Tensions in cosmology and implications for the standard model

October 25th 2022
QFC2022- Quantum gases, fundamental interactions and cosmology
PISA

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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 approximation 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.

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Cosmology Intertwined: A Review of the Particle Physics, Astrophysics, and Cosmology Associated with the Cosmological Tensions and Anomalies

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JHEAp 34 (2022) 49-211

The current cosmological tensions and anomalies are the argument of Review Paper we submitted for the SNOWMASS call, that includes contributions from more than 200 people, who participated in brainstorming sessions from August 2020, and provided feedback via regular Zoom seminars and meetings.

This White Paper is based on the 4 LoIs we submitted in August 2020, published in Astroparticle Physics.

Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 25 Aug 2020 (v1), last revised 13 Oct 2020 (this version, v4)]

Cosmology Intertwined I: Perspectives for the Next Decade

Eleonora Di Valentino, Luis A. Anchordoqui, Ozgur Akarsu, Yacine Ali-Haimoud, Luca Amendola, Nikki Arendse, Marika Asgari, Mario Ballardini, Spyros Basilakos, Elia Battistelli, Micol Benetti, Simon Birrer, François R. Bouchet, Marco Bruni, Erminia Calabrese, David Camarena, Salvatore Capozziello, Angela Chen, Jens Chluba, Anton Chudaykin, Eoin Ó Colgáin, Francis-Yan Cyr-Racine, Paolo de Bernardis, Javier de Cruz Pérez, Jacques Delabrouille, Jo Dunkley, Celia Escamilla-Rivera, Agnès Ferté, Fabio Finelli, Wendy Freedman, Noemi Frusciante, Elena Giusarma, Adrià Gómez-Valent, Will Handley, Ian Harrison, Luke Hart, Alan Heavens, Hendrik Hildebrandt, Daniel Holz, Dragan Huterer, Mikhail M. Ivanov, Shahab Joudaki, Marc Kamionkowski, Tanvi Karwal, Lloyd Knox, Suresh Kumar, Luca Lamagna, Julien Lesgourgues, Matteo Lucca, Valerio Marra, Silvia Masi, Sabino Matarrese, Arindam Mazumdar, Alessandro Melchiorri, Olga Mena, Laura Mersini-Houghton, Vivian Miranda, Cristian Moreno-Pulido, David F. Mota, Jessica Muir, Ankan Mukherjee, Florian Niedermann, Alessio Notari, Rafael C. Nunes, Francesco Pace, Andronikos Paliathanasis, Antonella Palmese, Supriya Pan, Daniela Paoletti, Valeria Pettorino, Francesco Piacentini, Vivian Poulin, Marco Raveri, Adam G. Riess, Vincenzo Salzano, Emmanuel N. Saridakis, Anjan A. Sen, Arman Shafieloo, Anowar J. Shajib, Joseph Silk, Alessandra Silvestri, Martin S. Sloth, Tristan L. Smith, Joan Solà, Carsten van de Bruck, Licia Verde, Luca Visinelli, Benjamin D. Wandelt, Deng Wang, Jian-Min Wang, Anil K. Yadav, Weiqiang Yang

The standard Λ Cold Dark Matter cosmological model provides an amazing description of a wide range of astrophysical and astronomical data. However, there are a few big open questions, that make the standard model look like a first-order approximation to a more realistic scenario that still needs to be fully understood. In this Letter of Interest we will list a few important goals that need to be addressed in the next decade, also taking into account the current discordances present between the different cosmological probes, as the Hubble constant H_0 value, the $\sigma_8 - S_8$ tension, and the anomalies present in the Planck results. Finally, we will give an overview of upgraded experiments and next-generation space-missions and facilities on Earth, that will be of crucial importance to address all these questions.

Comments:	Snowmass2021 - Letter of Interest
Subjects:	**Cosmology and Nongalactic Astrophysics (astro-ph.CO)**; High Energy Physics - Phenomenology (hep-ph)
Journal reference:	Astropart. Phys. 131, 102606 (2021)
DOI:	10.1016/j.astropartphys.2021.102606

This White Paper is based on the 4 LoIs we submitted in August 2020, published in Astroparticle Physics.

Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 25 Aug 2020 (v1), last revised 13 Oct 2020 (this version, v4)]

Cosmology Intertwined II: The Hubble Constant Tension

Eleonora Di Valentino, Luis A. Anchordoqui, Ozgur Akarsu, Yacine Ali-Haimoud, Luca Amendola, Nikki Arendse, Marika Asgari, Mario Ballardini, Spyros Basilakos, Elia Battistelli, Micol Benetti, Simon Birrer, François R. Bouchet, Marco Bruni, Erminia Calabrese, David Camarena, Salvatore Capozziello, Angela Chen, Jens Chluba, Anton Chudaykin, Eoin Ó Colgáin, Francis-Yan Cyr-Racine, Paolo de Bernardis, Javier de Cruz Pérez, Jacques Delabrouille, Jo Dunkley, Celia Escamilla-Rivera, Agnès Ferté, Fabio Finelli, Wendy Freedman, Noemi Frusciante, Elena Giusarma, Adrià Gómez-Valent, Julien Guy, Will Handley, Ian Harrison, Luke Hart, Alan Heavens, Hendrik Hildebrandt, Daniel Holz, Dragan Huterer, Mikhail M. Ivanov, Shahab Joudaki, Marc Kamionkowski, Tanvi Karwal, Lloyd Knox, Suresh Kumar, Luca Lamagna, Julien Lesgourgues, Matteo Lucca, Valerio Marra, Silvia Masi, Sabino Matarrese, Arindam Mazumdar, Alessandro Melchiorri, Olga Mena, Laura Mersini-Houghton, Vivian Miranda, Cristian Moreno-Pulido, David F. Mota, Jessica Muir, Ankan Mukherjee, Florian Niedermann, Alessio Notari, Rafael C. Nunes, Francesco Pace, Andronikos Paliathanasis, Antonella Palmese, Supriya Pan, Daniela Paoletti, Valeria Pettorino, Francesco Piacentini, Vivian Poulin, Marco Raveri, Adam G. Riess, Vincenzo Salzano, Emmanuel N. Saridakis, Anjan A. Sen, Arman Shafieloo, Anowar J. Shajib, Joseph Silk, Alessandra Silvestri, Martin S. Sloth, Tristan L. Smith, Joan Solà, Carsten van de Bruck, Licia Verde, Luca Visinelli, Benjamin D. Wandelt, Deng Wang, Jian-Min Wang, Anil K. Yadav, Weiqiang Yang

The current cosmological probes have provided a fantastic confirmation of the standard Λ Cold Dark Matter cosmological model, that has been constrained with unprecedented accuracy. However, with the increase of the experimental sensitivity a few statistically significant tensions between different independent cosmological datasets emerged. While these tensions can be in portion the result of systematic errors, the persistence after several years of accurate analysis strongly hints at cracks in the standard cosmological scenario and the need for new physics. In this Letter of Interest we will focus on the 4.4σ tension between the Planck estimate of the Hubble constant H_0 and the SH0ES collaboration measurements. After showing the H_0 evaluations made from different teams using different methods and geometric calibrations, we will list a few interesting new physics models that could solve this tension and discuss how the next decade experiments will be crucial.

Comments:	Snowmass2021 - Letter of Interest
Subjects:	**Cosmology and Nongalactic Astrophysics (astro-ph.CO)**; High Energy Physics - Phenomenology (hep-ph)
Journal reference:	Astropart. Phys. 131, 102605 (2021)
DOI:	10.1016/j.astropartphys.2021.102605

This White Paper is based on the 4 LoIs we submitted in August 2020, published in Astroparticle Physics.

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Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 25 Aug 2020 (v1), last revised 13 Oct 2020 (this version, v4)]

Cosmology Intertwined III: $f\sigma_8$ and S_8

Eleonora Di Valentino, Luis A. Anchordoqui, Ozgur Akarsu, Yacine Ali-Haimoud, Luca Amendola, Nikki Arendse, Marika Asgari, Mario Ballardini, Spyros Basilakos, Elia Battistelli, Micol Benetti, Simon Birrer, François R. Bouchet, Marco Bruni, Erminia Calabrese, David Camarena, Salvatore Capozziello, Angela Chen, Jens Chluba, Anton Chudaykin, Eoin Ó Colgáin, Francis-Yan Cyr-Racine, Paolo de Bernardis, Javier de Cruz Pérez, Jacques Delabrouille, Jo Dunkley, Celia Escamilla-Rivera, Agnès Ferté, Fabio Finelli, Wendy Freedman, Noemi Frusciante, Elena Giusarma, Adrià Gómez-Valent, Will Handley, Ian Harrison, Luke Hart, Alan Heavens, Hendrik Hildebrandt, Daniel Holz, Dragan Huterer, Mikhail M. Ivanov, Shahab Joudaki, Marc Kamionkowski, Tanvi Karwal, Lloyd Knox, Suresh Kumar, Luca Lamagna, Julien Lesgourgues, Matteo Lucca, Valerio Marra, Silvia Masi, Sabino Matarrese, Arindam Mazumdar, Alessandro Melchiorri, Olga Mena, Laura Mersini-Houghton, Vivian Miranda, Cristian Moreno-Pulido, David F. Mota, Jessica Muir, Ankan Mukherjee, Florian Niedermann, Alessio Notari, Rafael C. Nunes, Francesco Pace, Andronikos Paliathanasis, Antonella Palmese, Supriya Pan, Daniela Paoletti, Valeria Pettorino, Francesco Piacentini, Vivian Poulin, Marco Raveri, Adam G. Riess, Vincenzo Salzano, Emmanuel N. Saridakis, Anjan A. Sen, Arman Shafieloo, Anowar J. Shajib, Joseph Silk, Alessandra Silvestri, Martin S. Sloth, Tristan L. Smith, Joan Solà, Carsten van de Bruck, Licia Verde, Luca Visinelli, Benjamin D. Wandelt, Deng Wang, Jian-Min Wang, Anil K. Yadav, Weiqiang Yang

The standard Λ Cold Dark Matter cosmological model provides a wonderful fit to current cosmological data, but a few tensions and anomalies became statistically significant with the latest data analyses. While these anomalies could be due to the presence of systematic errors in the experiments, they could also indicate the need for new physics beyond the standard model. In this Letter of Interest we focus on the tension of the Planck data with weak lensing measurements and redshift surveys, about the value of the matter energy density Ω_m, and the amplitude or rate of the growth of structure ($\sigma_8, f\sigma_8$). We list a few interesting models for solving this tension, and we discuss the importance of trying to fit with a single model a full array of data and not just one parameter at a time.

Comments: Snowmass2021 - Letter of Interest
Subjects: **Cosmology and Nongalactic Astrophysics (astro-ph.CO)**; High Energy Physics - Phenomenology (hep-ph)
Journal reference: Astropart. Phys. 131, 102604 (2021)
DOI: 10.1016/j.astropartphys.2021.102604

This White Paper is based on the 4 LoIs we submitted in August 2020, published in Astroparticle Physics.

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[Submitted on 25 Aug 2020 (v1), last revised 13 Oct 2020 (this version, v4)]

Cosmology Intertwined IV: The Age of the Universe and its Curvature

Eleonora Di Valentino, Luis A. Anchordoqui, Ozgur Akarsu, Yacine Ali-Haimoud, Luca Amendola, Nikki Arendse, Marika Asgari, Mario Ballardini, Spyros Basilakos, Elia Battistelli, Micol Benetti, Simon Birrer, François R. Bouchet, Marco Bruni, Erminia Calabrese, David Camarena, Salvatore Capozziello, Angela Chen, Jens Chluba, Anton Chudaykin, Eoin Ó Colgáin, Francis-Yan Cyr-Racine, Paolo de Bernardis, Javier de Cruz Pérez, Jacques Delabrouille, Celia Escamilla-Rivera, Agnès Ferté, Fabio Finelli, Wendy Freedman, Noemi Frusciante, Elena Giusarma, Adrià Gómez-Valent, Will Handley, Ian Harrison, Luke Hart, Alan Heavens, Hendrik Hildebrandt, Daniel Holz, Dragan Huterer, Mikhail M. Ivanov, Shahab Joudaki, Marc Kamionkowski, Tanvi Karwal, Lloyd Knox, Suresh Kumar, Luca Lamagna, Julien Lesgourgues, Matteo Lucca, Valerio Marra, Silvia Masi, Sabino Matarrese, Arindam Mazumdar, Alessandro Melchiorri, Olga Mena, Laura Mersini-Houghton, Vivian Miranda, Cristian Moreno-Pulido, David F. Mota, Jessica Muir, Ankan Mukherjee, Florian Niedermann, Alessio Notari, Rafael C. Nunes, Francesco Pace, Andronikos Paliathanasis, Antonella Palmese, Supriya Pan, Daniela Paoletti, Valeria Pettorino, Francesco Piacentini, Vivian Poulin, Marco Raveri, Adam G. Riess, Vincenzo Salzano, Emmanuel N. Saridakis, Anjan A. Sen, Arman Shafieloo, Anowar J. Shajib, Joseph Silk, Alessandra Silvestri, Martin S. Sloth, Tristan L. Smith, Joan Solà, Carsten van de Bruck, Licia Verde, Luca Visinelli, Benjamin D. Wandelt, Deng Wang, Jian-Min Wang, Anil K. Yadav, Weiqiang Yang

A precise measurement of the curvature of the Universe is of primeval importance for cosmology since it could not only confirm the paradigm of primordial inflation but also help in discriminating between different early Universe scenarios. The recent observations, while broadly consistent with a spatially flat standard Λ Cold Dark Matter (ΛCDM) model, are showing tensions that still allow (and, in some cases, even suggest) a few percent deviations from a flat universe. In particular, the Planck Cosmic Microwave Background power spectra, assuming the nominal likelihood, prefer a closed universe at more than 99\% confidence level. While new physics could be in action, this anomaly may be the result of an unresolved systematic error or just a statistical fluctuation. However, since a positive curvature allows a larger age of the Universe, an accurate determination of the age of the oldest objects provides a smoking gun in confirming or falsifying the current flat ΛCDM model.

Comments: Snowmass2021 - Letter of Interest
Subjects: **Cosmology and Nongalactic Astrophysics (astro-ph.CO)**; High Energy Physics - Phenomenology (hep-ph)
Journal reference: Astropart. Phys. 131, 102607 (2021)
DOI: 10.1016/j.astropartphys.2021.102607

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Cosmology Intertwined:
A Review of the Particle Physics, Astrophysics, and Cosmology Associated with the Cosmological Tensions and Anomalies

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Finally, you can also find a section where we discuss in a unified manner many less discussed less-standard existing signals in cosmological and astrophysical data that appear to be in some tension (2σ or larger) with the standard ΛCDM model as defined by the Planck 2018 parameter values.

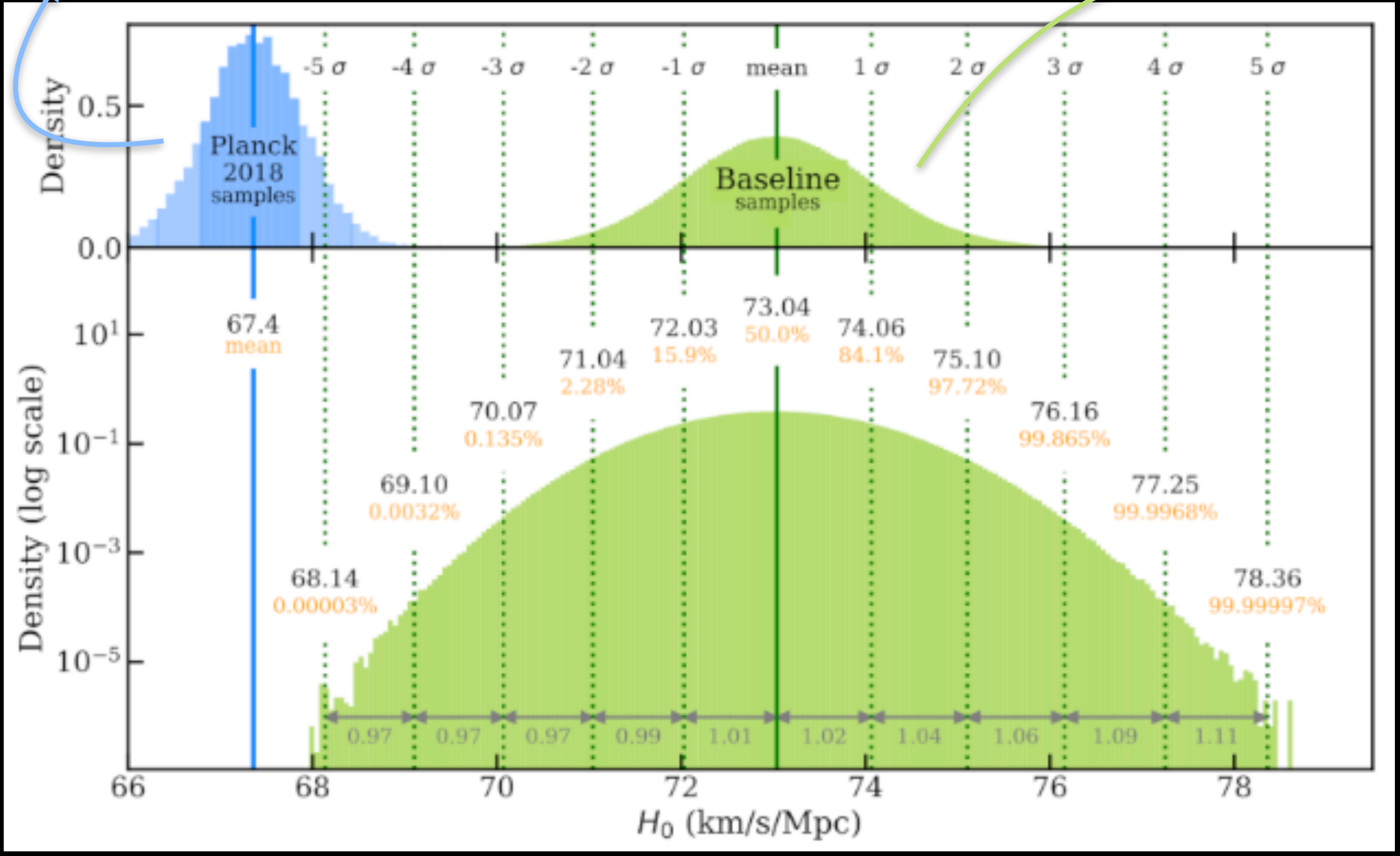
In many cases the signals are controversial and there is currently debate in the literature on the possible systematics origin of some of these signals.

I encourage you to have a look at the paper if you are interested in learning more.

The H0 tension exceeds 5σ!!

The H0 tension is the most statistically significant, long-lasting and widely persisting disagreement we have currently in cosmology.

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

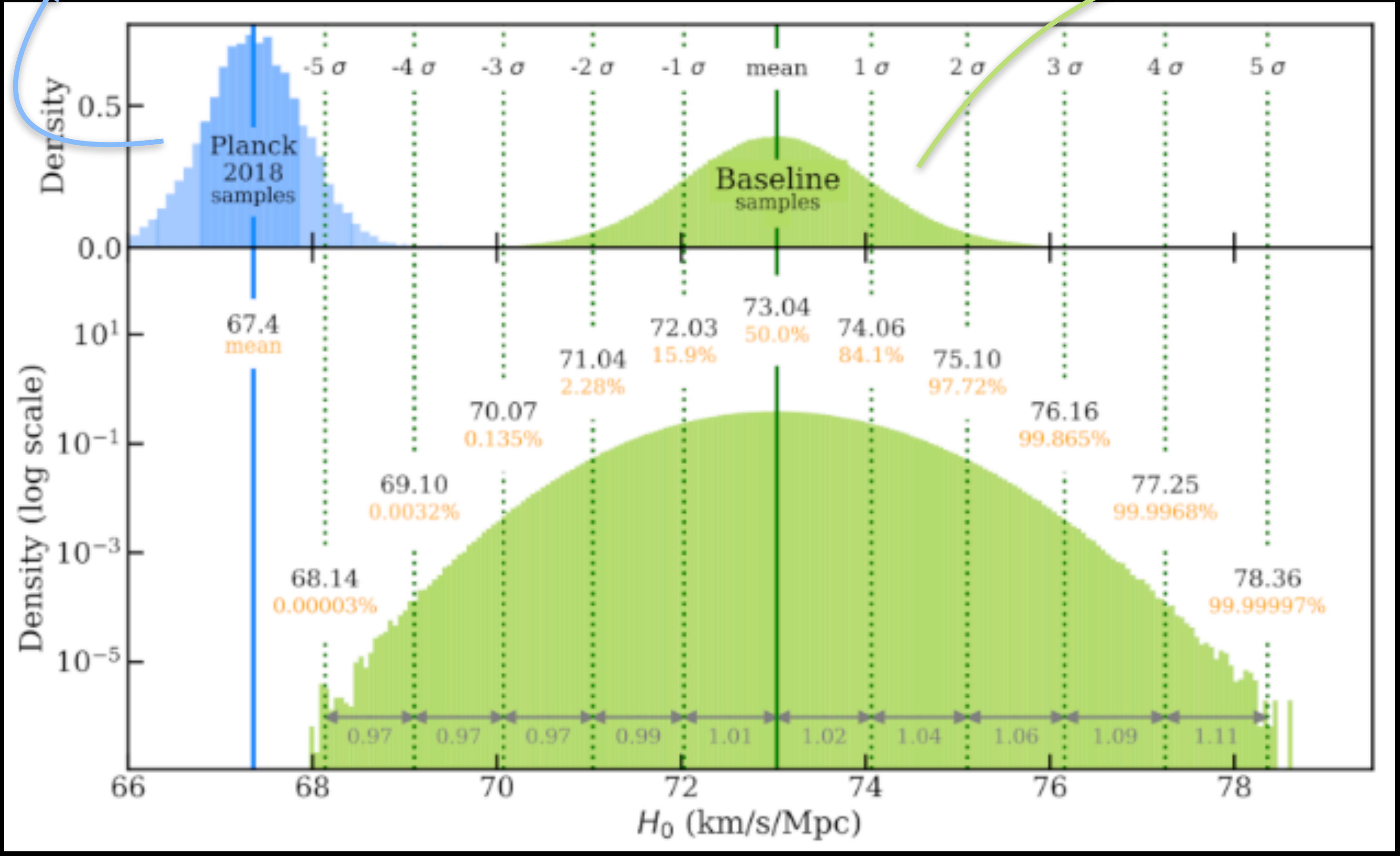
H0 = 73.04 ± 1.04 km/s/Mpc

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



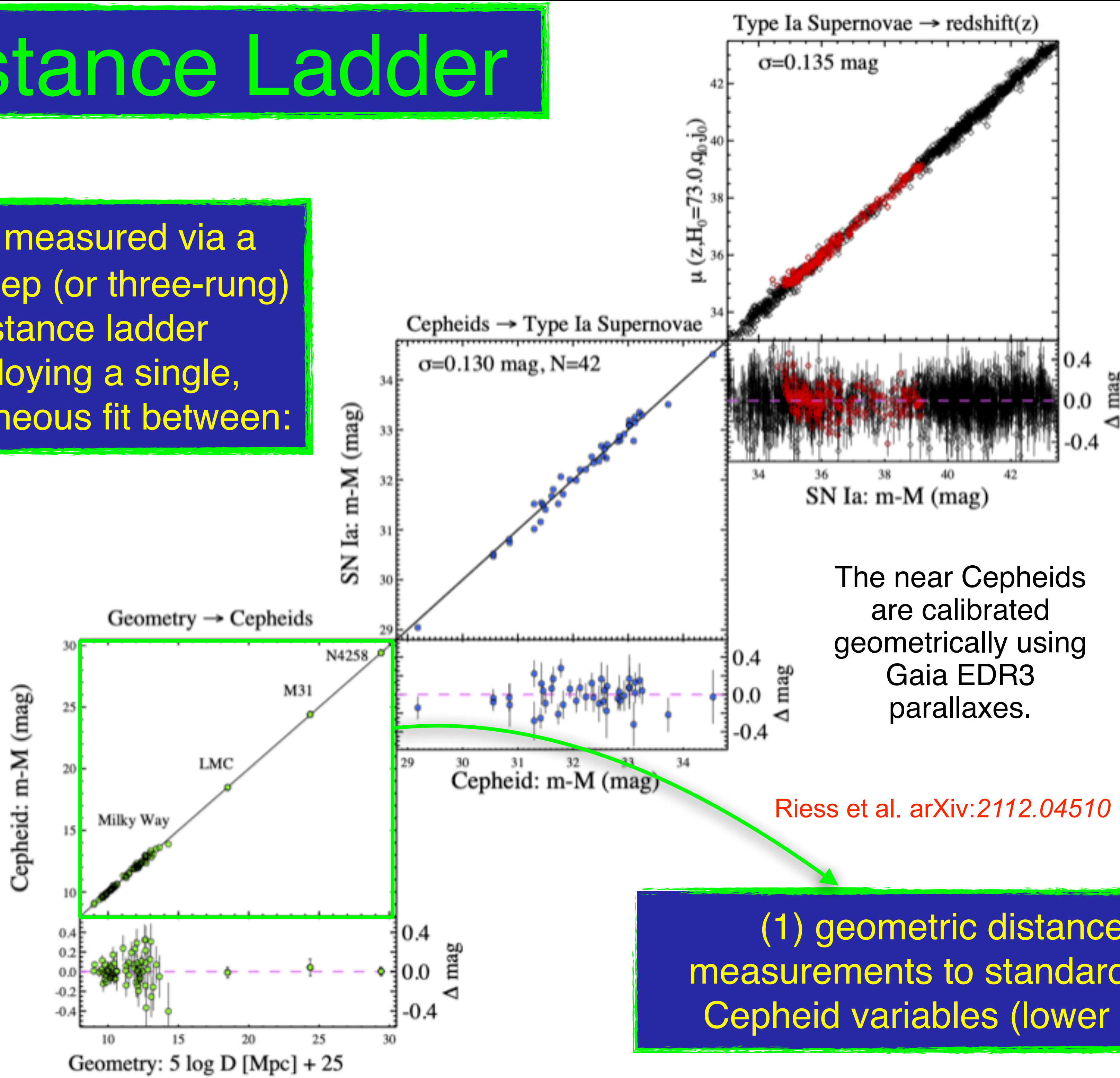
The latest local measurements obtained by the SH0ES collaboration

H0 = 73.04 ± 1.04 km/s/Mpc

Riess et al. arXiv:*2112.04510*

Distance Ladder

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



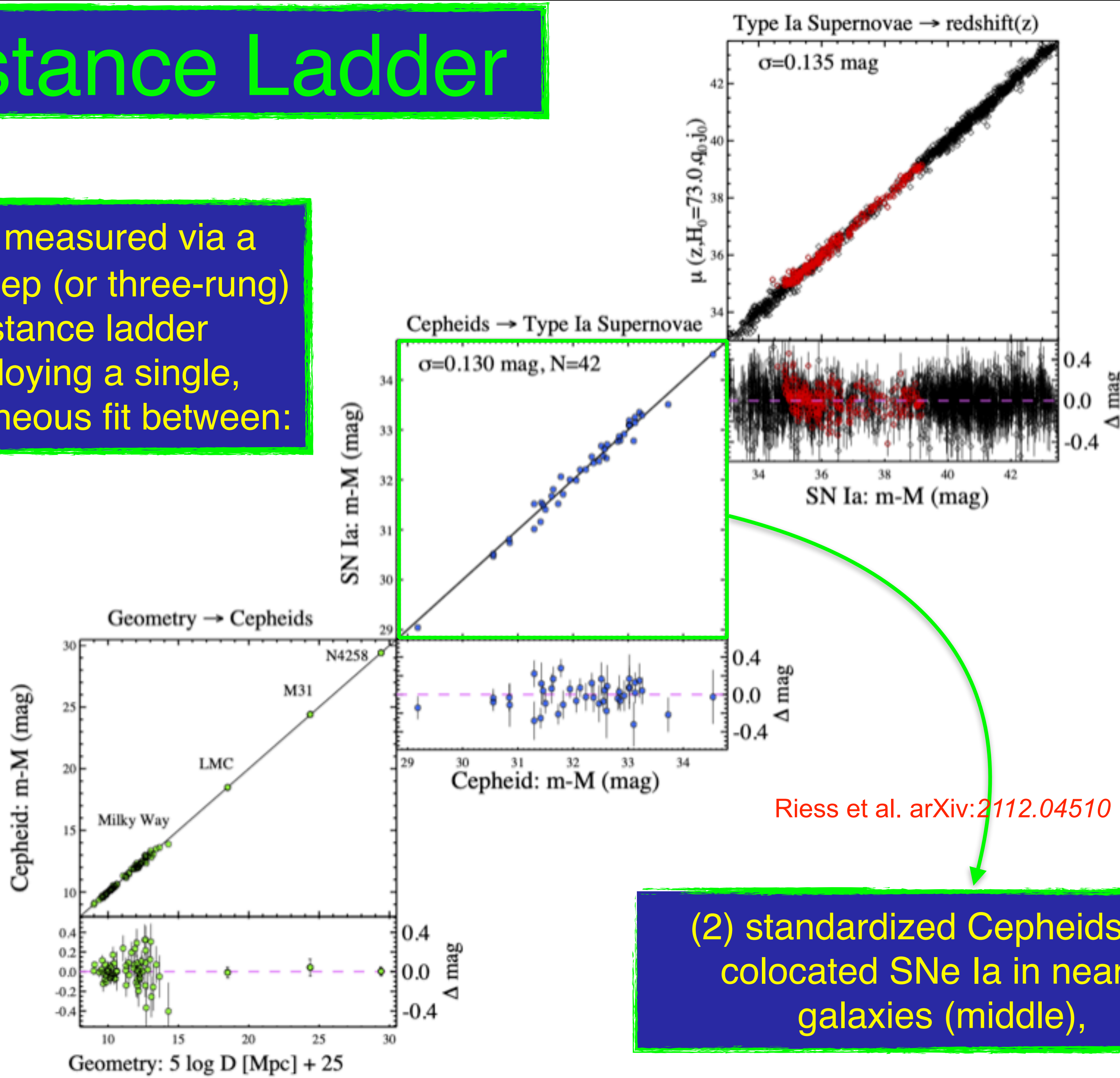
The near Cepheids are calibrated geometrically using Gaia EDR3 parallaxes.

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:

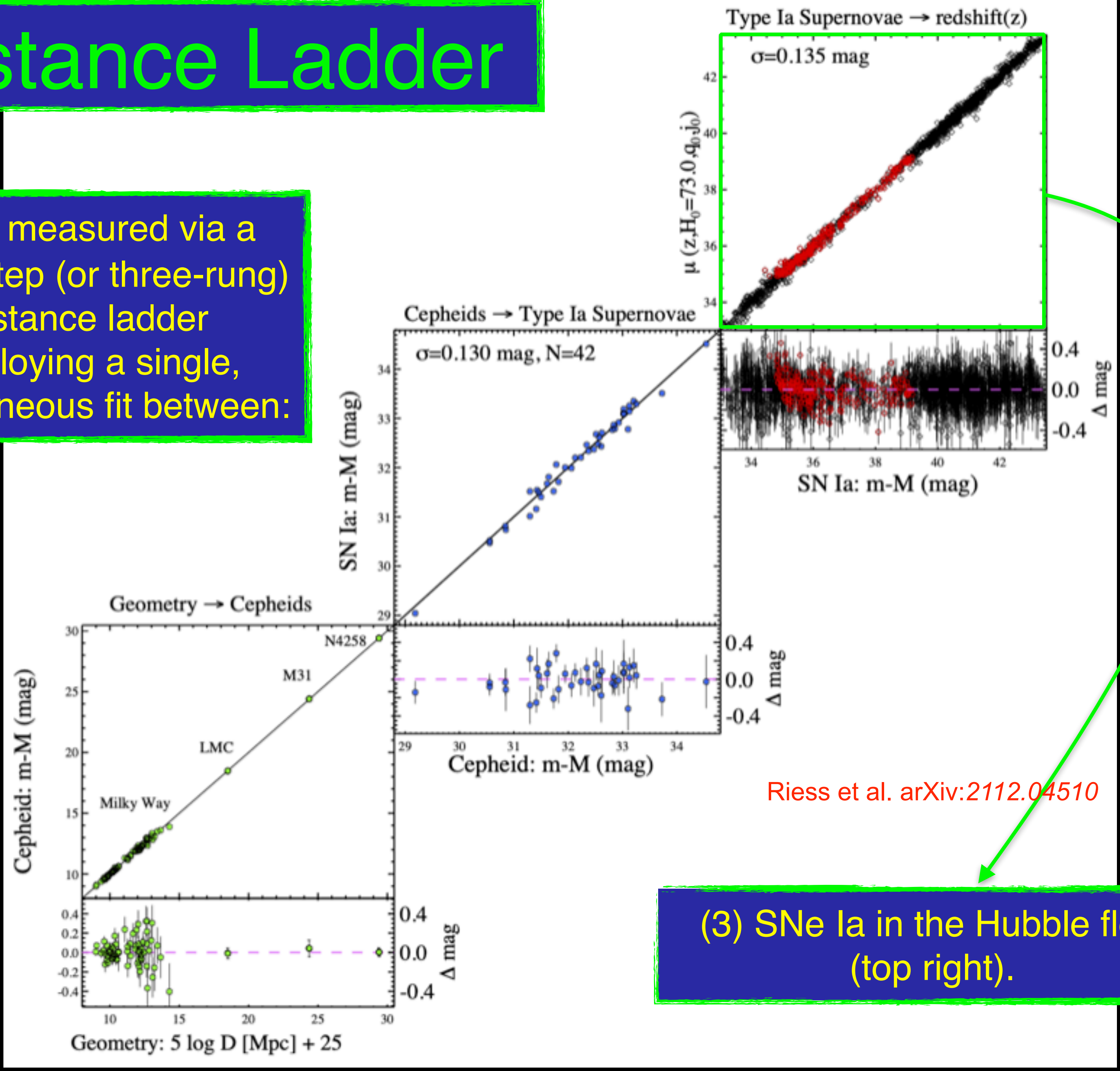


Riess et al. arXiv:*2112.04510*

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

Distance Ladder

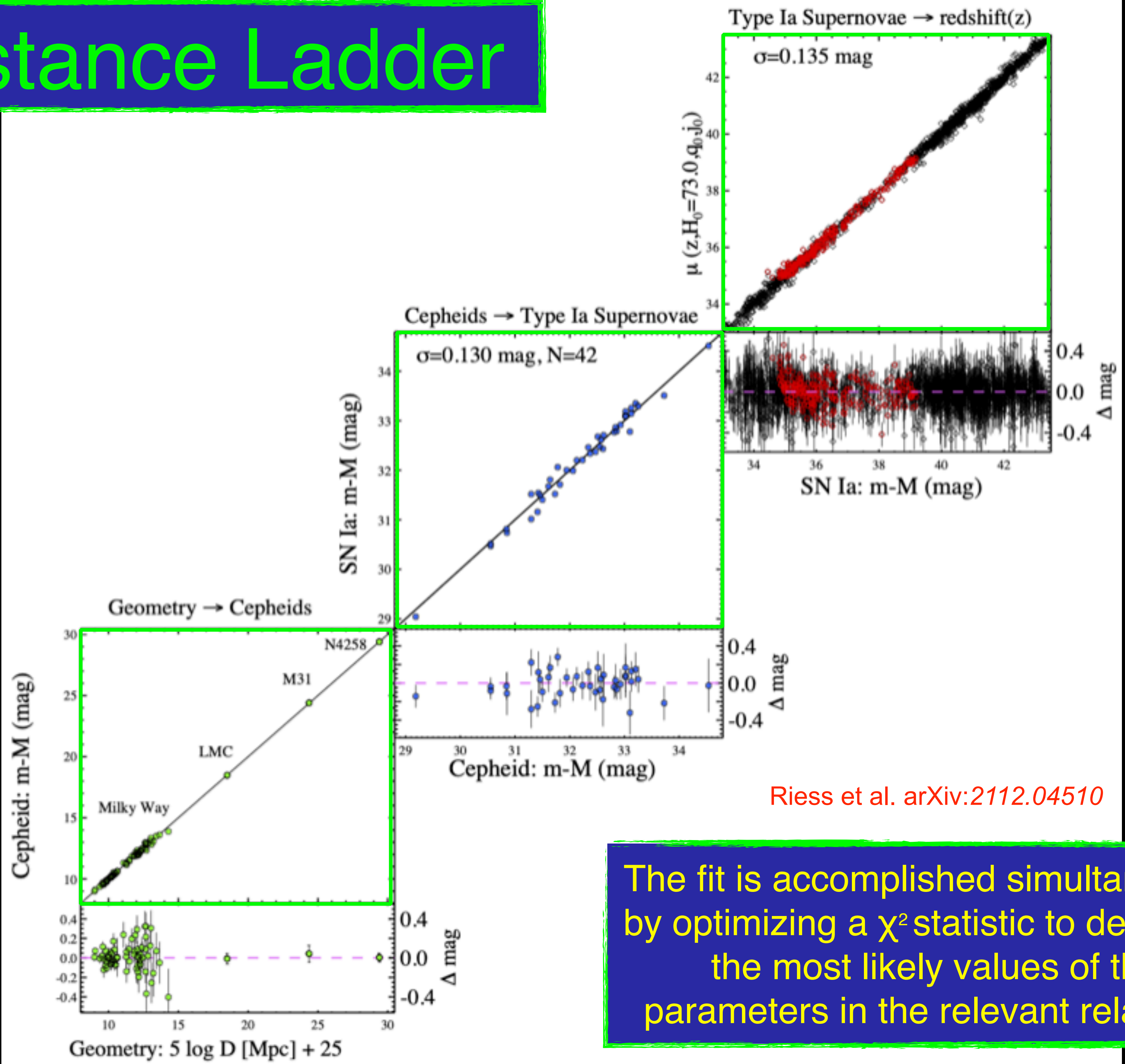
H0 is measured via a three-step (or three-rung) distance ladder employing a single, simultaneous fit between:



Riess et al. arXiv:*2112.04510*

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

Distance Ladder



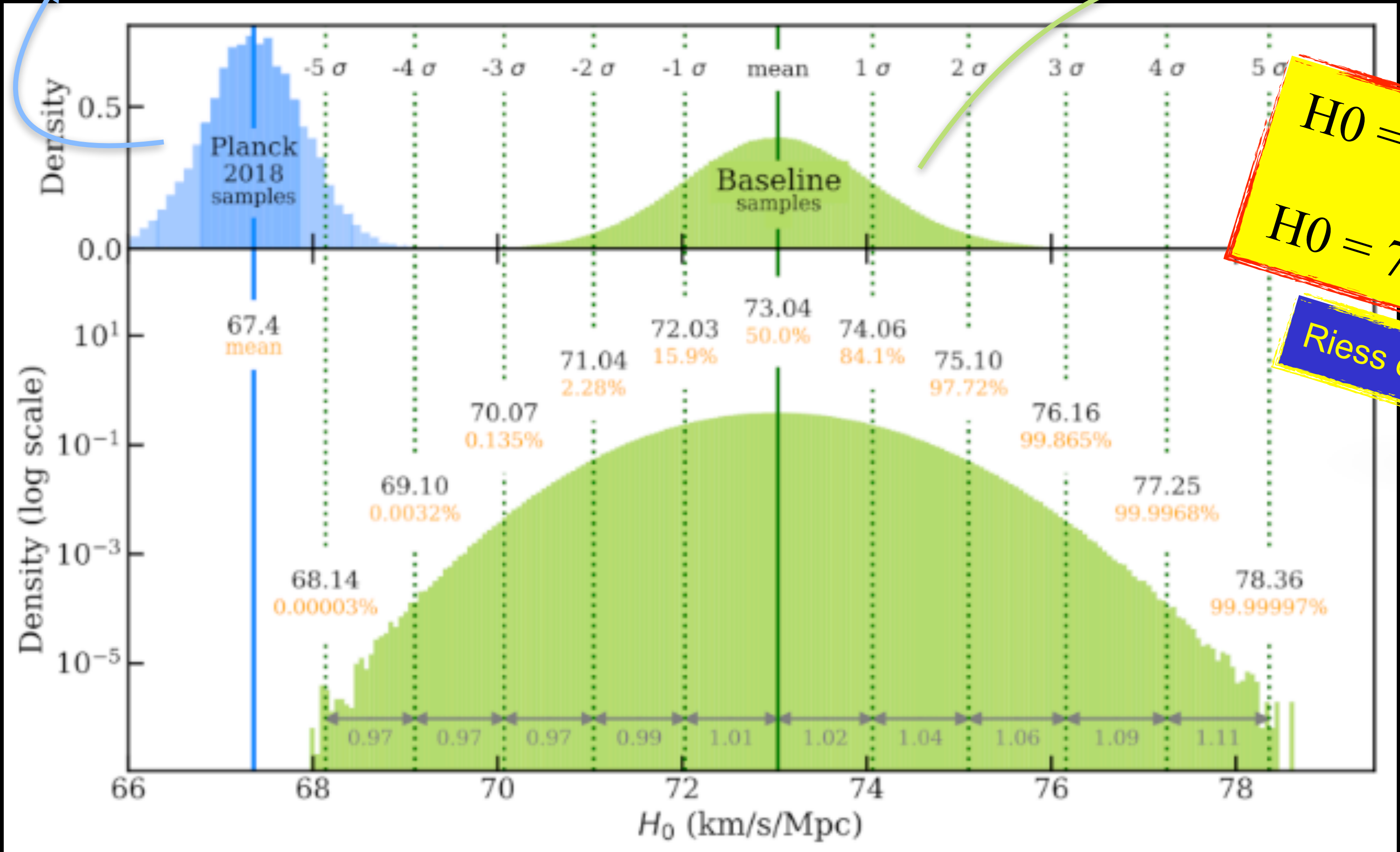
Riess et al. arXiv:*2112.04510*

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

The H0 tension exceeds 5σ!!

The H0 tension at 5.3σ

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 ... by the ...

H0 = 73.01 ± 0.99 km/s/Mpc

H0 = 73.15 ± 0.97 km/s/Mpc

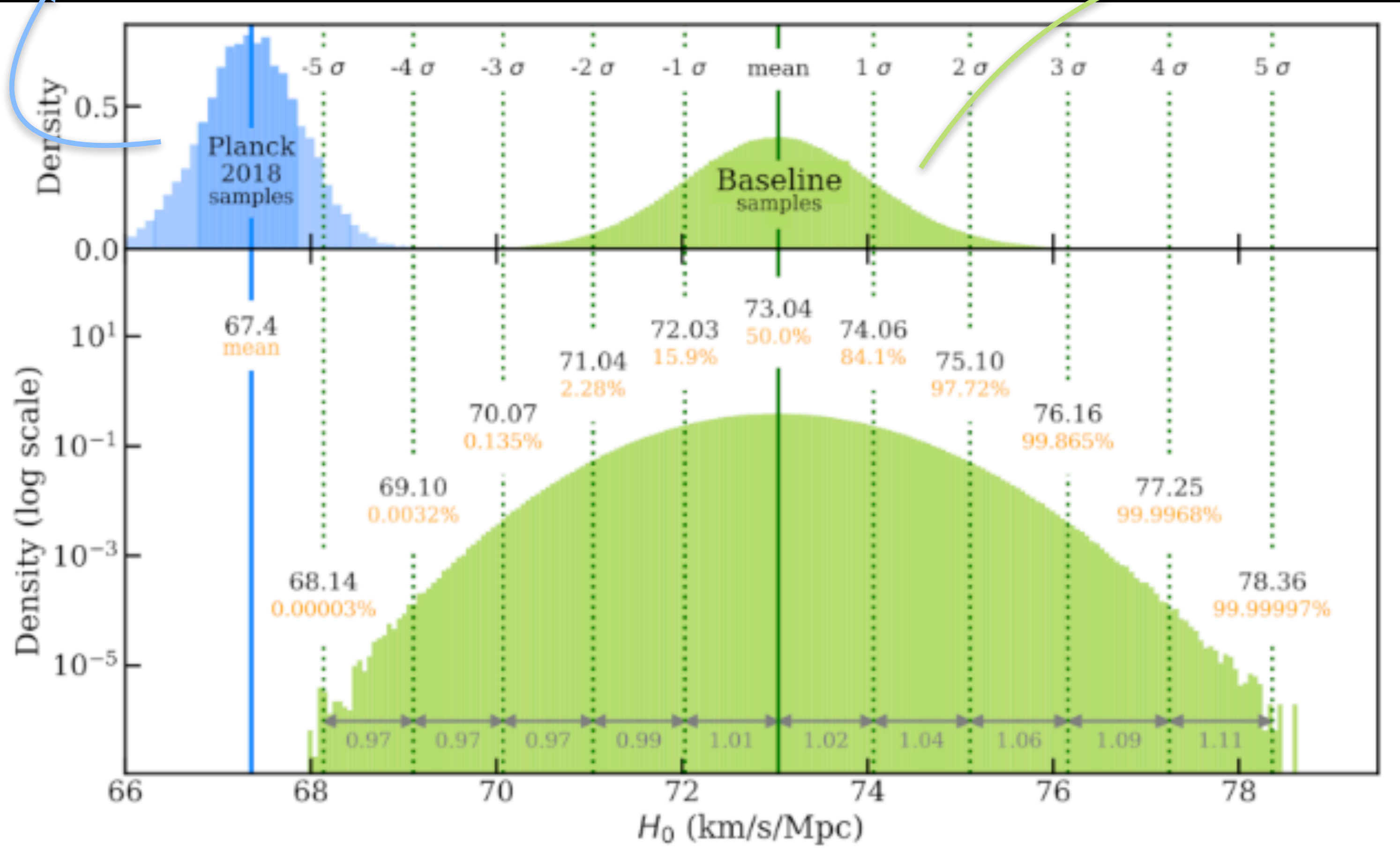
Riess et al. arXiv:2208.01045

Riess et al. ... 2.04510

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

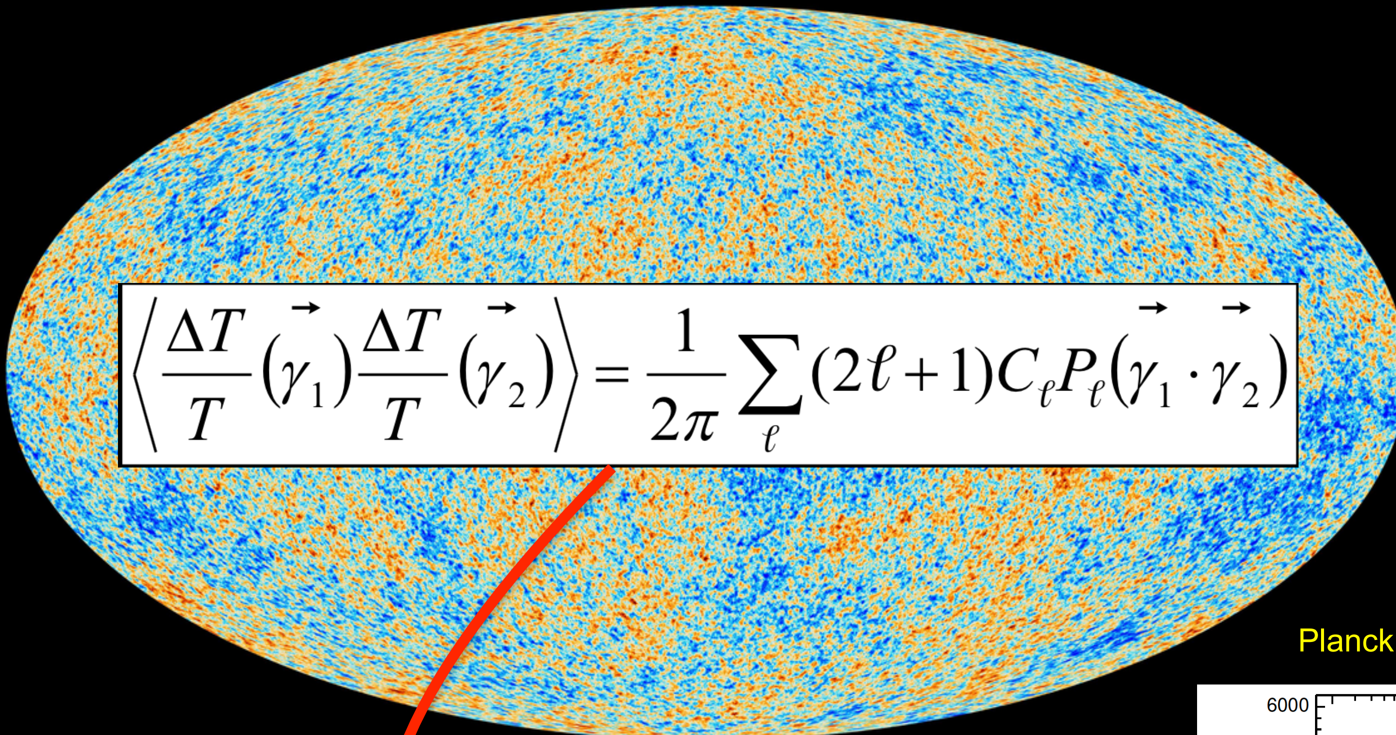


The latest local measurements obtained by the SH0ES collaboration

H0 = 73.04 ± 1.04 km/s/Mpc

Riess et al. arXiv:*2112.04510*

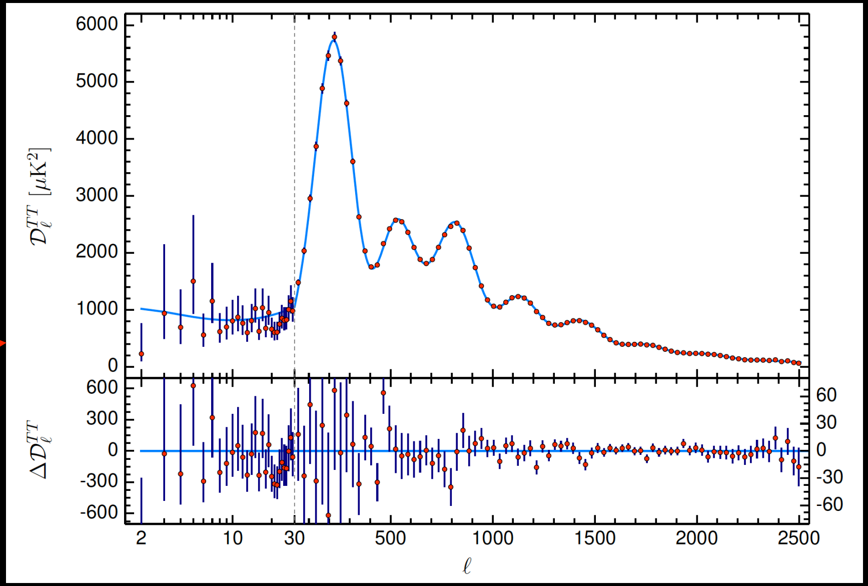
CMB constraints



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

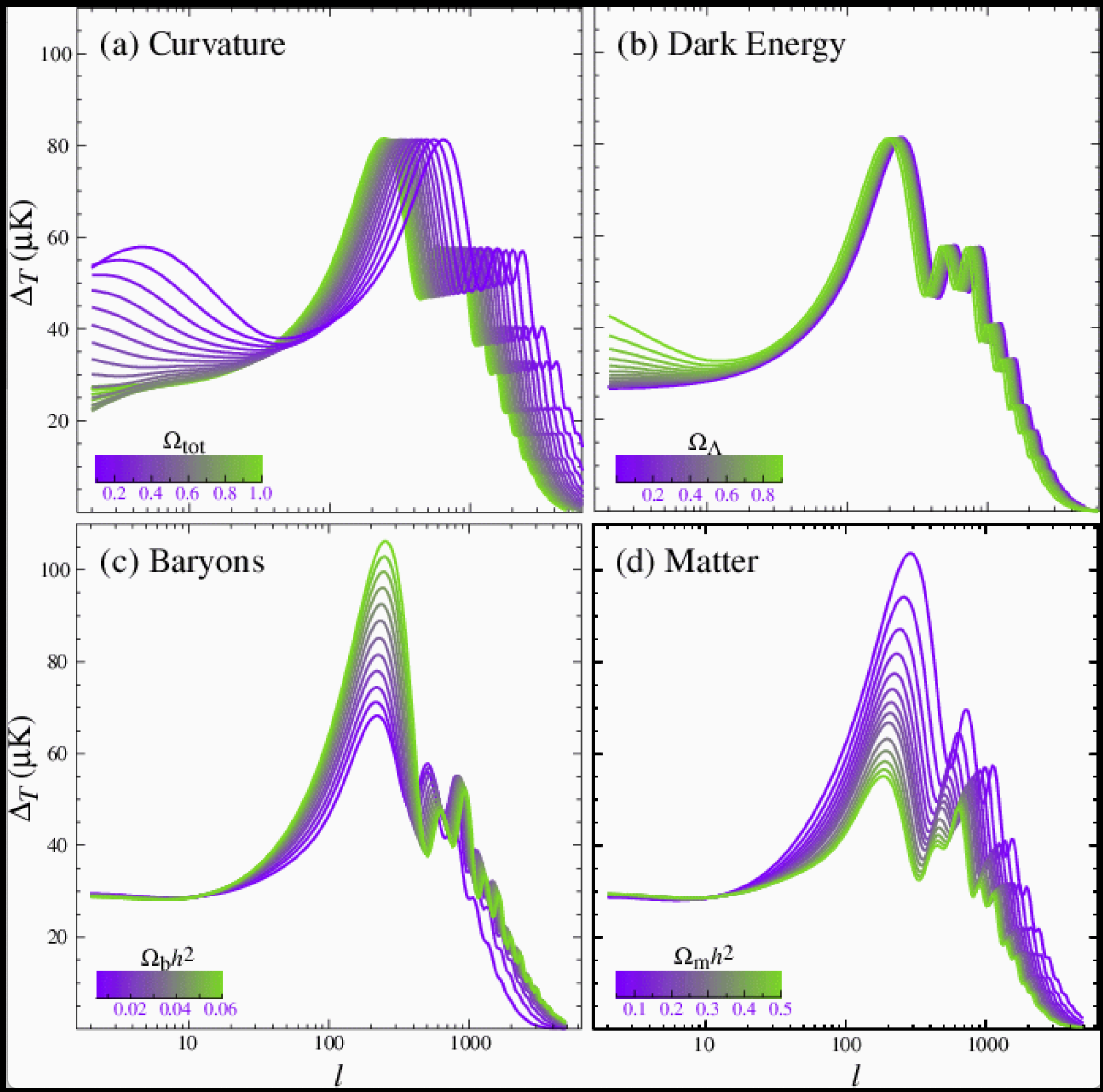
From the map of the CMB anisotropies we can extract the temperature angular power spectrum.

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



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

Wayne Hu's tutorial



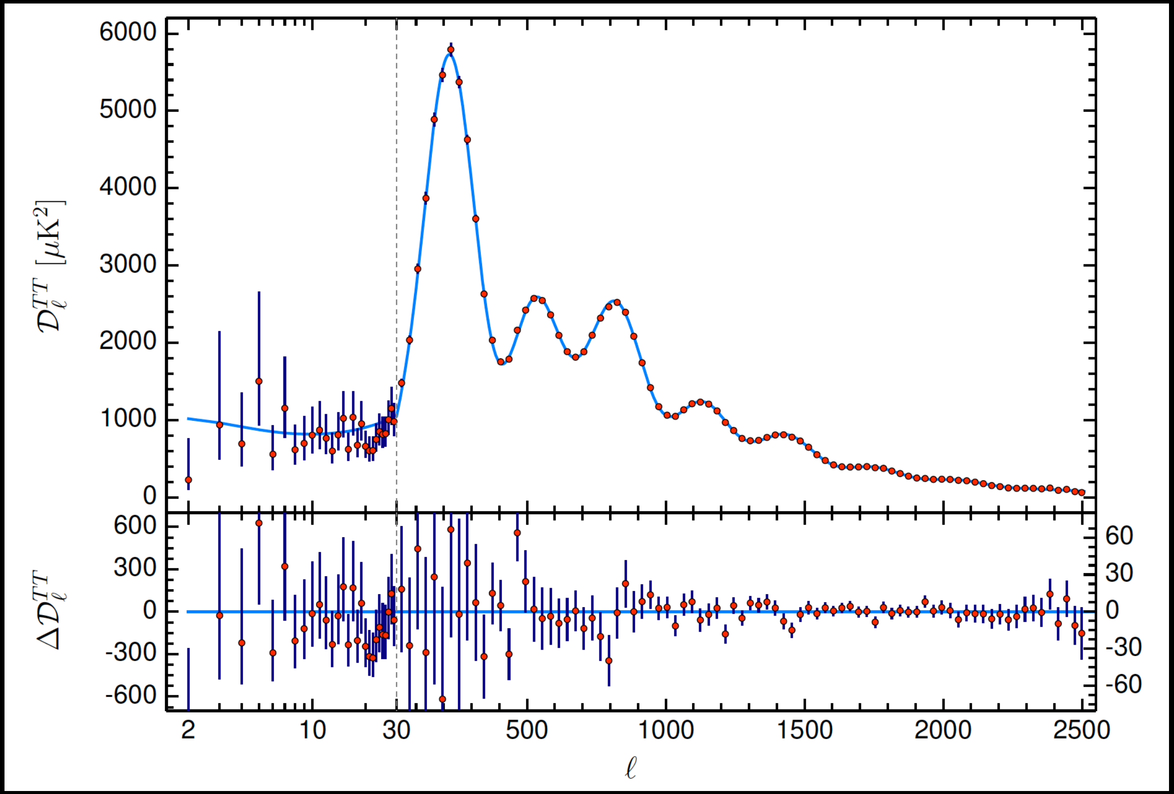
We choose a set of cosmological parameters that describes our theoretical model and compute the angular power spectra.

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

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

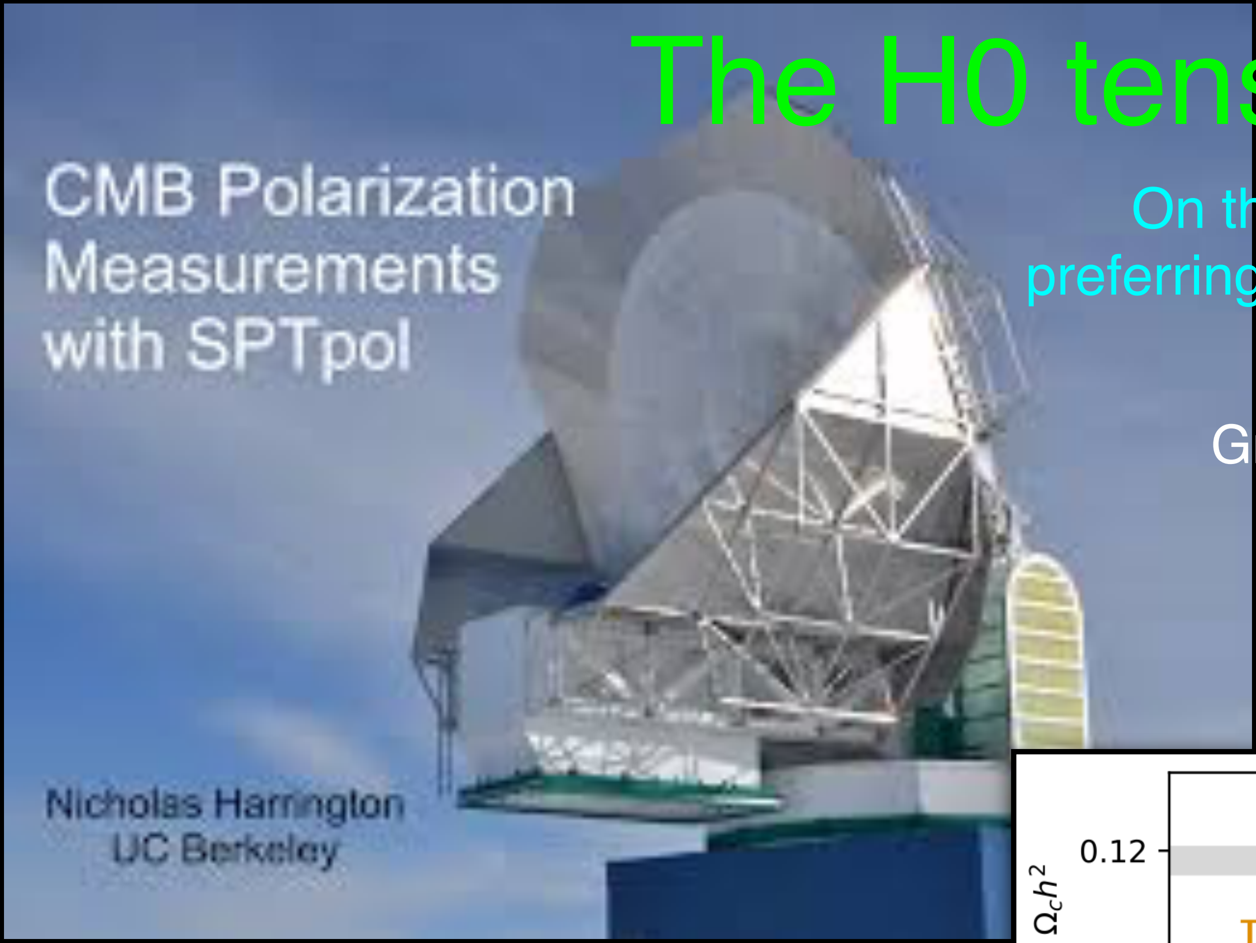
Planck 2018, Astron.Astrophys. 641 (2020) A6

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?

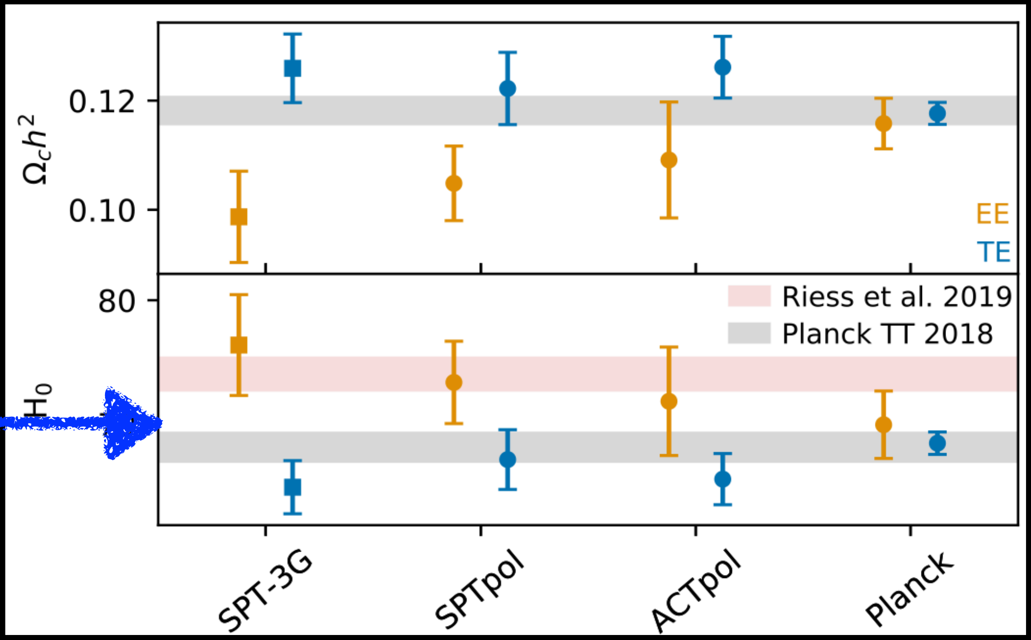
The H0 tension



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

Ground based CMB telescope

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

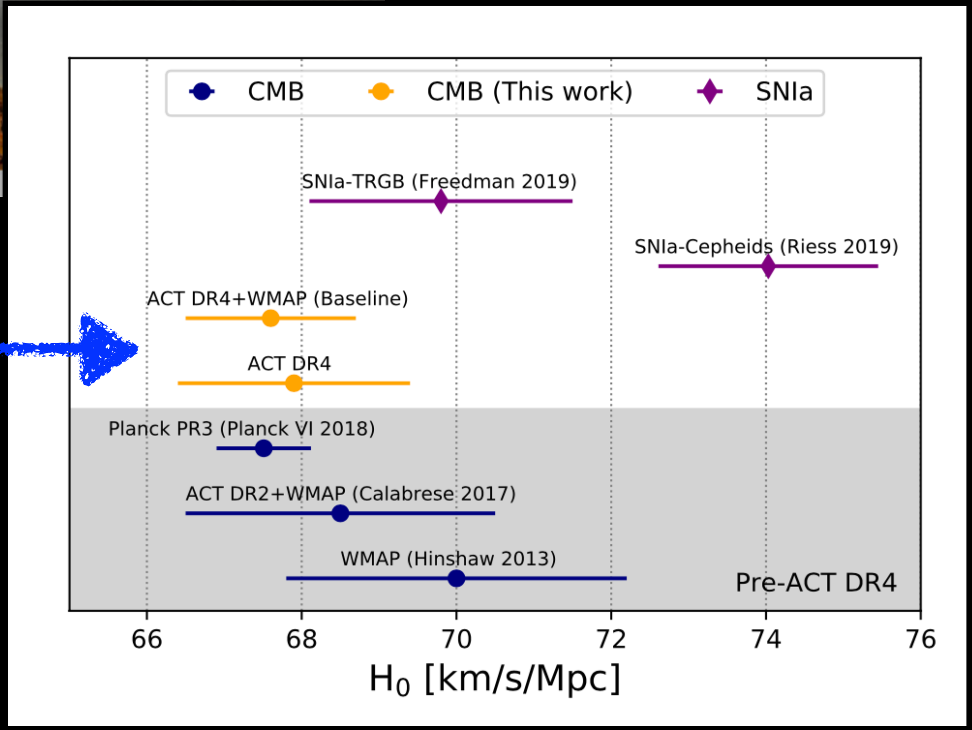
On the same side of Planck, i.e. preferring smaller values of H_0 we have:

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+$\theta_{MC, Planck}$:

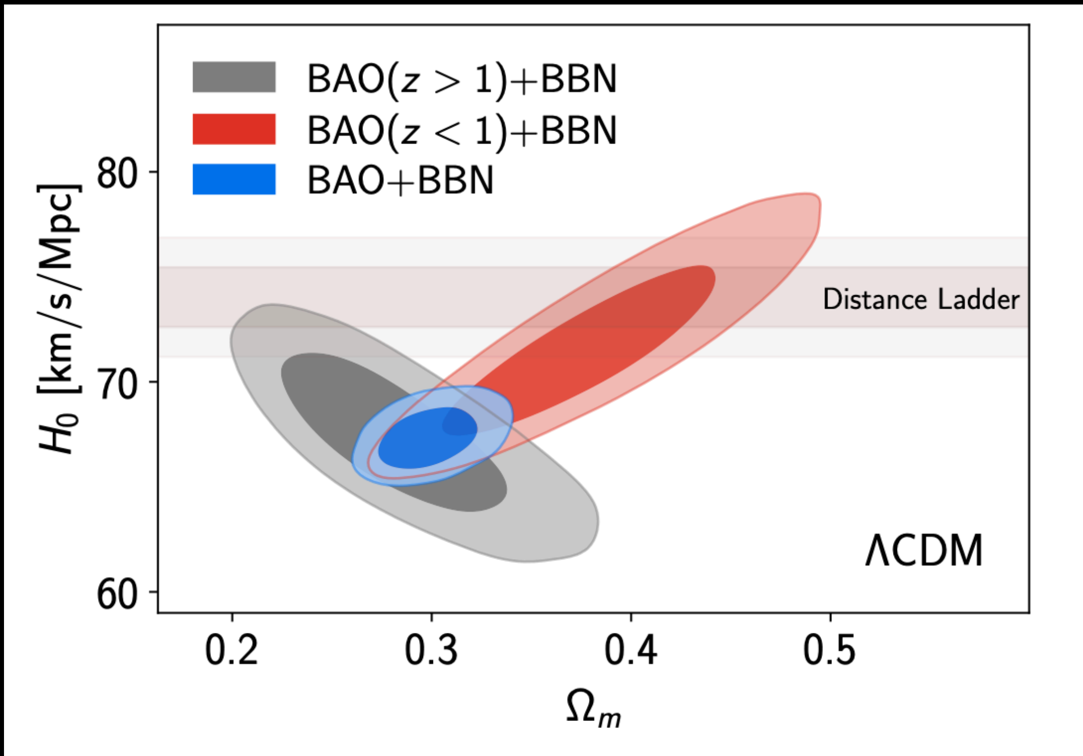
H0 = 67.9 ± 0.8 km/s/Mpc

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

BAO+BBN from BOSS and eBOSS:

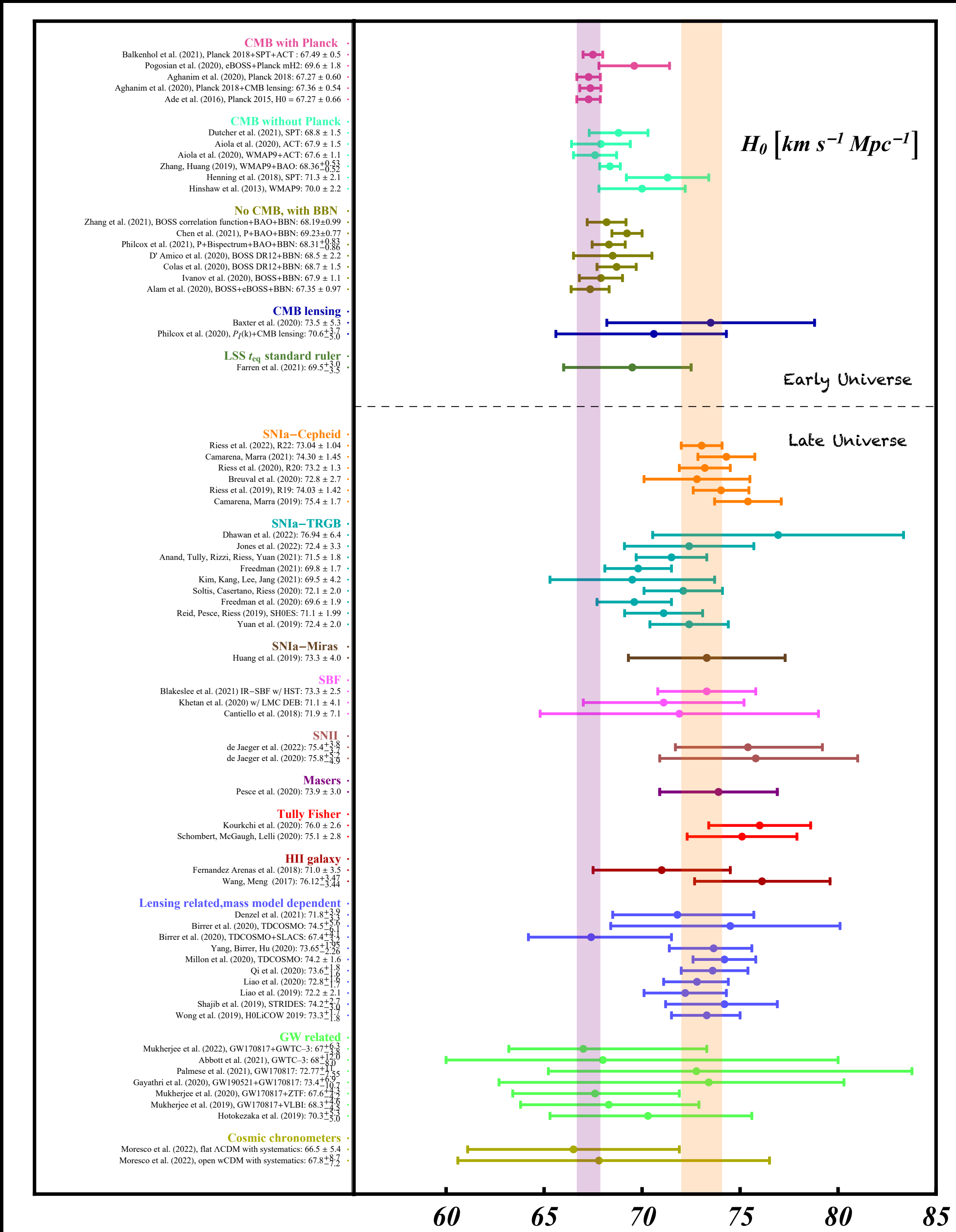
H_0 = 67.35 ± 0.97 km/s/Mpc

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



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

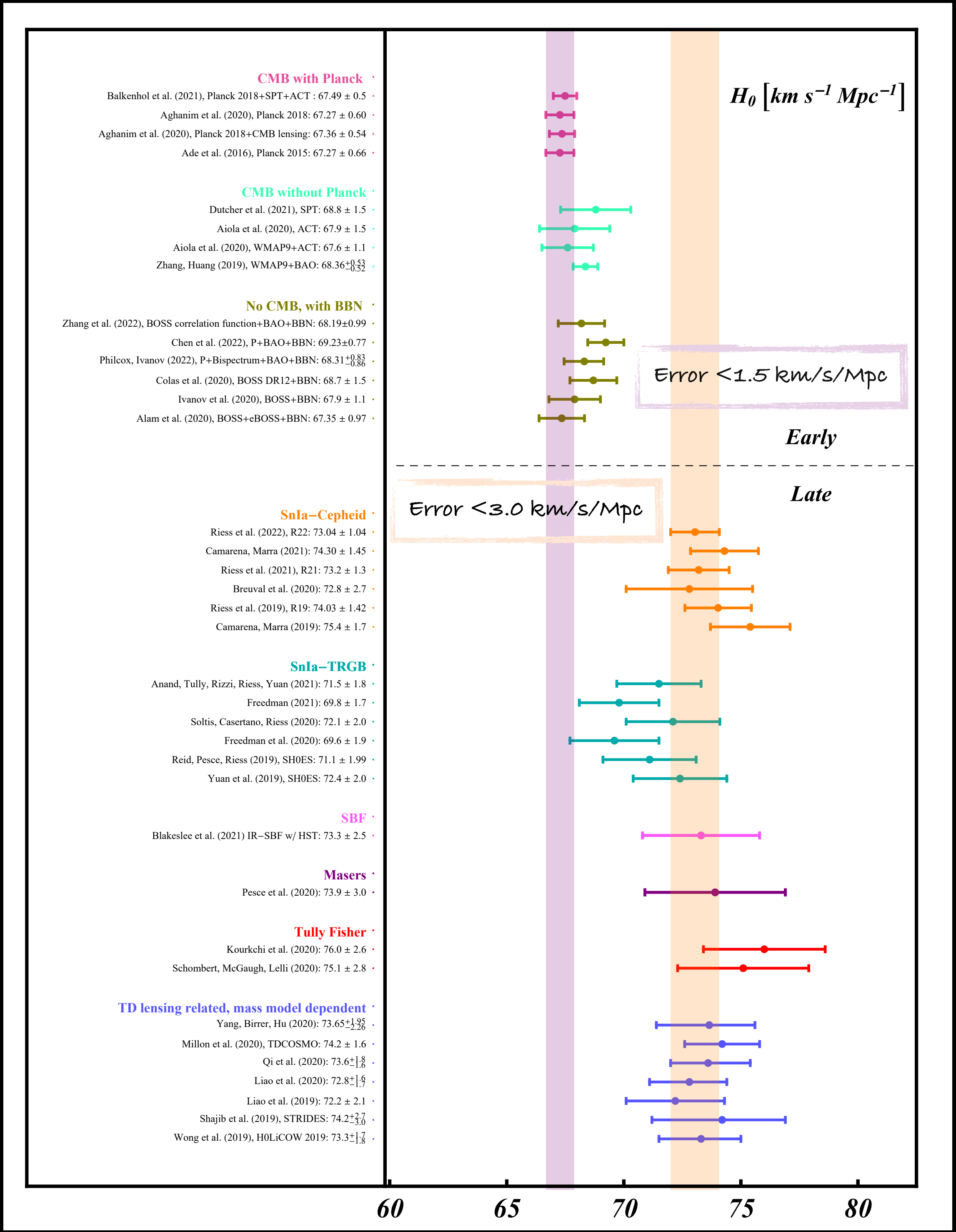
LCDM - dependent



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.

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



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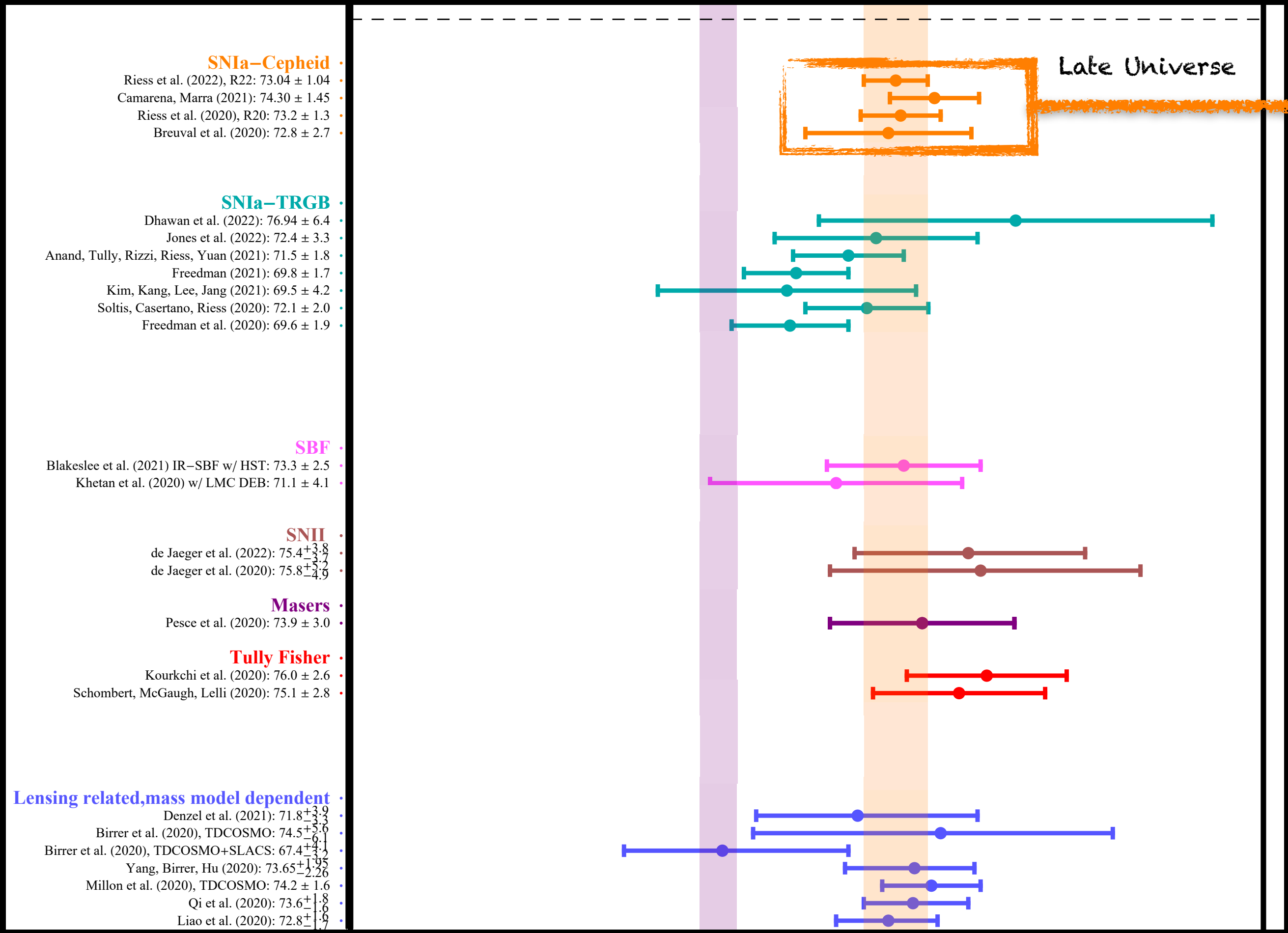
High precision measurements of H0

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



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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

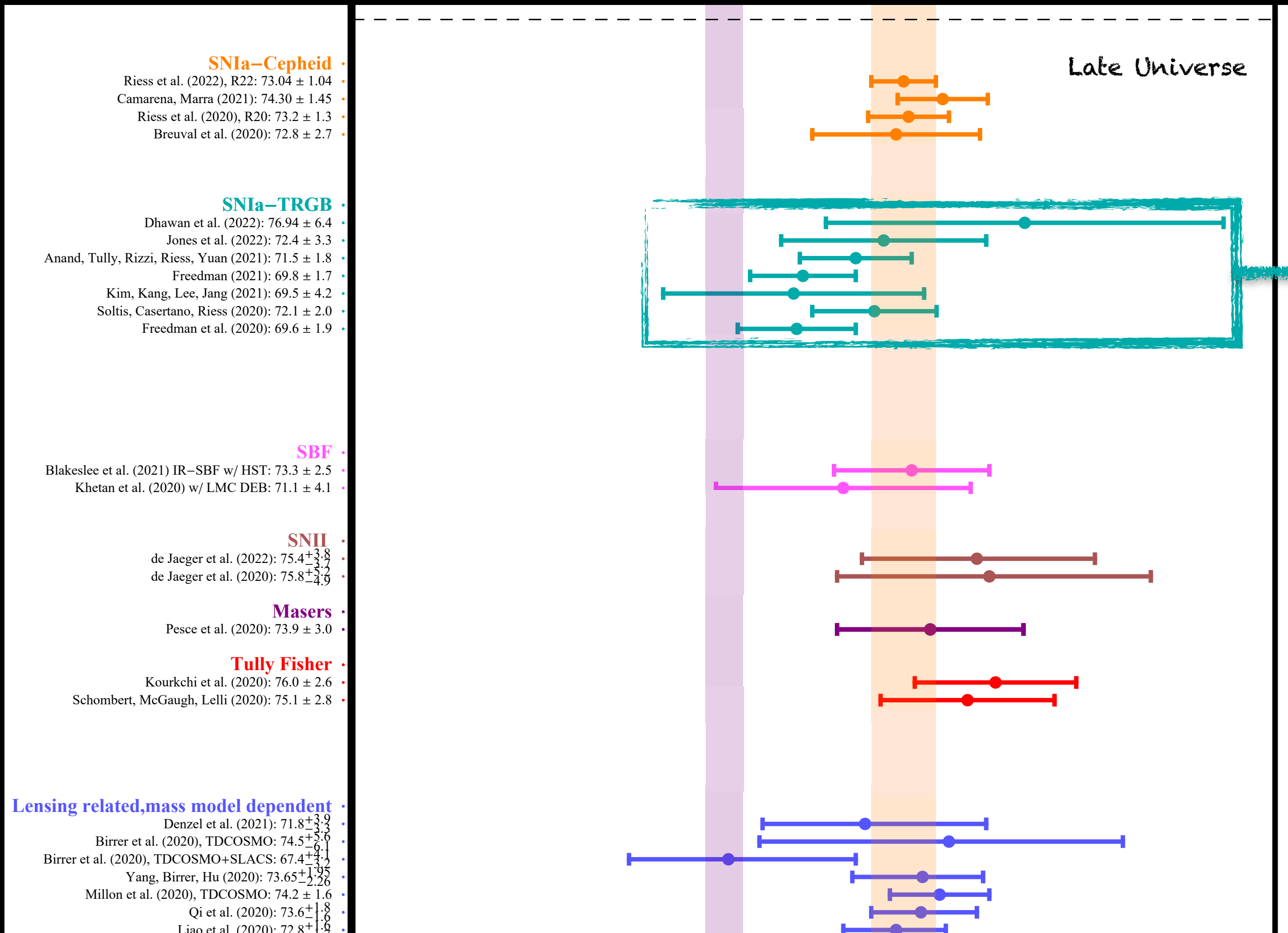
H0 = 73.2 ± 1.3 km/s/Mpc

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



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

H_0 = 76.9±6.4 km/s/Mpc

Dhawan et al., arXiv:2203.04241

H_0 = 72.4±3.3 km/s/Mpc

Jones et al., arXiv:2201.07801

H_0 = 71.5±1.8 km/s/Mpc

Anand et al., arXiv:2108.00007

H_0 = 69.8±1.7 km/s/Mpc

Freedman, arXiv:2106.15656

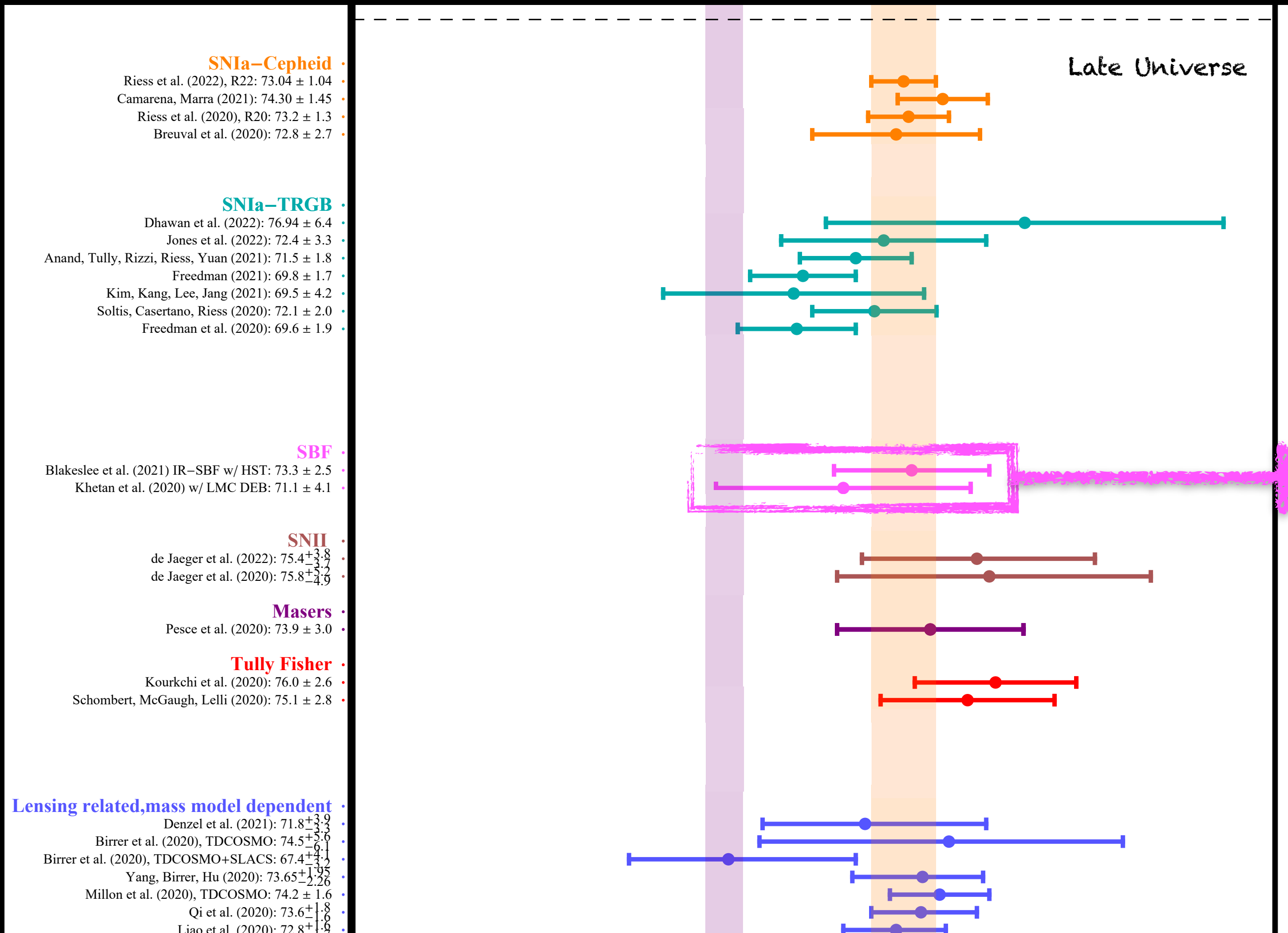
H_0 = 72.1±2.0 km/s/Mpc

Soltis et al., arXiv:2012.09196

H_0 = 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

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

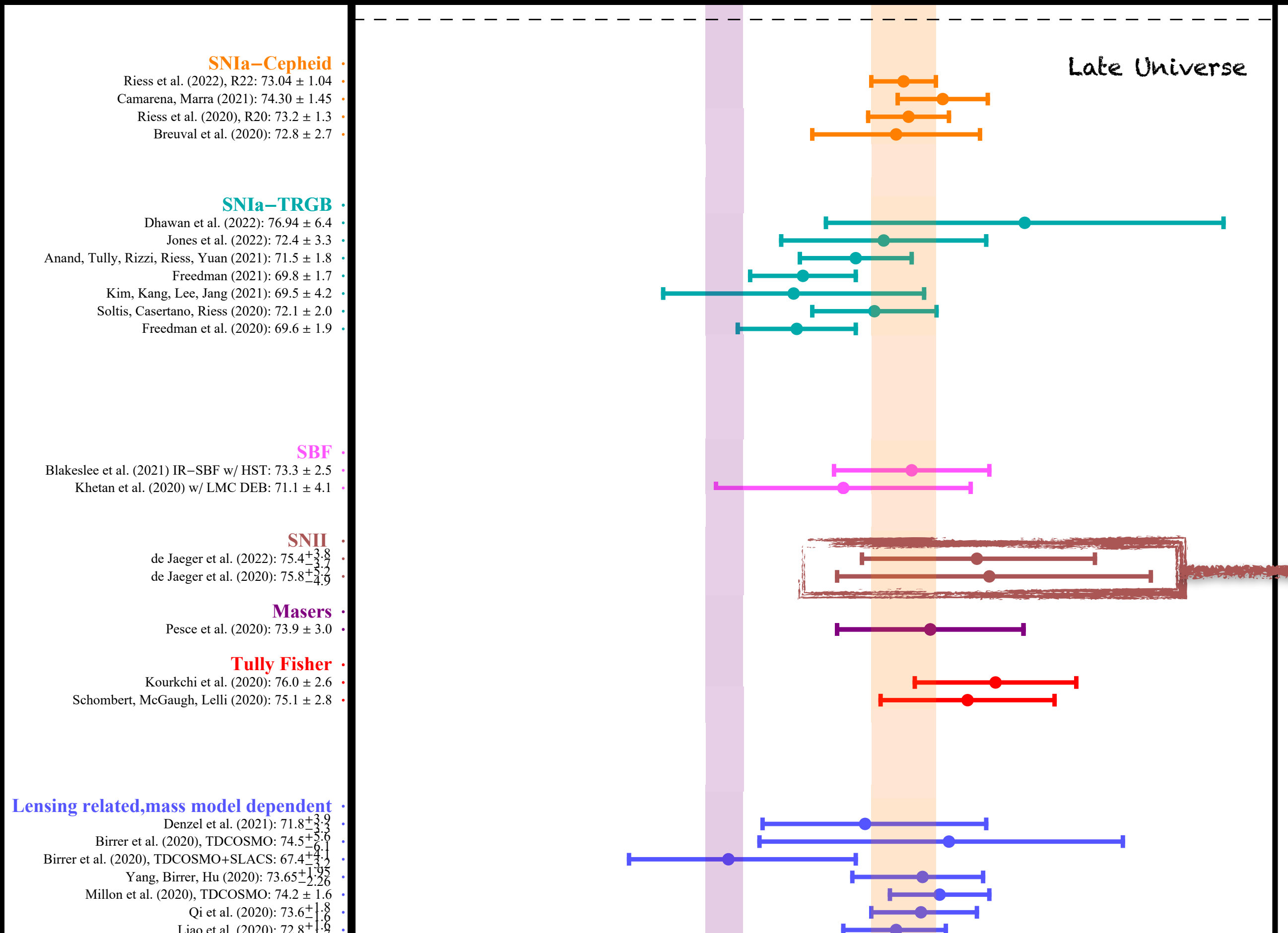
H0 = 73.3 ± 2.5 km/s/Mpc

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

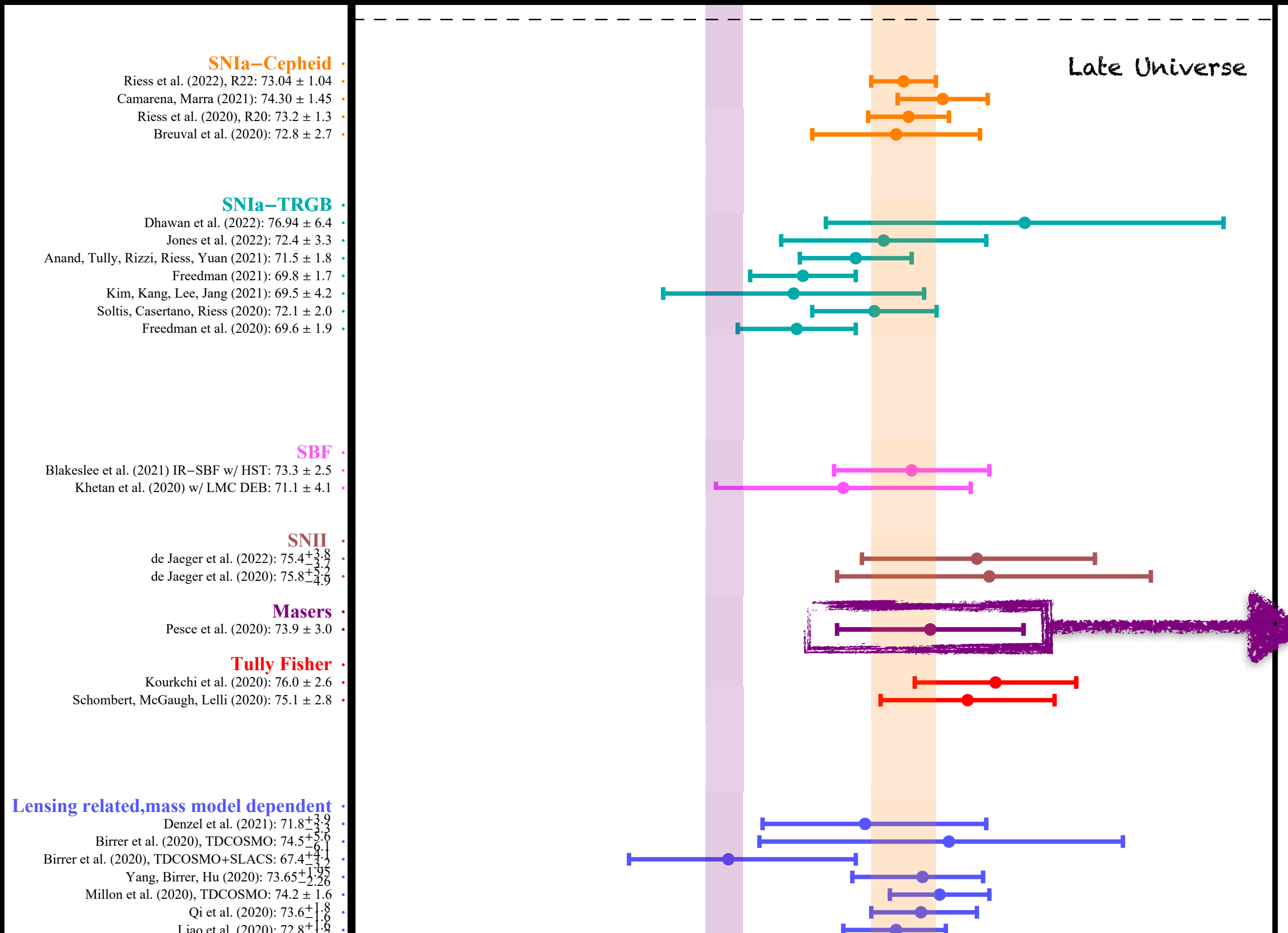
$H0 = 75.4^{+3.8}_{-3.7}$ km/s/Mpc

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



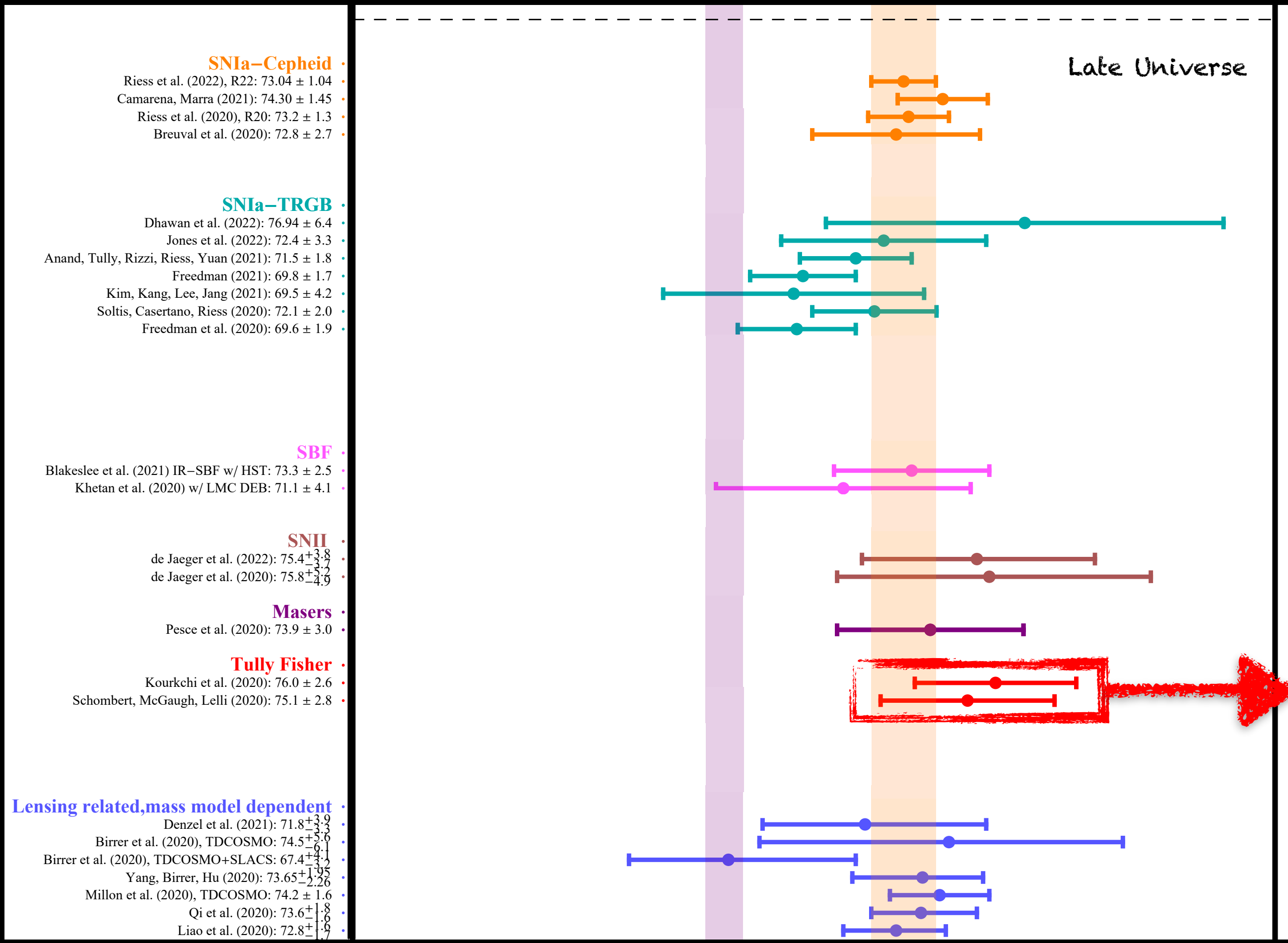
Abdalla et al., *JHEAp* 34 (2022) 49-211

H0 = 73.9 ± 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

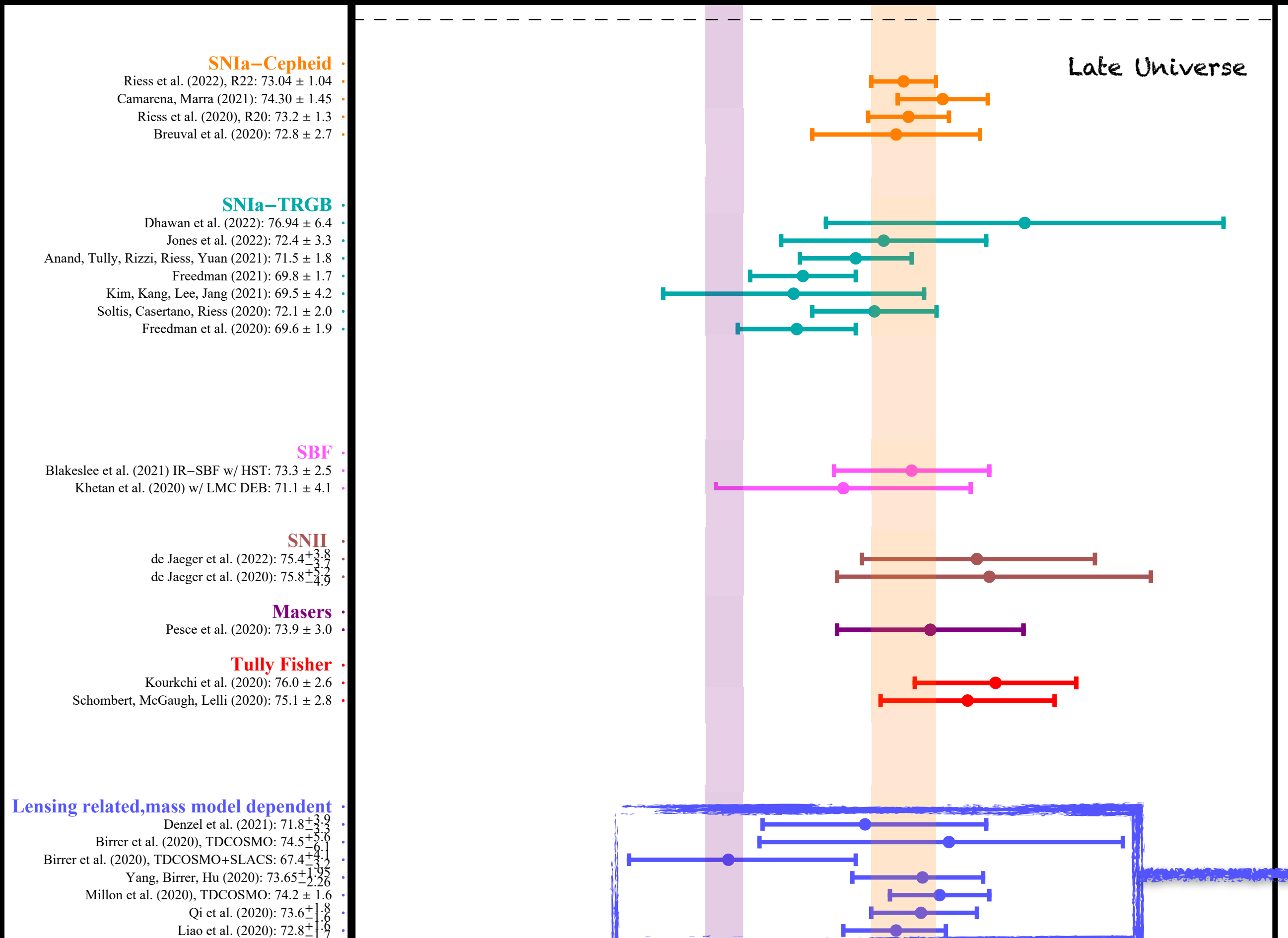
Kourkchi et al. arXiv:2004.14499

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

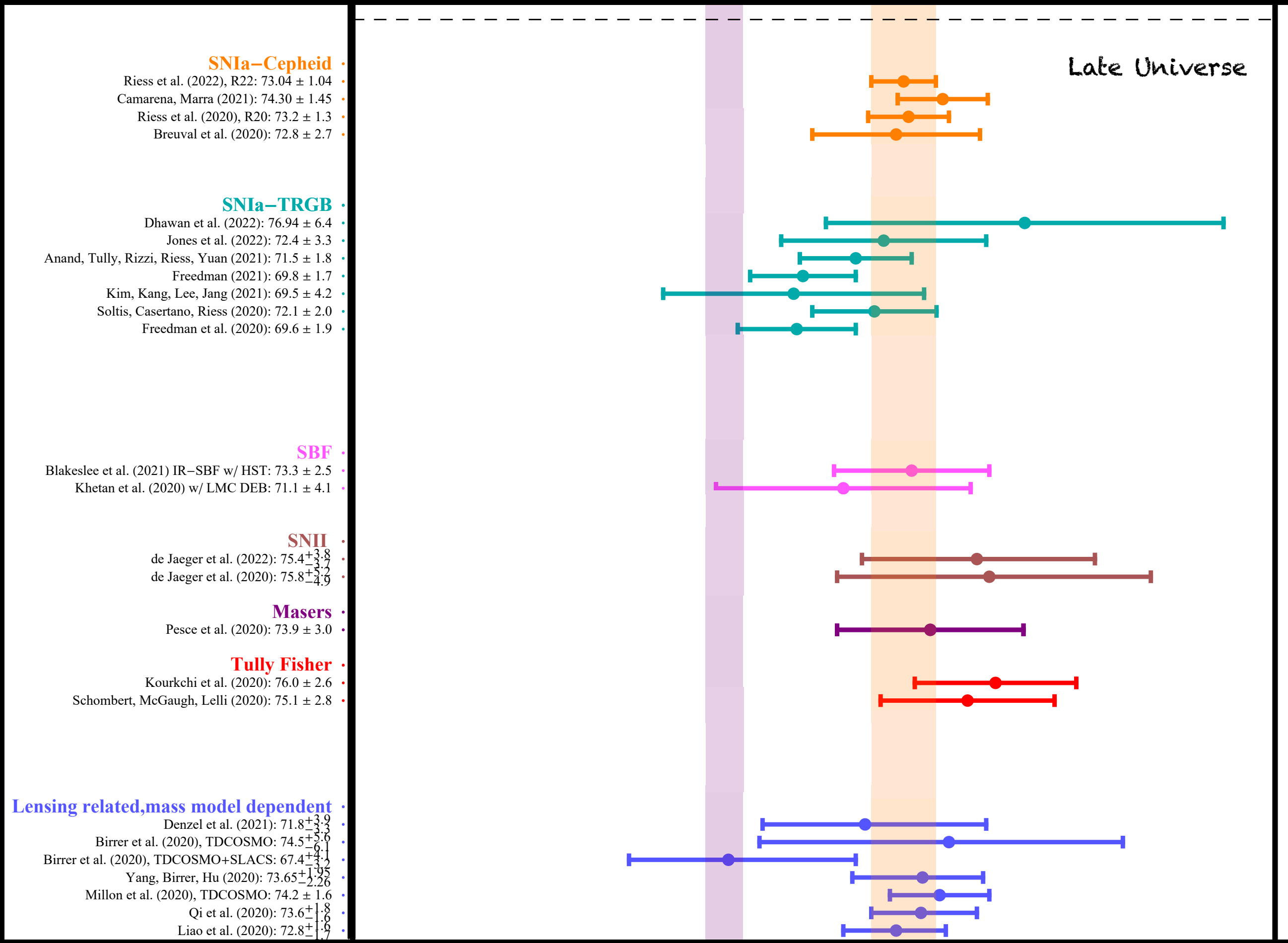
$H0 = 71.8^{+3.9}_{-3.3}$ km/s/Mpc

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

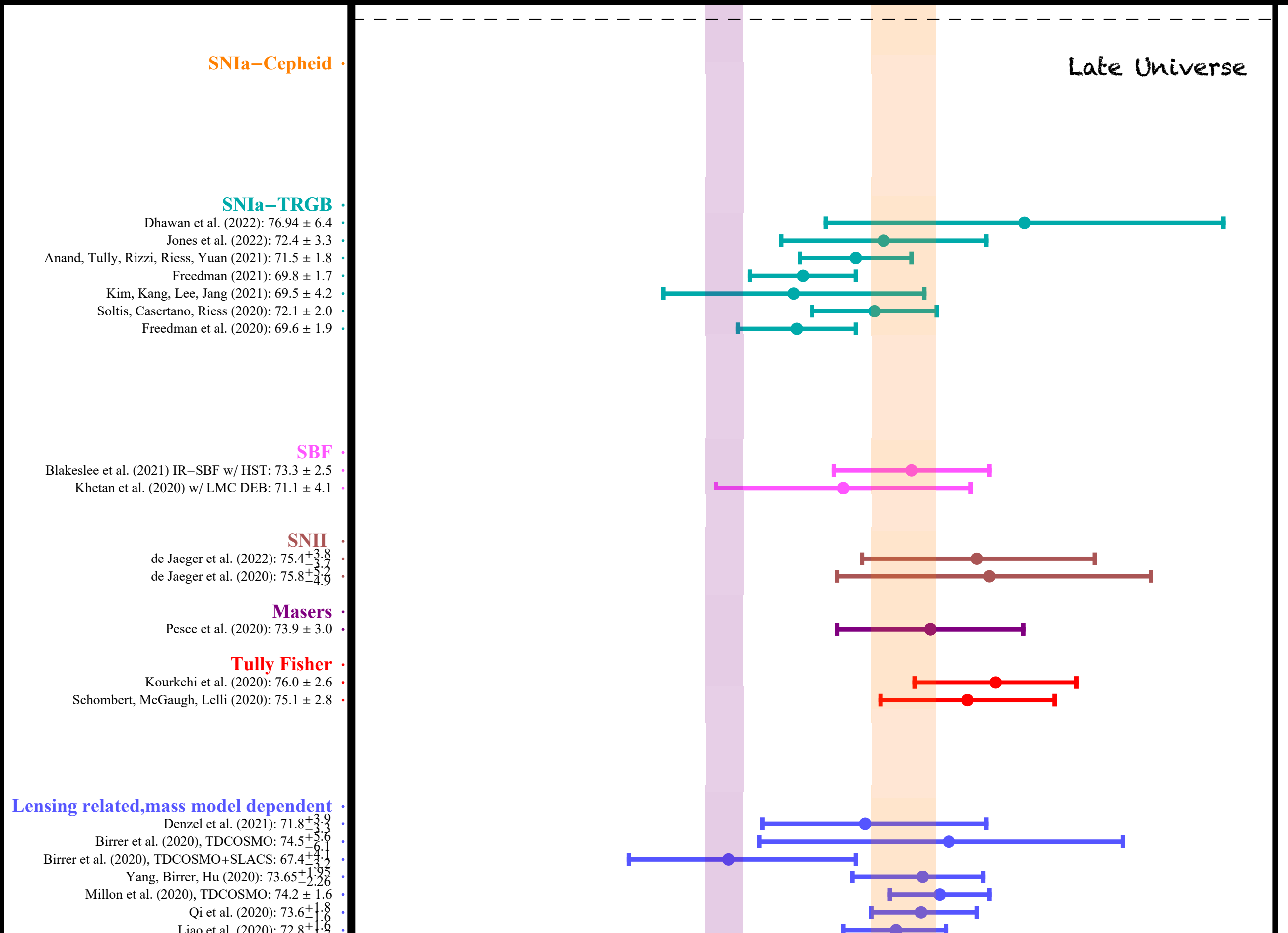
Following the method used in Di Valentino, *MNRAS* 502 (2021) 2, 2065-2073 we can combine all of them together and have

6.55σ tension with Planck

$H0 = 72.97 \pm 0.63$ km/s/Mpc

Di Valentino, Universe 2022, 8(8), 399

Late universe measurements since 2020



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

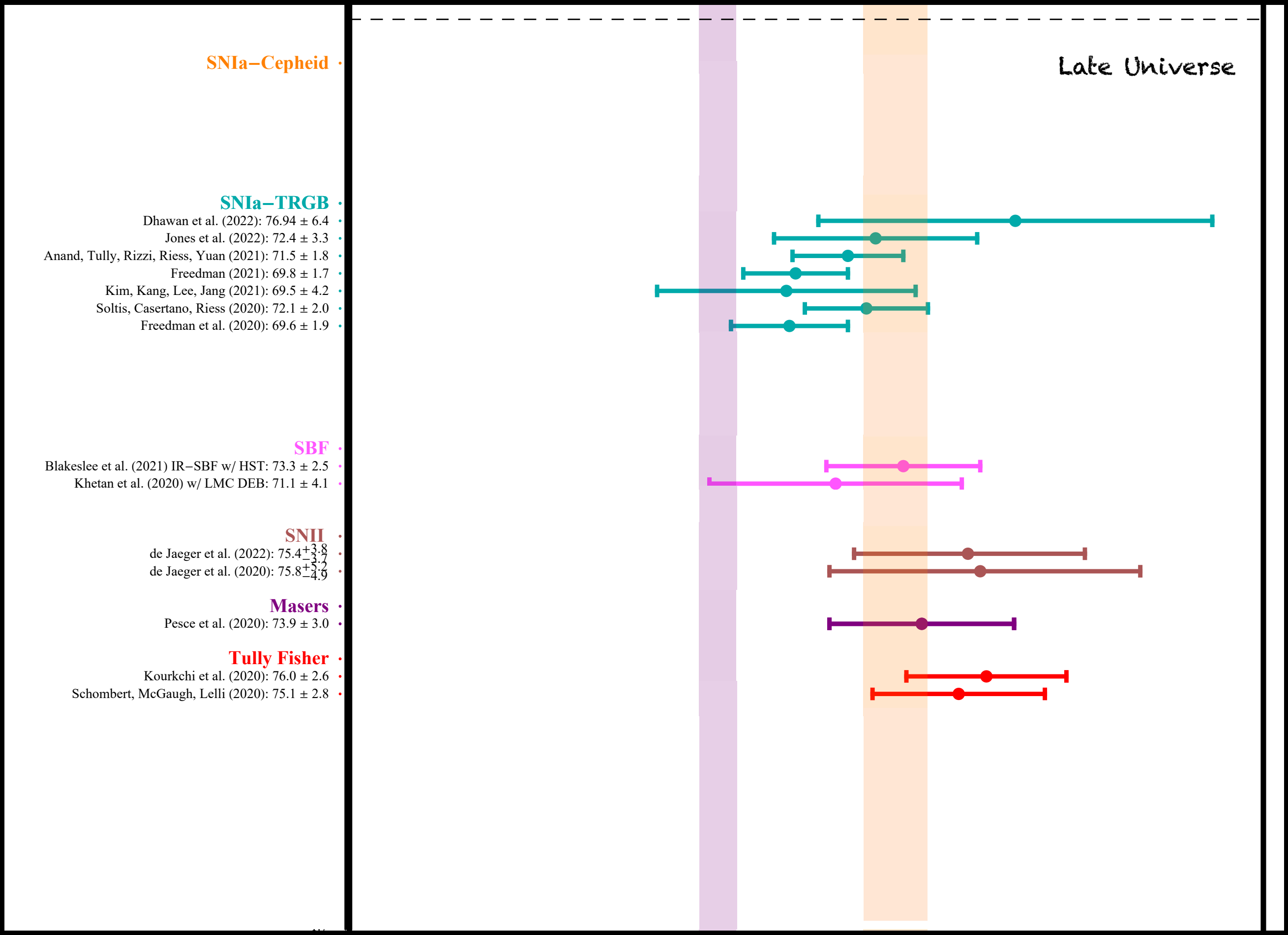
Following the method used in Di Valentino, *MNRAS* 502 (2021) 2, 2065-2073 excluding one group of data and taking the result with the largest error bar, i.e. excluding the most precise measurements based on Cepheids-SN Ia, we obtain a

conservative estimate (5.5σ tension with Planck)

$H0 = 72.73 \pm 0.80$ km/s/Mpc

Di Valentino, Universe 2022, 8(8), 399

Late universe measurements since 2020



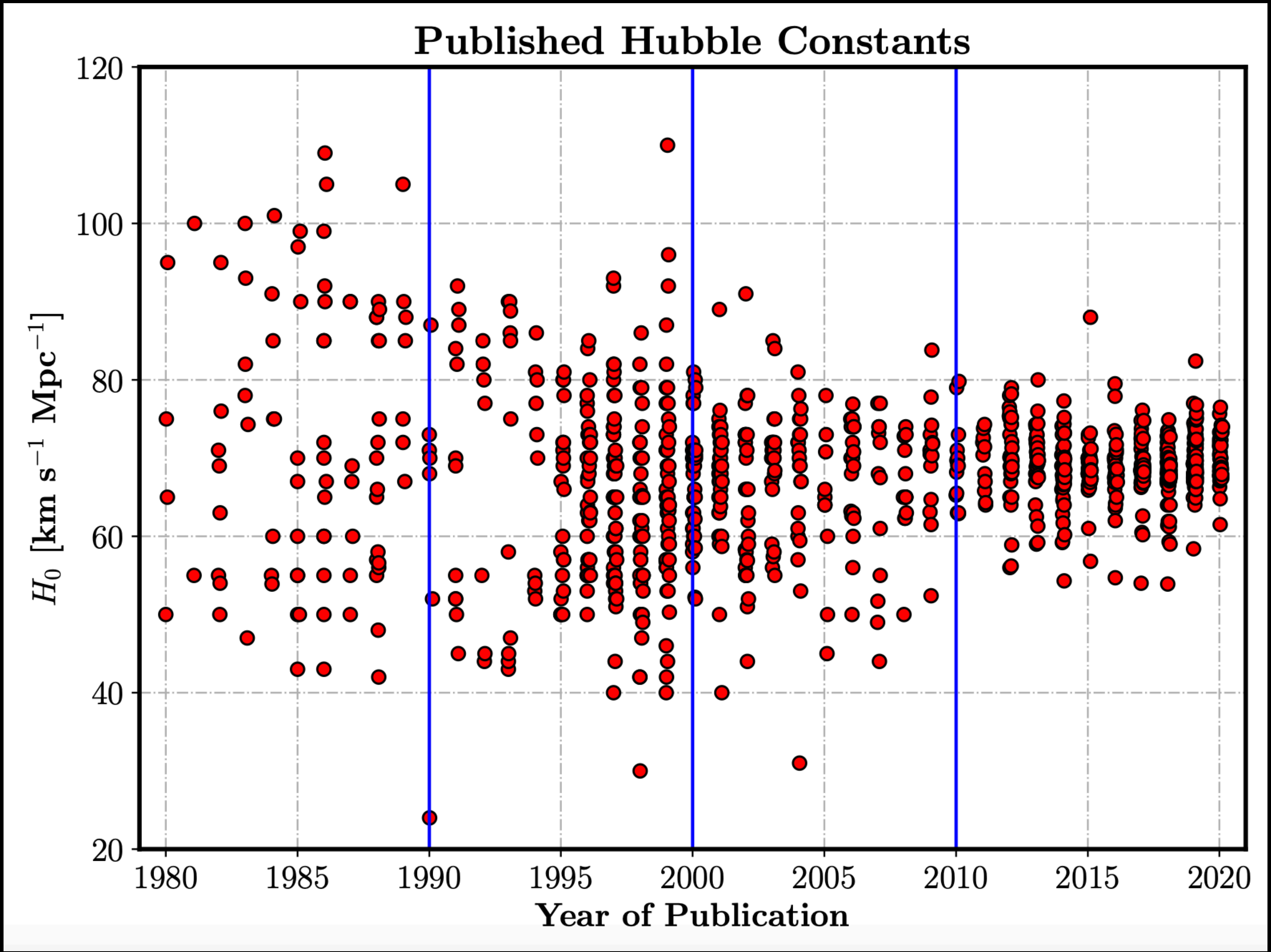
Following the method used in Di Valentino, *MNRAS* 502 (2021) 2, 2065-2073 excluding two groups of data and taking the result with the largest error bar, i.e. excluding the most precise measurements based on Cepheids-SN Ia and Time-delay Lensing, we obtain an

ultra-conservative estimate (4.8σ tension with Planck)

$H0 = 73.3 \pm 1.1$ km/s/Mpc

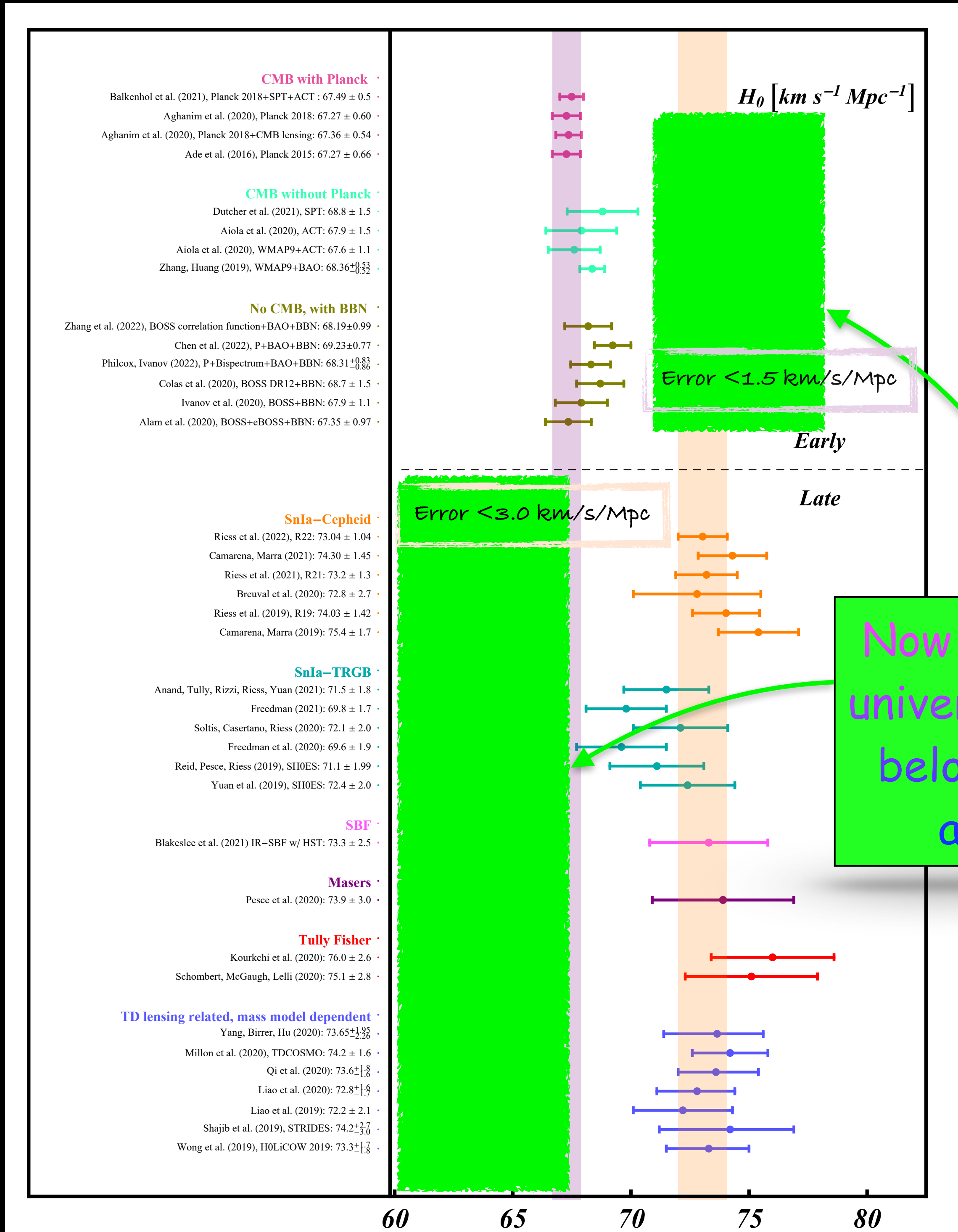
Di Valentino, Universe 2022, 8(8), 399

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



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 early universe (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.

Let’s modify the ΛCDM model…

The Neutrino effective number

We can consider modifications in the
dark matter sector.

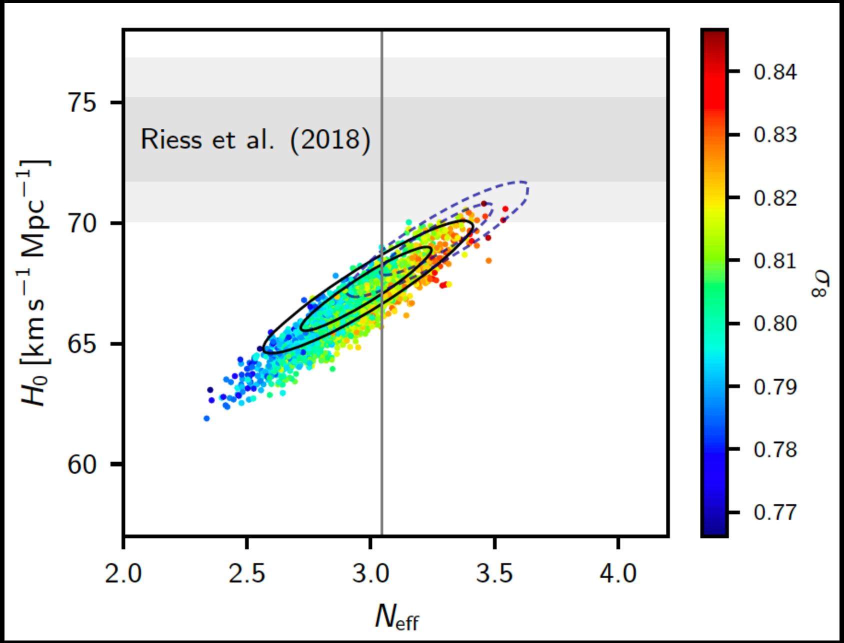
A classical extension is the
effective number of relativistic degrees of freedom,
i.e. additional relativistic matter at recombination,
corresponding to a modification of the expansion history
of the universe at early times.

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 vary Neff at 68% cl H0 passes is equal to 66.4 ± 1.4 km/s/Mpc, and the tension with SH0ES increases from 1.7σ to 3.9σ also varying Neff.

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



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:

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

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

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

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 m^2, 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

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

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 m^2, 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

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

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

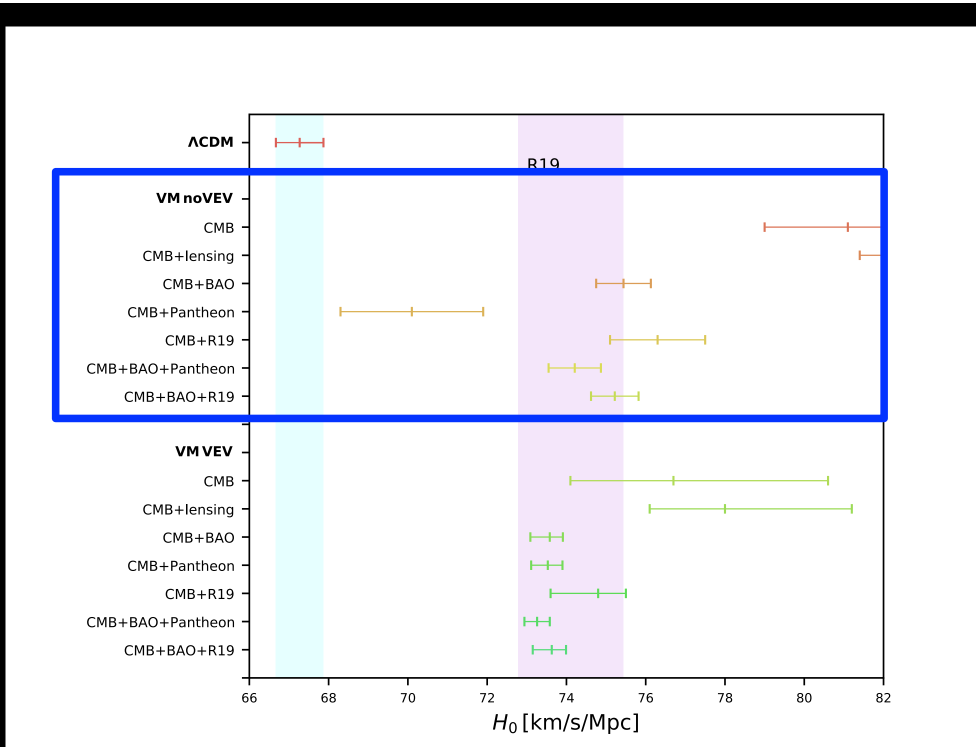
$$\Omega_m = \frac{4}{3}\left[3M(1-M-\Omega_k-\Omega_r)^3\right]^{1/4}$$

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.

Parker Vacuum Metamorphosis

Constraints at 68% cl.

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	$+95.83$	$+11.29$



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

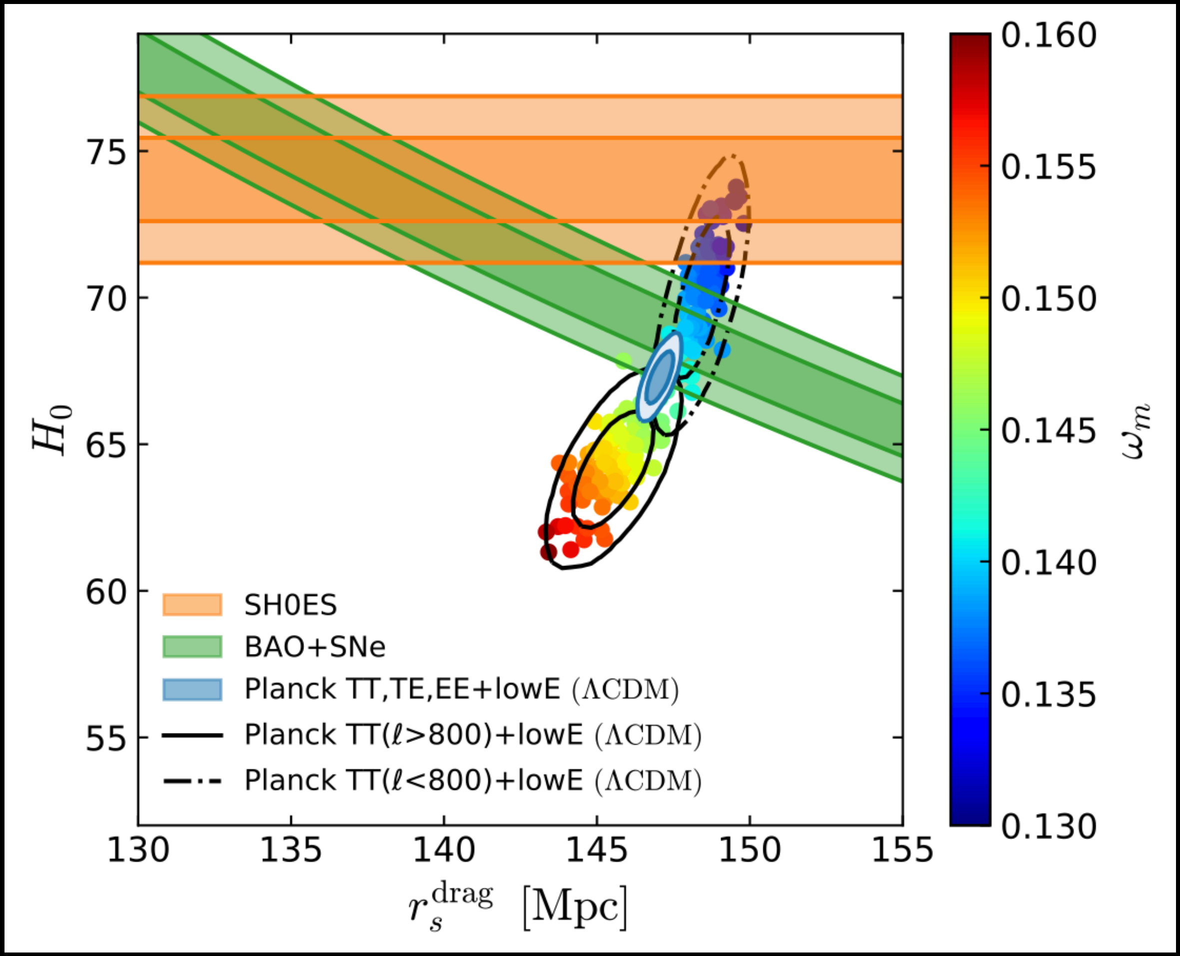
H0 is exactly in agreement with SH0ES even if BAO and Pantheon are included. However, this worsen considerably the fit of the data because the model fails in recover the shape of H(z) at low redshifts.

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.

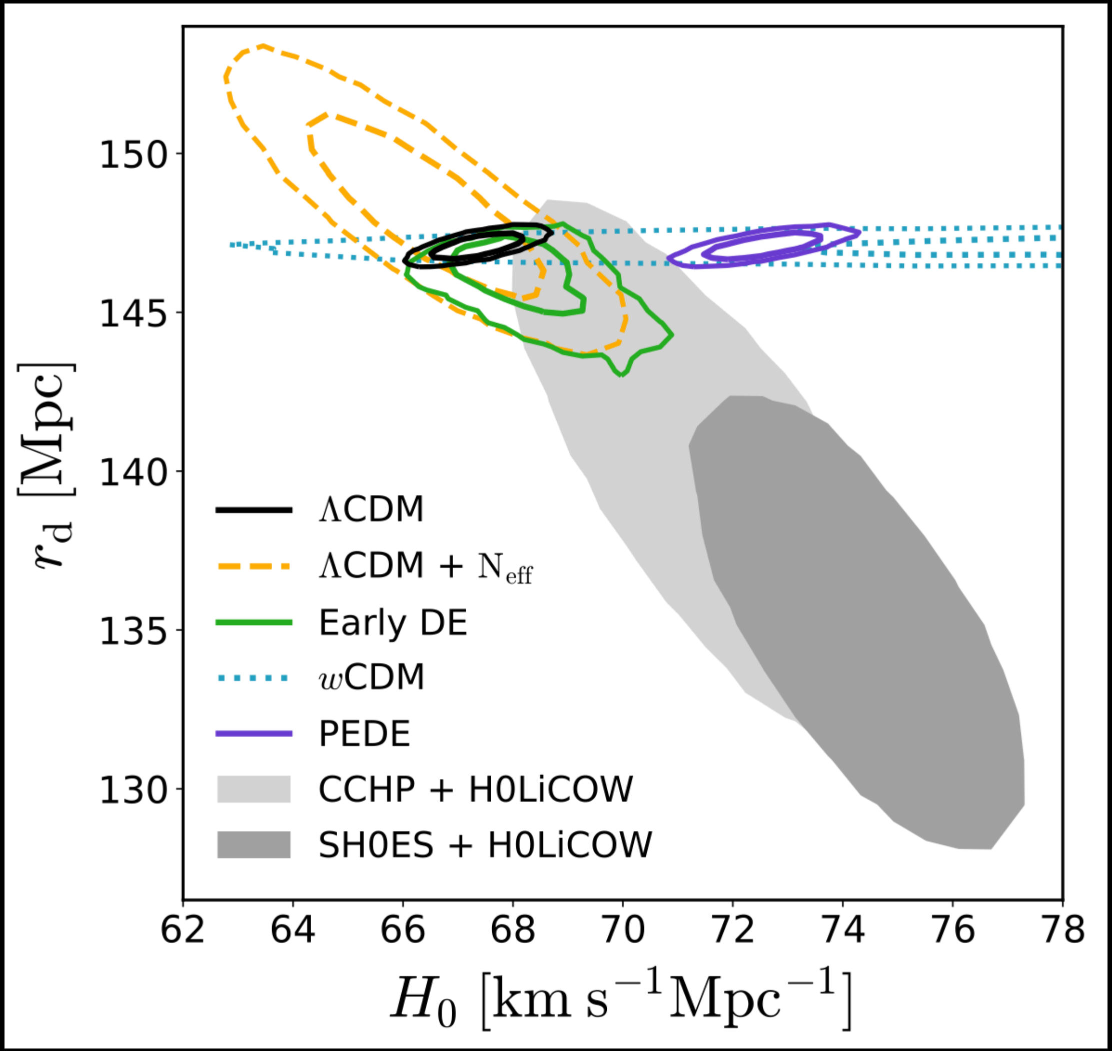


Knox and Millea, *Phys.Rev.D* 101 (2020) 4, 043533

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.

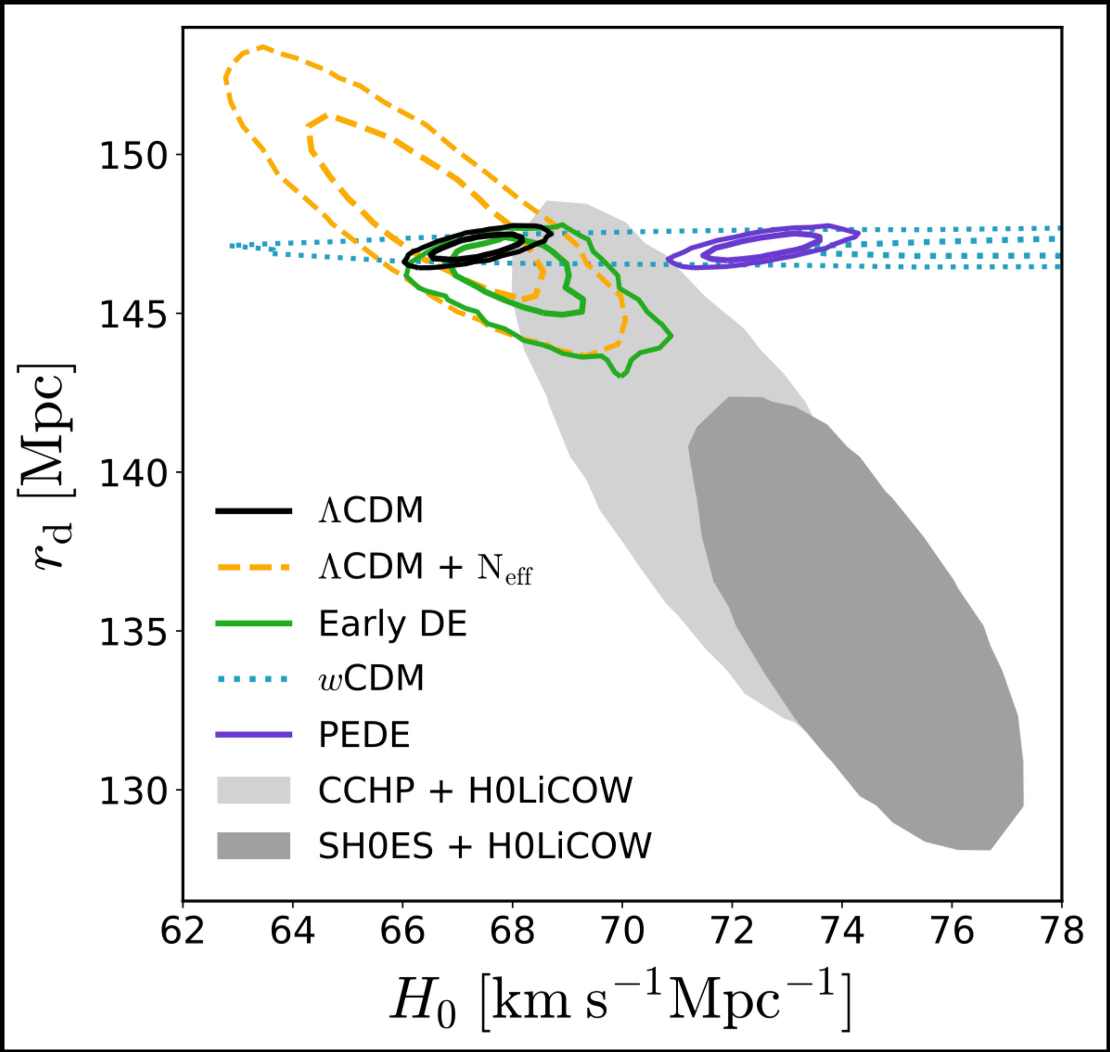


Arendse et al., Astron.Astrophys. 639 (2020) A57

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

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]
ΛCDM [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 3 … *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 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 $\Omega_m h^2$.

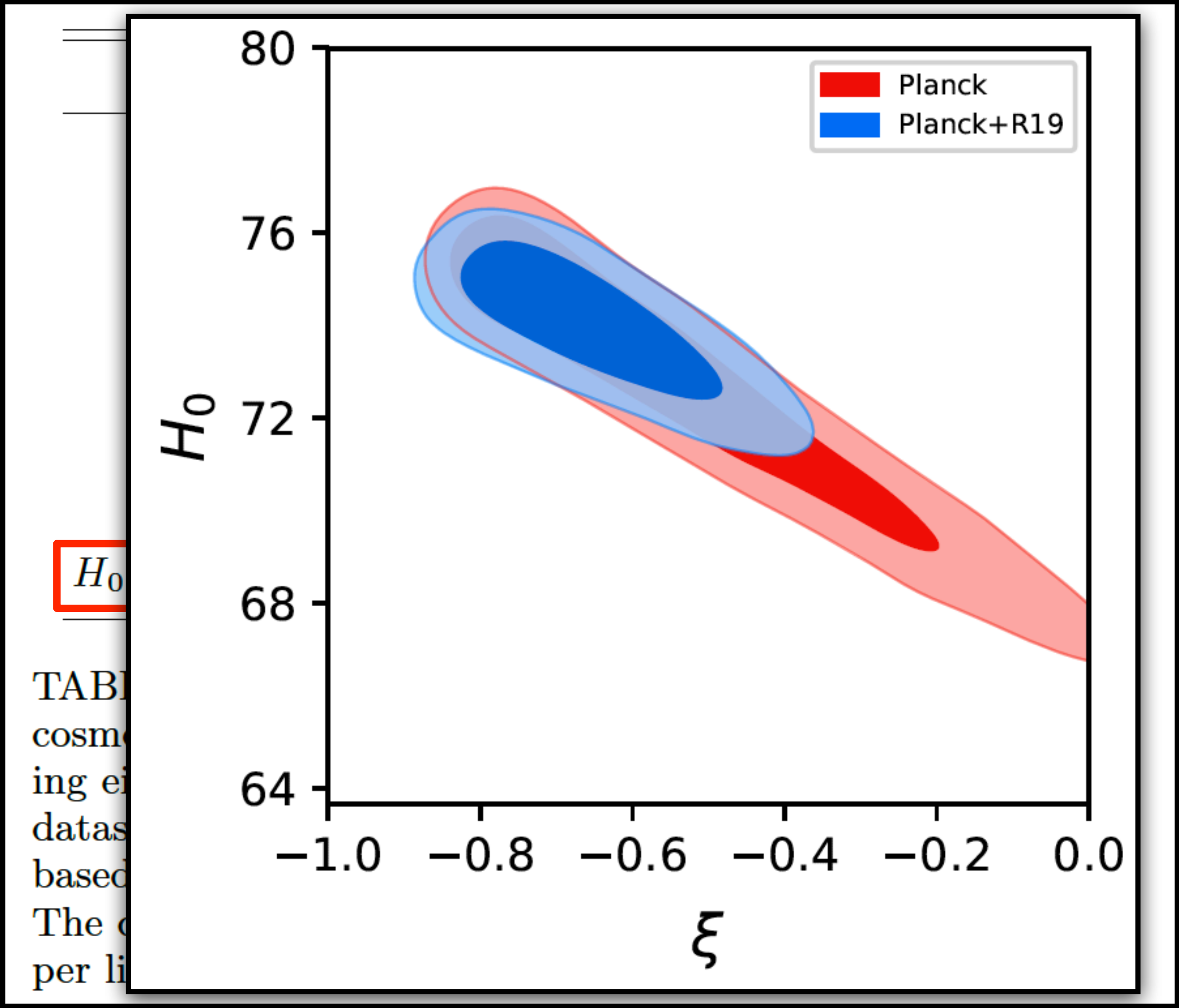
Parameter	*Planck*	*Planck+R19*
$\Omega_b h^2$	0.02239 ± 0.00015	0.02239 ± 0.00015
$\Omega_c h^2$	< 0.105	< 0.0615
n_s	0.9655 ± 0.0043	0.9656 ± 0.0044
$100\theta_s$	$1.0458^{+0.0033}_{-0.0021}$	1.0470 ± 0.0015
τ	0.0541 ± 0.0076	0.0534 ± 0.0080
ξ	$-0.54^{+0.12}_{-0.28}$	$-0.66^{+0.09}_{-0.13}$
H_0 [km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

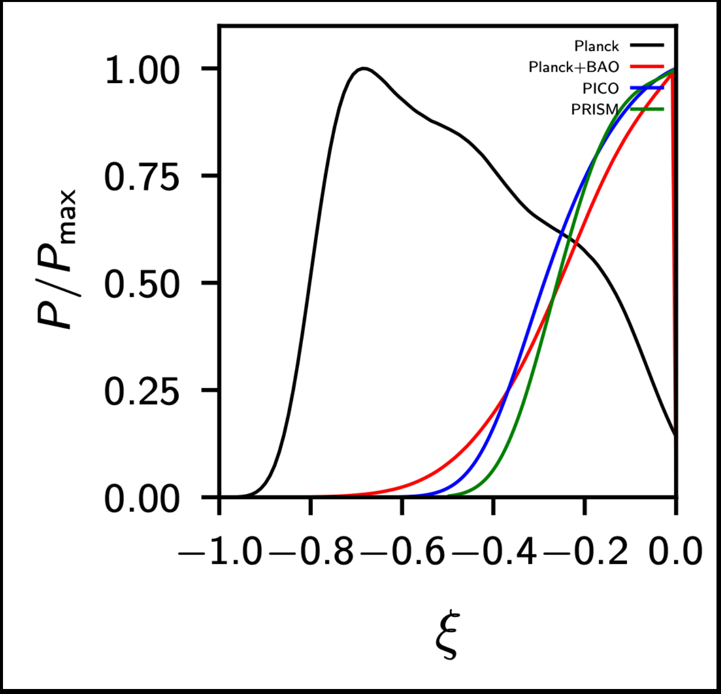
fake IDE detection

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 simulated 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 $\xi = 0$:

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



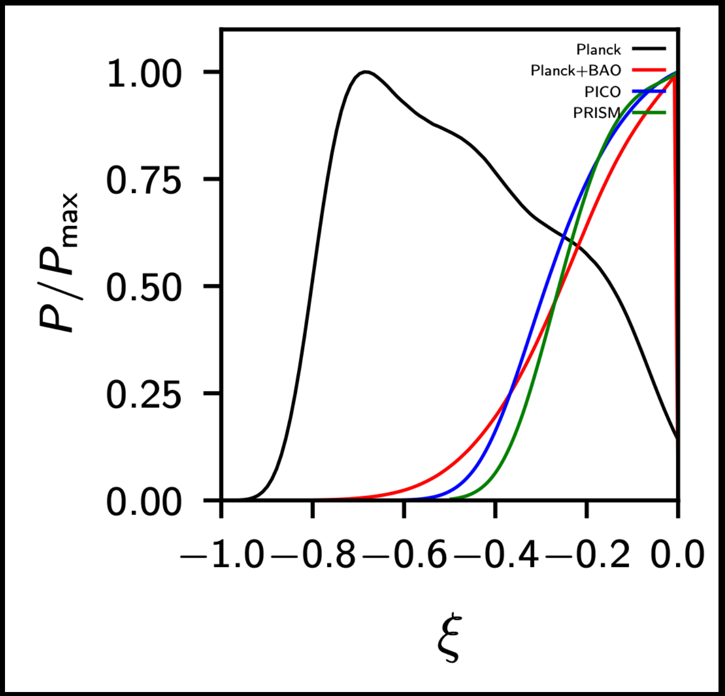
Simulated experiments

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 simulated 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.



Simulated experiments

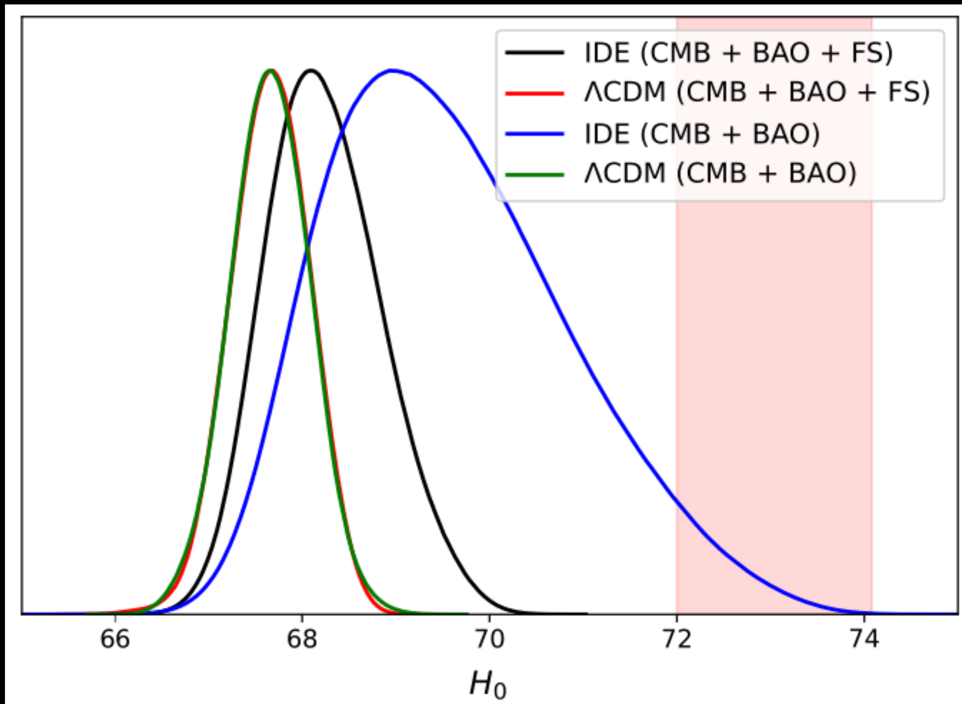
IDE can solve the H0 tension

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



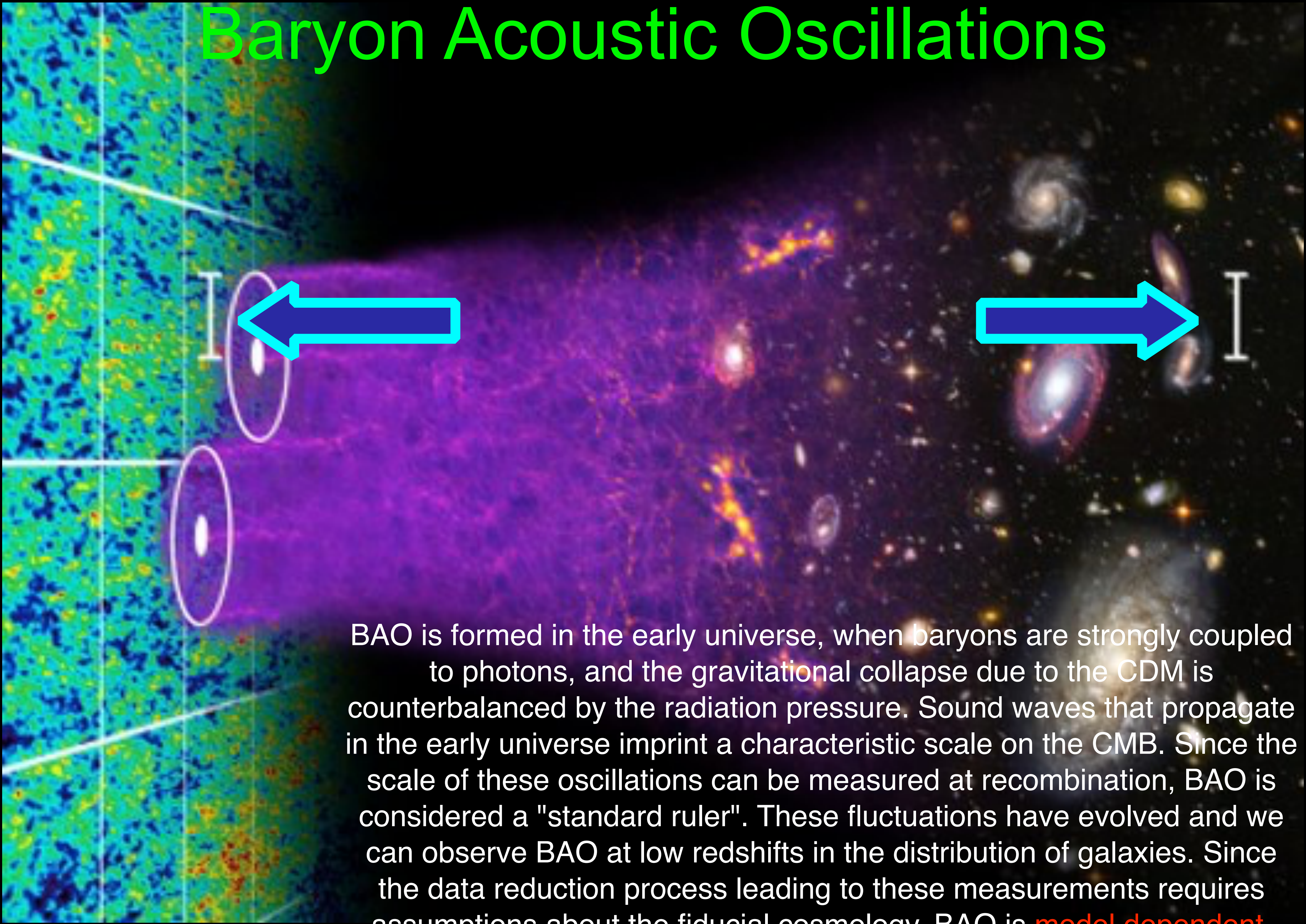
	CMB+FS	CMB+BAO+FS
	$0.101^{+0.015}_{-0.009}$	$0.115^{+0.005}_{-0.001}$
48]	> -0.35	> -0.12
	$69.04^{+0.84}_{-1.10}$	$68.02^{+0.49}_{-0.60}$
	$0.261^{+0.038}_{-0.025}$	$0.299^{+0.015}_{-0.007}$

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.

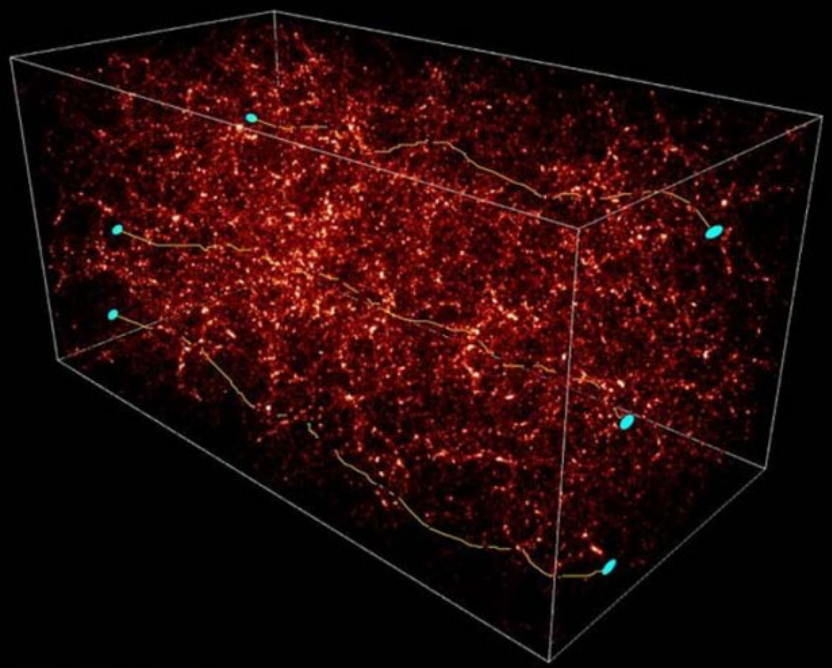
Actually, BAO and FS data are extracted under the assumption of LCDM, and the modified scenario of interacting dark energy could affect the result.

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!

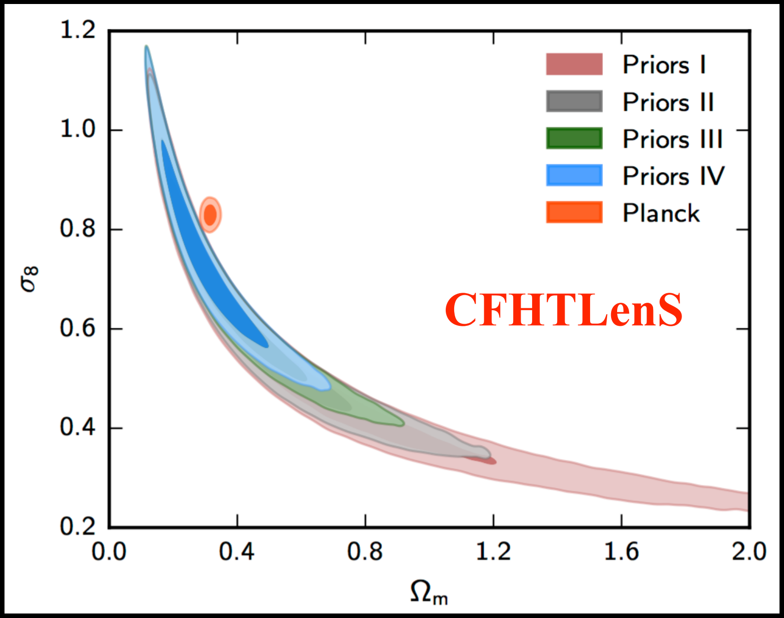
The S8 tension



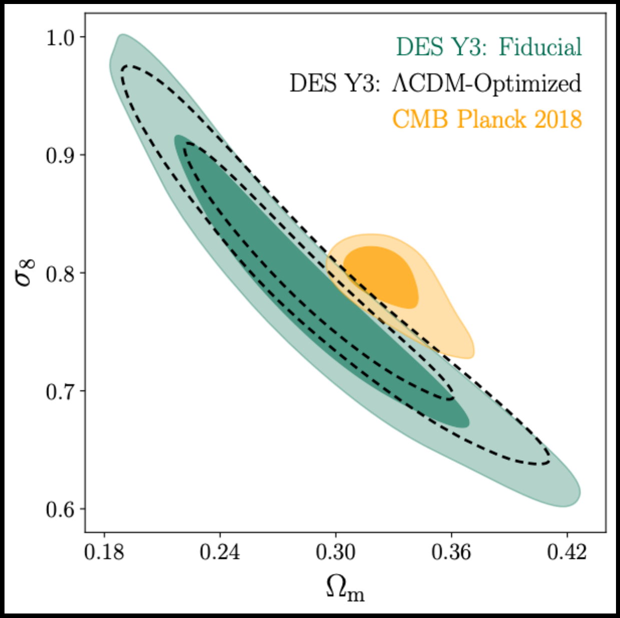
$$S_8 \equiv \sigma_8 \sqrt{\Omega_m / 0.3}$$

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

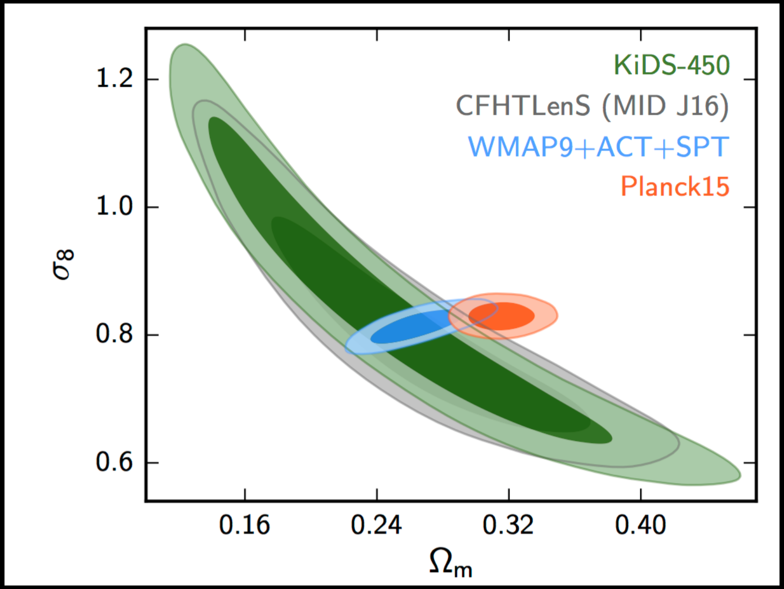
The S8 tension



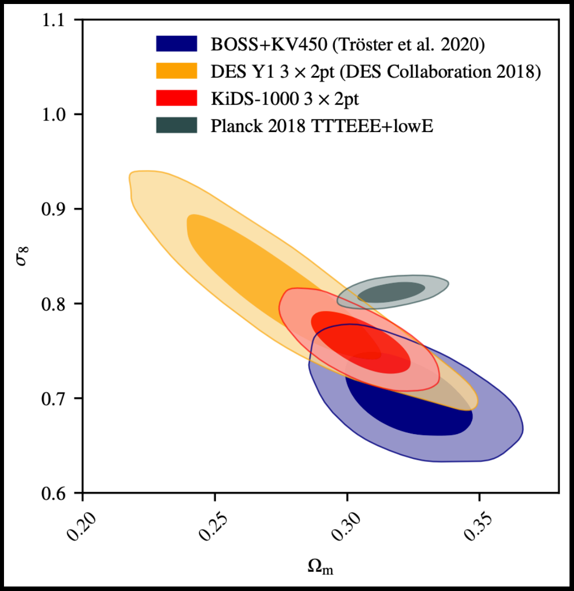
Joudaki et al, arXiv:1601.05786



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



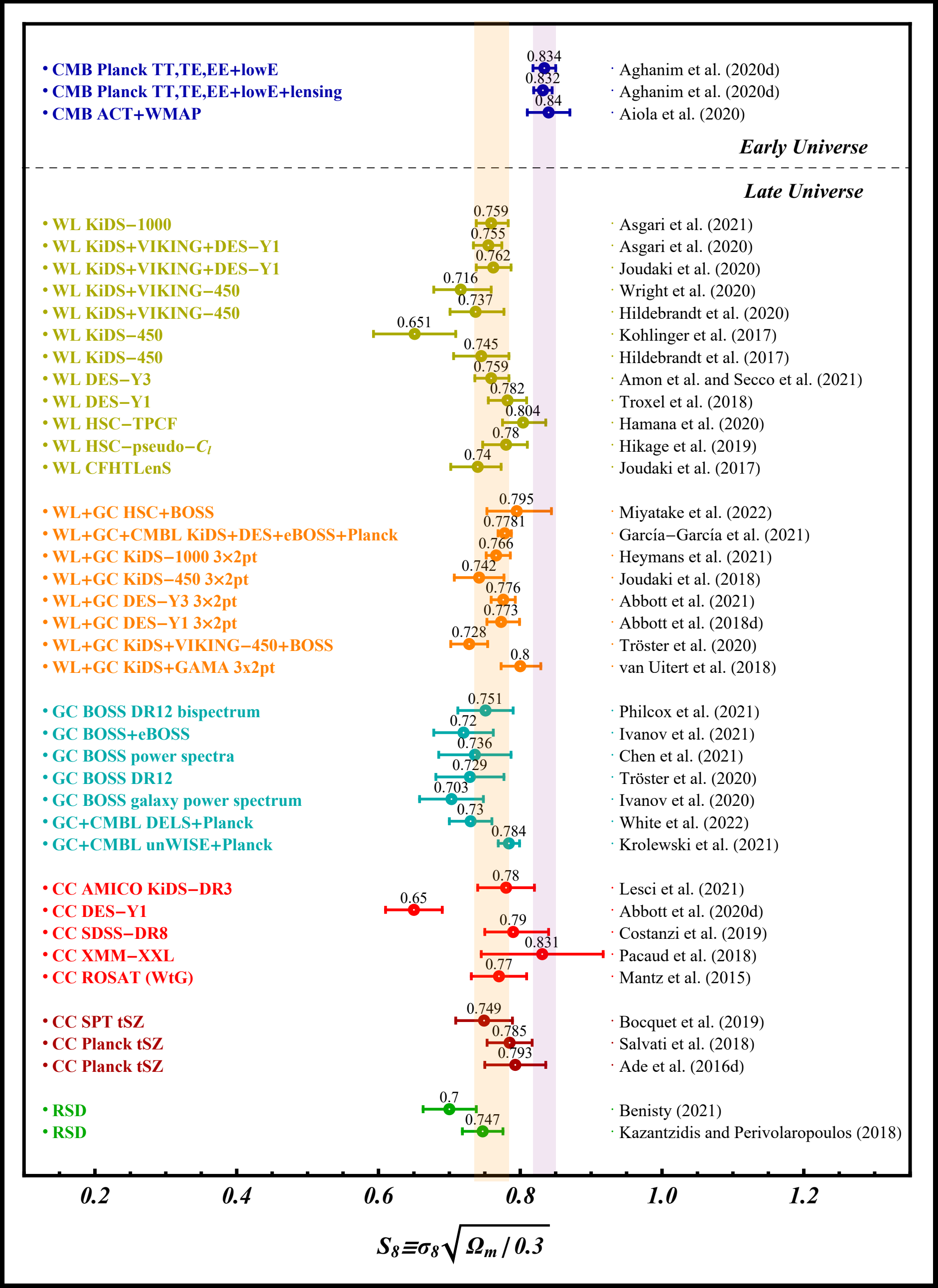
Hildebrandt et al., arXiv:1606.05338



Heymans et al., arXiv:2007.15632

The S8 tension is now at 3.4σ between Planck assuming ΛCDM and KiDS+VIKING-450 and BOSS combined together, or 3.1σ with KiDS-1000, or 2.5σ with DES-Y3.

The S8 tension



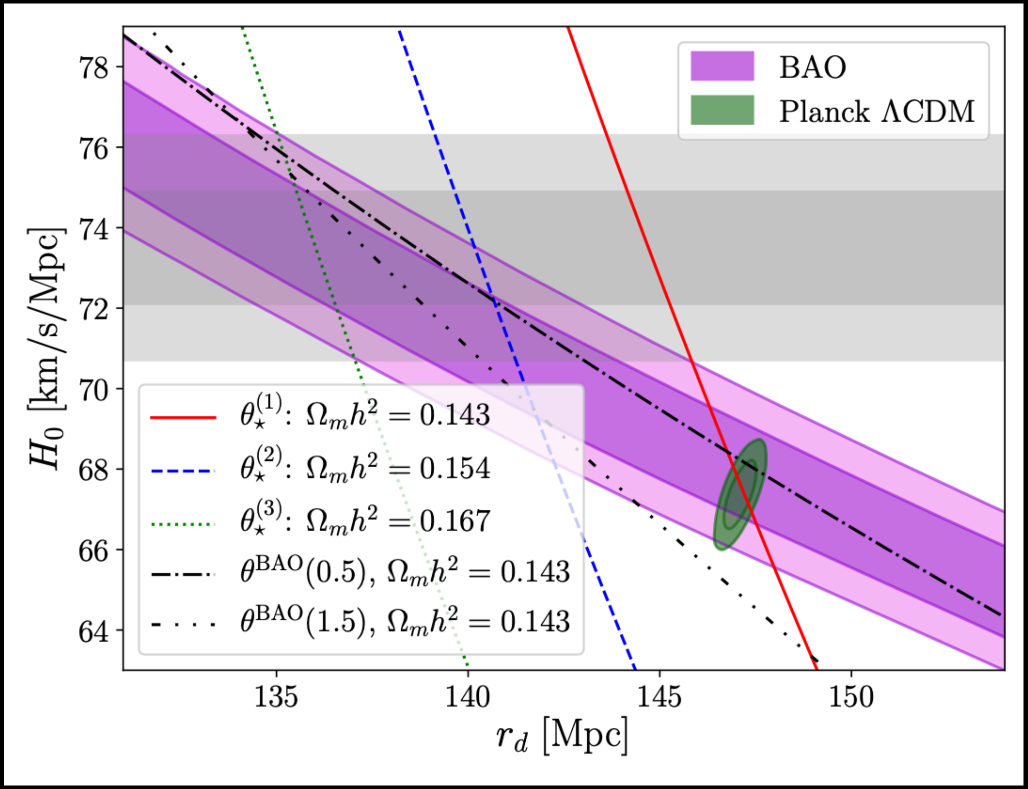
Abdalla et al., *JHEAp* 34 (2022) 49-211

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 $\Omega_m h^2$.



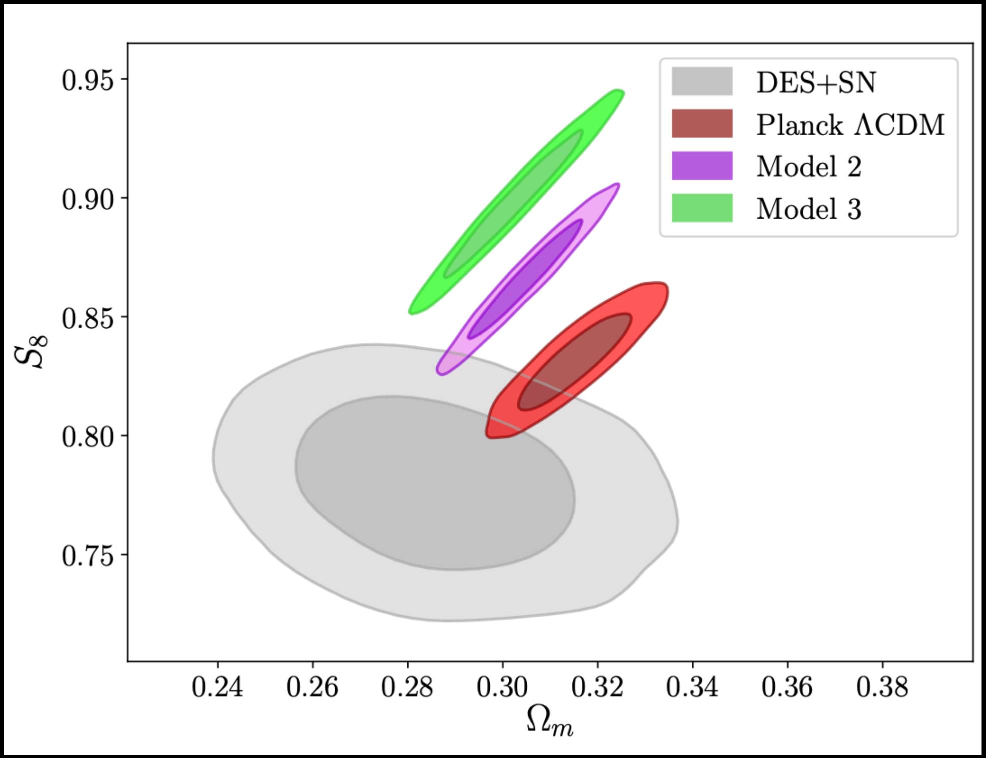
Jedamzik et al., Commun.in Phys. 4 (2021) 123

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.

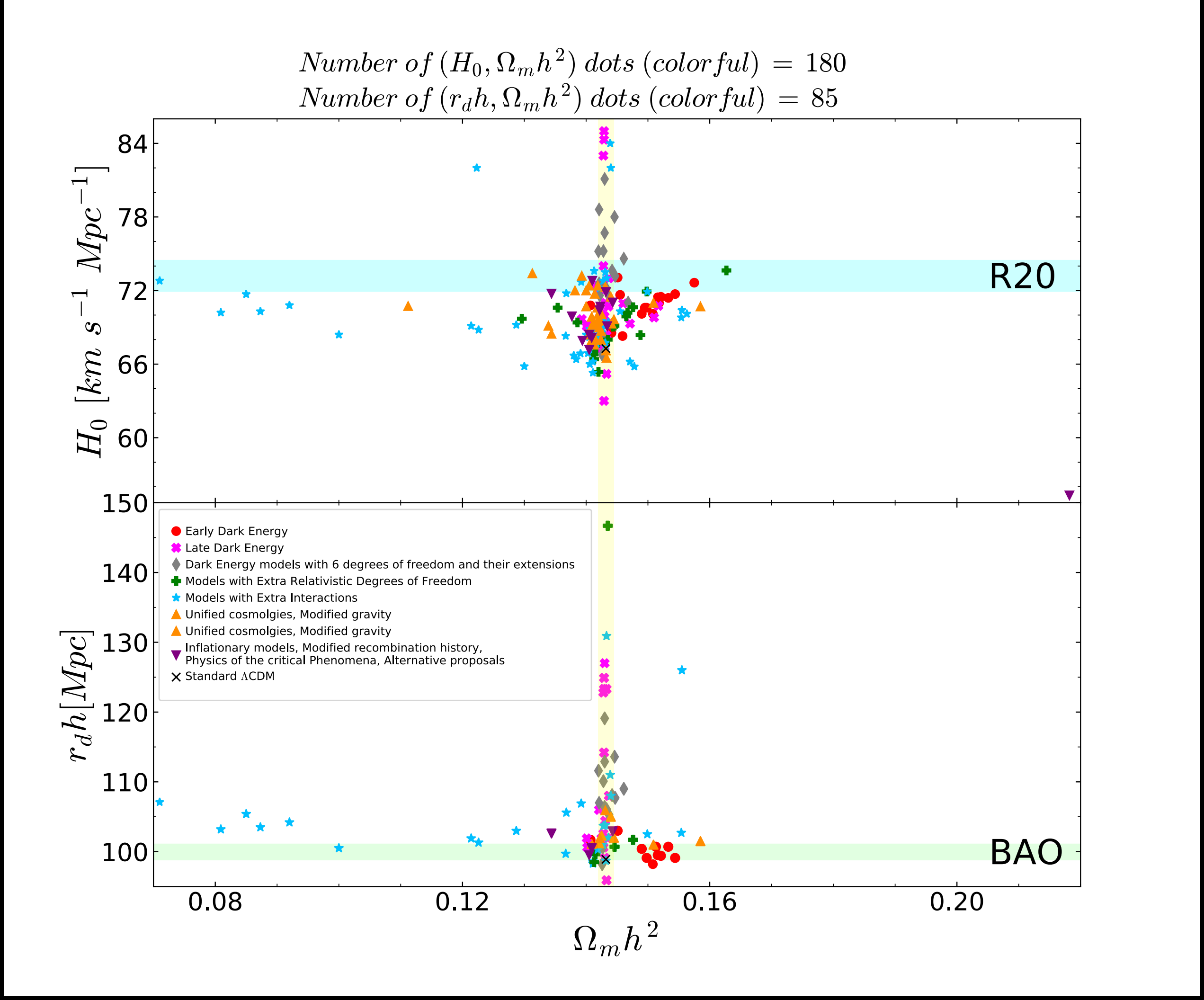
The figure shows that when attempting to find a full resolution of the Hubble tension, with CMB, BAO and SH0ES in agreement with each other, one exacerbates the tension with DES and KiDS.



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

Successful models?

This is the density of the proposed cosmological models:

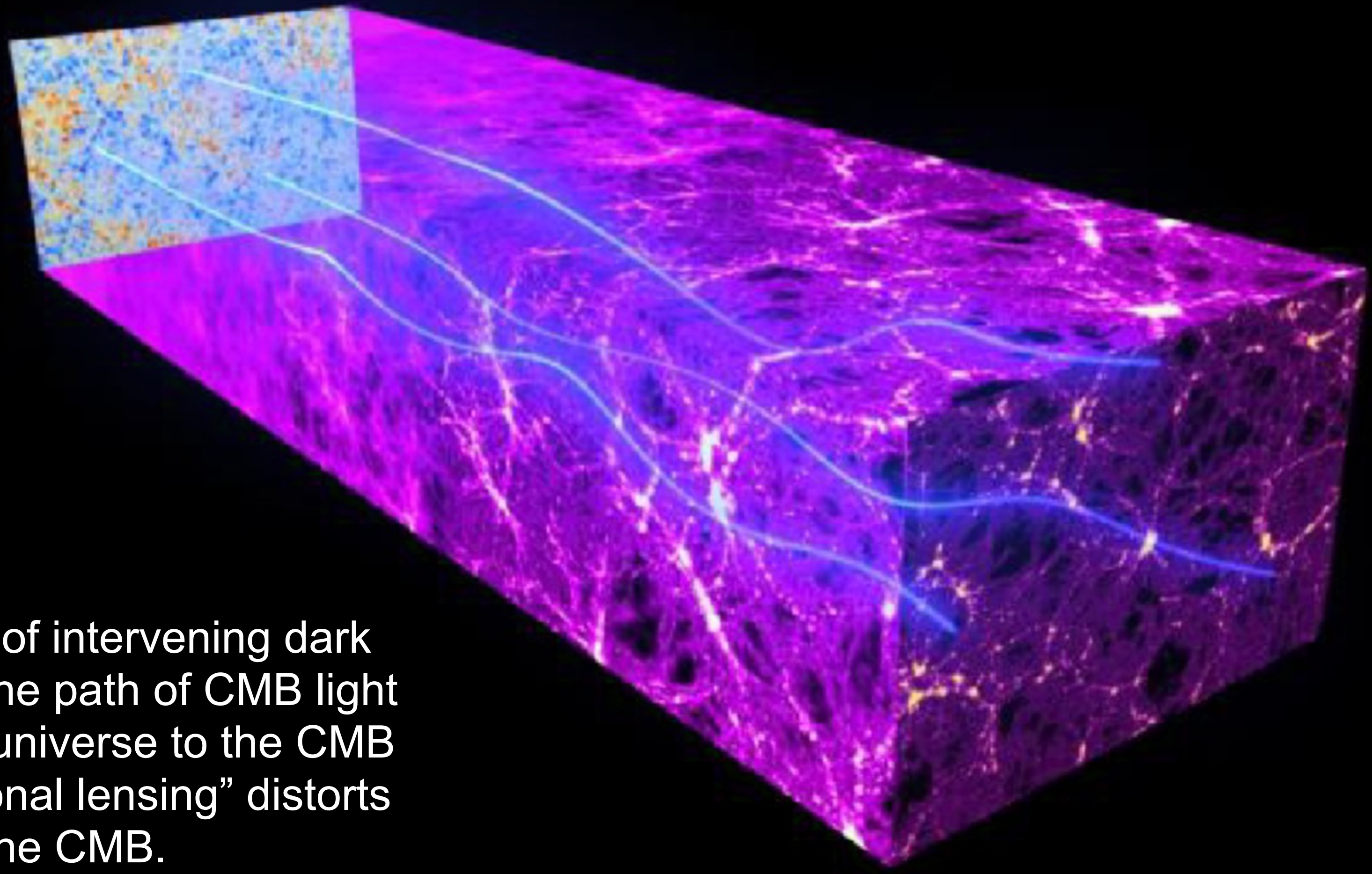


At the moment no specific proposal makes a strong case for being highly likely or far better than all others !!!

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

…but the excess of lensing in Planck could explain S8…

A_L internal anomaly



The gravitational effects of intervening dark matter fluctuations bend the path of CMB light on its way from the early universe to the CMB telescope. This "gravitational lensing" distorts our image of the CMB.

The lensing amplitude A_L parameterizes the rescaling of the lensing potential $\phi(n)$, then the power spectrum of the lensing field:

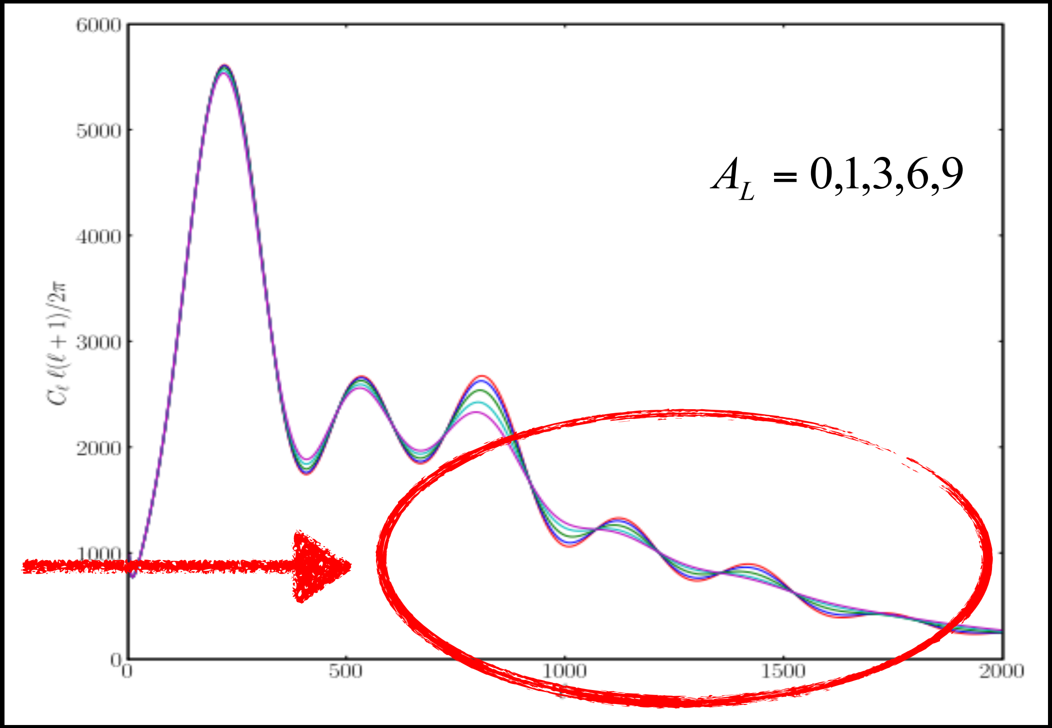
$$C_\ell^{\phi\phi} \rightarrow A_L C_\ell^{\phi\phi}$$

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

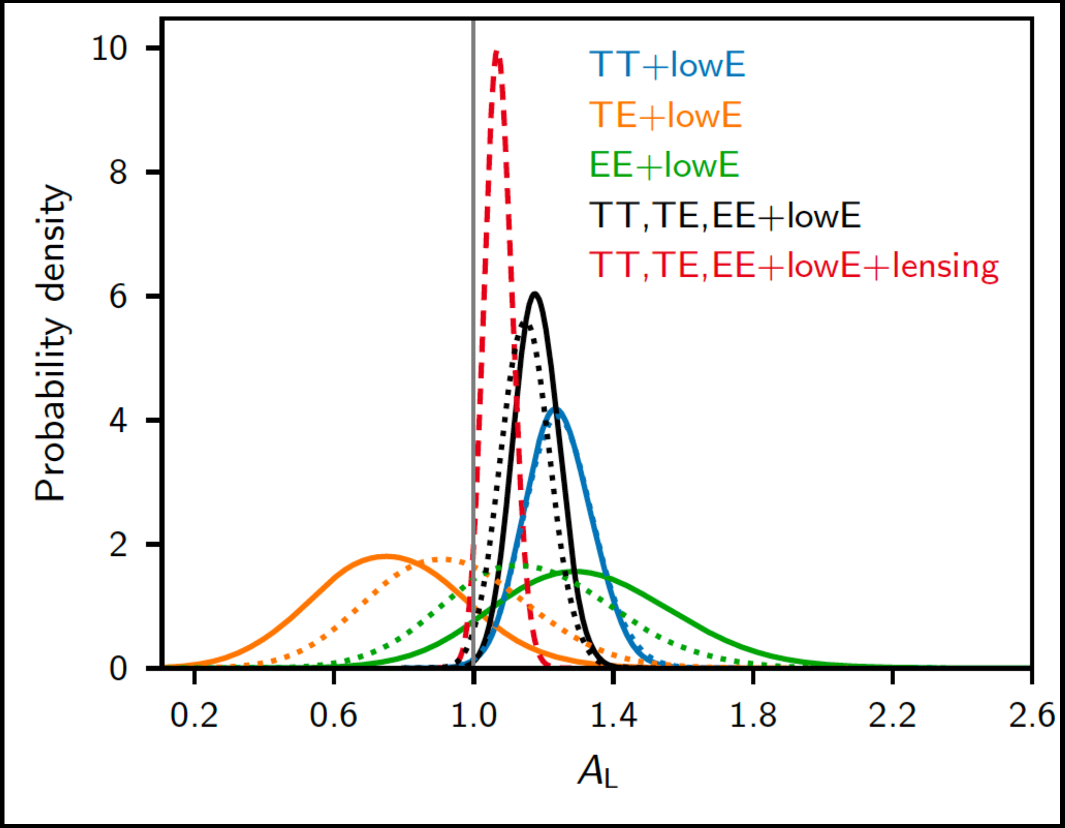
The Planck lensing-reconstruction power spectrum is consistent with the amplitude expected for LCDM models that fit the CMB spectra, so the Planck lensing measurement is compatible with AL = 1.

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.

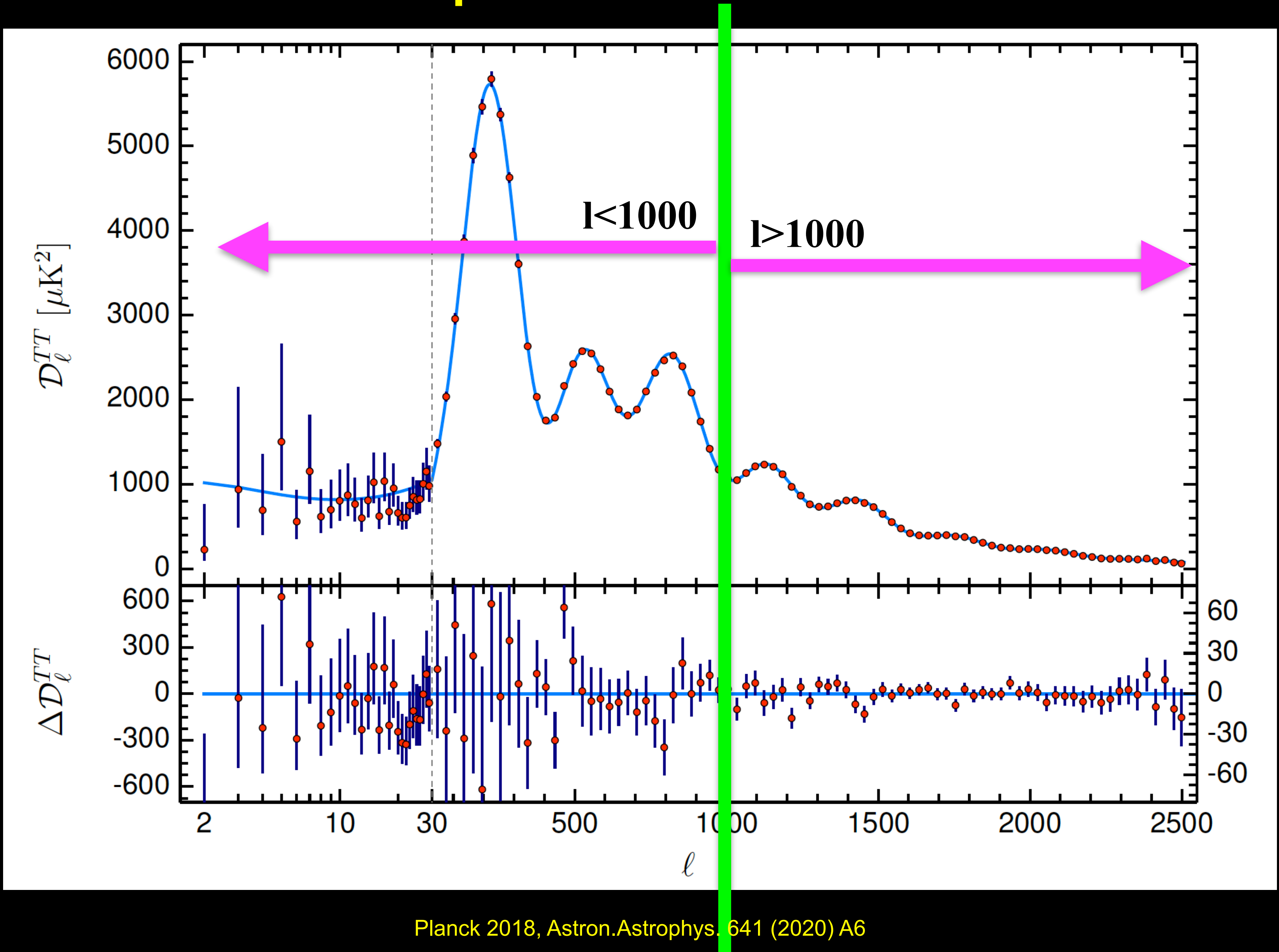
The preference for high AL is not just a volume effect in the full parameter space, with the best fit improved by $\Delta\chi^2 \sim 9$ when adding AL for TT+lowE and 10 for TTTEEE+lowE.

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



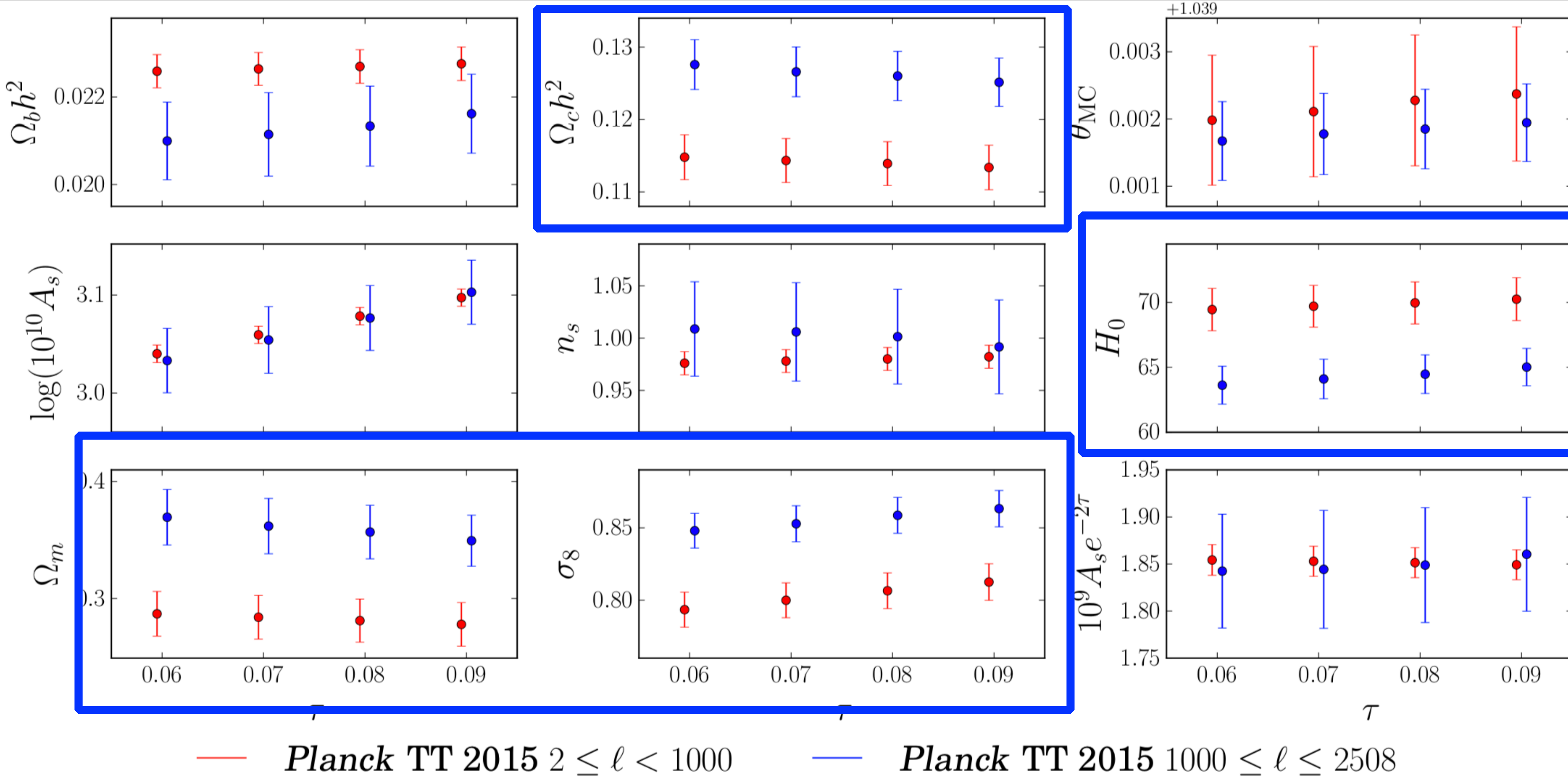
$$A_L = 1.243 \pm 0.096 \quad (68\,\%,\ \textit{Planck}\ \mathrm{TT+lowE}),$$
$$A_L = 1.180 \pm 0.065 \quad (68\,\%,\ \textit{Planck}\ \mathrm{TT,TE,EE+lowE}),$$

A_L can explain internal tension



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

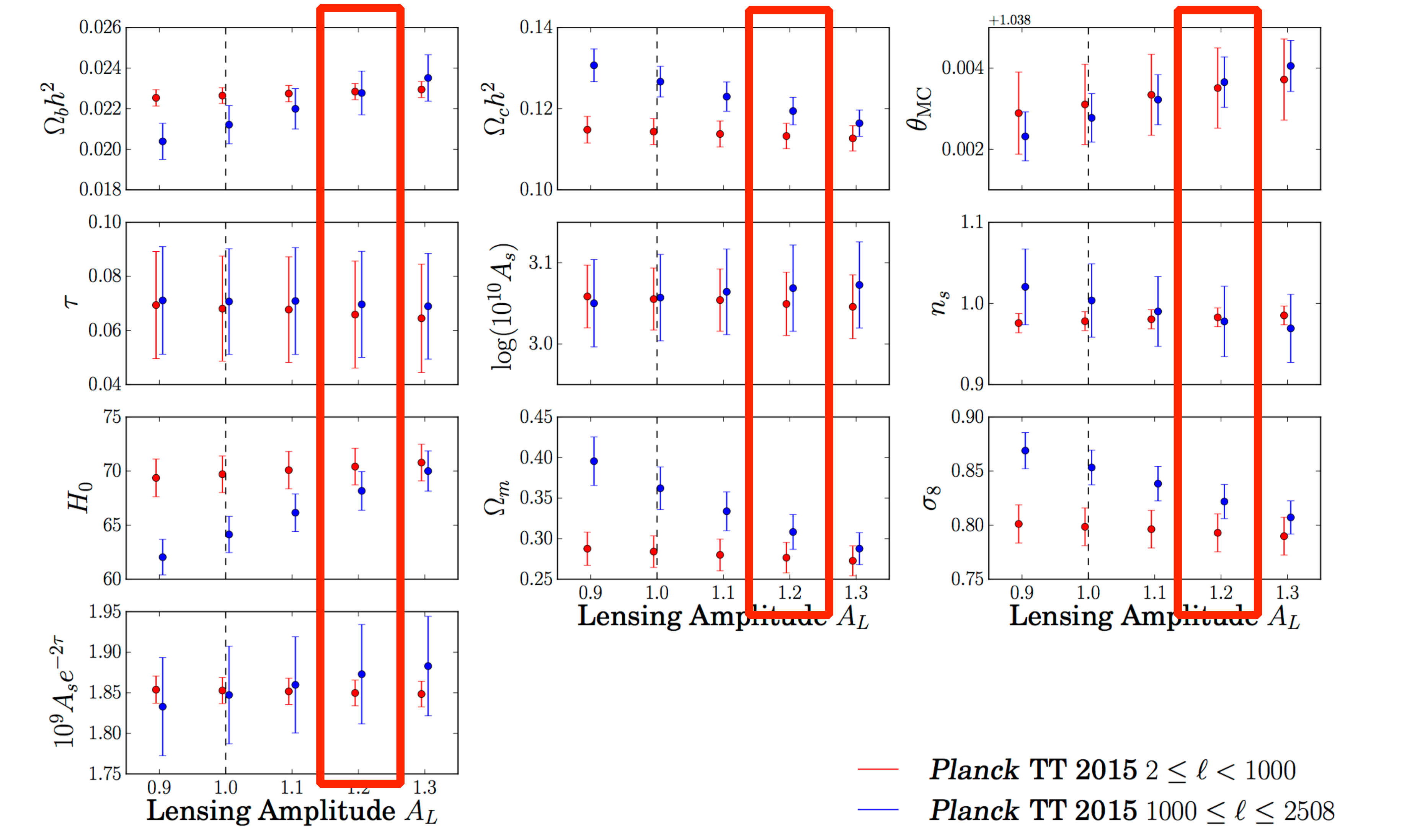
A_L can explain internal tension



Marginalized 68.3% confidence ΛCDM parameter constraints from fits to the l < 1000 and l ≥ 1000 Planck TT 2015 spectra. Tension at more than 2σ level appears in $\Omega_c h^2$ and derived parameters, including H0, Ωm, and σ8.

Addison et al., Astrophys.J. 818 (2016) no.2, 132

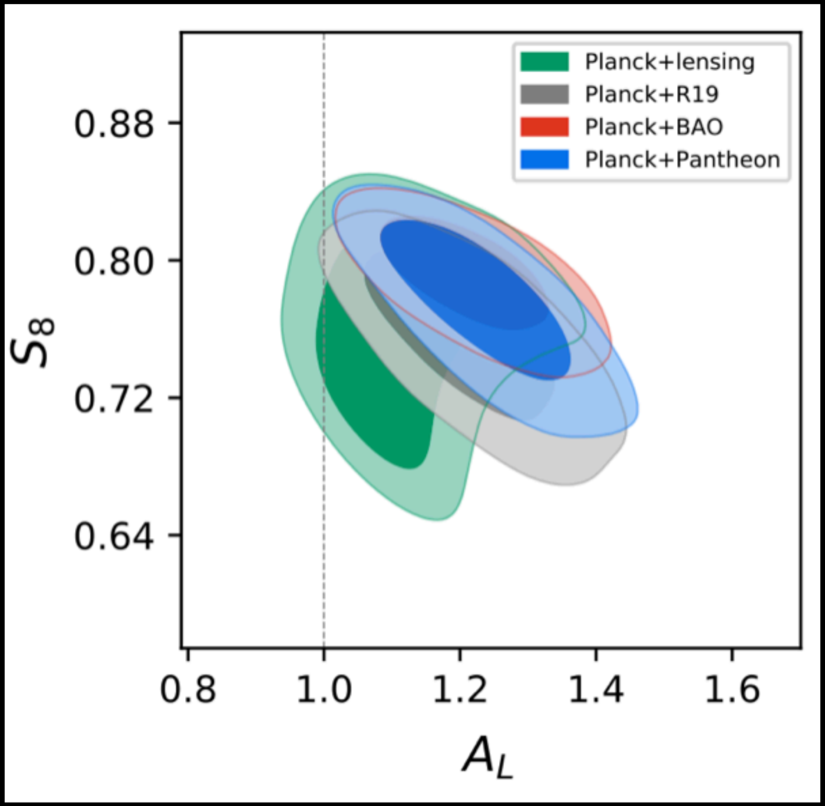
A_L can explain internal tension



Increasing AL smooths out the high order acoustic peaks, improving the agreement between the two multipole ranges.

Addison et al., Astrophys.J. 818 (2016) no.2, 132

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 an indication for Modified Gravity models…

MG could explains AL

Assuming a flat universe, we can write the line element of the Friedmann-Lemaitre-Robertson-Walker (FLRW) metric in the conformal Newtonian gauge as:

$$ds^2 = a(\tau)^2[-(1+2\Psi)d\tau^2 + (1-2\Phi)dx^i dx_i]$$

where a is the scale factor, τ is the conformal time,
Ψ is the Newton's gravitational potential, and Φ the space curvature.
We can use a phenomenological parametrization
of the gravitational potentials Ψ and Φ and their combinations given by:

- μ(k, a) modifies the Poisson equation for the Newton's gravitational potential Ψ

$$k^2\Psi = -4\pi G a^2 \mu(k,a)\rho\Delta$$

- η(k,a) takes into account the presence of a non-zero anisotropic stress, with Φ the space curvature:

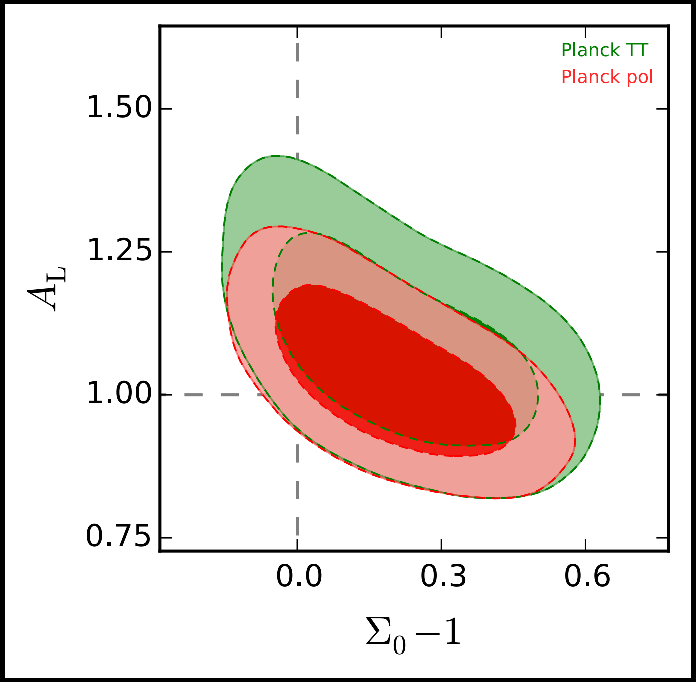
$$\eta(k,a) = \frac{\Phi}{\Psi}\,.$$

- Σ(k, a) modifies the lensing/Weyl potential Φ+Ψ:

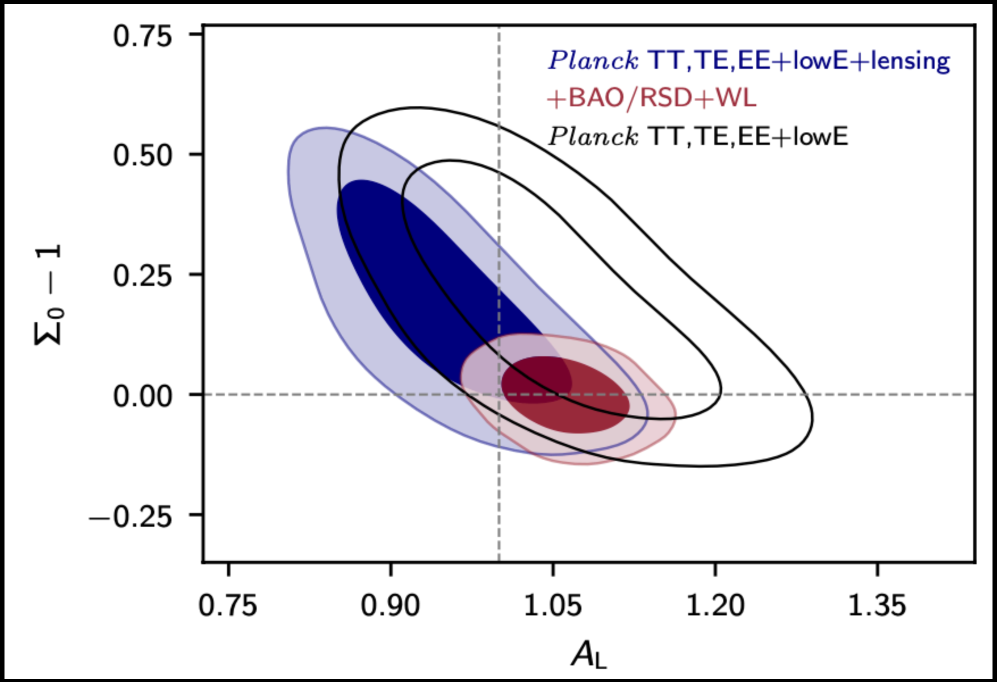
$$-k^2(\Phi+\Psi) \equiv 8\pi G a^2 \Sigma(k,a)\rho\Delta \quad \longrightarrow \quad \Sigma = \frac{\mu}{2}(1+\eta)\,.$$

MG could explains AL

A strong degeneracy is present between Σ0 and AL:
if we fix Σ0=1 we have a larger value for AL,
but when AL =1 then some indication for Σ0>1 appears.



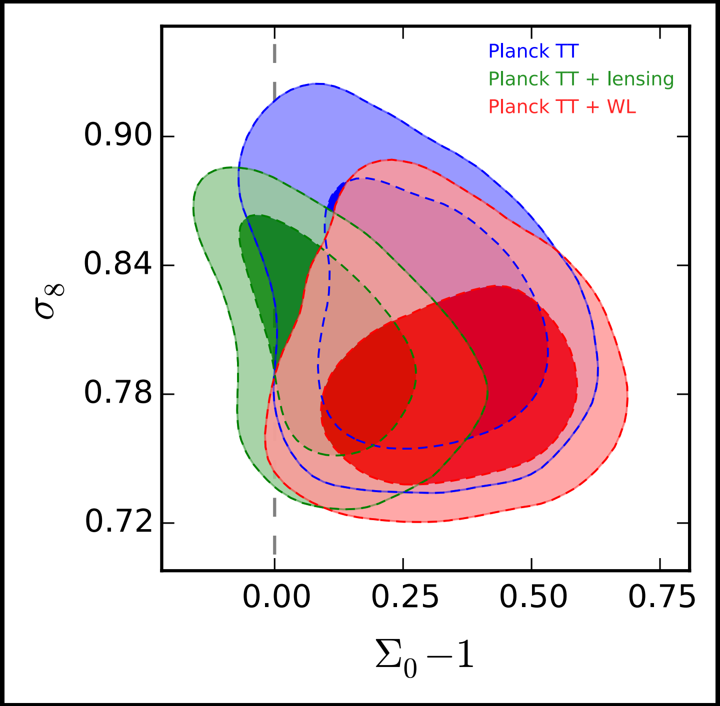
Di Valentino et al., Phys.Rev. D93 (2016) no.2, 023513

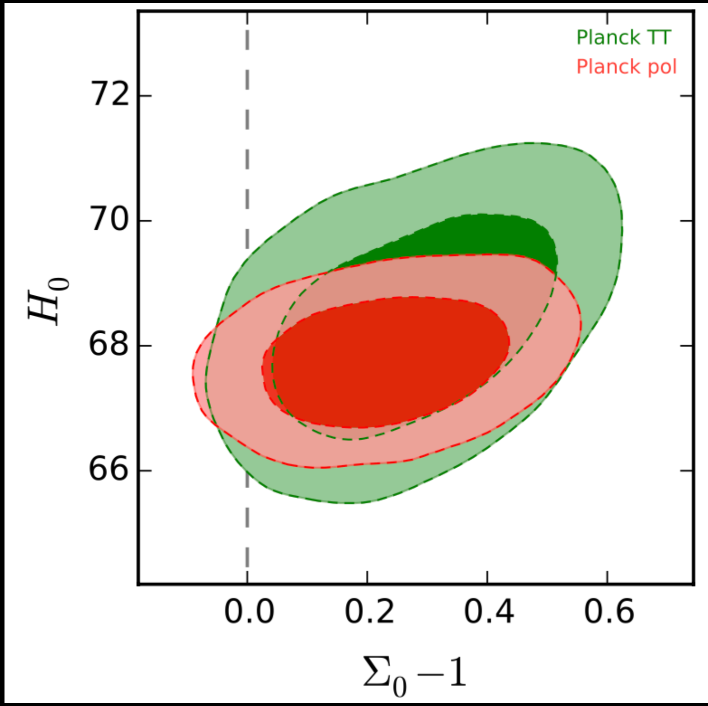


Planck 2018, Astron.Astrophys. 641 (2020) A6

MG could explains S8 and H0

The constraints on the amplitude of matter density fluctuations σ8 are relaxed and in better agreement with weak lensing measurements.
Moreover, we have a positive correlation with H0, potentially solving the Hubble constant tension.





Di Valentino et al., Phys.Rev. D93 (2016) no.2, 023513

MG could explains 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 3σ considering *Planck* in combination with additional cosmological probes. Details of the combined datasets are discussed in the main text.

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

…or assuming General Relativity, a curved universe can be a physical explanation for A_L…

Astronomy & Astrophysics manuscript no. ms
September 24, 2019

Planck 2018 results. VI. Cosmological parameters

Page 40

$$\Omega_K = -0.044^{+0.018}_{-0.015} \quad (68\,\%, \textit{Planck}\ \mathrm{TT,TE,EE{+}lowE}), \qquad (46b)$$

a detection of curvature at about 3.4σ

an apparent detection of curvature at well over $2\,\sigma$. The 99 % probability region for the TT,TE,EE+lowE result is $-0.095 < \Omega_K < -0.007$, with only about 1/10000 samples at $\Omega_K \geq 0$. This is not entirely a volume effect, since the best-fit χ^2 changes by $\Delta\chi^2_{\rm eff} = -11$ compared to base ΛCDM when adding the one additional curvature parameter. The reasons for the pull towards

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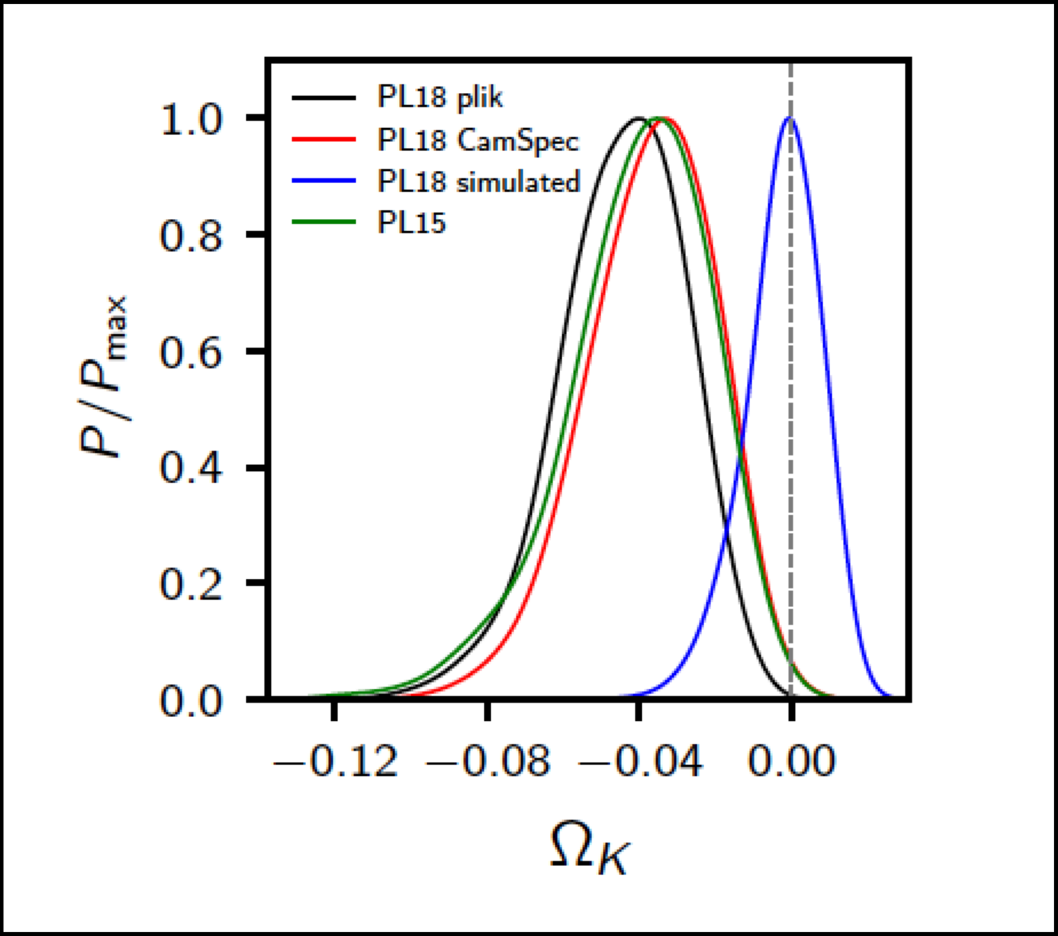
‡Corresponding author: A. Lewis, antony@cosmologist.info

Curvature of the universe

Curvature of the universe

Can Planck provide an unbiased and reliable estimate of the curvature of the Universe?
This may not be the case since a "geometrical degeneracy" is present with Ωm.
When precise CMB measurements at arc-minute angular scales are included, since gravitational lensing depends on the matter density, its detection breaks the geometrical degeneracy. The Planck experiment with its improved angular resolution offers the unique opportunity of a precise measurement of curvature from a single CMB experiment.
We simulated Planck, finding that such experiment could constrain curvature with a 2% uncertainty, without any significant bias towards closed models.

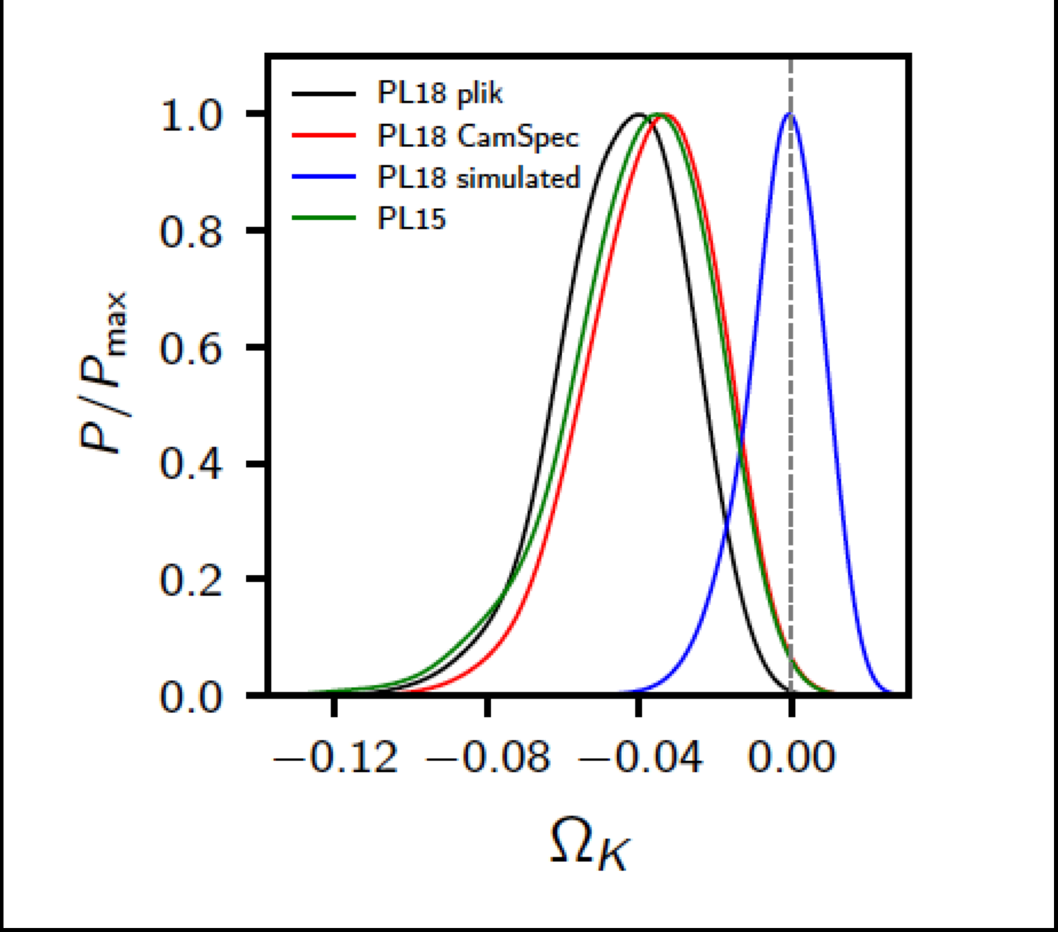


Di Valentino, Melchiorri and Silk, *Nature Astron.* 4 (2019) 2, 196-203

Curvature of the universe

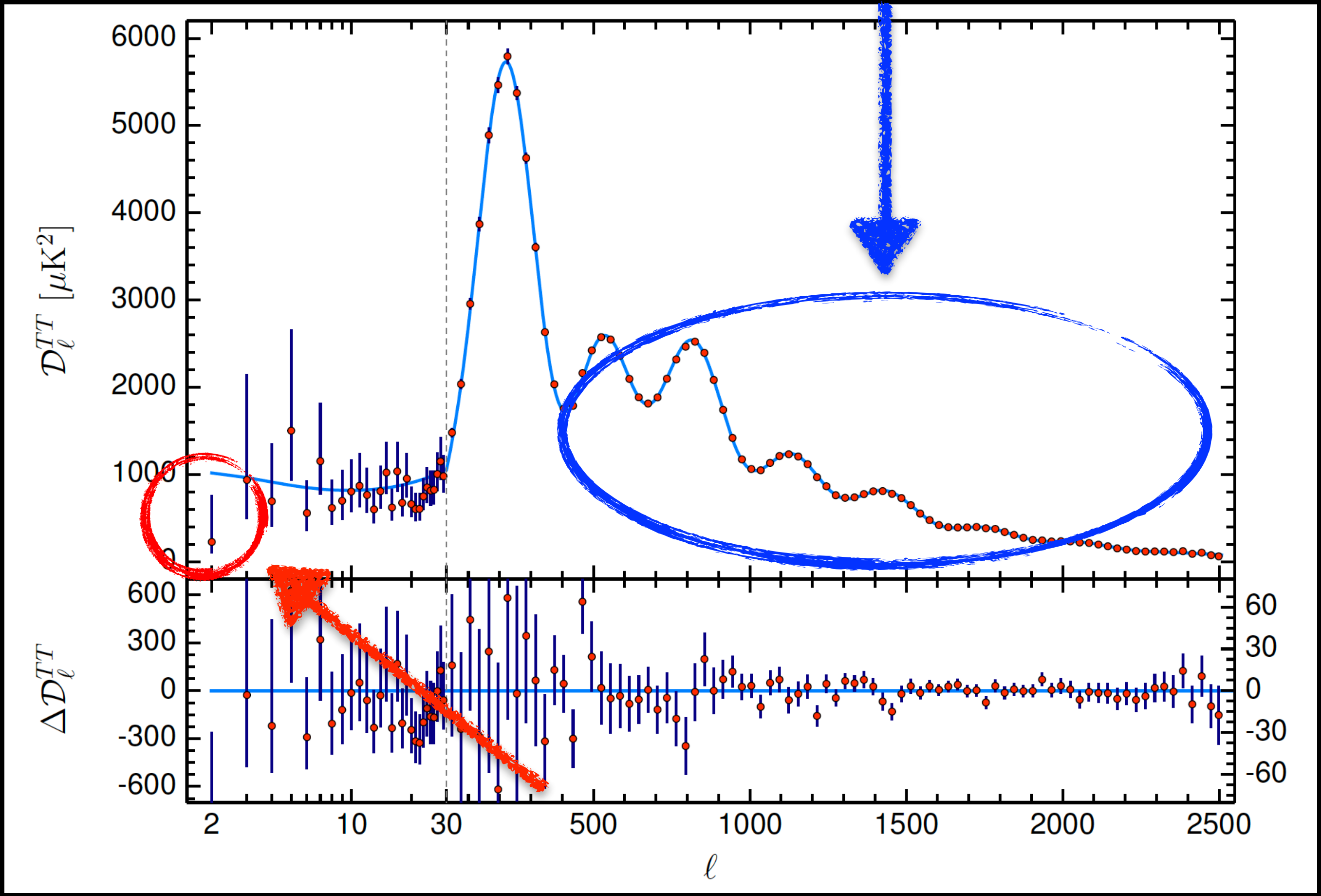
Planck favours a closed Universe ($\Omega k<0$) with 99.985% probability.
A closed Universe with $\Omega K = -0.0438$ provides a better fit to PL18 with respect to a flat model.

This is not entirely a volume effect, since the best-fit $\Delta\chi^2$ changes by -11 compared to base ΛCDM when adding the one additional curvature parameter.
The improvement is due also to the fact that closed models could also lead to a large-scale cut-off in the primordial density fluctuations in agreement with the observed low CMB anisotropy quadrupole.



Di Valentino, Melchiorri and Silk, *Nature Astron.* 4 (2019) 2, 196-203

Low CMB anisotropy quadrupole



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

A model with $\Omega_K < 0$ is slightly preferred with respect to a flat model with $A_L > 1$, because closed models better fit not only the damping tail, but also the low-multipole data, especially the quadrupole.

arXiv.org > astro-ph > arXiv:astro-ph/0303127

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Astrophysics

[Submitted on 5 Mar 2003 (v1), last revised 30 Jul 2003 (this version, v2)]

Is the Low CMB Quadrupole a Signature of Spatial Curvature?

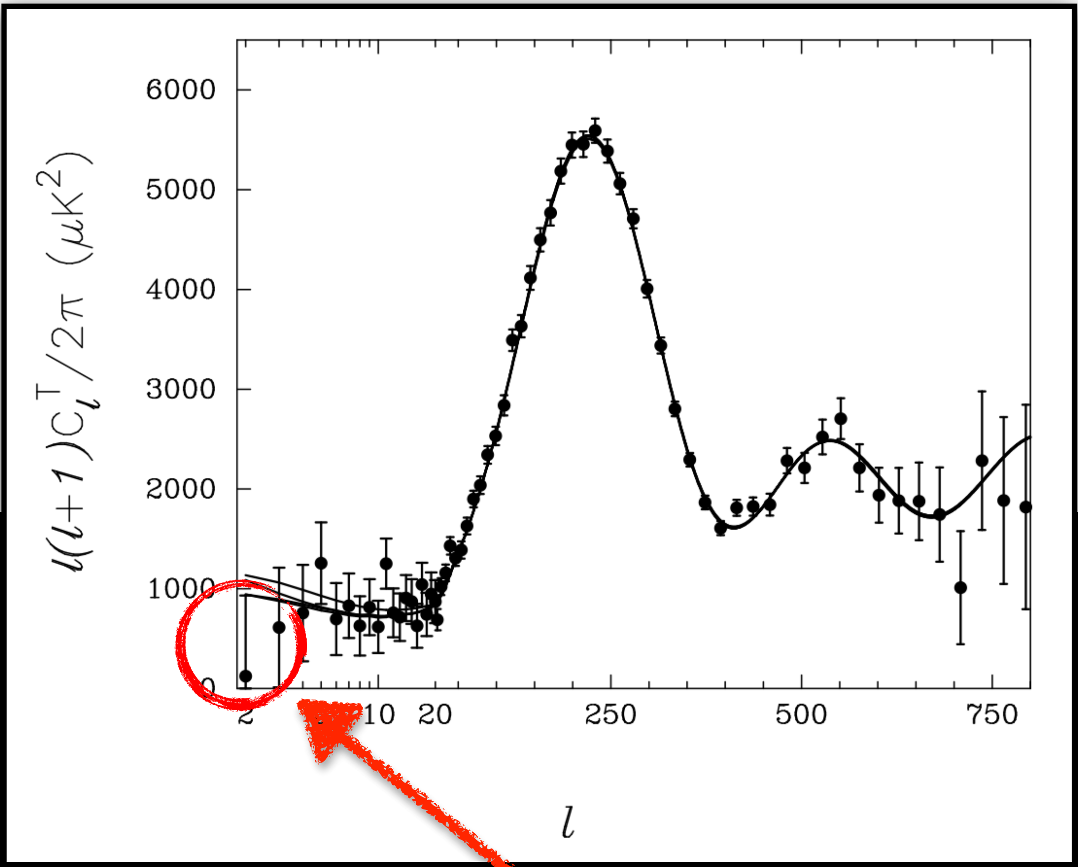
G. Efstathiou (University of Cambridge)

The temperature anisotropy power spectrum measured with the Wilkinson Microwave Anisotropy Probe (WMAP) at high multipoles is in spectacular agreement with an inflationary Lambda-dominated cold dark matter cosmology. However, the low order multipoles (especially the quadrupole) have lower amplitudes than expected from this cosmology, indicating a need for new physics. Here we speculate that the low quadrupole amplitude is associated with spatial curvature. We show that positively curved models are consistent with the WMAP data and that the quadrupole amplitude can be reproduced if the primordial spectrum truncates on scales comparable to the curvature scale.

Comments: 4 pages, Latex, 2 figs, revised version accepted by MNRAS
Subjects: **Astrophysics (astro-ph)**
Journal reference: Mon.Not.Roy.Astron.Soc. 343 (2003) L95
DOI: 10.1046/j.1365-8711.2003.06940.x
Cite as: arXiv:astro-ph/0303127
(or arXiv:astro-ph/0303127v2 for this version)

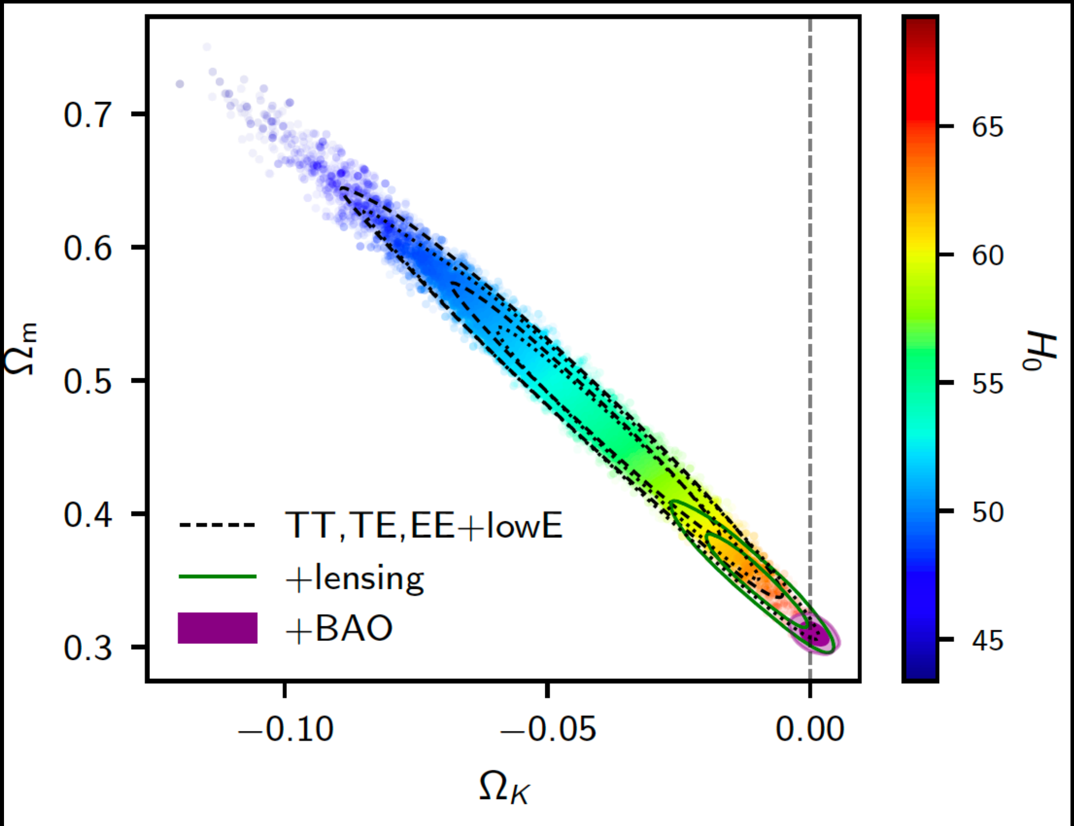
Submission history

From: George Efstathiou [view email]
[v1] Wed, 5 Mar 2003 23:30:33 UTC (21 KB)
[v2] Wed, 30 Jul 2003 10:16:45 UTC (22 KB)



A lower quadrupole than predicted by the ΛCDM was already present in WMAP, and a closed universe to explain this effect was already taken into account.

What about Planck+BAO?



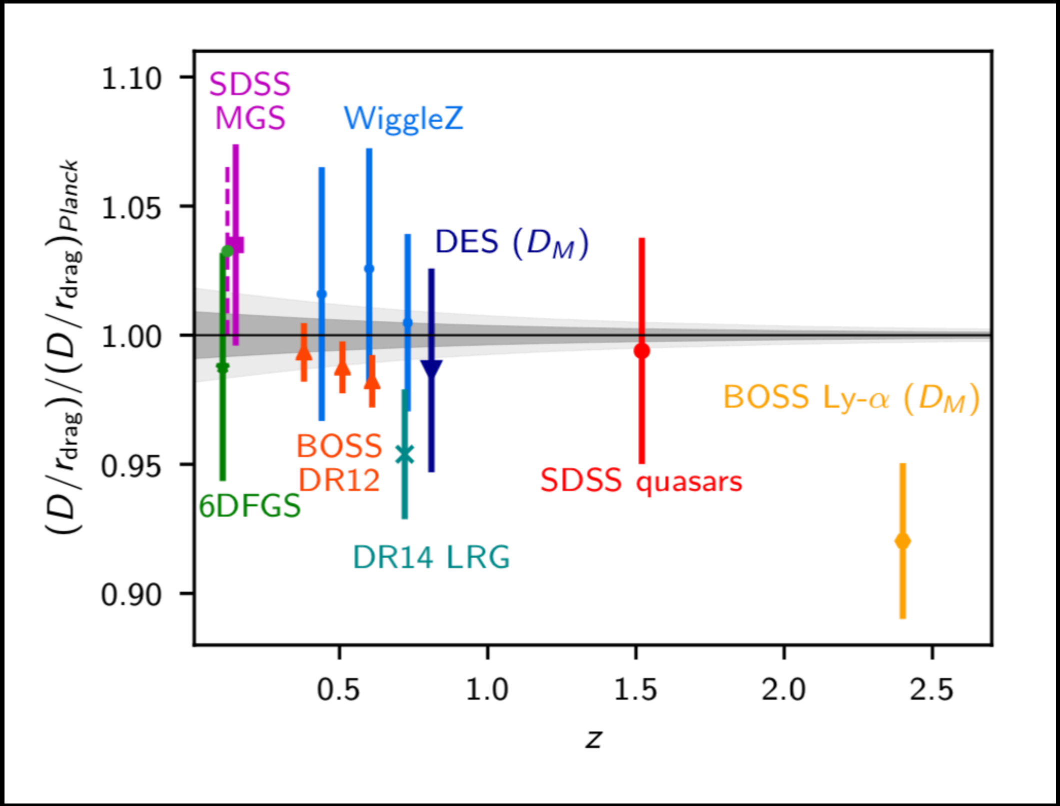
Planck 2018, Astron.Astrophys. 641 (2020) A6

Adding BAO data, a joint constraint is very consistent with a flat universe.

$$\Omega_K = 0.0007 \pm 0.0019 \quad \text{(68 \%, TT,TE,EE+lowE +lensing+BAO).}$$

Given the significant change in the conclusions from Planck alone, it is reasonable to investigate whether they are actually consistent. In fact, a basic assumption for combining complementary datasets is that these ones must be consistent, i.e. they must plausibly arise from the same cosmological model.

BAO tension

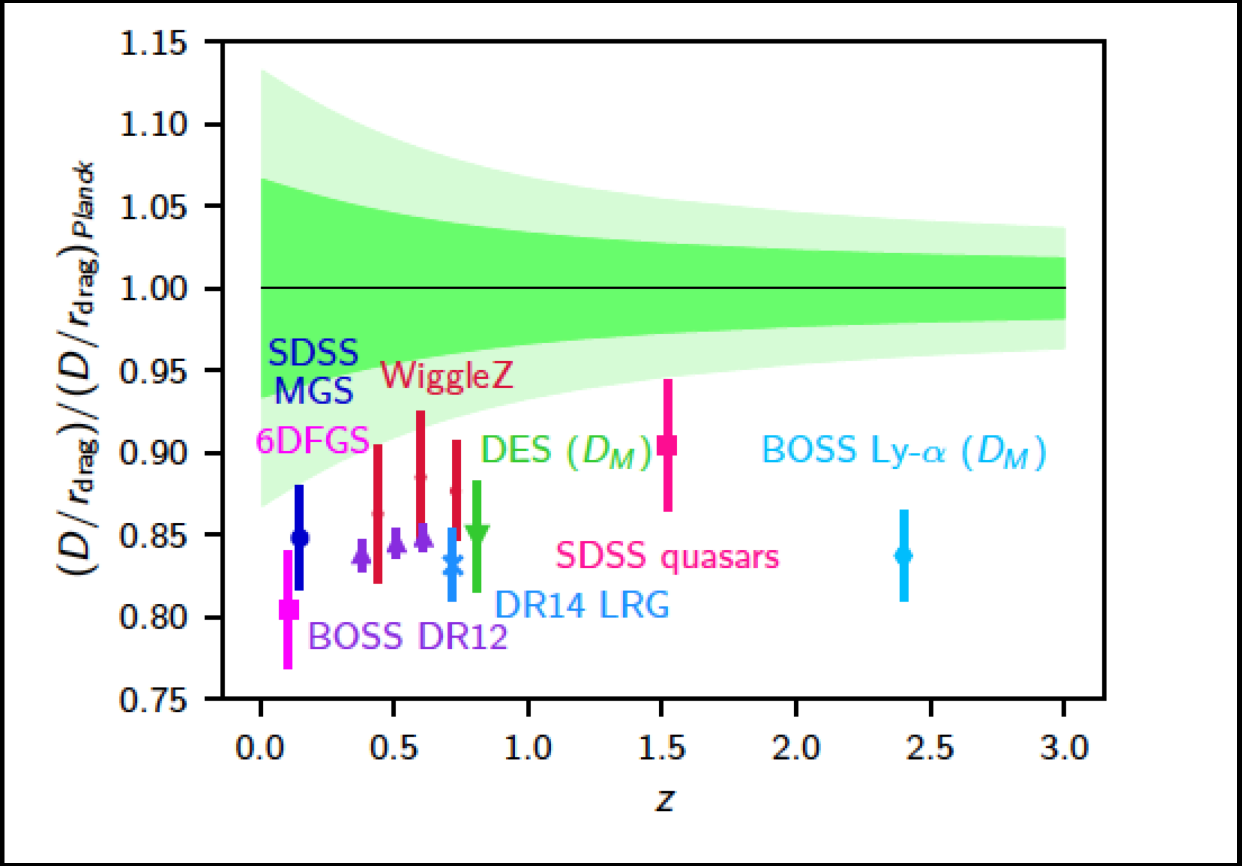


Planck 2018, Astron.Astrophys. 641 (2020) A6

This is a plot of the acoustic-scale distance ratio, DV(z)/rdrag, as a function of redshift, taken from several recent BAO surveys, and divided by the mean acoustic-scale ratio obtained by Planck adopting a model. rdrag is the comoving size of the sound horizon at the baryon drag epoch, and DV, the dilation scale, is a combination of the Hubble parameter H(z) and the comoving angular diameter distance DM(z).

In a ΛCDM model the BAO data agree really well with the Planck measurements…

BAO tension

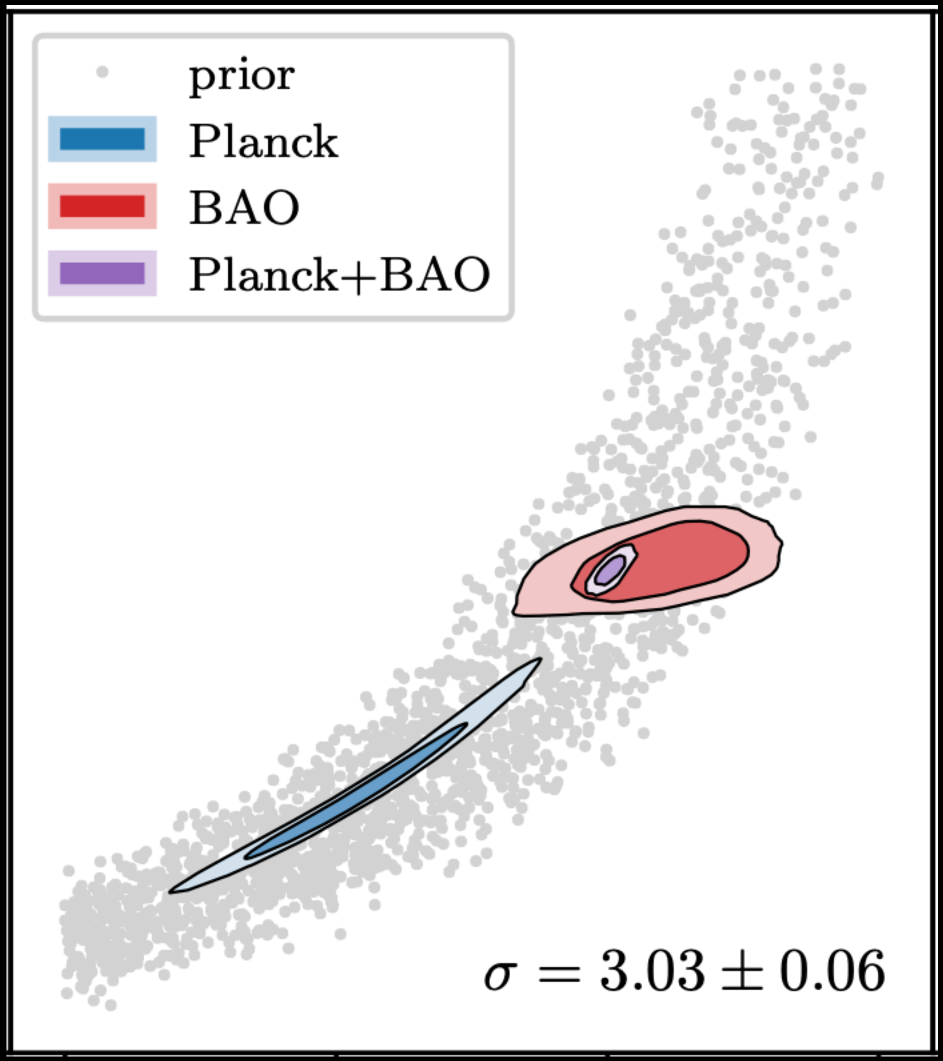


Di Valentino, Melchiorri and Silk, *Nature Astron.* 4 (2019) 2, 196-203

… but when we let curvature to vary

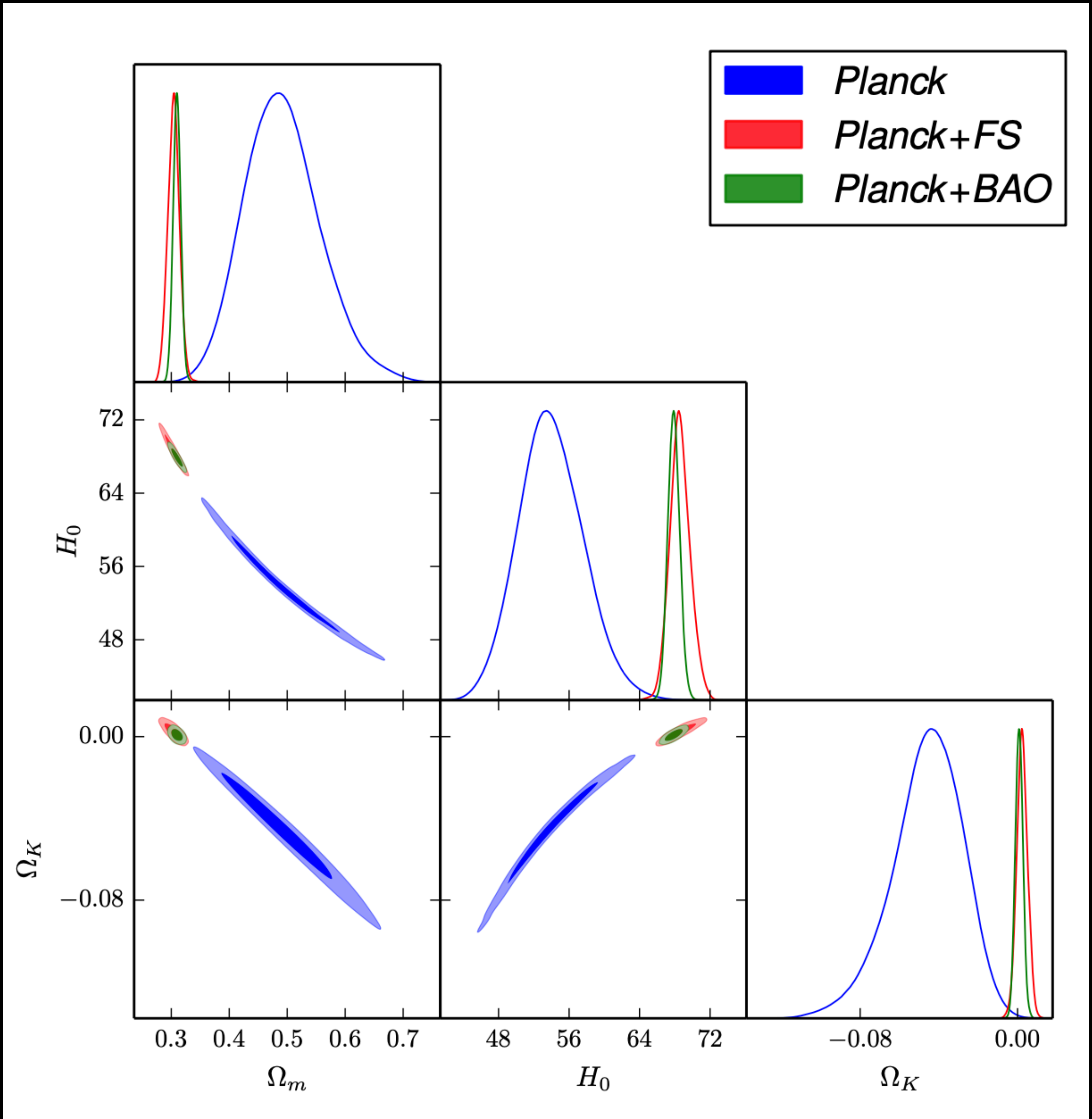
there is a striking disagreement between Planck spectra and BAO measurements!

BAO tension



In agreement with
Handley, Phys.Rev.D 103 (2021) 4, L041301

What about Planck+FS?

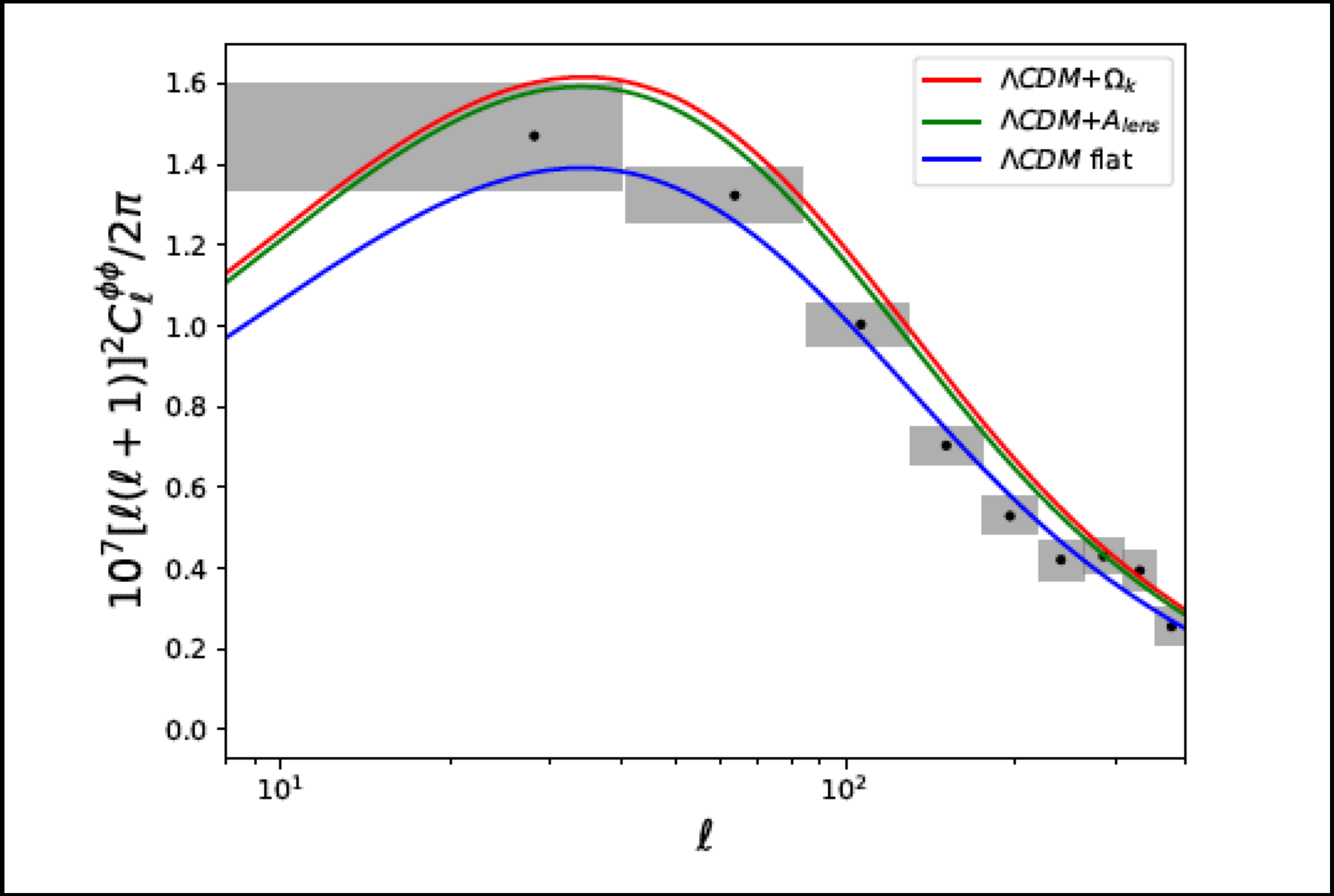


The strong disagreement between Planck and BAO it is evident in this triangular plot, as well as that with the full-shape (FS) galaxy power spectrum measurements from the BOSS DR12 CMASS sample, at an effective redshift $z_{eff} = 0.57$.

Vagnozzi, Di Valentino, et al., *Phys.Dark Univ.* 33 (2021) 100851

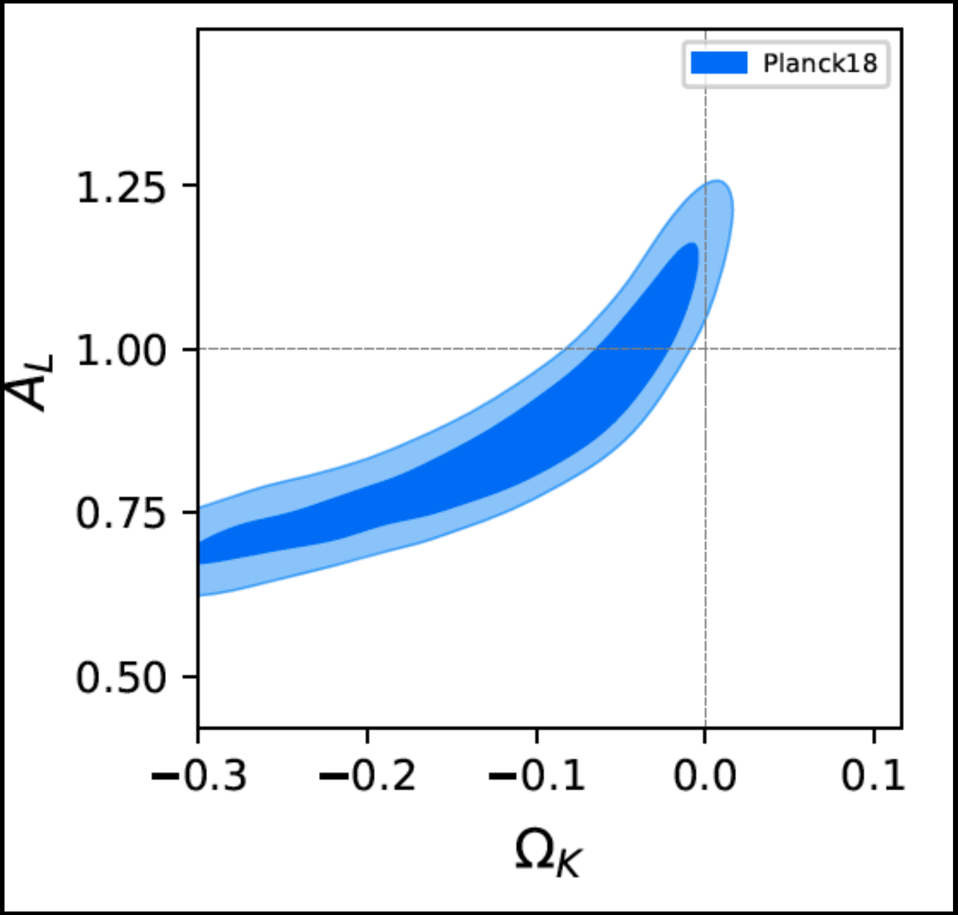
What about CMB lensing?

Closed models predict substantially higher lensing amplitudes than in ΛCDM, because the dark matter content can be greater, leading to a larger lensing signal. The reasons for the pull towards negative values of Ω_K are essentially the same as those that lead to the preference for AL > 1.



Di Valentino, Melchiorri and Silk, *Nature Astron.* 4 (2019) 2, 196-203

A closed universe (Friedmann 1922) can explain A_L!



Di Valentino, Melchiorri and Silk, *Nature Astron.* 4 (2019) 2, 196-203

A degeneracy between curvature and the AL parameter is clearly present. A closed universe can provide a robust physical explanation to the enhancement of the lensing amplitude. In fact, the curvature of the Universe is not new physics beyond the standard model, but it is predicted by the General Relativity, and depends on the energy content of the Universe.

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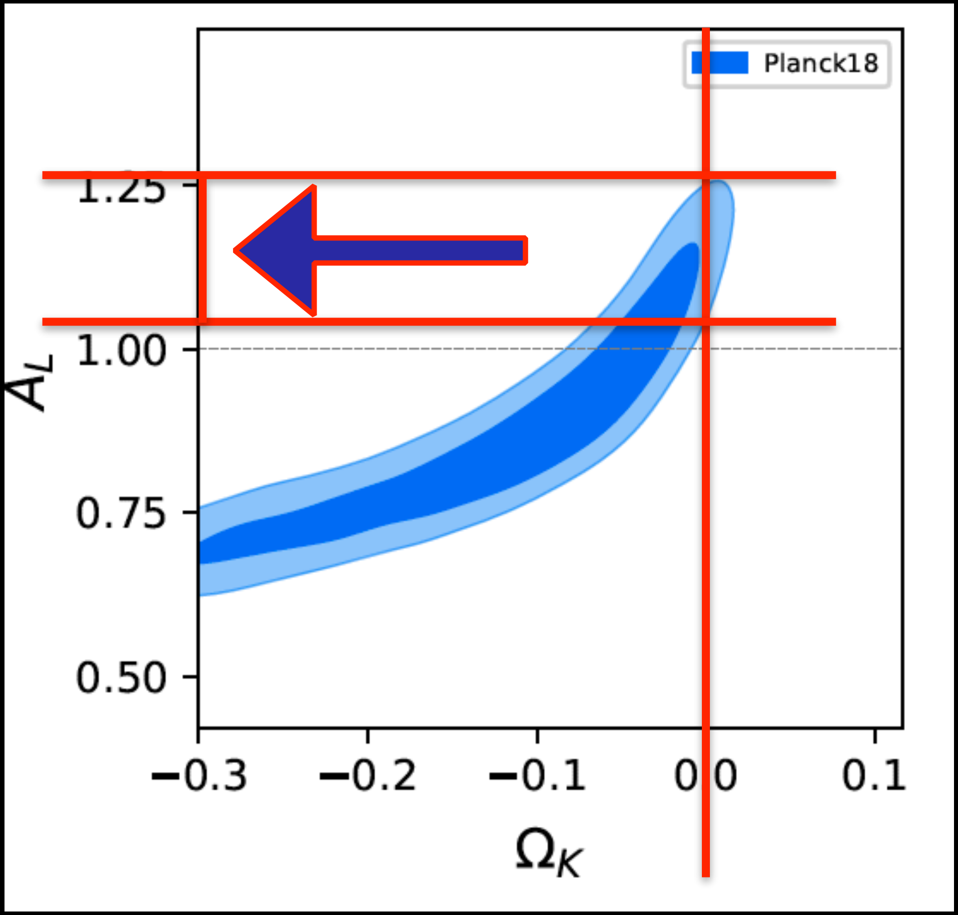

Di Valentino, Melchiorri and Silk, *Nature Astron.* 4 (2019) 2, 196-203

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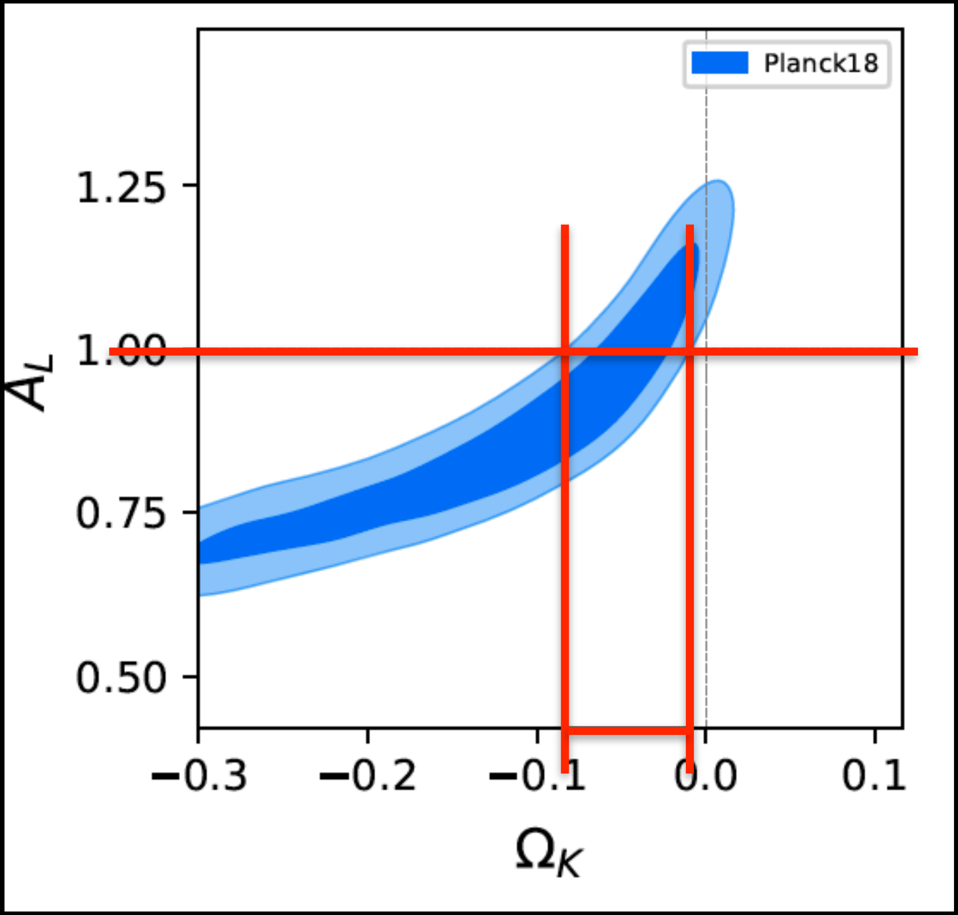

Di Valentino, Melchiorri and Silk, *Nature Astron.* 4 (2019) 2, 196-203

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The evolution over time of the geometry of the universe is described by Einstein's equations:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^2} T_{\mu\nu} + \Lambda g_{\mu\nu}$$

which relate the purely geometric properties of space-time, with the distribution of energy of the universe. For this it is sufficient to know the energy content of the Universe to determine its geometry and vice-versa.

Adopting a 4-dimensional coordinate system for the space-time and the Cosmological Principle, i.e. a universe homogeneous and isotropic at large scales, the resulting metric is the Friedmann-Lemaitre-Robertson-Walker (FLRW), that describes the distance between two events in space-time.

$$ds^2 = c^2dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2\left(d\theta^2 + sin^2\theta d\varphi^2\right)\right]$$

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The curvature parameter k can be positive, null or negative, depending on the value of the curvature of the universe: positive, flat or negative.

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Combining together the FLRW metric and Einstein's equations we obtain the Friedmann equations that describe the expansion history of the universe:

1st

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2} + \frac{\Lambda}{3}$$

2nd

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P) + \frac{\Lambda}{3}$$

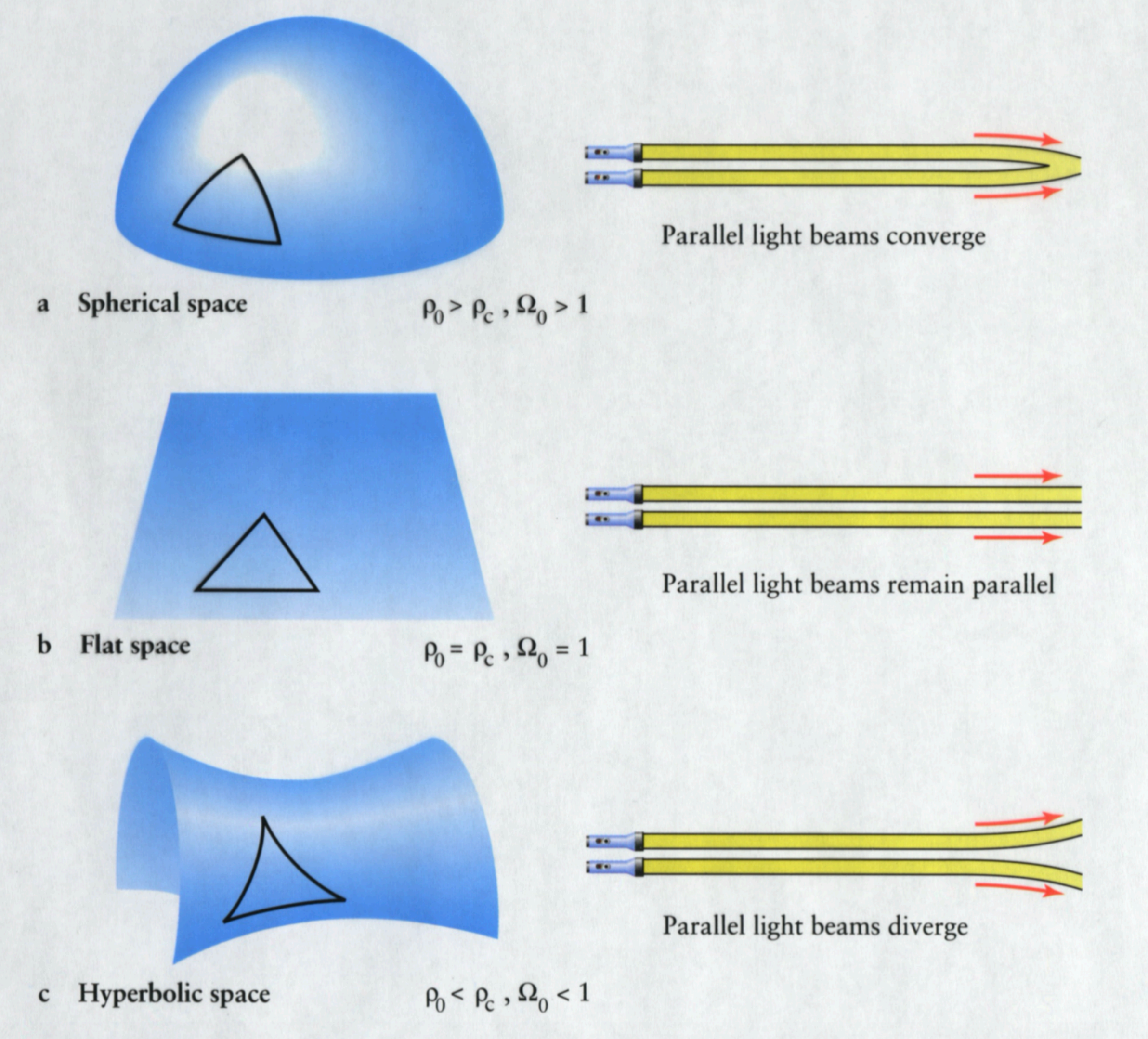


Figure: http://w3.phys.nthu.edu.tw

If we divide the 1st Friedmann equation, for the critical density (density of a flat universe), we obtain today:

$$\Omega = \sum_i \Omega_i = \Omega_m + \Omega_\Lambda + \Omega_r = 1 - \Omega_k$$

From this equation it is possible to estimate the curvature of the universe, independently measuring the various contributions to the total density parameter Ω.

$$\begin{cases} \Omega > 1 & \Omega_k < 0 \\ \Omega = 1 & \Omega_k = 0 \\ \Omega < 1 & \Omega_k > 0 \end{cases}$$

→ k>0 : closed Universe

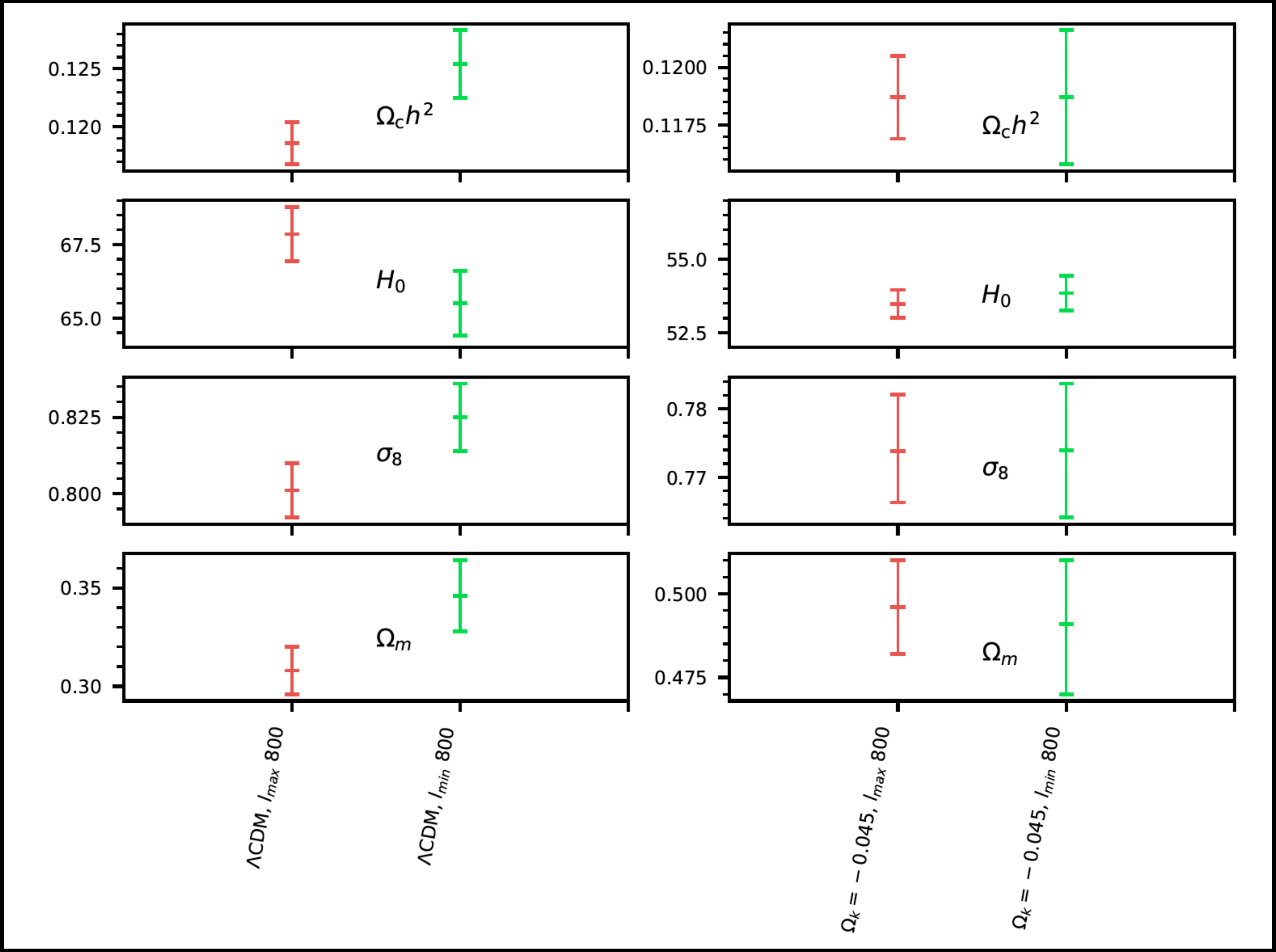
→ k=0 : flat Universe

→ k<0 : open Universe

LCDM+ Ω_k: a 7 parameter standard model

As it has been convincingly pointed out in Anselmi et al., arXiv:2207.06547,
absent any theoretical arguments,
we cannot use observations that suggest small Ω_k to enforce Ω_k=0.
The common practice to set Ω_k=0 places the onus on proponents of
"curved LCDM" to present sufficient evidence that $\Omega_k \neq 0$,
and this is needed as an additional parameter.
Given the current tensions in cosmological parameters and
CMB anomalies this choice is at least debatable.
So it would be desirable to have the standard cosmological
phenomenological model with at least 7 parameters.

Curvature can explain internal tension



Di Valentino, Melchiorri and Silk, *Nature Astron.* 4 (2019) 2, 196-203

In a closed Universe with ΩK = –0.045, the cosmological parameters derived in the two different multipole ranges are now fully compatible.

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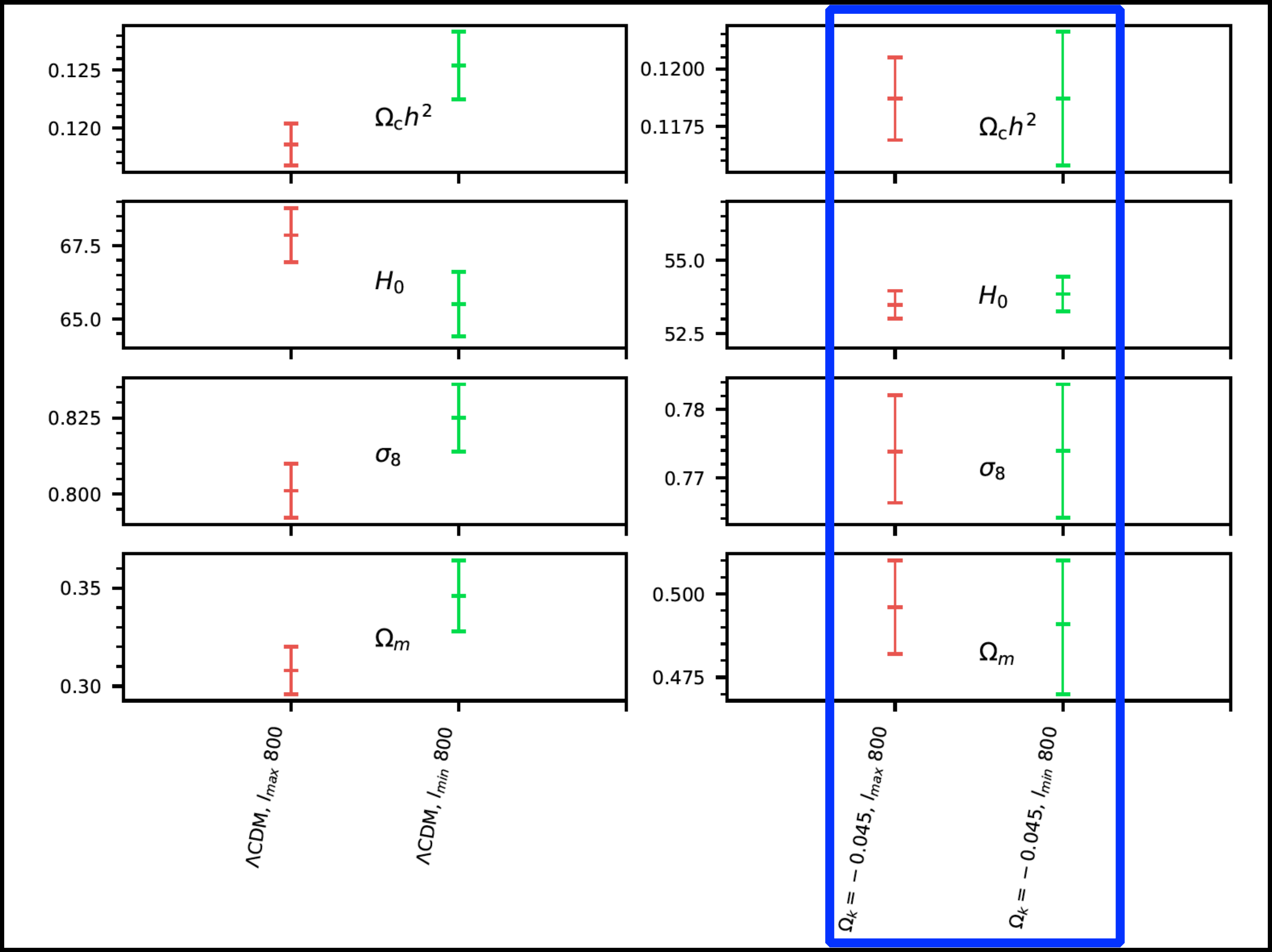

Di Valentino, Melchiorri and Silk, *Nature Astron.* 4 (2019) 2, 196-203

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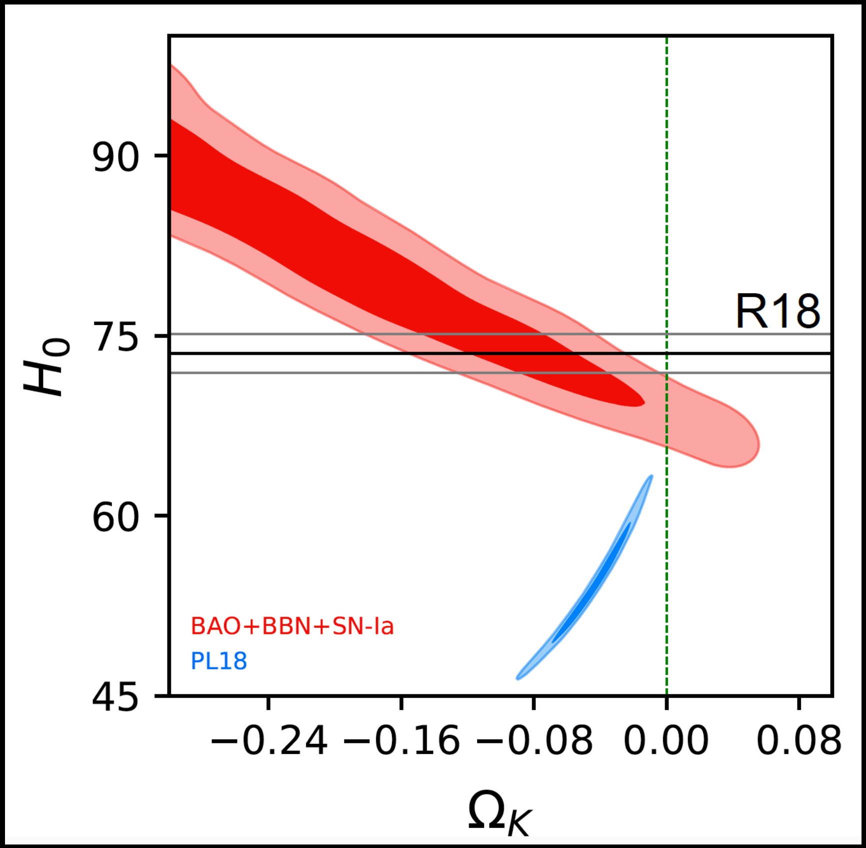
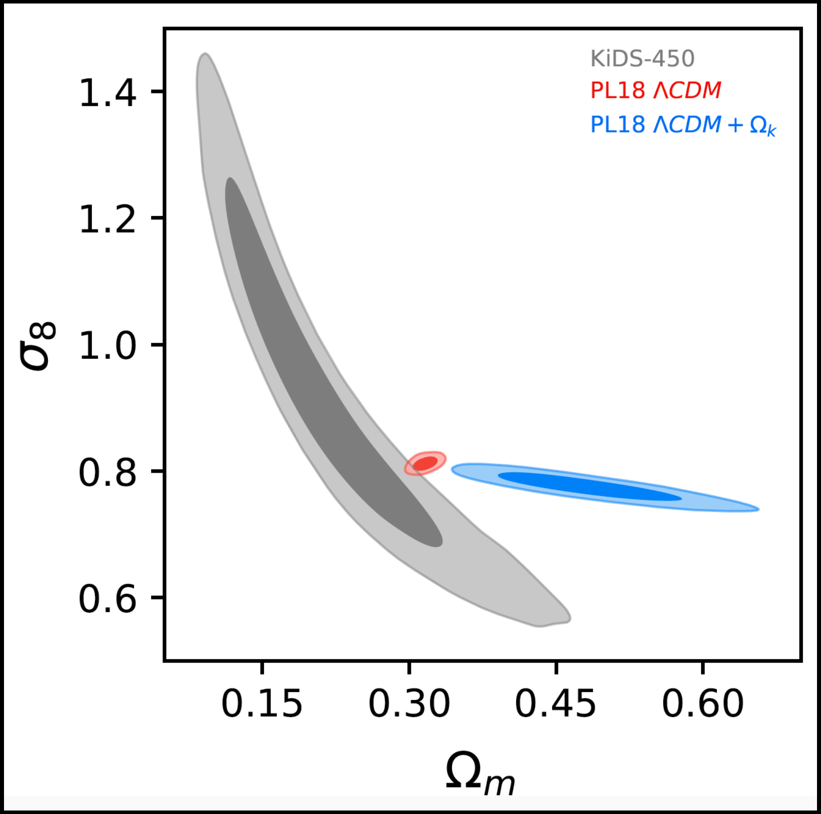
Curvature can't explain external tensions



Di Valentino, Melchiorri and Silk, *Nature Astron.* 4 (2019) 2, 196-203

Varying Ωκ, both the well known tensions on H0 and S8 are exacerbated.
In a ΛCDM + ΩK model, Planck gives $H0 = 54.4^{+3.3}_{-4.0}$ km/s/Mpc at 68% cl., increasing the tension with SH0ES at 5.5σ.

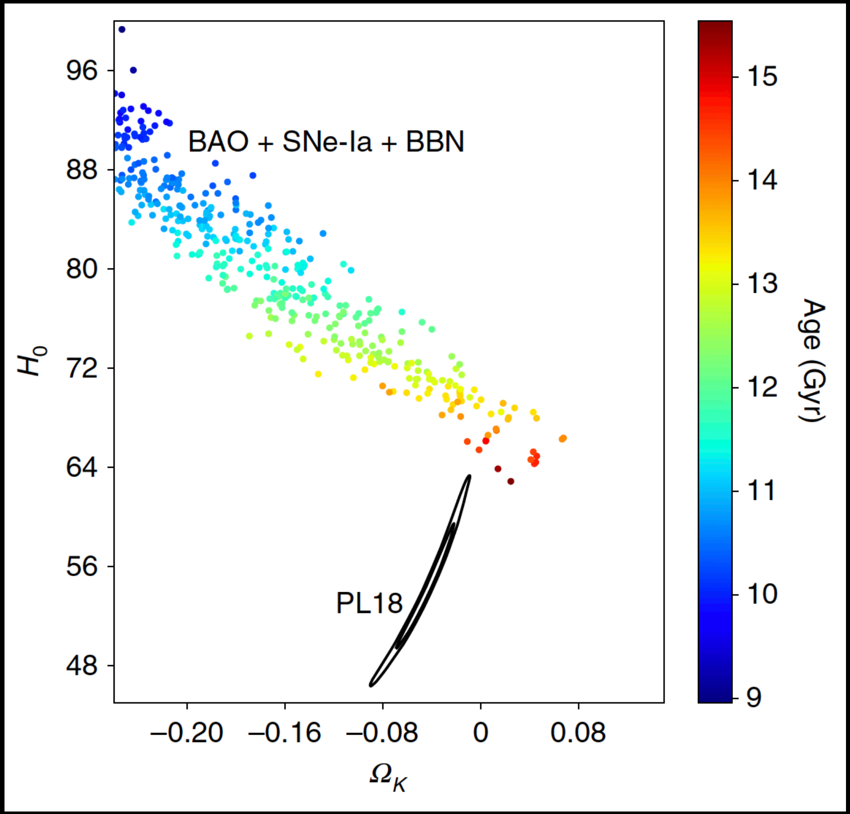
Curvature can't explain external tensions



Di Valentino, Melchiorri and Silk, *Nature Astron.* 4 (2019) 2, 196-203

Varying Ωκ, both the well known tensions on H0 and S8 are exacerbated.
In a ΛCDM + ΩK model, Planck gives S8 in disagreement at about 3.8σ with KiDS-450, and more than 3.5σ with DES.

What about non-CMB data?



Di Valentino, Melchiorri and Silk, *Nature Astron.* 4 (2019) 2, 196-203

It is now interesting to address the compatibility of Planck with combined datasets, like BAO + type-Ia supernovae + big bang nucleosynthesis data.
In principle, each dataset prefers a closed universe,
but BAO+SN-Ia+BBN gives $H0 = 79.6 \pm 6.8$ km/s/Mpc at 68%cl, perfectly consistent with SH0ES, but at 3.4σ tension with Planck.

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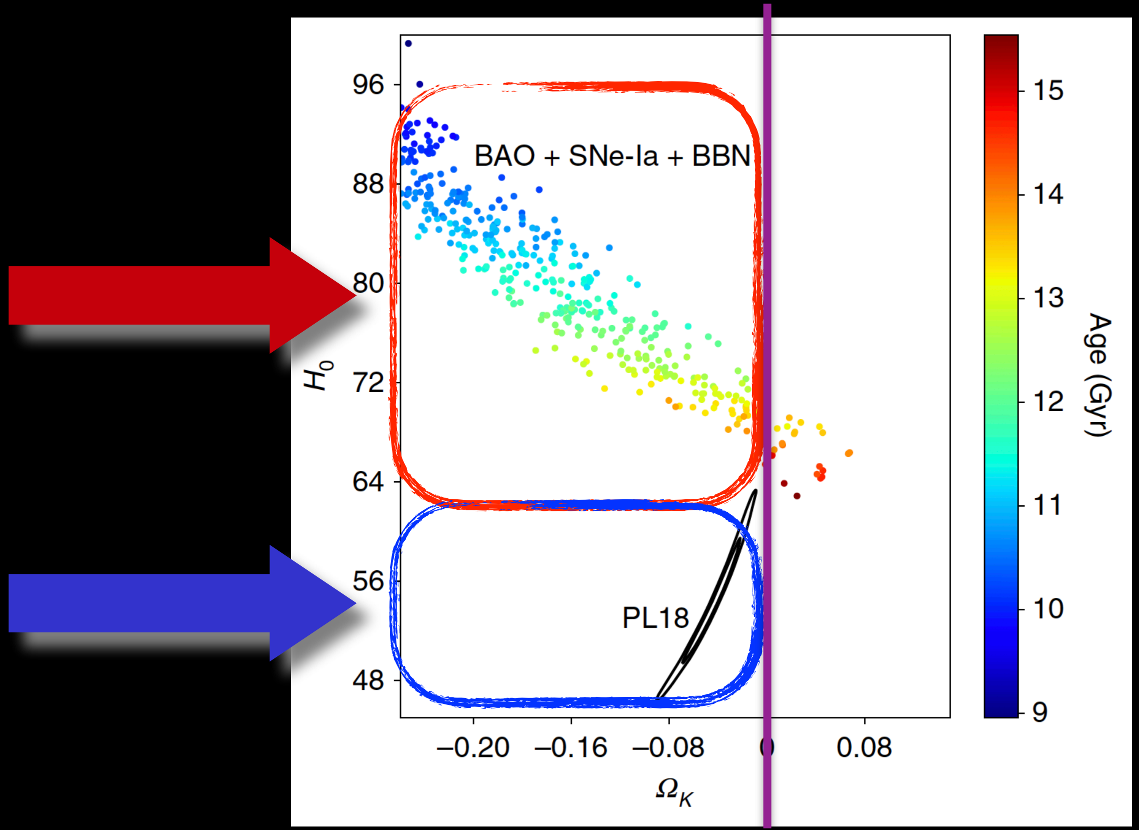

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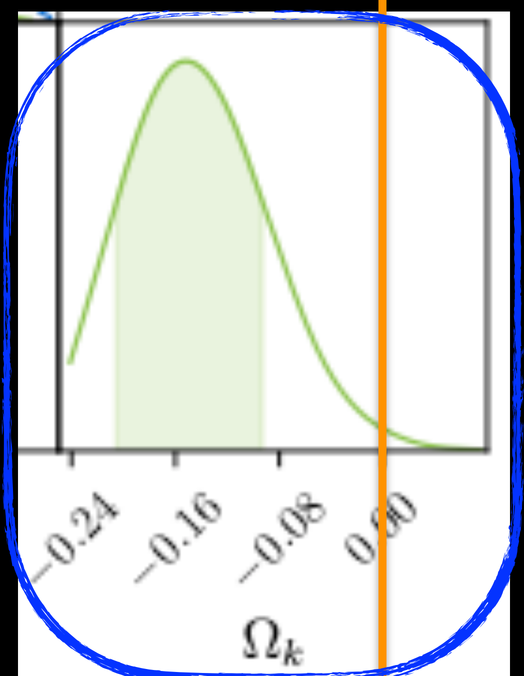
BAO+SNIa+BBN+R18 gives Ωk = −0.091 ± 0.037 at 68%cl.

EFTofLSS to investigate FS data

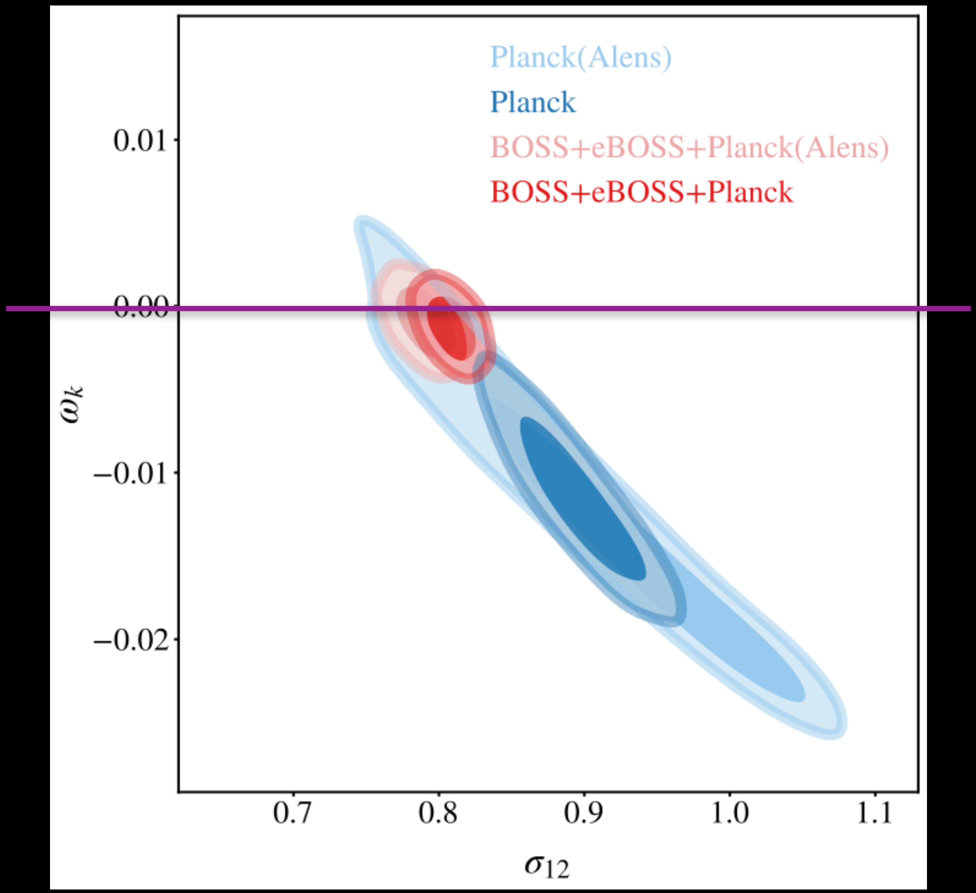
	$\ln(10^{10}A_s)$	h	$\Omega_{cdm}h^2$	Ω_m	Ω_k	n_s	$2*\log(\mathcal{L})$
Flat, fixed n_s	$2.85^{+0.11}_{-0.12}$ (3.03)	$0.667^{+0.011}_{-0.011}$ (0.672)	$0.114^{+0.005}_{-0.004}$ (0.115)	$0.307^{+0.010}_{-0.011}$ (0.304)	-	-	367.2
Curved, fixed n_s	$2.55^{+0.21}_{-0.22}$ (2.77)	$0.686^{+0.015}_{-0.016}$ (0.665)	$0.115^{+0.004}_{-0.005}$ (0.111)	$0.291^{+0.014}_{-0.013}$ (0.302)	$-0.089^{+0.049}_{-0.046}$ (−0.042)	-	366.3
Flat, varying n_s	$2.80^{+0.14}_{-0.13}$ (2.97)	$0.669^{+0.012}_{-0.011}$ (0.668)	$0.117^{+0.009}_{-0.008}$ (0.114)	$0.312^{+0.017}_{-0.014}$ (0.304)	-	$0.950^{+0.04}_{-0.051}$ (0.972)	367.1
Curved, varying n_s	$2.19^{+0.29}_{-0.28}$ (2.62)	$0.707^{+0.021}_{-0.021}$ (0.686)	$0.127^{+0.011}_{-0.009}$ (0.116)	$0.300^{+0.016}_{-0.014}$ (0.295)	$-0.152^{+0.059}_{-0.053}$ (−0.089)	$0.878^{+0.053}_{-0.055}$ (0.932)	364.8



Glanville et al., *arXiv:2205.05892*

In this paper they use EFTofLSS to simultaneously constrain measurements from the 6dFGS, BOSS, and eBOSS catalogues, in order to remove some of the assumptions of flatness that enter into other large-scale structure analyses. Fitting the FS data with a BBN prior they measure a >2σ preference for a closed universe.

Beyond six parameters: extending ΛCDM+Ωk



Semenaite et al., arXiv:2210.07304

A similar result has been obtained by analysing a wKCDM model, and the parameter $\omega_K = \Omega_k h^2$ that gives

$$\omega_K = -0.0116^{+0.0029}_{-0.0036}$$

i.e. a 4σ preference for a closed universe.

Constraints at 68% cl.

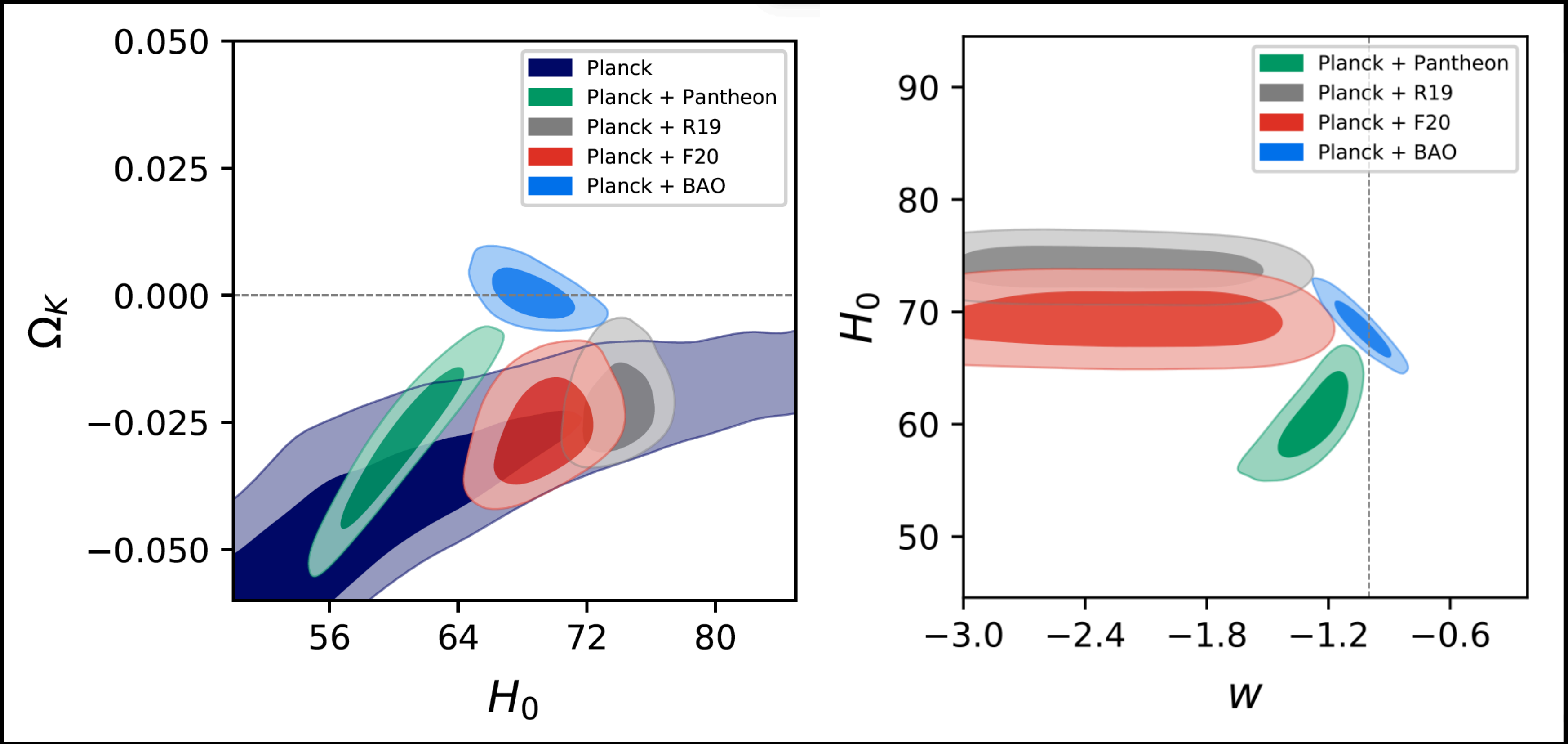
Beyond six parameters: extending ΛCDM+Ωk

Parameters	Planck	Planck +R19	Planck +F20	Planck +BAO	Planck + Pantheon
$\Omega_b h^2$	0.02253 ± 0.00019	$0.02253^{+0.00020}_{-0.00016}$	$0.02255^{+0.00019}_{-0.00017}$	0.02243 ± 0.00016	0.02255 ± 0.00018
$\Omega_c h^2$	0.1183 ± 0.0016	$0.1187^{+0.0015}_{-0.0018}$	0.1184 ± 0.0015	0.1198 ± 0.0014	0.1186 ± 0.0015
$100\theta_{\rm MC}$	1.04099 ± 0.00035	$1.04103^{+0.00034}_{-0.00031}$	1.04105 ± 0.00034	1.04095 ± 0.00032	1.04107 ± 0.00034
τ	0.0473 ± 0.0083	$0.052^{+0.009}_{-0.011}$	0.0491 ± 0.0079	0.0563 ± 0.0081	0.0506 ± 0.0082
Σm_ν [eV]	$0.43^{+0.16}_{-0.37}$	< 0.513	$0.28^{+0.11}_{-0.23}$	< 0.194	< 0.420
w	$-1.6^{+1.0}_{-0.8}$	$-2.11^{+0.35}_{-0.77}$	-2.14 ± 0.46	$-1.038^{+0.098}_{-0.088}$	$-1.27^{+0.14}_{-0.09}$
Ω_k	$-0.074^{+0.058}_{-0.025}$	$-0.0192^{+0.0036}_{-0.0099}$	$-0.0263^{+0.0060}_{-0.0077}$	$0.0003^{+0.0027}_{-0.0037}$	$-0.029^{+0.011}_{-0.010}$
$\ln(10^{10}A_s)$	3.025 ± 0.018	$3.037^{+0.016}_{-0.026}$	3.030 ± 0.017	3.049 ± 0.017	3.034 ± 0.017
n_s	0.9689 ± 0.0054	$0.9686^{+0.0056}_{-0.0050}$	0.9693 ± 0.0051	0.9648 ± 0.0048	0.9685 ± 0.0051
α_S	-0.0005 ± 0.0067	-0.0012 ± 0.0066	-0.0010 ± 0.0068	-0.0054 ± 0.0068	-0.0023 ± 0.0065
H_0[km/s/Mpc]	53^{+6}_{-16}	73.8 ± 1.4	69.3 ± 2.0	$68.6^{+1.5}_{-1.8}$	60.5 ± 2.5
σ_8	$0.74^{+0.08}_{-0.16}$	0.932 ± 0.040	0.900 ± 0.039	0.821 ± 0.027	$0.812^{+0.031}_{-0.018}$
S_8	$0.989^{+0.095}_{-0.063}$	0.874 ± 0.032	$0.900^{+0.034}_{-0.031}$	0.826 ± 0.016	0.927 ± 0.037
Age[Gyr]	$16.10^{+0.92}_{-0.80}$	$14.90^{+0.72}_{-0.32}$	$15.22^{+0.054}_{-0.038}$	13.77 ± 0.10	14.98 ± 0.39
Ω_m	$0.61^{+0.21}_{-0.34}$	$0.264^{+0.010}_{-0.013}$	$0.300^{+0.017}_{-0.020}$	0.305 ± 0.016	$0.393^{+0.030}_{-0.036}$
$\Delta\chi^2_{bestfit}$	0.0	0.62	0.88	14.77	1037.82

We want to check the robustness of these results further increasing the number of parameters, in addition to curvature.

Di Valentino, Melchiorri and Silk, ApJ Letters, 908, L9 (2021), arXiv:2003.04935

Cosmic Discordance

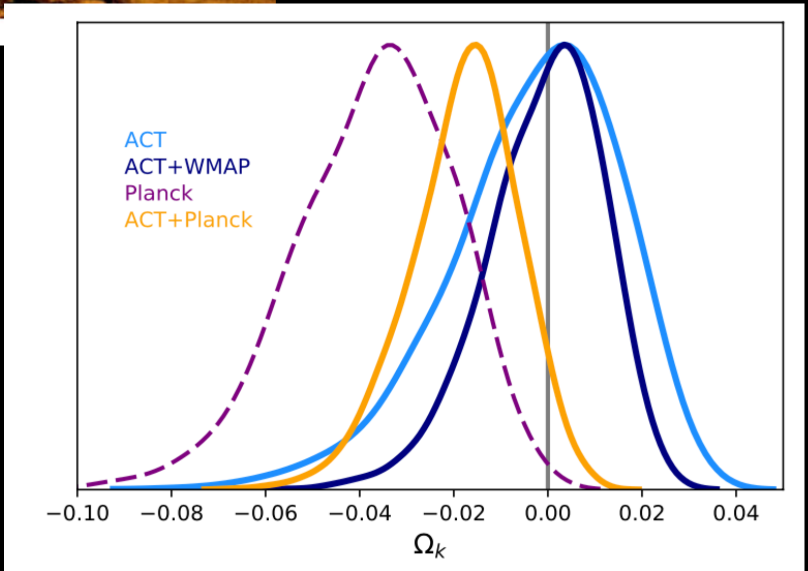


Evidence for a phantom closed Universe at more than 99% CL!!

It is interesting to note that if a closed universe increases the fine-tuning of the theory, the removal of a cosmological constant reduces it. It is, therefore, difficult to decide whether a phantom closed model is less or more theoretically convoluted than ΛCDM.

Di Valentino, Melchiorri and Silk, ApJ Letters, 908, L9 (2021), arXiv:2003.04935

What about different CMB experiments?



ACT-DR4 + WMAP gives at 68% CL

$$\Omega_k = -0.001 \pm 0.012$$

ACT-DR4 2020, Aiola et al., arXiv:2007.07288 [astro-ph.CO]

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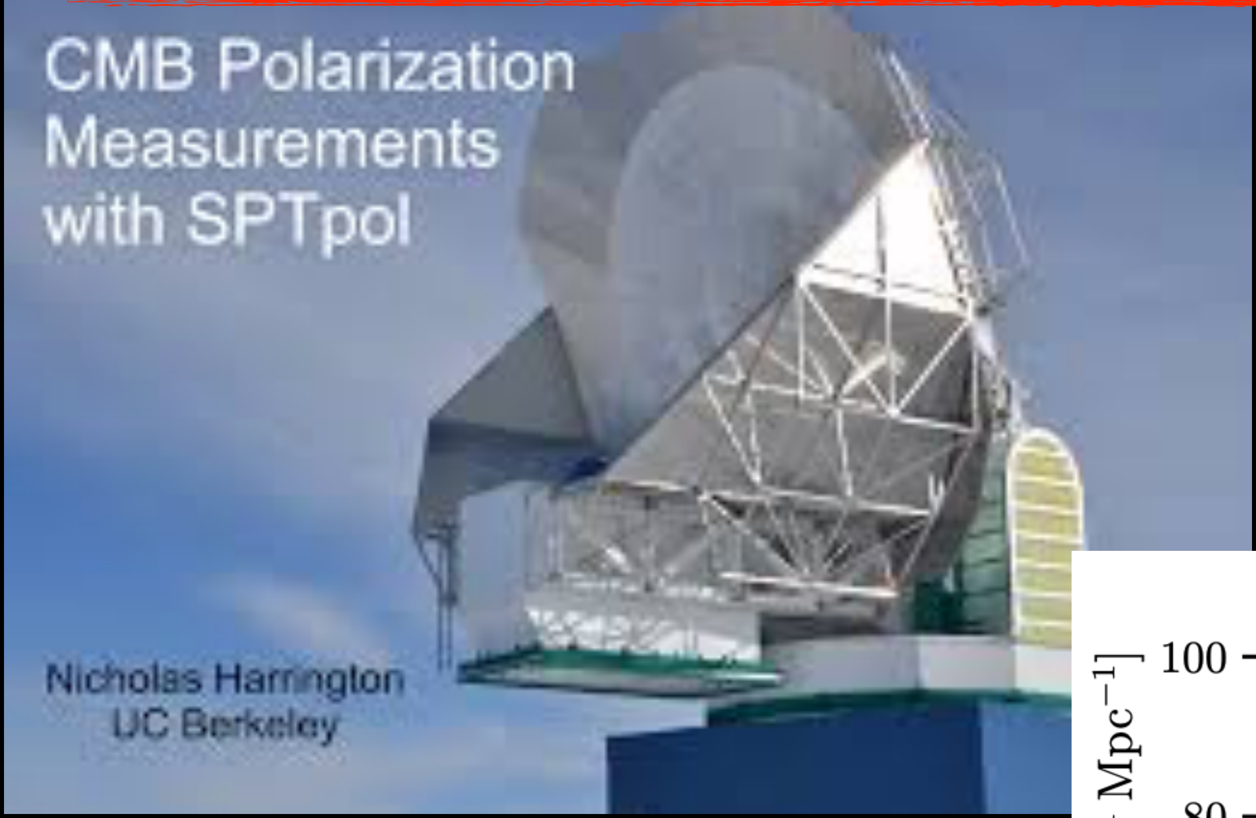
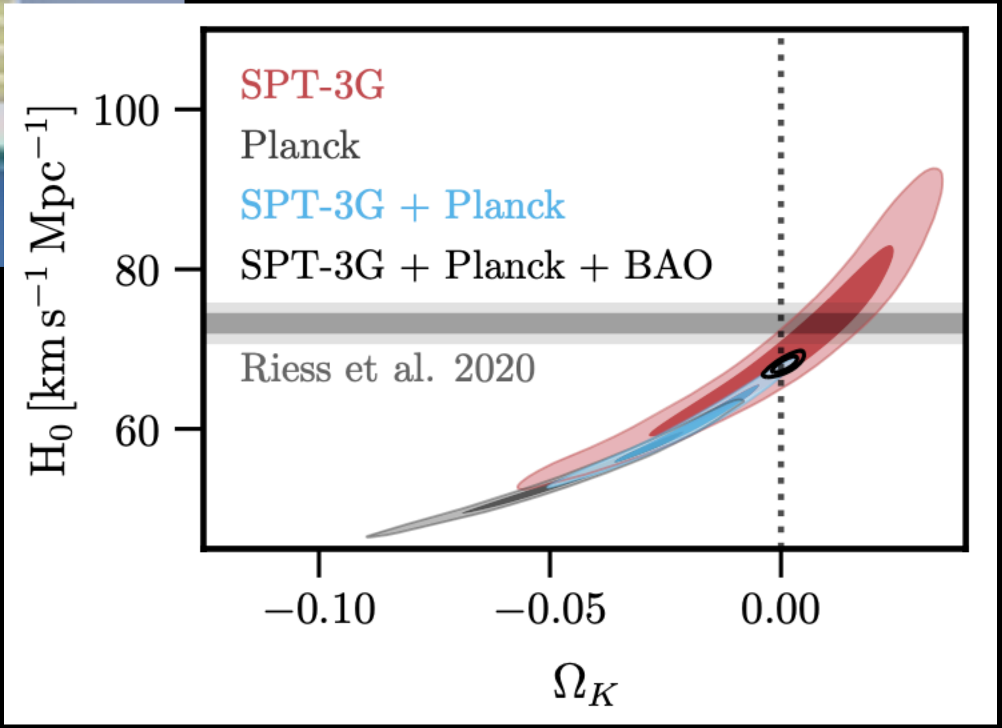


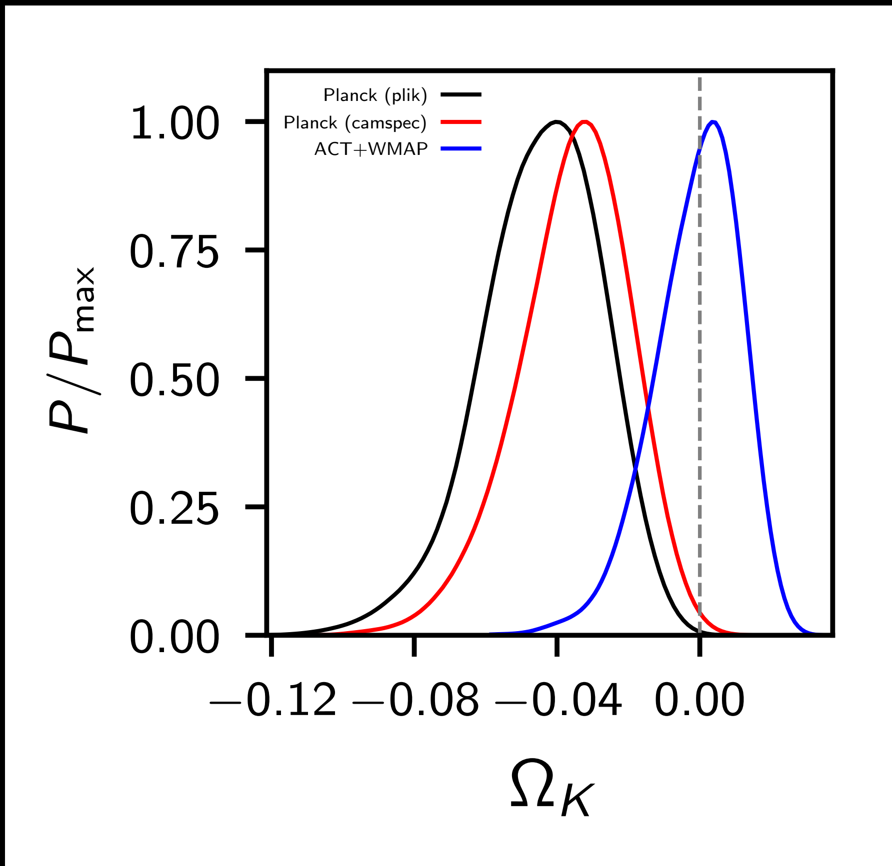


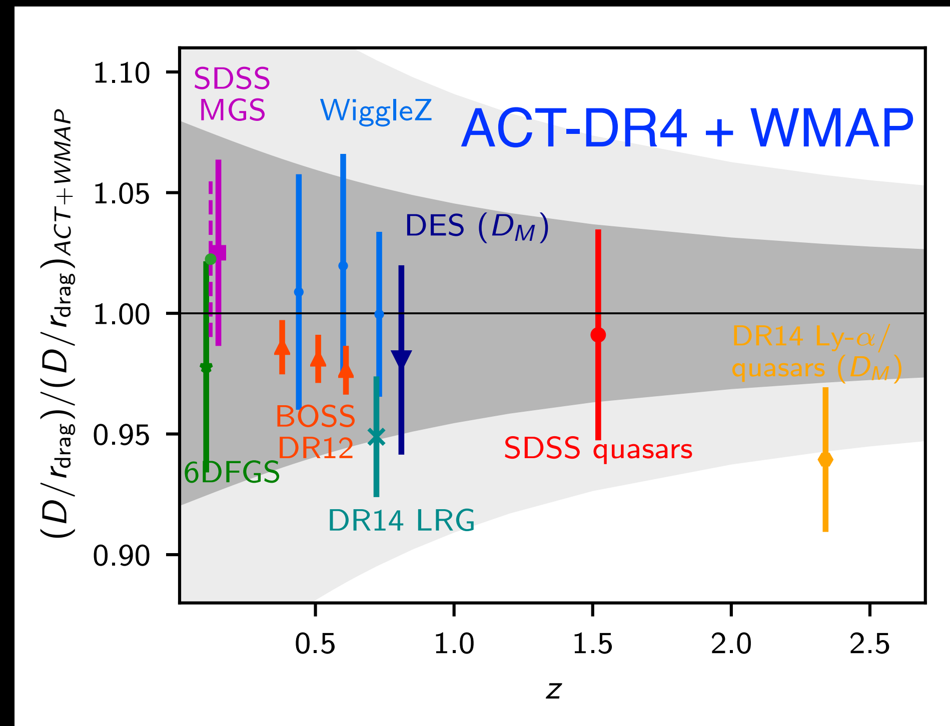
SPT-3G, arXiv:2103.13618 [astro-ph.CO]

SPT-3G gives at 68% CL:

$$\Omega_K = 0.001^{+0.018}_{-0.019}$$

ACT-DR4



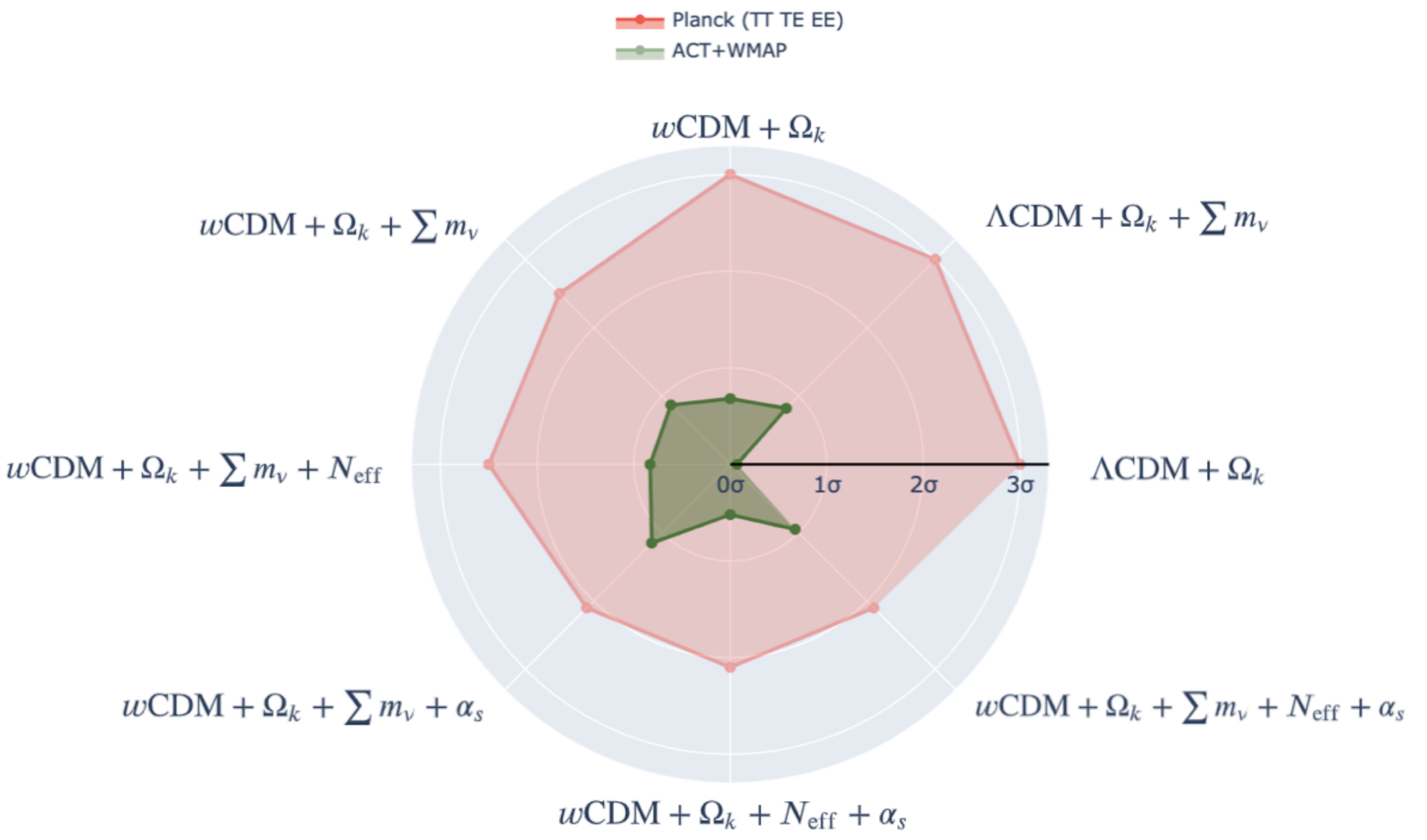


Di Valentino, Universe 2022, 8(8), 399

Confirmation that from a CMB experiment you can obtain OmegaK!

When precise CMB measurements at arc-minute angular scales are included, since gravitational lensing depends on the matter density, its detection breaks the geometrical degeneracy.

Tension with $\Omega_k = 0$



Di Valentino et al., arXiv:2209.12872

And the indication we see in the simplest LCDM+ Ω_k model is robust also in its extensions.

Inflation: $\Omega_k < 0$ or HZ?

Dataset	Scalar Spectral Index (n_s)
	ΛCDM
ACT	1.009 ± 0.015
ACT+BAO (DR12)	1.006 ± 0.013
ACT+BAO (DR16)	1.006 ± 0.014
ACT+DESy1	1.007 ± 0.013
ACT+SPT+BAO (DR12)	0.996 ± 0.012
Planck	0.9649 ± 0.0044
Planck+BAO (DR12)	0.9668 ± 0.0038
Planck+BAO (DR16)	0.9677 ± 0.0037
Planck ($2 \leq \ell \leq 650$)	0.9655 ± 0.0043
Planck ($\ell > 650$)	0.9634 ± 0.0085

Giarè, Renzi, Mena, Di Valentino, and Melchiorri, arXiv:2210.09018

At this point, if Planck seems to disfavour the inflationary prediction for a flat background geometry at more than 3σ, ACT, although in perfect agreement with spatial flatness, shows a preference for a larger spectral index consistent with a Harrison-Zel'dovich scale-invariant spectrum ns=1 of primordial density perturbations introducing a tension with a significance of 2.7σ with the results from the Planck satellite.

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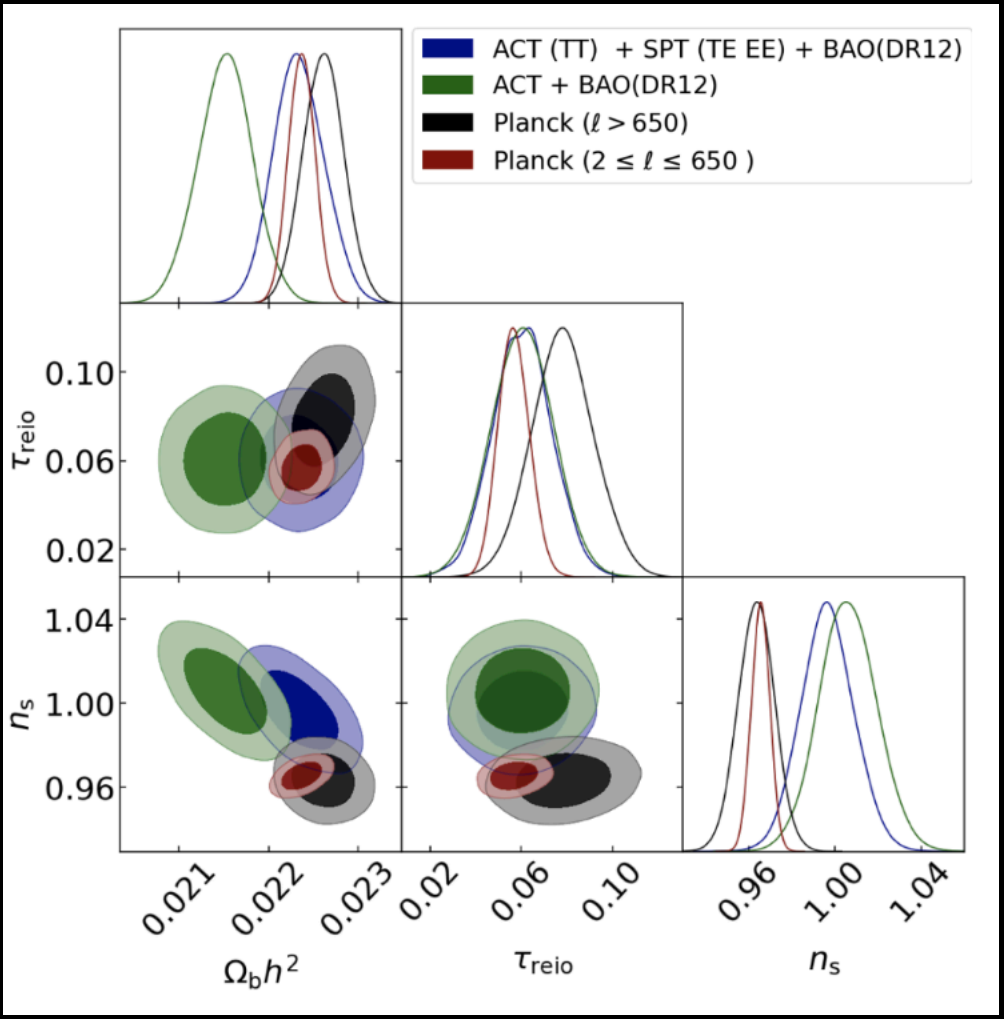
Giarè, Renzi, Mena, Di Valentino, and Melchiorri, arXiv:2210.09018

In ACT-DR4 2020, arXiv:2007.07288 [astro-ph.CO] this discrepancy was interpreted as a consequence of the lack of information concerning the first acoustic peak of the temperature power spectrum.
To verify this origin of the discrepancy in the CMB values of ns, we have performed two separate analyses of the Planck observations, splitting the likelihood into low 2< l < 650 and high l > 650 multipoles. We find that the discrepancy still persists at the level of 3σ (2σ) for low (high) multiple temperature data.
Planck data still prefer a value of the scalar spectral index smaller than unity at ~4.3σ when the information about the first acoustic peak is removed.

Inflation: $\Omega_k < 0$ or HZ?

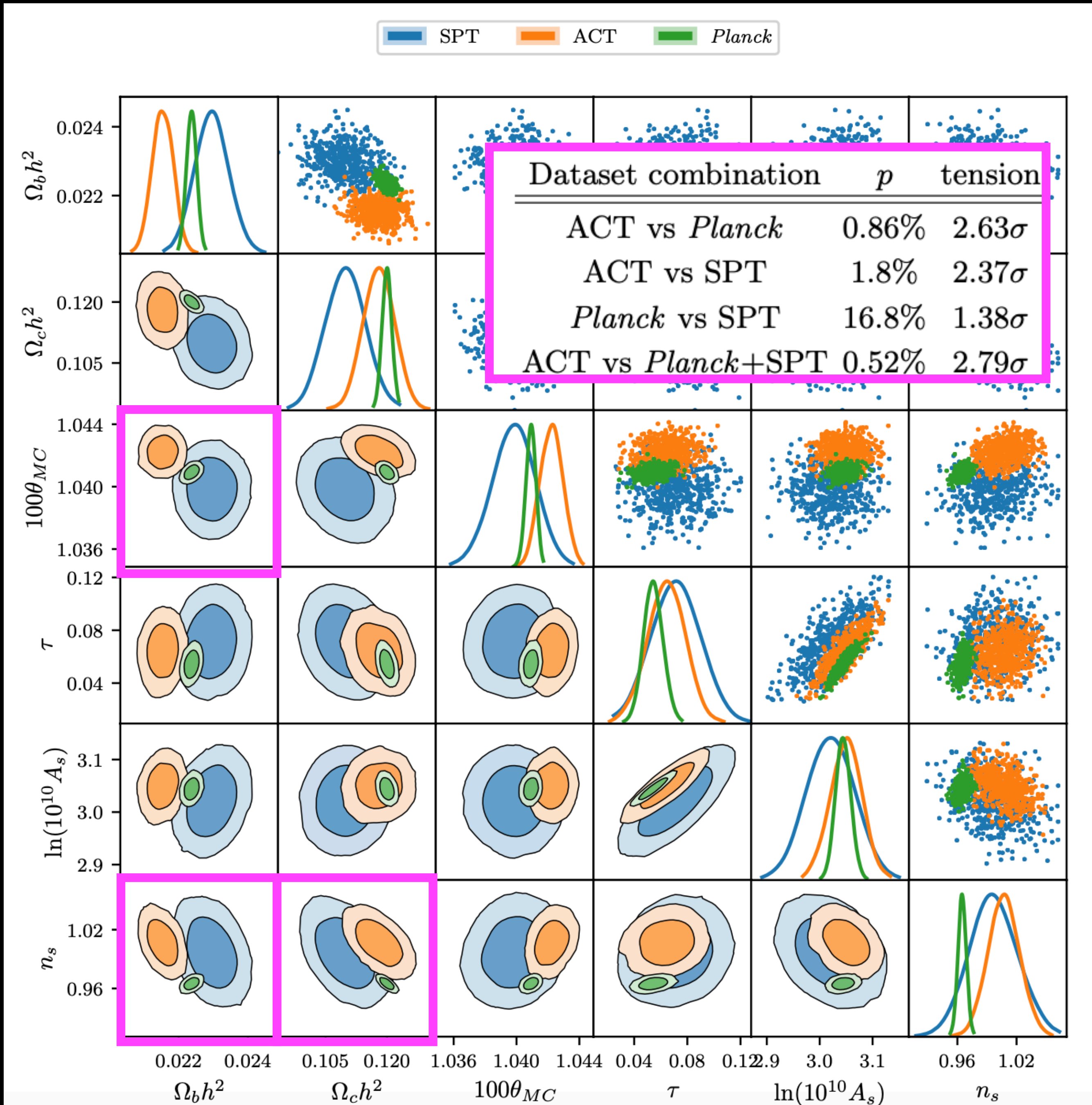


Such preference remains robust under the addition of large scale structure information, and in the two-dimensional plane it can be definitely noted that the direction of the $\Omega_b h^2$ - ns degeneracy is opposite for ACT and Planck, and the disagreement here is significantly exceeding 3σ. This tension is partially driven by the ACT polarization data, as we can see replacing it with the SPT polarization measurements, but while the tension is relaxed in the plane $\Omega_b h^2$ - ns, this combination is still preferring ns=1.

Giarè, Renzi, Mena, Di Valentino, and Melchiorri, arXiv:2210.09018

Alternative CMB 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.

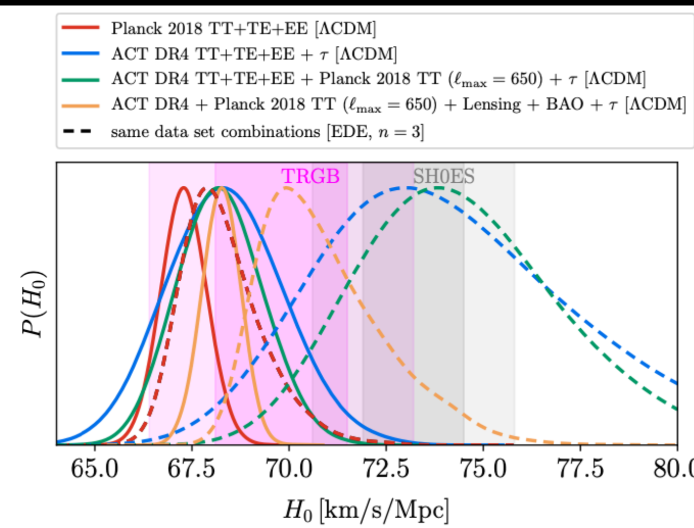
Between Planck and ACT there is a 2.6σ tension.

Assuming LCDM

ACT-DR4 vs Planck: EDE

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	$3.66^{+[illegible]}_{-0.28}$	$3.54^{+[illegible]}_{-0.20}$
$\boldsymbol{\theta_i}$	> 0.24	< 2.89	< 2.82	> 0.36	> 0.51
$\boldsymbol{\Omega_c h^2}$	$0.1307^{+0.0054}_{-0.0120}$	$0.1291^{+0.0051}_{[illegible]}$	$0.1286^{+0.0027}_{[illegible]}$	$0.1234^{+0.0019}_{-0.0038}$	$0.1244^{+0.0025}_{-0.0051}$
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*

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.
The evidence for EDE > 3σ persists with the inclusion of Planck lensing + BAO data, but shifting H0 towards a lower value.
Once the full Planck data are considered, the evidence for EDE disappears and H0 is again in tension with SH0ES.

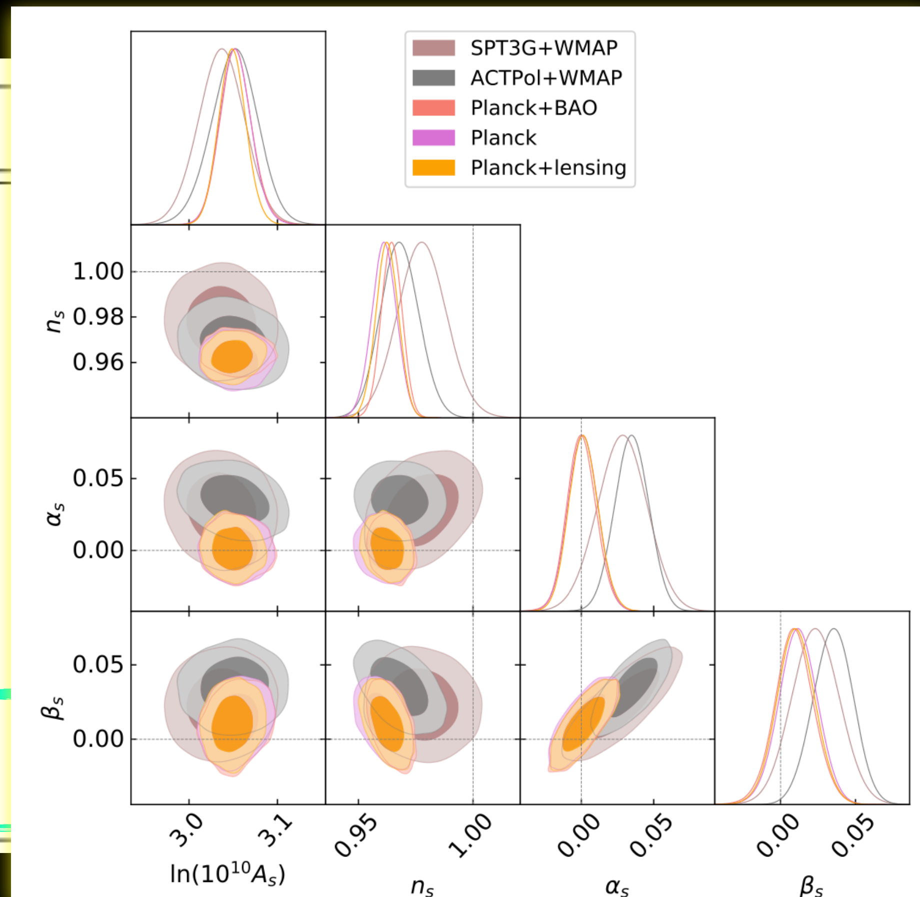
The Planck damping tail is in disagreement with EDE different from zero.

ACT-DR4 vs Planck: α_s and β_s.

Forconi, Giarè, Di Valentino and Melchiorri, *Phys.Rev.D* 104 (2021) 10, 103528

Parameter	Planck18	ACTPol + WMAP
$\Omega_b h^2$	0.02235 ± 0.00017	0.02195 ± 0.00025
$\Omega_c h^2$	0.1207 ± 0.0015	0.1190 ± 0.0029
		1.04174 ± 0.00066
		0.061 ± 0.013
$\log(10^{10} A_S)$	3.053 ± 0.018	3.051 ± 0.026
n_s	0.9612 ± 0.0054	0.9680 ± 0.0082
α_s	0.001 ± 0.010	0.035 ± 0.012
β_s	0.012 ± 0.013	0.035 ± 0.013

$$\alpha_s \doteq \left[\frac{dn_s}{d\log k}\right]_{k=k_*} \qquad \beta_s \doteq \left[\frac{d\alpha_s}{d\log k}\right]_{k=k_*}$$



ACT-DR4 and SPT-3G are in agreement one with each other, but in disagreement with Planck, for the value of the running of the scalar spectral index α_s and of the running of the running β_s.

In particular ACT-DR4 + WMAP prefer both a non vanishing running α_s and running of the running β_s at the level of 2.9σ and 2.7σ, respectively.

Alternative CMB vs Planck: Σmν

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

Constraints at 68% CL

	Σm_ν [eV]
Planck ($+A_{\rm lens}$)	< 0.51
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

Moreover, we have a mildly suggestion from both the ACT-DR4 and SPT-3G data, when combined with WMAP, of 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.

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

Quantifying global CMB tension

Cosmological model	d	χ^2	p	$\log S$	Tension
ΛCDM	6	16.3	0.012	−5.17	$2.51\,\sigma$
$\Lambda\text{CDM} + A_{\text{lens}}$	7	18.5	0.00977	−5.77	$2.58\,\sigma$
$\Lambda\text{CDM} + N_{\text{eff}}$	7	13	0.0719	−3	$1.80\,\sigma$
$\Lambda\text{CDM} + \Omega_k$	7	16.5	0.0209	−4.75	$2.31\,\sigma$
wCDM	7	16.8	0.0187	−4.9	$2.35\,\sigma$
$\Lambda\text{CDM} + \sum m_\nu$	7	20.7	0.00421	−6.86	$2.86\,\sigma$
$\Lambda\text{CDM} + \alpha_s$	7	20.6	0.00448	−6.78	$2.84\,\sigma$
$w\text{CDM} + \Omega_k$	8	17.6	0.0249	−4.78	$2.24\,\sigma$
$\Lambda\text{CDM} + \Omega_k + \sum m_\nu$	8	21.2	0.00651	−6.62	$2.72\,\sigma$
$w\text{CDM} + \Omega_k + \sum m_\nu$	9	19.8	0.0195	−5.38	$2.34\,\sigma$
$w\text{CDM} + \Omega_k + \sum m_\nu + N_{\text{eff}}$	10	18.8	0.0434	−4.38	$2.02\,\sigma$
$w\text{CDM} + \Omega_k + \sum m_\nu + \alpha_s$	10	22	0.015	−6.01	$2.43\,\sigma$
$w\text{CDM} + \Omega_k + N_{\text{eff}} + \alpha_s$	10	20.9	0.0218	−5.45	$2.29\,\sigma$
$w\text{CDM} + \sum m_\nu + N_{\text{eff}} + \alpha_s$	10	31.1	0.000575	−10.5	$3.44\,\sigma$
$w\text{CDM} + \Omega_k + \sum m_\nu + N_{\text{eff}} + \alpha_s$	11	24.7	0.0102	−6.83	$2.57\,\sigma$

Di Valentino et al., arXiv:2209.14054

$\Lambda\text{CDM} + N_{\text{eff}}$	Planck	–	2.92 ± 0.19
	ACT-DR4	–	$2.35^{+0.40}_{-0.47}$

If we now study the global agreement between Planck and ACT in various cosmological models that differ by the inclusion of different combinations of additional parameters, we can use the Suspiciousness statistic, to quantify their global "CMB tension".

We find that the 2.5σ tension within the baseline ΛCDM, is reduced at the level of 1.8σ when Neff is significantly less than 3.044, while it ranges between 2.3σ and 3.5σ in all the other extended models.

Concluding

Most of the anomalies and tensions are involving the CMB data:

- H0 tension
- S8 tension
- $A_L > 1$ or $\Omega_K < 0$ for Planck
- α_s, β_s or 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!

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CA21136 - Addressing observational tensions in cosmology with systematics and fundamental physics (CosmoVerse)

Working Groups

Number	Title
1	Observational Cosmology and systematics
2	Data Analysis in Cosmology
3	Fundamental Physics

Action keywords

Cosmological surveys - Observation systematics - Gravitation - Fundamental physics - Dark Energy, Dark Matter