
0.5 mag scatter at H-band; LMC+MW+N4258

Riess et al. (2011) LMC+Milky Way + N4258:

- HST optical plus H-band
- 0.5 mag scatter at H-band

$H_o = 73.9 \pm 2.4$ km s^{-1} Mpc^{-1}

MCMC histogram: Results for H_0



H_0 = 72.7 ± 2.5 km s^{-1} Mpc^{-1}
[1 - σ standard deviation from MCMC chains]

H_0 = 72.7 ± 2.0 [stat] ± 0.5 [sys] km s^{-1} Mpc^{-1}

- **LMC, N4258 + photometric zp Independent systematics; i.e., not determined from data in hand.**
- **All other parameters are nuisance parameters determined from the data**