

Increasing Accuracy and Increasing Tension in H_o



December 7, 2016
University of Chicago

Accuracy vs Precision



Precision



Accuracy

Increasing Tension in H_0 at the University of Chicago

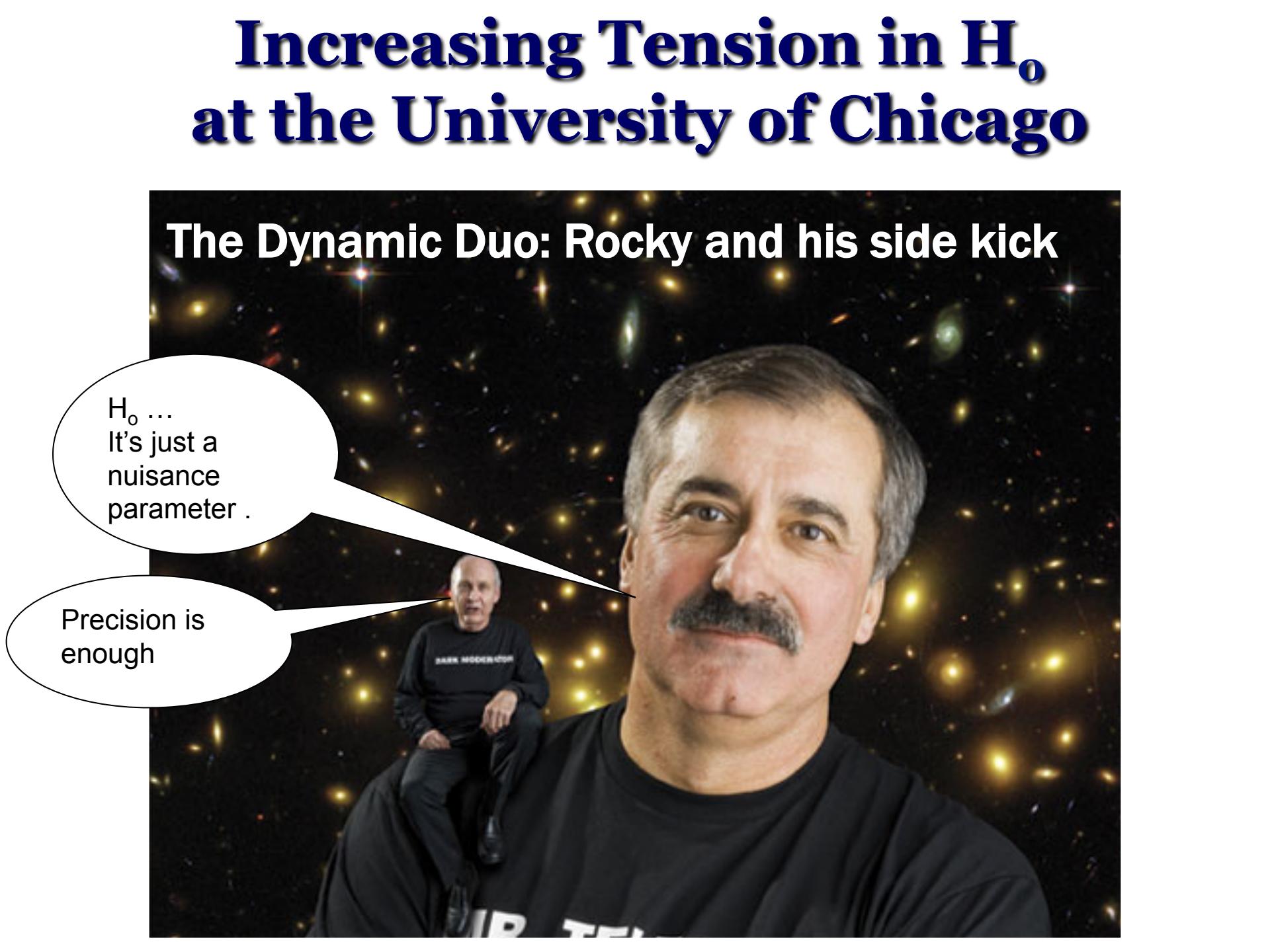


“... to test the cosmological hypothesis and measure the equation of state of dark energy at $z \sim 0.4-0.5$, the best complement to current and future CMB measurements is a measurement of the Hubble constant that is accurate at the few percent level.” (Hu 2005)

Wayne Hu, Horace B. Horton Professor

Increasing Tension in H_0 at the University of Chicago

The Dynamic Duo: Rocky and his side kick



$H_0 \dots$
It's just a
nuisance
parameter .

Precision is
enough

Measuring Cosmological Parameters

1) The Current Cosmological Model

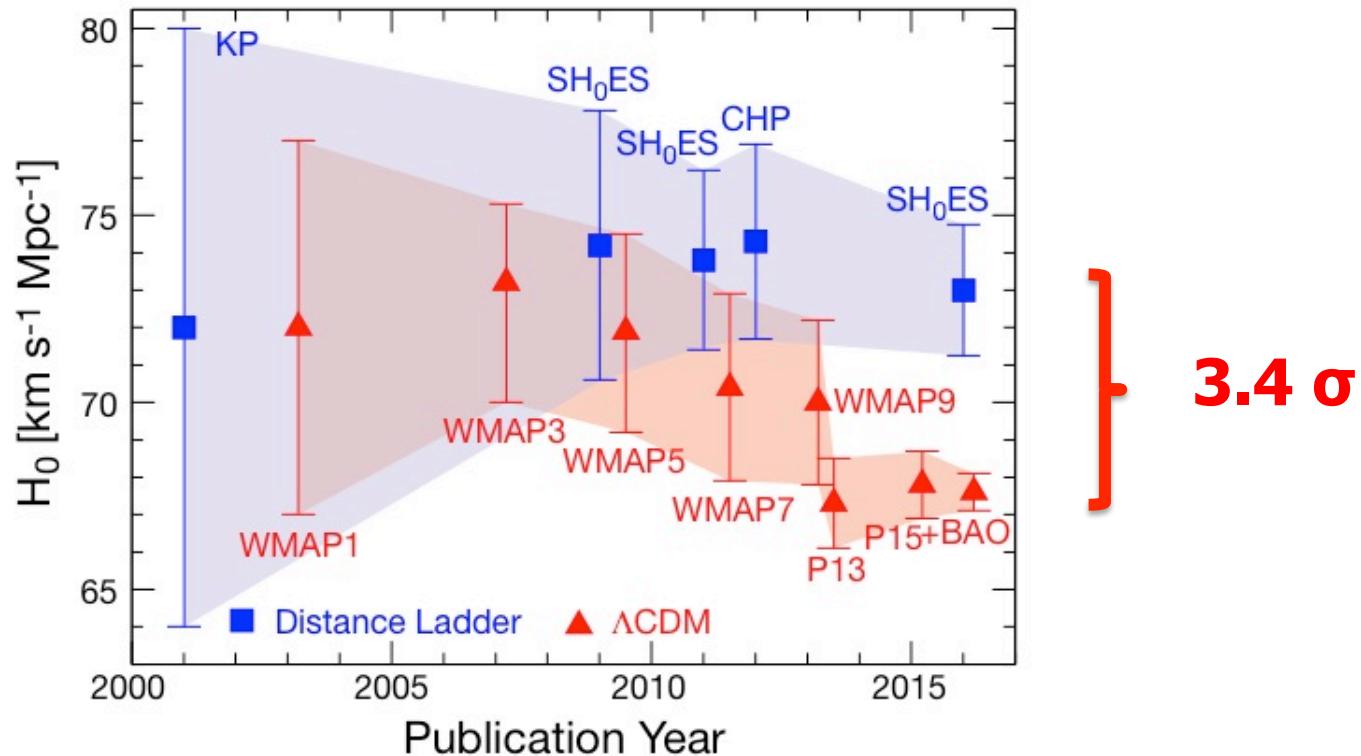
- Motivation for higher accuracy

2) Measurements of the Hubble Constant

- History
- Progress Since HST Key Project
- The Carnegie/Chicago Hubble Project (CCHP)

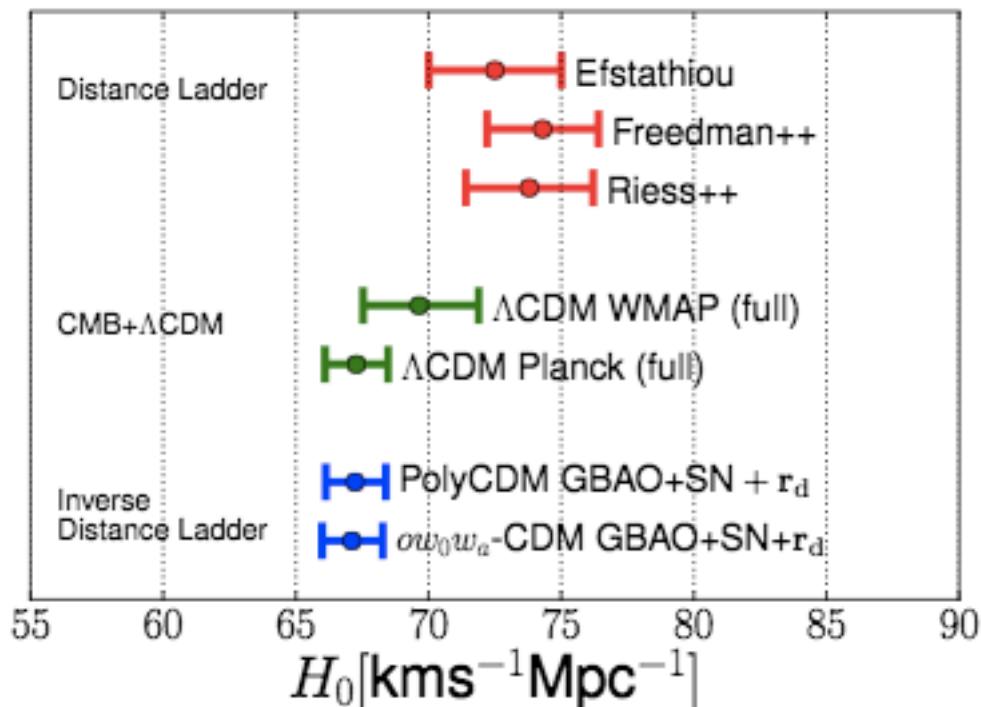
3) The Future

The Issue



W. Hu adaptation of Beaton et al. 2016: arXiv: 1604.01788

Recent Summary of H_0 Measurements and Model Estimates



-- Assumes flat universe with a cosmological constant

-- Assumes $r_d = 147.49 \pm 0.59$ Mpc based on Planck constraints for a standard radiation background

Summary of Recent H_0 Values

Λ CDM:	67.8 ± 0.9	(1.3%)	[Planck 2015]
Cepheids + SNIa :	74.3 ± 2.1	(2.8%)	[WLF+ 2012]
	73.02 ± 1.79	(2.4%)	[Riess+ 2016]

**Planck, Cepheid errors both decreasing –
tension is worsening**

What to Make of the Current Tension?

Where could potential systematics reside?

- 1. Cepheid zero point (3 methods)**

What to Make of the Current Tension?

Where could potential systematics reside?

1. Cepheid zero point (3 methods)

1. Milky Way parallaxes (2%)
2. LMC (2.5%)
3. NGC 4258 (3%)

What to Make of the Current Tension?

Where could potential systematics reside?

- 1. Cepheid zero point (3 methods)**
- 2. Few independent checks on Cepheid/SN distances**
- 3. Small numbers of SNIa calibrators**

Cosmic Microwave Background Anisotropies:

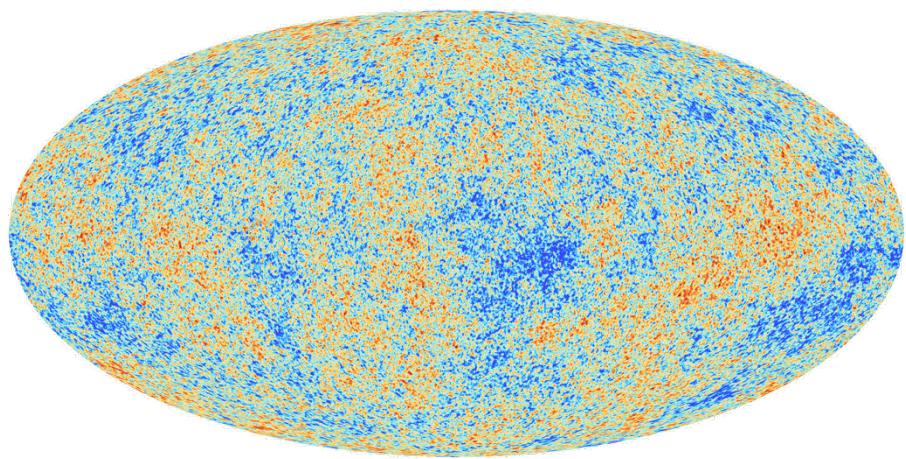
- H_0 estimate assumes a model**
- low ℓ / high ℓ discrepancy**

Potential New Physics Beyond Λ CDM, If Real

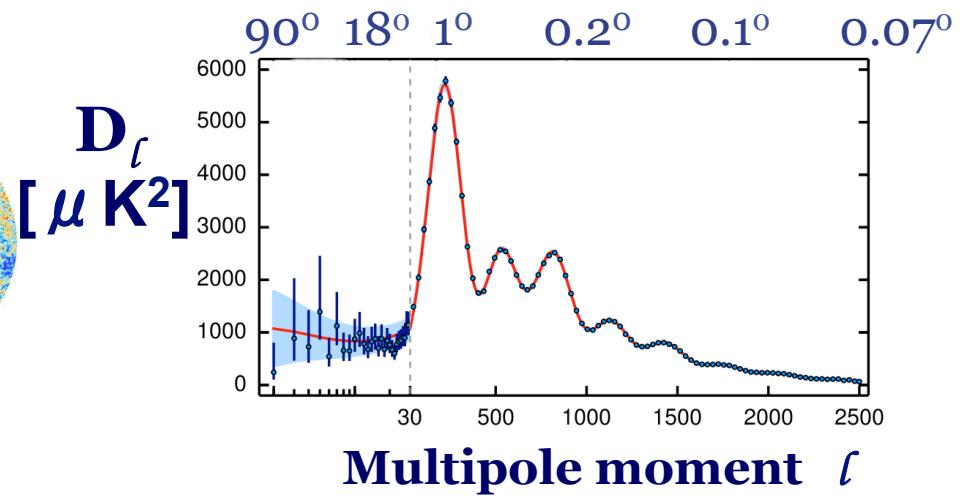
- 1. Different equation of state for dark energy**
- 2. Another relativistic species (e.g., an additional neutrino or other ‘dark radiation’)**
- 3. A decaying relic massive dark matter particle**
- 4. Non-zero spatial curvature**
- 5. Modified gravity**

CMB Measurements & The Current Cosmological Model

CMB Anisotropies



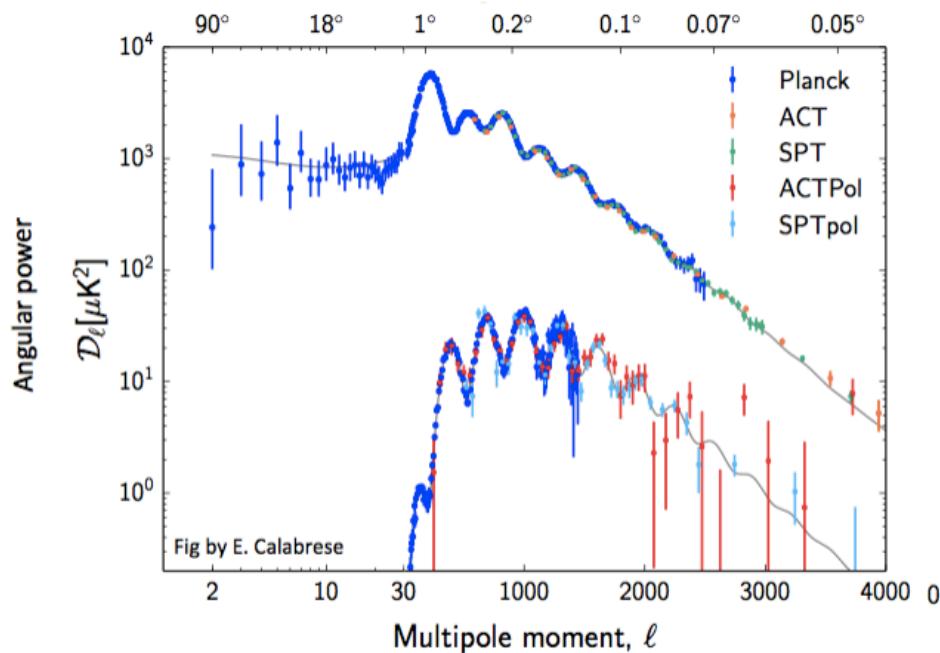
D_ℓ
[μK^2]



$$\ell = 200, \theta = 1^\circ$$

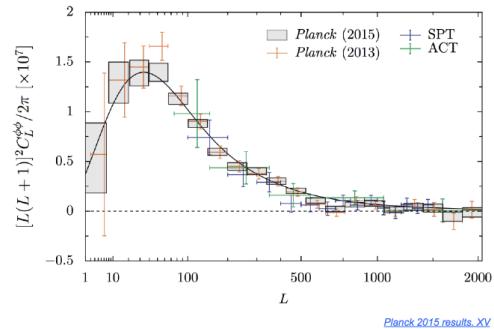
Planck 2015 + ACT + SPT Angular Power Spectrum

Polarization anisotropy ('small-scale' E-mode type)



A 6-parameter Λ CDM model provides an excellent fit to the Planck 2015, ACT and SPT data

Planck lensing – 40σ



E. Calabrese

Planck LCDM model:

Fit for 6 CDM parameters:

$\Omega_b h^2$

Baryon density

$\Omega_c h^2$

Cold dark matter density

$100\Theta_{MC}$

100 x approx to r_s/D_A

τ

**Thomson scattering optical depth
to reionization**

n_s

Scalar spectrum power-law index

$\ln(10^{10} A_s)$

**Log power of the primordial
curvature perturbations**

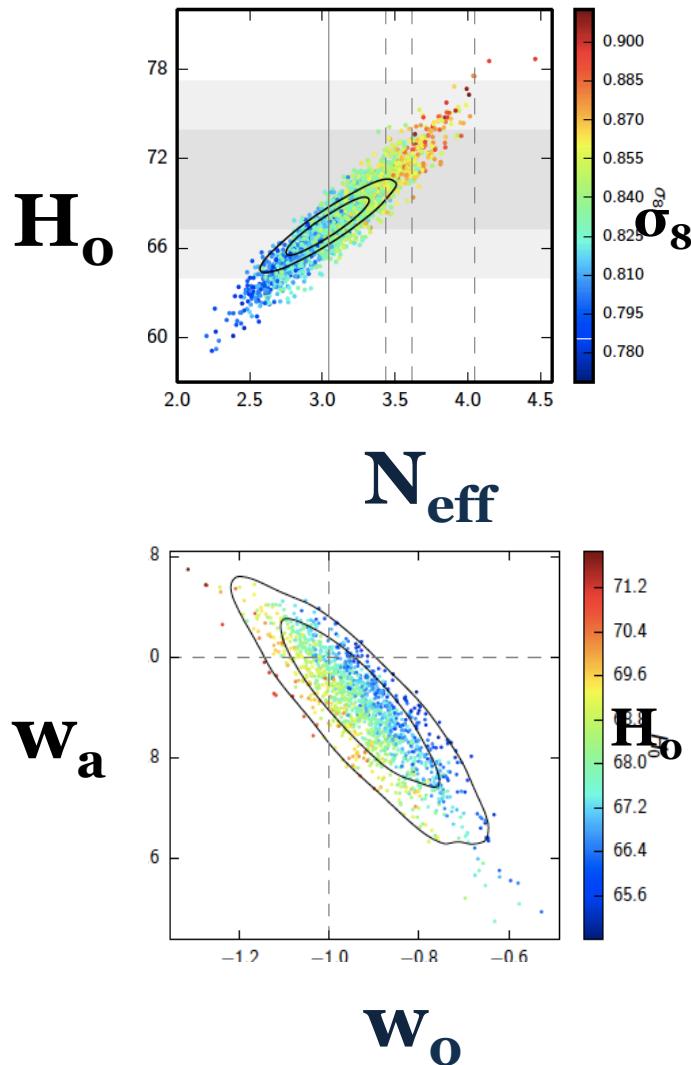
Derived Cosmological Parameters Planck (2015)

H_0	67.8 ± 0.9 km/s/Mpc
Ω_M	0.308 ± 0.012
Ω_Λ	0.692 ± 0.012
w	-1.54** $_{-0.50}^{+0.62}$ (** -1.02 Add BAO+SNIa+H ₀)

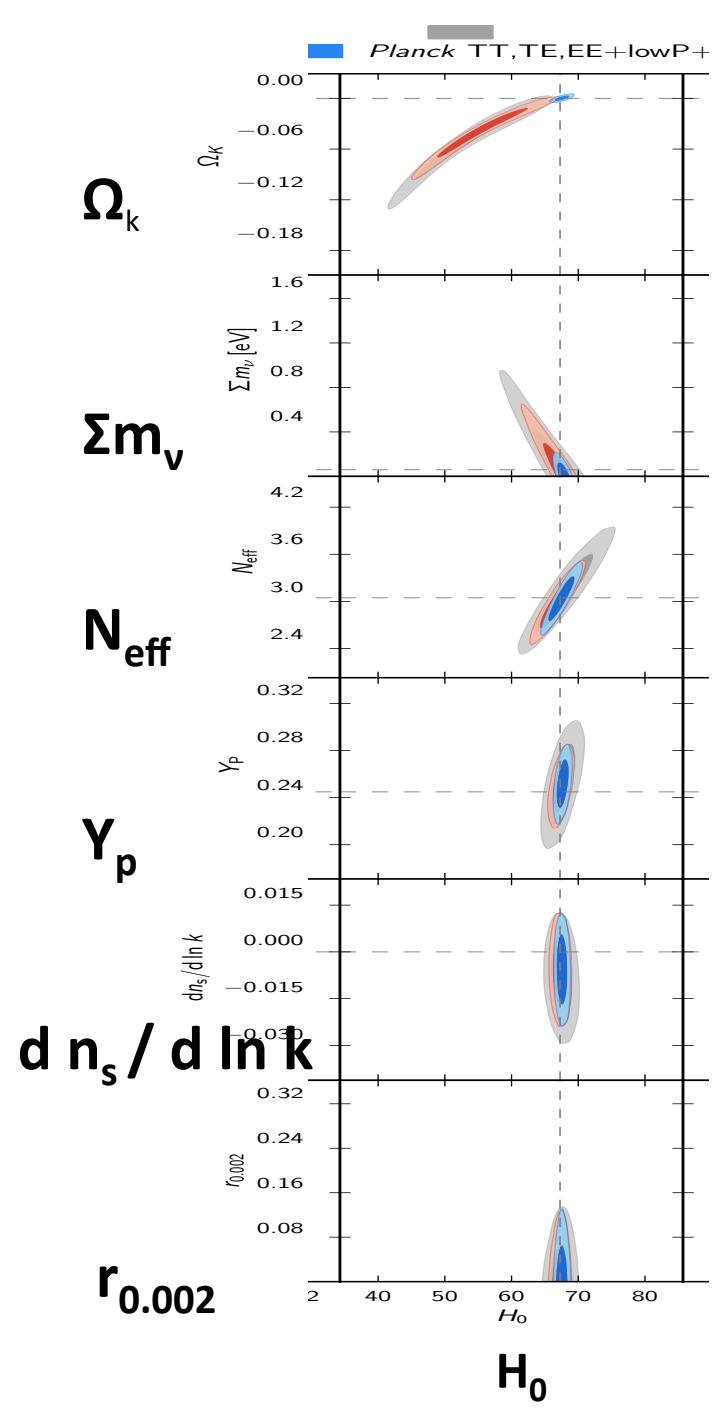
Based on temp + lensing data

** For w in addition BAO+SNIa+H0

Planck Cosmology 2015

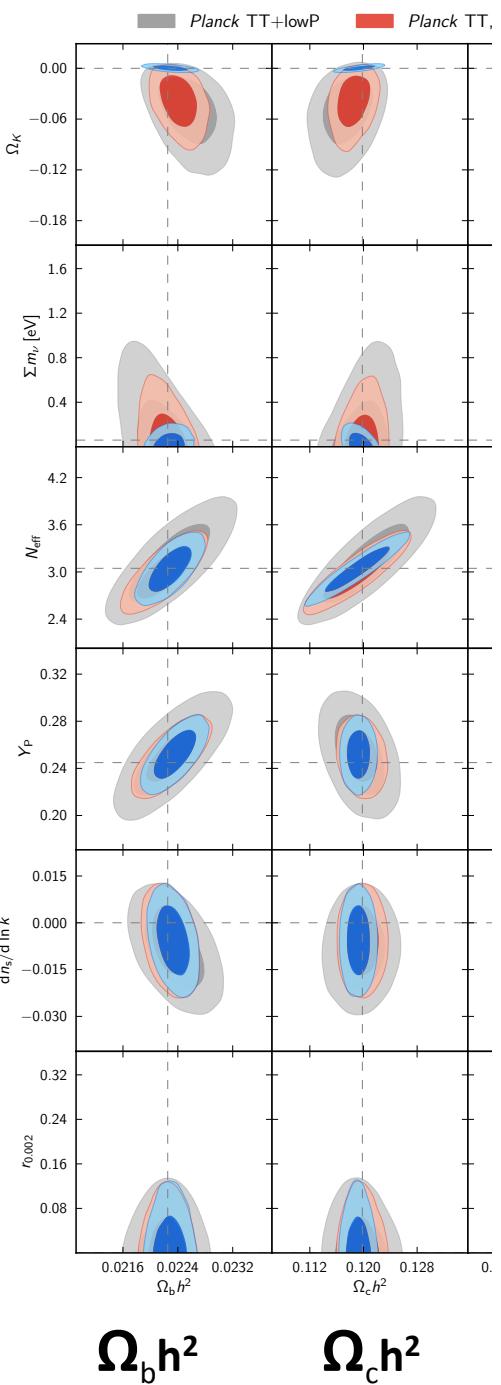


CMB power spectrum
Nearly exact degeneracies
Non-uniqueness

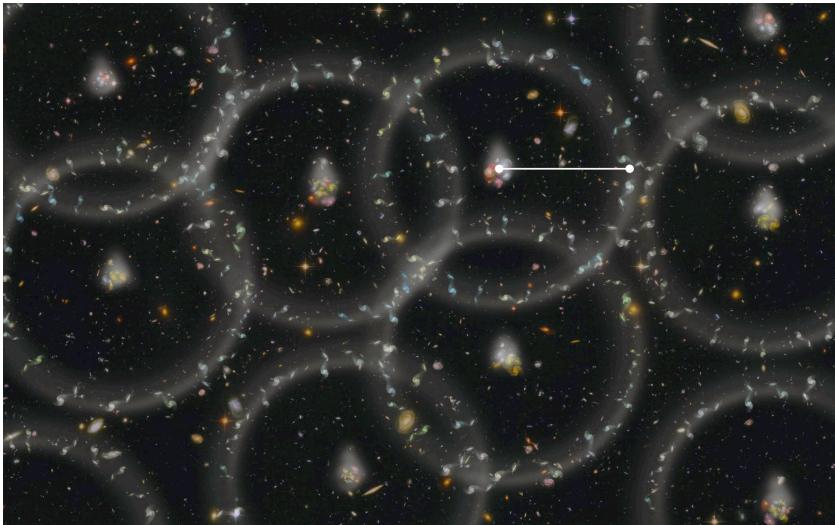


Planck cosmology paper 2015

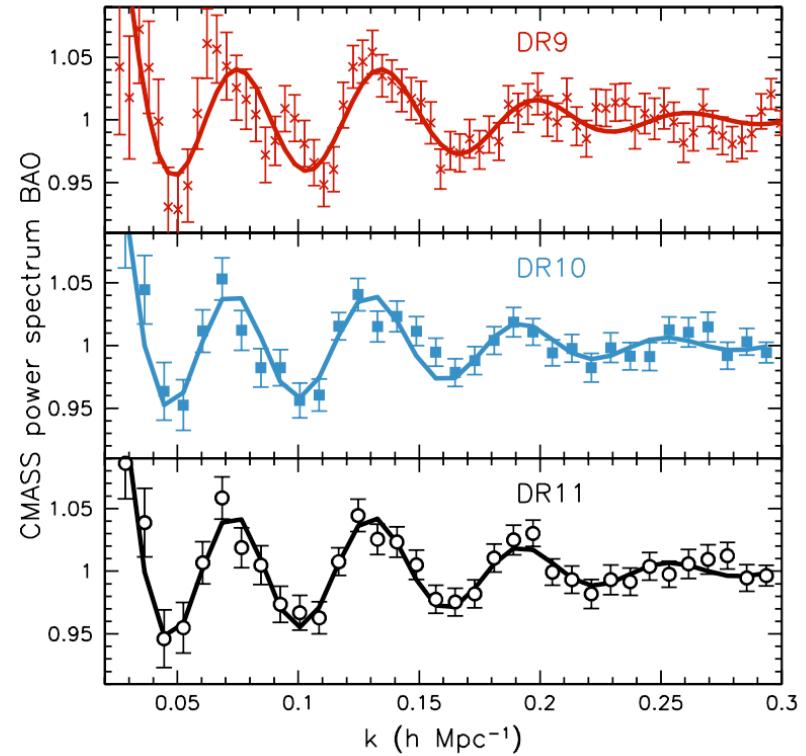
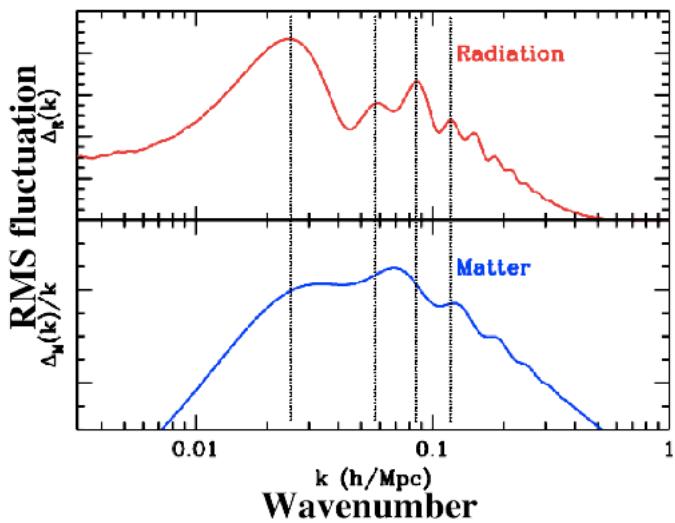
Planck TT+lowP (grey)
 Planck TT,TE,EE+lowP (red)
 Planck TT,TE,EE+lowP +BAO (blue)



Baryon Acoustic Oscillations

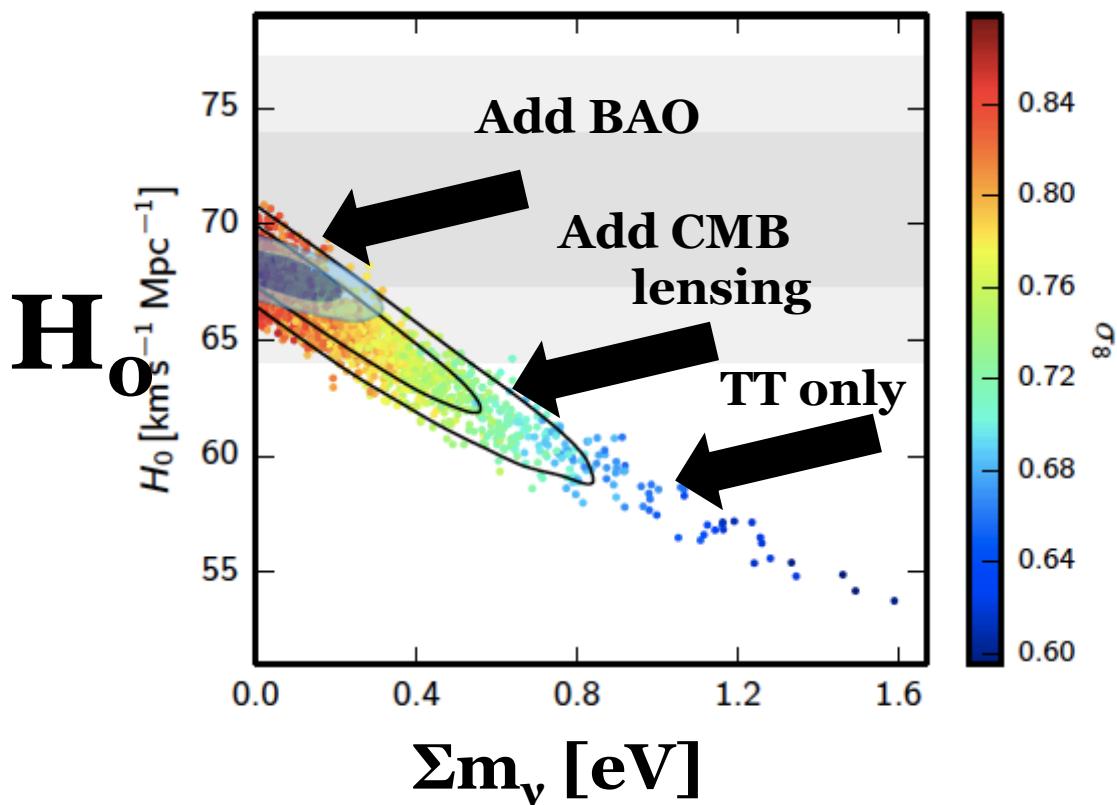


Power spectrum



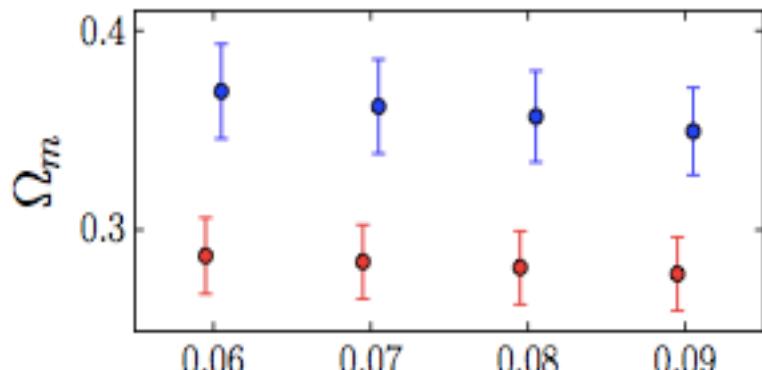
Anderson et al. (2014)
BOSS survey

BAO + Planck 2015: Σm_v

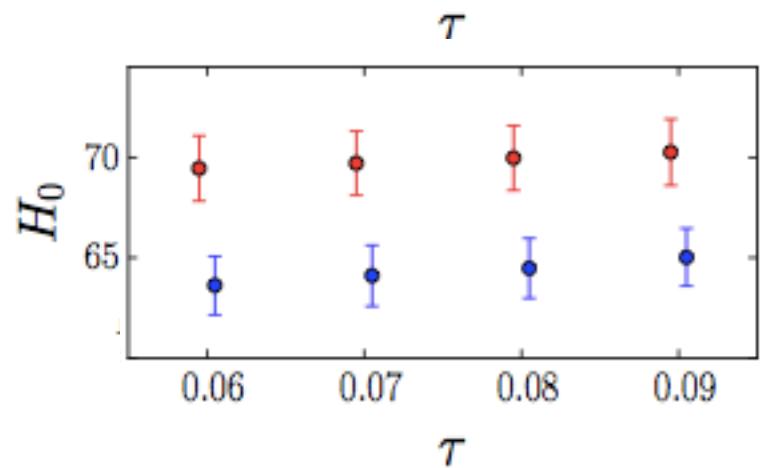


- $\Sigma m_v < 0.49 \text{ eV}$ [95% CL]
Planck TT; TE; EE+lowP
- $\Sigma m_v < 0.23 \text{ eV}$ [95% CL]
Best estimate
TT + pol + lensing
+ BAO + H_o + SNIa

Tensions with Planck 2015 High- ℓ Data



— $\text{Planck TT 2015 } 2 \leq \ell < 1000$
— $\text{Planck TT 2015 } 1000 \leq \ell \leq 2508$



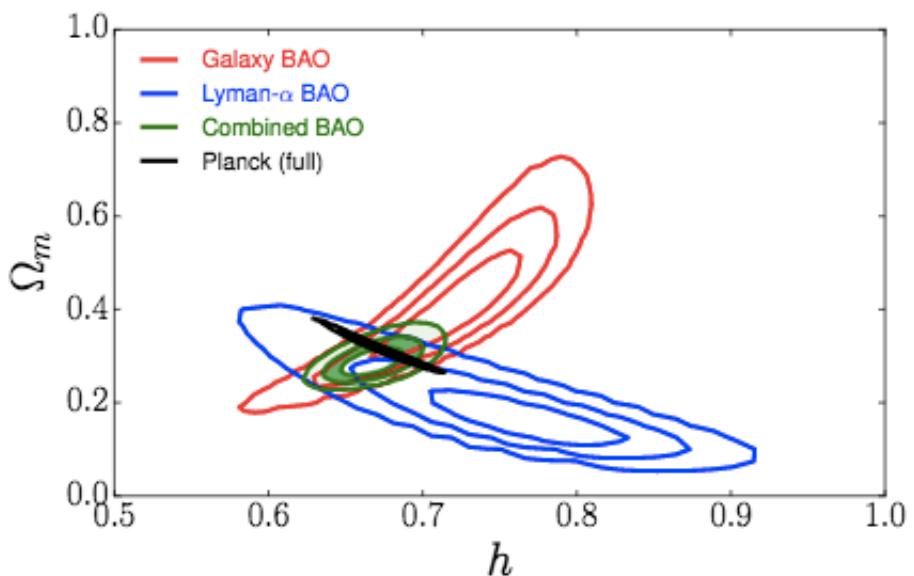
◆ Values of Ω_{cdm} , H_0 discrepant by $>2\sigma$

Aghanim et al. arXiv:1608.02487

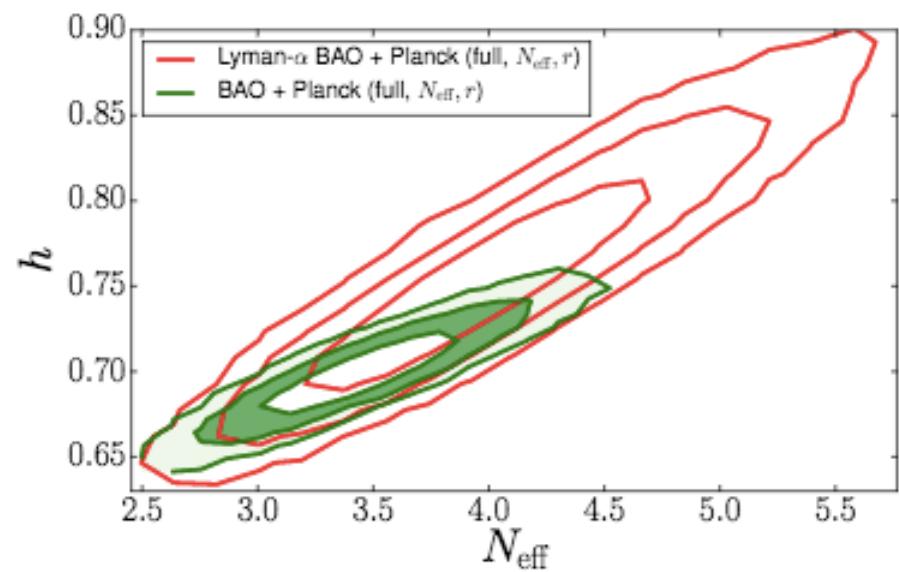
Difference between $\ell < 1000$ and $1000 < \ell < 2500$ comes mainly from $\ell < 30$

Addison et al. 2016, ApJ

Baryon Acoustic Oscillation Constraints

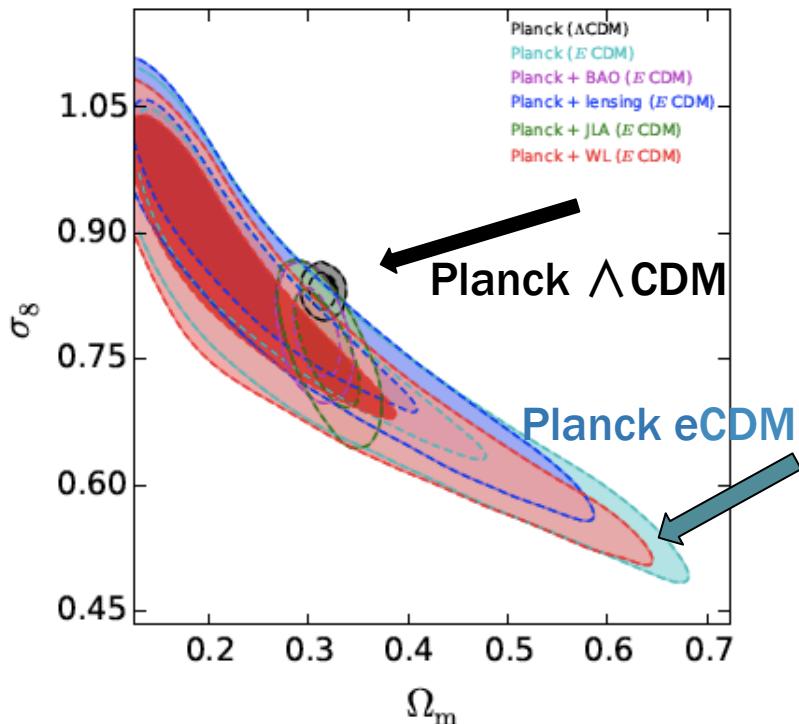


Prior on Ω_b
Standard physics for r_d



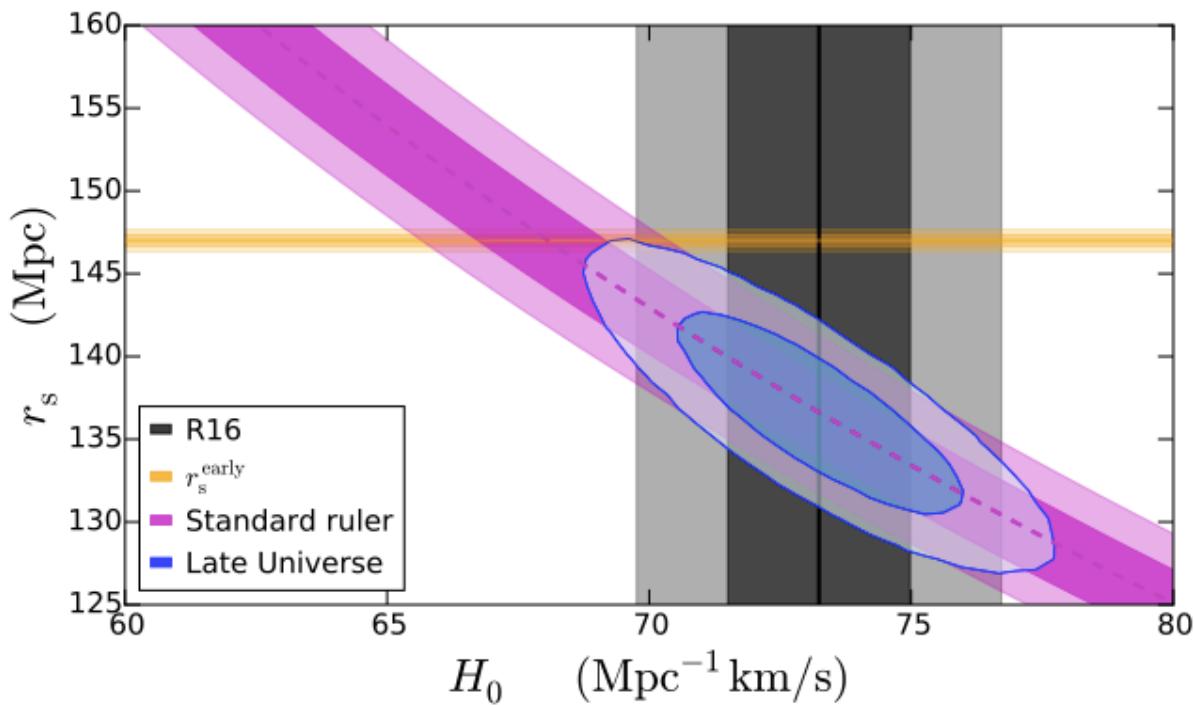
Assuming $w = -1$ and $\Omega_k = 0$
Marginalize over tensor-to-scalar
ratio, r

Planck: Relaxing Parameter Constraints



- ◆ Planck 2015 data
- ◆ 12-parameter fit (including w , N_{eff} , r)
- ◆ Biggest effects:
 - ◆ Hubble constant
 - ◆ σ_8 , r.m.s. amplitude of density fluctuations
- ◆ practically undetermined from Planck measurements alone even when external datasets such as BAO are included

Using Local H_0 Measurements to Constrain $r_s h$



BAO measurements constrain $r_s h = \text{constant}$

Planck – assume LCDM + early universe physics
 $r_s = 147.00 \pm 0.34 \text{ Mpc}$

Assume $H_0 = 73$
No early universe assumptions
 $r_s = 136.7 \pm 4.1 \text{ Mpc}$

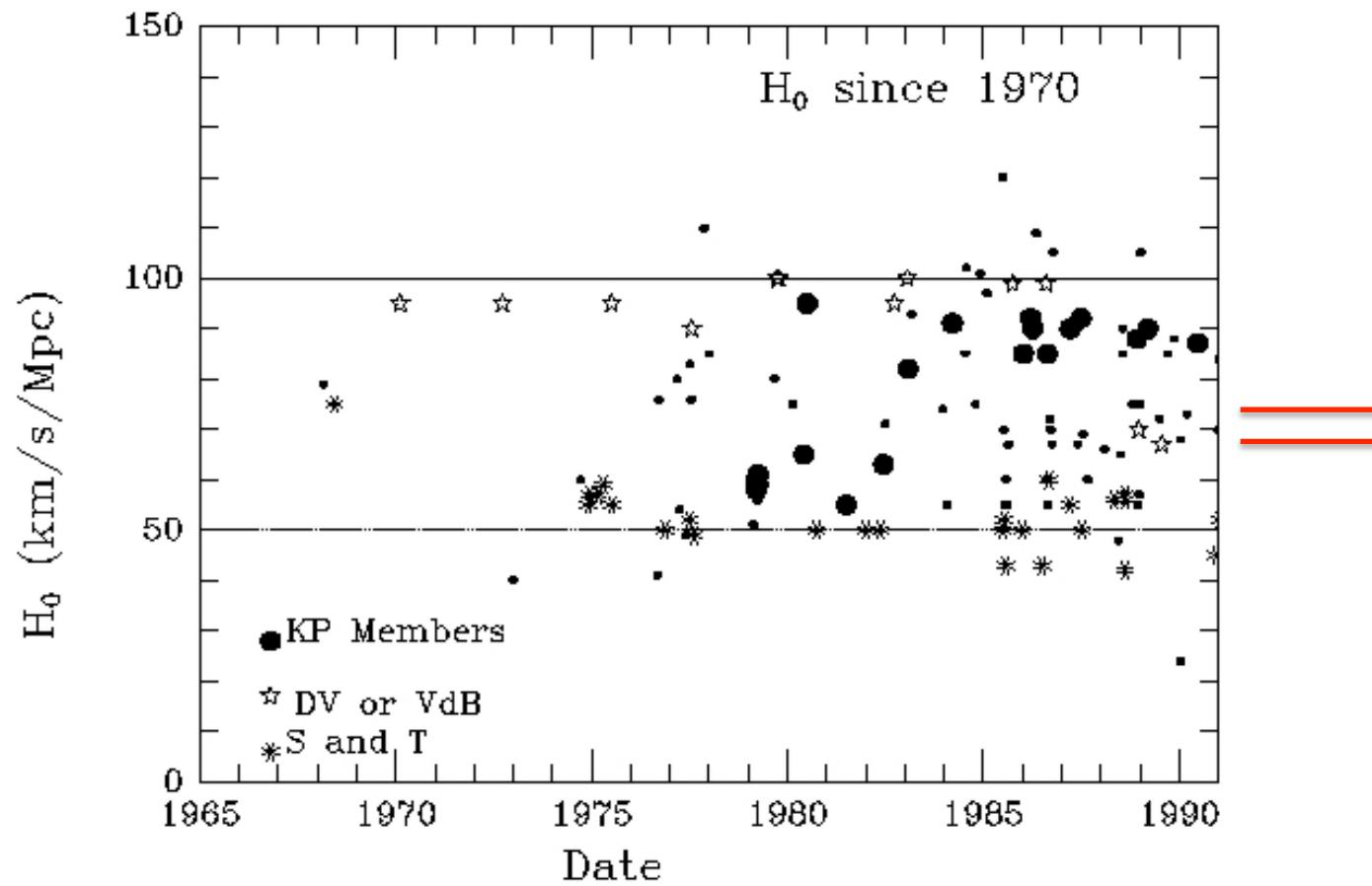
Critical Missing Pieces to the Current Standard Model

- Cold dark matter dominates the matter density **and is in an unknown form**
- The overall mass-energy density is dominated by dark energy, **for which there is currently no theory**
- The dynamics of inflation depends on particle physics at high energy, **and nothing is known of the hypothetical scalar field that drives inflation**

Measurement of the Hubble Constant

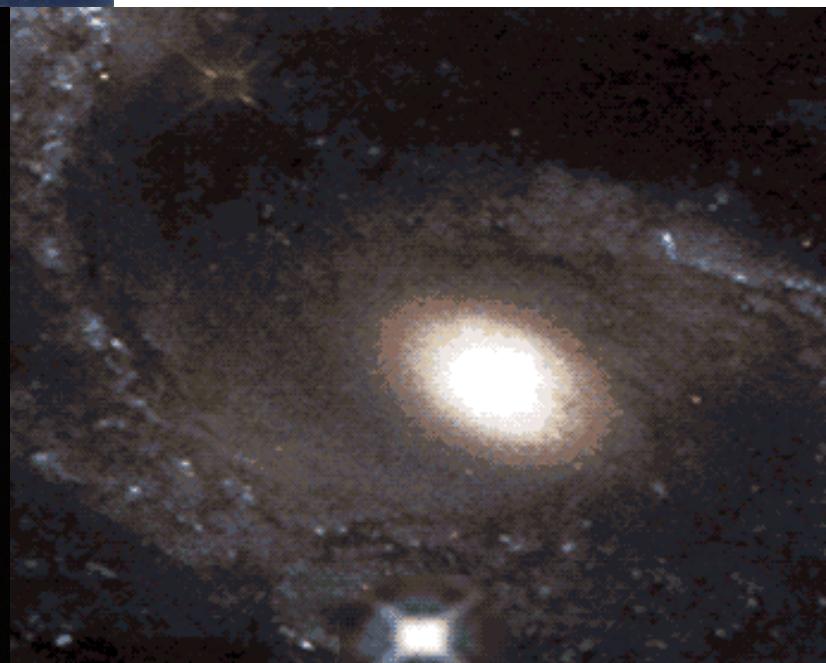
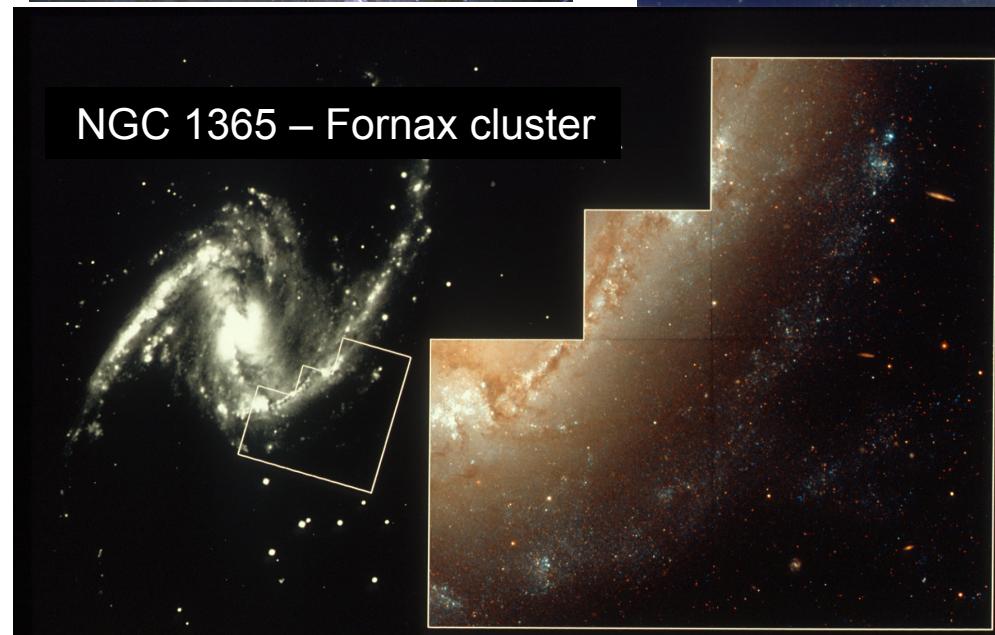
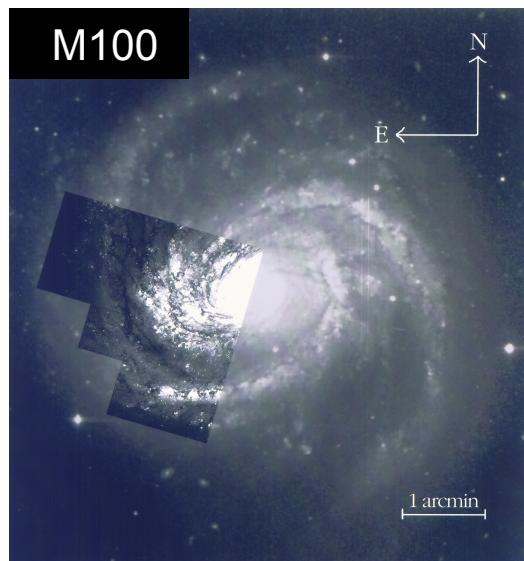
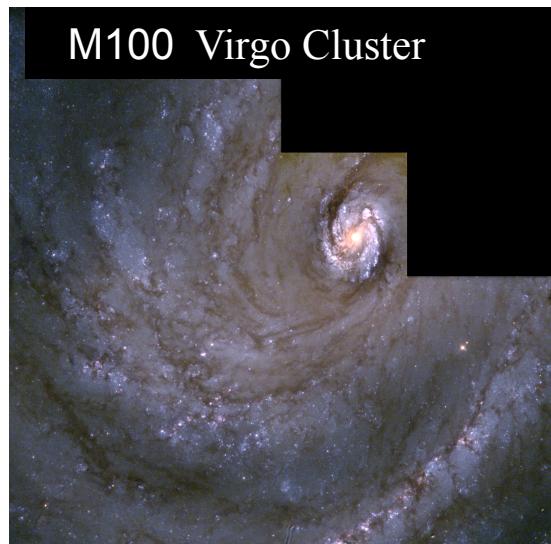
- **Historical**
- **State of the Art**
- **Improvements on the Horizon**

History of the Hubble Constant

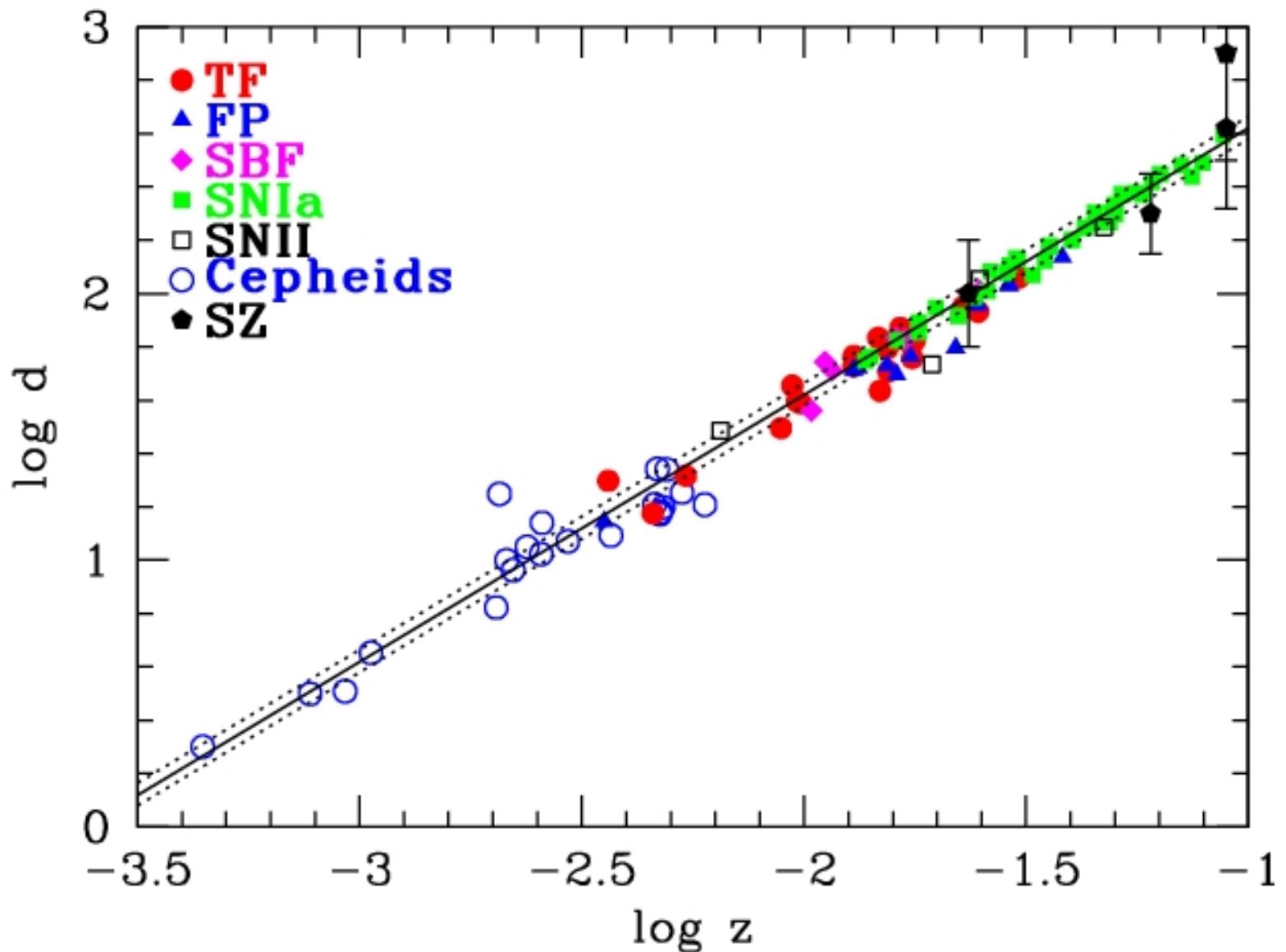


Copyright J. Huchra 2008

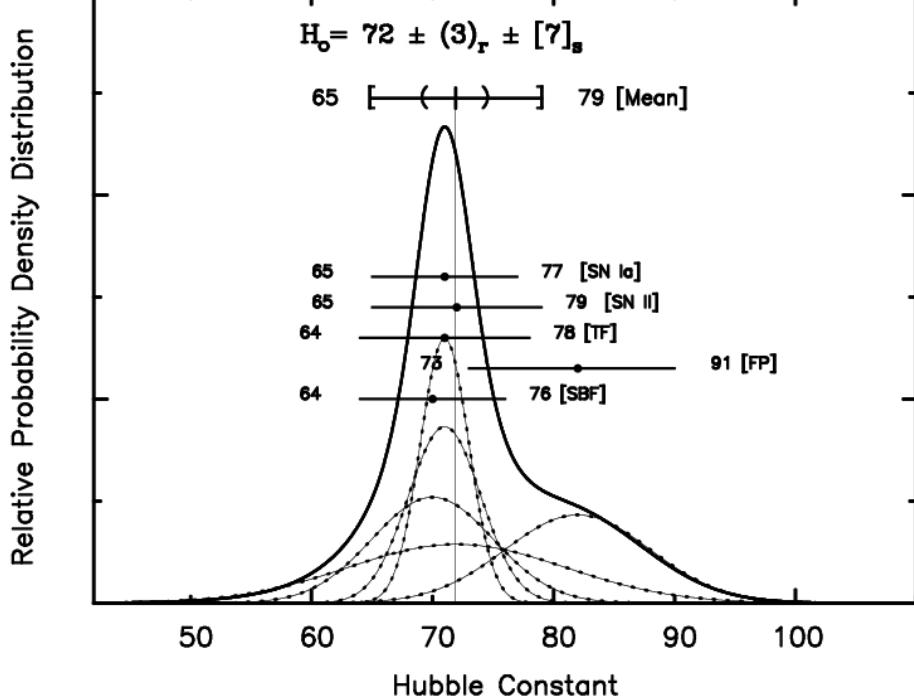
HST Key Project Cepheid Searches



Key Project Results

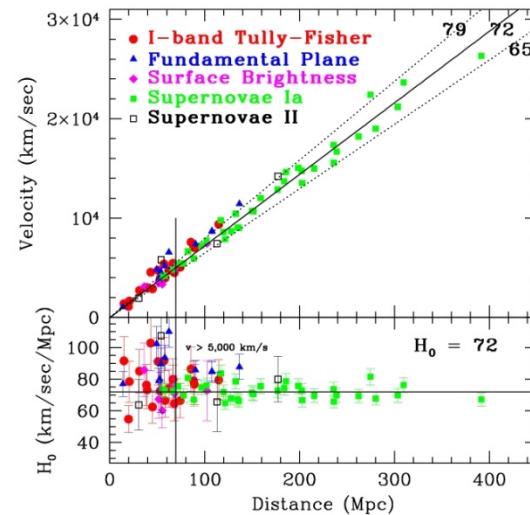


Final Combined HST Key Project Results



WLF et al. (2001)

$$H_0 = 72 \pm 3 \text{ (stat.)} \\ \pm 7 \text{ (sys.)} \\ \text{km s}^{-1} \text{ Mpc}^{-1}$$



Current Status

H_0 measurements based on :

Cepheids ^{**}

+

Type Ia Supernovae

WLF et al.
Riess et al.

1. The Data
2. Systematics

^{**} + 1 maser galaxy
+ a few EB

1. The Data

CHP I : Spitzer as a Tool for Testing the Cepheid Calibration

Advantage of Spitzer for the extragalactic distance scale:

At $3.6 \mu\text{m}$, A_{λ} is ~ 17 times smaller than at optical (V-band) wavelengths.

Dispersion in Cepheid PL relation a factor of two to three smaller than in optical.

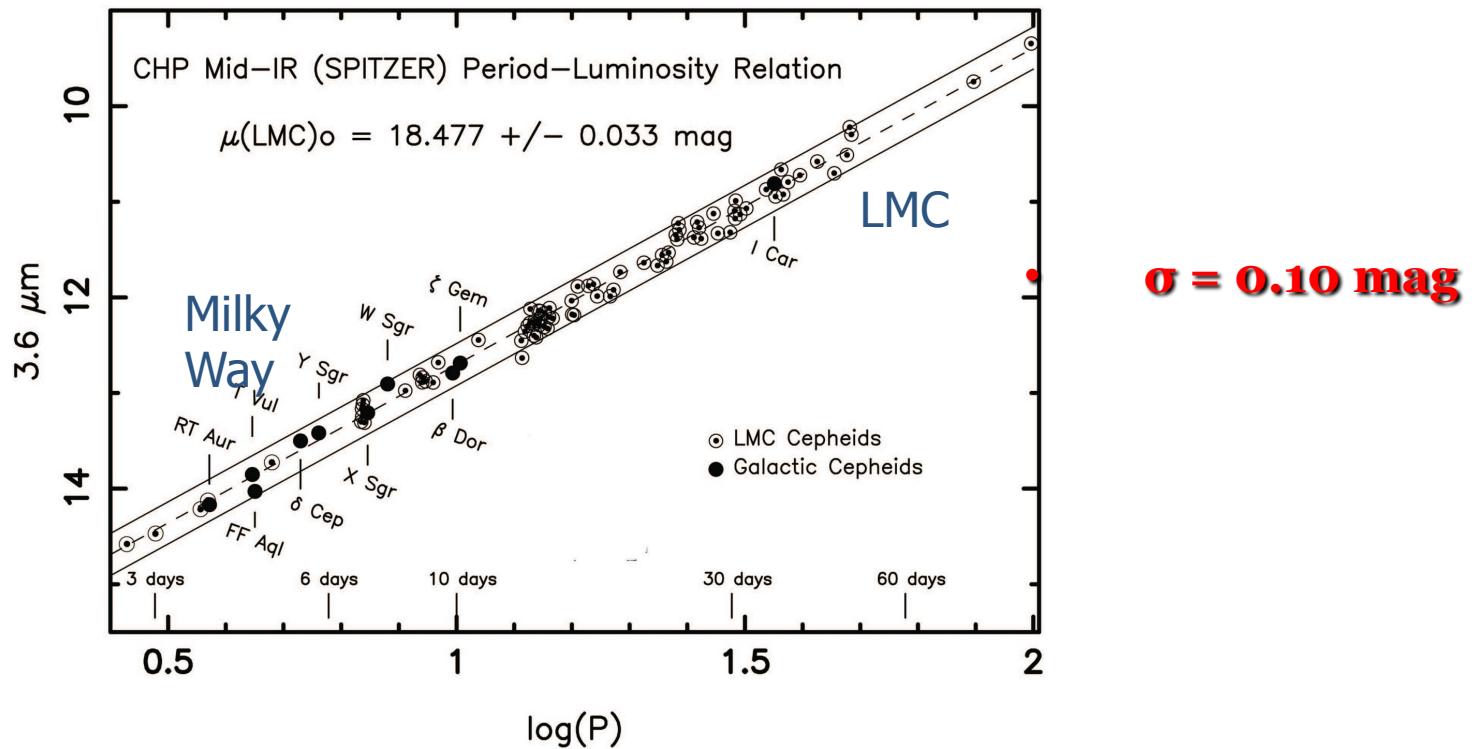
Metallicity effects predicted to be negligible.



Spitzer Infrared Telescope

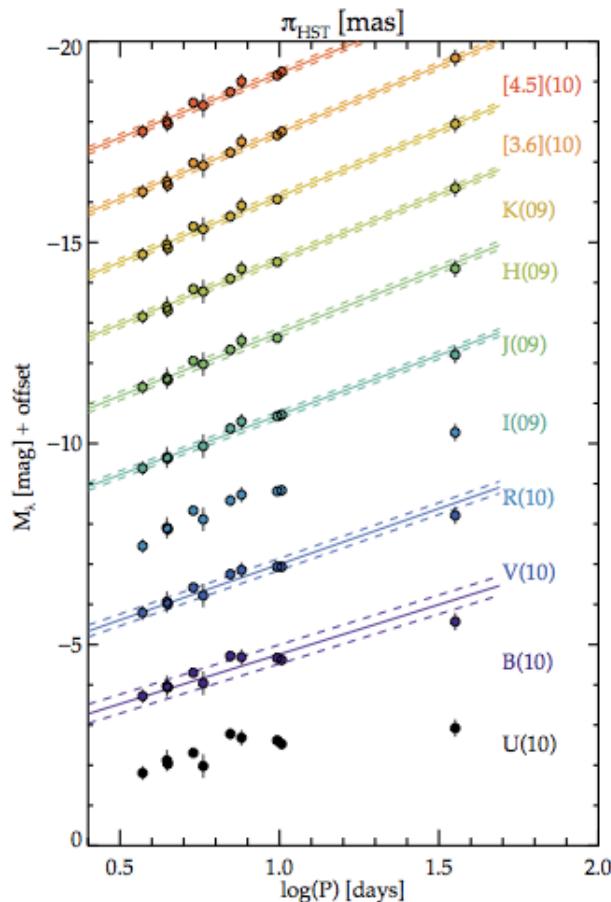
The Data: Cepheids

Spitzer Observations



WLF et al. 2012

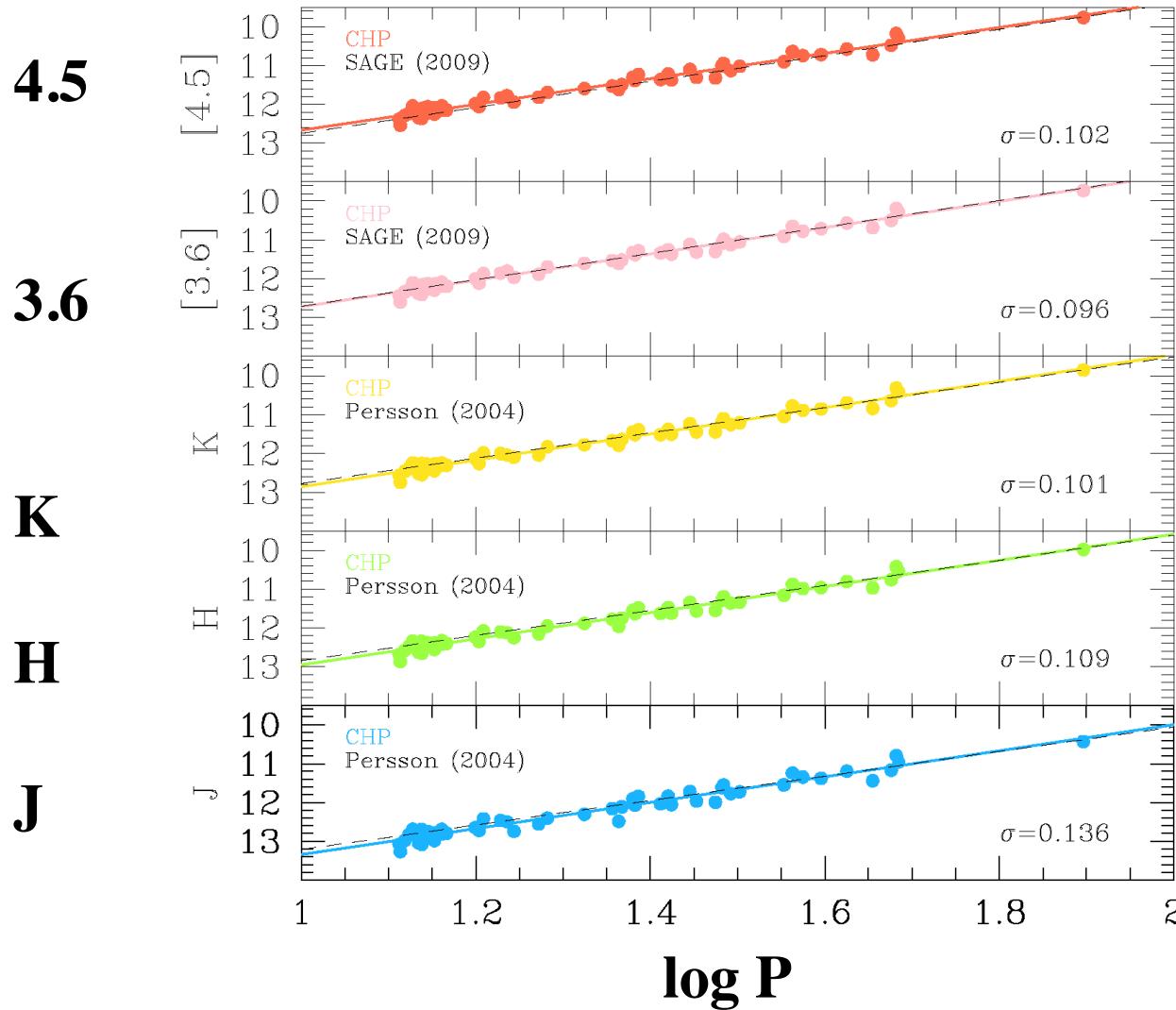
The Data: Parallaxes for Milky Way Cepheids



$\sigma = 0.10 \text{ mag}$

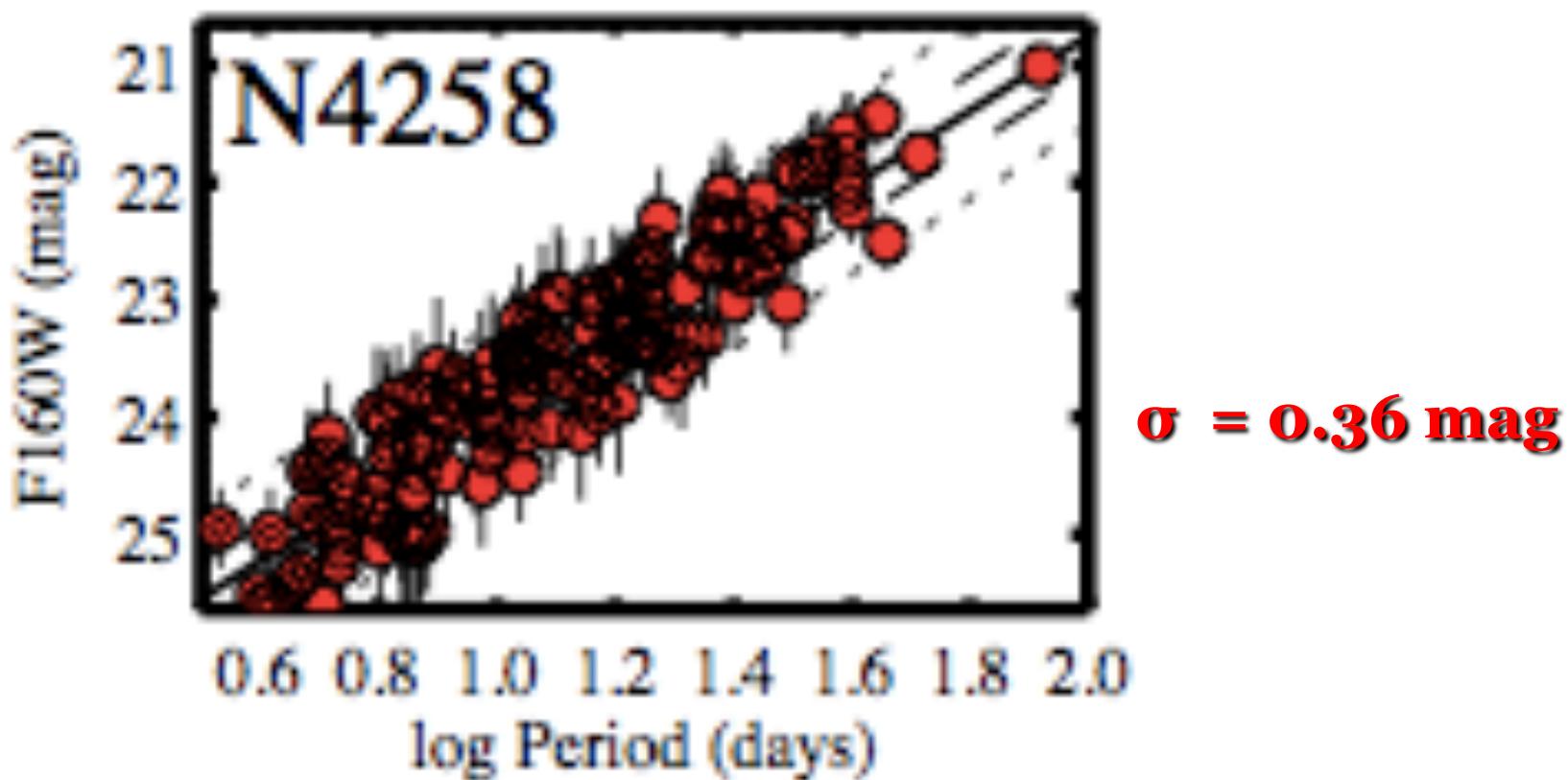
**Published UV/optical
CCHP IR data**
**+HST parallaxes
(Benedict et al. 2007)**

The Data: Near- and Mid-IR LMC PL (Leavitt) Relations



Persson et al
(2004)
Scowcroft et
al (2011)
WLF et al
(2012)

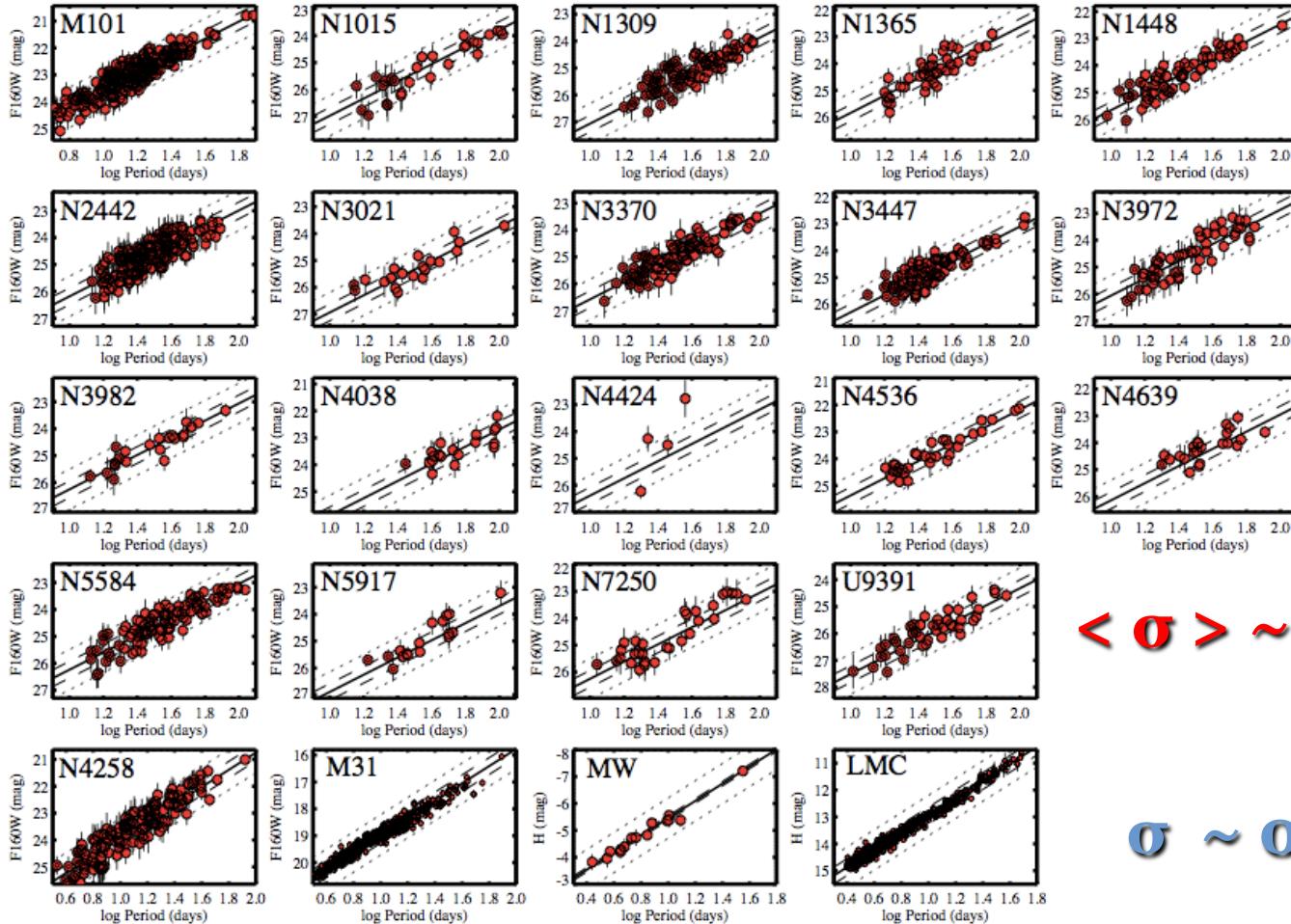
The Data: Cepheids - NGC 4258



Riess et al. 2016

The Data: Cepheids in SN hosts

Increase
from 8 to
19
calibrators



$$\langle \sigma \rangle \sim 0.4 \text{ mag}$$

$$\sigma \sim 0.1 \text{ mag}$$

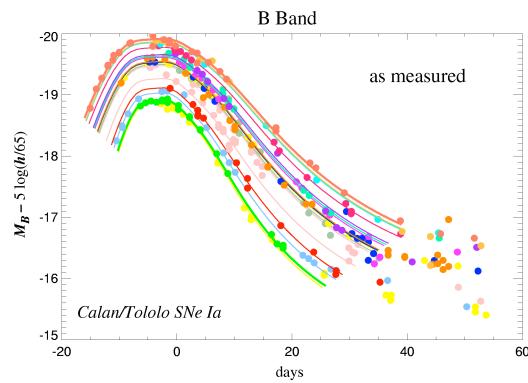
Riess et al. 2016

The Data: SNe Ia

- **Several ongoing surveys**
(e.g., CSP, PanStarrs, CfA)
- **Scolnic supercalibration (2015)**
SNe : $0.02 < z < 0.15$
- **Multiwavelength**
- **$\sigma \sim 0.12$ mag**

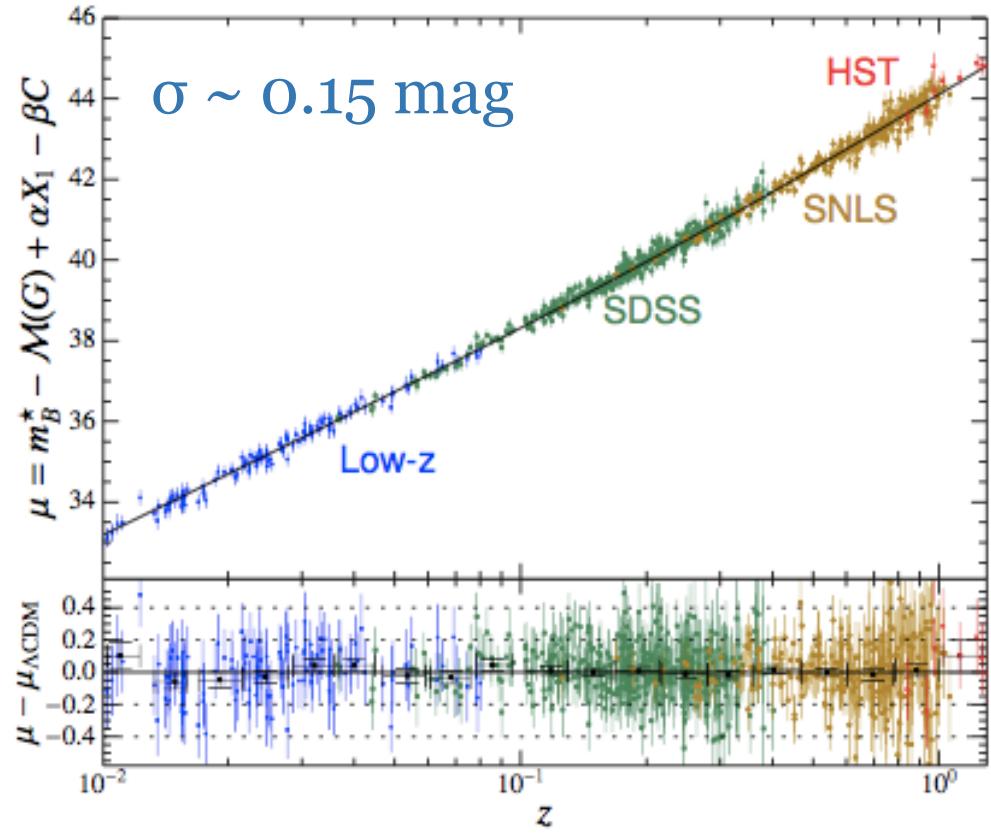
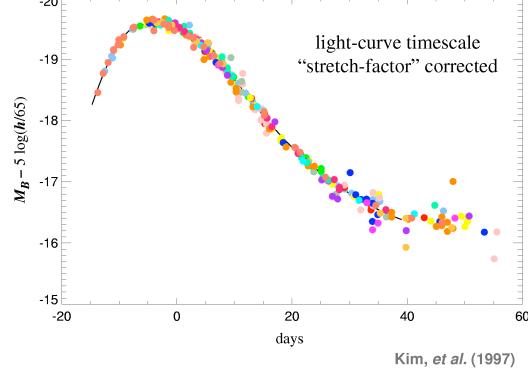
Use of SNe Ia to Measure Distances

As measured



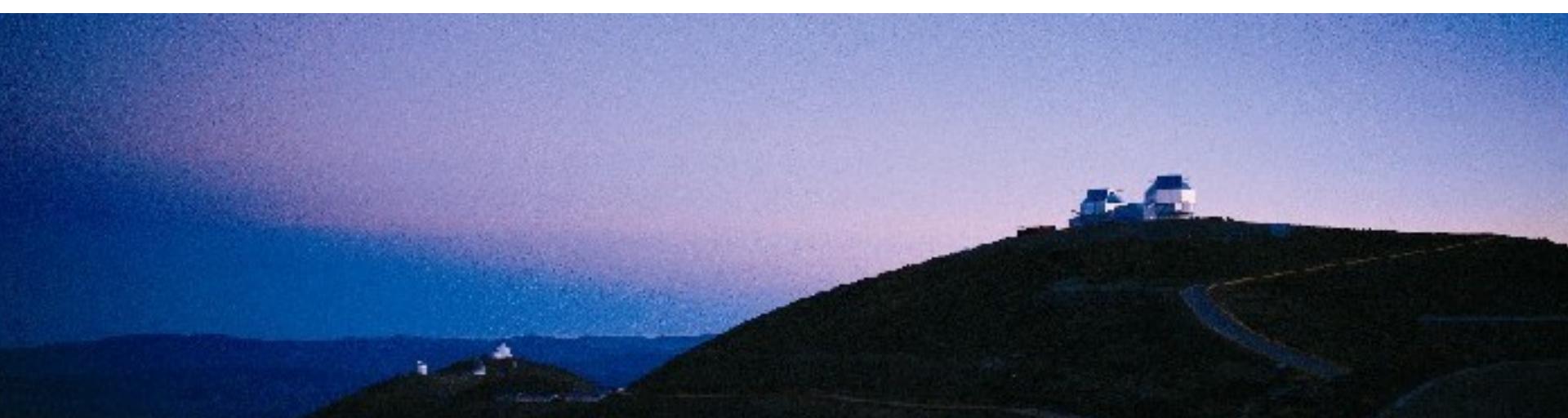
‘Stretch’
factor

Corrected



Betoule et al. 2014

The Carnegie Supernova Project (CSP)



Carnegie Supernova Project (CSP)



Swope 1-meter

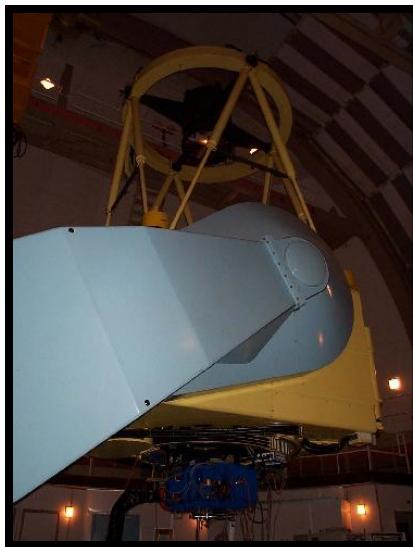
M. Phillips, PI

- $u' BVg'r'i'YJHK$ photometry
- 2.5-meter, 6.5-meter optical spectroscopy

CSPII:

$0.03 < z < 0.1$

- $BVg'r'i'YJHK$ photometry
- Magellan FIRE 6.5-meter spectroscopy



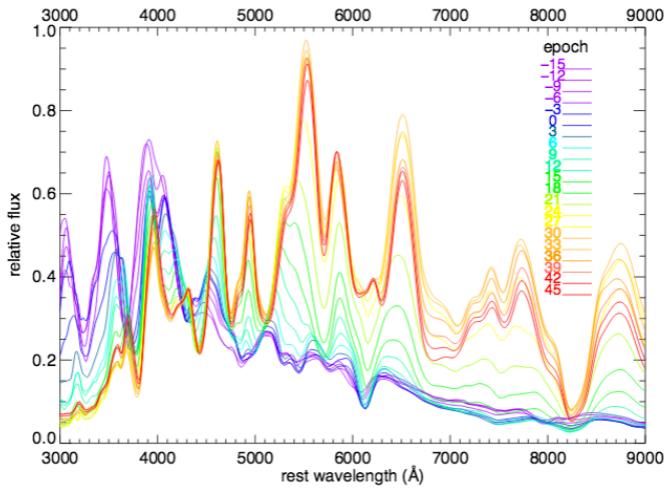
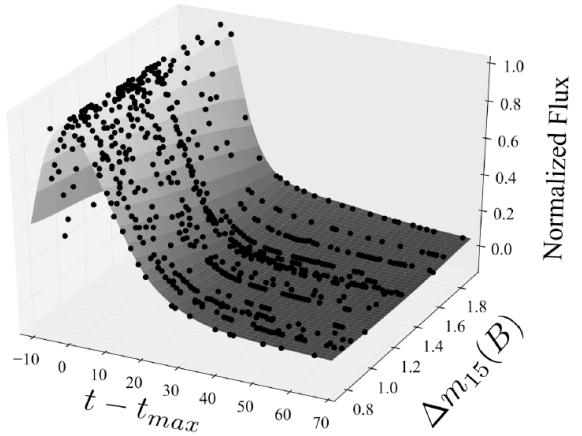
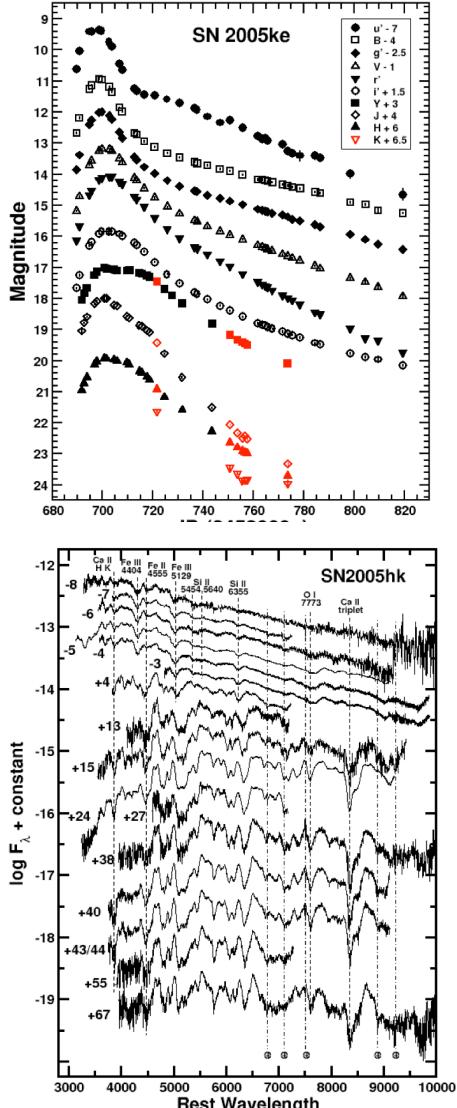
Dupont 2.5-meter



Magellan 6.5-meter

Multi-wavelength
Light curves

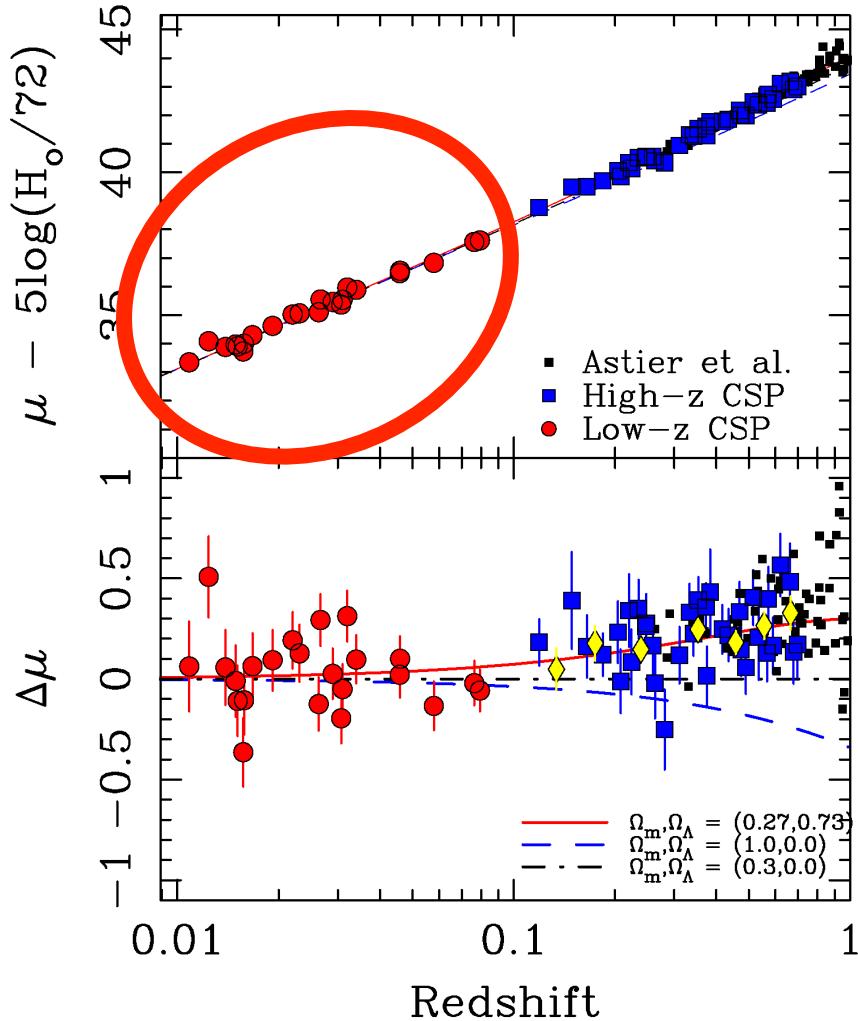
CSP: Dealing With Systematics



- Well-sampled:
 - Photometry
 - Spectra
- Reddening
- K-corrections
- Evolution
- Most extensive data set for dealing with systematics
- Comparison sample for future space missions (e.g., WFIRST)

Carnege Supernova Project (CSP)

i'-band Hubble Diagram



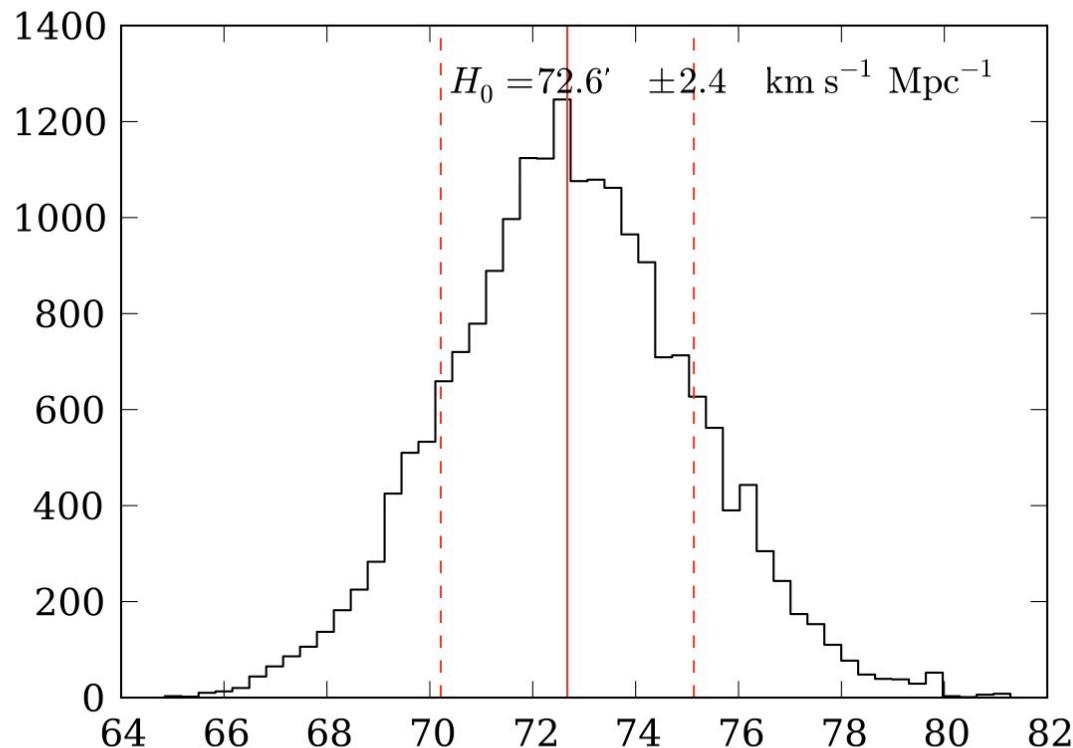
CSP data:

First I-band
Hubble diagram
at $z > 0.07$

$$w_0 = -1.05 \pm 0.13 \text{ (stat)} \\ \pm 0.09 \text{ (sys)}$$

WLF et al. (2009)
Folatelli et al. (2009)

MCMC histogram: CSP I data H_0



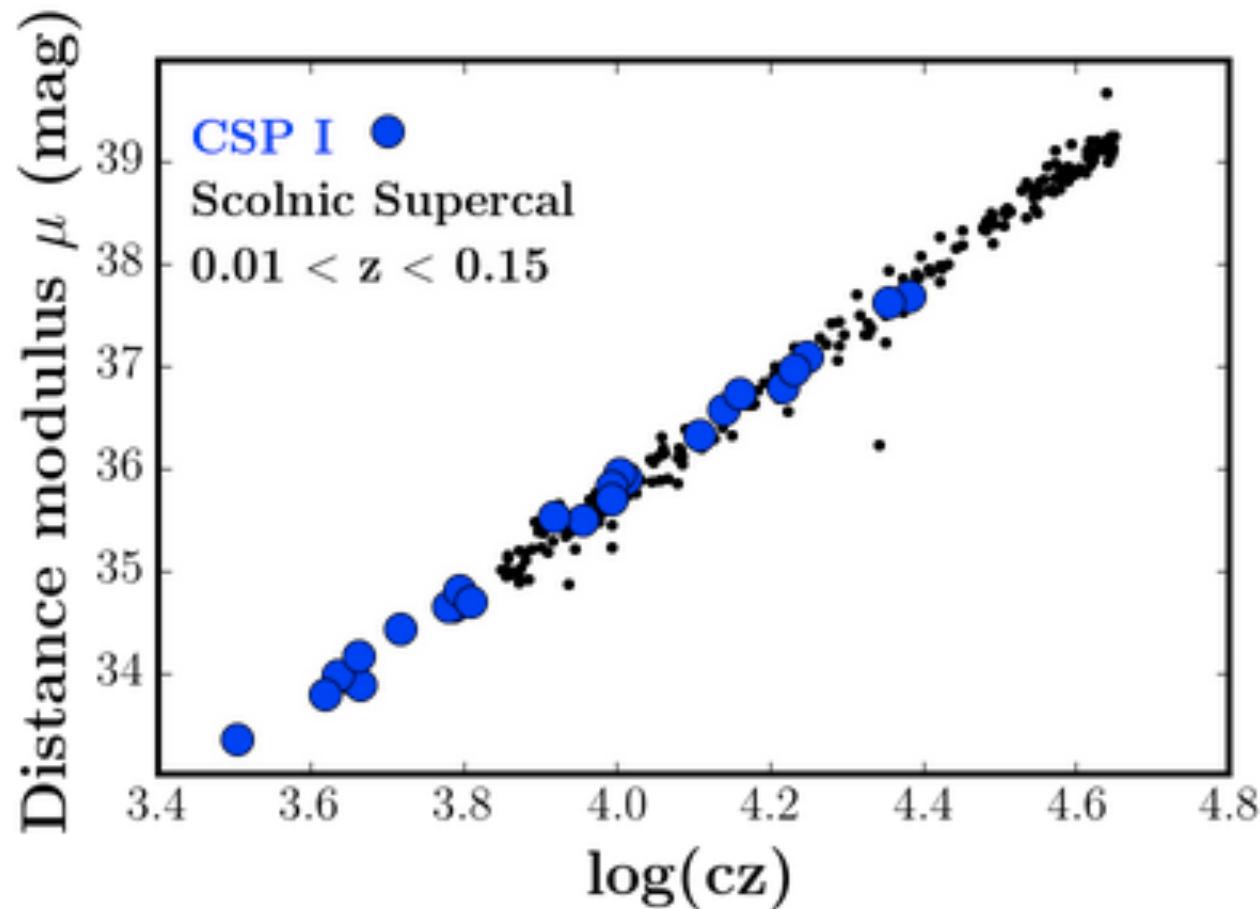
$$H_0 = 72.6 \pm 2.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

[$1 - \sigma$ standard deviation
from MCMC chains]

◆ MW, LMC, N4258 zero point

.

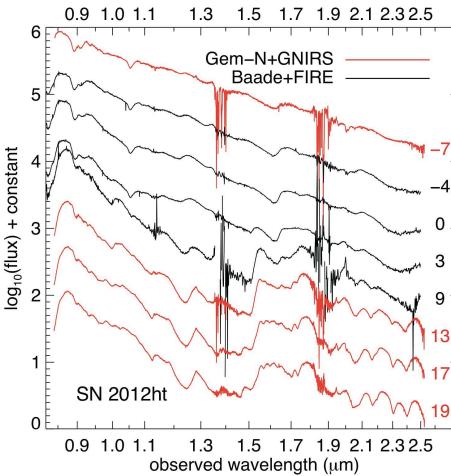
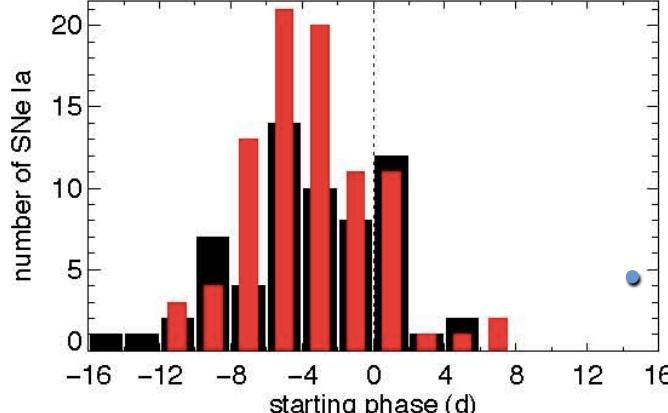
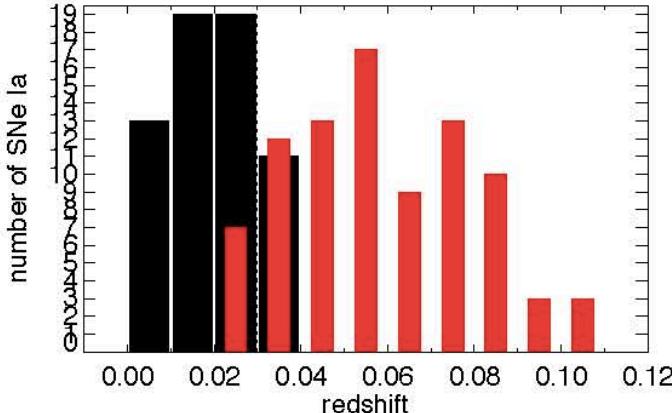
1. The Data: Low z Supernova Hubble Diagram



Carnegie Supernova Project (CSP) II (low z)

IR photometry
and spectra

FIRE instrument
on Magellan



- Photometry now complete
 - Obtaining follow up spectra
 - WFIRST proposal for high-z observations
- S. Perlmutter, PI
R. Foley, D. Scolnic

2. Systematics

Where Are the Challenges?

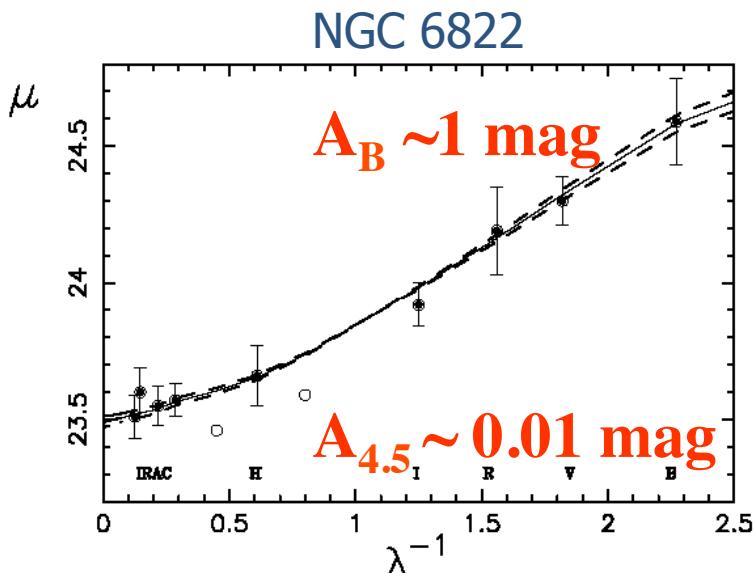
Systematic Effects:

- 1 Reddening
- 2 Metallicity
- 3 Crowding
- 4 Zero-Point Calibration of Cepheids
- 5 “Hubble bubble”
- 6 Small numbers of SN calibrators

Addressing Systematics

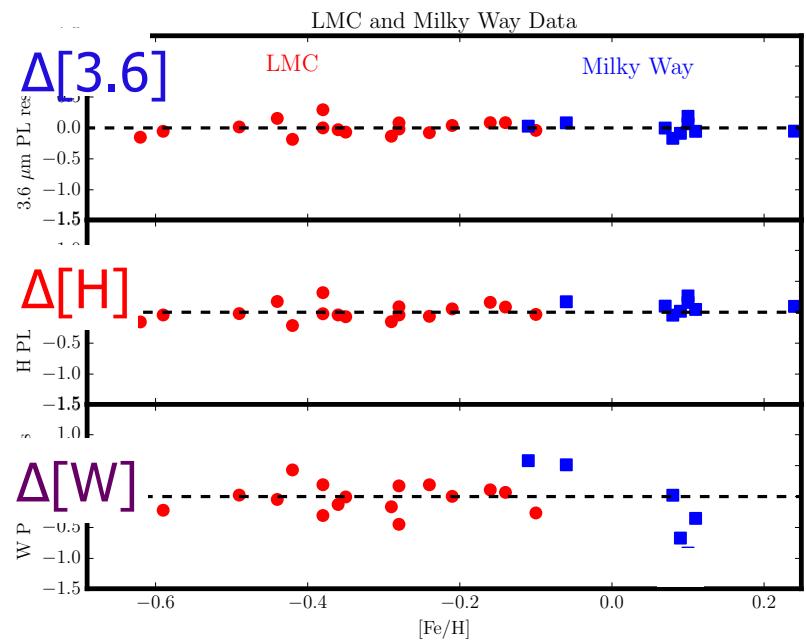
- 1 Reddening
- 2 Metallicity

1 Reddening



Madore et al (2009)

2 Metallicity

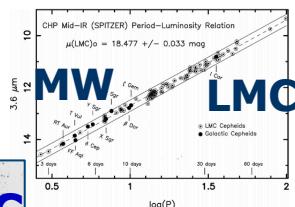
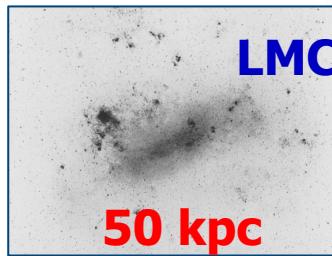


RomanIELLO et al. 2008; Genovali et al (2014);
WLF et al. 2012, 2016

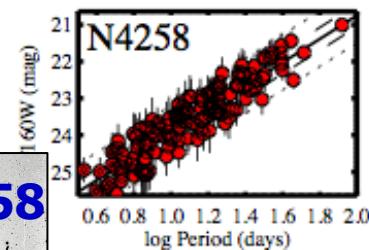
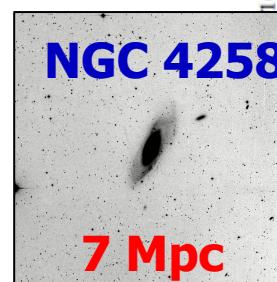
Systematics (3): Cepheids

3 Crowding

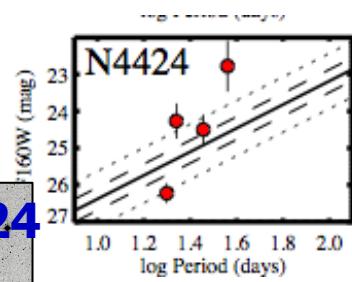
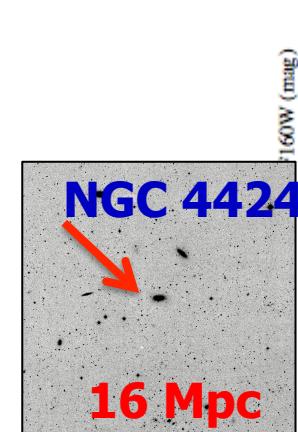
MW, LMC



N4258



NGC 4424



— 1 ° —

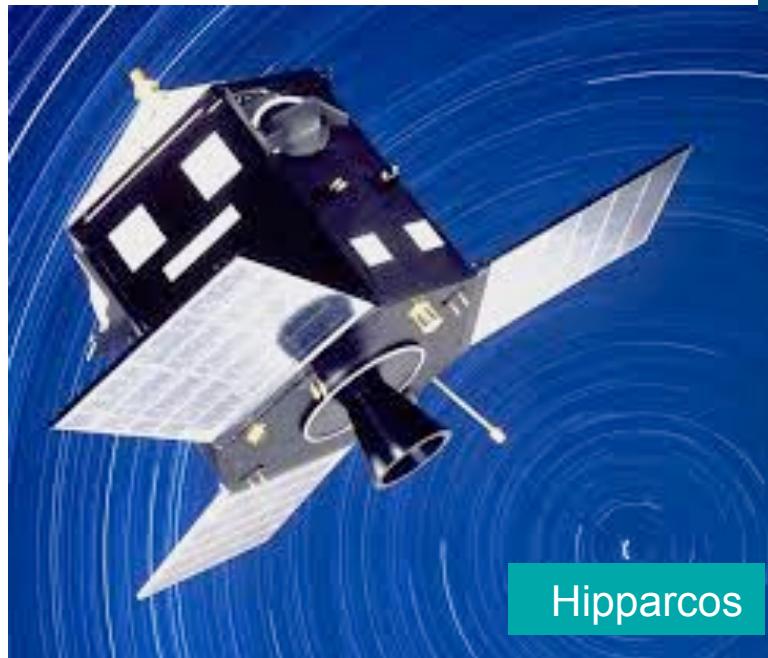
Riess et al.
(2016)

— 1 ° —

Systematics (4): Cepheids Parallax: The Next Generation

4 Cepheid Zero Point

μas -- A very small angle!



Hipparcos



Gaia

Nearby Cepheids: $2-3 \pm 0.2-0.3$ mas
RR Lyrae stars: $\sigma_{\pi} / \pi > 0.18$
TRGB: $\langle \sigma_{\pi} / \pi \rangle \sim 0.3$

Nearby Cepheids: $\sim 20-30 \mu\text{as}$
RR Lyrae stars: $\leq 10 \mu\text{as}; \sigma_{\pi} / \pi < 0.1$
TRGB: $\langle \sigma_{\pi} / \pi \rangle < 0.03$

Gaia – Data Release 1



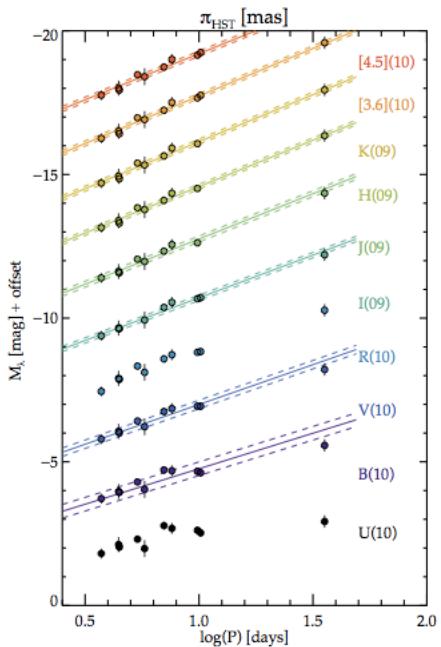
- September 14, 2016
- Positions and G magnitude for ~1 billion stars, 1 year of data
- Stars in common with Tycho2 catalog from Hipparcos (TGAS)
- 300 μ as typical accuracy

When complete (2022):

- $\sigma_\pi / \pi < 1\%$ out to several kiloparsecs
- Cepheids, RR Lyrae, red giants in Milky Way to <<1%
- Distance to LMC to 1-2%

Status: Parallaxes for Milky Way Cepheids

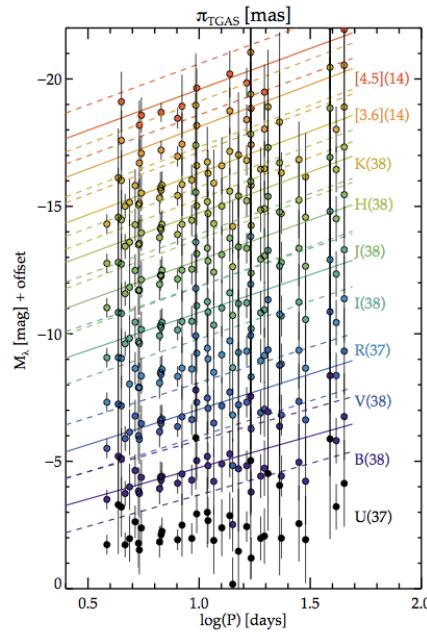
HST



N = 10 stars

**CCHP data +
HST parallaxes**

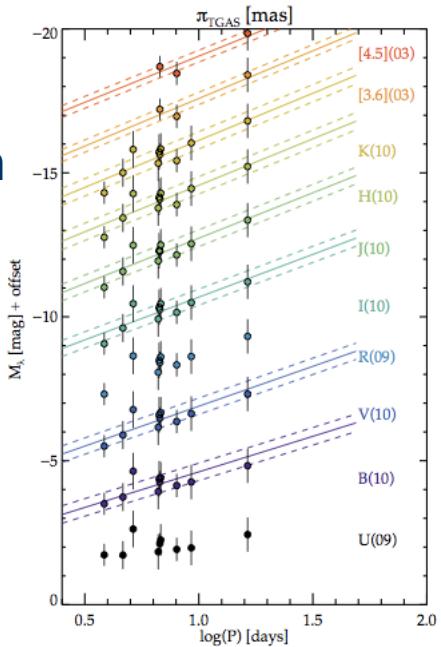
Gaia – DR1 -CCHP



N = 14 - 38 stars

**CCHP data +
Gaia parallaxes**

Gaia – DR1 ($\sigma_{\pi} / \pi < 0.5$)



R. Beaton

N = 9 stars

**CCHP data +
Gaia parallaxes**

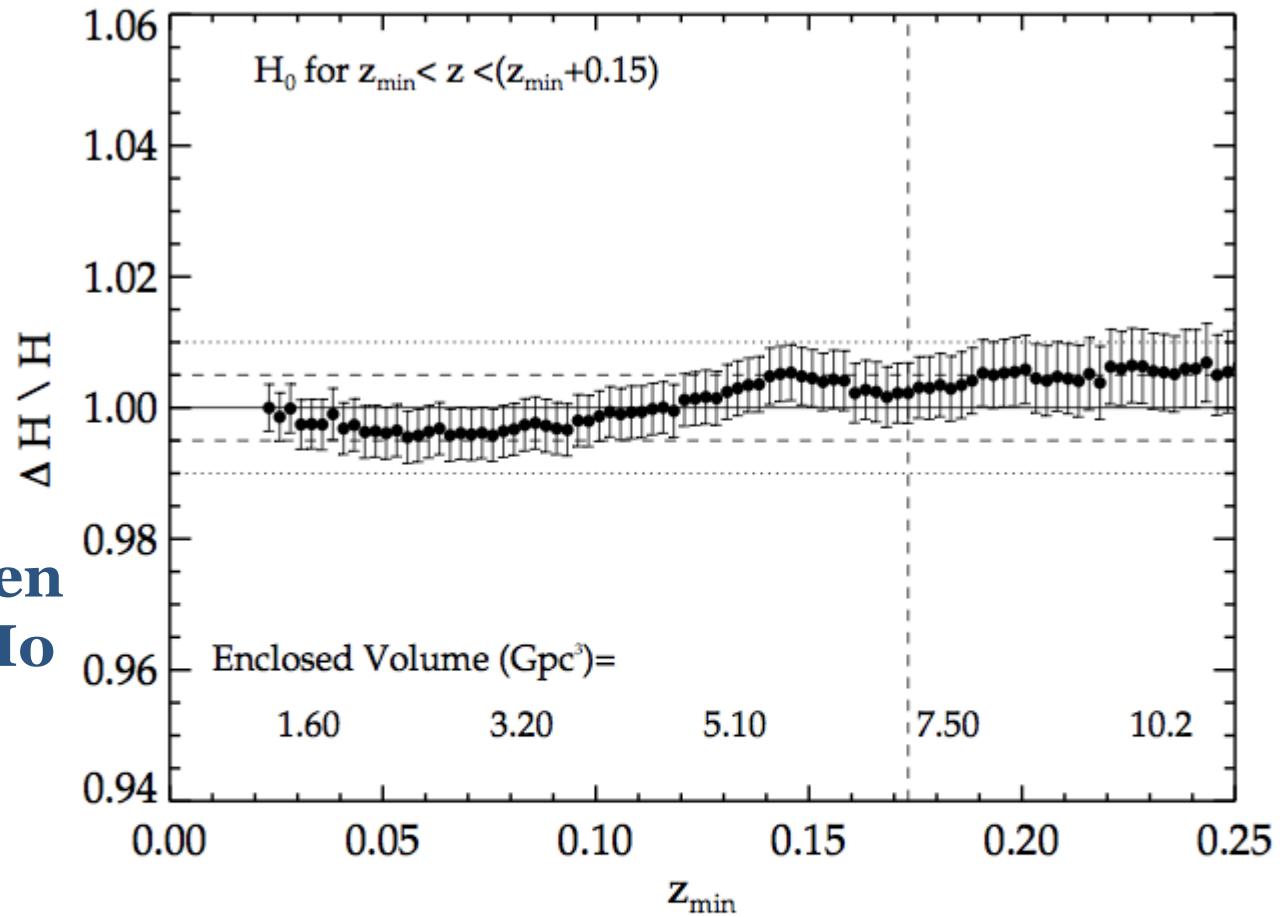
Systematics (5) : SNe Ia

5 Constraints on Local Bubble

Z_{\min} : 0.02 to 0.25

Z_{\max} : 0.15 to 0.40

Difference between local and global H_0 of even 1% very unlikely.



Primary fit:
 $0.0233 < z < 0.15$

Riess et al. (2016)

Systematics (6): Numbers of SNe Ia Calibrators

6 Small number of SN Ia calibrators

There are 19 galaxies with SNeIa calibrated with Cepheids.

$$0.12 / \sqrt{19} (8) = 0.03 \text{ (0.04) mag}$$

1.5% uncertainty

Where Are the Challenges?

Systematic Effects: Getting to <1%

- 1 Reddening
- 2 Metallicity [TRGB independent check]
- 3 Crowding [TRGB independent check]
- 4 Zero-Point Calibration of Cepheids [Gaia]
- 5 “Hubble bubble”
- 6 Small numbers of SN calibrators [JWST]

The Future: Decreasing the Systematics in H_0

- 1 Gaia parallaxes
- 2 Independent tests of the Cepheid zero point
- 3 Increase number of SN calibrators (JWST)
- 4 Minimize known systematics - e.g., crowding (JWST)

The Carnegie Hubble Project (CCHP) : Summary

- | | |
|----------------------|-------------------------------------|
| 1. Cepheids | Magellan, HST, Spitzer, Gaia |
| 2. RR Lyrae | TMMT, HST, Spitzer, Gaia |
| 3. TRGB | TMMT, Magellan, Gaia, JWST |
| 4. Supernovae | LCO (CSP) |

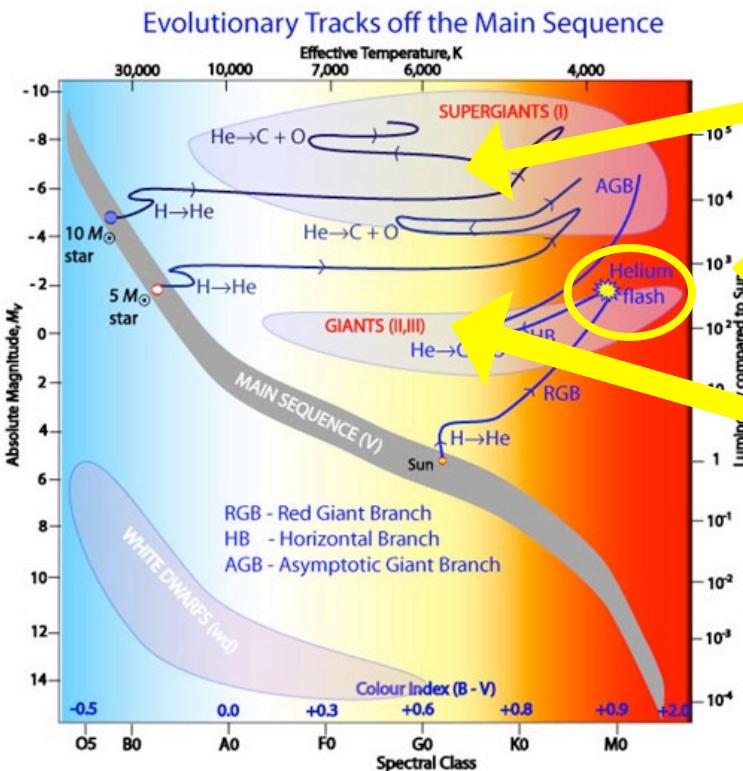
Consistent optical, near-infrared mid-infrared photometric zero points: from Milky Way through Local Group to Hubble flow.
Minimize / eliminate current systematics.

H_0 to 1.5% (statistical +systematic)



Stellar Astrophysics: Using Stars as Probes of Distance

Hertzsprung – Russell Diagram



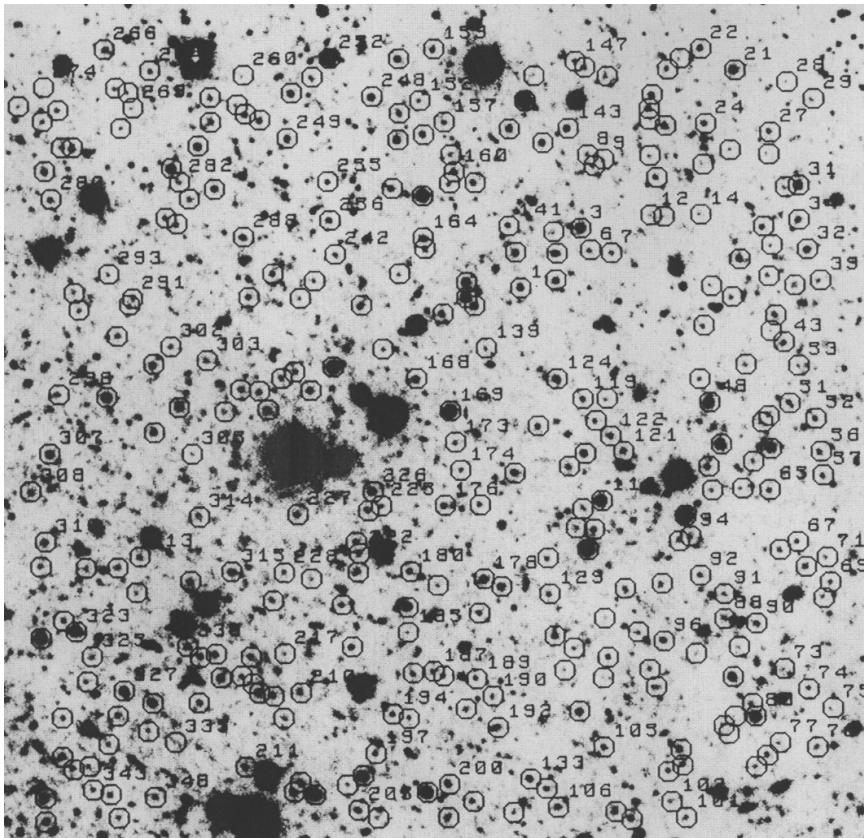
Cepheids

Tip of the Red Giant Branch
(TRGB)

RR Lyrae stars

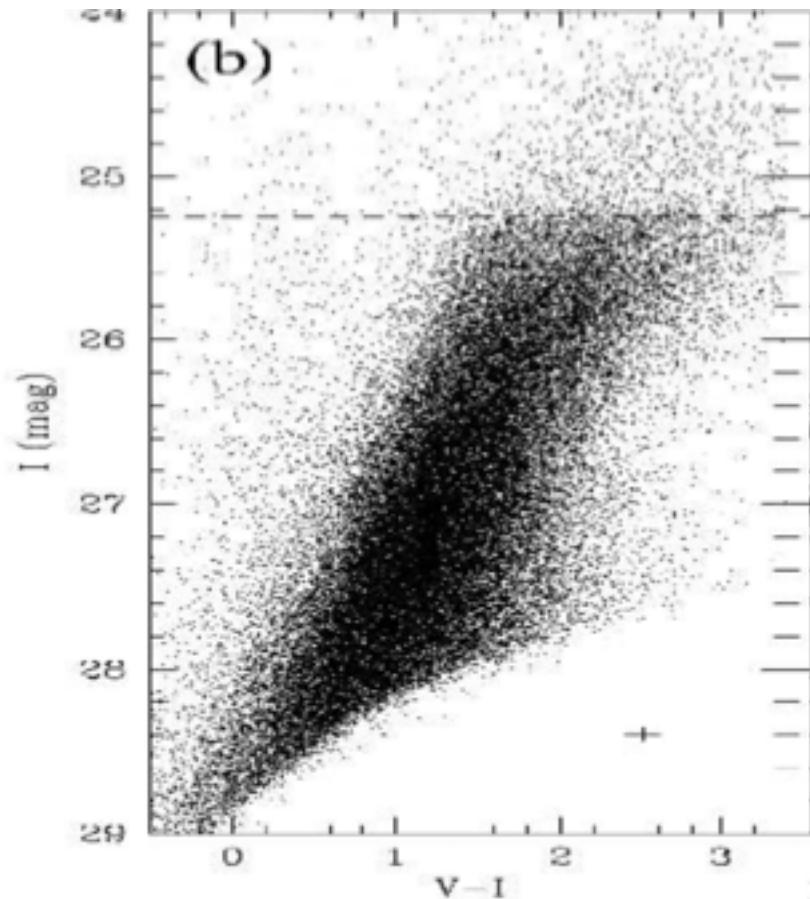
Temperature

Tip of the Red Giant Branch (TRGB) as a Distance Indicator



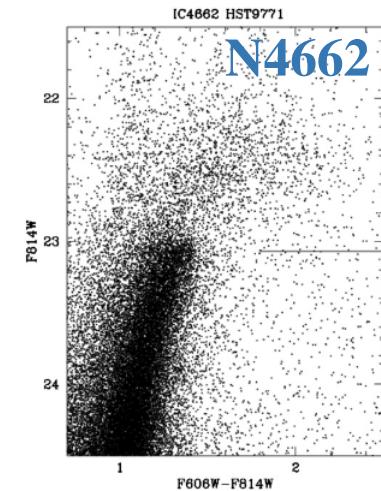
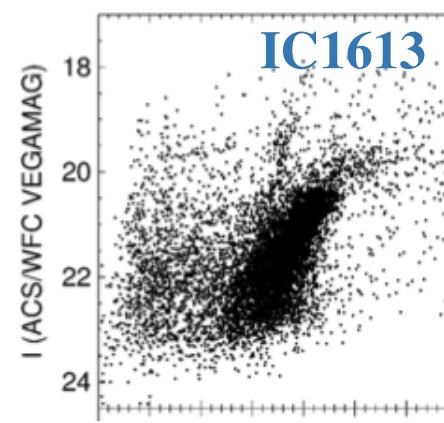
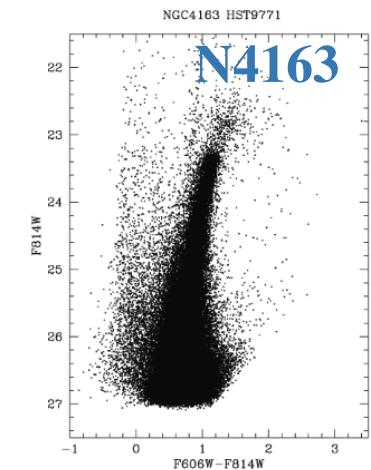
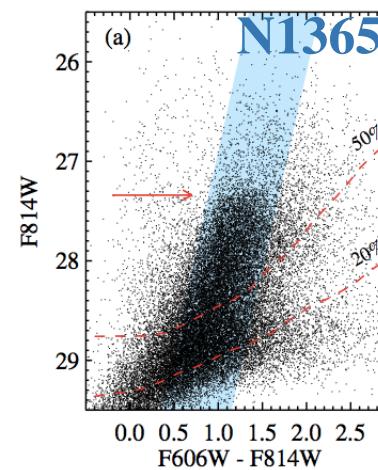
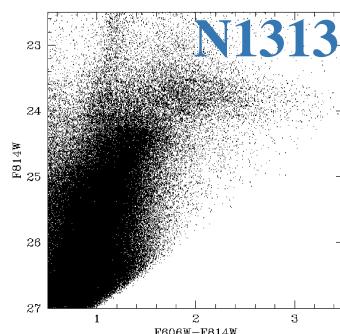
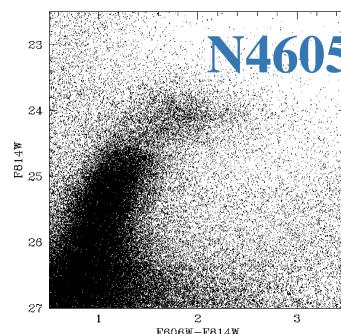
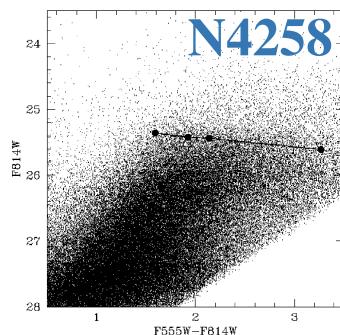
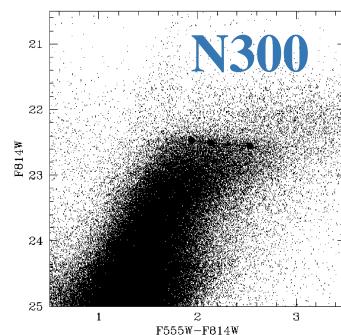
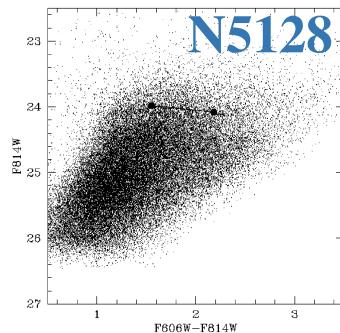
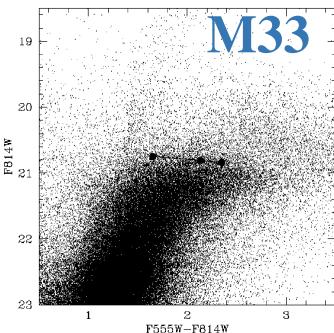
**Lee, Freedman & Madore (1993)
Application of Sobel edge detector
Madore & Freedman (1997)**

The Tip of the Red Giant Branch



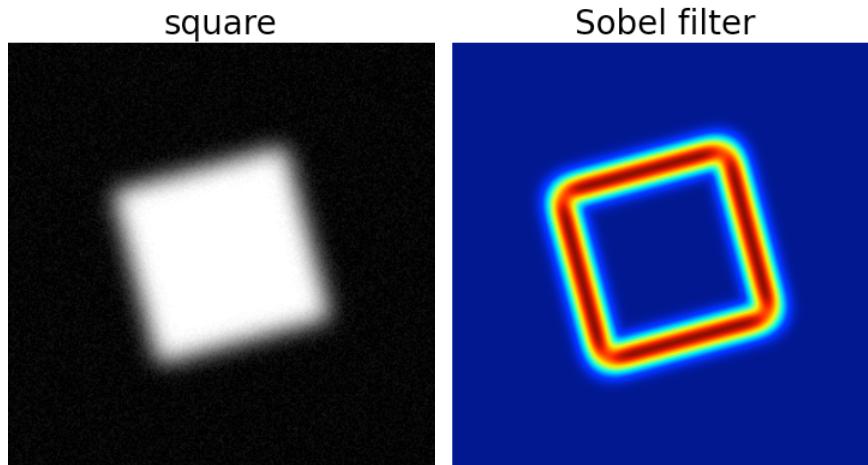
Mager, Madore & WLF (2008)

Tip of the Red Giant Branch (TRGB) as a Distance Indicator



Jang et al. 2016, Hatt et al. 2016;
Jacobs et al. (2009)

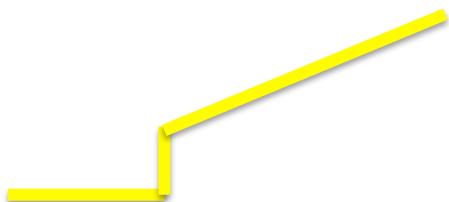
Finding Edges: The Sobel Filter



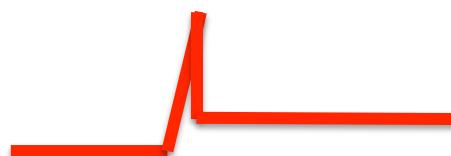
$$\text{kernel} = \begin{bmatrix} -1 & 0 & +1 \\ -2 & 0 & +2 \\ -1 & 0 & +1 \end{bmatrix}$$

$$\text{kernel} = \begin{bmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ +1 & +2 & +1 \end{bmatrix}$$

Giant Branch
Luminosity
Function

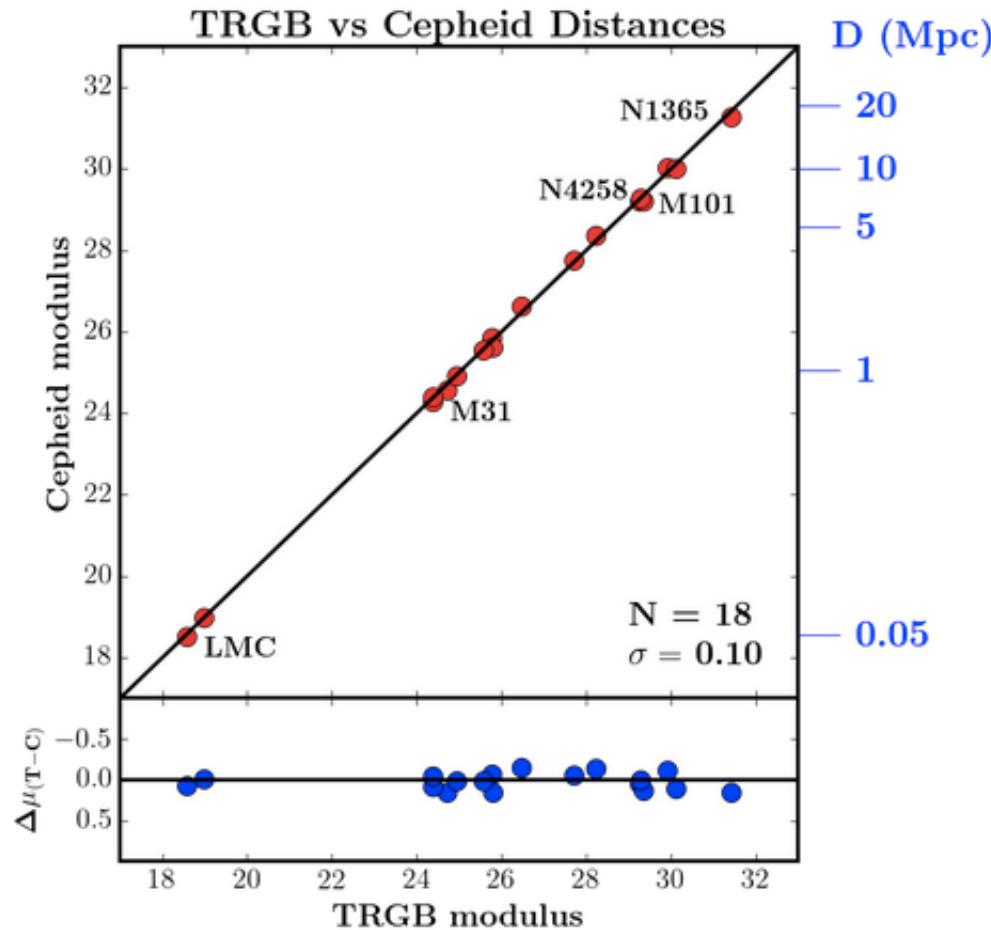


Sobel Filter Output



$$\text{kernel} = \begin{bmatrix} -1 & 0 & +1 \\ -1 & -2 & 0 \\ +2 & +1 \end{bmatrix}$$

Tip of the Red Giant Branch Distances



TRGB: Rizzi et al. (2008); Jang et al. (2015, 2016)

CCHP II : TMMT***



*** Three hundred Millimeter Telescope at Las Campanas

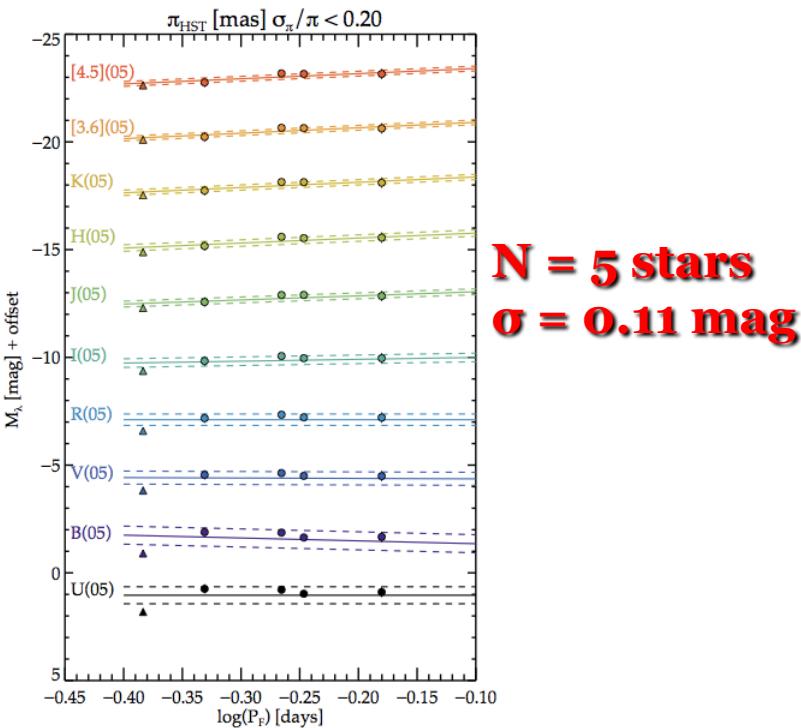
Anticipating Gaia: The Carnegie – Chicago Hubble Program (CCHP)

- o. Cepheids [59 stars; 10 bands]
- 1. RR Lyrae stars [55 stars; 10 bands]
- 2. Tip of the Red Giant Branch** [1000 stars; VI]

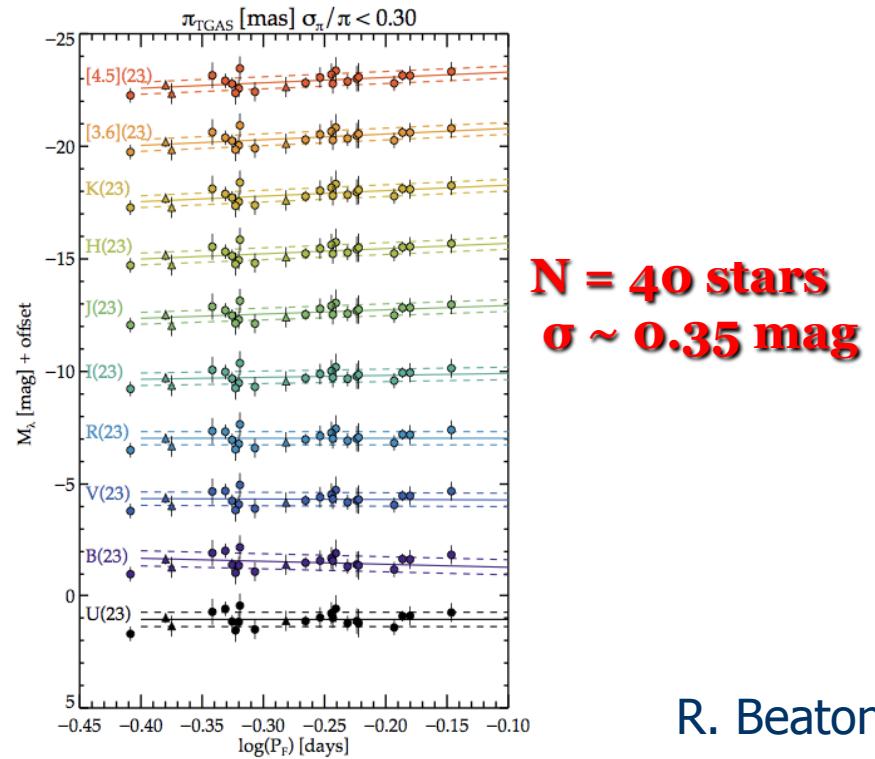
Multiwavelength (Hubble, Spitzer, TMMT, Magellan) observations for robust calibration of H_0

Parallaxes for Milky Way RR Lyrae Stars

HST



Gaia – DR1



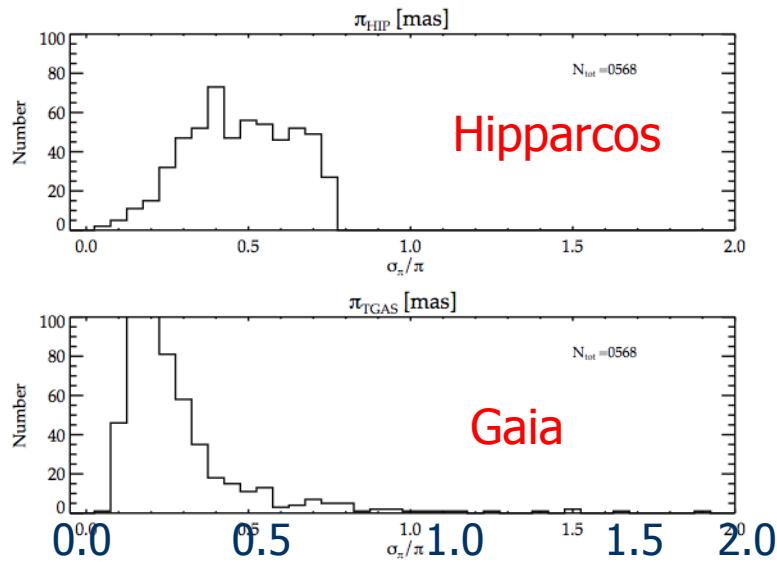
CCHP data +
HST parallaxes

CCHP data +
Gaia parallaxes

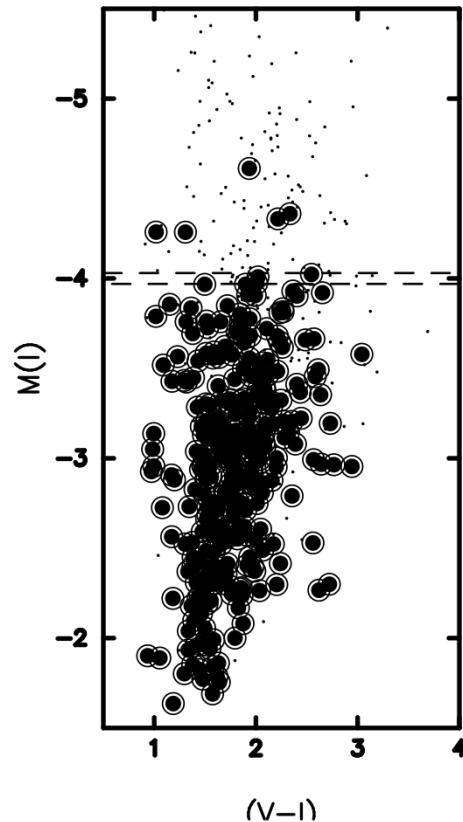
R. Beaton

First Gaia + CCHP Results: TRGB

Hipparcos vs Gaia TRGB
(σ_π / π Comparison 568 stars)



Gaia mas Parallaxes
($\sigma_\pi / \pi < 0.25$)



How To Break the Impasse

- 1. Gaia: Geometric Parallaxes**
- 2. JWST : TRGB / Cepheids / SNe Ia**

TRGB Future Observations

HST : The IR-TRGB Error Budget on the Hubble Constant

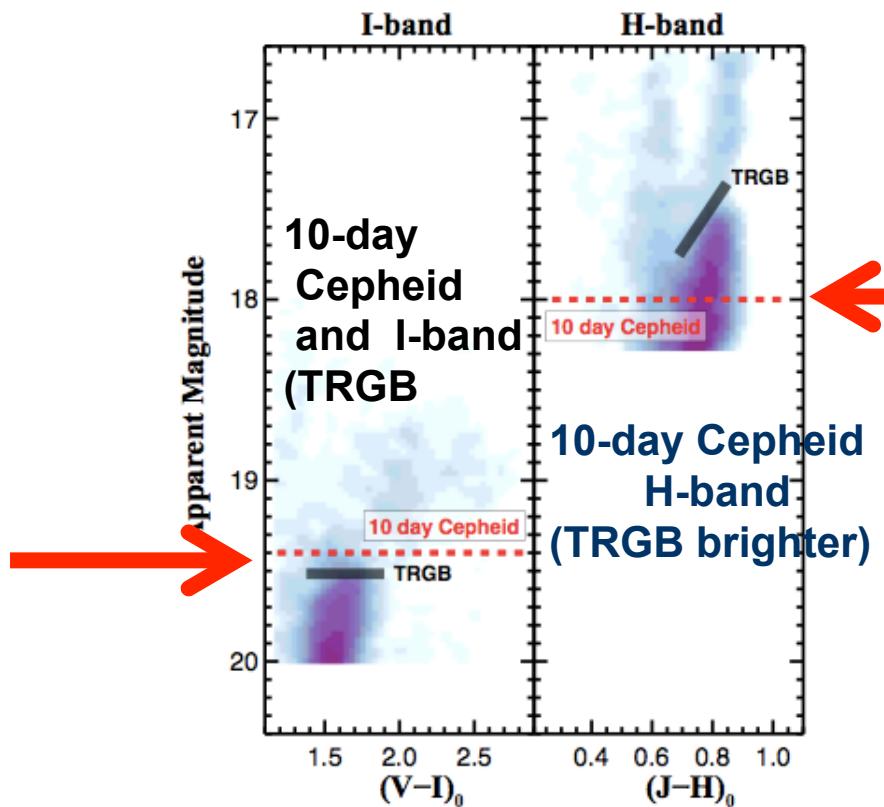
Source of Uncertainty	Dist. Modulus Uncertainty	Dist. Uncertainty (%)
(1) TRGB Zero Point	$0.009 \text{ mag} = \sqrt{(0.06^2 + 0.03^2)} / \sqrt{50}$	0.4%
(2) SNe Ia Zero Point	$0.031 \text{ mag} = \sqrt{(0.12^2 + 0.10^2)} / \sqrt{26}$	1.4%
(3) Tie-in to Hubble Flow	$0.011 \text{ mag} = 0.16 / \sqrt{221}$	0.5%
Total Uncertainty on H_0	0.034 mag	1.6%

Measurement of H_0 based on IR TRGB + SNeIa

H_0 to 1% feasible

Advantage of JWST and H-band: TRGB, Cepheids, SNels

- 3x resolution of HST
- ~30x volume can survey
- RGB stars 2.5 mag brighter at H than I



Comparison of HST Key Project and CHP/CCHP H_0 Error Budgets

Known Systematics	Key Project (2001)	Parallax+SNe (2007/2009)	HST, Spitzer (2011 / 2012)	Anticipated Gaia/JWST
(1) Cepheid Zero Point	± 0.12 mag	± 0.06 mag	± 0.04 mag	± 0.015 mag**
(2) Metallicity	± 0.10 mag	± 0.05 mag	± 0.03 mag	± 0.015 mag
(3) Reddening	± 0.05 mag	± 0.03 mag	± 0.01 mag	± 0.01 mag
(4) SNe + other	± 0.05 mag	± 0.03 mag	± 0.02 mag	± 0.02 mag
Final Uncertainty	± 0.20 mag	± 0.09 mag	± 0.06 mag	± 0.03 mag
Percentage Error on H_0	$\pm 10\%$	$\pm 5\%$	$\pm 3\%$	$\pm 1.5\%$

** + TRGB + RRL

Summary

1. $H_0 = 73 \pm 3\%$
2. Discrepancy with CMB/Planck model $\sim 3\sigma$
3. Gaia + JWST
 - double number of high-quality calibrators
 - tests of systematics (Ceph+TRGB+RRL)
 - remove zero-point uncertainties ($<<1\%$)
 - infrared (minimize reddening, metallicity)
 - IR Cepheid + SNeIa observations
4. DES (gravitational lensing) + LIGO sirens
5. H_0 to $\sim 1\%$ is feasible

