Constraints on Cosmological Parameters: Combining Planck With Other Measurements

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University of Chicago

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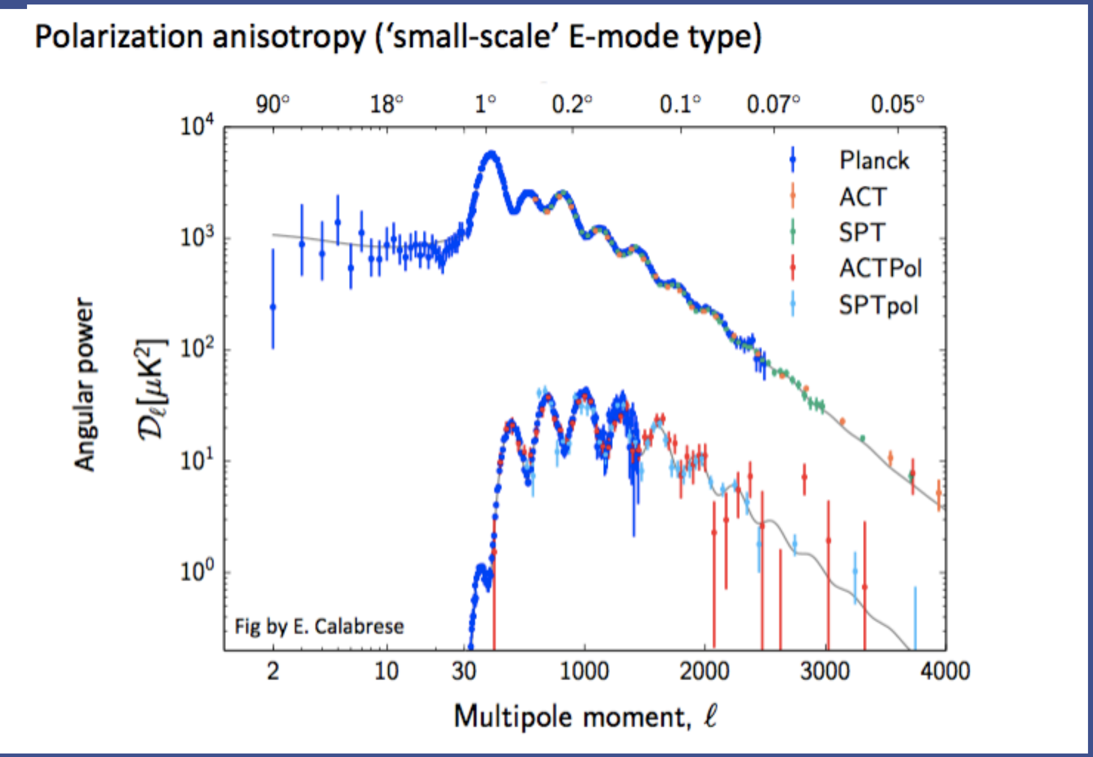
Legacy of Planck
IAU meeting
Honolulu, Hawaii

Cosmological Parameters

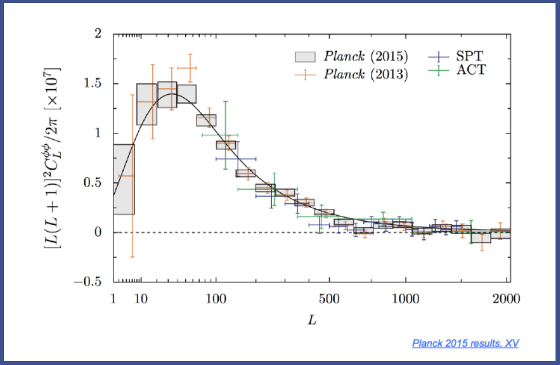
- Planck 2015: ΛCDM model
  - Big Bang Nucleosynthesis
  - Baryon Acoustic Oscillations
  - Type Ia Supernovae
- Improvements to Hubble Constant Measurements
- Beyond the ΛCDM model?

Planck 2015 + ACT + SPT Angular Power Spectrum



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

Planck lensing – 40σ!



E. Calabrese

Planck 6-parameter LCDM model

$\Omega_b h^2$	Baryon density
$\Omega_c h^2$	Cold dark matter density
$100\Theta_{MC}$	100 x approx to r_s/D_A
T	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

Cosmic Microwave Background Anisotropies

Planck Cosmological Parameters (2013)

$H_0 = 67.3 \pm 1.2$ km/s/Mpc**

$\Omega_M = 0.315 \pm 0.017$**

$\Omega_\Lambda = 0.686 \pm 0.020$**

$n_s = 0.9603 \pm 0.0074$

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

** model-dependent

Planck Cosmological Parameters (2015)

$H_0 = 67.8 \pm 0.9$ km/s/Mpc**

$\Omega_M = 0.308 \pm 0.012$**

$\Omega_\Lambda = 0.692 \pm 0.012$**

$n_s = 0.9677 \pm 0.0060$

$w = -1.54_{-0.50}^{+0.62}$** (-1.02 Add BAO SNIa H_0)

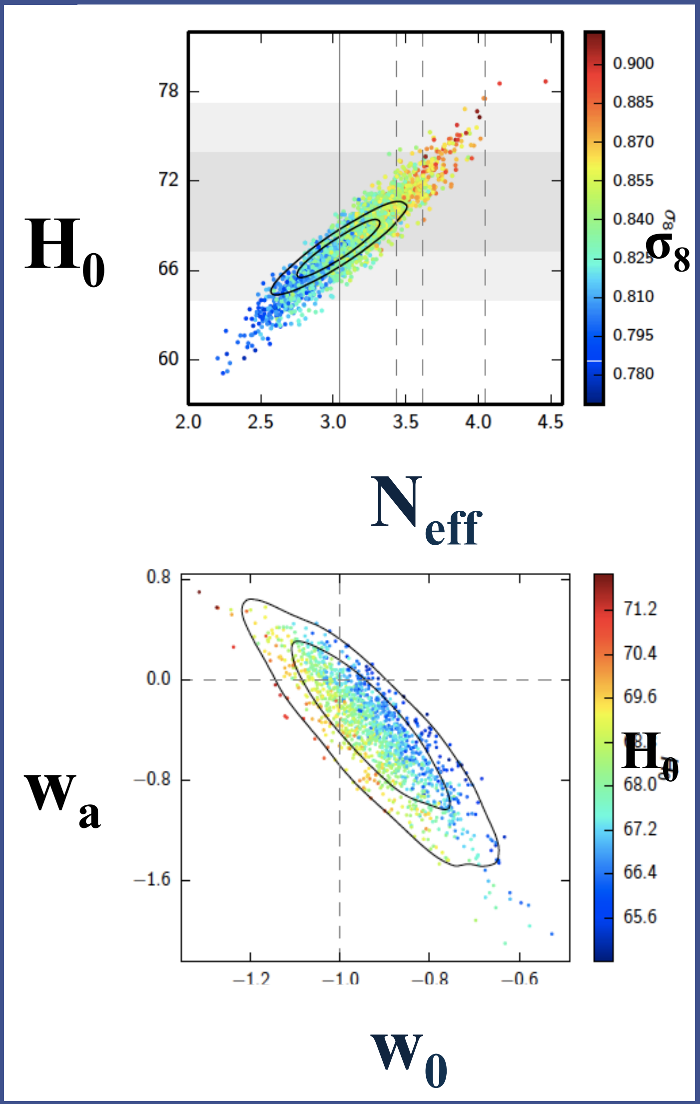
** model-dependent

Planck 2015 temp + lensing (except for w) ;

Planck 2013 Cosmology Paper XVI

Planck 2015 Cosmology Paper XIII

Planck Cosmology 2015

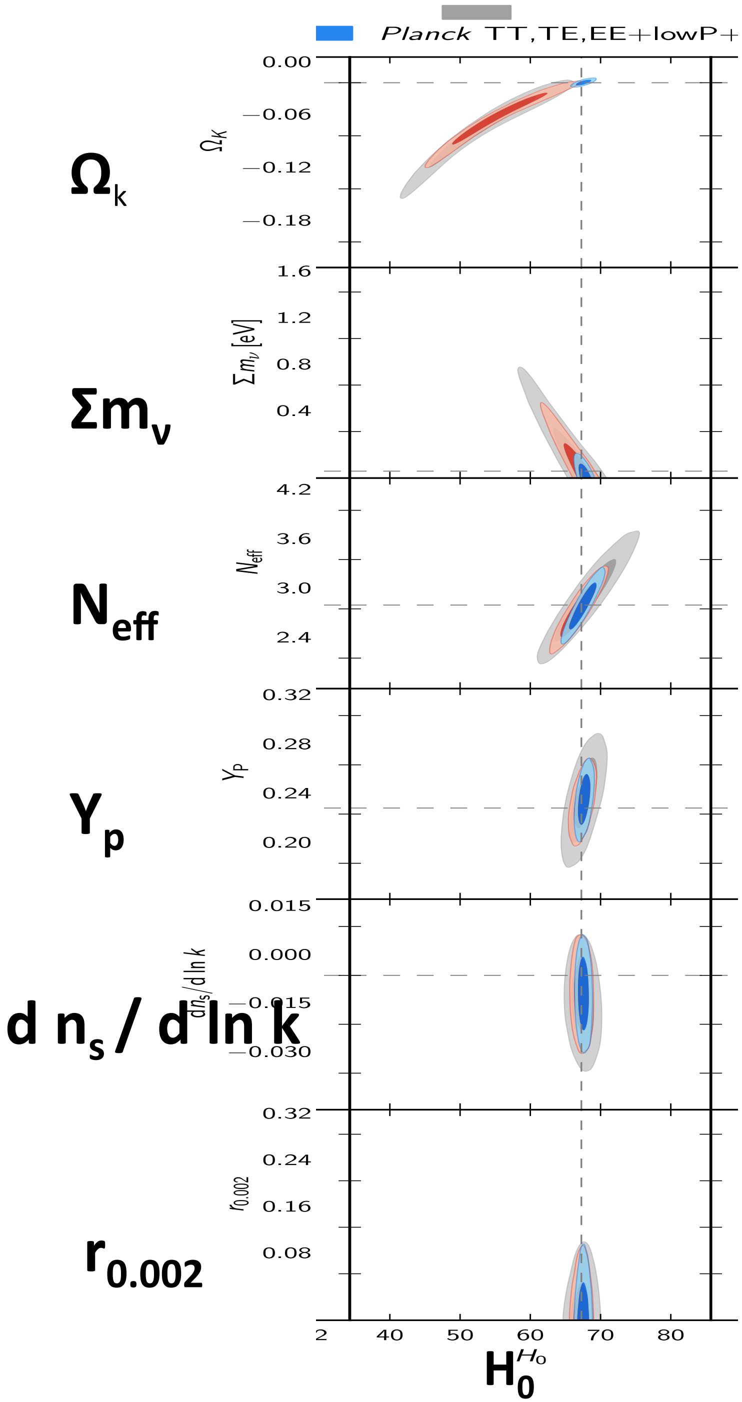


The nearly exact degeneracy -- i.e., nearly the same CMB anisotropies in models with different geometries but the same matter content –

Is a limit to deriving parameters such as the Hubble constant from CMB data alone

It also means that an accurate independent measure of H_0 provides a key means of constraining other cosmological parameters in combination with CMB anisotropies

$\Omega_b h^2$, $\Omega_c h^2$ well measured

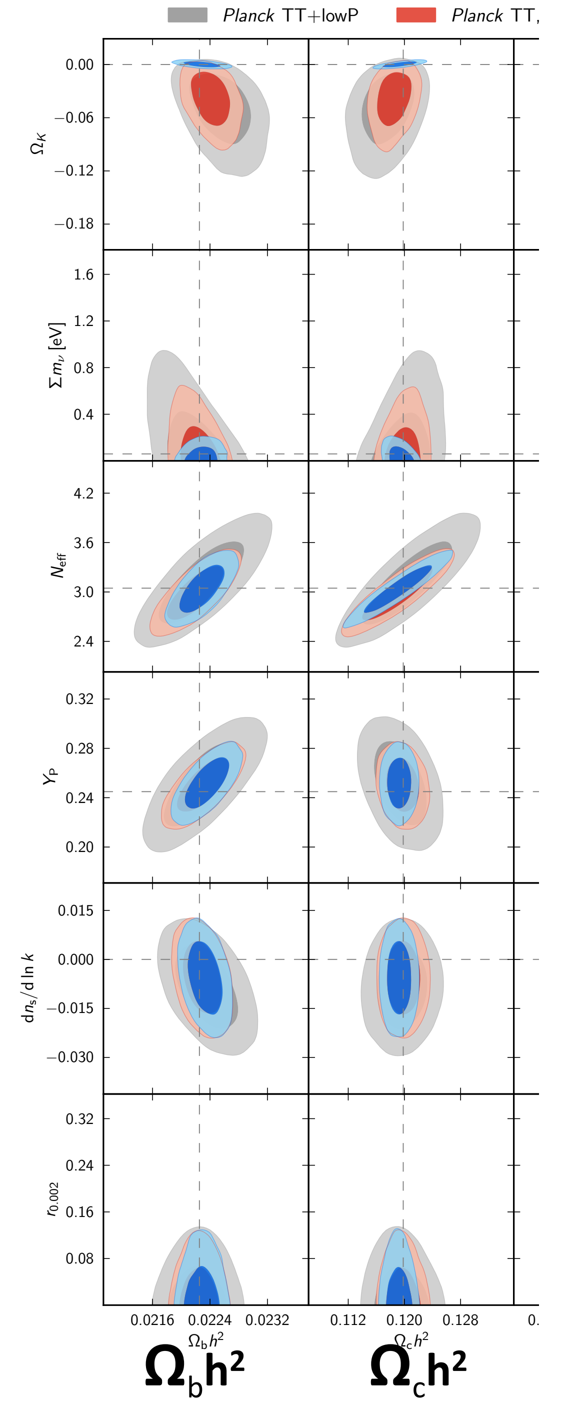


Planck cosmology paper 2015

Planck TT+lowP (grey)

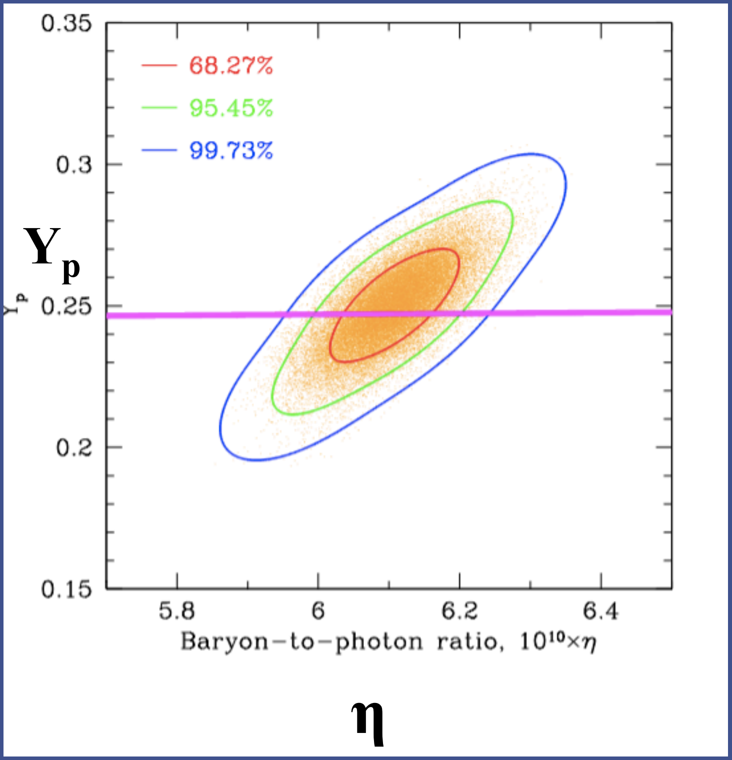
Planck TT,TE,EE+lowP (red)

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



Big Bang Nucleosynthesis

He abundance



- Planck 2015 contours
- Fixed N = 3 (points)

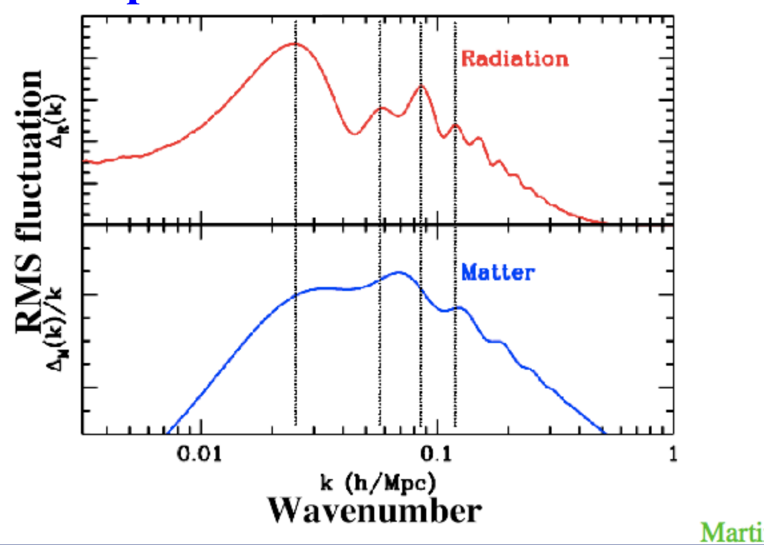
- BBN relation for Y_p
- Includes 3-σ nuclear rate uncertainties

Completely independent test of standard BBN CMB data only

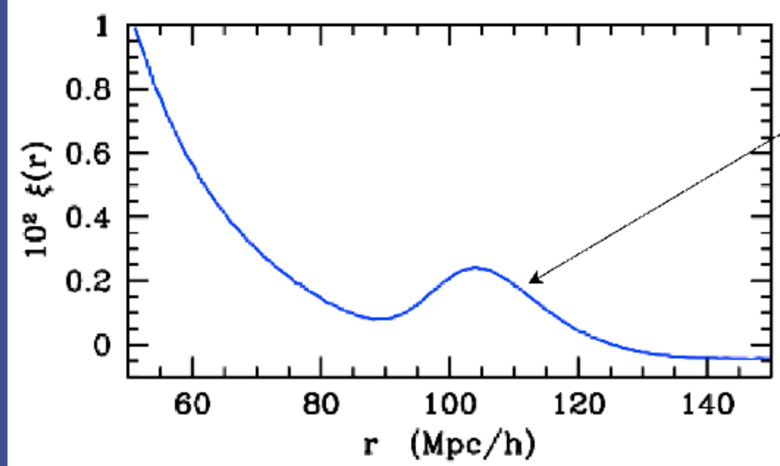
Cybert et al. 2015 1505.01076

Baryon Acoustic Oscillations

Power spectrum

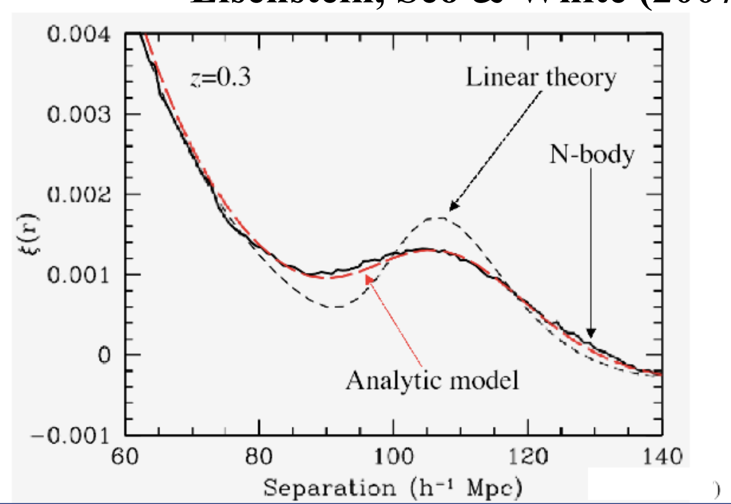


Correlation function



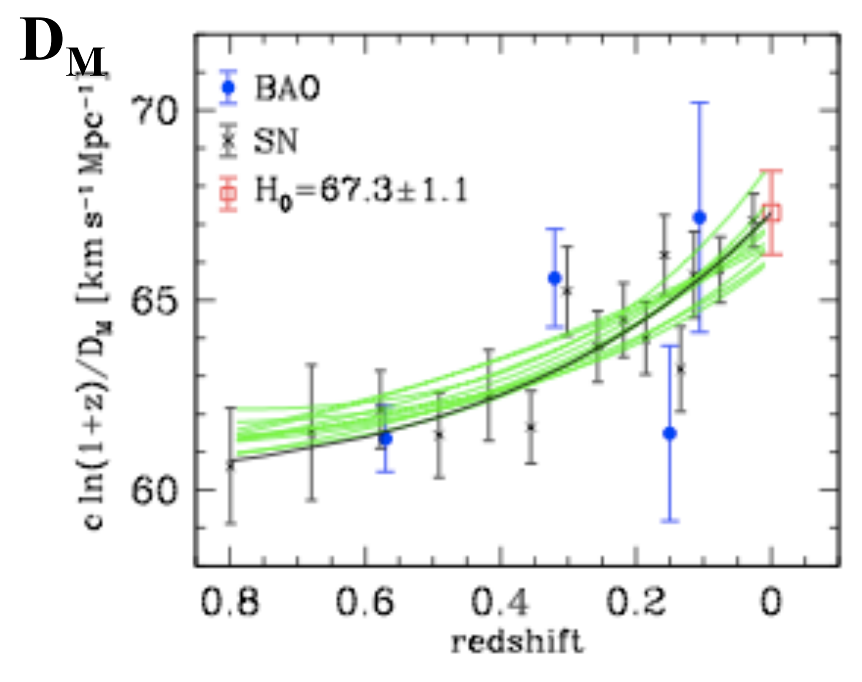
Non-linearities

Eisenstein, Seo & White (2007)



Baryon Acoustic Oscillations

"Inverse Distance Ladder"



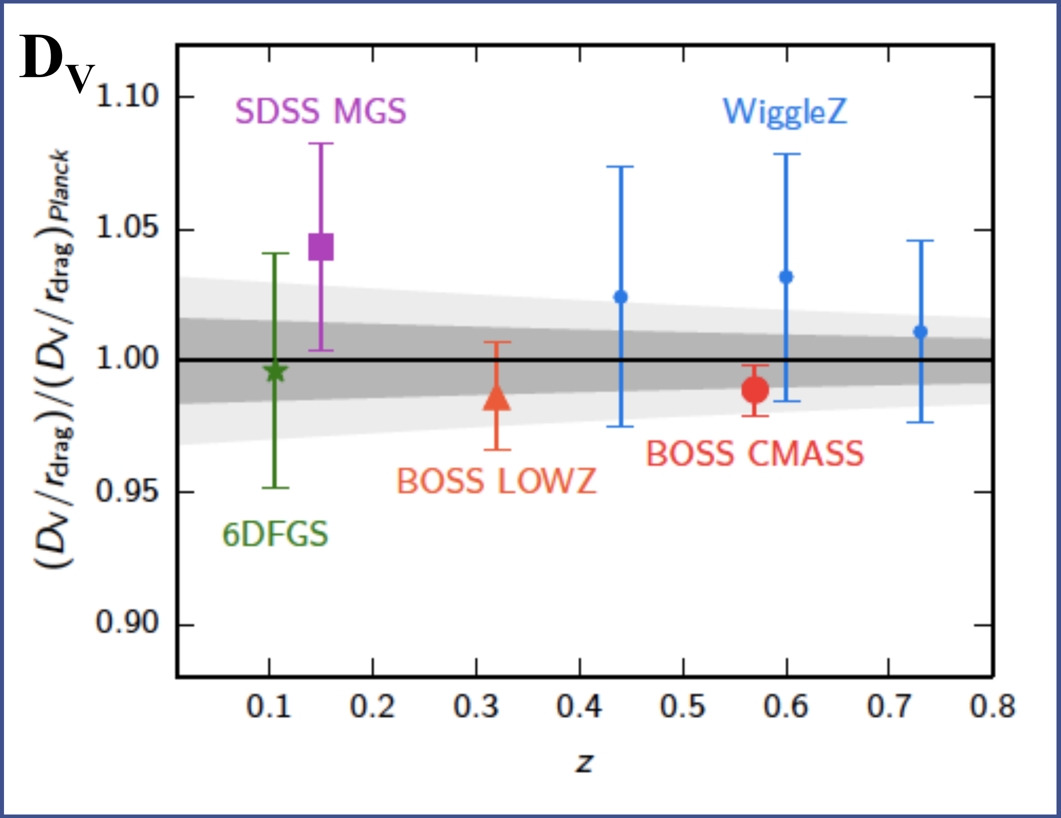
- BAO, SNIa distances
- Planck CMB calibrates sound horizon scale, r_d
- BAO points normalized with r_d = 147.49 Mpc
- D_v is converted to D_M assuming ΛCDM.
- The SNIa points are shifted vertically to match the BAO data

$$D_V(z) \equiv \left[D_M^2(z) \times cz/H(z)\right]^{1/3}$$

$$D_V(z) = \left[(1+z)^2 D_A^2(z) \frac{cz}{H(z)}\right]^{1/3}$$

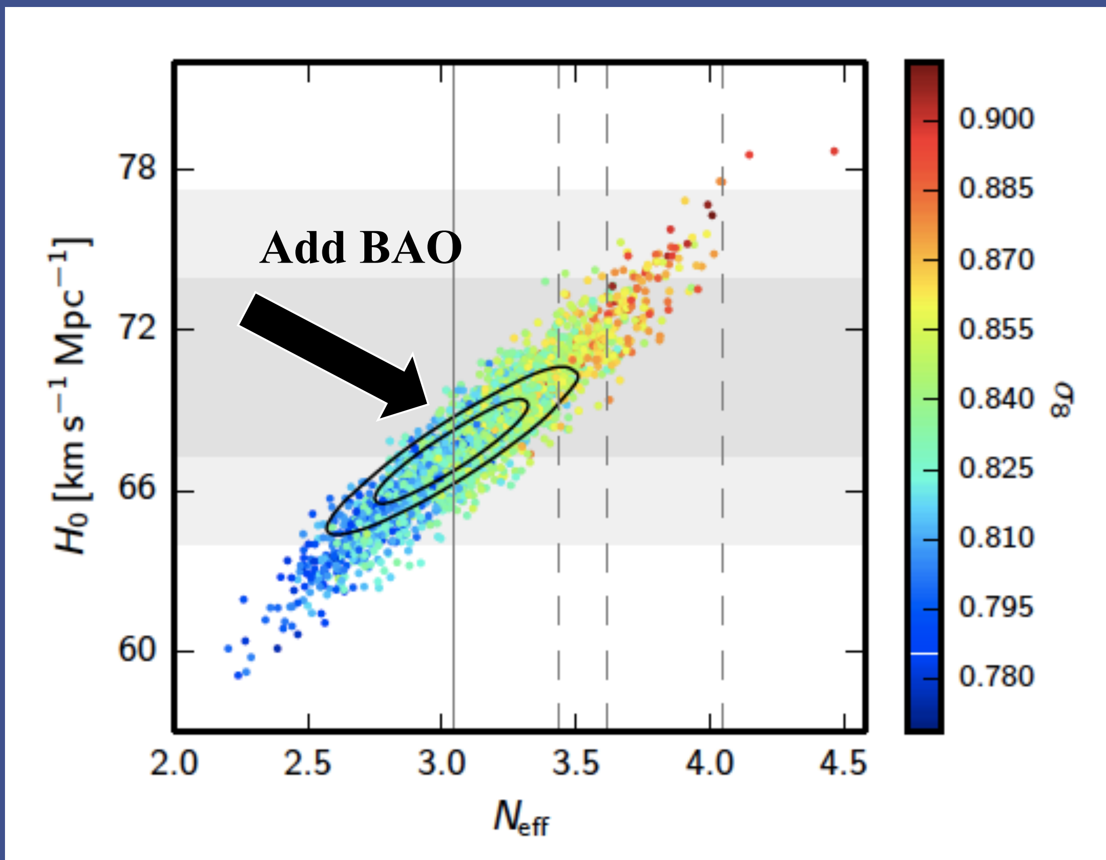
Aubourg et al. 2015

BAO + Planck 2015



Planck 2015 XIII

BAO + Planck 2015

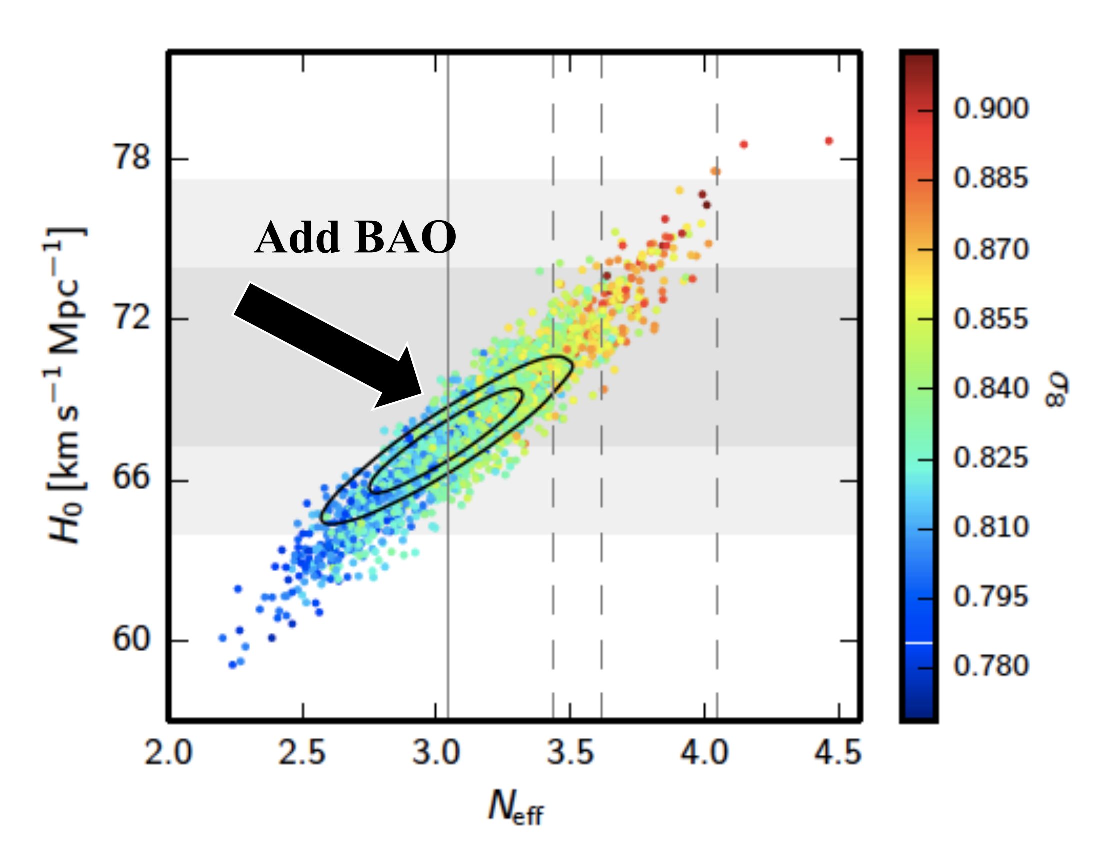


Samples from Planck TT+lowP chains in the N_{eff}–H_0 plane, color-coded by σ_8.

Add BAO
Solid contours:
Planck TT,TE,EE+lowP+BAO.

Planck 2015 XIII

BAO + Planck 2015



LCDM model

Planck 2015 TT+lowP

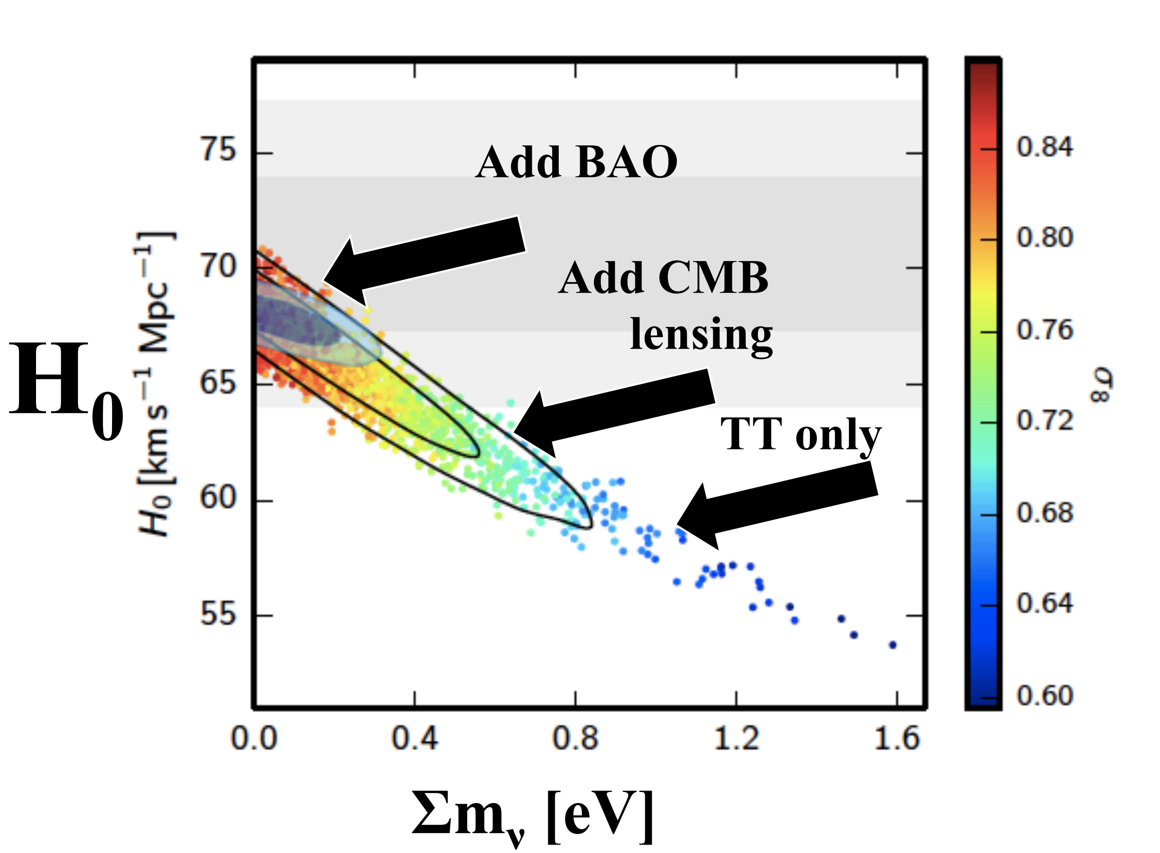
$H_0 = 67.3 \pm 1.0$ km/s/Mpc
$\Omega_m = 0.315 \pm 0.013$

Planck 2015 TT+lowP + BAO

$H_0 = 67.6 \pm 0.6$ km/s/Mpc
$\Omega_m = 0.310 \pm 0.008$

Planck 2015 XIII

BAO + Planck 2015



- TT + pol + lensing + BAO + H_0 + SNIa

- $\Sigma m_\nu < 0.23$ eV [95% CL]

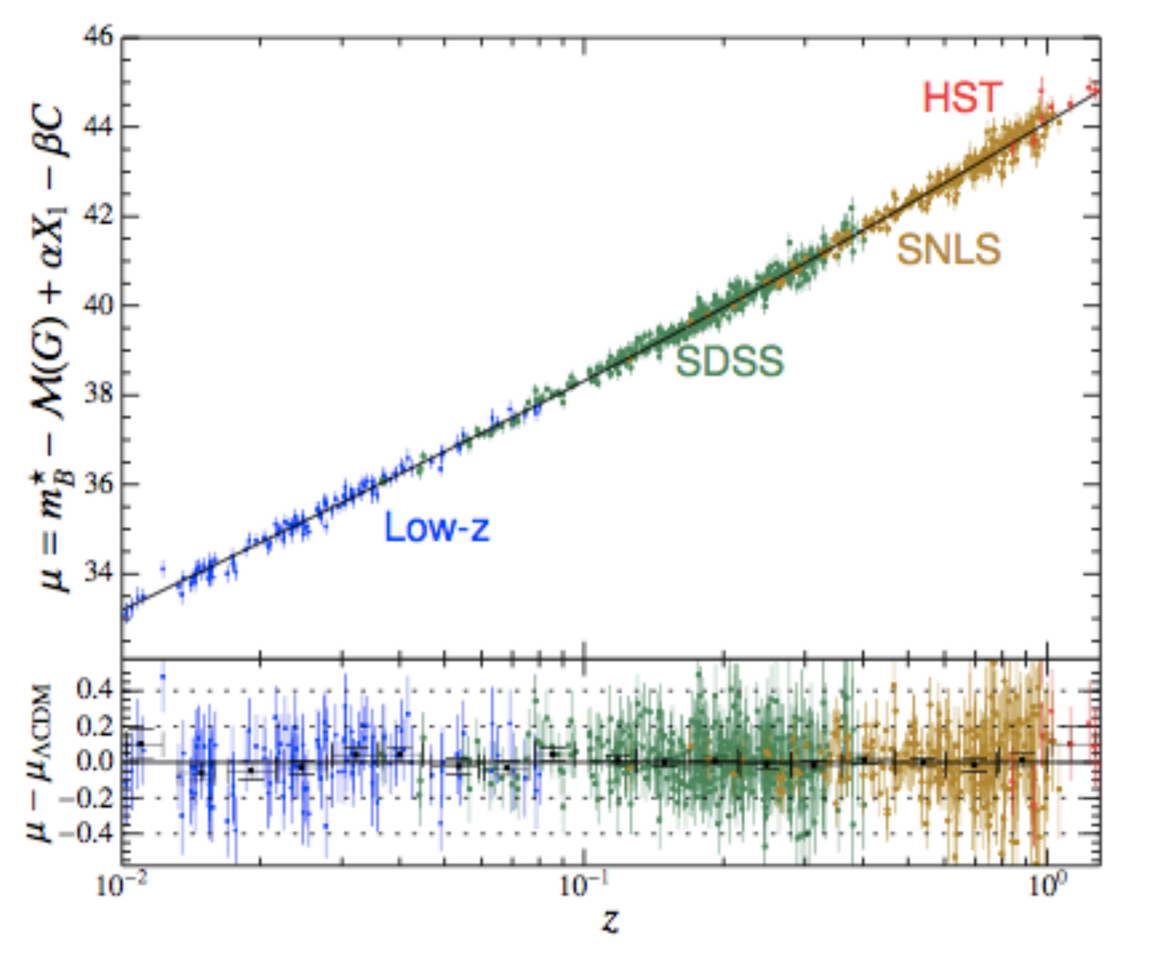
"Best estimate"

- $\Sigma m_\nu < 0.49$ eV [95% CL]

Planck TT; TE; EE+lowP

Planck 2015 XIII

Type Ia Supernovae



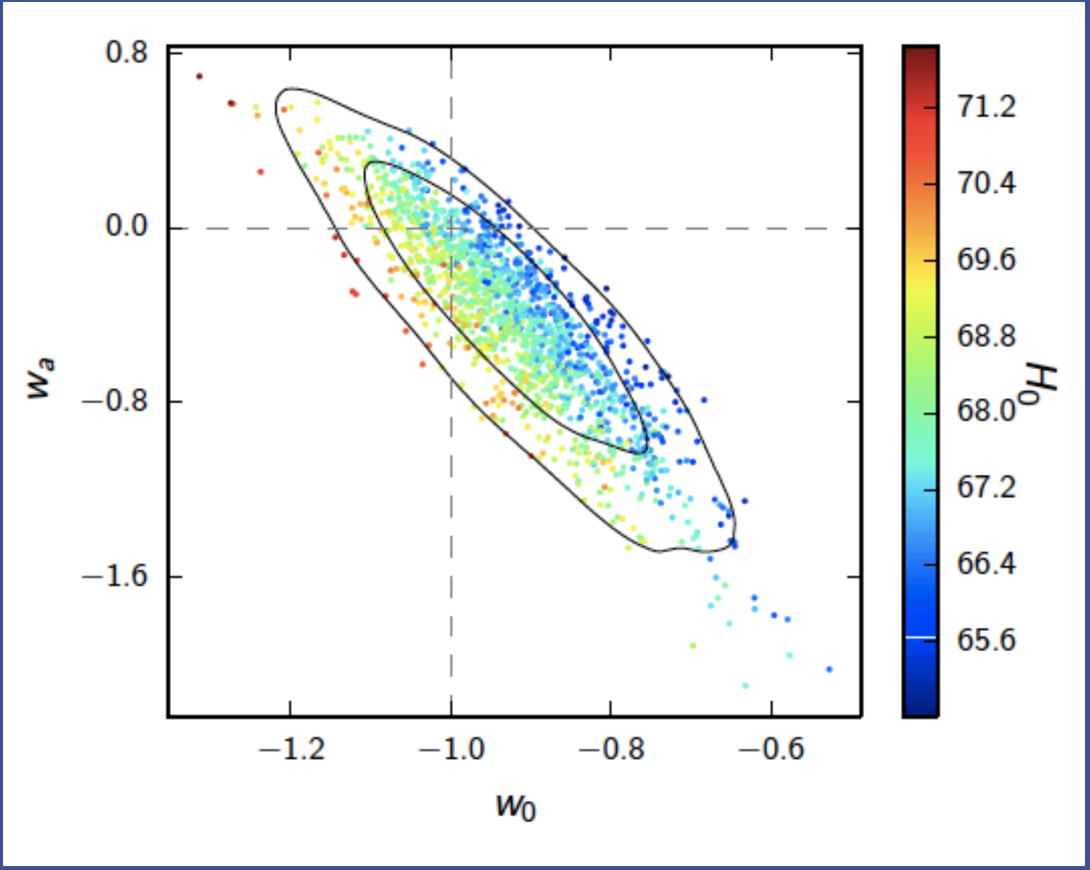
Betoule et al. 2014
Joint Light-Curve Analysis

$\Omega_m = 0.295 \pm 0.034$

w = -1.018 ± 0.057 with
Planck13 + flat universe
w = -1.027 ± 0.055 with
Planck13 + flat universe
+ BAO

$H_0 = 68.5 \pm 1.27$ km/s/Mpc
including BAO

Type Ia Supernovae



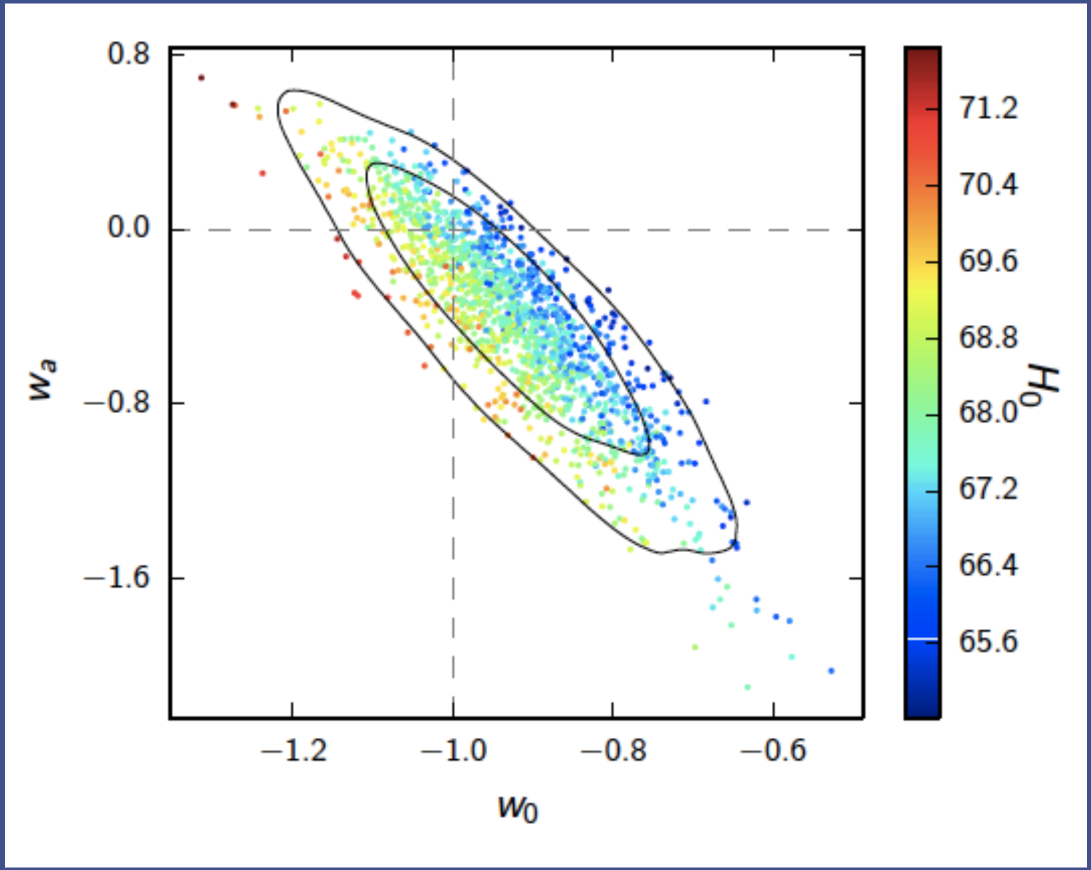
Planck 2015 XIII
Betoule et al. 2014 SNe

$$w = w_0 + (1\text{-}a)\, w_a$$

Joint analysis consistent with LCDM

Planck 2015 XIII

Type Ia Supernovae



From Planck alone:
TT + low P (95%CL)

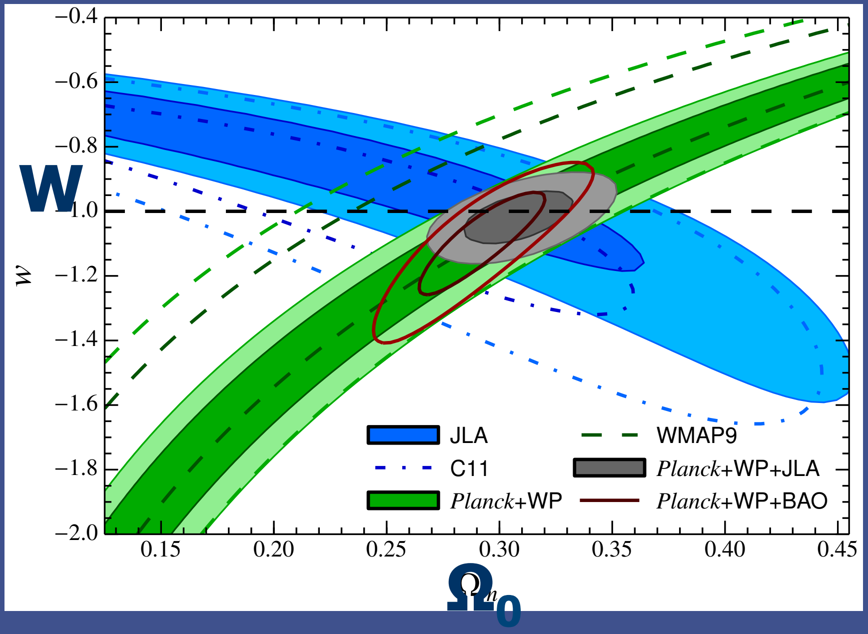
$$w = -1.54^{+0.62}_{-0.50}$$

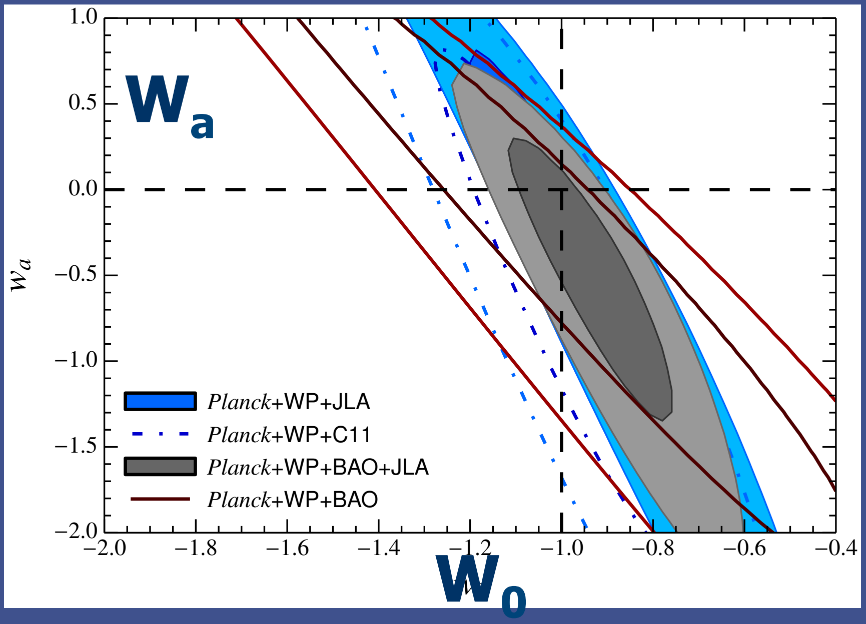
Add in Planck lensing + BAO + SNIa + H_0

$$w = -1.019^{+0.075}_{-0.080}$$

Planck 2015 XIII

Combining Constraints





Betoule et al. 2014
Combining CMB, SN, BAO, WL, Clusters

Improvements to H_0

Recent Direct Measurements of H_0

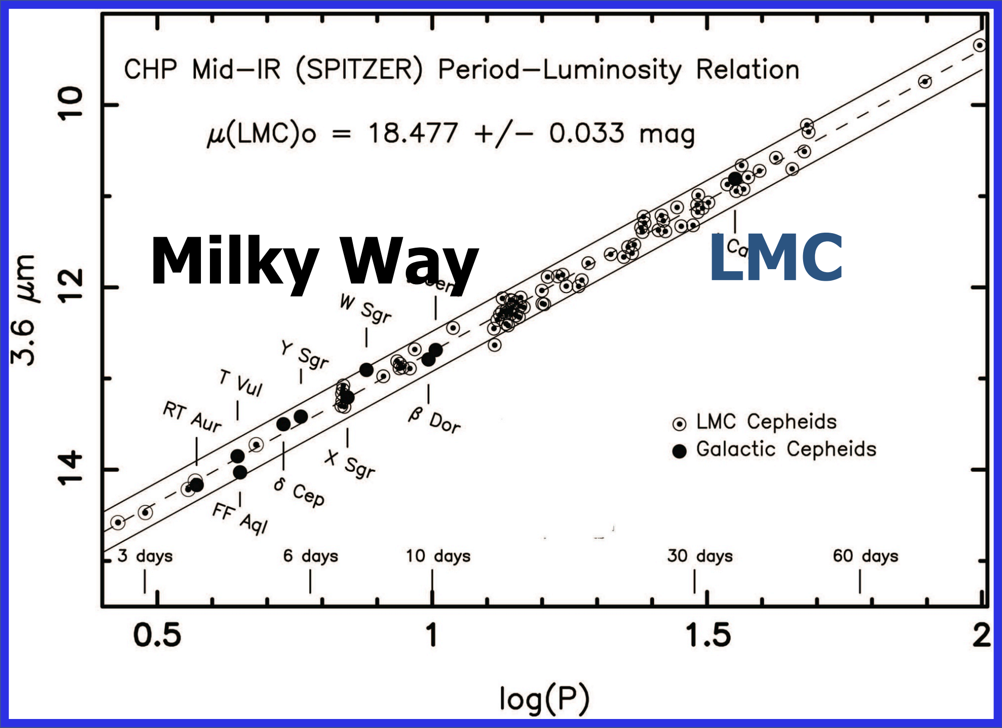
- **SH$_0$ES (Riess et al. 2011) :**
  $H_o = 73.9 \pm 2.4$ km s^{-1} Mpc^{-1}

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

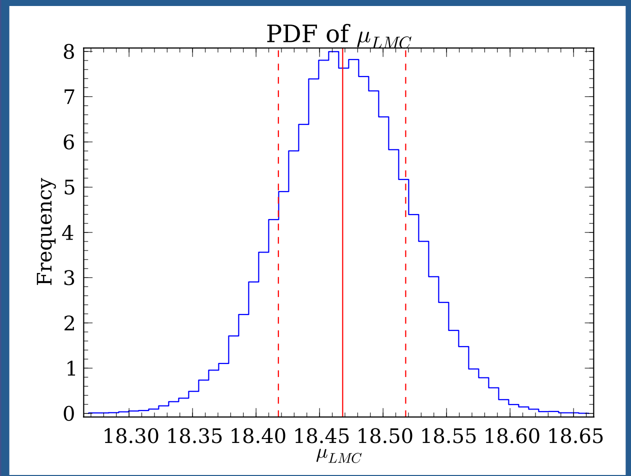
Planck LCDM estimate of H_0

- **Planck 2015**
  $H_o = 67.3 \pm 1.3$ km s^{-1} Mpc^{-1}

Comparison of Spitzer LMC and Milky Way Leavitt Laws



WLF *et al.* (2012)

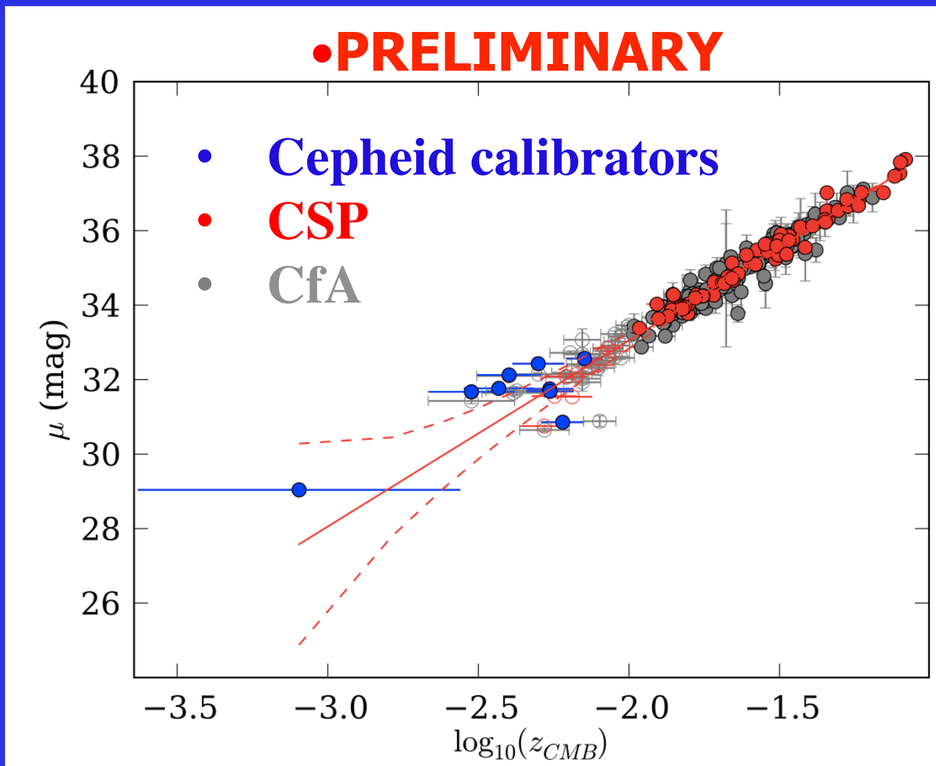


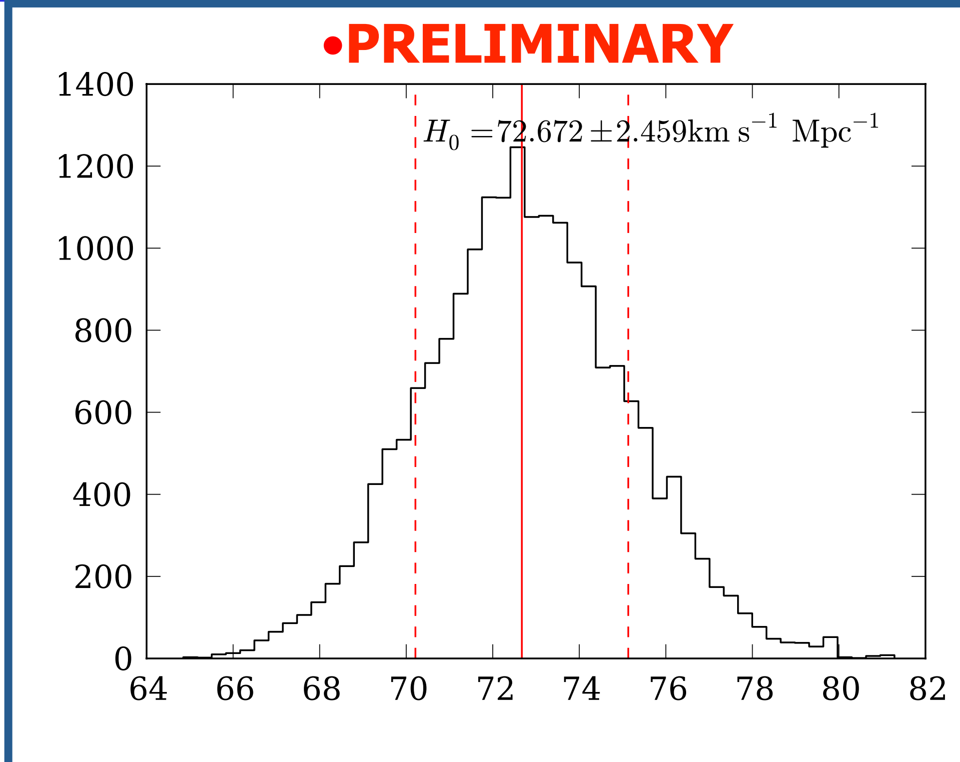
$\mu_{\mathrm{LMC}} = 18.48 \pm 0.01$ (stat) ± 0.03(sys)

d = 49.6 ± 0.8 kpc

WLF *et al.* (2015)

H_0 From Enlarged Sample of Type Ia Supernovae

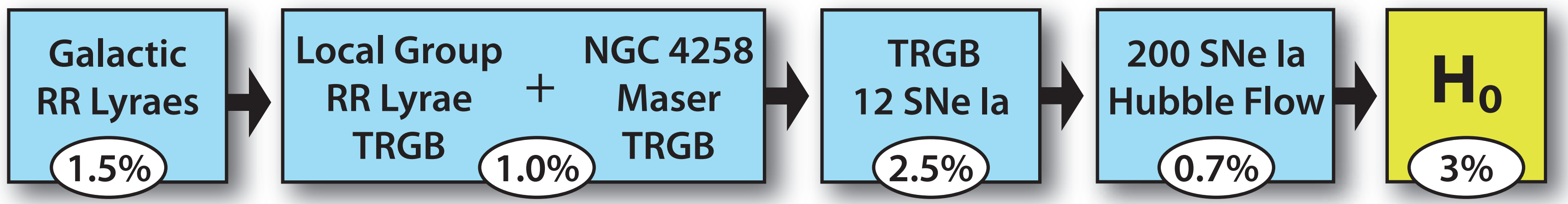




Beaton et al. (2015)

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

An Independent Route to H_0 (Carnegie Chicago Hubble Project: CHP II)



The CHP-II Path to a 3% Determination of the Hubble Constant

- The dispersion in the RR Lyrae period-luminosity relation is <0.05 mag; half that of Cepheids
- Measurement of H0 to 3% + Planck
- One of most accurate measurements of w

An Independent Calibration of H_0 Using RR Lyrae Stars

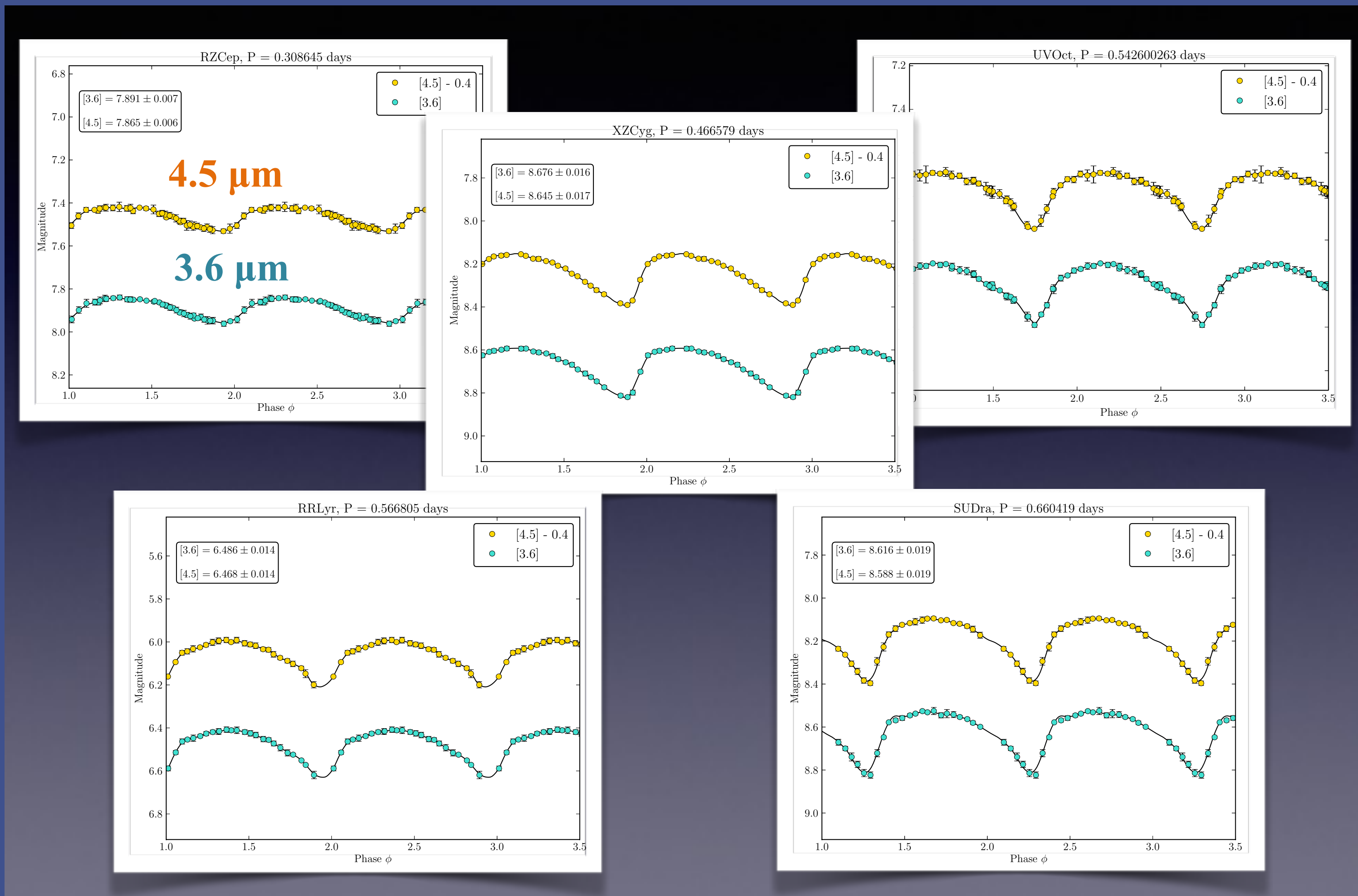
There exists a PL relation for RR Lyrae stars in the IR!

- (Not in the optical – it is a HORIZONTAL BRANCH)
- Extremely small scatter: $\sigma \sim 0.05$ mag in the mid-IR
- This distance scale is
  - Independent of the Cepheid scale
  - And more accurate!
- New distances to RR Lyrae stars (with parallaxes)
- New distance to the LMC

Carnegie Chicago Hubble Project (CCHP) II

- **HST Cycle 22: 132 hours prime, 52 parallel H-band observations**
- **Spitzer Cycle 9 (3.6 µm), Magellan (JHK), TMMT (BVI)**
- **RR Lyrae and TRGB distances**
- **Double the number of SNIa calibrators**
- **Goal: H_0 to 3%**

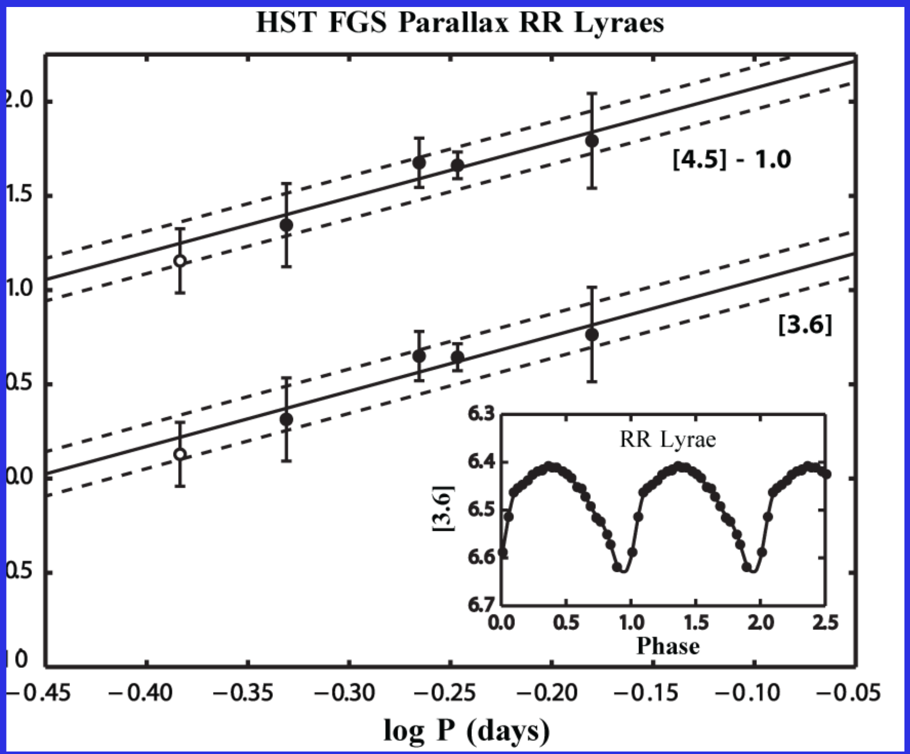
RR Lyrae Parallax Calibrator Sample



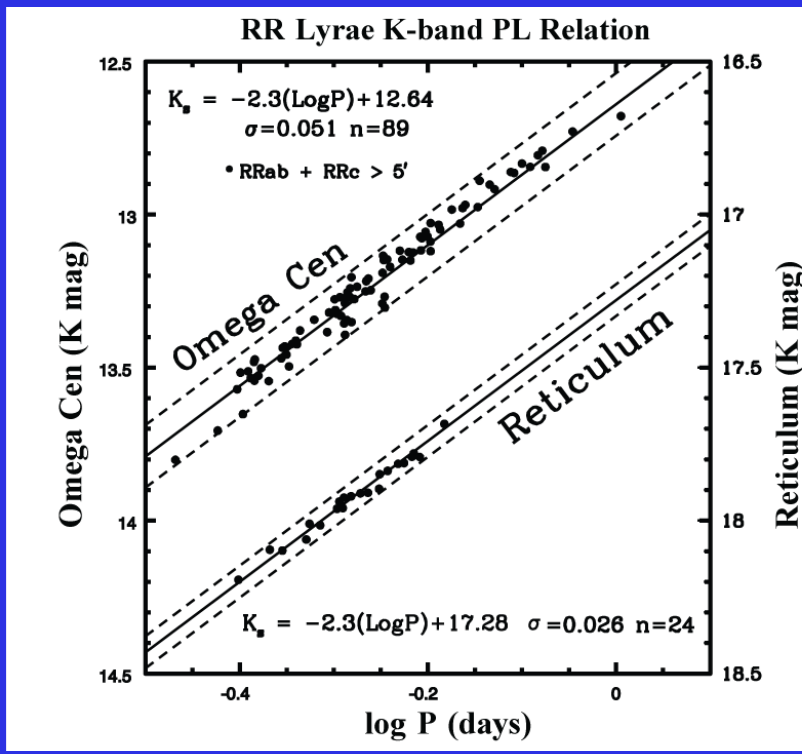
V. Scowcroft

Recent RR Lyrae Distances (Spitzer, Magellan, TMMT**)

Galactic Parallax Sample

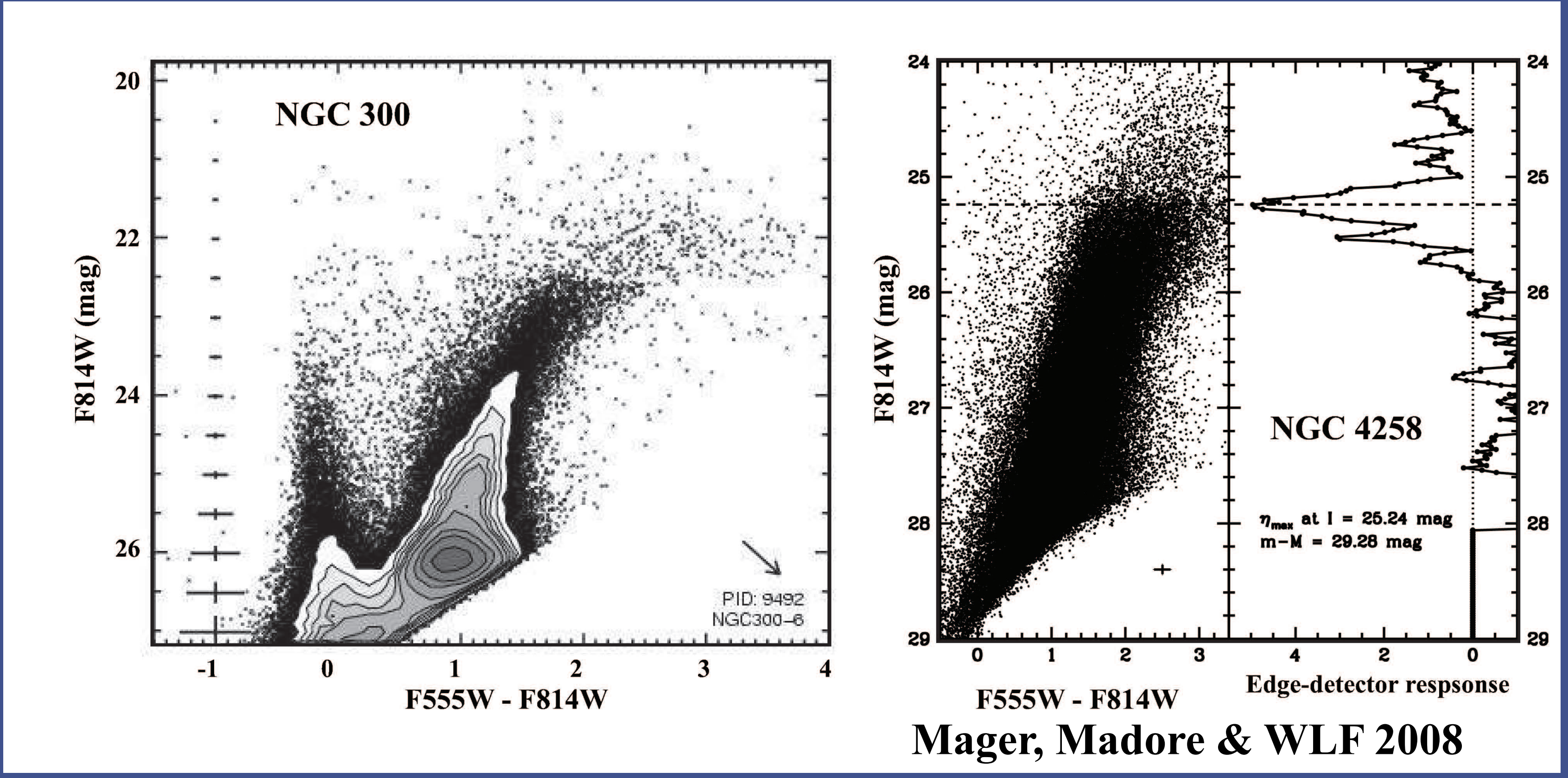


Omega Cen, Reticulum (LMC)



A. Monson, B. Madore, M. Durbin et al.

Tip of the Red Giant Branch (TRGB) Distances

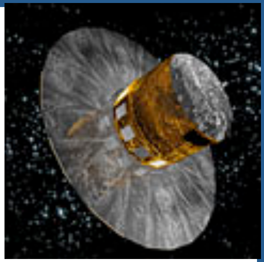


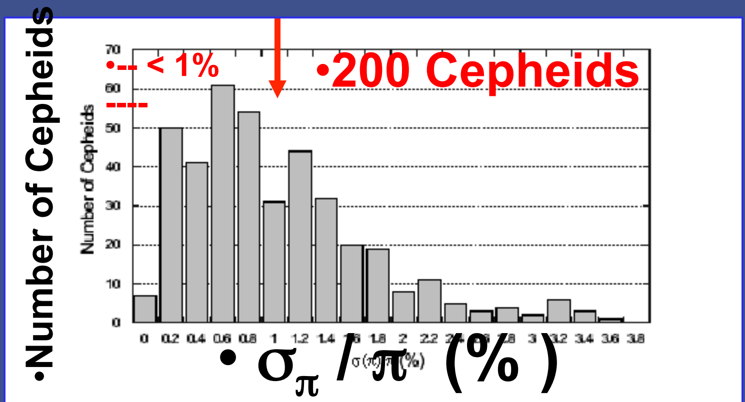
NGC 300 **NGC 4258**

Future Parallax Measurements

ESA’s Global Astrometric Interferometer for Astrophysics (Gaia)

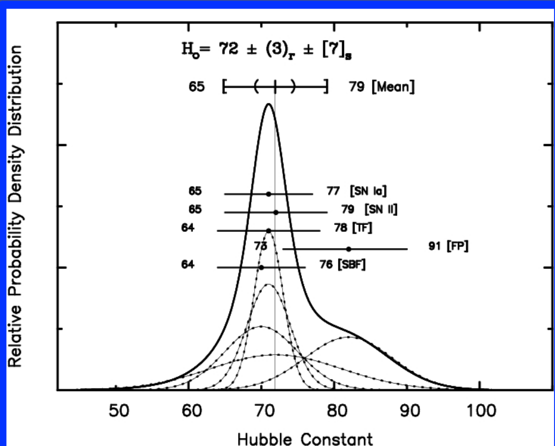
- ❖ A few microsecond accuracy
- ❖ Systematic survey of entire sky to 20 mag
- ❖ $\sigma_\pi / \pi < 1\%$ out to several kiloparsecs
- ❖ Accurate measurements of many Cepheids and RR Lyrae variables (~100’s of Cepheids; 1000’s of RR Lyraes) [~70 observations per object] + Spitzer, HST
- ❖ Distance to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

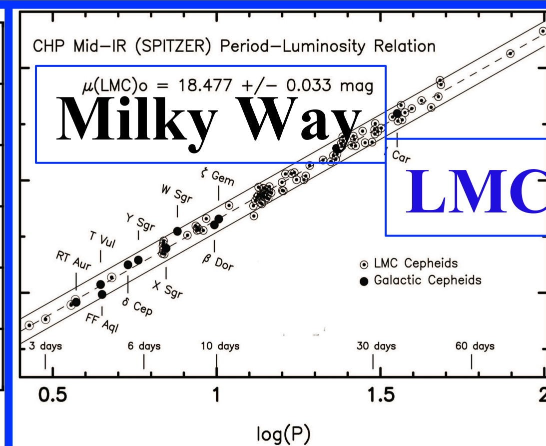


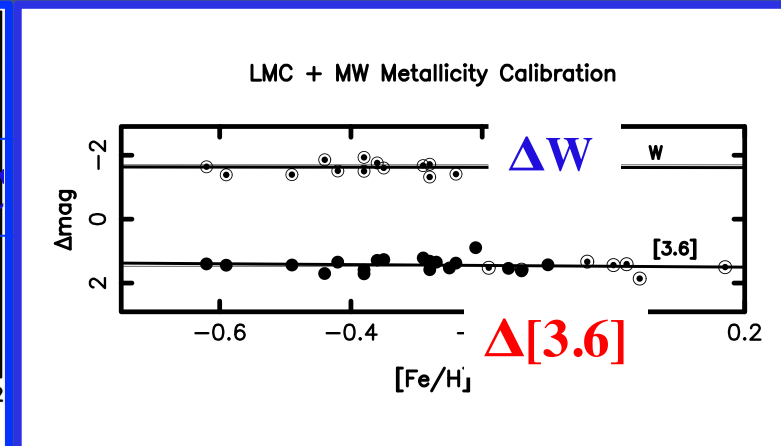


•Expected relative accuracy in the distance of Galactic Cepheids from Gaia.

Direct Measurements of H_0: Decreasing Systematics

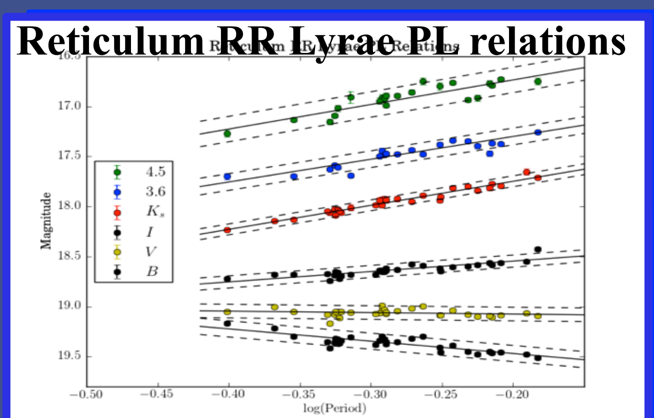


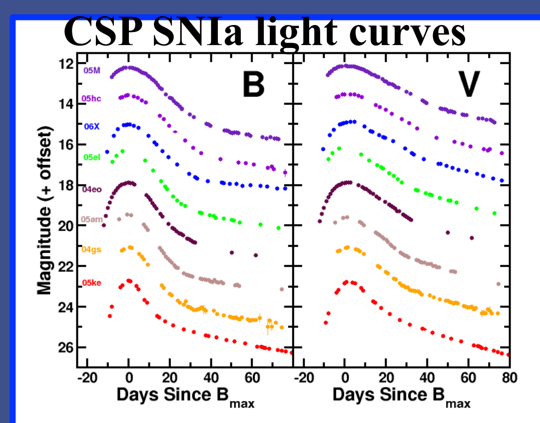


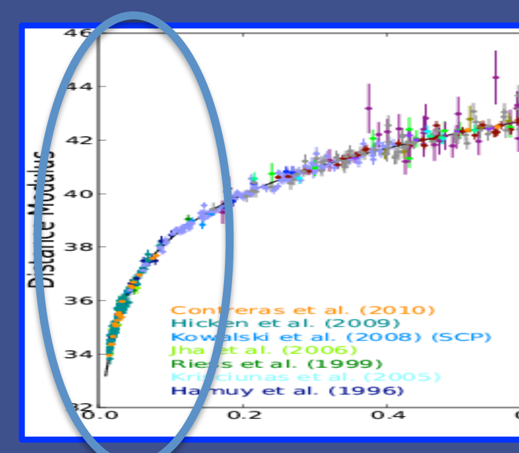


WLF et al. (2001)

WLF et al. 2012; Scowcroft et al. 2012; Monson et al 2015





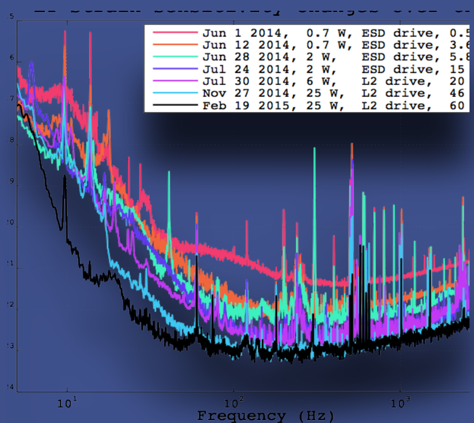


Other Future H_0 Measurements:
Target H_0 to 1%: (sys + stat)

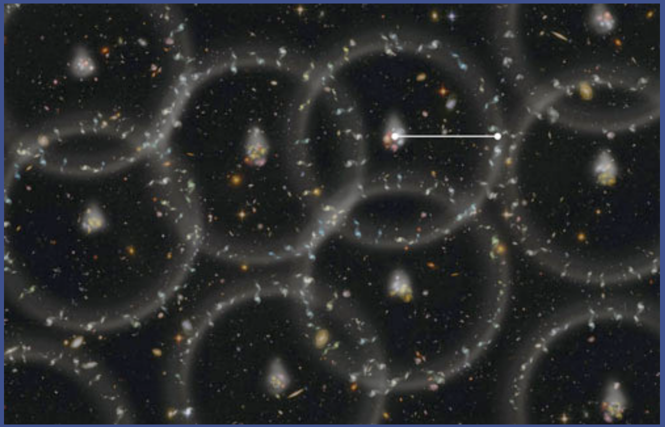
Overcoming Systematics

LIGO

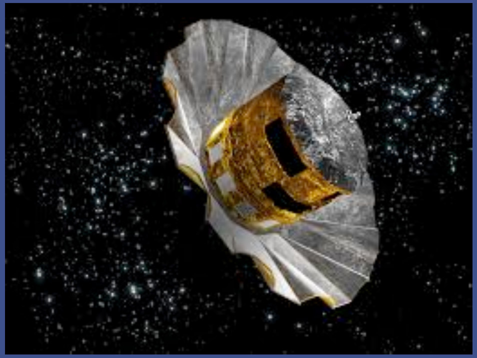
Gravitational Waves



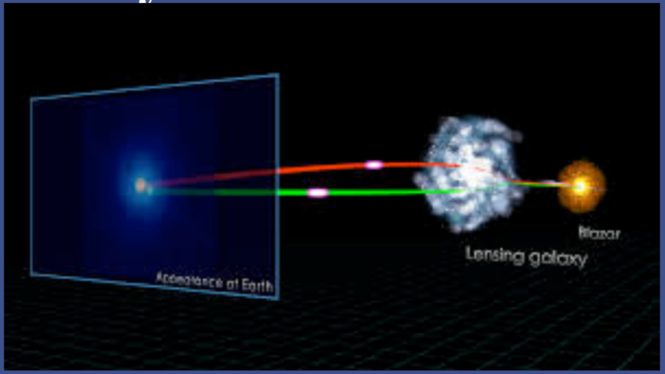
BAO



Gaia Calibration of Cepheid/RRL/SNIae

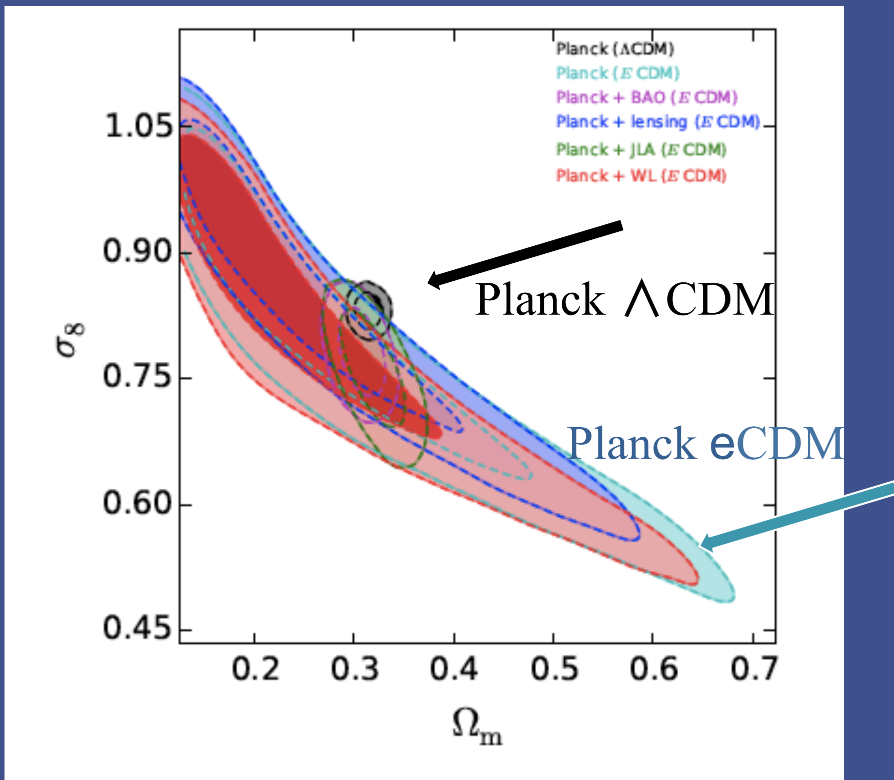


Gravitational Lens Time Delays



For robust measurement at least 3 independent methods with uncertainties at ~1% level

Planck: Relaxing Parameter Constraints



Planck 2015 data
6- to 12-parameter fit
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

Di Valentino, Melchiorri & Silk 2015

Cosmological Parameters from 12-parameter Fits to Planck 2015 Data

Model Dataset	$\Omega_b h^2$	$\Omega_c h^2$	H_0
Λ CDM Planck	$0.02226^{+0.00031}_{-0.00029}$	$0.1198^{+0.0028}_{-0.0028}$	$67.3^{+1.3}_{-1.3}$
Λ CDM Planck+ BAO	$0.02229^{+0.00028}_{-0.00027}$	$0.1193^{+0.0021}_{-0.0020}$	$67.52^{+0.93}_{-0.93}$
e CDM Planck	$0.02239^{+0.00060}_{-0.00056}$	$0.1186^{+0.0071}_{-0.0068}$	> 51.2
e CDM Planck+BAO	$0.02251^{+0.00056}_{-0.00052}$	$0.1185^{+0.0069}_{-0.0069}$	$68.4^{+4.3}_{-4.1}$
e CDM Planck+lensing	$0.02214^{+0.00053}_{-0.00052}$	$0.1176^{+0.0069}_{-0.0066}$	> 54.5
e CDM Planck+HST	$0.02239^{+0.00059}_{-0.00057}$	$0.1187^{+0.0072}_{-0.0070}$	$74.4^{+5.1}_{-5.1}$
e CDM Planck+JLA	$0.02242^{+0.00058}_{-0.00056}$	$0.1188^{+0.0071}_{-0.0067}$	$67.4^{+4.4}_{-4.2}$
e CDM Planck+WL	$0.02251^{+0.00056}_{-0.00055}$	$0.1188^{+0.0073}_{-0.0069}$	> 54.2
e CDM Planck+BAO-RSD	$0.02253^{+0.00052}_{-0.00050}$	$0.1184^{+0.0069}_{-0.0067}$	$68.6^{+4.2}_{-3.9}$
e CDM Planck+BKP	$0.02237^{+0.00057}_{-0.00056}$	$0.1186^{+0.0072}_{-0.0069}$	> 52.3

Σm_ν
w
r
$dn_s/d\ln k$
A_{lens}
N_{eff}

Di Valentino, Melchiorri & Silk 2015

Cosmological Parameters from 12-parameter Fits to Planck 2015 Data

Model Dataset	H_0	w	σ_8	$N_{\rm eff}$	$A_{\rm lens}$
Λ CDM Planck	$67.3^{+1.3}_{-1.3}$	-	$0.831^{+0.026}_{-0.026}$	-	-
Λ CDM Planck+ BAO	$67.52^{+0.93}_{-0.93}$	-	$0.832^{+0.025}_{-0.025}$	-	-
e CDM Planck	> 51.2	$-1.32^{+0.98}_{-0.85}$	$0.81^{+0.24}_{-0.26}$	$3.08^{+0.57}_{-0.51}$	$1.21^{+0.27}_{-0.24}$
e CDM Planck+BAO	$68.4^{+4.3}_{-4.1}$	$-1.04^{+0.20}_{-0.21}$	$0.781^{+0.065}_{-0.063}$	$3.11^{+0.52}_{-0.48}$	$1.20^{+0.19}_{-0.19}$
e CDM Planck+lensing	> 54.5	$-1.45^{+0.96}_{-0.83}$	$0.85^{+0.21}_{-0.24}$	$2.93^{+0.51}_{-0.48}$	$1.04^{+0.16}_{-0.15}$
e CDM Planck+HST	$74.4^{+5.1}_{-5.1}$	$-1.32^{+0.29}_{-0.31}$	$0.81^{+0.10}_{-0.11}$	$3.09^{+0.58}_{-0.55}$	$1.18^{+0.19}_{-0.18}$
e CDM Planck+JLA	$67.4^{+4.4}_{-4.2}$	$-1.06^{+0.13}_{-0.14}$	$0.759^{+0.088}_{-0.089}$	$3.10^{+0.57}_{-0.54}$	$1.20^{+0.19}_{-0.17}$
e CDM Planck+WL	> 54.2	$-1.41^{+0.98}_{-0.79}$	$0.82^{+0.22}_{-0.25}$	$3.16^{+0.58}_{-0.56}$	$1.24^{+0.23}_{-0.22}$
e CDM Planck+BAO-RSD	$68.6^{+4.2}_{-3.9}$	$-1.05^{+0.17}_{-0.19}$	$0.774^{+0.055}_{-0.058}$	$3.12^{+0.51}_{-0.48}$	$1.22^{+0.18}_{-0.17}$
e CDM Planck+BKP	> 52.3	$-1.31^{+0.96}_{-0.89}$	$0.81^{+0.23}_{-0.25}$	$3.07^{+0.57}_{-0.55}$	$1.20^{+0.24}_{-0.22}$

No evidence for new physics beyond the Standard model

Di Valentino, Melchiorri & Silk 2015

Looking Ahead

- **Current / Near Term:**
  - **DES, PanStarrs, BOSS, HETDEX**
  - **Hyper Suprime-Cam (HSC) on Subaru**
  - **DESI**
  - **SPT, ACT, Planck**
- **Major New Facilities**
  - **WFIRST / AFTA; Euclid (Dark Energy Missions)**
  - **LSST (Large Synoptic Survey Telescope)**
  - **GMT, TMT, E-ELT**
  - **JWST**
  - **SKA (BAO of HI in galaxies)**
  - **eRosita (ESA x-ray telescope – cluster survey)**

Summary

- The Planck data, including polarization, are consistent with a 6-parameter ΛCDM model
- Is there no new physics beyond this current standard model?
  - Planck data alone cannot answer this question
  - A new generation of experiments (BAO, SNe, H_0, WL, CMB polarization) are well-poised to address this question
- Planck has set the bar very high!

Landau – "Cosmologists are often in error but never in doubt"