H0 tension: current data and possible solutions

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Frontier Objects in Astrophysics and Particle Physics
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THE ROYAL SOCIETY

The ΛCDM model

Out of various cosmological models proposed in literature,
the Lambda cold dark matter (ΛCDM) scenario has been chosen
as the standard model for its simplicity and ability to accurately describe
a wide range of astrophysical and cosmological observations.

However, ΛCDM still has many unknown areas and lacks the ability to explain
fundamental concepts related to the structure and evolution of the universe.
These concepts are based on three unknown ingredients that are not supported by
theoretical first principles or laboratory experiments
but are instead inferred from cosmological and astrophysical observations.

The three unknown ingredients are:
inflation, dark matter (DM), and dark energy (DE).
In ΛCDM, inflation is given by a single, slow-rolling scalar field;
DM is assumed to interact only through gravity,
be cold and pressureless, and lack direct evidence of its existence;
DE is represented by the cosmological constant term Λ,
without any strong physical explanation.

The ΛCDM model

Despite its theoretical shortcomings, ΛCDM remains the preferred model due to its ability to accurately describe observed phenomena. However, the ΛCDM model with its six parameters is not based on deep-rooted physical principles and should be considered, at best, an approximation of an underlying physical theory that remains undiscovered.

Hence, as observations become more numerous and accurate, deviations from the ΛCDM model are expected to be detected. And in fact, discrepancies in important cosmological parameters, such as H0, have already arisen in various observations with different statistical significance.

While some of these tensions may have a systematic origin, their recurrence across multiple probes suggests that there may be flaws in the standard cosmological scenario, and that new physics may be necessary to explain these observational shortcomings.

Therefore, the persistence of these tensions could indicate the failure of the canonical ΛCDM model.

What is H0?

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

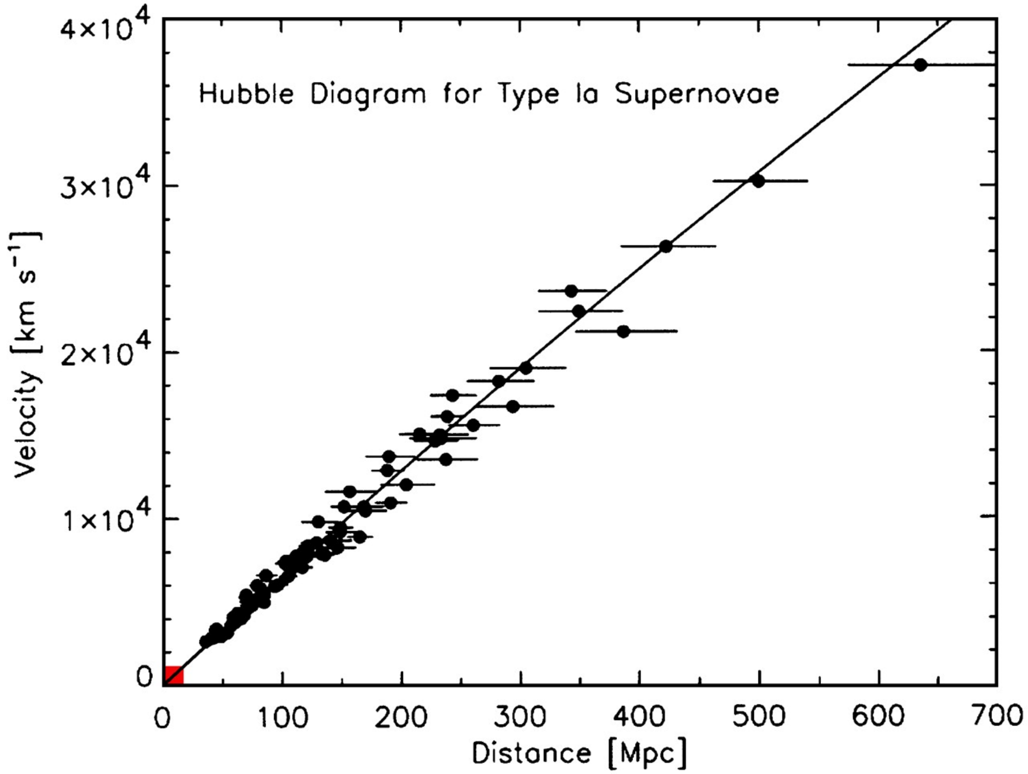
This can be obtained in two ways:

1. measuring the luminosity distance and the recessional velocity of known galaxies, and computing the proportionality factor.

Hubble's 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.

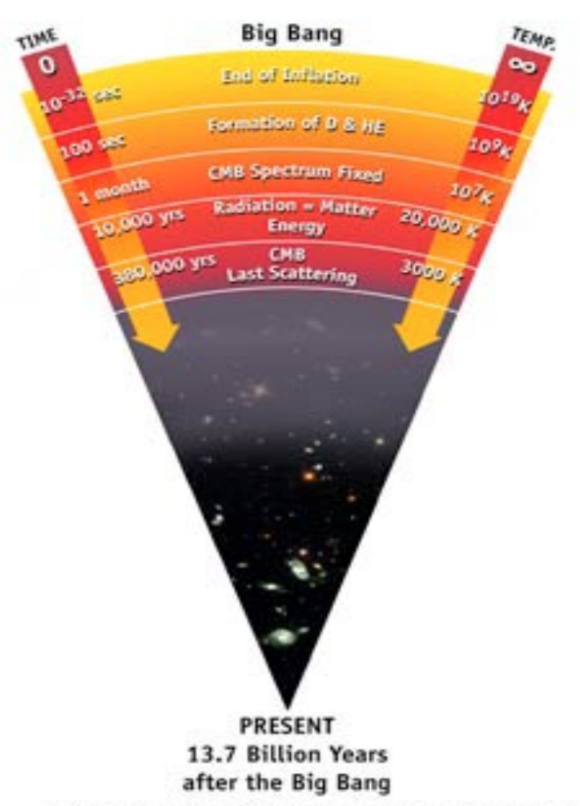
This can be obtained in two ways:

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

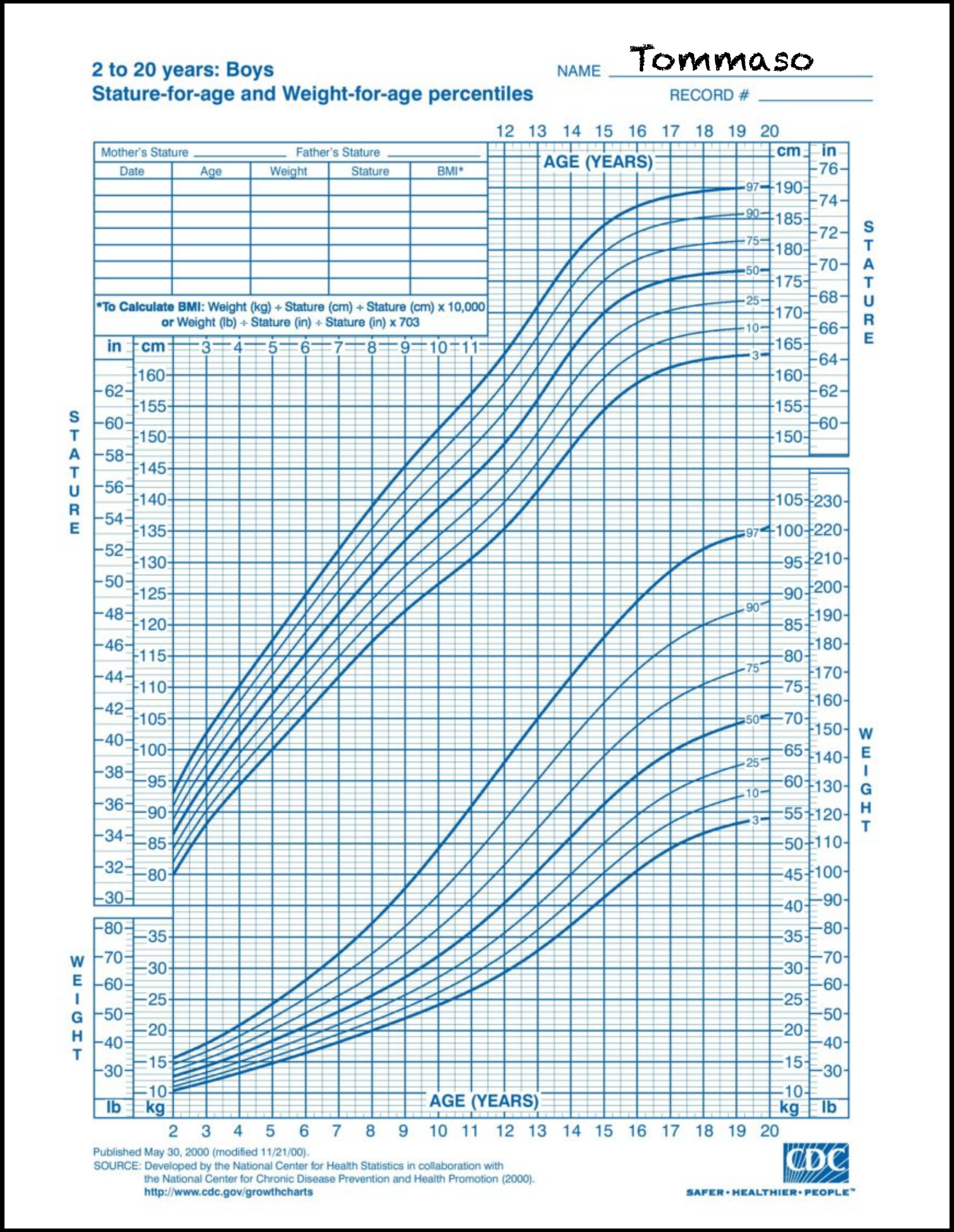
For example, we have CMB measurements and we assume the standard model of cosmology, i.e. the ΛCDM scenario.

1^{st} Friedmann equations describes the expansion history of the universe:

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




TRAINING SCHOOL
RUGBY


2 to 20 years: Boys
Stature-for-age and Weight-for-age percentiles
NAME Tommaso
RECORD #
Mother's Stature
Father's Stature
Date
Age
Weight
Stature
BMI*
*To Calculate BMI: Weight (kg) ÷ Stature (cm) ÷ Stature (cm) x 10,000
or Weight (lb) ÷ Stature (in) ÷ Stature (in) x 703
AGE (YEARS)
STATURE
WEIGHT
in
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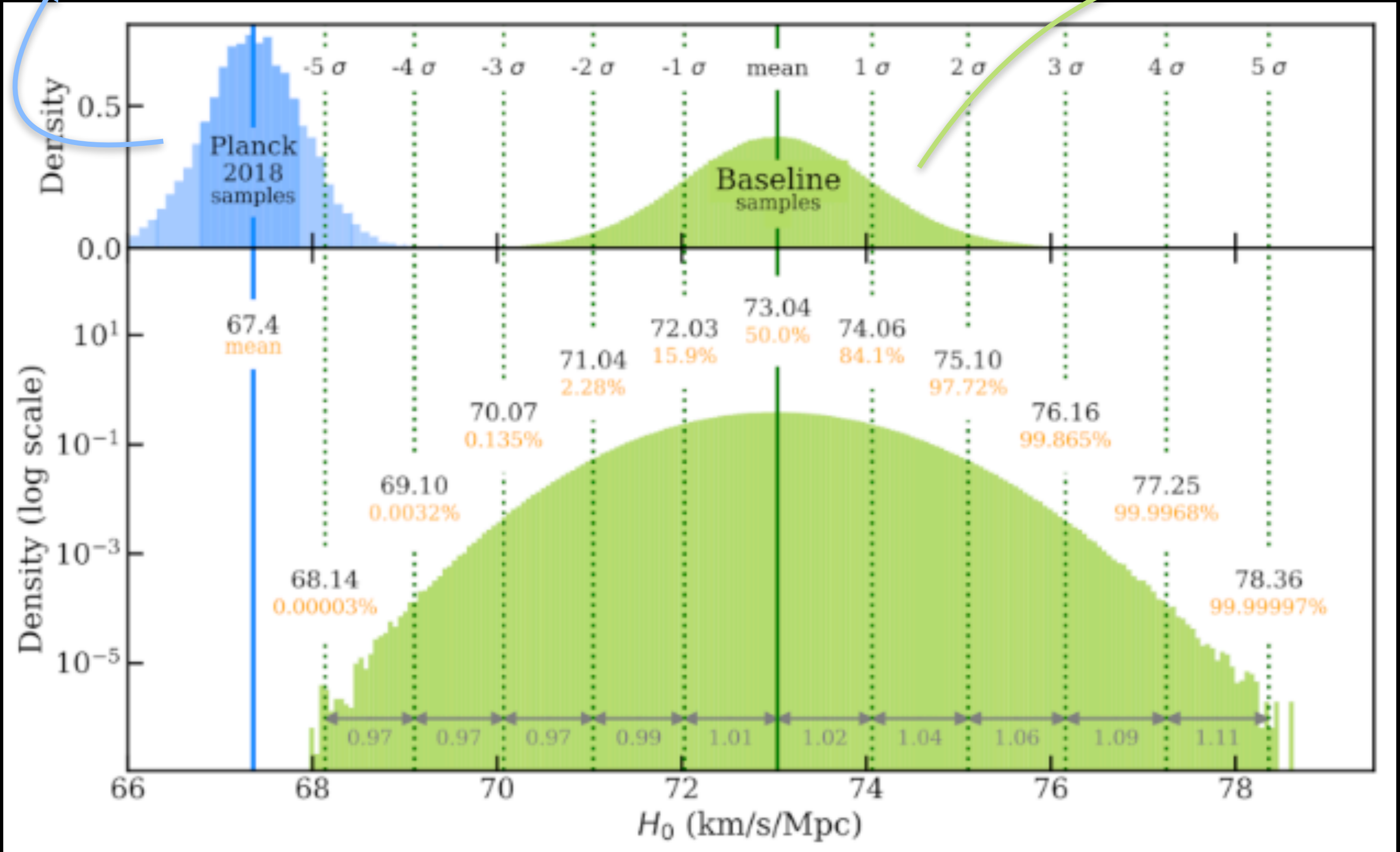
Published May 30, 2000 (modified 11/21/00).
SOURCE: Developed by the National Center for Health Statistics in collaboration with
the National Center for Chronic Disease Prevention and Health Promotion (2000).
http://www.cdc.gov/growthcharts
CDC
SAFER • HEALTHIER • PEOPLE™

H0 tension

If we compare the H0 estimates using these 2 methods they disagree.

The Planck estimate assuming a “vanilla" ΛCDM cosmological model:
H0 = 67.36 ± 0.54 km/s/Mpc

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



The latest local measurements obtained by the SH0ES collaboration

H0 = 73.04 ± 1.04 km/s/Mpc

Riess et al. arXiv:*2112.04510*

5σ = one in 3.5 million implausible to reconcile the two by chance

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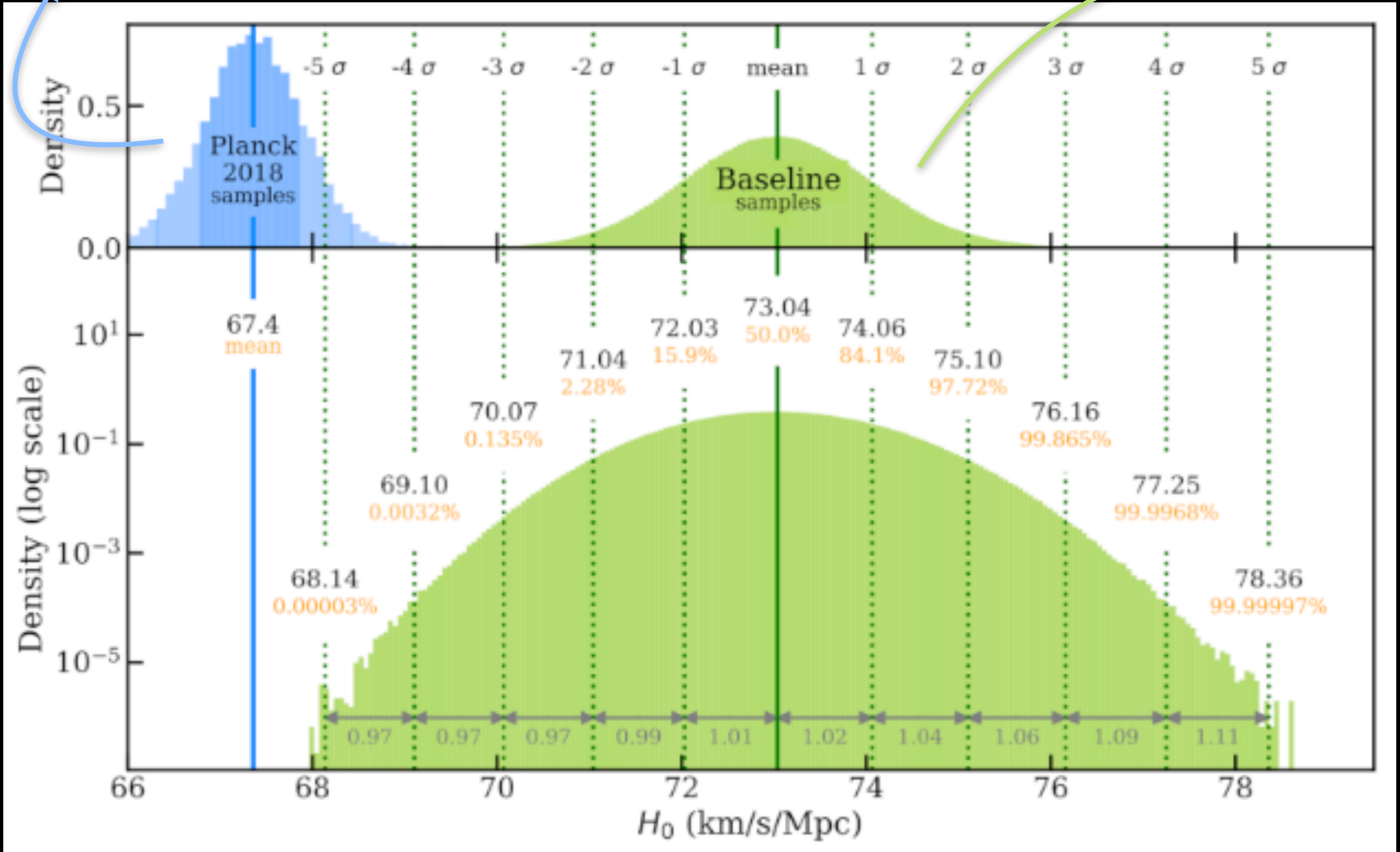
Planck 2018, Astron.Astrophys. 641 (2020) A6



Distance Ladder

The latest local measurements obtained by the SH0ES collaboration

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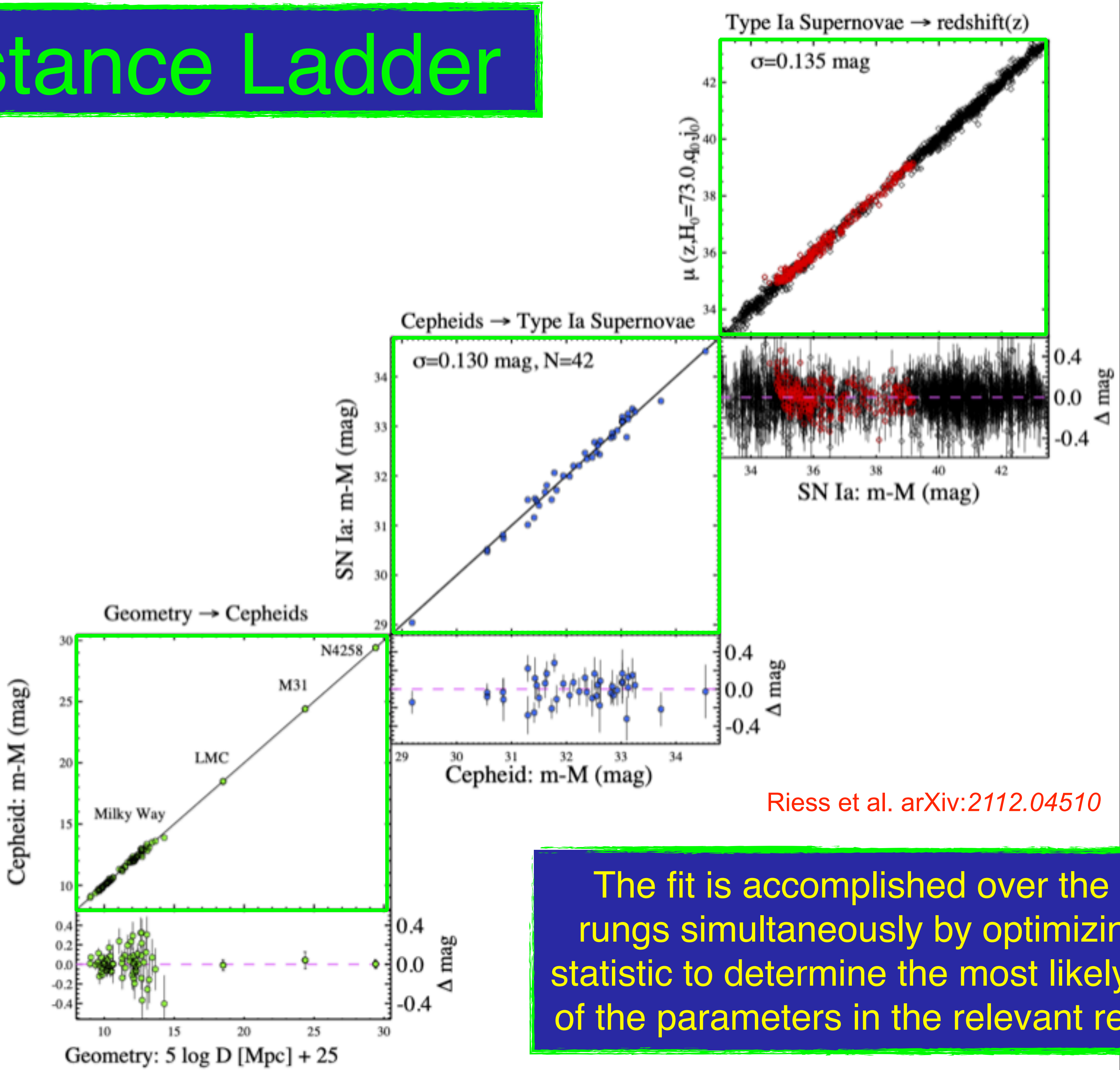
Riess et al. arXiv:*2112.04510*

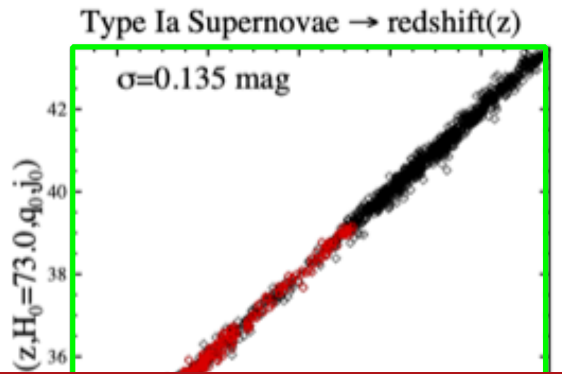
Distance Ladder

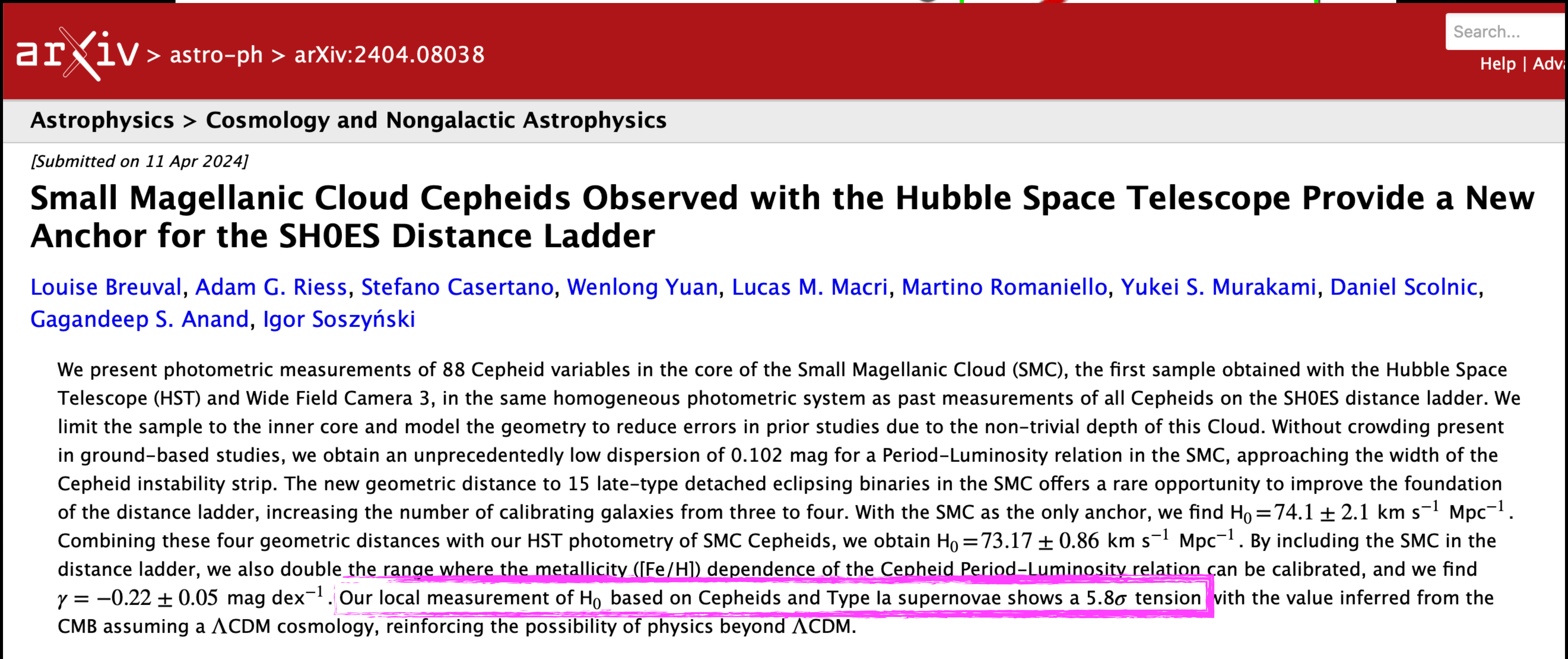


Riess et al. arXiv:*2112.04510*

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

Distance Ladder





arXiv > astro-ph > arXiv:2404.08038

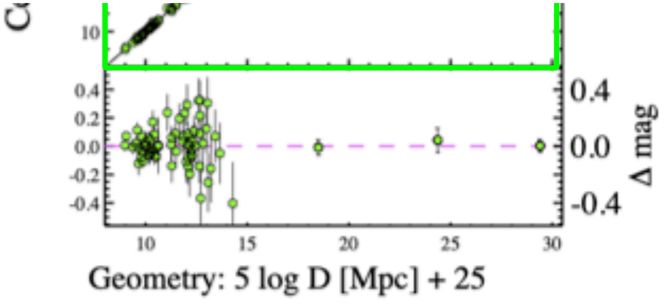
Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 11 Apr 2024]

Small Magellanic Cloud Cepheids Observed with the Hubble Space Telescope Provide a New Anchor for the SH0ES Distance Ladder

Louise Breuval, Adam G. Riess, Stefano Casertano, Wenlong Yuan, Lucas M. Macri, Martino Romaniello, Yukei S. Murakami, Daniel Scolnic, Gagandeep S. Anand, Igor Soszyński

We present photometric measurements of 88 Cepheid variables in the core of the Small Magellanic Cloud (SMC), the first sample obtained with the Hubble Space Telescope (HST) and Wide Field Camera 3, in the same homogeneous photometric system as past measurements of all Cepheids on the SH0ES distance ladder. We limit the sample to the inner core and model the geometry to reduce errors in prior studies due to the non-trivial depth of this Cloud. Without crowding present in ground-based studies, we obtain an unprecedentedly low dispersion of 0.102 mag for a Period-Luminosity relation in the SMC, approaching the width of the Cepheid instability strip. The new geometric distance to 15 late-type detached eclipsing binaries in the SMC offers a rare opportunity to improve the foundation of the distance ladder, increasing the number of calibrating galaxies from three to four. With the SMC as the only anchor, we find $H_0 = 74.1 \pm 2.1$ km s^{-1} Mpc^{-1}. Combining these four geometric distances with our HST photometry of SMC Cepheids, we obtain $H_0 = 73.17 \pm 0.86$ km s^{-1} Mpc^{-1}. By including the SMC in the distance ladder, we also double the range where the metallicity ([Fe/H]) dependence of the Cepheid Period-Luminosity relation can be calibrated, and we find $\gamma = -0.22 \pm 0.05$ mag dex^{-1}. Our local measurement of H_0 based on Cepheids and Type Ia supernovae shows a 5.8σ tension with the value inferred from the CMB assuming a ΛCDM cosmology, reinforcing the possibility of physics beyond ΛCDM.



CMB constraints

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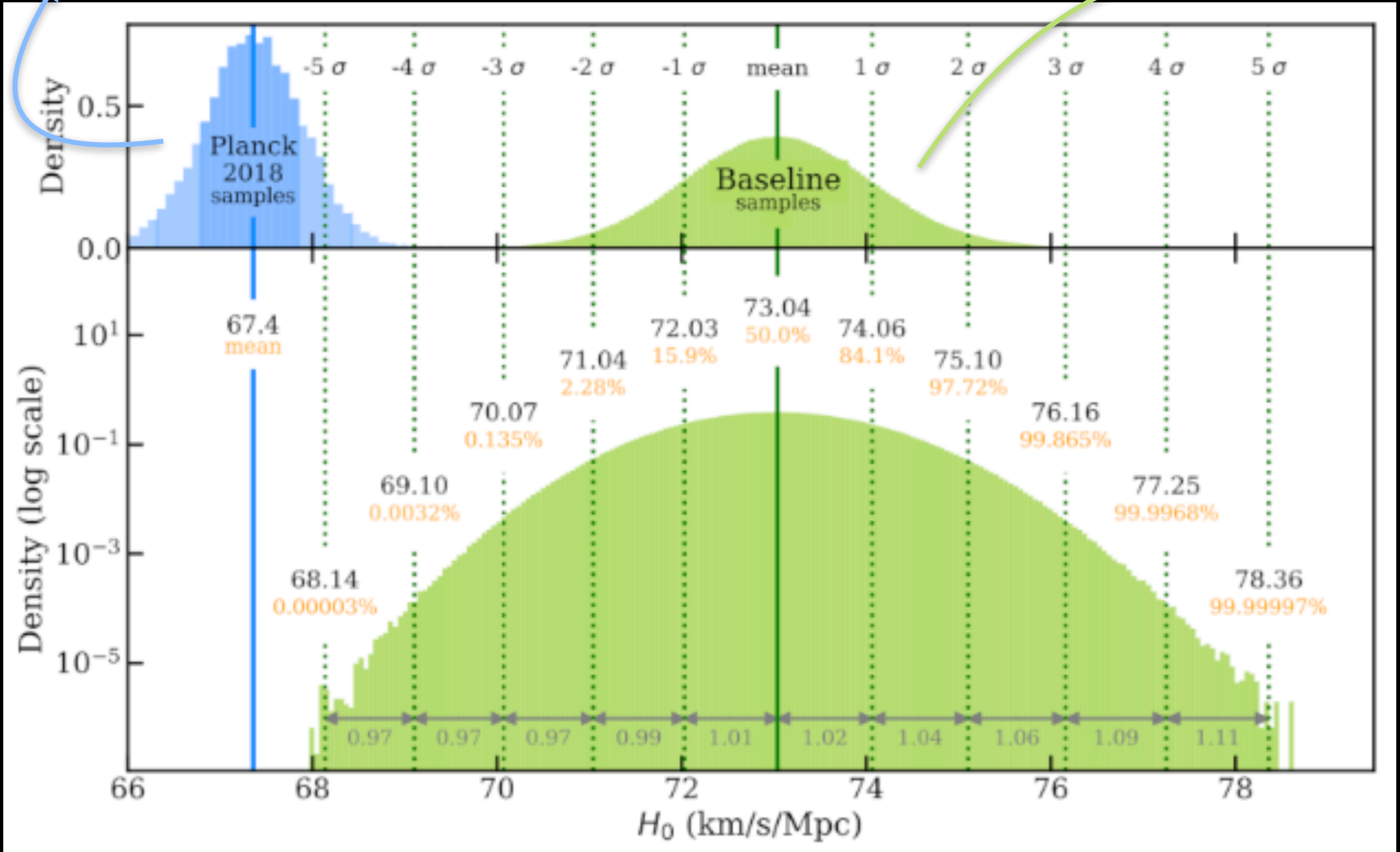

The latest local measurements obtained by the SH0ES collaboration

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CMB constraints

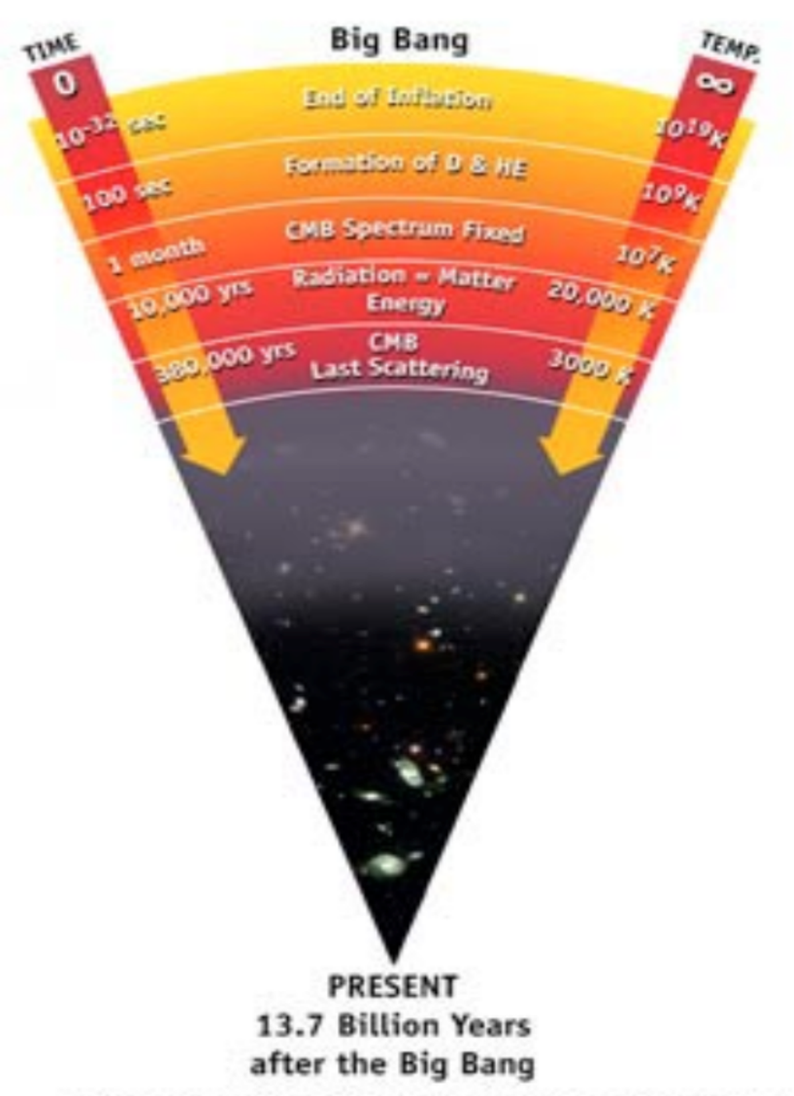


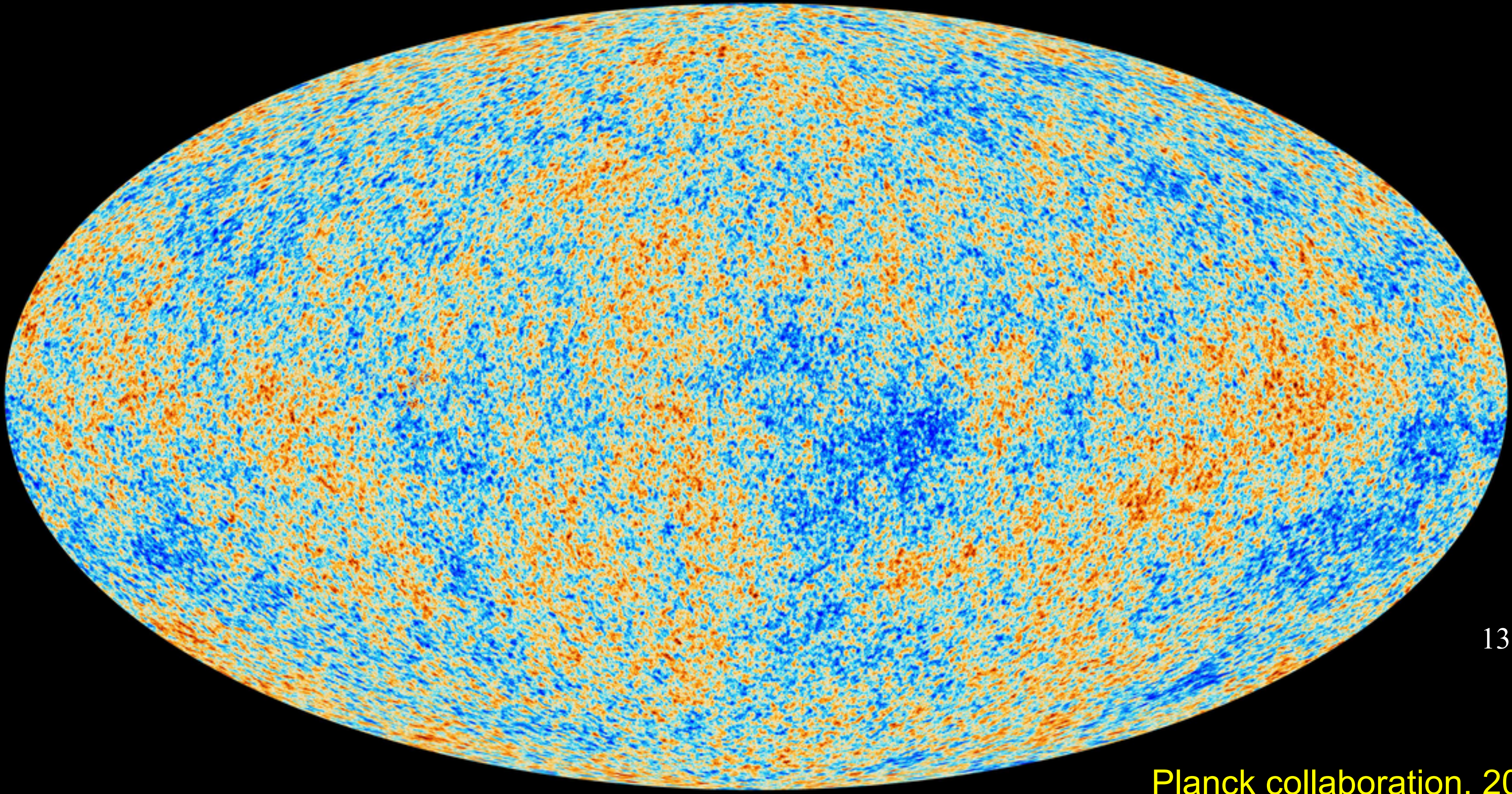
Figura: http://wmap.gsfc.nasa.gov

The Universe originates from a hot Big Bang.

The primordial plasma in thermodynamic equilibrium cools with the expansion of the Universe. It goes through the phase of recombination, where electrons and protons combine into hydrogen atoms, and decoupling, where the Universe becomes transparent to the motion of photons.

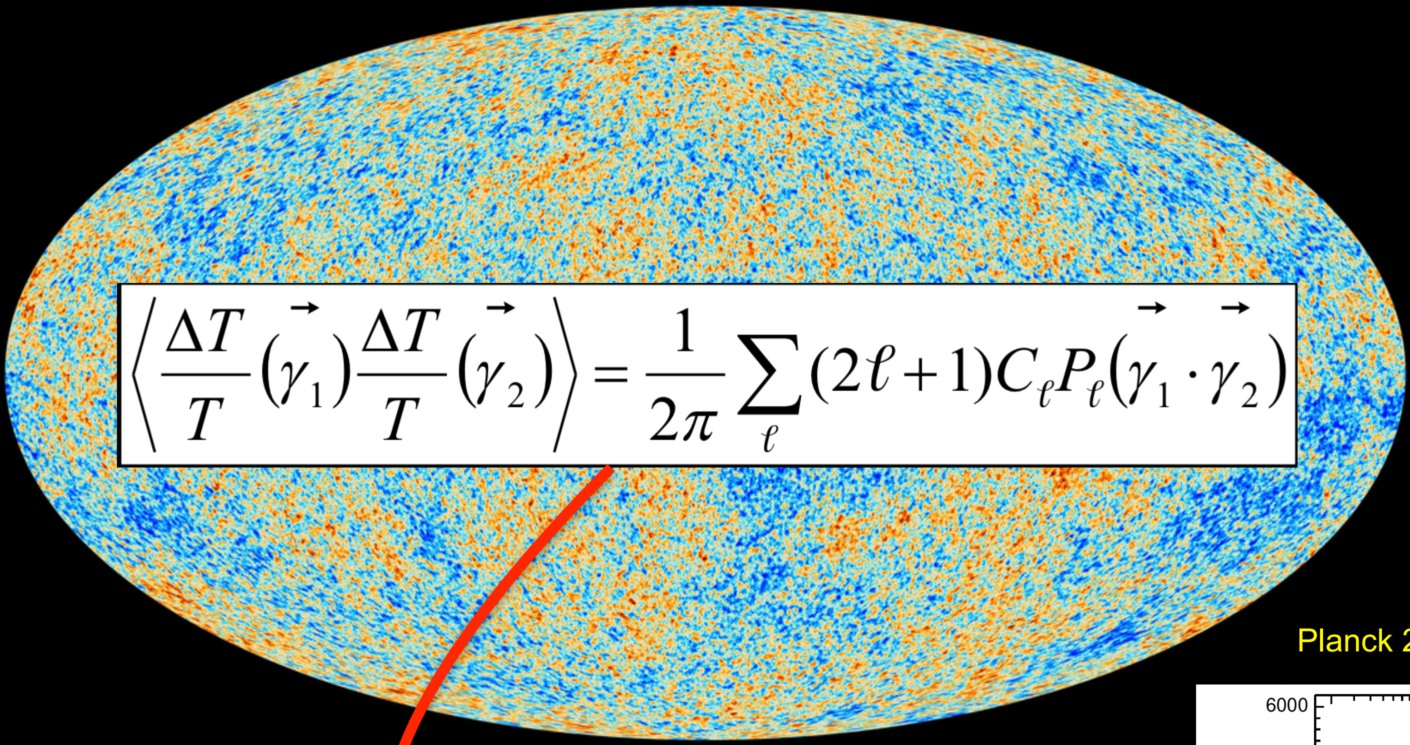
The Cosmic Microwave Background (CMB) is the radiation coming from recombination, emitted about 13 billion years ago, just 380,000 years after the Big Bang.

The CMB retains the shape of the primordial universe in which photons were in thermodynamic equilibrium, displaying a black-body spectrum that has cooled with the expansion of the universe, reaching a temperature of T=2.726K today.
This radiation coming from all directions is almost homogeneous, but also offers an image of the minuscule density differences present at recombination and bears witness to everything that happens to photons as they travel to us.
These effects result in small temperature variations among the photons themselves, on the order of 1/100000, known as anisotropies.



Planck collaboration, 2018

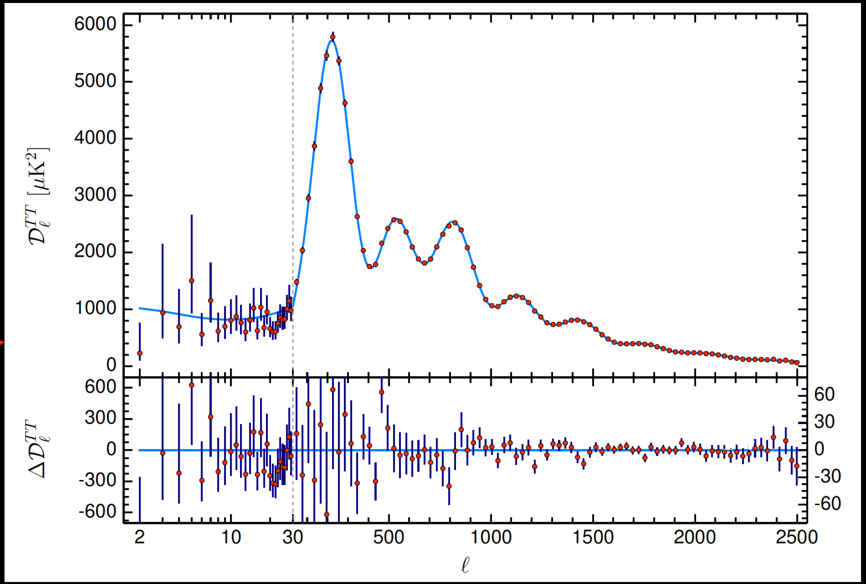
CMB constraints



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

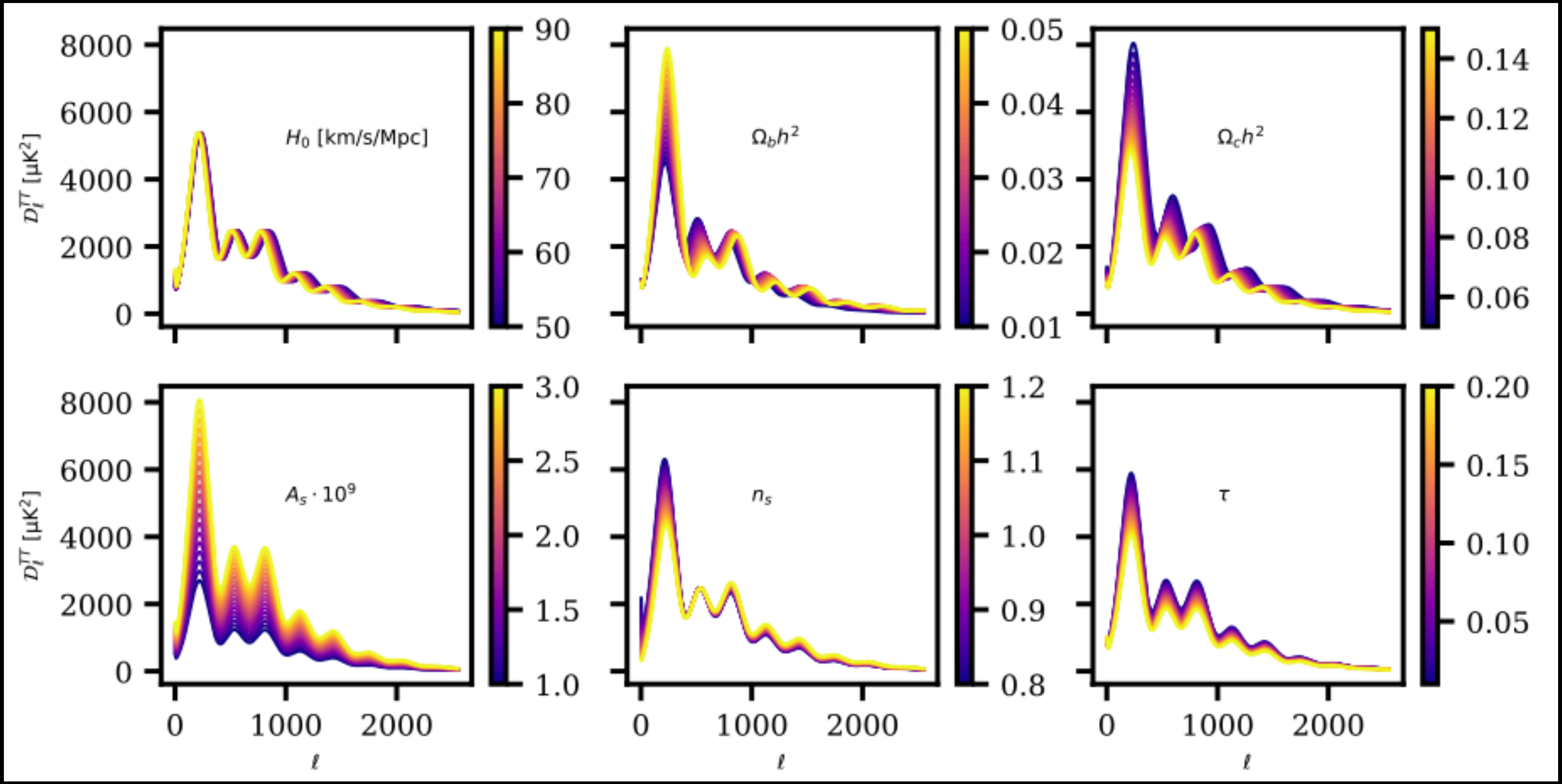
From the map of the CMB anisotropies we can extract the temperature angular power spectrum.

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



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

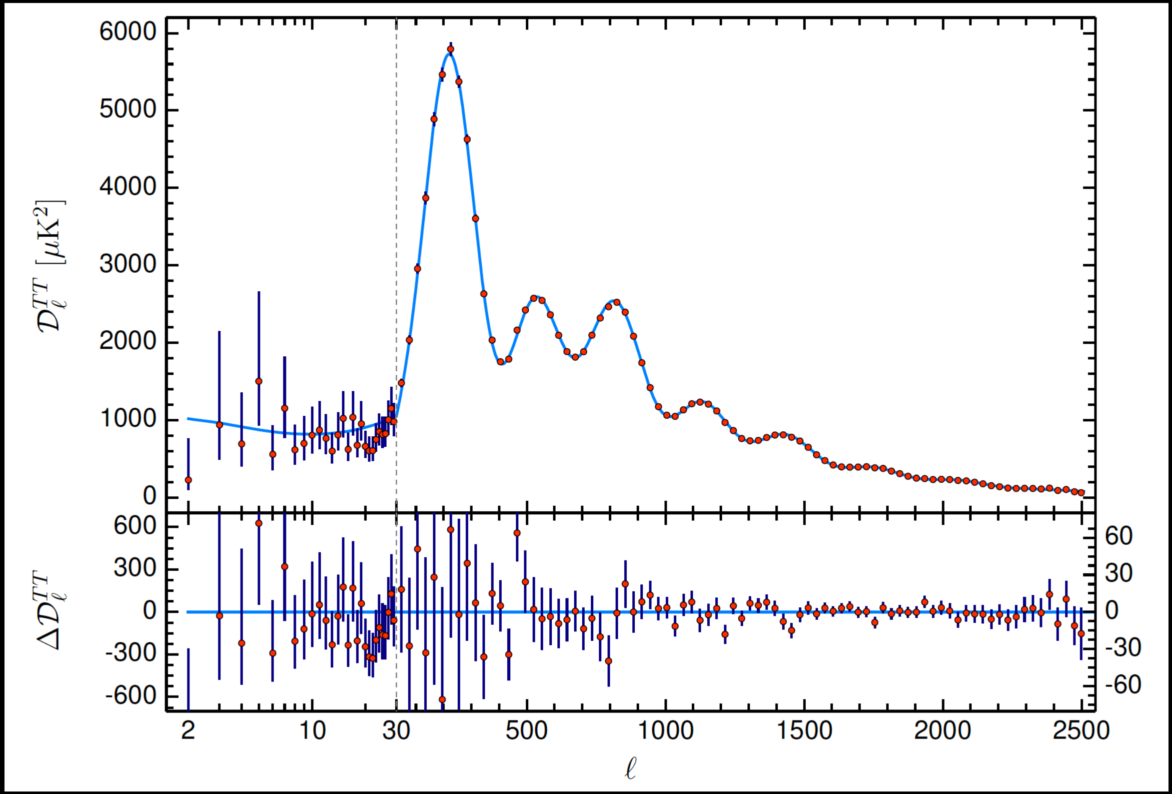


Lemos & Shah, arXiv:2307.13083

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.

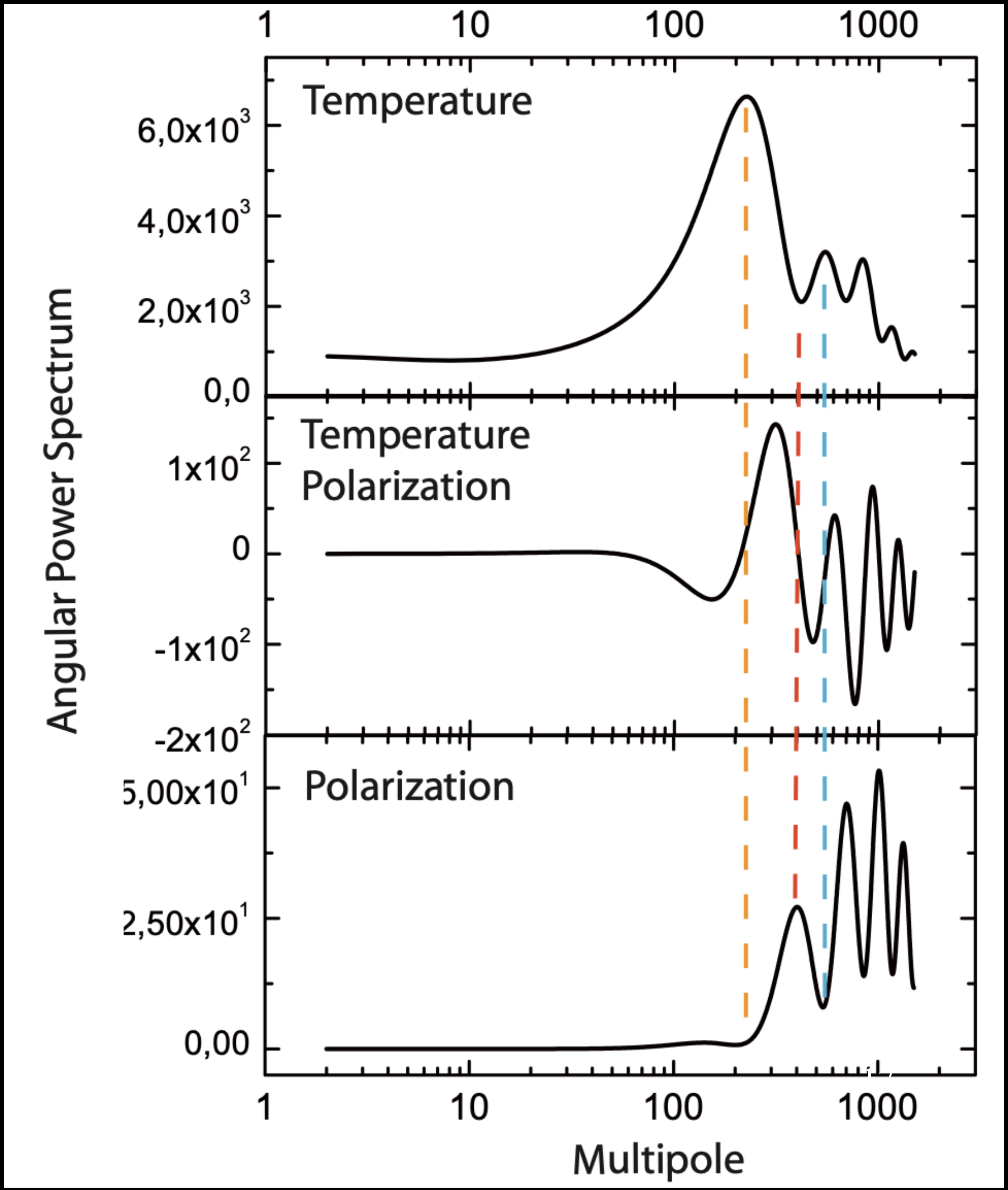


Planck 2018, Astron.Astrophys. 641 (2020) A6

Parameter constraints

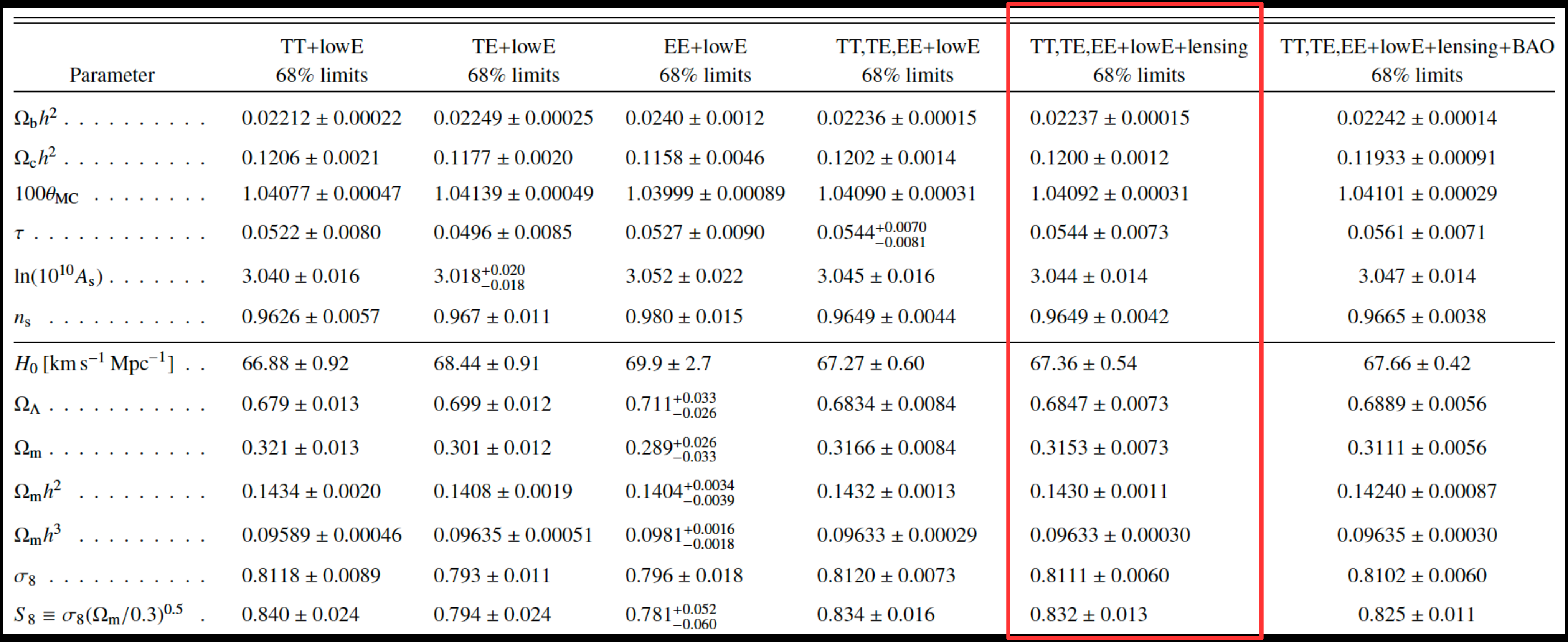
We can extract 4 independent angular spectra from the CMB:

- Temperature
- Cross Temperature Polarization E
- Polarization type E (density fluctuations)
- Polarization type B (gravitational waves)



Borstnik et al., hep-ph/0401043

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
$H_0\,[\mathrm{km\,s^{-1}\,Mpc^{-1}}]$ . .	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

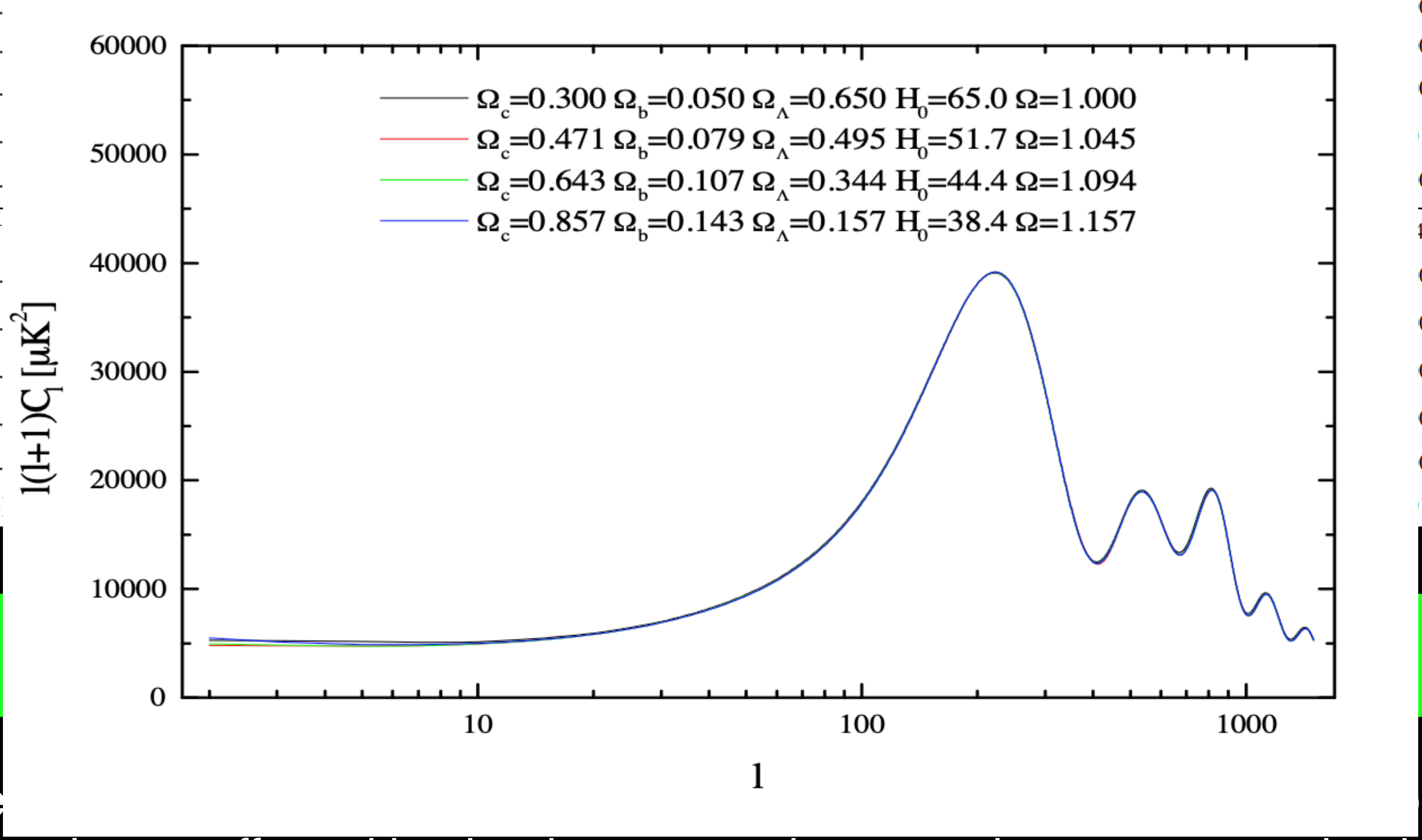
Planck 2018, Astron.Astrophys. 641 (2020) A6

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

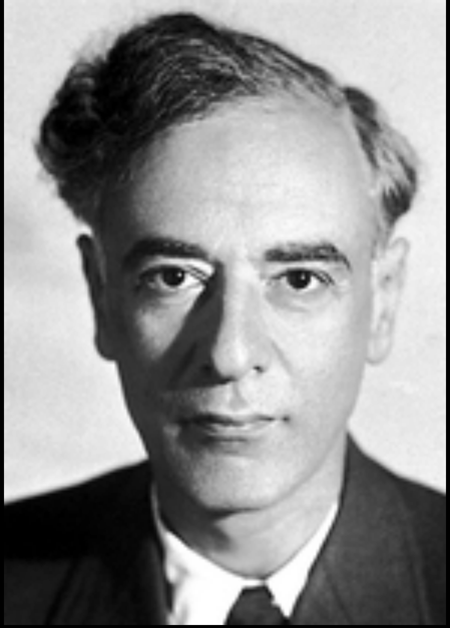
- The cosmological constraints are obtained assuming a cosmological model.
- The results are affected by the degeneracy between the parameters that induce similar effects on the observables.

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
$\Omega_c h^2$						0091
$100\theta_{MC}$						0029
τ						071
$\ln(10^{10} A_s)$						14
n_s						038
H_0 [km s^{-1} Mpc^{-}						42
Ω_Λ						056
Ω_m						056
$\Omega_m h^2$						0087
$\Omega_m h^3$						0030
σ_8						060
$S_8 \equiv \sigma_8(\Omega_m/0.3$						11



- The ... del.
- The results are affected by the degeneracy between the parameters that induce similar effects on the observables.

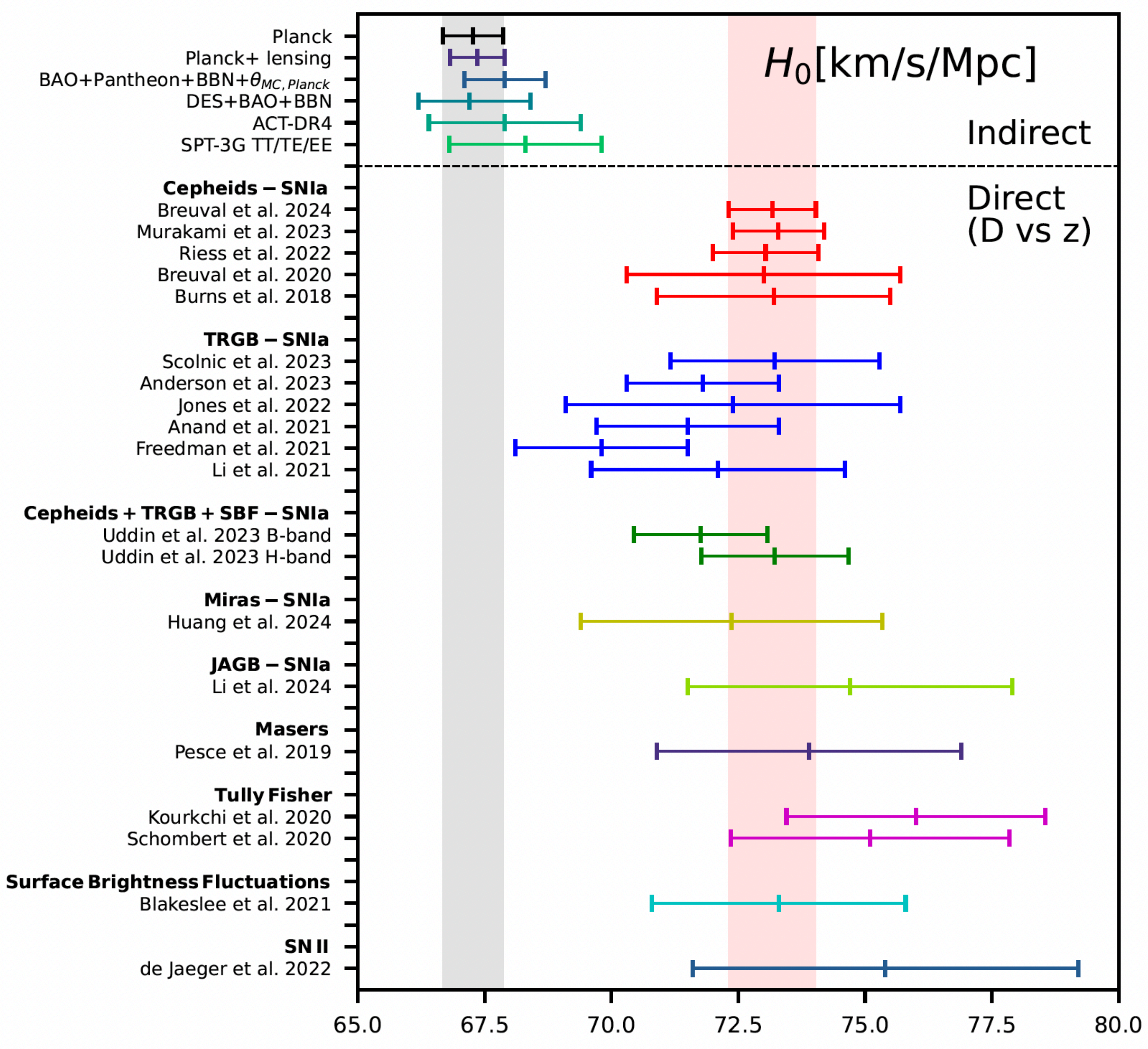


“Cosmologists are often in error but never in doubt”

Lev Landau

Are there other H0 estimates?

Latest H0 measurements



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

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

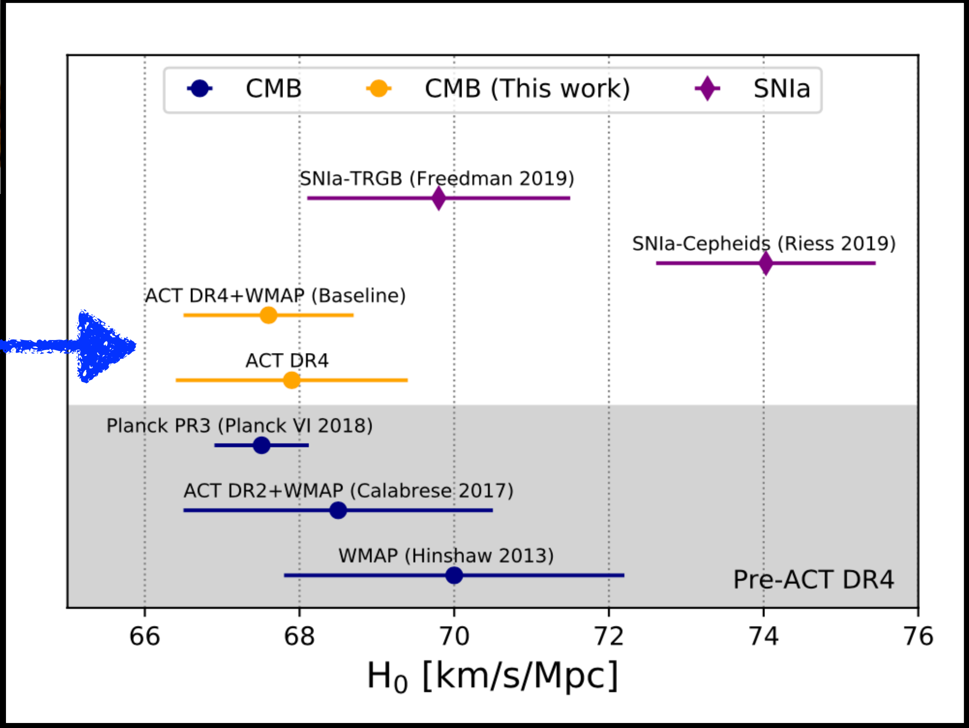
Di Valentino, *MNRAS* 502 (2021) 2, 2065-2073

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

Ground based CMB telescope

ACT-DR4:
$H_0 = 67.9 \pm 1.5$ km/s/Mpc in ΛCDM

ACT-DR4 + WMAP:
$H_0 = 67.6 \pm 1.1$ km/s/Mpc in ΛCDM



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

ΛCDM - dependent

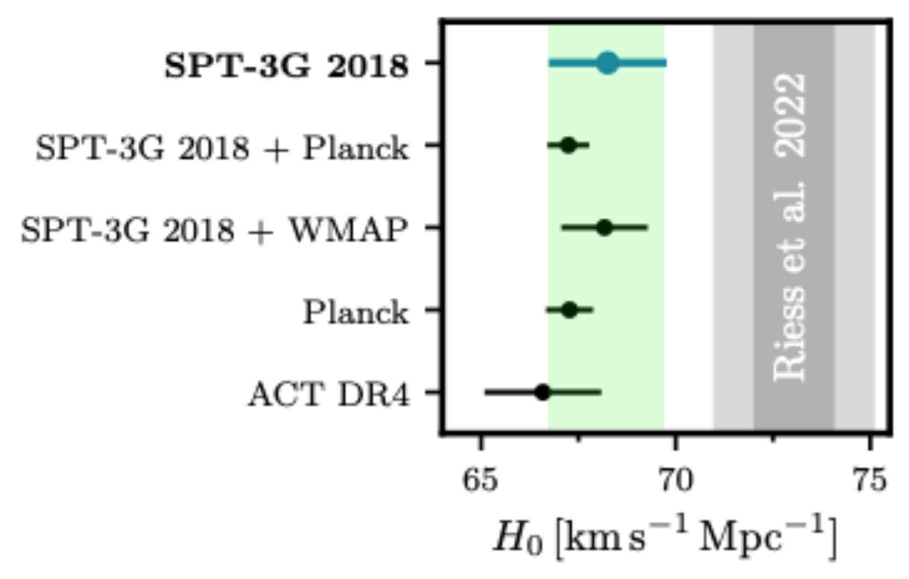
On the same side of Planck, i.e. preferring smaller values of H_0 we have:

Ground based CMB telescope

CMB Polarization Measurements with SPTpol

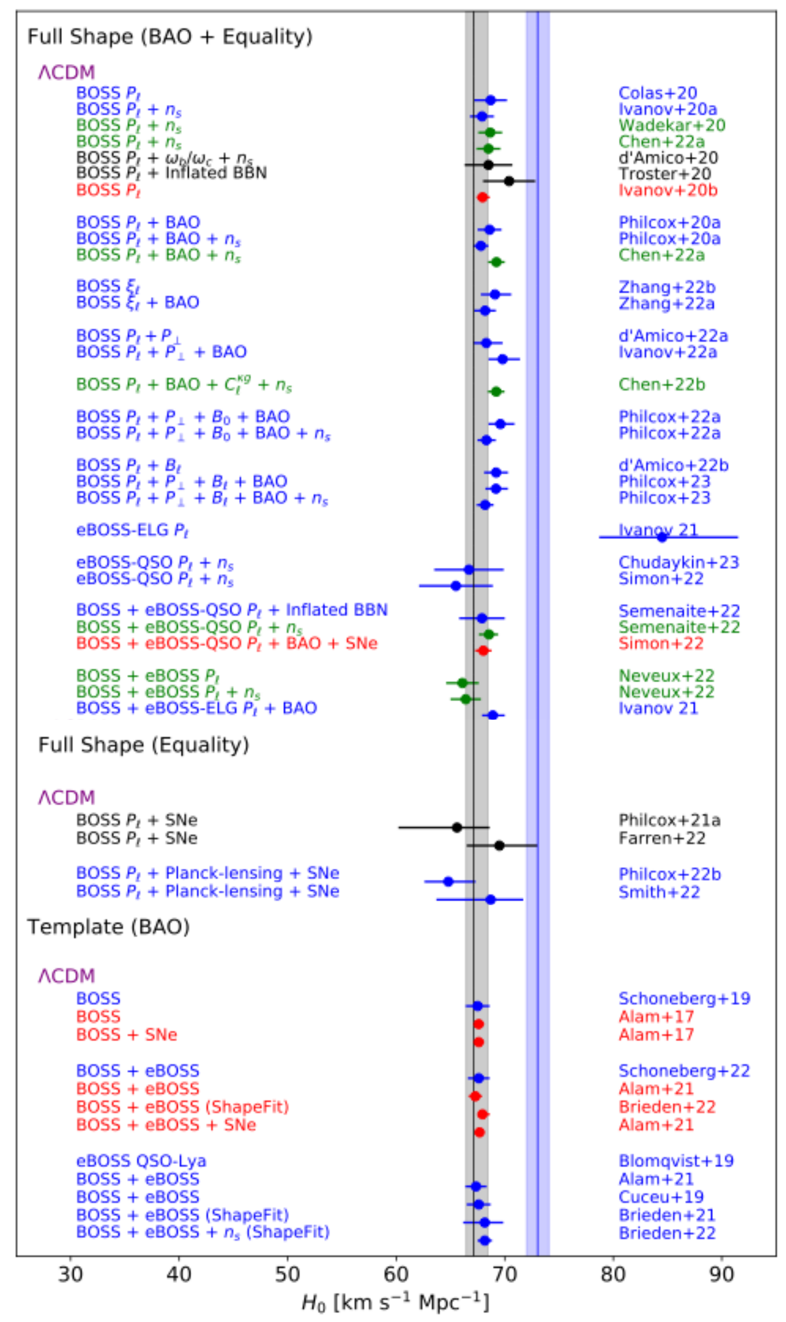
Nicholas Harrington
UC Berkeley

SPT-3G TT/TE/EE:
H0 = 68.3 ± 1.5 km/s/Mpc in ΛCDM



SPT-3G collaboration, arXiv:2212.05642

ΛCDM - dependent



Ivanov and Philcox, arXiv:2305.07977

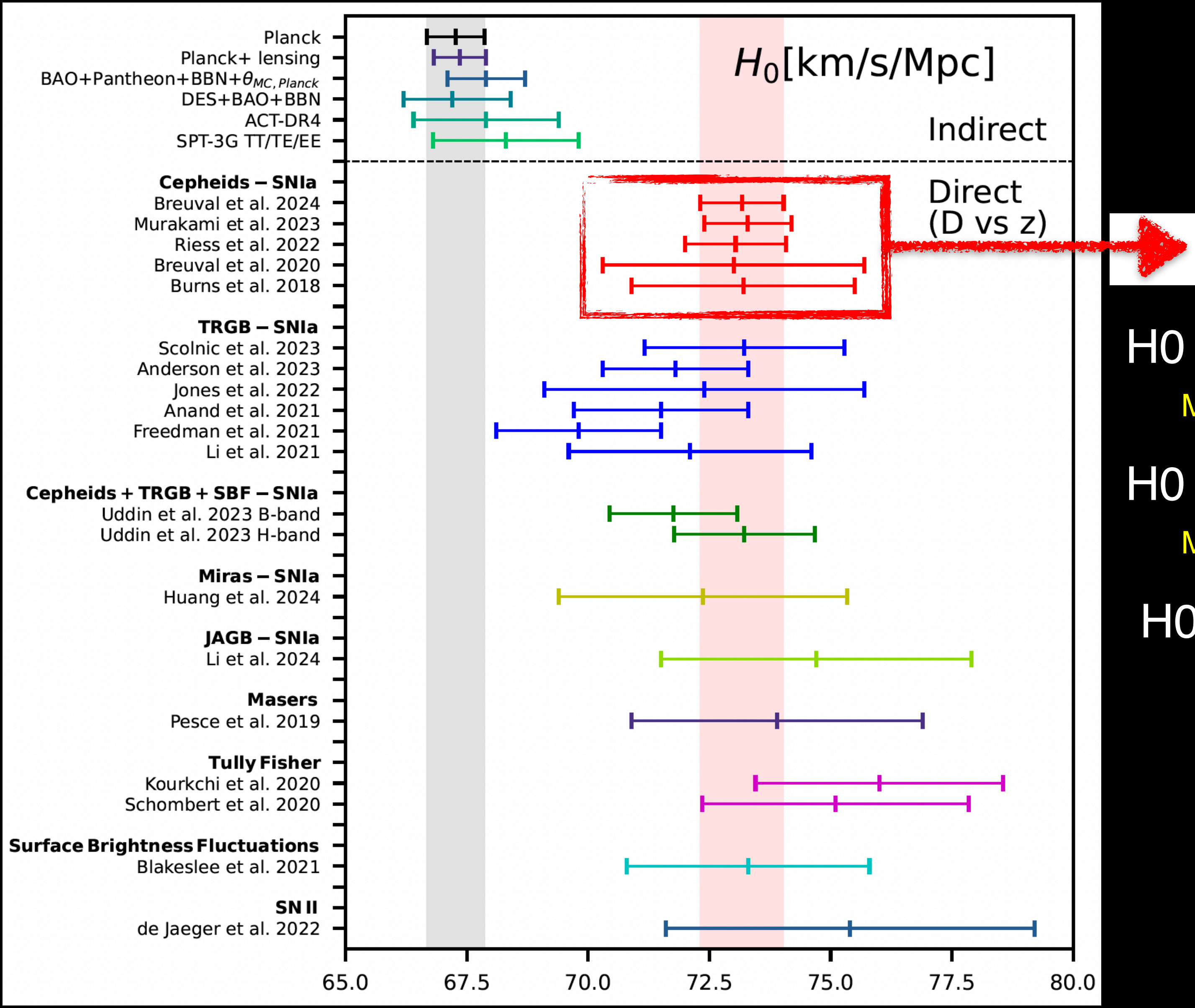
On the same side of Planck, i.e. preferring smaller values of H_0 we have:

Spectroscopic Surveys
BAO and Full Shape from BOSS and eBOSS

Results shown in blue include a BBN prior on ωb, in green use an ωb prior from *Planck*, in red are combined with the full *Planck* dataset.

ΛCDM - dependent

Latest H0 measurements



Cepheids-SN Ia:

H0 = 73.29 ± 0.90 km/s/Mpc

Murakami et al., arXiv:*2306.00070*

H0 = 73.29 ± 0.90 km/s/Mpc

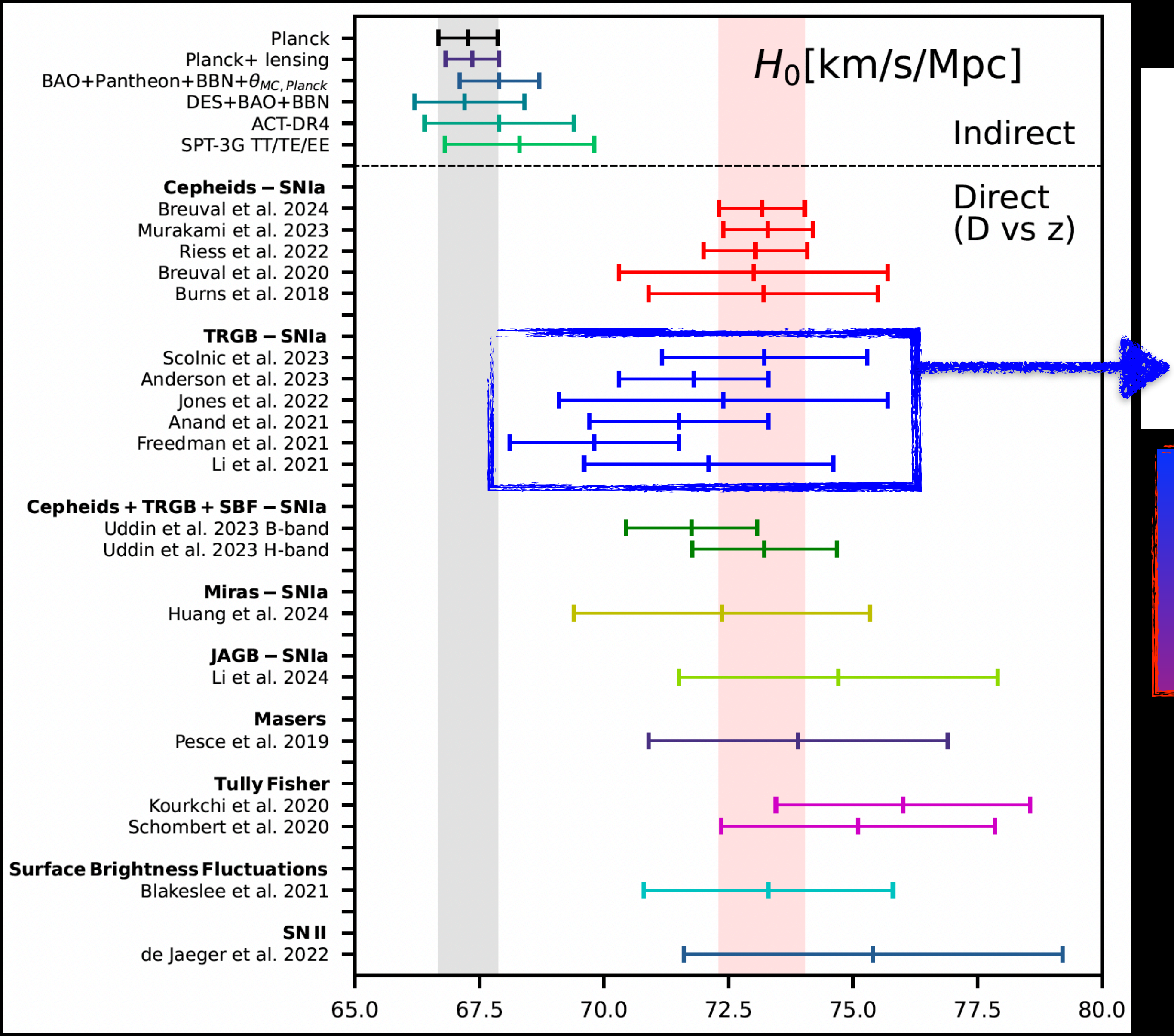
Murakami et al., arXiv:*2306.00070*

H0 = 73.04 ± 1.04 km/s/Mpc

Riess et al., arXiv:*2112.04510*

Di Valentino, *MNRAS* 502 (2021) 2, 2065-2073

Latest H0 measurements



Di Valentino, *MNRAS* 502 (2021) 2, 2065-2073

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 = 73.22±2.06 km/s/Mpc

Scolnic et al., arXiv:2304.06693

H0 = 71.8±1.5 km/s/Mpc

Anderson et al., arXiv:2303.04790

H0 = 72.4±3.3 km/s/Mpc

Jones et al., arXiv:2201.07801

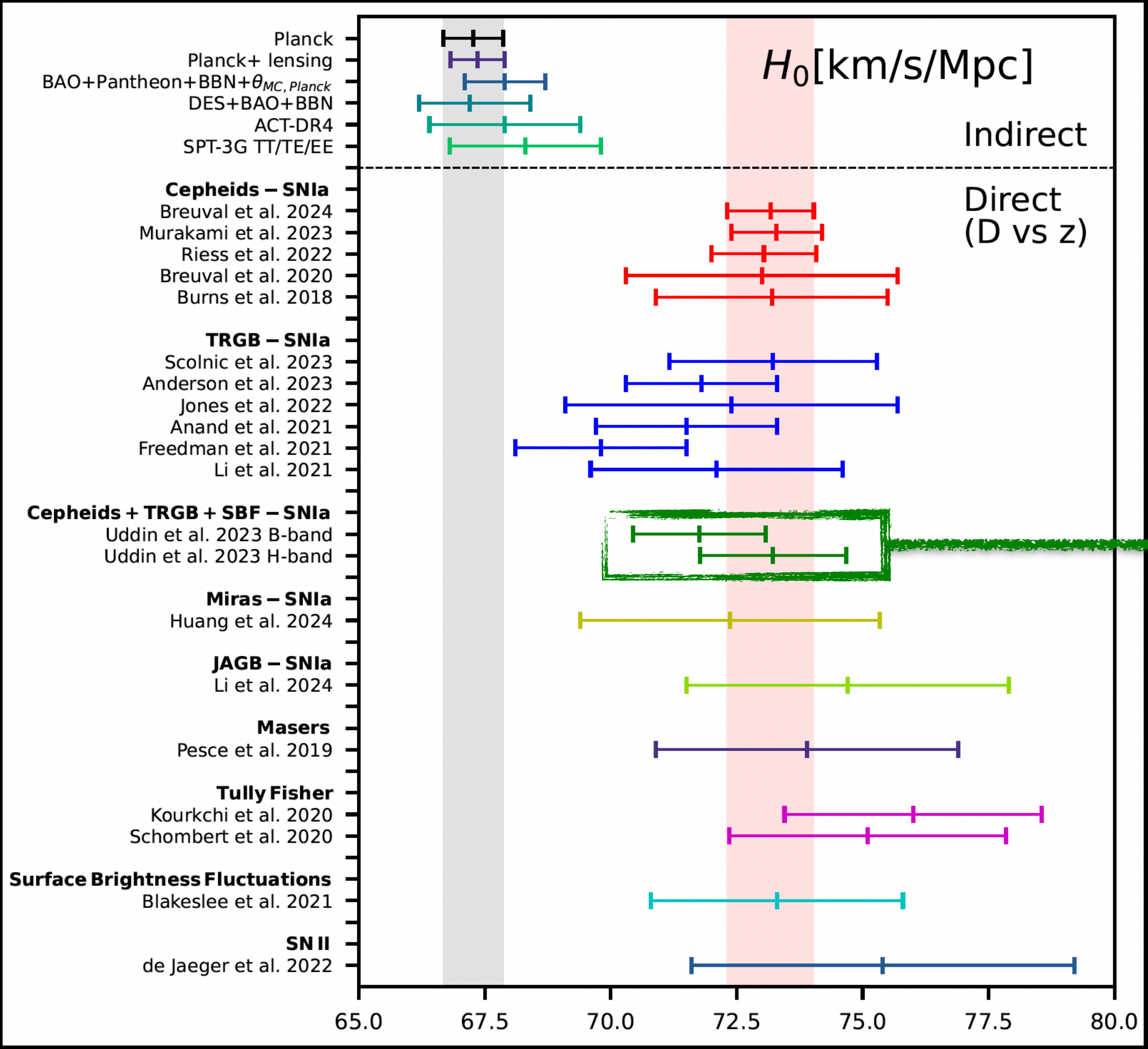
H0 = 71.5±1.8 km/s/Mpc

Anand et al., arXiv:2108.00007

H0 = 69.8±1.7 km/s/Mpc

Freedman, arXiv:2106.15656

Latest H0 measurements



Carnegie Supernova Project:

Measurements of H0 using Cepheids, TRGB, and SBF Distance Calibration to Type Ia Supernovae

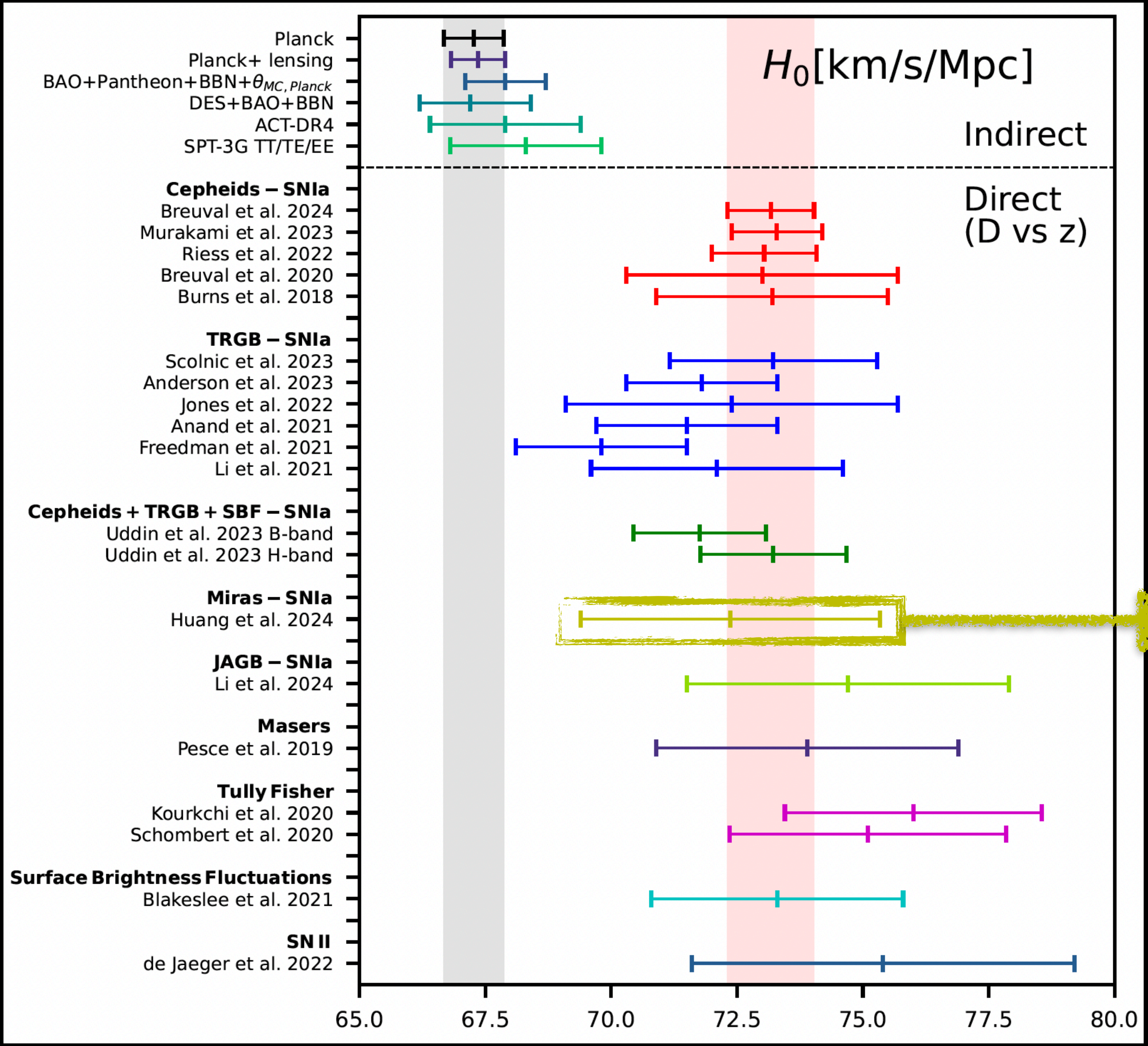
H0 = 71.76 ± 1.32 km/s/Mpc

H0 = 73.22 ± 1.45 km/s/Mpc

Uddin et al., arXiv:2308.01875 [astro-ph.CO]

Di Valentino, *MNRAS* 502 (2021) 2, 2065-2073

Latest H0 measurements



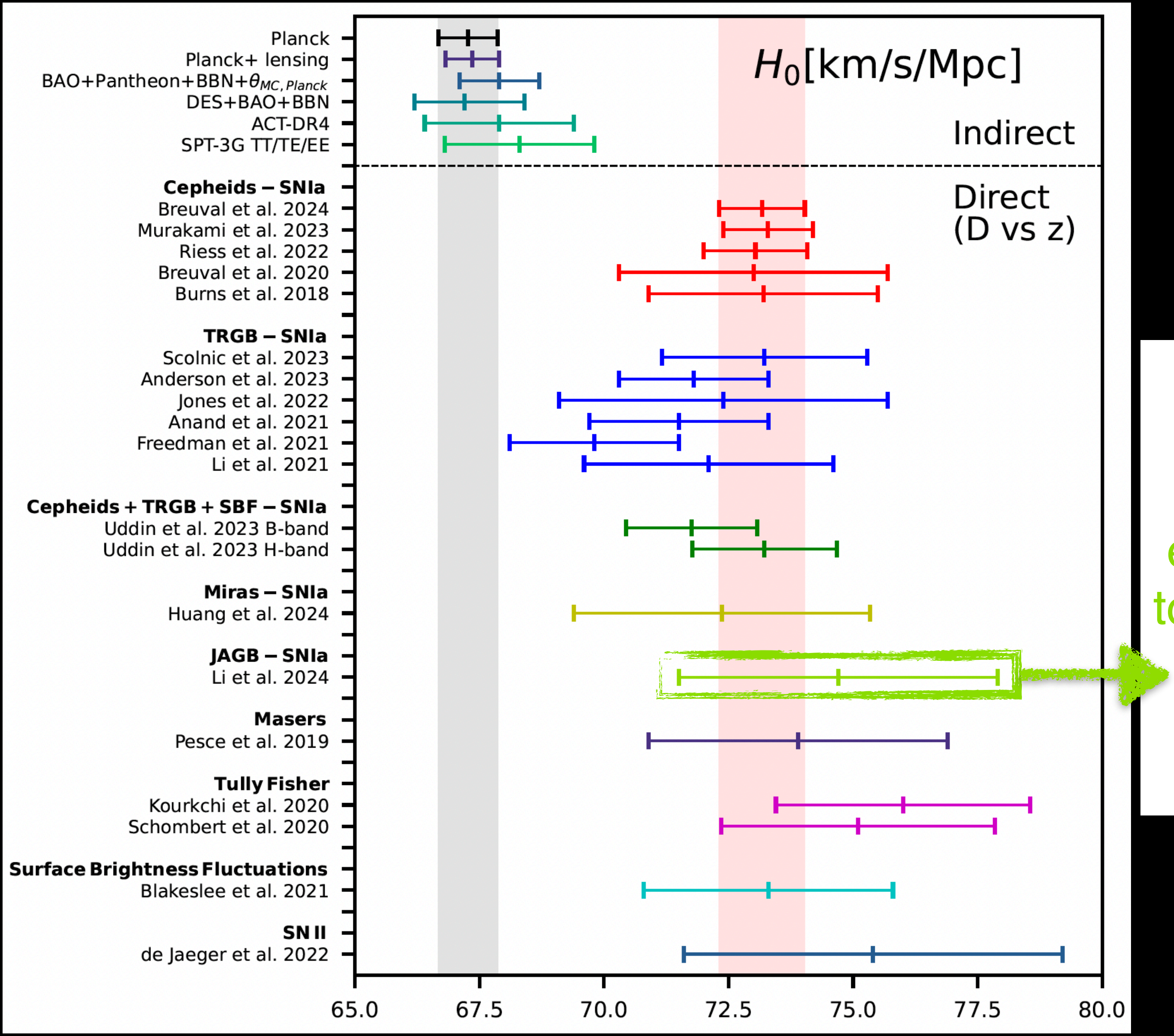
MIRAS
variable red giant stars from
older stellar populations

H0 = 72.37 ± 2.97 km/s/Mpc

Huang et al., arXiv:2312.08423 [astro-ph.CO]

Di Valentino, *MNRAS* 502 (2021) 2, 2065-2073

Latest H0 measurements



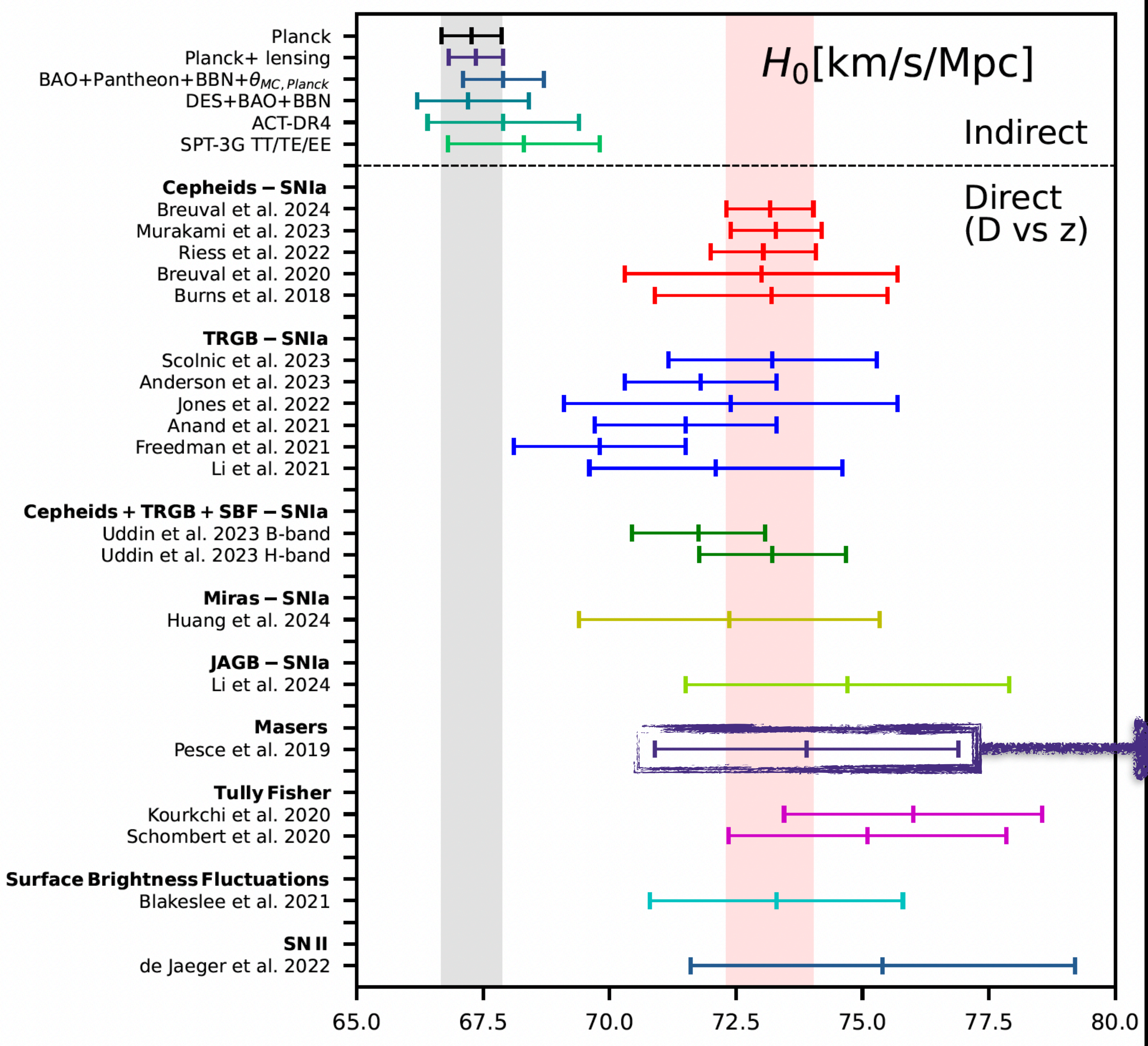
JAGB
The J-regions of the Asymptotic Giant Branch is expected from stellar theory to be populated by thermally-pulsing carbon-rich dust-producing asymptotic giant branch stars.

H0 = 74.7 ± 3.2 km/s/Mpc

Li et al., arXiv:2401.04777 [astro-ph.CO]

Di Valentino, *MNRAS* 502 (2021) 2, 2065-2073

Latest H0 measurements



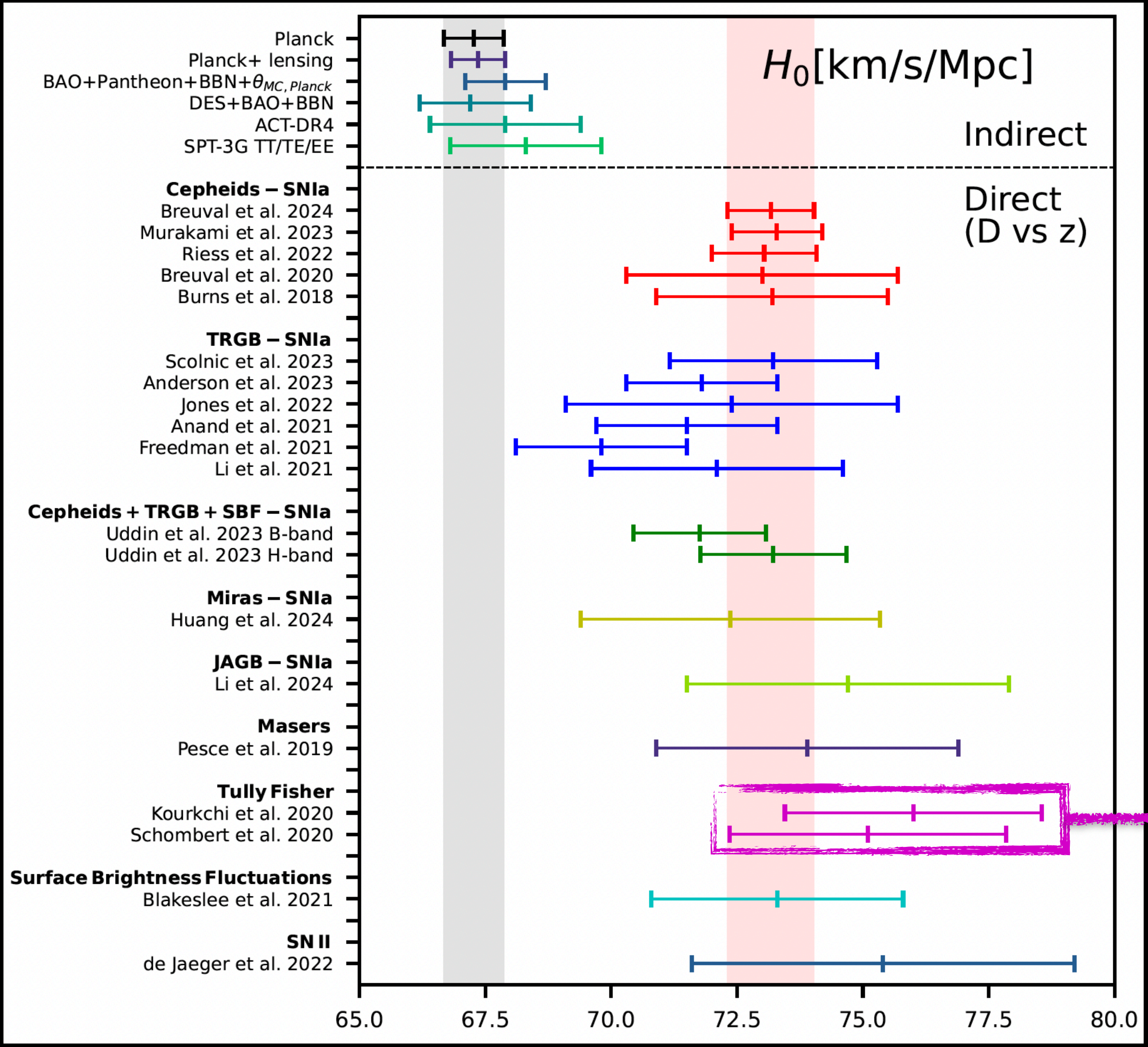
H0 = 73.9 ± 3.0 km/s/Mpc

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.

Di Valentino, *MNRAS* 502 (2021) 2, 2065-2073

Latest H0 measurements



H0 = 76.00 ± 2.55 km/s/Mpc

Kourkchi et al. arXiv:2004.14499

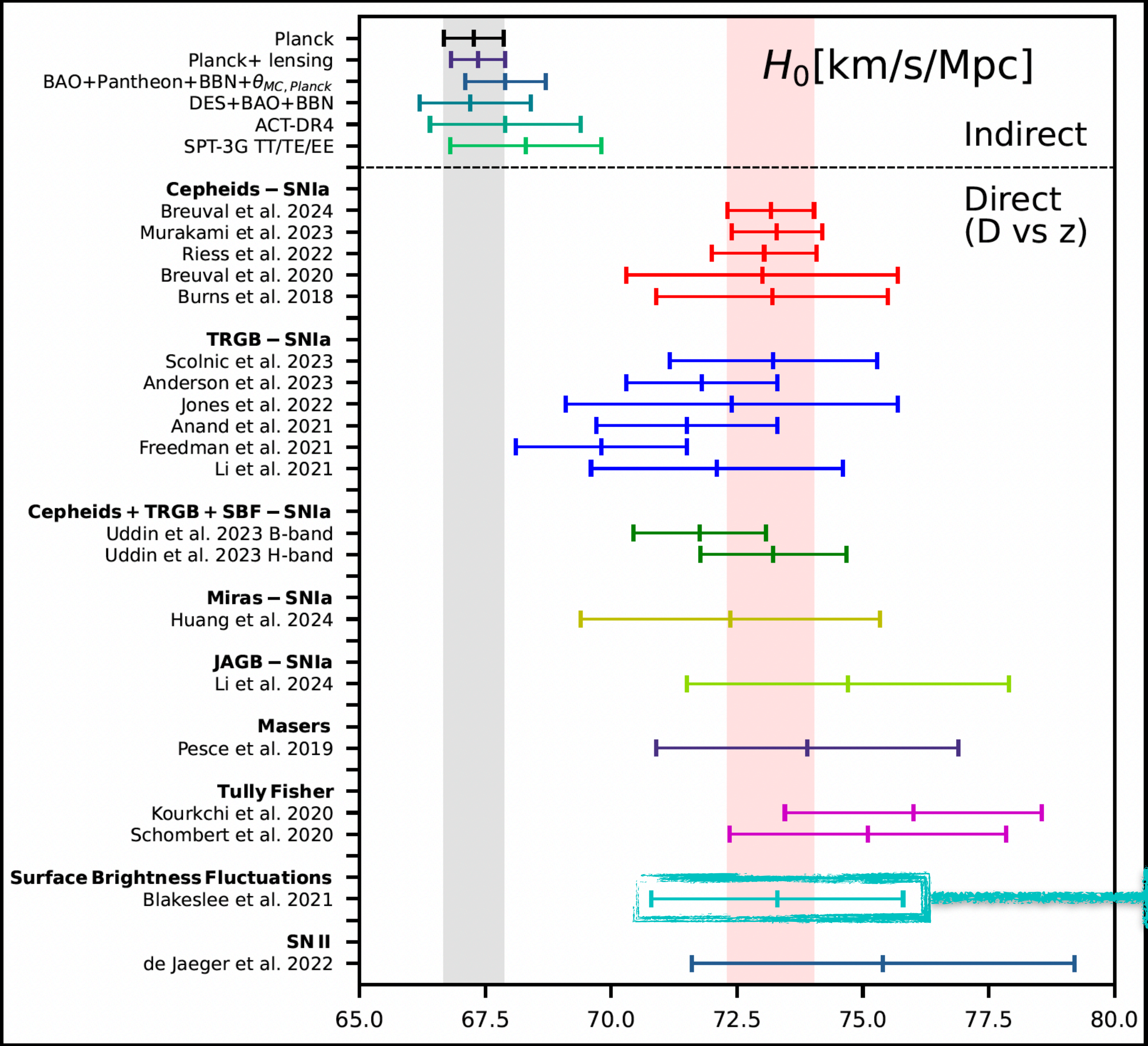
H0 = 75.10 ± 2.75 km/s/Mpc

Schombert et al. arXiv:2006.08615

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

Di Valentino, *MNRAS* 502 (2021) 2, 2065-2073

Latest H0 measurements



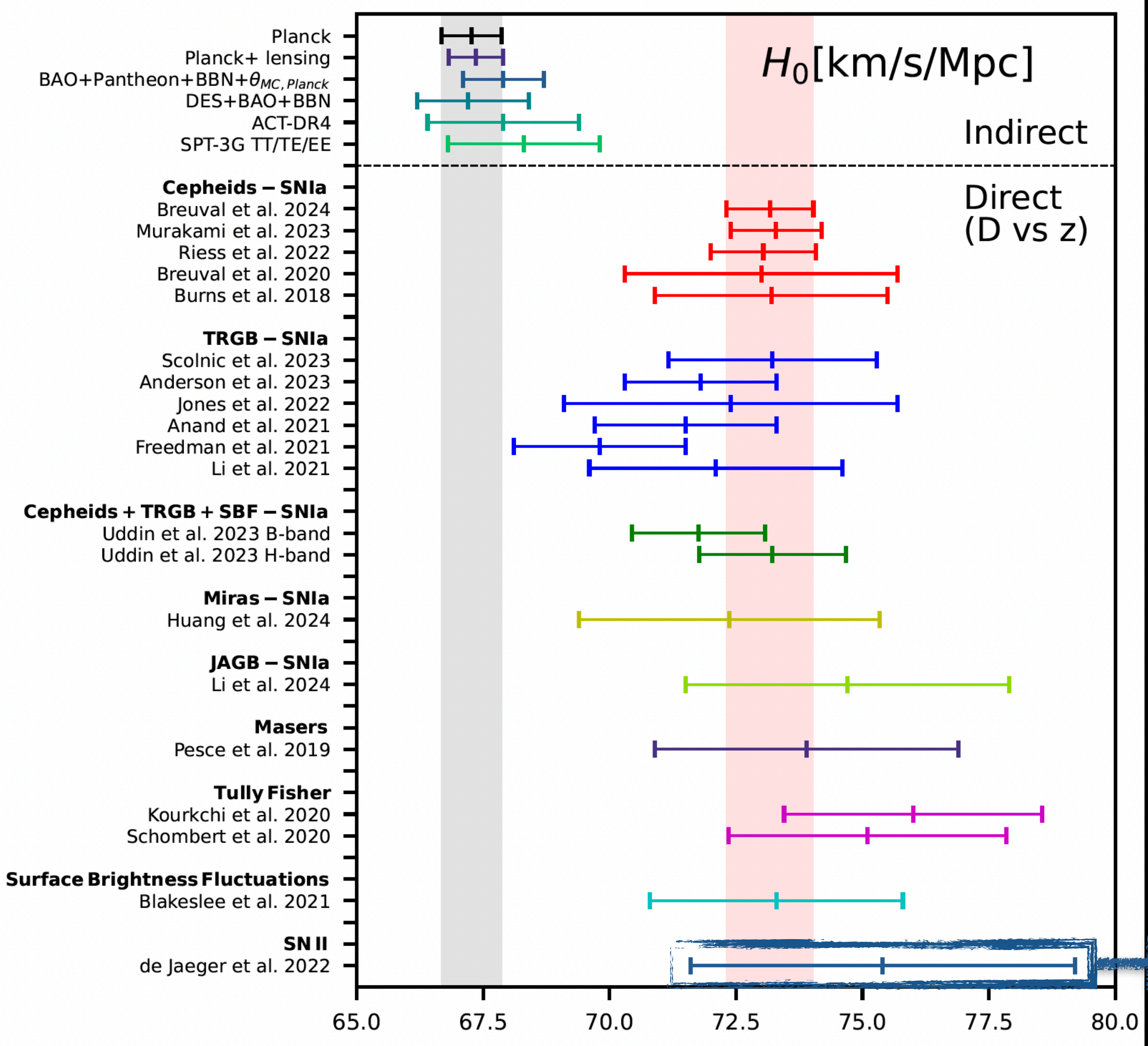
H0 = 73.3 ± 2.5 km/s/Mpc

Blakeslee et al., arXiv:2101.02221

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

Di Valentino, *MNRAS* 502 (2021) 2, 2065-2073

Latest H0 measurements



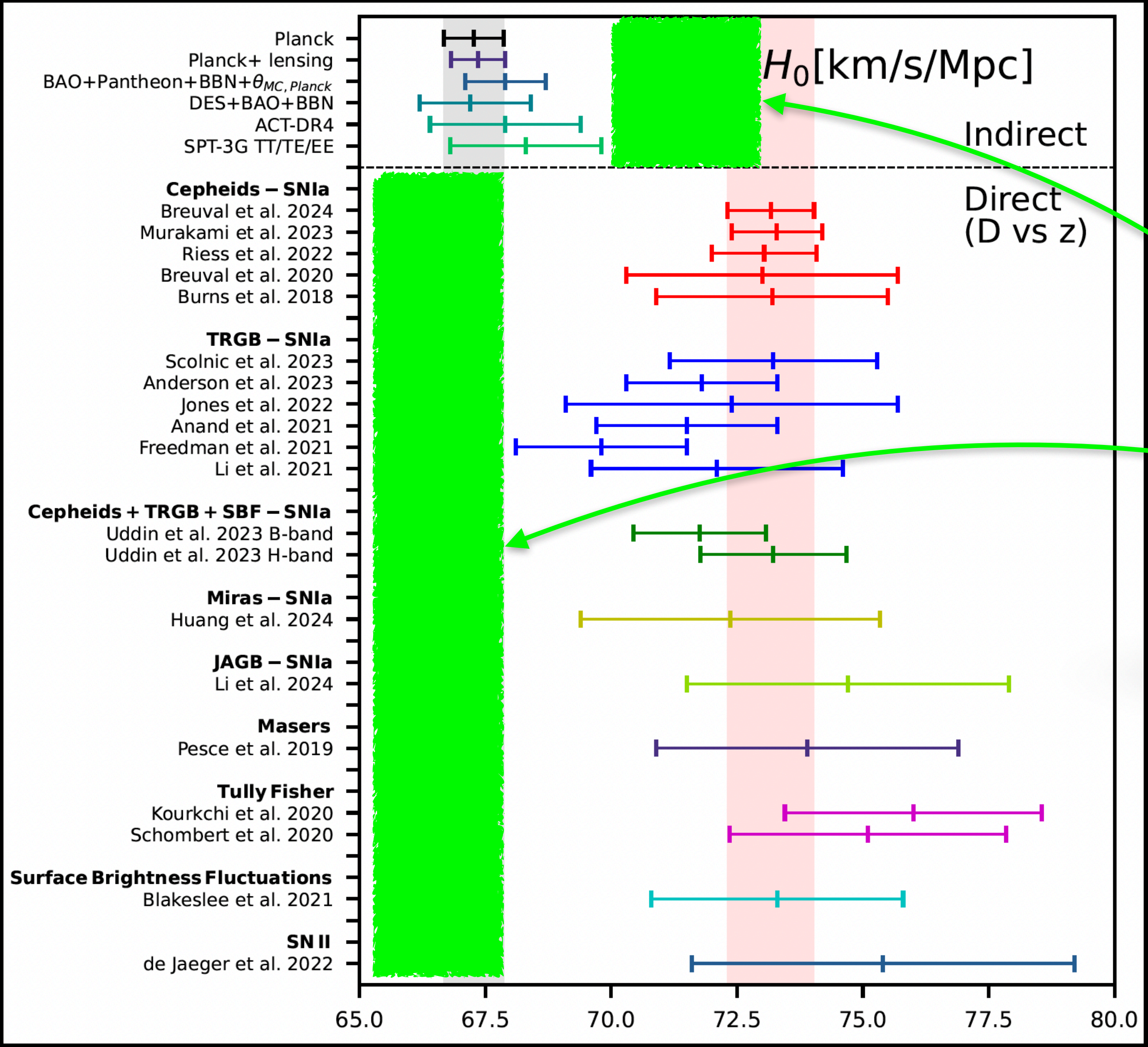
$H0 = 75.4^{+3.8}_{-3.7}$ km/s/Mpc

de Jaeger et al., arXiv:2203.08974

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

Di Valentino, *MNRAS* 502 (2021) 2, 2065-2073

Latest H0 measurements



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

Di Valentino, *MNRAS* 502 (2021) 2, 2065-2073

It is difficult to imagine a single systematic error that would consistently explain the discrepancies observed in the diverse range of phenomena that we have encountered earlier, thereby resolving the Hubble constant tension.

Since this tension persists in the 5 - 6.3σ range

(Riess, Nature Reviews Physics (2019); Di Valentino, *MNRAS* 502 (2021) 2, 2065-2073; Di Valentino, Universe 2022, 8(8), 399)

even after eliminating the measurements of any individual type of object, team, or calibration, it is challenging to identify a single error that could account for it. While multiple independent systematic errors could offer more flexibility in resolving the tension, they are less likely to occur.

Given that the indirect constraints are model-dependent, we can explore the possibility of expanding the cosmological scenario and examining which extensions can resolve the discrepancies between the various cosmological probes.

Let’s modify the ΛCDM model with a few example…

(Di Valentino et al. *Class.Quant.Grav.* 38 (2021) 15, 153001 and Abdalla et al., *JHEAp* 34 (2022) 49-211)

The Neutrino effective number

We can consider modifications in the
dark matter sector.

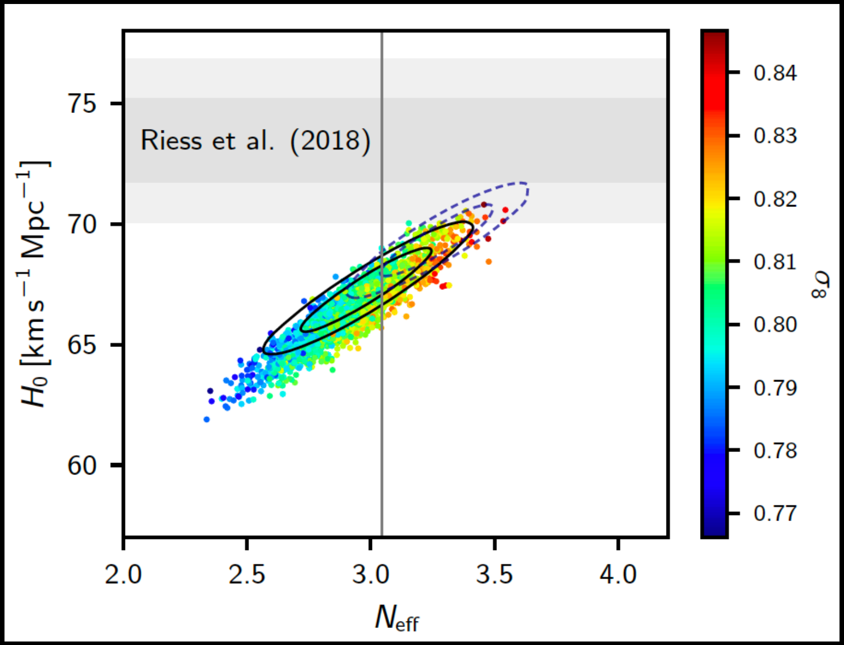
A classical extension is the
effective number of relativistic degrees of freedom,
i.e. additional relativistic matter at recombination,
corresponding to a modification of the expansion history
of the universe at early times.

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 vary Neff, at 68% cl H0 is equal to 66.4 ± 1.4 km/s/Mpc, and the tension with SH0ES is still 3.9σ.

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



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

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

If we change the cosmological constant with a Dark Energy with equation of state w, we are changing the expansion rate of the Universe:

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = H_0^2 \left(\frac{\Omega_r}{a^4} + \frac{\Omega_m}{a^3} + \frac{\Omega_k}{a^2} + \boxed{\Omega_\Lambda}\right)$$

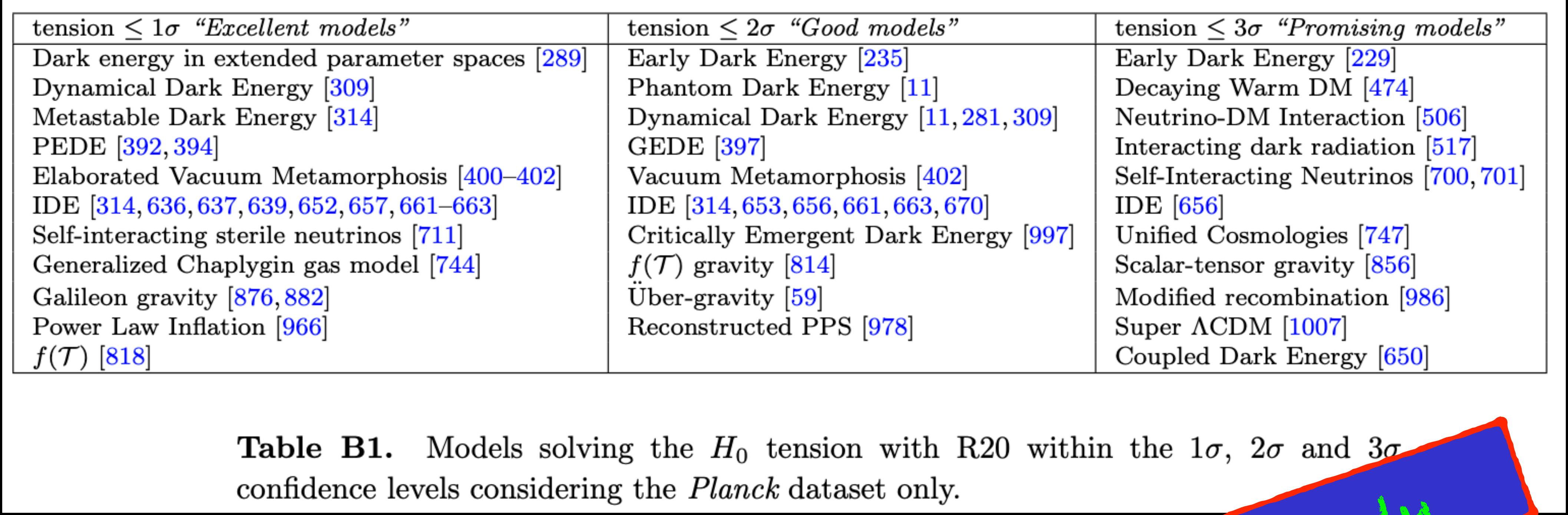
$$H^2 = H_0^2 \Big[\Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \boxed{\Omega_{\rm de}(1+z)^{3(1+w)}} + \Omega_k(1+z)^2\Big]$$

w introduces a geometrical degeneracy with the Hubble constant that is almost 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]

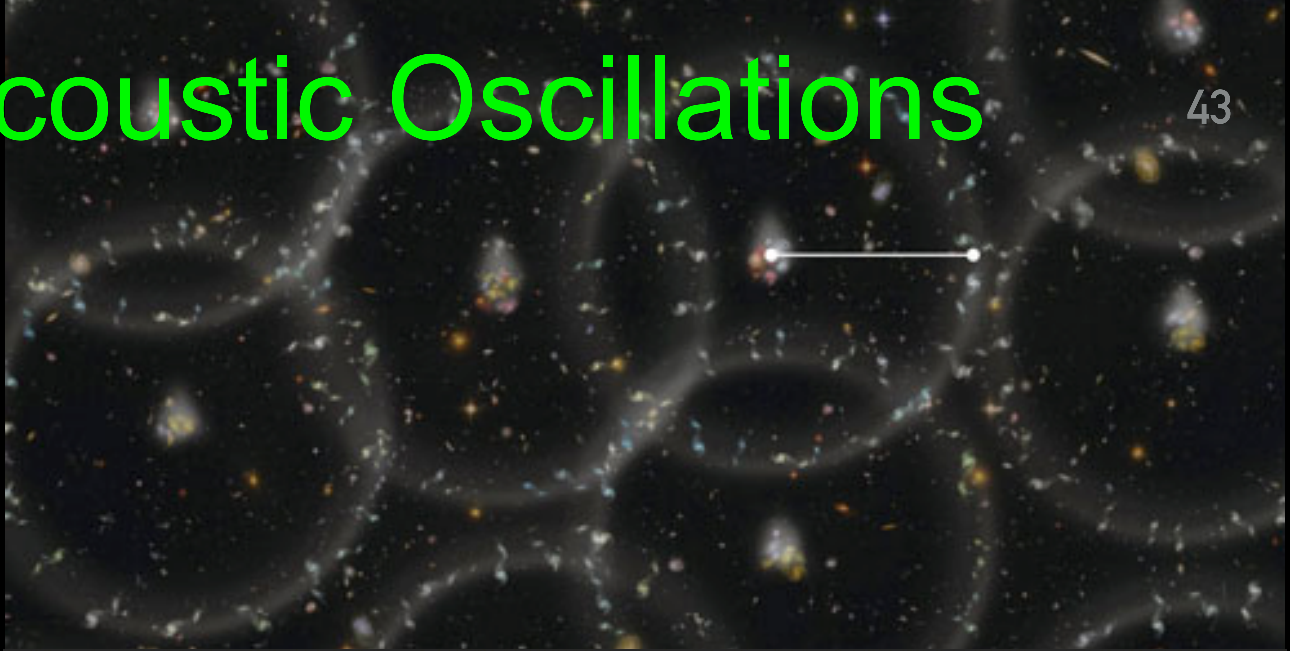
Table B1. Models solving the H_0 tension with R20 within the 1σ, 2σ and 3σ confidence levels considering the *Planck* dataset only.

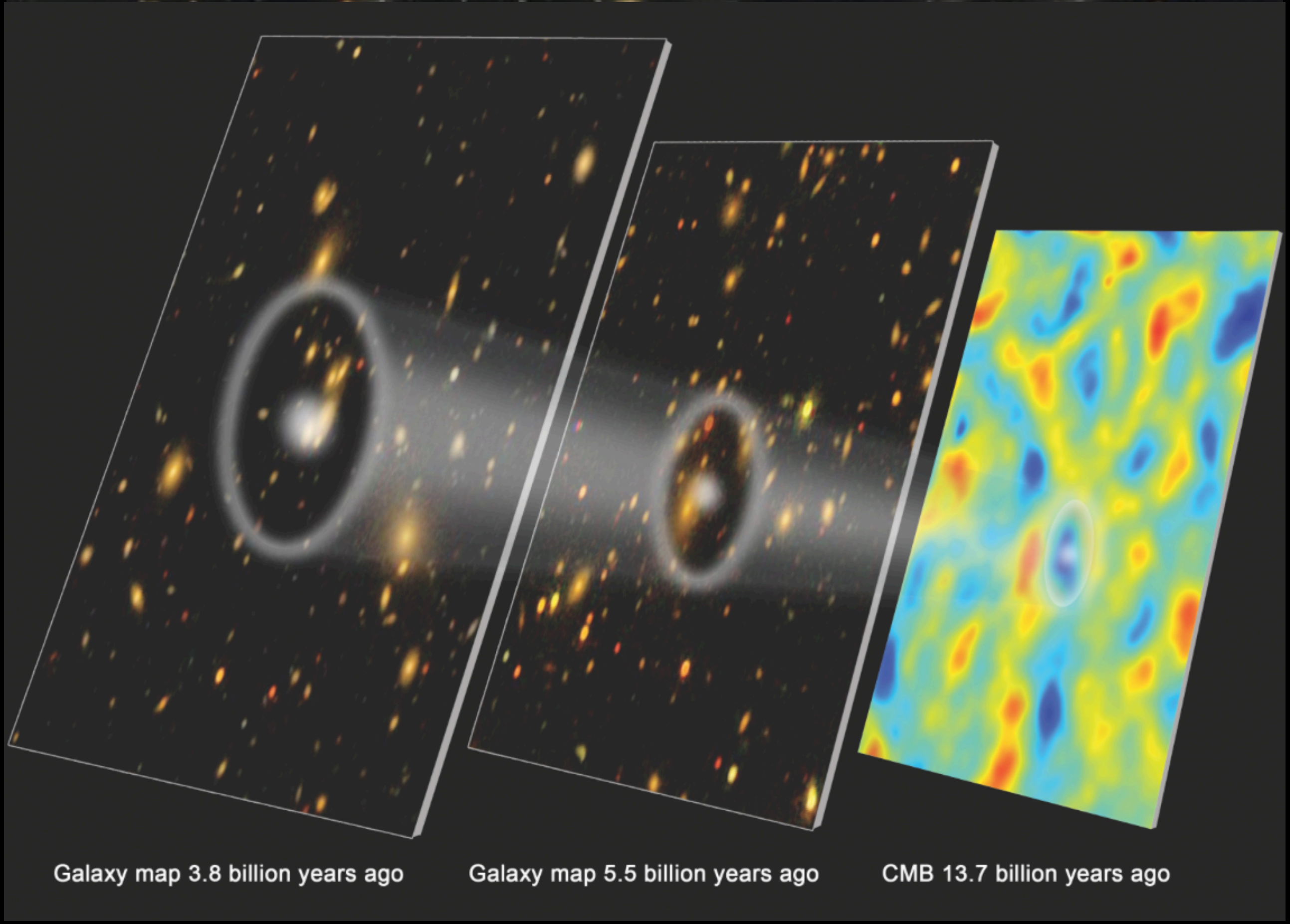
Di Valentino et al., Class.Quant.Grav. (2021), arXiv:2103.01183 [astro-ph.CO]

Planck only

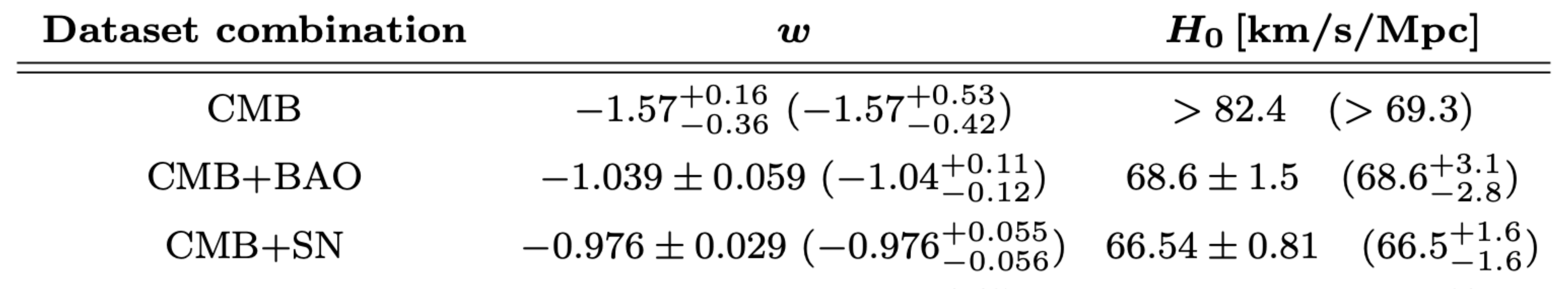
Baryon Acoustic Oscillations

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.





The state of the Dark energy equation of state



Dataset combination	w	H_0 [km/s/Mpc]
CMB	$-1.57^{+0.16}_{-0.36}$ $(-1.57^{+0.53}_{-0.42})$	> 82.4 (> 69.3)
CMB+BAO	-1.039 ± 0.059 $(-1.04^{+0.11}_{-0.12})$	68.6 ± 1.5 $(68.6^{+3.1}_{-2.8})$
CMB+SN	-0.976 ± 0.029 $(-0.976^{+0.055}_{-0.056})$	66.54 ± 0.81 $(66.5^{+1.6}_{-1.6})$

Escamilla, Giarè, Di Valentino et al., arXiv: 2307.14802

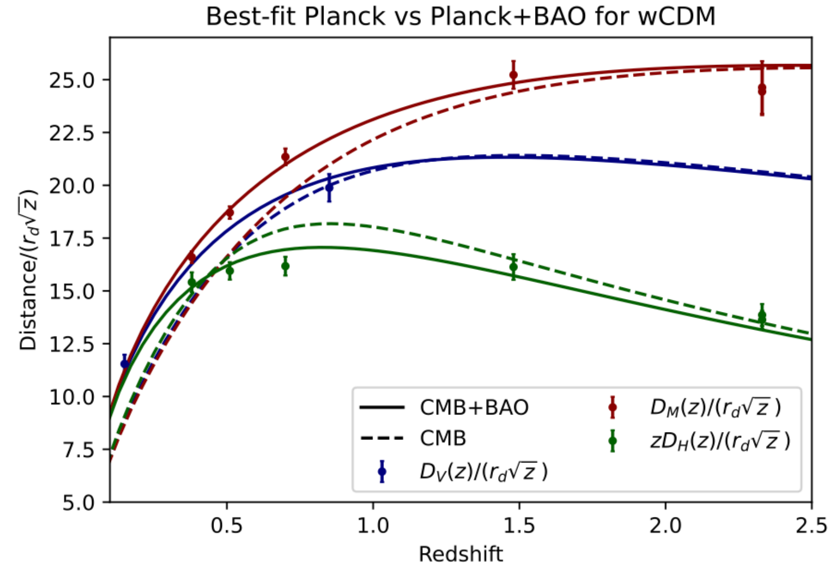


FIG. 5. Best-fit predictions for (rescaled) distance-redshift relations from a wCDM fit to *Planck* CMB data alone (dashed curves) and the CMB+BAO dataset (solid curves). These predictions are presented for the three different types of distances probed by BAO measurements (rescaled as per the y label), each indicated by the colors reported in the legend. The error bars represent $\pm 1\sigma$ uncertainties.

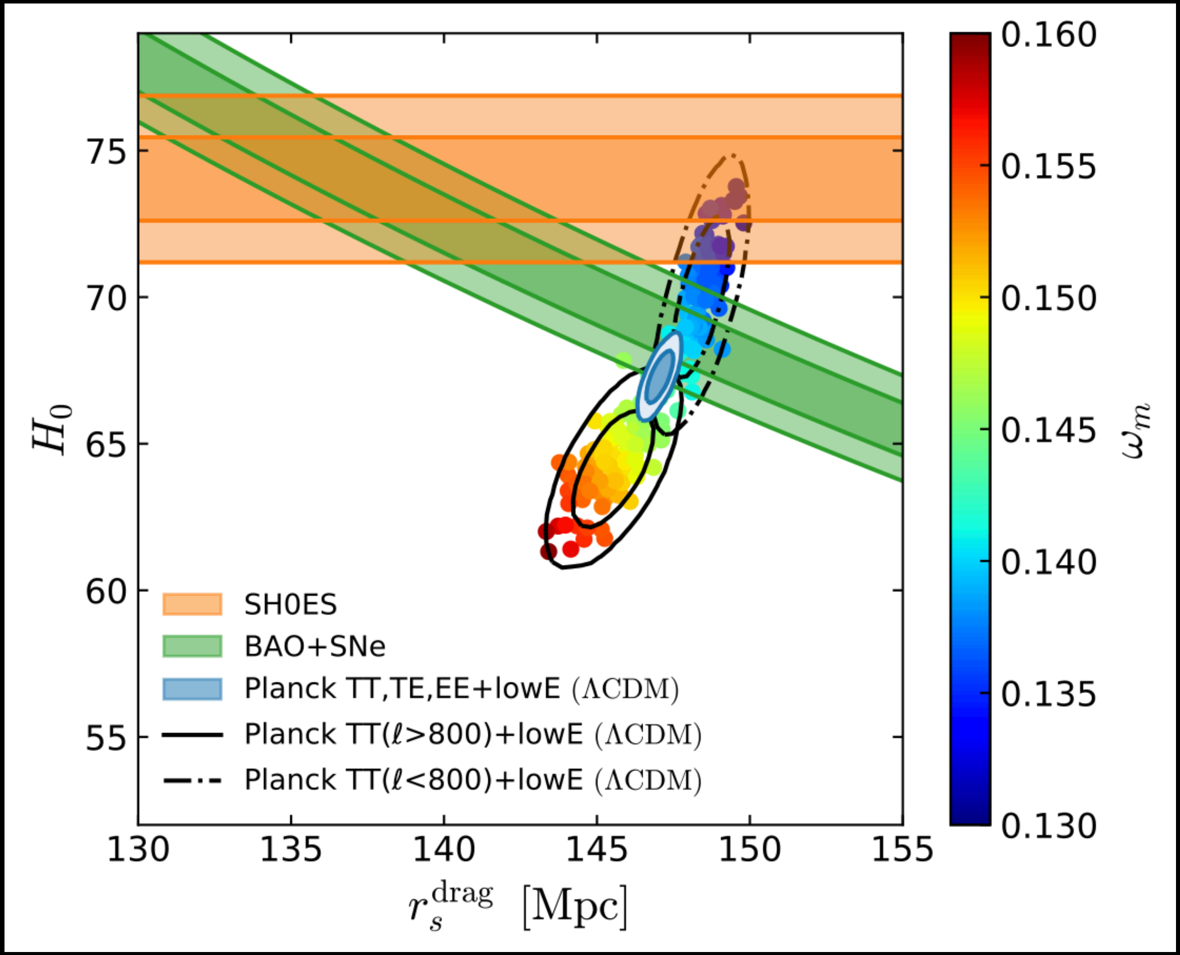
However, if BAO data are included, the wCDM model with w<-1 worsens considerably the fit of the BAO data because the best fit from Planck alone fails in recover the shape of H(z) at low redshifts. Therefore, when the CMB is combined with BAO data, the favoured model is again the ΛCDM one and the H0 tension is restored.

Complication:
the sound horizon problem

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.

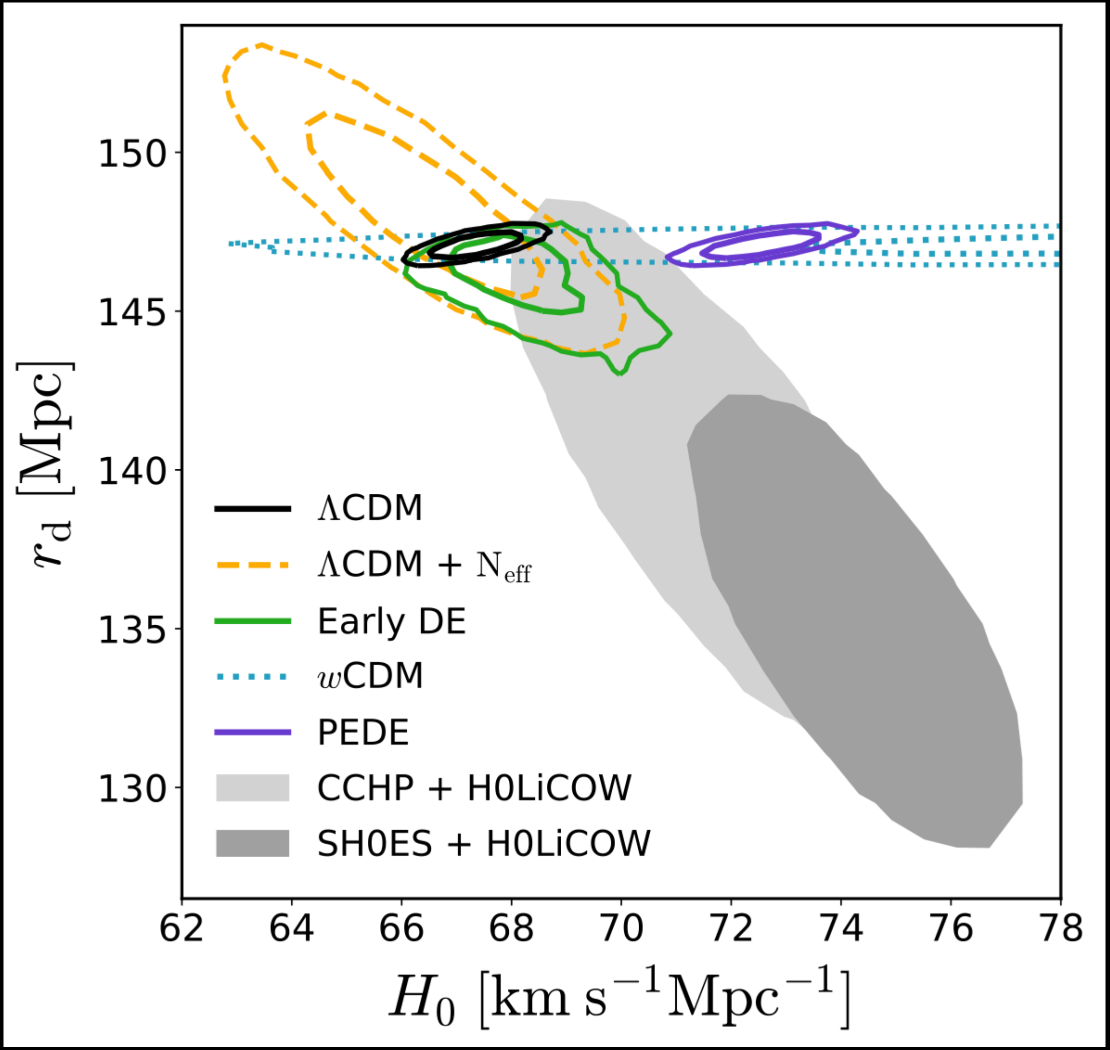


Knox and Millea, *Phys.Rev.D* 101 (2020) 4, 043533

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.

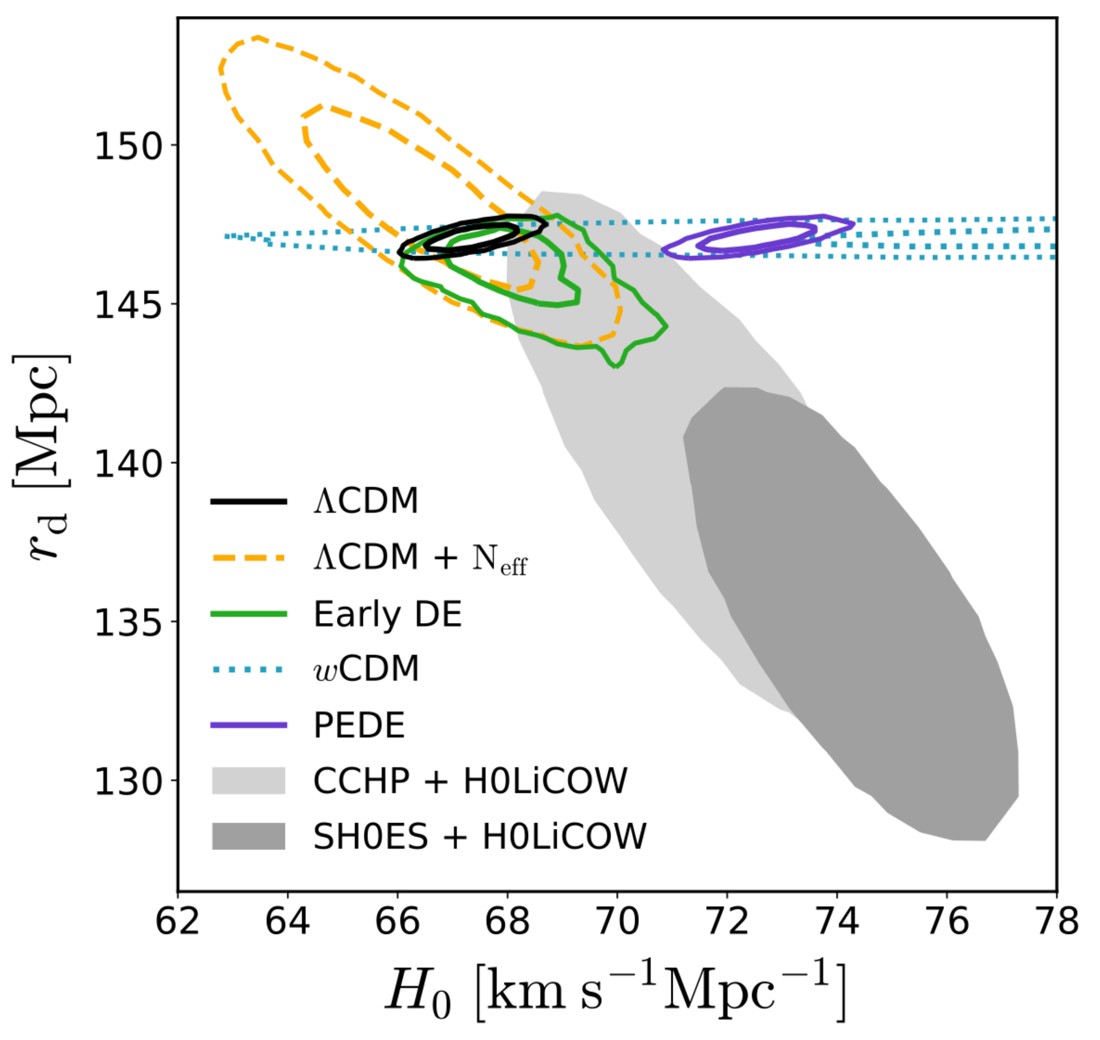


Arendse et al., Astron.Astrophys. 639 (2020) A57

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

Early dark energy (EDE) scenario assumes that there is a new fundamental field that accelerates the cosmic expansion rate before recombination. This field contributes roughly 10-12% of the total energy density near the matter-radiation equality, but eventually dissipates like radiation or at a faster rate (depending on the shape of the potential). In order to have an effect on the sound horizon we should have $H \sim T^2/M_{pl} \approx m$ just before the recombination, so the mass of the scalar field should be $m \approx 10^{-27}$ eV, similar to an axion particle:

$$V(\phi) = m^2 f^2 \left(1 - \cos(\phi/f)\right)^n$$

At the minimum of the potential the field oscillates yielding to an effective equation of state

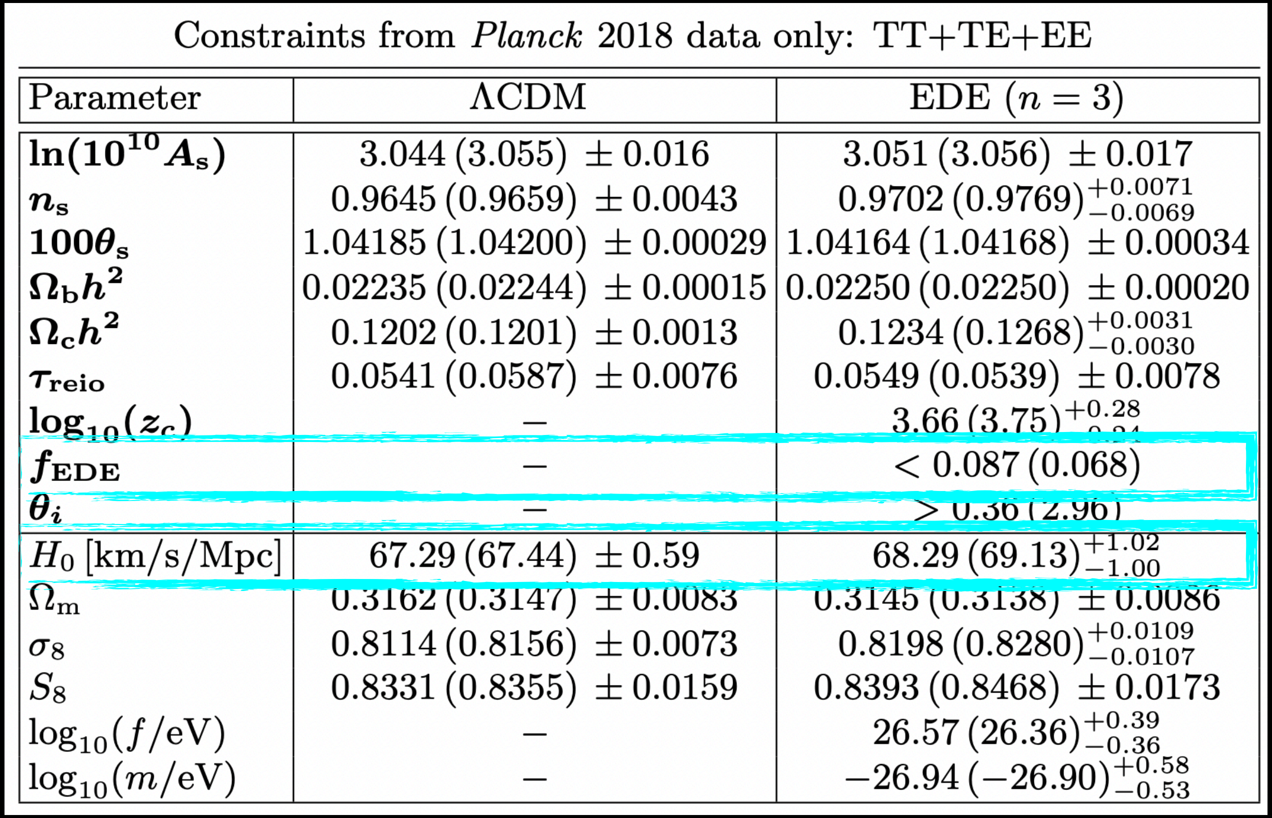
$$w_\phi = (n-1)/(n+1)$$

If we take n = 1 (the standard axion potential) then $w_\phi = 0$ near the potential minimum, and the EDE energy density redshifts as matter creating problems in the late-time cosmology, therefore it does not work phenomenologically.
For n = 2 instead it decays away like radiation ($\propto a^{-4}$),
and for $n \to \infty$ like kinetic energy ($\propto a^{-6}$). However, values n > 5 are disfavored.

Karwal & Kamionkowski *PRD* 94 (2016) 10, 103523 and Poulin et al. *PRL* 122 (2019) 22, 221301)

Early Dark Energy

Constraints at 68% cl.



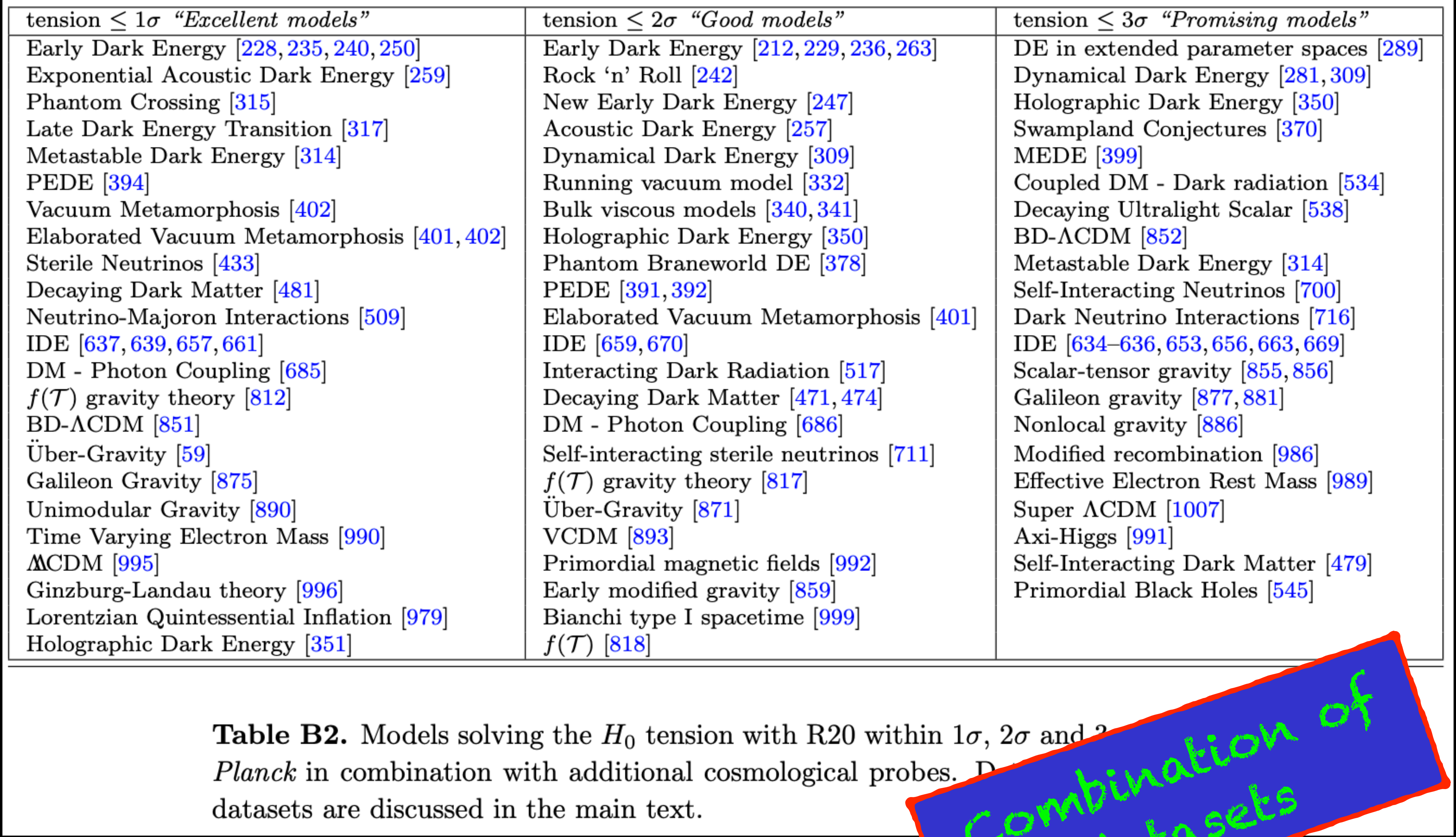
Constraints from *Planck* 2018 data only: TT+TE+EE

Parameter	ΛCDM	EDE ($n = 3$)
$\ln(10^{10} A_s)$	$3.044\,(3.055)\ \pm 0.016$	$3.051\,(3.056)\ \pm 0.017$
n_s	$0.9645\,(0.9659)\ \pm 0.0043$	$0.9702\,(0.9769)^{+0.0071}_{-0.0069}$
$100\theta_s$	$1.04185\,(1.04200)\ \pm 0.00029$	$1.04164\,(1.04168)\ \pm 0.00034$
$\Omega_b h^2$	$0.02235\,(0.02244)\ \pm 0.00015$	$0.02250\,(0.02250)\ \pm 0.00020$
$\Omega_c h^2$	$0.1202\,(0.1201)\ \pm 0.0013$	$0.1234\,(0.1268)^{+0.0031}_{-0.0030}$
τ_{reio}	$0.0541\,(0.0587)\ \pm 0.0076$	$0.0549\,(0.0539)\ \pm 0.0078$
$\log_{10}(z_c)$	$-$	$3.66\,(3.75)^{+0.28}_{-0.24}$
f_{EDE}	$-$	$< 0.087\,(0.068)$
θ_i	$-$	$> 0.36\,(2.96)$
H_0 [km/s/Mpc]	$67.29\,(67.44)\ \pm 0.59$	$68.29\,(69.13)^{+1.02}_{-1.00}$
Ω_m	$0.3162\,(0.3147)\ \pm 0.0083$	$0.3145\,(0.3138)\ \pm 0.0086$
σ_8	$0.8114\,(0.8156)\ \pm 0.0073$	$0.8198\,(0.8280)^{+0.0109}_{-0.0107}$
S_8	$0.8331\,(0.8355)\ \pm 0.0159$	$0.8393\,(0.8468)\ \pm 0.0173$
$\log_{10}(f/\mathrm{eV})$	$-$	$26.57\,(26.36)^{+0.39}_{-0.36}$
$\log_{10}(m/\mathrm{eV})$	$-$	$-26.94\,(-26.90)^{+0.58}_{-0.53}$

Hill et al. *Phys.Rev.D* 102 (2020) 4, 043507

Planck 2018 results shows no evidence for EDE
and H0 is in agreement with the value obtained assuming ΛCDM.

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]	

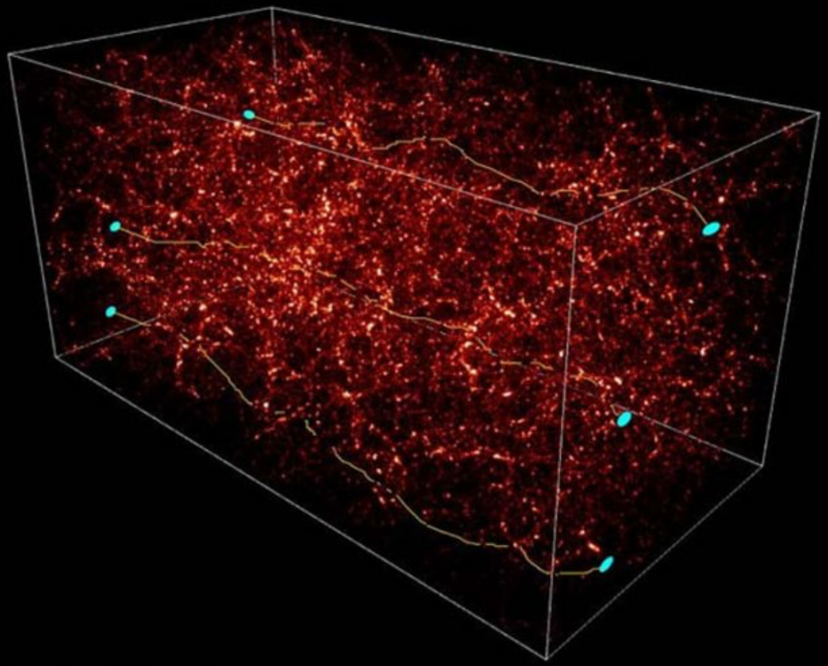
Table B2. Models solving the H_0 tension with R20 within 1σ, 2σ and
Planck in combination with additional cosmological probes.
datasets are discussed in the main text.

Combination of datasets

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

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

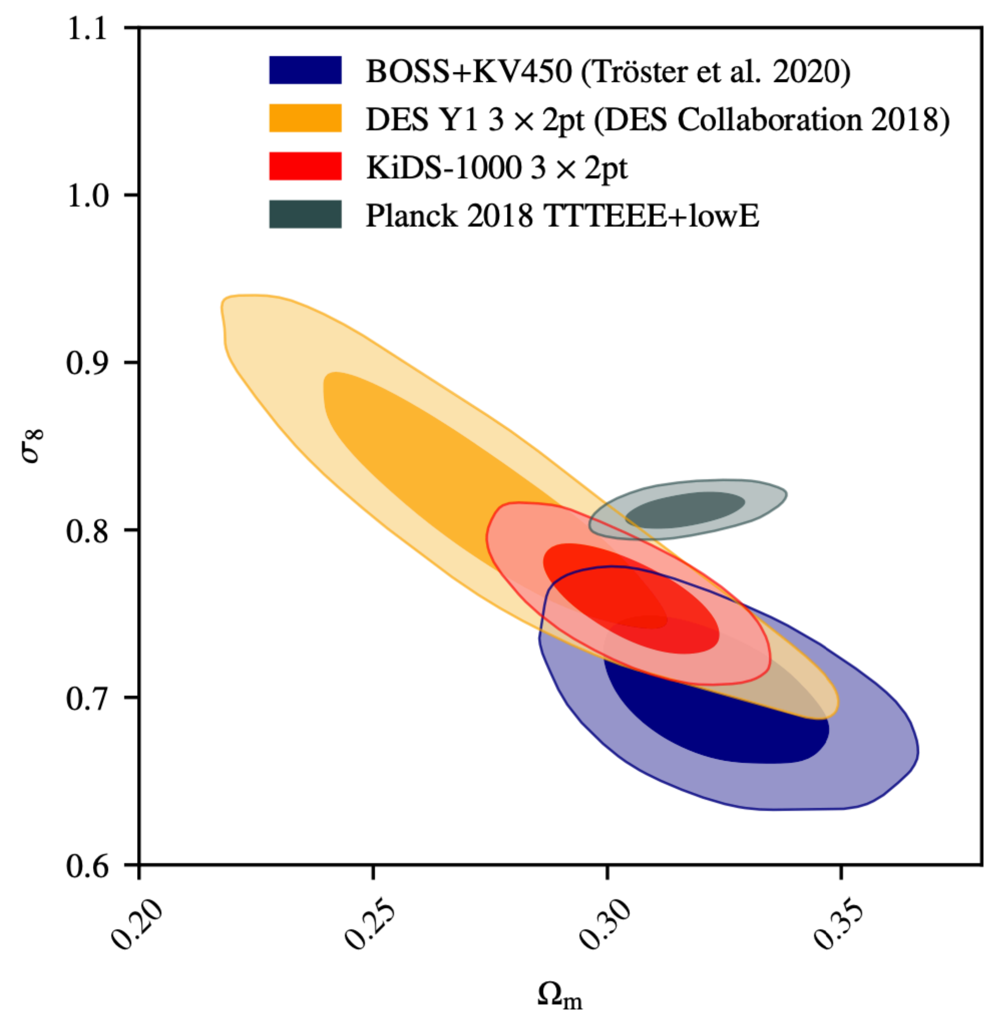
The S8 tension



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

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]

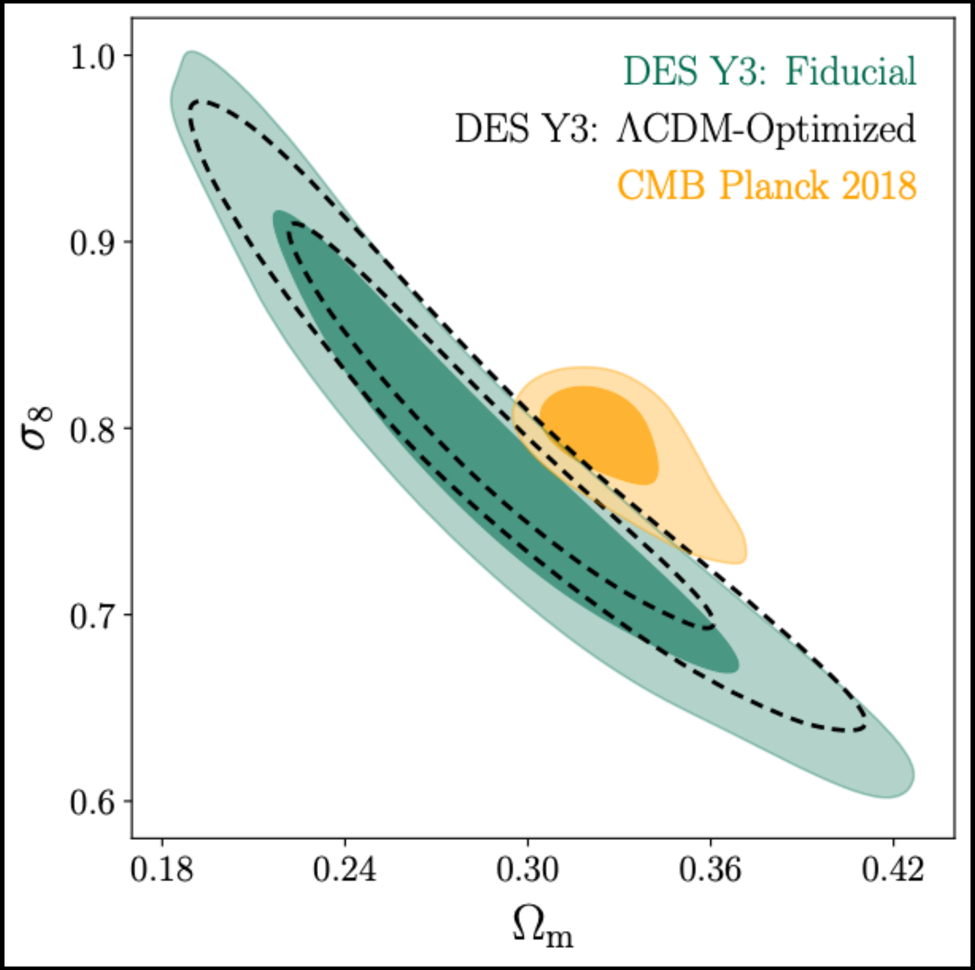
$S_8 = 0.728 \pm 0.045$

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]

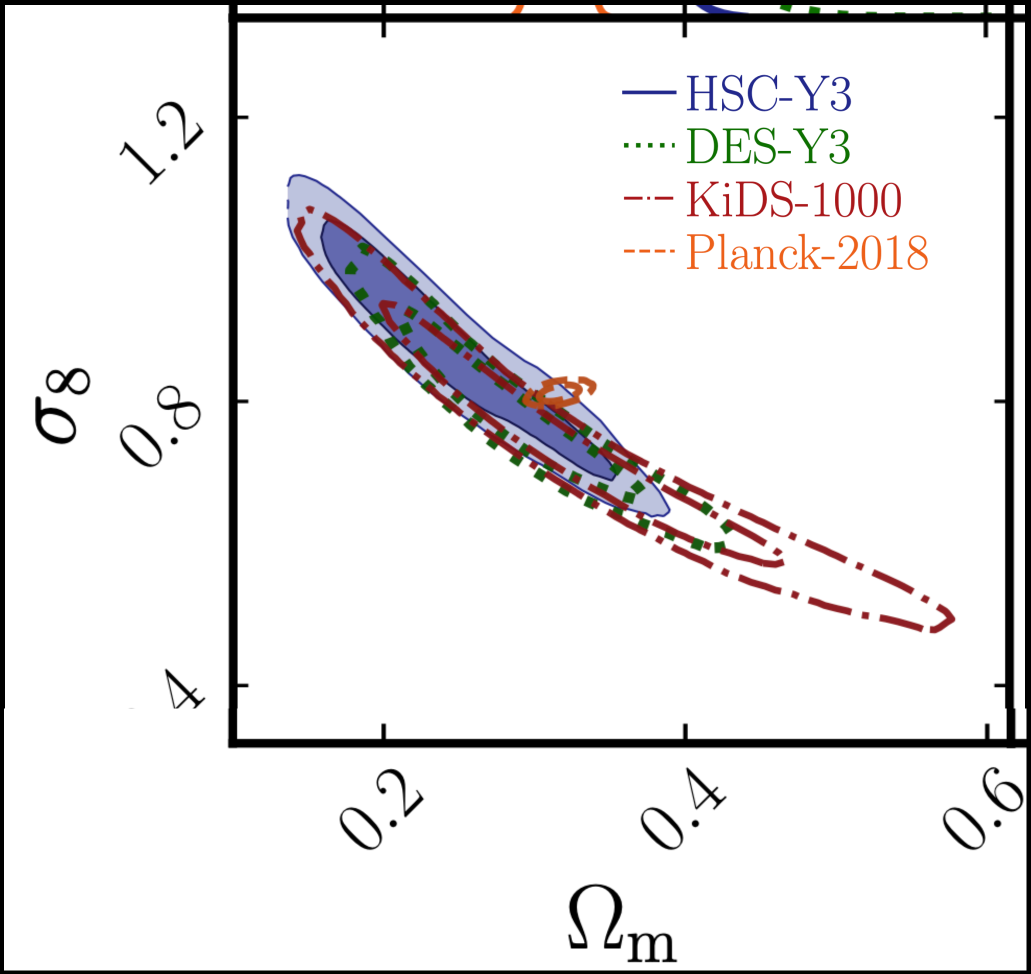
$S_8 = 0.776^{+0.017}_{-0.017}$

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



HSC-Y3, Dalal et al., arXiv:2304.00701 [astro-ph.CO]

The S8 tension is present at about 2σ between Planck assuming ΛCDM and HSC-Y3.

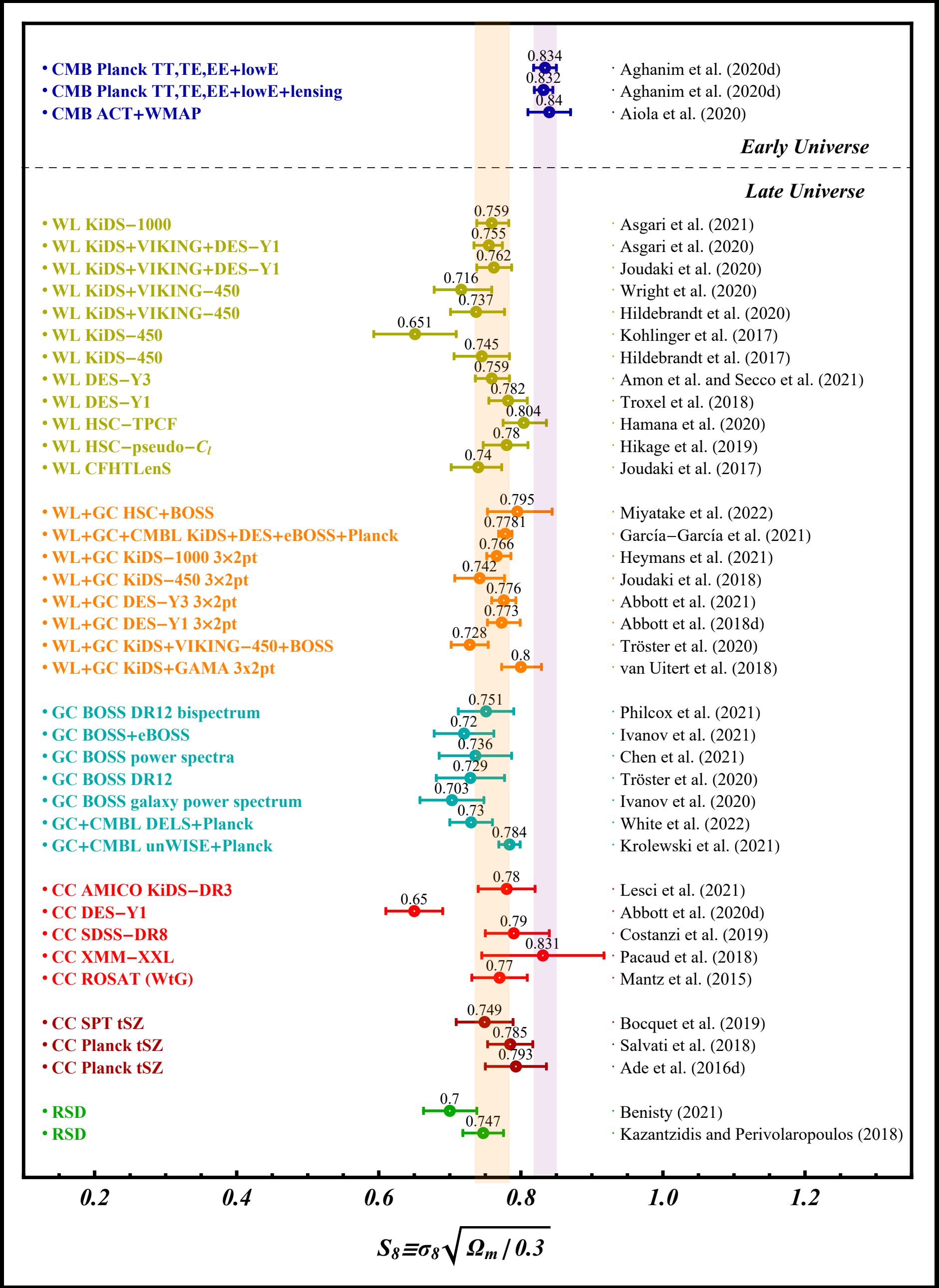
$S_8 = 0.834 \pm 0.016$

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

$S_8 = 0.776^{+0.032}_{-0.033}$

HSC-Y3, Dalal et al., arXiv:2304.00701 [astro-ph.CO]

The S8 tension



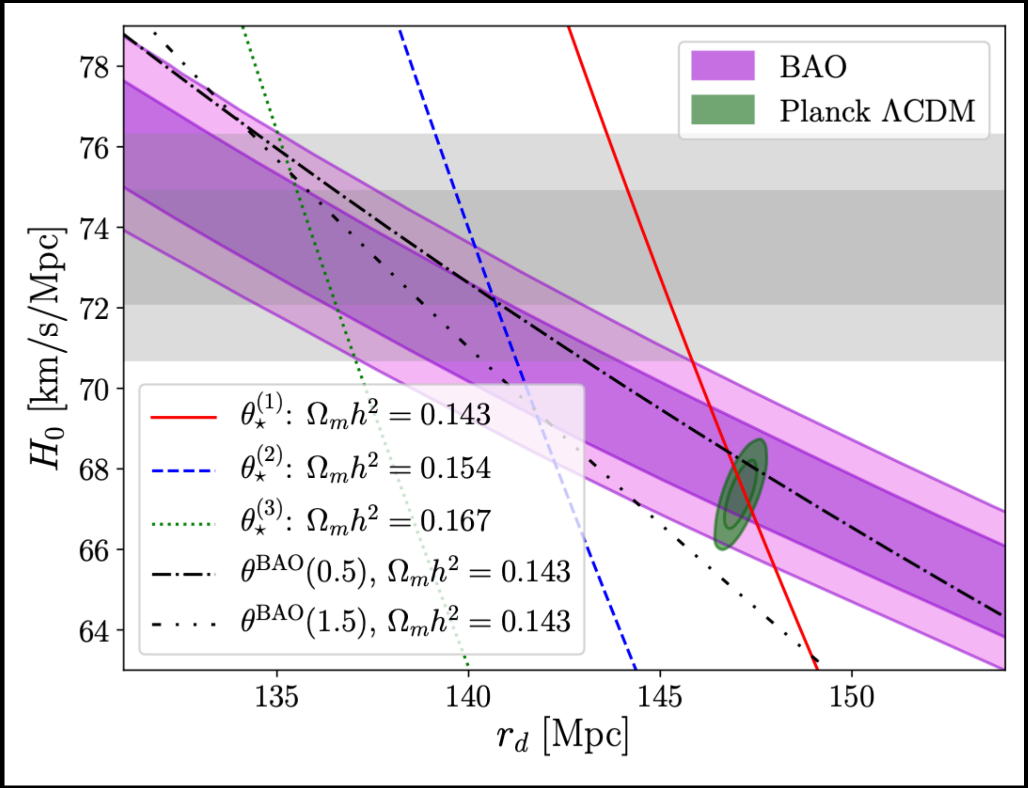
Abdalla et al., *JHEAp* 34 (2022) 49-211

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 $\Omega_m h^2$.



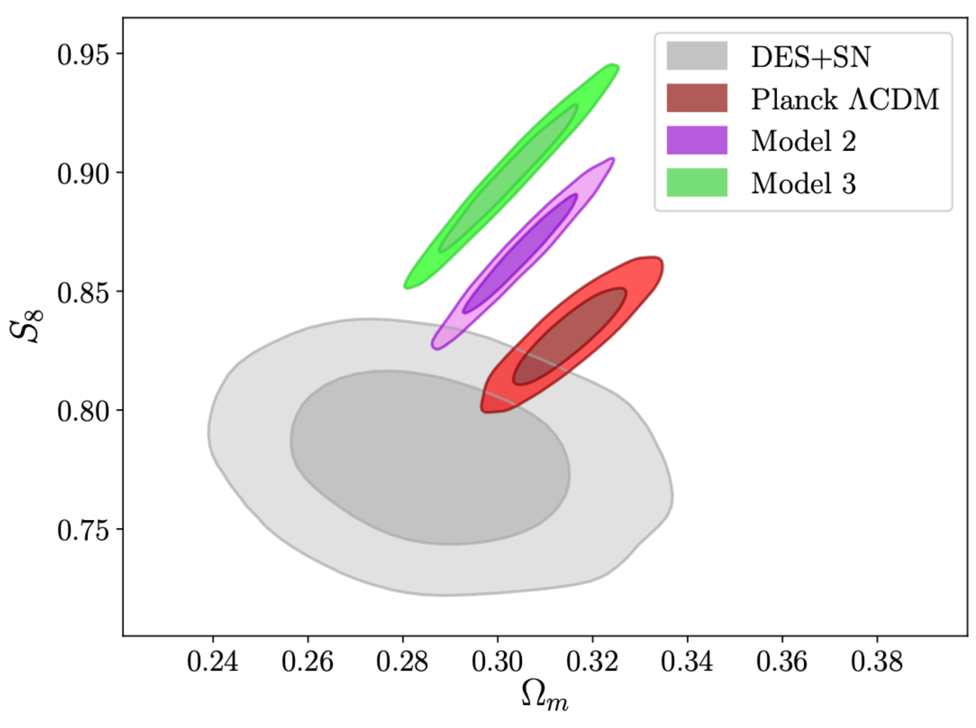
Jedamzik et al., Commun.in Phys. 4 (2021) 123

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, KiDS and HSC.

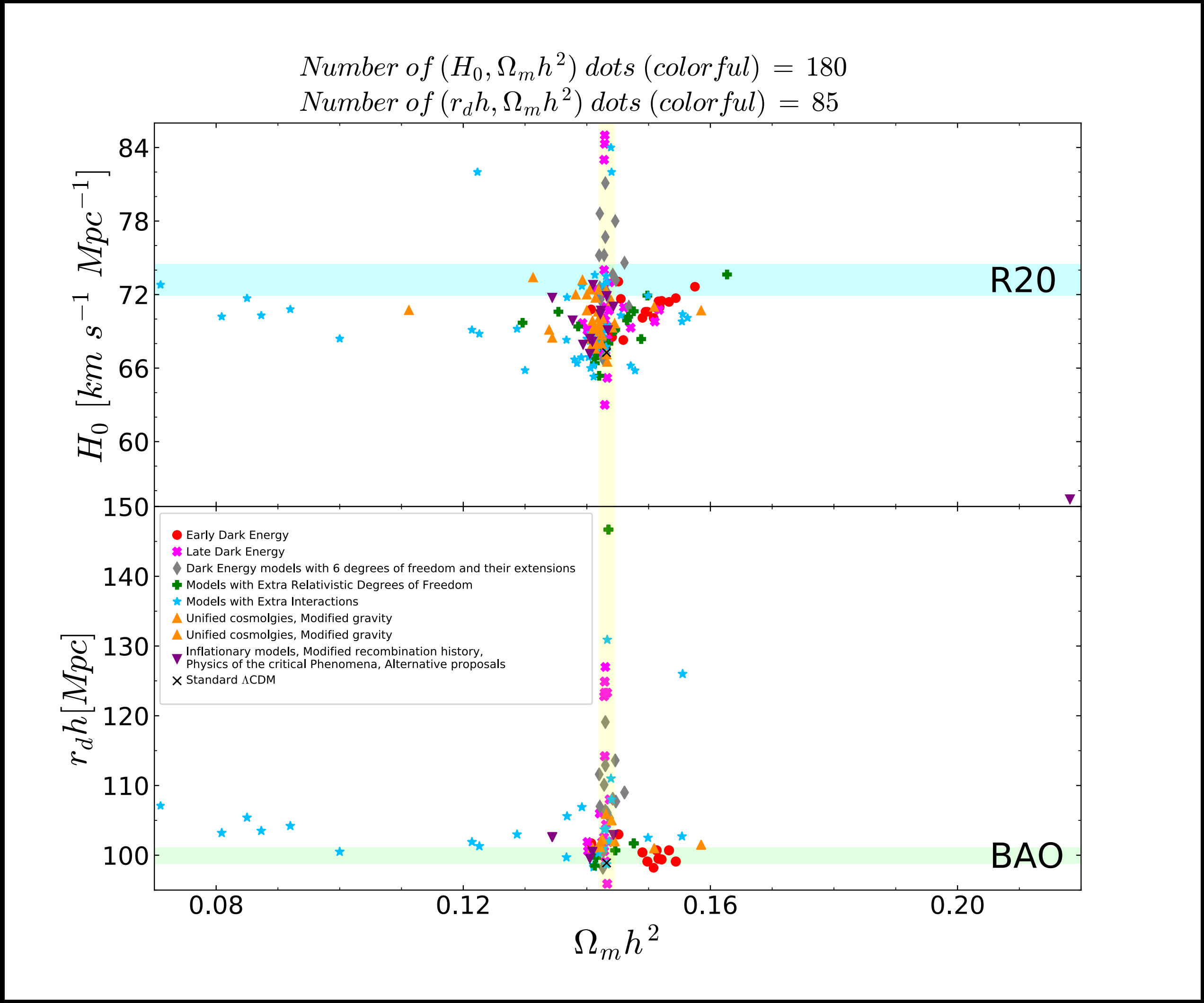


Jedamzik et al., Commun.in Phys. 4 (2021) 123

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]

What about the interacting DM-DE models?

The IDE case

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:

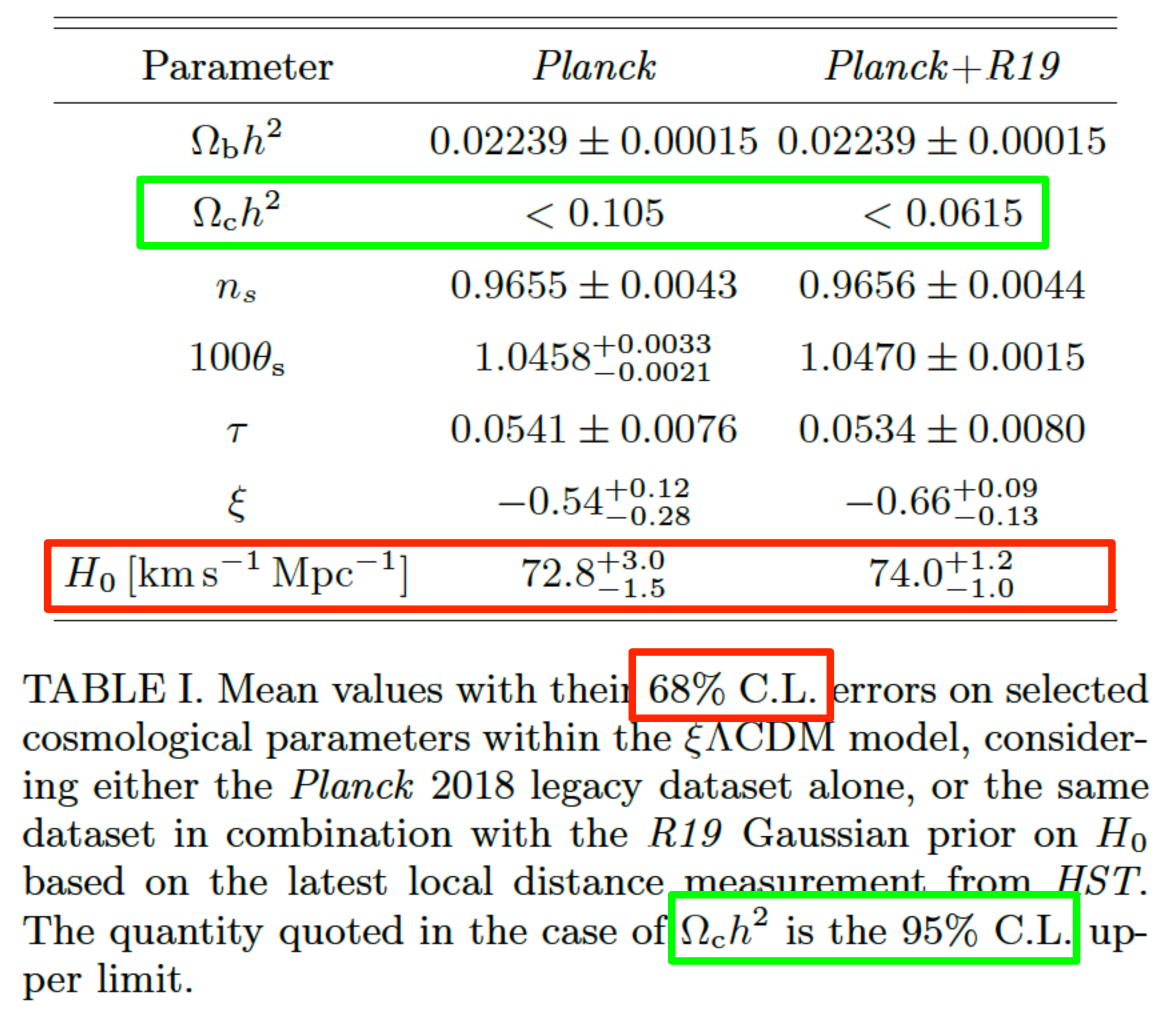
$$Q = \xi\mathcal{H}\rho_x$$

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

The IDE case

In this scenario of IDE the tension on H0 between the Planck satellite and SH0ES 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 $\Omega_m h^2$.



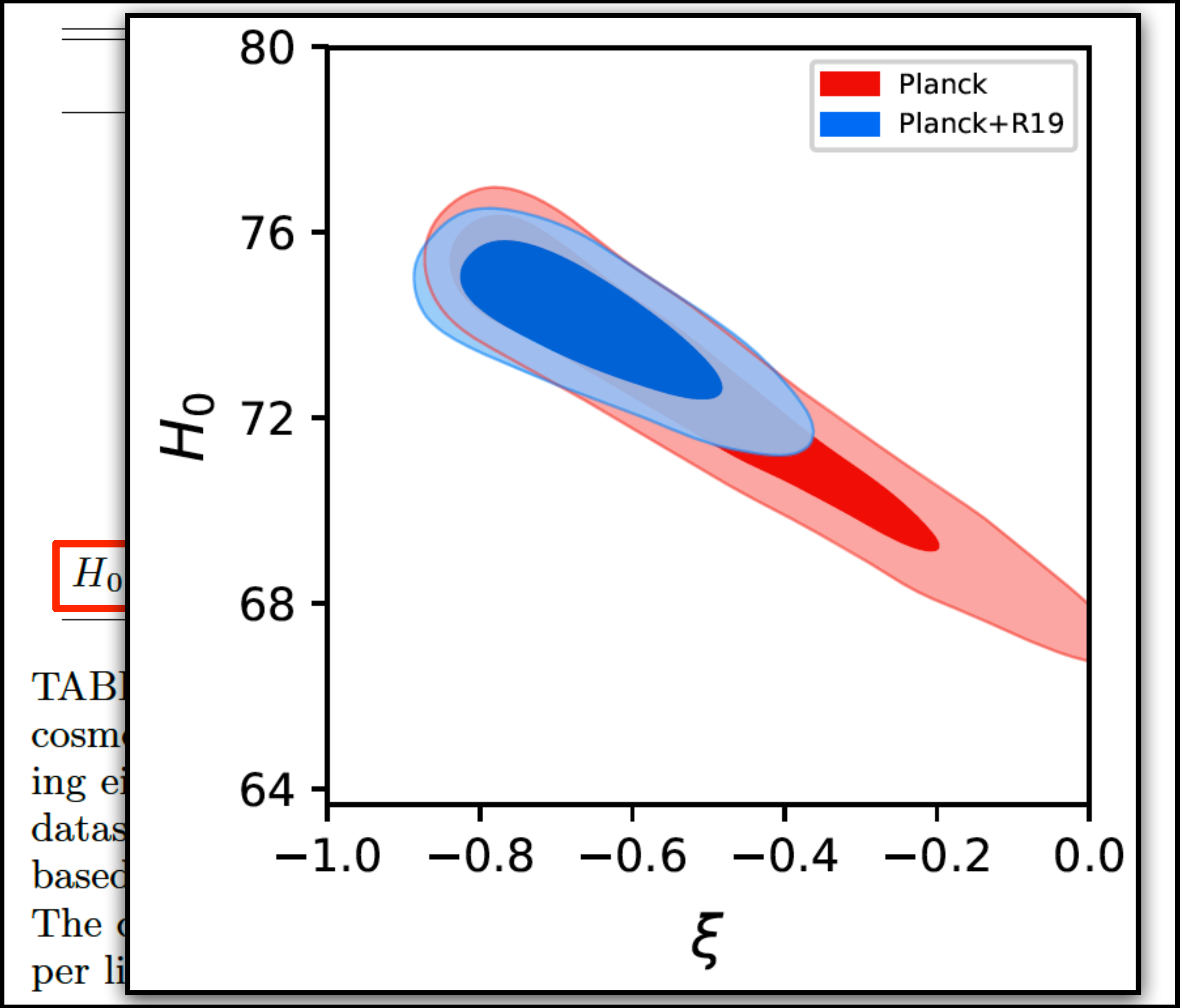
Parameter	*Planck*	*Planck*+*R19*
$\Omega_b h^2$	0.02239 ± 0.00015	0.02239 ± 0.00015
$\Omega_c h^2$	< 0.105	< 0.0615
n_s	0.9655 ± 0.0043	0.9656 ± 0.0044
$100\theta_s$	$1.0458^{+0.0033}_{-0.0021}$	1.0470 ± 0.0015
τ	0.0541 ± 0.0076	0.0534 ± 0.0080
ξ	$-0.54^{+0.12}_{-0.28}$	$-0.66^{+0.09}_{-0.13}$
$H_0\,[\mathrm{km\,s^{-1}\,Mpc^{-1}}]$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

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

The IDE case

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

The IDE case

Moreover, we find a shift of the clustering parameter σ_8 towards a higher value, compensated by a lowering of the matter density Ω_m, both with relaxed error bars.

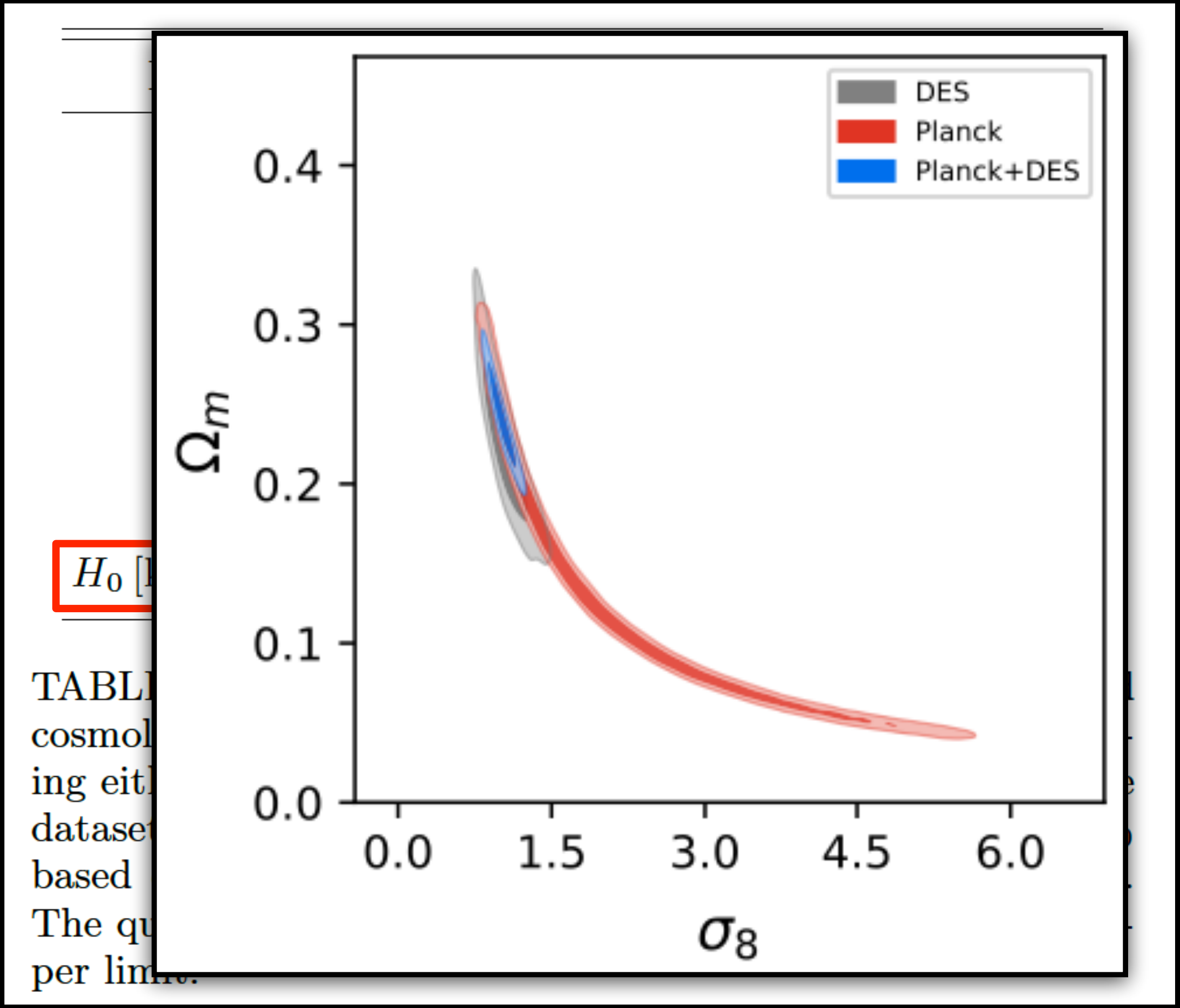
The reason is that once a coupling is switched on and

Ω_m becomes smaller,

the clustering parameter σ_8 must be larger to have a proper normalization of the (lensing and clustering) power spectra.

This model can therefore significantly reduce the significance of the S8 tension

(See also Lucca, *Phys.Dark Univ.* 34 (2021) 100899)



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

Bayes factor

Anyway it is clearly interesting to quantify the better accordance of a model with the data respect to another by using the marginal likelihood also known as the Bayesian evidence.

The Bayesian evidence weights the simplicity of the model with the improvement of the fit of the data. In other words, because of the Occam’s razor principle, models with additional parameters are penalised, if don’t improve significantly the fit.

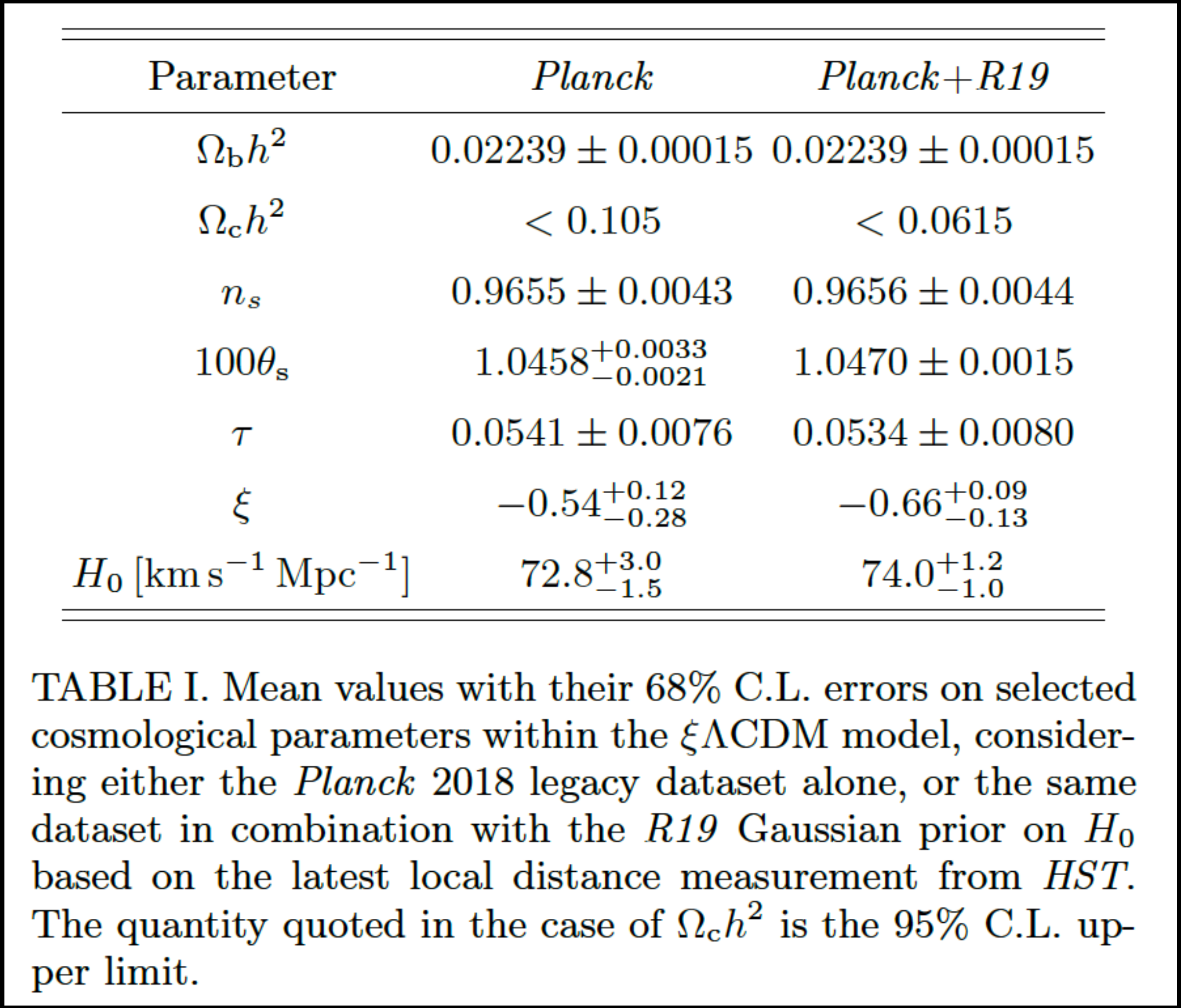
Given two competing models M_0 and M_1 it is useful to consider the ratio of the likelihood probability (the Bayes factor):

$$ln\mathcal{B} = p(\boldsymbol{x}|M_0)/p(\boldsymbol{x}|M_1)$$

According to the revised Jeffrey’s scale by Kass and Raftery 1995, the evidence for M_0 (against M_1) is considered as "weak" if $| \ln B | > 1.0$, "moderate" if $| \ln B | > 2.5$, and "strong" if $| \ln B | > 5.0$.

The IDE case

Computing the Bayes factor for the IDE model with respect to ΛCDM for the Planck dataset we find lnB = 1.2, i.e. a weak evidence for the IDE model. If we consider Planck + SH0ES we find the extremely high value lnB=10.0, indicating a strong evidence for the IDE model.

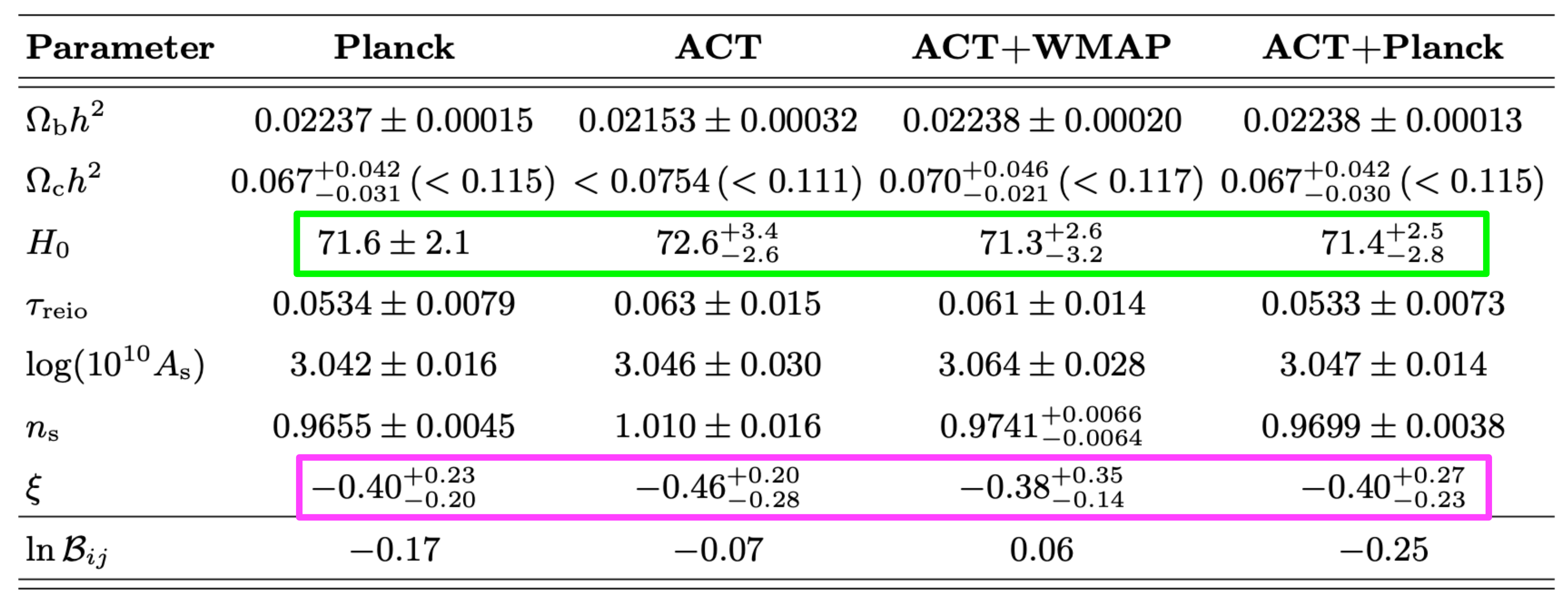


Parameter	*Planck*	*Planck+R19*
$\Omega_b h^2$	0.02239 ± 0.00015	0.02239 ± 0.00015
$\Omega_c h^2$	< 0.105	< 0.0615
n_s	0.9655 ± 0.0043	0.9656 ± 0.0044
$100\theta_s$	$1.0458^{+0.0033}_{-0.0021}$	1.0470 ± 0.0015
τ	0.0541 ± 0.0076	0.0534 ± 0.0080
ξ	$-0.54^{+0.12}_{-0.28}$	$-0.66^{+0.09}_{-0.13}$
$H_0\,[\mathrm{km\,s^{-1}\,Mpc^{-1}}]$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

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 from ACT



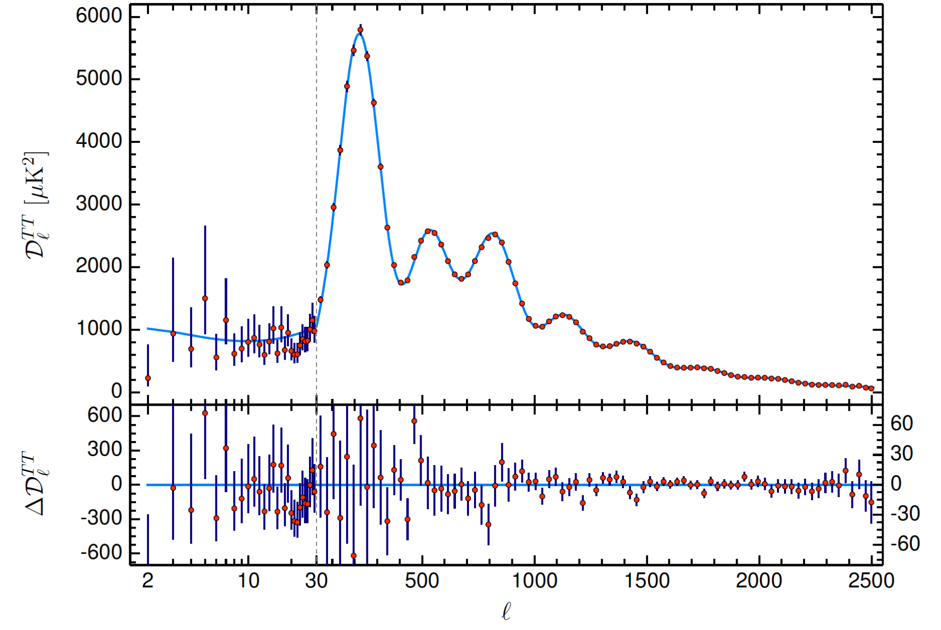
Parameter	Planck	ACT	ACT+WMAP	ACT+Planck
$\Omega_b h^2$	0.02237 ± 0.00015	0.02153 ± 0.00032	0.02238 ± 0.00020	0.02238 ± 0.00013
$\Omega_c h^2$	$0.067^{+0.042}_{-0.031}\,(< 0.115)$	$< 0.0754\,(< 0.111)$	$0.070^{+0.046}_{-0.021}\,(< 0.117)$	$0.067^{+0.042}_{-0.030}\,(< 0.115)$
H_0	71.6 ± 2.1	$72.6^{+3.4}_{-2.6}$	$71.3^{+2.6}_{-3.2}$	$71.4^{+2.5}_{-2.8}$
τ_{reio}	0.0534 ± 0.0079	0.063 ± 0.015	0.061 ± 0.014	0.0533 ± 0.0073
$\log(10^{10} A_s)$	3.042 ± 0.016	3.046 ± 0.030	3.064 ± 0.028	3.047 ± 0.014
n_s	0.9655 ± 0.0045	1.010 ± 0.016	$0.9741^{+0.0066}_{-0.0064}$	0.9699 ± 0.0038
ξ	$-0.40^{+0.23}_{-0.20}$	$-0.46^{+0.20}_{-0.28}$	$-0.38^{+0.35}_{-0.14}$	$-0.40^{+0.27}_{-0.23}$
$\ln \mathcal{B}_{ij}$	-0.17	-0.07	0.06	-0.25

Zhai, Giarè, van de Bruck, Di Valentino, et al, *JCAP* 07 (2023) 032

Let’s now consider different combinations of CMB datasets.

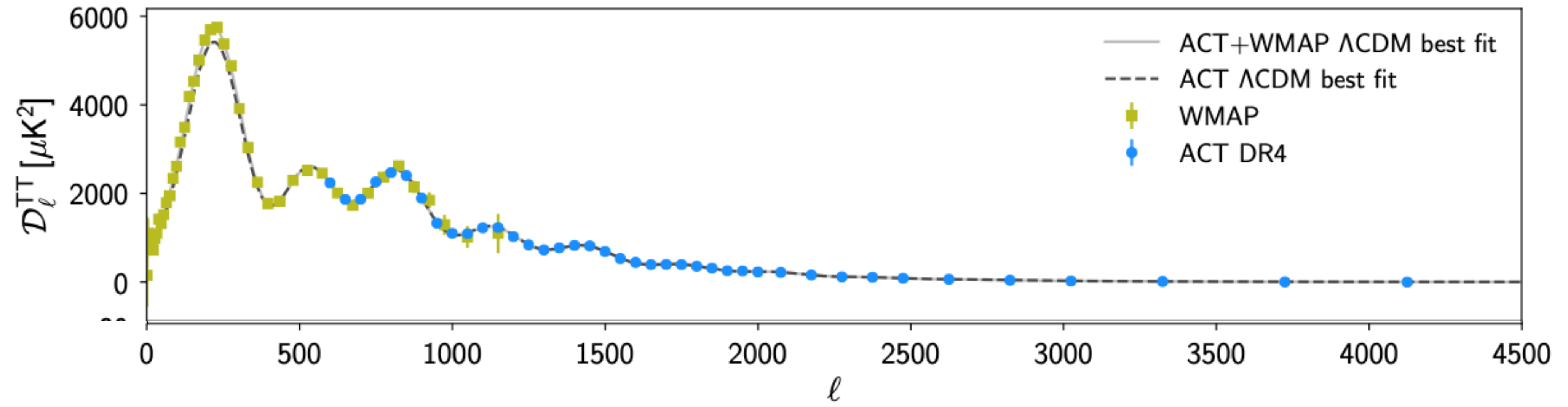
IDE from ACT

Parameter	Planck	ACT	ACT+WMAP	ACT+Planck
$\Omega_b h^2$	0.02237 ± 0.00015	0.02153 ± 0.00032	0.02238 ± 0.00020	0.02238 ± 0.00013
$\Omega_c h^2$	$0.067^{+0.}_{-0.}$		$7)$	$0.067^{+0.042}_{-0.030}$ (< 0.115)
H_0	$71.$			$71.4^{+2.5}_{-2.8}$
$\tau_{\rm reio}$	0.053			0.0533 ± 0.0073
$\log(10^{10} A_s)$	3.04			3.047 ± 0.014
n_s	0.965			0.9699 ± 0.0038
ξ	$-0.$			$-0.40^{+0.27}_{-0.23}$
$\ln \mathcal{B}_{ij}$	-			-0.25

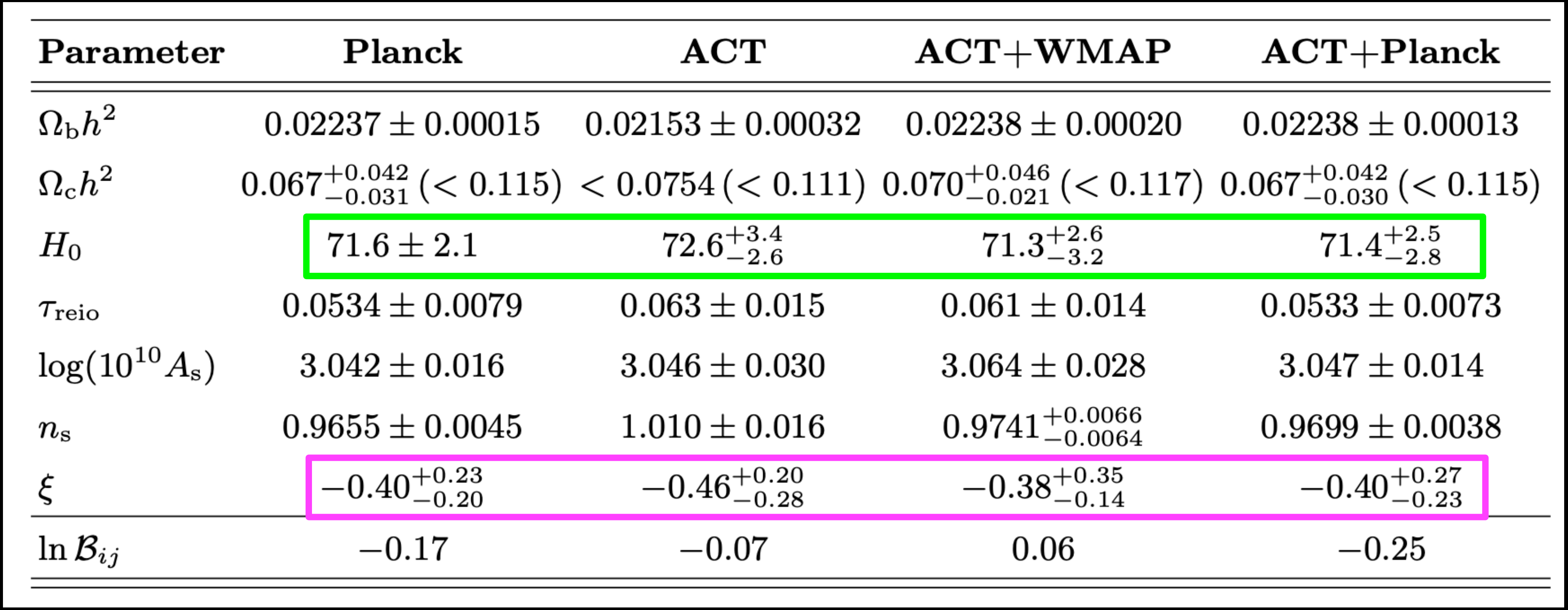


Zha

3) 032



IDE from ACT

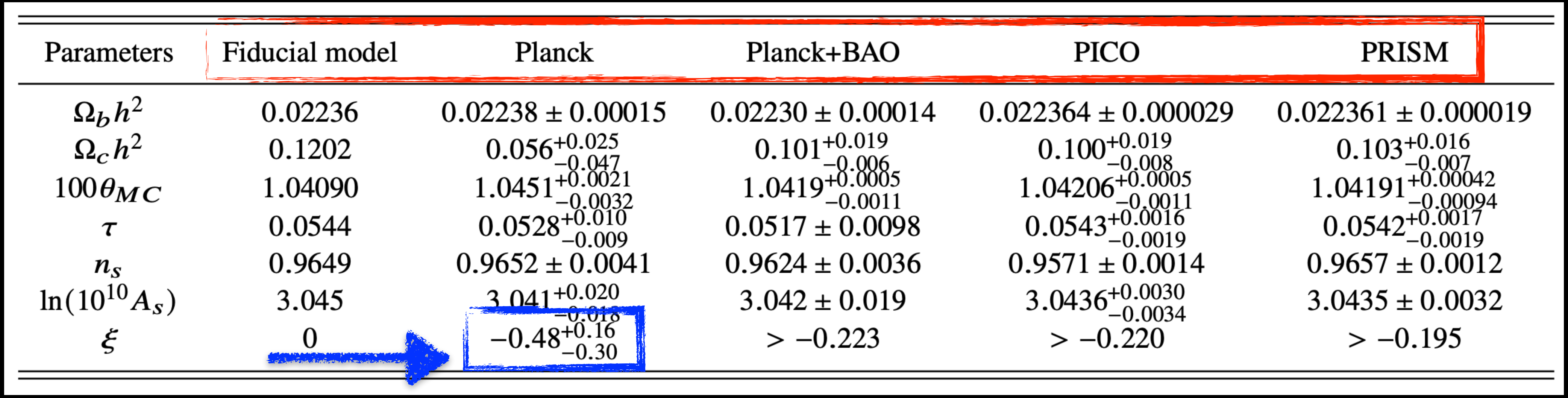


Parameter	Planck	ACT	ACT+WMAP	ACT+Planck
$\Omega_b h^2$	0.02237 ± 0.00015	0.02153 ± 0.00032	0.02238 ± 0.00020	0.02238 ± 0.00013
$\Omega_c h^2$	$0.067^{+0.042}_{-0.031}\,(< 0.115)$	$< 0.0754\,(< 0.111)$	$0.070^{+0.046}_{-0.021}\,(< 0.117)$	$0.067^{+0.042}_{-0.030}\,(< 0.115)$
H_0	71.6 ± 2.1	$72.6^{+3.4}_{-2.6}$	$71.3^{+2.6}_{-3.2}$	$71.4^{+2.5}_{-2.8}$
$\tau_{\rm reio}$	0.0534 ± 0.0079	0.063 ± 0.015	0.061 ± 0.014	0.0533 ± 0.0073
$\log(10^{10} A_s)$	3.042 ± 0.016	3.046 ± 0.030	3.064 ± 0.028	3.047 ± 0.014
n_s	0.9655 ± 0.0045	1.010 ± 0.016	$0.9741^{+0.0066}_{-0.0064}$	0.9699 ± 0.0038
ξ	$-0.40^{+0.23}_{-0.20}$	$-0.46^{+0.20}_{-0.28}$	$-0.38^{+0.35}_{-0.14}$	$-0.40^{+0.27}_{-0.23}$
$\ln \mathcal{B}_{ij}$	-0.17	-0.07	0.06	-0.25

Zhai, Giarè, van de Bruck, Di Valentino, et al, *JCAP* 07 (2023) 032

If we consider different combinations of CMB datasets, they provide similar results, favoring IDE with a 95% CL significance in the majority of the cases.
Remarkably, such a preference remains consistent
when cross-checked through independent probes,
while always yielding a value of the expansion rate H0 consistent
with the local distance ladder measurements.

fake IDE detection

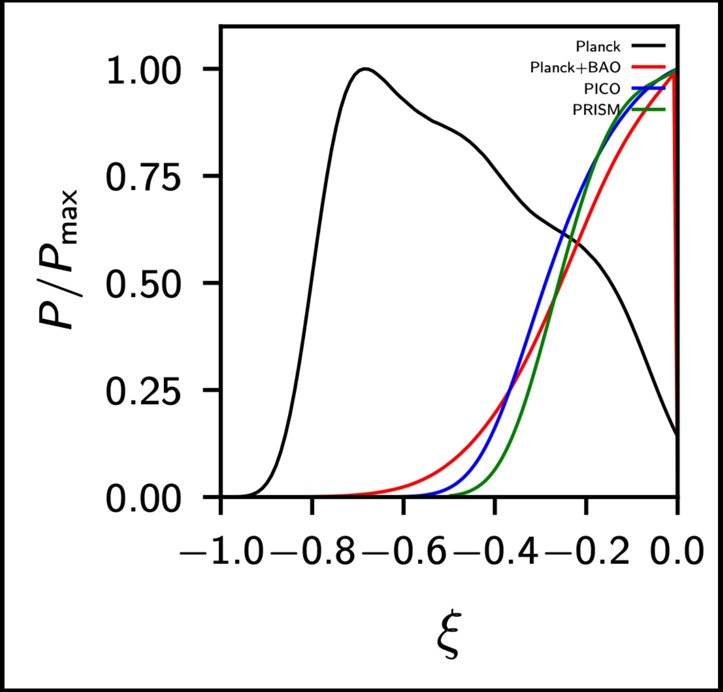


Parameters	Fiducial model	Planck	Planck+BAO	PICO	PRISM
$\Omega_b h^2$	0.02236	0.02238 ± 0.00015	0.02230 ± 0.00014	0.022364 ± 0.000029	0.022361 ± 0.000019
$\Omega_c h^2$	0.1202	$0.056^{+0.025}_{-0.047}$	$0.101^{+0.019}_{-0.006}$	$0.100^{+0.019}_{-0.008}$	$0.103^{+0.016}_{-0.007}$
$100\theta_{MC}$	1.04090	$1.0451^{+0.0021}_{-0.0032}$	$1.0419^{+0.0005}_{-0.0011}$	$1.04206^{+0.0005}_{-0.0011}$	$1.04191^{+0.00042}_{-0.00094}$
τ	0.0544	$0.0528^{+0.010}_{-0.009}$	0.0517 ± 0.0098	$0.0543^{+0.0016}_{-0.0019}$	$0.0542^{+0.0017}_{-0.0019}$
n_s	0.9649	0.9652 ± 0.0041	0.9624 ± 0.0036	0.9571 ± 0.0014	0.9657 ± 0.0012
$\ln(10^{10} A_s)$	3.045	$3.041^{+0.020}_{-0.018}$	3.042 ± 0.019	$3.0436^{+0.0030}_{-0.0034}$	3.0435 ± 0.0032
ξ	0	$-0.48^{+0.16}_{-0.30}$	> -0.223	> -0.220	> -0.195

Di Valentino & Mena, Mon.Not.Roy.Astron.Soc. 500 (2020) 1, L22-L26, arXiv:2009.12620

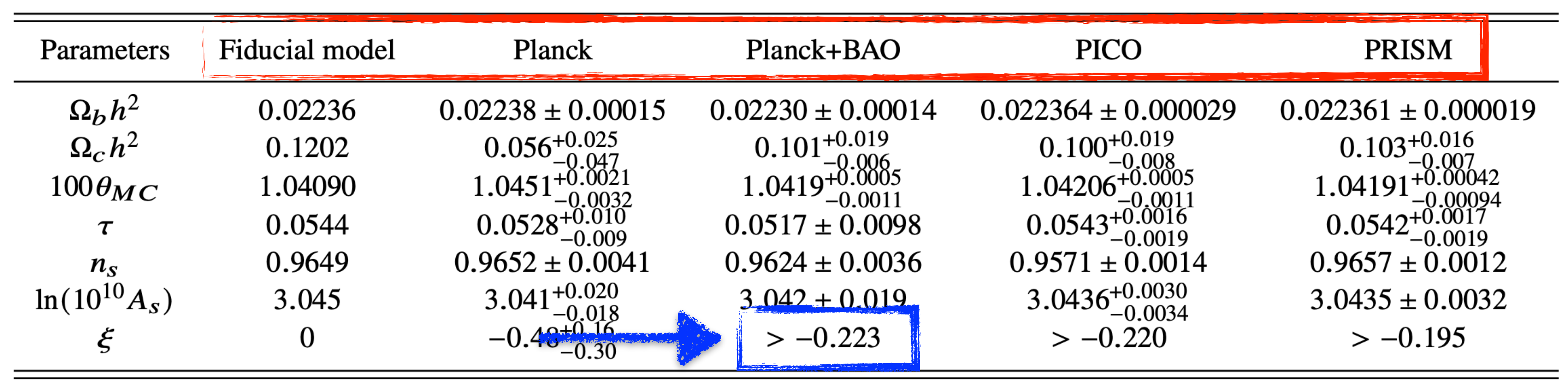
For a mock Planck-like experiment, due to the strong correlation present between the standard and the exotic physics parameters, there is a dangerous detection at more than 3σ for a coupling between dark matter and dark energy different from zero, even if the fiducial model has ξ =0:

$-0.85 < \xi < -0.02$ at 99% CL



Mock experiments

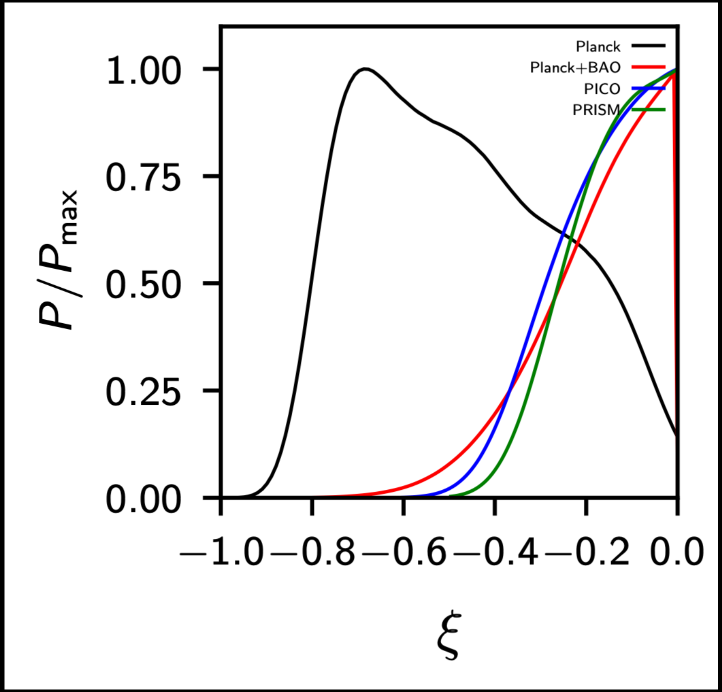
fake IDE detection



Parameters	Fiducial model	Planck	Planck+BAO	PICO	PRISM
$\Omega_b h^2$	0.02236	0.02238 ± 0.00015	0.02230 ± 0.00014	0.022364 ± 0.000029	0.022361 ± 0.000019
$\Omega_c h^2$	0.1202	$0.056^{+0.025}_{-0.047}$	$0.101^{+0.019}_{-0.006}$	$0.100^{+0.019}_{-0.008}$	$0.103^{+0.016}_{-0.007}$
$100\theta_{MC}$	1.04090	$1.0451^{+0.0021}_{-0.0032}$	$1.0419^{+0.0005}_{-0.0011}$	$1.04206^{+0.0005}_{-0.0011}$	$1.04191^{+0.00042}_{-0.00094}$
τ	0.0544	$0.0528^{+0.010}_{-0.009}$	0.0517 ± 0.0098	$0.0543^{+0.0016}_{-0.0019}$	$0.0542^{+0.0017}_{-0.0019}$
n_s	0.9649	0.9652 ± 0.0041	0.9624 ± 0.0036	0.9571 ± 0.0014	0.9657 ± 0.0012
$\ln(10^{10}A_s)$	3.045	$3.041^{+0.020}_{-0.018}$	3.042 ± 0.019	$3.0436^{+0.0030}_{-0.0034}$	3.0435 ± 0.0032
ξ	0	$-0.48^{+0.16}_{-0.30}$	> -0.223	> -0.220	> -0.195

Di Valentino & Mena, Mon.Not.Roy.Astron.Soc. 500 (2020) 1, L22-L26, arXiv:2009.12620

The inclusion of mock BAO data,
a mock dataset built using the same fiducial
cosmological model than that of the CMB,
helps in breaking the degeneracy,
providing a lower limit for the coupling ξ
in perfect agreement with zero.



Mock experiments

Baryon Acoustic Oscillations

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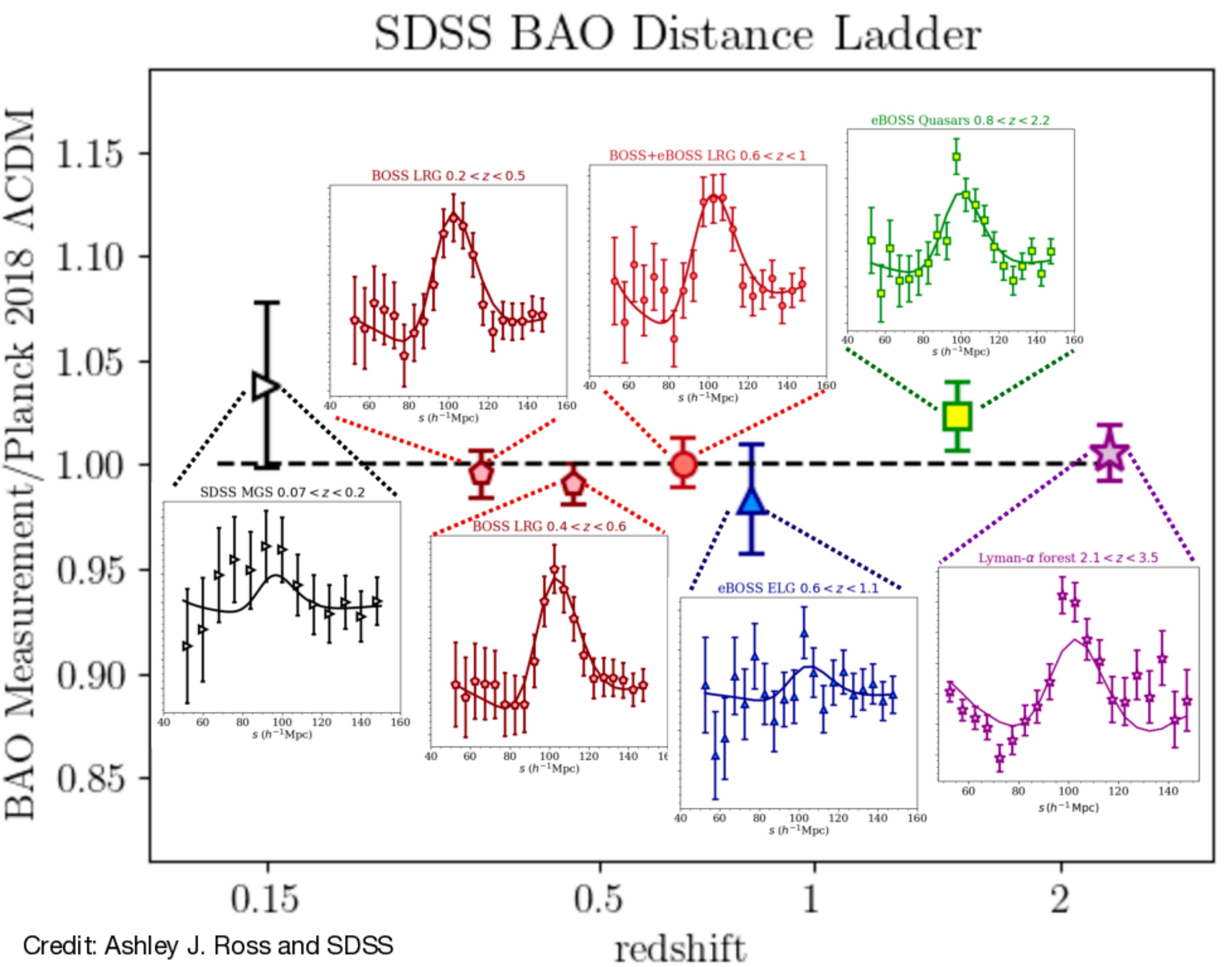
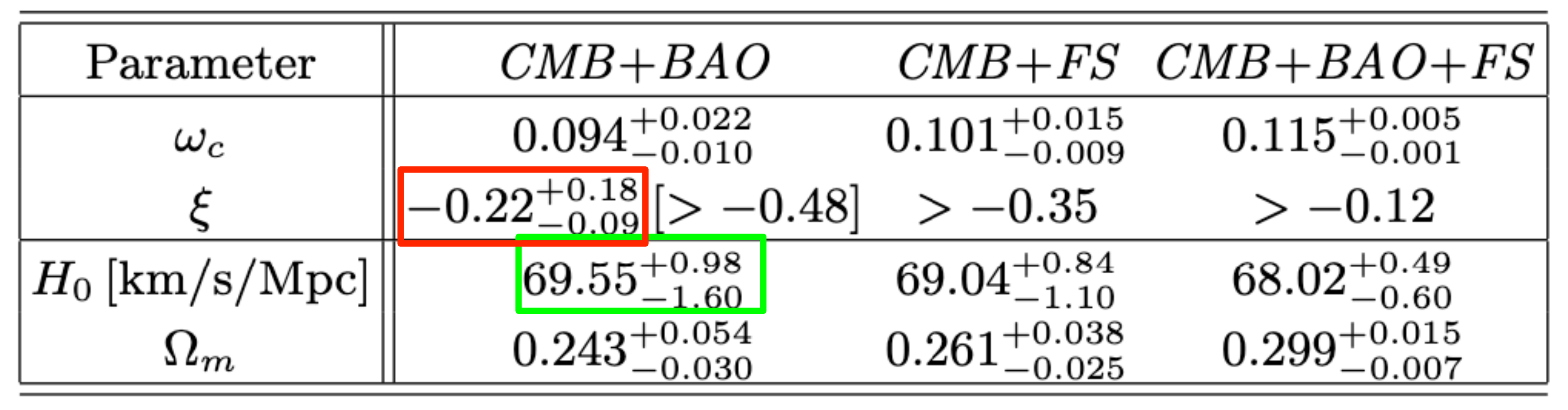


Credit: Ashley J. Ross and SDSS

The IDE case

Constraints at 68% cl.

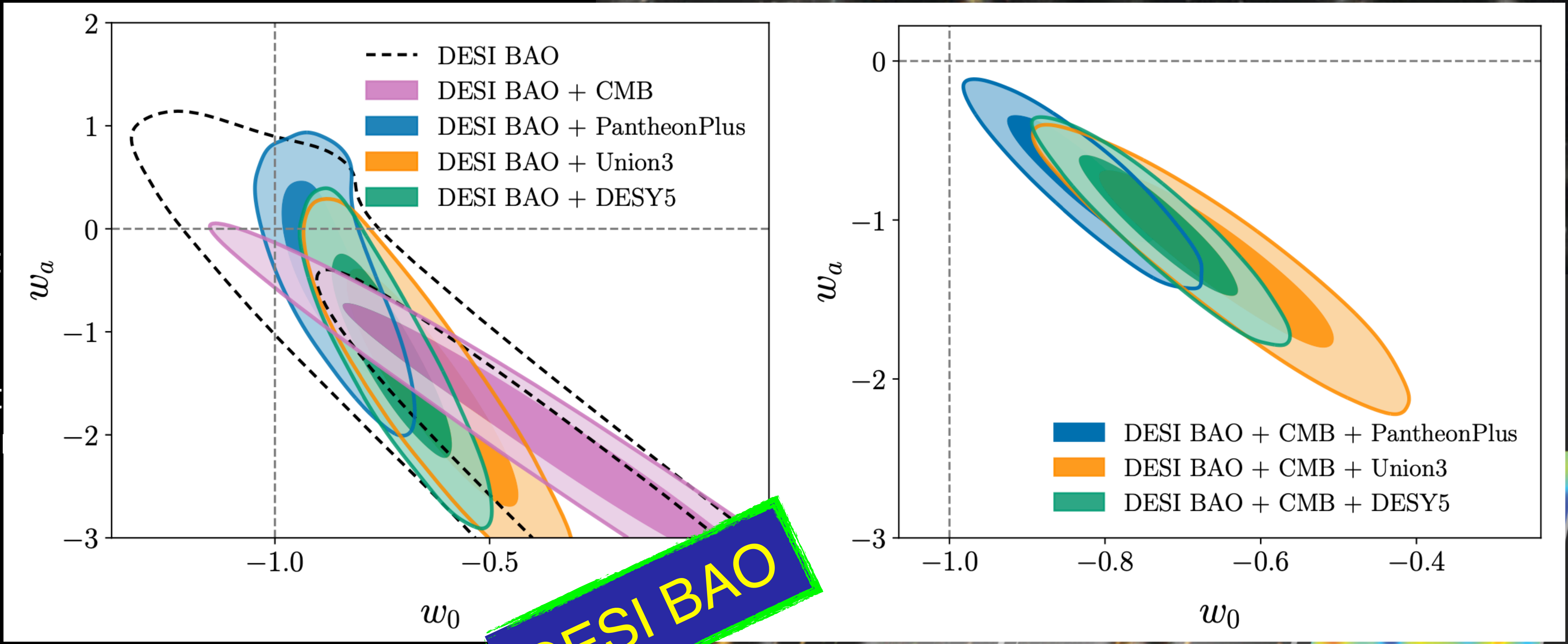


Parameter	$CMB+BAO$	$CMB+FS$	$CMB+BAO+FS$
ω_c	$0.094^{+0.022}_{-0.010}$	$0.101^{+0.015}_{-0.009}$	$0.115^{+0.005}_{-0.001}$
ξ	$-0.22^{+0.18}_{-0.09}[> -0.48]$	> -0.35	> -0.12
H_0 [km/s/Mpc]	$69.55^{+0.98}_{-1.60}$	$69.04^{+0.84}_{-1.10}$	$68.02^{+0.49}_{-0.60}$
Ω_m	$0.243^{+0.054}_{-0.030}$	$0.261^{+0.038}_{-0.025}$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

Nunes, Vagnozzi, Kumar, Di Valentino, and Mena, *Phys.Rev.D* 105 (2022) 12, 123506

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 value is larger than that obtained in the case of a pure ΛCDM scenario, enough to bring the H0 tension at 2.1σ with SH0ES.

Baryon Acoustic Oscillations



DESI BAO

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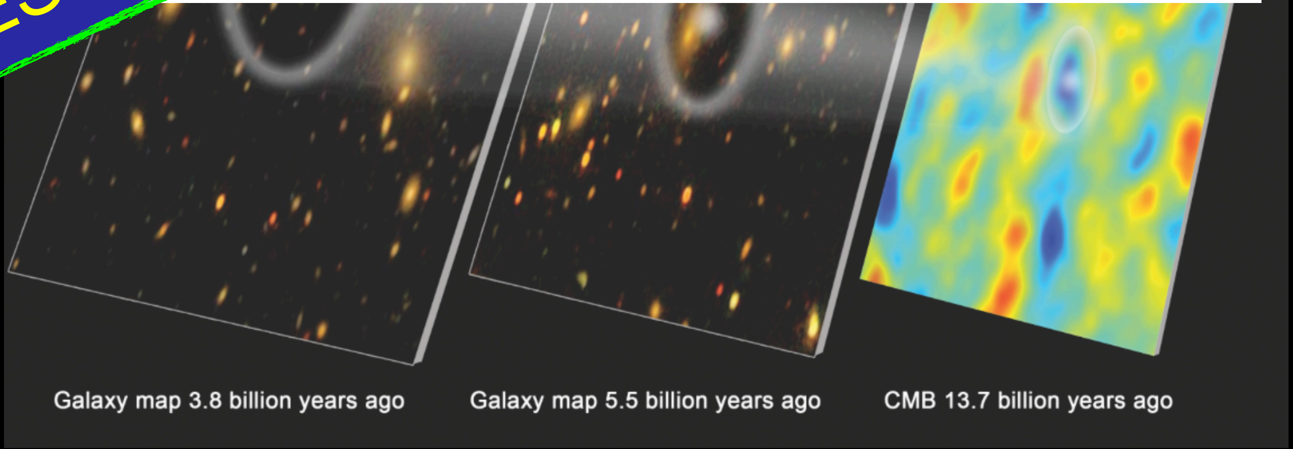
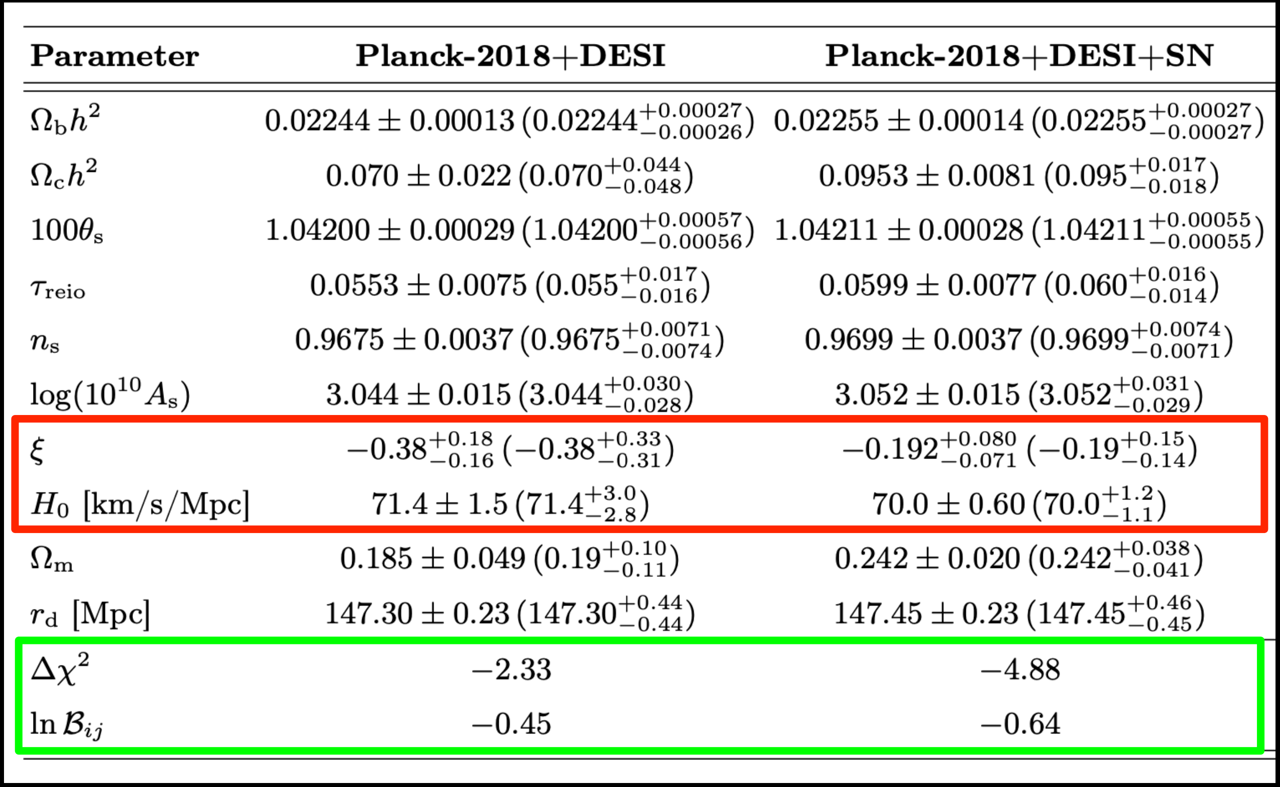
fluctuations have evolved and
can observe BAO at low redshi s
in the distribution of galaxies.

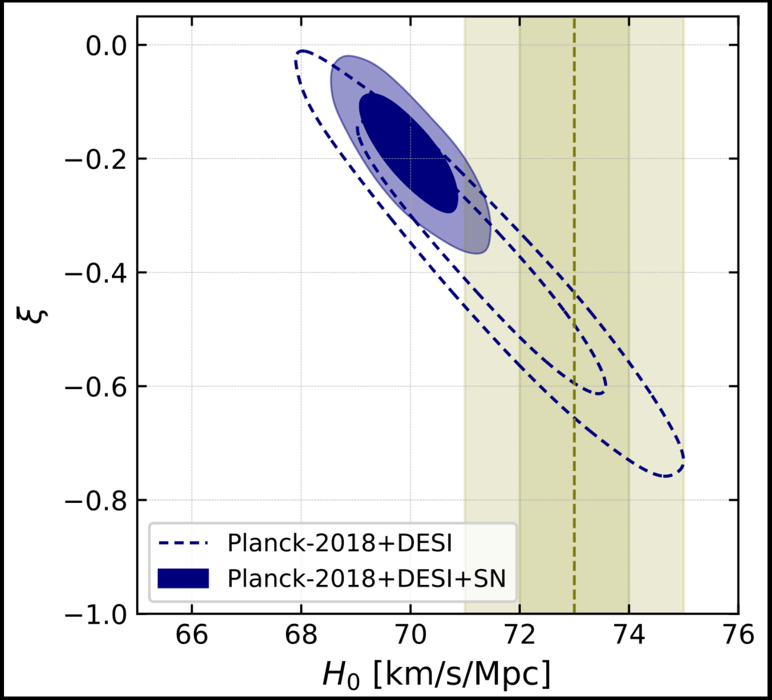


Constraints at 68% cl.

The IDE case



Parameter	Planck-2018+DESI	Planck-2018+DESI+SN
$\Omega_b h^2$	$0.02244 \pm 0.00013\,(0.02244^{+0.00027}_{-0.00026})$	$0.02255 \pm 0.00014\,(0.02255^{+0.00027}_{-0.00027})$
$\Omega_c h^2$	$0.070 \pm 0.022\,(0.070^{+0.044}_{-0.048})$	$0.0953 \pm 0.0081\,(0.095^{+0.017}_{-0.018})$
$100\theta_s$	$1.04200 \pm 0.00029\,(1.04200^{+0.00057}_{-0.00056})$	$1.04211 \pm 0.00028\,(1.04211^{+0.00055}_{-0.00055})$
τ_reio	$0.0553 \pm 0.0075\,(0.055^{+0.017}_{-0.016})$	$0.0599 \pm 0.0077\,(0.060^{+0.016}_{-0.014})$
n_s	$0.9675 \pm 0.0037\,(0.9675^{+0.0071}_{-0.0074})$	$0.9699 \pm 0.0037\,(0.9699^{+0.0074}_{-0.0071})$
$\log(10^{10}A_s)$	$3.044 \pm 0.015\,(3.044^{+0.030}_{-0.028})$	$3.052 \pm 0.015\,(3.052^{+0.031}_{-0.029})$
ξ	$-0.38^{+0.18}_{-0.16}\,(-0.38^{+0.33}_{-0.31})$	$-0.192^{+0.080}_{-0.071}\,(-0.19^{+0.15}_{-0.14})$
H_0 [km/s/Mpc]	$71.4 \pm 1.5\,(71.4^{+3.0}_{-2.8})$	$70.0 \pm 0.60\,(70.0^{+1.2}_{-1.1})$
Ω_m	$0.185 \pm 0.049\,(0.19^{+0.10}_{-0.11})$	$0.242 \pm 0.020\,(0.242^{+0.038}_{-0.041})$
r_d [Mpc]	$147.30 \pm 0.23\,(147.30^{+0.44}_{-0.44})$	$147.45 \pm 0.23\,(147.45^{+0.46}_{-0.45})$
$\Delta\chi^2$	-2.33	-4.88
$\ln \mathcal{B}_{ij}$	-0.45	-0.64

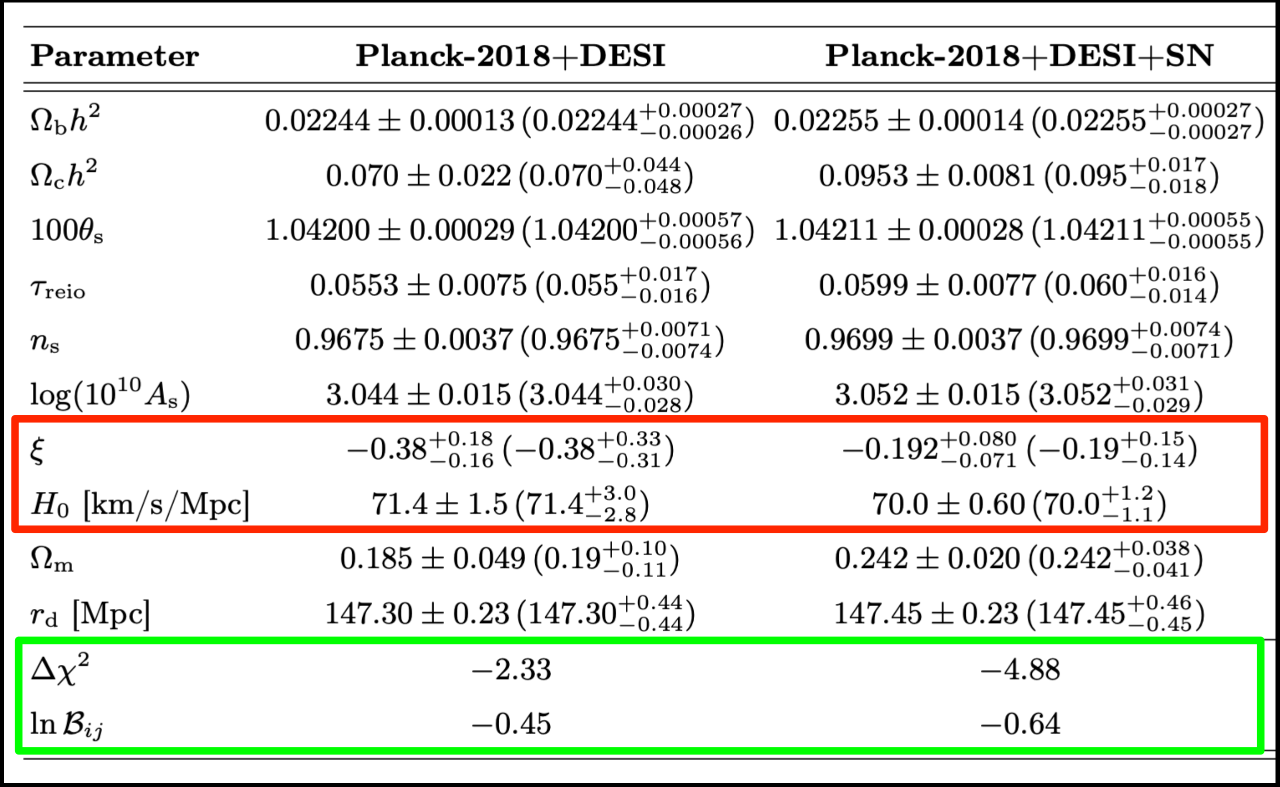


Giarè, Sabogal, Nunes, Di Valentino, arXiv:2404.15232

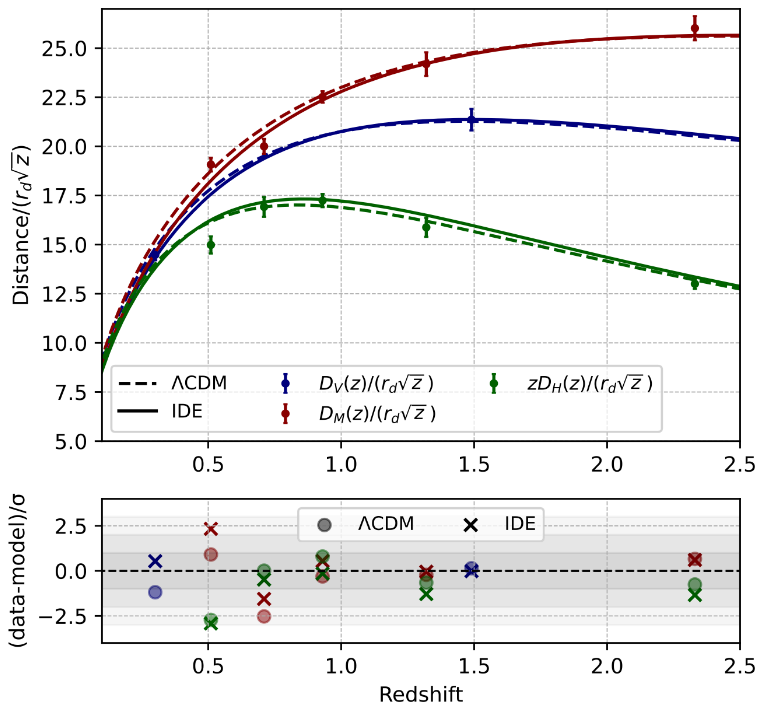
By combining Planck-2018 and DESI data,
we observe a preference for interactions exceeding the 95% CL, yielding a present-day expansion rate H0 = 71.4±1.5 km/s/Mpc, in agreement with SH0ES.
This preference remains robust when including Type-Ia Supernovae sourced from the Pantheon-plus catalog using the SH0ES Cepheid host distances as calibrators.

Constraints at 68% cl.

The IDE case



Parameter	Planck-2018+DESI	Planck-2018+DESI+SN
$\Omega_b h^2$	$0.02244 \pm 0.00013\,(0.02244^{+0.00027}_{-0.00026})$	$0.02255 \pm 0.00014\,(0.02255^{+0.00027}_{-0.00027})$
$\Omega_c h^2$	$0.070 \pm 0.022\,(0.070^{+0.044}_{-0.048})$	$0.0953 \pm 0.0081\,(0.095^{+0.017}_{-0.018})$
$100\theta_s$	$1.04200 \pm 0.00029\,(1.04200^{+0.00057}_{-0.00056})$	$1.04211 \pm 0.00028\,(1.04211^{+0.00055}_{-0.00055})$
$\tau_{\rm reio}$	$0.0553 \pm 0.0075\,(0.055^{+0.017}_{-0.016})$	$0.0599 \pm 0.0077\,(0.060^{+0.016}_{-0.014})$
n_s	$0.9675 \pm 0.0037\,(0.9675^{+0.0071}_{-0.0074})$	$0.9699 \pm 0.0037\,(0.9699^{+0.0074}_{-0.0071})$
$\log(10^{10}A_s)$	$3.044 \pm 0.015\,(3.044^{+0.030}_{-0.028})$	$3.052 \pm 0.015\,(3.052^{+0.031}_{-0.029})$
ξ	$-0.38^{+0.18}_{-0.16}\,(-0.38^{+0.33}_{-0.31})$	$-0.192^{+0.080}_{-0.071}\,(-0.19^{+0.15}_{-0.14})$
H_0 [km/s/Mpc]	$71.4 \pm 1.5\,(71.4^{+3.0}_{-2.8})$	$70.0 \pm 0.60\,(70.0^{+1.2}_{-1.1})$
Ω_m	$0.185 \pm 0.049\,(0.19^{+0.10}_{-0.11})$	$0.242 \pm 0.020\,(0.242^{+0.038}_{-0.041})$
r_d [Mpc]	$147.30 \pm 0.23\,(147.30^{+0.44}_{-0.44})$	$147.45 \pm 0.23\,(147.45^{+0.46}_{-0.45})$
$\Delta\chi^2$	-2.33	-4.88
$\ln \mathcal{B}_{ij}$	-0.45	-0.64



Giarè, Sabogal, Nunes, Di Valentino, arXiv:2404.15232

Overall, high and low redshift data can be equally or better explained within the IDE framework compared to ΛCDM, while also yielding higher values of H0 in better agreement with the local distance ladder estimate.

Concluding

At this point, given the quality of all the analyses at play,
probably these tensions are indicating a problem with the underlying cosmology
and our understanding of the Universe,
rather than the presence of systematic effects.
Therefore, this is presenting a serious limitation to the precision cosmology.

Many models have been proposed to solve the H0 tension.

However, looking for a solution by changing the standard model of
cosmology is challenging because of some additional complications,
such as the sound horizon problem (disfavouring late time solutions),
the S8 tension (disfavouring early time solutions),
and the correlation between the parameters and possible fake detection.

Overall, the new DESI BAO data add an intriguing twist to the situation.

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

Thank you!

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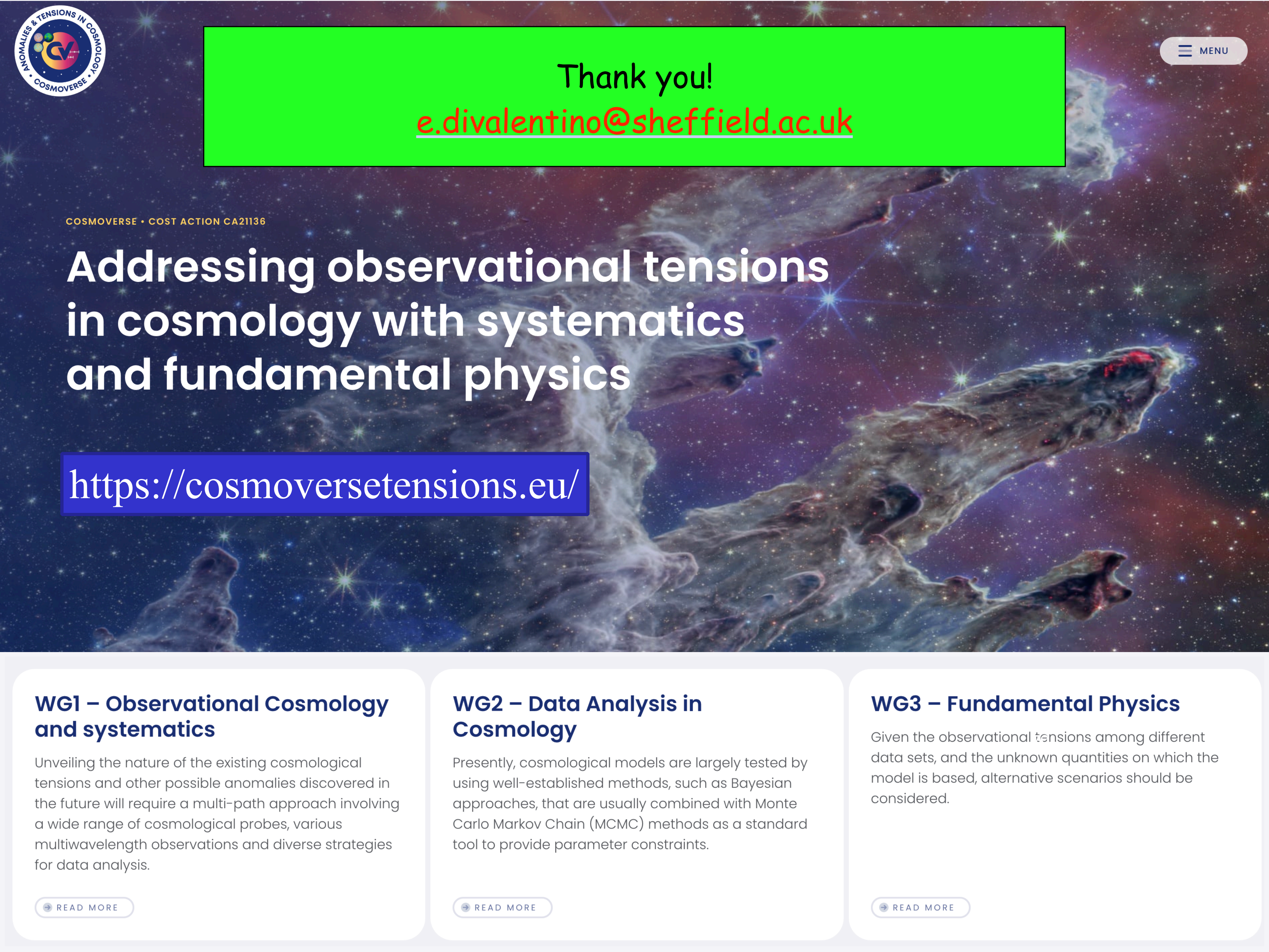

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Addressing observational tensions in cosmology with systematics and fundamental physics

https://cosmoversetensions.eu/

WG1 – Observational Cosmology and systematics

Unveiling the nature of the existing cosmological tensions and other possible anomalies discovered in the future will require a multi-path approach involving a wide range of cosmological probes, various multiwavelength observations and diverse strategies for data analysis.

WG2 – Data Analysis in Cosmology

Presently, cosmological models are largely tested by using well-established methods, such as Bayesian approaches, that are usually combined with Monte Carlo Markov Chain (MCMC) methods as a standard tool to provide parameter constraints.

WG3 – Fundamental Physics

Given the observational tensions among different data sets, and the unknown quantities on which the model is based, alternative scenarios should be considered.