H_0 from Planck

or

how a boring LCDM can still be a mischievous model

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CMB IS NOT DIRECTLY SENSITIVE TO H_0

THE MEASUREMENTS OF H_0 FROM CMB ARE MODEL DEPENDENT

ACOUSTIC SCALE

The best determined parameter in Planck

$$\boldsymbol{\theta_* = r_{s*}/D_{M*}}$$

COMOVING SOUND HORIZON

It depends on early Universe physics like the species present at recombination

$$r_s = \int_0^{t_\mathrm{d}} c_\mathrm{s} dt/a = \int_0^{a_\mathrm{d}} c_\mathrm{s} \frac{da}{a^2 H(a)}$$

$$\boldsymbol{H(a) = 8\pi G(\rho_\gamma + \rho_v + \rho_m + \cdots ?)}$$

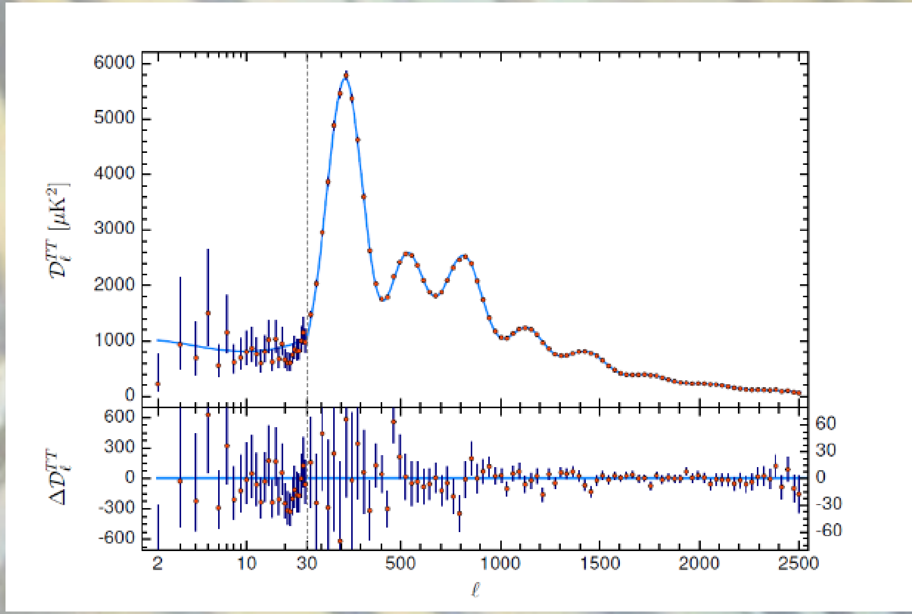
$$\boldsymbol{c_s \longrightarrow \frac{\rho_b}{\rho_\gamma}}$$

ANGULAR DIAMETER DISTANCE

$$\boldsymbol{D_M = (1+z)D_A}$$

It depends on late time cosmology like the expansion rate (e.g. the dark energy behaviour)

$$D_A(z) = \int_0^z dz'/H(z')$$



θ_* is very robust since it depends on the positions of the peaks

Parameter	*Planck* Best fit	*Planck* 68% limits	*Planck*+lensing Best fit	*Planck*+lensing 68% limits	*Planck*+WP Best fit	*Planck*+WP 68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$

2013

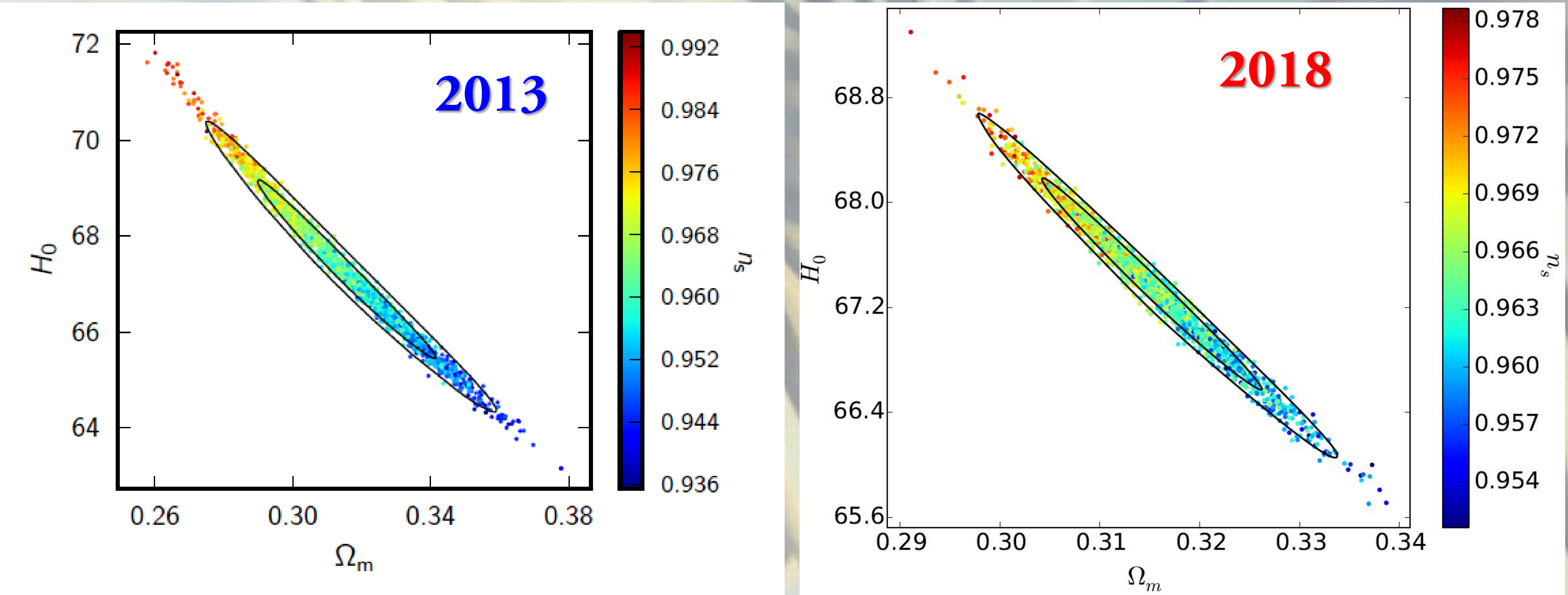
Parameter	[1] *Planck* TT+lowP	[2] *Planck* TE+lowP	[3] *Planck* EE+lowP	[4] *Planck* TT,TE,EE+lowP	$([1]-[4])/\sigma_{[1]}$
$\Omega_b h^2$	0.02222 ± 0.00023	0.02228 ± 0.00025	0.0240 ± 0.0013	0.02225 ± 0.00016	-0.1
$\Omega_c h^2$	0.1197 ± 0.0022	0.1187 ± 0.0021	$0.1150^{+0.0048}_{-0.0055}$	0.1198 ± 0.0015	0.0
$100\theta_{MC}$	1.04085 ± 0.00047	1.04094 ± 0.00051	1.03988 ± 0.00094	1.04077 ± 0.00032	0.2
τ	0.078 ± 0.019	0.053 ± 0.019	$0.059^{+0.022}_{-0.019}$	0.079 ± 0.017	-0.1
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.031 ± 0.041	$3.066^{+0.046}_{-0.041}$	3.094 ± 0.034	-0.1
n_s	0.9655 ± 0.0062	0.965 ± 0.012	0.973 ± 0.016	0.9645 ± 0.0049	0.2

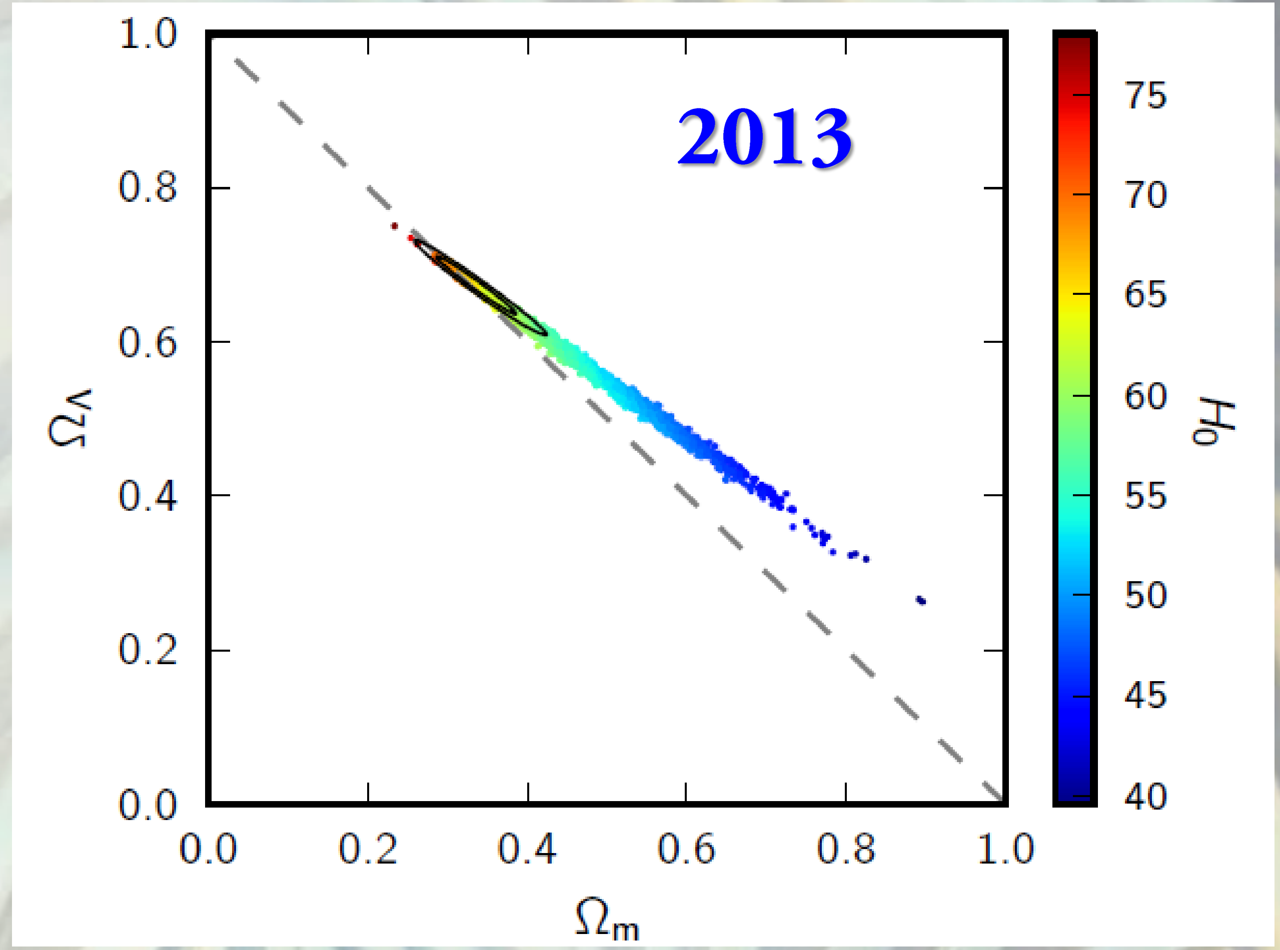
2015

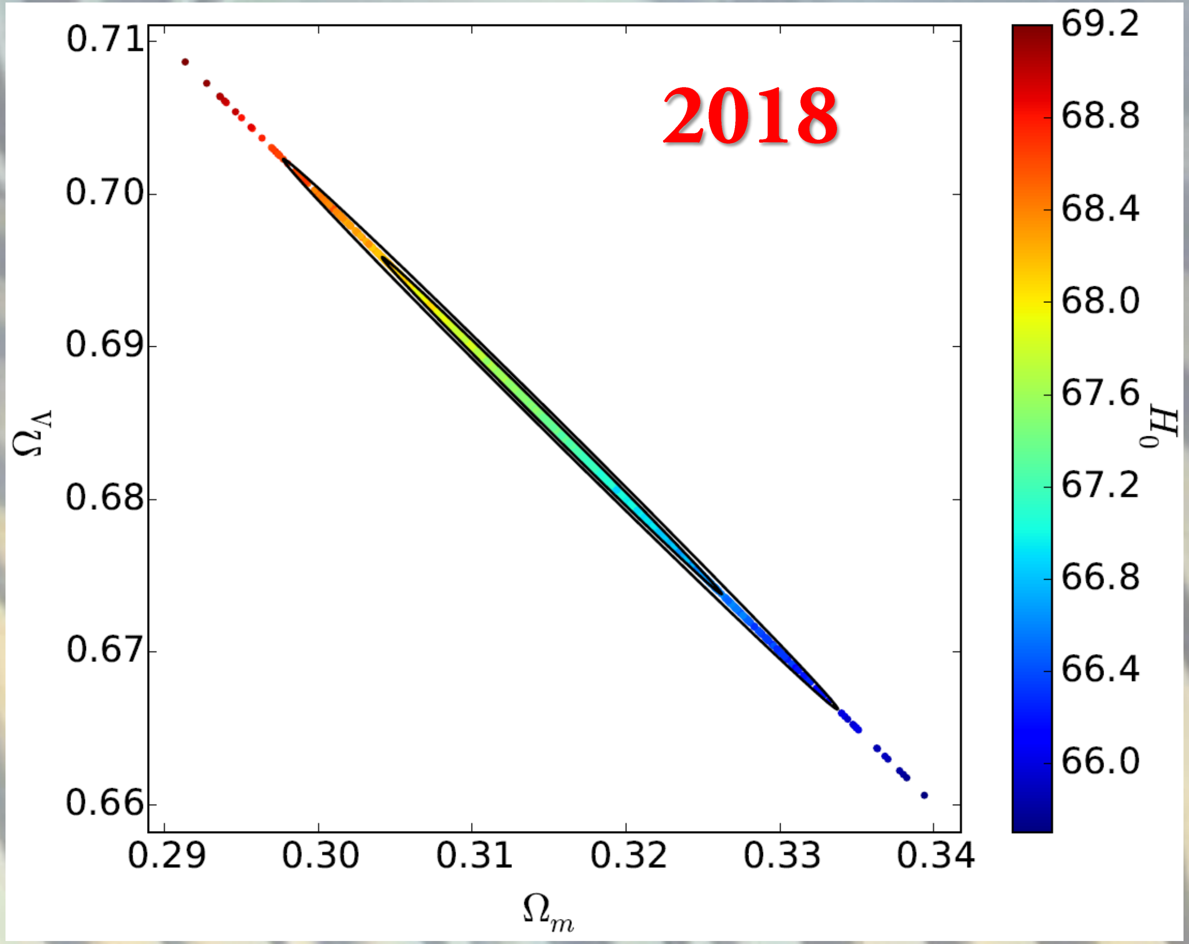
Parameter	TT+lowE 68% limits	TE+lowE 68% limits	EE+lowE 68% limits	TT,TE,EE+lowE 68% limits	TT,TE,EE+lowE+lensing 68% limits	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	0.02212 ± 0.00022	0.02249 ± 0.00025	0.0240 ± 0.0012	0.02236 ± 0.00015	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1206 ± 0.0021	0.1177 ± 0.0020	0.1158 ± 0.0046	0.1202 ± 0.0014	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04077 ± 0.00047	1.04139 ± 0.00049	1.03999 ± 0.00089	1.04090 ± 0.00031	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0522 ± 0.0080	0.0496 ± 0.0085	0.0527 ± 0.0090	$0.0544^{+0.0070}_{-0.0081}$	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.040 ± 0.016	$3.018^{+0.020}_{-0.018}$	3.052 ± 0.022	3.045 ± 0.016	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9626 ± 0.0057	0.967 ± 0.011	0.980 ± 0.015	0.9649 ± 0.0044	0.9649 ± 0.0042	0.9665 ± 0.0038

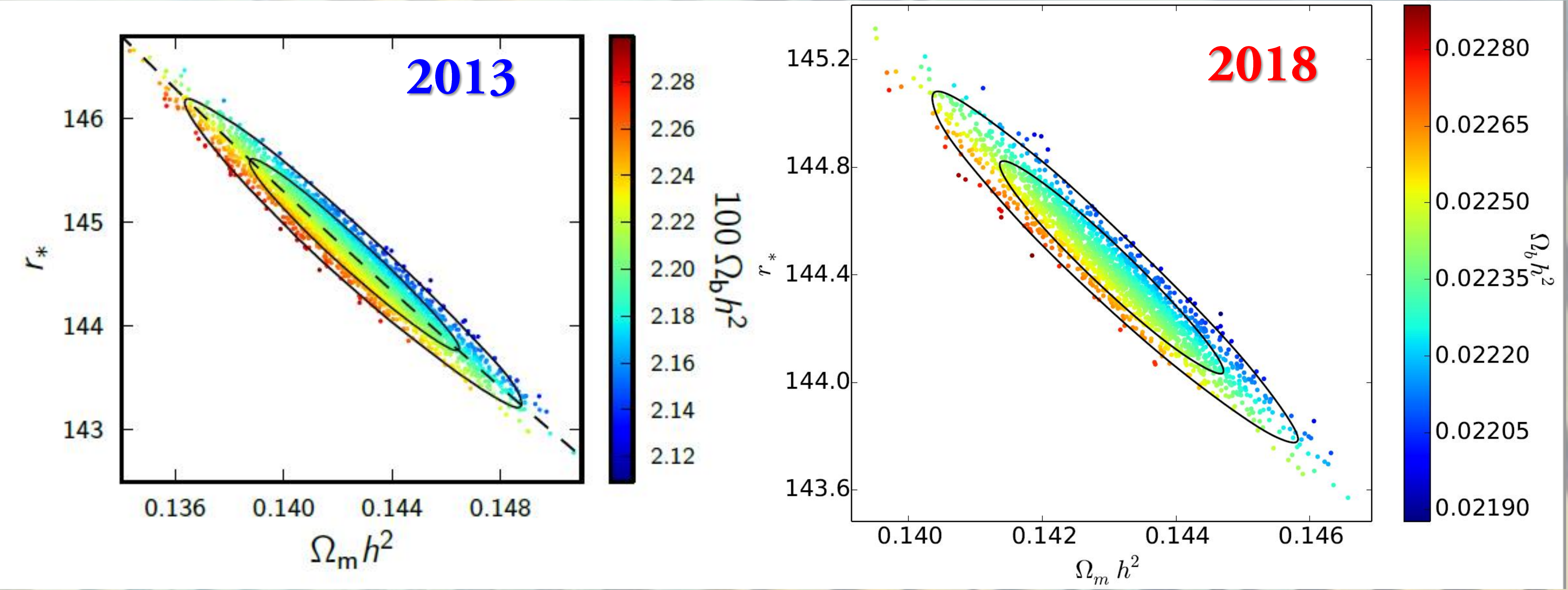
2018

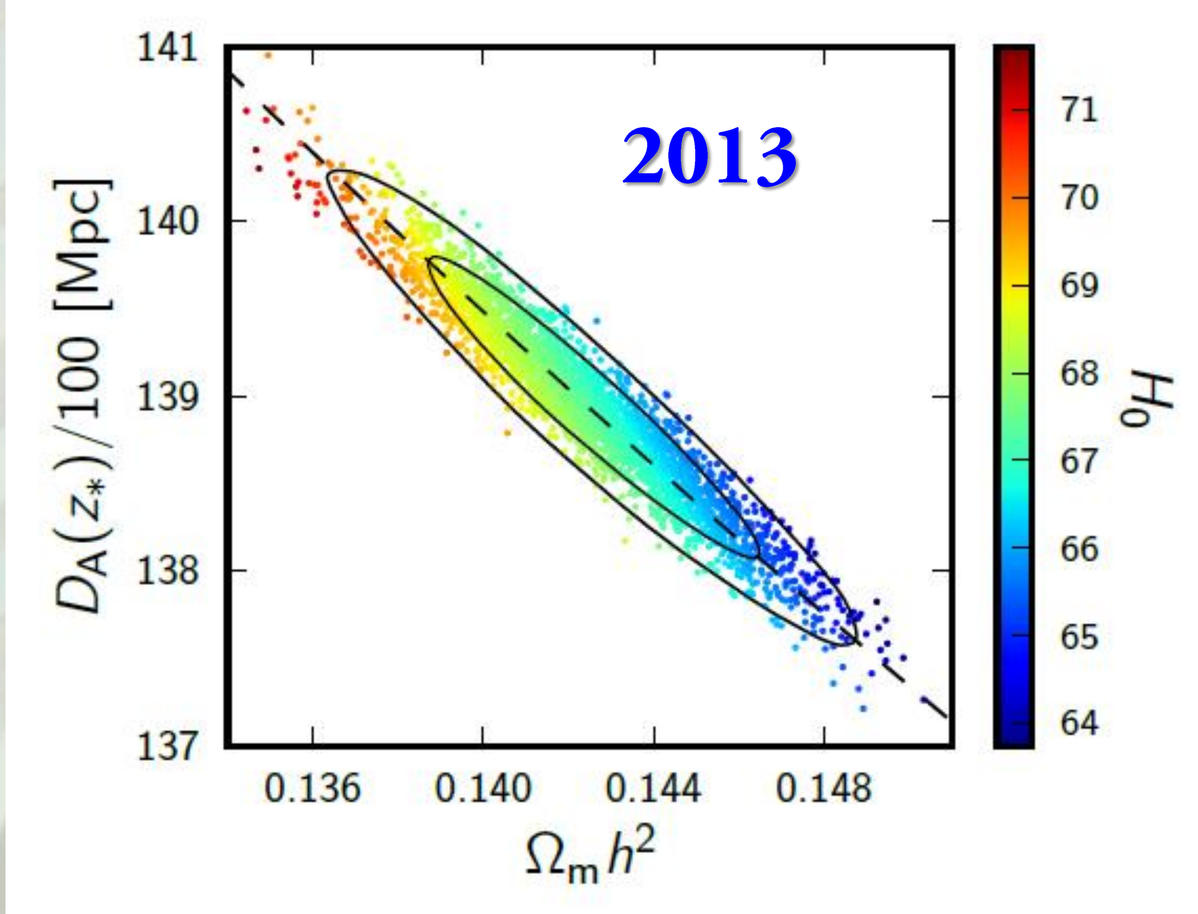
Many parameters enter into the conversion to H_0 making it prone to degeneracies: maintaining a fixed θ_* we may change different parameters sets



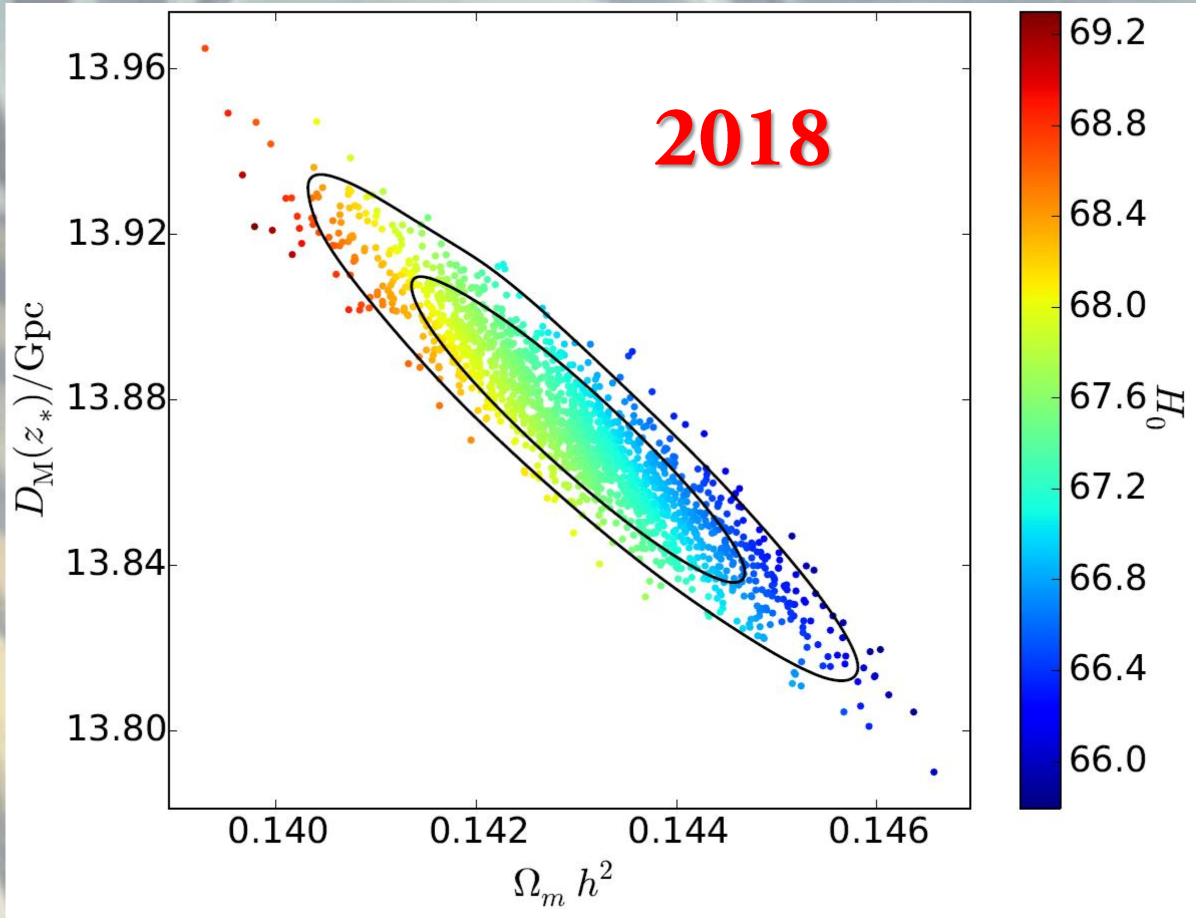

2013
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
Ω_Λ
Ω_m
75
70
65
60
55
50
45
40
H_0


2018
0.71
0.70
0.69
0.68
0.67
0.66
0.29
0.30
0.31
0.32
0.33
0.34
Ω_Λ
Ω_m
69.2
68.8
68.4
68.0
67.6
67.2
66.8
66.4
66.0
H_0


2013
r_*
146
145
144
143
0.136
0.140
0.144
0.148
$\Omega_m h^2$
$100\,\Omega_b h^2$
2.28
2.26
2.24
2.22
2.20
2.18
2.16
2.14
2.12
2018
r_*
145.2
144.8
144.4
144.0
143.6
0.140
0.142
0.144
0.146
$\Omega_m h^2$
$\Omega_b h^2$
0.02280
0.02265
0.02250
0.02235
0.02220
0.02205
0.02190



2013
$D_A(z_*)/100$ [Mpc]
$\Omega_m h^2$
H_0
141
140
139
138
137
0.136
0.140
0.144
0.148
71
70
69
68
67
66
65
64



2018
$D_M(z_*)/\mathrm{Gpc}$
$\Omega_m h^2$
H_0
13.96
13.92
13.88
13.84
13.80
0.140
0.142
0.144
0.146
69.2
68.8
68.4
68.0
67.6
67.2
66.8
66.4
66.0

2013

$$H_0 = (67.3 \pm 1.2)\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$$

2015

$$H_0 = (67.8 \pm 0.9)\ \mathrm{km\,s^{-1}Mpc^{-1}}$$

2018

$$\left.\begin{aligned} H_0 &= (67.27 \pm 0.60)\ \mathrm{km\,s^{-1}Mpc^{-1}}, \\ \Omega_m &= 0.3166 \pm 0.0084, \end{aligned}\right\} \quad \text{68 %, TT,TE,EE +lowE.}$$

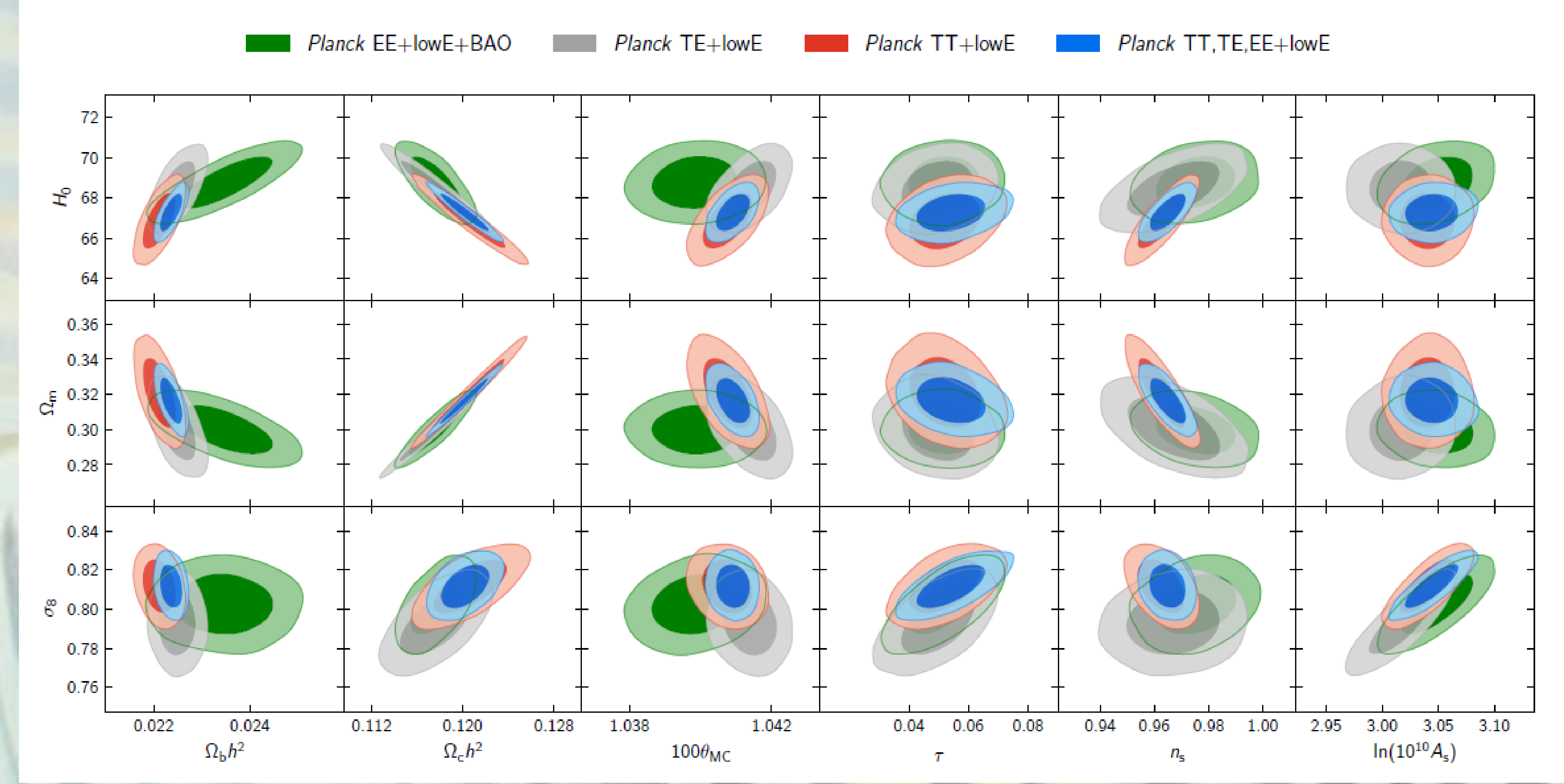
$$H_0 = (67.36 \pm 0.54)\ \mathrm{km\,s^{-1}Mpc^{-1}} \quad \text{(68 %, TT,TE,EE +lowE+lensing).}$$

$$\left.\begin{aligned} H_0 &= (67.66 \pm 0.42)\ \mathrm{km\,s^{-1}Mpc^{-1}}, \\ \Omega_m &= 0.3111 \pm 0.0056, \end{aligned}\right\} \quad \text{68 %, TT,TE,EE +lowE+lensing +BAO.}$$

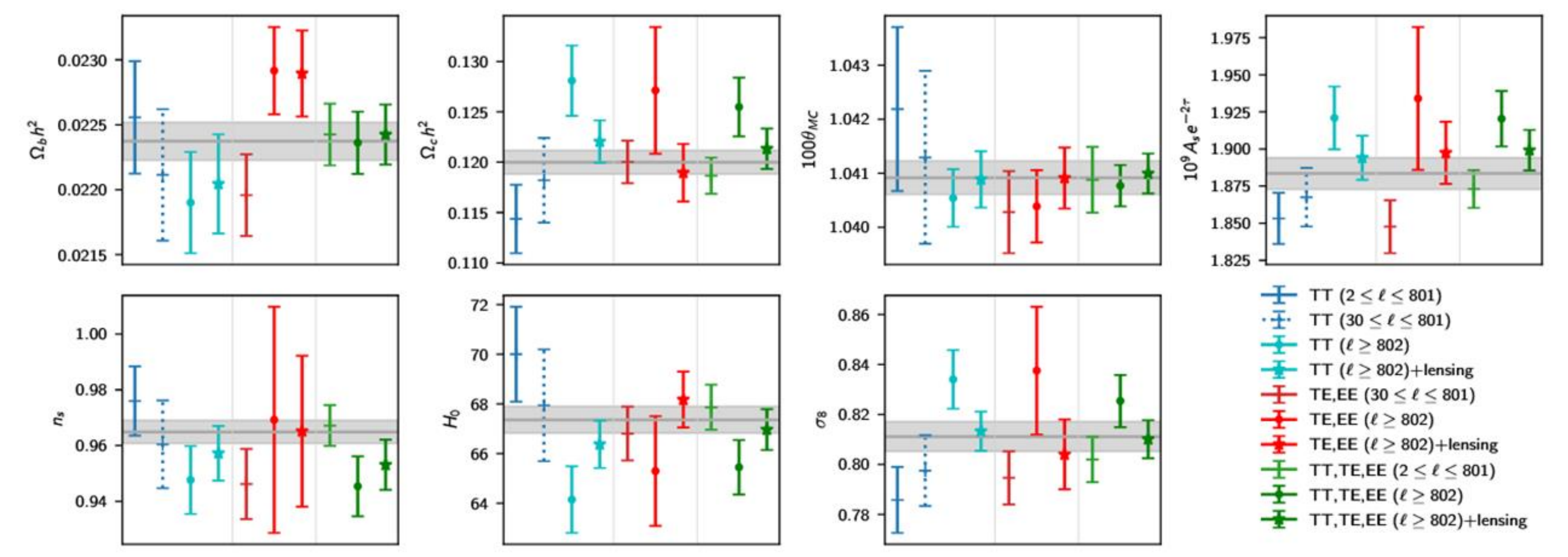
$$\left.\begin{aligned} H_0 &= 67.9^{+1.2}_{-1.3}\ \mathrm{km\,s^{-1}Mpc^{-1}}, \\ \sigma_8 &= 0.811 \pm 0.019, \\ \Omega_m &= 0.303^{+0.016}_{-0.018}, \end{aligned}\right\} \quad \text{68 %, lensing+BAO.}$$

Sub % level error
Stable against the addition of lensing and BAO and in agreement with the lensing alone+BAO

CONSISTENCY I



CONSISTENCY II



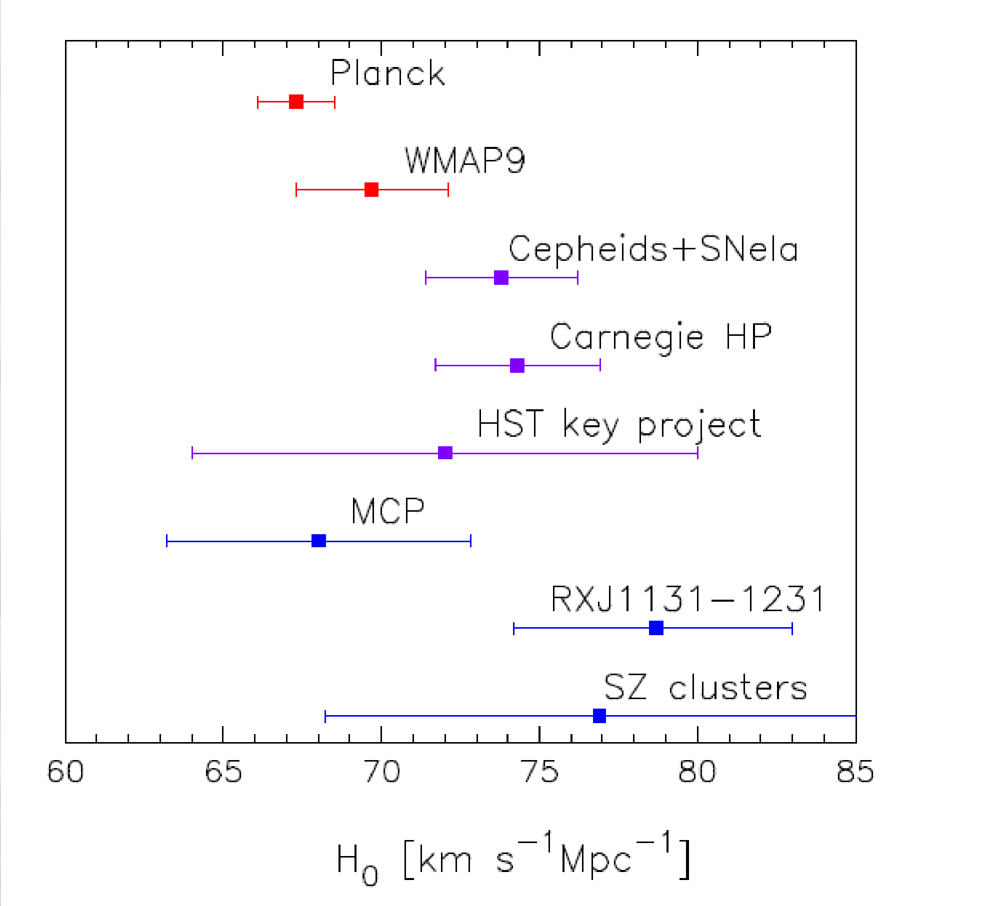
In LCDM Planck has been able to determine the Hubble constant to a sub% level accuracy

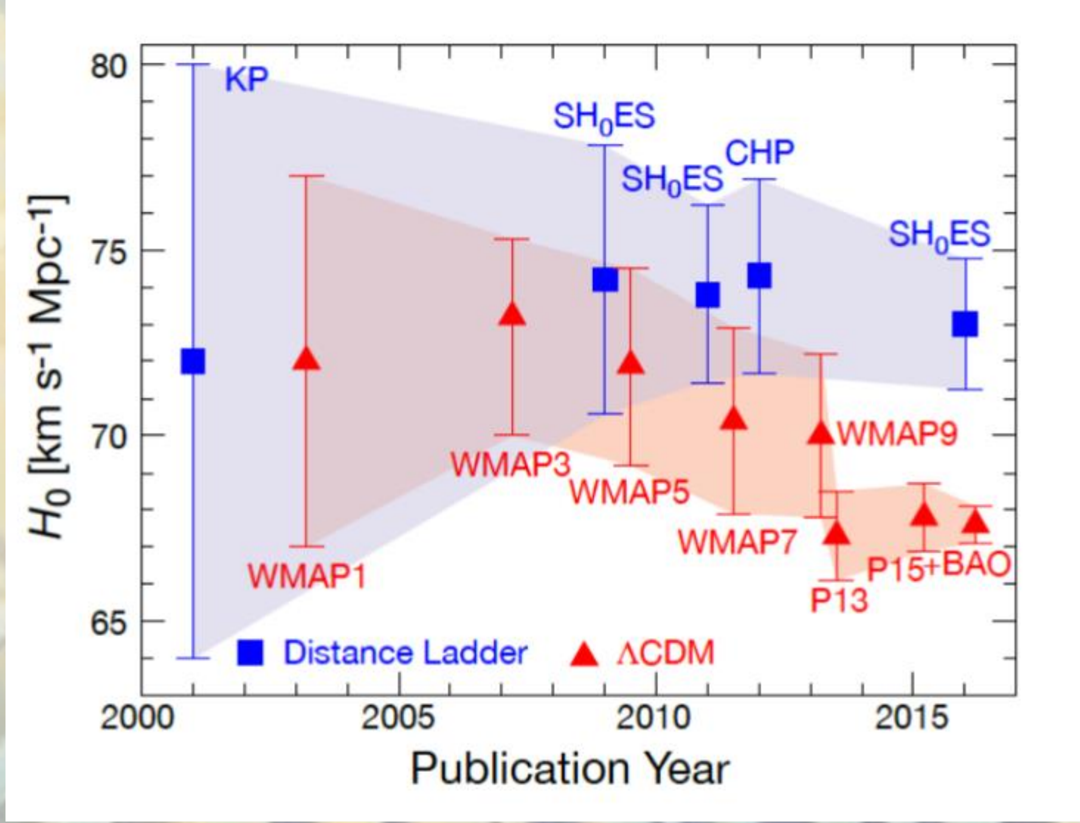
Planck CMB is very well fitted by the LCDM model

But the Hubble constant belongs to the late Universe where other probes may direct measure it with distance ladder

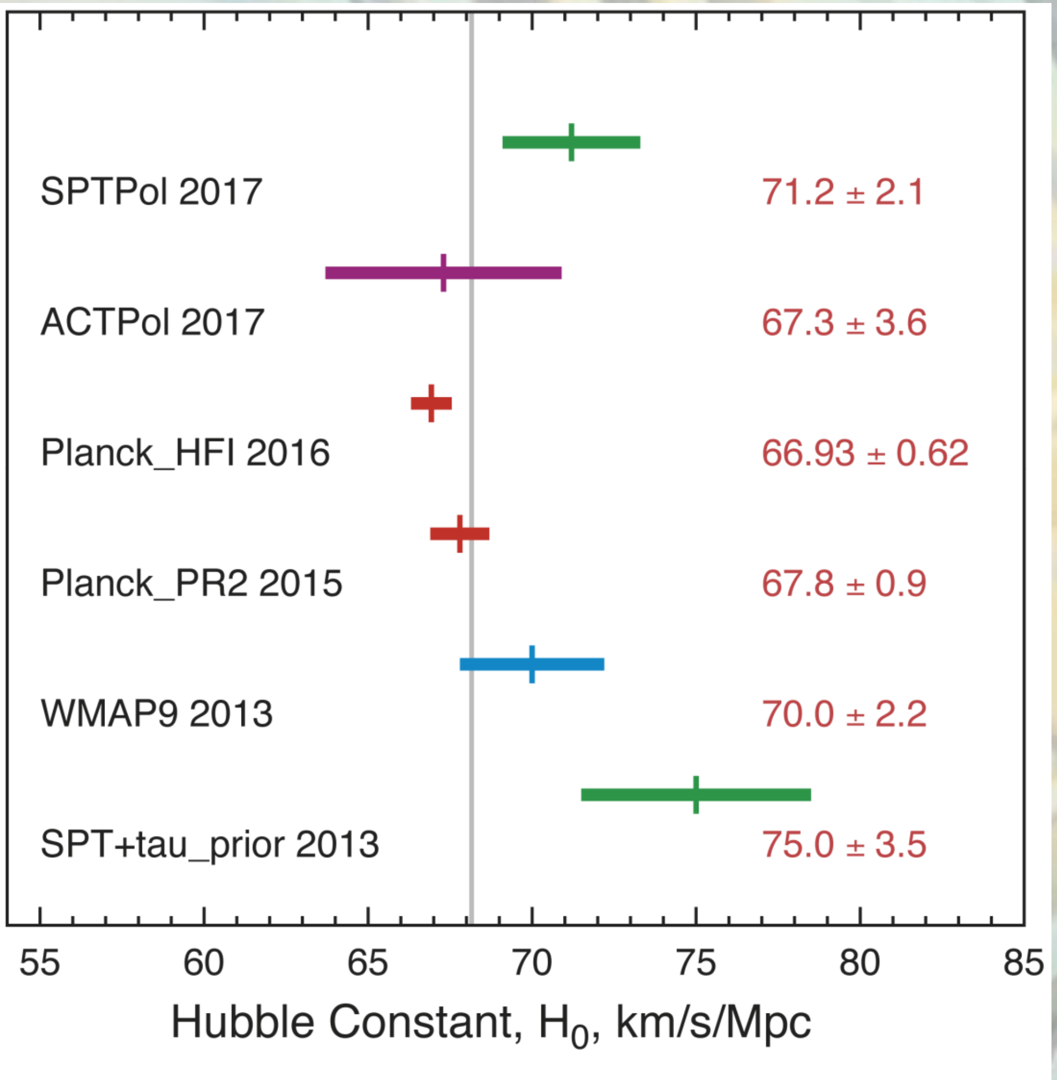
(see talks after coffee break)

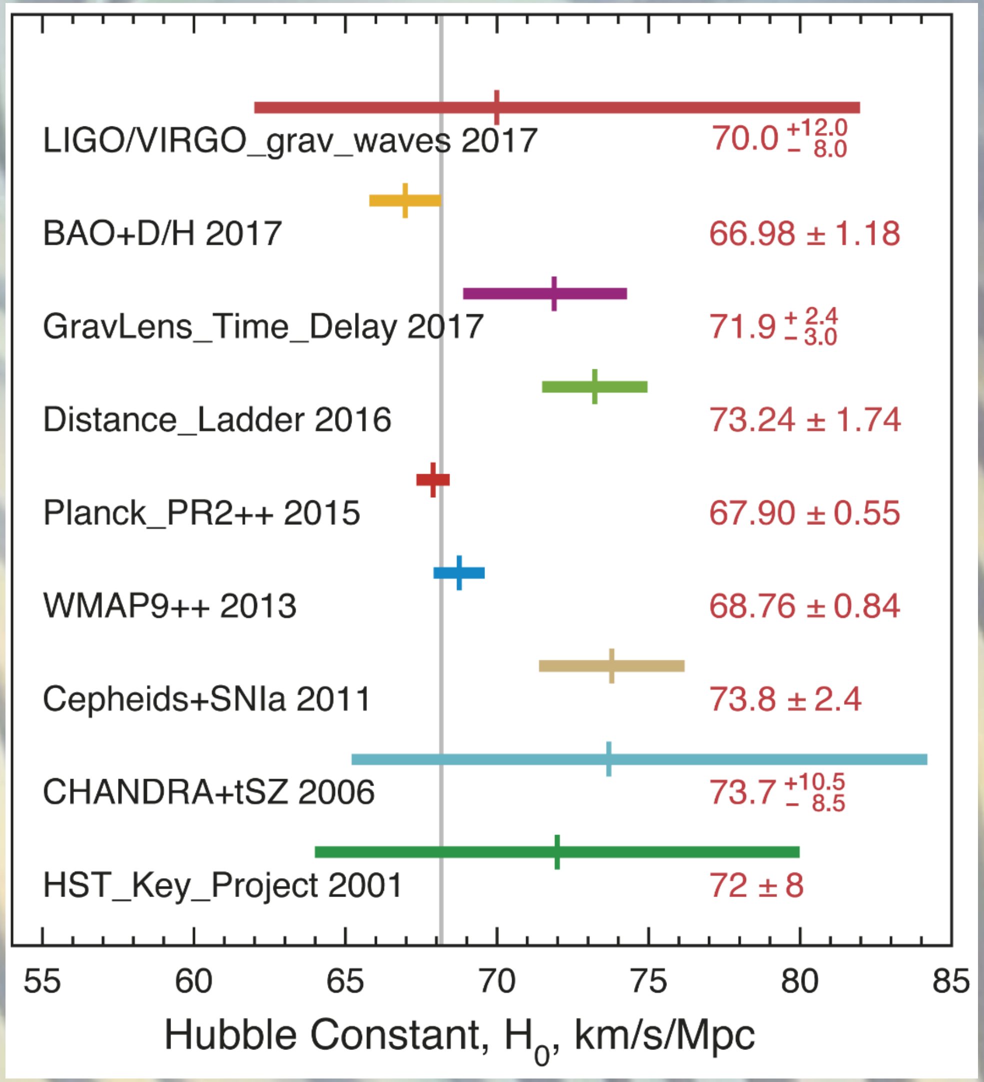
Supernova type Ia NGC4526 SN 1994D





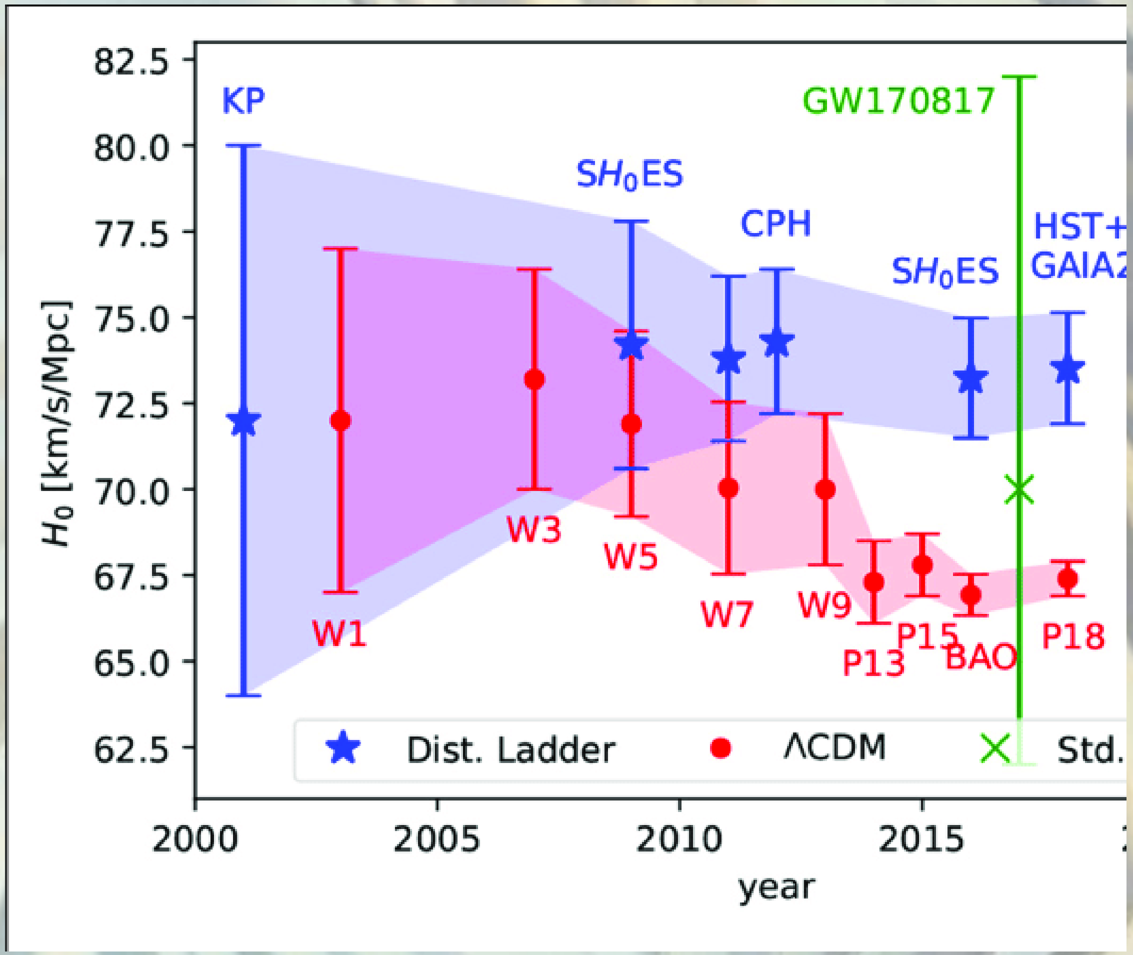
Freeman 2016



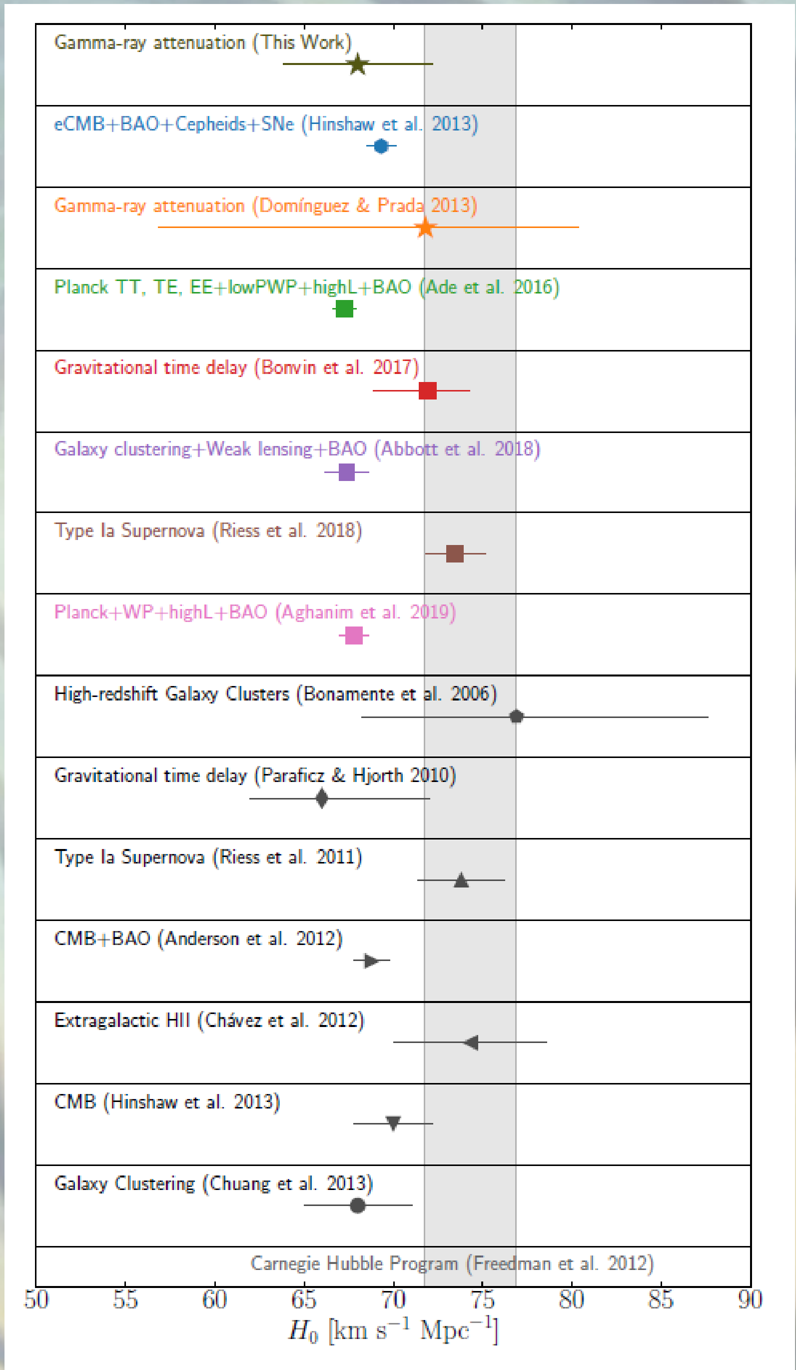


Source: LAMBDA NASA

Is getting worse….

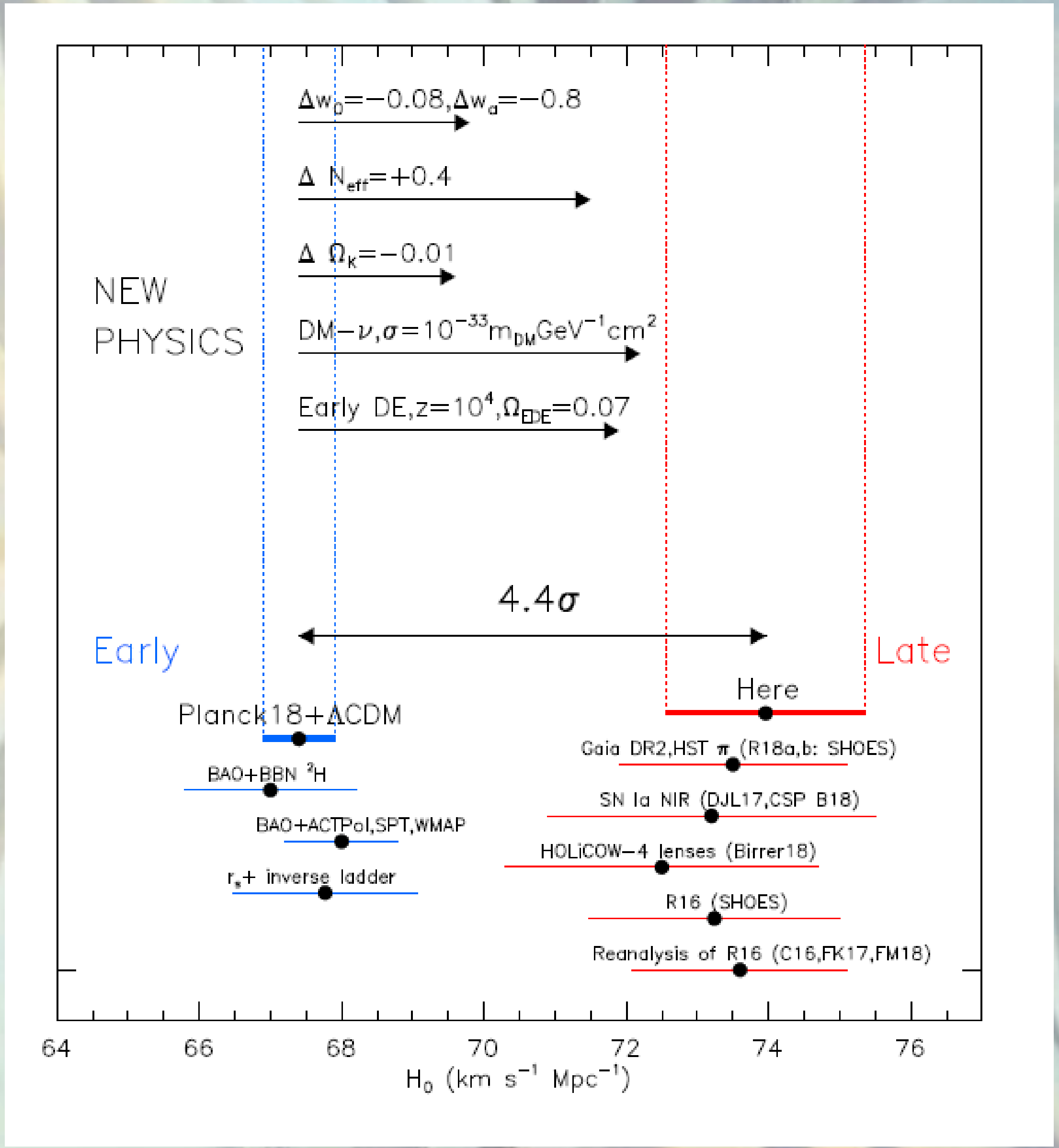


Ezquiaga & Zumalacarregui 2018



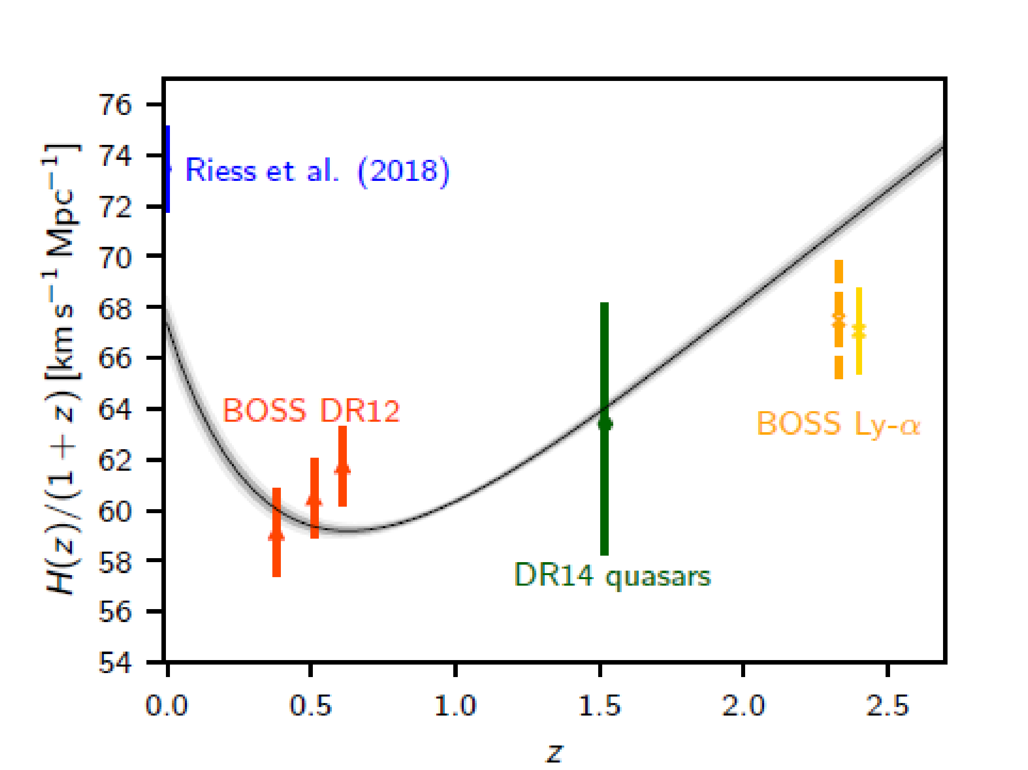
Dominguez et al. 2019

And worse….

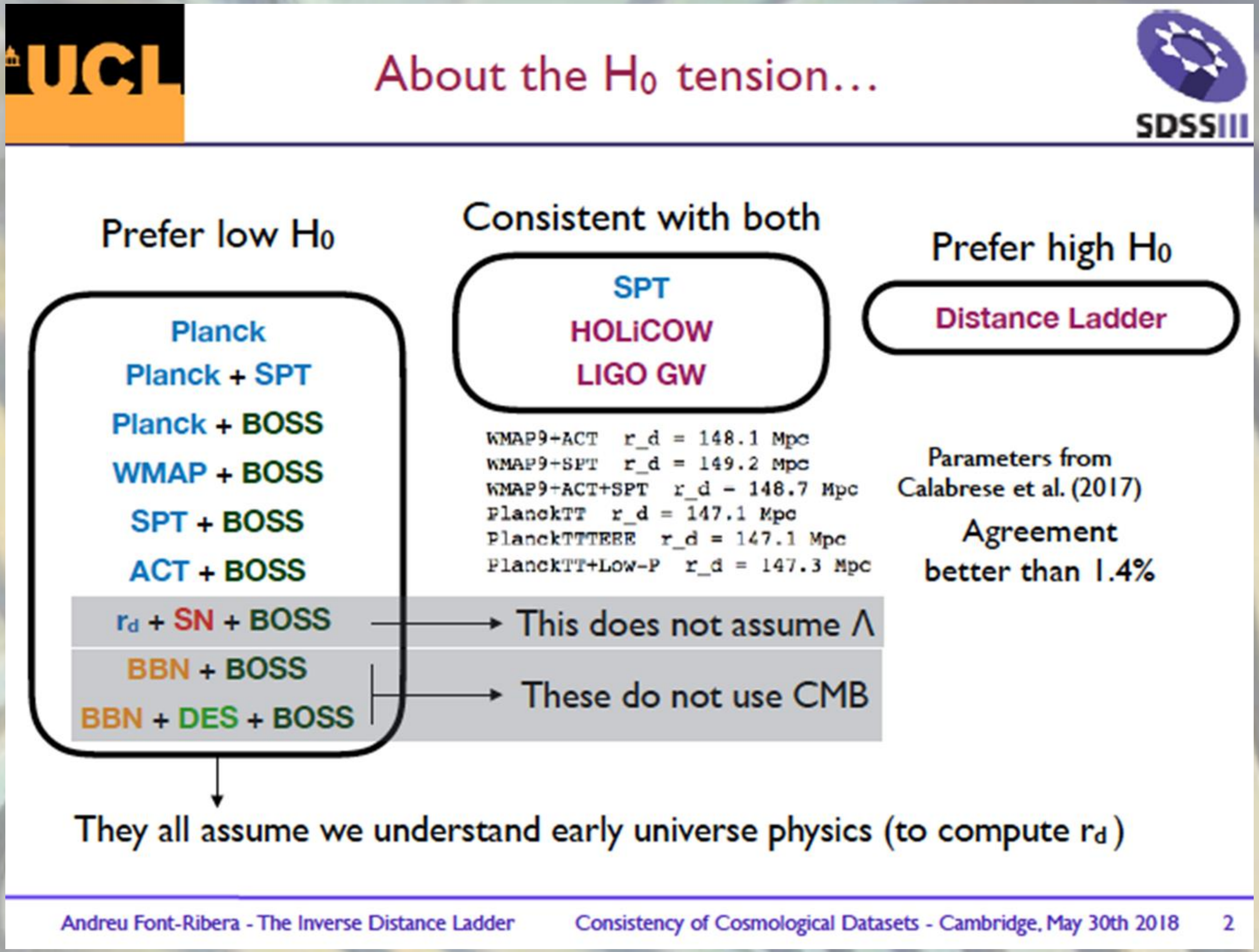


Riess et al. 2019

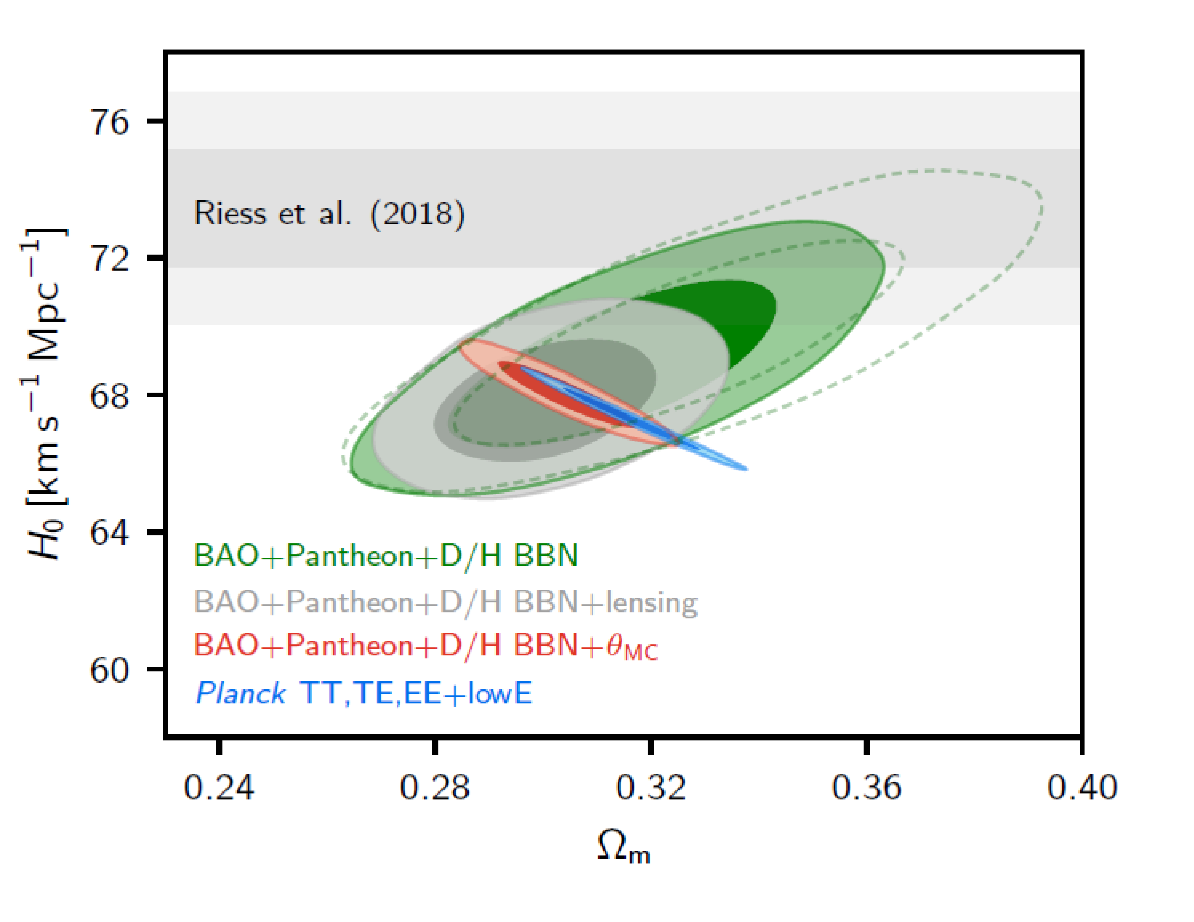
But there is agreement with Planck by several datasets



Measurements of the Hubble constant using strong gravitational lensing time delays are more model dependent, but also give a higher value than Planck



INVERSE DISTANCE LADDER



We can derive the value of H0 without using the CMB but only a subset of informations.
BAO+SNe can calibrate the distance-redshift relation down to low redshifts.

Baryon density is fixed from BBN constraints and it is considered the theta measurement from the CMB with different priors

WE ARE IN A LOBBY WITH TWO POSSIBLE DOORS

FIRST DOOR
CHANGE THE PHYSICS

SECOND DOOR
CHANGE THE DATA

From the Movie «Labirinth»

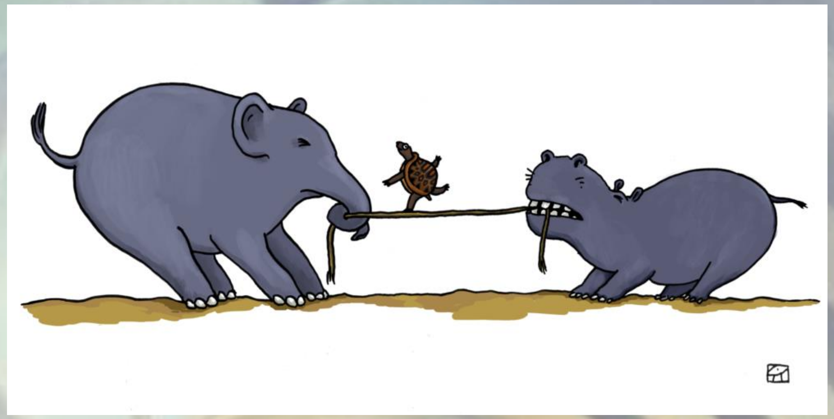
WE TRY THE FIRST DOOR

CHANGE THE PHYSICS

MIND THE OTHER TENSION!!!

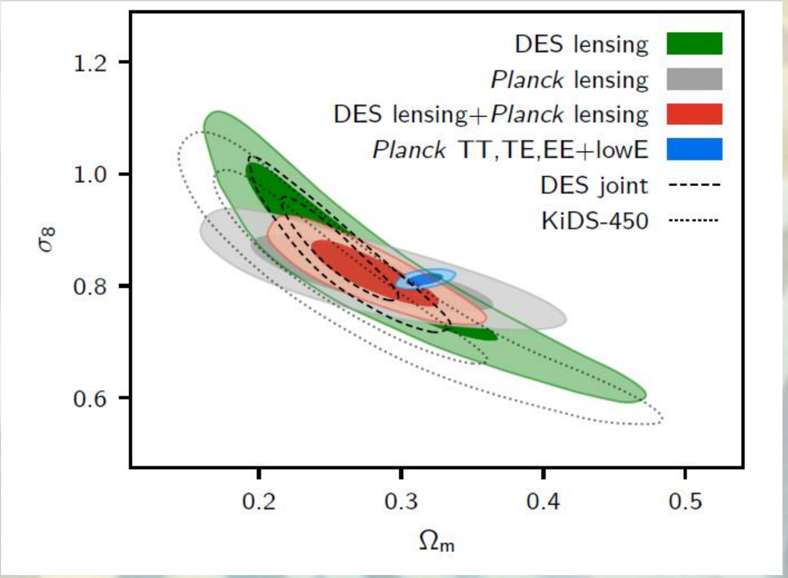
When we try to fix the H0 tension we must always keep in mind two things:

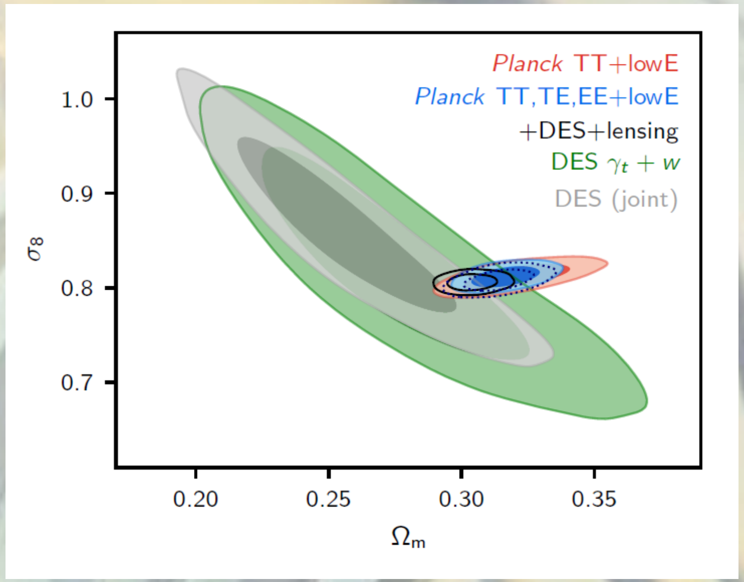
- **Whatever solution should still be compatible with CMB**
- **Whatever solution must not increase the other tension of Planck**



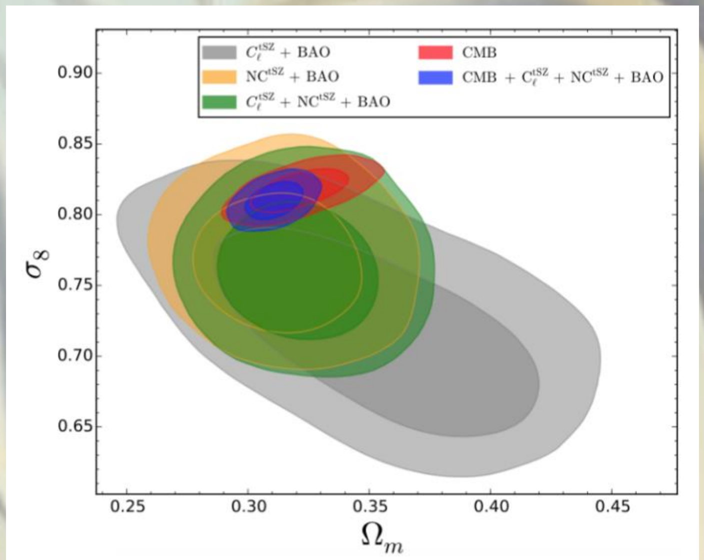
Sigma 8

Planck prefers higher values of with respect to WL surveys and galaxy clusters





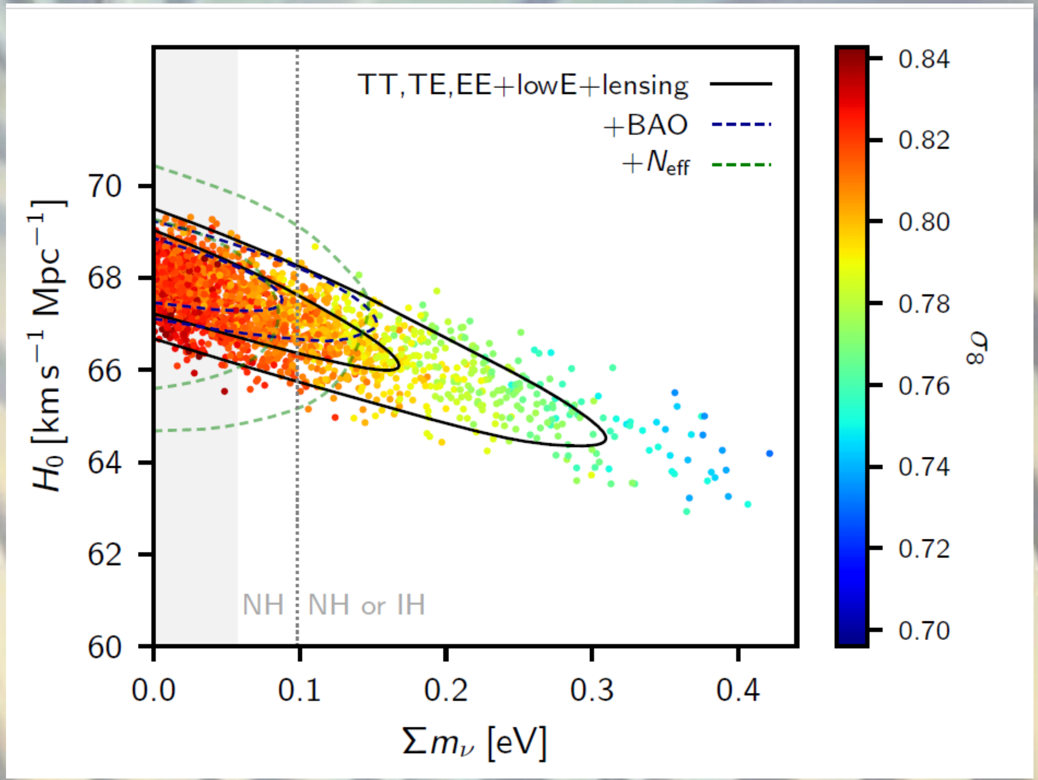
Planck 2018 VI 2018



Salvati et al 2018

NEUTRINO MASS

Allowing for a non-minimal neutrino mass impact the fitting of the acoustic oscillations on small angular scales.
Higher neutrino mass means lowering the lensing signal which result in a tight constraints on the sum of the masses due to the Alens issue. But higher neutrino mass calls for lowering H0 increasing the tension, improving the constraint on the mass highers both H0 and sigma 8



Planck 2018 VI 2018

See talks on neutrinos tomorrow (Gerbino, Lattanzi)

RELATIVISTIC SPECIES

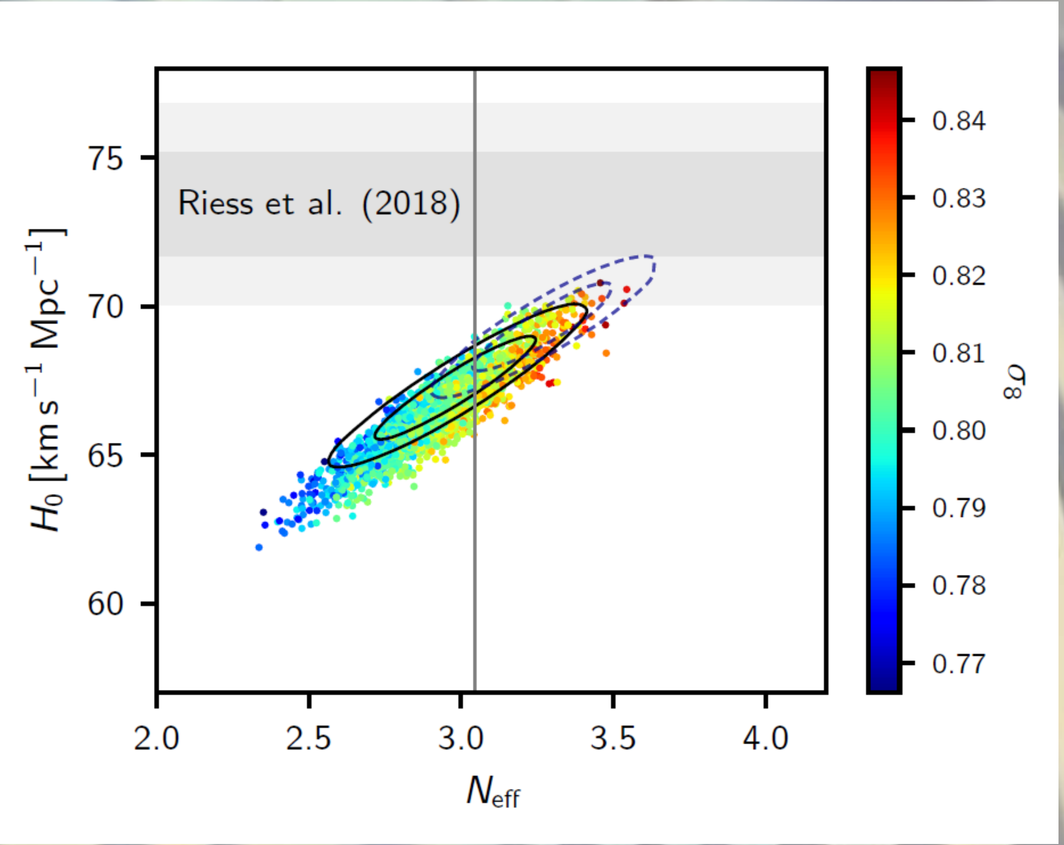
We have seen how the acoustic horizon depends on the energy densities of the plasma at recombination. For Neff higher than 3.046 to keep fix the acoustic scale, considering the change in the sound horizon, H0 must go to higher values.

$$\Delta N_{\rm eff} = g \left[\frac{43}{4\, g_s}\right]^{4/3} \times \begin{cases} 4/7 & \text{boson,} \\ 1/2 & \text{fermion,} \end{cases}$$

E.G.
-1 for a fully thermalized sterile neutrino decoupled at <100 MeV
-0.027 is consider the maximum sensitivity level, and corresponds to a fully thermalized boson

Varying Neff allows for a relief of the H0 tension but it also brings an increase in the error on H0 lowering the significance of the improvement
On the other side a larger Neff implies a larger sigma 8 increasing the tension with WL data.

$$\left.\begin{aligned} N_{\rm eff} &= 3.27 \pm 0.15 \\ H_0 &= (69.32 \pm 0.97)\ {\rm km\ s^{-1} Mpc^{-1}} \end{aligned}\right\} \begin{array}{l} 68\,\%,\ \text{TT,TE,EE} \\ \text{+lowE+lensing} \\ \text{+BAO+R18.} \end{array}$$

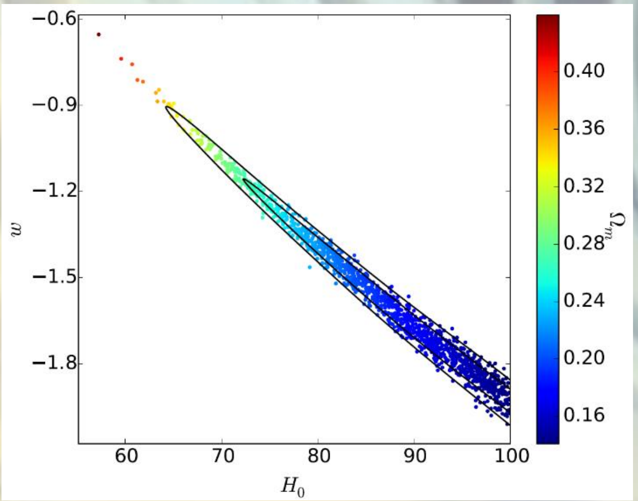


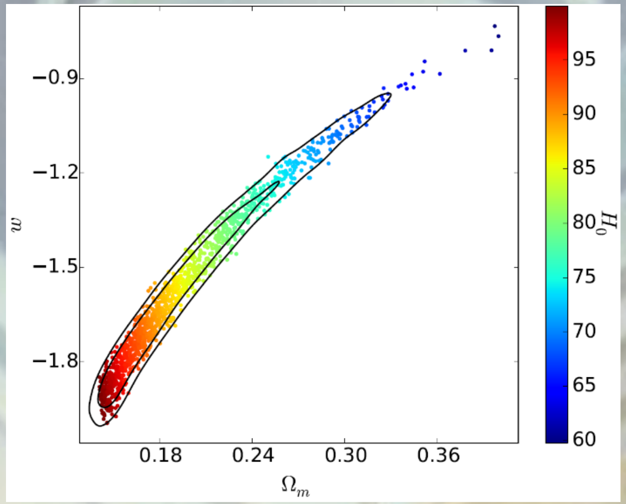
Planck 2018 VI 2018

Higher values starts also to be in disagreement with BBN

See talks on neutrinos tomorrow (Gerbino, Lattanzi)

LATE UNIVERSE

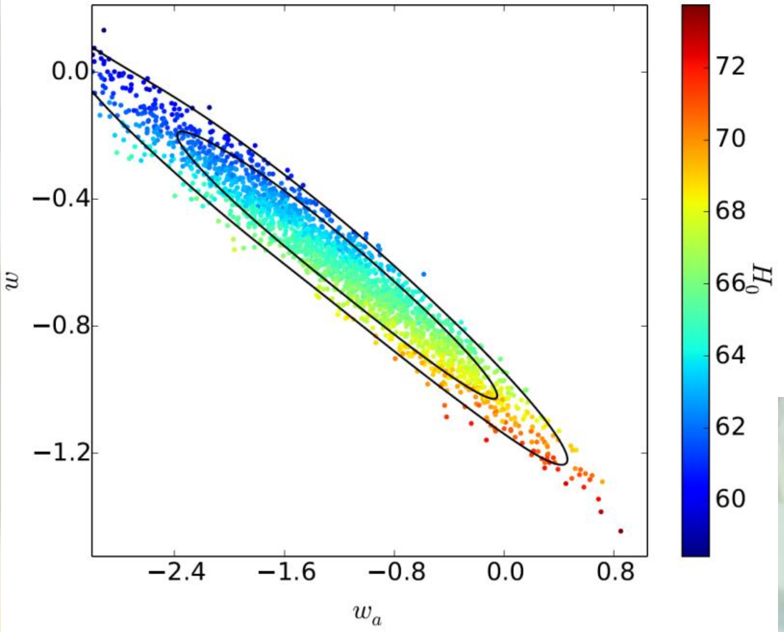




Higher H0-Phantom DE

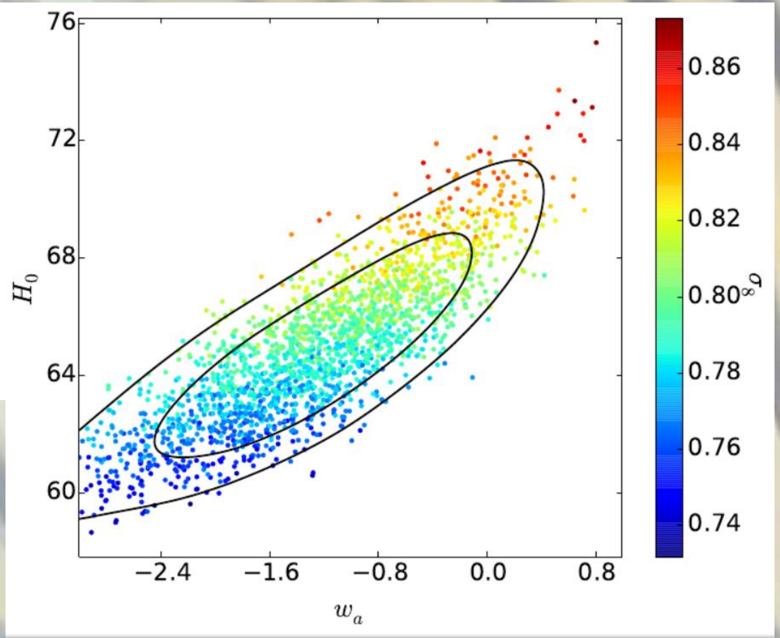
DARK ENERGY

See talks on DE tomorrow afternoon



Parameter	*Planck*+SNe+BAO	*Planck*+BAO/RSD+WL
w_0	-0.961 ± 0.077	-0.76 ± 0.20
w_a	$-0.28^{+0.31}_{-0.27}$	$-0.72^{+0.62}_{-0.54}$
H_0 [km s^{-1}Mpc^{-1}]	68.34 ± 0.83	66.3 ± 1.8
σ_8	0.821 ± 0.011	$0.800^{+0.015}_{-0.017}$
S_8	0.829 ± 0.011	0.832 ± 0.013
$\Delta\chi^2$	-1.4	-1.4

Higher H0-Higher sigma 8



MODIFIED GRAVITY

$$k^2\Psi = -\mu(a,k)\,4\pi G a^2\left[\rho\Delta + 3(\rho + P)\sigma\right],$$

$$k^2\left[\Phi - \eta(a,k)\Psi\right] = \mu(a,k)\,12\pi G a^2(\rho + P)\sigma.$$

$$k^2\left[\Phi + \Psi\right] = -\Sigma(a,k)4\pi G a^2\left[2\rho\Delta - 3(\rho + P)\sigma\right]$$

	With CMB lensing			Without CMB lensing		
Parameter	*Planck*	*Planck* +SNe+BAO	*Planck* +BAO/RSD+WL	*Planck*	*Planck* +SNe+BAO	*Planck* +BAO/RSD+WL
$\mu_0 - 1$	$0.10^{+0.30}_{-0.42}$	$0.05^{+0.26}_{-0.39}$	$-0.07^{+0.19}_{-0.32}$	$0.12^{+0.29}_{-0.51}$	$0.10^{+0.30}_{-0.50}$	$-0.12^{+0.17}_{-0.32}$
$\eta_0 - 1$	$0.22^{+0.55}_{-1.0}$	$0.32^{+0.63}_{-0.89}$	$0.32^{+0.63}_{-0.89}$	$0.55^{+0.78}_{-1.2}$	$0.62^{+0.79}_{-1.2}$	$0.52^{+0.67}_{-0.86}$
$\Sigma_0 - 1$	0.100 ± 0.093	0.106 ± 0.086	$0.018^{+0.059}_{-0.048}$	$0.27^{+0.15}_{-0.13}$	$0.27^{+0.15}_{-0.13}$	$0.017^{+0.058}_{-0.050}$
τ	$0.0481^{+0.0087}_{-0.0072}$	$0.0487^{+0.0088}_{-0.0074}$	0.0524 ± 0.0075	0.0504 ± 0.0080	0.0505 ± 0.0080	0.0526 ± 0.0079
H_0 [km s^{-1}Mpc^{-1}] . . .	68.20 ± 0.63	68.19 ± 0.45	68.09 ± 0.45	68.23 ± 0.71	68.26 ± 0.48	68.09 ± 0.46
σ_8	$0.812^{+0.034}_{-0.040}$	$0.807^{+0.029}_{-0.039}$	$0.799^{+0.023}_{-0.033}$	$0.817^{+0.032}_{-0.053}$	$0.814^{+0.033}_{-0.052}$	$0.794^{+0.020}_{-0.032}$
S_8	0.817 ± 0.037	$0.812^{+0.033}_{-0.038}$	$0.806^{+0.027}_{-0.034}$	$0.822^{+0.040}_{-0.051}$	$0.819^{+0.037}_{-0.052}$	$0.801^{+0.025}_{-0.034}$
$\langle d^2\rangle^{1/2}$ [arcmin]	$2.531^{+0.046}_{-0.052}$	2.529 ± 0.049	2.453 ± 0.032	$2.697^{+0.095}_{-0.082}$	$2.695^{+0.099}_{-0.080}$	2.456 ± 0.043
$\Sigma_0 S_8$	0.898 ± 0.067	$0.897^{+0.068}_{-0.061}$	$0.820^{+0.043}_{-0.035}$	$1.04^{+0.12}_{-0.099}$	$1.04^{+0.12}_{-0.098}$	$0.814^{+0.044}_{-0.038}$
$\Delta\chi^2$	-4.6	-5.5	-1.2	-10.2	-11.0	-0.7

Planck 2018 VI 2018

Slighty higher H0 but also higher sigma8

SUMMARY OF BASIC EXTENSIONS

Parameter(s)	$\Omega_b h^2$	$\Omega_c h^2$	$100\theta_{MC}$	H_0	n_s	$\ln(10^{10} A_s)$
Base ΛCDM	0.02237 ± 0.00015	0.1200 ± 0.0012	1.04092 ± 0.00031	67.36 ± 0.54	0.9649 ± 0.0042	3.044 ± 0.014
r	0.02237 ± 0.00014	0.1199 ± 0.0012	1.04092 ± 0.00031	67.40 ± 0.54	0.9659 ± 0.0041	3.044 ± 0.014
$dn_s/d\ln k$	0.02240 ± 0.00015	0.1200 ± 0.0012	1.04092 ± 0.00031	67.36 ± 0.53	0.9641 ± 0.0044	3.047 ± 0.015
$dn_s/d\ln k, r$	0.02243 ± 0.00015	0.1199 ± 0.0012	1.04093 ± 0.00030	67.44 ± 0.54	0.9647 ± 0.0044	3.049 ± 0.015
$d^2n_s/d\ln k^2, dn_s/d\ln k$.	0.02237 ± 0.00016	0.1202 ± 0.0012	1.04090 ± 0.00030	67.28 ± 0.56	0.9625 ± 0.0048	3.049 ± 0.015
N_{eff}	0.02224 ± 0.00022	0.1179 ± 0.0028	1.04116 ± 0.00043	66.3 ± 1.4	0.9589 ± 0.0084	3.036 ± 0.017
$N_{eff}, dn_s/d\ln k$	0.02216 ± 0.00022	0.1157 ± 0.0032	1.04144 ± 0.00048	65.2 ± 1.6	0.950 ± 0.011	3.034 ± 0.017
Σm_ν	0.02236 ± 0.00015	0.1201 ± 0.0013	1.04088 ± 0.00032	$67.1^{+1.2}_{-0.67}$	0.9647 ± 0.0043	3.046 ± 0.015
$\Sigma m_\nu, N_{eff}$	0.02223 ± 0.00023	0.1180 ± 0.0029	1.04113 ± 0.00044	$66.0^{+1.8}_{-1.6}$	0.9587 ± 0.0086	3.038 ± 0.017
$m^{eff}_{\nu,\,sterile}, N_{eff}$	$0.02242^{+0.00014}_{-0.00016}$	$0.1200^{+0.0032}_{-0.0020}$	$1.04074^{+0.00033}_{-0.00029}$	$67.11^{+0.63}_{-0.79}$	$0.9652^{+0.0045}_{-0.0056}$	$3.050^{+0.014}_{-0.016}$
α_{-1}	0.02238 ± 0.00015	0.1201 ± 0.0015	1.04087 ± 0.00043	67.30 ± 0.67	0.9645 ± 0.0061	3.045 ± 0.014
w_0	0.02243 ± 0.00015	0.1193 ± 0.0012	1.04099 ± 0.00031	. . .	0.9666 ± 0.0041	3.038 ± 0.014
Ω_K	0.02249 ± 0.00016	0.1185 ± 0.0015	1.04107 ± 0.00032	$63.6^{+2.1}_{-2.3}$	0.9688 ± 0.0047	$3.030^{+0.017}_{-0.015}$
Y_P	0.02230 ± 0.00020	0.1201 ± 0.0012	1.04067 ± 0.00055	67.19 ± 0.63	0.9621 ± 0.0070	3.042 ± 0.016
Y_P, N_{eff}	0.02224 ± 0.00022	$0.1171^{+0.0042}_{-0.0049}$	1.0415 ± 0.0012	$66.0^{+1.7}_{-1.9}$	0.9589 ± 0.0085	3.036 ± 0.018
A_L	0.02251 ± 0.00017	0.1182 ± 0.0015	1.04110 ± 0.00032	68.16 ± 0.70	0.9696 ± 0.0048	$3.029^{+0.018}_{-0.016}$

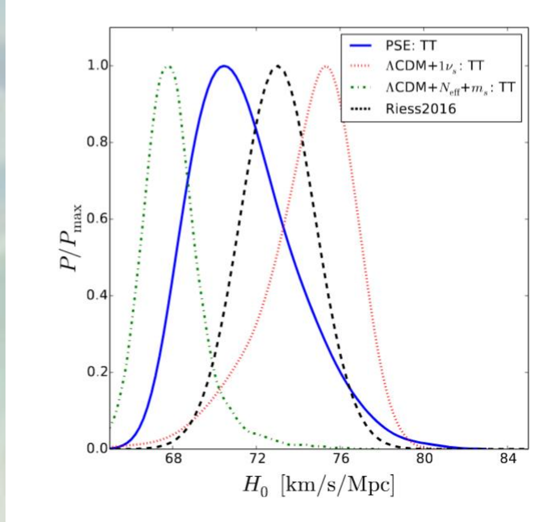
Planck 2018 VI 2018

Note that Alens is not a physical model..and opening dark energy equation of state results in not having constraining power on H0

No simple extensions of LCDM can fix the problem we need to be more creative

From the Movie «Labirinth», concept by Escher

NEW NEUTRINO PHYSICS?



Archidiacono et al. 2016

Sterile Neutrinos with secret interactions

"Secret" sterile neutrino self-interactions mediated by a light pseudoscalar allow for a sterile massive neutrino in cosmology because of early thermalization and late annihilation. The resulting H0 is on higher values.

Neutrino self interactions

New neutrino self interactions delay the onset of neutrino free-streaming affecting the value of H0 (through the change in the early Universe). Interactions requires anyway the addition of a light sterile species to be compatible with BBN..

Kreisch et al. 2019

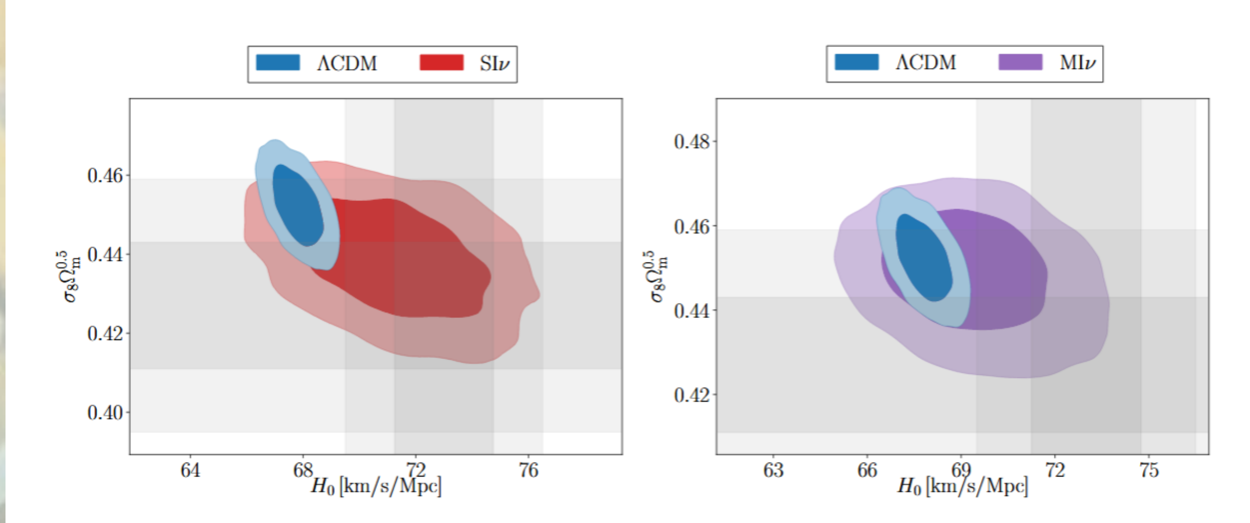


FIG. 4: 2D posteriors for S_8 and H_0 illustrating how neutrino self-interactions can remedy cosmological tensions. We compare the Planck TT + lens + BAO ΛCDM posterior to the SIν and MIν posteriors for TT + lens + BAO. We overlay 2σ bands for the measurements $S_8 = 0.427 \pm 0.016$ [79] and $H_0 = 73 \pm 1.75$ km/s/Mpc [73].

Kreisch et al. 2019

....

See talks on neutrinos tomorrow (Gerbino, Lattanzi)

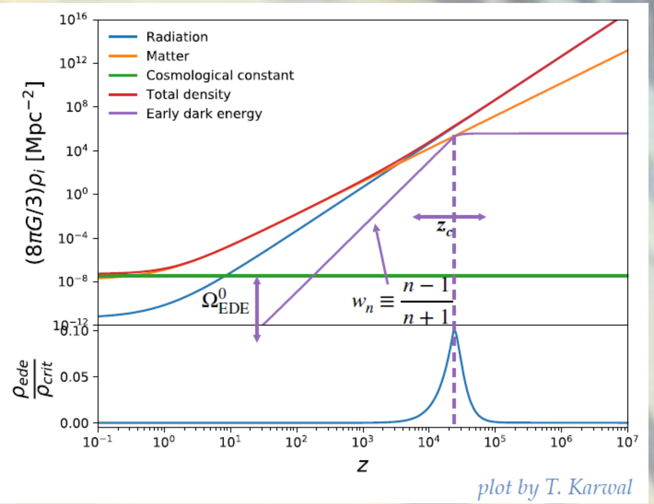
EARLY DARK ENERGY MODELS?

Early Dark Energy models consider a Dark Energy which behaves like a cosmological constant before a given critical redshift, increasing the expansion rate of the universe, and then rapidly decay not affecting the late universe.

Example Poulin et al 2018
Two different models:
-oscillating scalar field
-slow roll field

$$\Omega_\varphi(a) = \frac{2\Omega_\varphi(a_c)}{(a/a_c)^{3(w_n+1)} + 1}$$

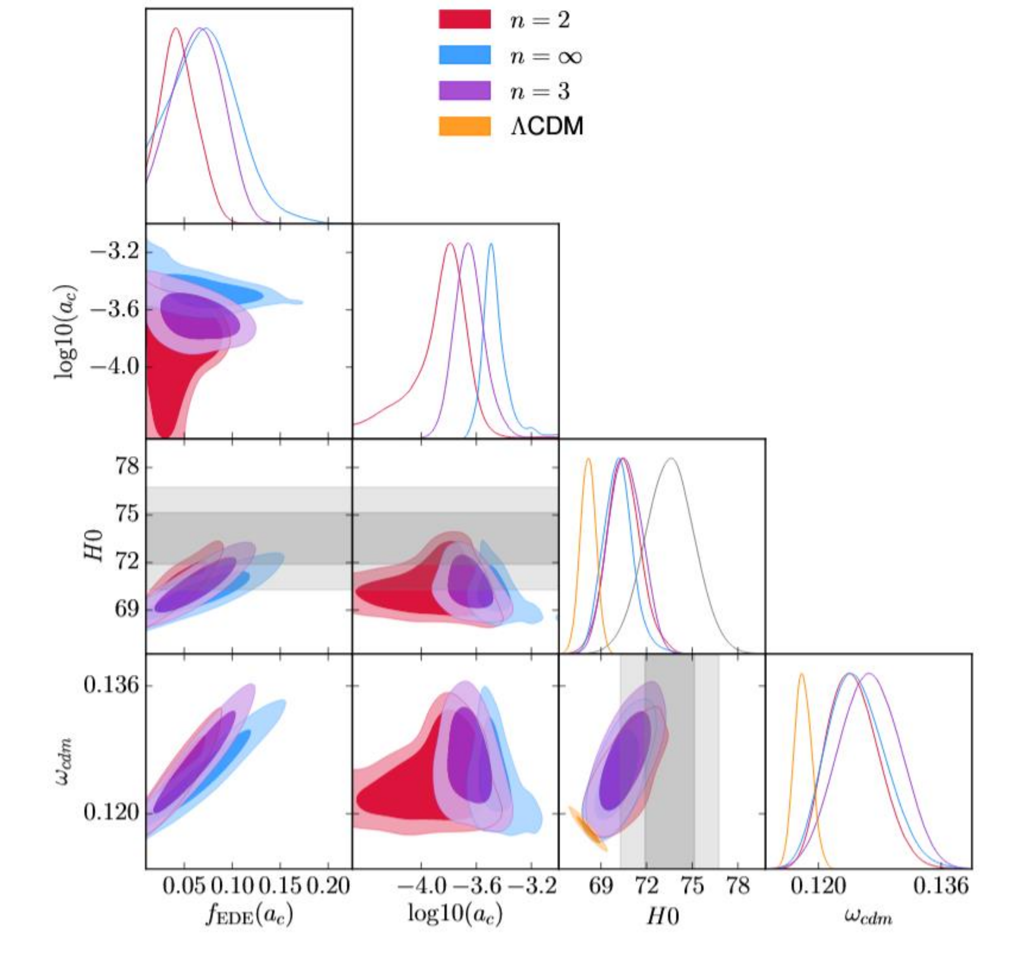
$$z_c = a_c^{-1} - 1,$$



Parameter	ΛCDM	$n = 2$	$n = 3$	$n = \infty$
$100\ \theta_s$	$1.04198(1.04201) \pm 0.0003$	$1.04182(1.04144)^{+0.00046}_{-0.00056}$	$1.04147(1.04130)^{+0.00043}_{-0.00037}$	$1.04159(1.04152) \pm 0.00035$
$100\ \omega_b$	$2.238\ (2.242) \pm 0.015$	$2.239\ (2.229) \pm 0.021$	$2.255\ (2.256) \pm 0.022$	$2.255\ (2.258) \pm 0.023$
$\omega_{\rm cdm}$	$0.1179\ (0.1181) \pm 0.0012$	$0.1241\ (0.1255) \pm 0.004$	$0.1273\ (0.1313) \pm 0.0043$	$0.1246\ (0.1263) \pm 0.0037$
$\ln(10^{10}A_s)$	$3.08\ (3.092) \pm 0.024$	$3.076\ (3.072) \pm 0.024$	$3.075\ (3.0709) \pm 0.023$	$3.067\ (3.067) \pm 0.024$
n_s	$0.9684\ (0.9674) \pm 0.0044$	$0.9749\ (0.9733) \pm 0.0073$	$0.9799\ (0.9865) \pm 0.0082$	$0.9753\ (0.9791) \pm 0.0064$
$\tau_{\rm reio}$	$0.075\ (0.08066) \pm 0.013$	$0.0716\ (0.0692) \pm 0.013$	$0.06598\ (0.06134) \pm 0.012$	$0.06146\ (0.05837) \pm 0.013$
$\mathrm{Log}_{10}(a_c)$	–	$-4.178\ (-3.777)^{+0.62}_{-0.056}$	$-3.673\ (-3.692)^{+0.084}_{-0.093}$	$-3.462\ (-3.521)^{+0.051}_{-0.1}$
$f_{\rm EDE}(a_c)$	–	$0.04053\ (0.04201) \pm 0.02$	$0.06959\ (0.09802) \pm 0.028$	$0.06951\ (0.0871) \pm 0.04$
$100\ \theta_D$	$0.3855\ (0.3854) \pm 0.00014$	$0.3866\ (0.3863) \pm 0.0008$	$0.3872\ (0.3881) \pm 0.0001$	$0.3871\ (0.3879) \pm 0.0012$
H_0	$68.17\ (68.15) \pm 0.54$	$70.4\ (70.0) \pm 1.1$	$70.9\ (71.96) \pm 1.3$	$70.2\ (70.4) \pm 1$

Poulin et al. 2018

ISSUES: fine tuning



Poulin et al. 2018

BEYOND GR?

Scalar tensor theories of gravity may prefer higher values of H0

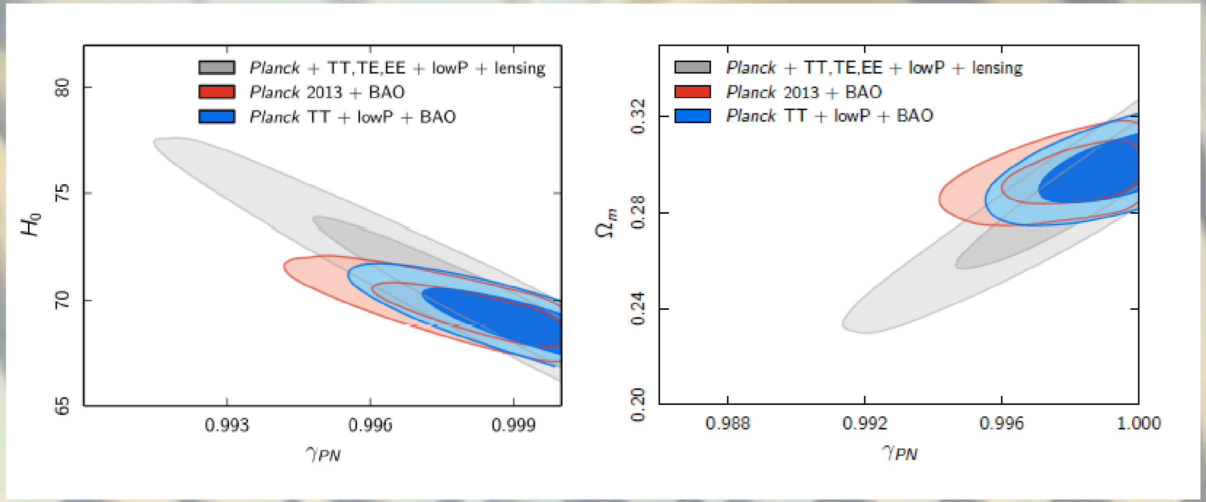
Scalar tensor theories in which the scalar field regulating the strength of the gravitational force also provides the acceleration of the expansion at later times.
Several models: Cooper, Venturi 1980; Wetterich 1988; Uzan 1999; Amendola, 1999: Chiba, 1999; Perrotta, Baccigalupi,Matarrese 1999; Boisseau et al. 2000; Bartolo & Pietroni 2000; Finelli, Tronconi, Venturi 2008, Baccigalupi et al. (2000)

Example Umiltà et al. 2015, Ballardini et al. 2016

$$S = \int d^4x\sqrt{-g}\left[\frac{\gamma\sigma^2 R}{2} - \frac{g^{\mu\nu}}{2}\partial_\mu\sigma\partial_\nu\sigma - V(\sigma) + \mathcal{L}_m\right] \qquad V(\sigma) \propto \sigma^n$$

	Planck 2013 + BAO	*Planck* TT + lowP + BAO	*Planck* TT + lowP + lensing + BAO
$10^5\Omega_b h^2$	2203 ± 25	2224 ± 21	2224^{+20}_{-21}
$10^4\Omega_c h^2$	1207^{+18}_{-22}	1198^{+16}_{-17}	1191 ± 14
H_0 [km s^{-1} Mpc^{-1}]	$69.5^{+0.9}_{-1.2}$	$69.4^{+0.8}_{-1.0}$	$69.4^{+0.7}_{-0.9}$
τ	$0.088^{+0.012}_{-0.013}$	$0.076^{+0.019}_{-0.018}$	$0.063^{+0.012}_{-0.014}$
$\ln(10^{10}A_s)$	$3.090^{+0.024}_{-0.026}$	3.087 ± 0.036	$3.059^{+0.022}_{-0.026}$
n_s	0.9611 ± 0.0053	0.9665 ± 0.0046	$0.9669^{-0.0042}_{-0.0047}$
ζ	< 0.0047 (95% CL)	< 0.0036 (95% CL)	< 0.0031 (95% CL)
$10^3\gamma$	< 1.2 (95% CL)	< 0.89 (95% CL)	< 0.75 (95% CL)
γ_{PN}	> 0.9953 (95% CL)	> 0.9965 (95% CL)	> 0.9970 (95% CL)
Ω_m	0.295 ± 0.009	0.295 ± 0.008	0.294 ± 0.008
$\delta G_N/G_N$	$-0.015^{+0.013}_{-0.006}$	$-0.011^{+0.010}_{-0.004}$	$-0.009^{+0.003}_{-0.009}$
$10^{13}\dot{G}_N(z=0)/G_N$ [yr^{-1}]	$-0.61^{+0.55}_{-0.25}$	$-0.45^{+0.43}_{-0.16}$	$-0.37^{+0.34}_{-0.12}$
$10^{23}\ddot{G}_N(z=0)/G_N$ [yr^{-2}]	$0.86^{+0.33}_{-0.78}$	$0.63^{+0.22}_{-0.58}$	$0.52^{+0.17}_{-0.50}$

Ballardini et al. 2016



Ballardini et al. 2016

Extension to non-minimally coupled case on going – Rossi et al. In prep.

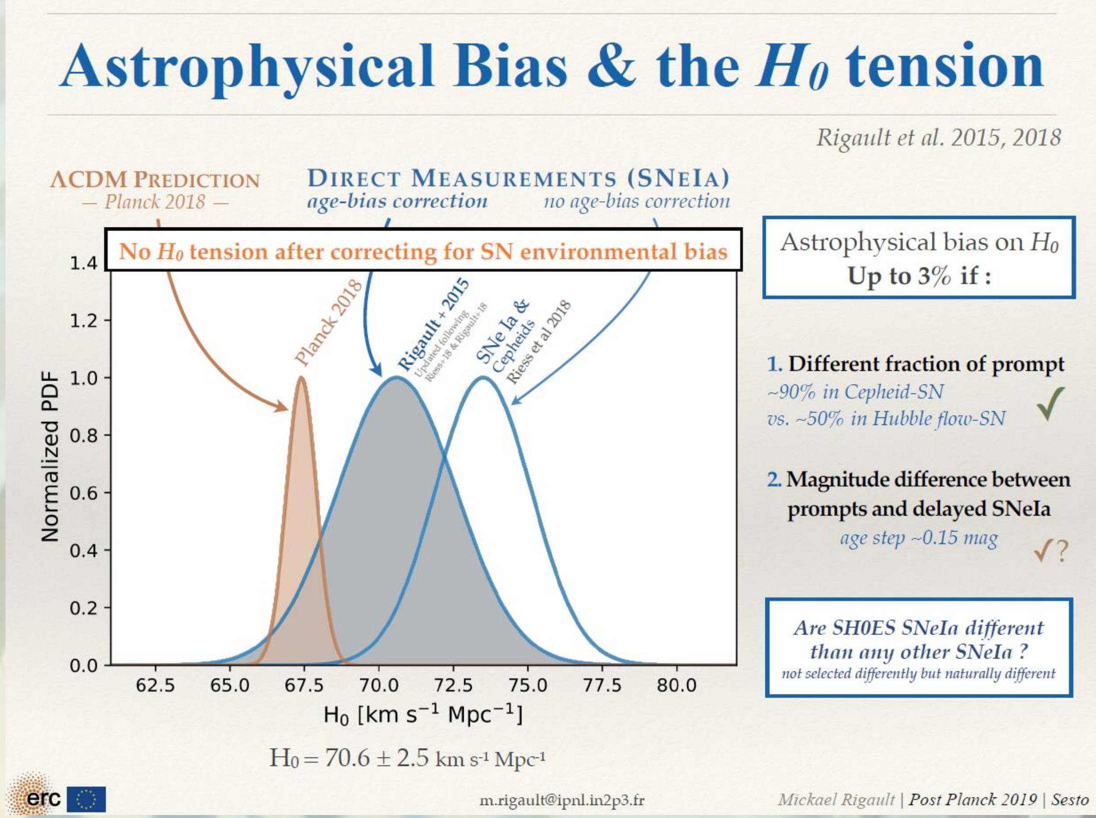
WHAT ABOUT THE SECOND DOOR?

CHANGE THE DATA

PROBLEMS WITH CURRENT DATA?

LOCAL UNIVERSE

SN enviromental bias?
Rigault et al. 2018



EARLY UNIVERSE

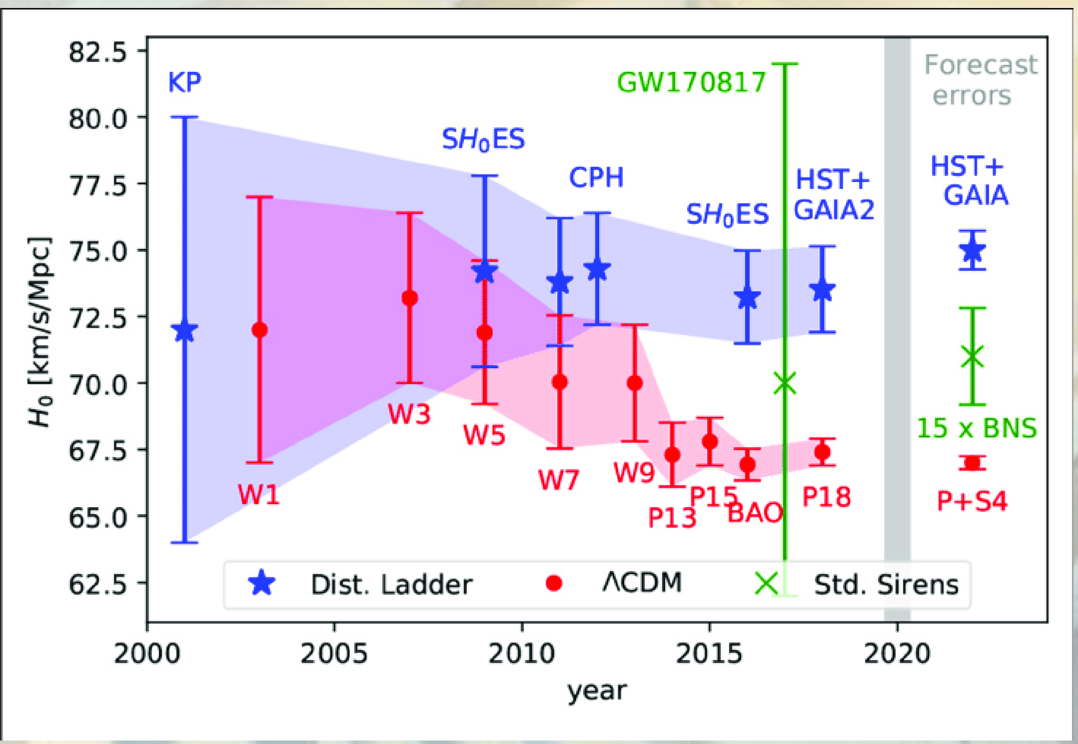
Planck
Unknown unknowns always possible

WAIT FOR FUTURE EXPERIMENTS
LITEBIRD COMING!

NEW AVENUES I

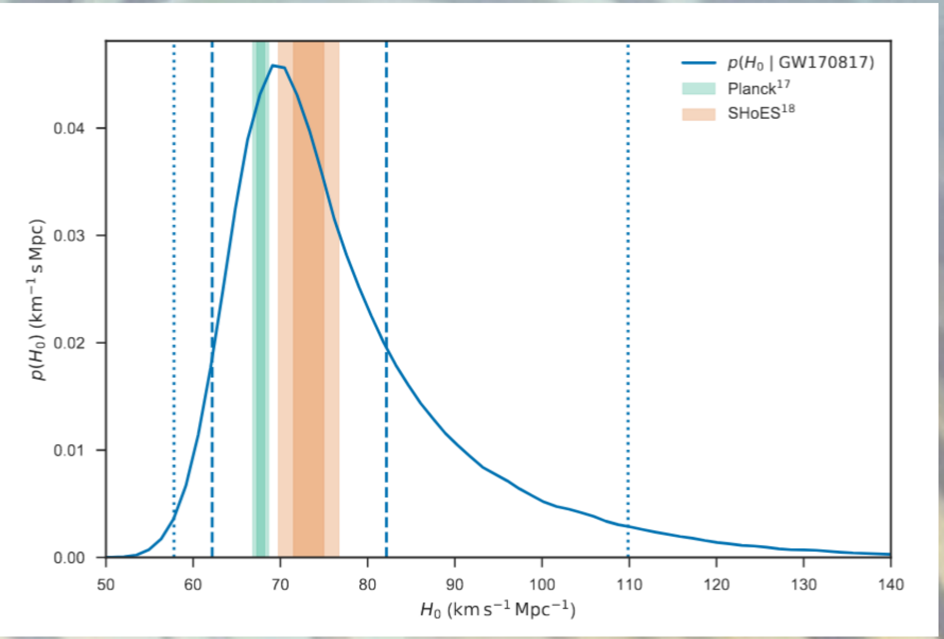
Gravitational waves as STANDARD SIRENS

With the observation of the EM counterpart it is possible to estimate the redshift of the source. The amplitude of the GW provides the luminosity distance creating a perfect standard siren

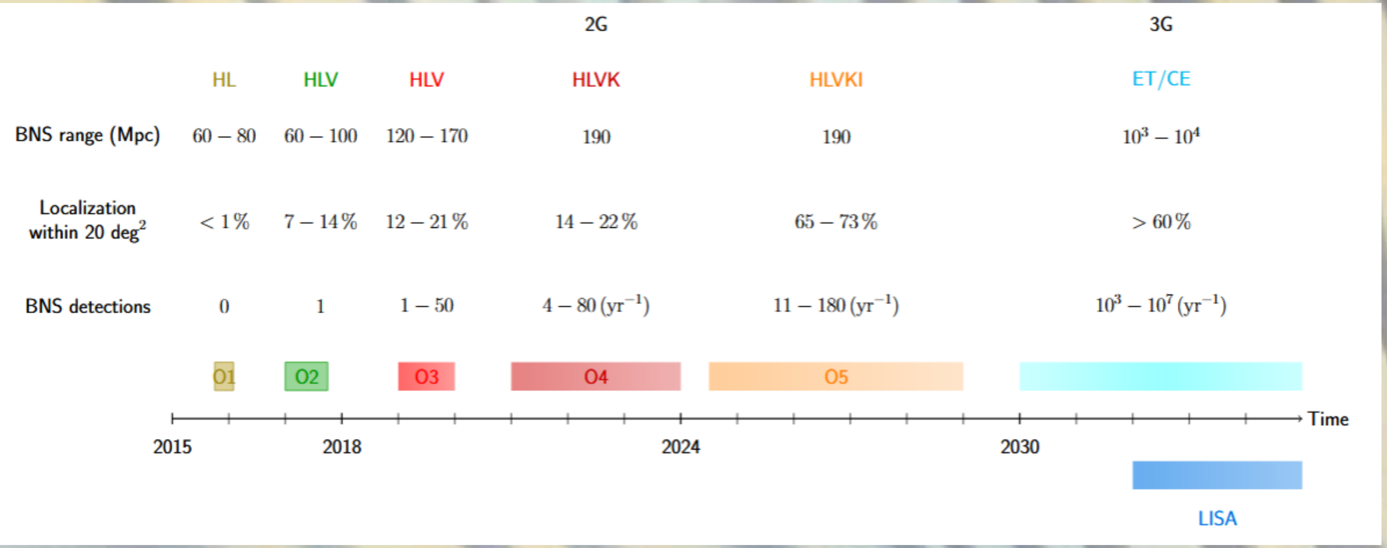


Ezquiaga & Zumalacarregui 2018

GW170817

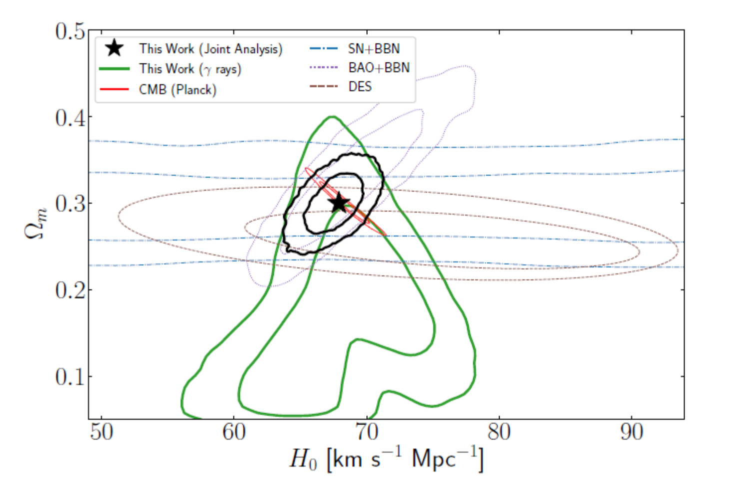


Abbott et al. 2018



NEW AVENUES II

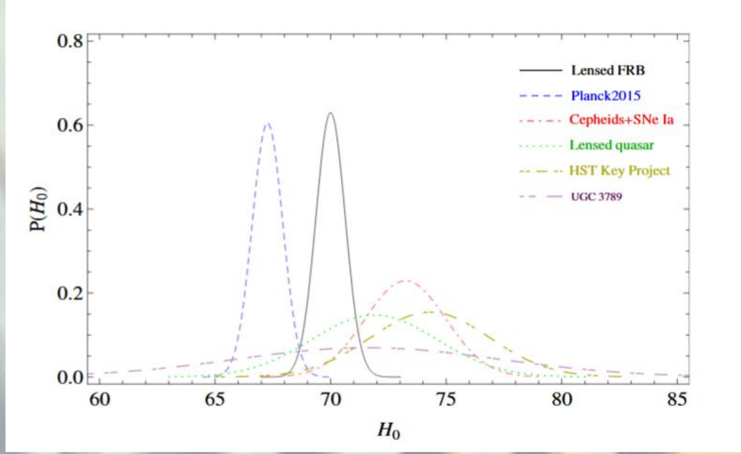
GAMMA RAY ATTENUATION
Dominguez et al 2019



Extragalactic background light interacting with photons from gamma ray sources provides a sort of opacity.
The density of the photons of the EBL and therefore the amount of γ-ray attenuation along the line of sight depends on the expansion rate and matter content of the Universe
Original concept by Salamon et al. 1994 and Mannheim et al. 1996

OTHER PROBES? WE'LL SEE WHAT FUTURE BRINGS

STRONGLY LENSED REPEATED FAST RADIO BURSTS
Li et al 2018



Strongly lensed non repeated FRB would appear as repeated FRB because the typical lensing delay time is of O(days) with angular separations of few arcsec (below radiotelescope resolution). The two to four apparent bursts would have repeated patterns and their dispersion measure and scatter broadening depend on the properties of the plasma ALOS

CONCLUSIONS

Future data for early and late Universe will shed light on the value of the Hubble constant

Alternative data from multifrequency and multimessenger astronomy will provide complementary probes

If the tension will remain the perspective for cosmology are shining

New physics in the neutrino sector

New physics in the dark energy

New physics in the gravitational sector

New physics in still unknown sectors

The old well known LCDM is always the best in fitting the Universe but it looks like it can still have some little trick up its sleeve