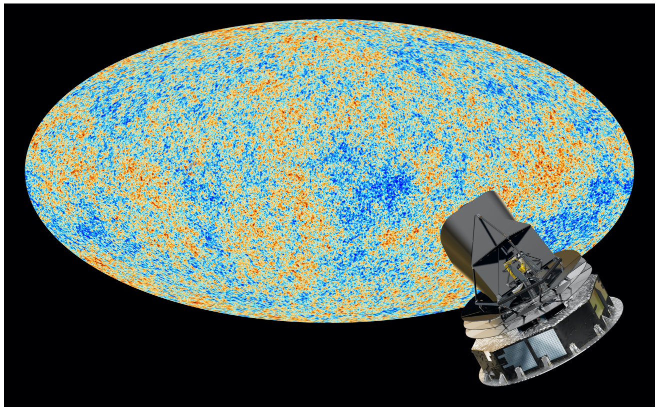
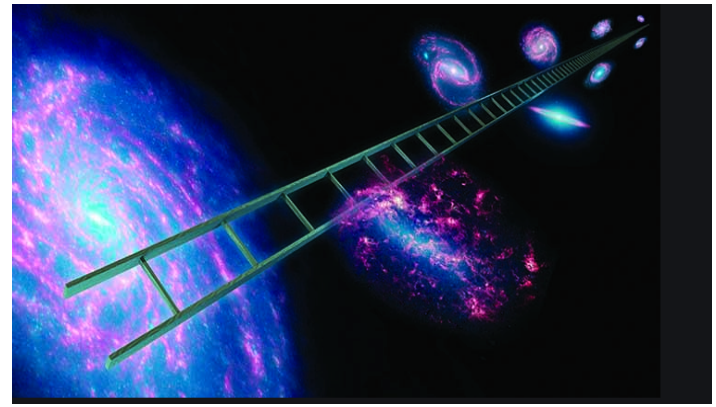
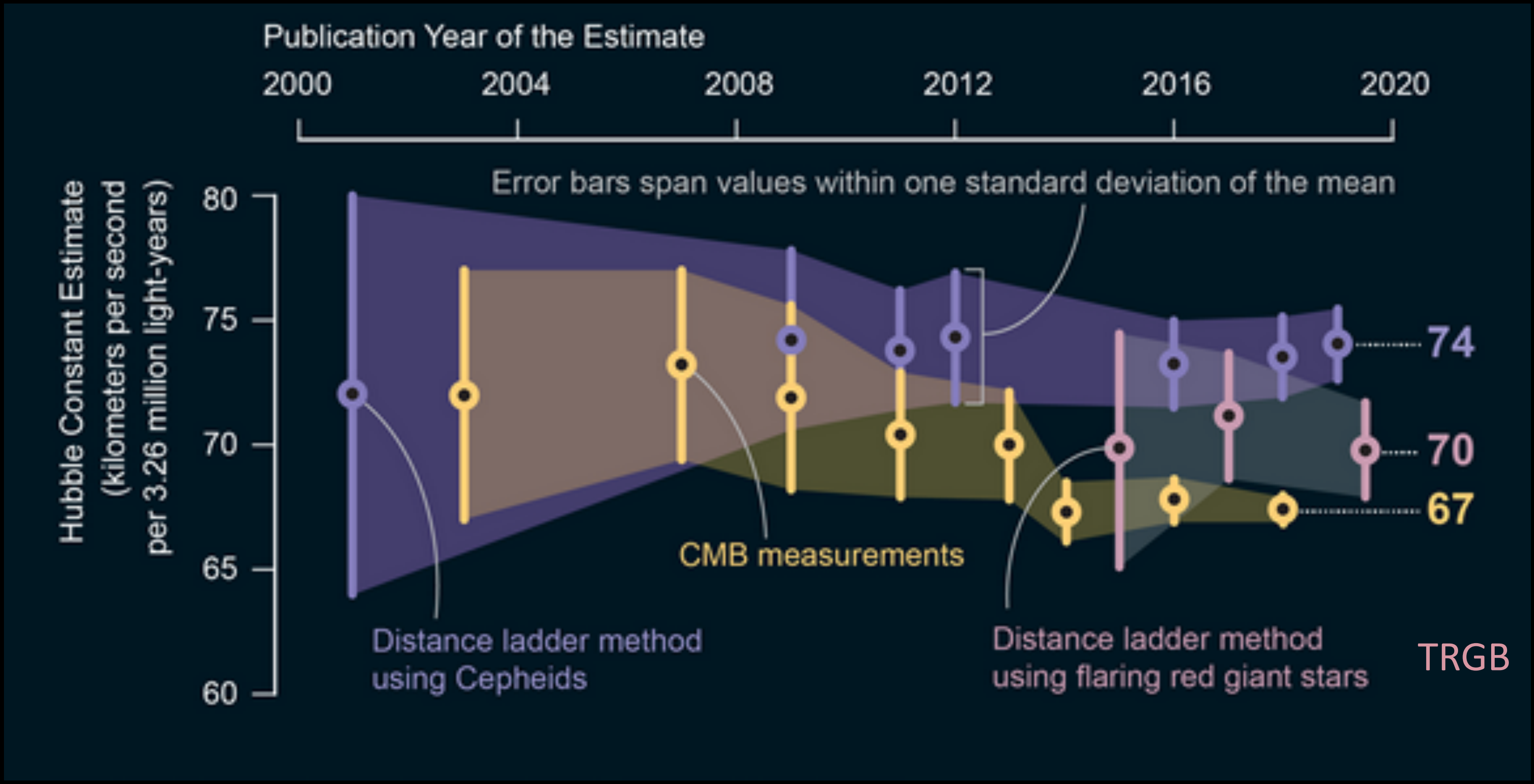
The H_0 tension





George Efstathiou, Kavli Institute forCosmology, Cambridge


Publication Year of the Estimate
2000
2004
2008
2012
2016
2020
Hubble Constant Estimate
(kilometers per second
per 3.26 million light-years)
80
75
70
65
60
Error bars span values within one standard deviation of the mean
74
70
67
CMB measurements
Distance ladder method
using Cepheids
Distance ladder method
using flaring red giant stars
TRGB

H_0 tension

Riess etal (2019):

H_0 = 74.03 ± 1.42 km/s/Mpc

(1.9% measurement)

Planck (2019):

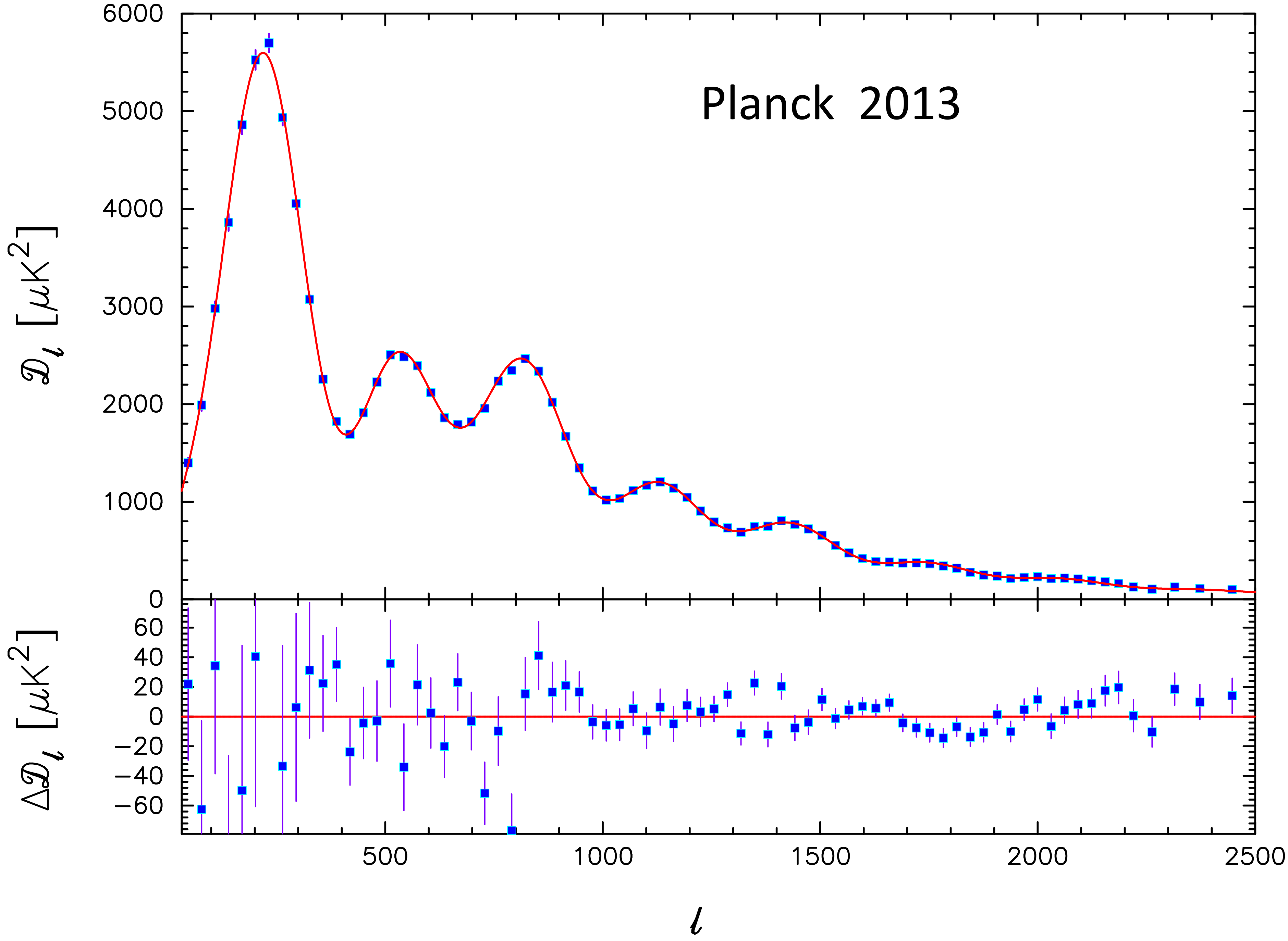
H_0 = 67.44 ± 0.58 km/s/Mpc

(0.9% measurement)

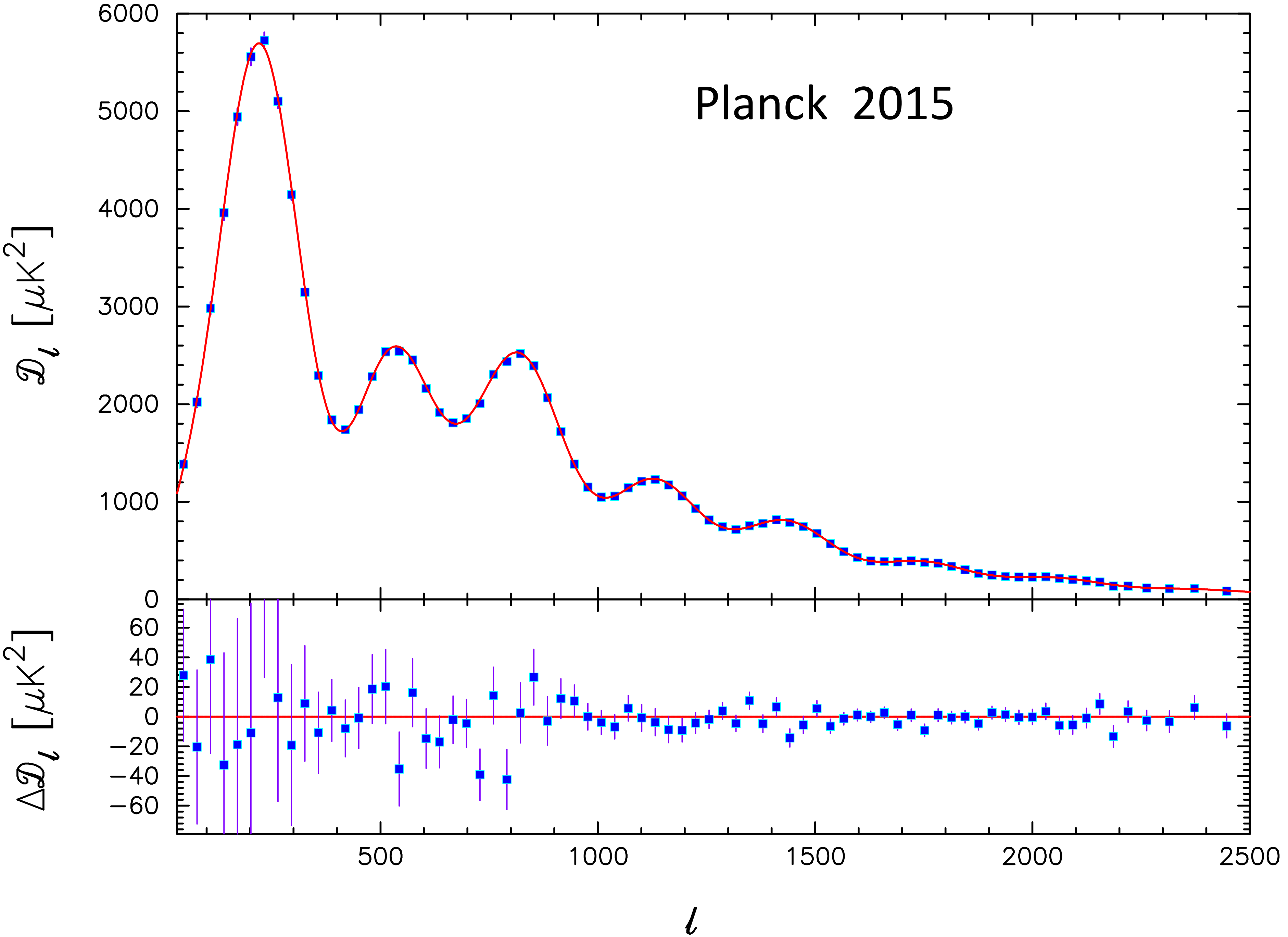
Discrepant by 6.59 km/s/Mpc

(≈ 10% discrepancy, or 4.3σ)

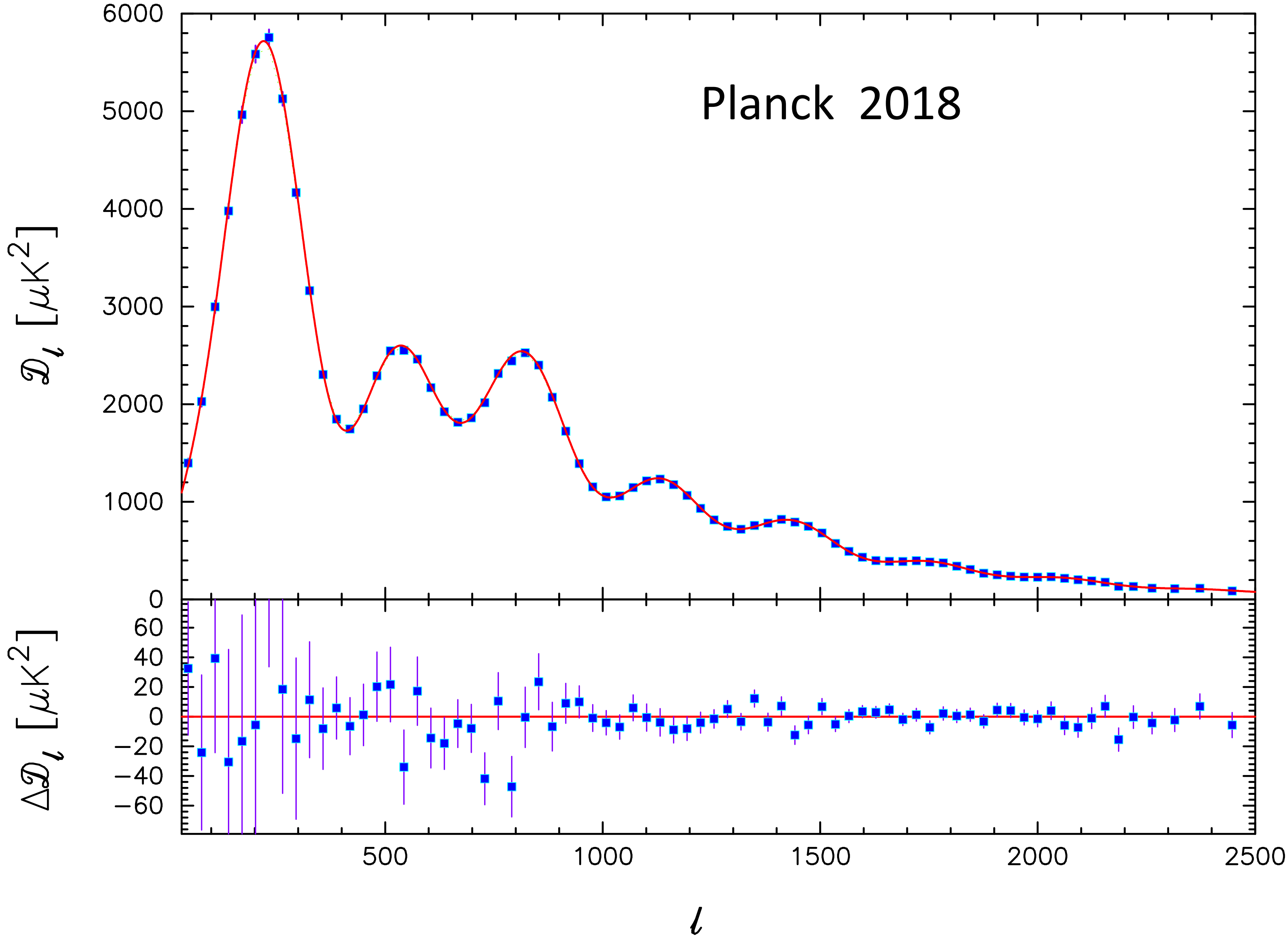
As Adam Riess emphasises *this is not a small discrepancy.*



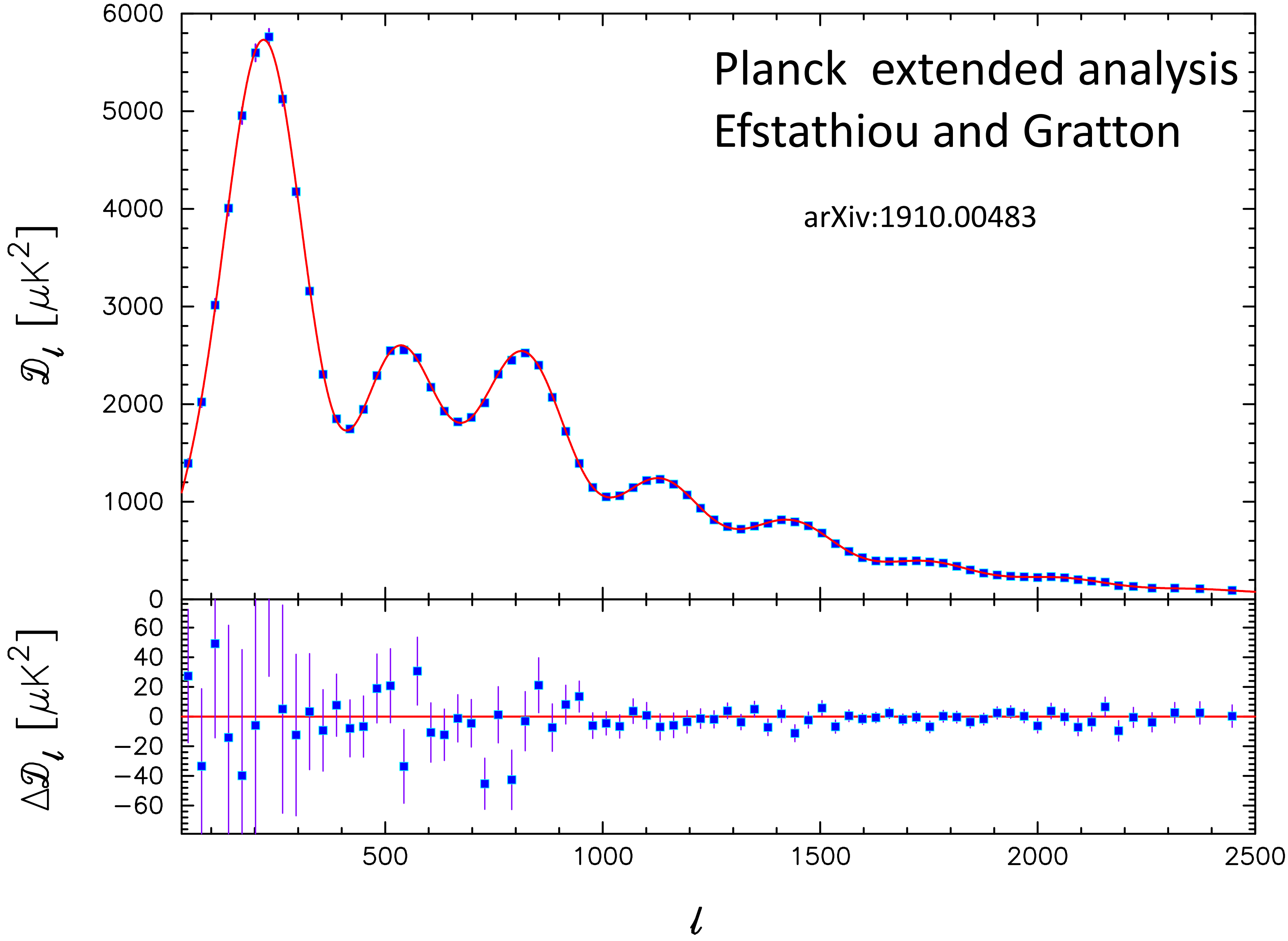
Planck 2013
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_l$ [μK^2]
60
40
20
0
−20
−40
−60
$\Delta\mathcal{D}_l$ [μK^2]
500
1000
1500
2000
2500
l

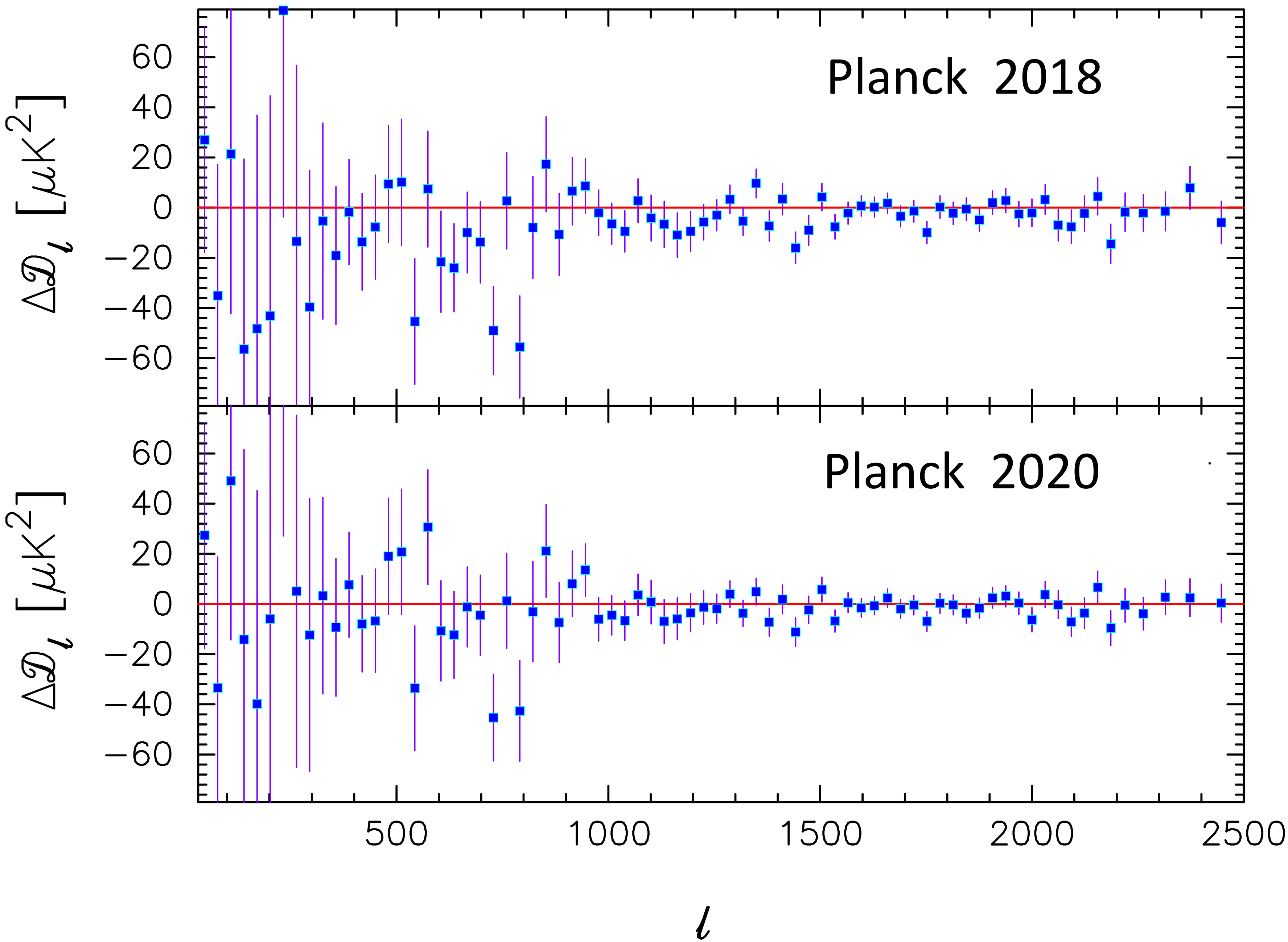


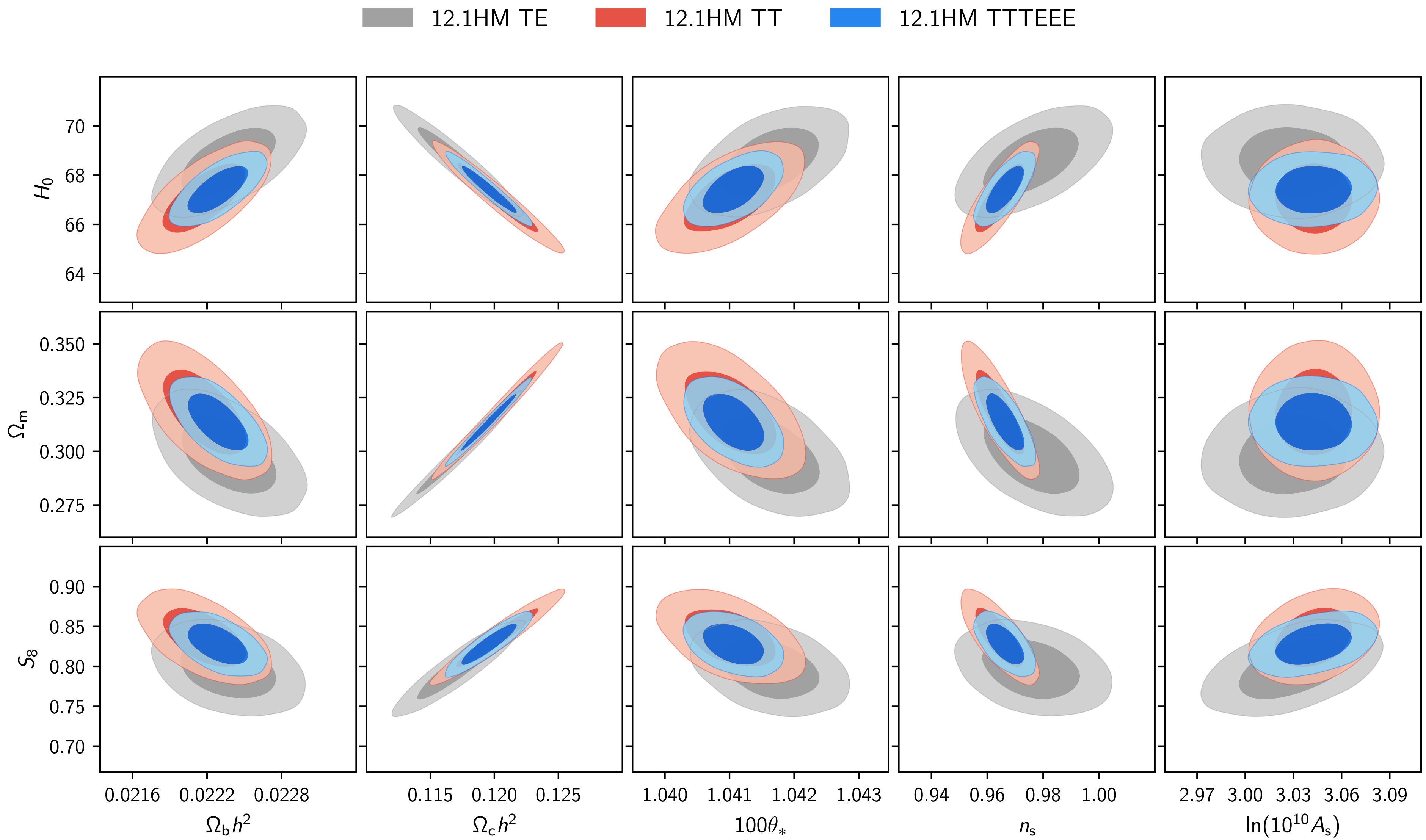
Planck 2015
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell$ [μK^2]
60
40
20
0
−20
−40
−60
$\Delta\mathcal{D}_\ell$ [μK^2]
500
1000
1500
2000
2500
ℓ



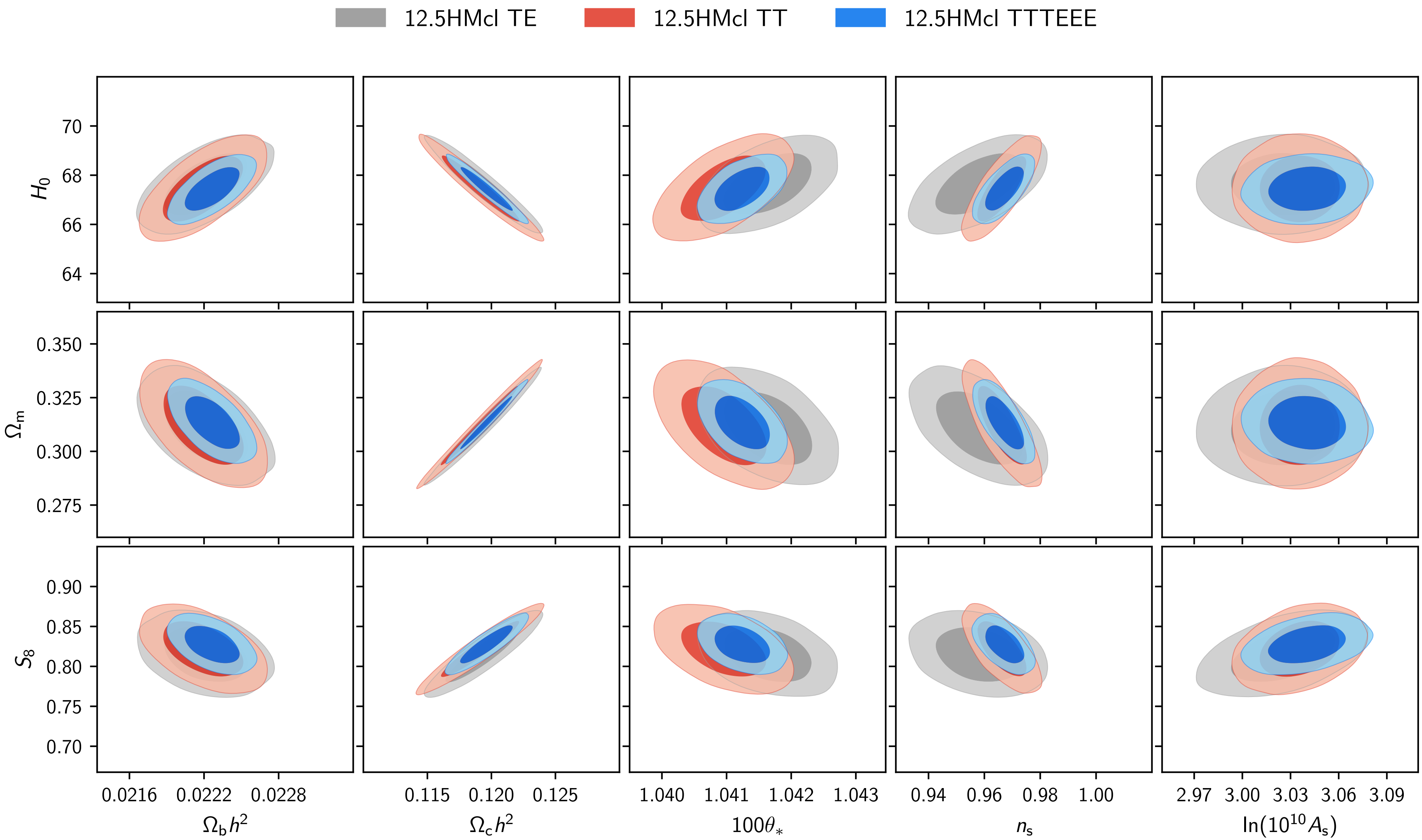
Planck 2018
6000
5000
4000
3000
2000
1000
0
60
40
20
0
−20
−40
−60
500
1000
1500
2000
2500
$\mathcal{D}_\ell\ [\mu K^2]$
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
ℓ


Planck extended analysis
Efstathiou and Gratton
arXiv:1910.00483
$\mathcal{D}_\ell$ [μK^2]
$\Delta\mathcal{D}_\ell$ [μK^2]
ℓ

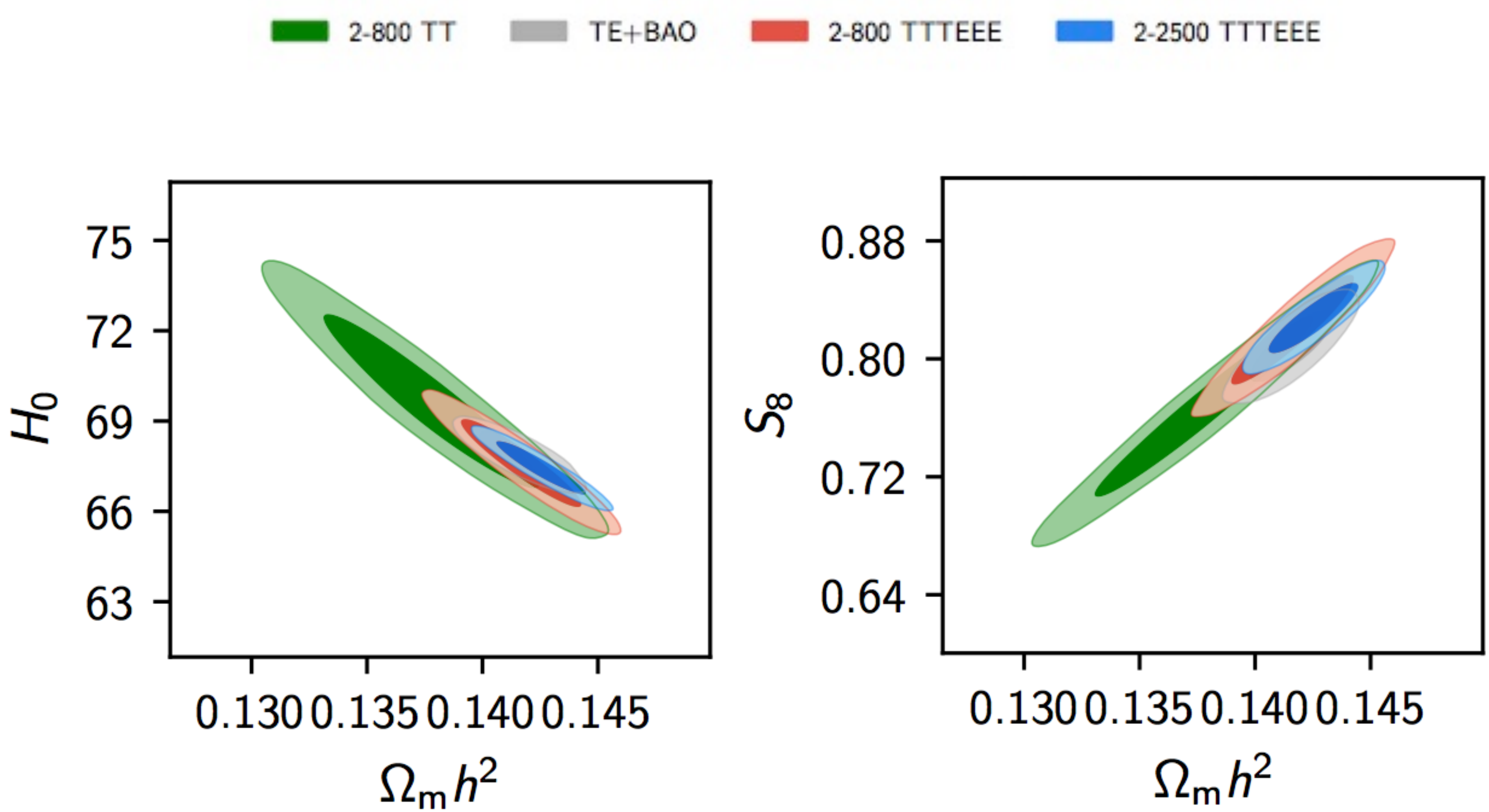

Planck 2018
Planck 2020
$\Delta\mathcal{D}_\ell$ [μK^2]
$\Delta\mathcal{D}_\ell$ [μK^2]
60
40
20
0
−20
−40
−60
60
40
20
0
−20
−40
−60
500
1000
1500
2000
2500
ℓ



12.1HM TE
12.1HM TT
12.1HM TTTEEE
H_0
Ω_m
S_8
$\Omega_b h^2$
$\Omega_c h^2$
$100\theta_*$
n_s
$\ln(10^{10} A_s)$



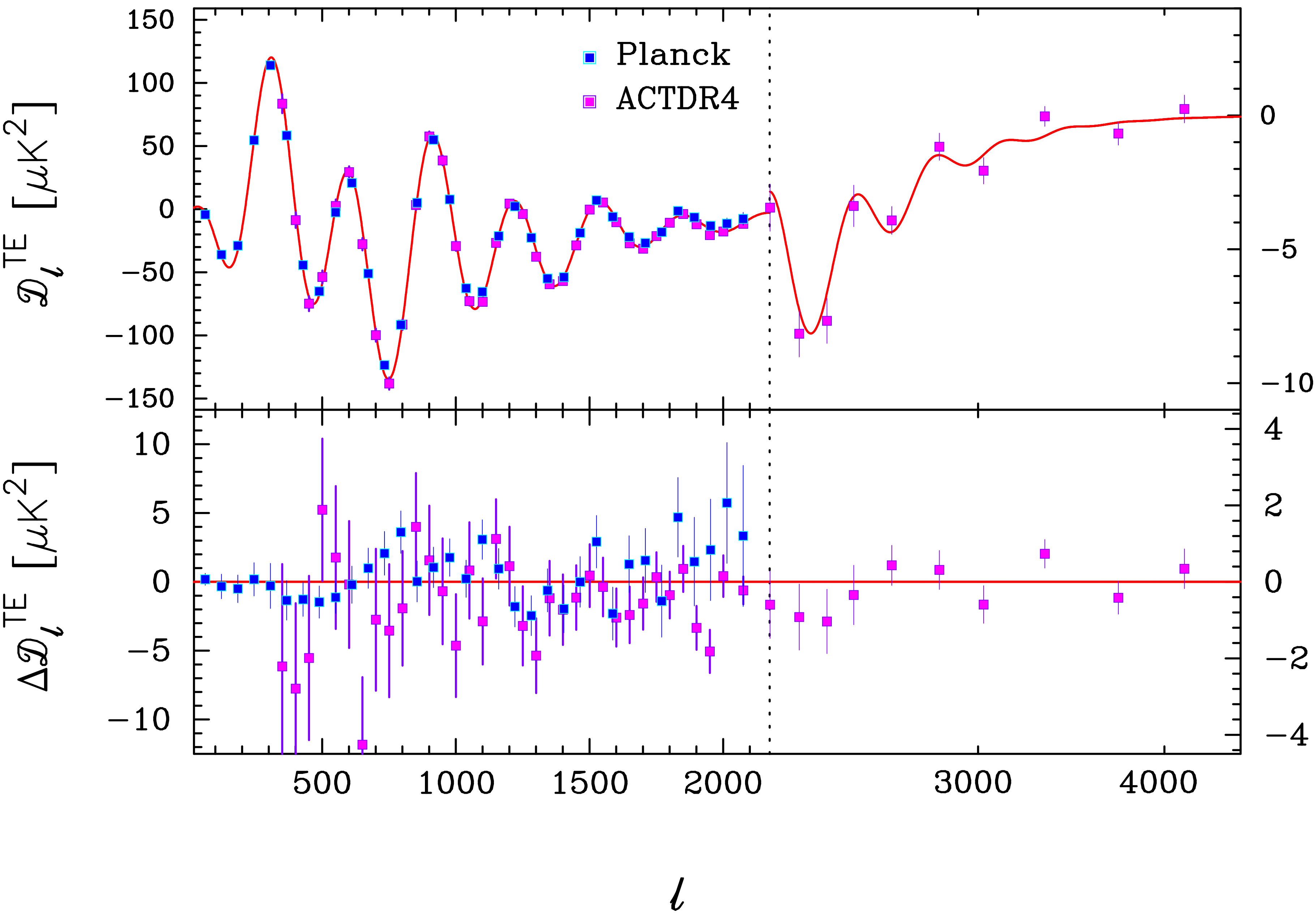
12.5HMcl TE
12.5HMcl TT
12.5HMcl TTTEEE
H_0
Ω_m
S_8
$\Omega_b h^2$
$\Omega_c h^2$
$100\theta_*$
n_s
$\ln(10^{10} A_s)$


2-800 TT
TE+BAO
2-800 TTTEEE
2-2500 TTTEEE
H_0
75
72
69
66
63
0.130
0.135
0.140
0.145
$\Omega_m h^2$
S_8
0.88
0.80
0.72
0.64
0.130
0.135
0.140
0.145
$\Omega_m h^2$

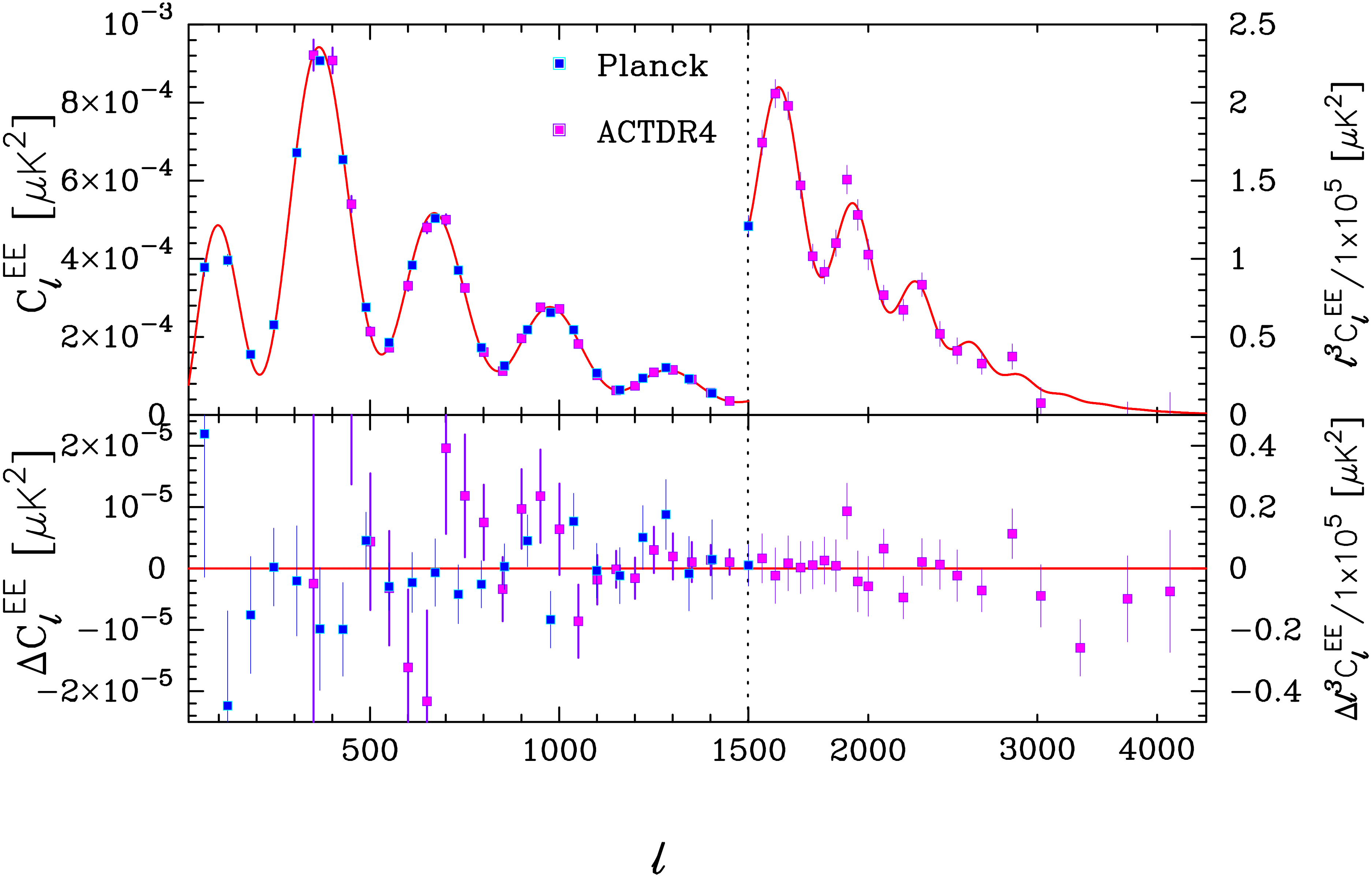
H_0 in extensions to ΛCDM

Model	Planck TTTEEE	Planck TTTEEE+BAO
ΛCDM	67.44 ± 0.58	67.69 ± 0.42
ΛCDM+m_ν	66.8 ± 1.2	67.8 ± 0.6
ΛCDM+N_ν	66.4 ± 1.6	67.4 ± 1.2
ΛCDM+$m_\nu + N_\nu$	$66.1^{+1.9}_{-1.6}$	67.5 ± 1.2
ΛCDM+$m_{\rm str} + N_\nu$	67.1 ± 0.7	$67.89^{+0.45}_{-0.69}$
ΛCDM+$\Omega_{\rm k}$	56 ± 4	67.9 ± 0.7
ΛCDM+$w_0 + w_a$	—	64.9 ± 2.1
ΛCDM+$n_{\rm run}$	67.25 ± 0.60	67.66 ± 0.45

There is not even a *hint* of movement towards the SH0ES value of H_0



Planck
ACTDR4
$\mathcal{D}_\ell^{TE}$ [μK^2]
$\Delta\mathcal{D}_\ell^{TE}$ [μK^2]
ℓ
150
100
50
0
−50
−100
−150
−5
−10
10
5
4
2
−2
−4
500
1000
1500
2000
3000
4000

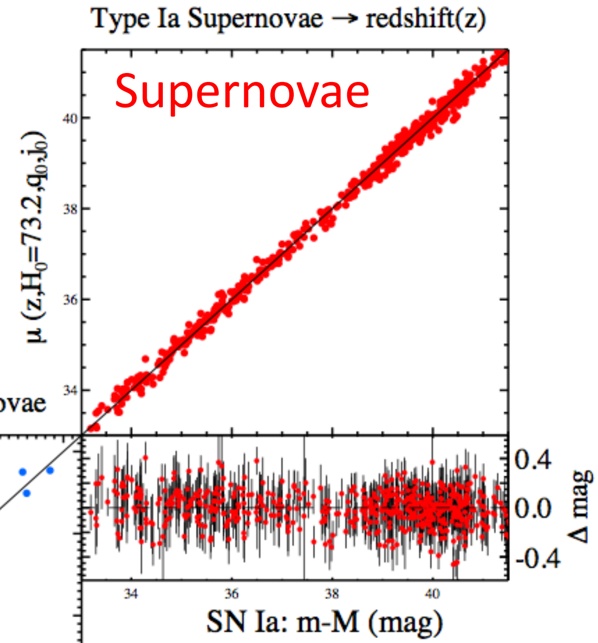


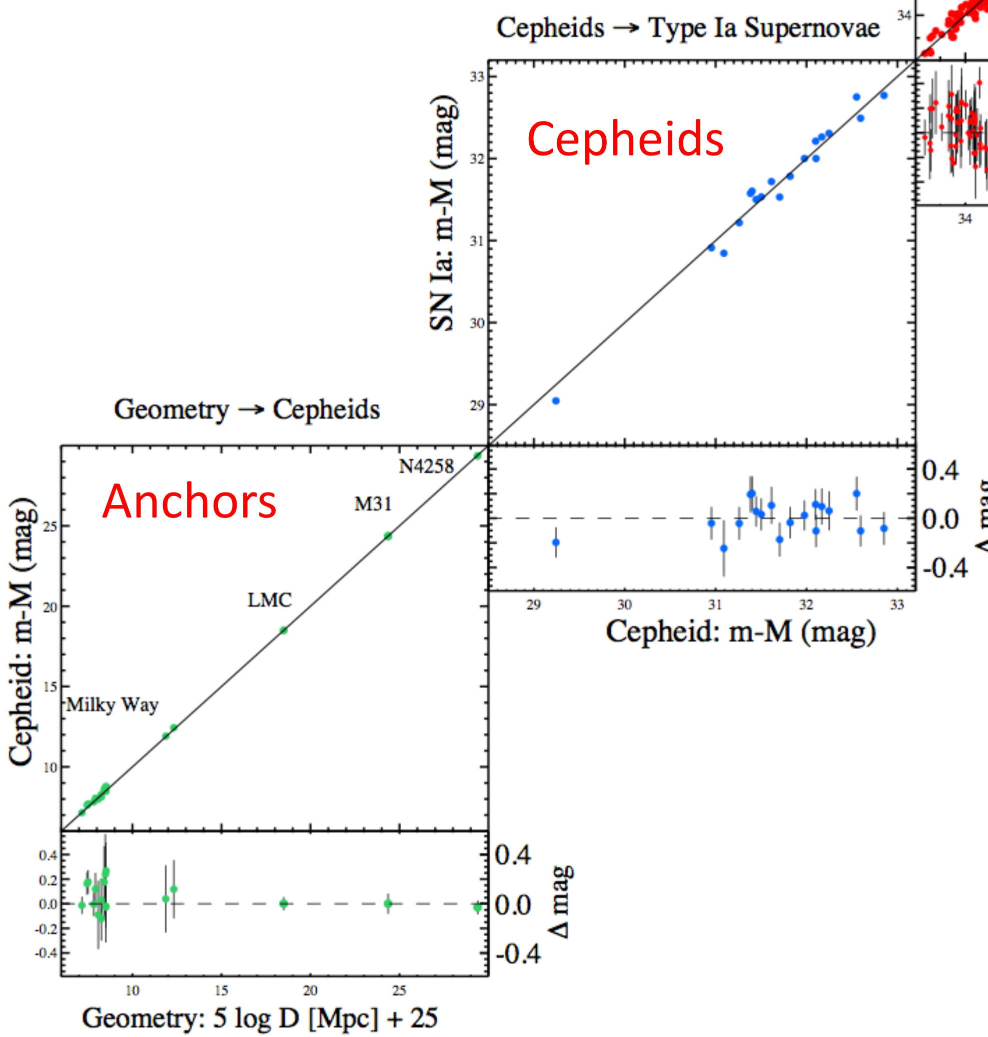
Planck
ACTDR4
C_ℓ^{EE} [μK^2]
$\ell^3 C_\ell^{EE}/1\times10^5$ [μK^2]
ΔC_ℓ^{EE} [μK^2]
$\Delta \ell^3 C_\ell^{EE}/1\times10^5$ [μK^2]
ℓ

Summary (part I)

- The CMB results for base ΛCDM are *totally* secure
- *No evidence for any new physics* from CMB including high multipole polarization spectra observed by ACT
- Inverse distance ladder (supernovae+BAO) gives low H_0 (68 ± 1 km s^{-1} Mpc^{-1}) *independent of nature of dark energy, dark matter and their interactions. No evidence for any new physics at late times.*
- Recent LUNA results on $d(p, \gamma)^3He$ reaction rate improve consistency between Planck, big bang nucleosynthesis and observed deuterium abundance. *No evidence for any new physics at early times.*

It is therefore reasonable to question the accuracy of the distance ladder.
If there is a problem, what is it likely to be?





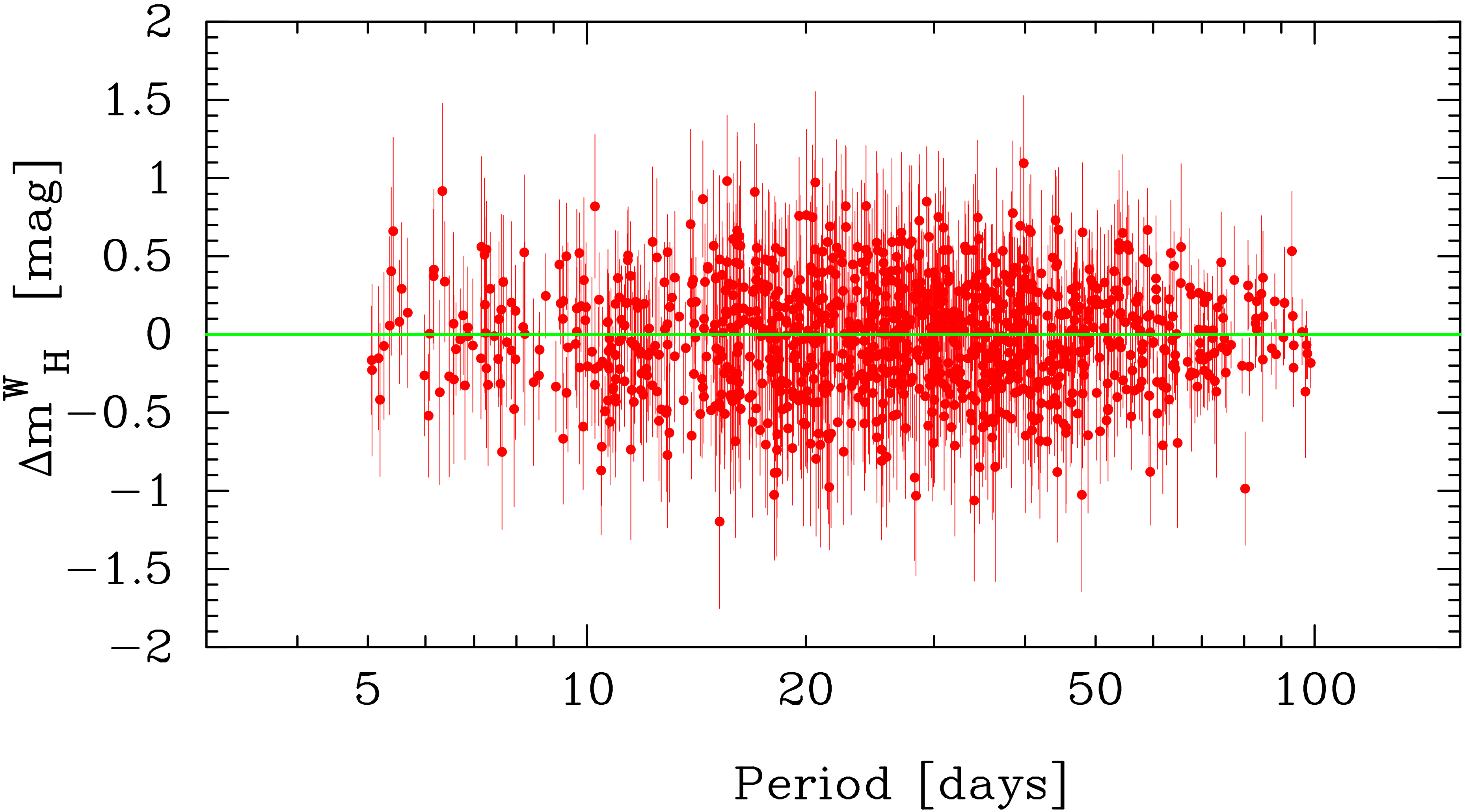
$$\delta H_0/H_0 = -0.2\ \delta m \ln 10$$
$$= -0.46\ \delta m$$

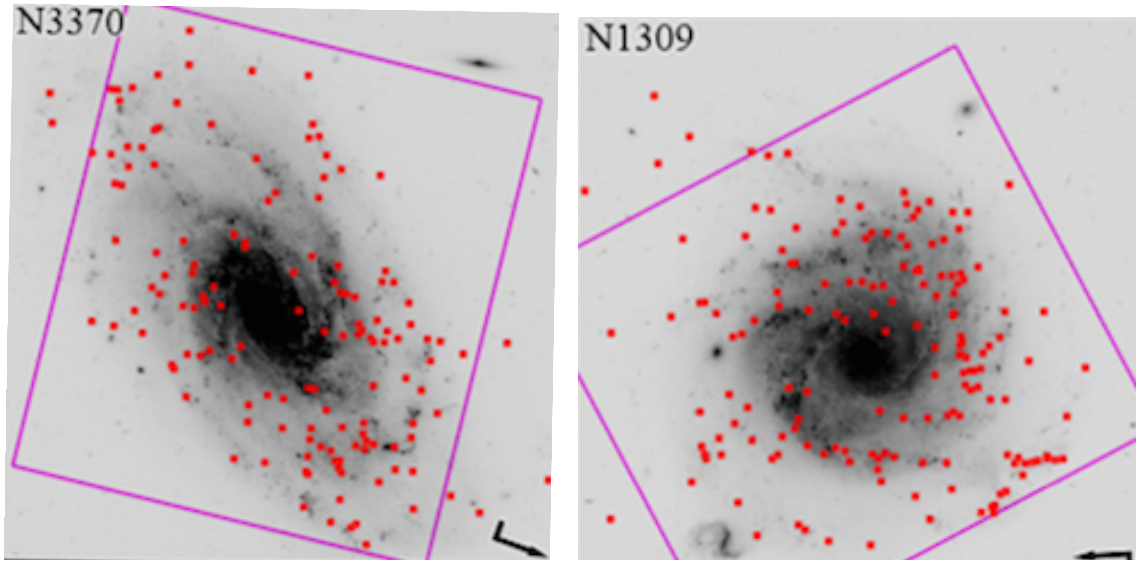
so we need a systematic of ~ 0.1 - 0.2 mag to match the Planck H_0.

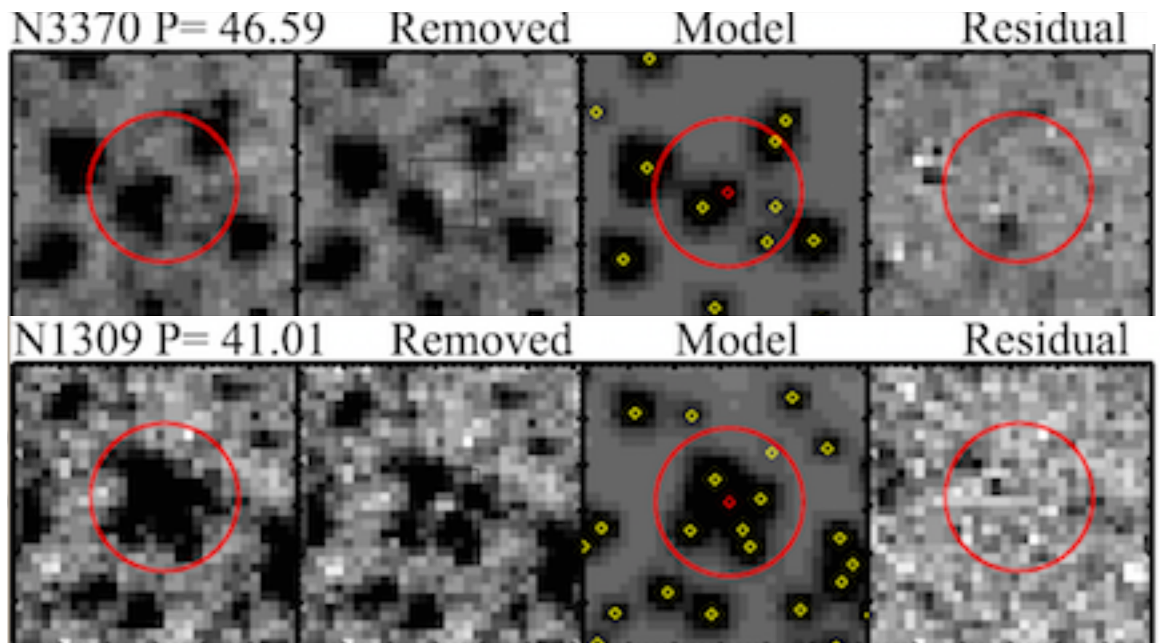
Riess etal 2016

$$m_H^W = m_H - 0.41(V - I)$$

$$m_H^W = a + b \log_{10}\left[\frac{P}{10 \text{ days}}\right] + Z \log_{10}(O/H)$$




N3370
N1309


N3370 P= 46.59
Removed
Model
Residual
N1309 P= 41.01
Removed
Model
Residual

Problems with the distance anchors:

Geometric distance distance (20 detached eclipsing binaries) to LMC:

μ_{LMC} = 18.477 ± 0.026 mag (Pietrzynski et al 2019) (1)

Geometric distance to maser galaxy NGC4258:

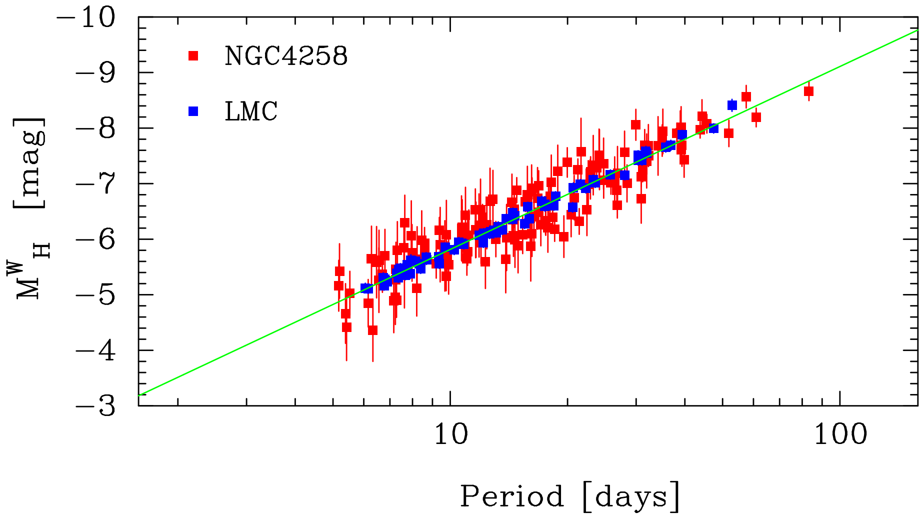
μ_{N4258} = 29.397 ± 0.033 mag (Reid etal 2019) (2)

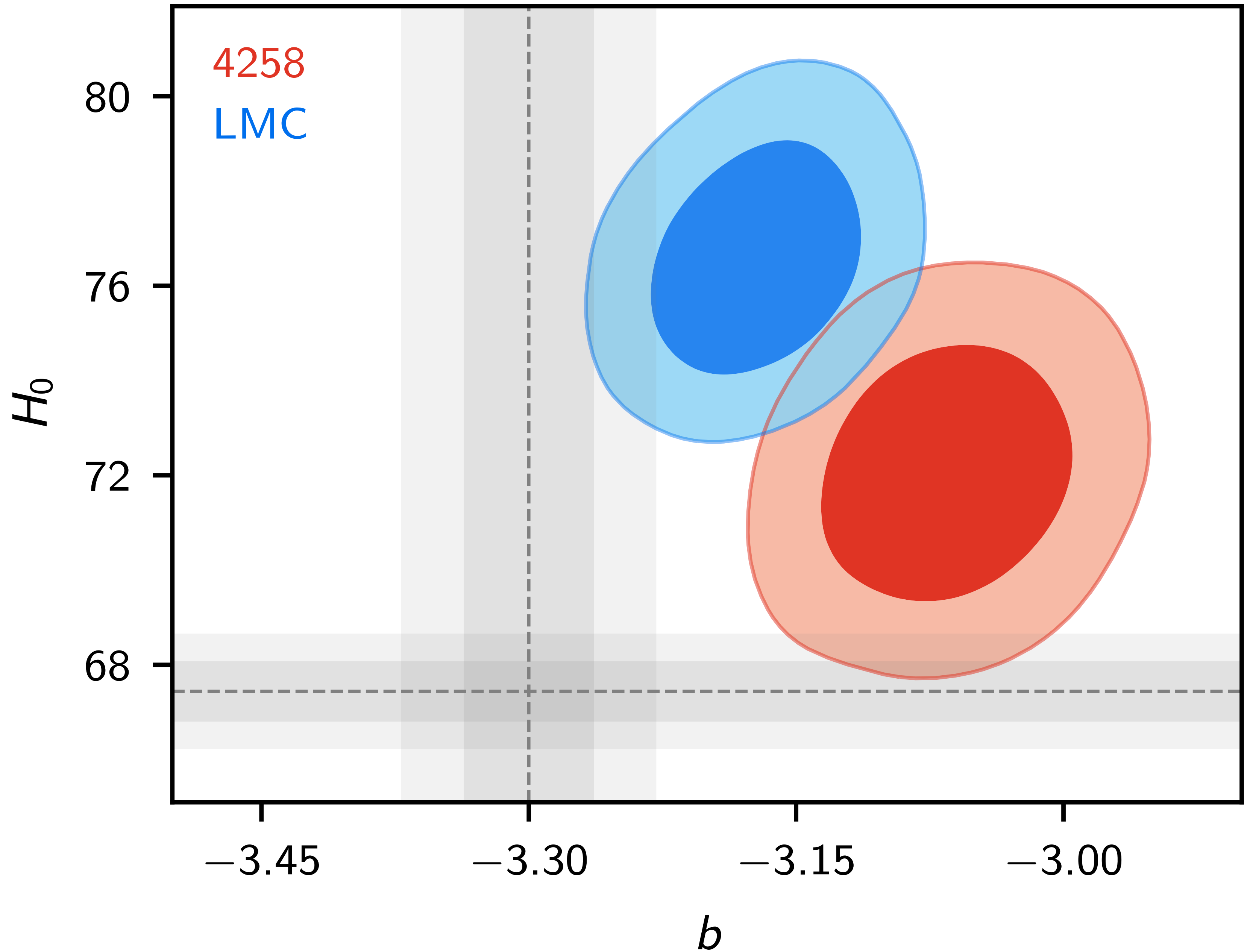
Nevertheless, if I use LMC Cepheids from Riess et al (70 Cepheids with HST photometry) and 4258 Cepheids from Riess etal (2016) and fix μ_{LMC} to (1), I infer a distance modulus to NGC 4258 of

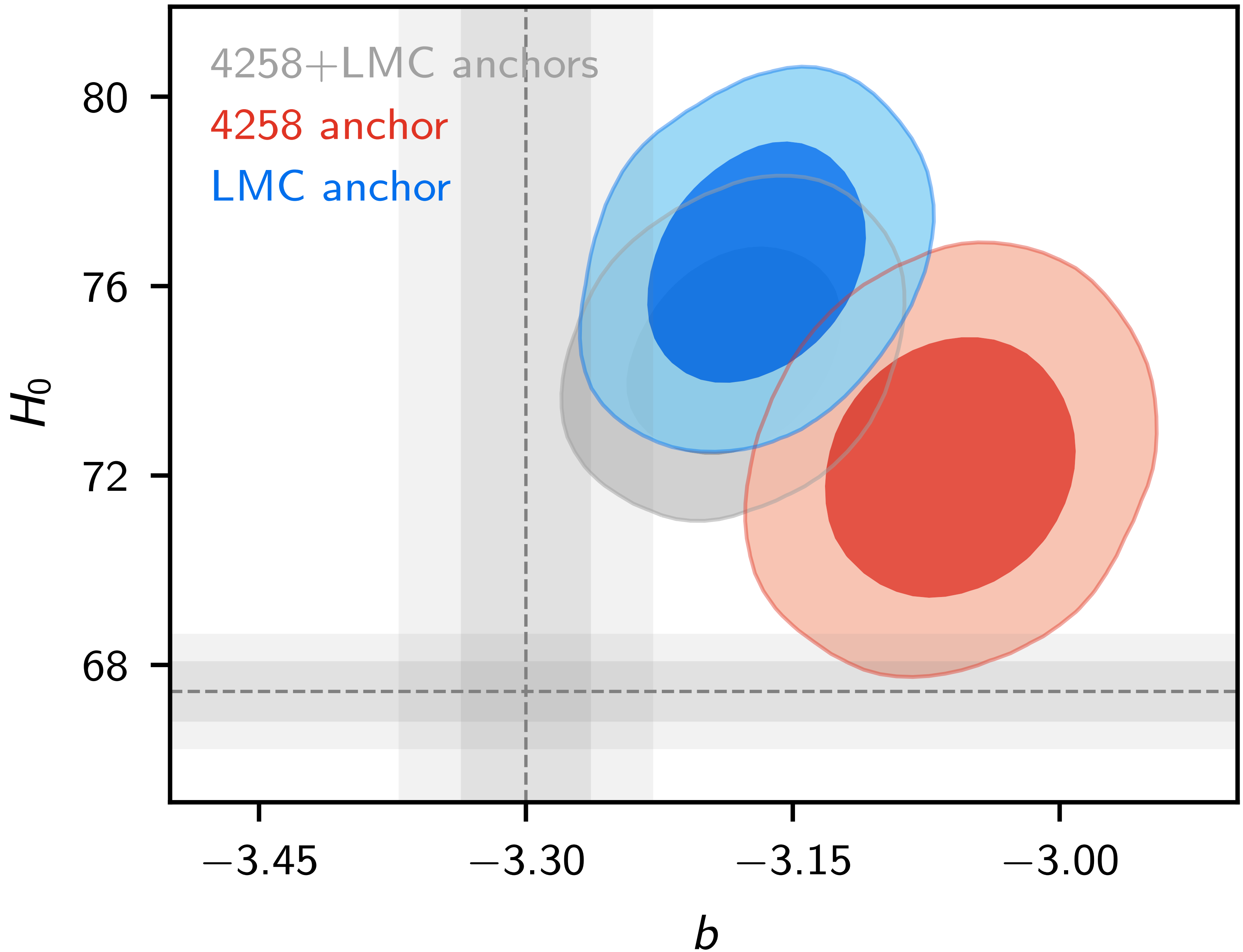
μ_{N4258} = 29.220 ± 0.029

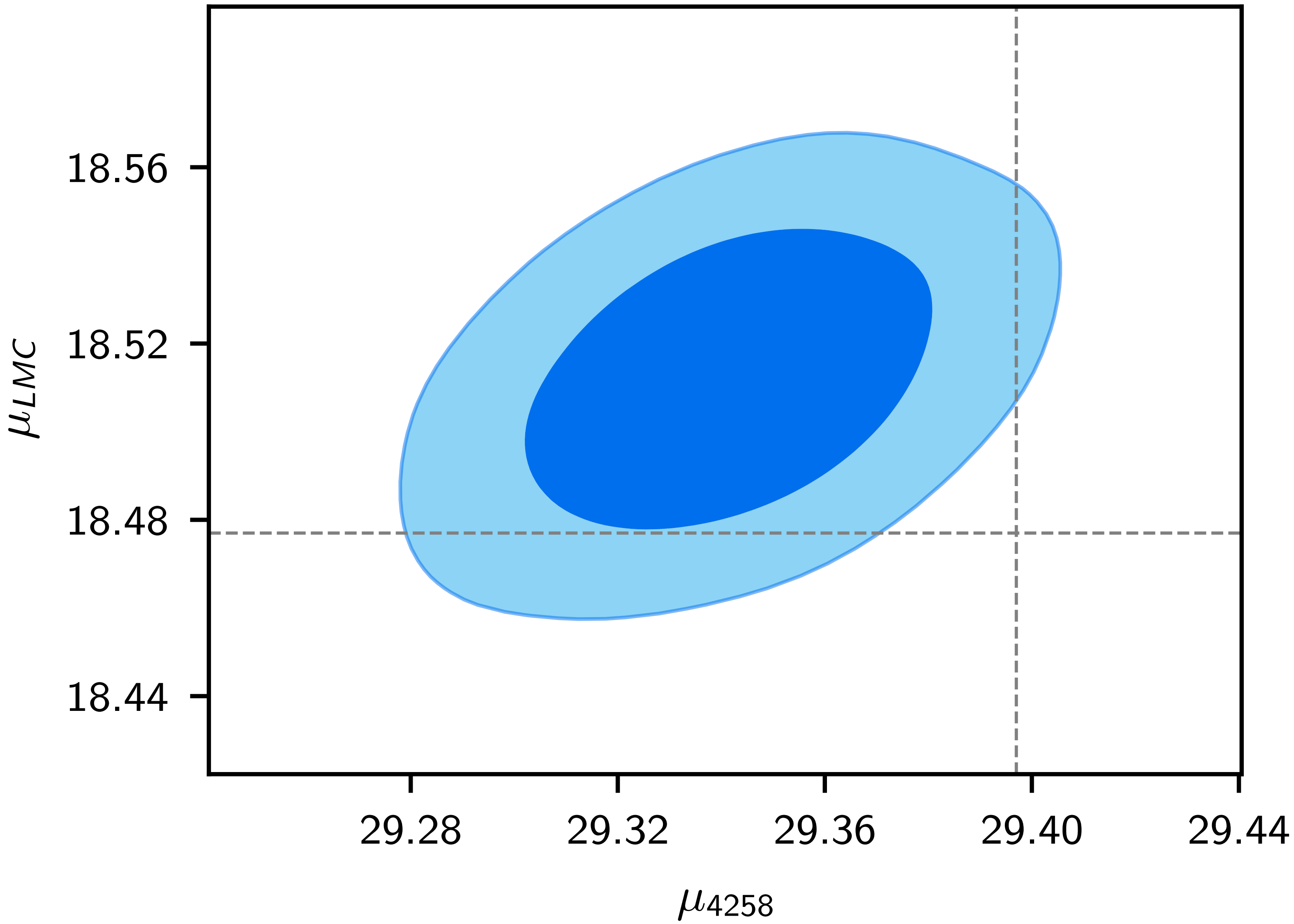
which is discrepant with (2) by 3.5σ.

(Δμ = 0.18 mag)




4258
LMC
80
76
72
68
H_0
−3.45
−3.30
−3.15
−3.00
b


4258+LMC anchors
4258 anchor
LMC anchor
80
76
72
68
H_0
−3.45
−3.30
−3.15
−3.00
b



18.56
18.52
18.48
18.44
μ_{LMC}
29.28
29.32
29.36
29.40
29.44
μ_{4258}

The SHOES degeneracy

Assume that crowded HST magnitudes are biased by a constant offset δa relative to resolved ground based photometry:

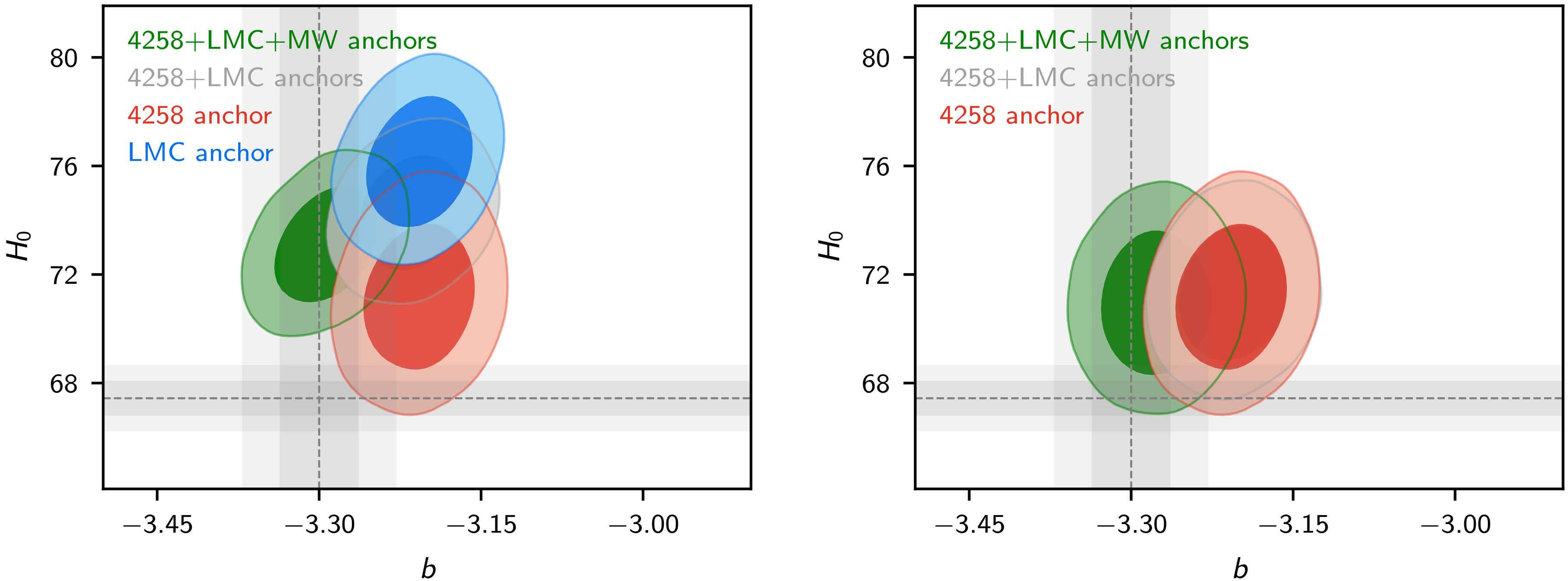
$$m = m_{\rm Riess} - \delta a$$

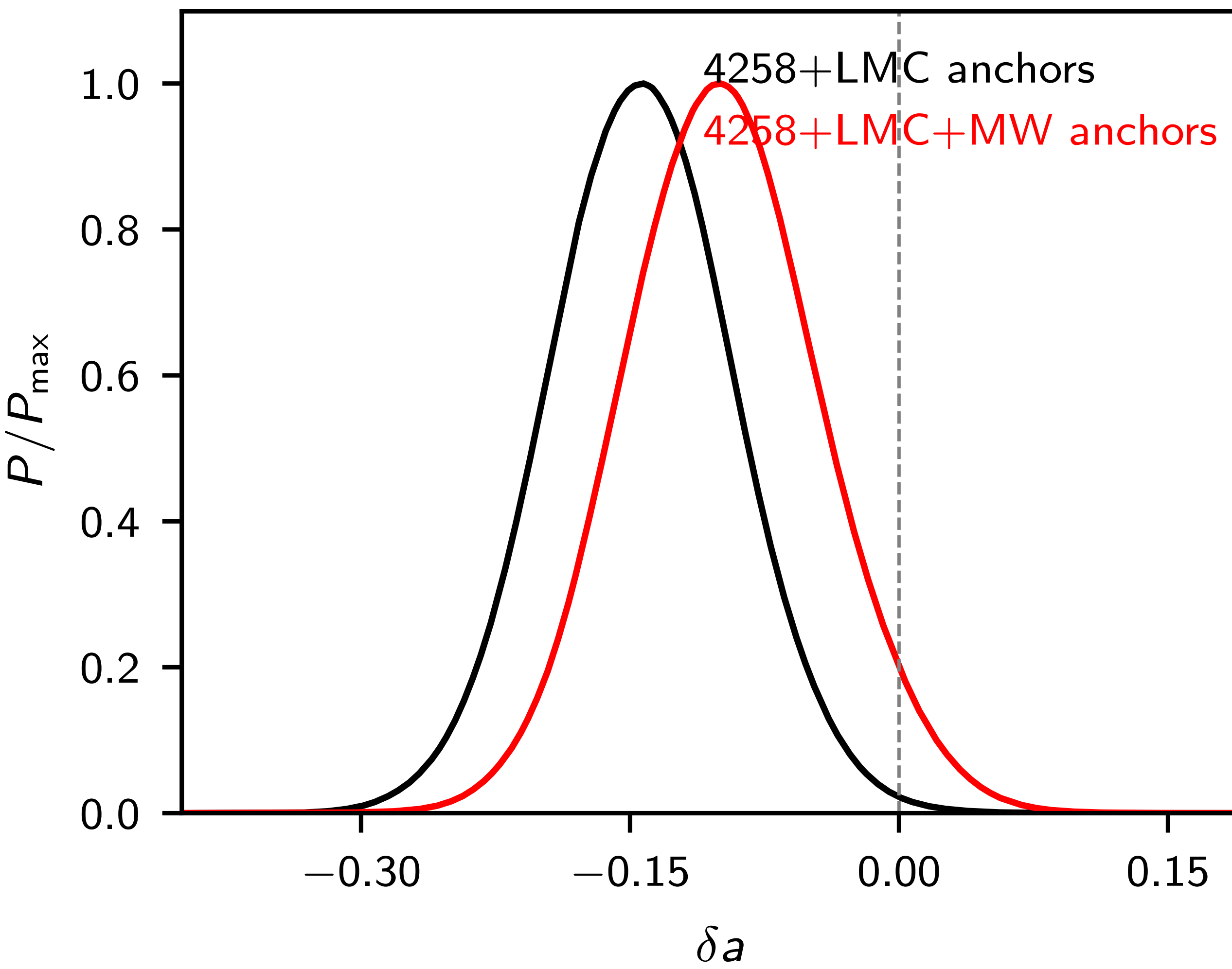
In such a model, the offset term will *cancel* if the NGC 4258 anchor is used to calibrate the Cepheid PL relations of the SN host galaxies.

The offset term will *not cancel* if one uses local resolved calibrators, i.e. LMC, Milky Way or M31. On this model, these local calibrators will ALL lead to biased values of H_0.

This is the SHOES degeneracy.

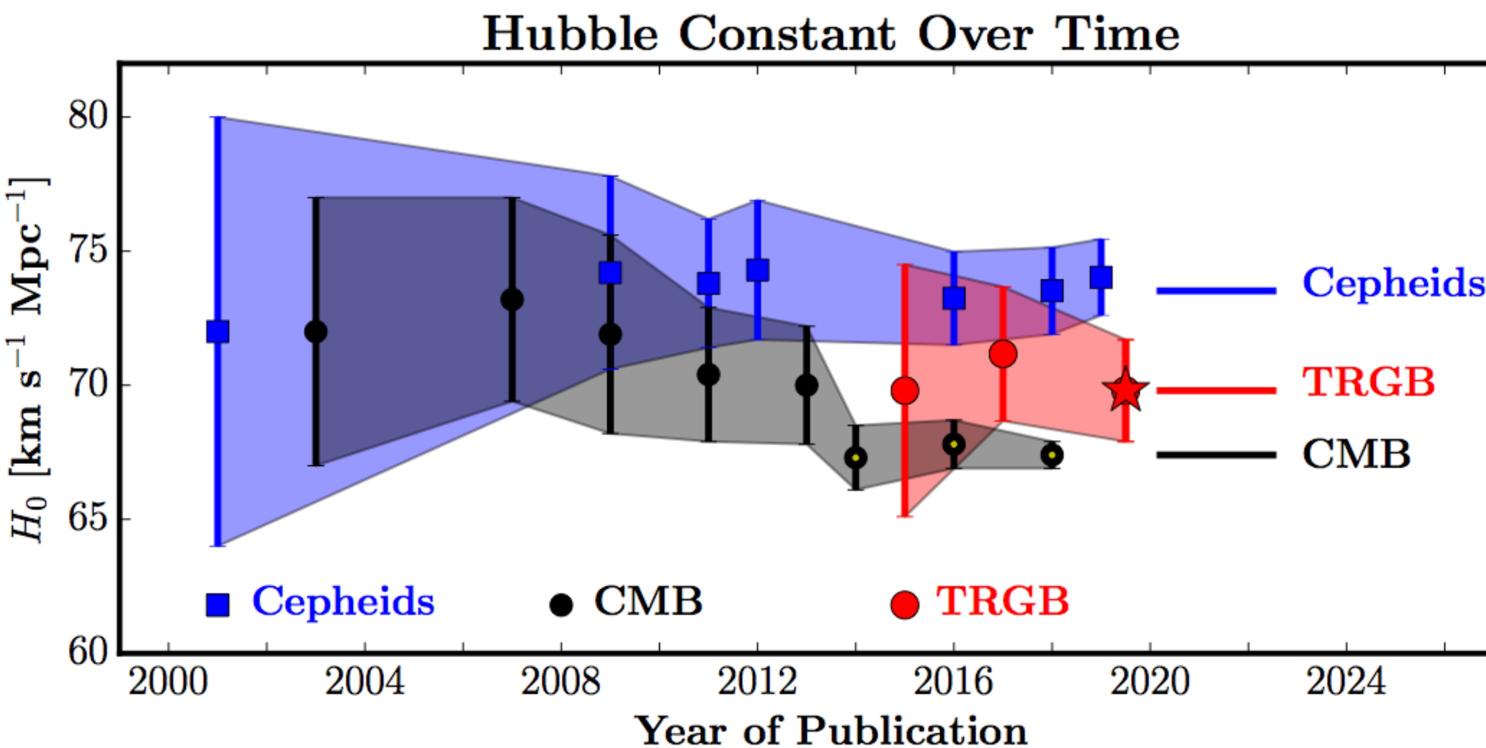
no PL offset (standard analysis) with PL offset (SHOES degeneracy)





4258+LMC anchors
4258+LMC+MW anchors
1.0
0.8
0.6
0.4
0.2
0.0
P/P_{max}
−0.30
−0.15
0.00
0.15
δa

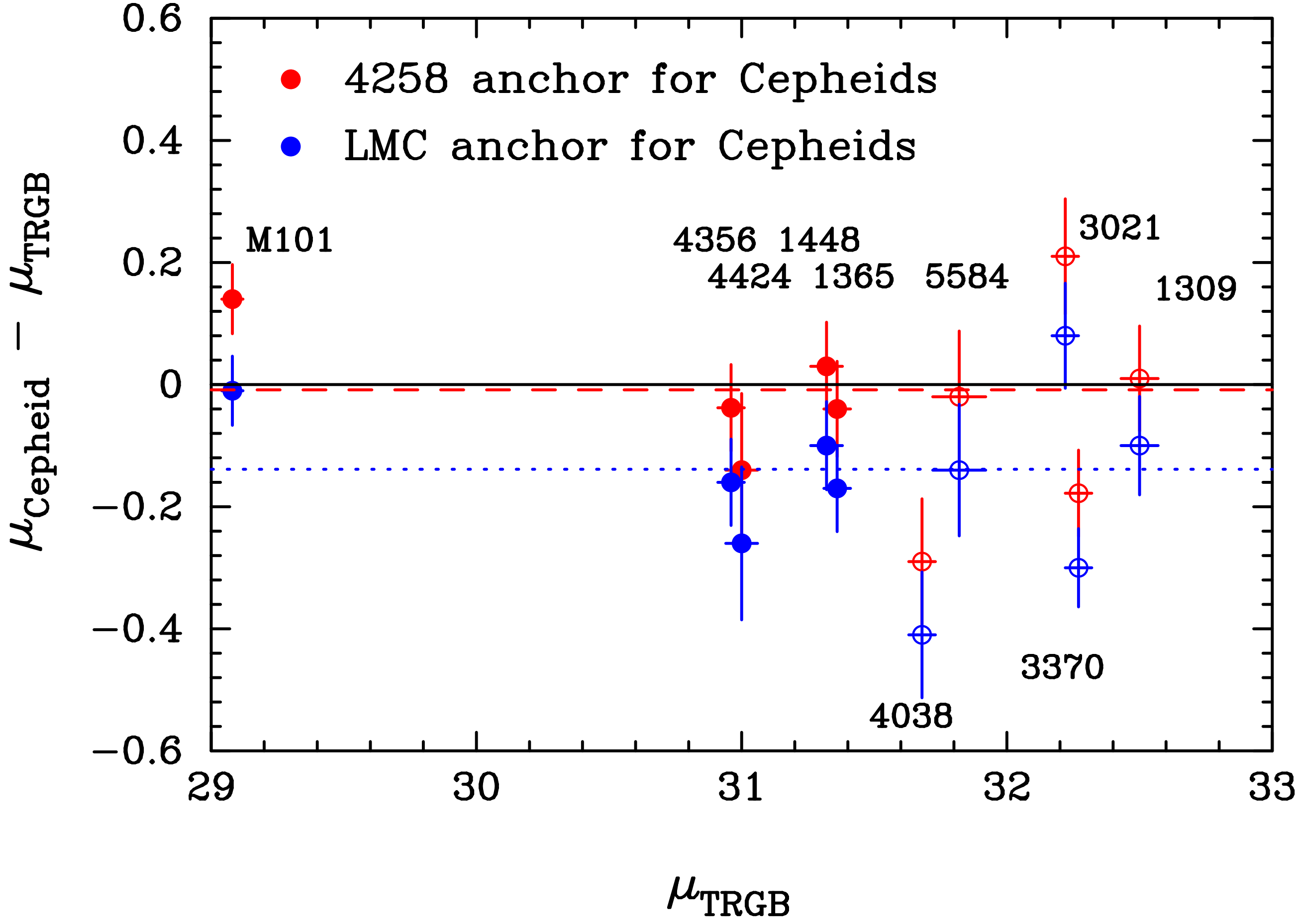
Is there any evidence for such an effect?



TRGB Freedman etal 2019 $H_0 = 69.8 \pm 0.8$ (stat) $\pm$ 1.7 (sys) km/s/Mpc

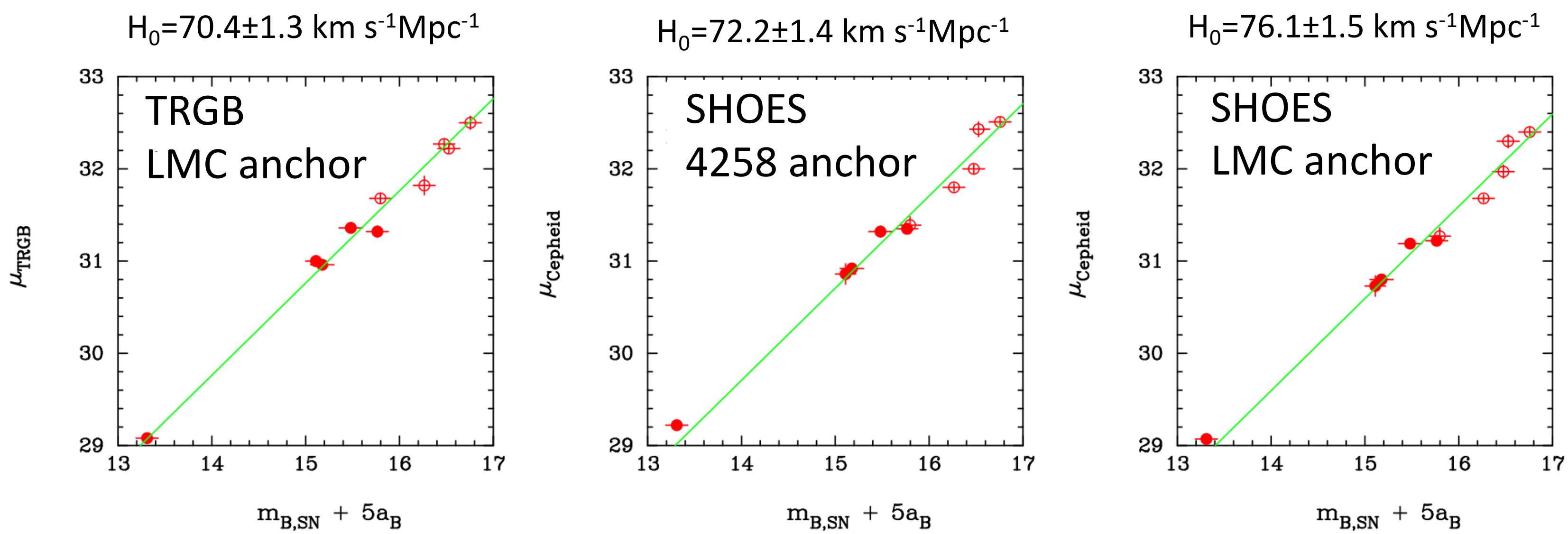
BUT -- many of the systematic errors are common to the TRGB and Cepheid measurements (SN mags, anchor distances etc). So my claim is that these measurements are discrepant.

For galaxies in common between Riess etal and Freedman etal:

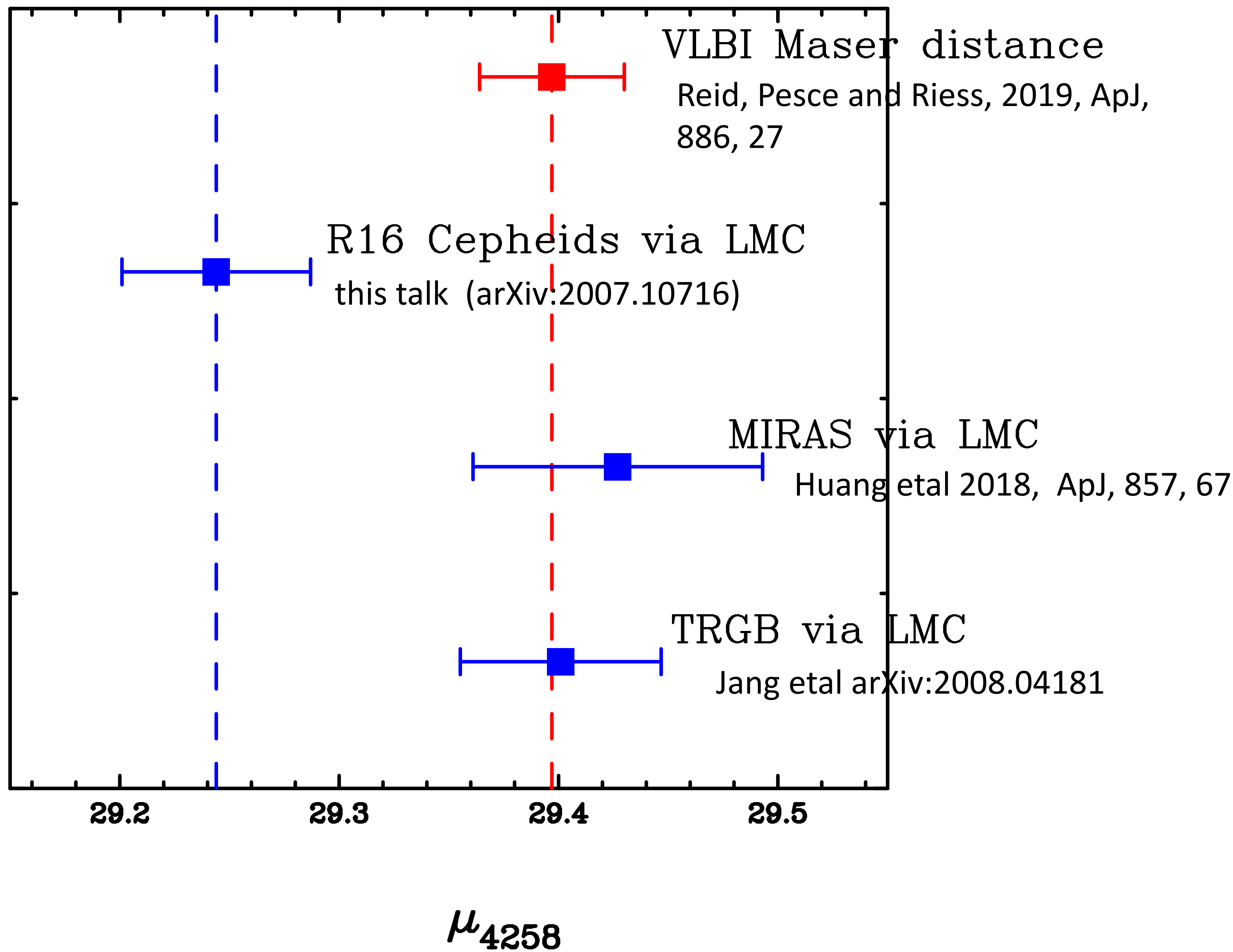


Calibration difference for blue points is $\mu_{TRGB} - \mu_{Cepheid(LMC)} = 0.14 \pm 0.02$ (7σ) !

The differences in H_0 between Riess etal and Freedman etal reflect differences in local calibration. For example, using the Pantheon SN magnitudes



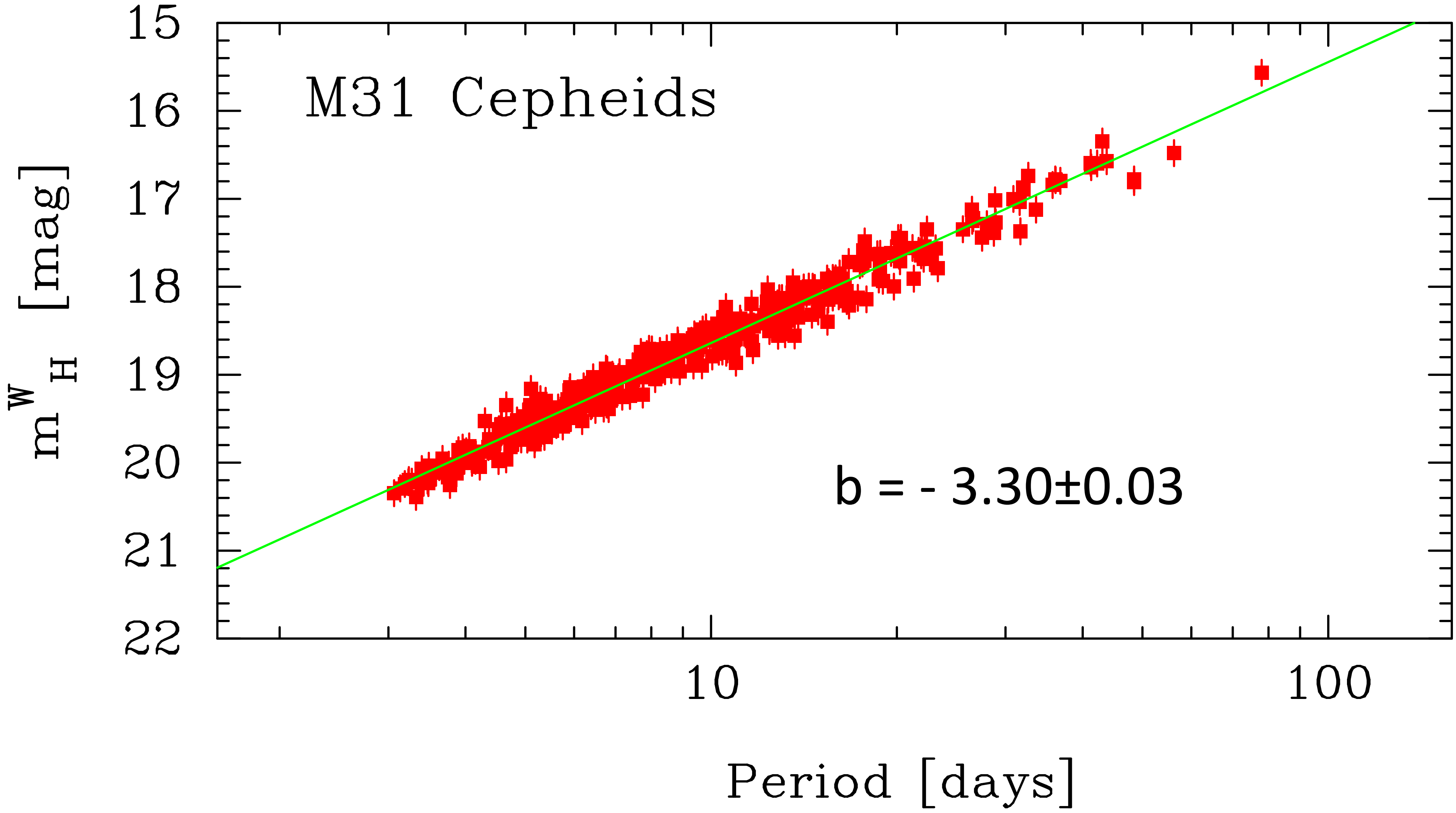
There is clearly a difference in the LMC calibrations of the TRGB and Cepheid distance scales.



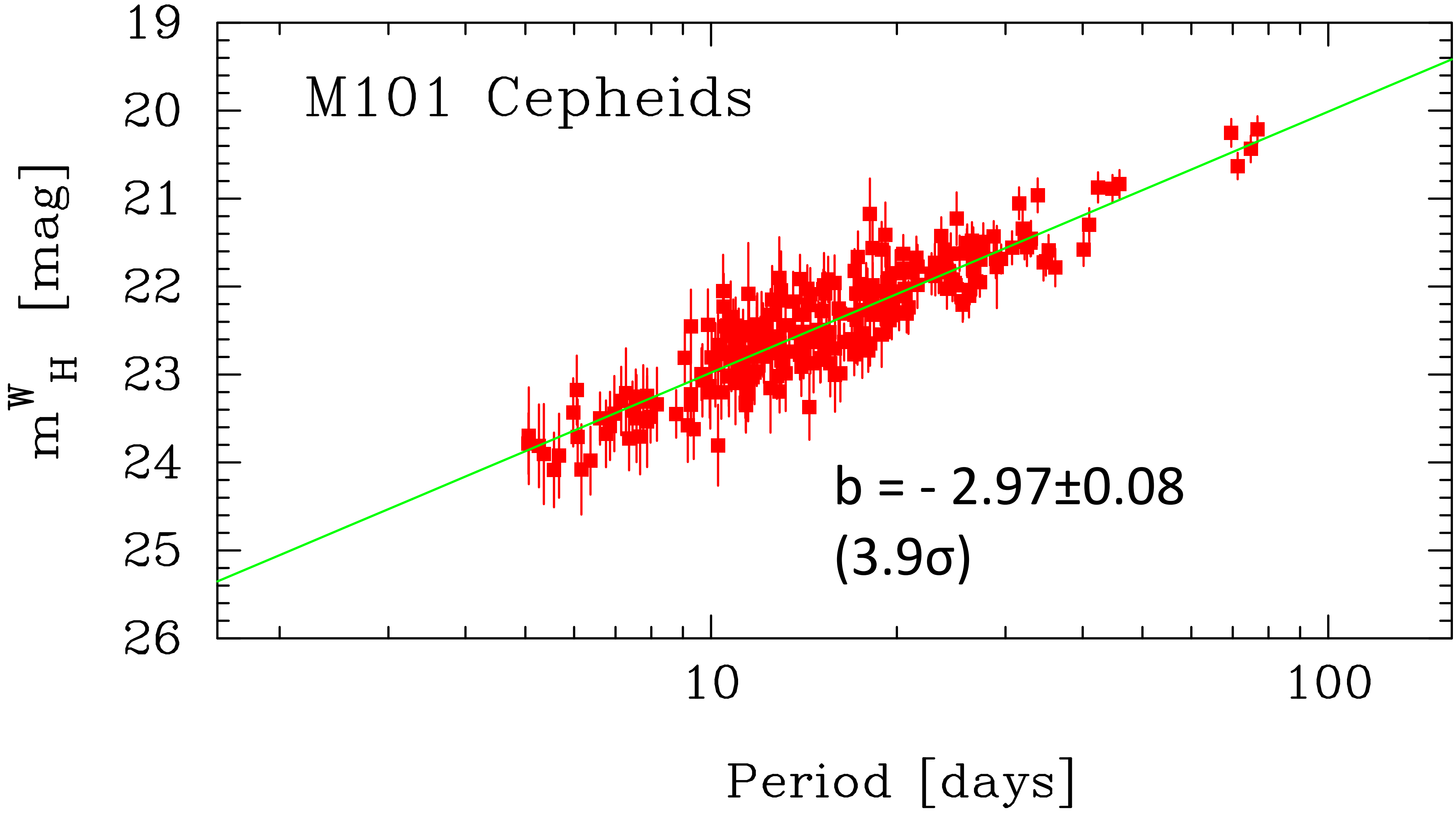
VLBI Maser distance
Reid, Pesce and Riess, 2019, ApJ, 886, 27
R16 Cepheids via LMC
this talk (arXiv:2007.10716)
MIRAS via LMC
Huang etal 2018, ApJ, 857, 67
TRGB via LMC
Jang etal arXiv:2008.04181
29.2
29.3
29.4
29.5
μ_{4258}

Summary (part II)

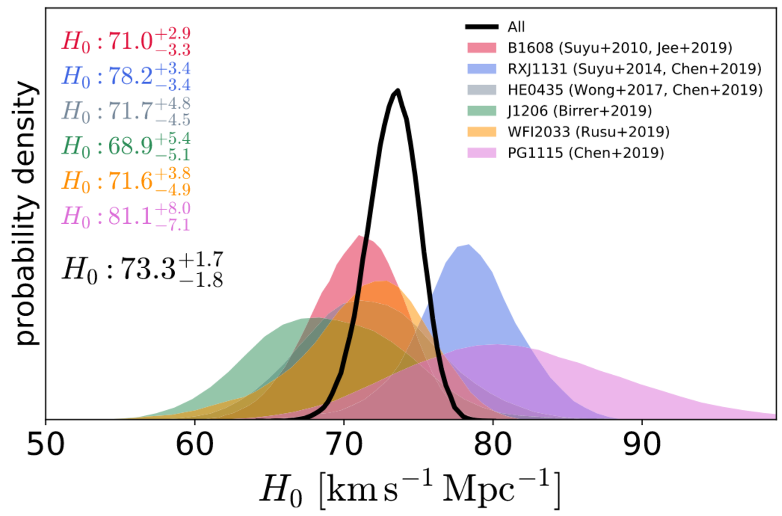
- Differences in the distance ladder measurements of H_0 are caused by differences in local calibration.
- These differences should be resolved on short timescale, therefore establishing definitively whether the Hubble tension exists.



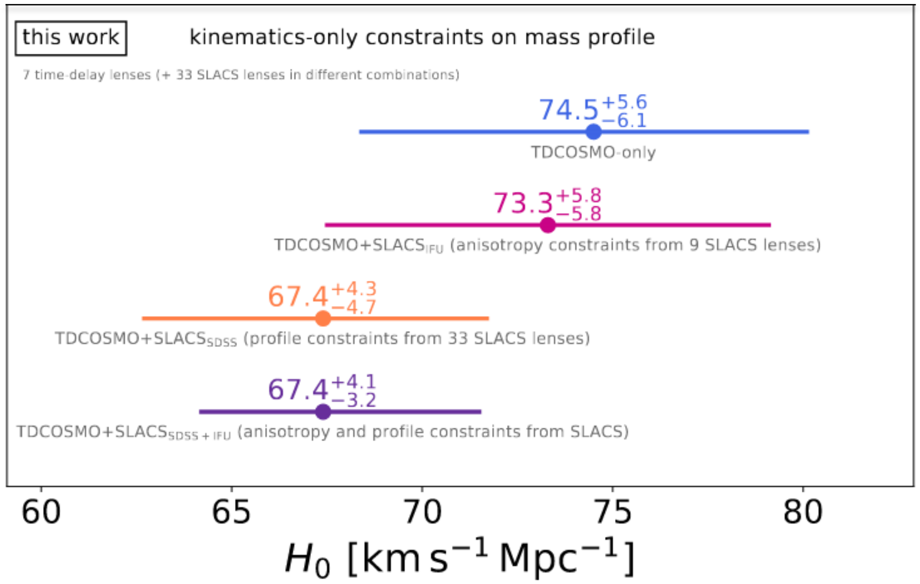
M31 Cepheids
b = - 3.30±0.03
15
16
17
18
19
20
21
22
m^W_H [mag]
10
100
Period [days]


M101 Cepheids
b = - 2.97±0.08
(3.9σ)
m^W_H [mag]
Period [days]
19
20
21
22
23
24
25
26
10
100

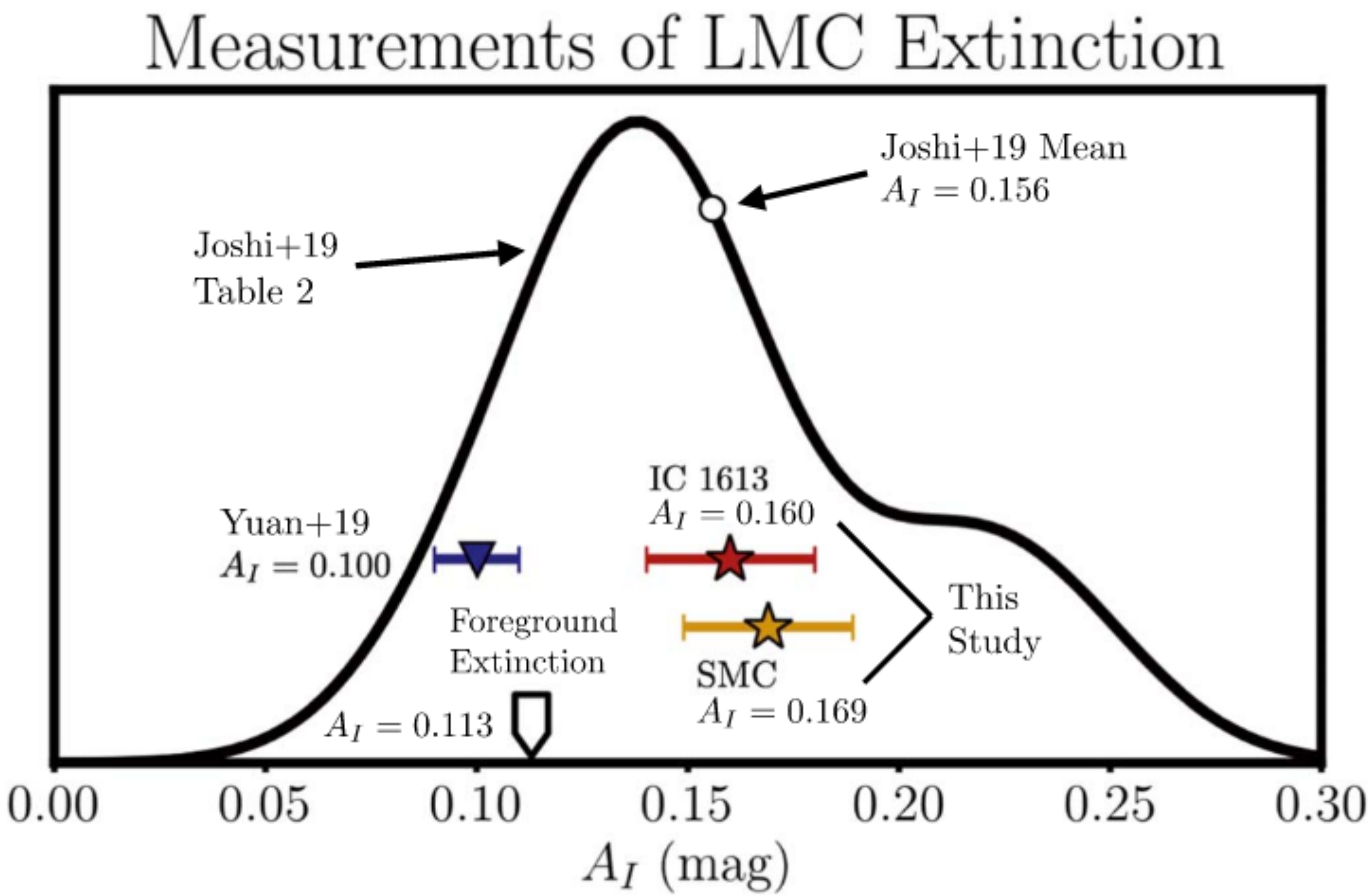
Gravitational lens time delays: Wong etal, 2020, MNRAS, 498, 1420.



but Birrer etal arXiv:2007.02941

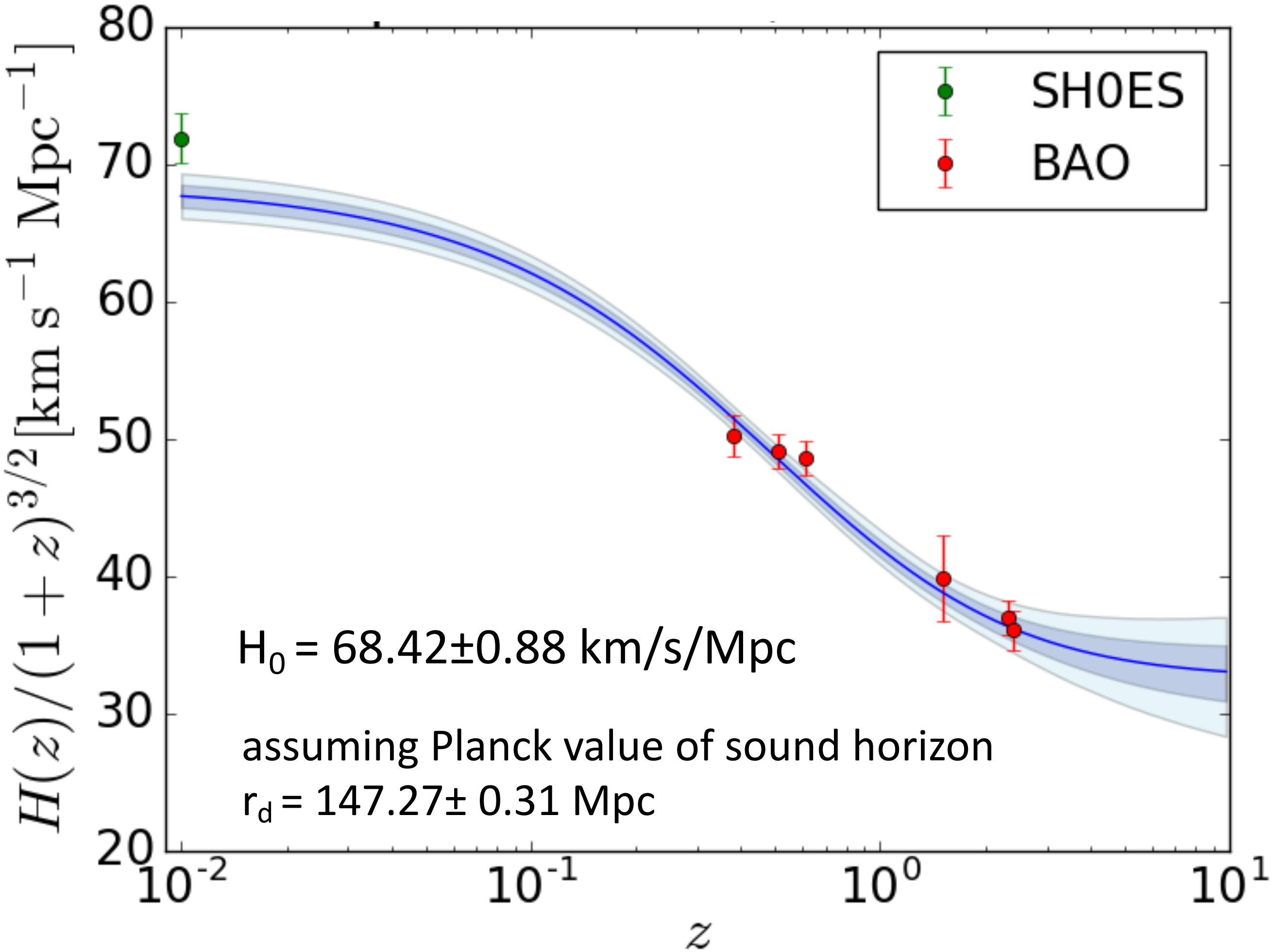


From Freedman etal 2020, ApJ 891, 57.

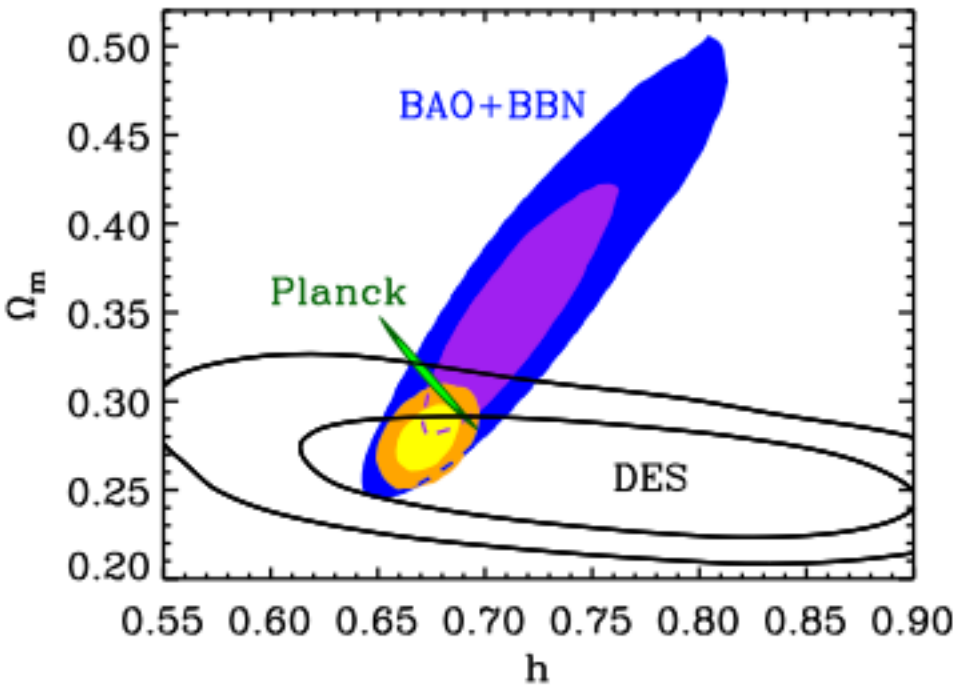


Inverse distance ladder

$$H^2(z) = H^2_f \,[\, A(1+z)^3 + B + Cz + D(1 + z)^{\varepsilon} \,]$$



$$r_d = \int_{z_d}^{\infty} \frac{c^2}{3} \left[1 + \frac{3\rho_b}{4\rho_\gamma}\right]^{-1} \frac{dz}{H(z)}$$



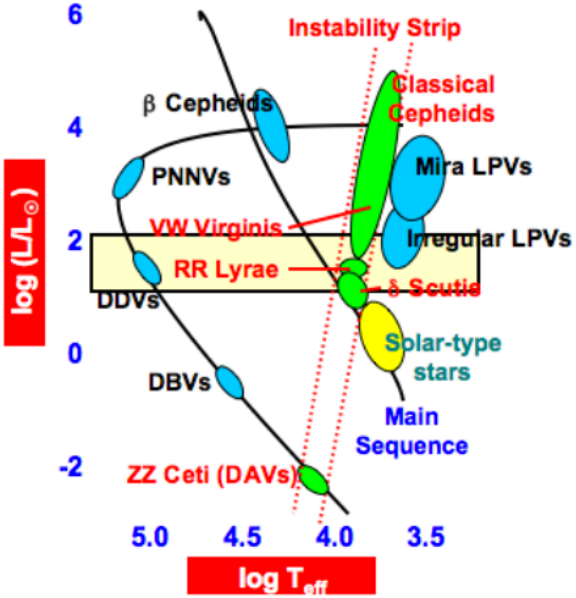
Abbott etal 2018 MNRAS 480, 3879

A precise H_0 estimate from DES Y1 [clustering and weak lensing], BAO and D/H

H_0 = 67.4 ± 1.2 km/s/Mpc.

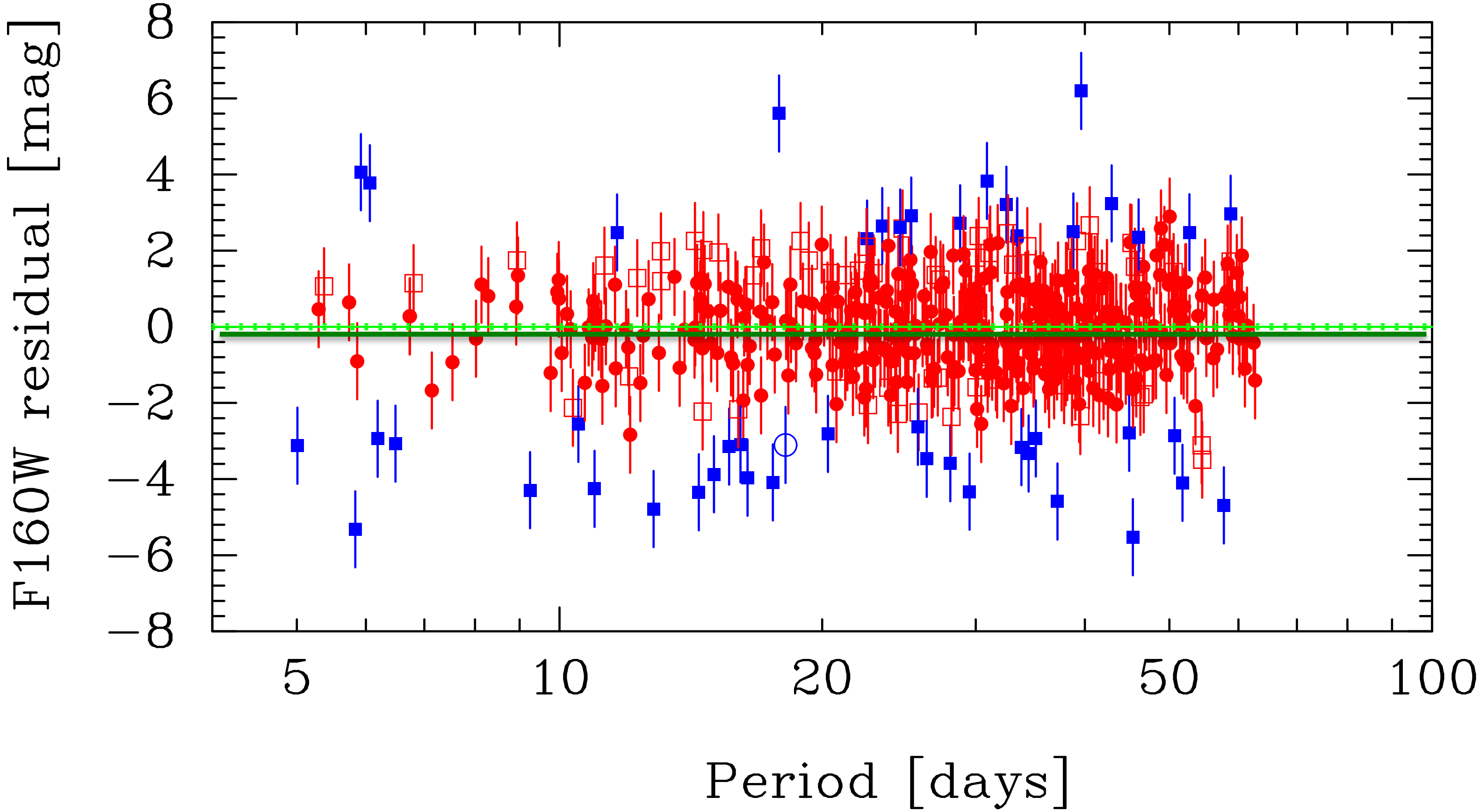
Classes of variable stars

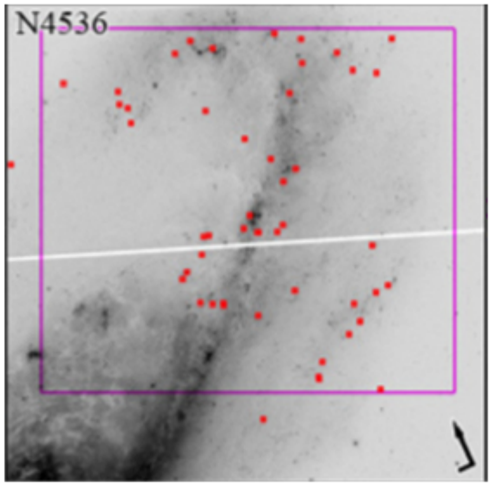
Type	Period	Population Type
Long period variables (LPVs)	100-700 days	I,II
Classical Cepheids	1-50 days	I
W Virginis stars	2-45 days	II
RR Lyrae stars	1.5-24 hours	II
δ Scuti stars	1-3 hours	I
β Cephei stars	3-7 hours	I
ZZ Ceti stars	100-1000 seconds	I

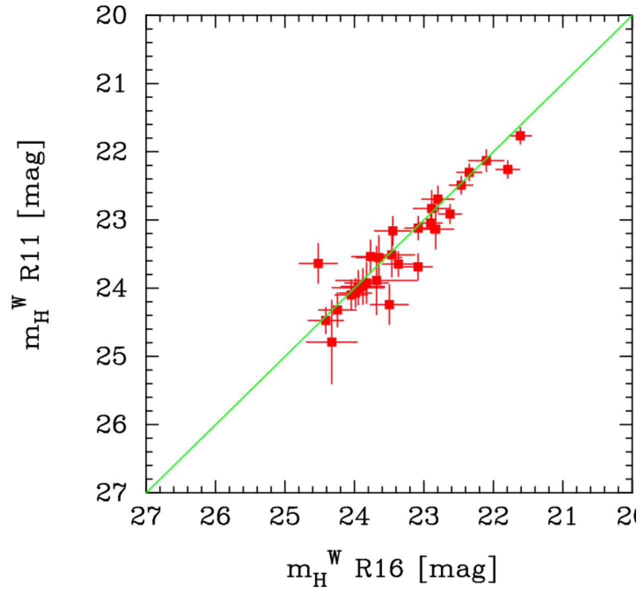


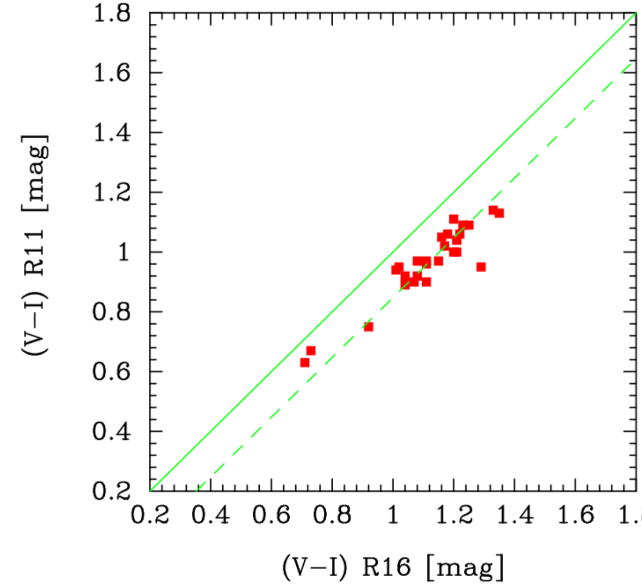
H_0 revisited

George Efstathiou★
Kavli Institute for Cosmology and Institute of Astronomy, Madingley Road, Cambridge CB3 OHA, UK

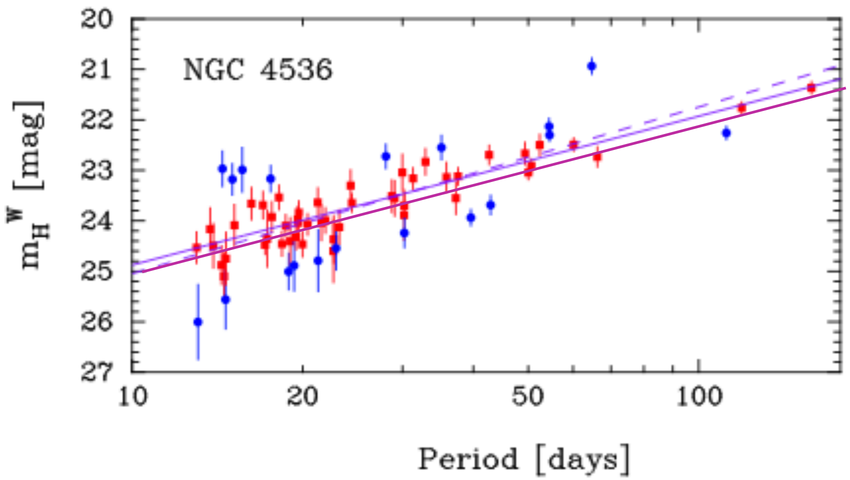




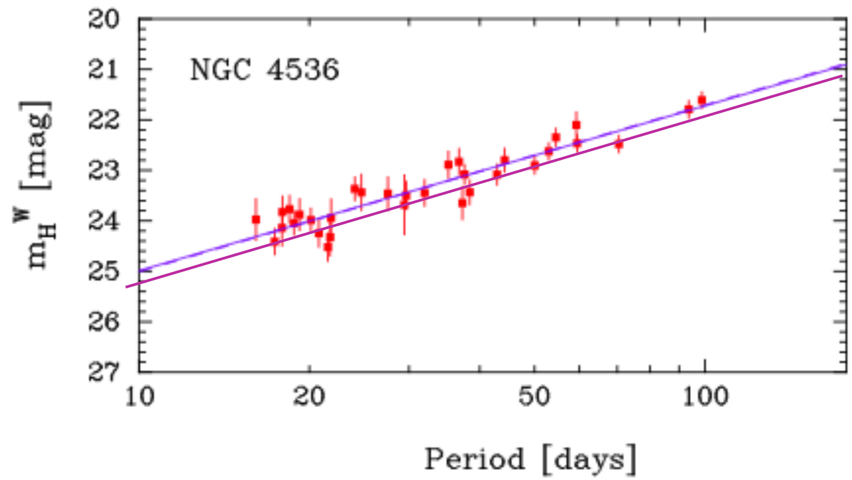




Riess etal 2011



Riess etal 2016



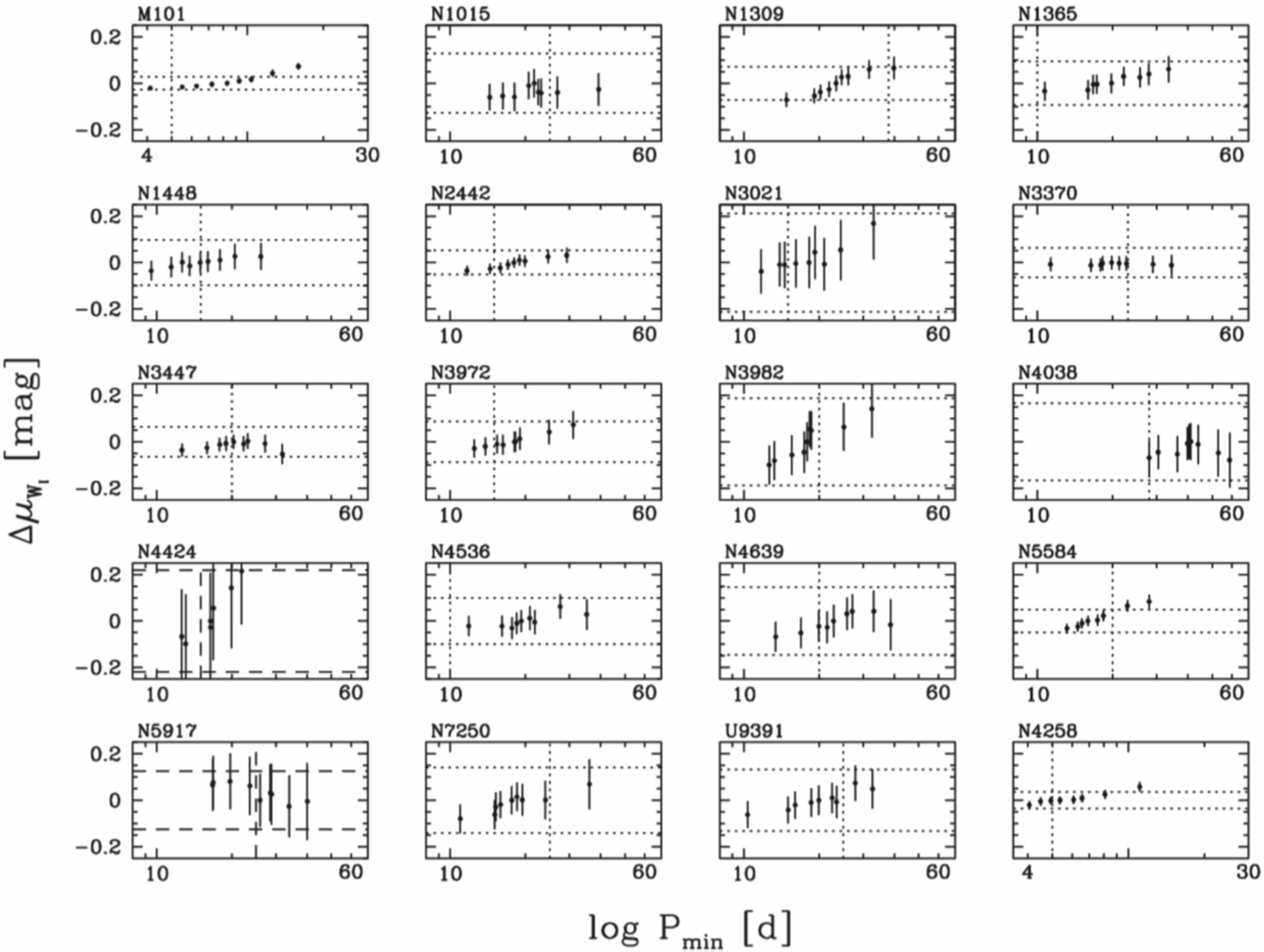
		all Cepheids		outliers removed	
galaxy	matches	$\langle\Delta m\rangle$	$\langle\Delta C\rangle$	$\langle\Delta m\rangle$	$\langle\Delta C\rangle$
N4536	28	-0.114 ± 0.057	0.153	-0.069 ± 0.062	0.153
N4639	17	-0.071 ± 0.100	0.091	-0.071 ± 0.100	0.091
N3370	51	-0.105 ± 0.055	0.146	-0.090 ± 0.055	0.145
N3982	12	-0.178 ± 0.090	0.092	-0.081 ± 0.094	0.092
N3021	13	$+0.120 \pm 0.146$	0.196	$+0.120 \pm 0.146$	0.196
N1309	16	-0.087 ± 0.091	0.330	-0.087 ± 0.091	0.330
N5584	65	-0.028 ± 0.049	0.039	$+0.001 \pm 0.051$	0.038
N4038	11	-0.239 ± 0.153	0.109	-0.239 ± 0.153	0.109
N4258	73	-0.217 ± 0.055	0.145	-0.020 ± 0.062	0.143

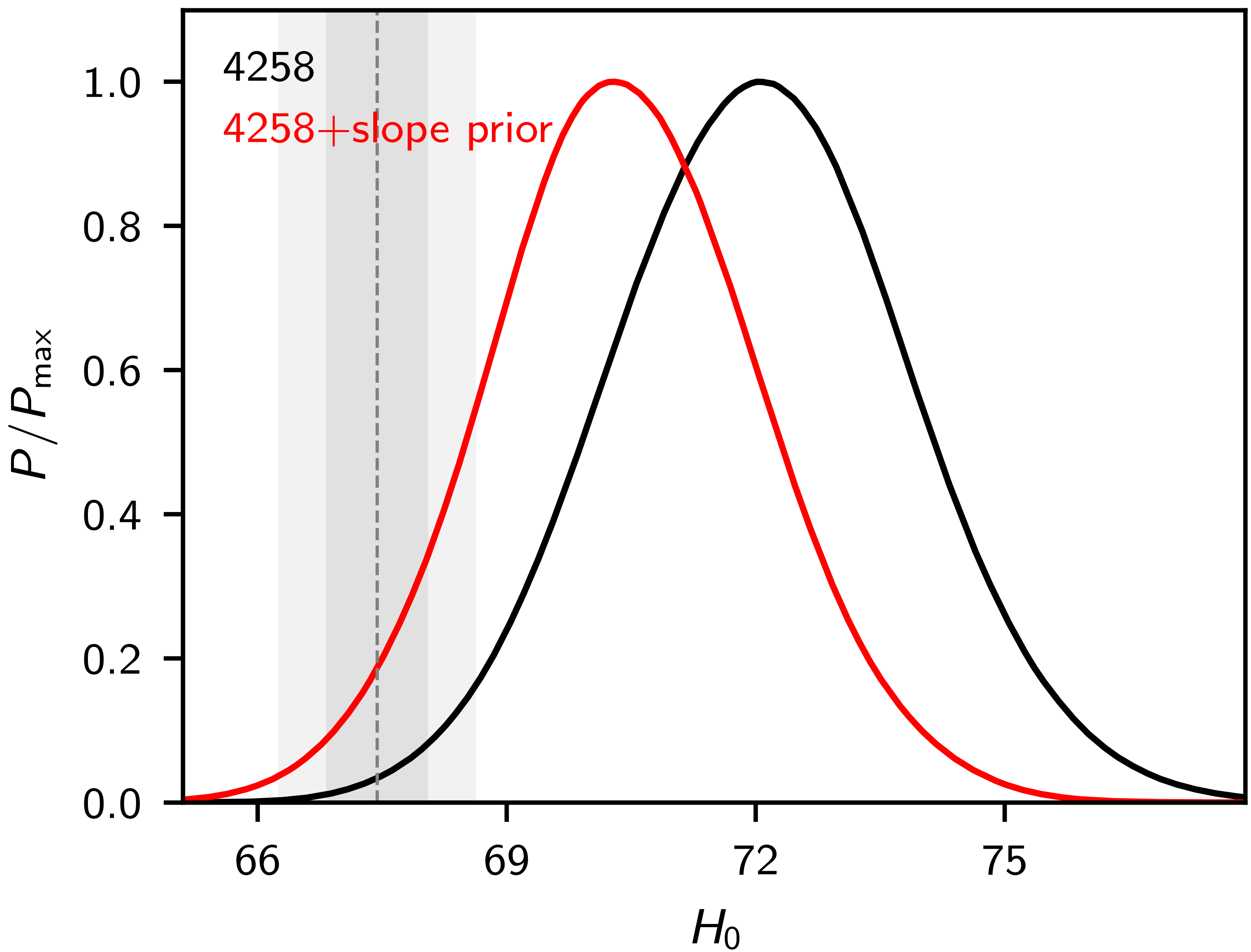
$$(m_H^W)_{\rm R16} = (m_H^W)_{\rm R11} + \langle\Delta m\rangle, \qquad \langle\Delta m\rangle = -0.051 \pm 0.025,$$

$$(V-I)_{\rm R16} = (V-I)_{\rm R11} + \langle\Delta C\rangle, \qquad \langle\Delta C\rangle = 0.14 \pm 0.03,$$

$\delta H_0 \approx 1.8$ km/s/Mpc from photometry (systematic)

From Hoffmann etal 2016 ApJ, 830, 10.





4258
4258+slope prior
1.0
0.8
0.6
0.4
0.2
0.0
66
69
72
75
H_0
$P\,/\,P_{\rm max}$

Possibilities:

- ❑ Difference between anchors is an unusual statistical fluctuation.
- ❑ Systematics in one or both geometrical anchor distances.
- ❑ Metallicity (population) differences between LMC and SN host Cepheids
- ❑ Offset between PL normalization for resolved Cepheid photometry and crowded (SN host) Cepheid photometry