Unraveling the Hubble constant tension

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Eleonora Di Valentino
Royal Society Dorothy Hodgkin Research Fellow
School of Mathematics and Statistics
University of Sheffield (UK)

The University Of Sheffield.

What is H0?

The Hubble constant H0 describes the expansion rate of the Universe today.

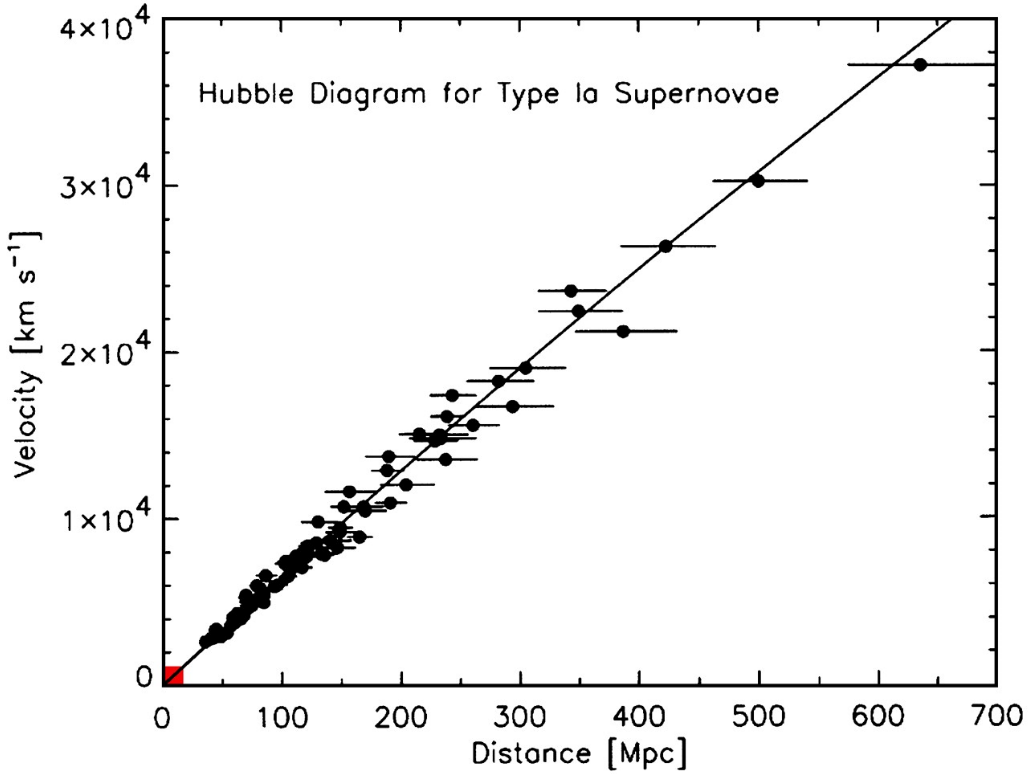
This can be obtained in mainly two ways:

1. measuring the distance and the recessional velocity of standard candles, and computing the proportionality factor.

Hubble–Lemaître law

$$v = H_0\, D$$

This approach is model independent and based on geometrical measurements.



Jha, S. (2002) Ph.D. thesis (Harvard Univ., Cambridge, MA).

What is H0?

The Hubble constant H0 describes the expansion rate of the Universe today.

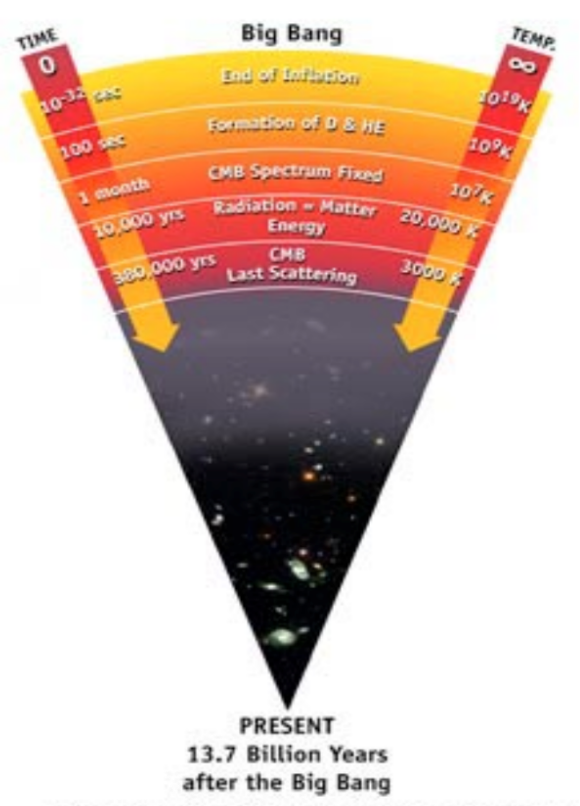
This can be obtained in mainly two ways:

1. measuring the distance and the recessional velocity of standard candles, and computing the proportionality factor.
2. considering early universe measurements, and assuming a model for the expansion history of the universe.

For example, we have CMB measurements and we assume the standard model of cosmology, i.e. the LCDM scenario.

1st Friedmann equations describes the expansion history of the universe:

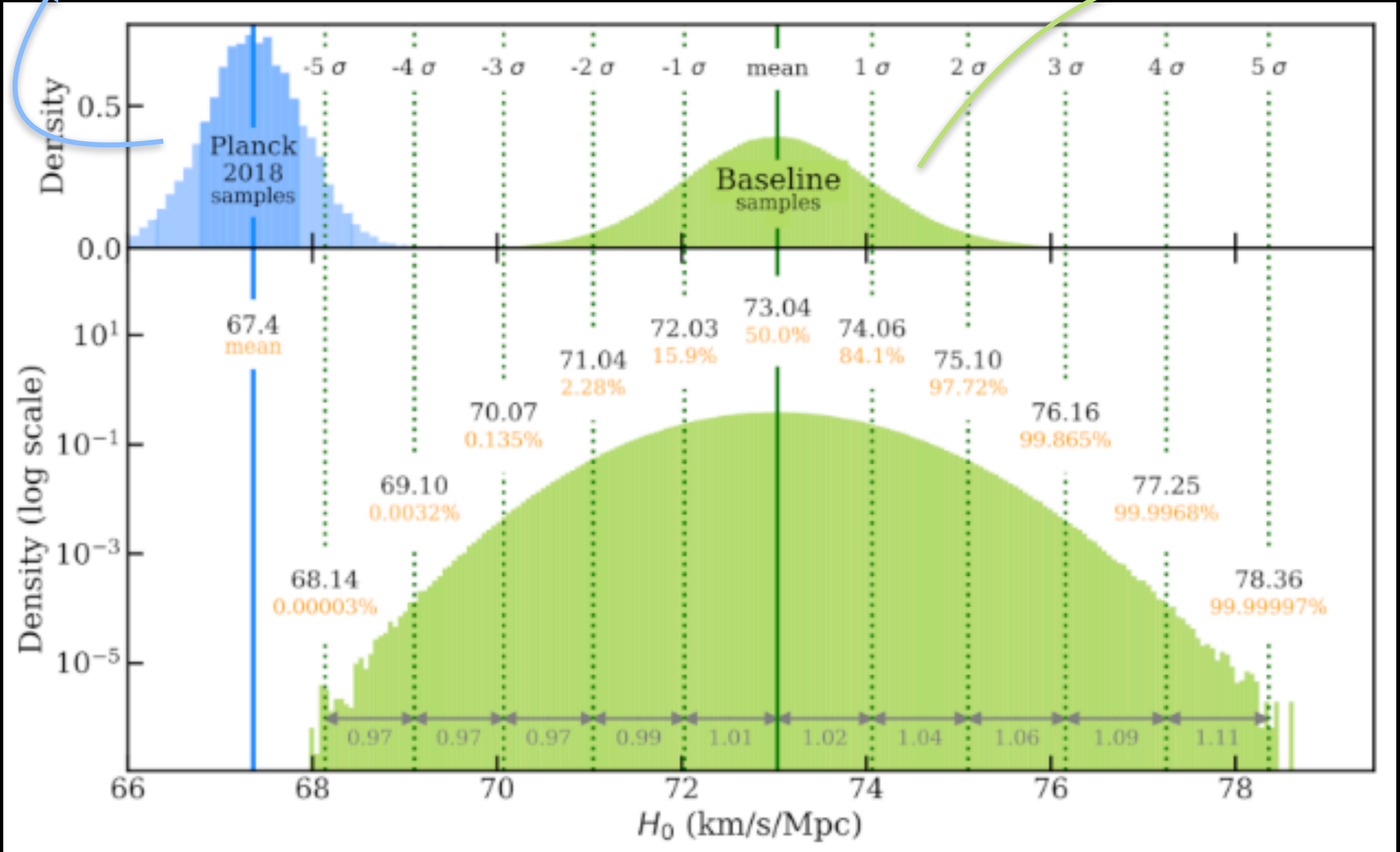
$$H^2(z) = H_0^2\left(\Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda\right).$$



The H0 tension at 5σ!!

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

The Planck estimate assuming a “vanilla" ΛCDM cosmological model:
$H0 = 67.27 \pm 0.60$ km/s/Mpc
Planck 2018, Astron.Astrophys. 641 (2020) A6



The latest local measurements obtained by the SH0ES collaboration (R21).

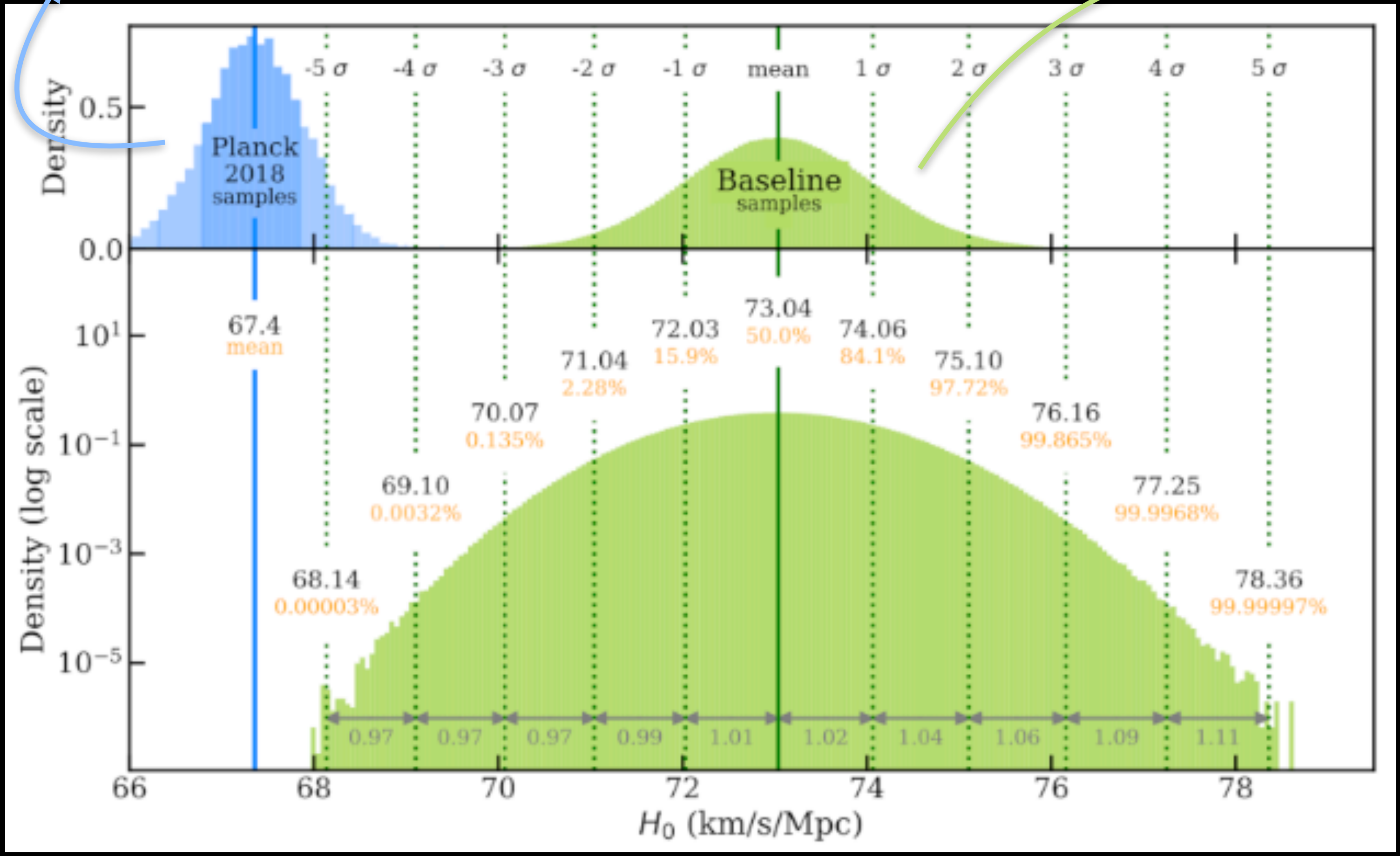
$H0 = 73.04 \pm 1.04$ km/s/Mpc

Riess et al. arXiv:*2112.04510*

Distance Ladder

The Planck estimate assuming a “vanilla" ΛCDM cosmological model:
H0 = 67.27 ± 0.60 km/s/Mpc

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



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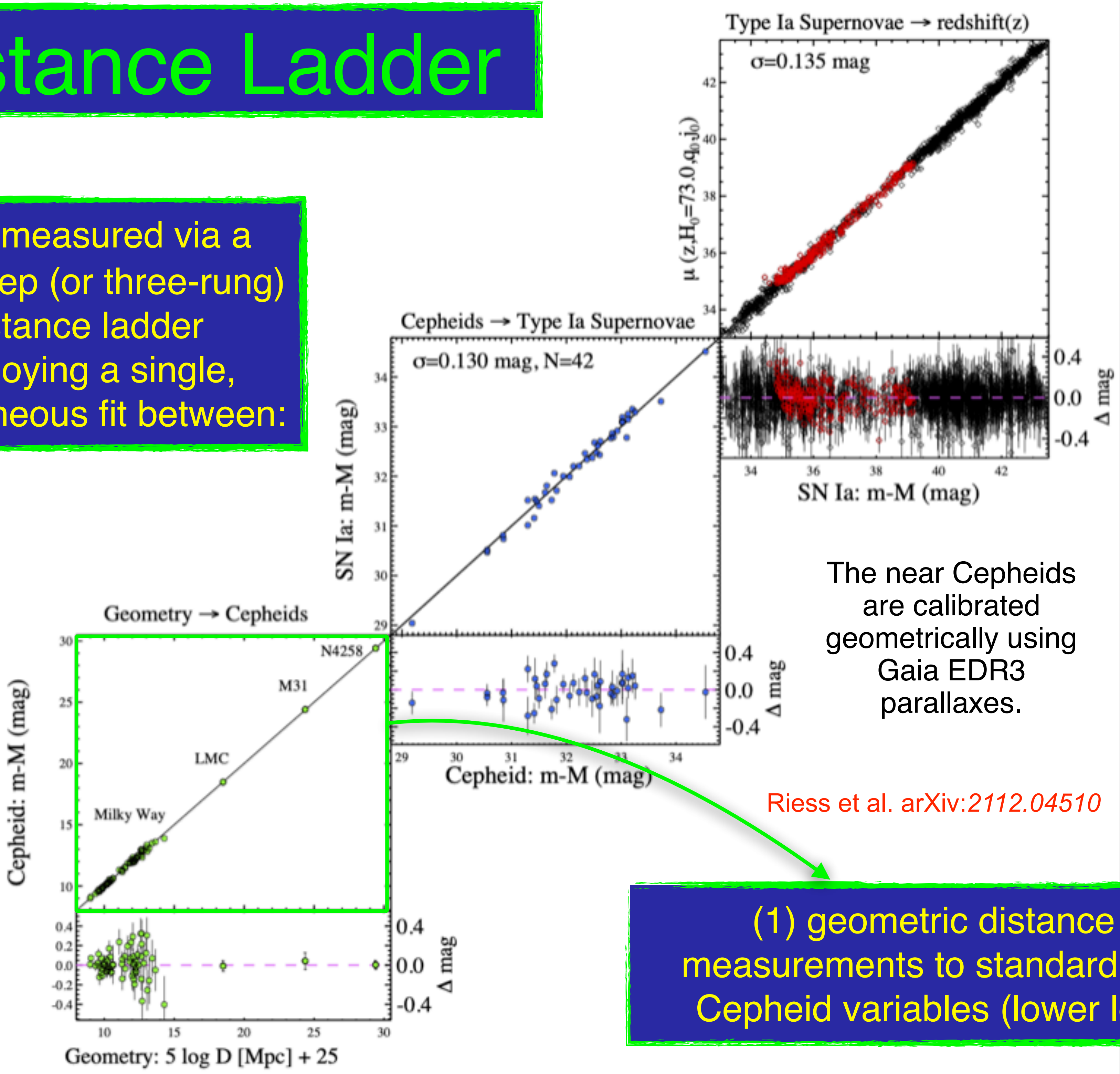
Distance Ladder

H0 is measured via a three-step (or three-rung) distance ladder employing a single, simultaneous fit between:



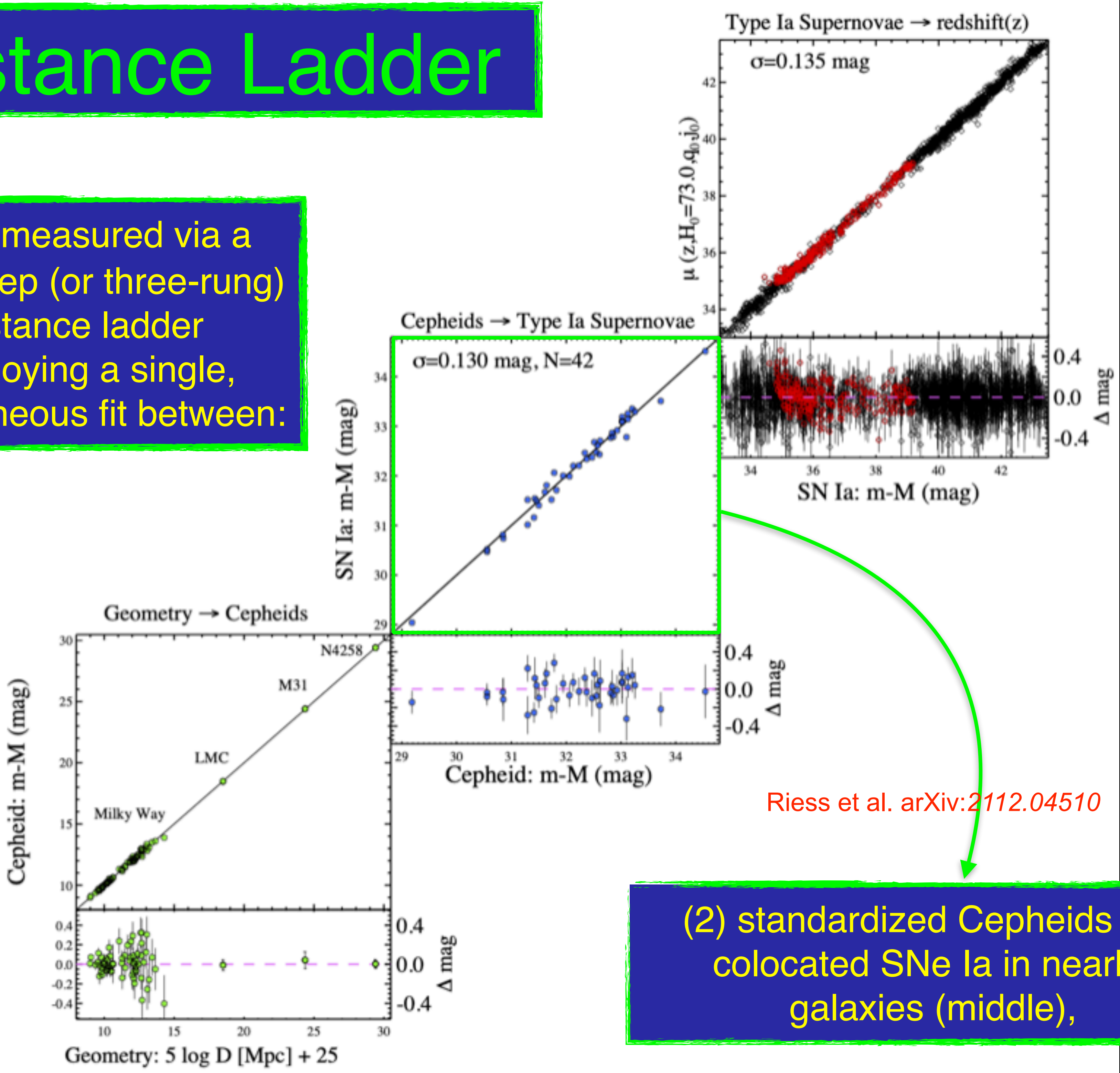
The near Cepheids are calibrated geometrically using Gaia EDR3 parallaxes.

Riess et al. arXiv:*2112.04510*

(1) geometric distance measurements to standardized Cepheid variables (lower left)

Distance Ladder

H0 is measured via a three-step (or three-rung) distance ladder employing a single, simultaneous fit between:

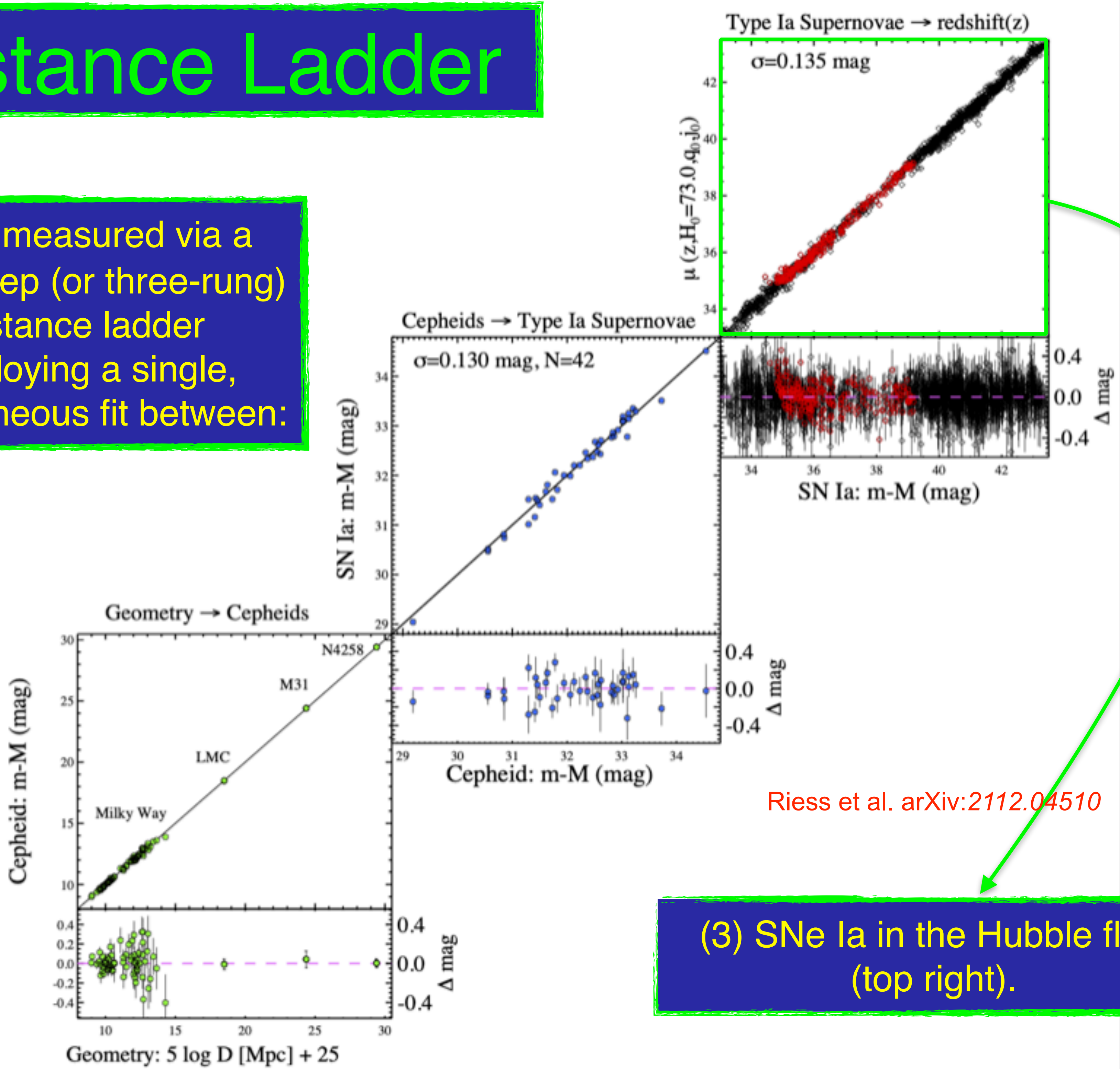


Riess et al. arXiv:*2112.04510*

(2) standardized Cepheids and colocated SNe Ia in nearby galaxies (middle),

Distance Ladder

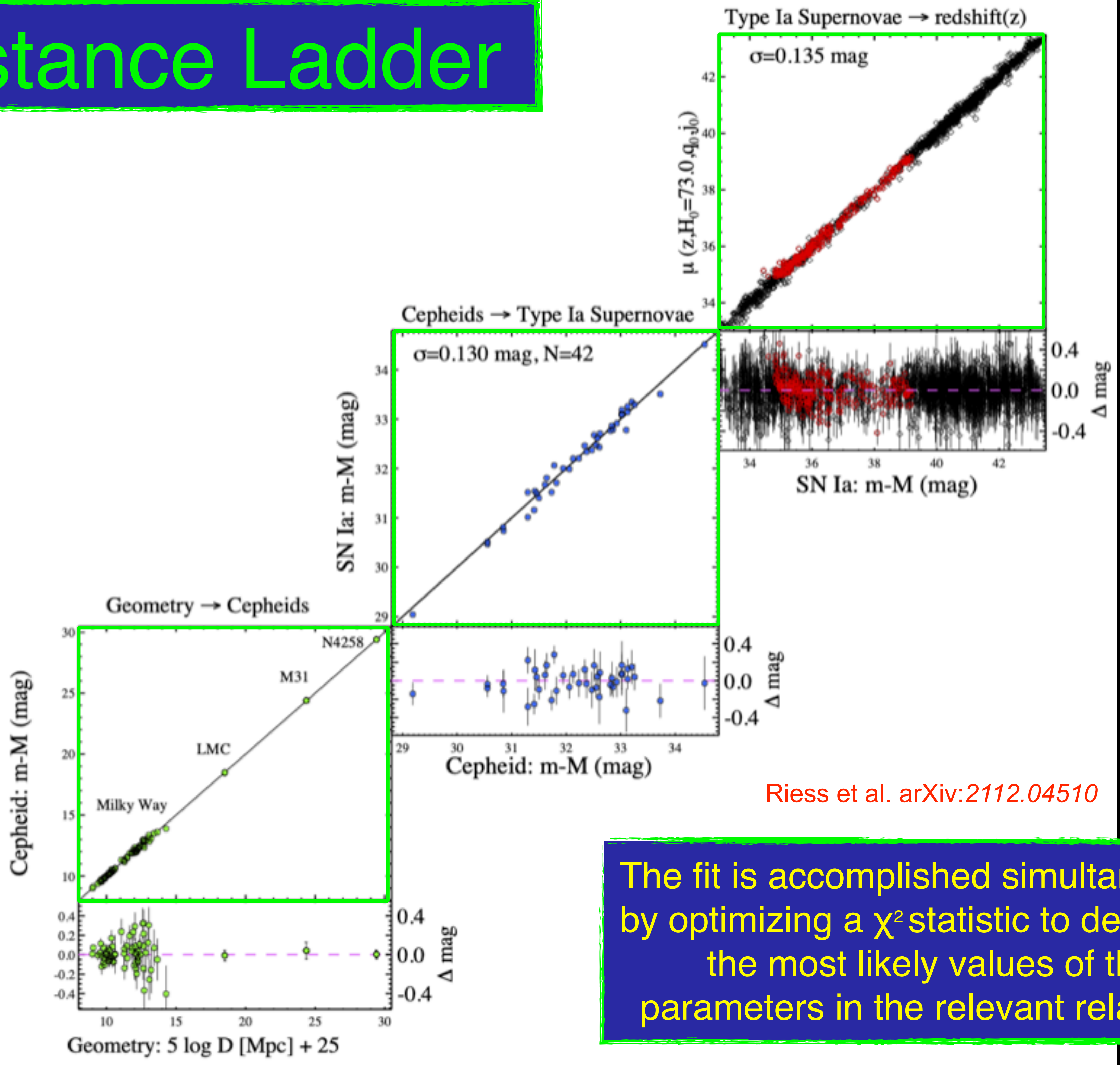
H0 is measured via a three-step (or three-rung) distance ladder employing a single, simultaneous fit between:



Riess et al. arXiv:*2112.04510*

(3) SNe Ia in the Hubble flow (top right).

Distance Ladder



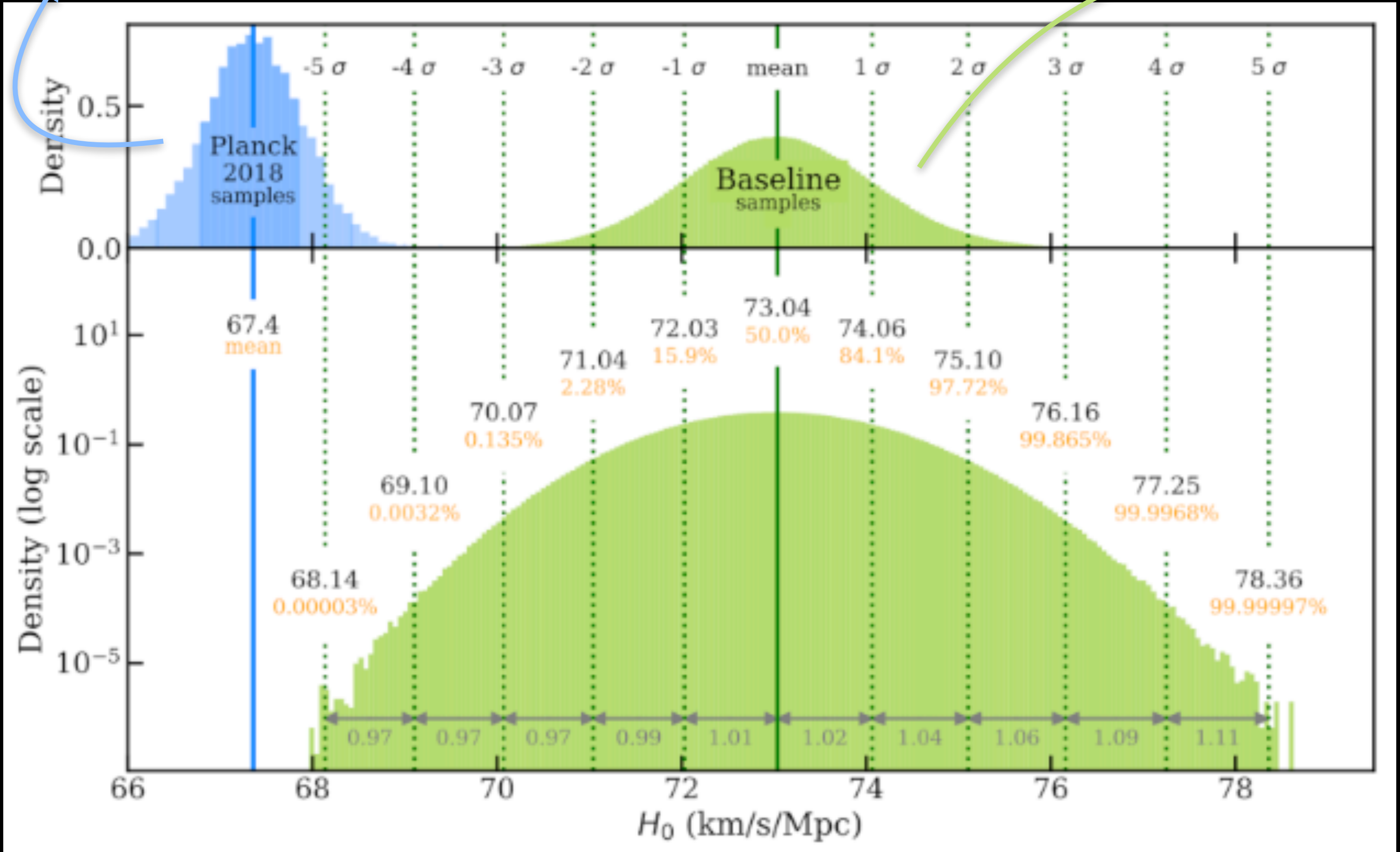
Riess et al. arXiv:*2112.04510*

The fit is accomplished simultaneously by optimizing a χ^2 statistic to determine the most likely values of the parameters in the relevant relations.

CMB constraints

The Planck estimate assuming a “vanilla" ΛCDM cosmological model:
H0 = 67.27 ± 0.60 km/s/Mpc

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



The latest local measurements obtained by the SH0ES collaboration (R21).

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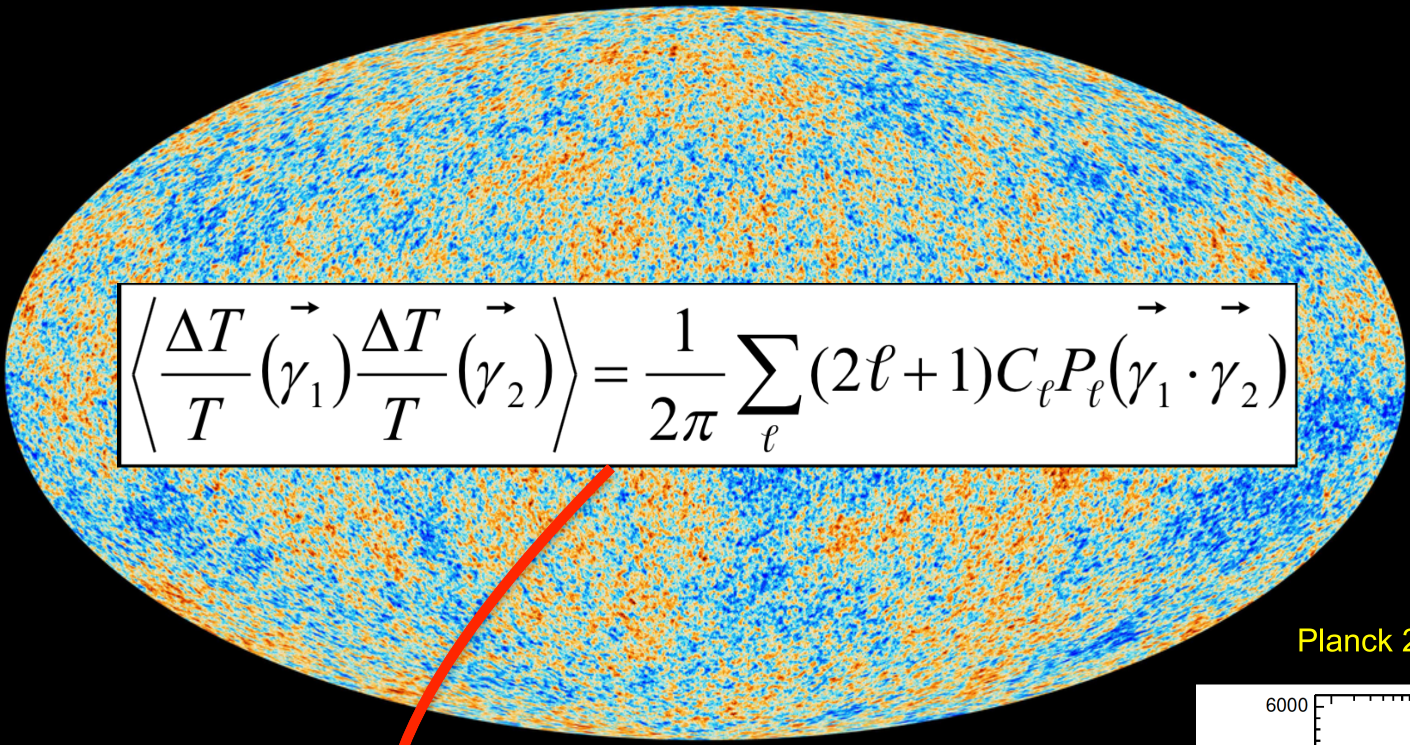
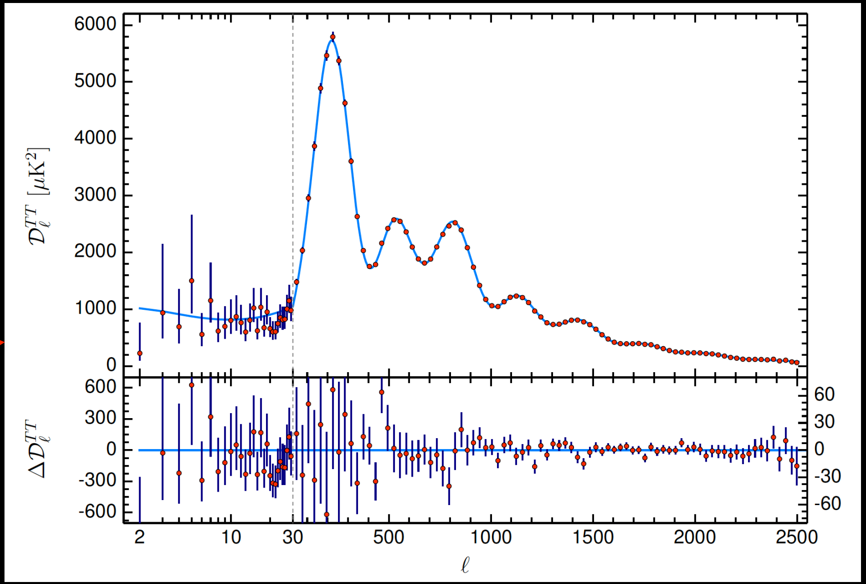
CMB constraints



$$\left\langle \frac{\Delta T}{T}(\vec{\gamma}_1)\frac{\Delta T}{T}(\vec{\gamma}_2)\right\rangle = \frac{1}{2\pi}\sum_{\ell}(2\ell+1)C_\ell P_\ell(\vec{\gamma}_1\cdot\vec{\gamma}_2)$$

From the map of the CMB anisotropies we can extract the temperature angular power spectrum.

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



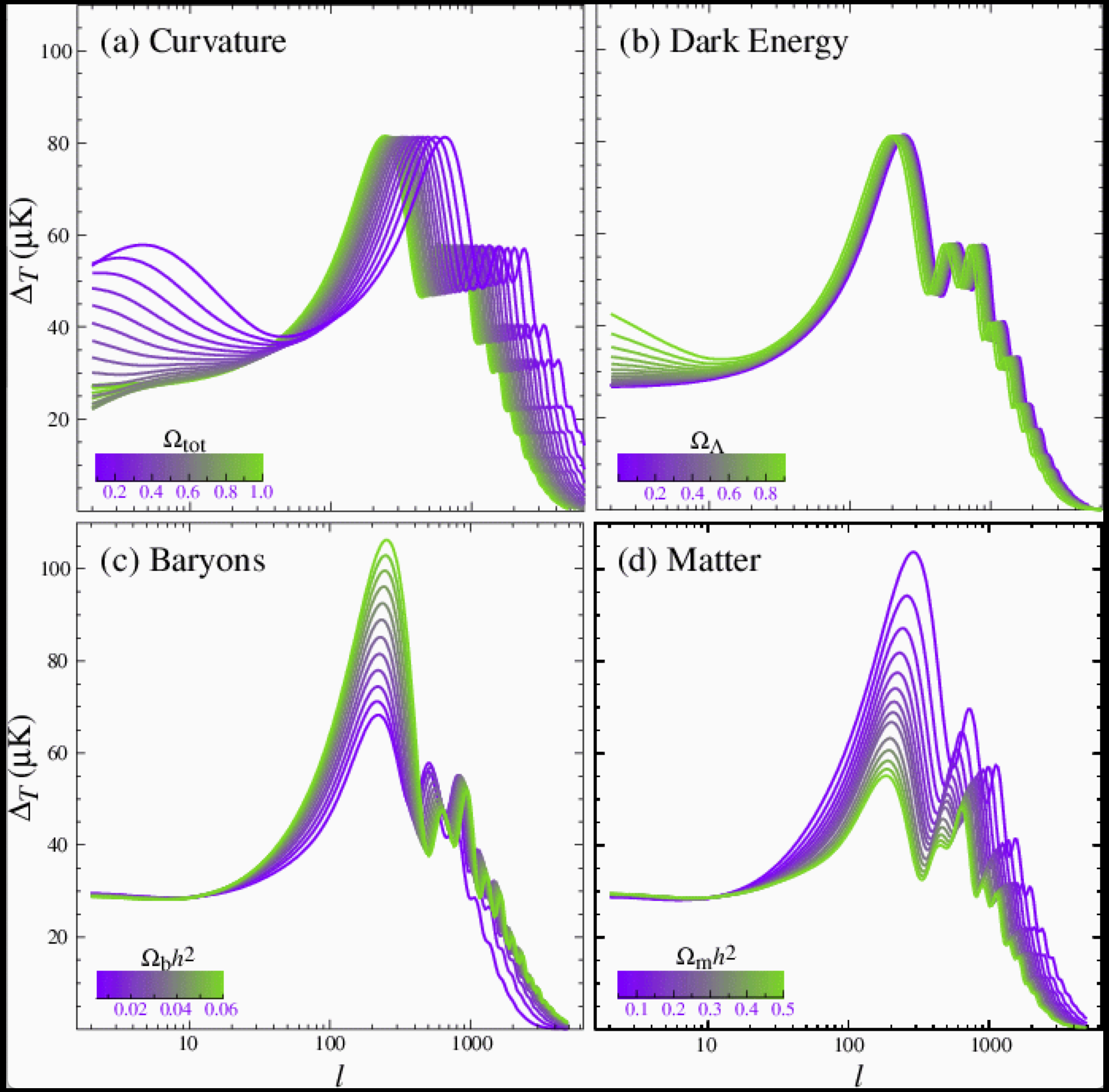
Cosmological parameters:
$(\Omega_b h^2 , \Omega_m h^2 , H0 , n_s , \tau, As)$

Theoretical model

We choose a set of cosmological parameters that describes our theoretical model and compute the angular power spectra.

Because of the correlations present between the parameters, variation of different quantities can produce similar effects on the CMB.

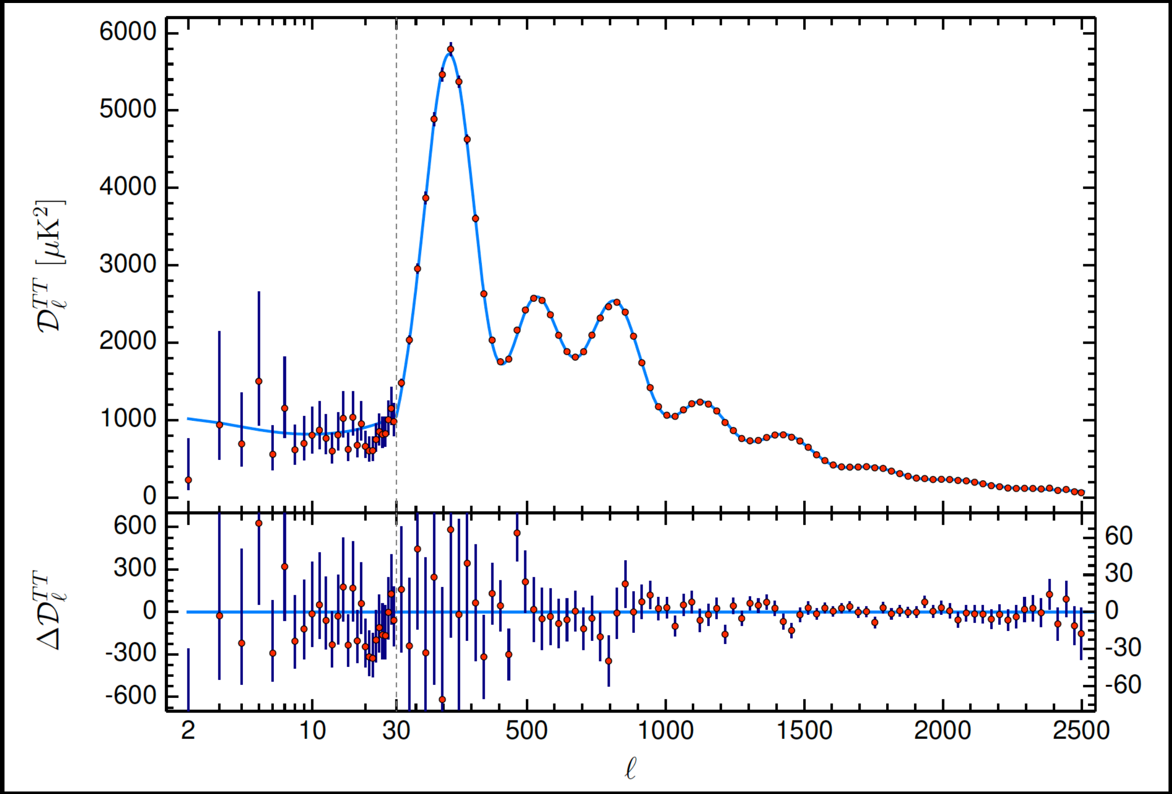
Wayne Hu's tutorial



Cosmological parameters:
($\Omega_b h^2$, $\Omega_m h^2$, H0 , n_s , τ, As)

Theoretical model

We compare the angular power spectra we computed with the data and, using a bayesian analysis, we get a combination of cosmological parameter values in agreement with these.



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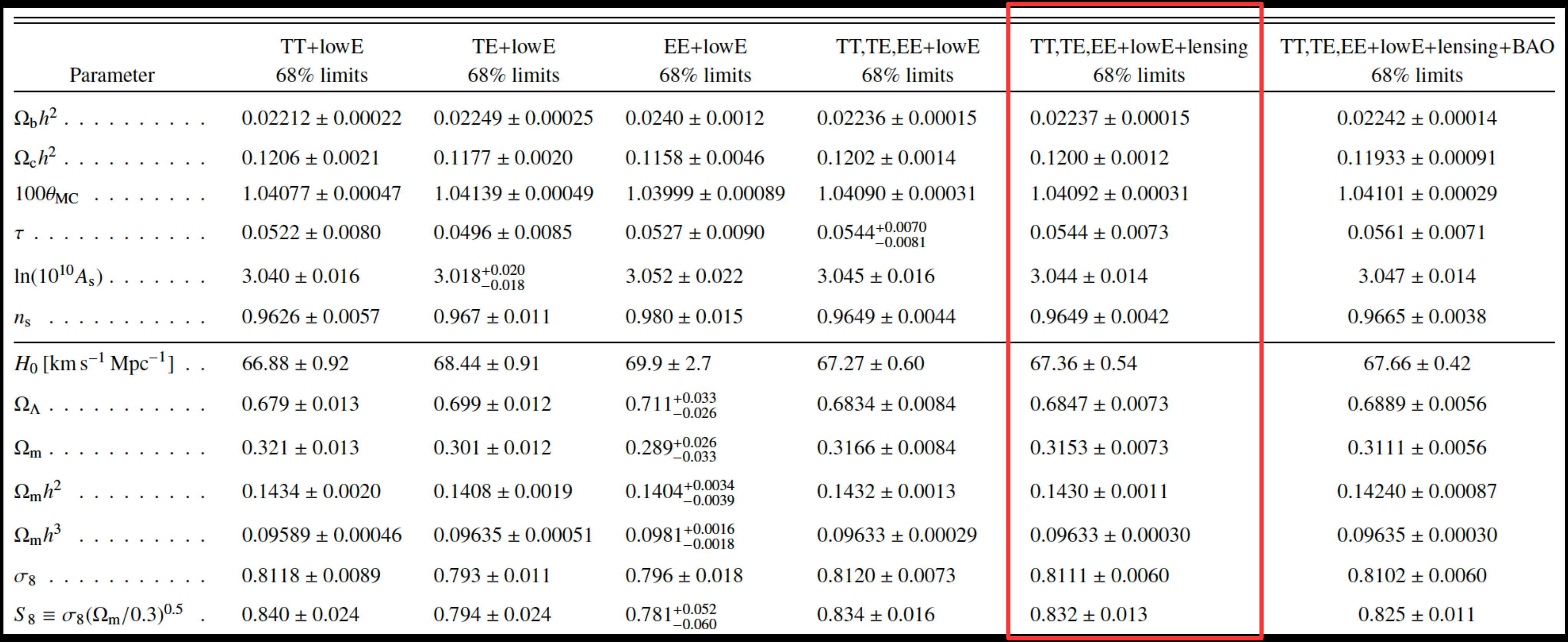
Parameter constraints

CMB constraints



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
H_0 [km s^{-1} Mpc^{-1}] . .	66.88 ± 0.92	68.44 ± 0.91	69.9 ± 2.7	67.27 ± 0.60	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.679 ± 0.013	0.699 ± 0.012	$0.711^{+0.033}_{-0.026}$	0.6834 ± 0.0084	0.6847 ± 0.0073	0.6889 ± 0.0056
Ω_m	0.321 ± 0.013	0.301 ± 0.012	$0.289^{+0.026}_{-0.033}$	0.3166 ± 0.0084	0.3153 ± 0.0073	0.3111 ± 0.0056
$\Omega_m h^2$	0.1434 ± 0.0020	0.1408 ± 0.0019	$0.1404^{+0.0034}_{-0.0039}$	0.1432 ± 0.0013	0.1430 ± 0.0011	0.14240 ± 0.00087
$\Omega_m h^3$	0.09589 ± 0.00046	0.09635 ± 0.00051	$0.0981^{+0.0016}_{-0.0018}$	0.09633 ± 0.00029	0.09633 ± 0.00030	0.09635 ± 0.00030
σ_8	0.8118 ± 0.0089	0.793 ± 0.011	0.796 ± 0.018	0.8120 ± 0.0073	0.8111 ± 0.0060	0.8102 ± 0.0060
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$.	0.840 ± 0.024	0.794 ± 0.024	$0.781^{+0.052}_{-0.060}$	0.834 ± 0.016	0.832 ± 0.013	0.825 ± 0.011

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

2018 Planck results are a wonderful confirmation of the flat standard ΛCDM cosmological model, but are model dependent!

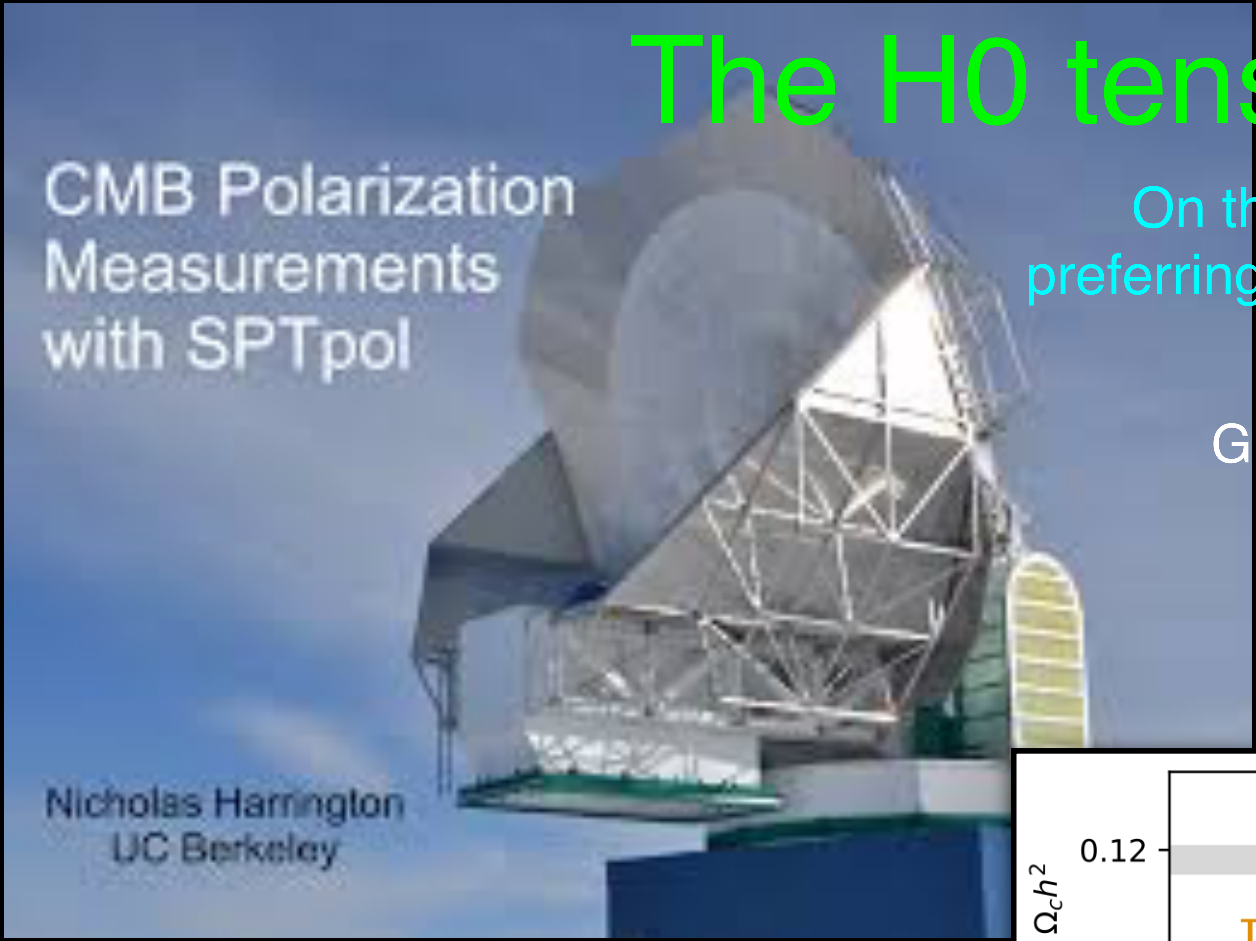
- The cosmological constraints are obtained assuming a cosmological model.
- The results are affected by the degeneracy between the parameters that induce similar effects on the observables.

Are there other H0 estimates?

The H0 tension

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

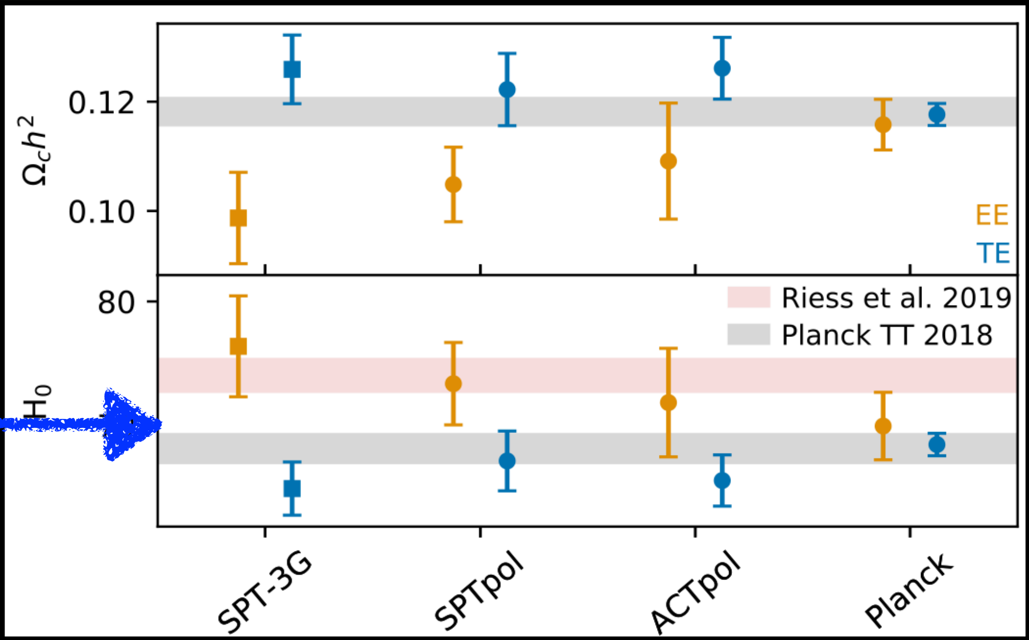
Ground based CMB telescope



CMB Polarization
Measurements
with SPTpol

Nicholas Harrington
UC Berkeley

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



SPT-3G, Dutcher et al., *Phys.Rev.D* 104 (2021) 2, 022003

LCDM - dependent

The H0 tension

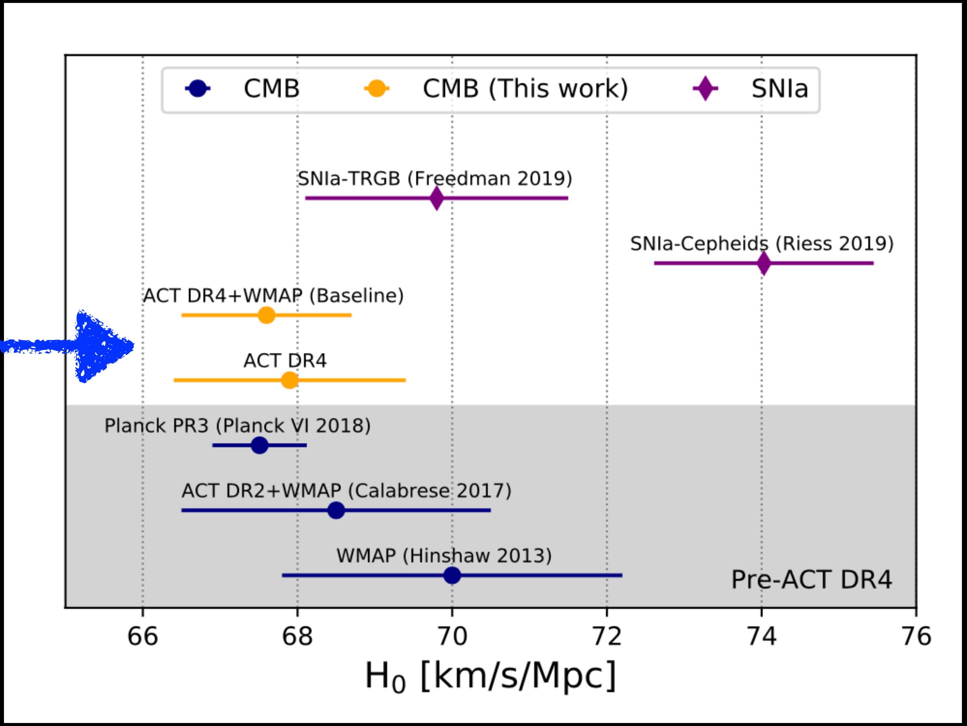
On the same side of Planck, i.e. preferring smaller values of H_0 we have:

Ground based CMB telescope

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 collaboration, Aiola et al., *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+$\theta_{\mathrm{MC,\ Planck}}$:

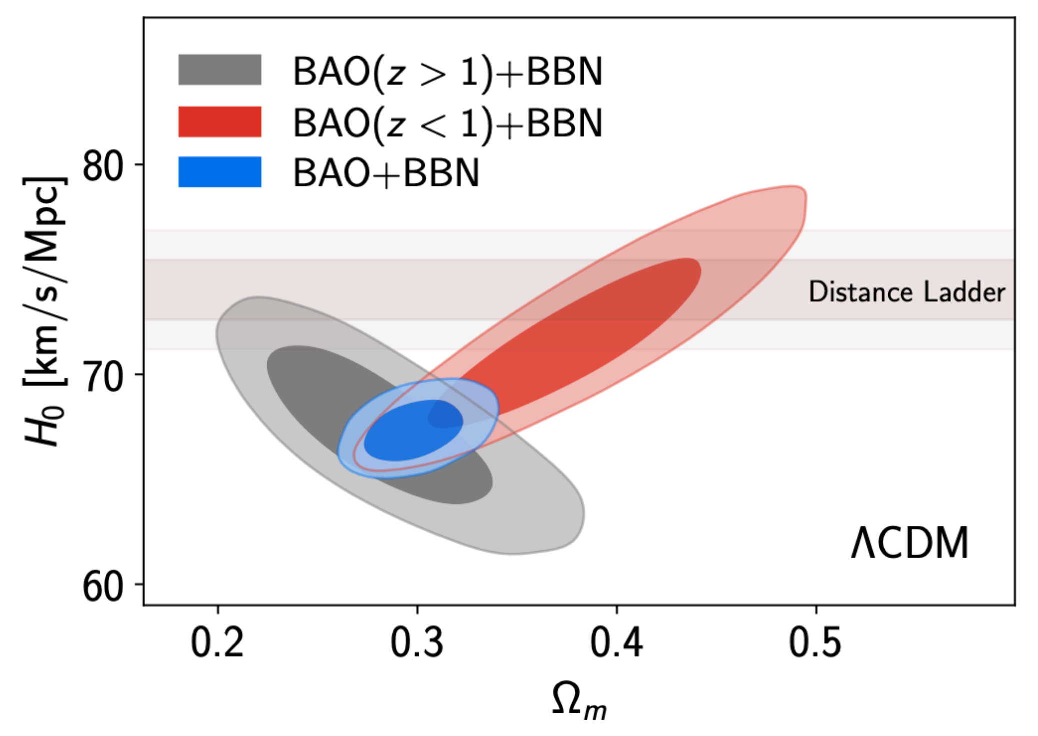
H0 = 67.9 ± 0.8 km/s/Mpc

Planck 2018, Aghanim et al., Astron.Astrophys. 641 (2020) A6

BAO+BBN from BOSS and eBOSS:

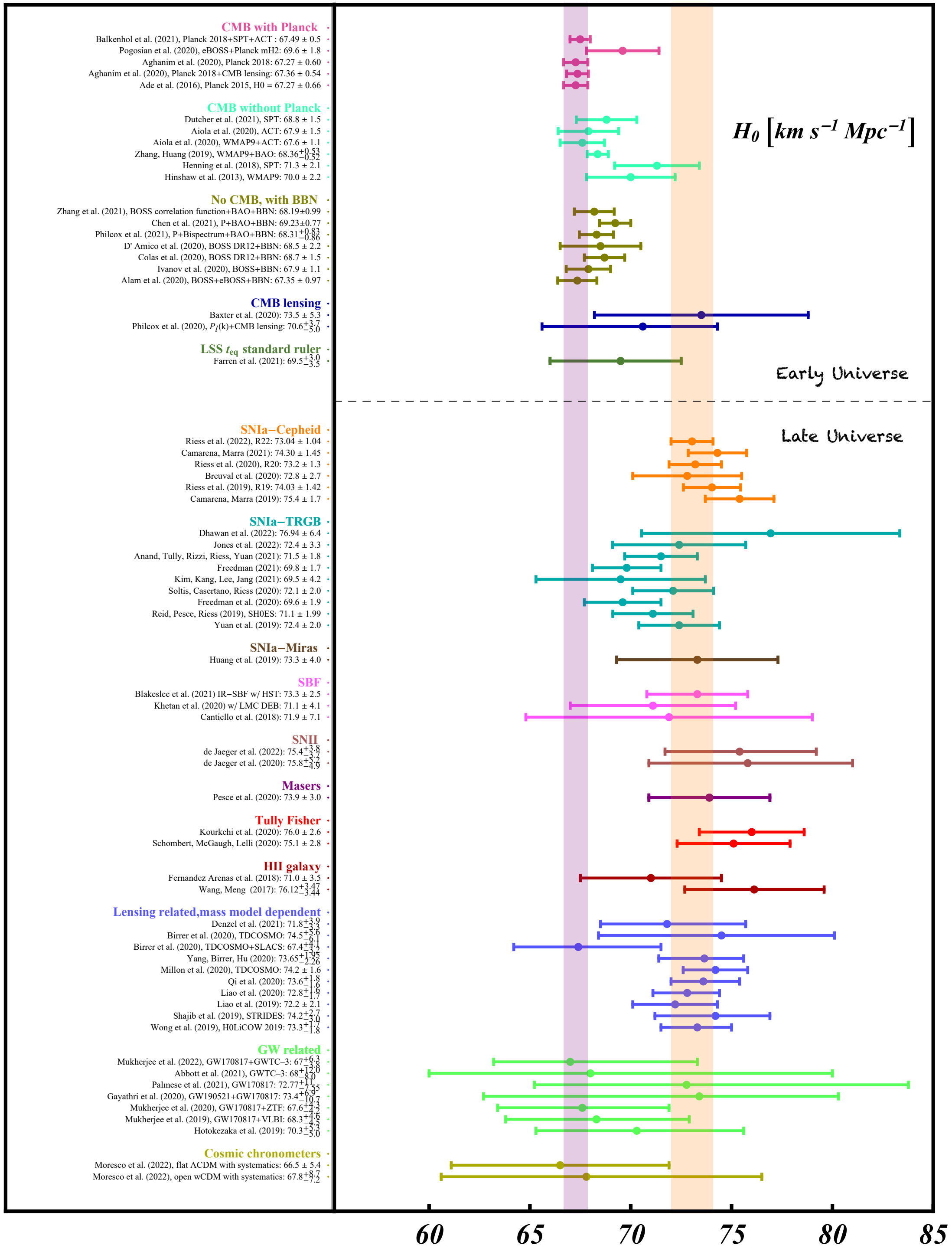
H_0 = 67.35 ± 0.97 km/s/Mpc

eBOSS, Alam et al., *Phys.Rev.D* 103 (2021) 8, 083533



eBOSS, Alam et al., *Phys.Rev.D* 103 (2021) 8, 083533

LCDM - dependent



Abdalla et al., *JHEAp* 34 (2022) 49-211

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

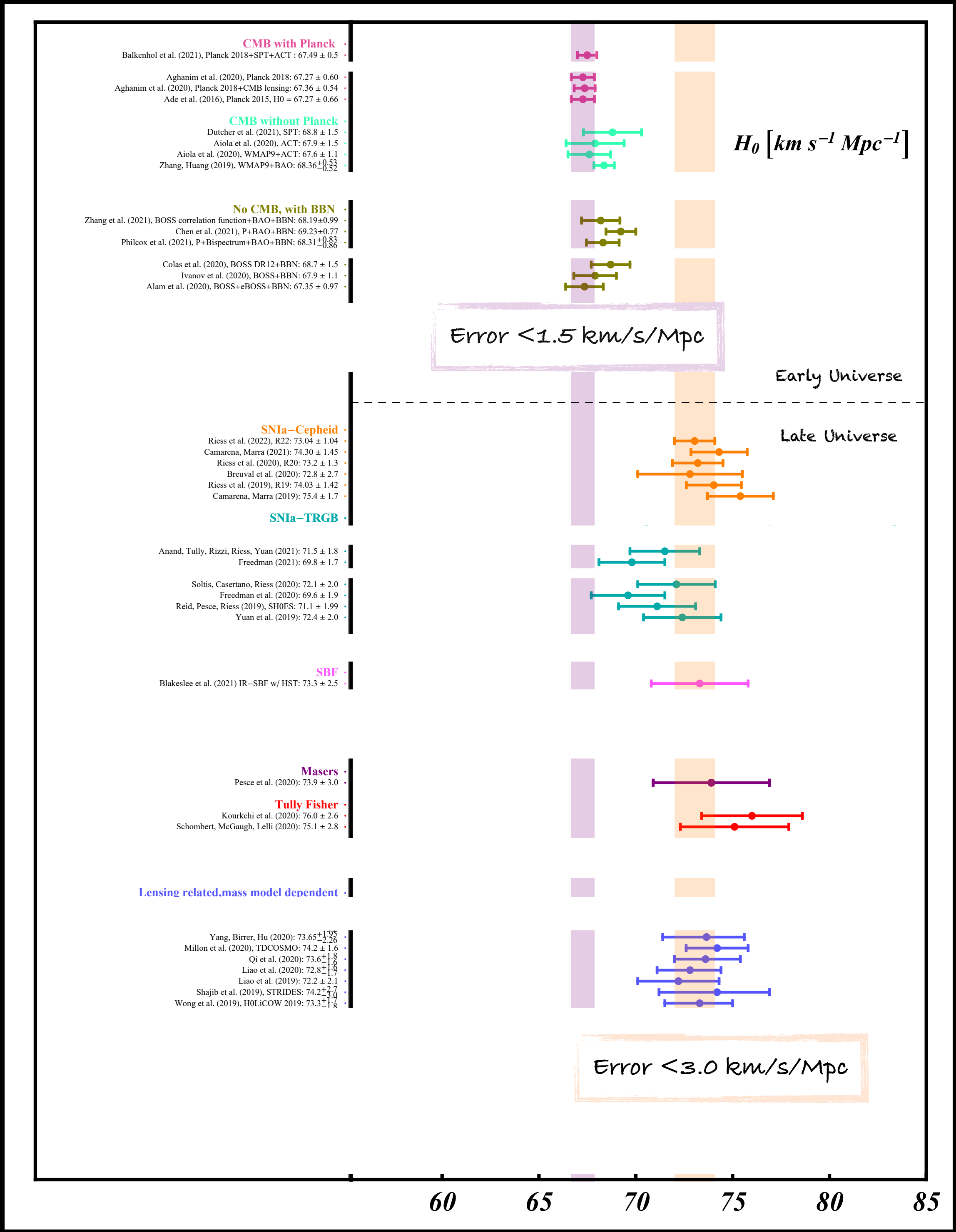
The orange vertical band corresponds to the H0 value from SH0ES Team and the light pink vertical band corresponds to the H0 value as reported by Planck 2018 team within a ΛCDM scenario.

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]

High precision measurements of H0



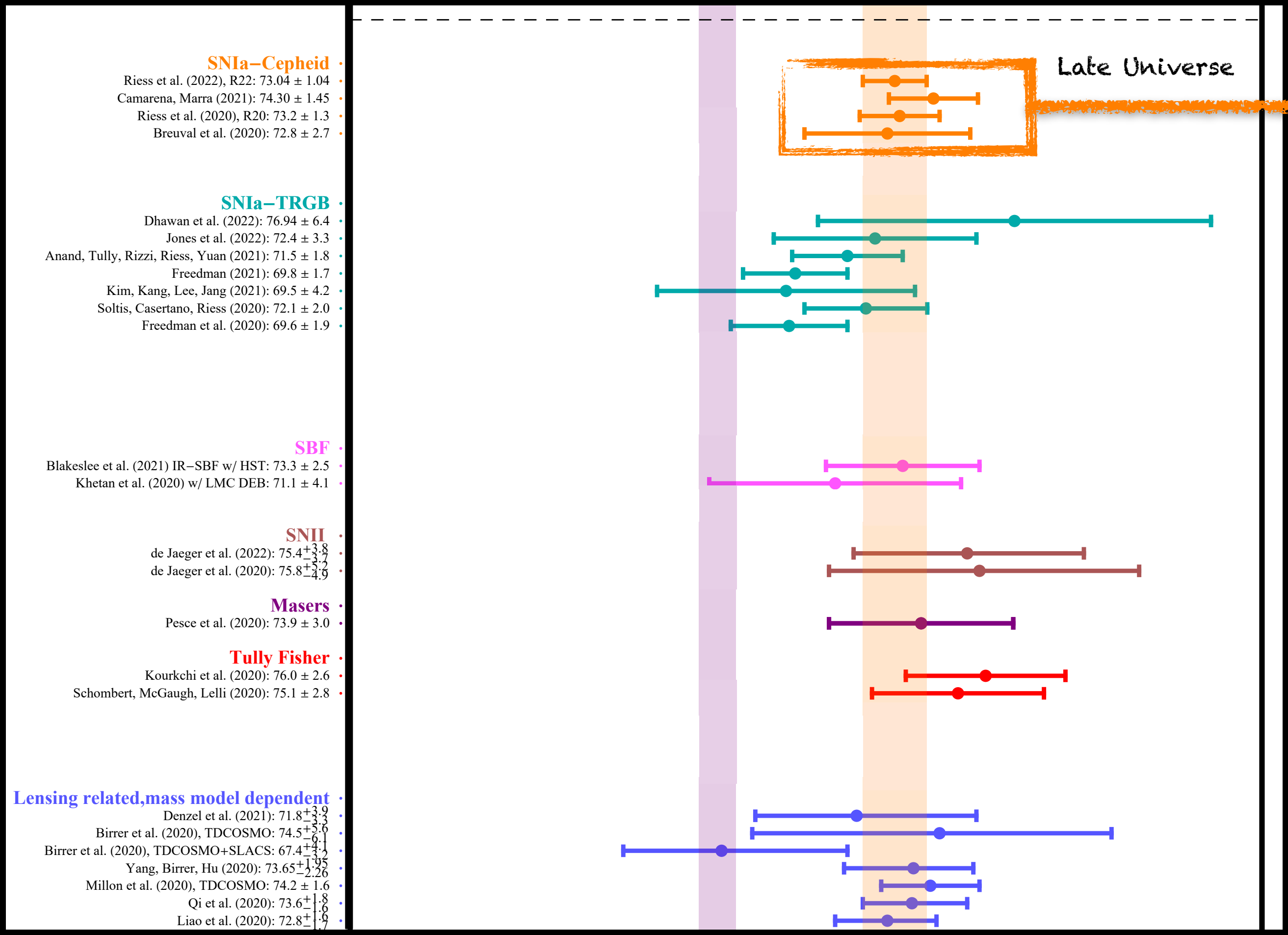
Error <1.5 km/s/Mpc

Error <3.0 km/s/Mpc

Abdalla et al., *JHEAp* 34 (2022) 49-211

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.

Late universe measurements since 2020



Abdalla et al., *JHEAp* 34 (2022) 49-211

Cepheids-SN Ia:

H0 = 73.04 ± 1.04 km/s/Mpc

Riess et al., arXiv:*2112.04510*

H0 = 74.30 ± 1.45 km/s/Mpc

Camarena & Marra, arXiv:2101.08641

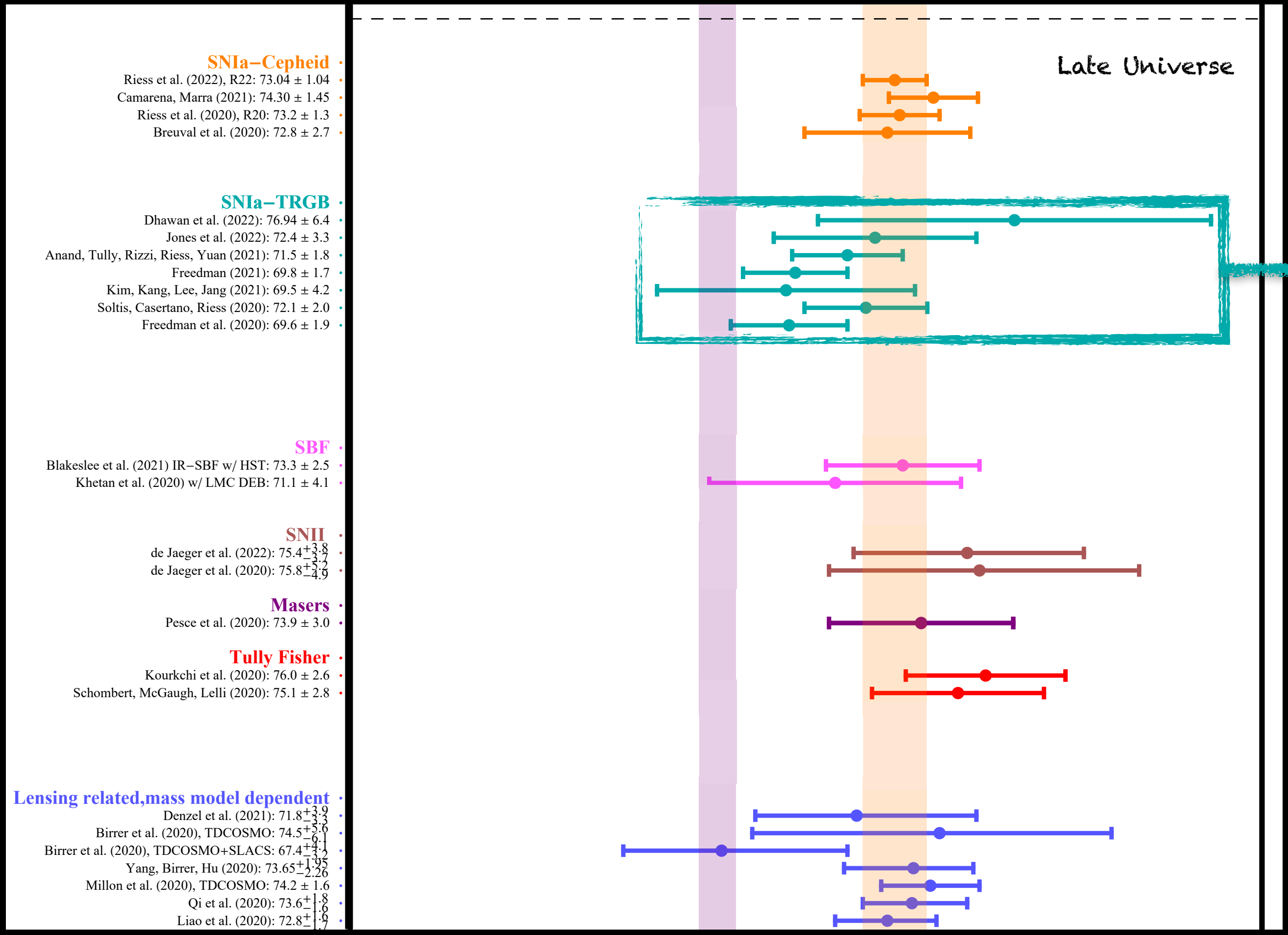
H0 = 73.2 ± 1.3 km/s/Mpc

Riess et al., arXiv:2012.08534

H0 = 73.0 ± 2.7 km/s/Mpc

Breuval et al., arXiv:2006.08763

Late universe measurements since 2020



Abdalla et al., *JHEAp* 34 (2022) 49-211

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 = 76.9±6.4 km/s/Mpc

Dhawan et al., arXiv:2203.04241

H0 = 72.4±3.3 km/s/Mpc

Jones et al., arXiv:2201.07801

H0 = 71.5±1.8 km/s/Mpc

Anand et al., arXiv:2108.00007

H0 = 69.8±1.7 km/s/Mpc

Freedman, arXiv:2106.15656

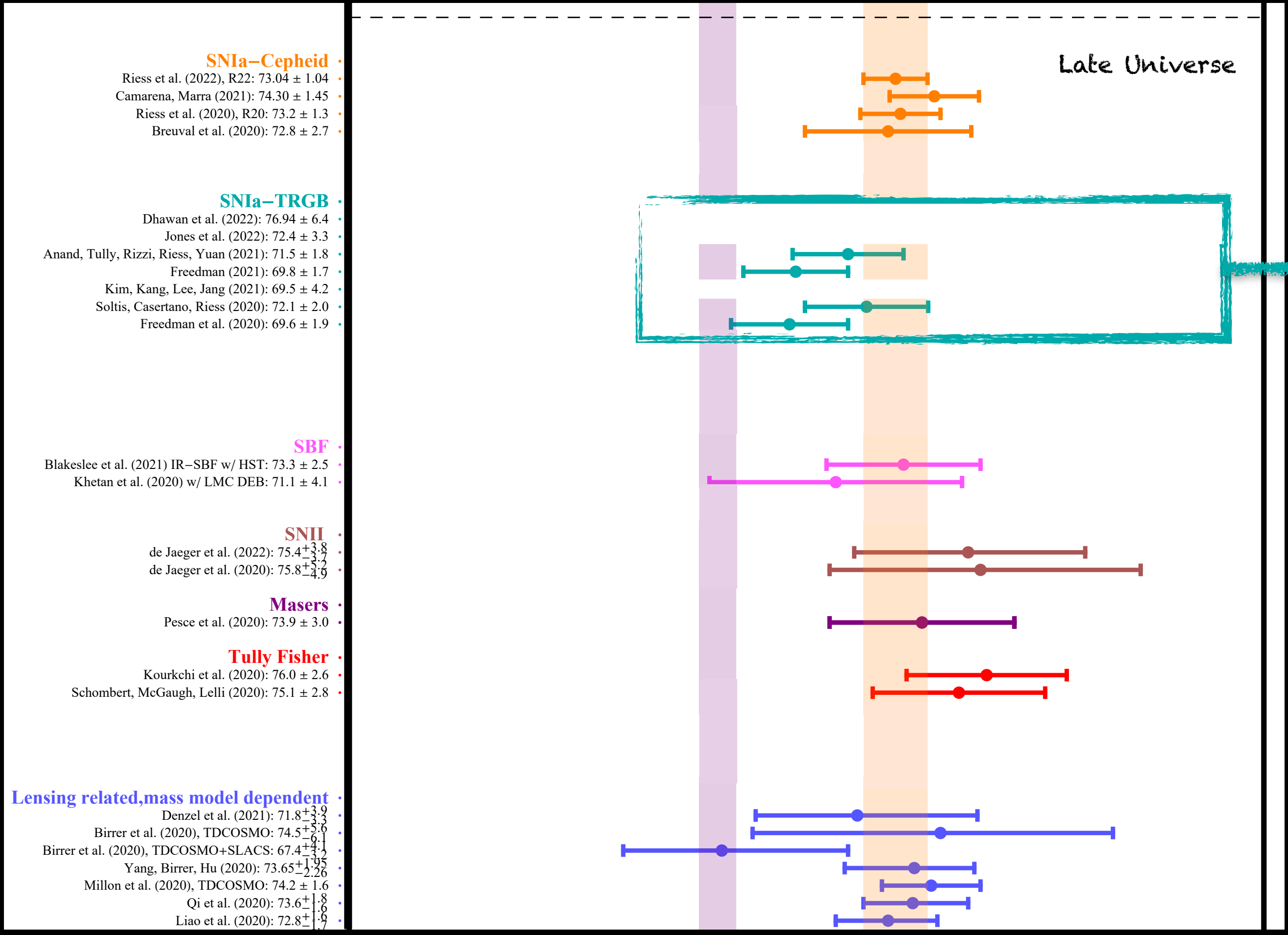
H0 = 72.1±2.0 km/s/Mpc

Soltis et al., arXiv:2012.09196

H0 = 69.6±1.9 km/s/Mpc

Freedman et al., arXiv:2002.01550

Late universe measurements since 2020



Abdalla et al., *JHEAp* 34 (2022) 49-211

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.

New independent re-analysis of the targets presented by the Carnegie-Chicago Hubble Program (CCHP).

H0 = 71.5±1.8 km/s/Mpc

Anand et al., arXiv:2108.00007

H0 = 69.8±1.7 km/s/Mpc

Freedman, arXiv:2106.15656

H0 = 72.1±2.0 km/s/Mpc

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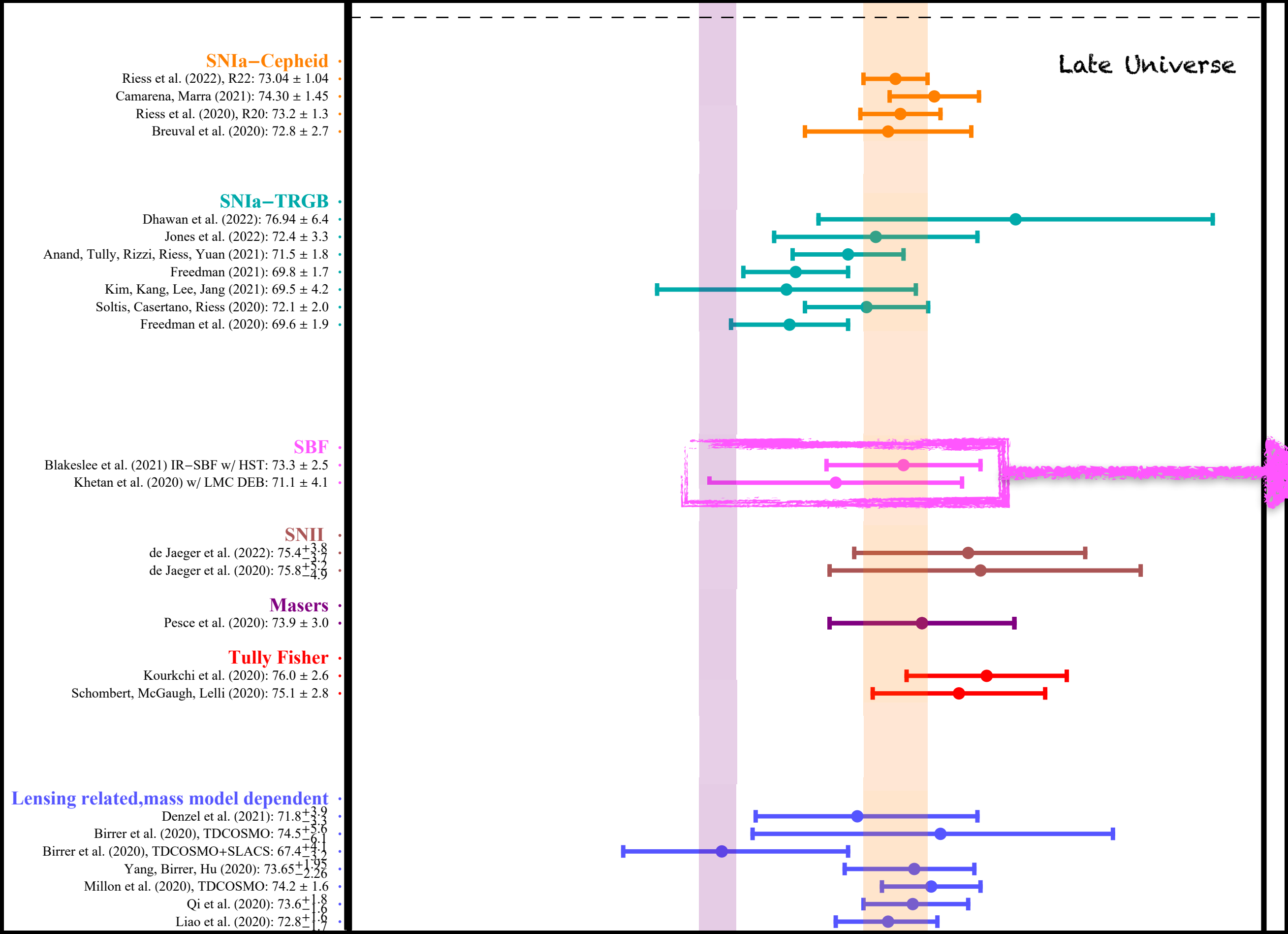
Late universe measurements since 2020



Abdalla et al., *JHEAp* 34 (2022) 49-211

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

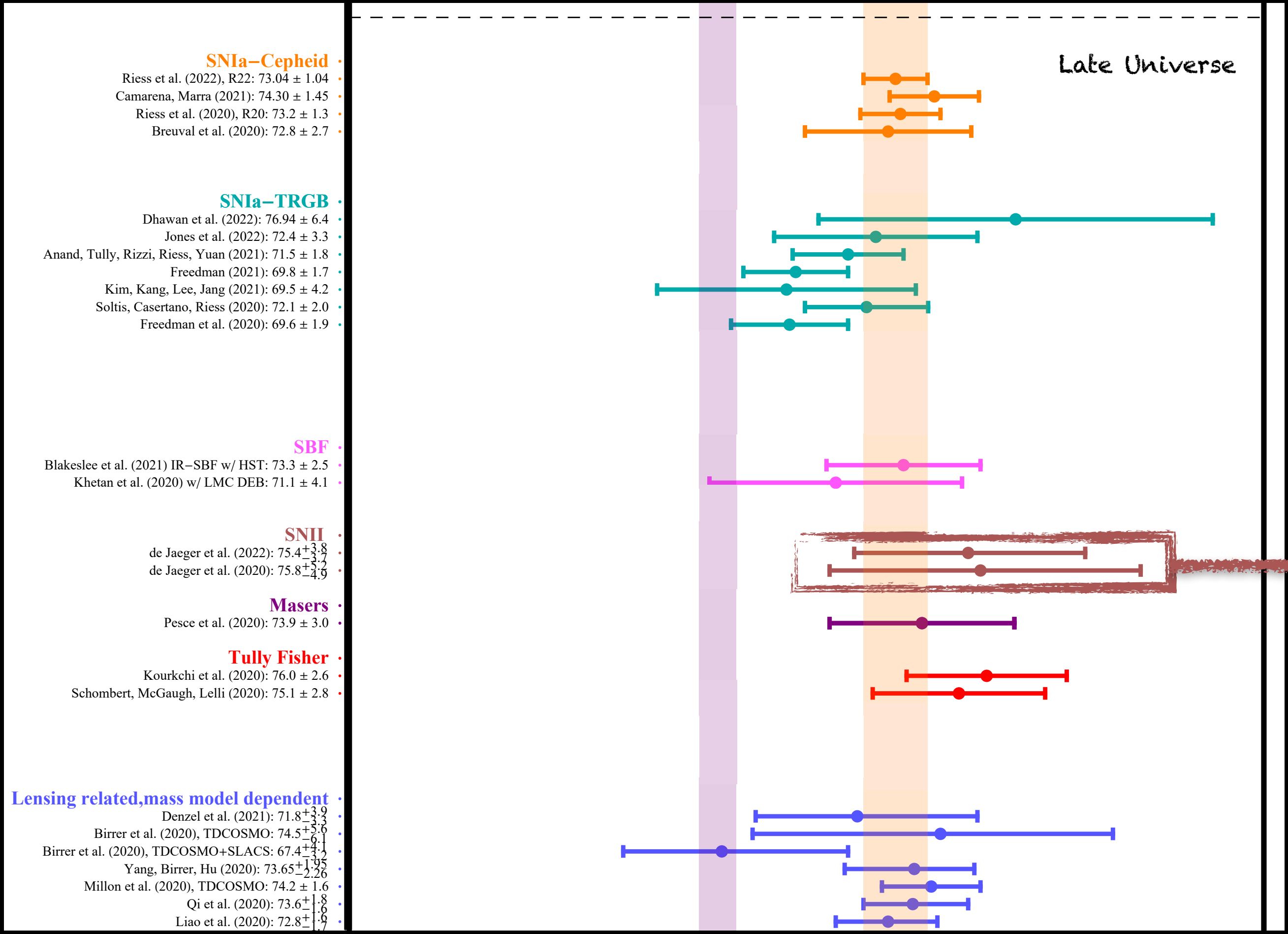
H0 = 73.3 ± 2.5 km/s/Mpc

Blakeslee et al., arXiv:2101.02221

H0 = 70.5 ± 4.1 km/s/Mpc

Khetan et al. arXiv:2008.07754

Late universe measurements since 2020



Abdalla et al., *JHEAp* 34 (2022) 49-211

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

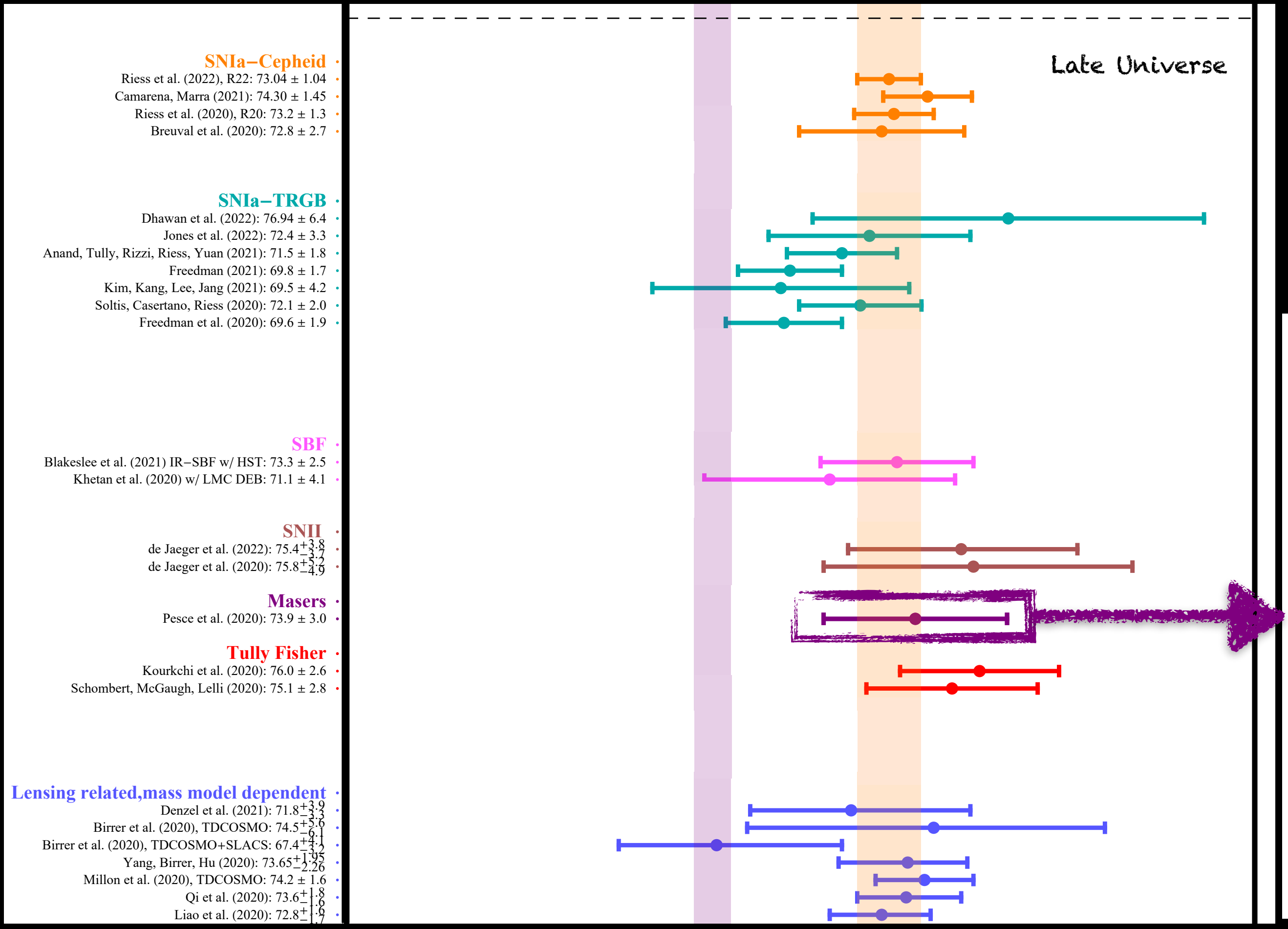
$H0 = 75.4^{+3.8}_{-3.7}$ km/s/Mpc

de Jaeger et al., arXiv:2203.08974

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

de Jaeger et al., arXiv:2006.03412

Late universe measurements since 2020



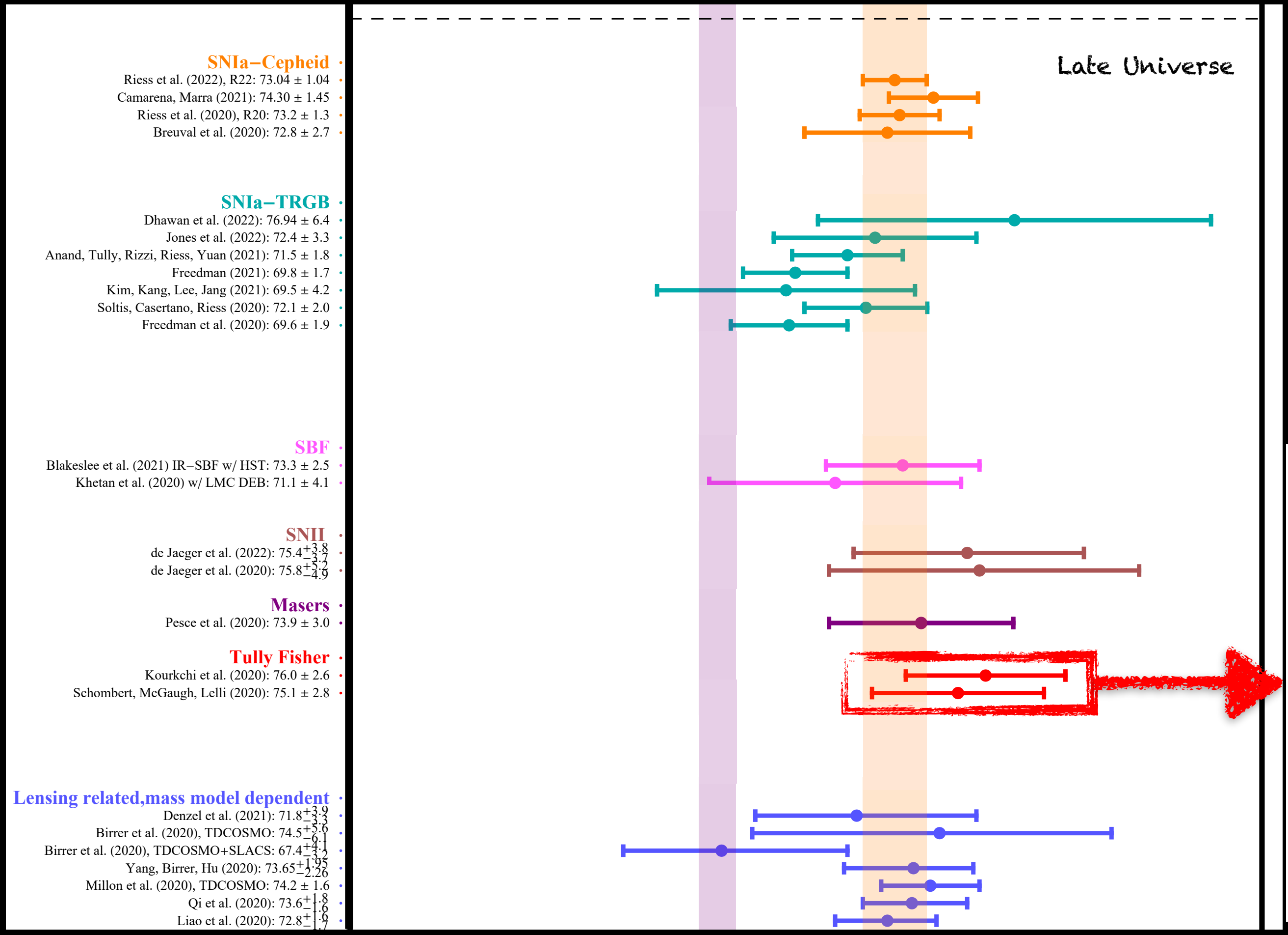
Abdalla et al., *JHEAp* 34 (2022) 49-211

$H0 = 73.9 \pm 3.0$ km/s/Mpc

Pesce et al. arXiv:2001.09213

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 since 2020



Abdalla et al., *JHEAp* 34 (2022) 49-211

H0 = 76.00 ± 2.55 km/s/Mpc

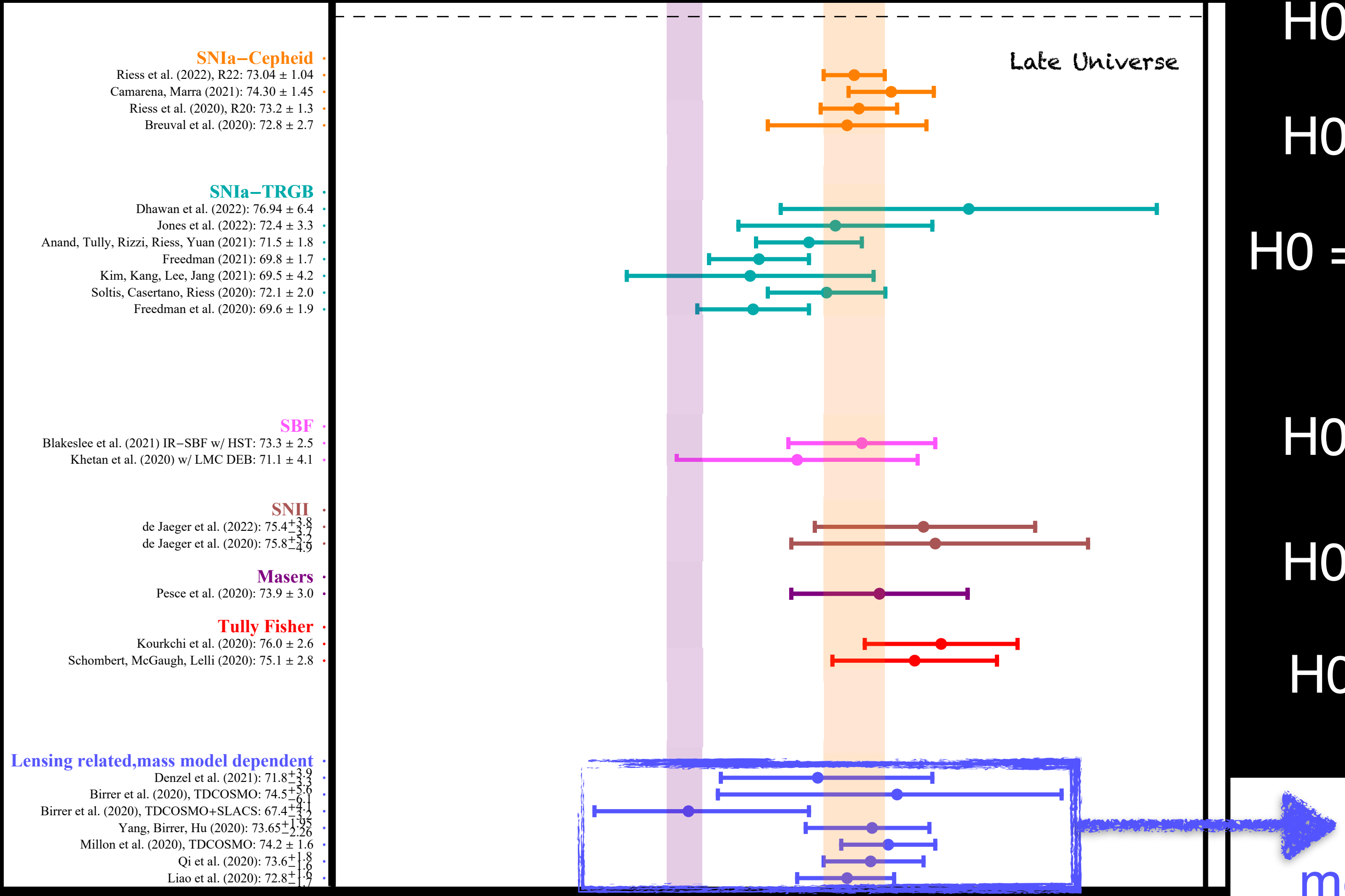
Kourkchi et al. arXiv:2004.14499

H0 = 75.10 ± 2.75 km/s/Mpc

Schombert et al. arXiv:2006.08615

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)

Late universe measurements since 2020



Abdalla et al., *JHEAp* 34 (2022) 49-211

$H0 = 72.8^{+1.6}_{-1.7}$ km/s/Mpc

Liao et al. arXiv:2002.10605

$H0 = 73.6^{+1.8}_{-1.6}$ km/s/Mpc

Qi et al. arXiv:2011.00713

$H0 = 73.65^{+1.95}_{-2.26}$ km/s/Mpc

Yang et al. arXiv:2003.03277

TDCOSMO

$H0 = 74.5^{+5.6}_{-6.1}$ km/s/Mpc

TDCOSMO+SLACS

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

Birrer et al. arXiv:2007.02941

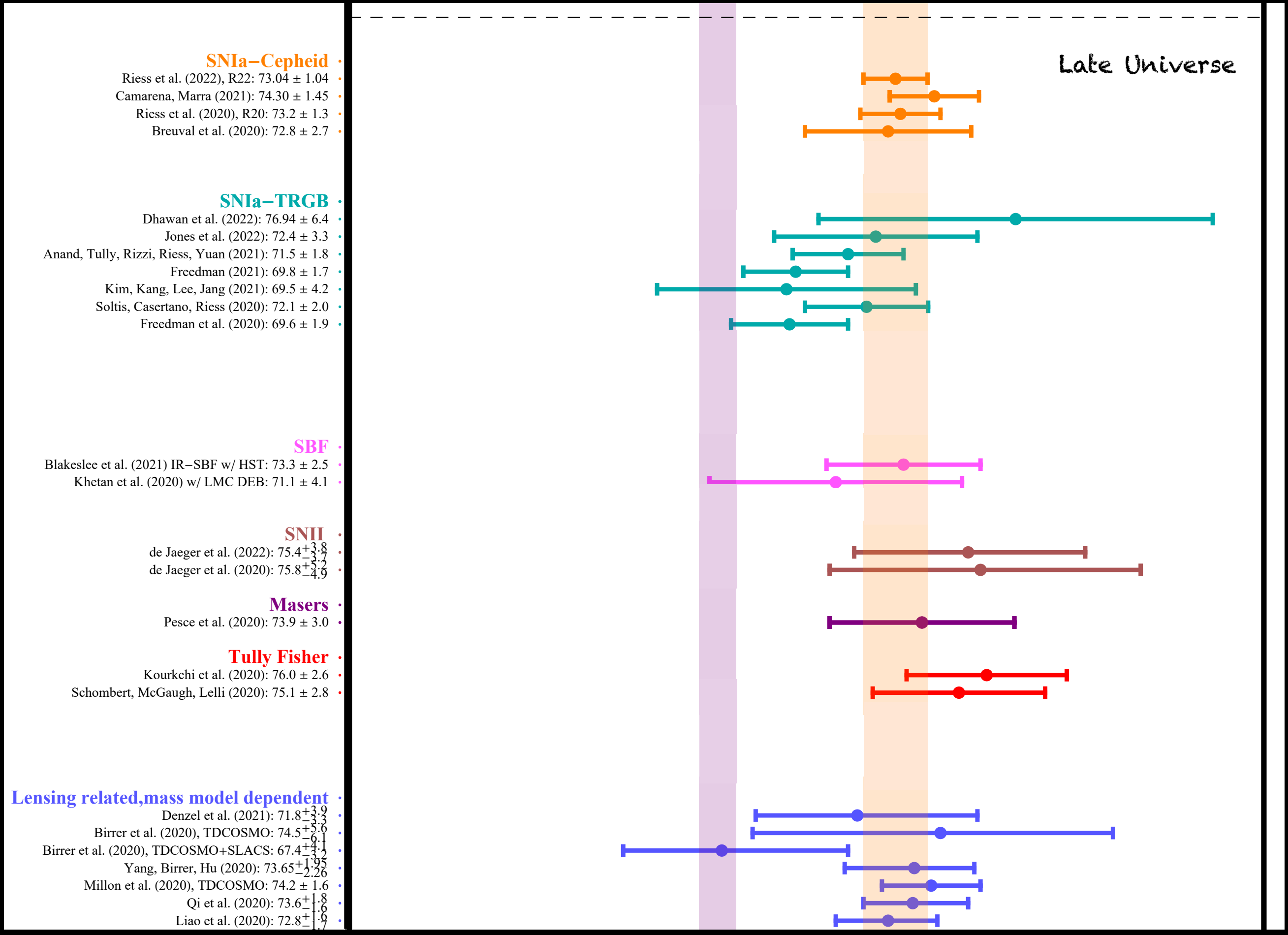
$H0 = 71.8^{+3.9}_{-3.3}$ km/s/Mpc

Denzel et al. arXiv:2007.14398

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.

Model Dependent

Late universe measurements since 2020



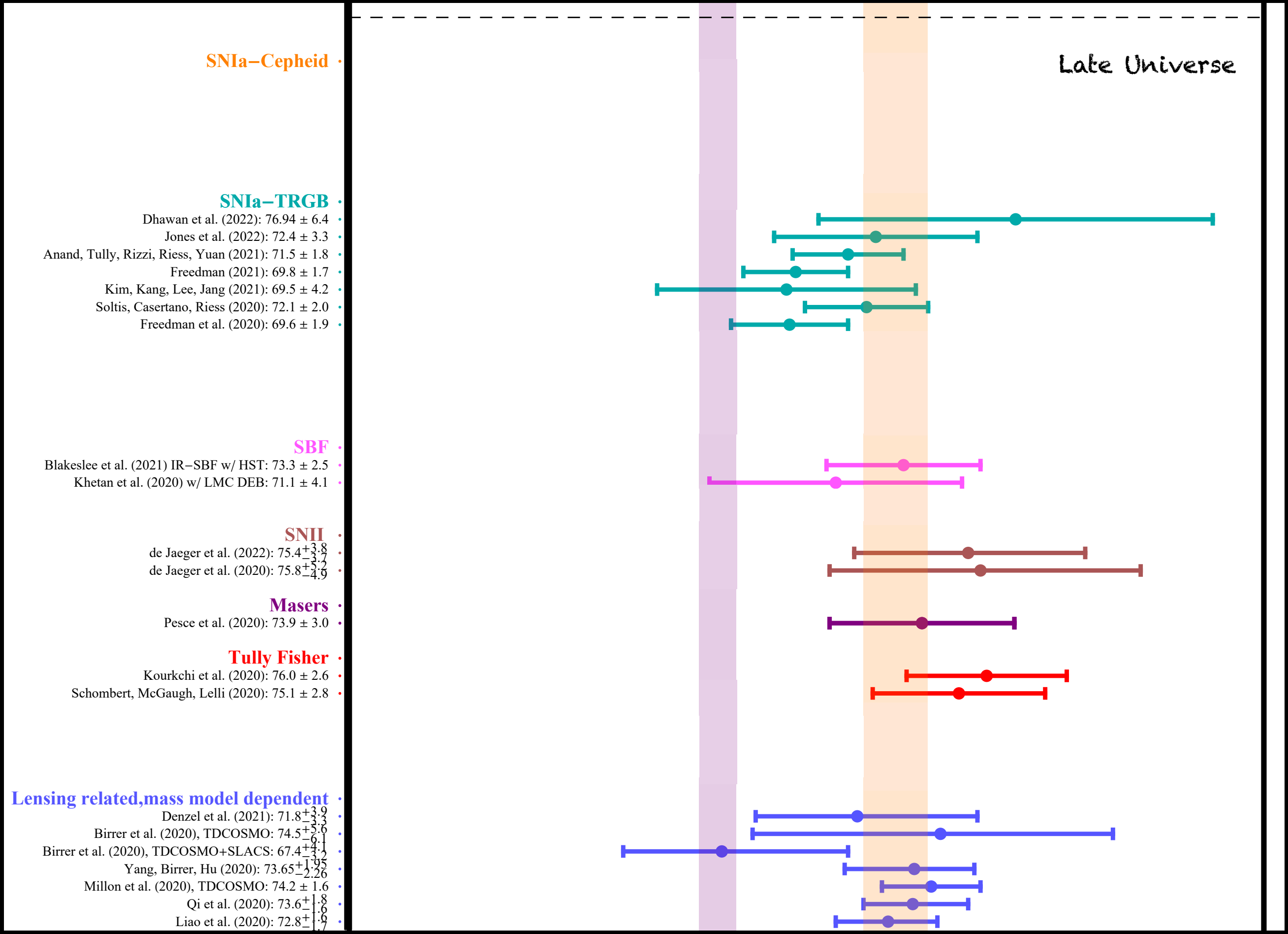
Abdalla et al., *JHEAp* 34 (2022) 49-211

Following the method used in
Di Valentino, *MNRAS* 502 (2021) 2, 2065-2073
we can combine all of them together and have

6.55σ tension with Planck

H0 = 72.97 ± 0.63 km/s/Mpc

Late universe measurements since 2020



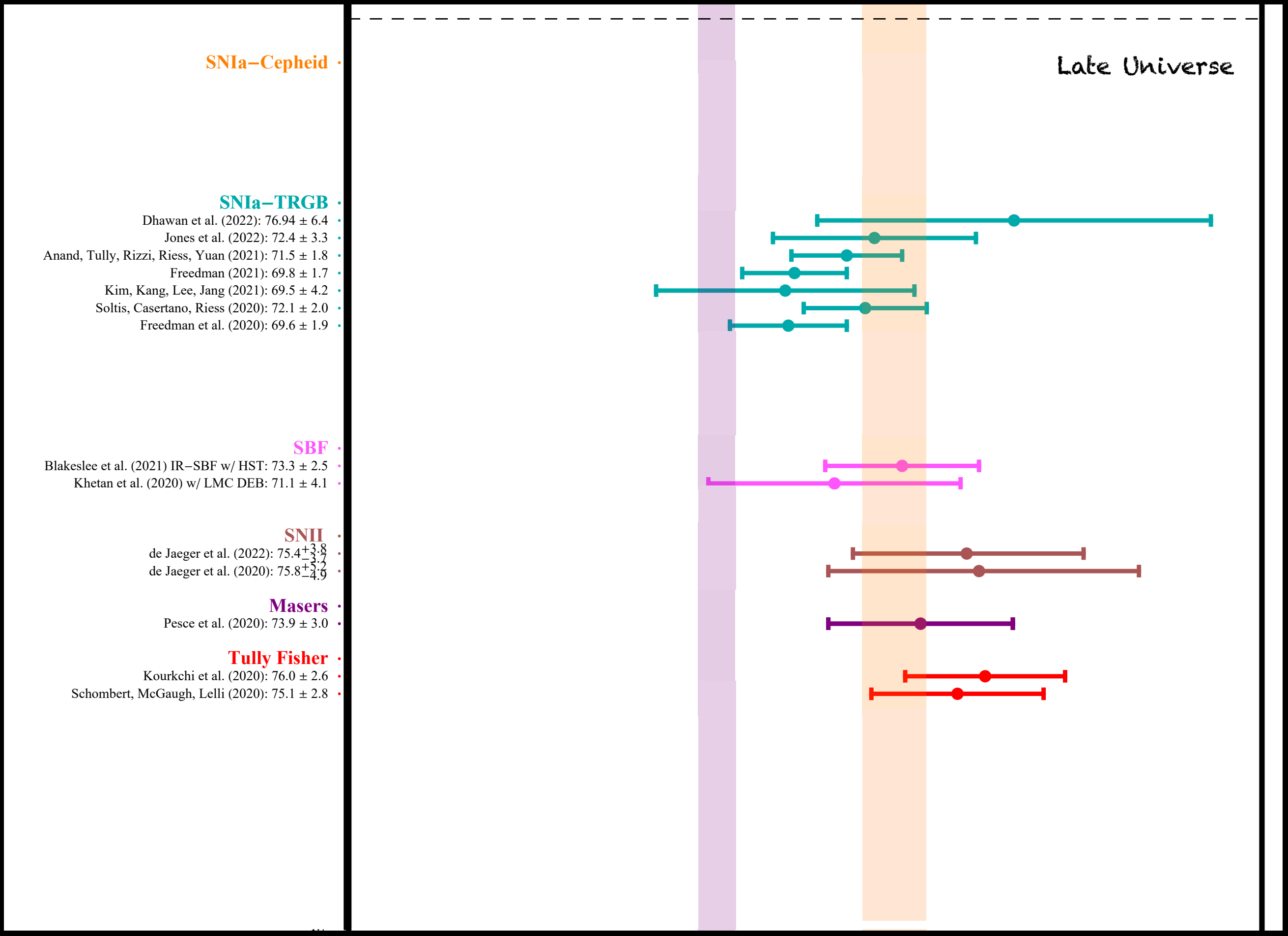
Abdalla et al., *JHEAp* 34 (2022) 49-211

Following the method used in Di Valentino, *MNRAS* 502 (2021) 2, 2065-2073 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 a

conservative estimate (5.5σ tension with Planck)

H0 = 72.73 ± 0.80 km/s/Mpc

Late universe measurements since 2020

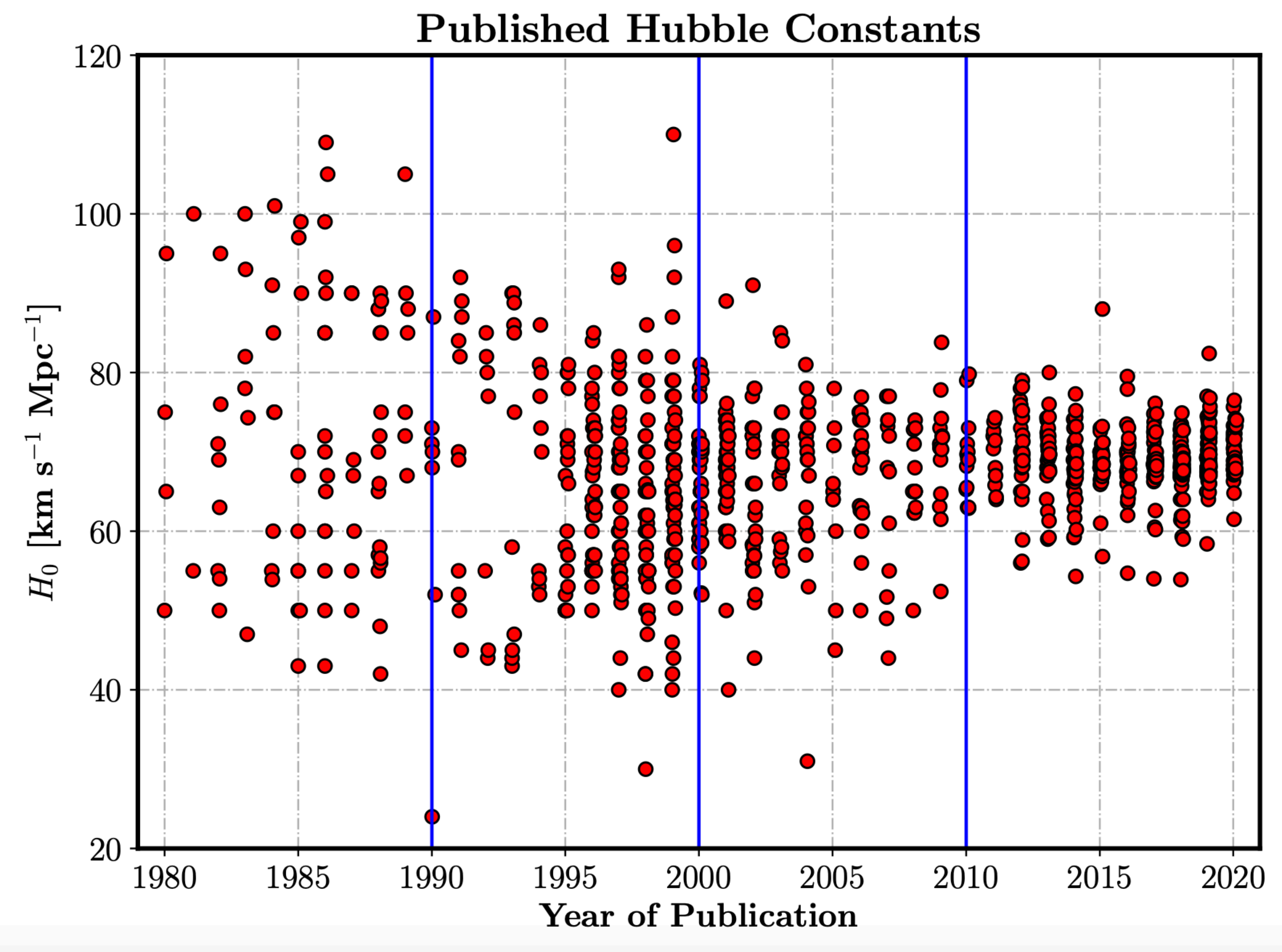


Abdalla et al., *JHEAp* 34 (2022) 49-211

Following the method used in
Di Valentino, *MNRAS* 502 (2021) 2, 2065-2073
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 an

ultra-conservative estimate (4.8σ tension with Planck)

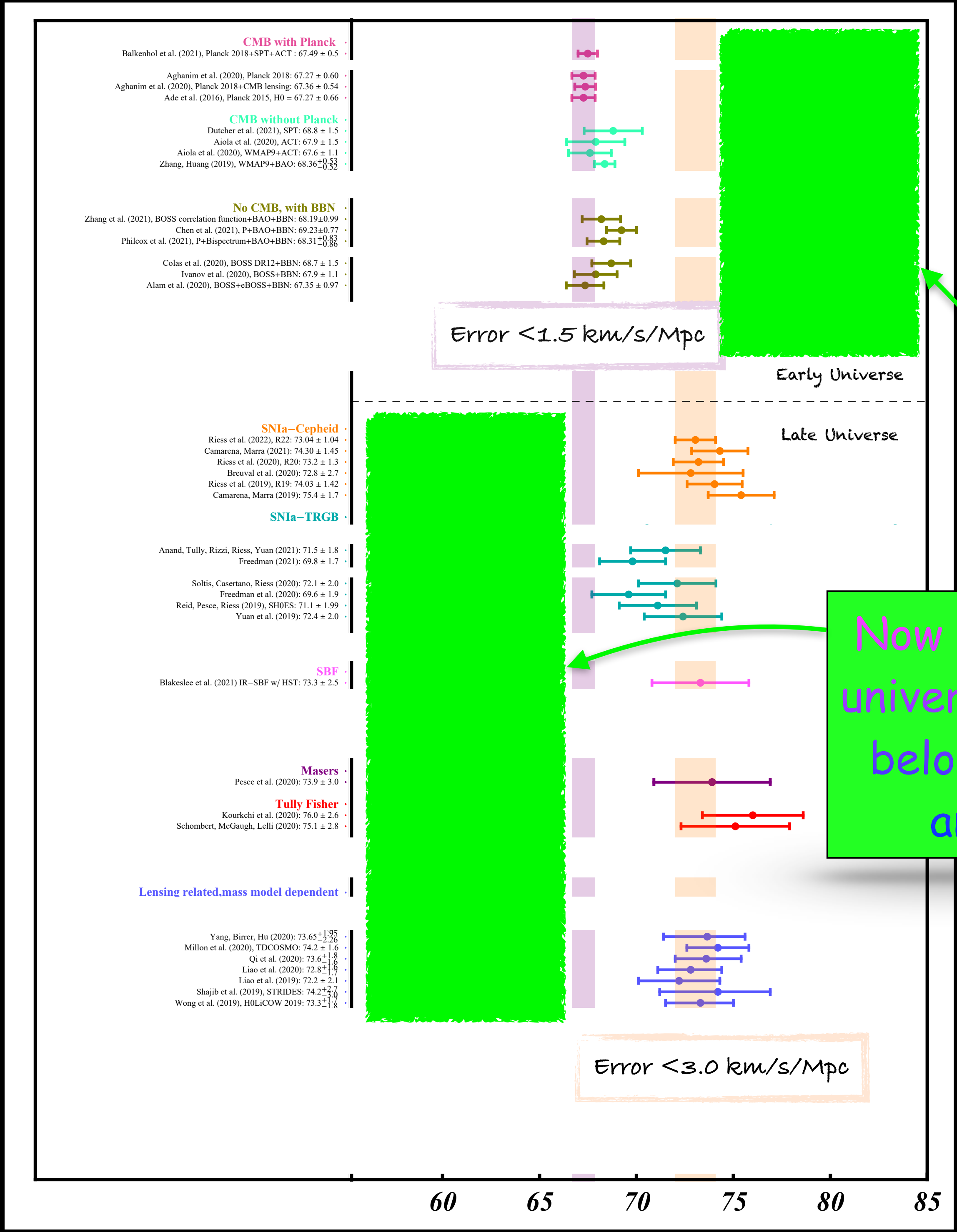
H0 = 73.3 ± 1.1 km/s/Mpc



Freedman, *Astrophys.J.* 919 (2021) 1, 16

In the past the tension was within the same types of measurements and at the same redshifts and thus pointing directly to systematics.

High precision measurements of H0



Now there are no late universe measurements below the early ones and vice versa.

Abdalla et al., *JHEAp* 34 (2022) 49-211

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.

The ΛCDM model

Among a number of cosmological models introduced in the literature, the Lambda Cold Dark Matter (ΛCDM) cosmological model is the mathematically simplest model, and has now practically been selected as the “standard” cosmological scenario, because it provides a remarkable description of a wide range of astrophysical and cosmological probes.

However, despite its marvelous fit to the available observations, ΛCDM harbours large areas of phenomenology and ignorance. For example, it still cannot explain key pillars in our understanding of the structure and evolution of the Universe, namely, Dark Energy, Dark Matter and Inflation.

The ΛCDM model

In the ΛCDM paradigm these three pillars are our simplest guesses.

- DE assumes its simplest form, that is the cosmological constant, without any strong physical basis.
- The nature of DM is still a mystery except for its gravitational interaction, as suggested by the observational evidence. We know, however, that DM is essential for structure formation in the late Universe, so most of it must be pressure-less, cold, and stable on cosmological time scales. Moreover, despite the significant efforts in the last decades to investigate DM and the physics beyond the SM of particle physics, in laboratory experiments and from devised astrophysical observations, no evidence pointing to the dark matter particle has been found.
- Finally, even though the theory of inflation has solved a number of crucial puzzles related to the early evolution of the Universe, in the standard model this is given by a single, minimally coupled, slow-rolling scalar field.

The ΛCDM model

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.

Let’s modify the ΛCDM model…

The Neutrino effective number

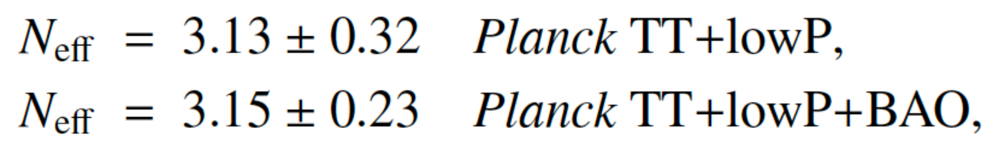
We can consider modifications in the
dark matter sector.

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

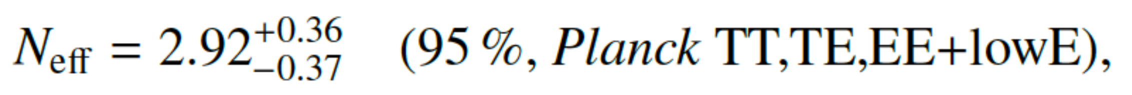
The expected value is Neff = 3.044, if we assume standard electroweak interactions and three active massless neutrinos. If we measure a Neff > 3.044, we are in presence of extra radiation.

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



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

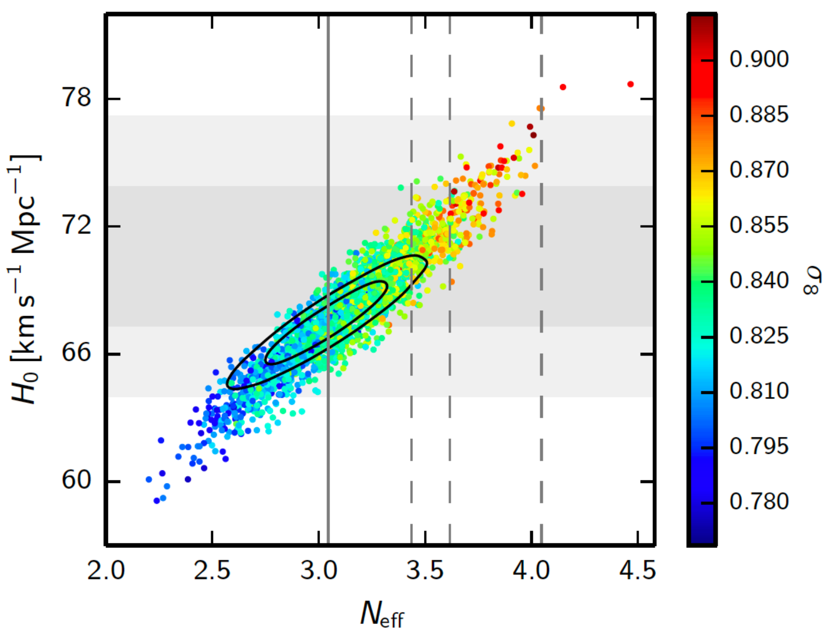
with the new Planck 2018 bound,



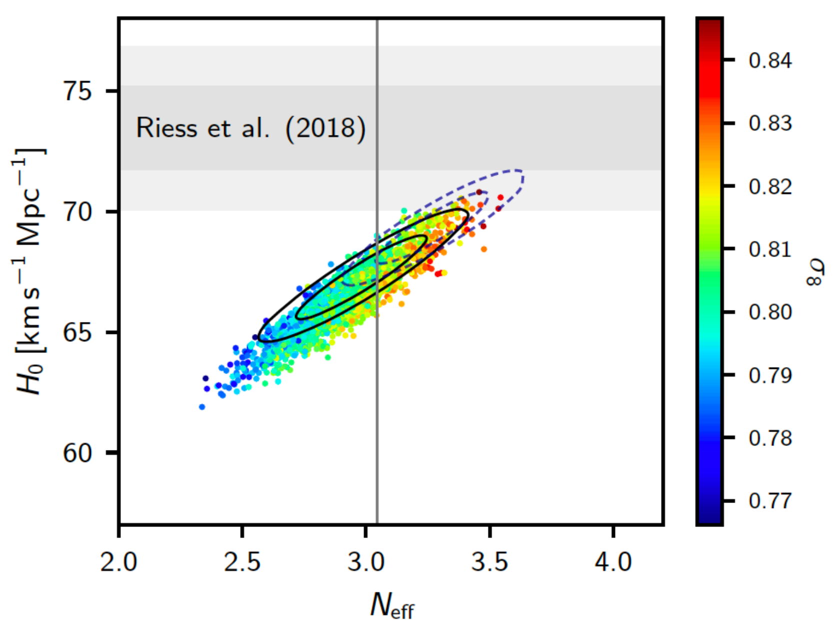
$$N_{\rm eff} = 2.92^{+0.36}_{-0.37} \quad (95\,\%,\ \textit{Planck}\ \mathrm{TT,TE,EE+lowE}),$$

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 SH0ES increases from 1.7σ to 3.9σ also varying Neff.



Planck collaboration, 2015



Planck collaboration, 2018

The Dark energy equation of state

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:

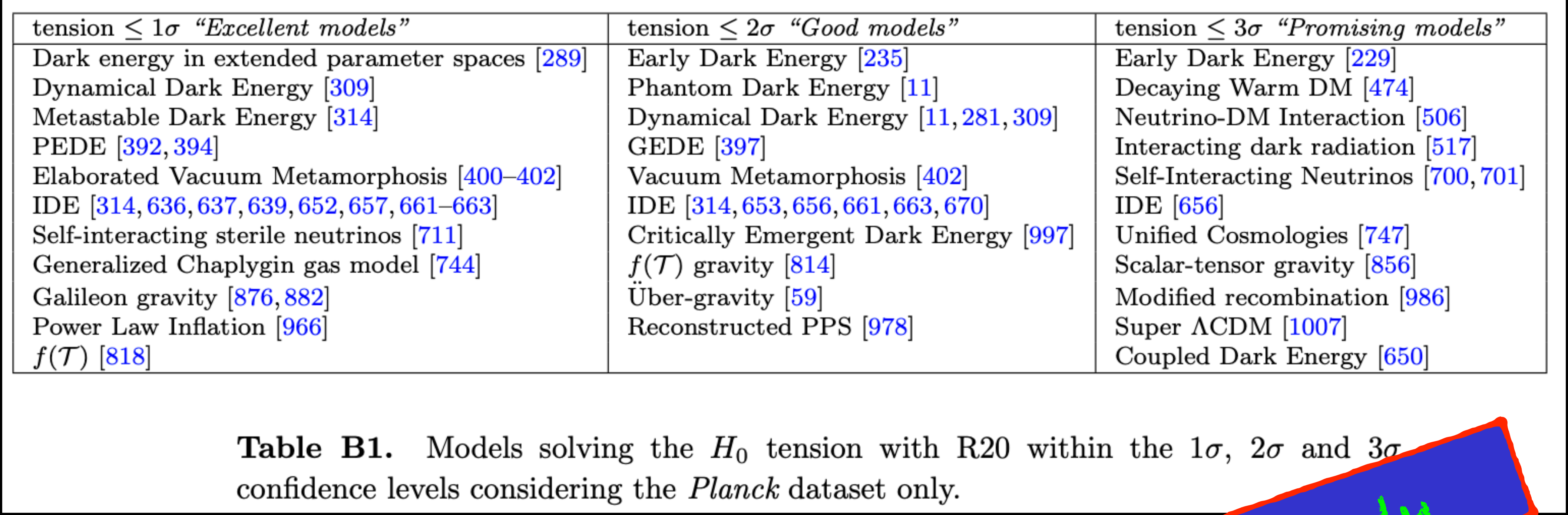
$$H^2 = H_0^2 \Big[\Omega_m(1+z)^3 + \Omega_r(1+z)^4 \\ + \Omega_{\rm de}(1+z)^{3(1+w)} + \Omega_k(1+z)^2\Big]$$

w introduces a geometrical degeneracy with the Hubble constant that will be unconstrained using the CMB data only, resulting in agreement with SH0ES.

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.

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

Let’s see an example…

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

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

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

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

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

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

with

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

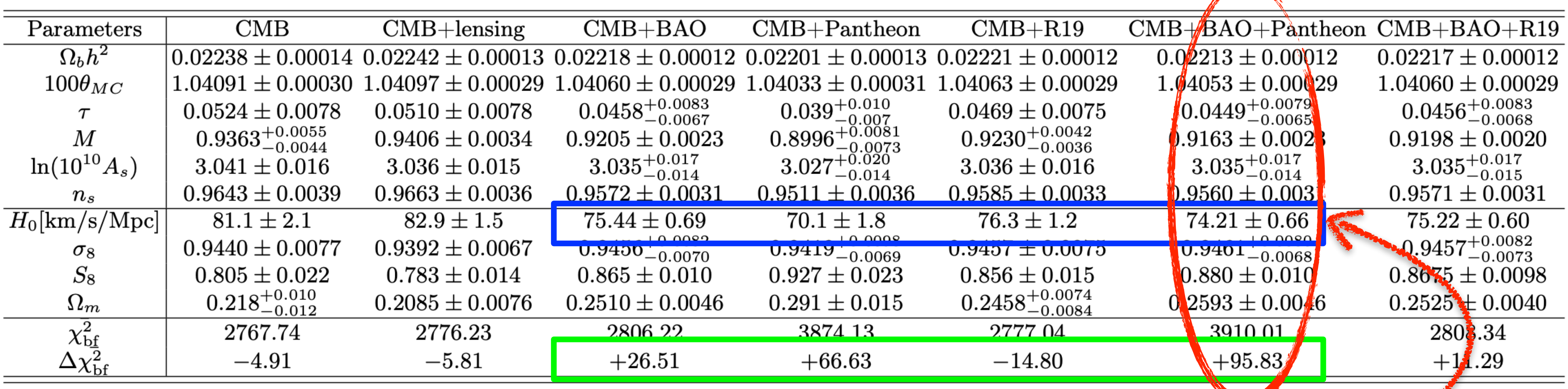
The original model did not include an explicit high redshift cosmological constant; we see that this implies that

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

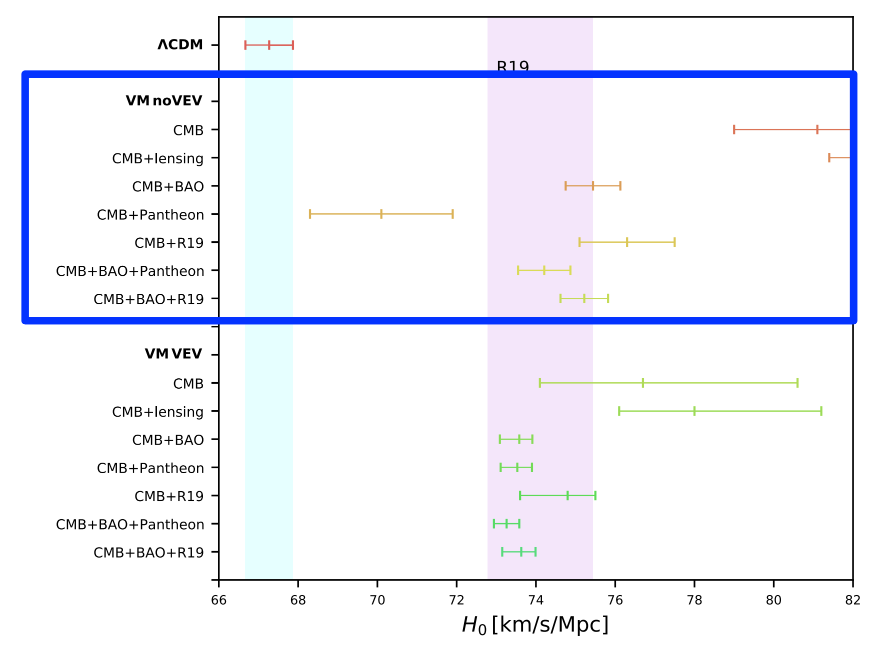
i.e. the parameter M is fixed and depends on the matter density, and this model has the same number of degrees of freedom as ΛCDM.

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	$0.9456^{+0.0083}_{-0.0070}$	$0.9419^{+0.0098}_{-0.0069}$	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 H0~73-74 km/s/Mpc !!

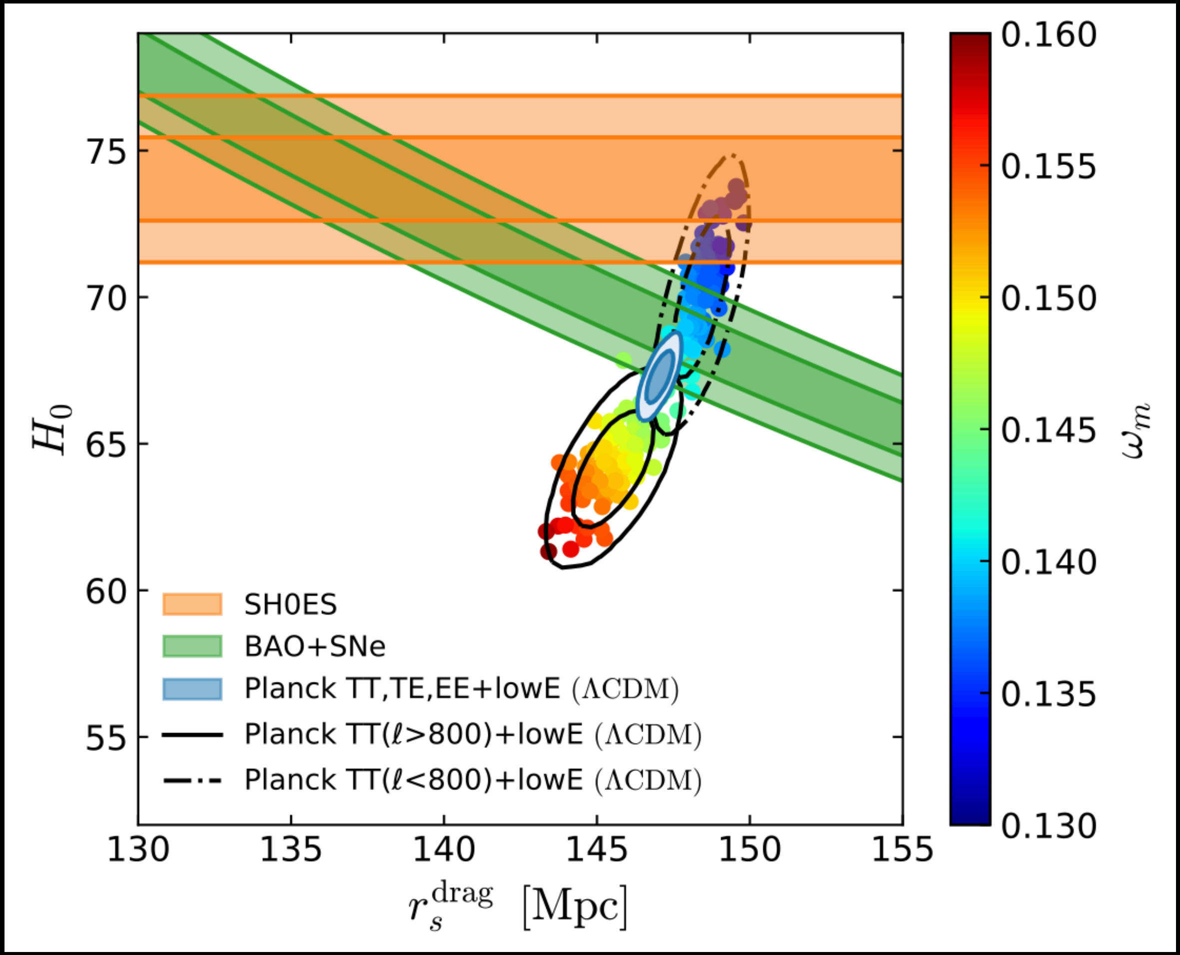
H0 is exactly in agreement with SH0ES even if BAO and Pantheon are included. However, this worsen considerably the fit of the data because the model fails in recover the shape of H(z) at low redshifts.

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

What about BAO+Pantheon?

BAO+Pantheon measurements constrain the product of H0 and the sound horizon r_s .

In order to have a higher H0 value in agreement with SH0ES, 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 is the most promising way to put in agreement all the measurements.

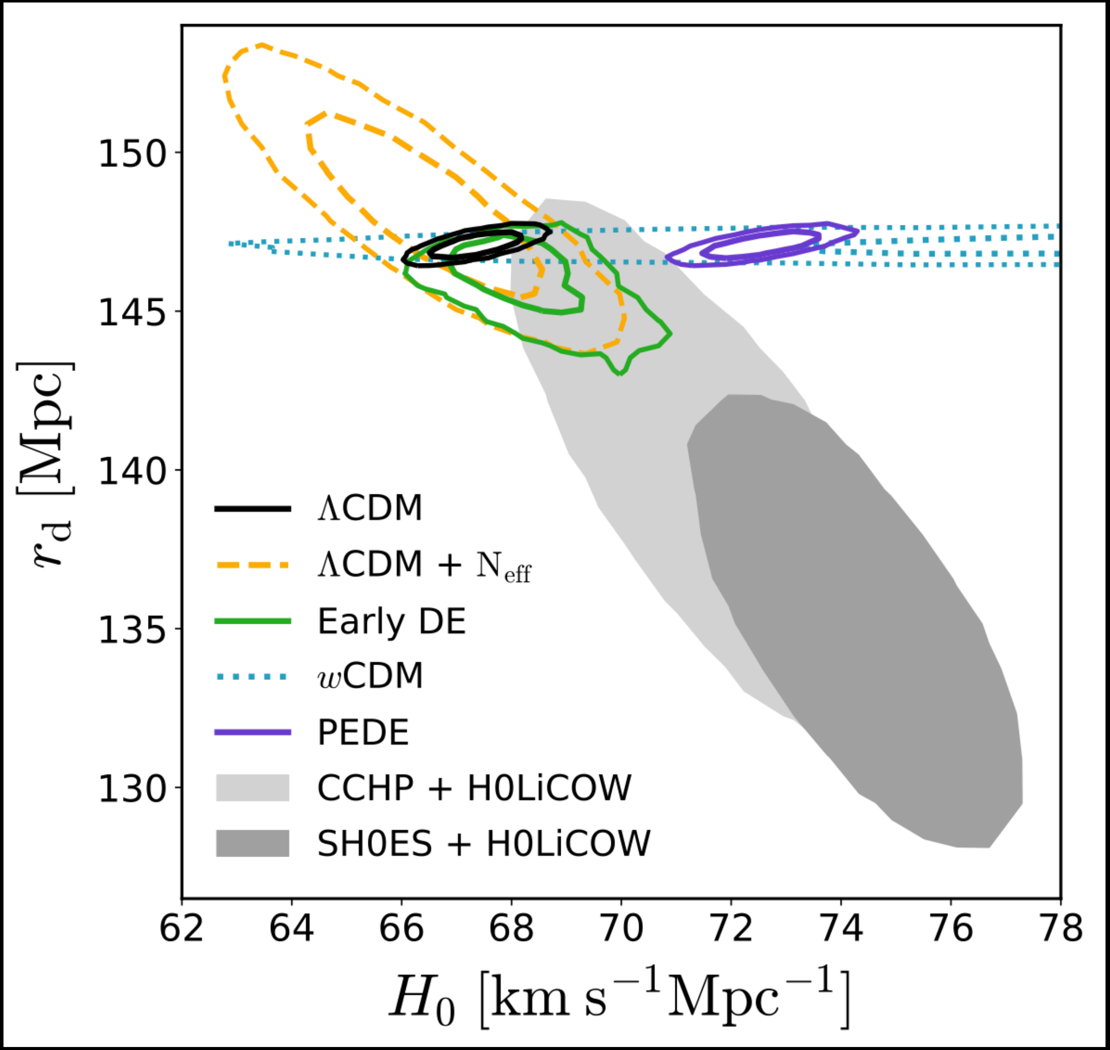


Knox and Millea, *Phys.Rev.D* 101 (2020) 4, 043533

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 because they decrease the expansion history at intermediate redshift, but leave r_s unaltered.

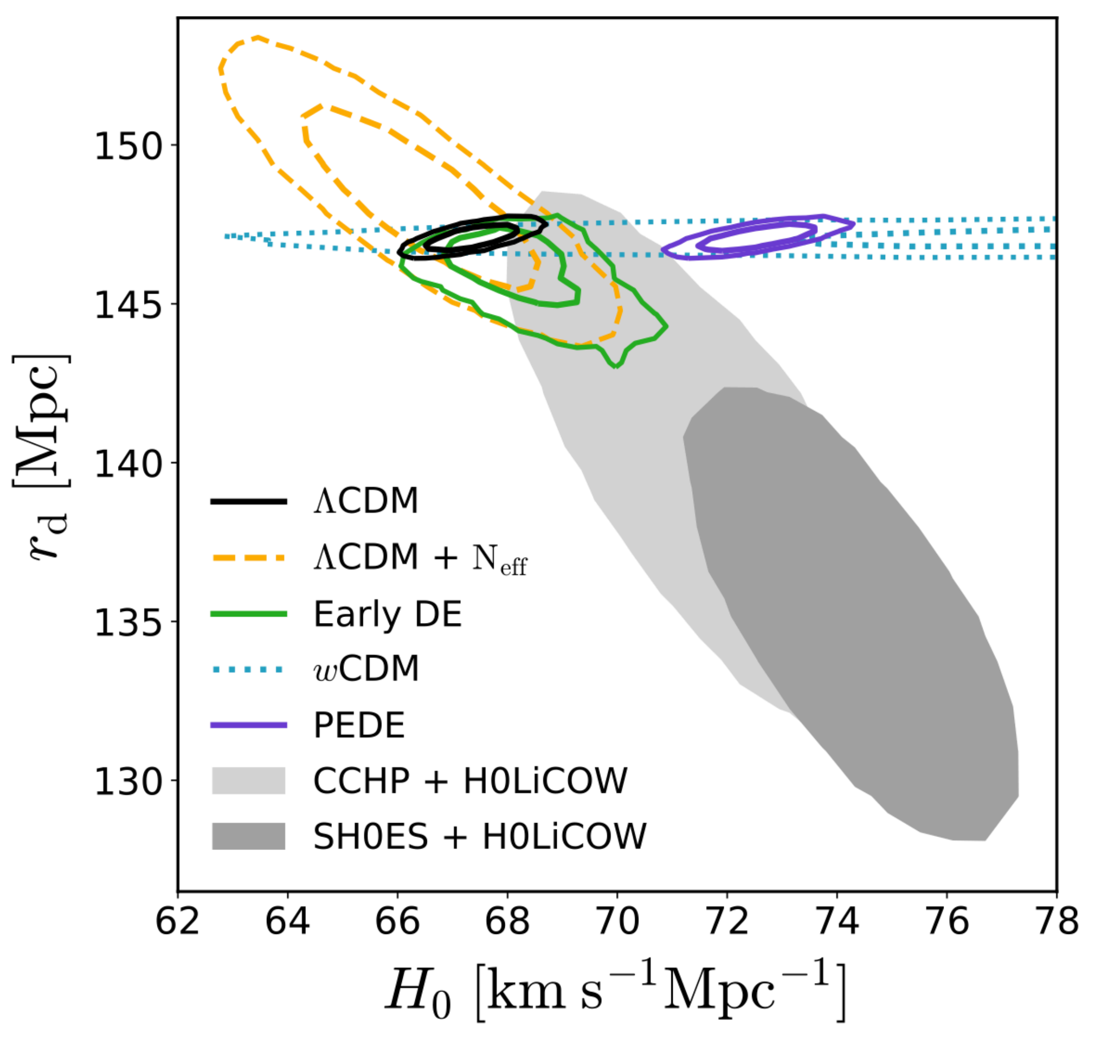


Arendse et al., Astron.Astrophys. 639 (2020) A57

Early vs late time solutions

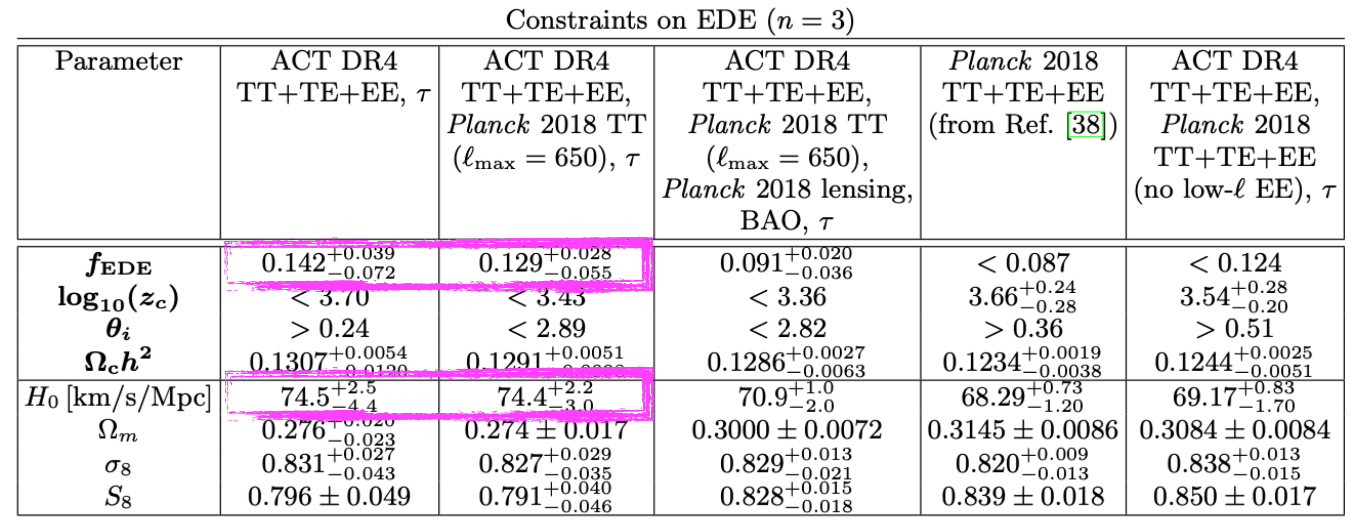
Here we can see the comparison of the 2σ credibility regions of the CMB constraints and the measurements from late-time observations (SN + BAO + H0LiCOW + SH0ES).

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 between Planck and SH0ES.



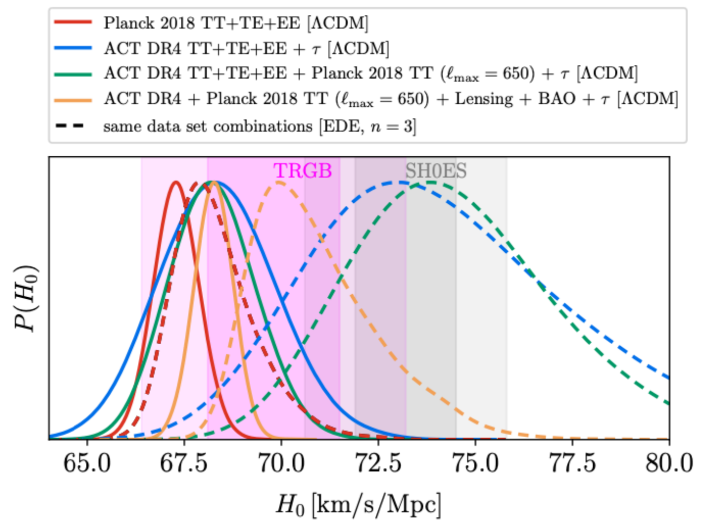
Arendse et al., Astron.Astrophys. 639 (2020) A57

Early Dark Energy



Constraints on EDE ($n = 3$)

Parameter	ACT DR4 TT+TE+EE, τ	ACT DR4 TT+TE+EE, *Planck* 2018 TT ($\ell_{\rm max} = 650$), τ	ACT DR4 TT+TE+EE, *Planck* 2018 TT ($\ell_{\rm max} = 650$), *Planck* 2018 lensing, BAO, τ	*Planck* 2018 TT+TE+EE (from Ref. [38])	ACT DR4 TT+TE+EE, *Planck* 2018 TT+TE+EE (no low-ℓ EE), τ
$\boldsymbol{f_{\rm EDE}}$	$0.142^{+0.039}_{-0.072}$	$0.129^{+0.028}_{-0.055}$	$0.091^{+0.020}_{-0.036}$	< 0.087	< 0.124
$\boldsymbol{\log_{10}(z_c)}$	< 3.70	< 3.43	< 3.36	$3.66^{+0.24}_{-0.28}$	$3.54^{+0.28}_{-0.20}$
$\boldsymbol{\theta_i}$	> 0.24	< 2.89	< 2.82	> 0.36	> 0.51
$\boldsymbol{\Omega_c h^2}$	$0.1307^{+0.0054}_{-0.0120}$	$0.1291^{+0.0051}_{[illegible]}$	$0.1286^{+0.0027}_{-0.0063}$	$0.1234^{+0.0019}_{-0.0038}$	$0.1244^{+0.0025}_{-0.0051}$
H_0 [km/s/Mpc]	$74.5^{+2.5}_{-4.4}$	$74.4^{+2.2}_{-3.0}$	$70.9^{+1.0}_{-2.0}$	$68.29^{+0.73}_{-1.20}$	$69.17^{+0.83}_{-1.70}$
Ω_m	$0.276^{+0.020}_{-0.023}$	0.274 ± 0.017	0.3000 ± 0.0072	0.3145 ± 0.0086	0.3084 ± 0.0084
σ_8	$0.831^{+0.027}_{-0.043}$	$0.827^{+0.029}_{-0.035}$	$0.829^{+0.013}_{-0.021}$	$0.820^{+0.009}_{-0.013}$	$0.838^{+0.013}_{-0.015}$
S_8	0.796 ± 0.049	$0.791^{+0.040}_{-0.046}$	$0.828^{+0.015}_{-0.018}$	0.839 ± 0.018	0.850 ± 0.017

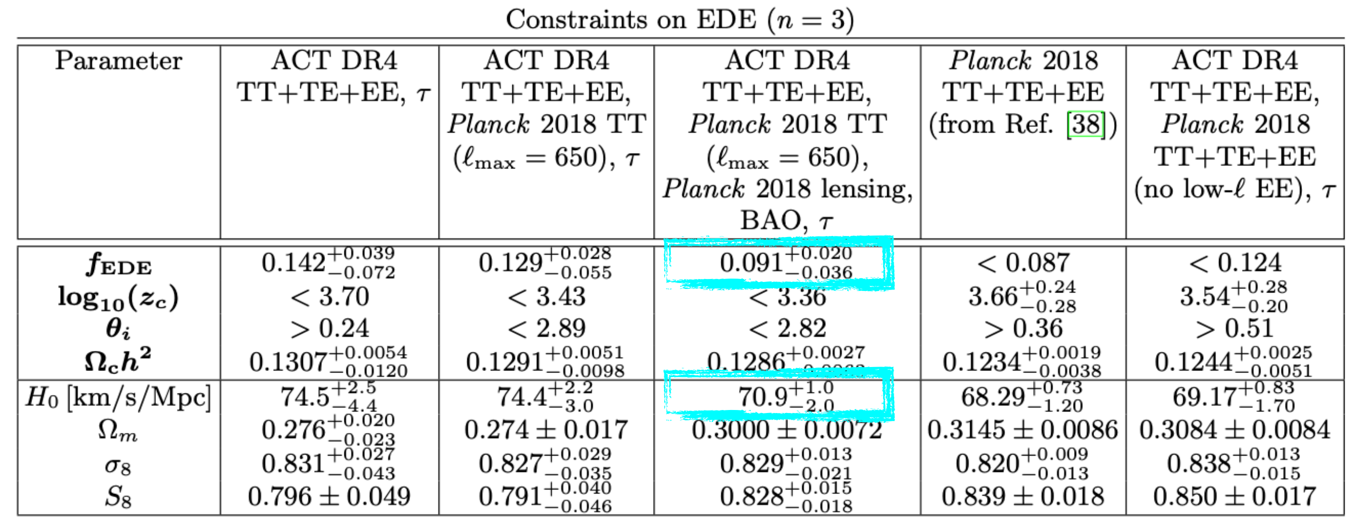


ACT collaboration, Hill et al. arXiv:*2109.04451*

Considering ACT only data or combined with Planck TT up to multipoles 650, there is an evidence for EDE > 3σ, solving completely the Hubble tension.

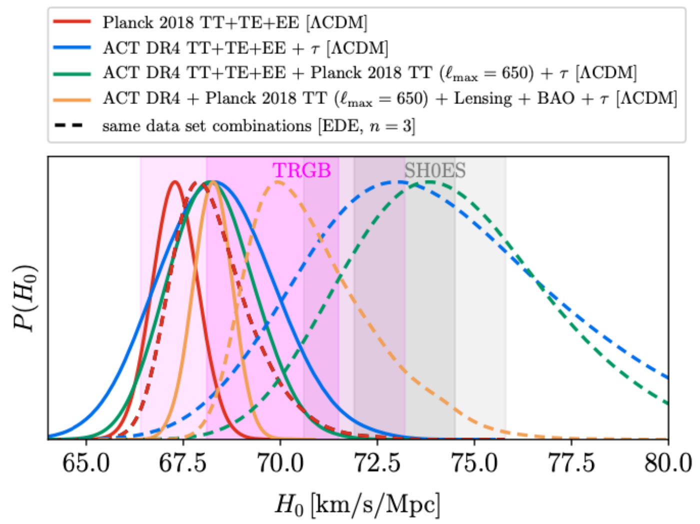
See also Poulin et al. *Phys.Rev.D* 104 (2021) 12, 123550

Early Dark Energy



Constraints on EDE ($n = 3$)

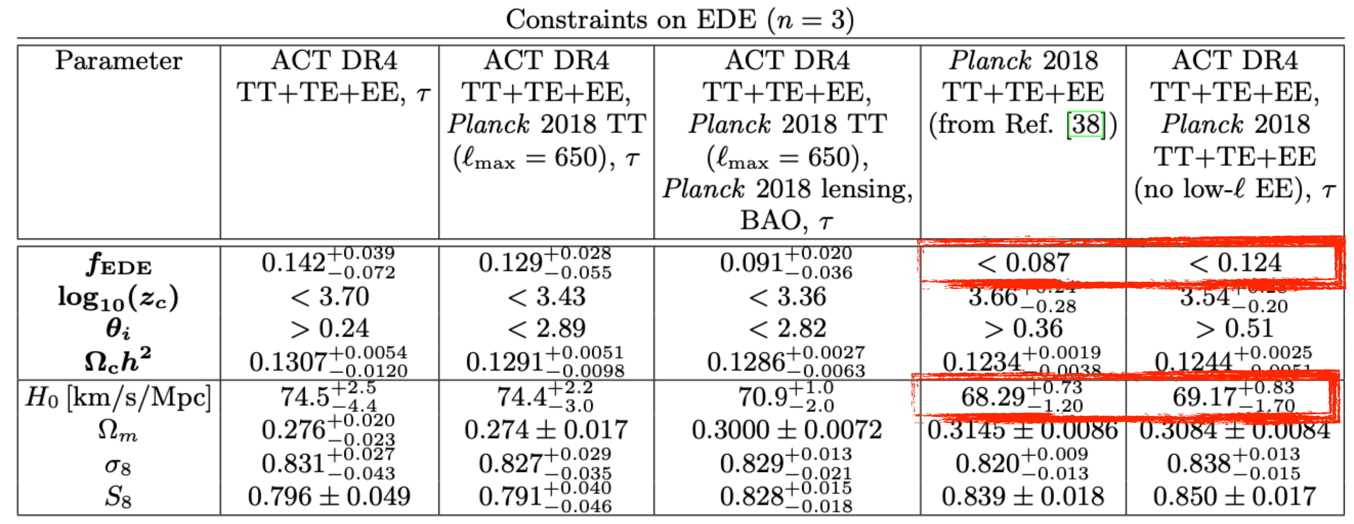
Parameter	ACT DR4 TT+TE+EE, τ	ACT DR4 TT+TE+EE, *Planck* 2018 TT ($\ell_{\rm max} = 650$), τ	ACT DR4 TT+TE+EE, *Planck* 2018 TT ($\ell_{\rm max} = 650$), *Planck* 2018 lensing, BAO, τ	*Planck* 2018 TT+TE+EE (from Ref. [38])	ACT DR4 TT+TE+EE, *Planck* 2018 TT+TE+EE (no low-ℓ EE), τ
$\boldsymbol{f_{\rm EDE}}$	$0.142^{+0.039}_{-0.072}$	$0.129^{+0.028}_{-0.055}$	$0.091^{+0.020}_{-0.036}$	< 0.087	< 0.124
$\boldsymbol{\log_{10}(z_c)}$	< 3.70	< 3.43	< 3.36	$3.66^{+0.24}_{-0.28}$	$3.54^{+0.28}_{-0.20}$
$\boldsymbol{\theta_i}$	> 0.24	< 2.89	< 2.82	> 0.36	> 0.51
$\boldsymbol{\Omega_c h^2}$	$0.1307^{+0.0054}_{-0.0120}$	$0.1291^{+0.0051}_{-0.0098}$	$0.1286^{+0.0027}$ [illegible]	$0.1234^{+0.0019}_{-0.0038}$	$0.1244^{+0.0025}_{-0.0051}$
H_0 [km/s/Mpc]	$74.5^{+2.5}_{-4.4}$	$74.4^{+2.2}_{-3.0}$	$70.9^{+1.0}_{-2.0}$	$68.29^{+0.73}_{-1.20}$	$69.17^{+0.83}_{-1.70}$
Ω_m	$0.276^{+0.020}_{-0.023}$	0.274 ± 0.017	0.3000 ± 0.0072	0.3145 ± 0.0086	0.3084 ± 0.0084
σ_8	$0.831^{+0.027}_{-0.043}$	$0.827^{+0.029}_{-0.035}$	$0.829^{+0.013}_{-0.021}$	$0.820^{+0.009}_{-0.013}$	$0.838^{+0.013}_{-0.015}$
S_8	0.796 ± 0.049	$0.791^{+0.040}_{-0.046}$	$0.828^{+0.015}_{-0.018}$	0.839 ± 0.018	0.850 ± 0.017



ACT collaboration, Hill et al. arXiv:*2109.04451*

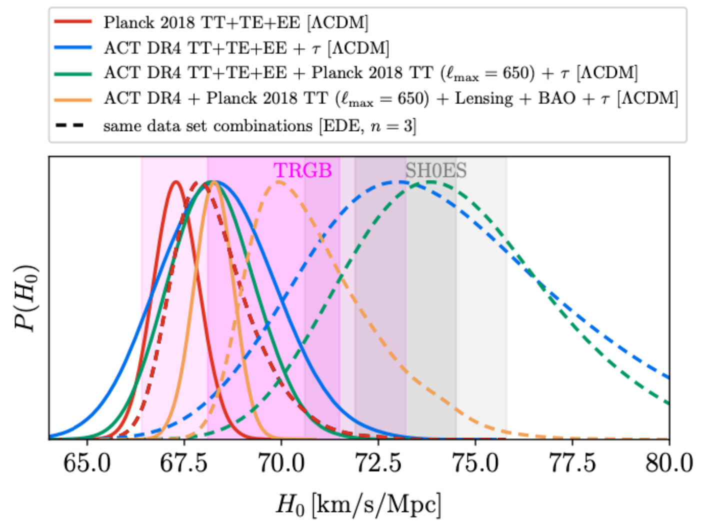
The evidence for EDE > 3σ persists with the inclusion of Planck lensing + BAO data, but shifting H0 towards a lower value.

Early Dark Energy



Constraints on EDE ($n = 3$)

Parameter	ACT DR4 TT+TE+EE, τ	ACT DR4 TT+TE+EE, *Planck* 2018 TT ($\ell_{\max} = 650$), τ	ACT DR4 TT+TE+EE, *Planck* 2018 TT ($\ell_{\max} = 650$), *Planck* 2018 lensing, BAO, τ	*Planck* 2018 TT+TE+EE (from Ref. [38])	ACT DR4 TT+TE+EE, *Planck* 2018 TT+TE+EE (no low-ℓ EE), τ
$\boldsymbol{f_{\mathrm{EDE}}}$	$0.142^{+0.039}_{-0.072}$	$0.129^{+0.028}_{-0.055}$	$0.091^{+0.020}_{-0.036}$	< 0.087	< 0.124
$\boldsymbol{\log_{10}(z_c)}$	< 3.70	< 3.43	< 3.36	$3.66^{+0.21}_{-0.28}$	$3.54^{[illegible]}_{-0.20}$
$\boldsymbol{\theta_i}$	> 0.24	< 2.89	< 2.82	> 0.36	> 0.51
$\boldsymbol{\Omega_c h^2}$	$0.1307^{+0.0054}_{-0.0120}$	$0.1291^{+0.0051}_{-0.0098}$	$0.1286^{+0.0027}_{-0.0063}$	$0.1234^{+0.0019}_{-0.0038}$	$0.1244^{+0.0025}_{-0.0051}$
H_0 [km/s/Mpc]	$74.5^{+2.5}_{-4.4}$	$74.4^{+2.2}_{-3.0}$	$70.9^{+1.0}_{-2.0}$	$68.29^{+0.73}_{-1.20}$	$69.17^{+0.83}_{-1.70}$
Ω_m	$0.276^{+0.020}_{-0.023}$	0.274 ± 0.017	0.3000 ± 0.0072	0.3145 ± 0.0086	0.3084 ± 0.0084
σ_8	$0.831^{+0.027}_{-0.043}$	$0.827^{+0.029}_{-0.035}$	$0.829^{+0.013}_{-0.021}$	$0.820^{+0.009}_{-0.013}$	$0.838^{+0.013}_{-0.015}$
S_8	0.796 ± 0.049	$0.791^{+0.040}_{-0.046}$	$0.828^{+0.015}_{-0.018}$	0.839 ± 0.018	0.850 ± 0.017



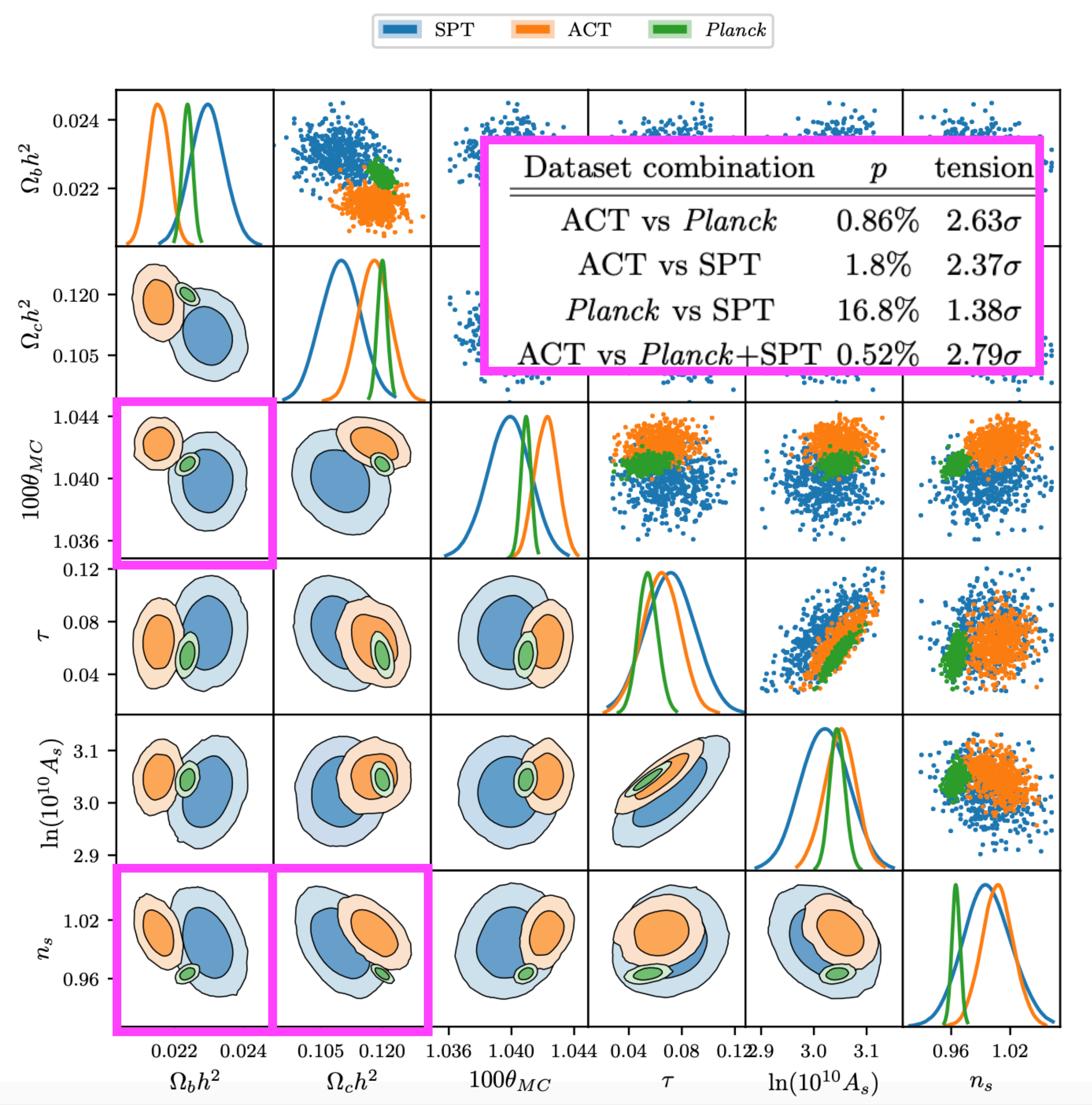
ACT collaboration, Hill et al. arXiv:*2109.04451*

Once the full Planck data are considered, the evidence for EDE disappears and H0 is again in tension with SH0ES.

The Planck damping tail is in disagreement with EDE different from zero.

ACT DR4 vs Planck: LCDM

Handley and Lemos, arXiv:2007.08496 [astro-ph.CO]



Dataset combination	p	tension
ACT vs *Planck*	0.86%	2.63σ
ACT vs SPT	1.8%	2.37σ
Planck vs SPT	16.8%	1.38σ
ACT vs *Planck*+SPT	0.52%	2.79σ

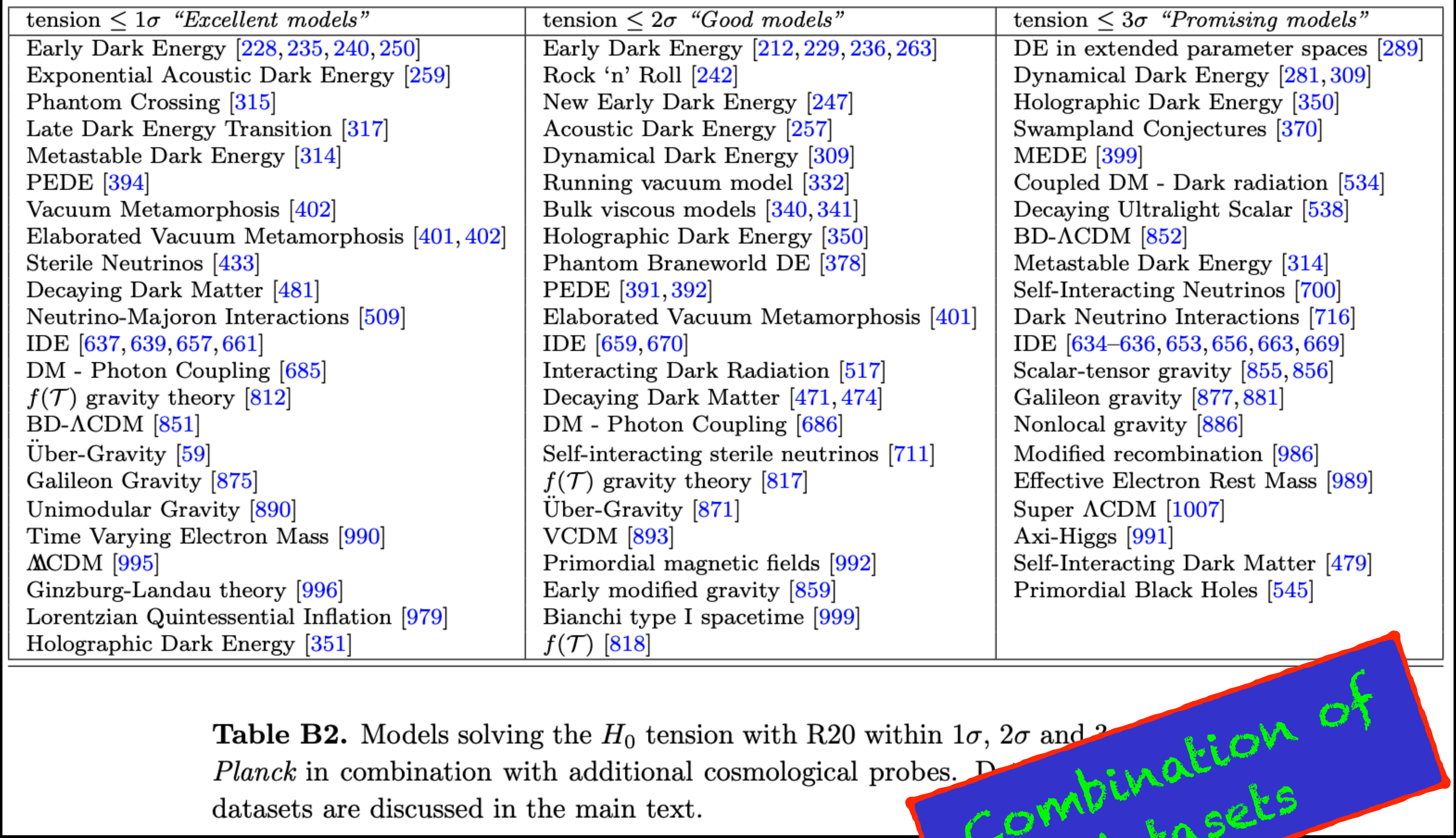
Global tensions between CMB datasets.

For each pairing of datasets this is the tension probability p that such datasets would be this discordant by (Bayesian) chance, as well as a conversion into a Gaussian-equivalent tension.

Between Planck and ACT there is a 2.6σ tension.

Assuming LCDM

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. D
datasets are discussed in the main text.

Combination of datasets

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

Let’s see another example…

IDE can solve the H0 tension

In the standard cosmological framework, DM and DE are described as separate fluids not sharing interactions beyond gravitational ones.
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:

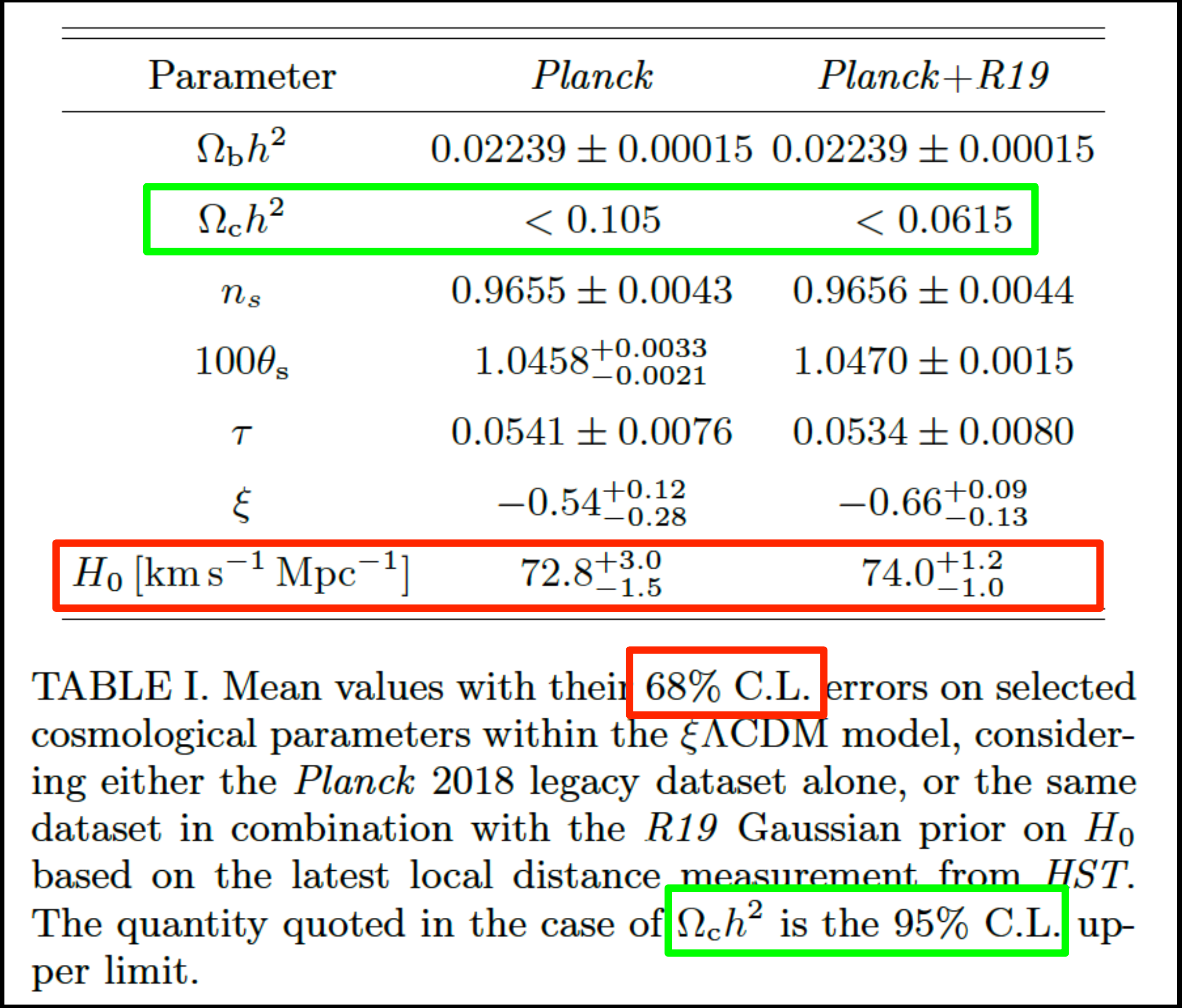
$$Q = \xi \mathcal{H} \rho_x$$

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 $\Omega_m h^2$.



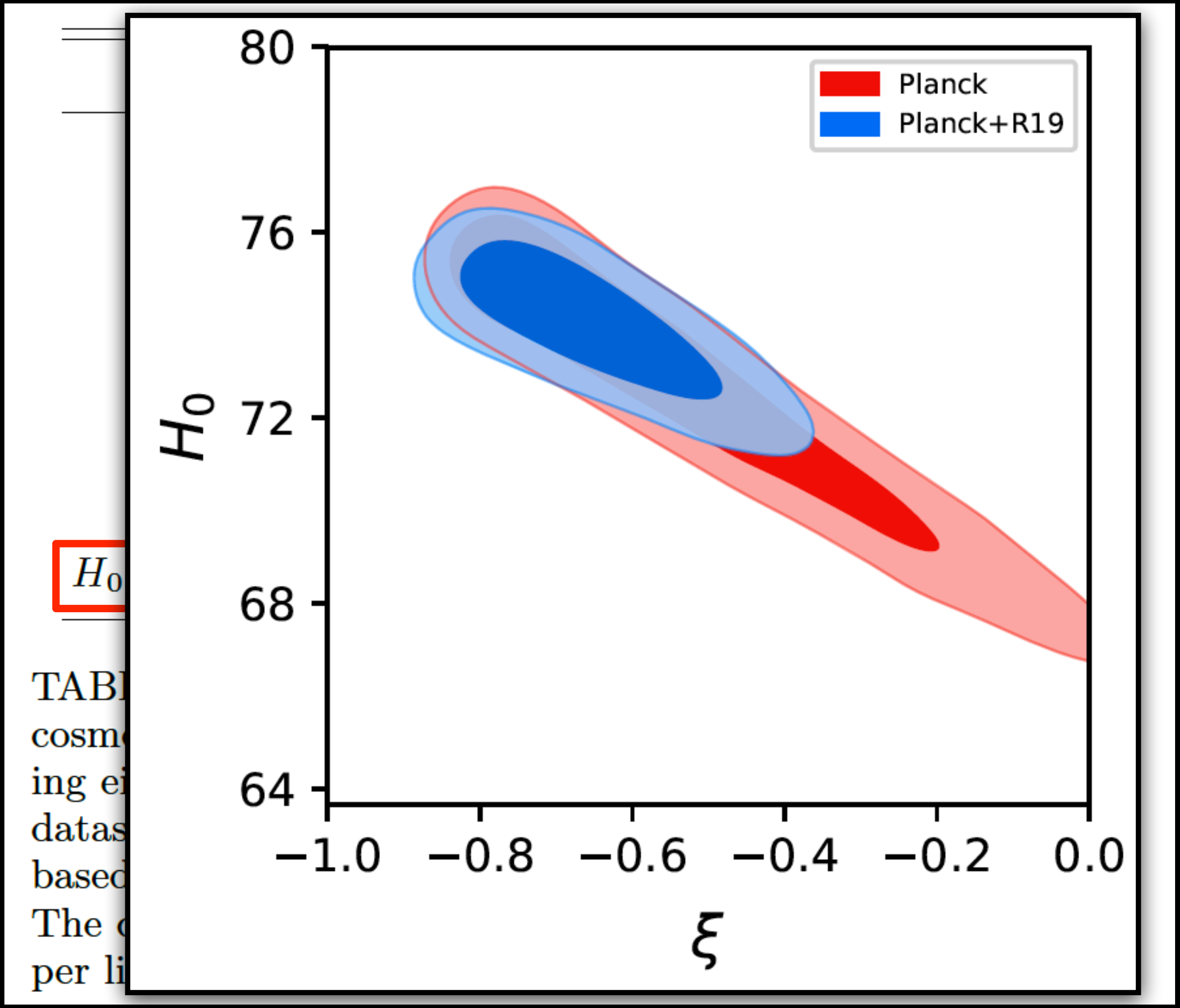
Parameter	*Planck*	*Planck+R19*
$\Omega_b h^2$	0.02239 ± 0.00015	0.02239 ± 0.00015
$\Omega_c h^2$	< 0.105	< 0.0615
n_s	0.9655 ± 0.0043	0.9656 ± 0.0044
$100\theta_s$	$1.0458^{+0.0033}_{-0.0021}$	1.0470 ± 0.0015
τ	0.0541 ± 0.0076	0.0534 ± 0.0080
ξ	$-0.54^{+0.12}_{-0.28}$	$-0.66^{+0.09}_{-0.13}$
H_0 [km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

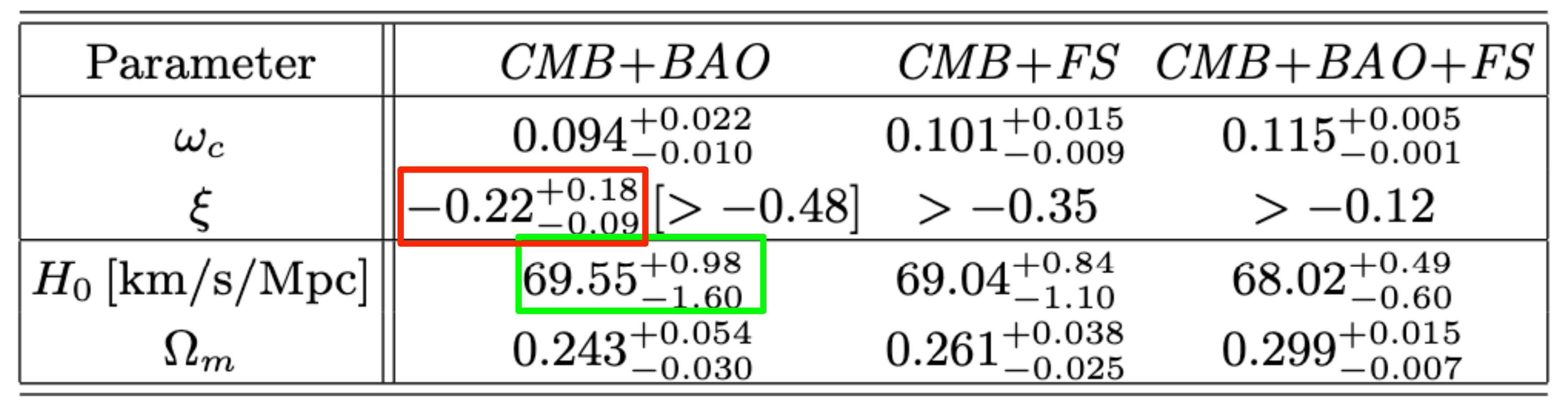
IDE can solve the H0 tension

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 can solve the H0 tension

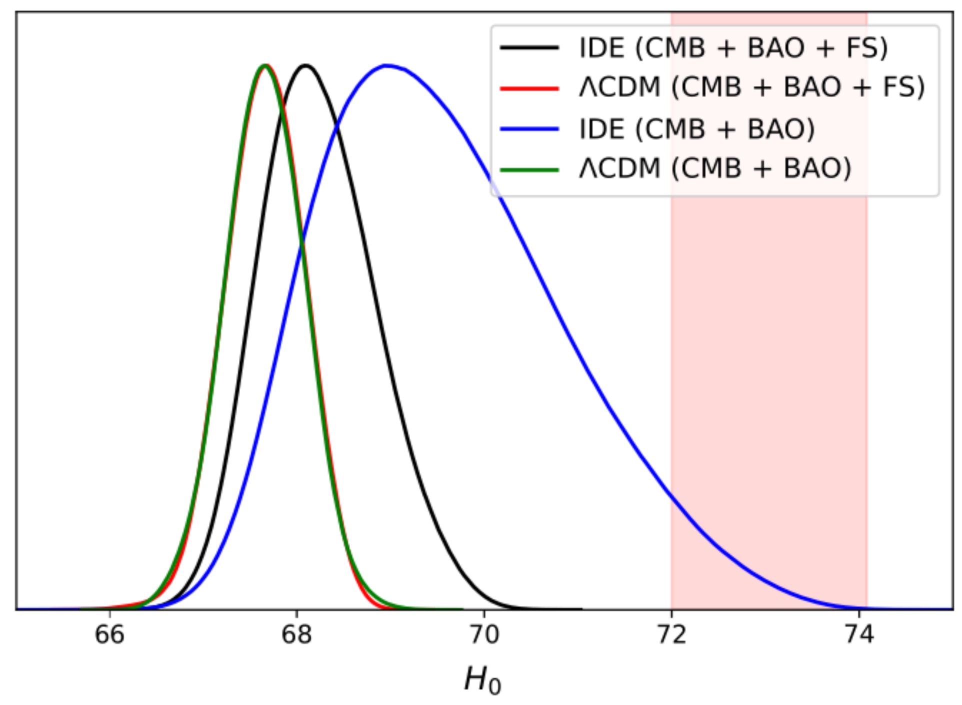


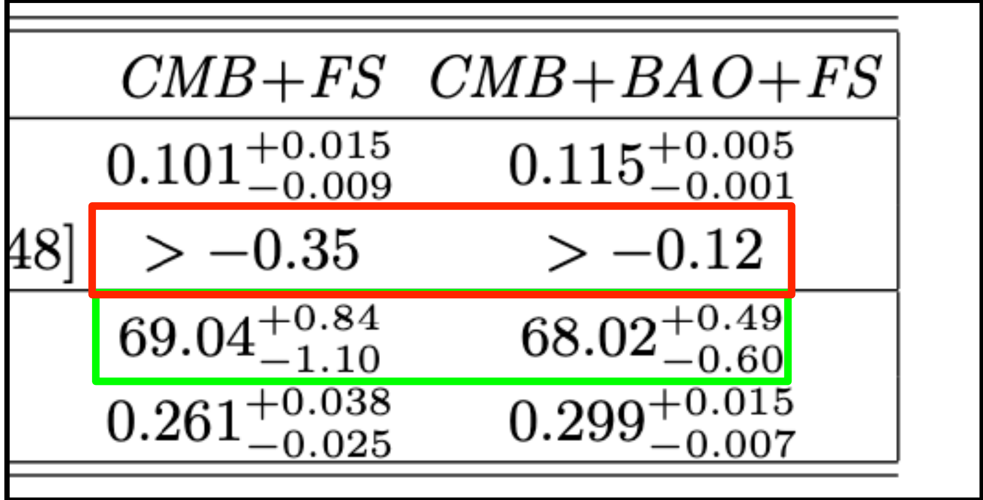
Parameter	$CMB+BAO$	$CMB+FS$	$CMB+BAO+FS$
ω_c	$0.094^{+0.022}_{-0.010}$	$0.101^{+0.015}_{-0.009}$	$0.115^{+0.005}_{-0.001}$
ξ	$-0.22^{+0.18}_{-0.09}\,[> -0.48]$	> -0.35	> -0.12
H_0 [km/s/Mpc]	$69.55^{+0.98}_{-1.60}$	$69.04^{+0.84}_{-1.10}$	$68.02^{+0.49}_{-0.60}$
Ω_m	$0.243^{+0.054}_{-0.030}$	$0.261^{+0.038}_{-0.025}$	$0.299^{+0.015}_{-0.007}$

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 2.1σ with SH0ES.

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

IDE can solve the H0 tension





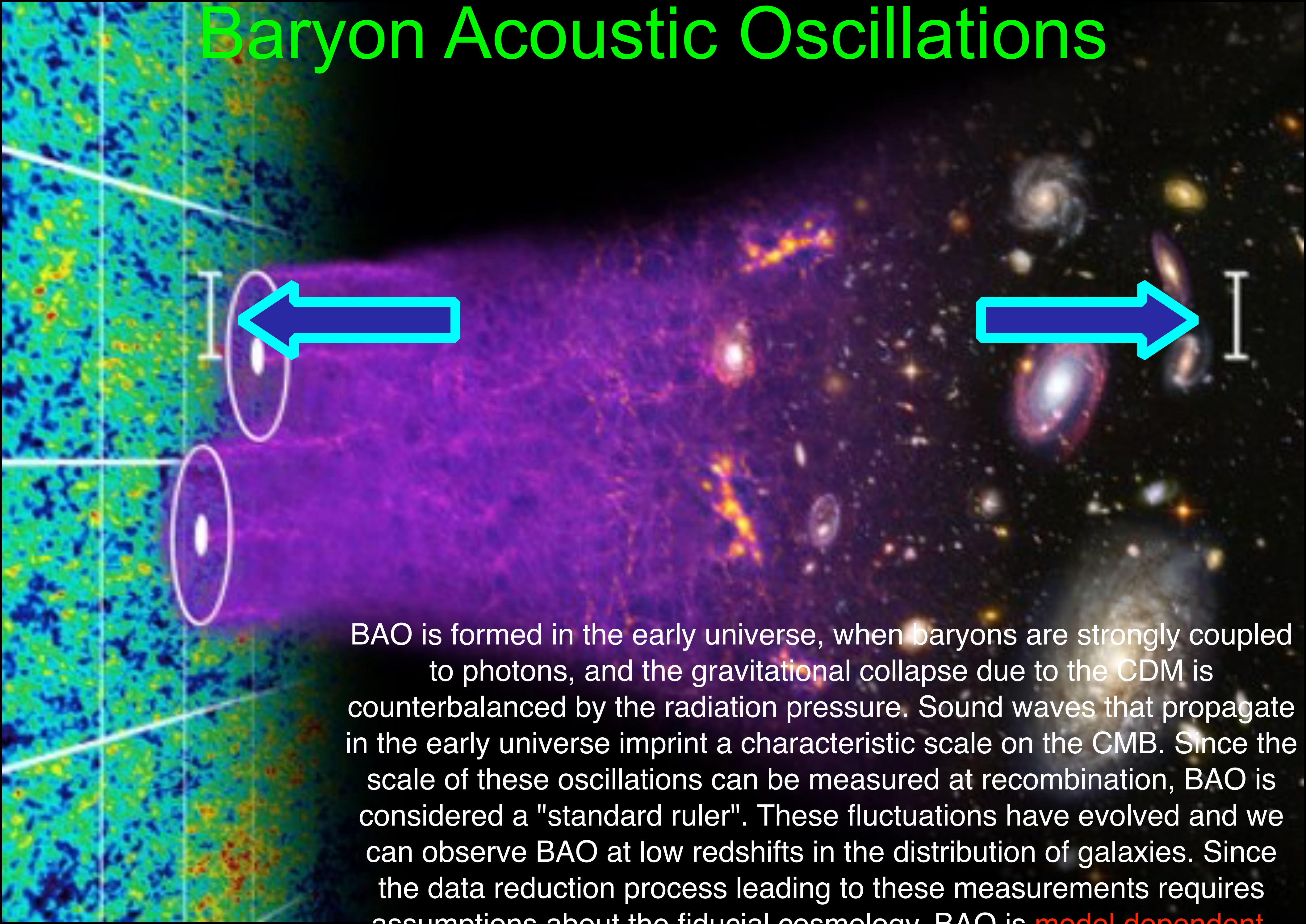
	CMB+FS	*CMB+BAO+FS*
	$0.101^{+0.015}_{-0.009}$	$0.115^{+0.005}_{-0.001}$
48]	> -0.35	> -0.12
	$69.04^{+0.84}_{-1.10}$	$68.02^{+0.49}_{-0.60}$
	$0.261^{+0.038}_{-0.025}$	$0.299^{+0.015}_{-0.007}$

Nunes, Vagnozzi, Kumar, Di Valentino, and Mena, arXiv:2203.08093 [astro-ph.CO]

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 2.1σ with SH0ES.

However, the IDE model does not survive to the additional information coming from the full shape (FS) power spectrum of the BOSS DR12 galaxies.

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 or Planck+FS and SH0ES could be due to a statistical fluctuation in this case.

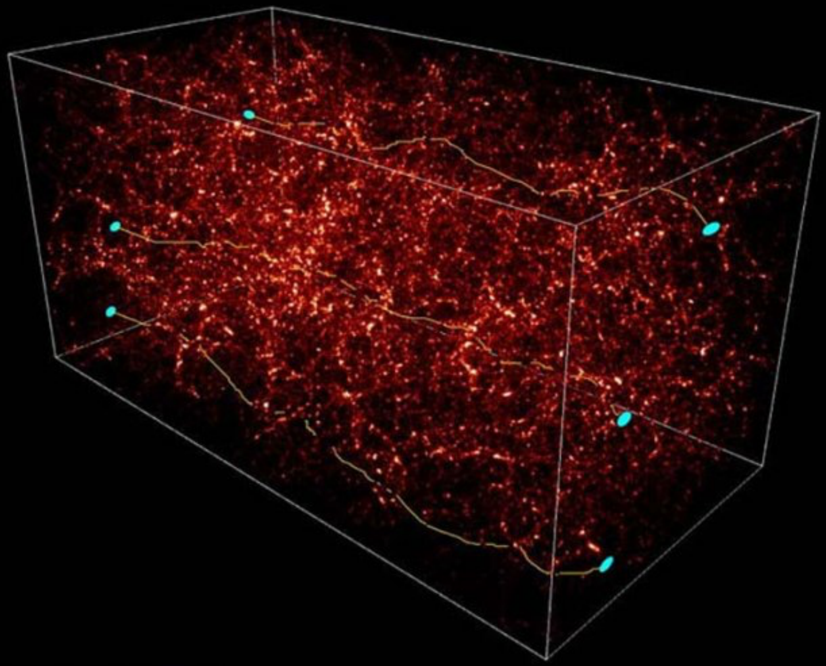
Actually, BAO and FS data are extracted under the assumption of LCDM, and the modified scenario of interacting dark energy could affect the result.

In fact, the full procedure which leads to the BAO and FS datasets carried out by the different collaborations might be not necessarily valid in extended DE models with important perturbations in the non-linear scales.

BAO and FS datasets (both the pre- and post- reconstruction measurements) might need to be revised in a non-trivial manner when applied to constrain more exotic dark energy cosmologies.

Additional complication:
the models proposed to alleviate
the H0 tension increase the S8
tension!

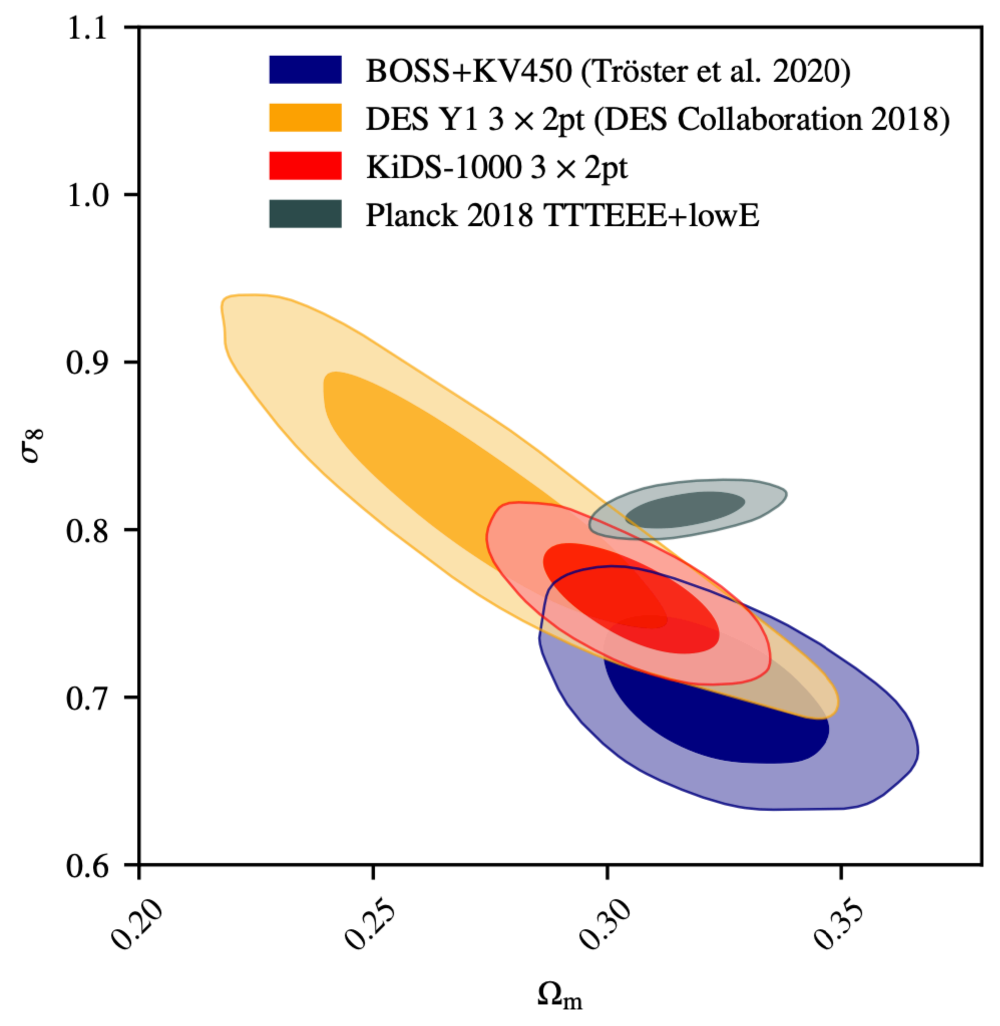
The S8 tension



$$S_8 \equiv \sigma_8 \sqrt{\Omega_m / 0.3}$$

A tension on S8 is present between the Planck data in the ΛCDM scenario and the cosmic shear data.

The S8 tension



KiDS-1000, Heymans et al., arXiv:2007.15632 [astro-ph.CO]

The S8 tension is present at 3.4σ between Planck assuming ΛCDM and KiDS+VIKING-450 and BOSS combined together, or 3.1σ with KiDS-1000.

$S_8 = 0.834 \pm 0.016$

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

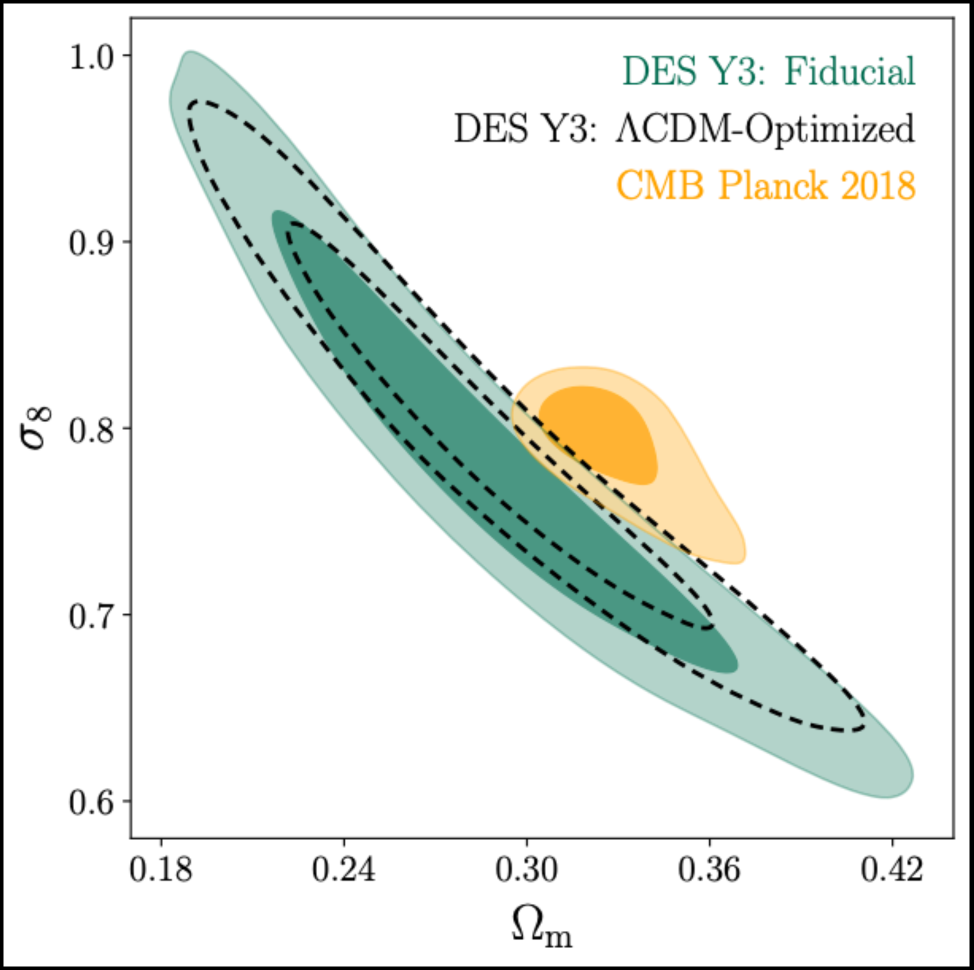
$S_8 = 0.728 \pm 0.045$

Troster et al., arXiv:1909.11006 [astro-ph.CO]

$S_8 = 0.766^{+0.020}_{-0.014}$

KiDS-1000, Heymans et al., arXiv:2007.15632 [astro-ph.CO]

The S8 tension



DES-Y3, Amon et al., arXiv:2105.13543 [astro-ph.CO]

The S8 tension is present at 2.5σ between Planck assuming ΛCDM and DES-Y3.

$S_8 = 0.834 \pm 0.016$

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

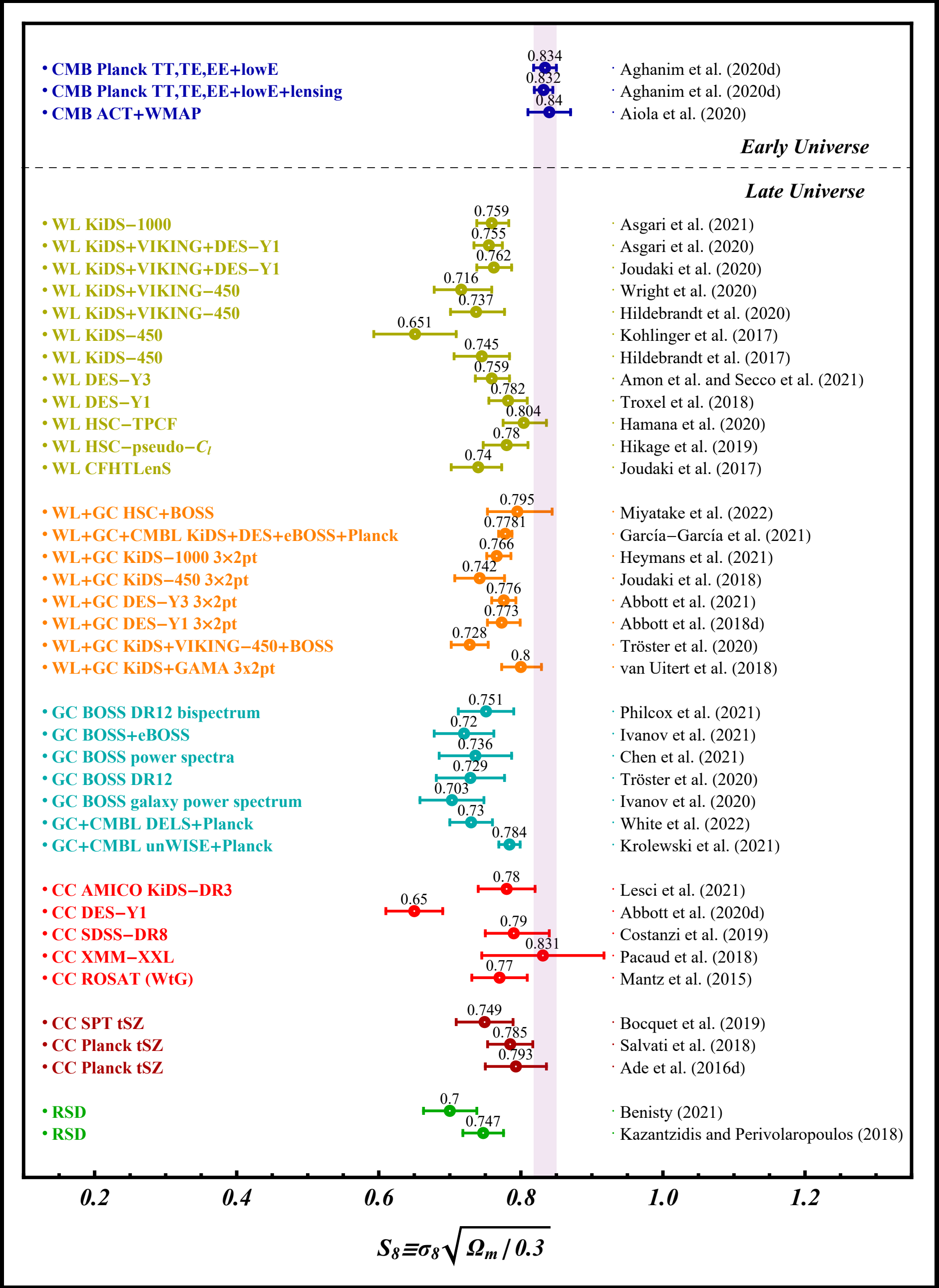
$S_8 = 0.776^{+0.017}_{-0.017}$

DES-Y3, Abbott et al., arXiv:2105.13549 [astro-ph.CO]

$S_8 = 0.759^{+0.025}_{-0.025}$

DES-Y3 fiducial, Amon et al., arXiv:2105.13543 [astro-ph.CO]

The S8 tension



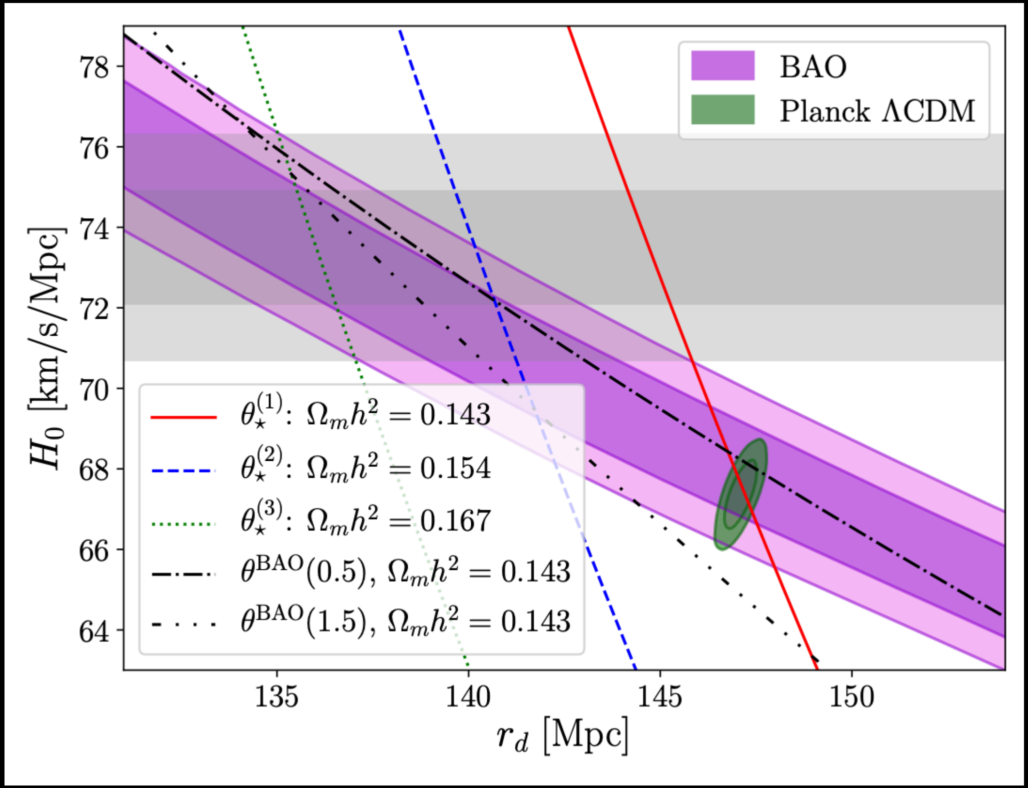
Abdalla et al., *JHEAp* 34 (2022) 49-211

See Di Valentino et al. *Astropart.Phys.* 131 (2021) 102604 and Abdalla et al., arXiv:2203.06142 [astro-ph.CO] for a summary of the possible candidates proposed to solve the S8 tension.

Early solutions to the H0 tension

Actually, a dark energy model that merely changes the value of rd would not completely resolve the tension, since it will affect the inferred value of Ωm and transfer the tension to it.

This is a plot illustrating that achieving a full agreement between CMB, BAO and SH0ES through a reduction of rd requires a higher value of $\Omega_m h^2$.



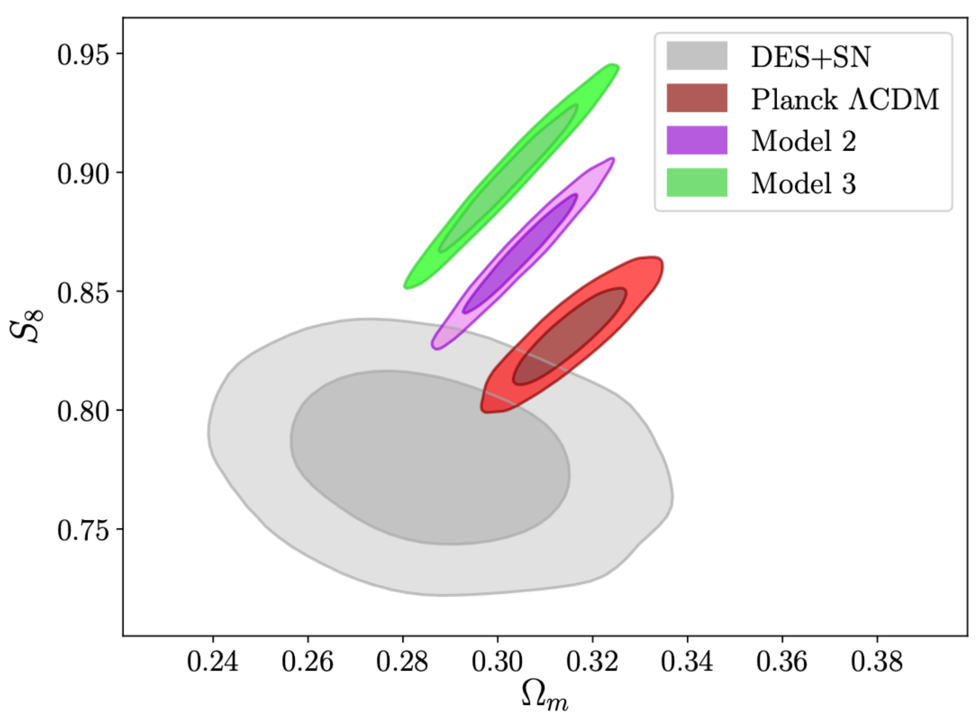
Jedamzik et al., Commun.in Phys. 4 (2021) 123

Early solutions to the H0 tension

Model 2 is defined by the simultaneous fit to BAO and CMB acoustic peaks at $\Omega_m h^2 = 0.155$, while model 3 has $\Omega_m h^2 = 0.167$

The sound horizon problem should be considered not only in the plane H0–rd, but it should be extended to the parameters triplet H0–rd–Ωm.

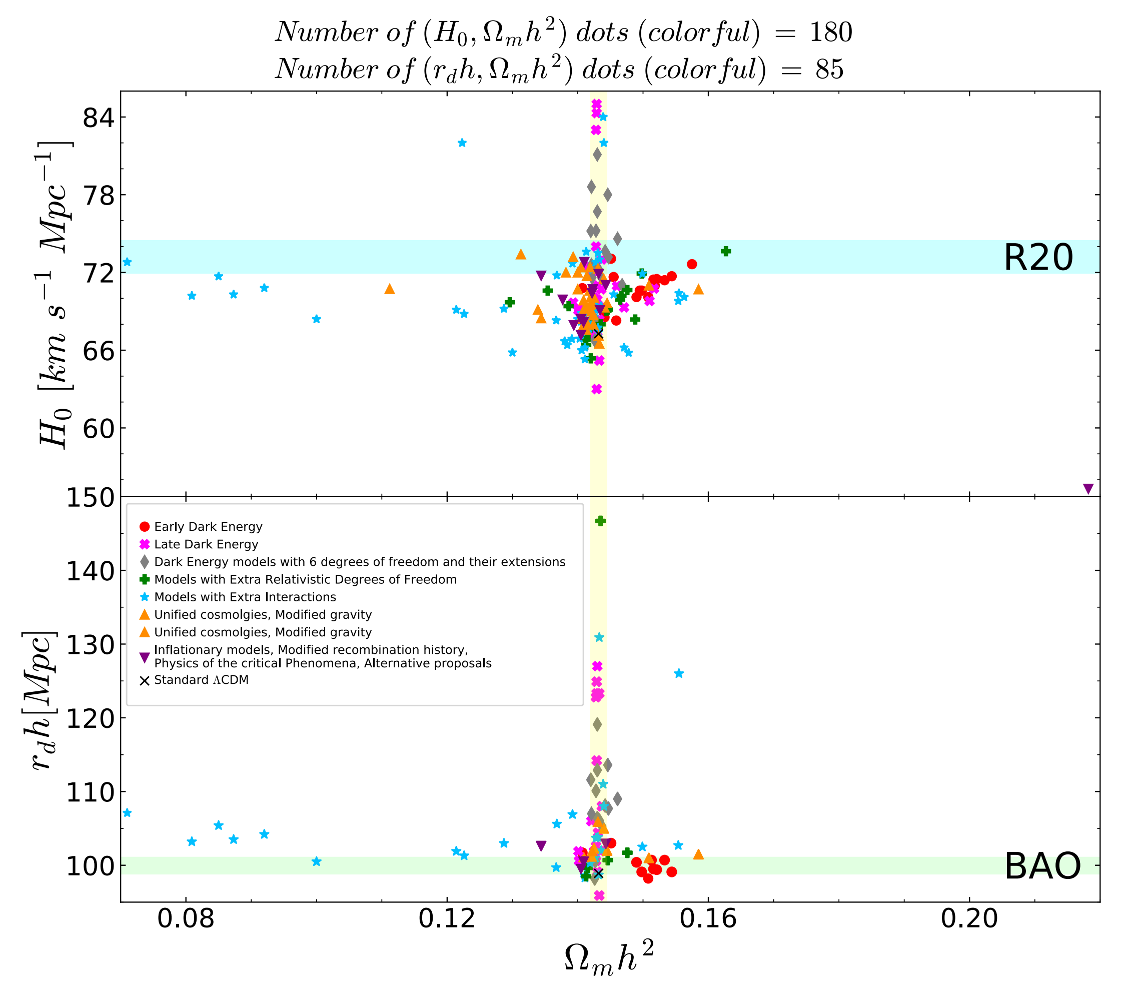
The figure shows that when attempting to find a full resolution of the Hubble tension, with CMB, BAO and SH0ES in agreement with each other, one exacerbates the tension with DES and KiDS.



Jedamzik et al., Commun.in Phys. 4 (2021) 123

Successful models?

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]

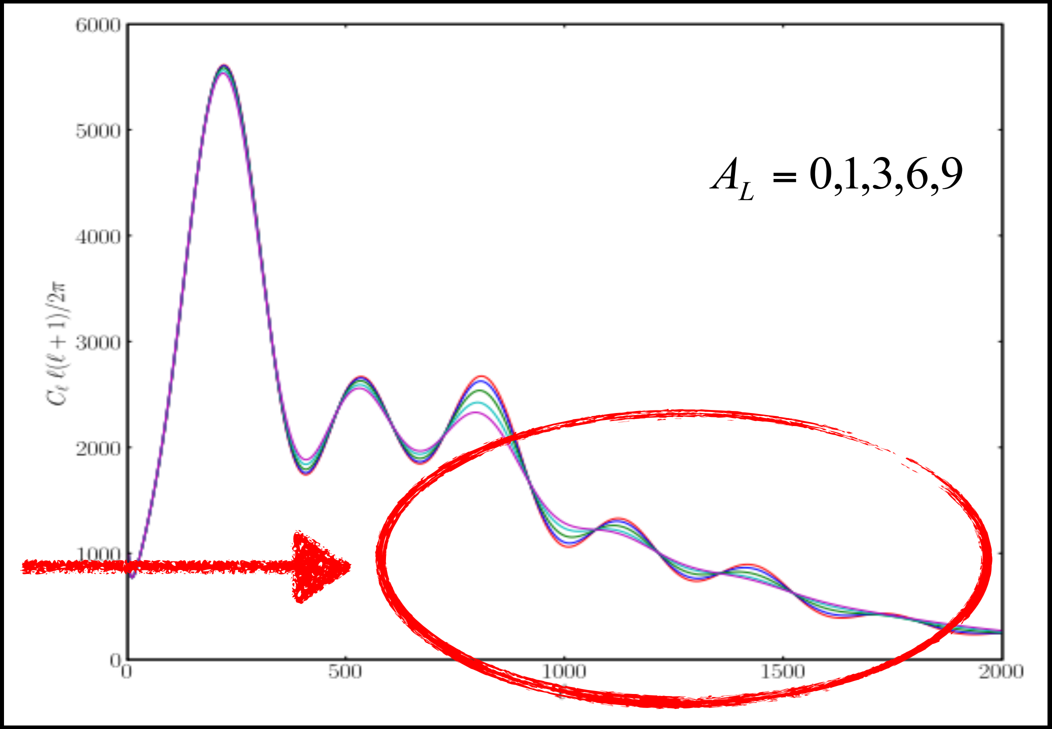
…but a systematic error in
Planck could explain S8…

A_L internal anomaly

The lensing effect on the power spectrum is the smoothing of the acoustic peaks, increasing AL.

Interesting consistency checks is if the amplitude of the smoothing effect in the CMB power spectra matches the theoretical expectation AL = 1 and whether the amplitude of the smoothing is consistent with that measured by the lensing reconstruction.

If AL =1 then the theory is correct, otherwise we have a new physics or systematics.



Calabrese et al., Phys. Rev. D, 77, 123531

A_L : a failed consistency check

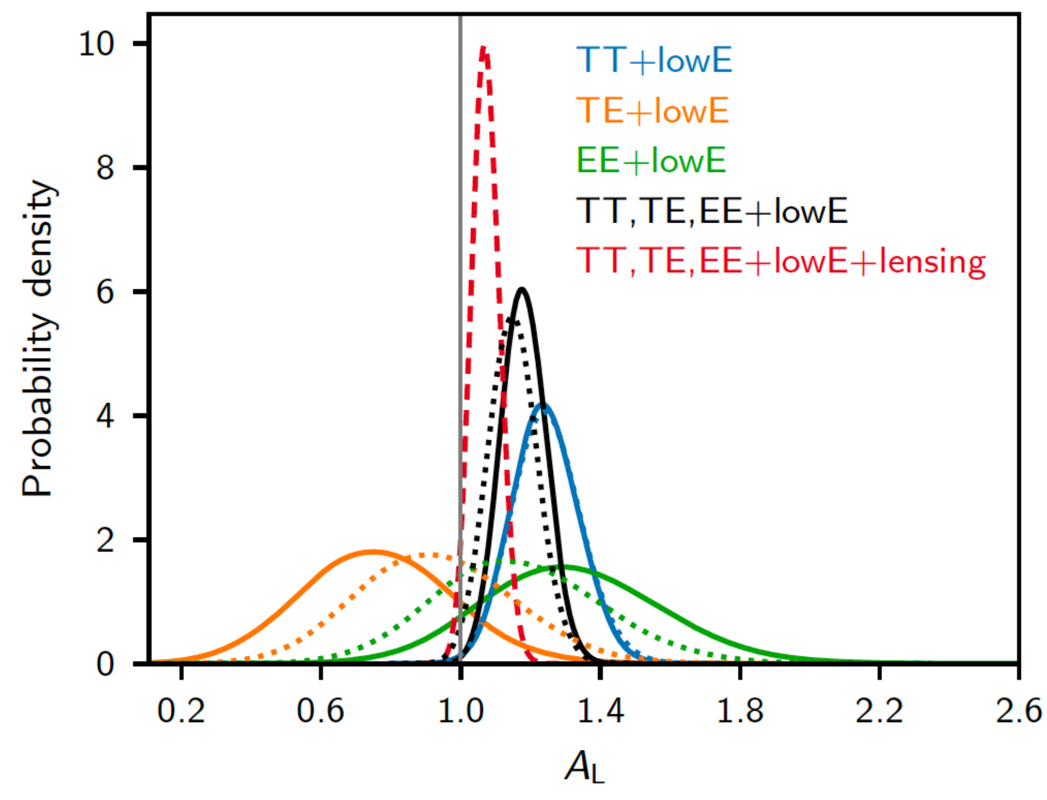
The Planck lensing-reconstruction power spectrum is consistent with the amplitude expected for LCDM models that fit the CMB spectra, so the Planck lensing measurement is compatible with AL = 1.

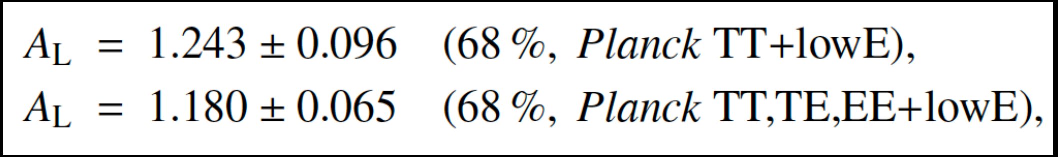
However, the distributions of AL inferred from the CMB power spectra alone indicate a preference for AL > 1.

The joint combined likelihood shifts the value preferred by the TT data downwards towards AL = 1, but the error also shrinks, increasing the significance of AL > 1 to 2.8σ.

The preference for high AL is not just a volume effect in the full parameter space, with the best fit improved by $\Delta\chi^2 \sim 9$ when adding AL for TT+lowE and 10 for TTTEEE+lowE.

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

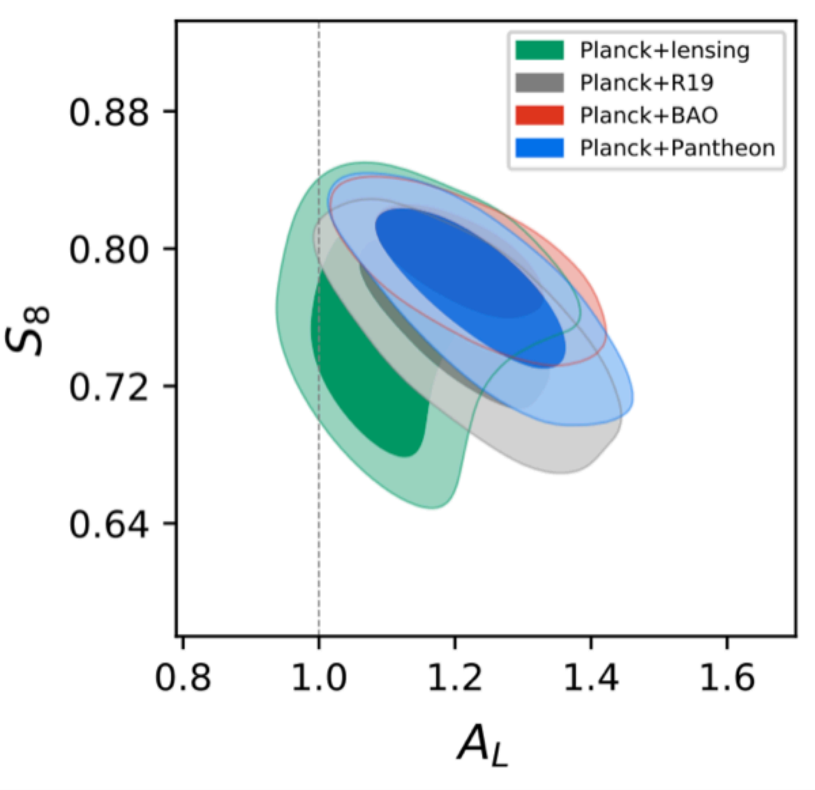




$$A_L = 1.243 \pm 0.096 \quad (68\,\%,\ \textit{Planck}\ \mathrm{TT{+}lowE}),$$

$$A_L = 1.180 \pm 0.065 \quad (68\,\%,\ \textit{Planck}\ \mathrm{TT,TE,EE{+}lowE}),$$

A_L can explain the S8 tension

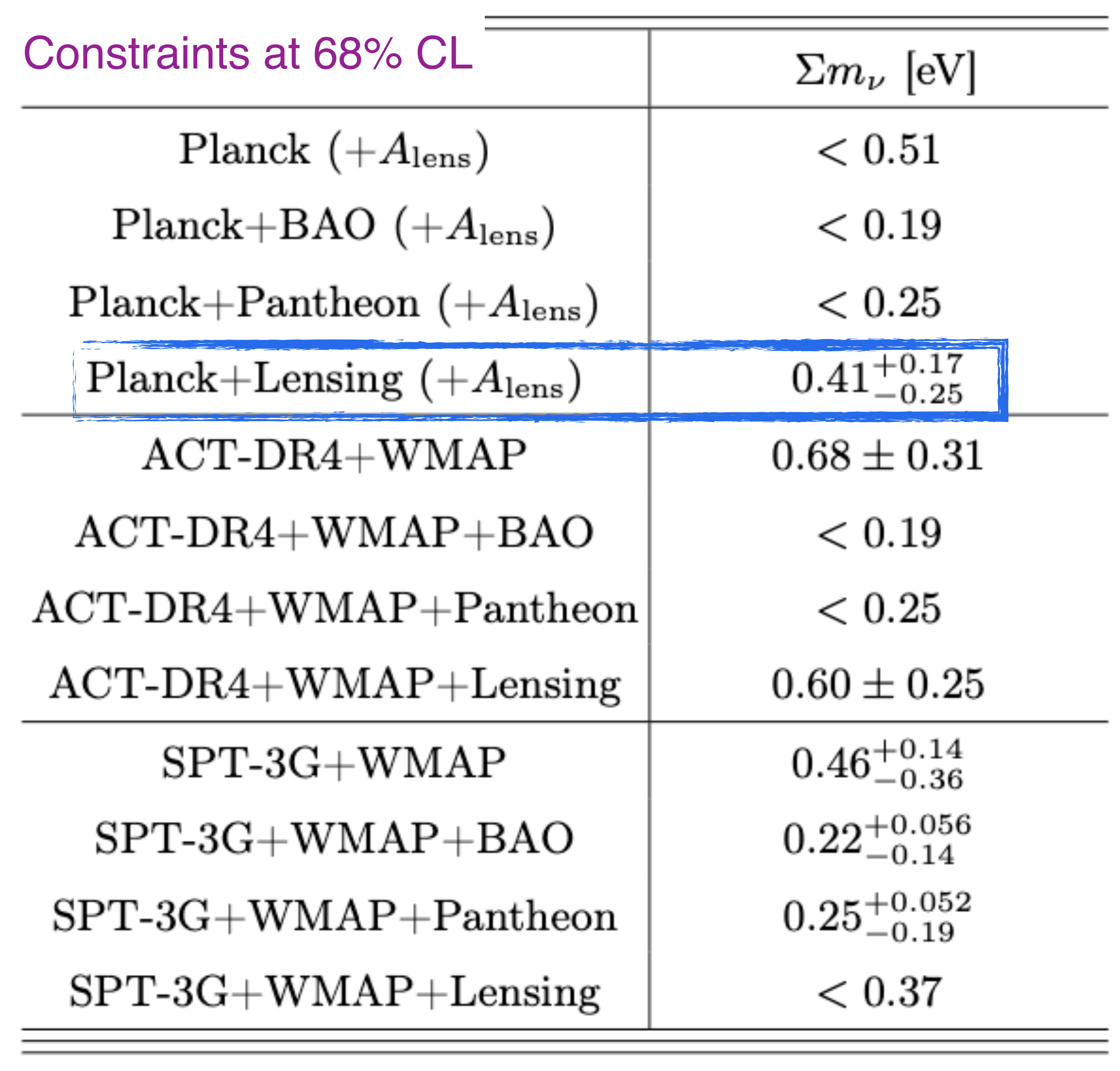


Di Valentino, Melchiorri and Silk, JCAP 2001 (2020) no.01, 013

A_L that is larger than the expected value at about 3 standard deviations even when combining the Planck data with BAO and supernovae type Ia external datasets.

A_L can be a systematic?

Di Valentino and Melchiorri, 2022 *ApJL* **931** L18

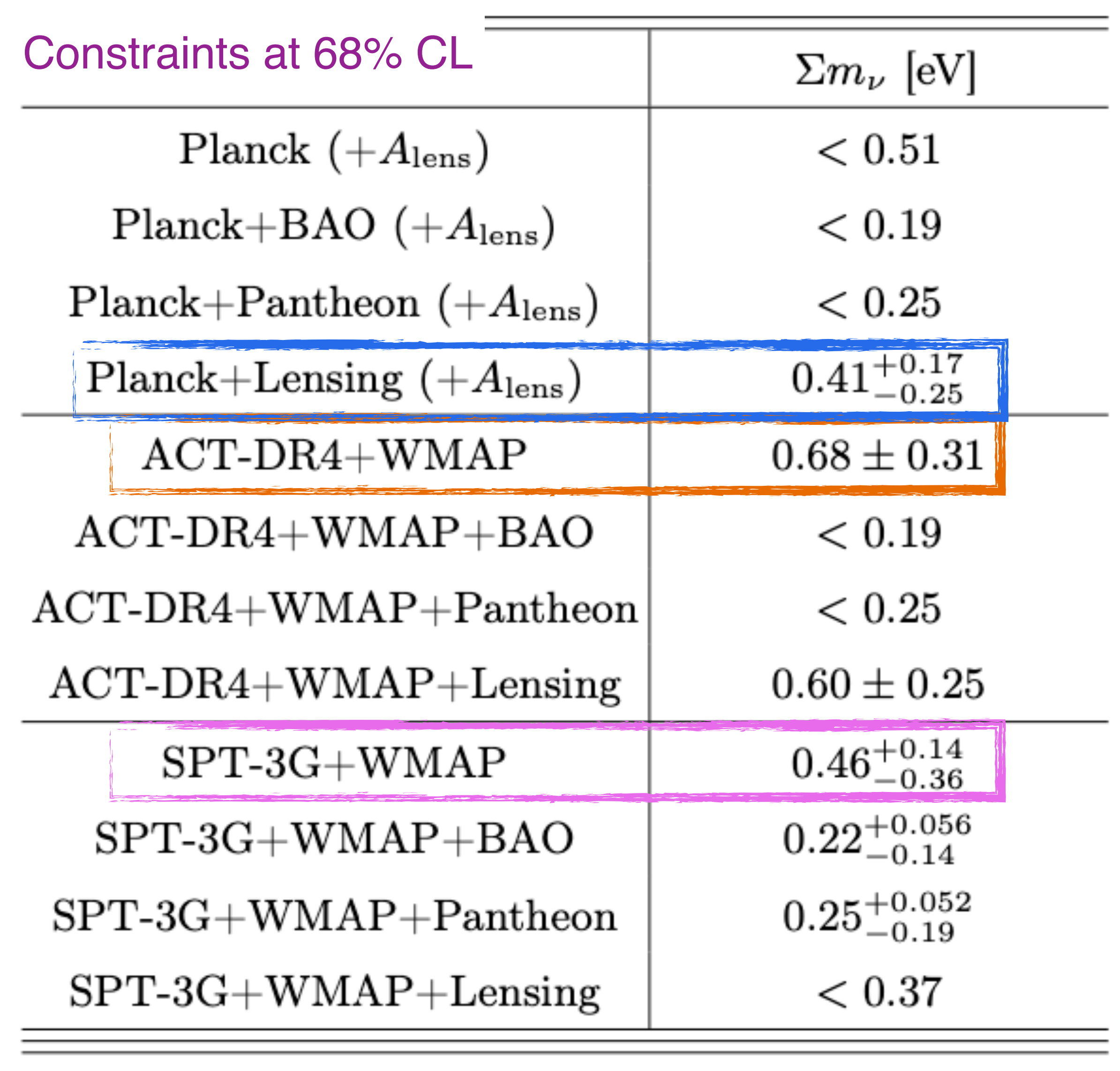


Constraints at 68% CL	Σm_ν [eV]
Planck (+$A_{\rm lens}$)	< 0.51
Planck+BAO (+$A_{\rm lens}$)	< 0.19
Planck+Pantheon (+$A_{\rm lens}$)	< 0.25
Planck+Lensing (+$A_{\rm lens}$)	$0.41^{+0.17}_{-0.25}$
ACT-DR4+WMAP	0.68 ± 0.31
ACT-DR4+WMAP+BAO	< 0.19
ACT-DR4+WMAP+Pantheon	< 0.25
ACT-DR4+WMAP+Lensing	0.60 ± 0.25
SPT-3G+WMAP	$0.46^{+0.14}_{-0.36}$
SPT-3G+WMAP+BAO	$0.22^{+0.056}_{-0.14}$
SPT-3G+WMAP+Pantheon	$0.25^{+0.052}_{-0.19}$
SPT-3G+WMAP+Lensing	< 0.37

A combination of Planck CMB+Lensing constrain $\Sigma m_\nu = 0.41^{+0.17}_{-0.25}$ eV at 68% CL when variation in the Alens parameter are considered.

Alternative CMB vs Planck: Σmν

Di Valentino and Melchiorri, 2022 *ApJL* **931** L18



Constraints at 68% CL	Σm_ν [eV]
Planck ($+A_{\rm lens}$)	< 0.51
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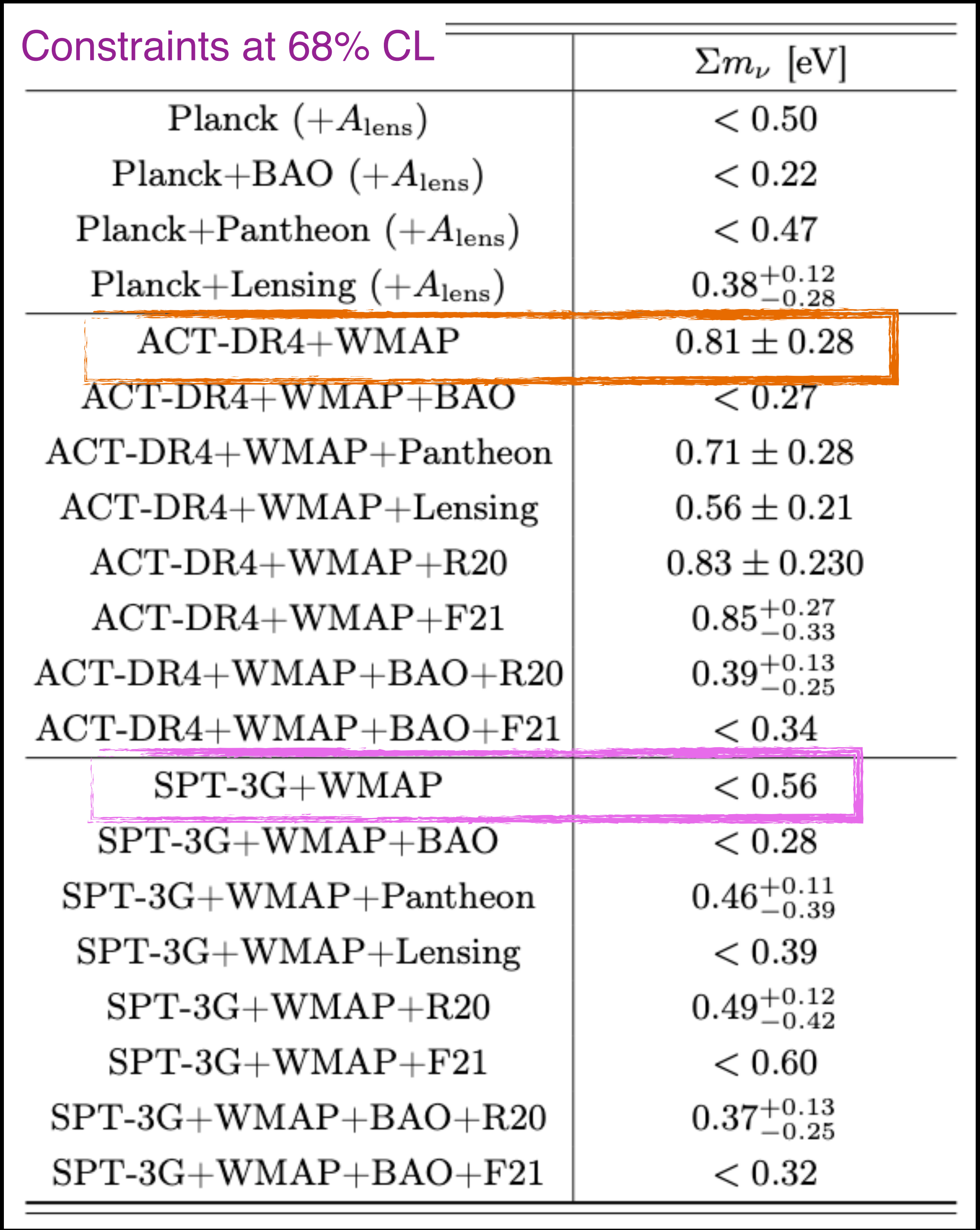
Planck+Pantheon ($+A_{\rm lens}$)	< 0.25
Planck+Lensing ($+A_{\rm lens}$)	$0.41^{+0.17}_{-0.25}$
ACT-DR4+WMAP	0.68 ± 0.31
ACT-DR4+WMAP+BAO	< 0.19
ACT-DR4+WMAP+Pantheon	< 0.25
ACT-DR4+WMAP+Lensing	0.60 ± 0.25
SPT-3G+WMAP	$0.46^{+0.14}_{-0.36}$
SPT-3G+WMAP+BAO	$0.22^{+0.056}_{-0.14}$
SPT-3G+WMAP+Pantheon	$0.25^{+0.052}_{-0.19}$
SPT-3G+WMAP+Lensing	< 0.37

We found that both the ACT-DR4 and SPT-3G data, when combined with WMAP, mildly suggest a neutrino mass with $\Sigma m_\nu = 0.68 \pm 0.31$ eV and $\Sigma m_\nu = 0.46^{+0.14}_{-0.36}$ eV at 68% CL, respectively.

Alternative CMB vs Planck: Σmν

Di Valentino and Melchiorri,
2022 *ApJL* **931** L18



Constraints at 68% CL

	Σm_ν [eV]
Planck ($+A_{\rm lens}$)	< 0.50
Planck+BAO ($+A_{\rm lens}$)	< 0.22
Planck+Pantheon ($+A_{\rm lens}$)	< 0.47
Planck+Lensing ($+A_{\rm lens}$)	$0.38^{+0.12}_{-0.28}$
ACT-DR4+WMAP	0.81 ± 0.28
ACT-DR4+WMAP+BAO	< 0.27
ACT-DR4+WMAP+Pantheon	0.71 ± 0.28
ACT-DR4+WMAP+Lensing	0.56 ± 0.21
ACT-DR4+WMAP+R20	0.83 ± 0.230
ACT-DR4+WMAP+F21	$0.85^{+0.27}_{-0.33}$
ACT-DR4+WMAP+BAO+R20	$0.39^{+0.13}_{-0.25}$
ACT-DR4+WMAP+BAO+F21	< 0.34
SPT-3G+WMAP	< 0.56
SPT-3G+WMAP+BAO	< 0.28
SPT-3G+WMAP+Pantheon	$0.46^{+0.11}_{-0.39}$
SPT-3G+WMAP+Lensing	< 0.39
SPT-3G+WMAP+R20	$0.49^{+0.12}_{-0.42}$
SPT-3G+WMAP+F21	< 0.60
SPT-3G+WMAP+BAO+R20	$0.37^{+0.13}_{-0.25}$
SPT-3G+WMAP+BAO+F21	< 0.32

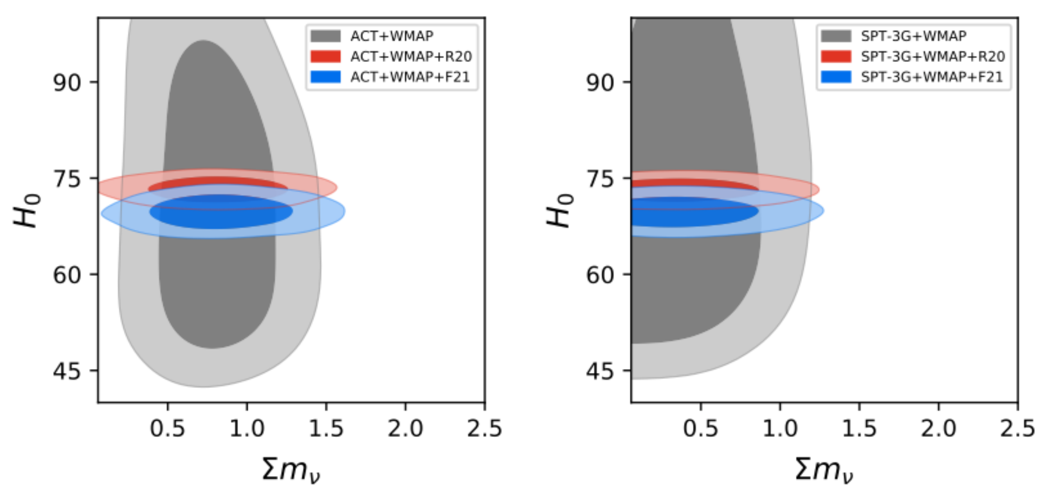
What about the 10 parameters extended model?

ACT-DR4 suggests a neutrino mass with Σmν = 0.81 ± 0.28 eV and SPT-3G

Σmν < 0.56 eV at 68% CL.

Alternative CMB vs Planck: Σmν

Constraints at 68% CL



	Σm_ν [eV]
ACT-DR4+WMAP+R20	0.83 ± 0.230
ACT-DR4+WMAP+F21	$0.85^{+0.27}_{-0.33}$
ACT-DR4+WMAP+BAO+R20	$0.39^{+0.13}_{-0.25}$
ACT-DR4+WMAP+BAO+F21	< 0.34
SPT-3G+WMAP	< 0.56
SPT-3G+WMAP+BAO	< 0.28
SPT-3G+WMAP+Pantheon	$0.46^{+0.11}_{-0.39}$
SPT-3G+WMAP+Lensing	< 0.39
SPT-3G+WMAP+R20	$0.49^{+0.12}_{-0.42}$
SPT-3G+WMAP+F21	< 0.60
SPT-3G+WMAP+BAO+R20	$0.37^{+0.13}_{-0.25}$
SPT-3G+WMAP+BAO+F21	< 0.32

Di Valentino and Melchiorri,
2022 *ApJL* **931** L18

What about the 10 parameters extended model?

We can notice that the inclusion of the R20 or F21 priors does not affect the total neutrino mass constraints, because H0 and Σmν do not show any correlation.

Moreover, in this case it is alleviated also the S_8 tension with the weak lensing measurements. We find for

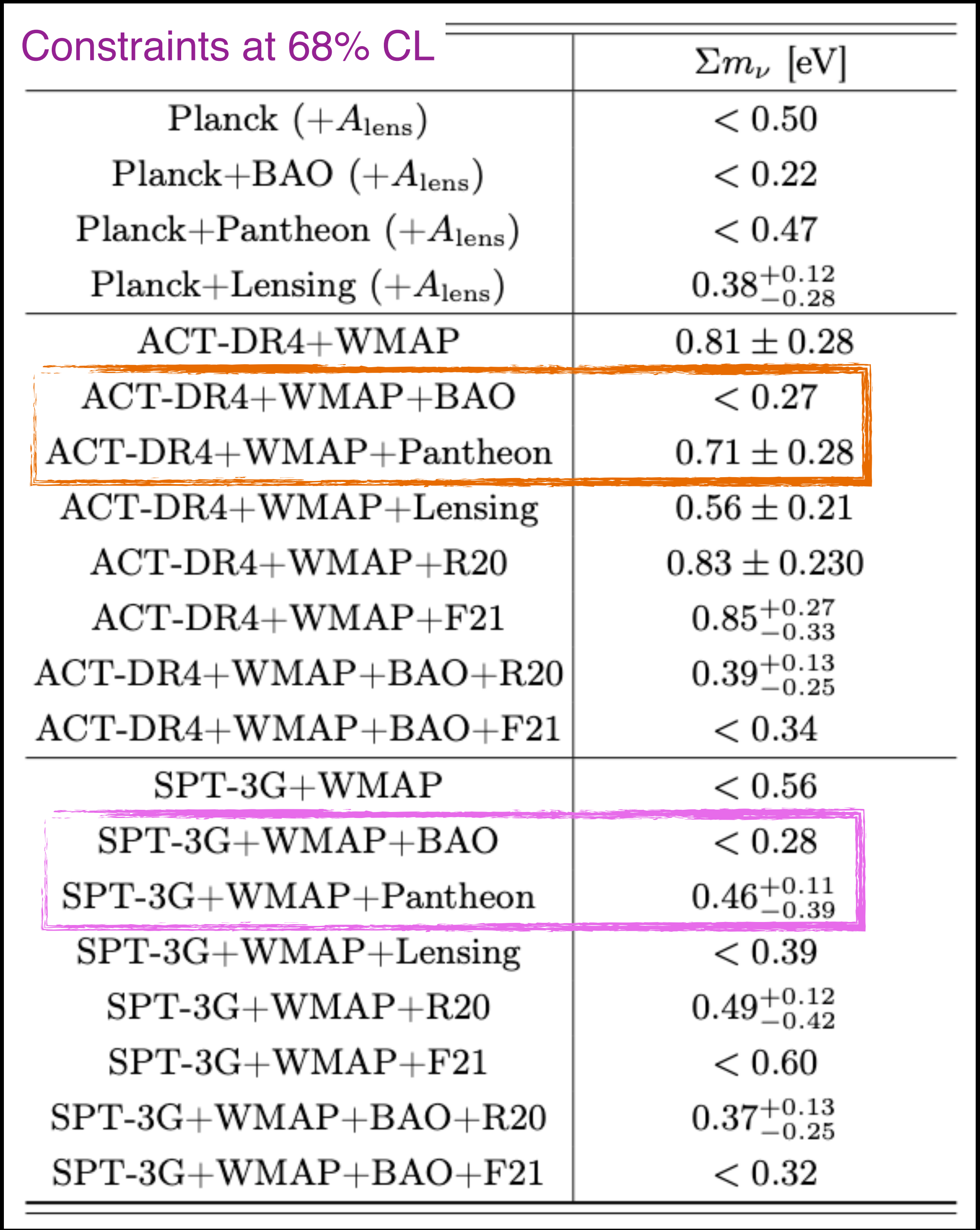
ACT-DR4 + WMAP + R20

$S_8 = 0.726 \pm 0.037$ at 68% C.L.,

while for SPT-3G + WMAP + R20

$S_8 = 0.732 \pm 0.037$ at 68% C.L..

Alternative CMB vs Planck: Σmν



Constraints at 68% CL

	Σm_ν [eV]
Planck ($+A_{\rm lens}$)	< 0.50
Planck+BAO ($+A_{\rm lens}$)	< 0.22
Planck+Pantheon ($+A_{\rm lens}$)	< 0.47
Planck+Lensing ($+A_{\rm lens}$)	$0.38^{+0.12}_{-0.28}$
ACT-DR4+WMAP	0.81 ± 0.28
ACT-DR4+WMAP+BAO	< 0.27
ACT-DR4+WMAP+Pantheon	0.71 ± 0.28
ACT-DR4+WMAP+Lensing	0.56 ± 0.21
ACT-DR4+WMAP+R20	0.83 ± 0.230
ACT-DR4+WMAP+F21	$0.85^{+0.27}_{-0.33}$
ACT-DR4+WMAP+BAO+R20	$0.39^{+0.13}_{-0.25}$
ACT-DR4+WMAP+BAO+F21	< 0.34
SPT-3G+WMAP	< 0.56
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SPT-3G+WMAP+F21	< 0.60
SPT-3G+WMAP+BAO+R20	$0.37^{+0.13}_{-0.25}$
SPT-3G+WMAP+BAO+F21	< 0.32

Di Valentino and Melchiorri,
2022 *ApJL* **931** L18

What about the 10 parameters extended model?

ACT-DR4 suggests a neutrino mass with Σmν = 0.81 ± 0.28 eV and SPT-3G

Σmν < 0.56 eV at 68% CL.

Interestingly, this indication for a higher neutrino mass is present also the BAO and Pantheon data are considered.

Alternative CMB vs Planck: Σmν

Di Valentino and Melchiorri,
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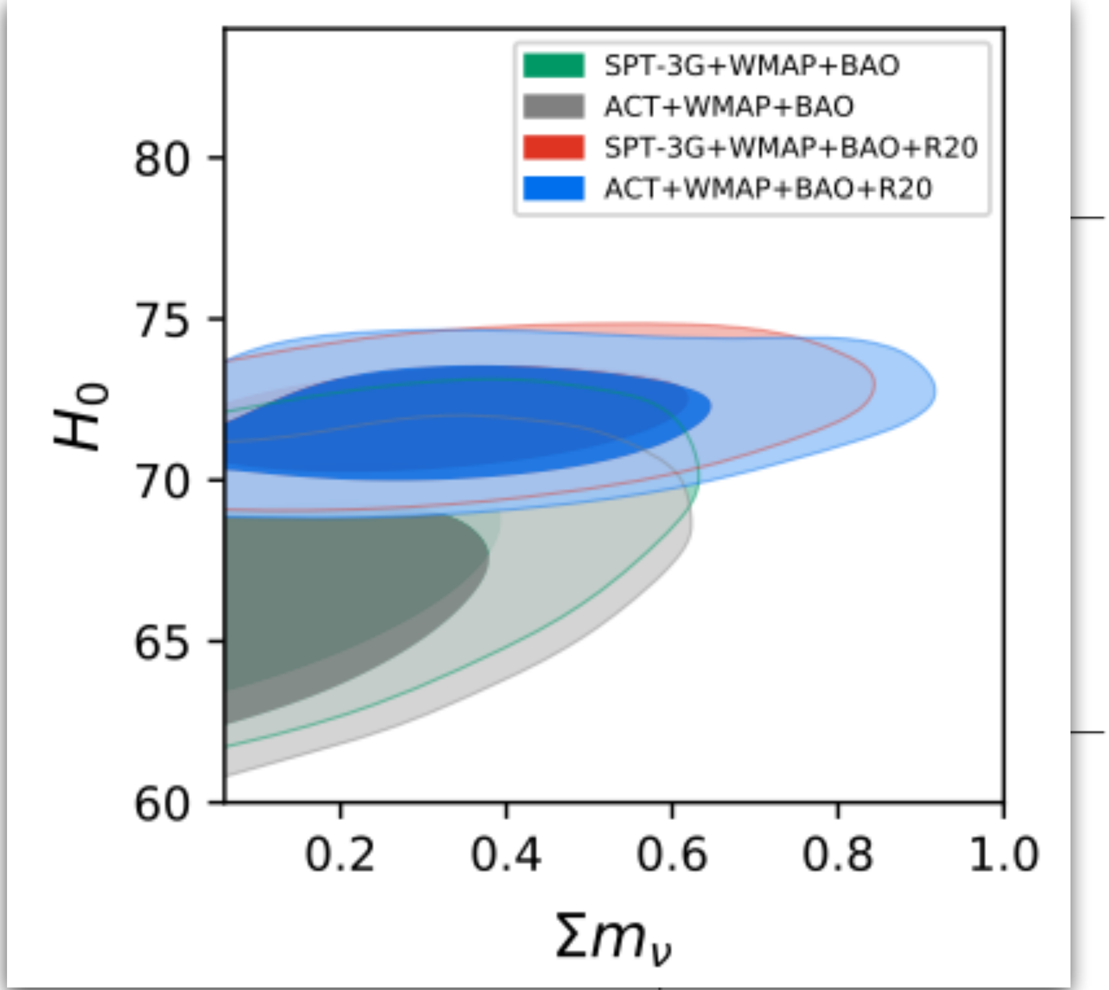
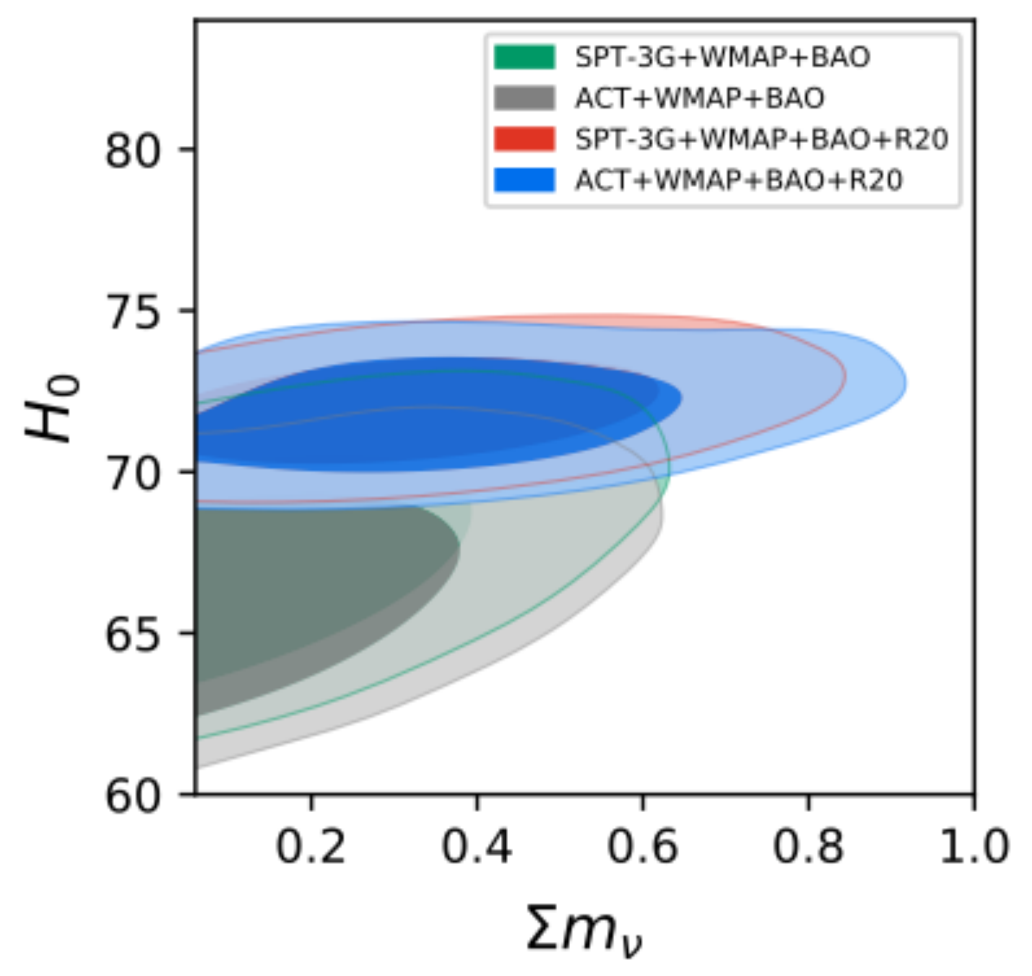
Constraints at 68% CL	Σm_ν [eV]
Planck ($+A_{lens}$)	< 0.50
SPT-3G+WMAP+R20	$0.49^{+0.12}_{-0.42}$
SPT-3G+WMAP+F21	< 0.60
SPT-3G+WMAP+BAO+R20	$0.37^{+0.13}_{-0.25}$
SPT-3G+WMAP+BAO+F21	< 0.32



What about the 10 parameters extended model?

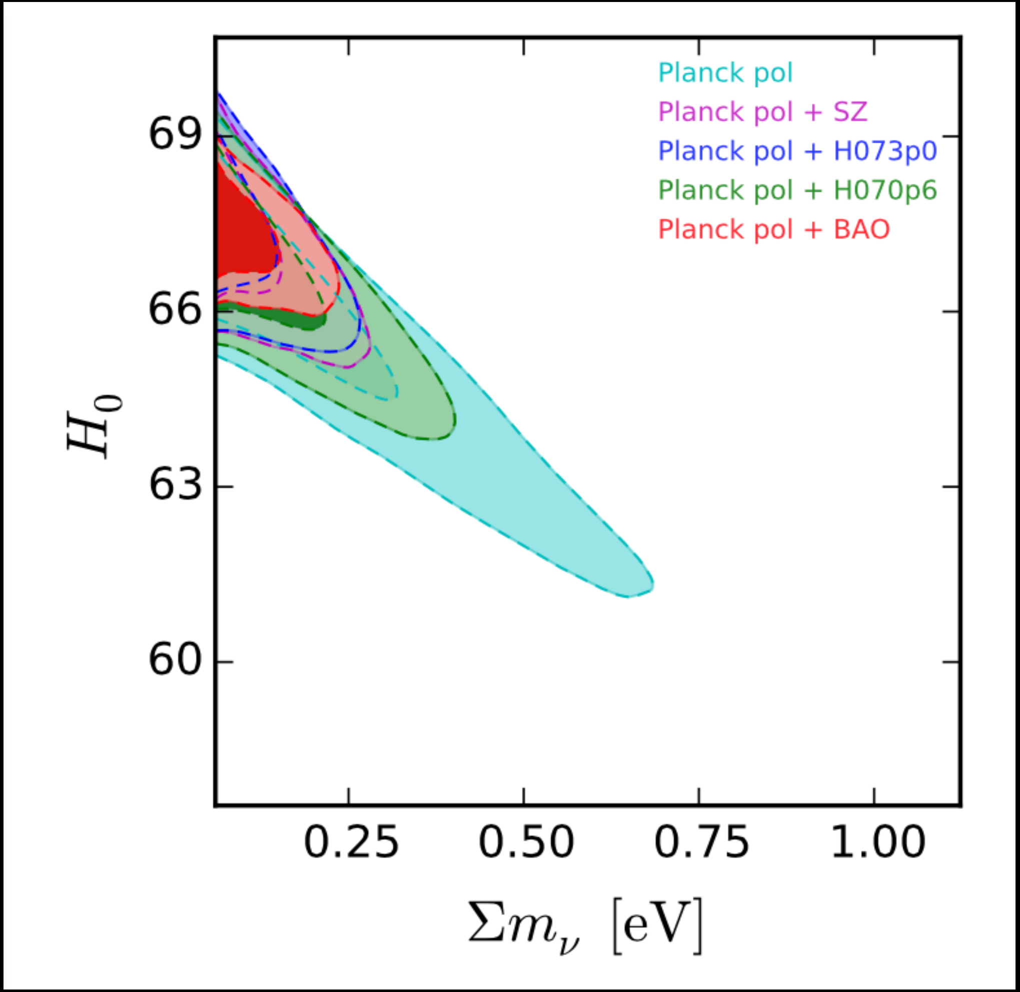
When CMB and BAO constraints are considered in these extended cosmologies, they provide constraints on the Σmν vs H0 plane that clearly show a correlation between these two parameters, that is exactly the opposite of what is obtained under standard LCDM.

10 parameters



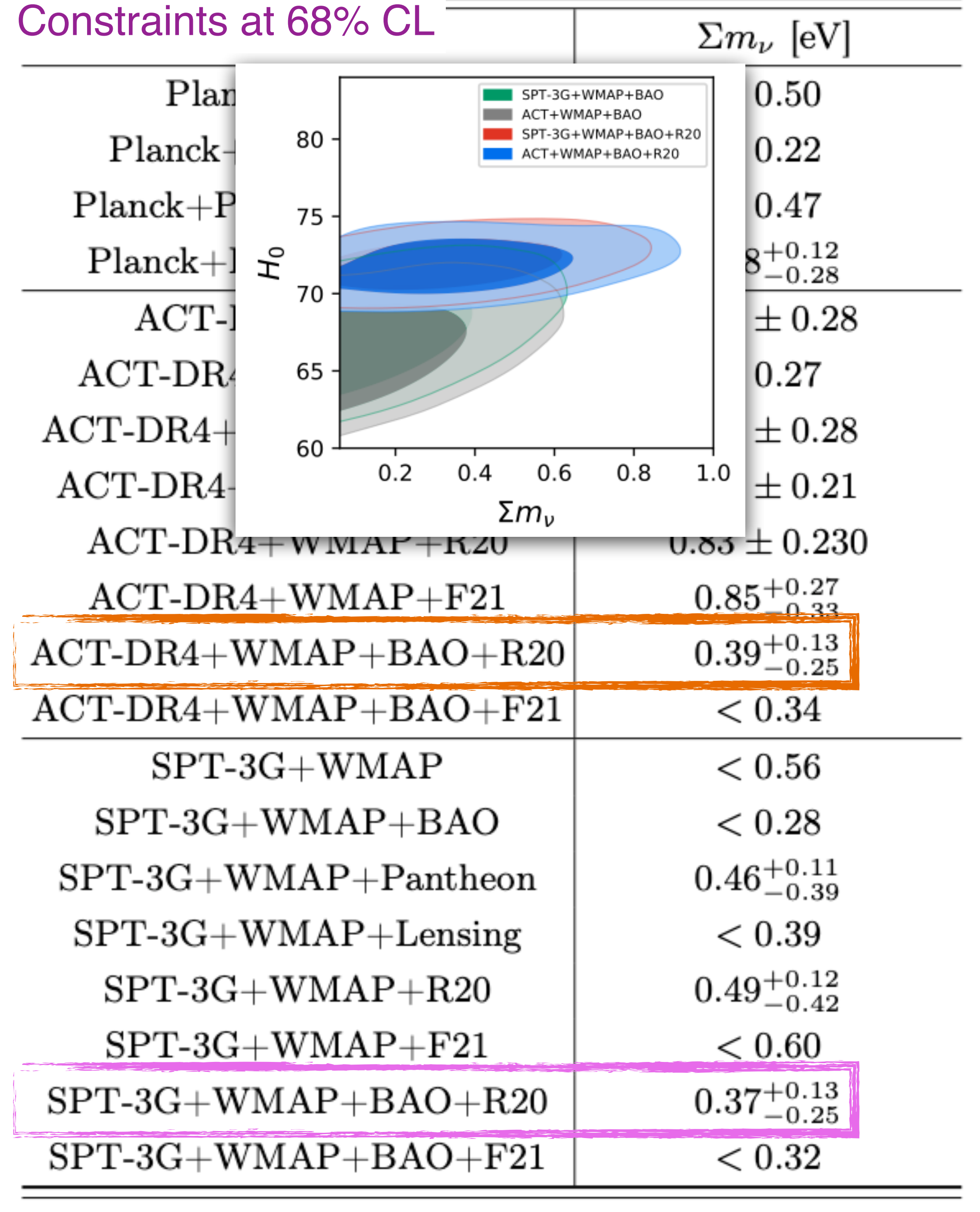
Di Valentino and Melchiorri, arXiv:2112.02993 [astro-ph.CO]

standard LCDM



Di Valentino et al. Phys.Rev. D93 (2016) no.8, 083527

Alternative CMB vs Planck: Σmν



Constraints at 68% CL

	Σm_ν [eV]
Plan	0.50
Planck+	0.22
Planck+P	0.47
Planck+	$8^{+0.12}_{-0.28}$
ACT-	± 0.28
ACT-DR	0.27
ACT-DR4+	± 0.28
ACT-DR4	± 0.21
ACT-DR4+WMAP+R20	0.83 ± 0.230
ACT-DR4+WMAP+F21	$0.85^{+0.27}_{-0.33}$
ACT-DR4+WMAP+BAO+R20	$0.39^{+0.13}_{-0.25}$
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SPT-3G+WMAP+BAO+F21	< 0.32

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What about the 10 parameters extended model?

Therefore, in extended cosmologies that can solve the Hubble tension, a neutrino mass is preferred by the cosmological data:

ACT-DR4+BAO+R20 gives

$\Sigma m_\nu = 0.39^{+0.13}_{-0.25}$ eV,

while SPT-3G+BAO+R20

$\Sigma m_\nu = 0.60^{+0.44}_{-0.50}$ eV at 68% CL.

Concluding

There are many anomalies and tensions involving the CMB data:

- H0 tension
- S8 tension
- $A_L > 1$ for Planck
- Σm_ν for ACT and SPT
- EDE for ACT

presenting a serious limitation to the precision cosmology.

Are we sure that the CMB results are still a confirmation of the flat standard ΛCDM cosmological model?

At this point, given the quality of all the analyses,
probably these discrepancies are indicating a problem with the underlying cosmology and our understanding of the Universe,
rather than the presence of systematic effects.

These cosmic discordances
call for new observations and stimulate the investigation of
alternative theoretical models and solutions.

Thank you!

e.divalentino@sheffield.ac.uk