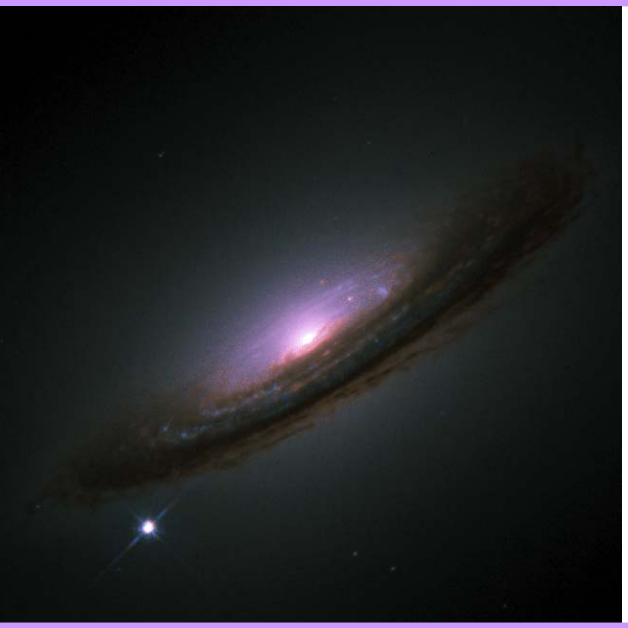
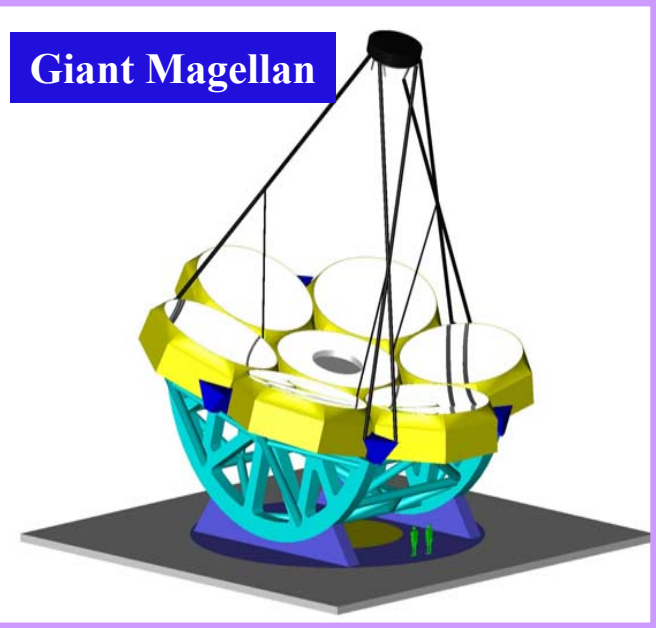
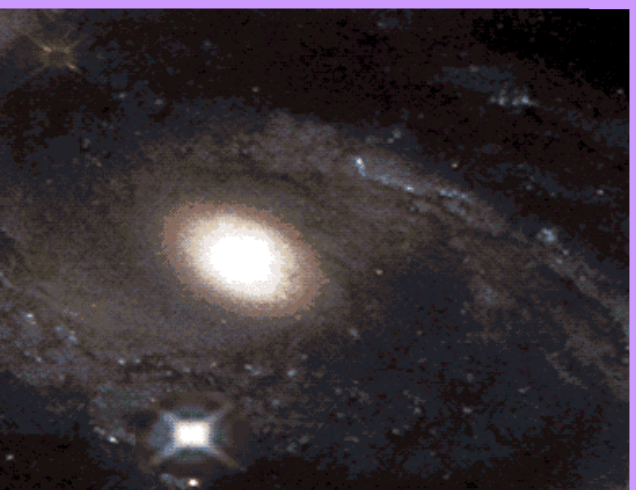
The Future of H_0





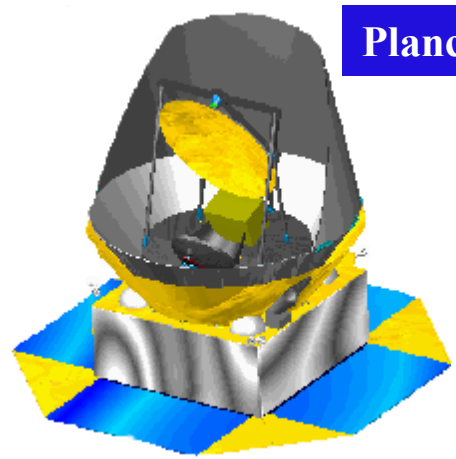


Wendy Freedman

Carnegie Observatories

Chicago: New Views of the Universe

December 9, 2005

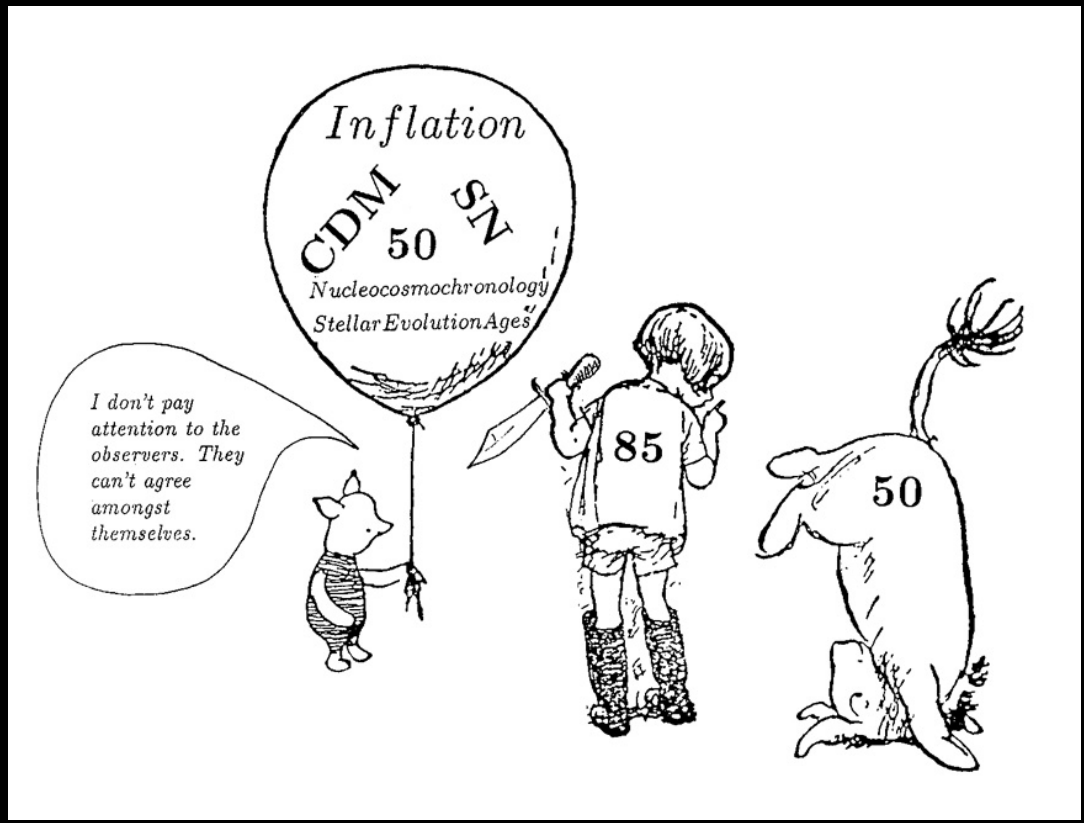


Why do we want to know H_o?

It's just a number!

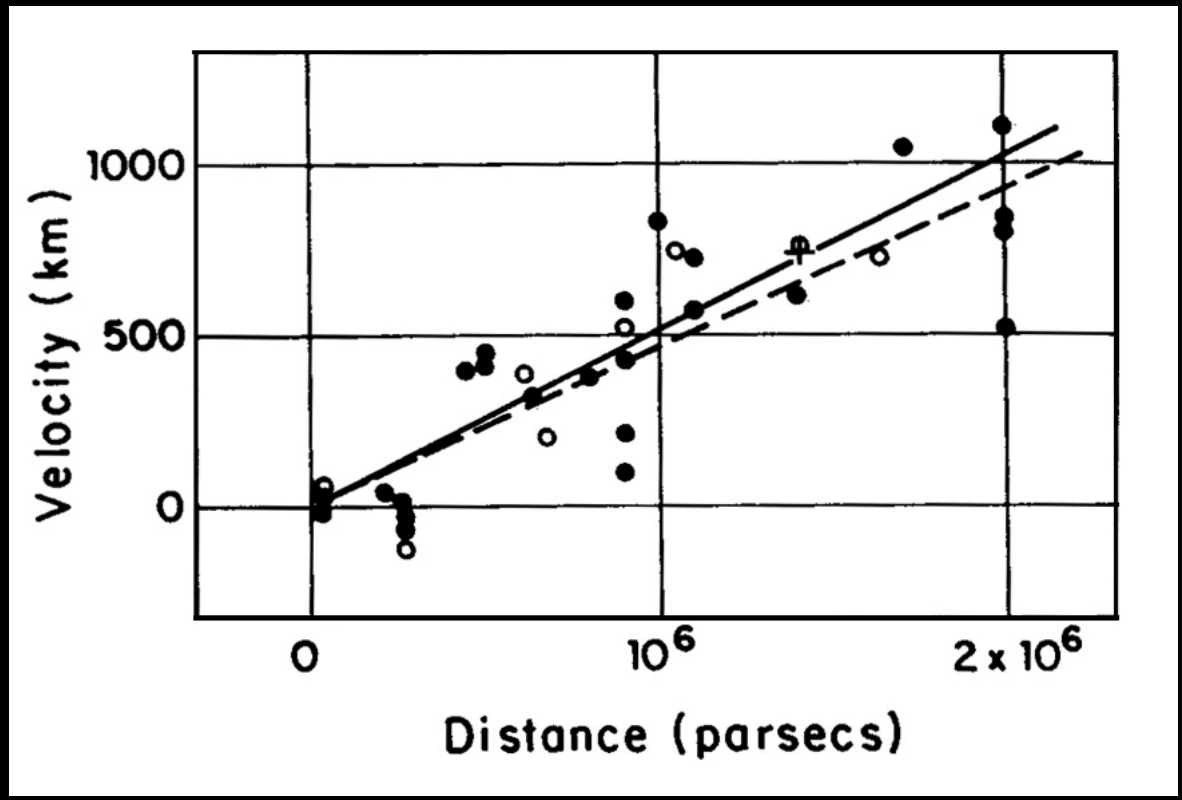
Prior to launch of HST:

$40 < H_0 < 100$



First Determination of H_o

Hubble (1929)



Difficulties:

- photometry
- reddening
- distance indicators
- peculiar velocities
- Earth's atmosphere

Why do we want to know H_o?

The Hubble constant is one of the most important parameters in Big Bang cosmology.

- The square of the Hubble constant relates the total energy density of the Universe to its geometry.

$$H^2 = 8\pi G\rho/3 - k/r^2 + \Lambda c^2/3$$

- It **sets the age** of the Universe ($H_0^{-1} = 9.78h^{-1} \times 10^9$ yr)
- It **sets the size** of the observable Universe ($R_{obs} = ct = 3000h^{-1}$ Mpc)
- It determines the Universe's **radius of curvature** ($R_{curv} = c/H_o ((\Omega - 1/k^{1/2}))$)
- It defines the **critical density** of the Universe: $\rho_{crit} = 3H_0^2 / 8\pi G$

- Improved accuracy on H_o **critical for breaking physical degeneracies** in CMB measurements.

How well can we determine H_o?

That depends on two things:[1]

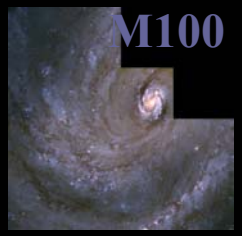
1. How well can we account for SYSTEMATICS?

and/or

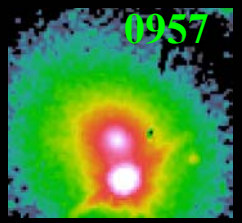
2. What PRIORS have been assumed?

[1] "In principle" is different than "in practice."

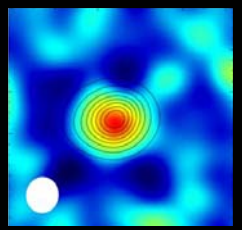
Current Independent Methods for Measuring H_0



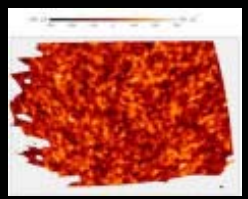
- Extragalactic Distance Scale



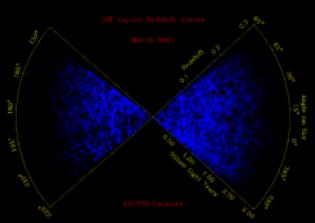
- Gravitational lens time delays



- Sunyaev-Zel'dovich effect



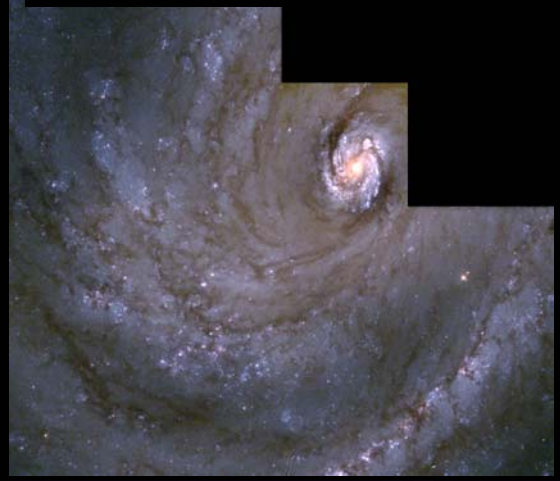
- Anisotropy in CMB



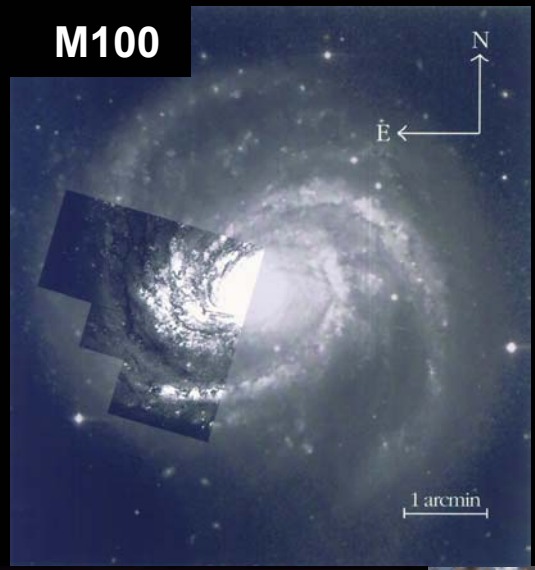
- Large-scale structure

HST Key Project Cepheid Searches

M100 Virgo Cluster

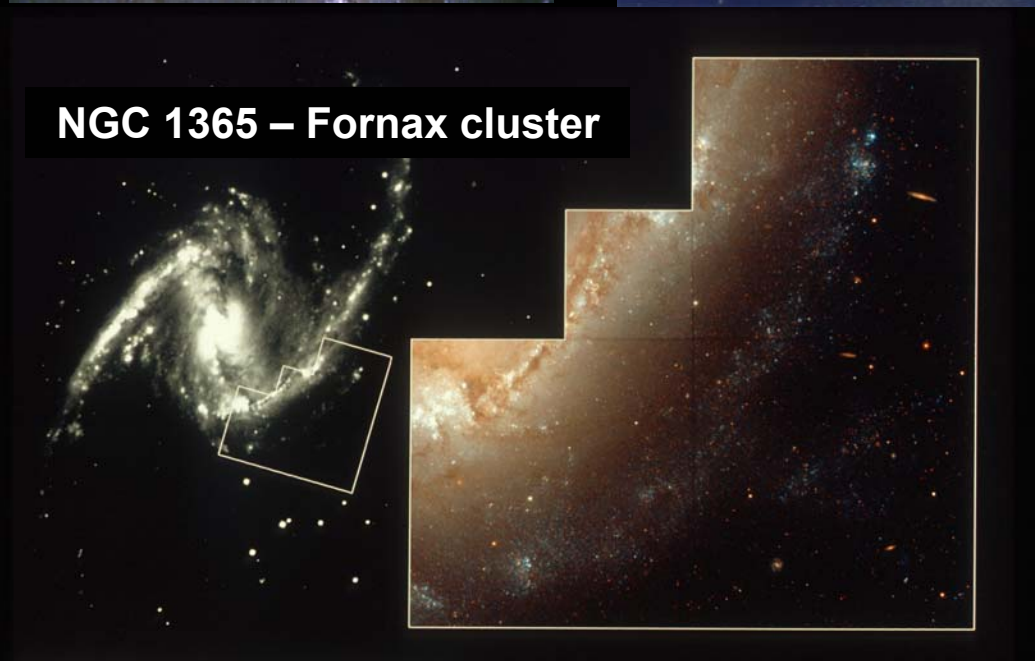


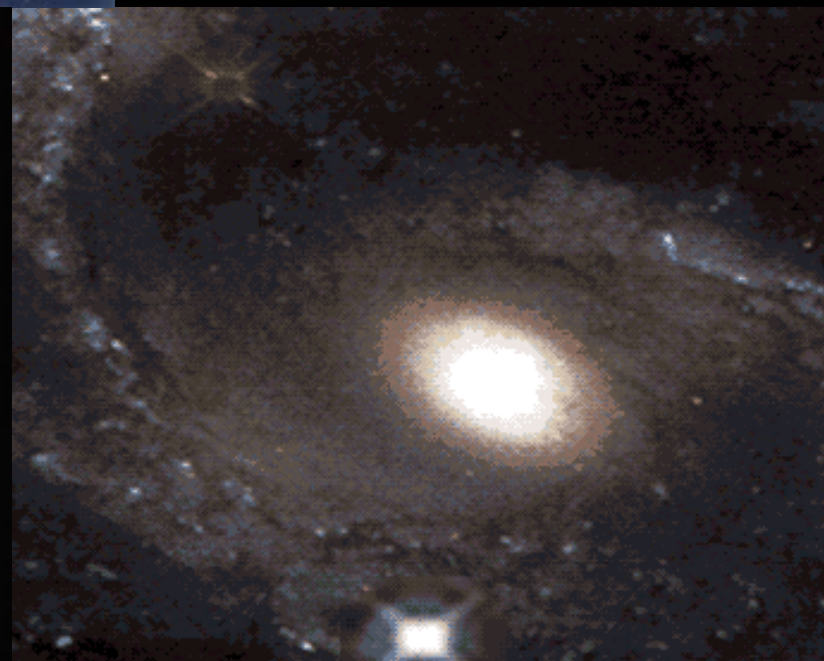
M100



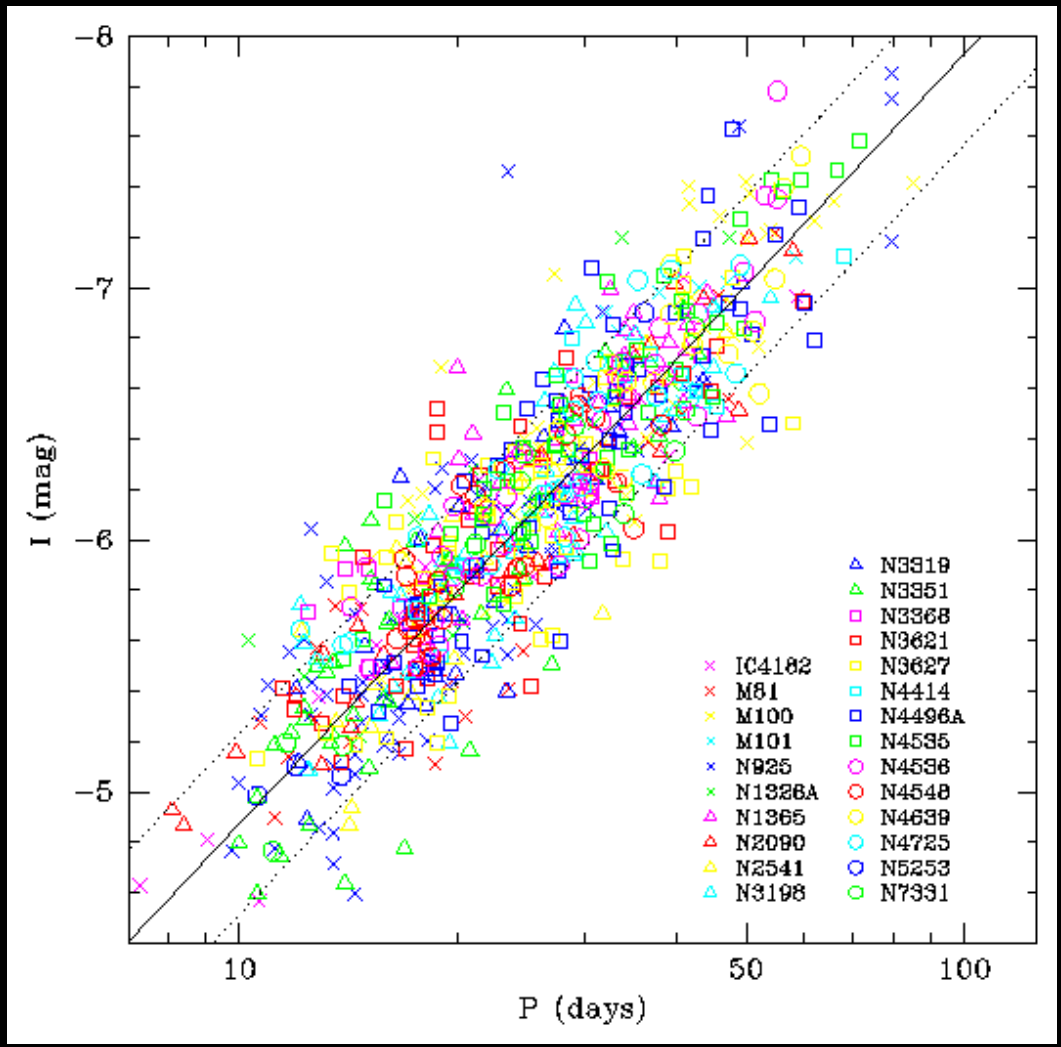
N4414

NGC 1365 – Fornax cluster





Key Project Cepheids

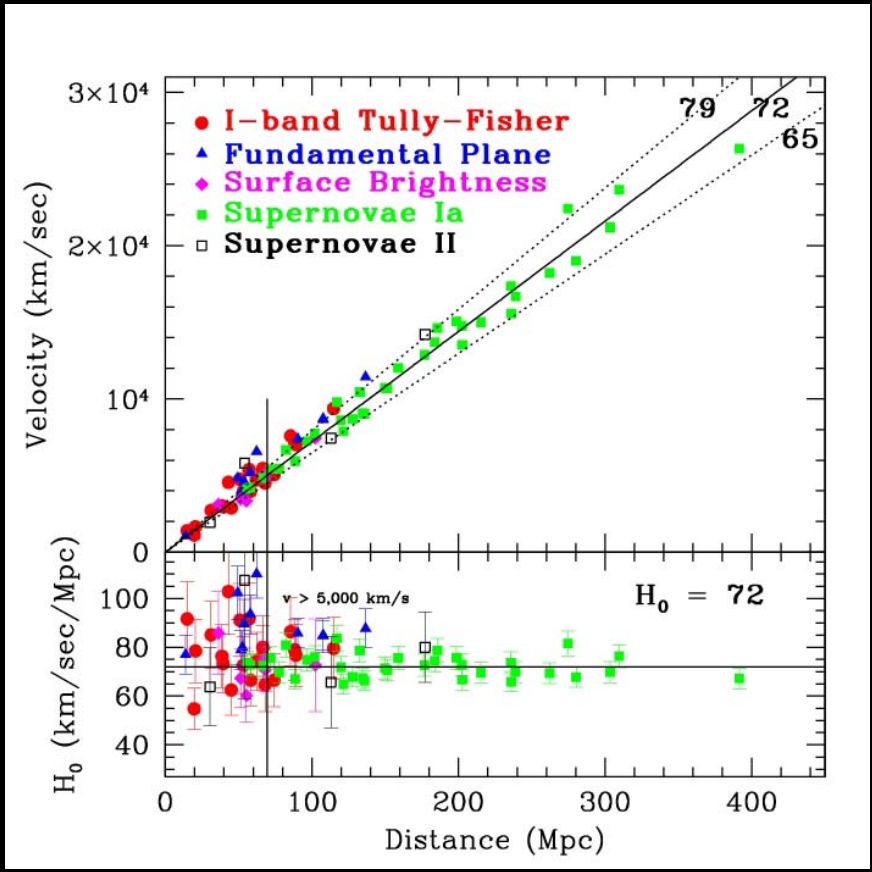


- Composite I- band PL relation
- 24 galaxies
- ~800 Cepheids
- PL dispersion ~0.2 mag

$\mu = m - M$
$= 5 \log d(\mathrm{Mpc}) - 5$

Ferrarese et al. (2000)

HST Key Project Results



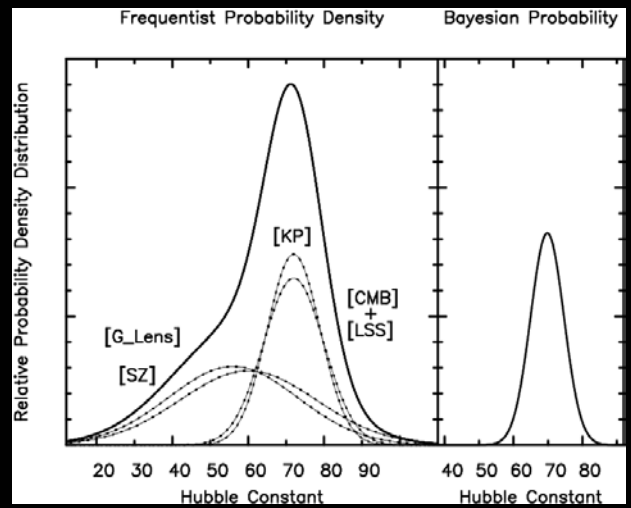
$H_0 = 72 \pm 3$ (stat.) ± 7 (sys.) km/sec/Mpc

WLF et al. (2001), ApJ , 553, 47

Combined Current Value of H_0

Key Project:	**72 ± 8 km s^{-1} Mpc^{-1}**
Gravitational Lensing:	**56 ± 17 [6] km s^{-1} Mpc^{-1}**
Sunyaev-Zeldovich:	**[60 ± 18 km s^{-1} Mpc $^{-1}$]**
	77 ± 11 km s^{-1} Mpc $^{-1}$
CMB + LSS:	**72 ± 7 km s^{-1} Mpc $^{-1}$**

Bayesian (flat prior):
$H_0 = 70 \pm 5$ km s^{-1} Mpc $^{-1}$

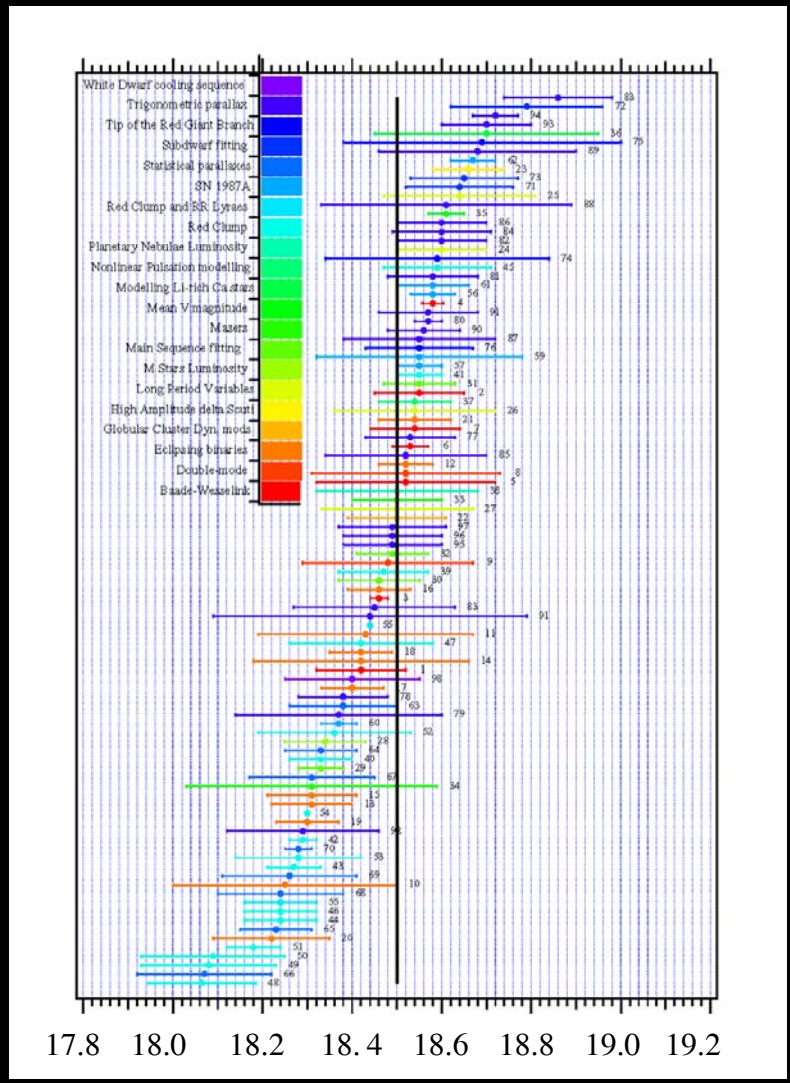


Remaining Dominant Systematics in Cepheid-Based Extragalactic Distance Scale

- **Zero point of Cepheid PL relation (distance to the LMC) [+/- 5% 1-σ]**
- **Effects of Metallicity on Cepheid luminosities [+/- 4% 1-σ]**

The Distance to the LMC (2005)

μ= *18.5 mag*
= 50 kpc



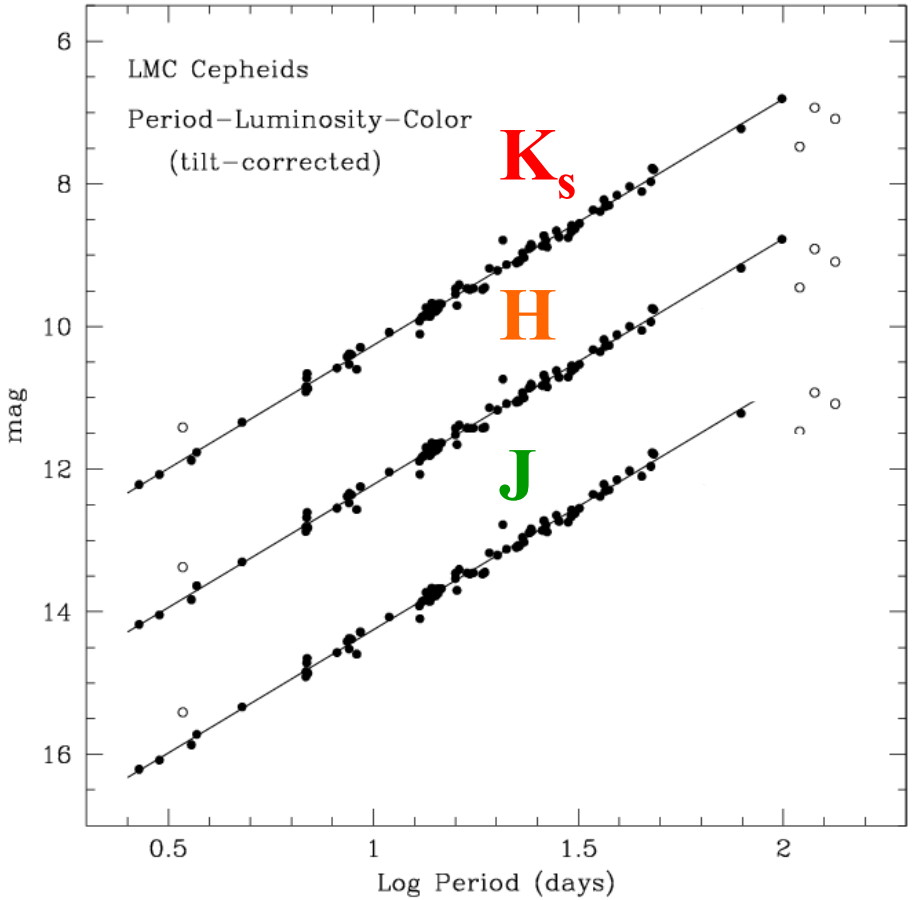
http://clyde.as.utexas.edu/SpAstNEW/head.ps

New Measurements of LMC Cepheids

- Las Campanas C40, C100
- 92 Cepheids
- PLC Dispersions ~0.08 mag
  (4 % in distance)
- Corrected for 3D tilt
- Best PL/PLC relations to date

- μ = 18.52 +/- 0.05 mag
  [Galactic Cepheid calibration
  Gieren et al. 1998]

LMC JHK PL relations:



Persson, Madore, WLF et al. (2004)

Promise for Future H_0 Measurements

- Parallaxes (SIM, GAIA)
- H_20 Masers (SKA)
- Supernovae (ground: IR)
- Gravitational Waves (LIGO, LISA)
- CMB (Planck)
- Baryon Oscillations (ground)

Parallax: Current State of the Art -Hipparcos

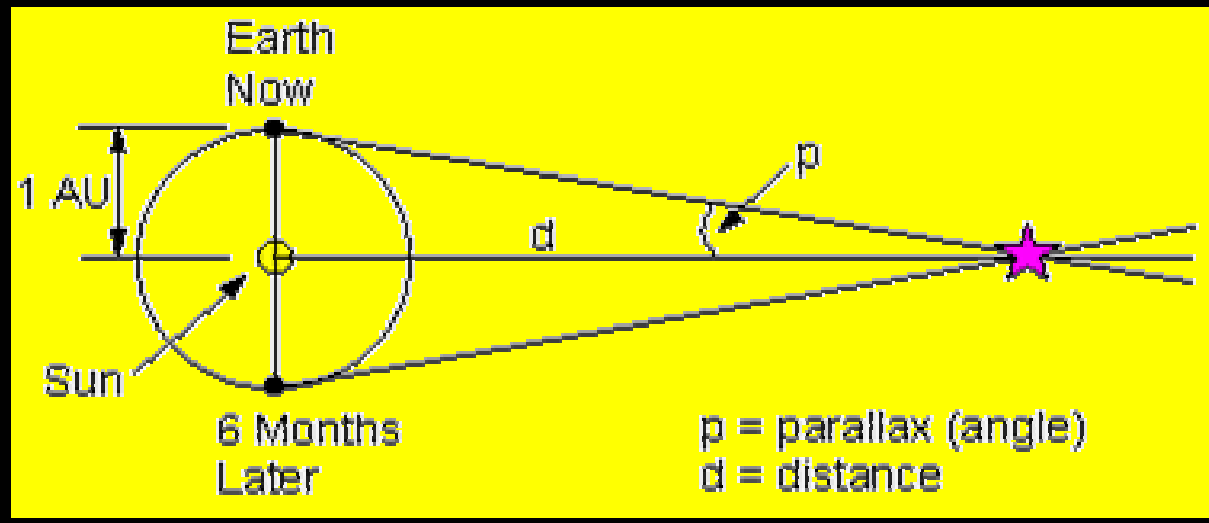
Best measurements of parallax to date (118,000 stars, 223 Cepheids).

Milliarcsecond level: physical distance of 1000 pc

However, parallax is only highly accurate (within a few %) to distances out to a few hundred parsecs.

Cepheid Parallaxes

Advantage: purely geometric distances



Current State:

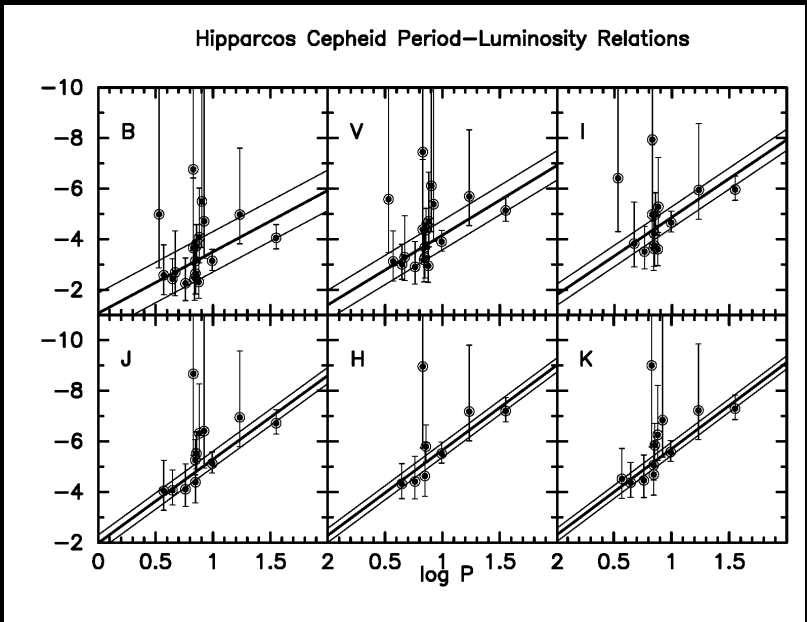
Hipparcos

- $\pi / \sigma_\pi > 5$ for 1 Cepheid [!]
- zeropoint uncertain at 5% level

  [Feast & Catchpole 1997, Madore & Freedman 1998]

Parallax: Current State of the Art -- Hipparcos

Madore & Freedman (1998)

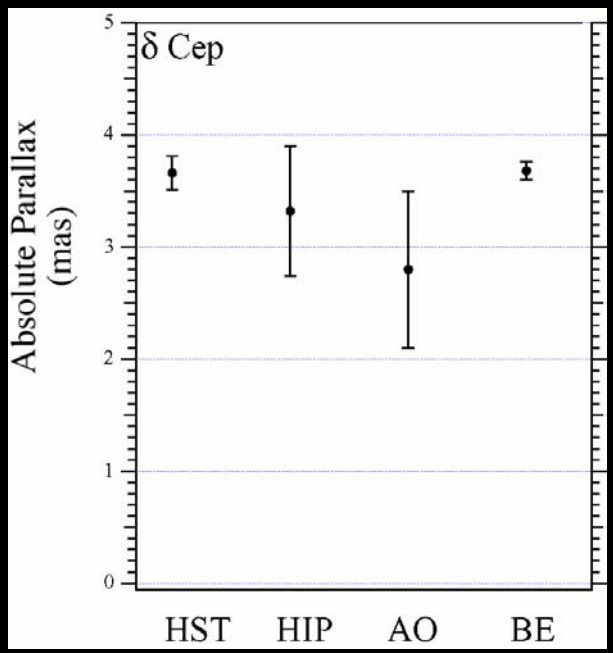


Improvement to Cepheid parallaxes critical.

Multiwavelength (BVIJHK) Period-luminosity relationsfor Galactic Cepheids with Hipparcos parallaxes from Feast & Catchpole (1997).

Parallaxes: Current State of the Art-HST

HST Parallax: δ Cep



Near future:

Benedict et al. 2006

11 HST Cepheid parallaxes

Benedict et al. 2002
Comparison:HST, HIPPARCOS, Allegheny Observatory, parallax derived from Barnes Evans

Parallax: The Next Generation

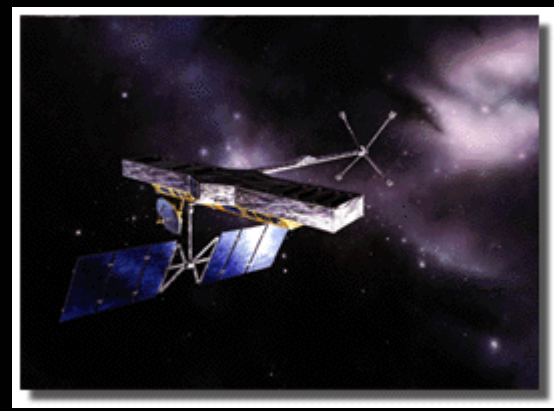
Goal: 1 μas -- A very small angle

- **Earth-Sun system seen from 1 Mpc (by definition)**

Future Parallax Measurements

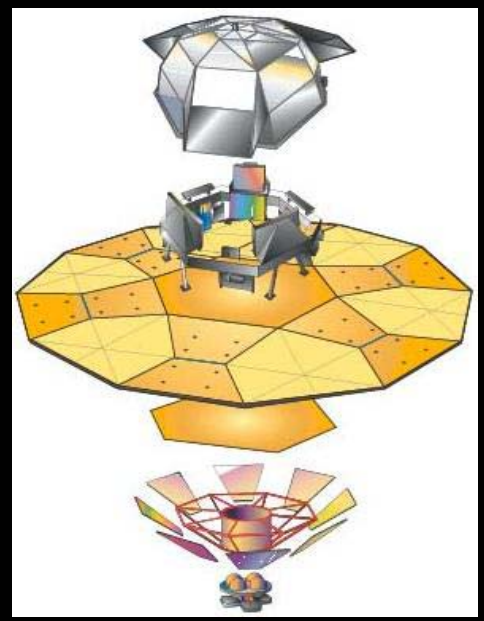
- **NASA's Space Interferometry Mission (SIM)**

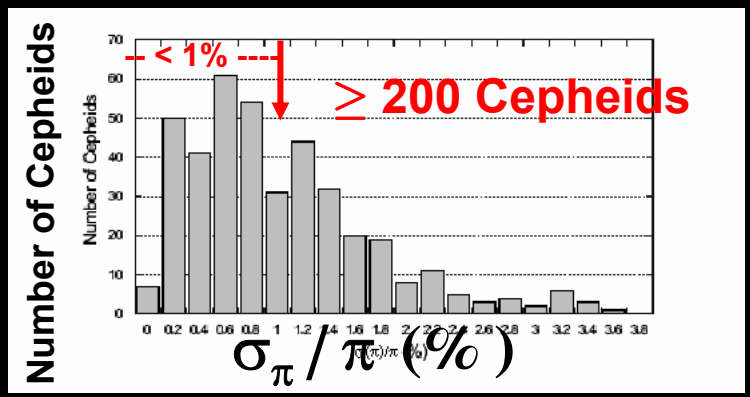
  - Currently planned launch: ~2013.
  - A few microsecond accuracy (2-3 orders of magnitude more accurate parallaxes than Hipparcos)
  - Accurate measurements of many Cepheids and RR Lyrae variables.
  - Improved distance to the LMC
  - Measurement of rotational parallaxes of nearby spiral galaxies.



Future Parallax Measurements

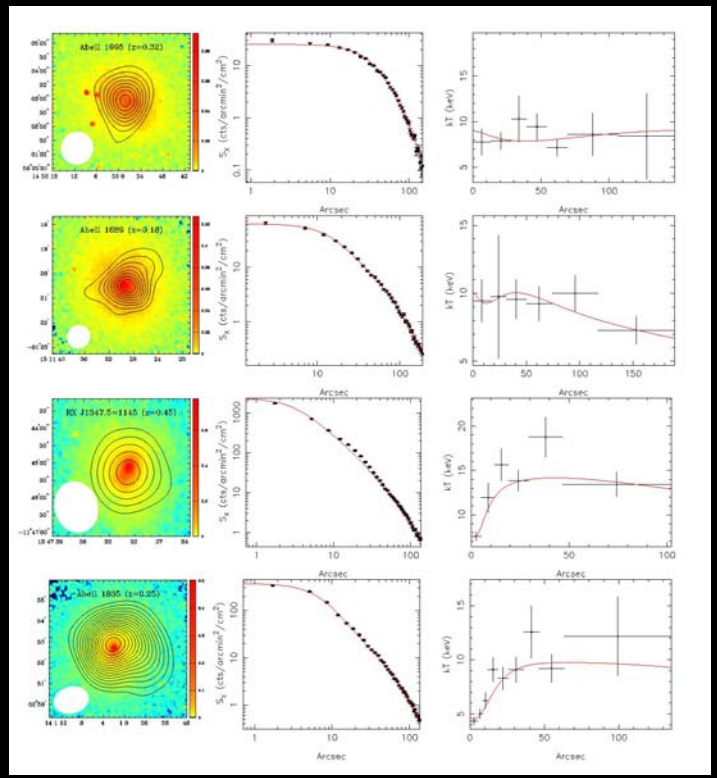
- **ESA's Global Astrometric Interferometer for Astrophysics (GAIA)**
  - Currently planned launch: >2012
  - A few microsecond accuracy
  - Systematic survey of entire sky
  - $\sigma_\pi / \pi < 1\%$ out to several kiloparsecs
  - Accurate measurements of many Cepheids and RR Lyrae variables (~100's of Cepheids; 1000's of RR Lyraes)
  - Distance to LMC to 0.02-0.04 mag (1-2% in distance).

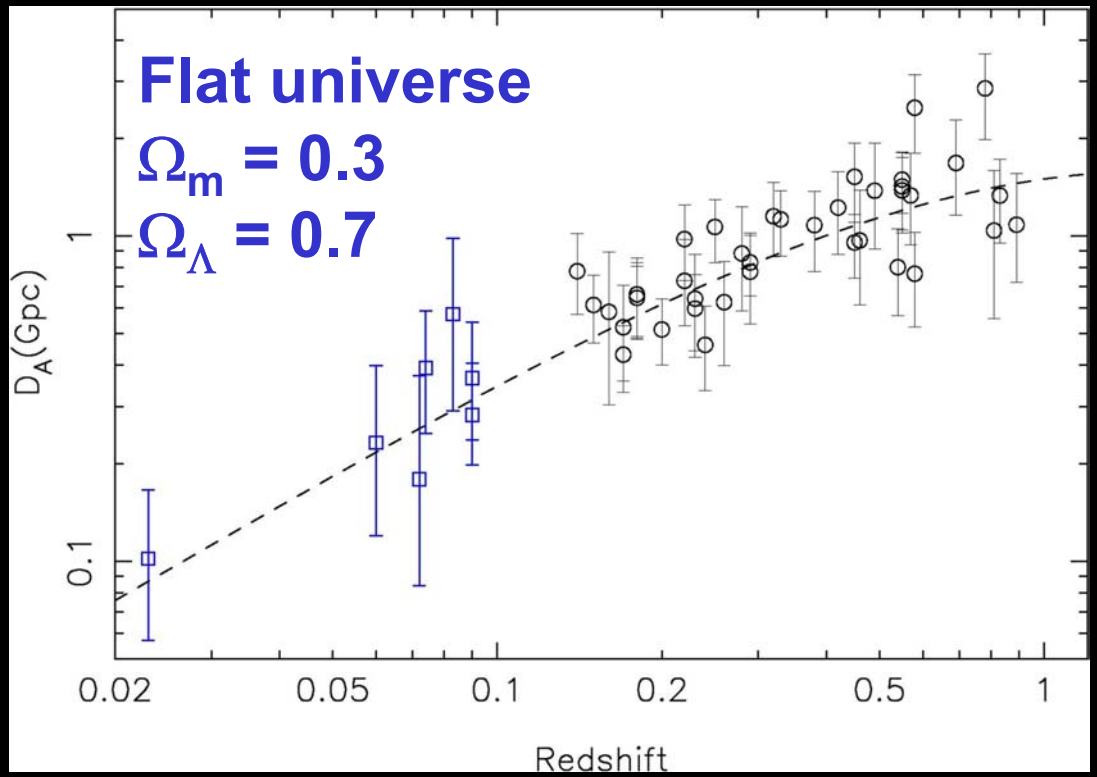




Expected relative accuracy in the distance of Galactic Cepheids from GAIA. Mignard (2004)

Recent Sunyaev-Zel'dovich Determination of H_0





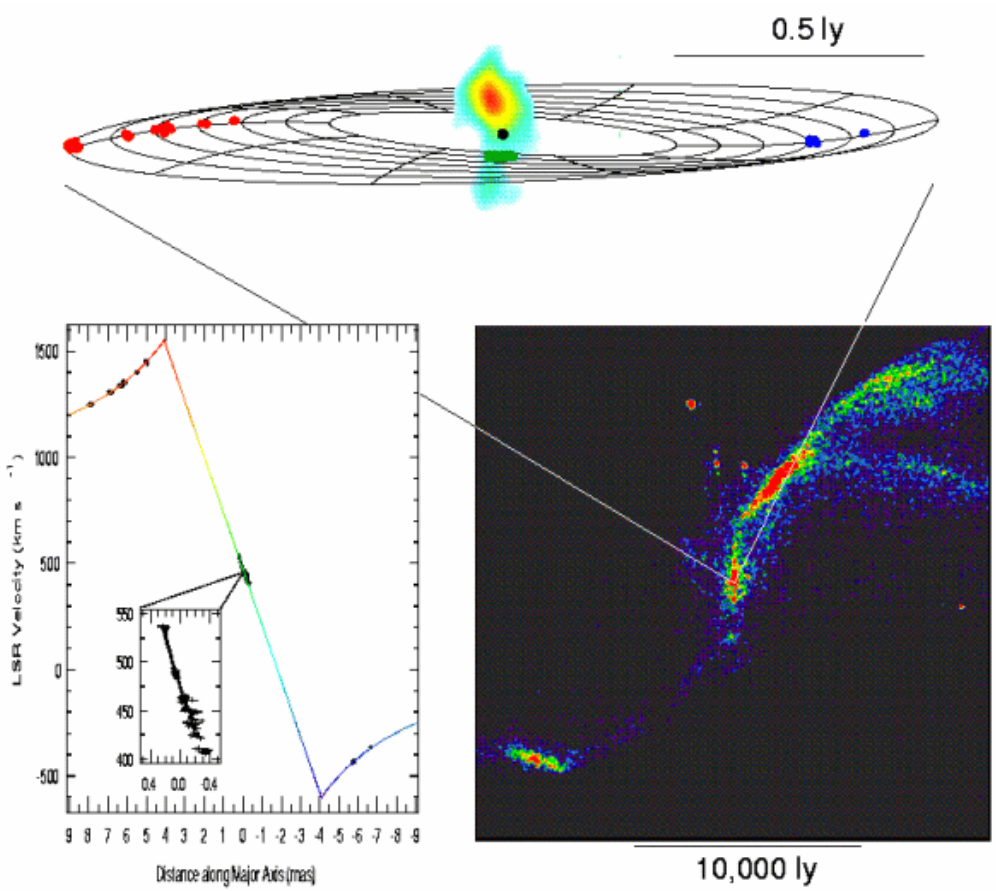
Bonamente et al. (2005) $H0 = 77.1 \pm^{3.8}_{3.4} \pm^{10.0}_{8.0}$ km s^{-1} Mpc^{-1}

39 clusters, 0.14 < z < 0.89, Chandra, OVRO/BIMA radio interferometers

The Future: Gravitational Lensing and Time Delays

- **Not yet achieved 10% accuracy due to systematics.**
- **Currently no plans for achieving a few percent.**

Current Maser Measurements



- Geometric distance
- Proper motions
- Acceleration
- Keplerian rotation curve
- Assume: distinct peaks in spectrum come from individual clumps of gas.

NGC 4258 : one object to date

NGC 4258

Maser distance:

7.2 ± 0.3 Mpc

Hernstein et al.

Cepheids :

7.8 ± 0.3 ± 0.5 Mpc

Newman et al.

TRGB:

7.3 ± 0.3 Mpc

Mouhcine et al.

Future Maser Measurements

- **The Square Kilometer Array (SKA)**

- ❖ Next radio telescope following ALMA
- ❖ 2 orders of magnitude more sensitivity than VLA
- ❖ International Collaboration (US, Europe, Australia)
- ❖ Meter to cm wavelengths

Masers with SKA (e.g., Greenhill, 2004):

- ➢ Many thousands of H_20 maser sources
- ➢ Perhaps few hundred suitable for distances
- ➢ Systematic errors expected to be uncorrelated
- ➢ Uncertainty in H_0 will scale as sqrt(N)

>>>>> **Prediction: H_0 to $\lesssim$ 1%** <<<<<

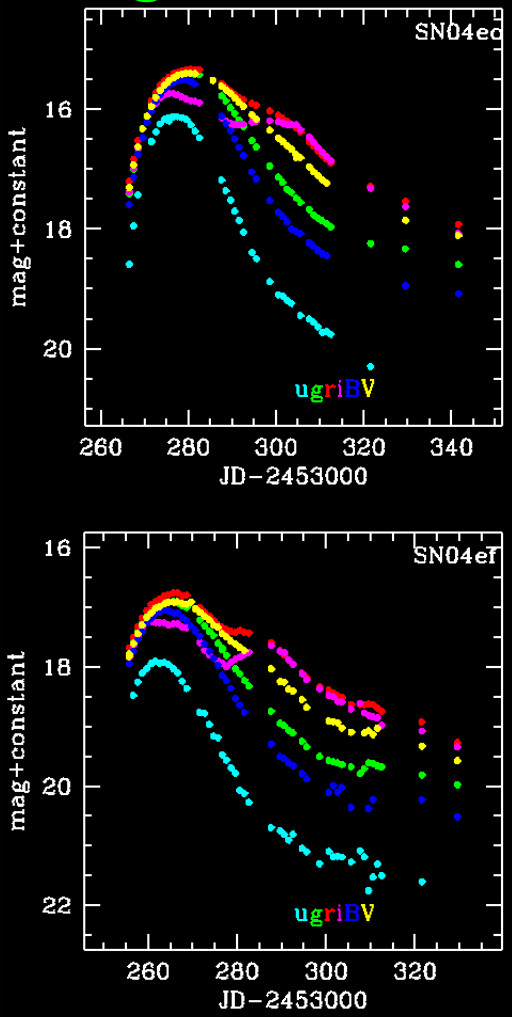
Future IR SNIa Measurements

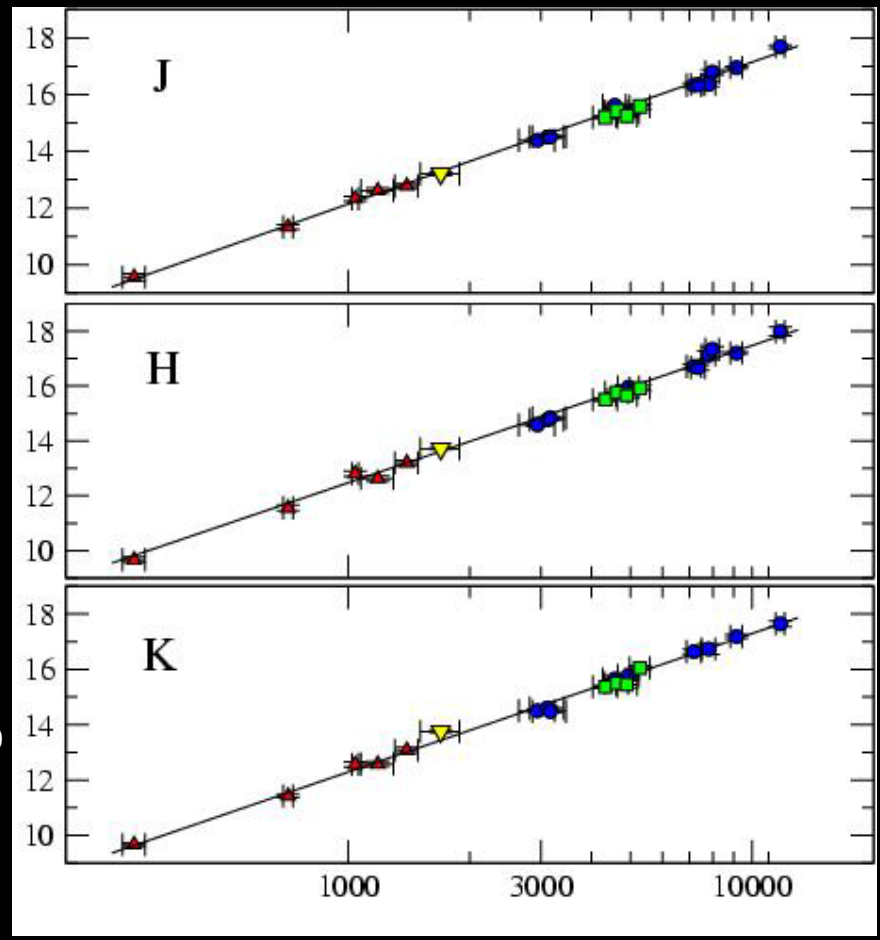
Carnegie Supernova Project (CSP)

- YJHK photometry of 100 SNIa
- Sampling every 2-3 nights
- Shallow decline-rate vs magnitude relation
- IR Cepheid distances
- Decreased sensitivity to reddening, metallicity

Future SNIa (IR) H_0 Measurements

CSP light curves





Krisciunas et al.

Gravitational Waves and H_0

"Chirping" Binaries:

- as orbit shrinks, energy loss due to gravitational waves
- frequency of GW increases with time
- produce "chirp" waveforms

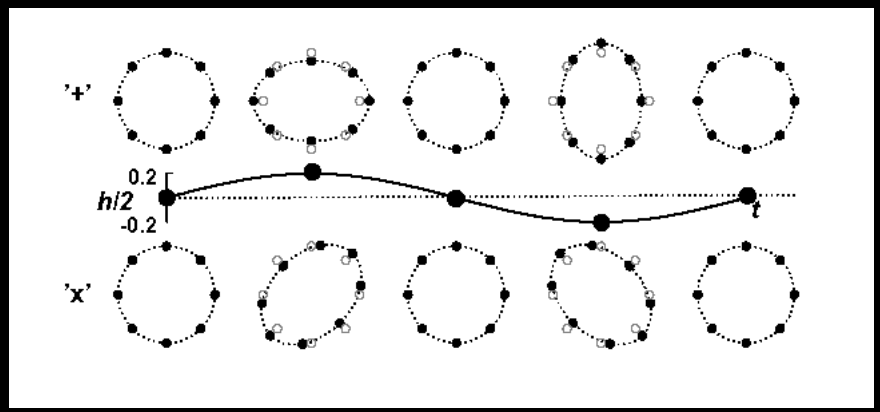
- e.g., chirps from neutron-star binaries (Advanced LIGO)
  - advance notice of rough positions of inspiral events
  - optical identification of afterglows
  - redshifts
  - chirps from inspiraling nuclear black holes (LISA)

In principle: H_0 to a few percent

Gravitational Waves and H_0

Standard Candle:

- binary objects whose orbits shrink measurably with time.
- e.g., NS/NS, NS/BH, BH/BH binaries



H_0: Advanced LIGO

Dark energy: LISA

- Measure two independent polarizations of a plane gravitational wave
- The action of any plane wave is a superposition of these 2 polarizations
- Central waveform: size of strain (half the amplitude, h, of the wave)

Gravitational Wave Measurements

- **"Chirping Binaries"** (Schutz, 2004)
- Measure **luminosity distances**

$$\mathrm{SNR} = 8\Theta\frac{r_0}{d_L}\left(\frac{\mathcal{M}}{1.2M_\odot}\right)^{5/6}\varsigma(f_{\max}).$$

Chirp mass:

$$\mathcal{M} := \mu^{3/5}M_T^{2/5} = (m_1 m_2)^{3/5}(m_1+m_2)^{-1/5}.$$

Θ — Projection of wave polarisation on antenna pattern

r_0 — Range of detector; function of detector sensitivity

$\varsigma(f_{\max})$ — Response of detector to different frequencies

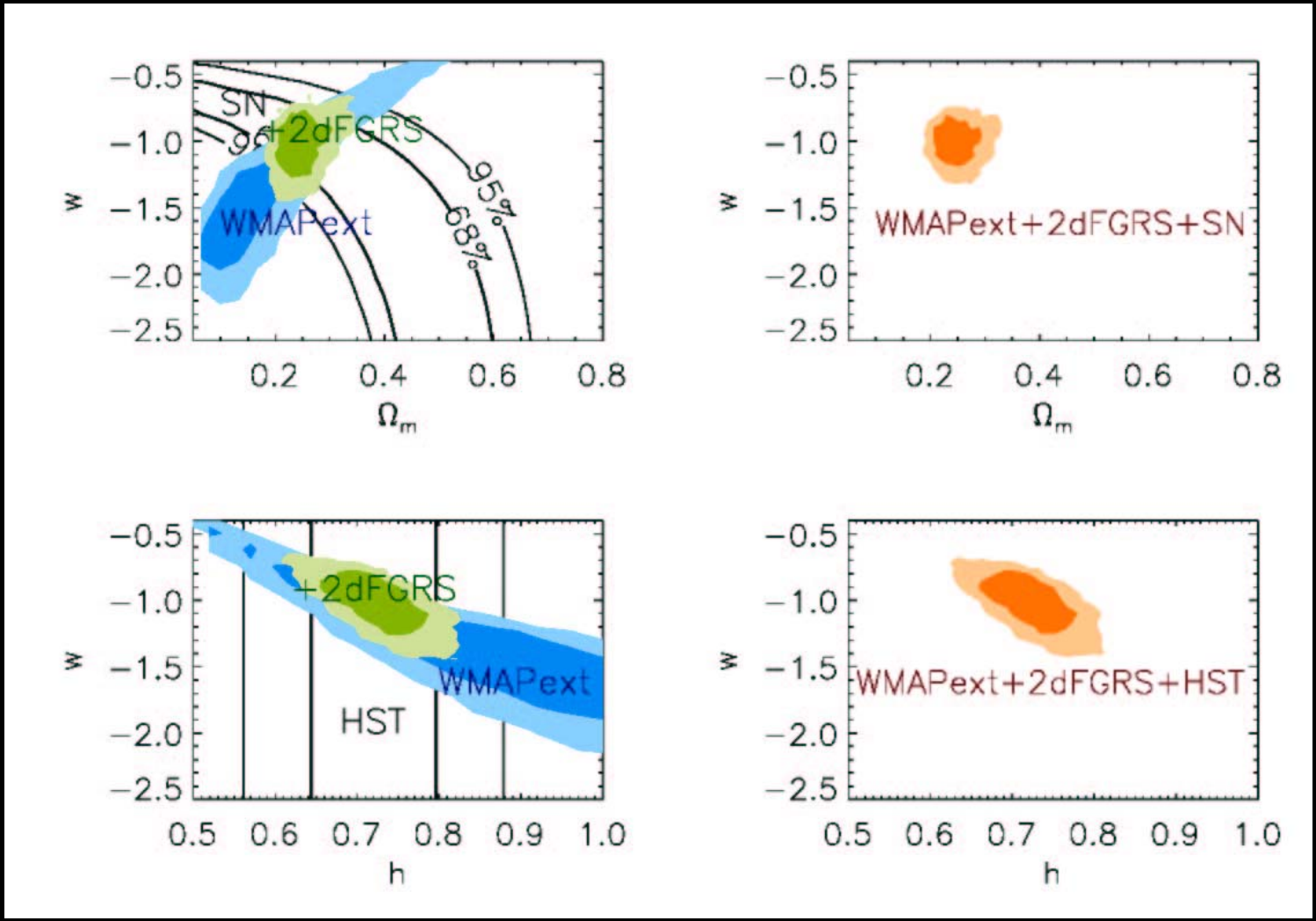
Gravitational Waves and H_0

Phinney (2005) projections:

Advanced LIGO:

- **Pessimistic** assumptions about rates and performance (3×10^{-6}/yr in Milky Way, SNR>10 detection to 200Mpc) yields 100 sources in 3 years.
- **Optimistic** rates and performance (3×10^{-5}/yr in Milky Way and SNR 10 detection to 350Mpc) gives ~5000 NS/NS sources in 3 years.
- The distance measurement precision per source is about 0.9/sqrt(SNR).
- If 10% of sources have usable electromagnetic counterparts, one could have 10-500 sources with several percent individual precision, for a **net 7% (pessimistic) to 1% (optimistic) determination of H_0.**

WMAP and H_0: Large Degeneracies!



$h = 0.71 \pm 0.04$

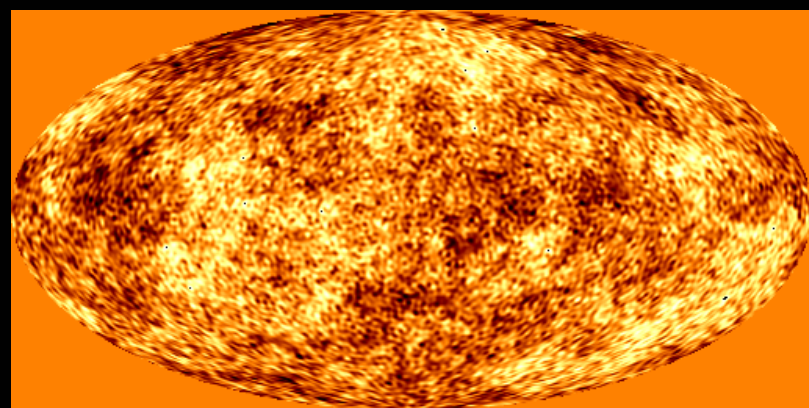
(Spergel et al. 2003)

Future CMB Measurements

- **ESA's Planck mission**

- Currently planned launch: 2007
- Full-sky maps in 9 frequency bands between 30 and 857 GHz.
- 5-10 arcmin angular resolution
- Sensitivity of $\Delta T / T =$ few x 10^{-6} at <200GHz

- H_0 , Ω_0 , Λ to 1% given a cosmological model



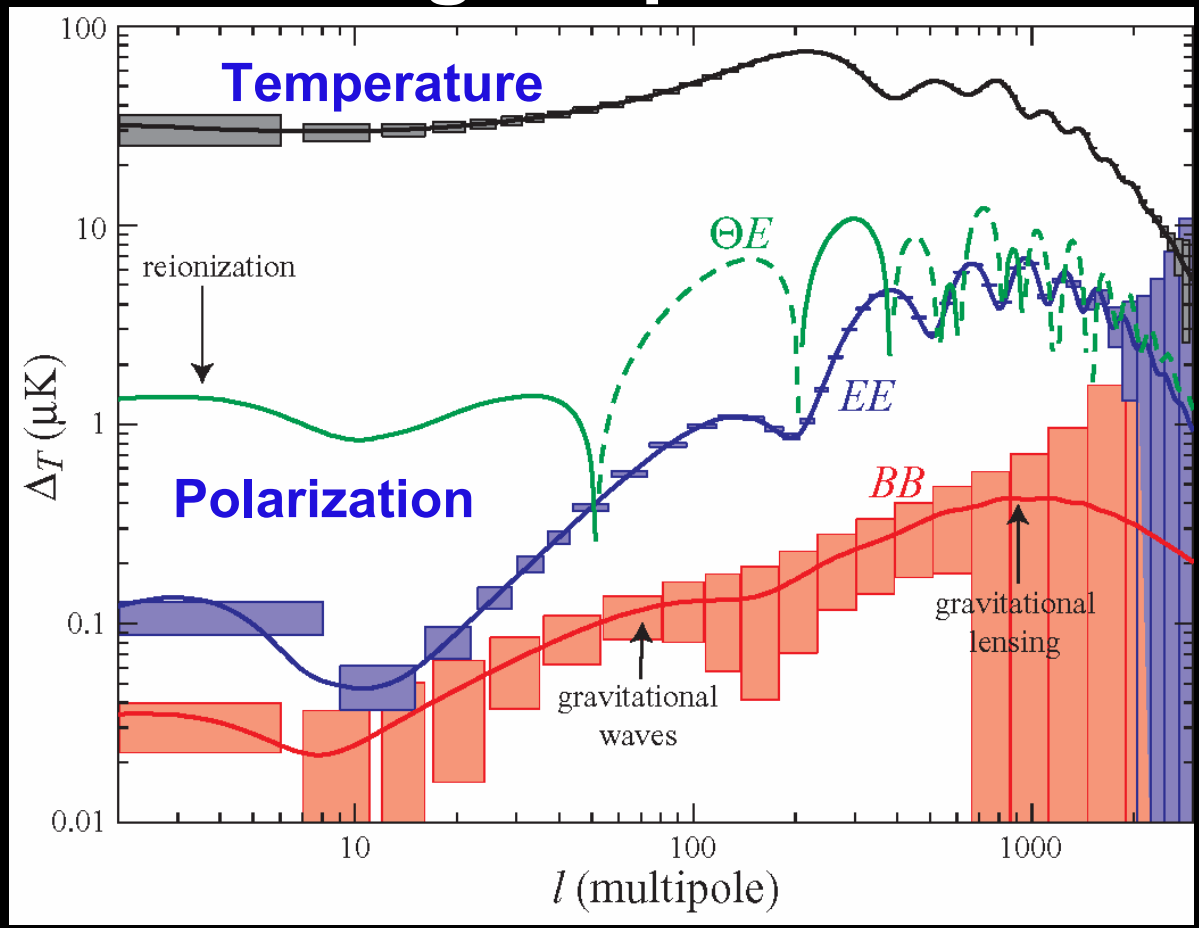
Future CMB Measurements

- Quoted cosmological parameters with Planck

Parameter	No constraints	r=-7 n_t	r=0 n_t
$\delta \omega_b/\omega_b$	0.0064	0.0056	0.0056
$\delta \omega_c / \omega_c$	0.0042	0.0042	0.0039
$\delta\omega_\Lambda$	0.012	0.012	0.011
δQ	0.0013	0.0010	0.0011
δr	0.33	0.023	------
δn_s	0.0049	0.0032	0.0042
δn_t	0.4	0.0032	------
$\delta h/h$	0.0045	0.0045	0.041

Future CMB Measurements

- Cosmological parameters with Planck

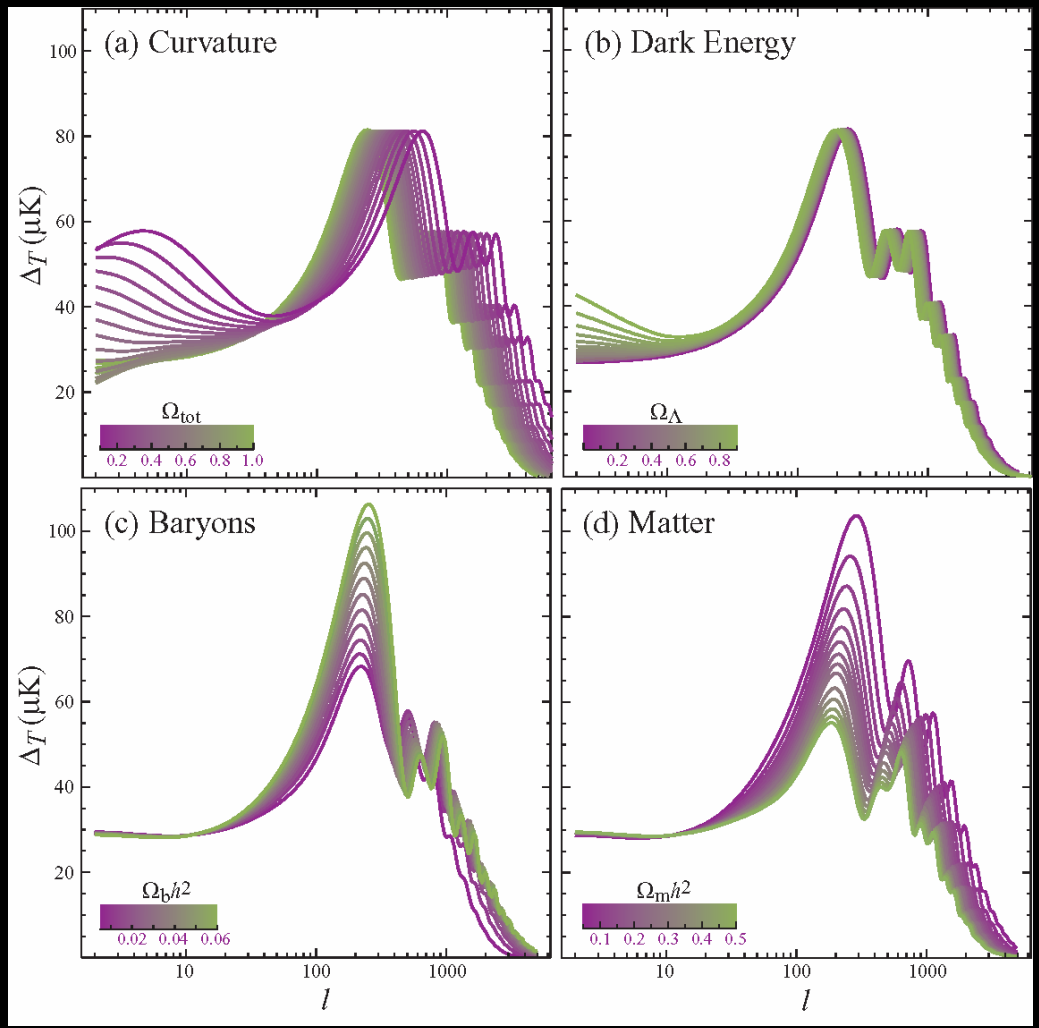


Most important complement to the CMB for measuring the dark energy equation of state at z~0.5 is a determination of the Hubble constant to better than a few percent

Hu 2005

Hu & Dodelson 2002 ARAA

CMB and H_0: Large Degeneracies!



Hu & Dodelson ARAA(2002)

Variation about fiducial model:

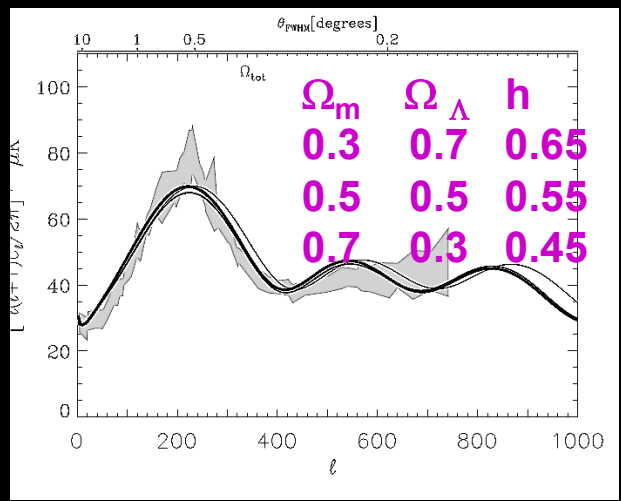
$\Omega_{TOT} = 1$

$\Omega_\Lambda = 0.65$

$\Omega_b h^2 = 0.02$

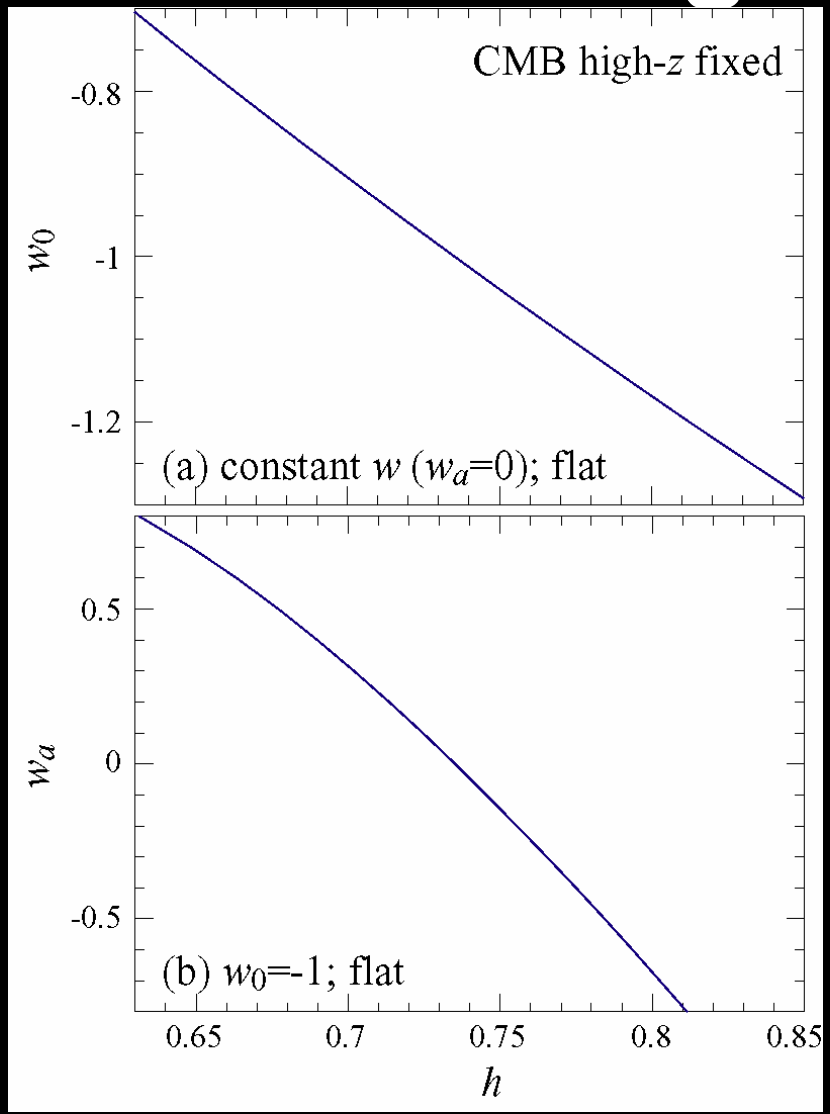
$\Omega_m h^2 = 0.147$

$n = 1$



Lineweaver (2001)

Importance of H_0 for Breaking CMB Degeneracies

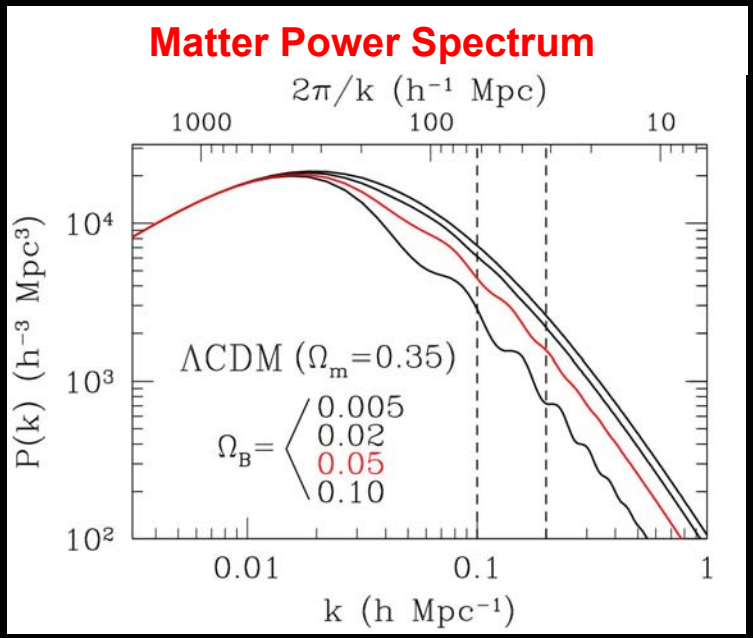


- Assuming flat universe
- Assuming Planck reaches statistical errors.

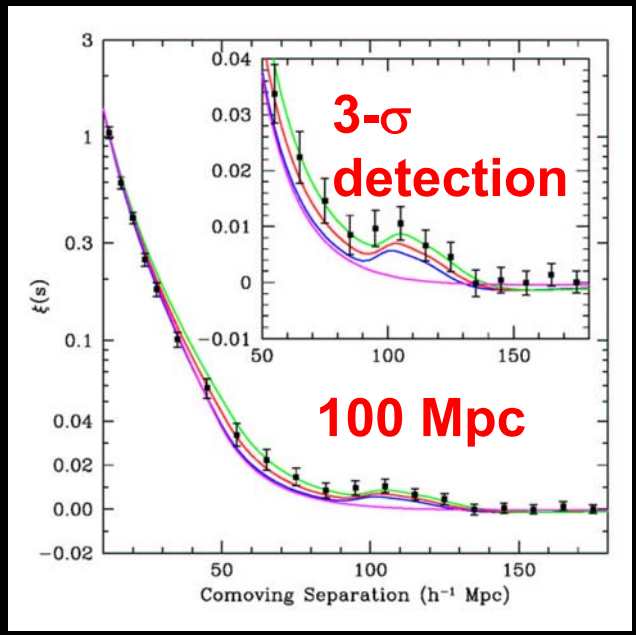
$w = w_0 + w_a (1 - a)$

Wayne Hu – adapted from Hu (2005) Tucson Dark Energy Workshop

Baryon Oscillations and H_0



Eisenstein et al. 2002



Eisenstein et al. 2005

Redshift-space correlation function of the SDSS red galaxy sample

- measure scale of acoustic signature across and along line of sight (infer H(z) and $D_A(z)$). Locally very sensitive to H_0.
- **standard ruler :** sharp break near the sound horizon
- **Given independent measures of Ω_m, w: get constraints on H_0.**

Summary

There is much promise for the future of H_0.

Next generation of experiments:

- **Parallaxes (SIM, GAIA)**
- **H_20 Masers (SKA)**
- **Supernovae (ground: IR)**
- **Gravitational Waves (LIGO, LISA)**
- **CMB (Planck)**
- **Baryon Oscillations (ground)**

H_0 to accuracy of ± 3% (95% CL) in 10-15 years.

<1% possible in principle.