Cosmological tensions: hints for a new concordance model?

July 5th, 2021
Sixteenth Marcel Grossmann Meeting

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All the models are wrong, but some are useful

The model that has now practically been selected as the “standard” cosmological model is the Lambda Cold Dark Matter (ΛCDM) model, that provides a remarkable fit to the bulk of available cosmological data.

However, despite its incredible success,
ΛCDM harbours large areas of phenomenology and ignorance.
For example, it still cannot explain key concepts in our understanding of the structure and evolution of the Universe, at the moment based on unknown quantities, that are also its largest components.
In addition, their physical evidence comes from cosmological and astrophysical observations only, without strong theoretical motivations.

The ΛCDM model

Three unknown pillars:

- an early stage of accelerated expansion (Inflation) which produces the initial, tiny, density perturbations, needed for structure formation.
- a clustering matter component to facilitate structure formation (Dark Matter),
- an energy component to explain the current stage of accelerated expansion (Dark Energy).

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In addition, the ΛCDM model is based on the simplest form for these unknown quantities, mostly motivated by computational simplicity, i.e. the theoretical predictions under ΛCDM for several observables are, in general, easier to compute and include fewer free parameters than most other solutions.

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Specific solutions for ΛCDM:

- Inflation is given by a single, minimally coupled, slow-rolling scalar field;
- Dark Matter is a pressureless fluid made of cold, i.e., with low momentum, and collisionless particles;
- Dark Energy is a cosmological constant term.

Warning!

Therefore, the 6 parameter ΛCDM model lacks the deep underpinnings a model requires to approach fundamental physics laws.
It can be rightly considered, at best, as
an effective theory of an underlying physical theory, yet to be discovered.
In this situation, we must be careful not to cling to the model too tightly or to risk missing the appearance of departures from the paradigm.

With the improvement of the number and the accuracy of the observations,
deviations from ΛCDM may be expected.
And, actually, discrepancies among key cosmological parameters of the models have emerged with different statistical significance.

While some proportion of these discrepancies may have a systematic origin, their persistence across probes should require multiple and unrelated errors, strongly hinting at cracks in the standard cosmological scenario and the necessity of new physics.

These tensions can indicate a failure of the canonical ΛCDM model.

The H0 tension

The most statistically significant, long-lasting and widely persisting tension is the H0 disagreement between

- The Planck estimate assuming a “vanilla" ΛCDM cosmological model:

Planck 2018, Astron.Astrophys. 641 (2020) A6

H0 = 67.27 ± 0.60 km/s/Mpc in ΛCDM

- the local measurements obtained by the SH0ES collaboration.

The so called R19:

Riess et al. *Astrophys.J.* 876 (2019) 1, 85

H0 = 74.03 ± 1.42 km/s/Mcc

4.4σ

or R20 using the parallax measurements of Gaia EDR3:

Riess et al., Astrophys.J.Lett. 908 (2021) 1, L6

H0 = 73.2 ± 1.3 km/s/Mpc

4.2σ

The H0 tension

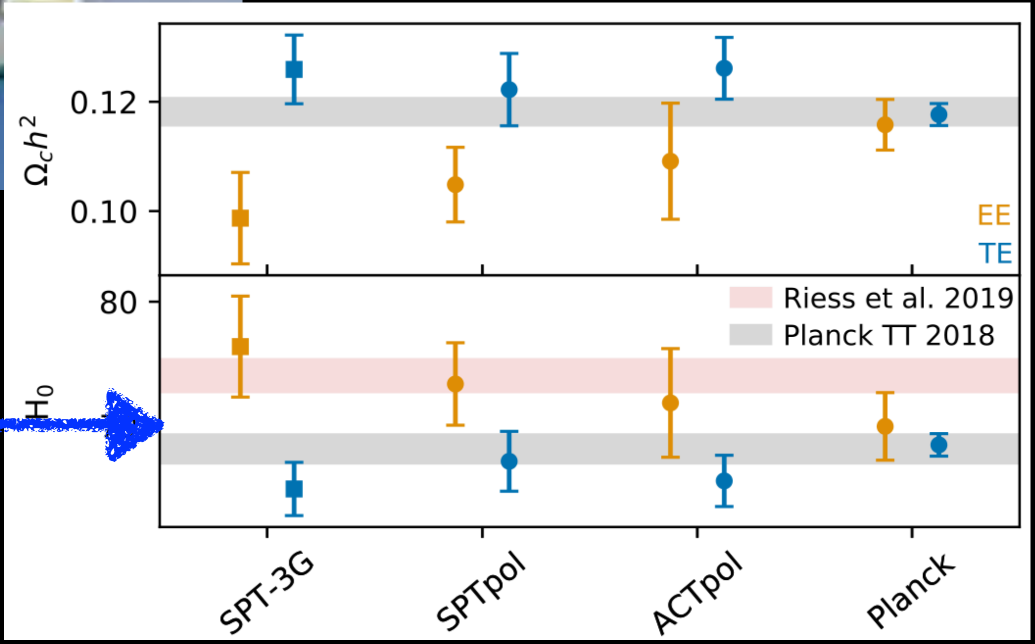
CMB Polarization Measurements with SPTpol

Nicholas Harrington
UC Berkeley

On the same side of Planck, i.e. preferring smaller values of H_0 we have:

Ground based CMB telescope

SPT-3G:
H0 = 68.8 ± 1.5 km/s/Mpc in ΛCDM



SPT-3G, arXiv:2101.01684 [astro-ph.CO]

LCDM - dependent

The H0 tension

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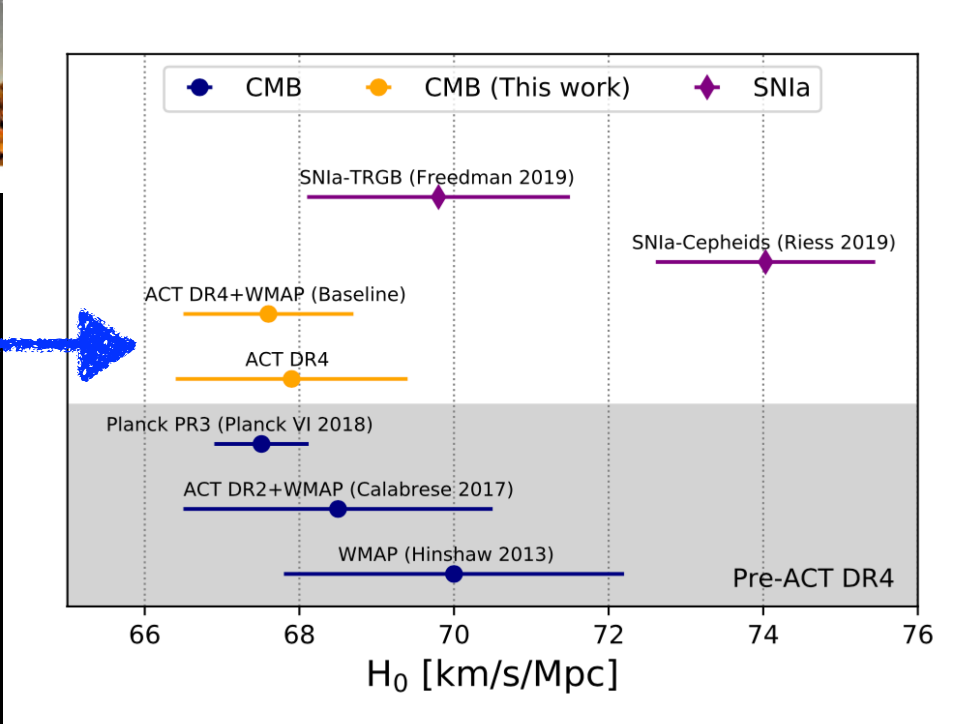


ACT-DR4:
H0 = 67.9 ± 1.5 km/s/Mpc in ΛCDM

ACT-DR4 + WMAP:
H0 = 67.6 ± 1.1 km/s/Mpc in ΛCDM

LCDM - dependent

ACT-DR4 2020, *JCAP* 12 (2020) 047

The H0 tension

On the same side of Planck, i.e.
preferring smaller values of H_0 we have:

BAO+Pantheon+BBN+$\theta_{\text{MC, Planck}}$:

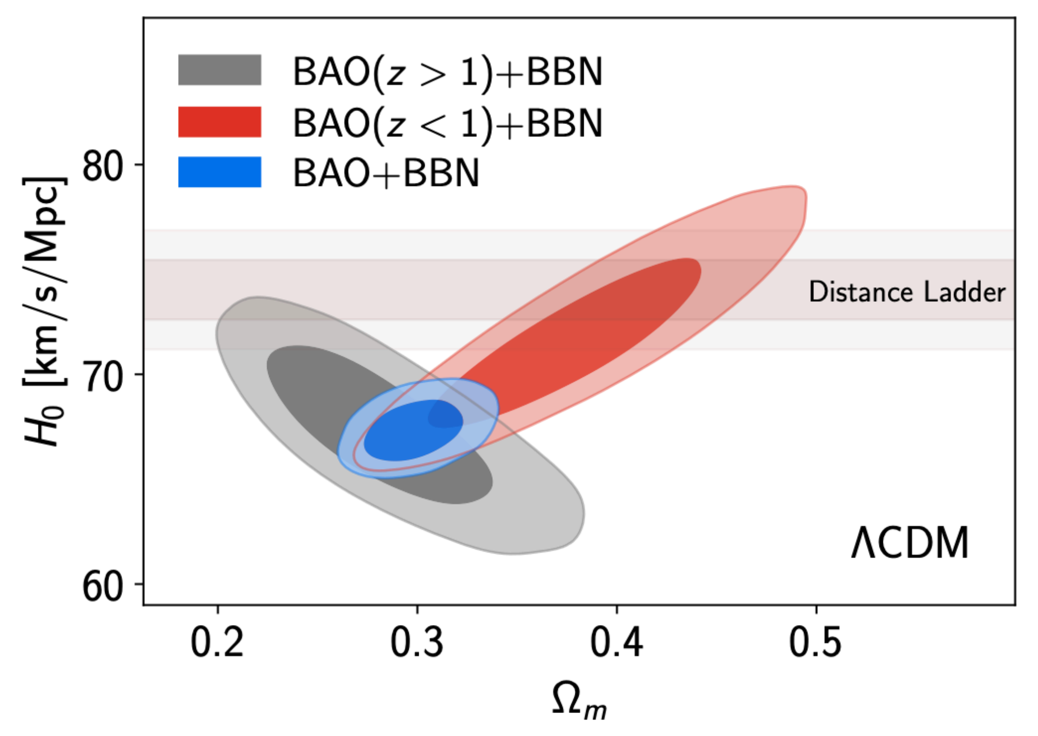
H0 = 67.9 ± 0.8 km/s/Mpc

Planck 2018, Aghanim et al., arXiv:1807.06209 [astro-ph.CO]

BAO+BBN from BOSS and eBOSS:

H_0 = 67.35 ± 0.97 km/s/Mpc

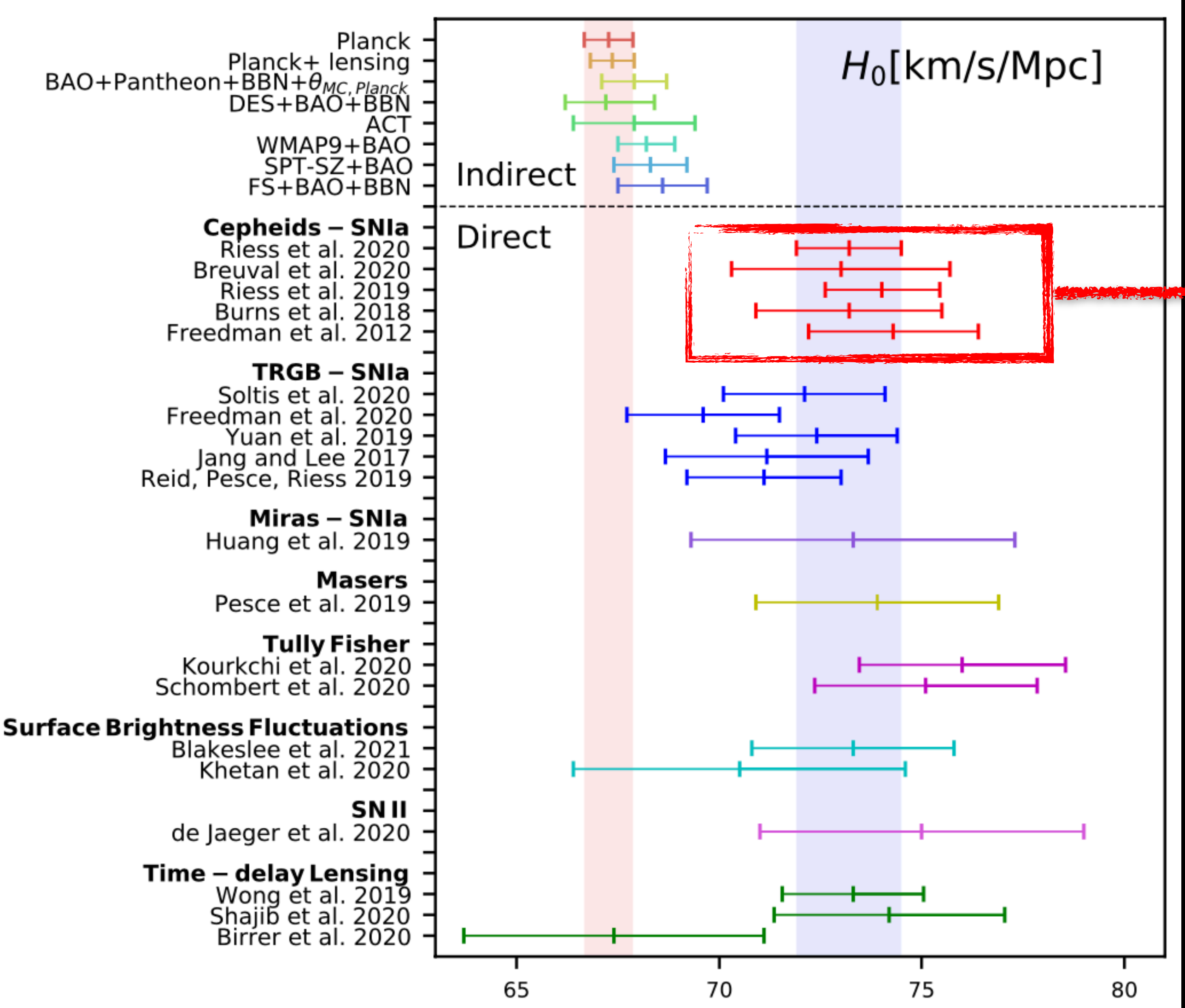
eBOSS, Alam et al., arXiv:2007.08991 [astro-ph.CO]



eBOSS, Alam et al., arXiv:2007.08991 [astro-ph.CO]

LCDM - dependent

Late universe measurements



Di Valentino, *Mon.Not.Roy.Astron.Soc.* 502 (2021) 2, 2065-2073

On the same side of SH0ES, i.e. preferring large values, we have the direct estimates of H0.

Cepheids-SN Ia:

H0 = 73.2 ± 1.3 km/s/Mpc

Riess et al., arXiv:2012.08534 [astro-ph.CO]

H0 = 73.5 ± 1.4 km/s/Mpc

Reid et al., arXiv:1908.05625 [astro-ph.CO]

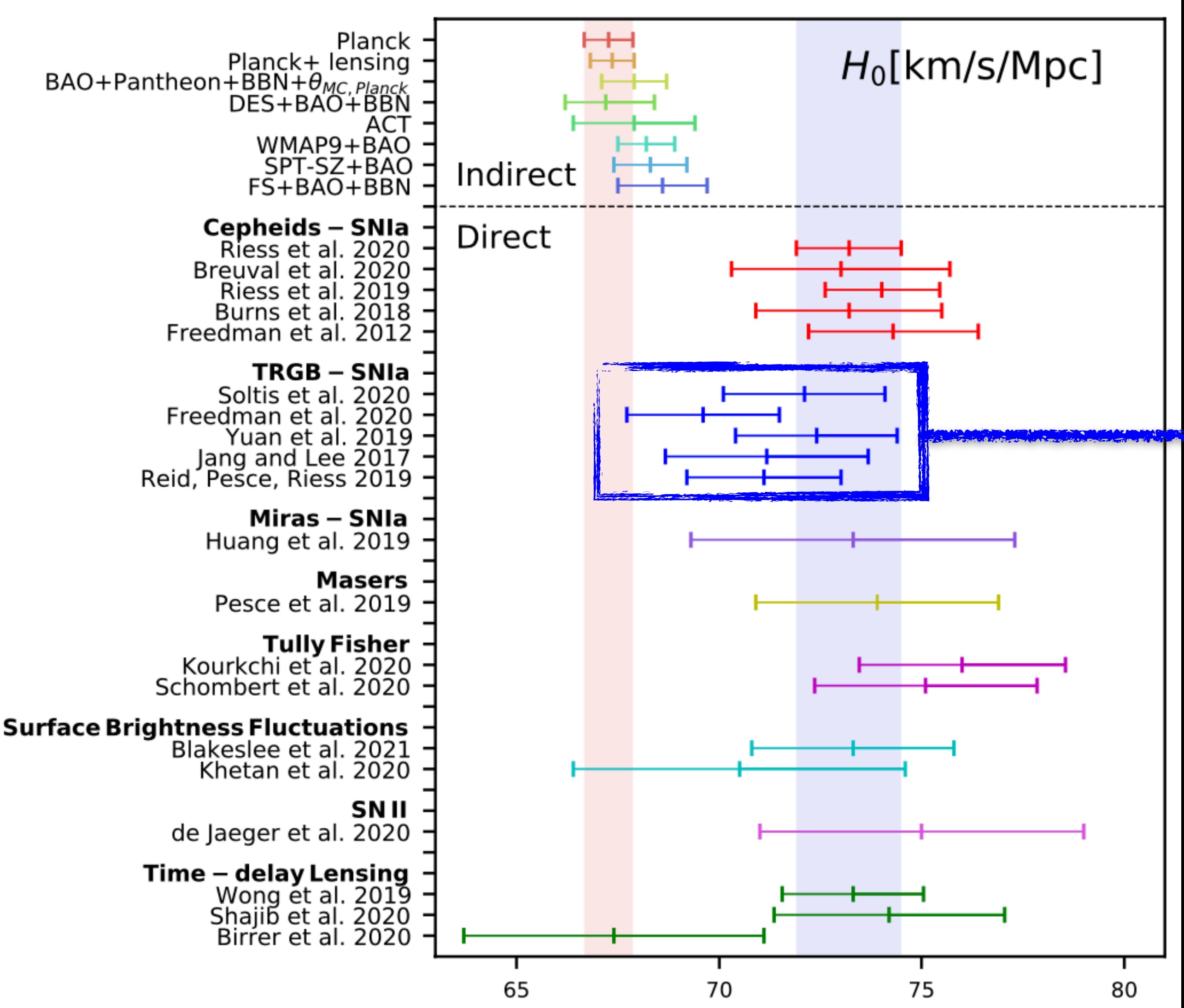
H0 = 73.0 ± 2.7 km/s/Mpc

Breuval et al., arXiv:2006.08763 [astro-ph.CO]

H0 = 73.2 ± 2.3 km/s/Mpc

Burns et al., arXiv:1809.06381 [astro-ph.CO]

Late universe measurements



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The Tip of the Red Giant Branch (TRGB) is the peak brightness reached by red giant stars after they stop using hydrogen and begin fusing helium in their core.

H0 = 72.1±1.2 km/s/Mpc

Soltis et al., arXiv:2012.09196 [astro-ph.CO]

H0 = 69.6±1.88 km/s/Mpc

Freedman et al., arXiv:2002.01550 [astro-ph.CO]

H0 = 72.4±2.0 km/s/Mpc

Yuan and Lee., arXiv:1908.00993 [astro-ph.CO]

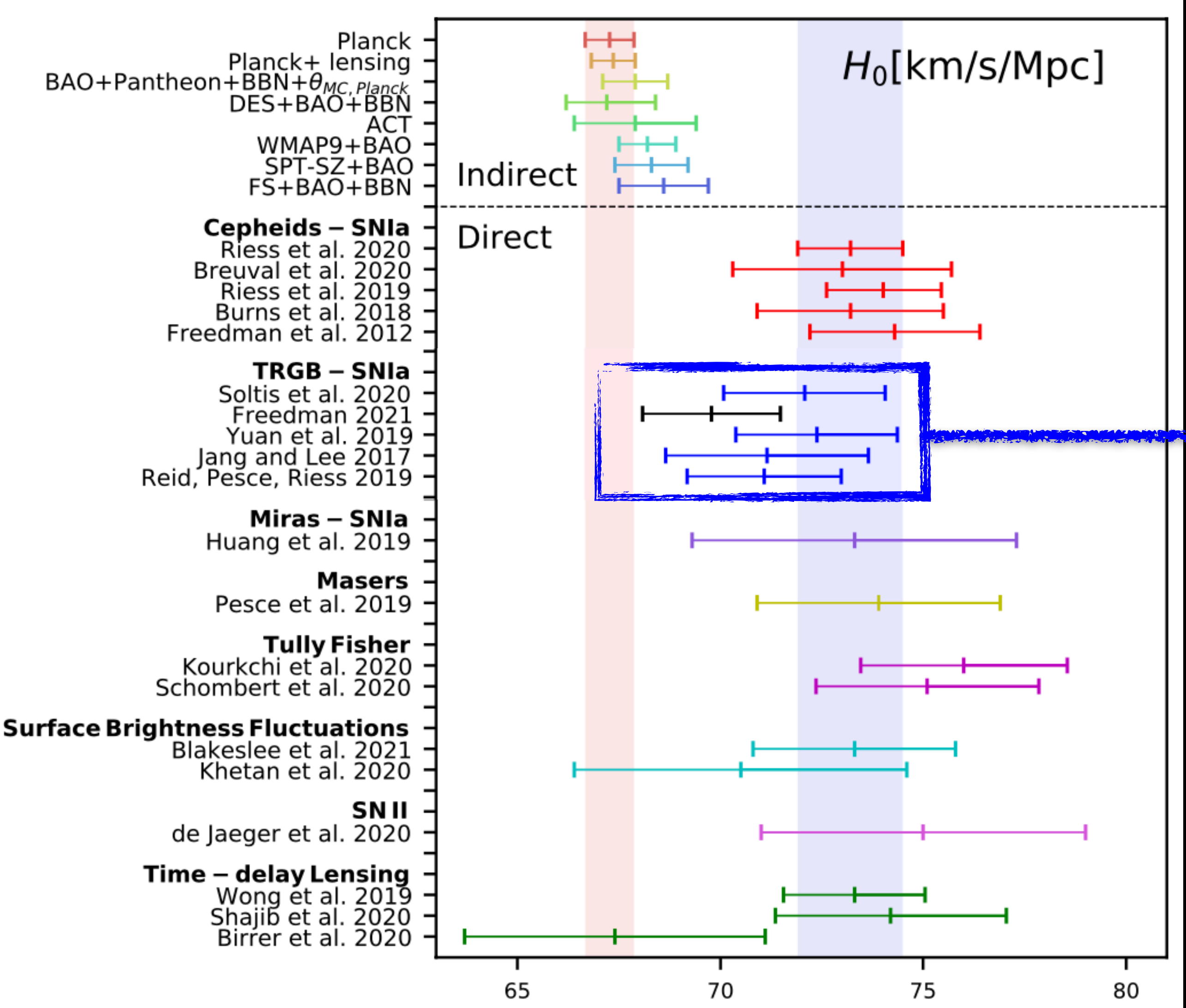
H0 = 71.17±2.50 km/s/Mpc

Jang et al., arXiv:1702.01118 [astro-ph.CO]

H0 = 71.1±1.9 km/s/Mpc

Reid et al., arXiv:1908.05625 [astro-ph.CO]

Late universe measurements



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Freedman, arXiv:2106.15656 [astro-ph.CO]

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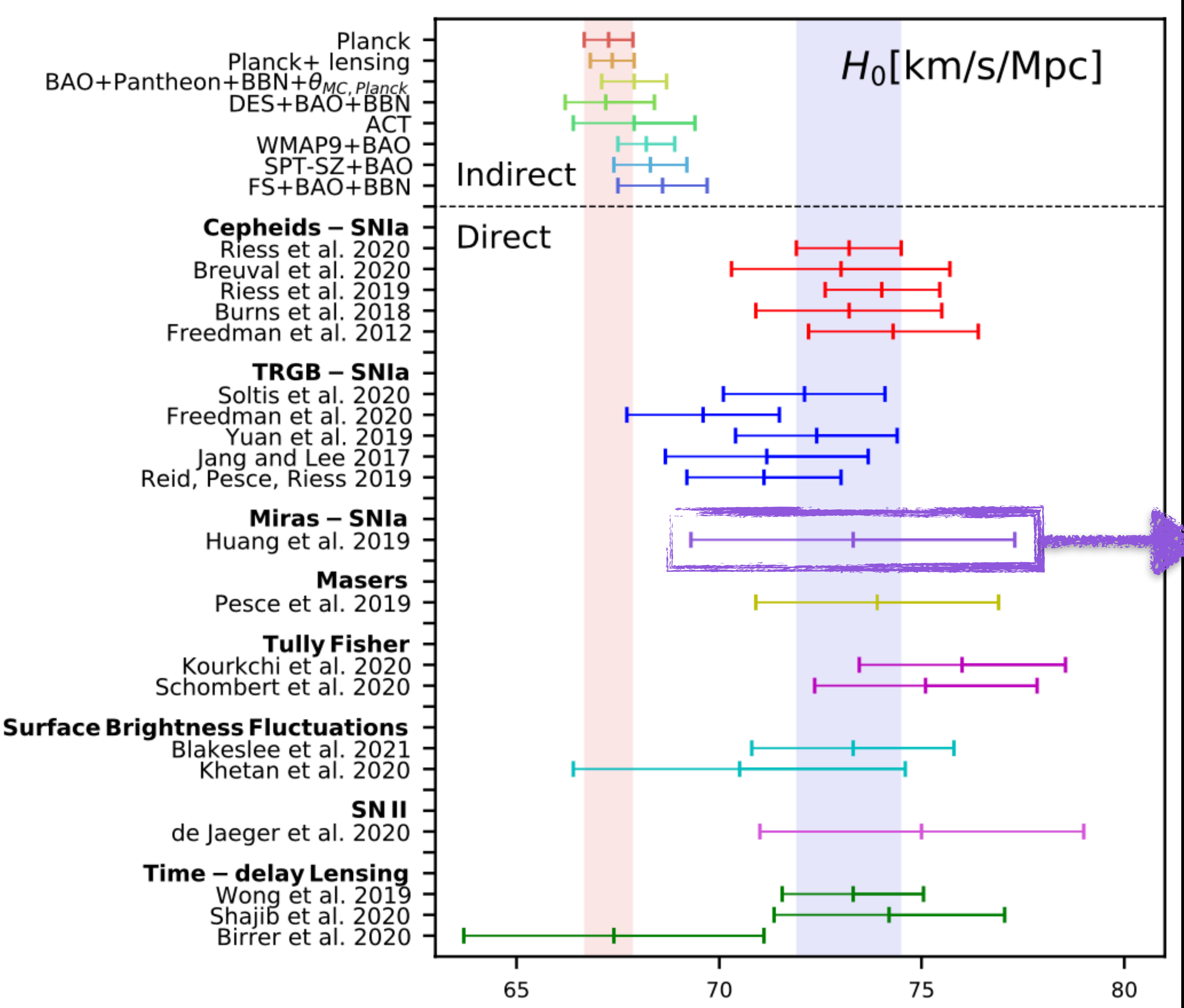

MIRAS
variable red giant stars form
older stellar populations

H0 = 73.3 ± 4.0 km/s/Mpc

Huang et al., arXiv:1908.10883 [astro-ph.CO]

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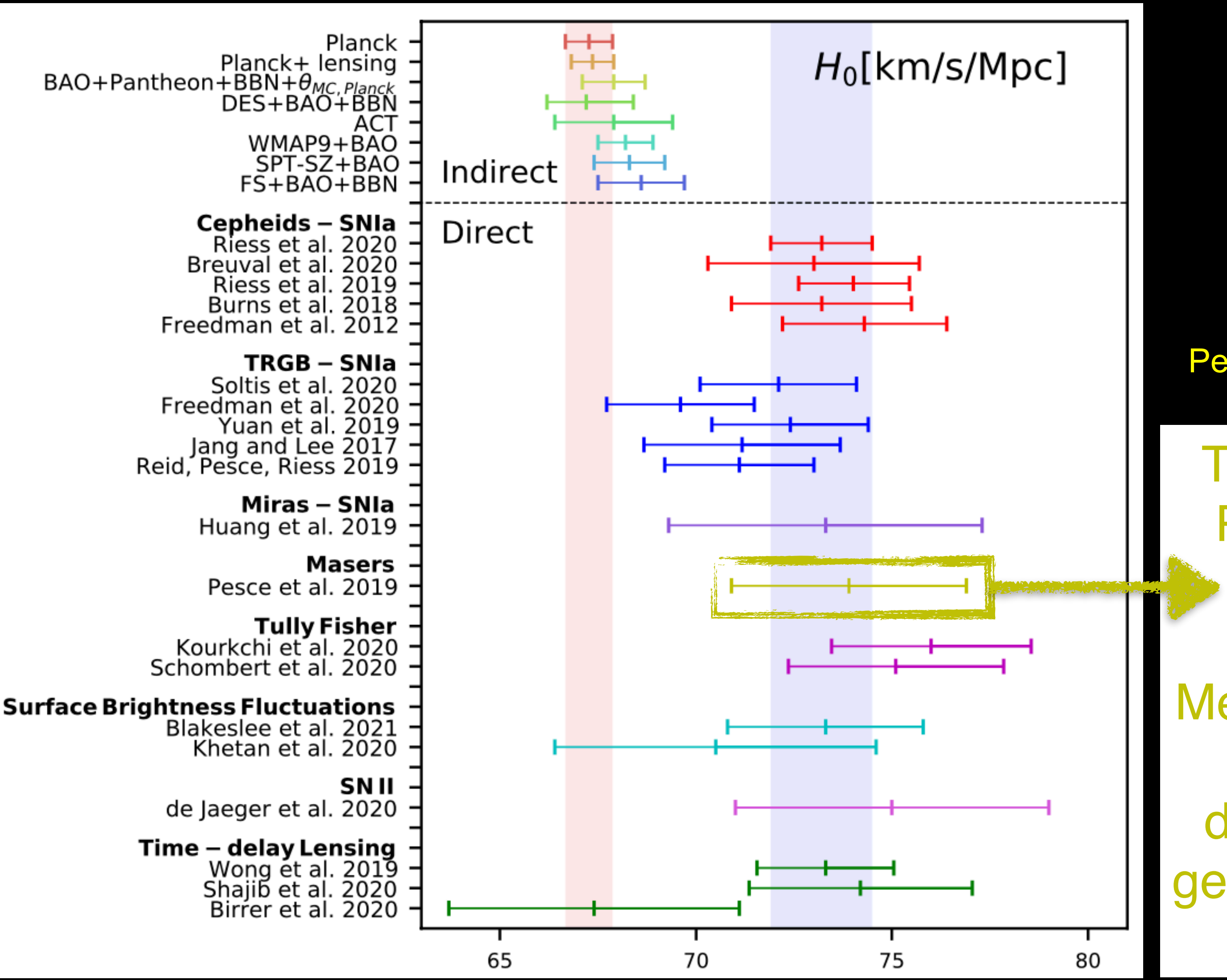
Late universe measurements



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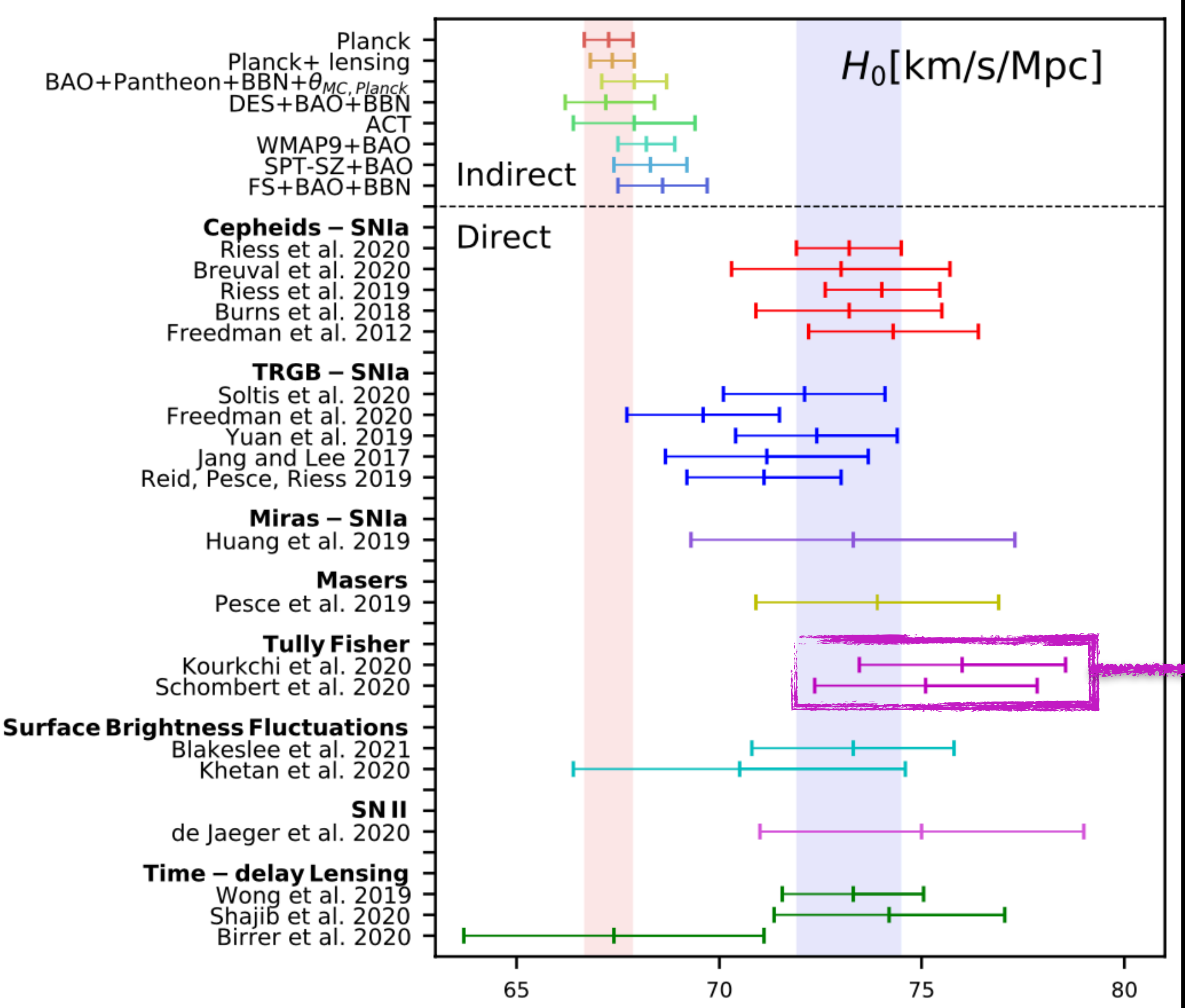
H0 = 73.9 ± 3.0 km/s/Mpc

Pesce et al. arXiv:2001.09213 [astro-ph.CO]

The Megamaser Cosmology Project measures H0 using geometric distance measurements to six Megamaser - hosting galaxies. This approach avoids any distance ladder by providing geometric distance directly into the Hubble flow.

Late universe measurements



H0 = 76.00 ± 2.55 km/s/Mpc

Kourkchi et al. arXiv:2004.14499 [astro-ph.CO]

H0 = 75.10 ± 2.75 km/s/Mpc

Schombert et al. arXiv:2006.08615 [astro-ph.CO]

Tully-Fisher Relation (based on the correlation between the rotation rate of spiral galaxies and their absolute luminosity, and using as calibrators Cepheids and TRGB)

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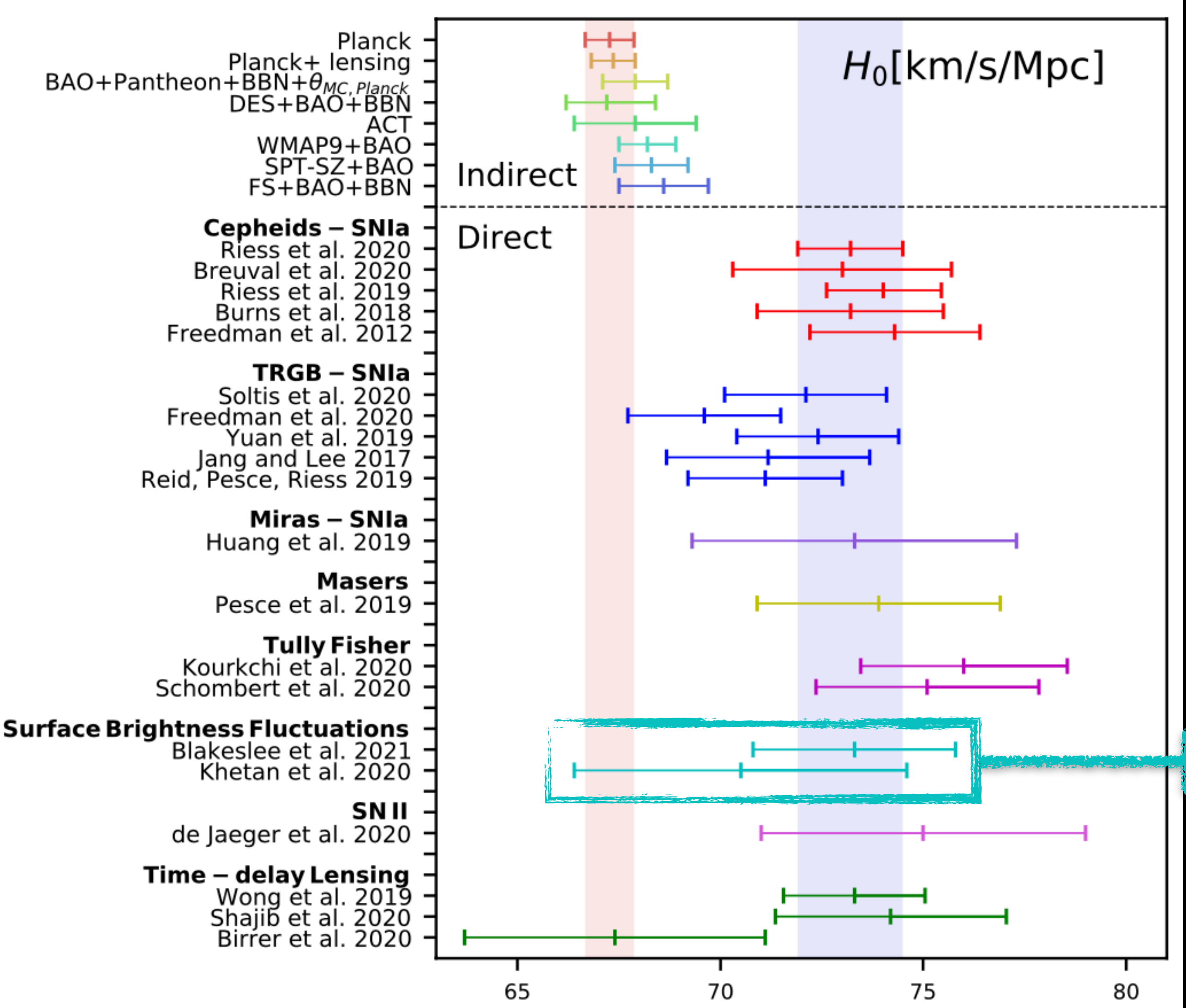
Late universe measurements



H0 = 73.3 ± 2.5 km/s/Mpc

Blakeslee et al., arXiv:2101.02221 [astro-ph.CO]

H0 = 70.5 ± 4.1 km/s/Mpc

Khetan et al. arXiv:2008.07754 [astro-ph.CO]

Surface Brightness Fluctuations (substitutive distance ladder for long range indicator, calibrated by both Cepheids and TRGB)

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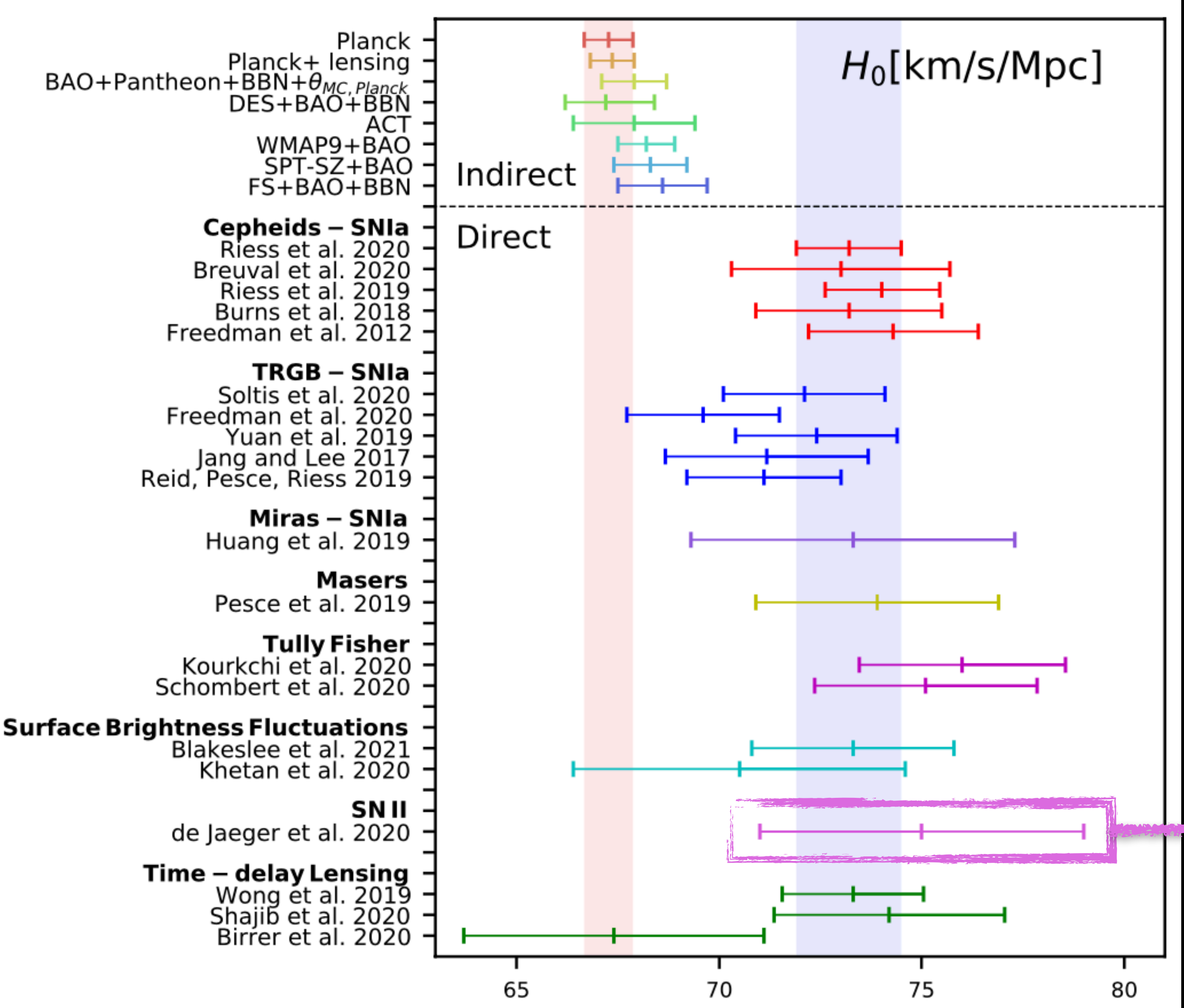
Late universe measurements



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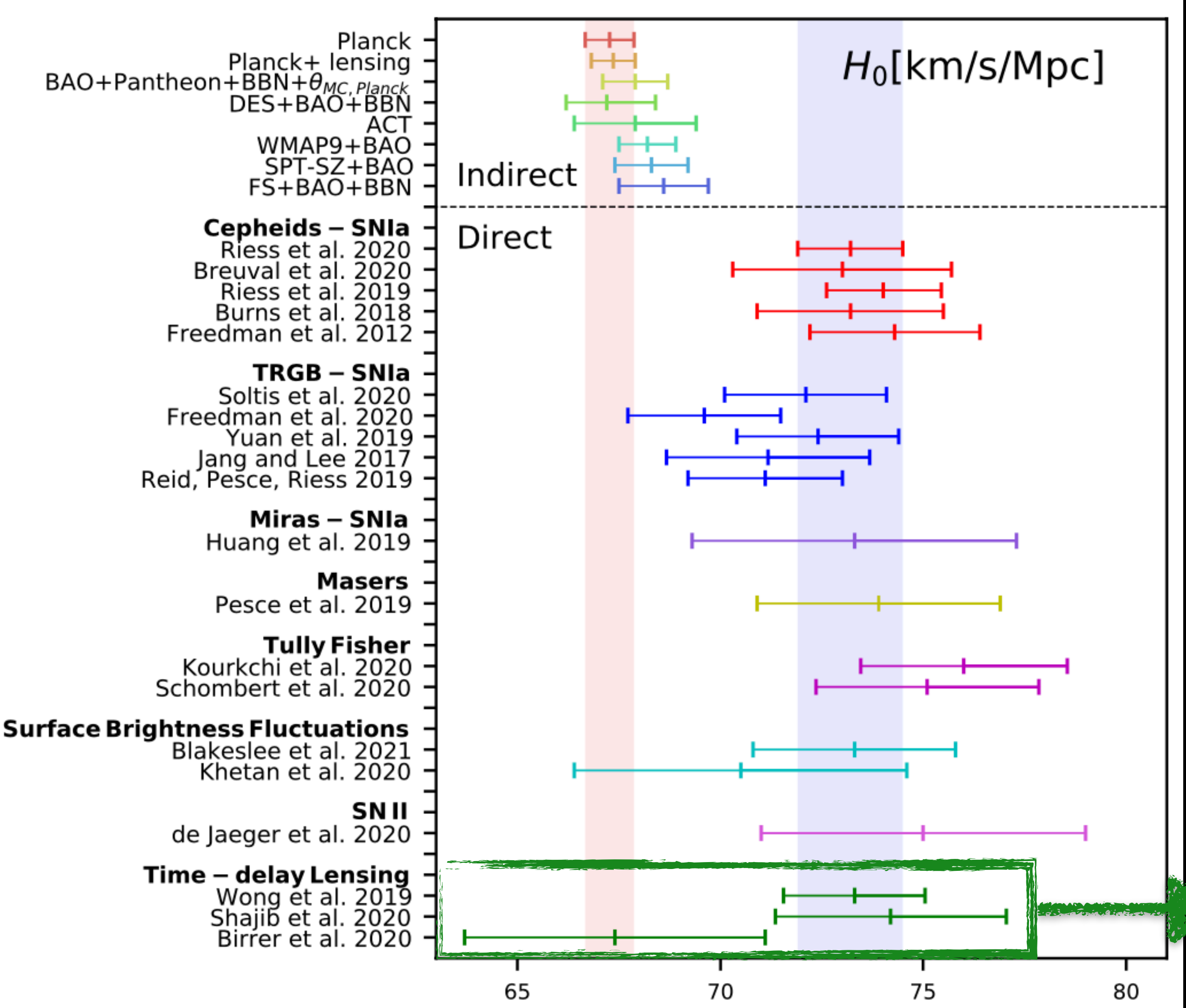
$H0 = 75.8^{+5.2}_{-4.9}$ km/s/Mpc

de Jaeger et al., arXiv:2006.03412 [astro-ph.CO]

Type II supernovae used as standardisable candles and calibrated by both Cepheids and TRGB

Late universe measurements



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H0LiCOW:

H0 = 73.3 $^{+1.7}_{-1.8}$ km/s/Mpc

Wong et al. arXiv:1907.04869 [astro-ph.CO]

STRIDES:

H0 = 74.2 $^{+2.7}_{-3.0}$ km/s/Mpc

Shajib et al. arXiv:1910.06306 [astro-ph.CO]

TDCOSMO+SLAC:

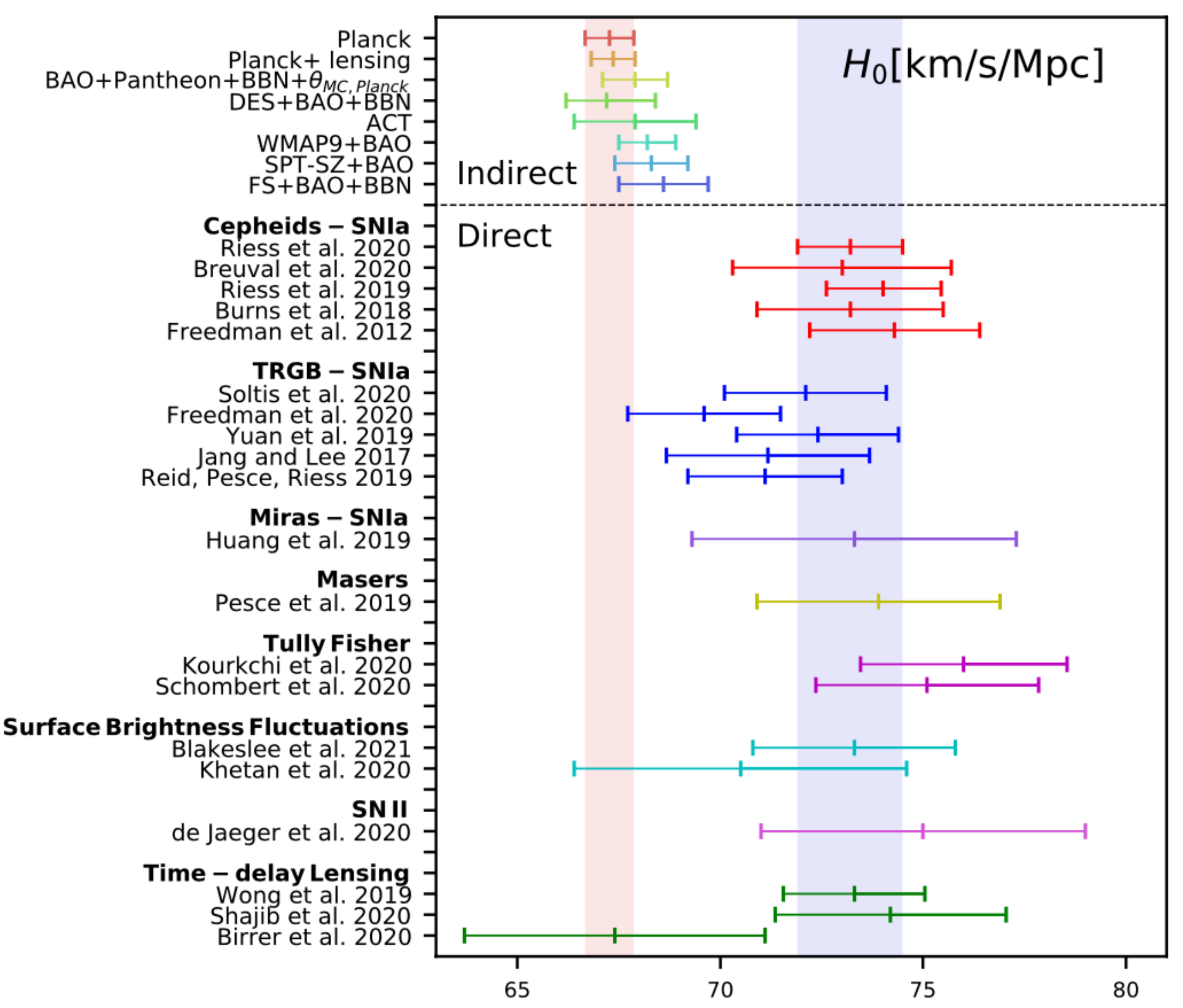
H0 = 67.4 $^{+4.1}_{-3.2}$ km/s/Mpc

Birrer et al. arXiv:2007.02941 [astro-ph.CO]

Strong Lensing measurements of the time delays of multiple images of quasar systems caused by the strong gravitational lensing from a foreground galaxy. Uncertainties coming from the lens mass profile.

Astrophysical model dependent

Late universe measurements



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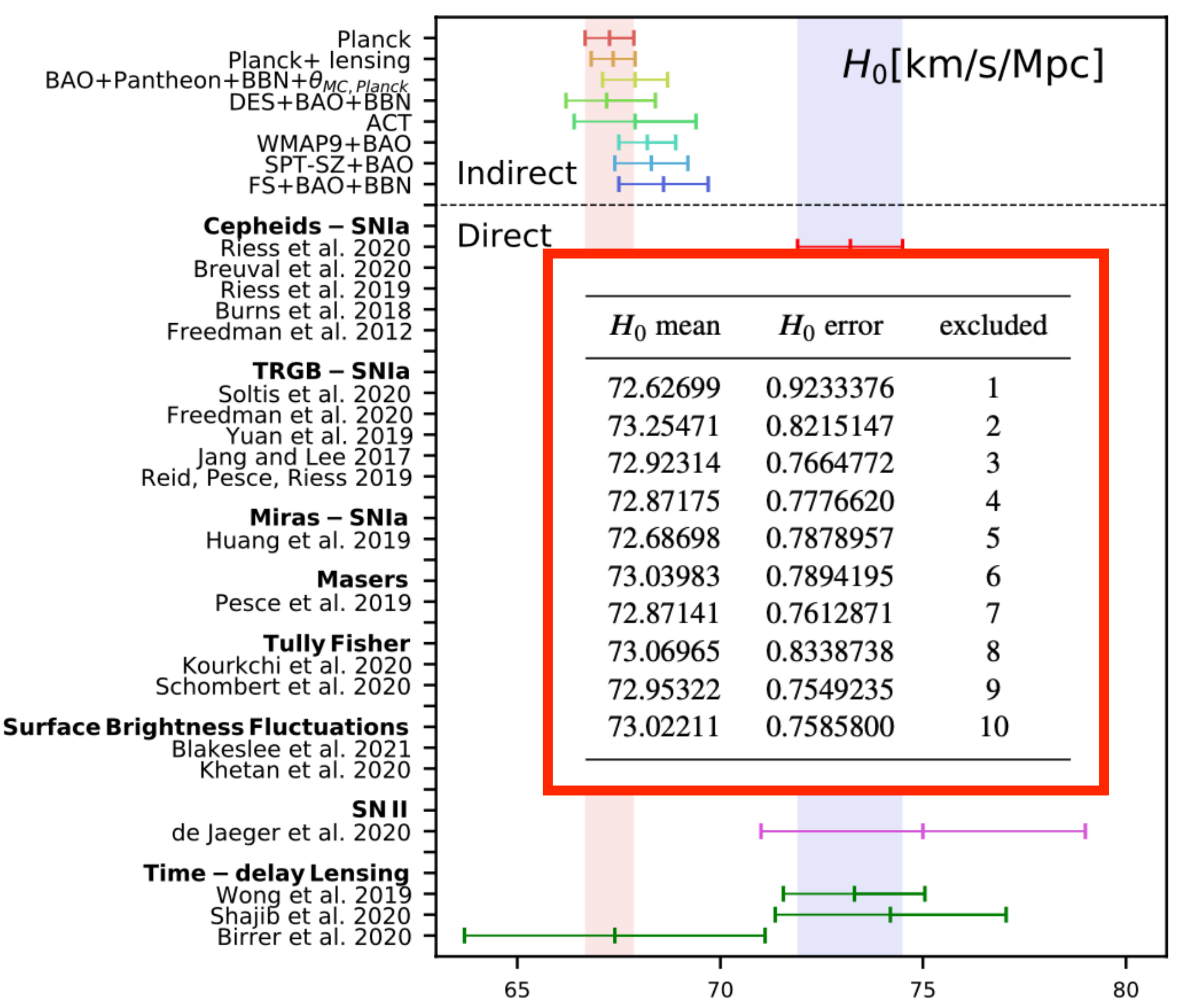
Combining all of them together (+Standard Sirens and + γ-ray Attenuation) we obtain our

Optimistic estimate (5.9σ tension with Planck)

H0 = 72.94 ± 0.75 km/s/Mpc

Late universe measurements



H_0 mean	H_0 error	excluded
72.62699	0.9233376	1
73.25471	0.8215147	2
72.92314	0.7664772	3
72.87175	0.7776620	4
72.68698	0.7878957	5
73.03983	0.7894195	6
72.87141	0.7612871	7
73.06965	0.8338738	8
72.95322	0.7549235	9
73.02211	0.7585800	10

Excluding one group of data and taking the result with the largest error bar, i.e. excluding the most precise measurements based on Cepheids-SN Ia, we obtain our

Conservative estimate
(4.8σ tension with Planck)

H0 = 72.63 ± 0.92 km/s/Mpc

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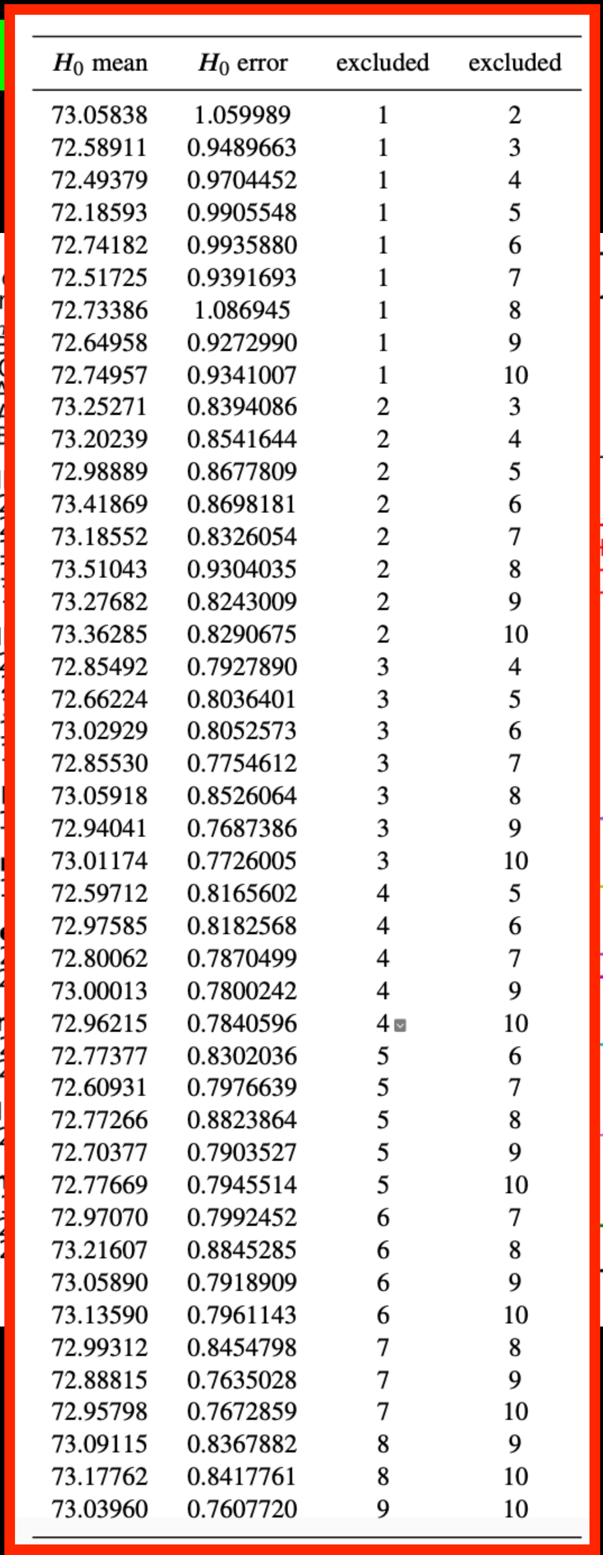
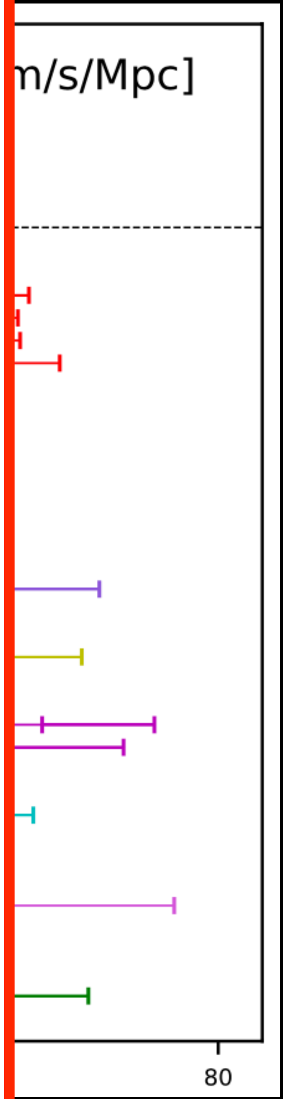
measurements



H_0 mean	H_0 error	excluded	excluded
73.05838	1.059989	1	2
72.58911	0.9489663	1	3
72.49379	0.9704452	1	4
72.18593	0.9905548	1	5
72.74182	0.9935880	1	6
72.51725	0.9391693	1	7
72.73386	1.086945	1	8
72.64958	0.9272990	1	9
72.74957	0.9341007	1	10
73.25271	0.8394086	2	3
73.20239	0.8541644	2	4
72.98889	0.8677809	2	5
73.41869	0.8698181	2	6
73.18552	0.8326054	2	7
73.51043	0.9304035	2	8
73.27682	0.8243009	2	9
73.36285	0.8290675	2	10
72.85492	0.7927890	3	4
72.66224	0.8036401	3	5
73.02929	0.8052573	3	6
72.85530	0.7754612	3	7
73.05918	0.8526064	3	8
72.94041	0.7687386	3	9
73.01174	0.7726005	3	10
72.59712	0.8165602	4	5
72.97585	0.8182568	4	6
72.80062	0.7870499	4	7
73.00013	0.7800242	4	9
72.96215	0.7840596	4	10
72.77377	0.8302036	5	6
72.60931	0.7976639	5	7
72.77266	0.8823864	5	8
72.70377	0.7903527	5	9
72.77669	0.7945514	5	10
72.97070	0.7992452	6	7
73.21607	0.8845285	6	8
73.05890	0.7918909	6	9
73.13590	0.7961143	6	10
72.99312	0.8454798	7	8
72.88815	0.7635028	7	9
72.95798	0.7672859	7	10
73.09115	0.8367882	8	9
73.17762	0.8417761	8	10
73.03960	0.7607720	9	10



Excluding two groups of data and taking the result with the largest error bar, i.e. excluding the most precise measurements based on Cepheids-SN Ia and Time-delay Lensing, we obtain our

Ultra-conservative estimate (3σ tension with Planck)

H0 = 72.7 ± 1.1 km/s/Mpc

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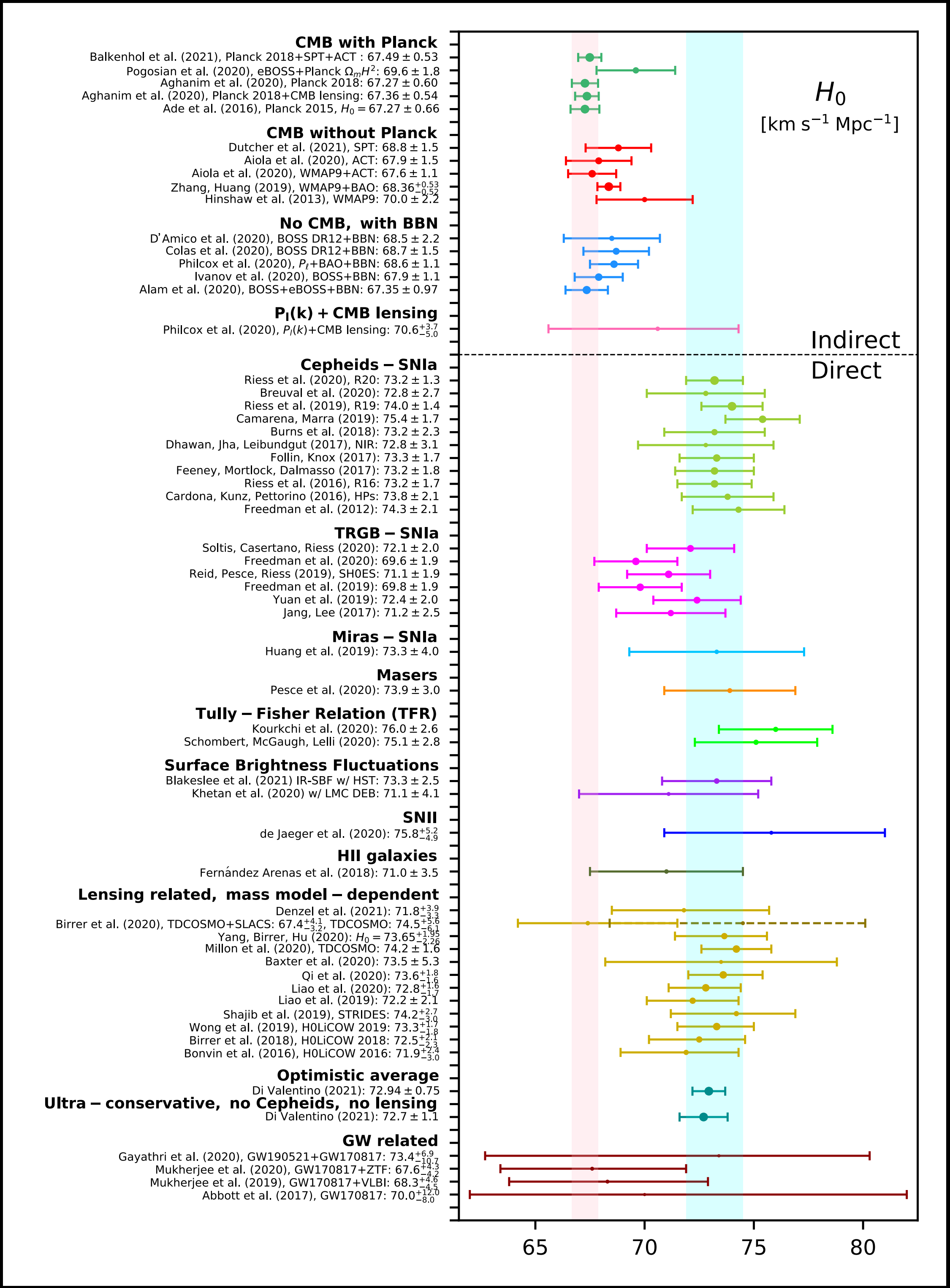


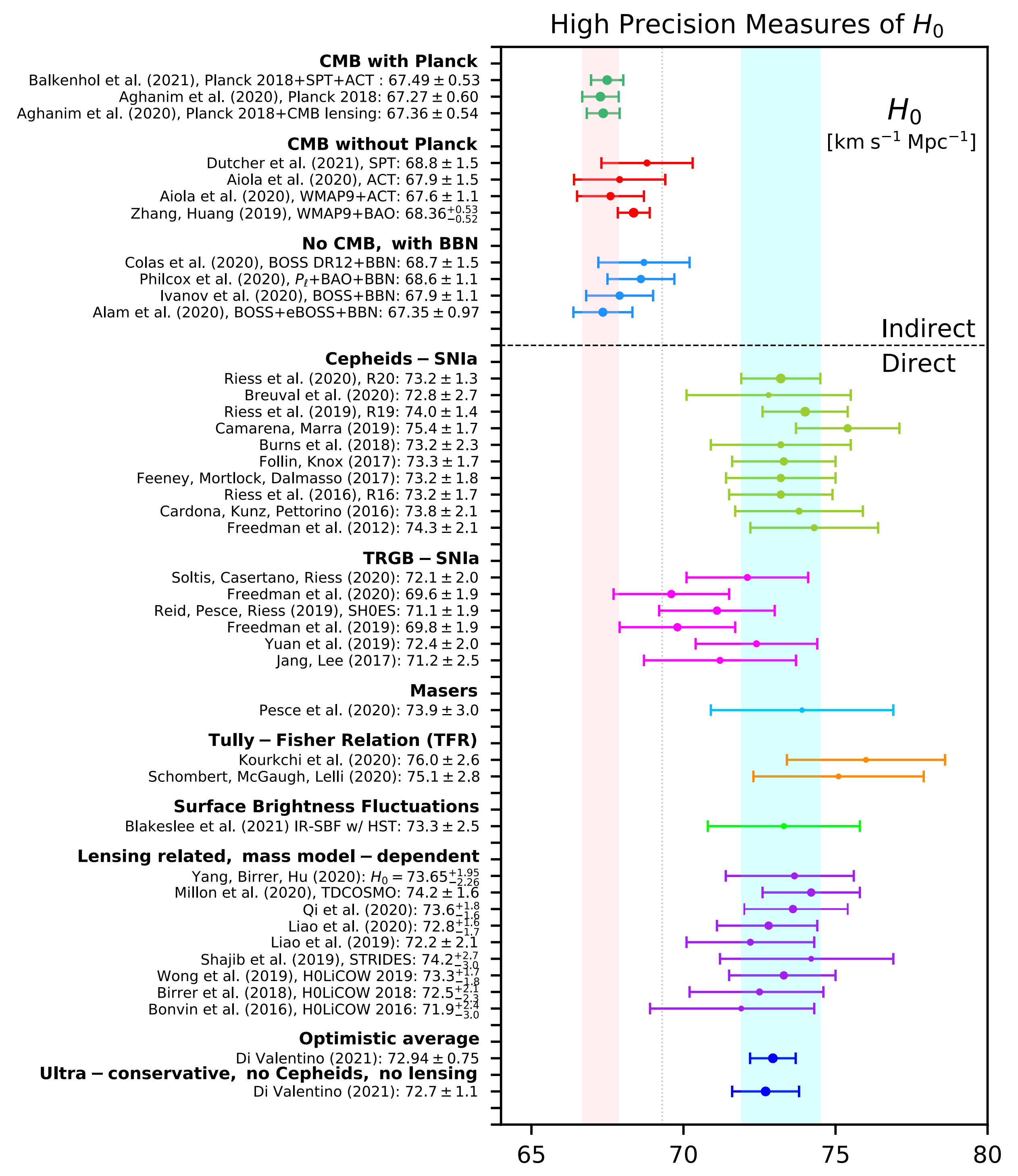
Hubble constant direct and indirect measurements made by different astronomical missions and groups over the years.

The cyan vertical band corresponds to the H0 value from SH0ES Team and the light pink vertical band corresponds to the H0 value as reported by Planck 2018 team within a ΛCDM scenario.

A sample code for producing similar figures with any choice of the data is made publicly available online at github.com/lucavisinelli/H0TensionRealm

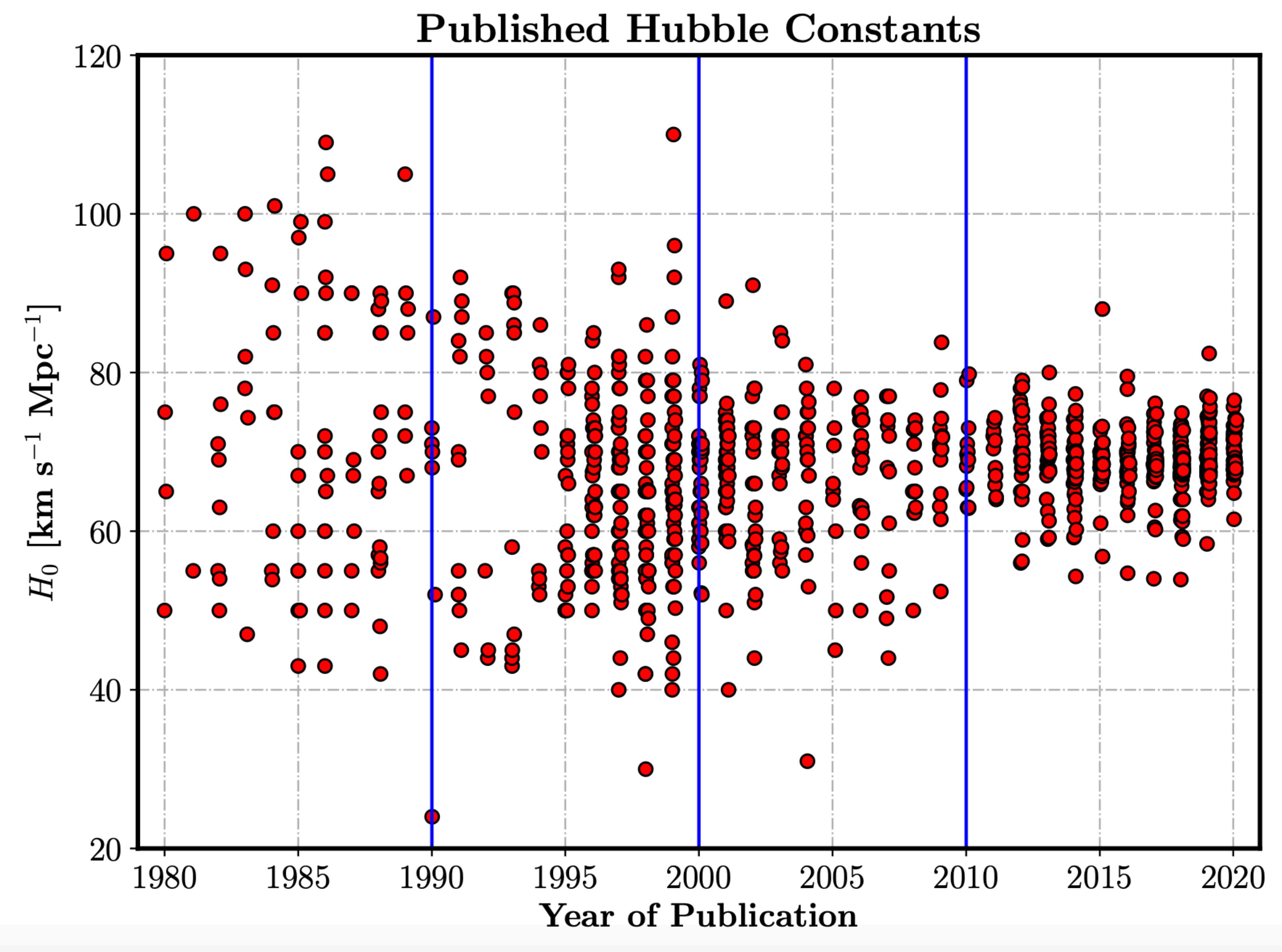
Make your plot!

Di Valentino et al., Class.Quant.Grav. (2021), arXiv:2103.01183 [astro-ph.CO]



Di Valentino et al., Class.Quant.Grav. (2021), arXiv:2103.01183 [astro-ph.CO]

The high precision and consistency of the data at both ends present strong challenges to the possible solution space and demands a hypothesis with enough rigor to explain multiple observations – whether these invoke new physics, unexpected large-scale structures or multiple, unrelated errors.



Freedman, arXiv:2106.15656 [astro-ph.CO]

In the past case the tension was within the same types of measurements and at the same redshifts and thus pointed directly to systematics.
Now there are not late universe measurements below early ones and viceversa.

It is hard to conceive of a single type of systematic error that would apply to the measurements of the disparate phenomena we saw before as to effectively resolve the Hubble constant tension.
Because the tension remains with the removal of the measurements of any single type of object, mode or calibration, it is challenging to devise a single error that would suffice.
While multiple, unrelated systematic errors have a great deal more flexibility to resolve the tension but become less likely by their inherent independence.

Since the indirect constraints are model dependent, we can try to expand the cosmological scenario and see which extensions work in solving the tensions between the cosmological probes.

First pillar: Dark Matter

For example, we can consider modifications
in the dark matter sector. A classical extension is the
effective number of relativistic degrees of freedom,
i.e. additional relativistic matter at recombination,
corresponding to a modification of the expansion history
of the universe at early times.

The Neutrino effective number

The expected value is Neff = 3.046, if we assume standard electroweak interactions and three active massless neutrinos. If we measure a Neff > 3.046, we are in presence of extra radiation.

If we compare the Planck 2015 constraint on Neff at 68% cl

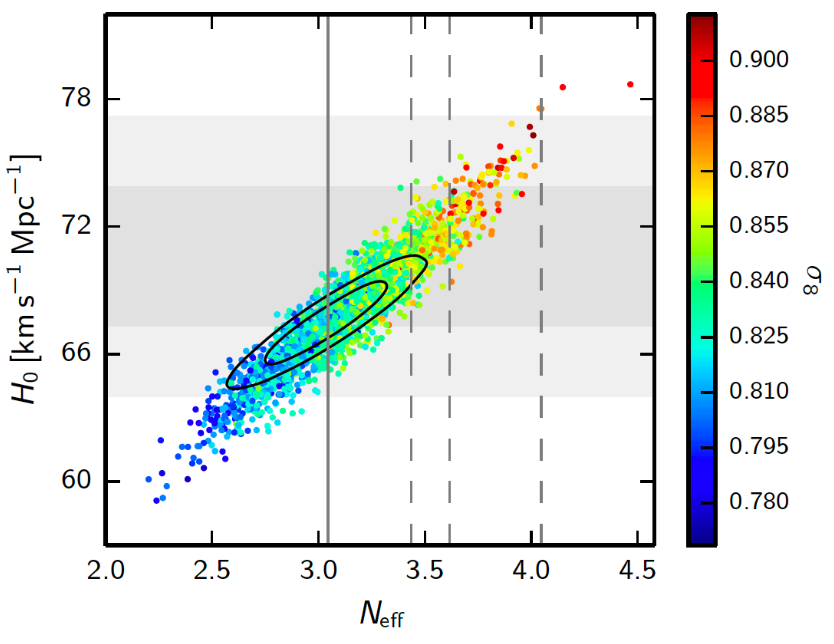
$$N_{\rm eff} = 3.13 \pm 0.32 \quad \textit{Planck}\ \text{TT+lowP},$$
$$N_{\rm eff} = 3.15 \pm 0.23 \quad \textit{Planck}\ \text{TT+lowP+BAO},$$

with the new Planck 2018 bound,

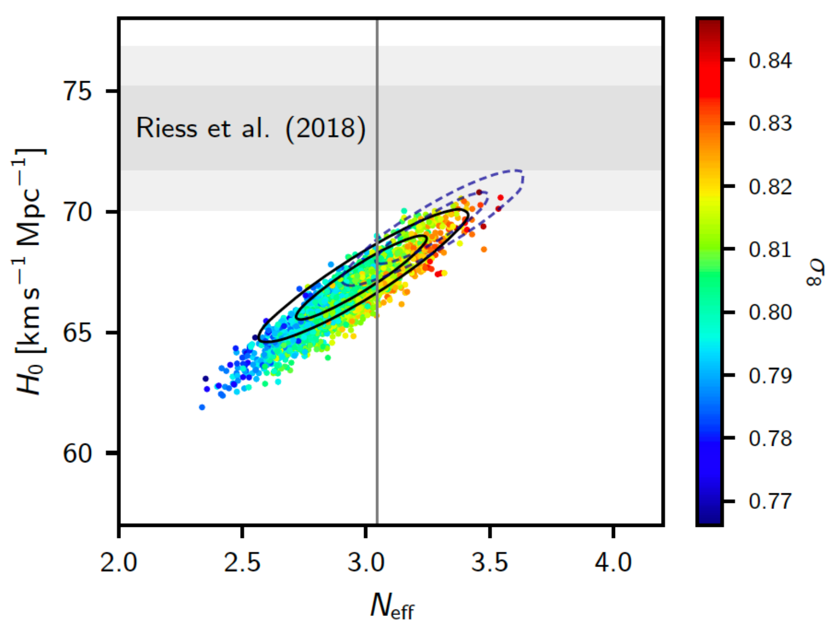
$$N_{\rm eff} = 2.92^{+0.36}_{-0.37} \quad (95\,\%,\ \textit{Planck}\ \text{TT,TE,EE+lowE}),$$

we see that the neutrino effective number is now very well constrained.

H0 passes from 68.0 ± 2.8 km/s/Mpc (2015) to 66.4 ± 1.4 km/s/Mpc (2018), and the tension with R20 increases from 1.7σ to 3.6σ also varying Neff.



Planck collaboration, 2015



Planck collaboration, 2018

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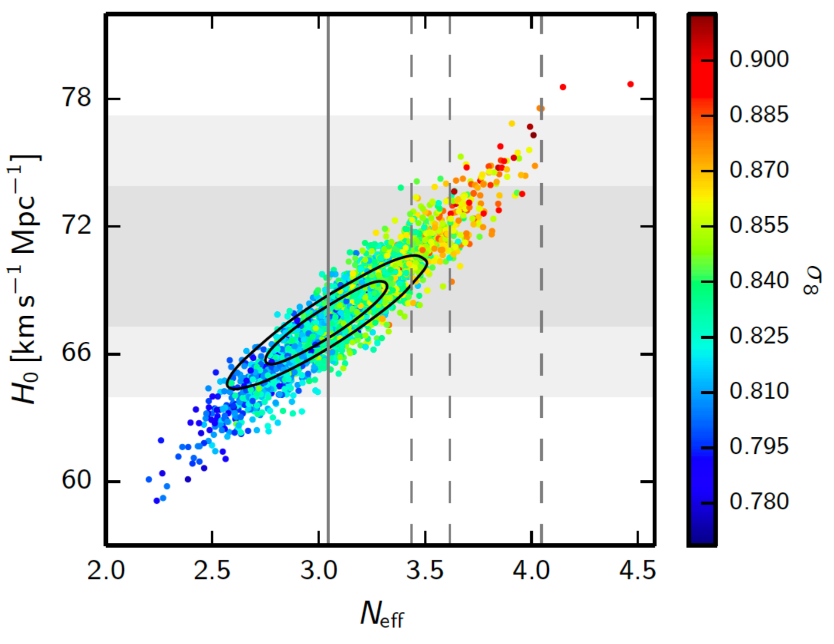
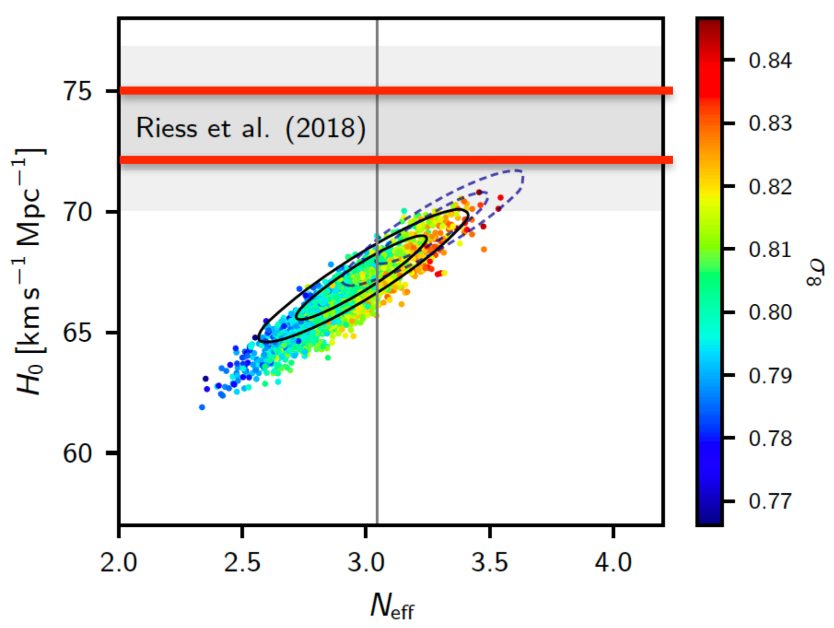


Planck collaboration, 2015



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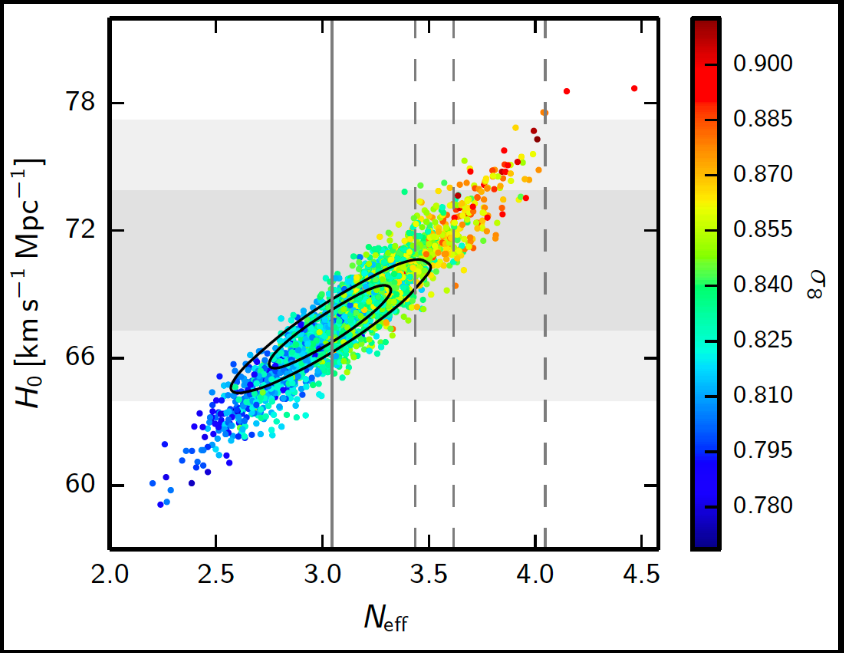
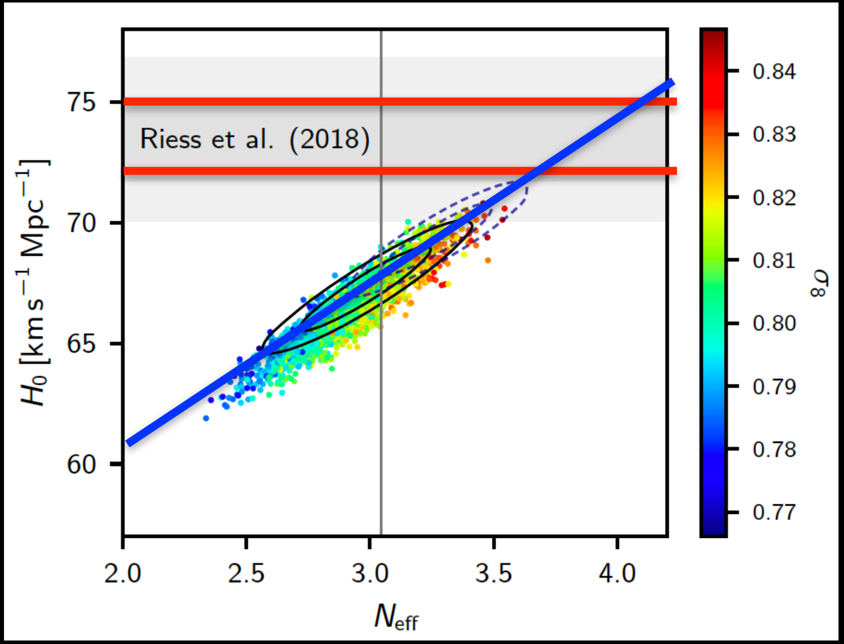


Planck collaboration, 2015



Planck collaboration, 2018

The Neutrino effective number

The expected value is Neff = 3.046, if we assume standard electroweak interactions and three active massless neutrinos. If we measure a Neff > 3.046, we are in presence of extra radiation.

If we compare the Planck 2015 constraint on Neff at 68% cl

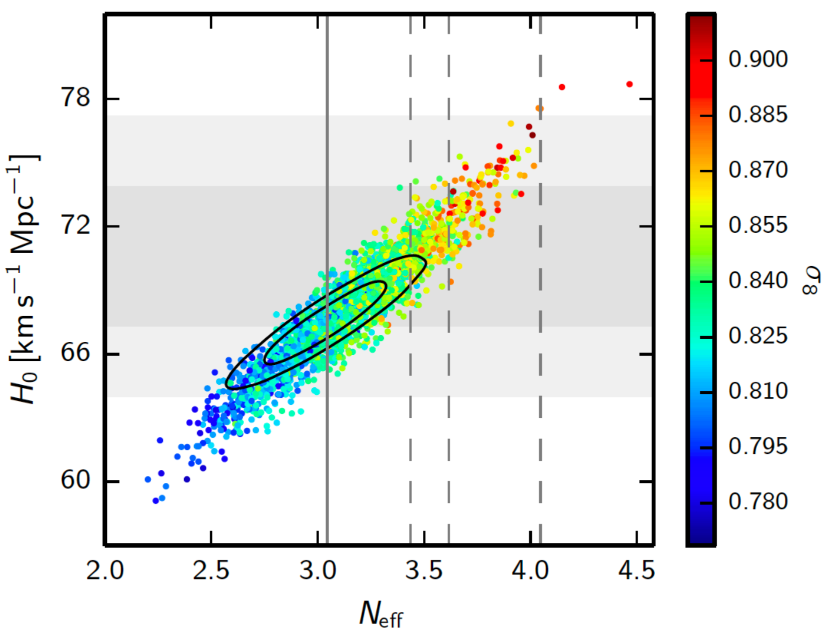
$$N_{\rm eff} = 3.13 \pm 0.32 \quad \textit{Planck}\ \text{TT+lowP},$$
$$N_{\rm eff} = 3.15 \pm 0.23 \quad \textit{Planck}\ \text{TT+lowP+BAO},$$

with the new Planck 2018 bound,

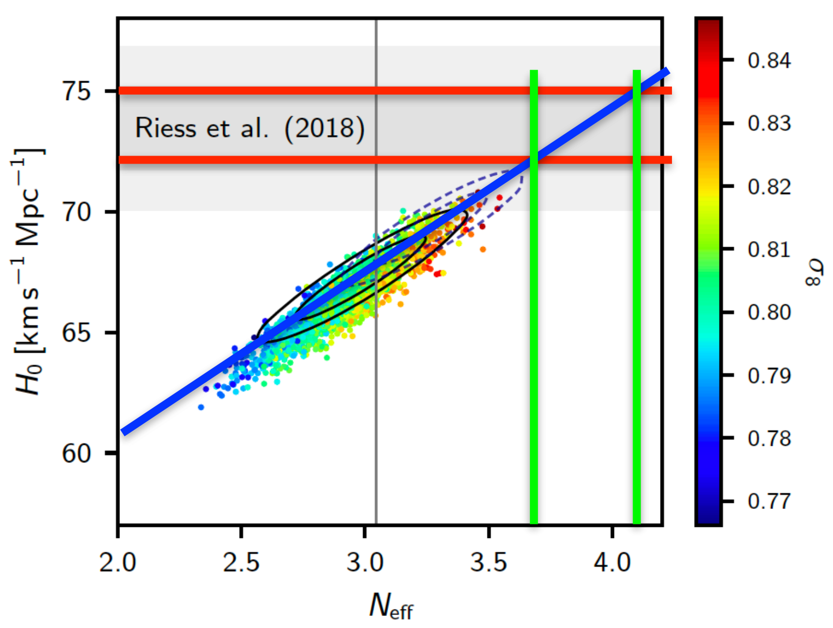
$$N_{\rm eff} = 2.92^{+0.36}_{-0.37} \quad (95\,\%,\ \textit{Planck}\ \text{TT,TE,EE+lowE}),$$

we see that the neutrino effective number is now very well constrained.

H0 passes from 68.0 ± 2.8 km/s/Mpc (2015) to 66.4 ± 1.4 km/s/Mpc (2018), and the tension with R20 increases from 1.7σ to 3.6σ also varying Neff.



Planck collaboration, 2015



Planck collaboration, 2018

Second pillar: Dark Energy

For example, we can consider modifications in the dark energy sector. A classical extension is a varying dark energy equation of state, that is a modification of the expansion history of the universe at late times.

The Dark energy equation of state

Changing the dark energy equation of state w, we are changing the expansion rate of the Universe:

$$H^2 = H_0^2 \Big[\Omega_m (1+z)^3 + \Omega_r (1+z)^4 \\ + \Omega_{\rm de} (1+z)^{3(1+w)} + \Omega_k (1+z)^2\Big]$$

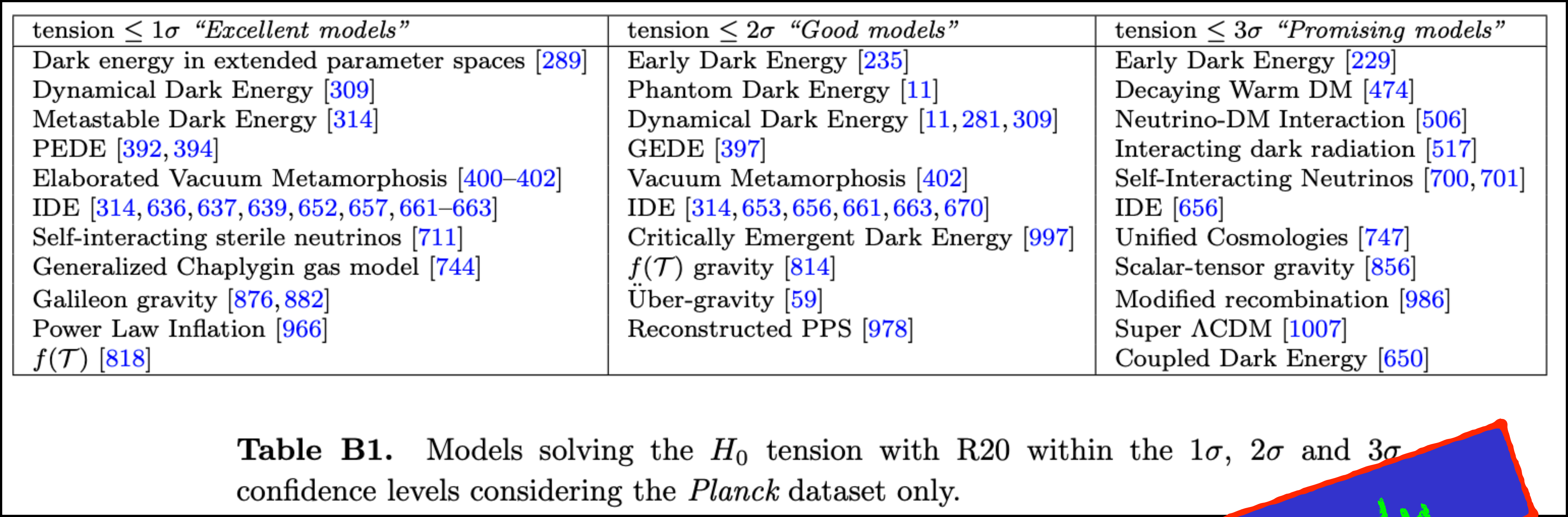
w introduces a geometrical degeneracy with the Hubble constant that will be unconstrained using the CMB data only, resulting in agreement with R20.

We have in 2018 $w = -1.58^{+0.52}_{-0.41}$ with $H0 > 69.9$ km/s/Mpc at 95% c.l.

Planck data prefer a phantom dark energy, with an energy component with $w < -1$, for which the density increases with time in an expanding universe that will end in a Big Rip. A phantom dark energy violates the energy condition $\rho \geq |p|$, that means that the matter could move faster than light and a comoving observer measure a negative energy density, and the Hamiltonian could have vacuum instabilities due to a negative kinetic energy.

Anyway, there exist models that expect an effective energy density with a phantom equation of state without showing the problems before.

Formally successful models in solving H0



tension $\leq 1\sigma$ *"Excellent models"*	tension $\leq 2\sigma$ *"Good models"*	tension $\leq 3\sigma$ *"Promising models"*
Dark energy in extended parameter spaces [289]	Early Dark Energy [235]	Early Dark Energy [229]
Dynamical Dark Energy [309]	Phantom Dark Energy [11]	Decaying Warm DM [474]
Metastable Dark Energy [314]	Dynamical Dark Energy [11, 281, 309]	Neutrino-DM Interaction [506]
PEDE [392, 394]	GEDE [397]	Interacting dark radiation [517]
Elaborated Vacuum Metamorphosis [400–402]	Vacuum Metamorphosis [402]	Self-Interacting Neutrinos [700, 701]
IDE [314, 636, 637, 639, 652, 657, 661–663]	IDE [314, 653, 656, 661, 663, 670]	IDE [656]
Self-interacting sterile neutrinos [711]	Critically Emergent Dark Energy [997]	Unified Cosmologies [747]
Generalized Chaplygin gas model [744]	$f(\mathcal{T})$ gravity [814]	Scalar-tensor gravity [856]
Galileon gravity [876, 882]	Über-gravity [59]	Modified recombination [986]
Power Law Inflation [966]	Reconstructed PPS [978]	Super ΛCDM [1007]
$f(\mathcal{T})$ [818]		Coupled Dark Energy [650]

Table B1. Models solving the H_0 tension with R20 within the 1σ, 2σ and 3σ confidence levels considering the *Planck* dataset only.

Di Valentino et al., Class.Quant.Grav. (2021), arXiv:2103.01183 [astro-ph.CO]

Planck only

Parker Vacuum Metamorphosis

There is a model considered in the early days of dark energy investigations that possesses the phenomenological properties needed to solve the H0 tension, but is based on a sound theoretical foundation: the vacuum metamorphosis model of Parker and Raval, Phys. Rev. D 62, 083503 (2000), Parker and Vanzella, Phys. Rev. D 69, 104009 (2004),

Caldwell, Komp, Parker and Vanzella,Phys. Rev. D 73, 023513 (2006), which has a phase transition in the nature of the vacuum.

Vacuum metamorphosis arises from a nonperturbative summation of quantum gravity loop corrections due to a massive scalar field.

We found that the Parker vacuum metamorphosis model, physically motivated by quantum gravitational effects, with the same number of parameters as LCDM, but not nested with it, can remove the H_0 tension, because can mimic a phantom DE behaviour at low redshifts.

First principles theory

Parker Vacuum Metamorphosis

When the Ricci scalar evolves during cosmic history to reach the scalar field mass squared, then a phase transition occurs and R freezes with

$R = 6(\dot{H} + 2H^2 + ka^{-2}) = m^2$ and defining $M = m^2/(12H_0^2)$

The expansion behaviour above and below the phase transition is

$$H^2/H_0^2 = \Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_k(1+z)^2 + M\left\{1 - \left[3\left(\frac{4}{3\Omega_m}\right)^4 M(1-M-\Omega_k-\Omega_r)^3\right]^{-1}\right\}, \quad z > z_t$$

$$H^2/H_0^2 = (1-M-\Omega_k)(1+z)^4 + \Omega_k(1+z)^2 + M\,, \quad z \leq z_t$$

with

$$z_t = -1 + \frac{3\Omega_m}{4(1-M-\Omega_k-\Omega_r)}$$

We see that above the phase transition, the universe behaves as one with matter (plus radiation plus spatial curvature) plus a constant, and after the phase transition it effectively has a dark radiation component that rapidly redshifts away leaving a de Sitter phase.

Parker Vacuum Metamorphosis

When the Ricci scalar evolves during cosmic history to reach the scalar field mass squared, then a phase transition occurs and R freezes with

$R = 6(\dot{H} + 2H^2 + ka^{-2}) = m^2$ and defining $M = m^2/(12H_0^2)$

The expansion behaviour above and below the phase transition is

$$
\begin{aligned}
H^2/H_0^2 &= \Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_k(1+z)^2 + M\left\{1 - \left[3\left(\frac{4}{3\Omega_m}\right)^4 M(1-M-\Omega_k-\Omega_r)^3\right]^{-1}\right\}, \quad z > z_t \\
H^2/H_0^2 &= (1-M-\Omega_k)(1+z)^4 + \Omega_k(1+z)^2 + M\,, \quad z \le z_t
\end{aligned}
$$

with

$$z_t = -1 + \frac{3\Omega_m}{4(1-M-\Omega_k-\Omega_r)}$$

The original model did not include an explicit high redshift cosmological constant; we see that this implies that

$$\Omega_m = \frac{4}{3}\left[3M(1-M-\Omega_k-\Omega_r)^3\right]^{1/4}$$

i.e the parameter M is fixed depending from the matter density, and this model has the same number of degrees of freedom as ΛCDM.

Parker Vacuum Metamorphosis

When the Ricci scalar evolves during cosmic history to reach the scalar field mass squared, then a phase transition occurs and R freezes with

$R = 6(\dot{H} + 2H^2 + ka^{-2}) = m^2$ and defining $M = m^2/(12H_0^2)$

The expansion behaviour above and below the phase transition is

$$H^2/H_0^2 = \Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_k(1+z)^2 + M\left\{1 - \left[3\left(\frac{4}{3\Omega_m}\right)^4 M(1-M-\Omega_k-\Omega_r)^3\right]^{-1}\right\}, \quad z > z_t$$

$$H^2/H_0^2 = (1-M-\Omega_k)(1+z)^4 + \Omega_k(1+z)^2 + M\,, \quad z \le z_t$$

with

$$z_t = -1 + \frac{3\Omega_m}{4(1-M-\Omega_k-\Omega_r)}$$

However, we can also consider an extended VM where M is an independent parameter. In this case, the massive scalar field has a vacuum expectation value that manifests as a cosmological constant, and these conditions are assumed:

$$\frac{4}{3}(1-M-\Omega_k-\Omega_r) \le \Omega_m \le \frac{4}{3}\left[3M(1-M-\Omega_k-\Omega_r)^3\right]^{1/4}$$

corresponding to

$z_t \ge 0$

$\Omega_{\rm de}(z > z_t) \ge 0$

A Vacuum Phase Transition Solves the H_0 Tension

The effective dark energy equation of state below the phase transition is

$$w(z) = -1 - \frac{1}{3}\frac{3\Omega_m(1+z)^3 - 4(1-M-\Omega_k-\Omega_r)(1+z)^4}{M + (1-M-\Omega_k-\Omega_r)(1+z)^4 - \Omega_m(1+z)^3}$$

The equation of state behaviour is phantom today, and more deeply phantom in the past.

In the case without the cosmological constant there is no DE above the transition.

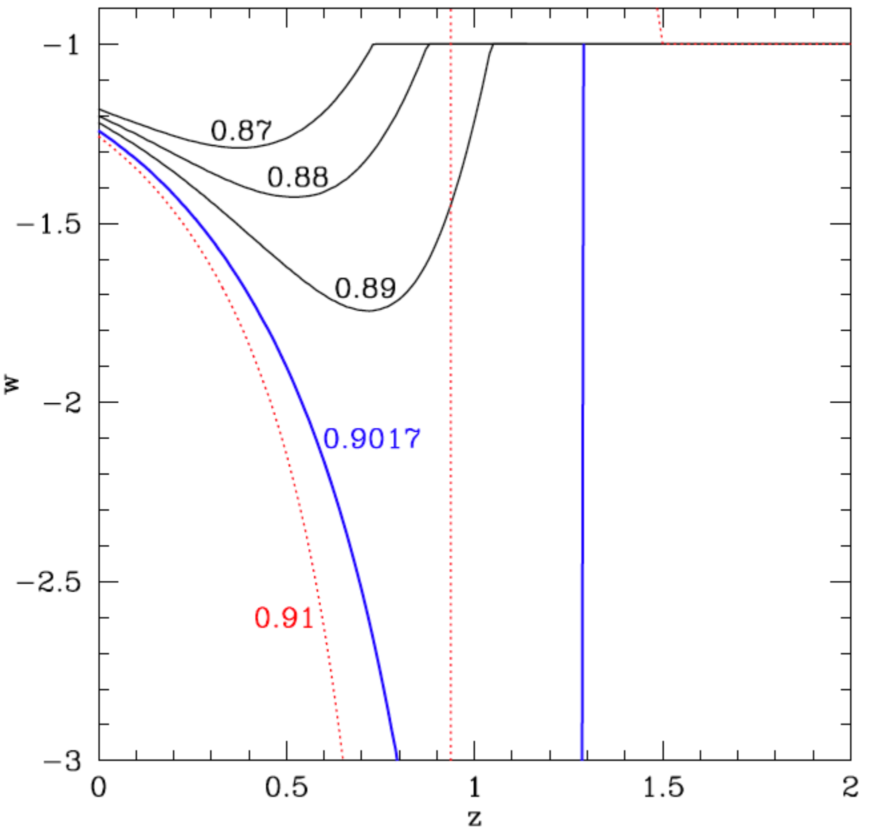
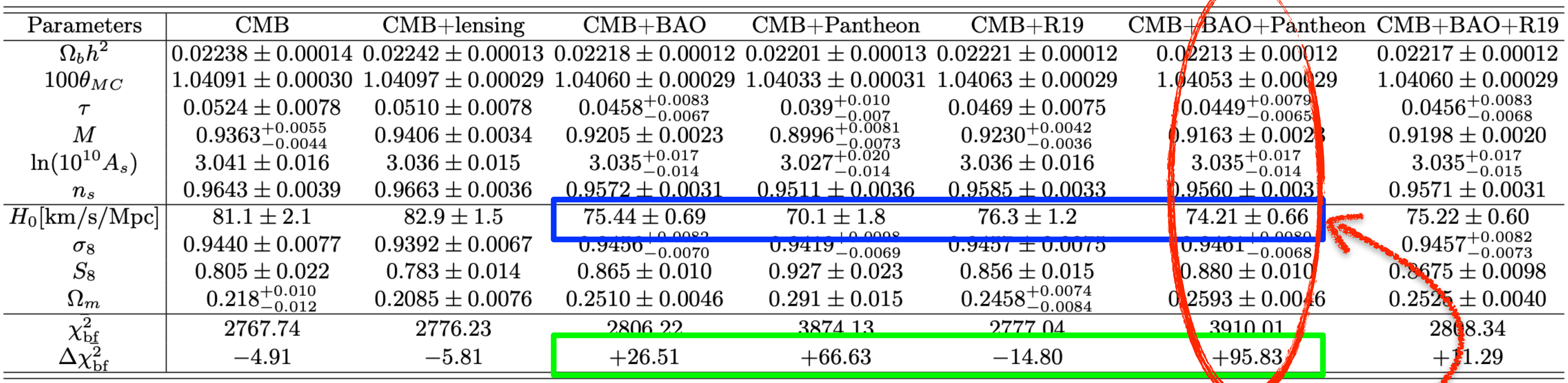


Figure 1. The effective dark energy equation of state evolution is plotted vs redshift for several values of the mass parameter M, for $\Omega_m = 0.3$. The bold blue curve shows the original case (our preferred model) where there is no cosmological constant, while the medium black curves show the elaborated case with an added cosmological constant, and the dotted red curve shows one with a negative cosmological constant (causing w to first shoot up to large positive values before it plummets to highly negative values).

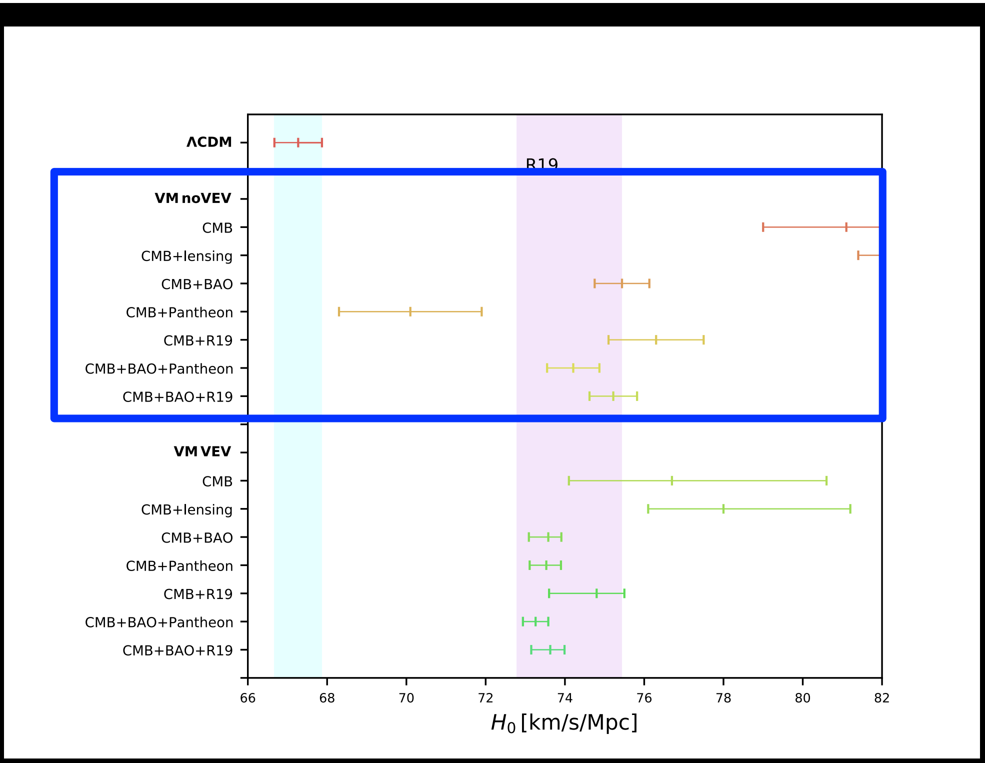
Di Valentino et al., Phys.Rev. D97 (2018) no.4, 043528

Constraints at 68% cl.

A Vacuum Phase Transition Solves the H_0 Tension



Parameters	CMB	CMB+lensing	CMB+BAO	CMB+Pantheon	CMB+R19	CMB+BAO+Pantheon	CMB+BAO+R19
$\Omega_b h^2$	0.02238 ± 0.00014	0.02242 ± 0.00013	0.02218 ± 0.00012	0.02201 ± 0.00013	0.02221 ± 0.00012	0.02213 ± 0.00012	0.02217 ± 0.00012
$100\theta_{MC}$	1.04091 ± 0.00030	1.04097 ± 0.00029	1.04060 ± 0.00029	1.04033 ± 0.00031	1.04063 ± 0.00029	1.04053 ± 0.00029	1.04060 ± 0.00029
τ	0.0524 ± 0.0078	0.0510 ± 0.0078	$0.0458^{+0.0083}_{-0.0067}$	$0.039^{+0.010}_{-0.007}$	0.0469 ± 0.0075	$0.0449^{+0.0079}_{-0.0065}$	$0.0456^{+0.0083}_{-0.0068}$
M	$0.9363^{+0.0055}_{-0.0044}$	0.9406 ± 0.0034	0.9205 ± 0.0023	$0.8996^{+0.0081}_{-0.0073}$	$0.9230^{+0.0042}_{-0.0036}$	0.9163 ± 0.0023	0.9198 ± 0.0020
$\ln(10^{10} A_s)$	3.041 ± 0.016	3.036 ± 0.015	$3.035^{+0.017}_{-0.014}$	$3.027^{+0.020}_{-0.014}$	3.036 ± 0.016	$3.035^{+0.017}_{-0.014}$	$3.035^{+0.017}_{-0.015}$
n_s	0.9643 ± 0.0039	0.9663 ± 0.0036	0.9572 ± 0.0031	0.9511 ± 0.0036	0.9585 ± 0.0033	0.9560 ± 0.0031	0.9571 ± 0.0031
H_0[km/s/Mpc]	81.1 ± 2.1	82.9 ± 1.5	75.44 ± 0.69	70.1 ± 1.8	76.3 ± 1.2	74.21 ± 0.66	75.22 ± 0.60
σ_8	0.9440 ± 0.0077	0.9392 ± 0.0067	$0.9456^{+0.0082}_{-0.0070}$	$0.9419^{+0.0098}_{-0.0069}$	0.9457 ± 0.0075	$0.9461^{+0.0080}_{-0.0068}$	$0.9457^{+0.0082}_{-0.0073}$
S_8	0.805 ± 0.022	0.783 ± 0.014	0.865 ± 0.010	0.927 ± 0.023	0.856 ± 0.015	0.880 ± 0.010	0.8675 ± 0.0098
Ω_m	$0.218^{+0.010}_{-0.012}$	0.2085 ± 0.0076	0.2510 ± 0.0046	0.291 ± 0.015	$0.2458^{+0.0074}_{-0.0084}$	0.2593 ± 0.0046	0.2525 ± 0.0040
$\chi^2_{\rm bf}$	2767.74	2776.23	2806.22	3874.13	2777.04	3910.01	2808.34
$\Delta\chi^2_{\rm bf}$	−4.91	−5.81	+26.51	+66.63	−14.80	+95.83	+11.29



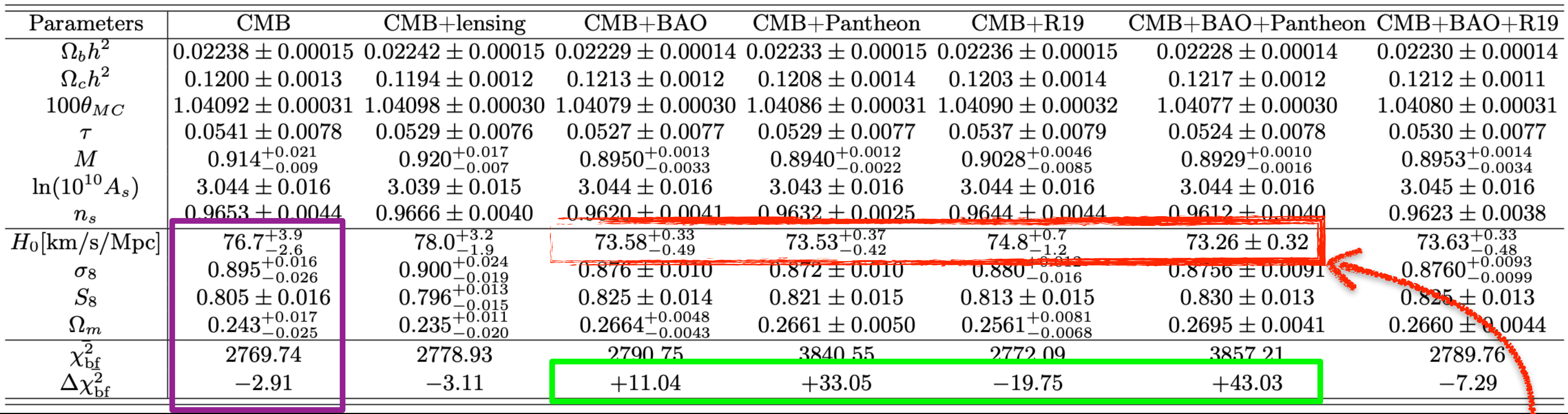
We dont solve the tension,
we do obtain H0~74 km/s/Mpc !!

H0 is exactly in agreement with R19 even if BAO and Pantheon are included. However, this worsen considerably the fit of the data because the model fails in recover the shape of H(z) at low redshifts.

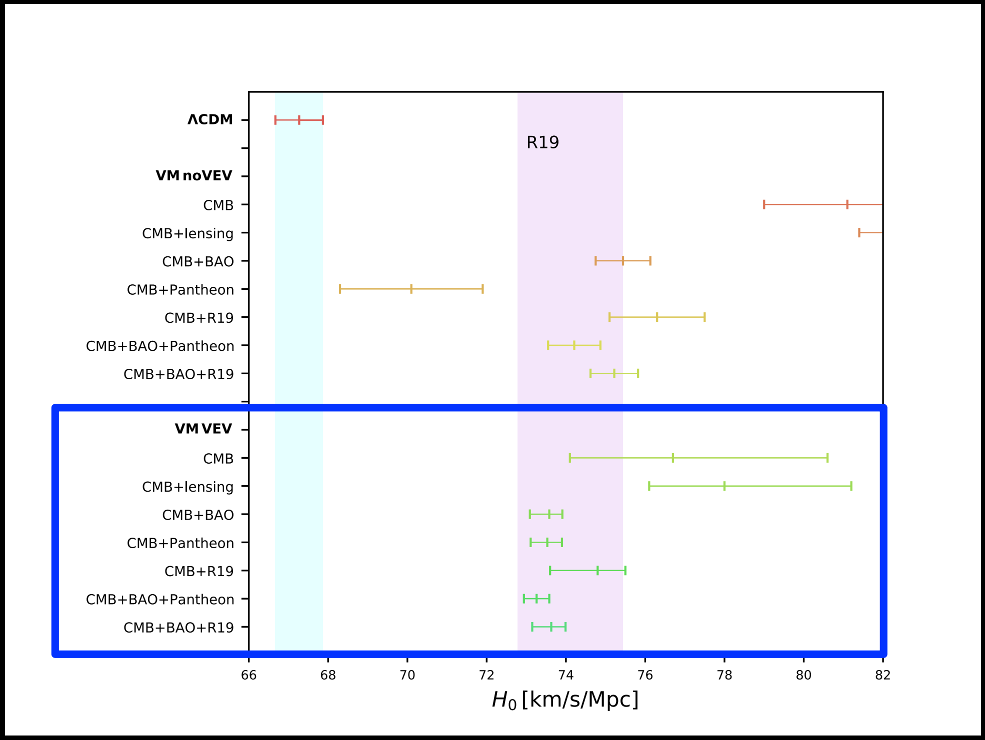
Di Valentino et al., Phys.Dark Univ. 30 (2020) 100733

Constraints at 68% cl.

A Vacuum Phase Transition Solves the H_0 Tension



Parameters	CMB	CMB+lensing	CMB+BAO	CMB+Pantheon	CMB+R19	CMB+BAO+Pantheon	CMB+BAO+R19
$\Omega_b h^2$	0.02238 ± 0.00015	0.02242 ± 0.00015	0.02229 ± 0.00014	0.02233 ± 0.00015	0.02236 ± 0.00015	0.02228 ± 0.00014	0.02230 ± 0.00014
$\Omega_c h^2$	0.1200 ± 0.0013	0.1194 ± 0.0012	0.1213 ± 0.0012	0.1208 ± 0.0014	0.1203 ± 0.0014	0.1217 ± 0.0012	0.1212 ± 0.0011
$100\theta_{MC}$	1.04092 ± 0.00031	1.04098 ± 0.00030	1.04079 ± 0.00030	1.04086 ± 0.00031	1.04090 ± 0.00032	1.04077 ± 0.00030	1.04080 ± 0.00031
τ	0.0541 ± 0.0078	0.0529 ± 0.0076	0.0527 ± 0.0077	0.0529 ± 0.0077	0.0537 ± 0.0079	0.0524 ± 0.0078	0.0530 ± 0.0077
M	$0.914^{+0.021}_{-0.009}$	$0.920^{+0.017}_{-0.007}$	$0.8950^{+0.0013}_{-0.0033}$	$0.8940^{+0.0012}_{-0.0022}$	$0.9028^{+0.0046}_{-0.0085}$	$0.8929^{+0.0010}_{-0.0016}$	$0.8953^{+0.0014}_{-0.0034}$
$\ln(10^{10}A_s)$	3.044 ± 0.016	3.039 ± 0.015	3.044 ± 0.016	3.043 ± 0.016	3.044 ± 0.016	3.044 ± 0.016	3.045 ± 0.016
n_s	0.9653 ± 0.0044	0.9666 ± 0.0040	0.9620 ± 0.0041	0.9632 ± 0.0025	0.9644 ± 0.0044	0.9612 ± 0.0040	0.9623 ± 0.0038
H_0[km/s/Mpc]	$76.7^{+3.9}_{-2.6}$	$78.0^{+3.2}_{-1.9}$	$73.58^{+0.33}_{-0.49}$	$73.53^{+0.37}_{-0.42}$	$74.8^{+0.7}_{-1.2}$	73.26 ± 0.32	$73.63^{+0.33}_{-0.48}$
σ_8	$0.895^{+0.016}_{-0.026}$	$0.900^{+0.024}_{-0.019}$	0.876 ± 0.010	0.872 ± 0.010	$0.880^{+0.012}_{-0.016}$	0.8756 ± 0.0091	$0.8760^{+0.0093}_{-0.0099}$
S_8	0.805 ± 0.016	$0.796^{+0.013}_{-0.015}$	0.825 ± 0.014	0.821 ± 0.015	0.813 ± 0.015	0.830 ± 0.013	0.825 ± 0.013
Ω_m	$0.243^{+0.017}_{-0.025}$	$0.235^{+0.011}_{-0.020}$	$0.2664^{+0.0048}_{-0.0043}$	0.2661 ± 0.0050	$0.2561^{+0.0081}_{-0.0068}$	0.2695 ± 0.0041	0.2660 ± 0.0044
$\chi^2_{\rm bf}$	2769.74	2778.93	2790.75	3840.55	2772.09	3857.21	2789.76
$\Delta\chi^2_{\rm bf}$	-2.91	-3.11	$+11.04$	$+33.05$	-19.75	$+43.03$	-7.29



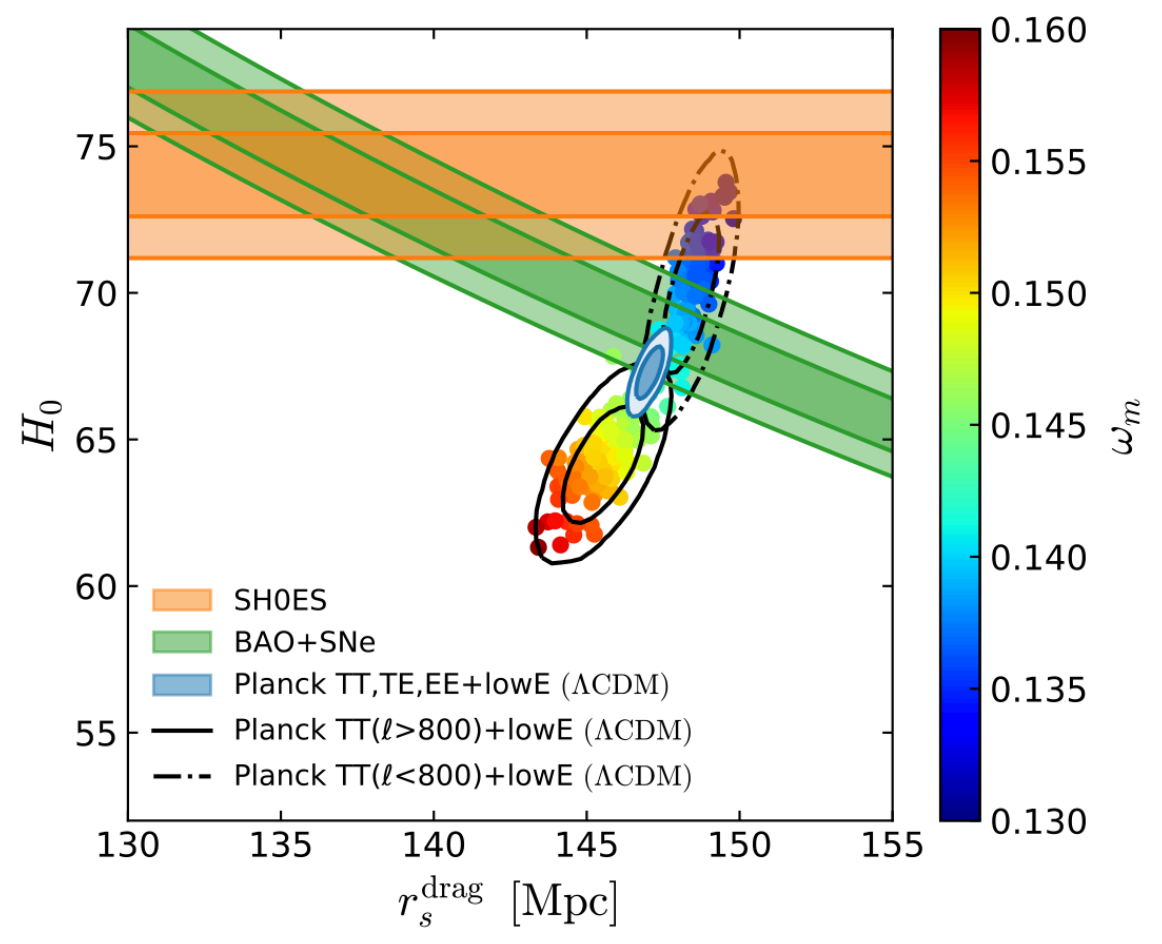
And a more ad hoc VM model that includes a cosmological constant, i.e. allowing the vacuum criticality parameter M to float, is even better.

For all the dataset combinations H0~74 km/s/Mpc !!

Di Valentino et al., Phys.Dark Univ. 30 (2020) 100733

The sound horizon problem

BAO measurements constrain the product of H0 and the sound horizon r_s .
In order to have a larger H0 value in agreement with R19,
we need r_s near 137 Mpc.
However, Planck by assuming ΛCDM, prefers r_s near 147 Mpc.
Therefore, a cosmological solution that can increase H0 and at the same time can lower the sound horizon inferred from CMB data it is promising to put in agreement all the measurements.



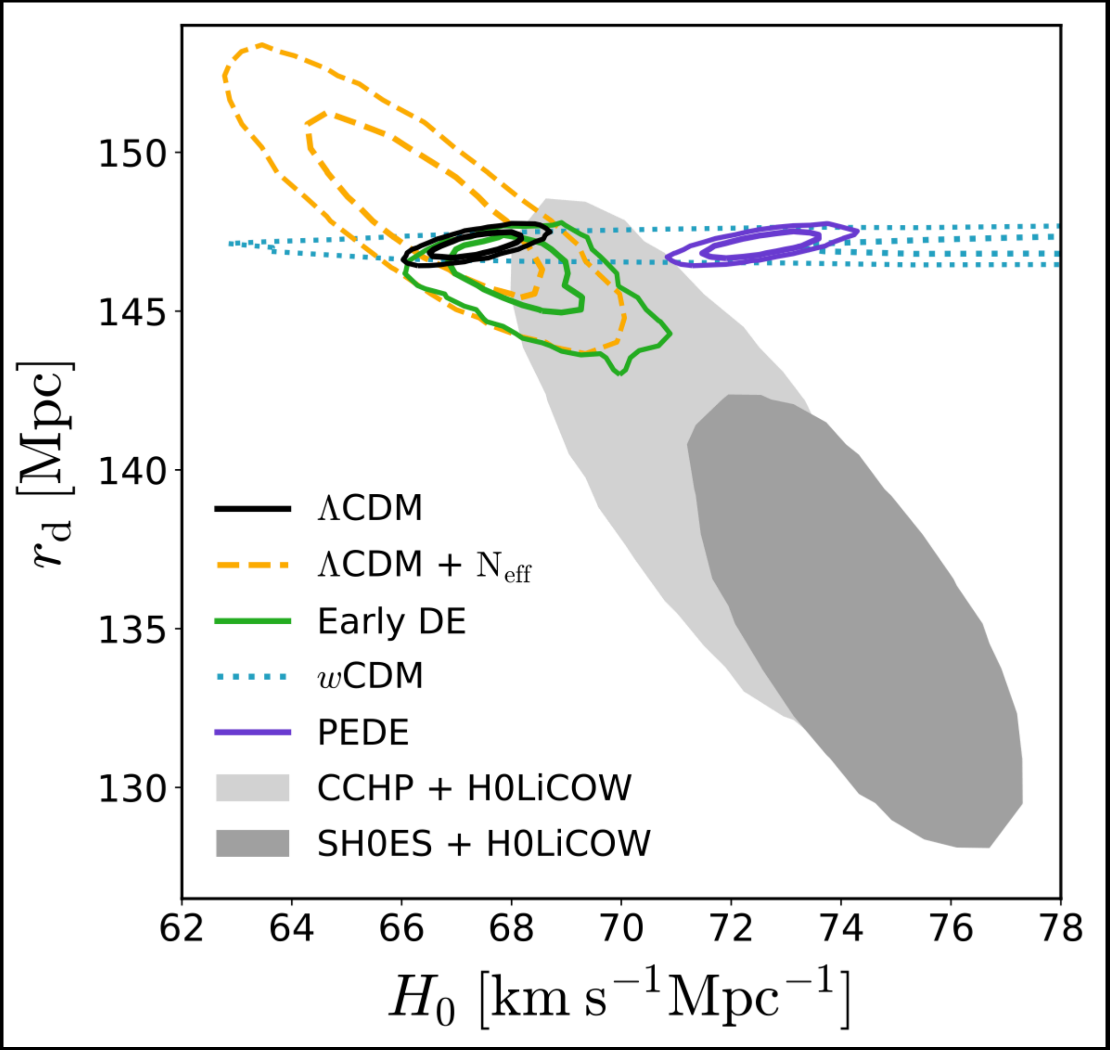
Knox and Millea, *Phys.Rev.D* 101 (2020) 4, 043533

Early vs late time solutions

Here we can see the comparison of the 2σ credibility regions of the CMB constraints and the measurements from late-time observations (SN + BAO + H0LiCOW + SH0ES).

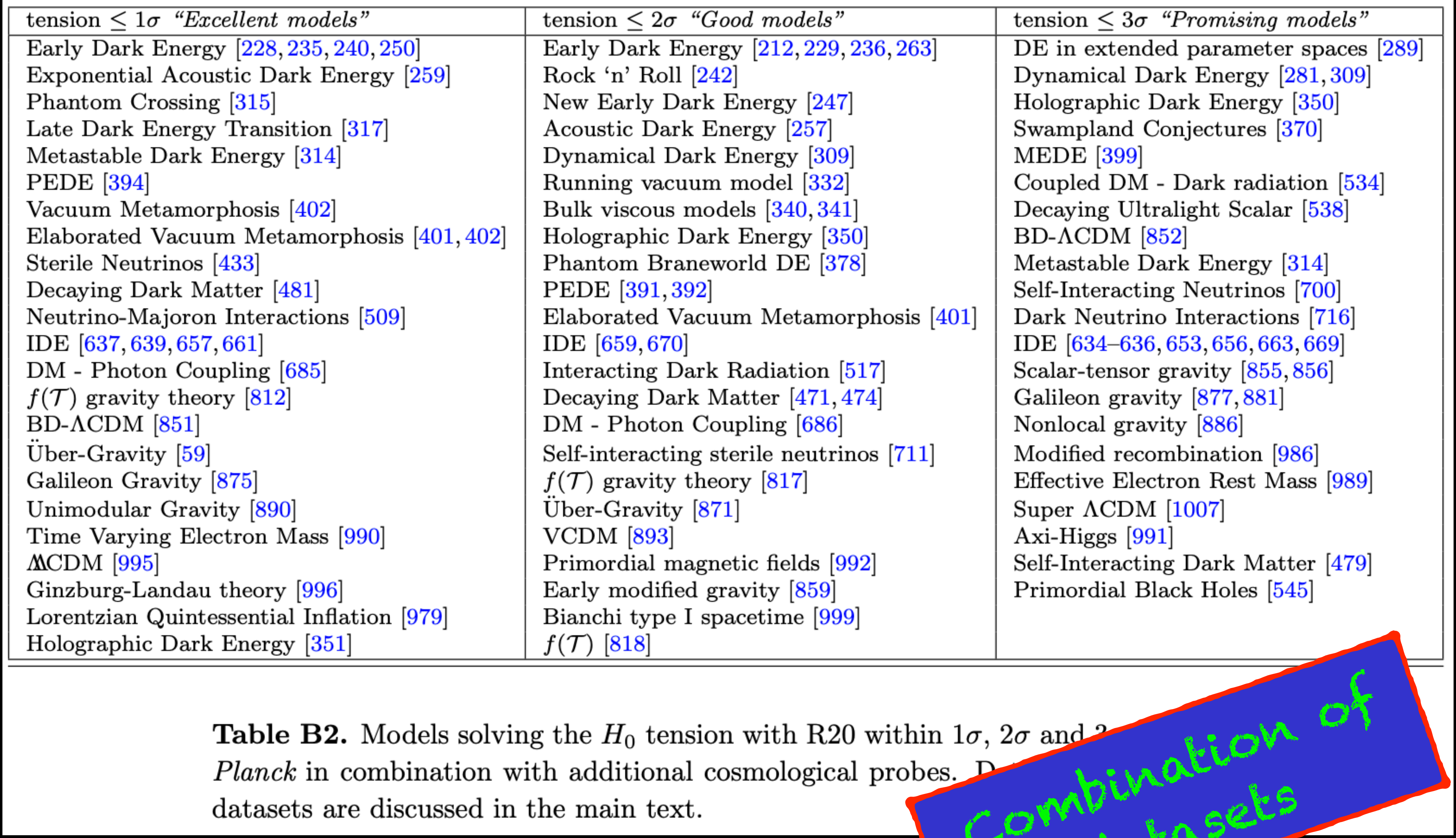
We see that the late time solutions, as wCDM, increase H0 but leave r_s unaltered.

However, the early time solutions, as Neff or Early Dark Energy, move in the right direction both the parameters, but can't solve completely the H0 tension with R19.



Arendse et al., Astron.Astrophys. 639 (2020) A57

Formally successful models in solving H0



tension $\leq 1\sigma$ *"Excellent models"*	tension $\leq 2\sigma$ *"Good models"*	tension $\leq 3\sigma$ *"Promising models"*
Early Dark Energy [228, 235, 240, 250]	Early Dark Energy [212, 229, 236, 263]	DE in extended parameter spaces [289]
Exponential Acoustic Dark Energy [259]	Rock 'n' Roll [242]	Dynamical Dark Energy [281, 309]
Phantom Crossing [315]	New Early Dark Energy [247]	Holographic Dark Energy [350]
Late Dark Energy Transition [317]	Acoustic Dark Energy [257]	Swampland Conjectures [370]
Metastable Dark Energy [314]	Dynamical Dark Energy [309]	MEDE [399]
PEDE [394]	Running vacuum model [332]	Coupled DM - Dark radiation [534]
Vacuum Metamorphosis [402]	Bulk viscous models [340, 341]	Decaying Ultralight Scalar [538]
Elaborated Vacuum Metamorphosis [401, 402]	Holographic Dark Energy [350]	BD-ΛCDM [852]
Sterile Neutrinos [433]	Phantom Braneworld DE [378]	Metastable Dark Energy [314]
Decaying Dark Matter [481]	PEDE [391, 392]	Self-Interacting Neutrinos [700]
Neutrino-Majoron Interactions [509]	Elaborated Vacuum Metamorphosis [401]	Dark Neutrino Interactions [716]
IDE [637, 639, 657, 661]	IDE [659, 670]	IDE [634–636, 653, 656, 663, 669]
DM - Photon Coupling [685]	Interacting Dark Radiation [517]	Scalar-tensor gravity [855, 856]
$f(\mathcal{T})$ gravity theory [812]	Decaying Dark Matter [471, 474]	Galileon gravity [877, 881]
BD-ΛCDM [851]	DM - Photon Coupling [686]	Nonlocal gravity [886]
Über-Gravity [59]	Self-interacting sterile neutrinos [711]	Modified recombination [986]
Galileon Gravity [875]	$f(\mathcal{T})$ gravity theory [817]	Effective Electron Rest Mass [989]
Unimodular Gravity [890]	Über-Gravity [871]	Super ΛCDM [1007]
Time Varying Electron Mass [990]	VCDM [893]	Axi-Higgs [991]
$\Lambda\!\!\!\Lambda$CDM [995]	Primordial magnetic fields [992]	Self-Interacting Dark Matter [479]
Ginzburg-Landau theory [996]	Early modified gravity [859]	Primordial Black Holes [545]
Lorentzian Quintessential Inflation [979]	Bianchi type I spacetime [999]	
Holographic Dark Energy [351]	$f(\mathcal{T})$ [818]	

Table B2. Models solving the H_0 tension with R20 within 1σ, 2σ and
Planck in combination with additional cosmological probes.
datasets are discussed in the main text.

Combination of datasets

Di Valentino et al., Class.Quant.Grav. (2021), arXiv:2103.01183 [astro-ph.CO]

IDE can solve the H0 tension

In the standard cosmological framework, the dark matter is assumed to be collisionless. In practice this means that one arbitrarily sets the dark matter interactions to zero when predicting the angular power spectrum of the CMB.

In particular, dark matter and dark energy are described as separate fluids not sharing interactions beyond gravitational ones. However, from a microphysical perspective it is hard to imagine how non-gravitational DM-DE interactions can be avoided, unless forbidden by a fundamental symmetry. This has motivated a large number of studies based on models where DM and DE share interactions other than gravitational.

IDE can solve the H0 tension

At the background level, the conservation equations for the pressureless DM and DE components can be decoupled into two separate equations with an inclusion of an arbitrary function, Q, known as the coupling or interacting function:

$$\begin{aligned} \dot{\rho}_c + 3\mathcal{H}\rho_c &= Q\,, \\ \dot{\rho}_x + 3\mathcal{H}(1+w)\rho_x &= -Q\,, \end{aligned}$$

and we assume the phenomenological form for the interaction rate:

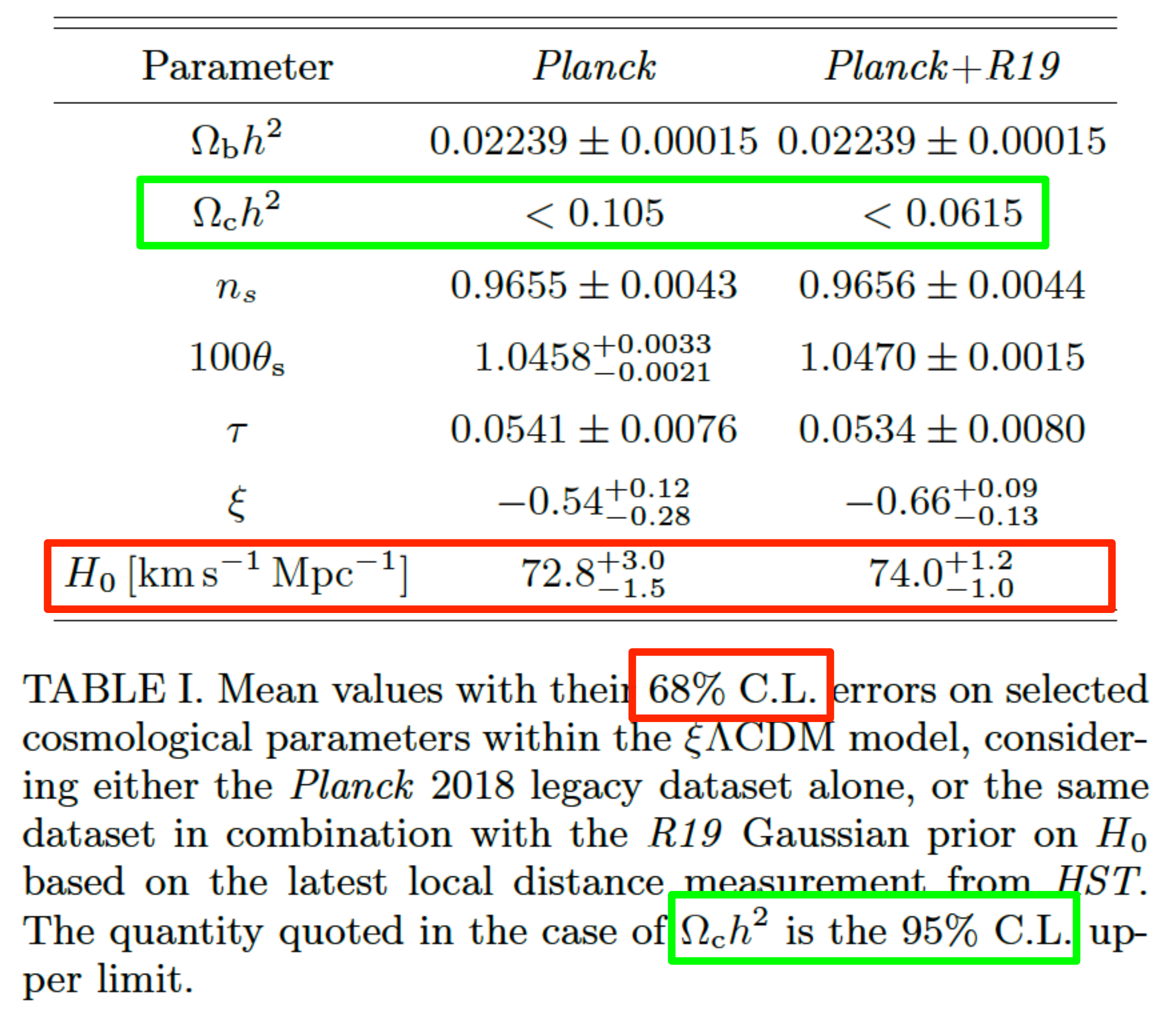
$$Q = \xi \mathcal{H} \rho_x$$

proportional to the dark energy density ρ_x and the conformal Hubble rate $\mathcal{H}$, via a negative dimensionless parameter ξ quantifying the strength of the coupling, to avoid early-time instabilities.

Gavela et al. J. Cosmol. Astropart. Phys. 07 (2009) 034

IDE can solve the H0 tension

In this scenario of IDE the tension on H0 between the Planck satellite and R19 is completely solved. The coupling could affect the value of the present matter energy density Ω_m. Therefore, if within an interacting model Ω_m is smaller (because for negative ξ the dark matter density will decay into the dark energy one), a larger value of H0 would be required in order to satisfy the peaks structure of CMB observations, which accurately determine the value of $\Omega_m h^2$.



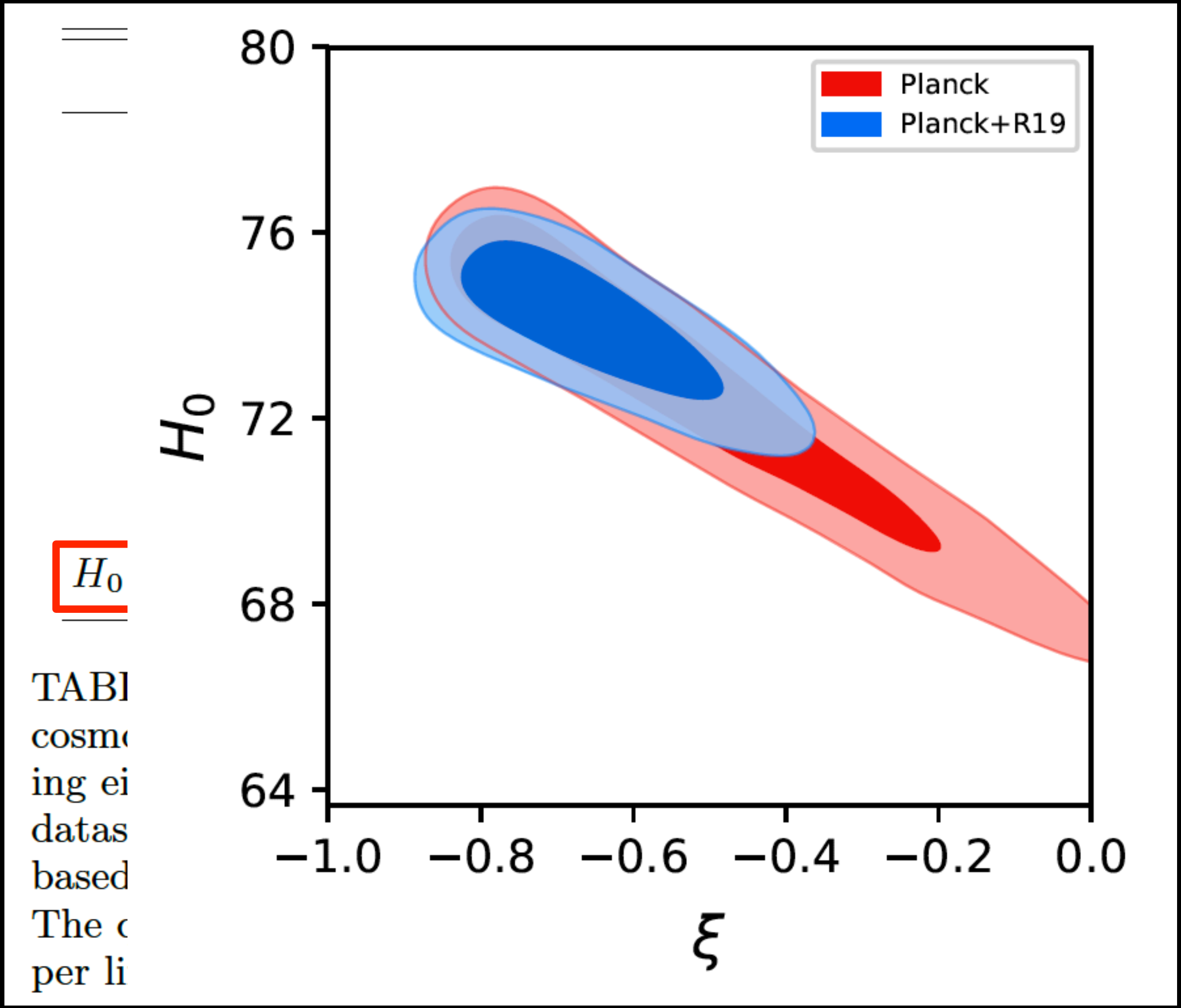
Parameter	*Planck*	*Planck*+*R19*
$\Omega_b h^2$	0.02239 ± 0.00015	0.02239 ± 0.00015
$\Omega_c h^2$	< 0.105	< 0.0615
n_s	0.9655 ± 0.0043	0.9656 ± 0.0044
$100\theta_s$	$1.0458^{+0.0033}_{-0.0021}$	1.0470 ± 0.0015
τ	0.0541 ± 0.0076	0.0534 ± 0.0080
ξ	$-0.54^{+0.12}_{-0.28}$	$-0.66^{+0.09}_{-0.13}$
$H_0\,[\mathrm{km\,s^{-1}\,Mpc^{-1}}]$	$72.8^{+3.0}_{-1.5}$	$74.0^{+1.2}_{-1.0}$

TABLE I. Mean values with their 68% C.L. errors on selected cosmological parameters within the $\xi\Lambda$CDM model, considering either the *Planck* 2018 legacy dataset alone, or the same dataset in combination with the *R19* Gaussian prior on H_0 based on the latest local distance measurement from *HST*. The quantity quoted in the case of $\Omega_c h^2$ is the 95% C.L. upper limit.

Di Valentino et al., Phys.Dark Univ. 30 (2020) 100666

IDE can solve the H0 tension

Therefore we can safely combine the two datasets together, and we obtain a non-zero dark matter-dark energy coupling ξ at more than FIVE standard deviations.



Di Valentino et al., Phys.Dark Univ. 30 (2020) 100666

IDE is in agreement with the near universe

Within interacting cosmologies the growth of dark matter perturbations will be larger than in uncoupled models.

This feature will be general for models with negative coupling and in which the energy exchange among the dark sectors is proportional to ρ_X,

due to a suppression of the friction term and an enhancement of the source term in the differential growth equation.

arXiv.org > astro-ph > arXiv:0905.0492

Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 5 May 2009 (v1), last revised 24 Jun 2009 (this version, v2)]

The Growth of Structure in Interacting Dark Energy Models

Gabriela Caldera-Cabral, Roy Maartens, Bjoern Malte Schaefer

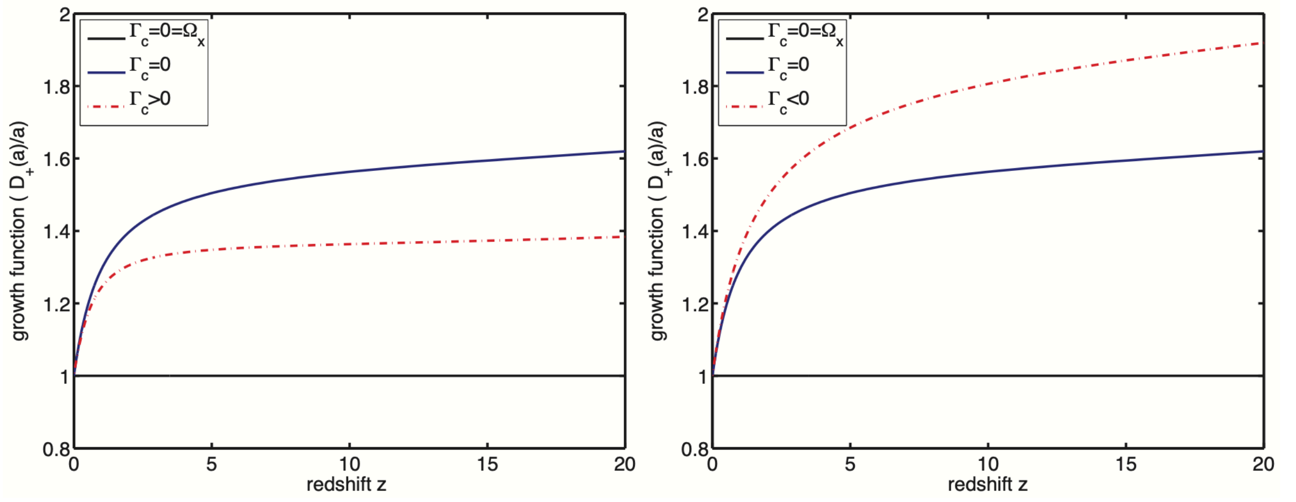
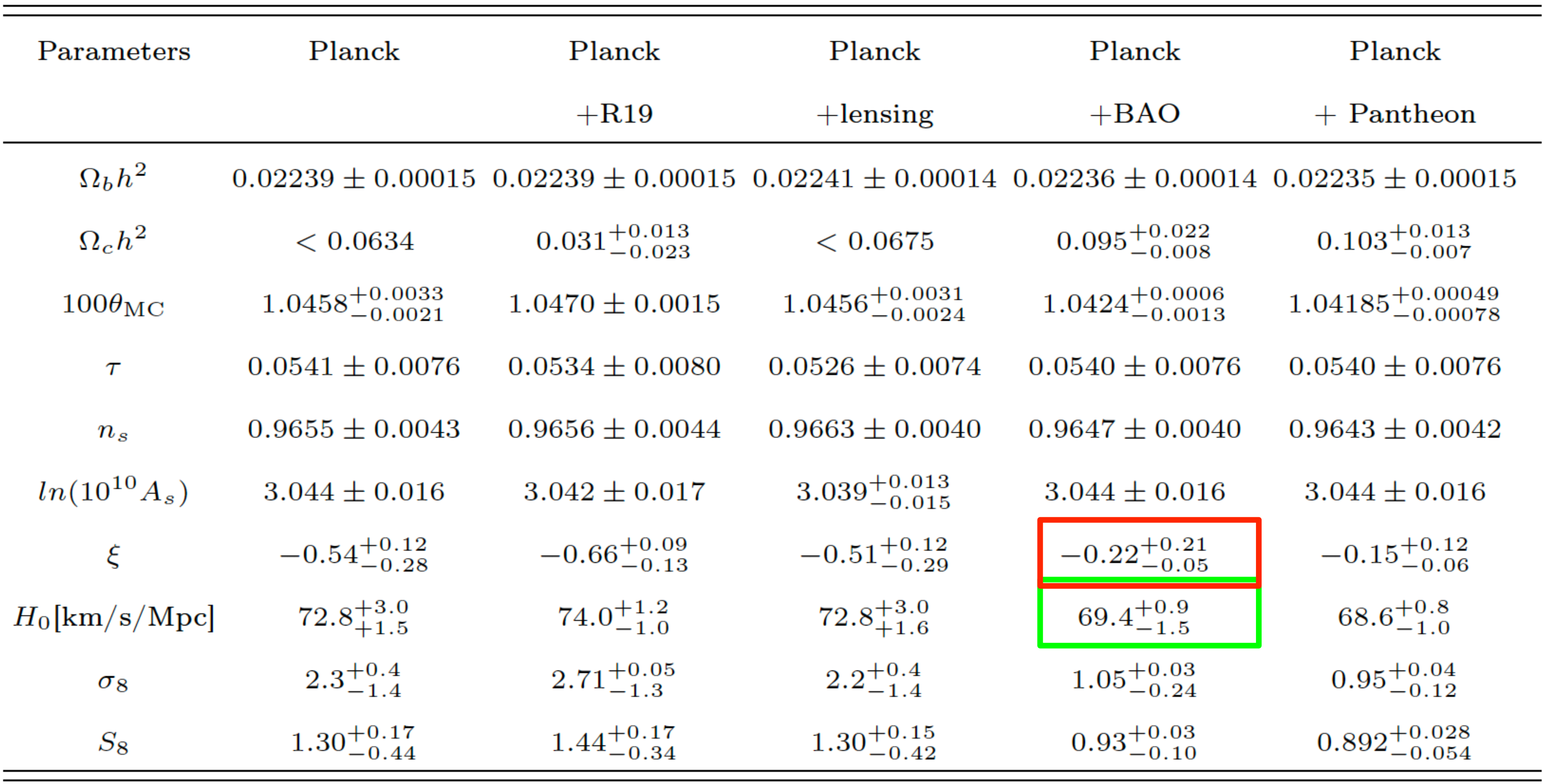


FIG. 2: Linear growth function $D_+ = \delta_c/\delta_{c0}$, normalized to today's value, relative to its value in a pure-matter model ($D_+ = a$). The interacting models (dashed-dotted lines), with $\Gamma_c = \pm 0.3 H_0$, are shown in comparison to non-interacting models (solid lines).

Constraints at 68% cl

IDE can solve the H0 tension

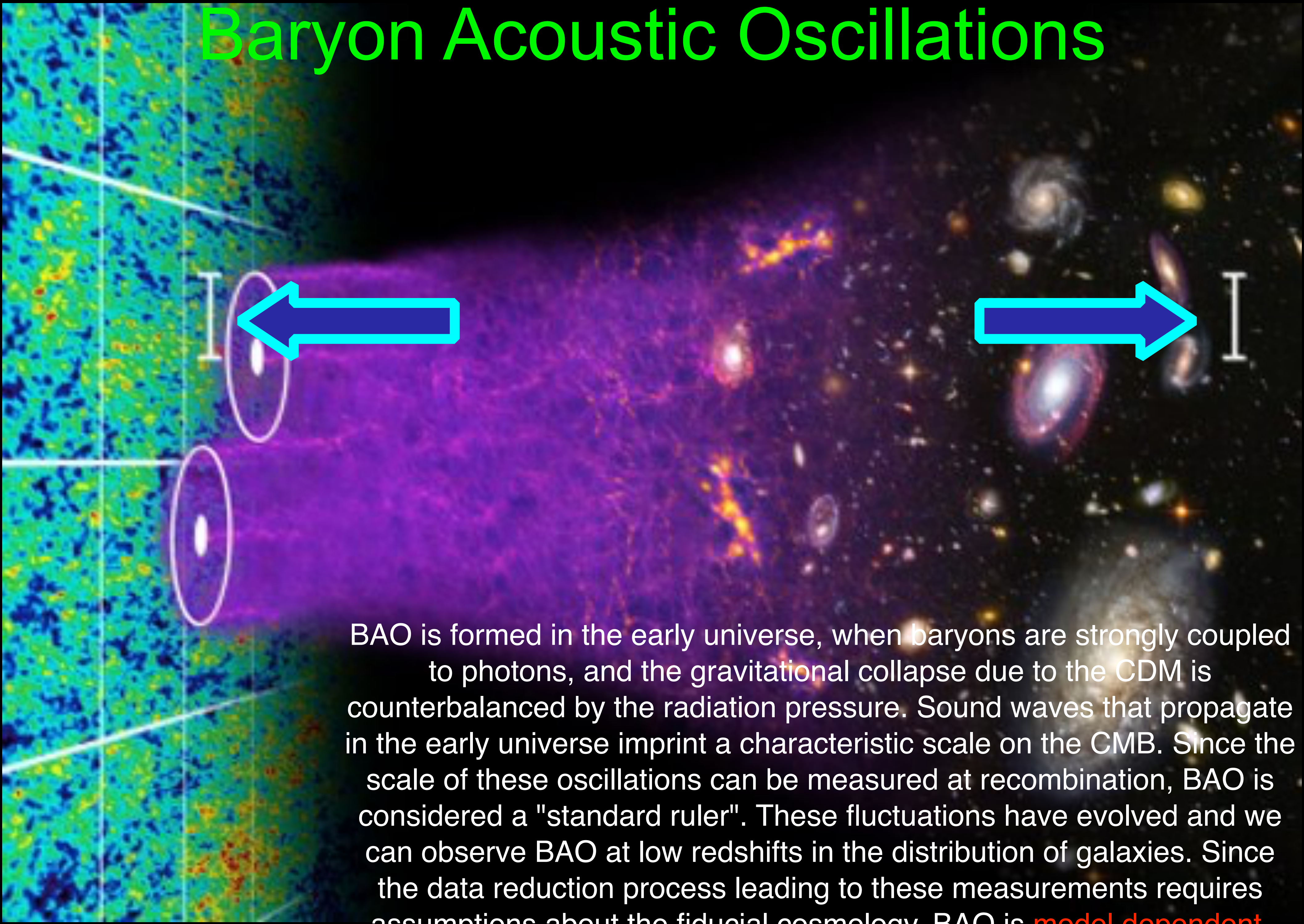


Parameters	Planck	Planck +R19	Planck +lensing	Planck +BAO	Planck + Pantheon
$\Omega_b h^2$	0.02239 ± 0.00015	0.02239 ± 0.00015	0.02241 ± 0.00014	0.02236 ± 0.00014	0.02235 ± 0.00015
$\Omega_c h^2$	< 0.0634	$0.031^{+0.013}_{-0.023}$	< 0.0675	$0.095^{+0.022}_{-0.008}$	$0.103^{+0.013}_{-0.007}$
$100\theta_{\rm MC}$	$1.0458^{+0.0033}_{-0.0021}$	1.0470 ± 0.0015	$1.0456^{+0.0031}_{-0.0024}$	$1.0424^{+0.0006}_{-0.0013}$	$1.04185^{+0.00049}_{-0.00078}$
τ	0.0541 ± 0.0076	0.0534 ± 0.0080	0.0526 ± 0.0074	0.0540 ± 0.0076	0.0540 ± 0.0076
n_s	0.9655 ± 0.0043	0.9656 ± 0.0044	0.9663 ± 0.0040	0.9647 ± 0.0040	0.9643 ± 0.0042
$ln(10^{10}A_s)$	3.044 ± 0.016	3.042 ± 0.017	$3.039^{+0.013}_{-0.015}$	3.044 ± 0.016	3.044 ± 0.016
ξ	$-0.54^{+0.12}_{-0.28}$	$-0.66^{+0.09}_{-0.13}$	$-0.51^{+0.12}_{-0.29}$	$-0.22^{+0.21}_{-0.05}$	$-0.15^{+0.12}_{-0.06}$
H_0[km/s/Mpc]	$72.8^{+3.0}_{+1.5}$	$74.0^{+1.2}_{-1.0}$	$72.8^{+3.0}_{+1.6}$	$69.4^{+0.9}_{-1.5}$	$68.6^{+0.8}_{-1.0}$
σ_8	$2.3^{+0.4}_{-1.4}$	$2.71^{+0.05}_{-1.3}$	$2.2^{+0.4}_{-1.4}$	$1.05^{+0.03}_{-0.24}$	$0.95^{+0.04}_{-0.12}$
S_8	$1.30^{+0.17}_{-0.44}$	$1.44^{+0.17}_{-0.34}$	$1.30^{+0.15}_{-0.42}$	$0.93^{+0.03}_{-0.10}$	$0.892^{+0.028}_{-0.054}$

The addition of low-redshift measurements, as BAO data, still hints to the presence of a coupling, albeit at a lower statistical significance. Also for this data sets the Hubble constant values is larger than that obtained in the case of a pure LCDM scenario, enough to bring the H0 tension at 2.4σ.

Di Valentino et al., *Phys.Rev.D* 101 (2020) 6, 063502

Baryon Acoustic Oscillations



BAO is formed in the early universe, when baryons are strongly coupled to photons, and the gravitational collapse due to the CDM is counterbalanced by the radiation pressure. Sound waves that propagate in the early universe imprint a characteristic scale on the CMB. Since the scale of these oscillations can be measured at recombination, BAO is considered a "standard ruler". These fluctuations have evolved and we can observe BAO at low redshifts in the distribution of galaxies. Since the data reduction process leading to these measurements requires assumptions about the fiducial cosmology, BAO is model dependent.

IDE can solve the H0 tension

In other words, the tension between Planck+BAO and R19 could be due to a statistical fluctuation in this case.

Moreover, BAO data is extracted under the assumption of LCDM, and the modified scenario of interacting dark energy could affect the result.
In fact, the full procedure which leads to the BAO constraints carried out by the different collaborations might be not necessarily valid in extended DE models.
For instance, the BOSS collaboration advises caution when using their BAO measurements (both the pre- and post- reconstruction measurements) in more exotic dark energy cosmologies.

BAO constraints themselves might need to be revised in a non-trivial manner when applied to constrain extended dark energy cosmologies.

Di Valentino et al., *Phys.Rev.D* 101 (2020) 6, 063502

Third pillar: Inflation

For example, we can consider modifications
in the inflationary sector.
Is the simple Harrison-Zel’dovich model able to solve
the Hubble tension, or is there support for a more
complicated perturbation spectrum?

Harrison-Zel’dovich spectrum

The inflationary theory predicts that the primordial spectrum should be a power law with a value of the spectral index to be nearly one,
ns ~ 1, reflecting the constancy of the Hubble horizon during inflation, but at the same time not exactly one, due to the dynamics of the inflaton field.

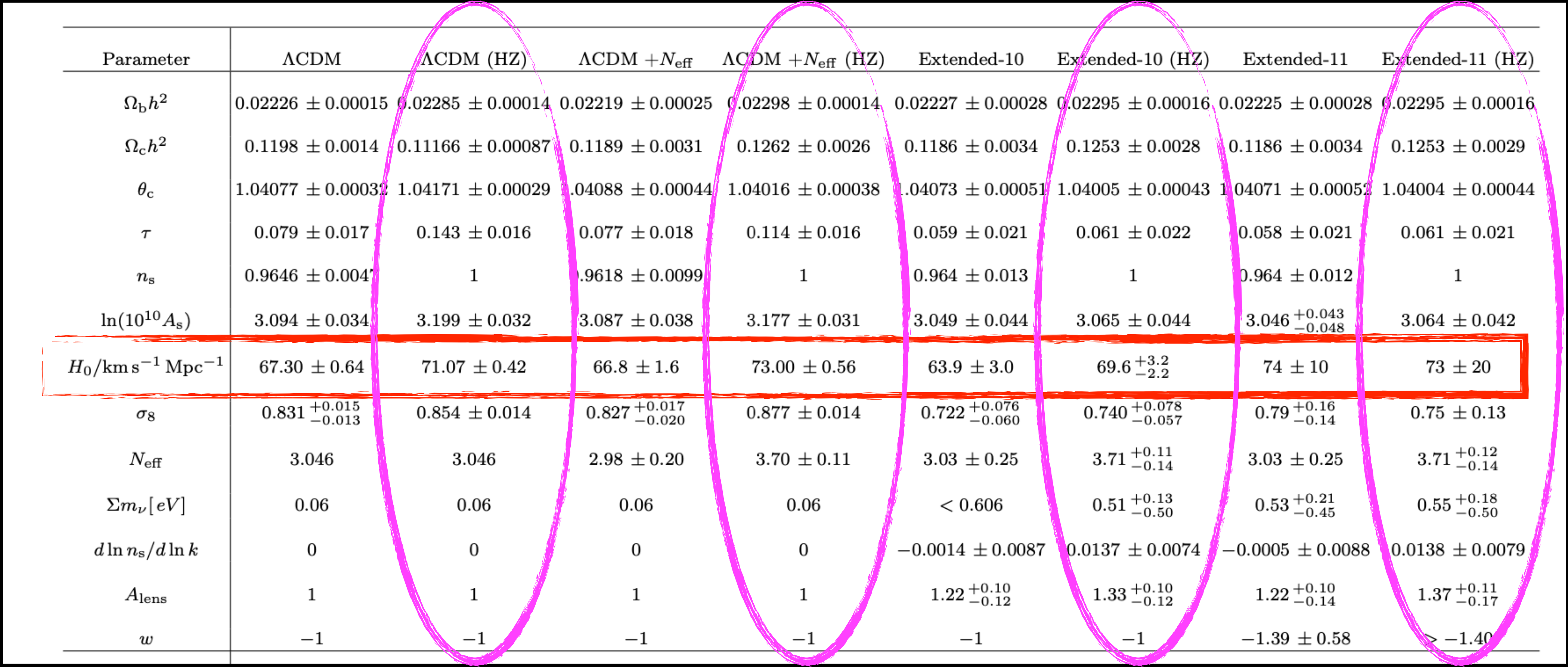
An exact value of ns = 1 is indeed not expected in inflation and would coincide with the phenomenological model proposed by
Harrison, Zel’dovich, Peebles, and Yu, known as
Harrison - Zel’dovich (HZ) spectrum,
proposed well before the formulation of inflation, and corresponding to perfect scale-invariance of the fluctuations.
This model has one parameter fewer than standard ΛCDM,
and it is therefore less complicated (from the point of view of the number of parameters).

While it is still possible to have inflationary models with spectral index nearly identical to HZ, a measurement of ns close to, but different from, one should be considered as a further corroboration of inflation.

Constraints at 68% cl.

Harrison-Zel’dovich spectrum

The presence of the Hubble tension in current cosmological data does not let to rule out a HZ spectrum at high statistical significance.



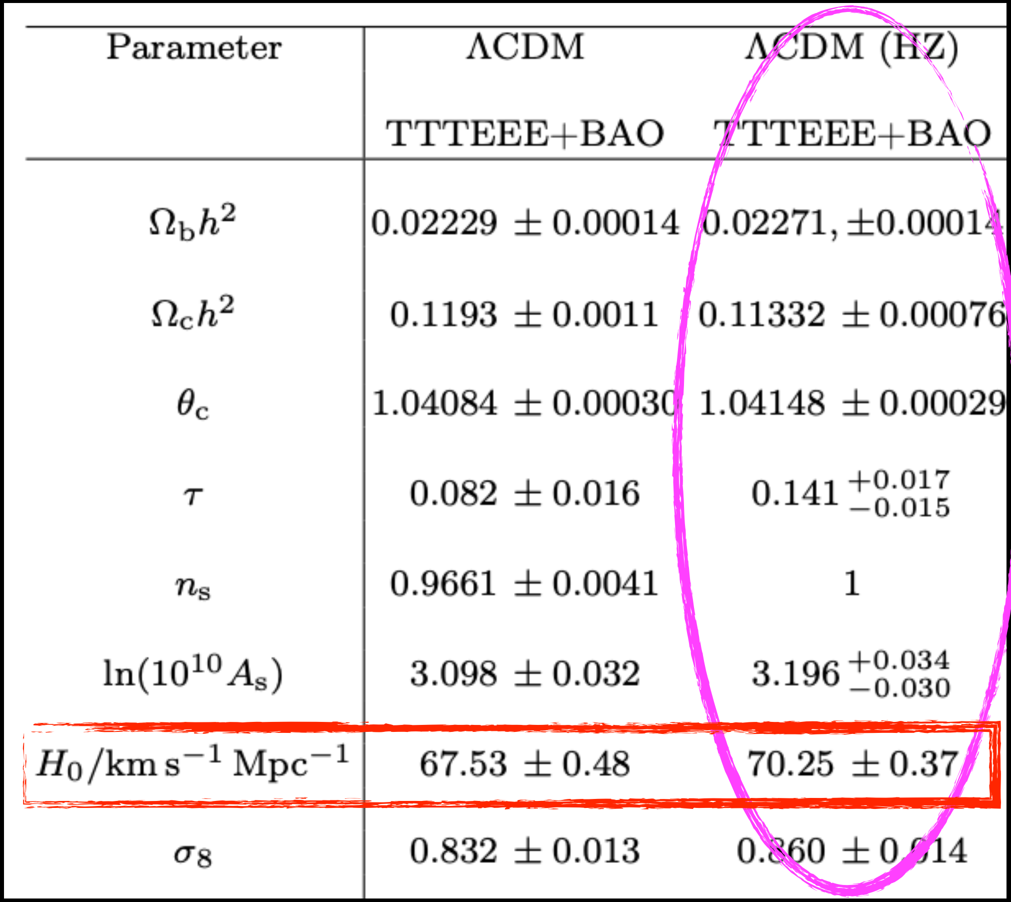
Parameter	ΛCDM	ΛCDM (HZ)	ΛCDM $+N_{\rm eff}$	ΛCDM $+N_{\rm eff}$ (HZ)	Extended-10	Extended-10 (HZ)	Extended-11	Extended-11 (HZ)
$\Omega_b h^2$	0.02226 ± 0.00015	0.02285 ± 0.00014	0.02219 ± 0.00025	0.02298 ± 0.00014	0.02227 ± 0.00028	0.02295 ± 0.00016	0.02225 ± 0.00028	0.02295 ± 0.00016
$\Omega_c h^2$	0.1198 ± 0.0014	0.11166 ± 0.00087	0.1189 ± 0.0031	0.1262 ± 0.0026	0.1186 ± 0.0034	0.1253 ± 0.0028	0.1186 ± 0.0034	0.1253 ± 0.0029
θ_c	1.04077 ± 0.00032	1.04171 ± 0.00029	1.04088 ± 0.00044	1.04016 ± 0.00038	1.04073 ± 0.00051	1.04005 ± 0.00043	1.04071 ± 0.00052	1.04004 ± 0.00044
τ	0.079 ± 0.017	0.143 ± 0.016	0.077 ± 0.018	0.114 ± 0.016	0.059 ± 0.021	0.061 ± 0.022	0.058 ± 0.021	0.061 ± 0.021
n_s	0.9646 ± 0.0047	1	0.9618 ± 0.0099	1	0.964 ± 0.013	1	0.964 ± 0.012	1
$\ln(10^{10} A_s)$	3.094 ± 0.034	3.199 ± 0.032	3.087 ± 0.038	3.177 ± 0.031	3.049 ± 0.044	3.065 ± 0.044	$3.046^{+0.043}_{-0.048}$	3.064 ± 0.042
$H_0/{\rm km\,s^{-1}\,Mpc^{-1}}$	67.30 ± 0.64	71.07 ± 0.42	66.8 ± 1.6	73.00 ± 0.56	63.9 ± 3.0	$69.6^{+3.2}_{-2.2}$	74 ± 10	73 ± 20
σ_8	$0.831^{+0.015}_{-0.013}$	0.854 ± 0.014	$0.827^{+0.017}_{-0.020}$	0.877 ± 0.014	$0.722^{+0.076}_{-0.060}$	$0.740^{+0.078}_{-0.057}$	$0.79^{+0.16}_{-0.14}$	0.75 ± 0.13
$N_{\rm eff}$	3.046	3.046	2.98 ± 0.20	3.70 ± 0.11	3.03 ± 0.25	$3.71^{+0.11}_{-0.14}$	3.03 ± 0.25	$3.71^{+0.12}_{-0.14}$
$\Sigma m_\nu [eV]$	0.06	0.06	0.06	0.06	< 0.606	$0.51^{+0.13}_{-0.50}$	$0.53^{+0.21}_{-0.45}$	$0.55^{+0.18}_{-0.50}$
$d\ln n_s/d\ln k$	0	0	0	0	-0.0014 ± 0.0087	0.0137 ± 0.0074	-0.0005 ± 0.0088	0.0138 ± 0.0079
$A_{\rm lens}$	1	1	1	1	$1.22^{+0.10}_{-0.12}$	$1.33^{+0.10}_{-0.12}$	$1.22^{+0.10}_{-0.14}$	$1.37^{+0.11}_{-0.17}$
w	-1	-1	-1	-1	-1	-1	-1.39 ± 0.58	> -1.40

Di Valentino et al. Phys.Rev. D98 (2018) no.6, 063508

Constraints at 68% cl.

Harrison-Zel’dovich spectrum

The presence of the Hubble tension in current cosmological data does not let to rule out a HZ spectrum at high statistical significance.



Parameter	ΛCDM TTTEEE+BAO	ΛCDM (HZ) TTTEEE+BAO
$\Omega_b h^2$	0.02229 ± 0.00014	$0.02271, \pm 0.00014$
$\Omega_c h^2$	0.1193 ± 0.0011	0.11332 ± 0.00076
θ_c	1.04084 ± 0.00030	1.04148 ± 0.00029
τ	0.082 ± 0.016	$0.141^{+0.017}_{-0.015}$
n_s	0.9661 ± 0.0041	1
$\ln(10^{10} A_s)$	3.098 ± 0.032	$3.196^{+0.034}_{-0.030}$
$H_0/\mathrm{km\,s^{-1}\,Mpc^{-1}}$	67.53 ± 0.48	70.25 ± 0.37
σ_8	0.832 ± 0.013	0.860 ± 0.014

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…also when BAO data are included in the analysis.

Summarising

Early time modifications of the standard models seem most promising for putting in agreement CMB and R19, and agree also with BAO+Pantheon data, but unfortunately they don't solve completely the H0 tension.

Late time modifications are instead more powerful in solving the H0 tension, but are producing a disagreement with the additional BAO+Pantheon data.

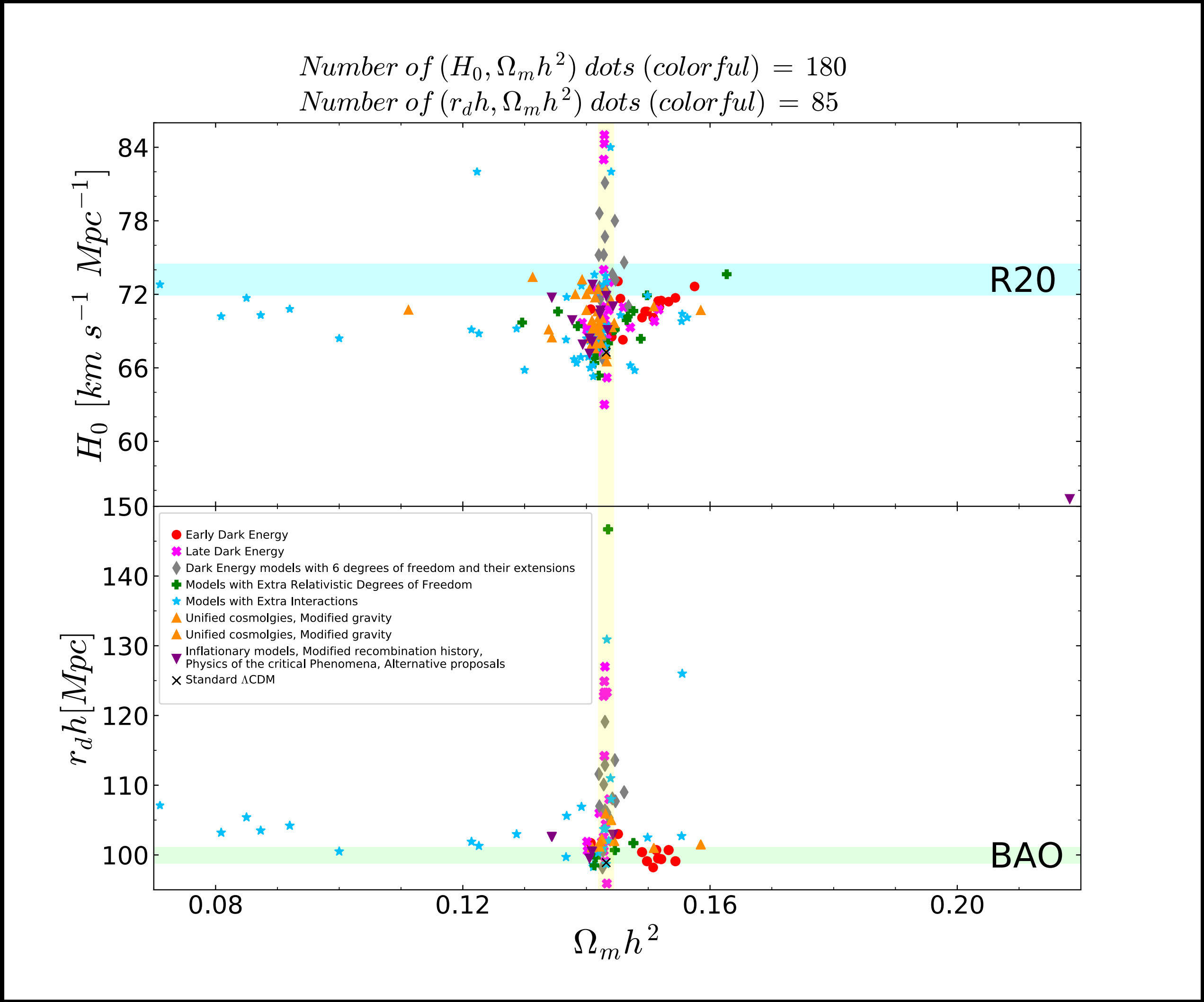
A simple IDE model can relieve the H0 tension hinting for an interaction different from zero at more than 5σ. However, when BAO data are added in the analysis the Hubble constant tension is restored at about 2.5σ.

A HZ spectrum can solve the H0 tension without new physics, but worsening the fit of the Planck data.

Concluding

This is the density of the proposed cosmological models: →

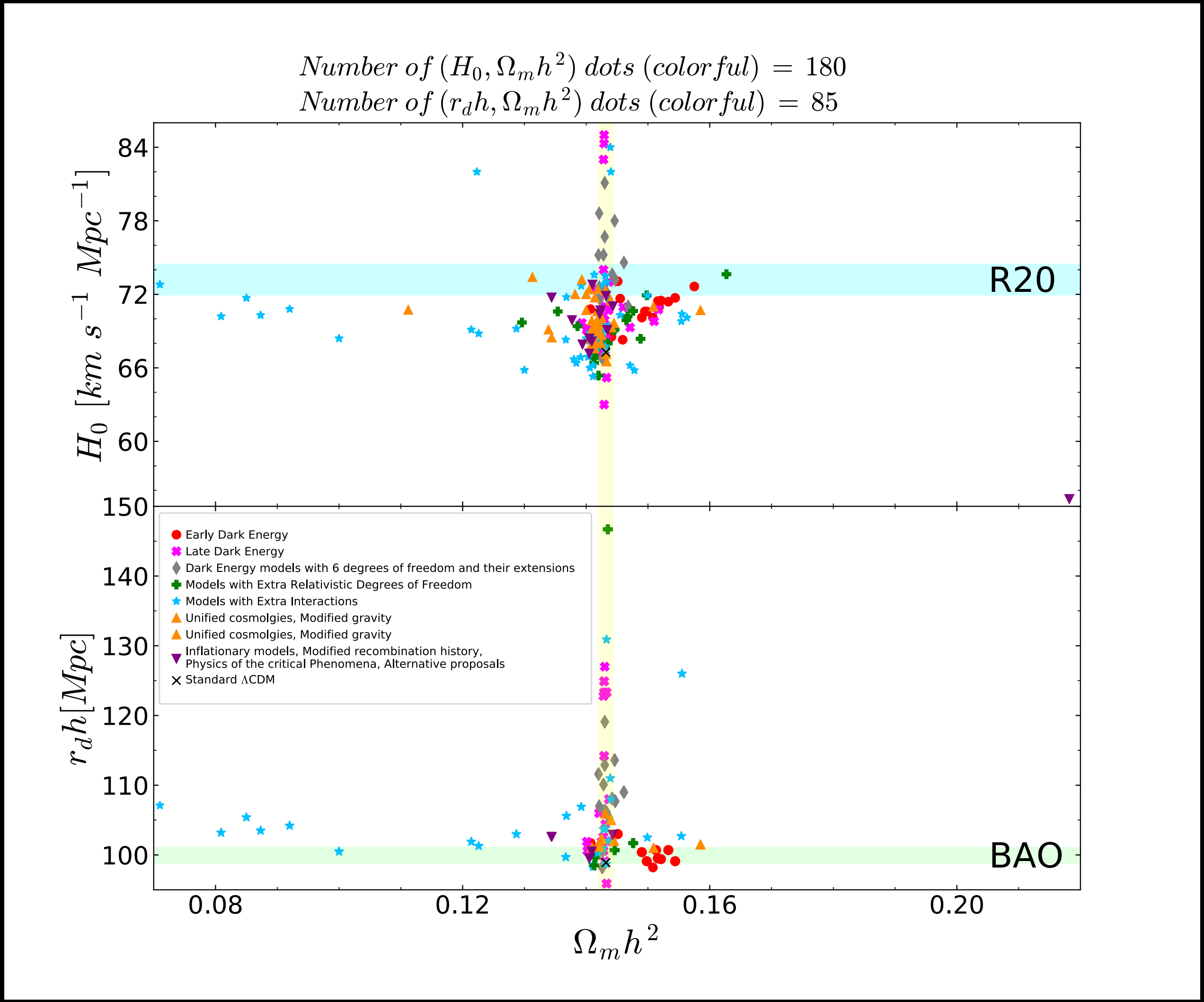
At the moment no specific proposal makes a strong case for being highly likely or far better than all others !!!



Di Valentino et al., Class.Quant.Grav. (2021), arXiv:2103.01183 [astro-ph.CO]

Concluding

This is the density of the proposed cosmological models:



At the moment no specific proposal makes a strong case for being highly likely or far better than all others !!!

Di Valentino et al., Class.Quant.Grav. (2021), arXiv:2103.01183 [astro-ph.CO]

We need new observations and a deep investigation of alternative theoretical models and solutions.

Thank you!

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