Implications of Planck Results for H_0

General Remarks:

- **A 6-parameter model provides an exquisite fit to the Planck data**
- **The value of H_0 can be derived assuming this model ($\Omega_b h^2$, $\Omega_c h^2$)**
- **Direct measurements of H_0 are *required* to test the model**
- **The key element is understanding the systematics affecting the accuracy 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**
- **Pre-HST $30 < H_0 < 110$ km/sec/Mpc** **
- **2-2.5-σ discrepancies are not interesting for claiming new physics**
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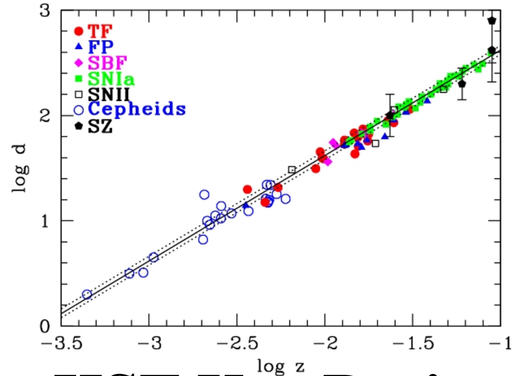

HST Key Project

Implications of Planck Results for H_0

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- Given
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What did you do wrong?...
… The SN Ω_m people already adjusted their results. What's taking you so long?

at z~0 with completely
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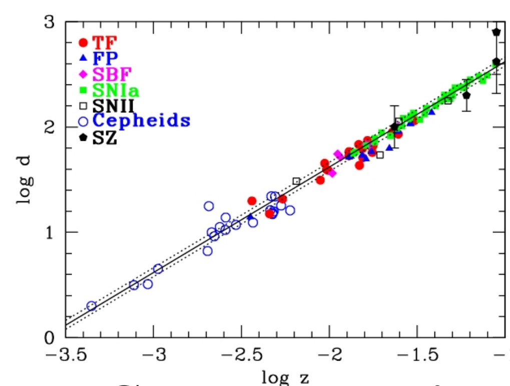

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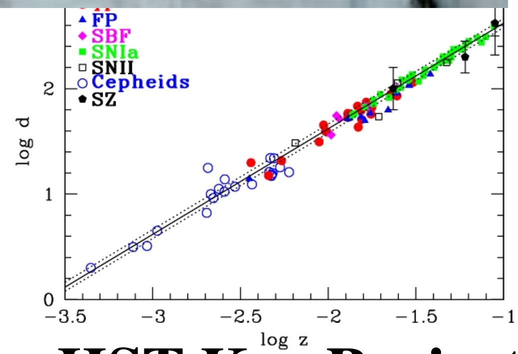
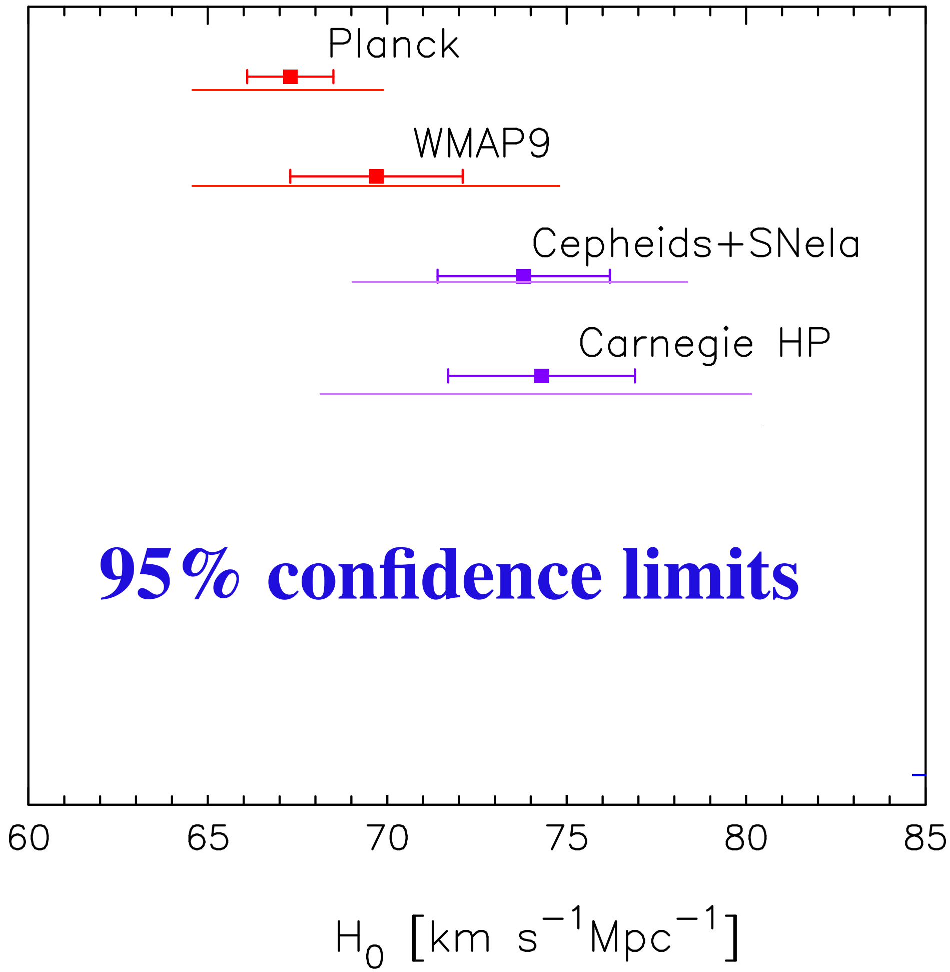
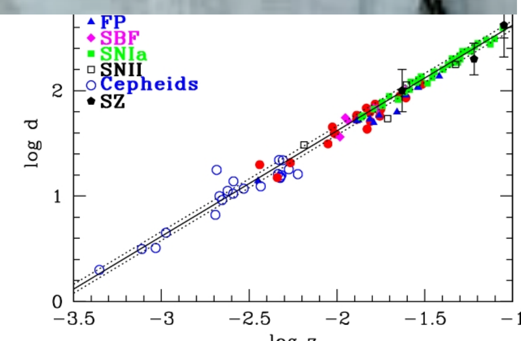


HST Key Project

Implications of Planck Results for H_0





HST Key Project

Recent Direct Measurements of H_0

- **Carnegie Hubble Project:** $H_o = 74.3 \pm 2.0$ [stat] ± 2.1 [sys] km s^{-1} Mpc^{-1}
  ± 2.9 [4%]
- **Carnegie supernovae:** in progress

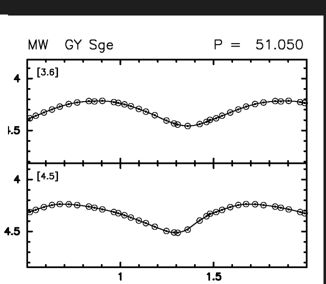
- SH_0ES (Riess et al. 2011) : $H_o = 73.9 \pm 2.4$ km s^{-1} Mpc^{-1} [3%]

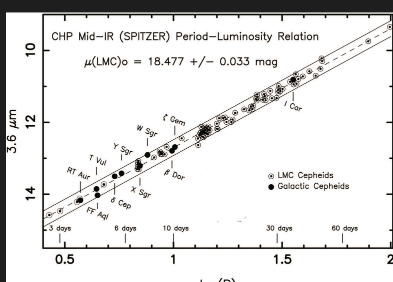
- GL (Suyu et al. 2010) : $H_o = 70.6 \pm 3.1$ km s^{-1} Mpc^{-1} [4%]

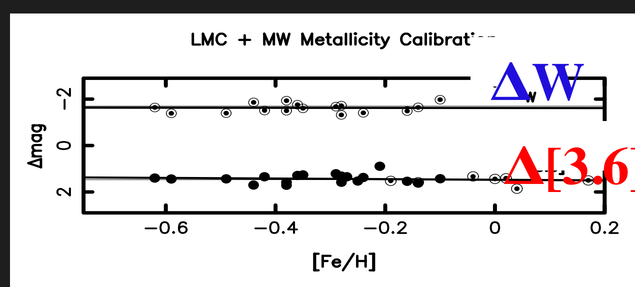
Recent improvements in direct measurements of H_0 :

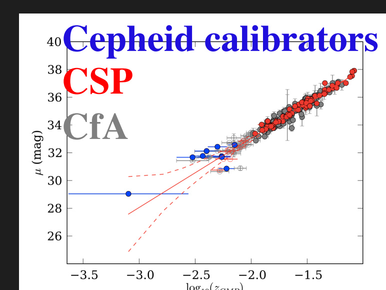
- mid-IR (Spitzer) independent Cepheid zero point [Milky Way + LMC]
- HST parallaxes for Milky Way Cepheids
- Improved metallicity constraints for Cepheids [direct [Fe/H] abundances]
- HST Cepheid distances to more SNeIa - H-band (Riess et al.)
- Higher precision observations of nearby SNe (CfA + CSP2 <= NIR)
- Gravitational lensing – detailed modeling (Suyu et al.)
- H_2O megamasers (Braatz et al)

3.6 um
4.5 μm









WLF et al. 2012, 2013

Sources of Systematic Errors in H_0

Freedman & Madore ARAA (2010) - dominant sources of error

Known	**Key Project**	**Revisions**	**Anticipated**	**Basis**
Systematics	(2001)	(2007/2009)	Spitzer/JWST	
(1) Cepheid Zero Point	±0.12 mag	±0.06 mag	±0.03 mag	Galactic Parallaxes
(2) Metallicity	± 0.10 mag	±0.05 mag	±0.02 mag	IR + Models
(3) Reddening	±0.05 mag	±0.03 mag	±0.01 mag	IR 20-30x Reduced
(4) Transformations	±0.05 mag	±0.03 mag	±0.02 mag	Flight Magnitudes
Final Uncertainty	±0.20 mag	±0.09 mag	±0.04 mag	Added in Quadrature
Percentage Error on H_0	±10%	±5%	±2%	Distances

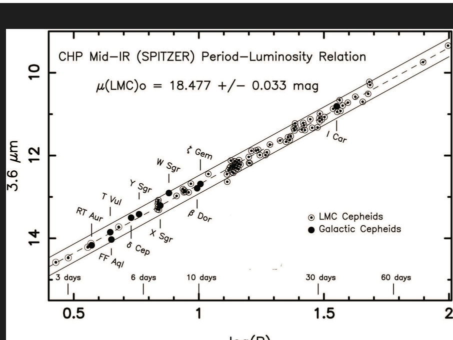
We are here

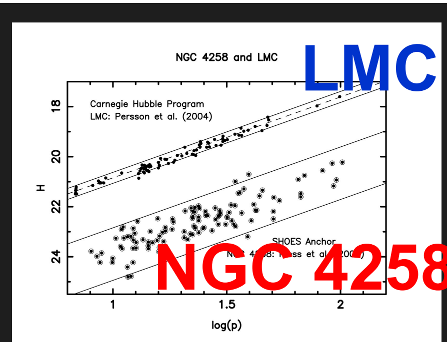
Improvements to Systematics:

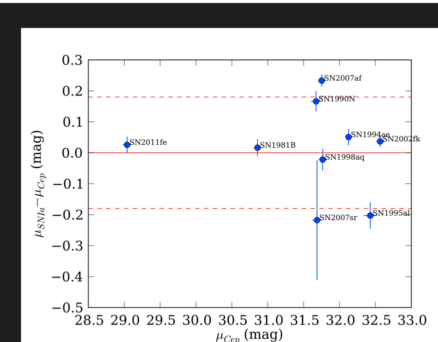
1. HST parallaxes

2. NGC 4258 scatter

3. Few SN calib.s







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. ☐

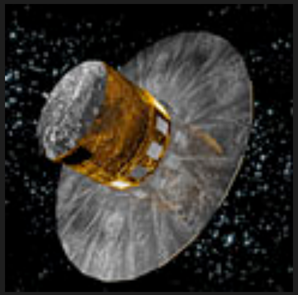
Future H_0 Measurements: **[±2-3%]**

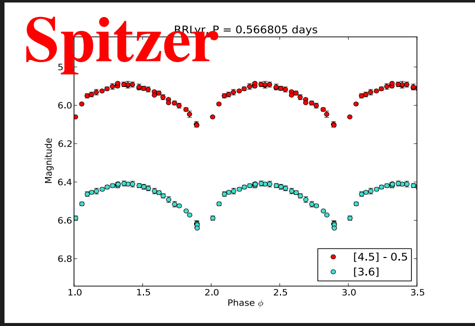
- Spitzer RR Lyrae independent distances (2% level)**
- Gaia parallaxes (<1%) for Cepheids and RR Lyraes.
- IR measurements of SNeIa
- Gravitational lensing, masers, Planck SZ clusters

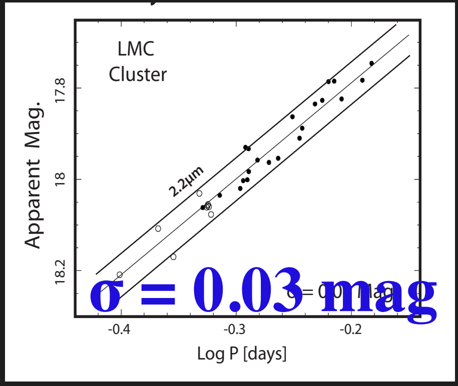
What is needed for H_0 to 1%?

- Several independent methods capable of 1% ☒

Gaia







Paper XVI

“We emphasize here that the CMB estimates are highly model dependent. It is important therefore to compare with astrophysical measurements of H0, since any discrepancies could be a pointer to new physics.”