

Modern cosmology 1: The Hubble Constant

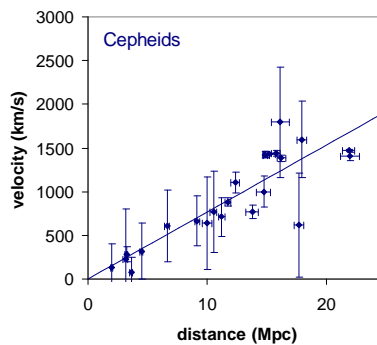
- **Extragalactic distance measurements**
- **Classical Cepheid calibration**
- **HST Key Project results**
- **Independent measurements**

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Extragalactic distance measurements

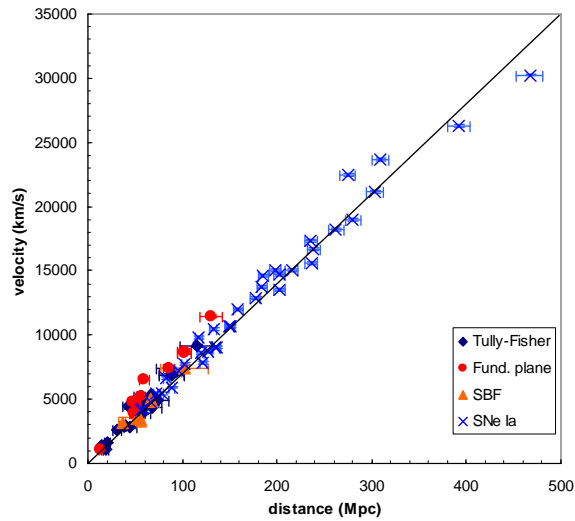
- **Cepheid-calibrated**
 - ▶ **Whole-galaxy methods: Tully-Fisher, fundamental plane, surface-brightness fluctuations**
 - ▶ **Type Ia supernovae**
- **Cepheid-checked**
 - ▶ **Type II supernovae**
- **Cepheid-independent**
 - ▶ **Sunyaev-Zeldovich effect**
 - ▶ **Gravitational lensing**



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Hubble diagram from HST



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Systematic errors

- **The Key Project systematic error budget:**

- ▶ LMC distance: $\pm 5\%$
- ▶ HST WFPC2 zero point: $\pm 3\frac{1}{2}\%$
- ▶ Reddening estimate: $\pm 1\%$
- ▶ Metallicity effects: $\pm 4\%$
- ▶ Bias: $\pm 1\%$
- ▶ Crowding: $+5\%, -0\%$
- ▶ Bulk flows: $\pm 5\%$

Systematics dominated.
No single source dominant – so improvement difficult

- **Total:** $+10\%, -9\%$

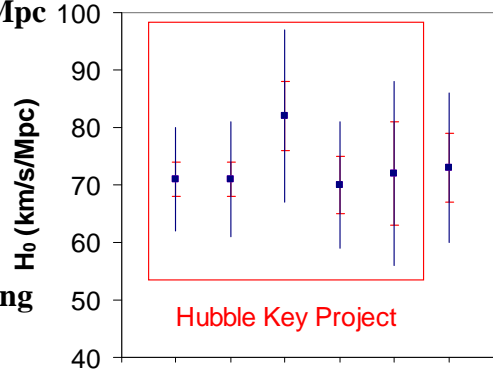
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Results for H_0

- Results are all consistent within statistical errors

- ▶ FP a bit high
- ▶ mean $72 \pm 3 \pm 7$ km/s/Mpc
- ▶ SN II result very consistent with earlier result from Schmidt et al.
- ▶ Error is dominated by systematics, so little point in collecting more data



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Update on H_0

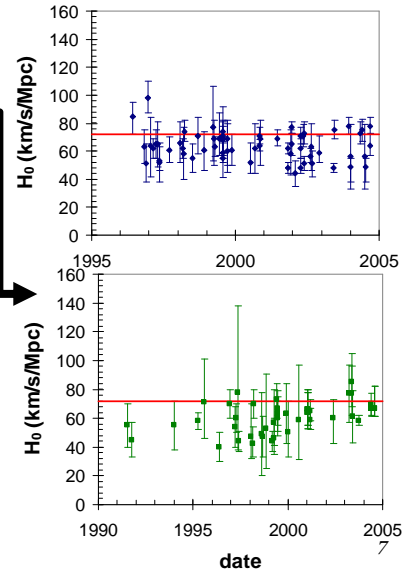
- Since Key Project, systematics improved by
 - ▶ using ACS/WFC3 instead of WFPC2 on HST
 - ▶ better Cepheid parallaxes (HST)
 - ▶ using maser galaxy NGC 4258 instead of LMC as basis of distance scale
 - ▶ focus on SNe Ia as distance indicator
- Result is to halve systematic error from $\pm 10\%$ to $\pm 5\%$ (Riess et al., *ApJ* 699 (2009) 536)
 - ▶ result: 74.2 ± 3.6 km s⁻¹ Mpc⁻¹

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Independent measurements

- **Gravitational lensing and Sunyaev-Zeldovich distances are in principle geometric**
 - ▶ both tend to give lower values (~ 60 km/s/Mpc)
 - ▶ both are new and difficult techniques
- **CMB fits give completely consistent result**
 - ▶ 70.1 ± 1.3 km/s/Mpc (WMAP+BAO+SN,2008)



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Conclusions

- **Precision of Hubble constant measurements driven by systematic errors in calibration**
 - ▶ best long-range geometric measurements are lower than best conventional values, but not convincingly so
- **Best estimate (HST Key Project 2001, WMAP fit 2008) is ~ 70 km/s/Mpc**
 - ▶ error $\sim 10\%$ from HST, $\sim 2\%$ from CMB
 - ▶ much better than factor 2 error in 1980s!

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