Current status of the H_0-tension

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DFG Deutsche Forschungsgemeinschaft

Outline

0. Introduction

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- Georges Lemaître (1927) and others had already worked out expanding cosmologies before Hubble's discovery.

Hubble's plot (1929)

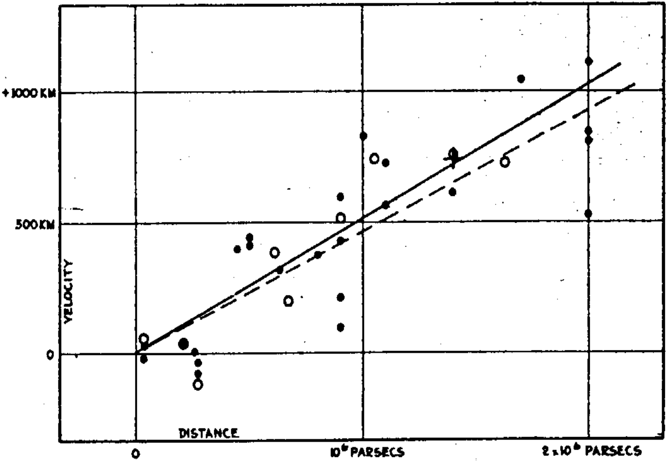

FIGURE 1

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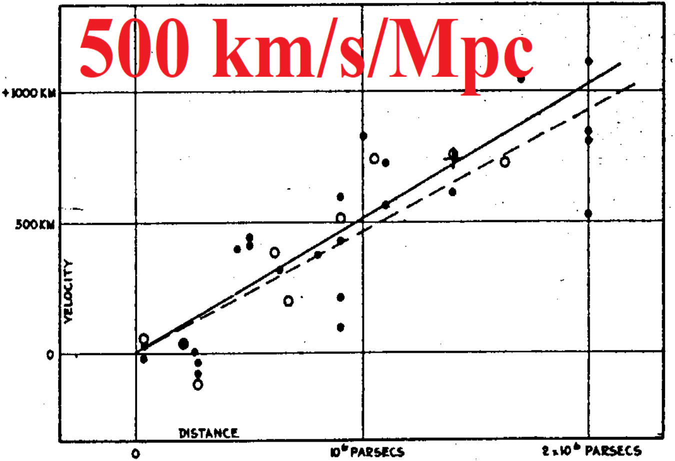
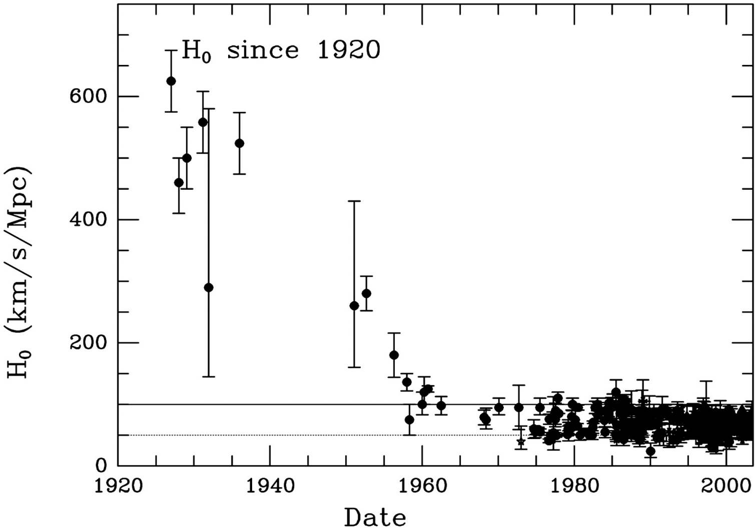


FIGURE 1

H_0 determinations .vs. time



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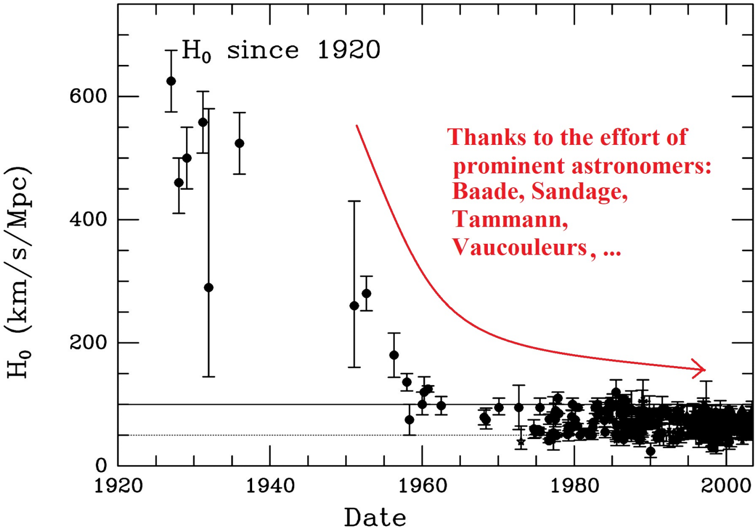

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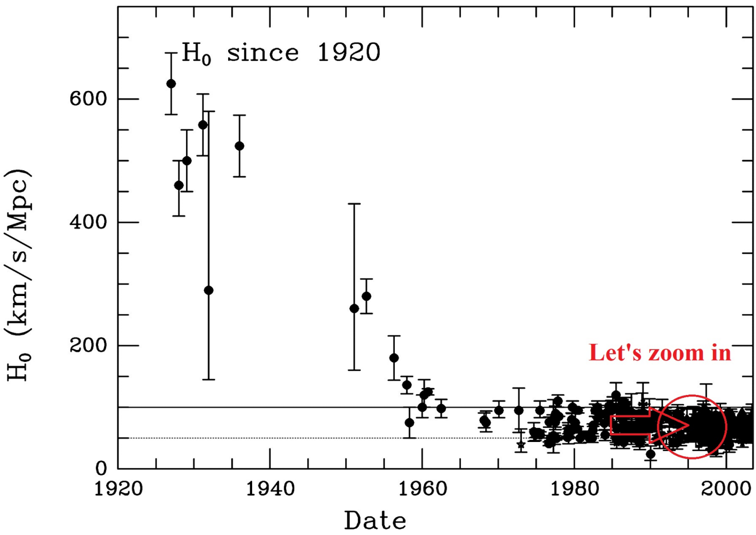


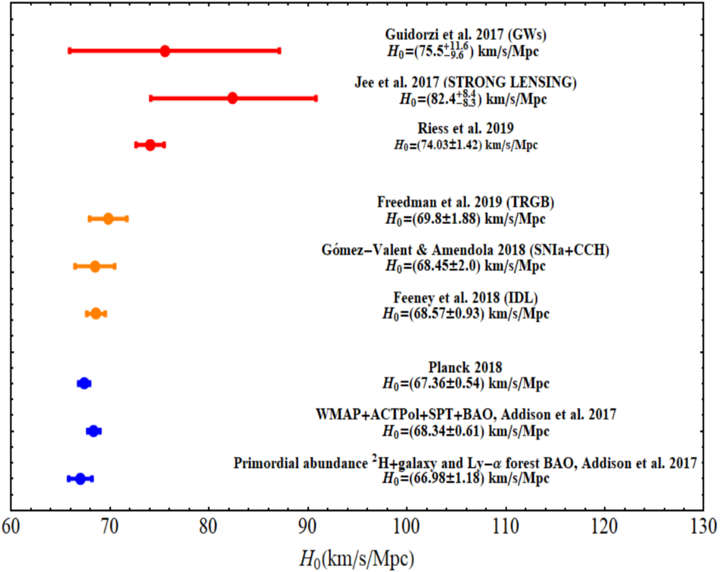
H_0 determinations .vs. time

In the 90s...

H_o (km s^{-1} Mpc^{-1})	Technique	Reference
94 ± 11[a]	Lens 0957 + 561	Grogin & Narayan (1996)
81 ± 8	Cepheids in 4 Virgo spirals	van den Bergh (1995a)
80 ± 12	SB fluctuations	Jacoby et al. (1992)
78 ± 11	Globulars in M87	Whitmore et al. (1995)
76 ± 7	PN in Virgo Cluster	Jacoby (1996)
75 ± 8	PN in Fornax cluster	McMillan et al. (1993)
74 ± 14	Tip of RG branch	Sakai et al. (1996)
73 ± 6 ± 7	SNe II exp. photospheres	Kirshner (1996)
73 ± 6	D_n -σ (Vir, For, Leo)	Mould (1996)
70 - 74	Tully-Fisher	Giovanelli (1996)
70 ± 13	Novae in Virgo	Della Valle & Livio (1995)
66 ± 12	IR Tully-Fisher	Malhotra et al. (1996)
65 ± 6	SN Ia lightcurves	Riess et al. (1996)
64 ± 3	4 SNe Ia	Hamuy et al. (1996)
55 ± 17	Sunyaev - Zel'dovich effect	Birkinshaw & Hughes (1994)
55 - 60	SNe Ia (theory)	van den Bergh (1995b)
52 ± 9	SNe Ia (1937C)	Saha et al. (1994)
52 ± 8	SNe Ia (1972E)	Saha et al. (1995)
43 ± 11	Galaxy diameters	Sandage (1993a)

I. The tension, nowadays

H_0-tension. Some recent determinations of H_0



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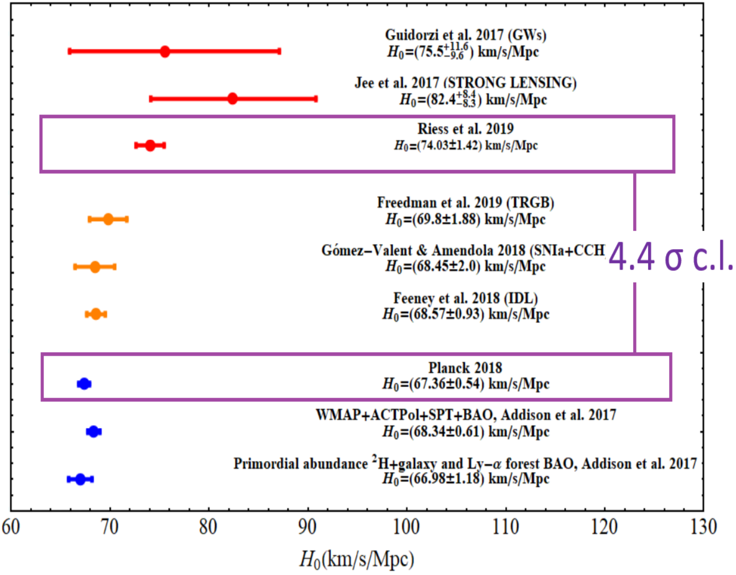


II. Observations and H_0

Local distance ladder

ANCHORS

Milky Way	LMC	NGC 4258
(30 kpc) parallaxes	(50 kpc) DEBs	(7.2 Mpc) Maser

Calibration of Cepheids, Mira Variables, TRGB

HOST GALAXIES

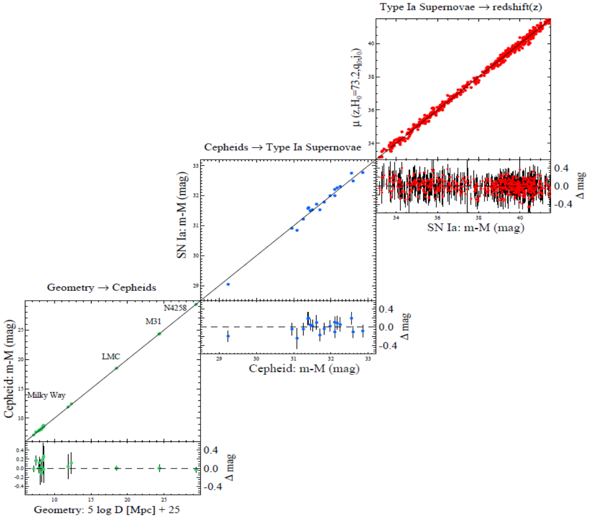
Cepheids/Miras/TRGBs + SNIa
19, up to now
($z<0.01$; $d<40$ Mpc)

Calibration of SNIa

HUBBLE FLOW

SNIa
($0.02<z<0.15$; $d<600$ Mpc)

Hubble's law


Type Ia Supernovae → redshift(z)
μ (z,H0=73.2,q0,j0)
Δ mag
SN Ia: m-M (mag)
Cepheids → Type Ia Supernovae
SN Ia: m-M (mag)
Δ mag
Cepheid: m-M (mag)
Geometry → Cepheids
Cepheid: m-M (mag)
N4258
M31
LMC
Milky Way
Δ mag
Geometry: 5 log D [Mpc] + 25

HST Key Project, HST Calibration Program, SH0ES

Year	Authors	$H_0\,(km/s/Mpc)$
2001	Freedman et al.	70 ± 8
2006	Sandage et al.	62.3 ± 5.2
2009	Riess et al.	74.2 ± 3.6
2016	Riess et al.	73.24 ± 1.74
2018	Riess et al.	73.48 ± 1.66
2019	Riess et al.	73.5 ± 1.4

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- Reanalyses of the results by Riess et al. in other frequency channels (Dhawan et al. 1707.00715), carrying out blinded studies (Zhang et al. 1706.07573) or making use of hyperparameters to see the impact of potential systematics (Cardona et al. 1611.06088) do not produce important shifts of the central value of H_0.

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But, still, there is no full consensus even among people working with the cosmic distance ladder using other approaches.

- Freedman et al. (arXiv:1907.05922) find $H_0 = (69.8 \pm 1.88)$ km/s/Mpc using the TRGBs instead of Cepheids. They argue that this way of measuring H_0 is less affected by metallicity, there are less reddening effects, there is more statistics to calibrate SnIa and the host galaxies are more similar to the ones employed in the Hubble flow.

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- Recently, Breuval et al. (arXiv:1910.04694) have also reported lower estimates of H_0 (68.43 ± 2.00, 69.30 ± 2.08 km/s/Mpc), calibrating Leavitt's law with GAIA DR2 parallaxes of Cepheids' companions. They argue that these parallaxes can be more reliably measured.

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- The effect of the offset in GAIA parallaxes was also studied by Shanks & Metcalfe (arXiv:1810.02595). They found that GAIA parallax distances of MW Cepheids may be between $7-18\%$ larger than previously estimated, with the potential to produce a corresponding reduction in the value of H_0. Then they showed the effect of $\sim 150Mpc$ Local Hole. Both effects combined can reduce H_0 a 9%.

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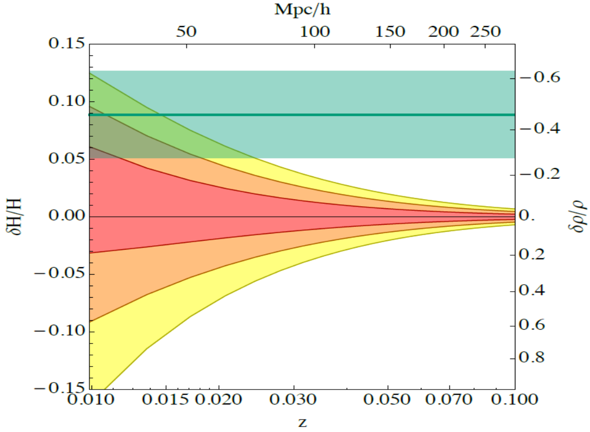
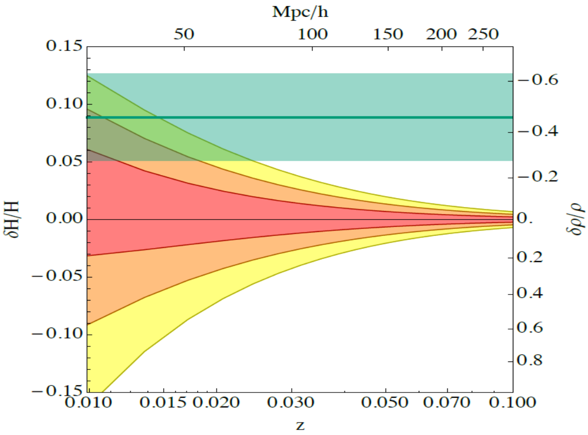
it is possible to know the (cosmic) variance for H_0 that affects the local determination.



Mpc/h
50
100
150
200
250
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
δH/H
−0.6
−0.4
−0.2
0.
0.2
0.4
0.6
0.8
δρ/ρ
0.010
0.015
0.020
0.030
0.050
0.070
0.100
z



Cosmic variance is important at low redshifts, precisely in the range explored in the last rung of the local ladder measurement!

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- Although this would not loosen completely the H_0-tension, the latter would decrease from $\sim 4\sigma$ to $\sim 3\sigma$.
- Cosmic variance should be taken into account in cosmological analyses that includes the local determination of H_0 as a prior.

Cosmic inverse distance ladder

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CMB data $\Rightarrow$ **Baryon Acoustic Oscillations** $\Rightarrow$ **SNIa**

Assuming standard pre-recombination physics:

$$r_s(z_d) = \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)}dz$$

Planck TT+lowE (2018)

$r_s(z_d) = (147.21 \pm 0.48)$ Mpc

$$H(z_i)r_s(z_d) \qquad \qquad E(z_i)H_0 r_s(z_d)$$

$$\frac{D_A(z_i)}{r_s(z_d)} \rightarrow \frac{\tilde{D}_A(z_i)}{H_0 r_s(z_d)}$$

Constrain E(z), and thanks to CMB+BAO data, this allows to constrain even more H0

Cosmic inverse distance ladder

Using cosmography...

Authors	Reference	Data	$H_0\,(km/s/Mpc)$
Aubourg et al.	1411.1074	Planck 2013 prior, BOSS BAO, JLA SNIa	67.3 ± 1.1
Feeney et al.	1802.03404	Planck 2015 prior, BOSS BAO, Pantheon SNIa	68.57 ± 0.93
Macaulay et al.	1811.02376	Planck 2018 prior, 6dFGS+SSDS MGS+BOSS BAO, DES SNIa	67.77 ± 1.30

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Inverse distance ladder estimations of H_0 are compatible and lie in the Planck's low range.

but...

what happens if pre-recombination physics is altered?

IT IS EXTREMELY IMPORTANT TO SEARCH FOR METHODS THAT MINIMIZE EVEN MORE THE NUMBER OF MODEL-DEPENDENT ASSUMPTIONS!

Calibrating SnIa with cosmic chronometers

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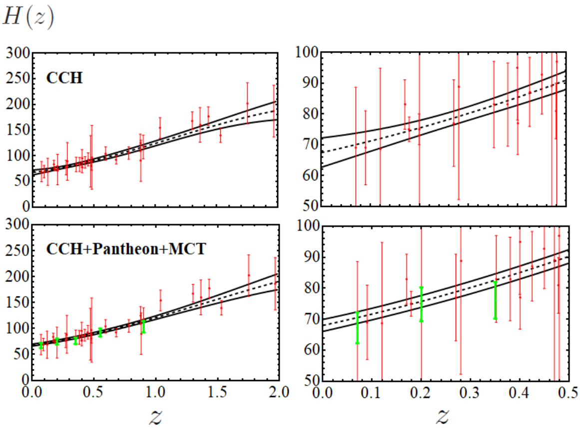
- We have 31 CCH data points, which can be employed to calibrate the SNIa.

Calibrating SnIa with cosmic chronometers

Done by AGV and L. Amendola (arXiv:1802.01505), using two model-independent reconstruction techniques.



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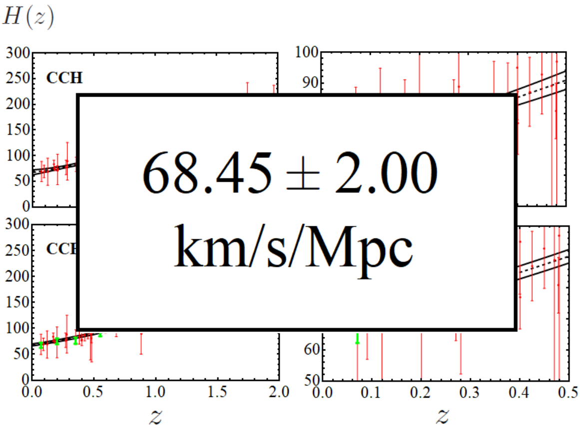
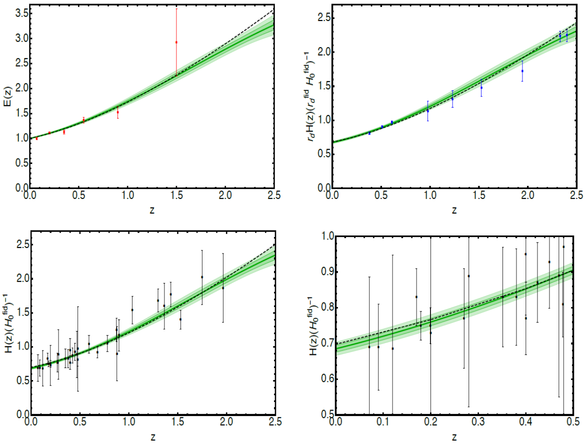


Few months later Haridasu et al. also included BAO (arXiv:1805.03595), and obtained similar results.



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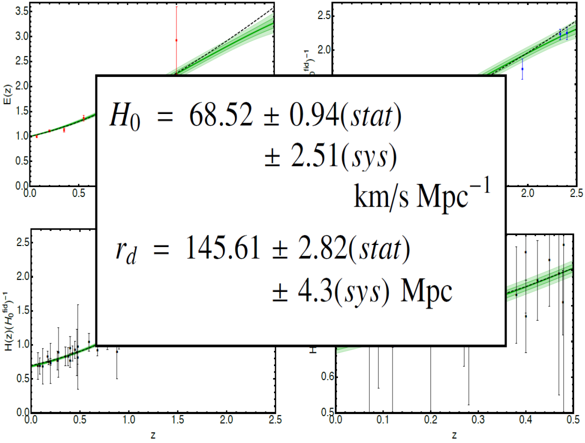
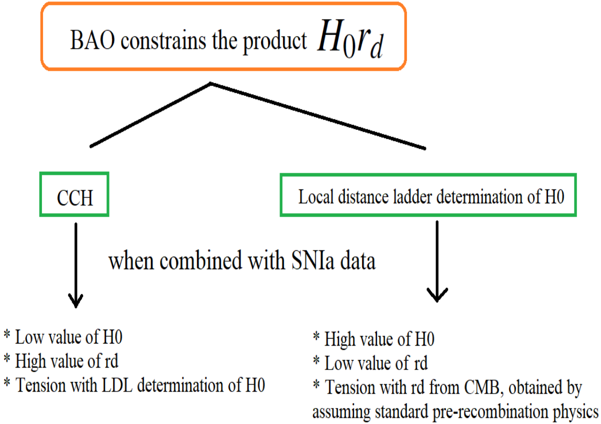
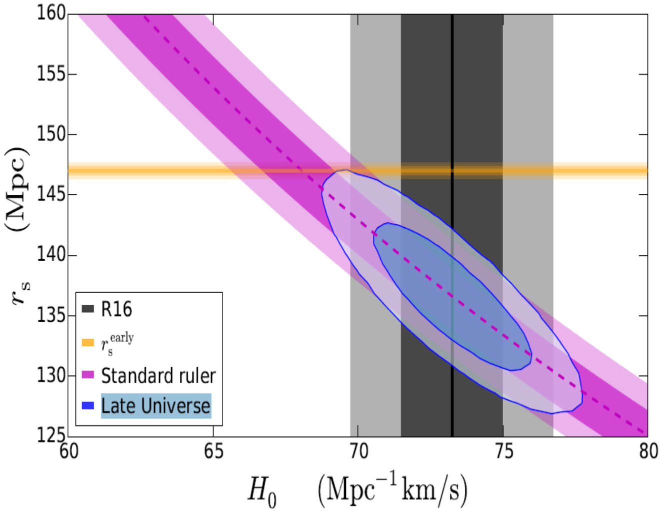


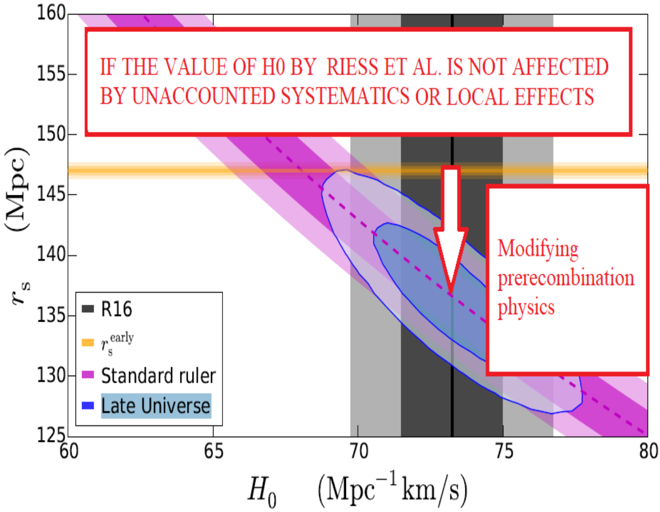
$$H_0 = 68.52 \pm 0.94(stat) \pm 2.51(sys) \text{ km/s Mpc}^{-1}$$

$$r_d = 145.61 \pm 2.82(stat) \pm 4.3(sys) \text{ Mpc}$$


BAO constrains the product $H_0 r_d$
CCH
Local distance ladder determination of H0
when combined with SNIa data
* Low value of H0
* High value of rd
* Tension with LDL determination of H0
* High value of H0
* Low value of rd
* Tension with rd from CMB, obtained by assuming standard pre-recombination physics



Bernal, Verde & Riess (2016)



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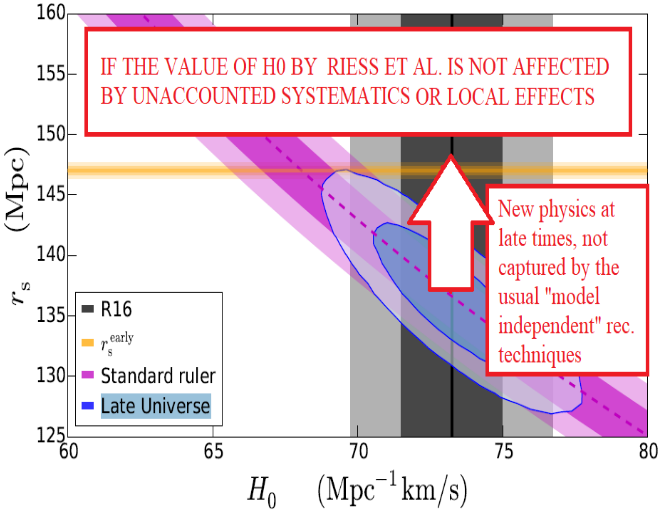

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- Addison et al. (1707.06547) compare the Planck results with those obtained with other CMB probes, combining them with BAO: SPT,WMAP,ACT+BAO, and obtain values of H_0 lying in the lower range, as Planck.

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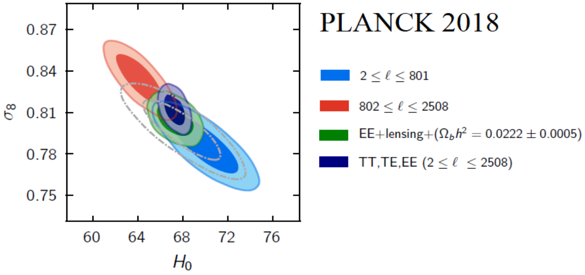

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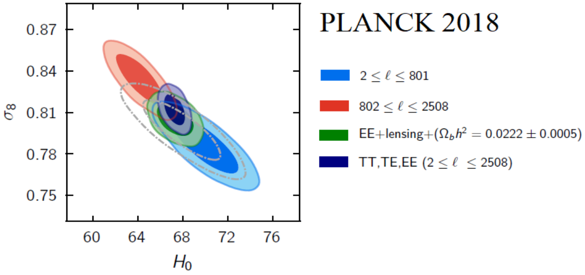

- When the low mutipoles are combined with BAO, again a low value of H_0 is recovered, but maybe ΛCDM is the responsible of such tension between low and high mutipoles in the CMB?

H_0 from gravitational waves

A GRAVITATIONAL-WAVE STANDARD SIREN MEASUREMENT OF THE HUBBLE CONSTANT

Abbott et al. (arXiv:1710.05835)

The detection of GW170817 (Abbott et al. 2017a) in both gravitational waves and electromagnetic waves heralds the age of gravitational-wave multi-messenger astronomy. On 17 August 2017 the Advanced Laser Interferometer Gravitational-wave Observatory (LIGO) (LIGO Scientific Collaboration et al. 2015) and Virgo (Acernese et al. 2015) detectors observed GW170817, a strong signal from the merger of a binary neutron-star system. Less than 2 seconds after the merger, a gamma-ray burst (GRB 170817A) was detected within a region of the sky consistent with the LIGO-Virgo-derived location of the gravitational-wave source (Abbott et al. 2017b; Goldstein et al. 2017; Savchenko et al. 2017). This sky region was subsequently observed by optical astronomy facilities (Abbott et al. 2017c), resulting in the identification of an optical transient signal within ~ 10 arcsec of the galaxy NGC 4993 (Coulter et al. 2017; Soares-Santos et al. 2017; Valenti et al. 2017; Arcavi et al. 2017; Tanvir et al. 2017; Lipunov et al. 2017). These multi-messenger observations allow us to use GW170817 as a standard siren (Schutz 1986; Holz & Hughes 2005; Dalal et al. 2006; Nissanke et al. 2010, 2013), the gravitational-wave analog of an astronomical standard candle, to measure the Hubble constant.

H_0 from gravitational waves

- Fitting the detected waveform of the GW assuming the validity of standard GR it is possible to extract the distance to the source and the viewing angle of the merger. They obtained $d = 43.8^{+2.9}_{-6.9}$ Mpc.

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- Guidorzi et al. (1710.06426) considered a larger uncertainty in the peculiar velocity, and used a better constrain on the inclination angle, available after the analysis of the afterglow. They obtained, $H_0 = (75.5^{+11.6}_{-9.6})$ km/s/Mpc.

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- Shafieloo et al. (arXiv:1812.07775) argued, though, that in order to have enough statistics we will have to make use of GW data from redshifts larger than ≈ 0.1. The determination of H_0 will not be as clean as desired, some model-dependence will have to be introduced, which can lead to a bias.

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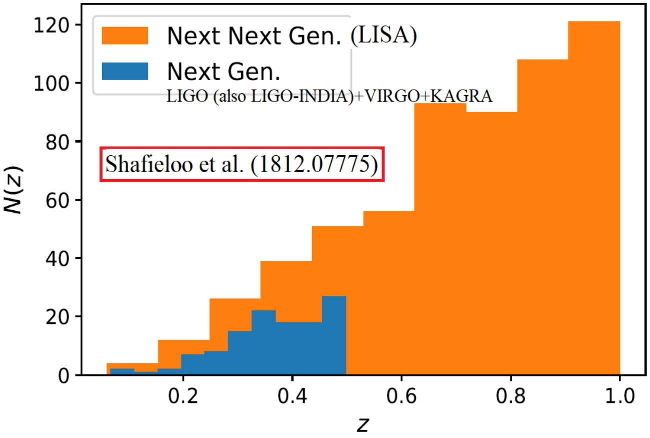
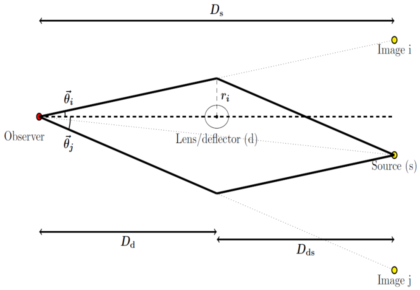
- They state that it will not be possibe to obtain a model-independent determination with precision better than 1%, even with LISA and the new interferometers that will be operative in India and Japan.

Forecast of the number of GW detections with EM counterpart



Time-delay strong lensing

Time-variable source, whose light is deflected by a massive object.



$$\sigma^2 \propto (\theta_1 + \theta_2)\frac{D_s}{D_{ds}} \qquad \Delta t = \underbrace{(1+z_d)\frac{D_d D_s}{D_{ds}}}_{=D_{\Delta t}}(1-\kappa_{ext})\frac{\Delta\phi}{c}$$

For a density profile $\rho(r) = \frac{\sigma^2}{2\pi G r^2}$ with constant σ,

$$\Delta t = D_{\Delta t}\left(\frac{\theta_1^2 - \theta_2^2}{2c}\right)$$

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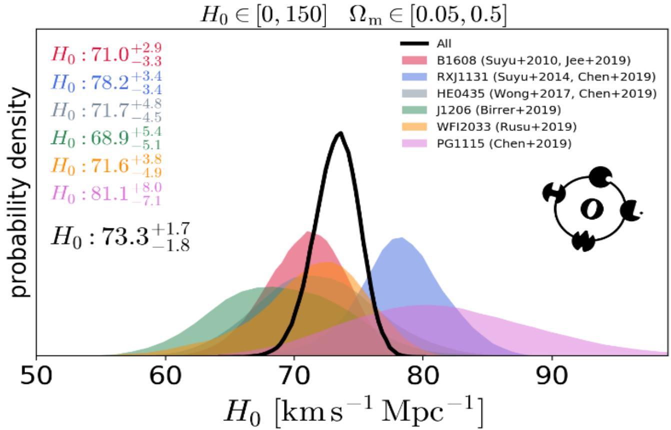
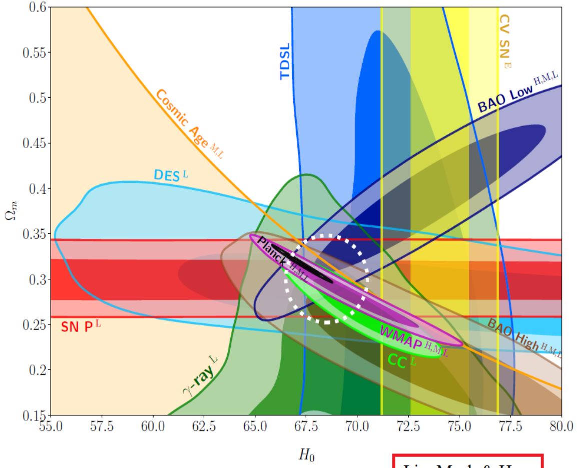
Cosmological diameter distance to the deflector can be measured after modeling the lens. And this distance can be used individually or combined with e.g. SnIa.

H0LICOW (H0 Lenses in COSMOGRAIL's Wellspring)



The tension in the ΛCDM



Lin, Mack & Hou
arXiv:1910.02978

See also the papers by Lin & Ishak (arXiv:1708.09813, 1910.01608).

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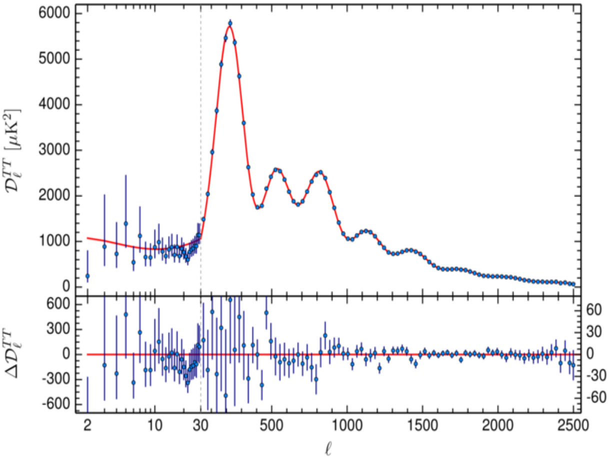

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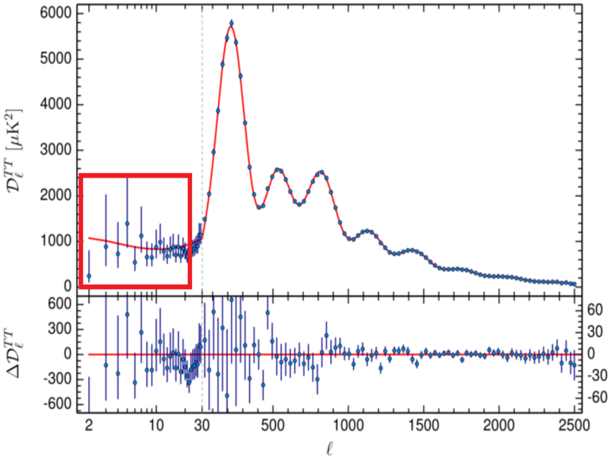

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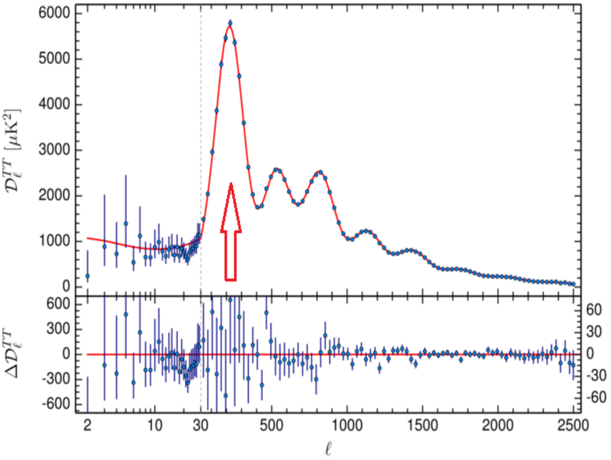

$$\theta_* = \frac{\pi}{l_*} = \frac{r_s(z_*)}{D_A(z_*)} = \frac{\int_{z_*}^{\infty} dz \frac{c_s(z)}{H(z)}}{c\int_0^{z*} \frac{dz}{H(z)}}$$

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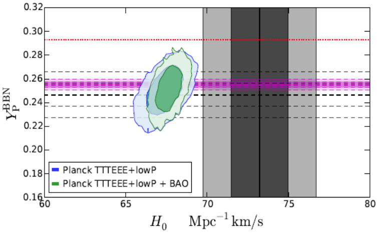
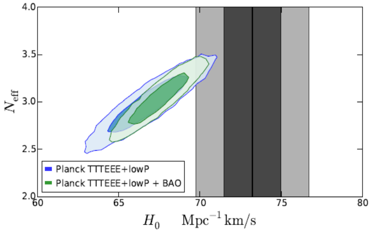
- $r_s(z_*)$ is basically fixed.
- In order to match pre-recombination physics and the observed value of θ_* in the ΛCDM one needs to tune the value of ρ_Λ or, equivalently, the value of H_0.

And it turns out that this value of H_0 is much lower than the local distance ladder determination:

$$H_0 = (67.36 \pm 0.57)\,\mathrm{km/s/Mpc}$$

III. Theory and H_0

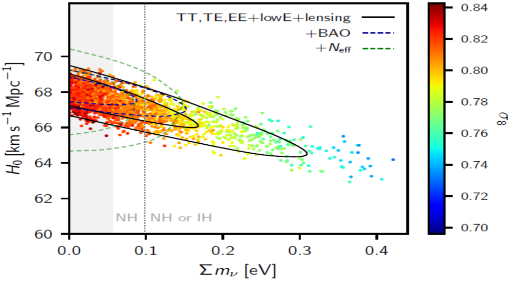




Comparison with Riess et al. (2016)

$\boxed{\text{Bernal, Verde \& Riess (2016)}}$

What about massive neutrinos?



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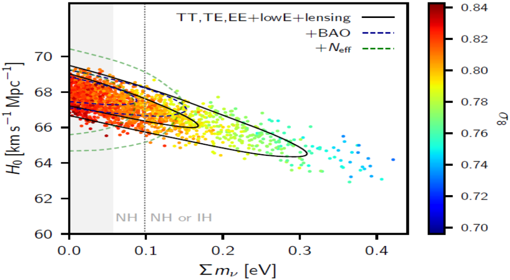

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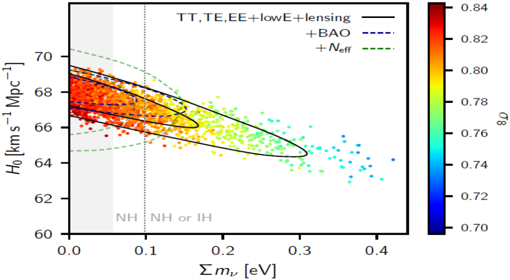


Increasing $\sum_\nu m_\nu$ we worsen even more the H_0-tension!

Coupled Quintessence

Amendola (astro-ph/9908023)

Quintessence exchanges energy with DM:

$$Q_\nu = \nabla^\mu T^{(\phi)}_{\mu\nu} = -\nabla^\mu T^{(c)}_{\mu\nu}$$

$$Q_\nu = \beta T^{(c)} \nabla_\nu \phi \,,$$

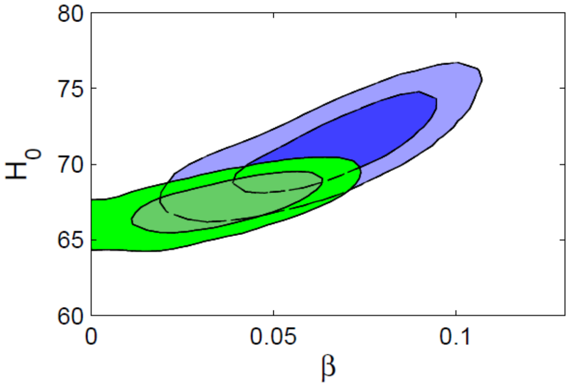
And ϕ is also governed by a Peebles-Ratra potential

$$V(\phi) = V_0 \phi^{-\alpha} \,.$$

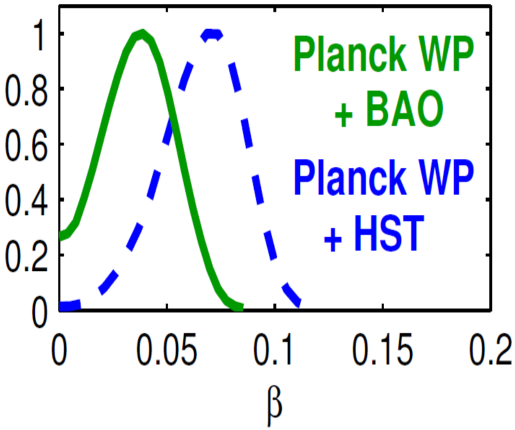
The dark matter density reads:

$$\rho_c(a) = \rho_c^{(0)} a^{-3} e^{\beta(\phi^{(0)} - \phi(a))} \,.$$

PlanckWP + BAO (green)
PlanckWP + HST (blue)



Pettorino and Amendola (1207.3293)
Pettorino (1305.7457)



We are working now in an update of these results, using Planck 2018, SNIa, CCH, BAO, WL, RSD (Amendola, AGV, Pettorino), and exploring non-constant couplings.

Brans-Dicke cosmology with Λ

$$S_{\rm BD}=\int d^4x\sqrt{-g}\left[\frac{1}{16\pi}\left(R\psi-\frac{\omega_{BD}}{\psi}g^{\mu\nu}\partial_\nu\psi\partial_\mu\psi\right)-\rho_\Lambda\right]+S_m\,.$$

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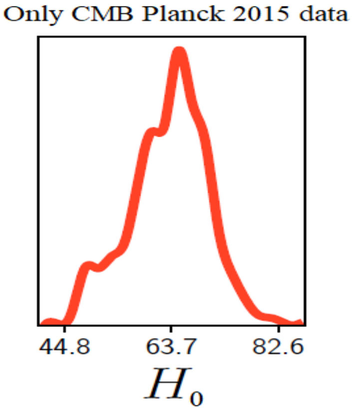
- Which is the response of the BD model to the cosmological data?

Solà, AGV, de Cruz Pérez, Moreno-Pulido (arXiv:1909.02554)



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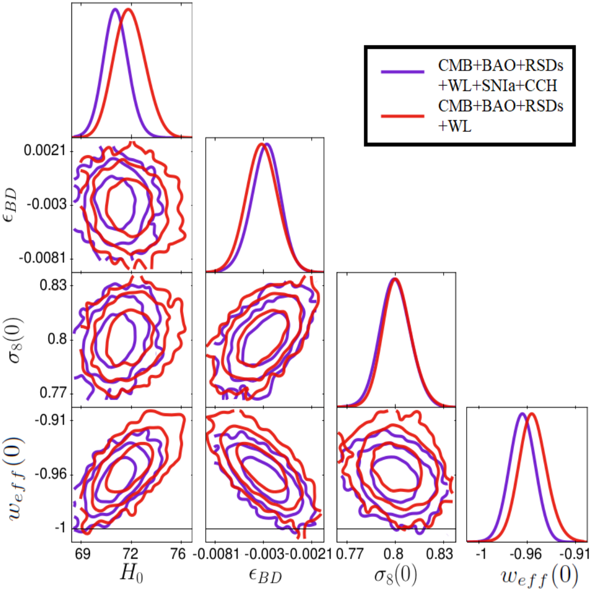

	CMB+BAO+RSD+WL+SNIa+CCH		CMB+BAO+RSD+WL	
Parameter	ΛCDM	BD-ΛCDM	ΛCDM	BD-ΛCDM
H_0 (km/s/Mpc)	$68.65^{+0.38}_{-0.40}$	$71.03^{+0.91}_{-0.86}$	$68.69^{+0.38}_{-0.39}$	$72.00^{+1.00}_{-1.10}$
Ω_{m0}	0.2955 ± 0.0048	0.2742 ± 0.0077	0.2950 ± 0.0047	0.2665 ± 0.0084
Ω_{b0}	0.0476 ± 0.0004	0.0453 ± 0.0010	0.0476 ± 0.0004	0.0443 ± 0.0012
τ	$0.063^{+0.010}_{-0.012}$	$0.081^{+0.015}_{-0.018}$	$0.063^{+0.010}_{-0.011}$	0.084 ± 0.018
n_s	$0.9700^{+0.0038}_{-0.0040}$	$0.9891^{+0.0070}_{-0.0082}$	0.9704 ± 0.0038	$0.9945^{+0.0081}_{-0.0086}$
$\sigma_8(0)$	$0.804^{+0.007}_{-0.009}$	0.801 ± 0.010	$0.804^{+0.007}_{-0.008}$	$0.803^{+0.011}_{-0.010}$
ϵ_{BD}	-	$-0.00277^{+0.00170}_{-0.00154}$	-	$-0.00315^{+0.00168}_{-0.00175}$
φ_{ini}	-	$0.924^{+0.021}_{-0.023}$	-	$0.901^{+0.026}_{-0.025}$
$\varphi(0)$	-	$0.904^{+0.028}_{-0.029}$	-	0.879 ± 0.032
$w_{eff}(0)$	-1	$-0.961^{+0.012}_{-0.011}$	-1	$-0.951^{+0.012}_{-0.013}$
$\dot{G}(0)/G(0)(10^{-13}yr^{-1})$	-	$3.149^{+1.741}_{-1.924}$	-	$3.625^{+1.994}_{-1.954}$
ΔDIC (ΔAIC)	-	8.34 (7.72)	-	9.89 (9.94)

Early dark energy

Poulin et al. (arXiv:1811.04083)

- A DE component behaves like a cosmological constant at very early times, but in the last decade before recombination (around a_c) exhibit a non-constant behavior, and then decays to radiation, having then no impact in the late-time universe.

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- DE should must constitute $\sim 7\%$ of the energy content of the universe around $z \sim 5000$, increasing in this way $H(z)$ in that epoch and reducing $r_s(z_d)$.

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

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	ΛCDM	$n=2$	$n=3$	$n=\infty$
H_0	68.17±0.54	70.4±1.1	70.9±1.3	70.2±1.0

CMB+BAO+SNIa+RSD

Self-conserved dynamical dark energy

- Although dynamical dark energy with $w > -1$ can loosen the σ_8-tension, and it does not worsen the H_0-tension, it does not loosen it neither! I have explicitly checked this in the context of Peebles-Ratra model and with a XCDM parametrization of the DE EoS parameter. See e.g. 1811.03505.

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If both, σ_8 and H_0-tensions are real: these kind of models cannot solve them together

Unscreening effects of MG theories affecting Cepheids

Desmond, Jain and Sakstein (arXiv:1907.03778)

If the screening mechanism of some modified theory of gravity is less efficient than expected in the regions where Cepheids are in the host galaxies...

Unscreening effects of MG theories affecting Cepheids

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If the screening mechanism of some modified theory of gravity is less efficient than expected in the regions where Cepheids are in the host galaxies...

- Taking into account that fifth forces add a force that scales like $\sim 1/r^2$, inefficient screening of such forces lead to a higher value of G_{eff}.

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- A lower value of H_0 is inferred.

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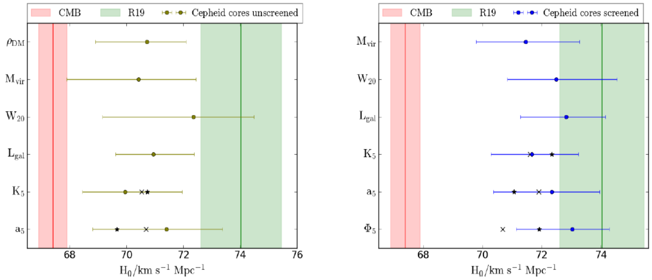
- Interestingly, in the last case obtain $H_0 = 70 - 72$ km/s/Mpc.



IV. Conclusions

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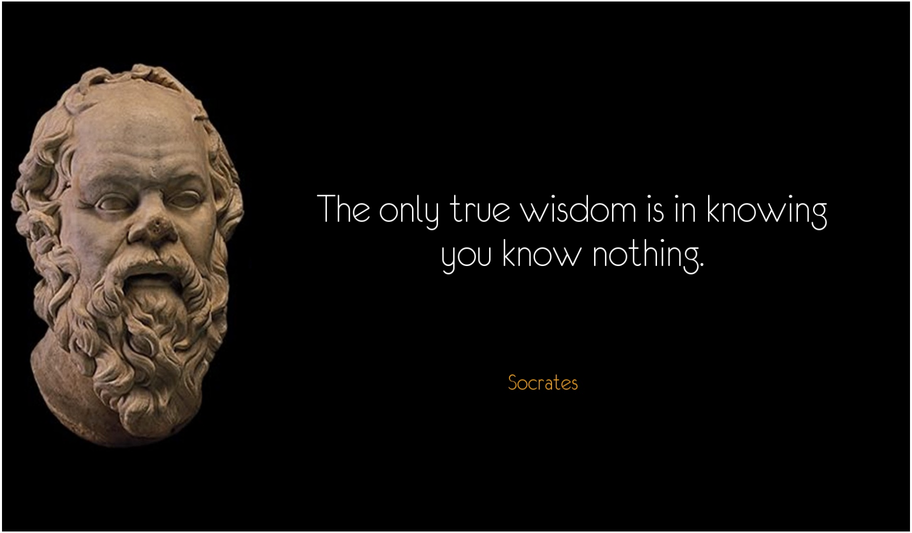
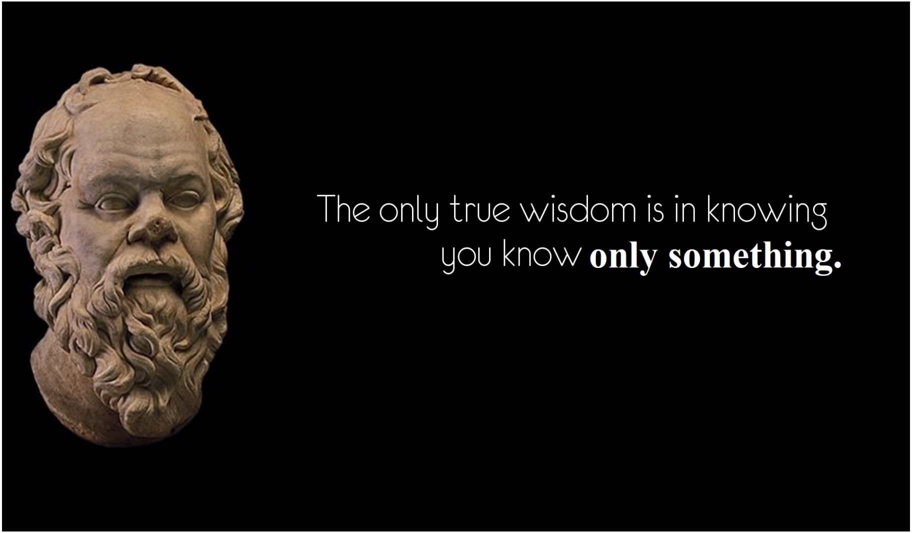
Conclusions

- We have made a quick review of some alternative techniques that have been employed to measure H_0.
- For me it is still unclear whether the 4.4σ tension between the local determination by Riess et al. and Planck+ΛCDM is driven or not (at least, partially) by systematics in the data.
- If the observational results are really free from systematics, then there are some interesting (and quite different) proposals of new physics in the market that could loosen the H_0-tension.


The only true wisdom is in knowing you know nothing.
Socrates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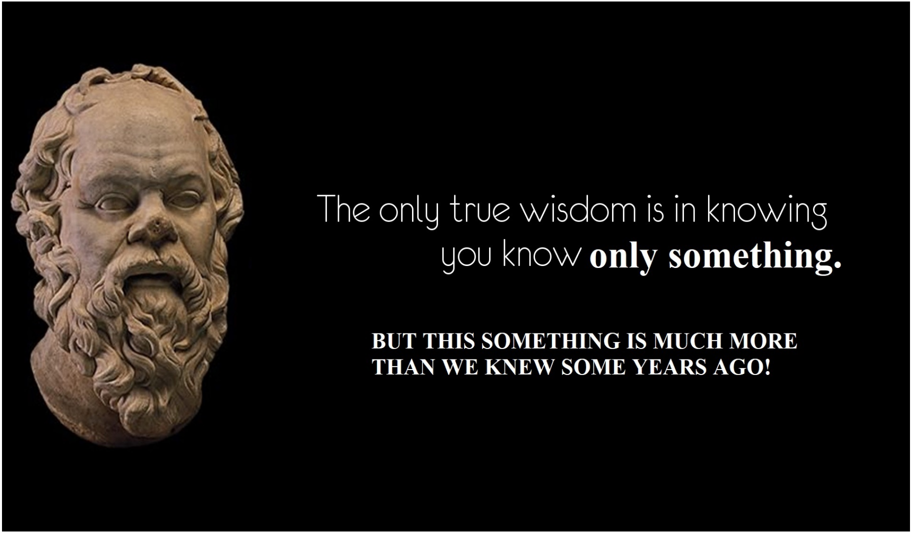
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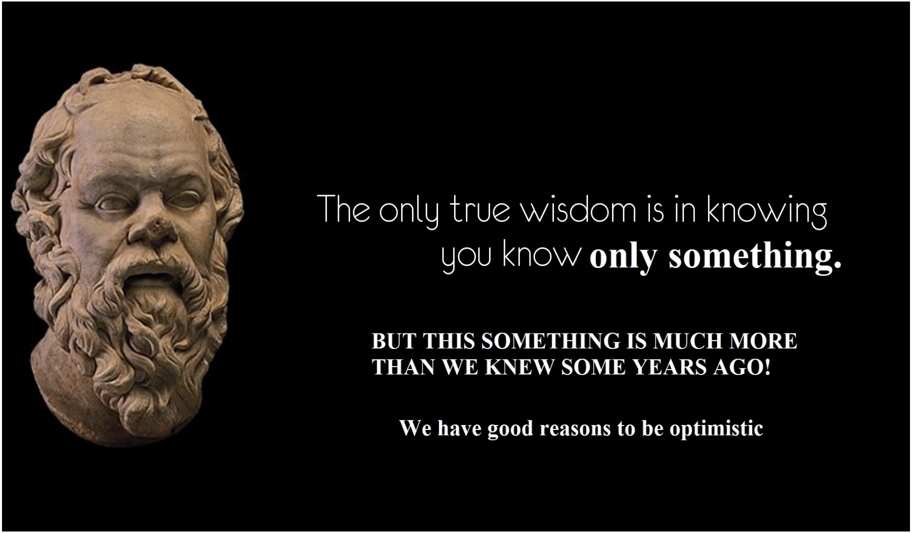
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We have good reasons to be optimistic

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Questions?