CONSTRAINTS ON COSMIC CURVATURE

September 11th 2022, Workshop on Tensions in Cosmology

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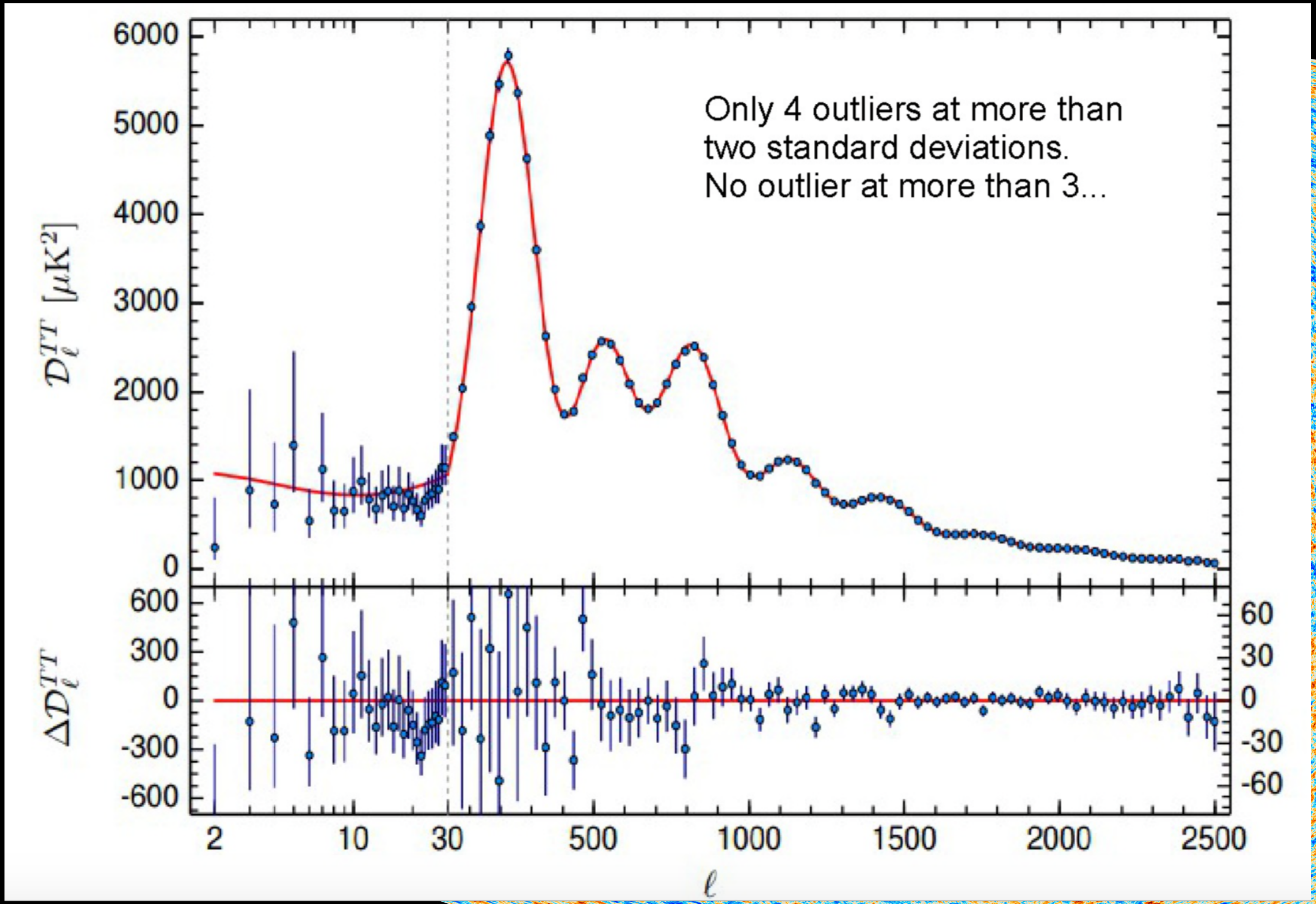
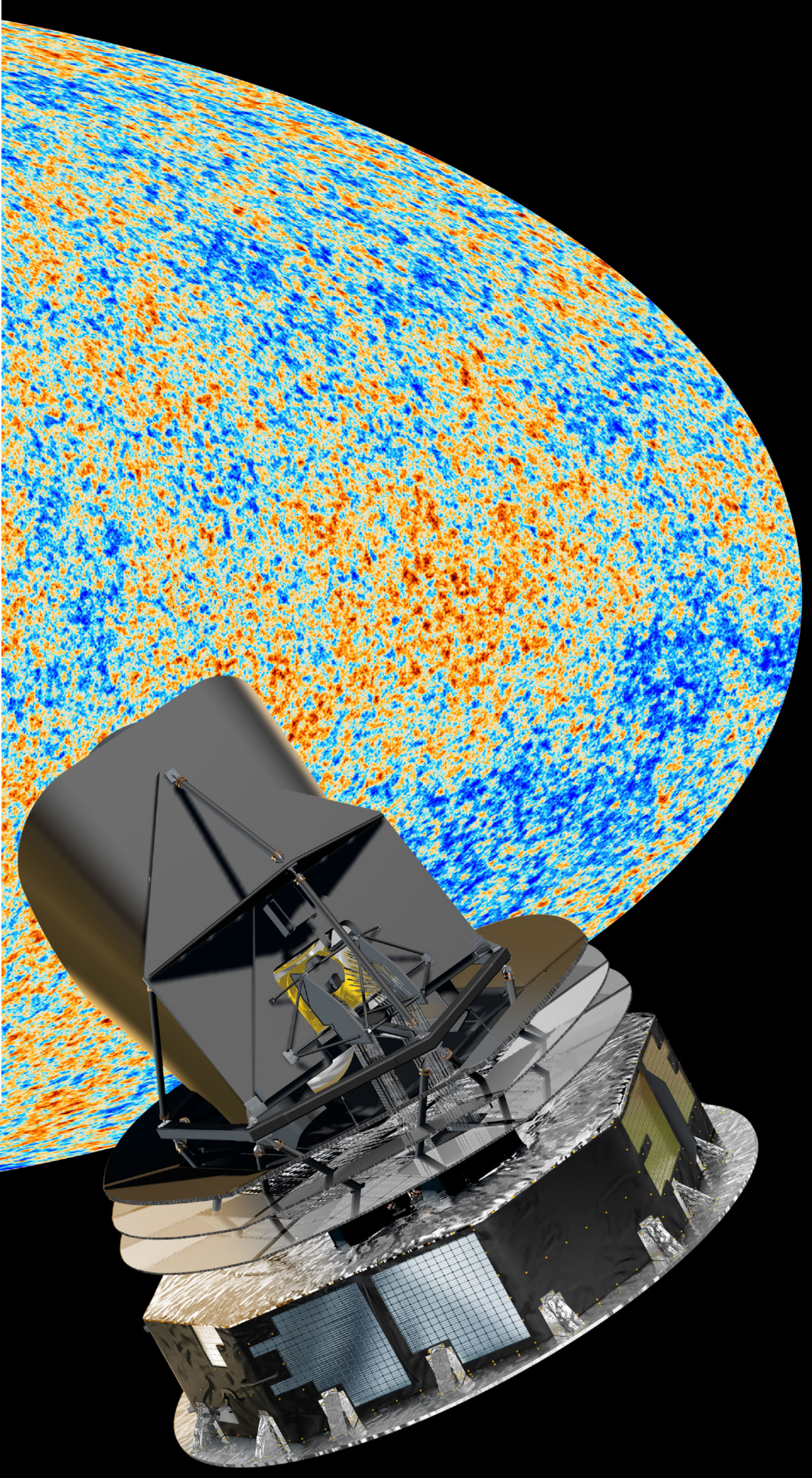
A PERFECT (LCDM) UNIVERSE ?



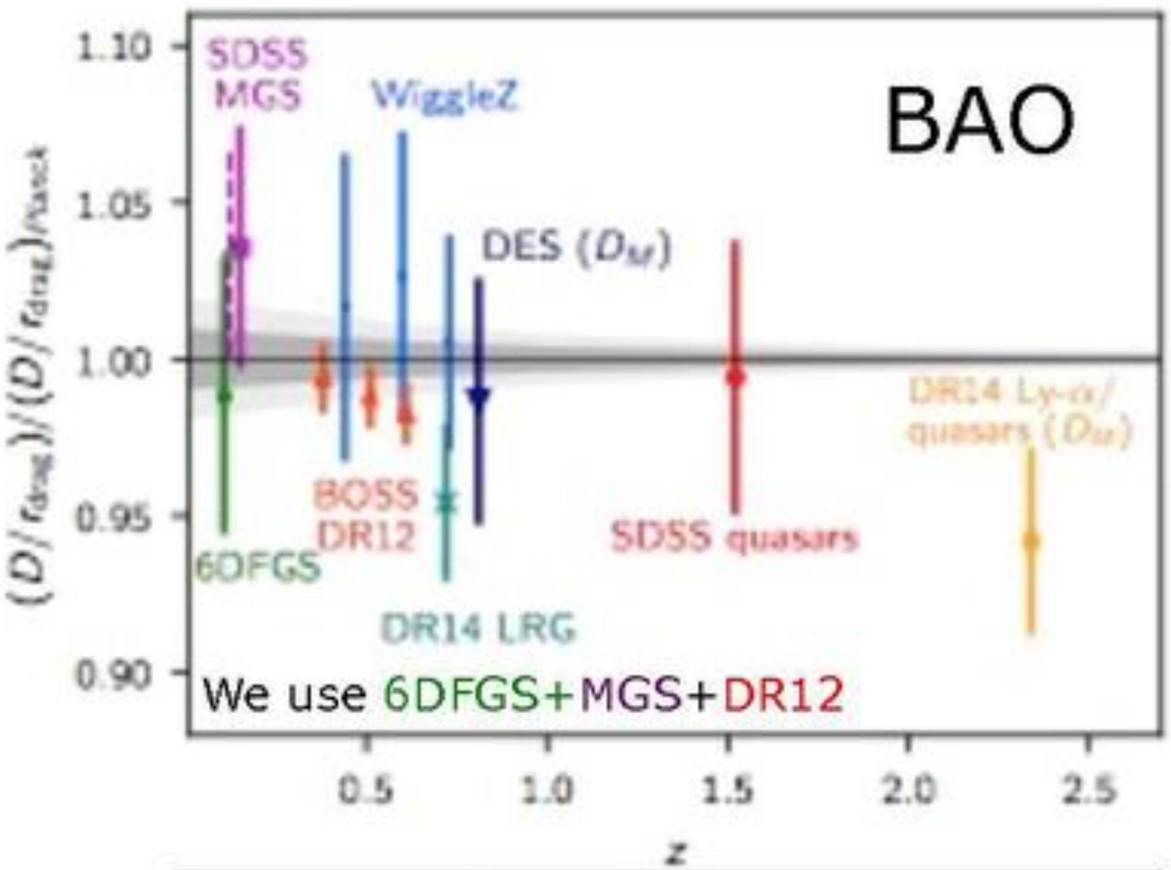
Only 4 outliers at more than two standard deviations. No outlier at more than 3...

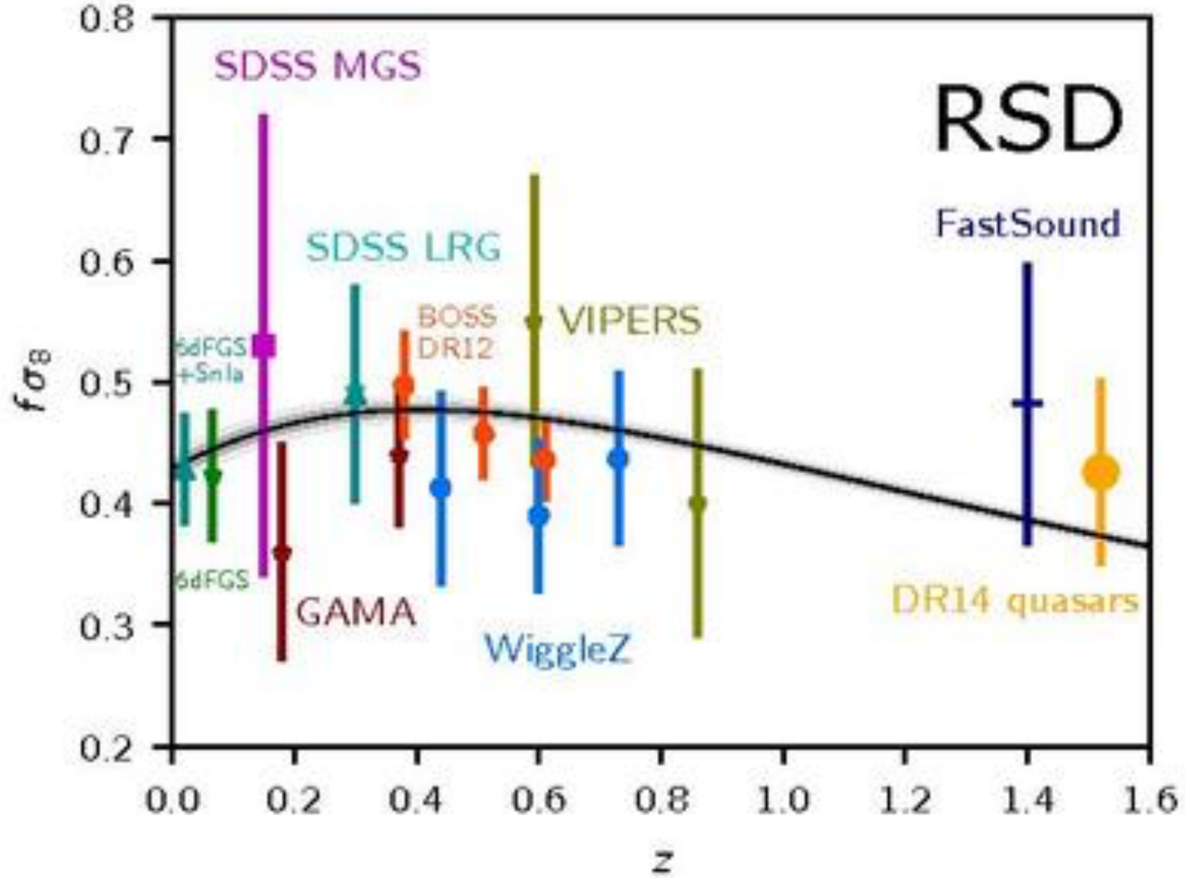


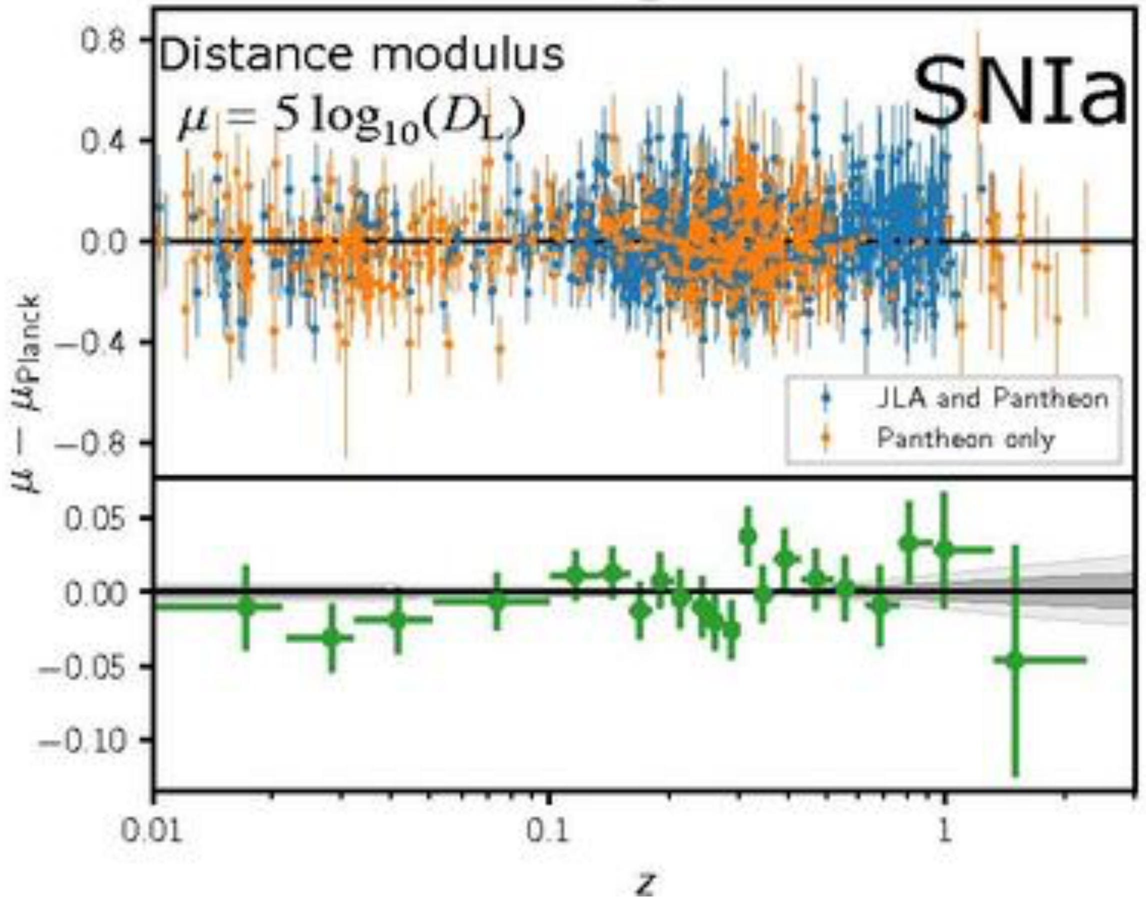
The recent CMB measurements made by the Planck satellite are in perfect agreement with the expectations of the LCDM model.

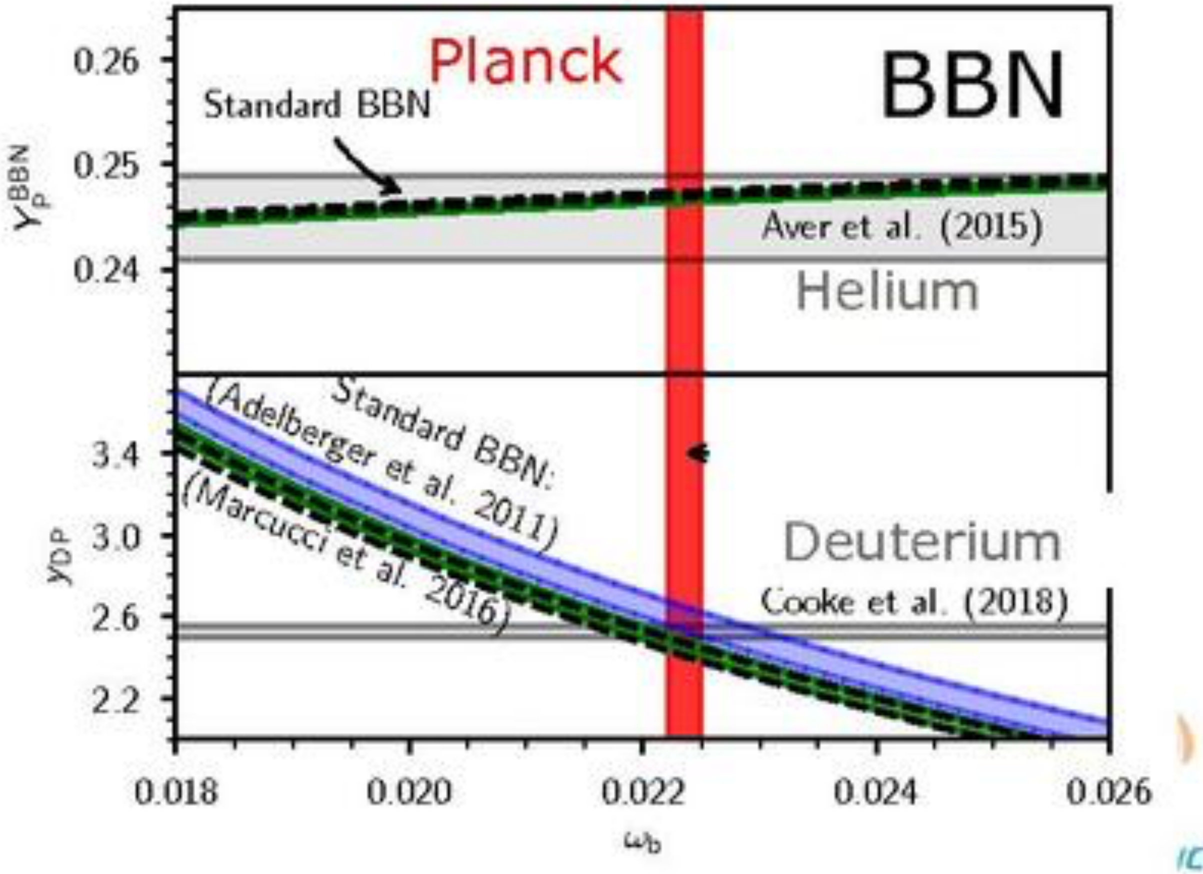
Planck collaboration, arXiv:1502.01589

Good consistency with BAO, RSD, SnIa, BBN









PLATO'S CAVE

True Model

LCDM

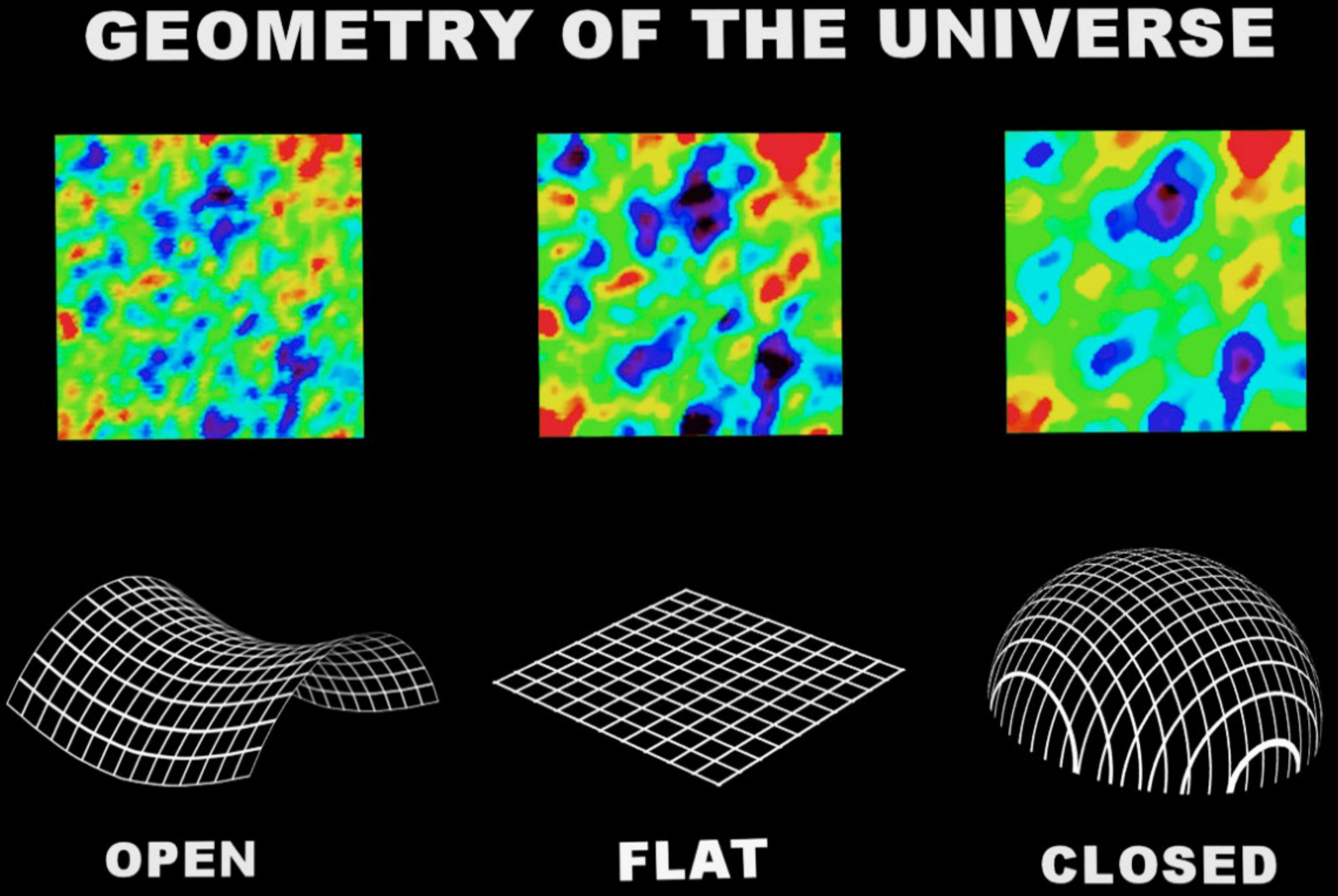
KEY ASSUMPTION: FLAT UNIVERSE

It is common practice to set the parameter that characterize the spatial curvature, ΩK , exactly to zero.

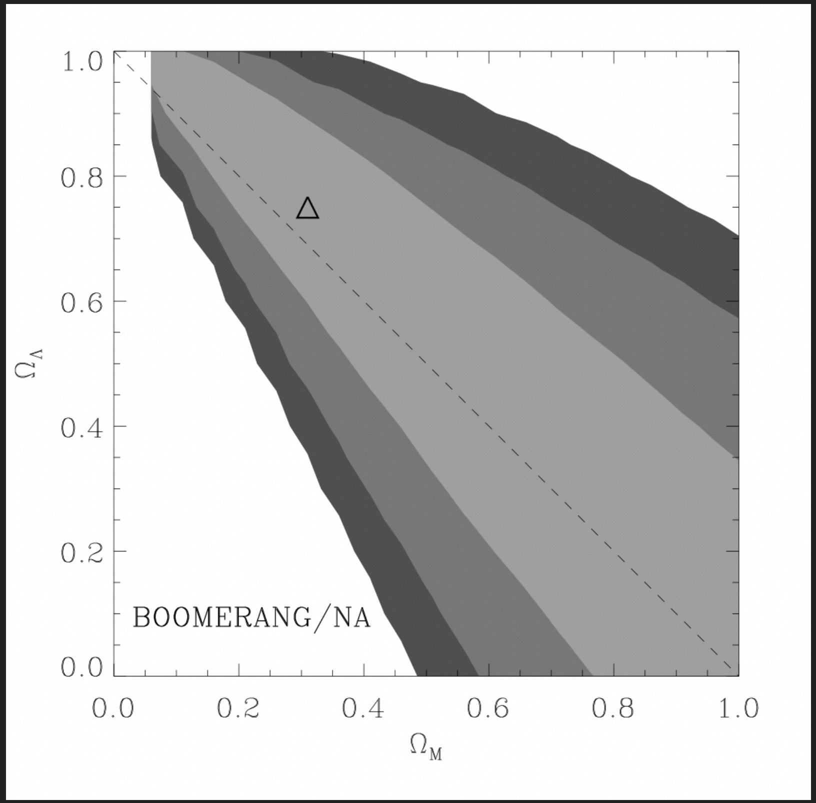
However (see Anselmi et al., 2022):

- Inflation generally predicts an Universe approximately flat, but models with curvature can be conceived.
- By assuming a flat universe we may introduce a bias in the determination of cosmological parameters and/or in the determination of the level of current tensions.
- Curvature is NOT new physics!
- If we have fluctuations we have curvature!

CMB ANISOTROPIES: MOST DIRECT WAY TO MEASURE CURVATURE!

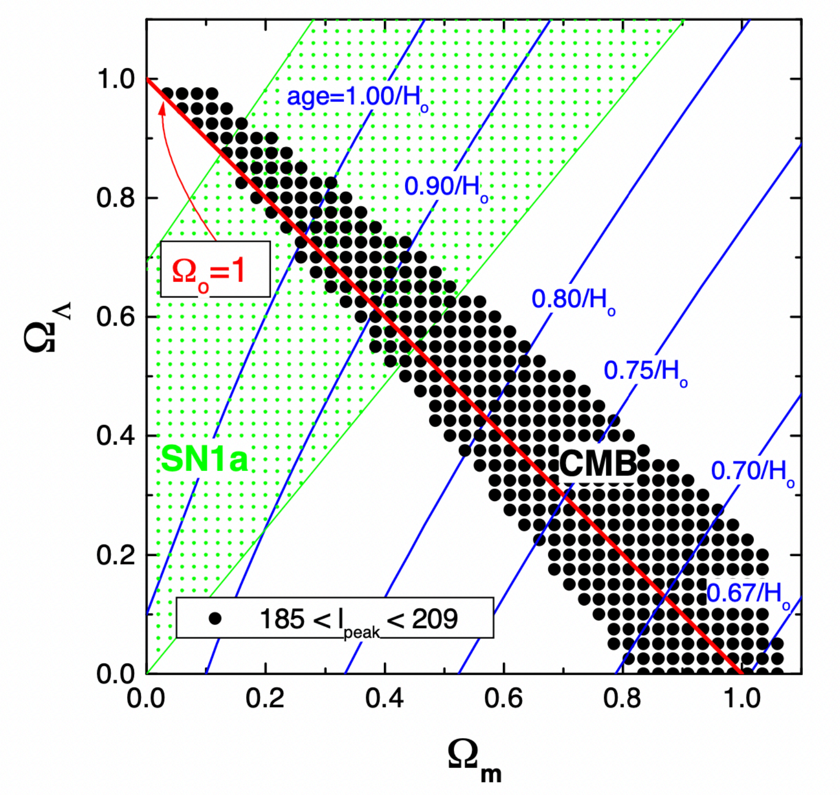


Boomerang 97



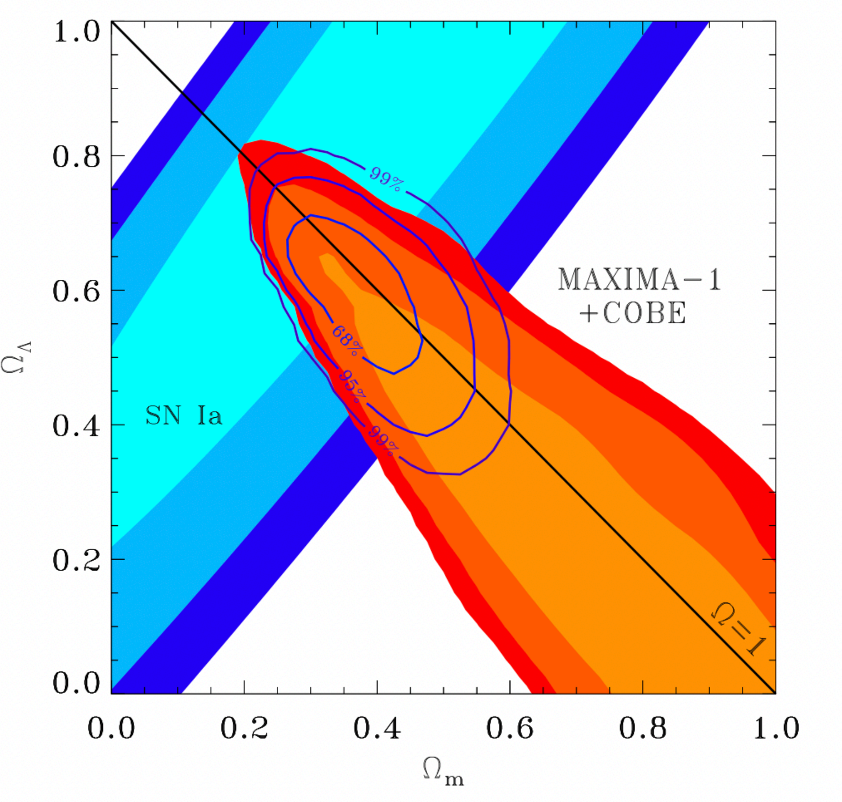
Melchiorri et al., 1999

Boomerang 98



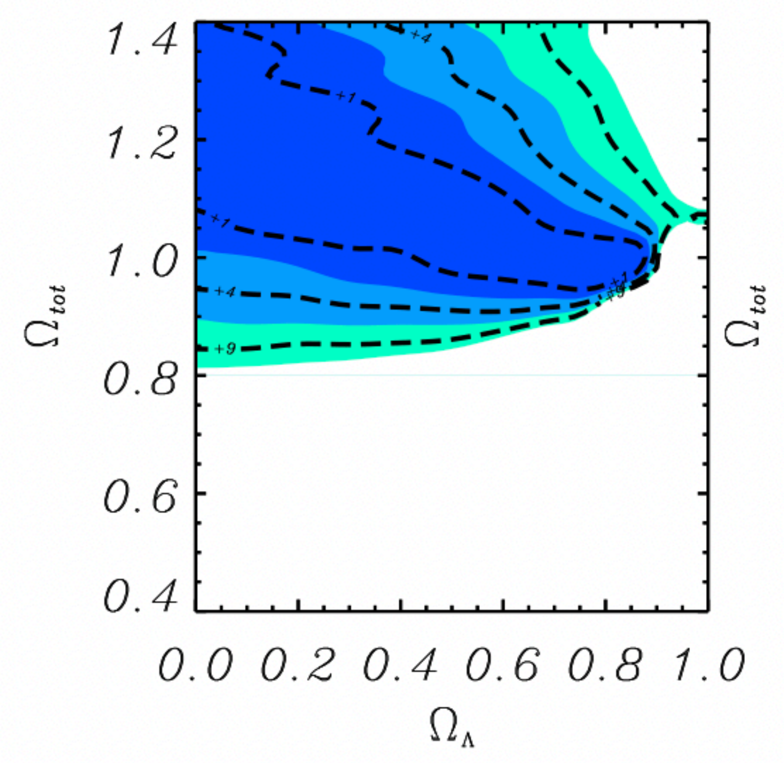
De Bernardis et al., 2000

Maxima-1



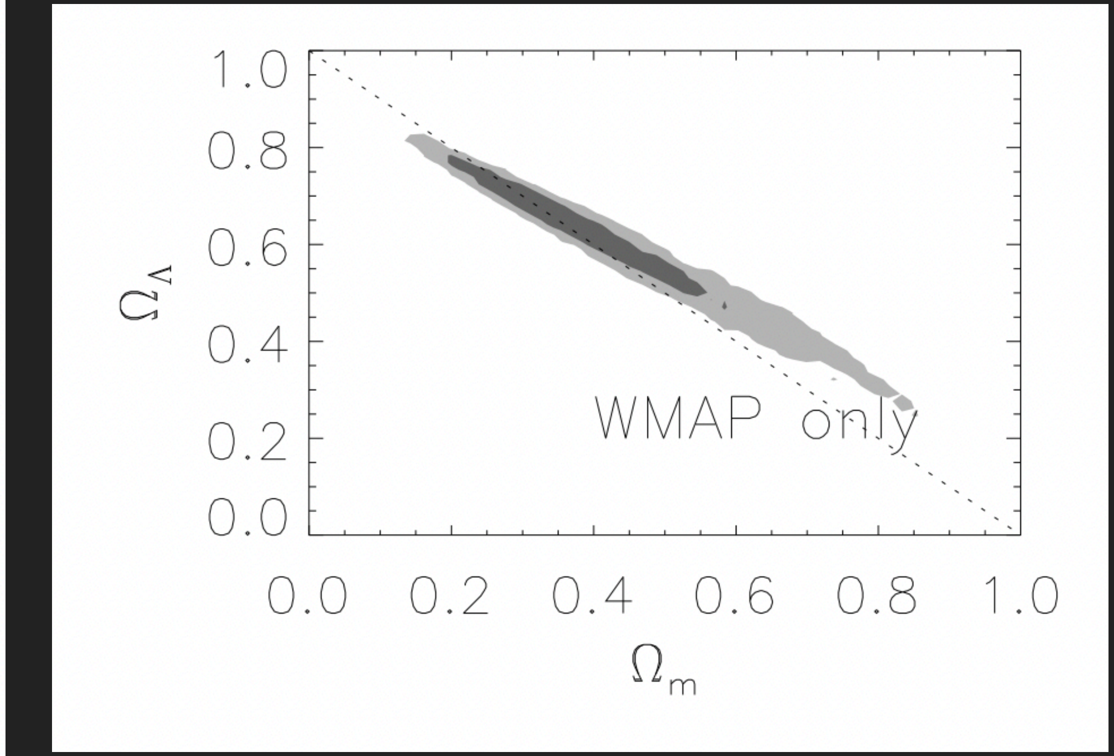
Balbi et al., 2000

Archeops



Benoit et al, 2003

WMAP-1



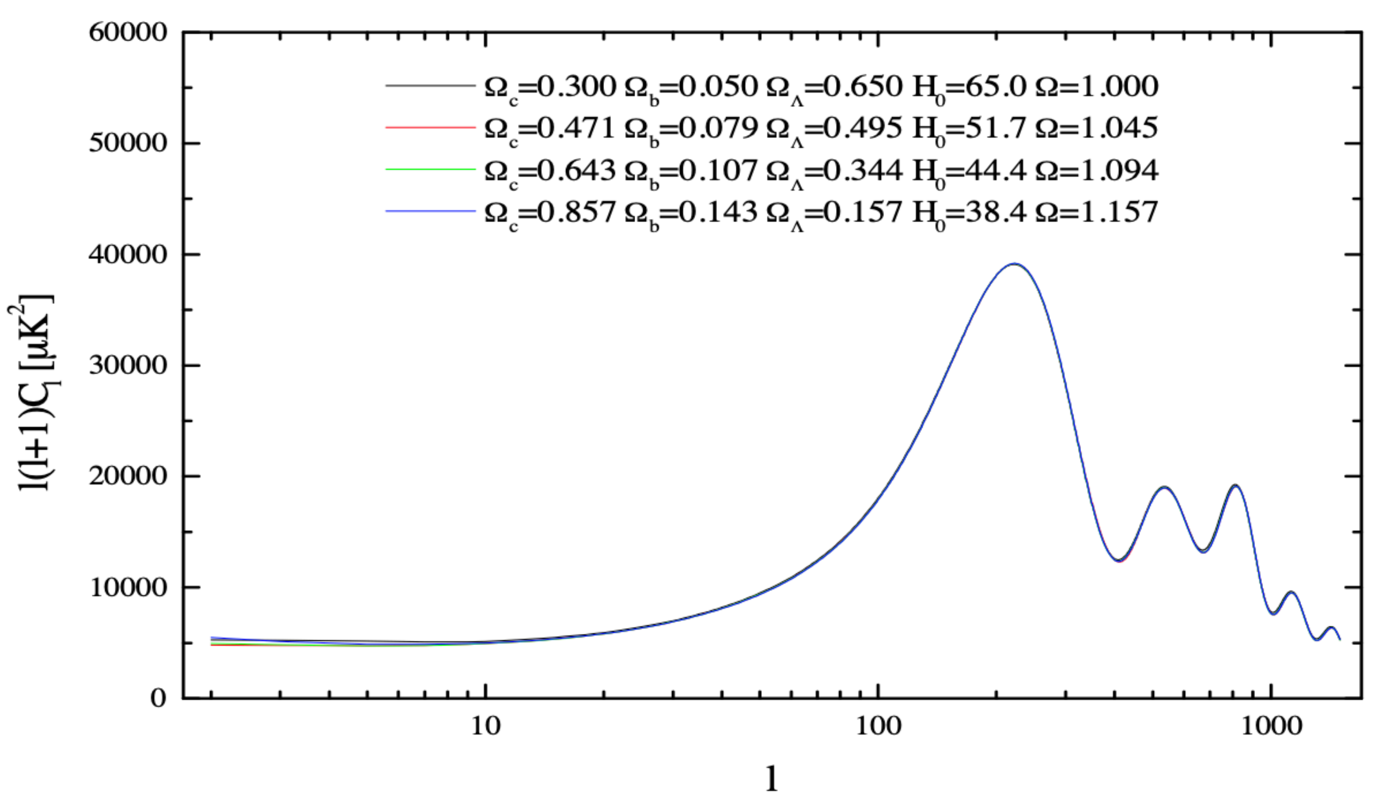
Spergel et al, 2003

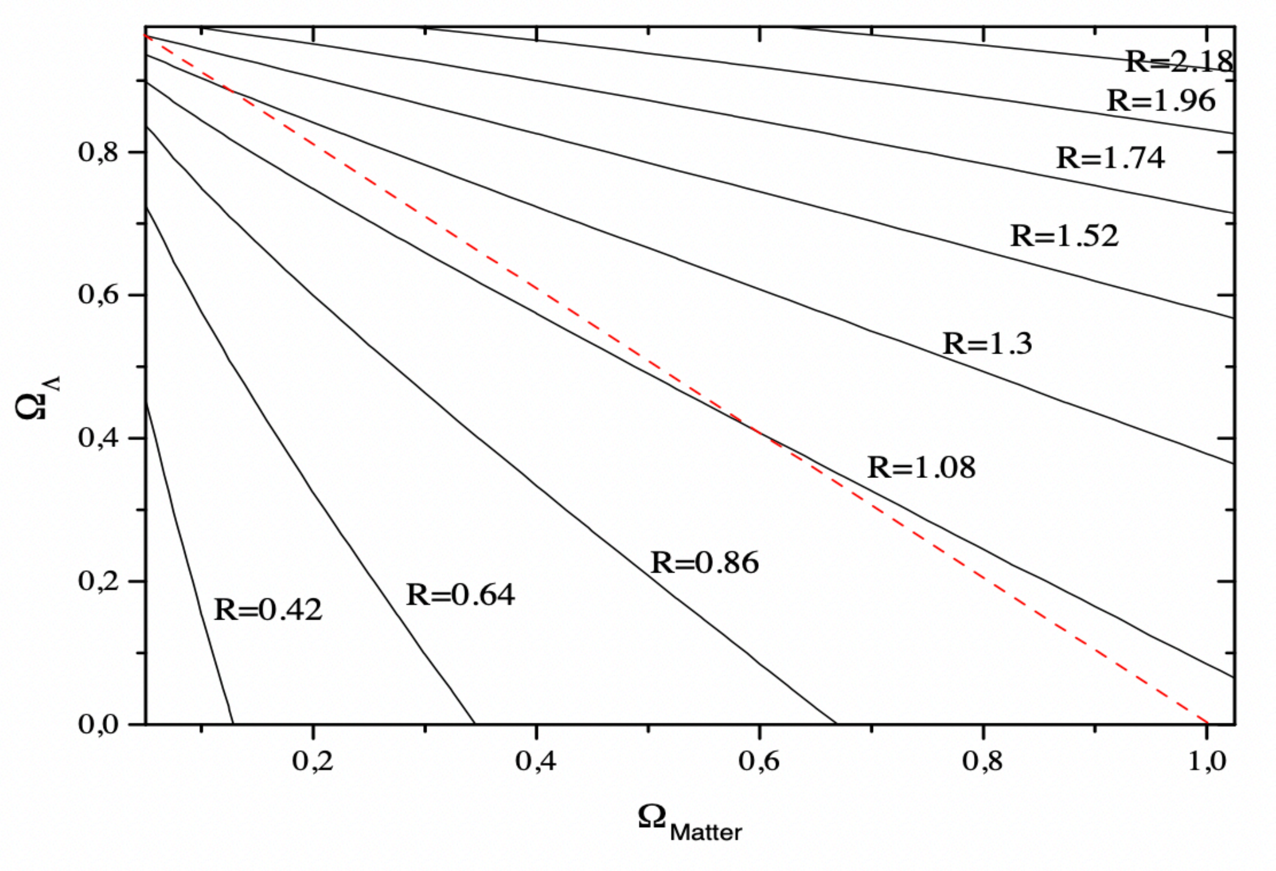
All consistent with a flat universe !

(but also with closed)

COSMIC DEGENERACY

Efstathiou & Bond MNRAS, 1999, Melchiorri & Griffiths 2000 (just primary anisotropies)



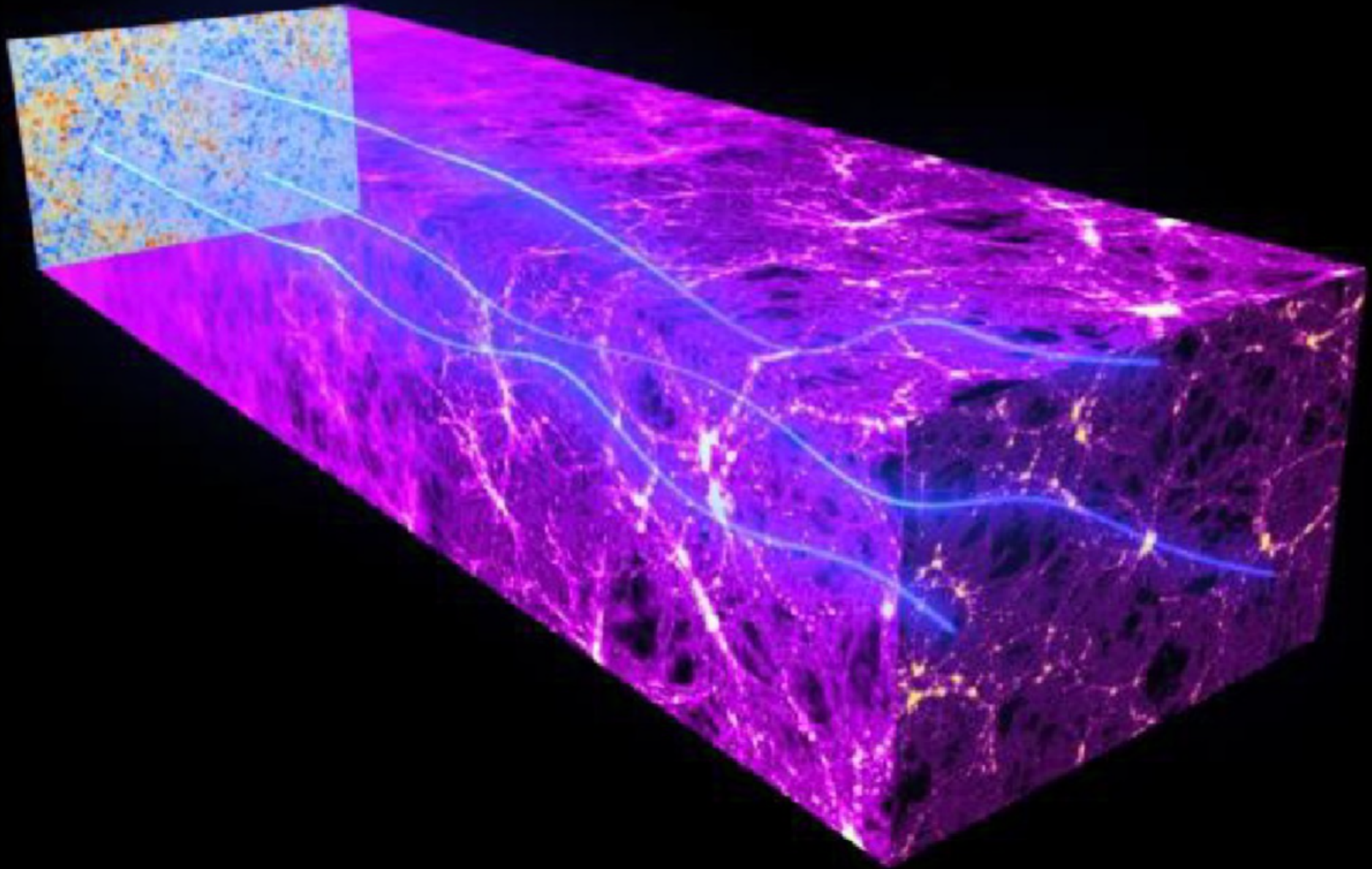


After fixing the acoustic horizon scale at LSS (fix matter and baryon physical densities) you can have nearly identical CMB angular spectra assuming the same angular distance at recombination. Curvature can be significantly different without altering the CMB peaks structure !!!!

CMB LENSING

CMB photons emitted at z=1100 are deflected by the gravitational lensing effect of massive cosmic structures.

This affects the CMB anisotropy angular spectrum by smearing the high l peaks.



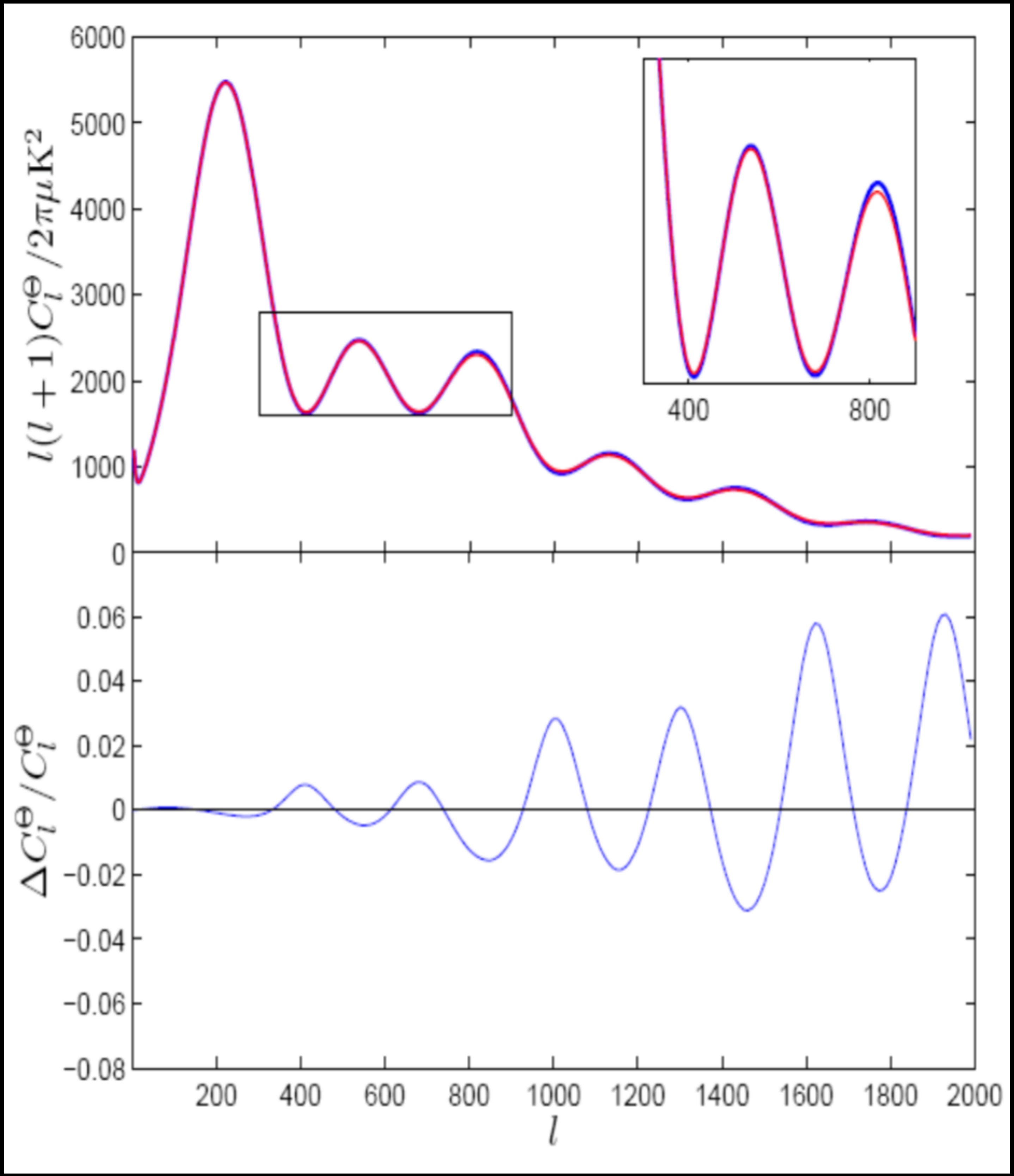
CMB LENSING

CMB photons emitted at z=1100 are deflected by the gravitational lensing effect of massive cosmic structures.

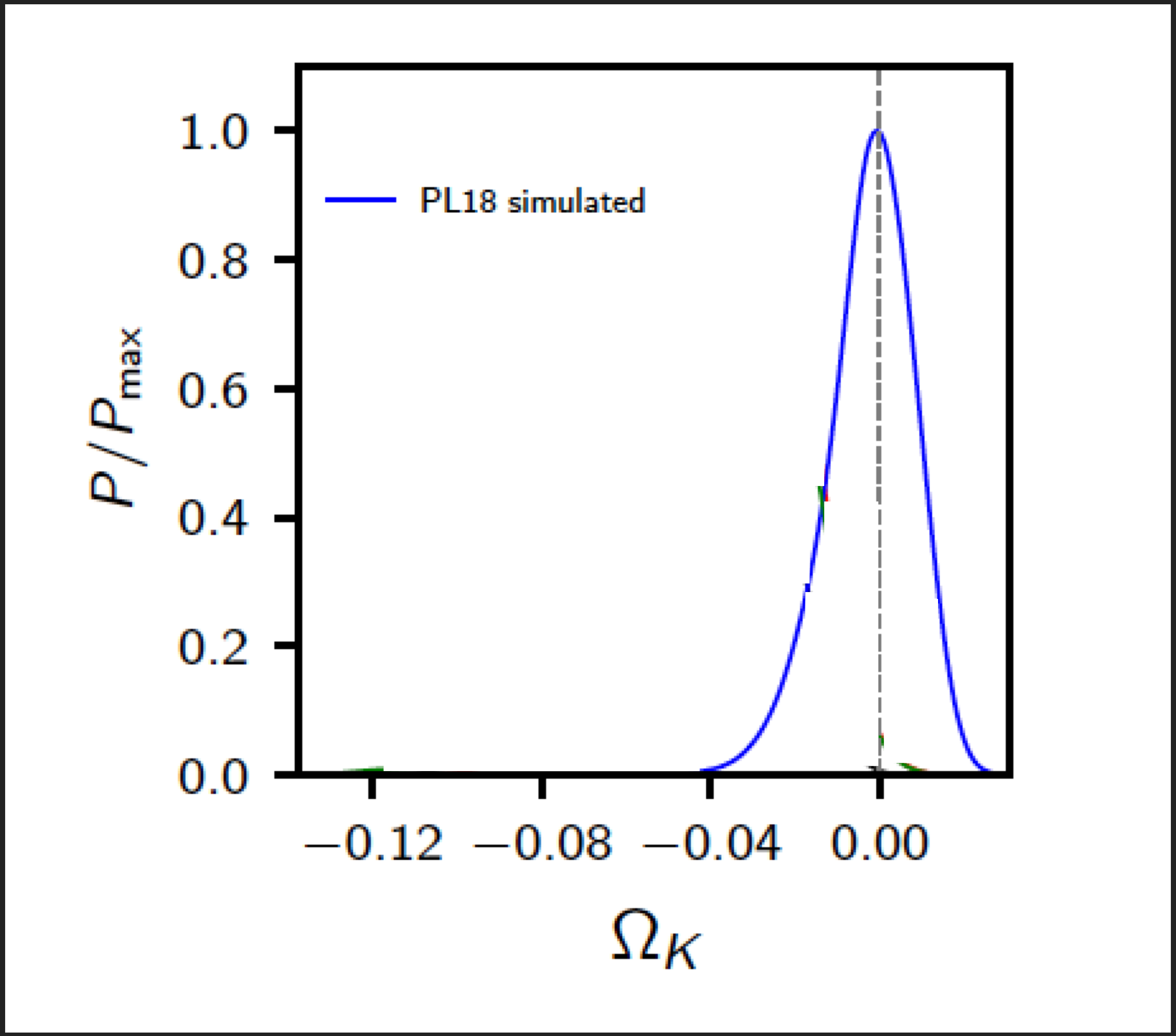
This affects the CMB anisotropy angular spectrum by smearing the high l peaks.

This effect depends on the CDM density.

We can break cosmic degeneracy with small scale CMB!!!



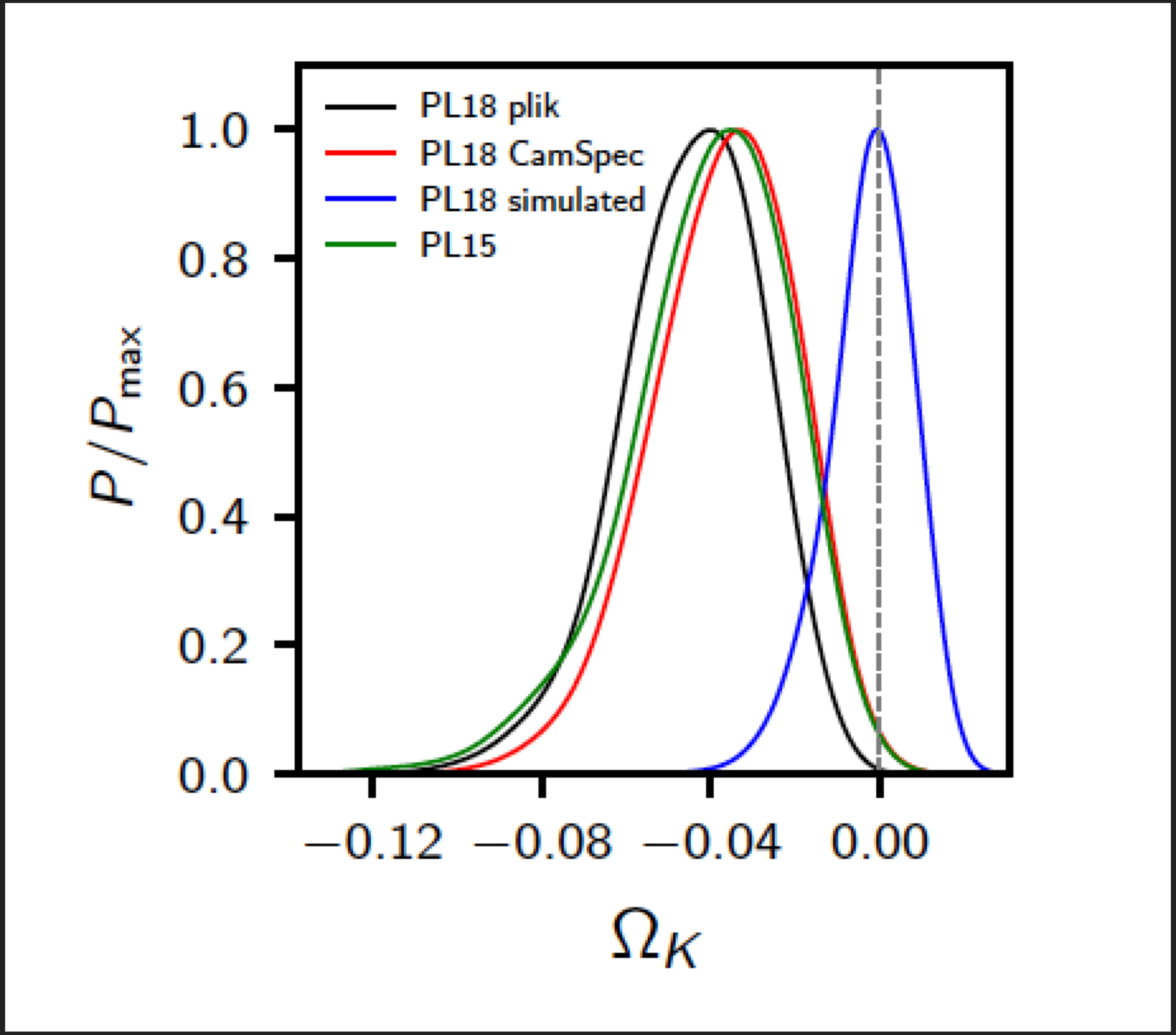
PLANCK IS THE FIRST EXPERIMENT THAT COULD MEASURE THE CURVATURE OF THE UNIVERSE WITH 3% PRECISION ALONE !



Di Valentino, Melchiorri, Silk Nature Astronomy 2020,

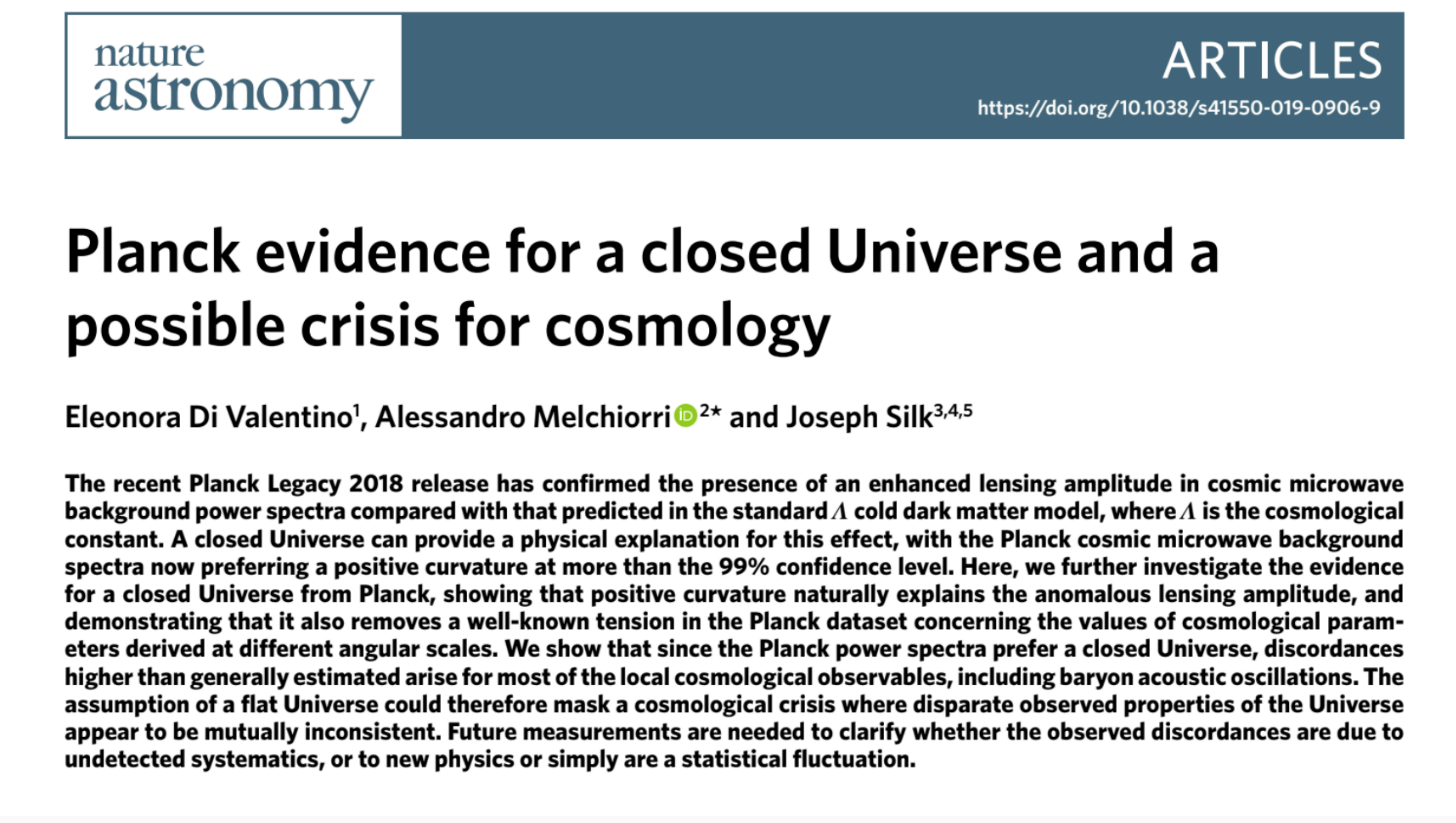
…AND THE RESULT IS…CLOSED AT 3.4 SIGMA

$$-0.007 > \Omega_K > -0.095 \quad \text{at } 99\% \text{ C.L.}$$



Di Valentino, Melchiorri, Silk Nature Astronomy 2020,

Handley 2020



nature astronomy

ARTICLES

https://doi.org/10.1038/s41550-019-0906-9

Planck evidence for a closed Universe and a possible crisis for cosmology

Eleonora Di Valentino[1], Alessandro Melchiorri[2*] and Joseph Silk[3,4,5]

The recent Planck Legacy 2018 release has confirmed the presence of an enhanced lensing amplitude in cosmic microwave background power spectra compared with that predicted in the standard Λ cold dark matter model, where Λ is the cosmological constant. A closed Universe can provide a physical explanation for this effect, with the Planck cosmic microwave background spectra now preferring a positive curvature at more than the 99% confidence level. Here, we further investigate the evidence for a closed Universe from Planck, showing that positive curvature naturally explains the anomalous lensing amplitude, and demonstrating that it also removes a well-known tension in the Planck dataset concerning the values of cosmological parameters derived at different angular scales. We show that since the Planck power spectra prefer a closed Universe, discordances higher than generally estimated arise for most of the local cosmological observables, including baryon acoustic oscillations. The assumption of a flat Universe could therefore mask a cosmological crisis where disparate observed properties of the Universe appear to be mutually inconsistent. Future measurements are needed to clarify whether the observed discordances are due to undetected systematics, or to new physics or simply are a statistical fluctuation.

(see also Handley, 2020)

SOME COMMENTS…

New Scientist:

“If this is true, it would have profound implications on our understanding of the universe,” says David Spergel at Princeton University. “It’s a really important claim, but I’m not sure it’s one that’s backed by the data. In fact, I’d say the evidence is actually against it.”

Quanta Magazine:

Antony Lewis, a cosmologist at the University of Sussex and a member of the Planck team who worked on that analysis, said:“is that it is just a statistical fluke.” Lewis and other experts say they’ve already closely scrutinized the issue, along with related puzzles in the data.

Salon:

“The result is intriguing, but only of borderline statistical significance to be believed. There are several independent lines of evidence that suggest the Universe is flat, and that this claim is a statistical fluke or a misinterpretation of the data,” Avi Loeb, chair of Harvard's astronomy department, told Salon via email.

Scientific American:

Efstathiou asked not to be directly quoted, but pointed out in an email to Live Science that if the universe were curved, it would raise a number of problems—contradicting those other data sets from the early universe and making discrepancies in the universe’s observed rate of expansion much worse. Gratton said he agreed.

Neue Zurich Zeitung:

Martin Kunz von der Universität Genf, wie Melchiorri ein Mitglied der Planck-Arbeitsgruppe, teilt diese Ansicht nicht. An der Analyse von Melchiorri und seinen Mitarbeitern hat er nichts auszusetzen. Was ihn stört, ist die Interpretation der Planck-Daten. Dass es in diesen Daten kleinere Unstimmigkeiten gebe, sei seit längerem bekannt.

Astronomy & Astrophysics manuscript no. ms
September 24, 2019

Planck 2018 results. VI. Cosmological parameters

Planck Collaboration: N. Aghanim[54], Y. Akrami[15,57,59], M. Ashdown[65,5], J. Aumont[95], C. Baccigalupi[78], M. Ballardini[21,41], A. J. Banday[95,8], R. B. Barreiro[61], N. Bartolo[29,62], S. Basak[85], R. Battye[64], K. Benabed[55,90], J.-P. Bernard[95,8], M. Bersanelli[32,45], P. Bielewicz[75,78], J. J. Bock[63,10], J. R. Bond[7], J. Borrill[12,93], F. R. Bouchet[55,90], F. Boulanger[89,54,55], M. Bucher[2,6], C. Burigana[44,30,47], R. C. Butler[41], E. Calabrese[82], J.-F. Cardoso[55,90], J. Carron[23], A. Challinor[58,65,11], H. C. Chiang[25,6], J. Chluba[64], L. P. L. Colombo[32], C. Combet[68], D. Contreras[20], B. P. Crill[63,10], F. Cuttaia[41], P. de Bernardis[31], G. de Zotti[42], J. Delabrouille[2], J.-M. Delouis[67], E. Di Valentino[64], J. M. Diego[61], O. Doré[63,10], M. Douspis[54], A. Ducout[66], X. Dupac[35], S. Dusini[62], G. Efstathiou[65,58*], F. Elsner[72], T. A. Enßlin[72], H. K. Eriksen[59], Y. Fantaye[3,19], M. Farhang[76], J. Fergusson[11], R. Fernandez-Cobos[61], F. Finelli[41,47], F. Forastieri[30,48], M. Frailis[43], A. A. Fraisse[25], E. Franceschi[41], A. Frolov[87], S. Galeotta[43], S. Galli[55,90†], K. Ganga[2], R. T. Génova-Santos[60,16], M. Gerbino[38], T. Ghosh[81,9], J. González-Nuevo[17], K. M. Górski[63,97], S. Gratton[65,58], A. Gruppuso[41,47], J. E. Gudmundsson[94,25], J. Hamann[86], W. Handley[65,5], F. K. Hansen[59], D. Herranz[61], S. R. Hildebrandt[63,10], E. Hivon[55,90], Z. Huang[83], A. H. Jaffe[53], W. C. Jones[25], A. Karakci[59], E. Keihänen[24], R. Keskitalo[12], K. Kiiveri[24,40], J. Kim[72], T. S. Kisner[70], L. Knox[27], N. Krachmalnicoff[78], M. Kunz[14,54,3], H. Kurki-Suonio[24,40], G. Lagache[4], J.-M. Lamarre[89], A. Lasenby[5,65], M. Lattanzi[48,30], C. R. Lawrence[63], M. Le Jeune[2], P. Lemos[58,65], J. Lesgourgues[56], F. Levrier[89], A. Lewis[23‡], M. Liguori[29,62], P. B. Lilje[59], M. Lilley[55,90], V. Lindholm[24,40], M. López-Caniego[35], P. M. Lubin[28], Y.-Z. Ma[77,80,74], J. F. Macías-Pérez[68], G. Maggio[43], D. Maino[32,45,49], N. Mandolesi[41,30], A. Mangilli[8], A. Marcos-Caballero[61], M. Maris[43], P. G. Martin[7], M. Martinelli[96], E. Martínez-González[61], S. Matarrese[29,62,37], N. Mauri[47], J. D. McEwen[73], P. R. Meinhold[28], A. Melchiorri[31,50], A. Mennella[32,45], M. Migliaccio[34,51], M. Millea[27,88,55], S. Mitra[52,63], M.-A. Miville-Deschênes[1,54], D. Molinari[30,41,48], L. Montier[95,8], G. Morgante[41], A. Moss[84], P. Natoli[30,92,48], H. U. Nørgaard-Nielsen[13], L. Pagano[30,48,54], D. Paoletti[41,47], B. Partridge[39], G. Patanchon[2], H. V. Peiris[22], F. Perrotta[78], V. Pettorino[1], F. Piacentini[31], L. Polastri[30,48], G. Polenta[92], J.-L. Puget[54,55], J. P. Rachen[18], M. Reinecke[72], M. Remazeilles[64], A. Renzi[62], G. Rocha[63,10], C. Rosset[2], G. Roudier[2,89,63], J. A. Rubiño-Martín[60,16], B. Ruiz-Granados[60,16], L. Salvati[54], M. Sandri[41], M. Savelainen[24,40,71], D. Scott[20], E. P. S. Shellard[11], C. Sirignano[29,62], G. Sirri[47], L. D. Spencer[82], R. Sunyaev[72,91], A.-S. Suur-Uski[24,40], J. A. Tauber[36], D. Tavagnacco[43,33], M. Tenti[46], L. Toffolatti[17,41], M. Tomasi[32,45], T. Trombetti[44,48], L. Valenziano[41], J. Valiviita[24,40], B. Van Tent[69], L. Vibert[54,55], P. Vielva[61], F. Villa[41], N. Vittorio[34], B. D. Wandelt[55,90], I. K. Wehus[59], M. White[26], S. D. M. White[72], A. Zacchei[43], and A. Zonca[79]

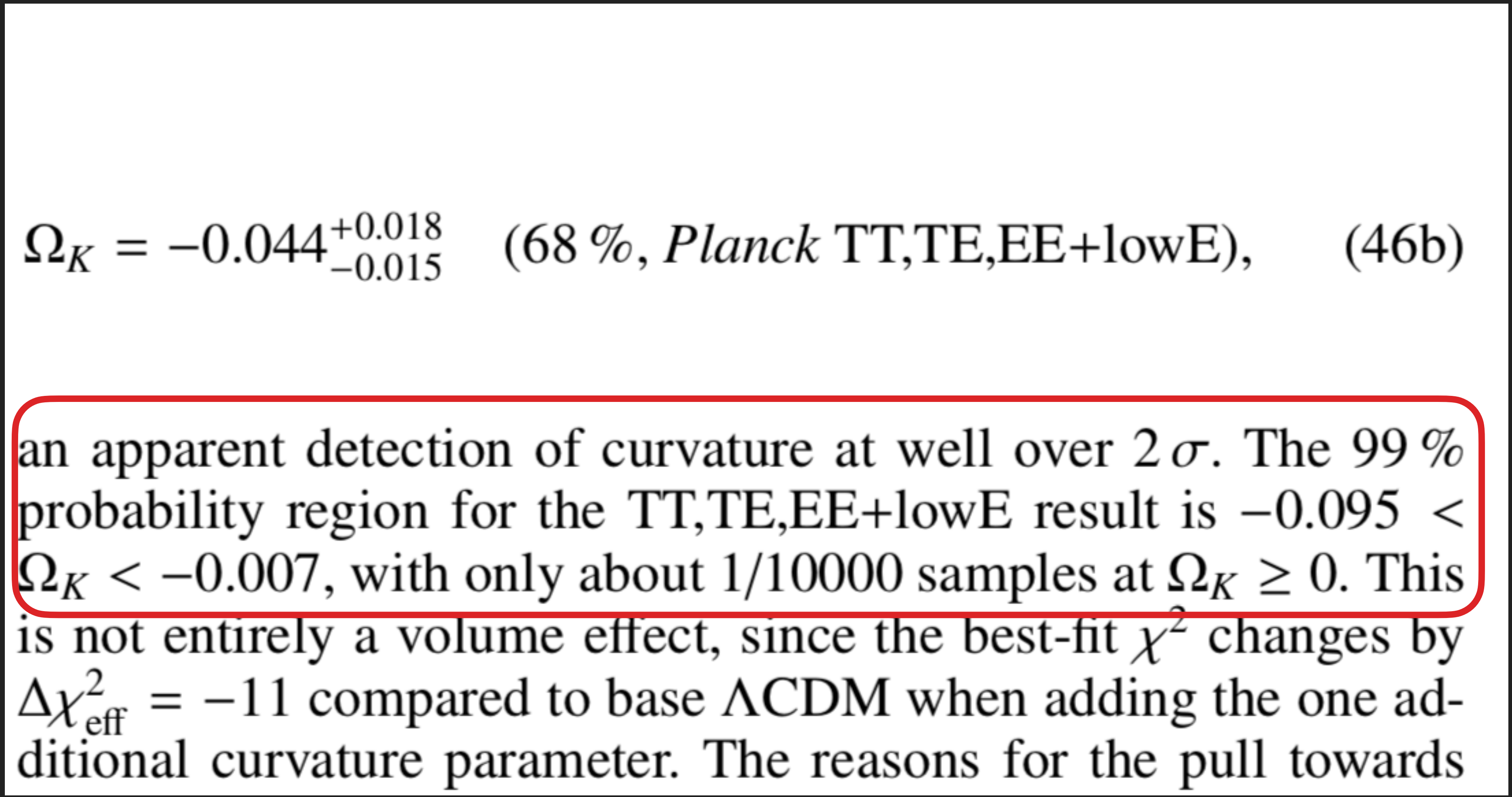
(Affiliations can be found after the references)

September 24, 2019

ABSTRACT

We present cosmological parameter results from the final full-mission *Planck* measurements of the cosmic microwave background (CMB) anisotropies, combining information from the temperature and polarization maps and the lensing reconstruction. Compared to the 2015 results, improved measurements of large-scale polarization allow the reionization optical depth to be measured with higher precision, leading to significant gains in the precision of other correlated parameters. Improved modelling of the small-scale polarization leads to more robust constraints on many parameters, with residual modelling uncertainties estimated to affect them only at the $0.5\,\sigma$ level. We find good consistency with the standard spatially-flat 6-parameter ΛCDM cosmology having a power-law spectrum of adiabatic scalar perturbations (denoted "base ΛCDM" in this paper), from polarization, temperature, and lensing, separately and in combination. A combined analysis gives dark matter density $\Omega_c h^2 = 0.120 \pm 0.001$, baryon density $\Omega_b h^2 = 0.0224 \pm 0.0001$, scalar spectral index $n_s = 0.965 \pm 0.004$, and optical depth $\tau = 0.054 \pm 0.007$ (in this abstract we quote 68 % confidence regions on measured parameters and 95 % on upper limits). The angular acoustic scale is measured to 0.03 % precision, with $100\theta_* = 1.0411 \pm 0.0003$. These results are only weakly dependent on the cosmological model and remain stable, with somewhat increased errors, in many commonly considered extensions. Assuming the base-ΛCDM cosmology, the inferred (model-dependent) late-Universe parameters are: Hubble constant $H_0 = (67.4 \pm 0.5)\,\mathrm{km\,s^{-1}Mpc^{-1}}$; matter density parameter $\Omega_m = 0.315 \pm 0.007$; and matter fluctuation amplitude $\sigma_8 = 0.811 \pm 0.006$. We find no compelling evidence for extensions to the base-ΛCDM model. Combining with baryon acoustic oscillation (BAO) measurements (and considering single-parameter extensions) we constrain the effective extra relativistic degrees of freedom to be $N_{\mathrm{eff}} = 2.99 \pm 0.17$, in agreement with the Standard Model prediction $N_{\mathrm{eff}} = 3.046$, and find that the neutrino mass is tightly constrained to $\sum m_\nu < 0.12$ eV. The CMB spectra continue to prefer higher lensing amplitudes than predicted in base ΛCDM at over $2\,\sigma$, which pulls some parameters that affect the lensing amplitude away from the ΛCDM model; however, this is not supported by the lensing reconstruction or (in models that also change the background geometry) BAO data. The joint constraint with BAO measurements on spatial curvature is consistent with a flat universe, $\Omega_K = 0.001 \pm 0.002$. Also combining with Type Ia supernovae (SNe), the dark-energy equation of state parameter is measured to be $w_0 = -1.03 \pm 0.03$, consistent with a cosmological constant. We find no evidence for deviations from a purely power-law primordial spectrum, and combining with data from BAO, BICEP2, and Keck Array data, we place a limit on the tensor-to-scalar ratio $r_{0.002} < 0.06$. Standard big-bang nucleosynthesis predictions for the helium and deuterium abundances for the base-ΛCDM cosmology are in excellent agreement with observations. The *Planck* base-ΛCDM results are in good agreement with BAO, SNe, and some galaxy lensing observations, but in slight tension with the Dark Energy Survey's combined-probe results including galaxy clustering (which prefers lower fluctuation amplitudes or matter density parameters), and in significant, $3.6\,\sigma$, tension with local measurements of the Hubble constant (which prefer a higher value). Simple model extensions that can partially resolve these tensions are not favoured by the *Planck* data.

Key words. Cosmology: observations – Cosmology: theory – Cosmic background radiation – cosmological parameters



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

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

Planck Parameters paper

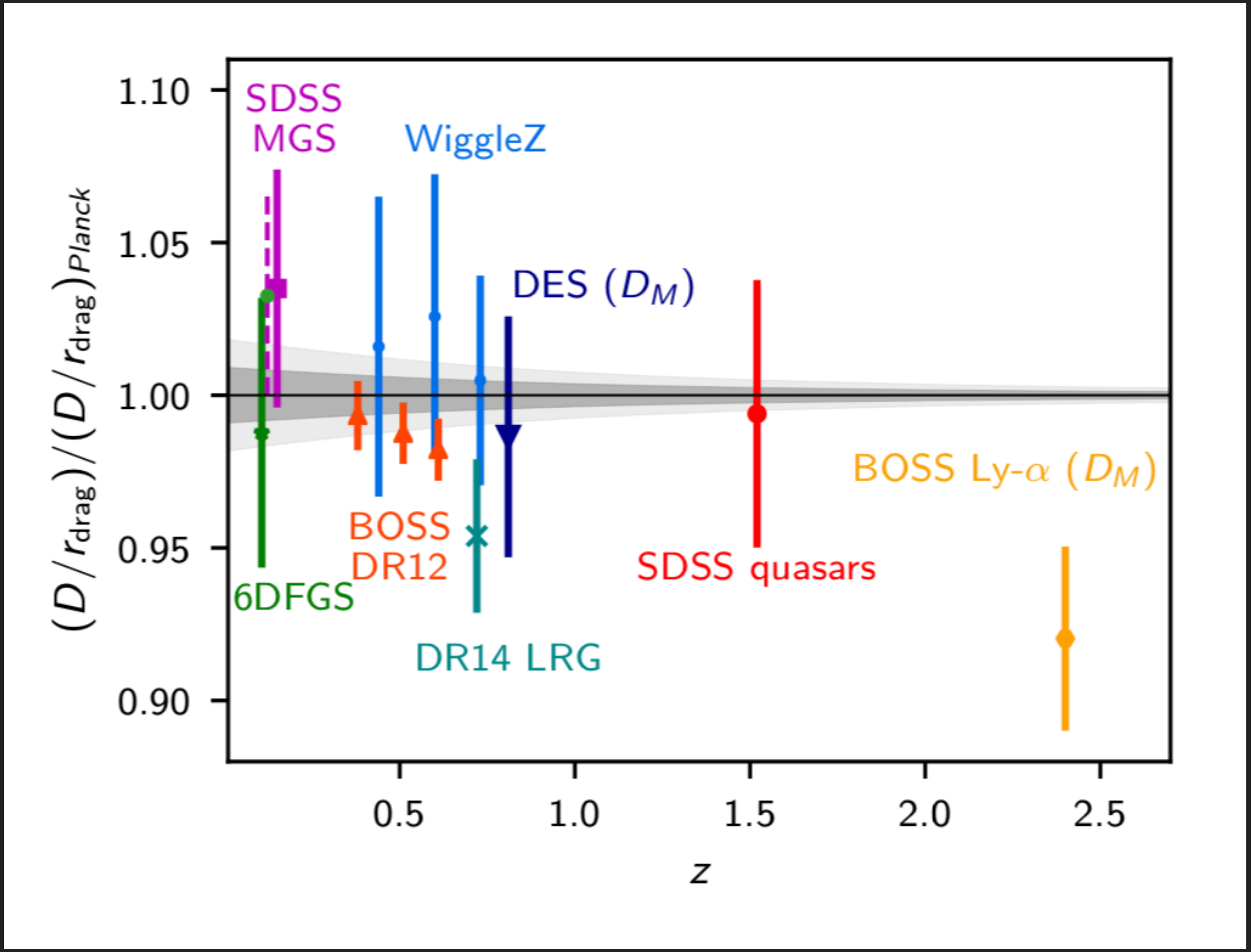
page. 41

TENSIONS IN A CURVED UNIVERSE

We have a strong constraint for a flat universe when we combine with BAO.

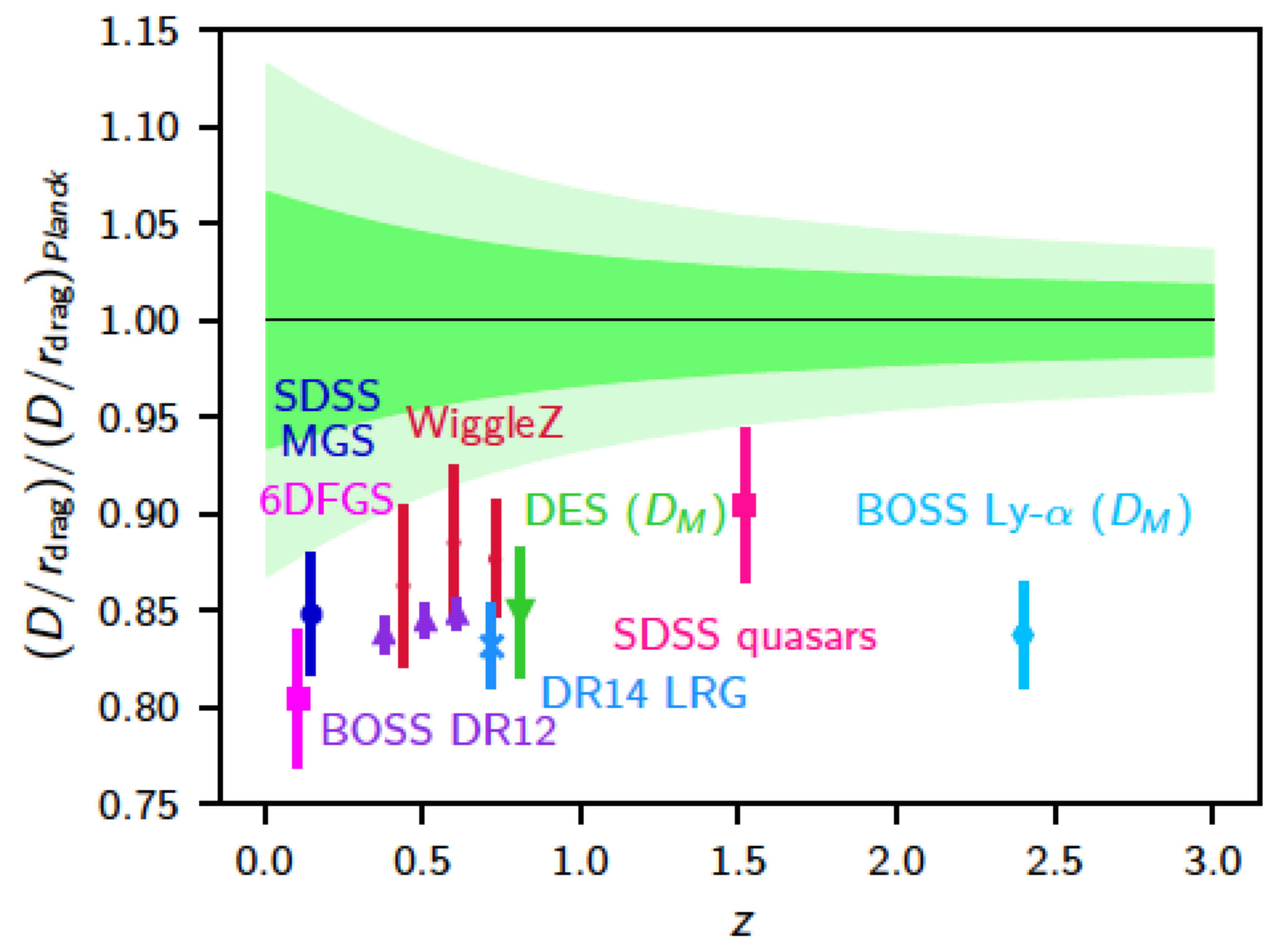
BAO are considered in good agreement with Planck but this result is obtained under the assumption of flatness.

What happens when we let curvature to vary ?



TENSIONS IN A CURVED UNIVERSE

When we let curvature to vary…Planck spectra are inconsistent with BAO DR12 measurements at the level of 3 standard deviations !



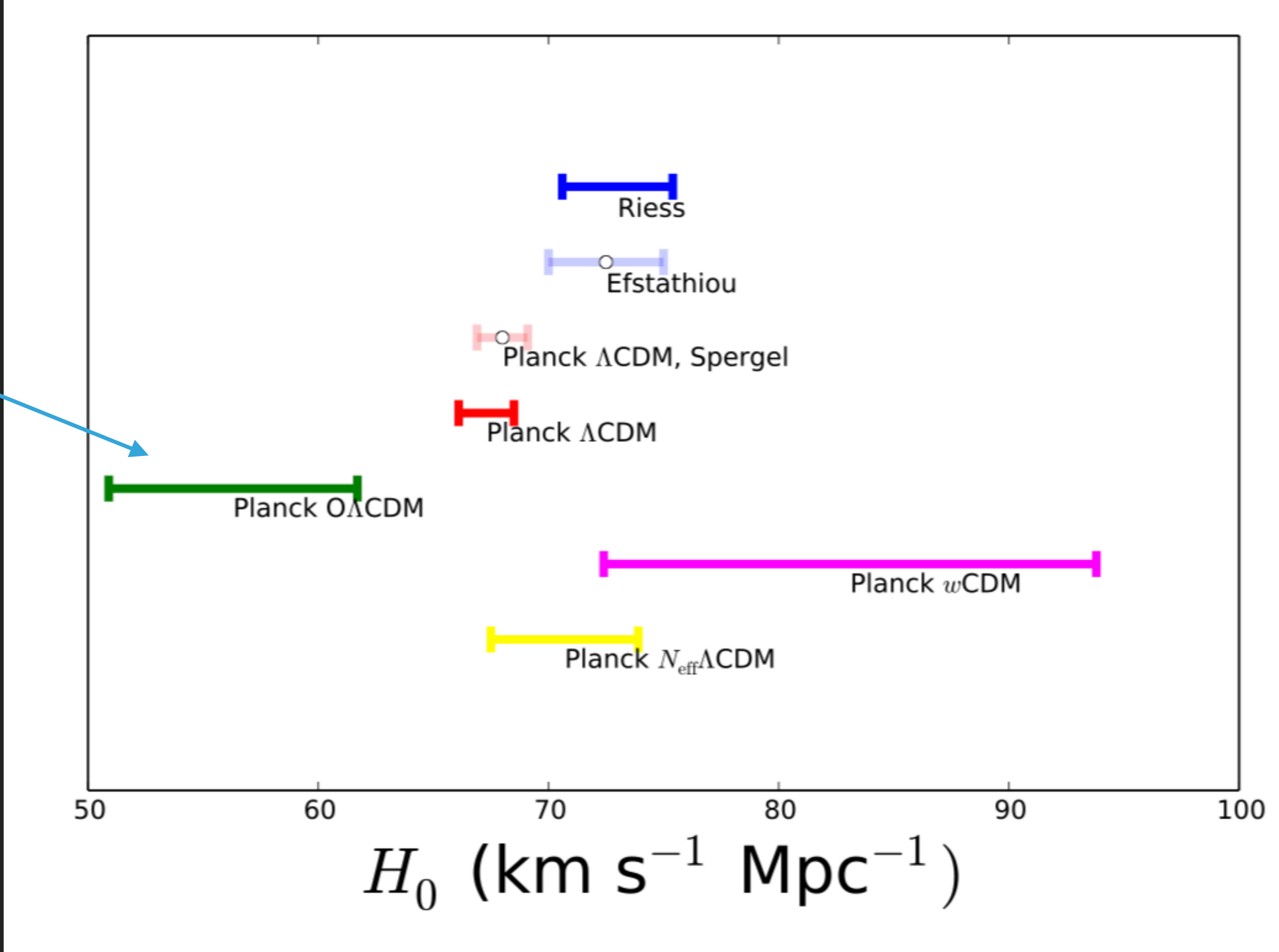
Di Valentino, Melchiorri, Silk 2020

H0 TENSION IN A CURVED UNIVERSE

Planck constraint is shifted

towards even smaller values

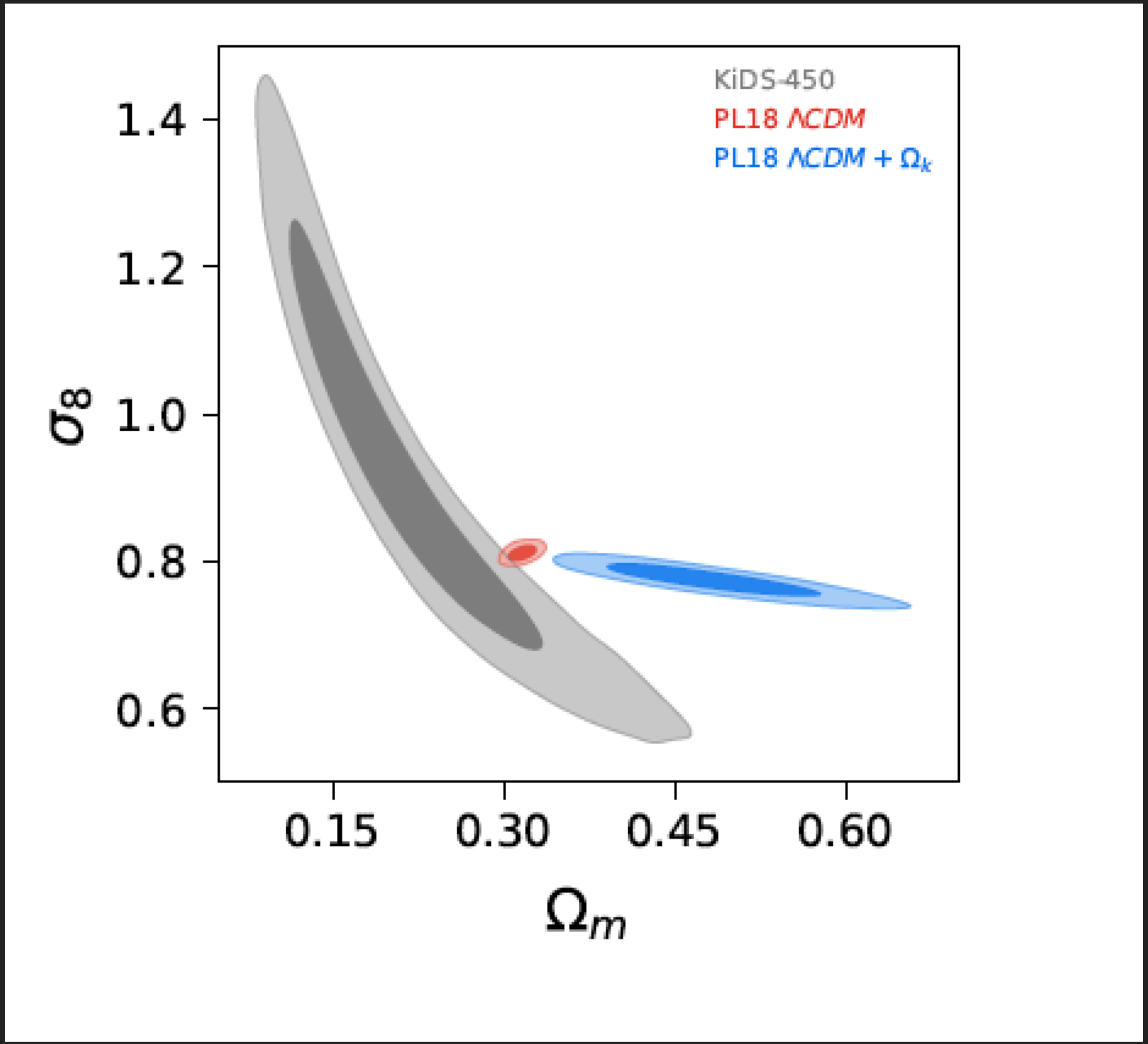
of H0 !



Cuesta et al, Mon.Not.Roy.Astron.Soc. 448 (2015)

TENSIONS IN A CURVED UNIVERSE

Tension with weak lensing measurements are even higher.



Di Valentino, Melchiorri, Silk 2020

ALL TENSIONS DISCUSSED IN THIS CONFERENCE COULD RESULT ‘MILDER’ JUST BECAUSE WE ASSUME A FLAT UNIVERSE…

…AND THERE IS NO FUNDAMENTAL REASON TO DO THAT!

TWO VERY DIFFERENT APPROACHES…YOU DECIDE!

Plato (Theory is useful to analyse data):

- We believe in inflation. Keep on assuming a flat universe and check for systematics in Planck data.

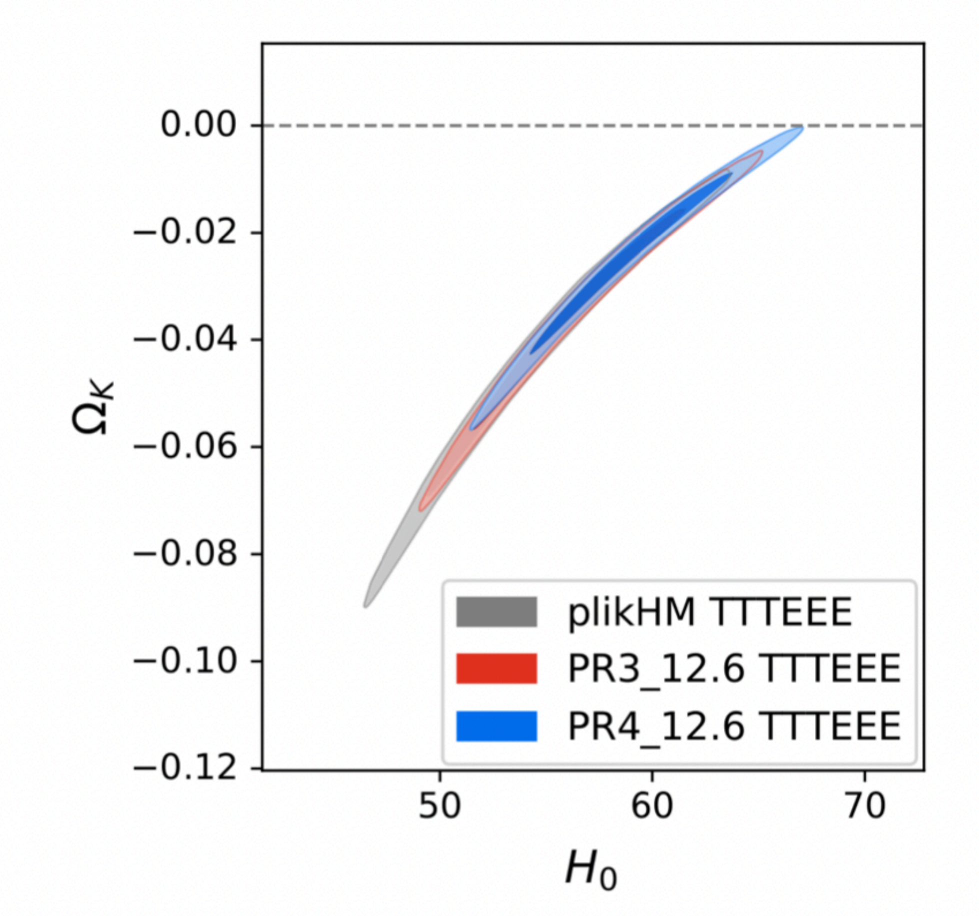
Aristotle (Data motivates theory):

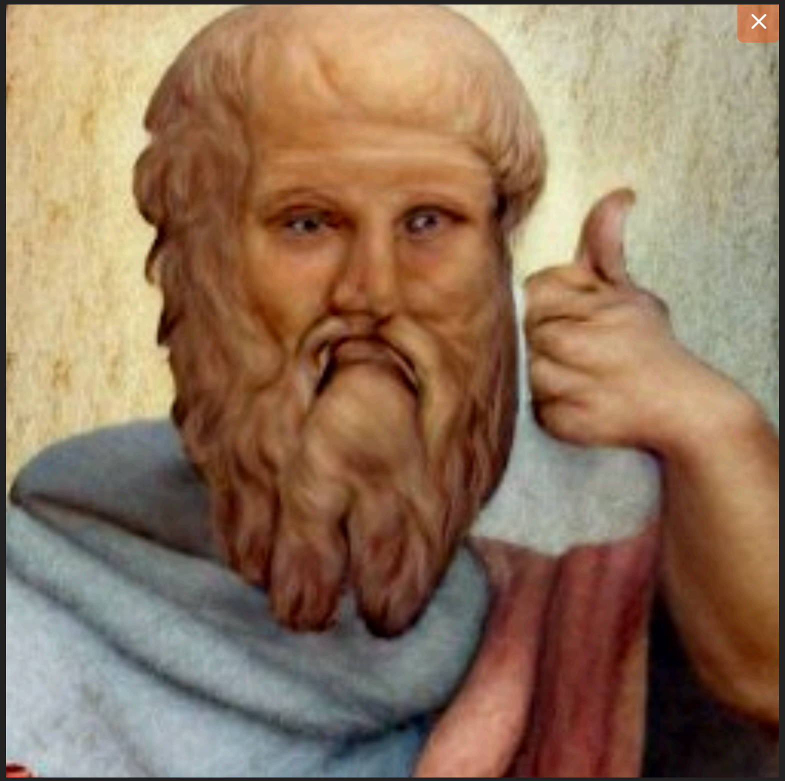
- We believe in the Planck data. We must include extra physics to accommodate a closed Universe with late universe observations.

PLATO'S WAY: IS JUST A SYSTEMATIC OR A STATISTICAL FLUCTUATION IN PLANCK DATA

NPIPE is a new and independent pipeline to produce frequency maps from the time-ordered data, with substantial differences in detector calibration and systematic corrections compared to previous releases.

Rosenberg, Efstathiou and Gratton 2020, applying a modified version of the CAMSPEC code to Planck NPIPE maps found a lower tension between Planck and flat model:

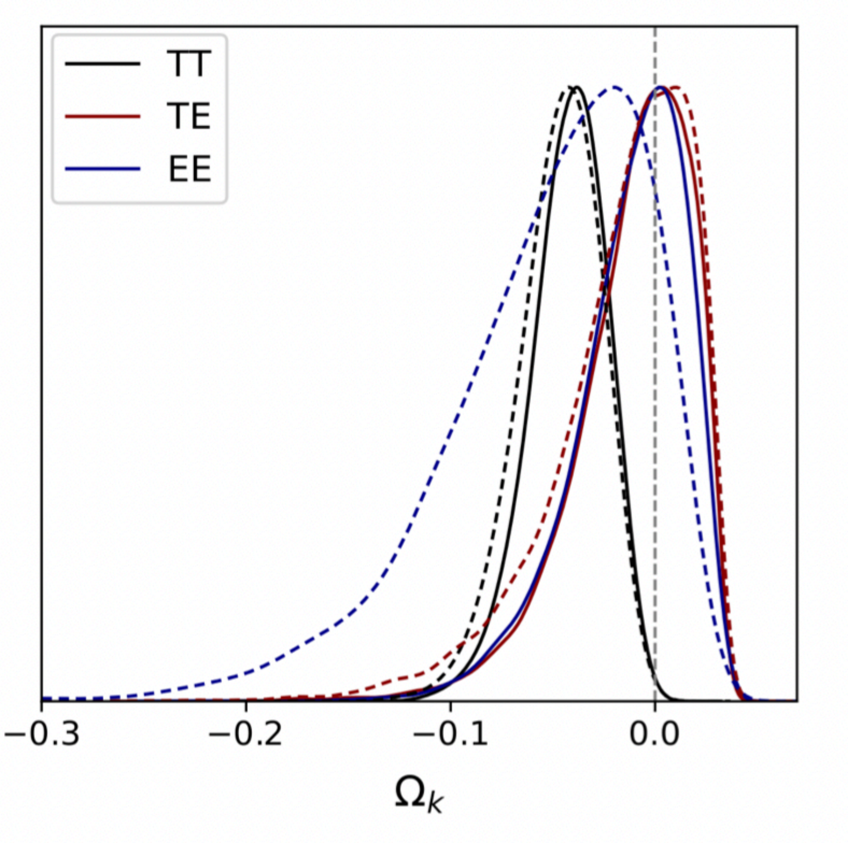


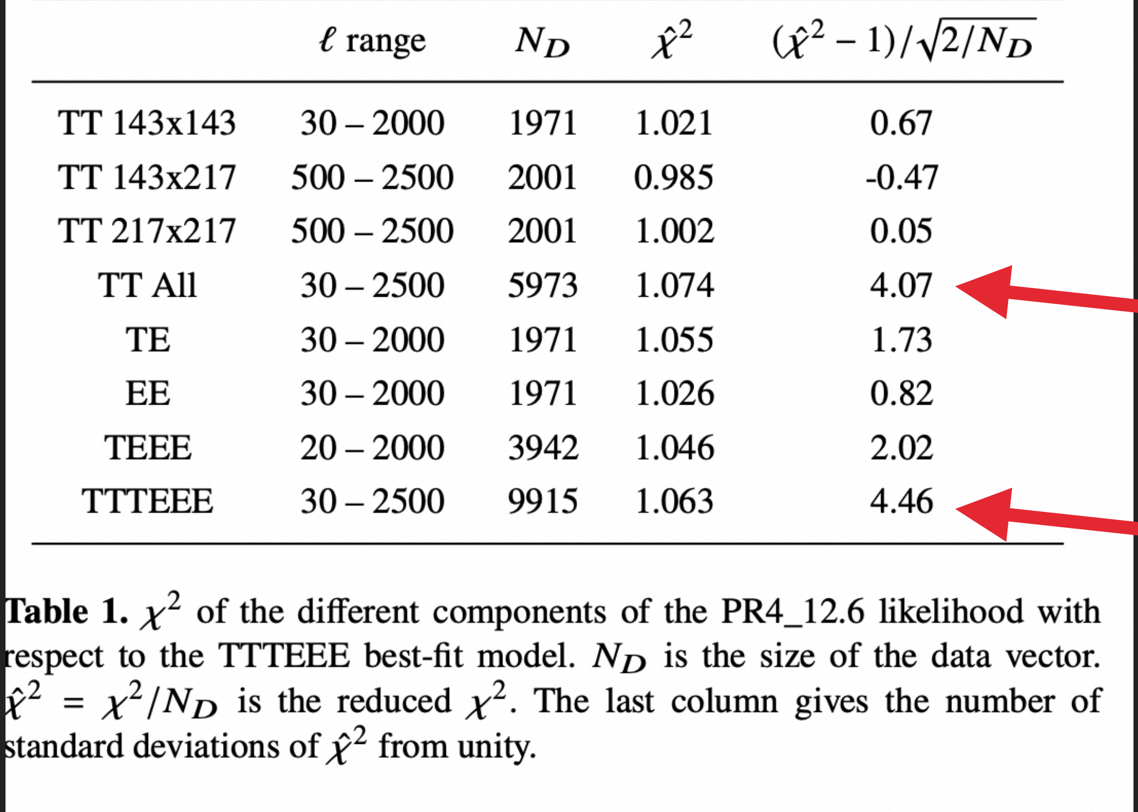


PLATO'S WAY: IS JUST A SYSTEMATIC OR A STATISTICAL FLUCTUATION IN PLANCK DATA

But result is driven by EE data while TT data still prefer a closed universe.

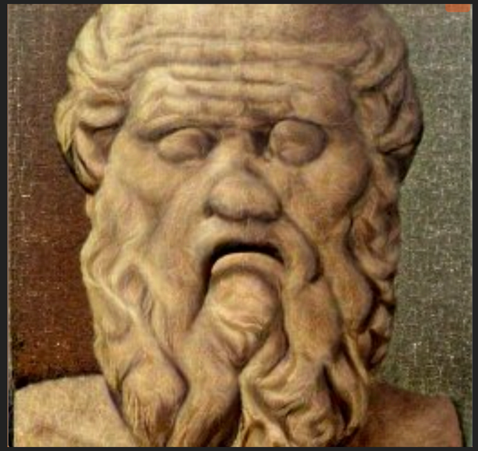
Internal inconsistency at 4.5 sigma level.





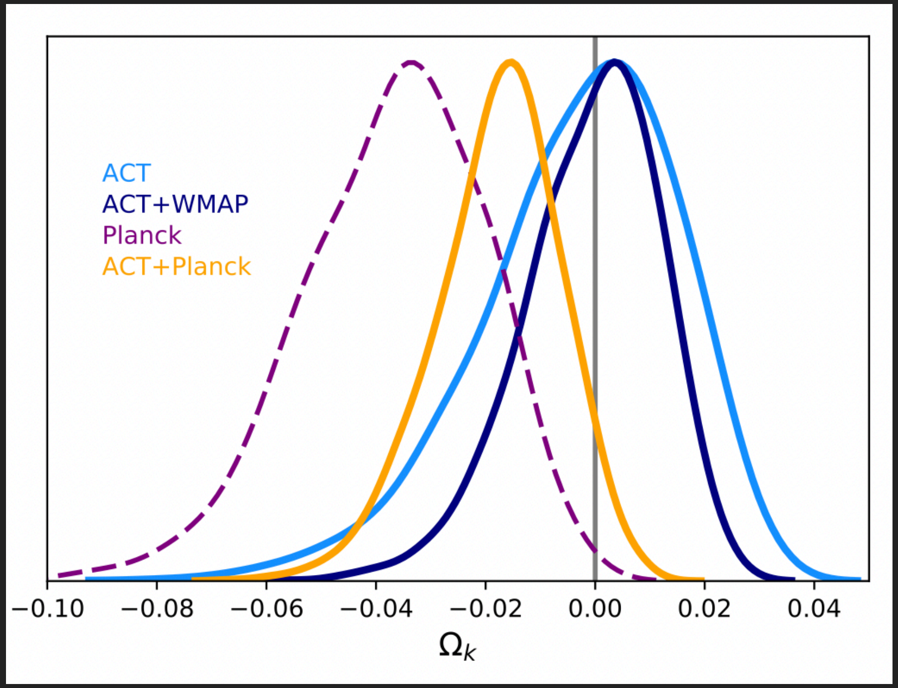
	ℓ range	N_D	$\hat{\chi}^2$	$(\hat{\chi}^2 - 1)/\sqrt{2/N_D}$
TT 143x143	30 – 2000	1971	1.021	0.67
TT 143x217	500 – 2500	2001	0.985	-0.47
TT 217x217	500 – 2500	2001	1.002	0.05
TT All	30 – 2500	5973	1.074	4.07
TE	30 – 2000	1971	1.055	1.73
EE	30 – 2000	1971	1.026	0.82
TEEE	20 – 2000	3942	1.046	2.02
TTTEEE	30 – 2500	9915	1.063	4.46

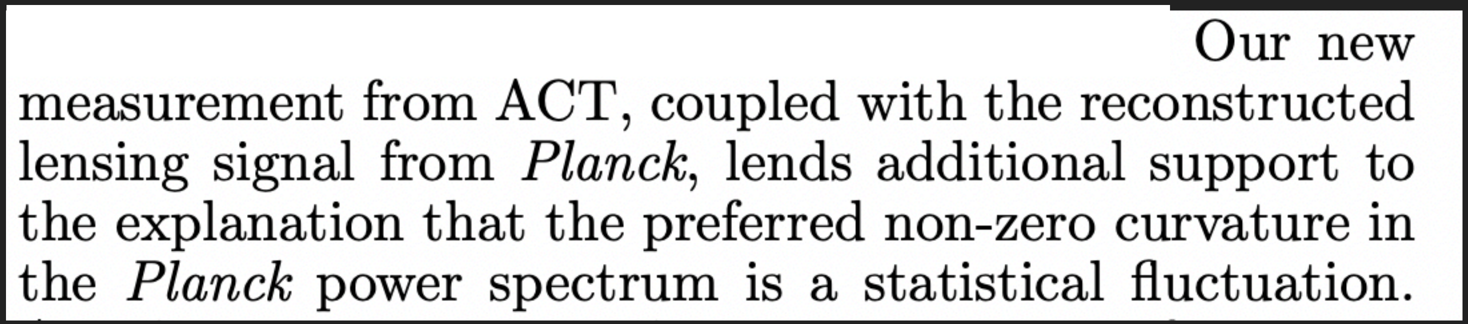
Table 1. χ^2 of the different components of the PR4_12.6 likelihood with respect to the TTTEEE best-fit model. N_D is the size of the data vector. $\hat{\chi}^2 = \chi^2/N_D$ is the reduced χ^2. The last column gives the number of standard deviations of $\hat{\chi}^2$ from unity.

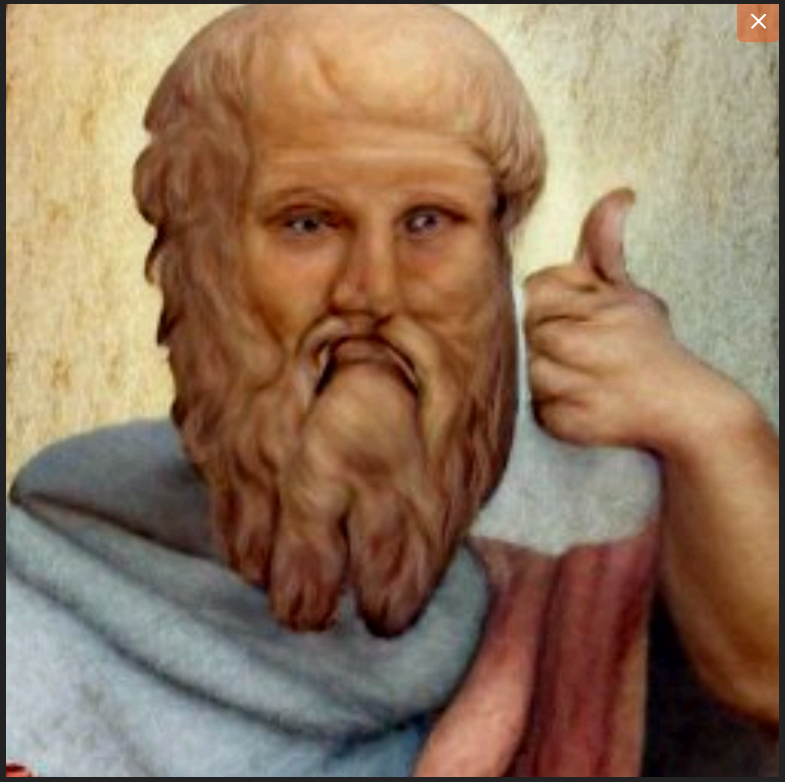


PLATO'S WAY: IS JUST A SYSTEMATIC OR A STATISTICAL FLUCTUATION IN PLANCK DATA

Independent CMB experiments as ACT-DR4 (Aiola et al., 2020) found very good consistency with flat universe




Our new measurement from ACT, coupled with the reconstructed lensing signal from *Planck*, lends additional support to the explanation that the preferred non-zero curvature in the *Planck* power spectrum is a statistical fluctuation.



PLATO'S WAY: IS JUST A SYSTEMATIC OR A STATISTICAL FLUCTUATION IN PLANCK DATA

…but how reliable is ACT-DR4 ? several 2-3 sigmas tensions in other parameters (not to mention Early Dark Energy) are there. Imagine the opposite case, Planck favouring a flat universe and ACT-DR4 favouring a closed one, whom we would have trusted more?

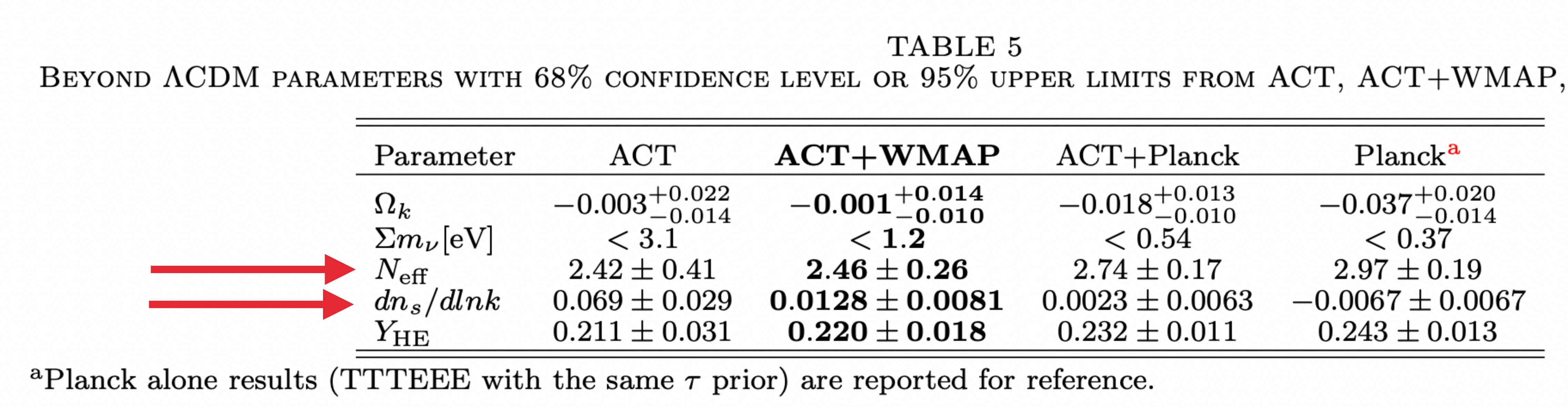
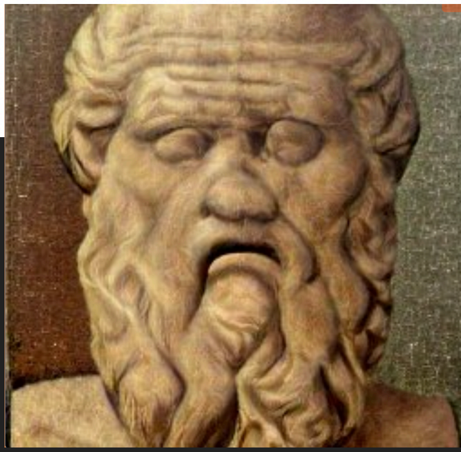


TABLE 5

BEYOND ΛCDM PARAMETERS WITH 68% CONFIDENCE LEVEL OR 95% UPPER LIMITS FROM ACT, ACT+WMAP, AND ACT+PLANCK.

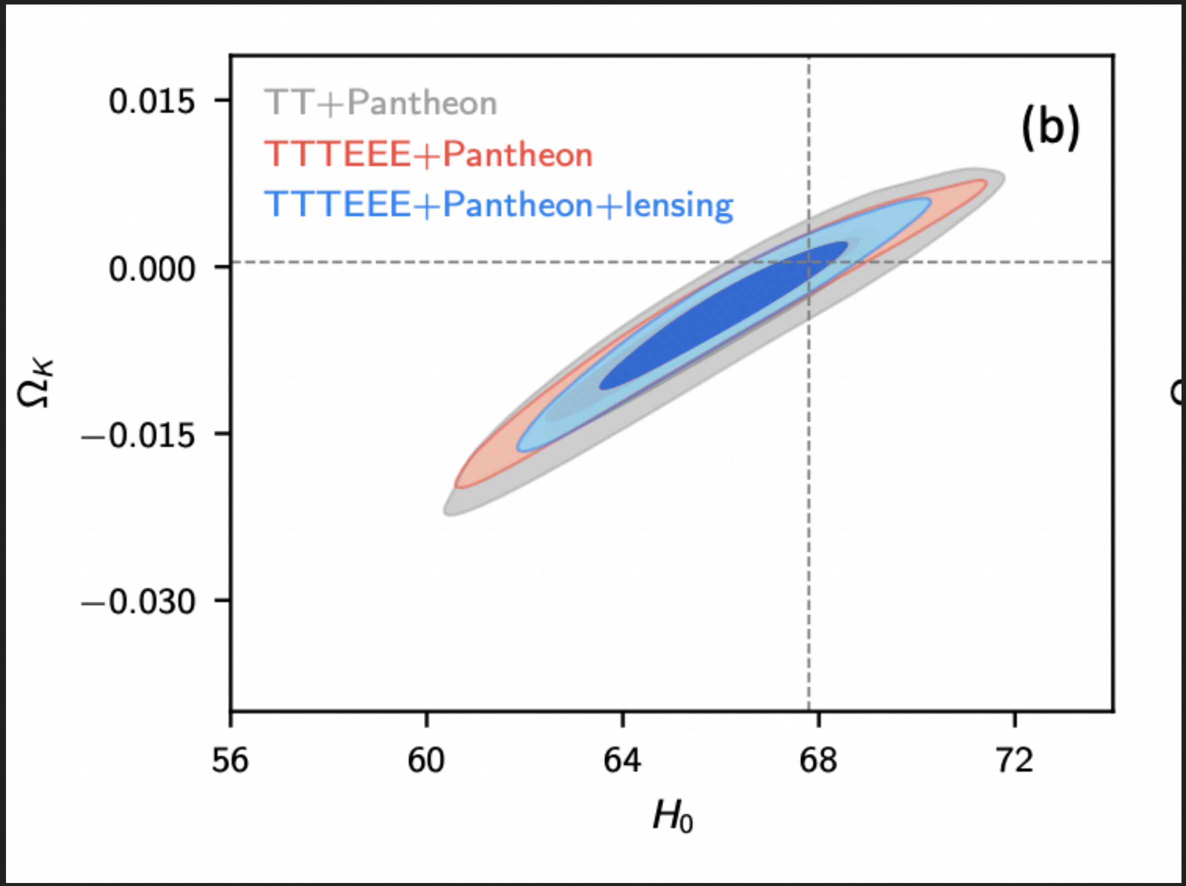
Parameter	ACT	**ACT+WMAP**	ACT+Planck	Planck[a]
Ω_k	$-0.003^{+0.022}_{-0.014}$	$\mathbf{-0.001^{+0.014}_{-0.010}}$	$-0.018^{+0.013}_{-0.010}$	$-0.037^{+0.020}_{-0.014}$
Σm_ν[eV]	< 3.1	$\mathbf{< 1.2}$	< 0.54	< 0.37
$N_{\rm eff}$	2.42 ± 0.41	$\mathbf{2.46 \pm 0.26}$	2.74 ± 0.17	2.97 ± 0.19
$dn_s/d\ln k$	0.069 ± 0.029	$\mathbf{0.0128 \pm 0.0081}$	0.0023 ± 0.0063	-0.0067 ± 0.0067
$Y_{\rm HE}$	0.211 ± 0.031	$\mathbf{0.220 \pm 0.018}$	0.232 ± 0.011	0.243 ± 0.013

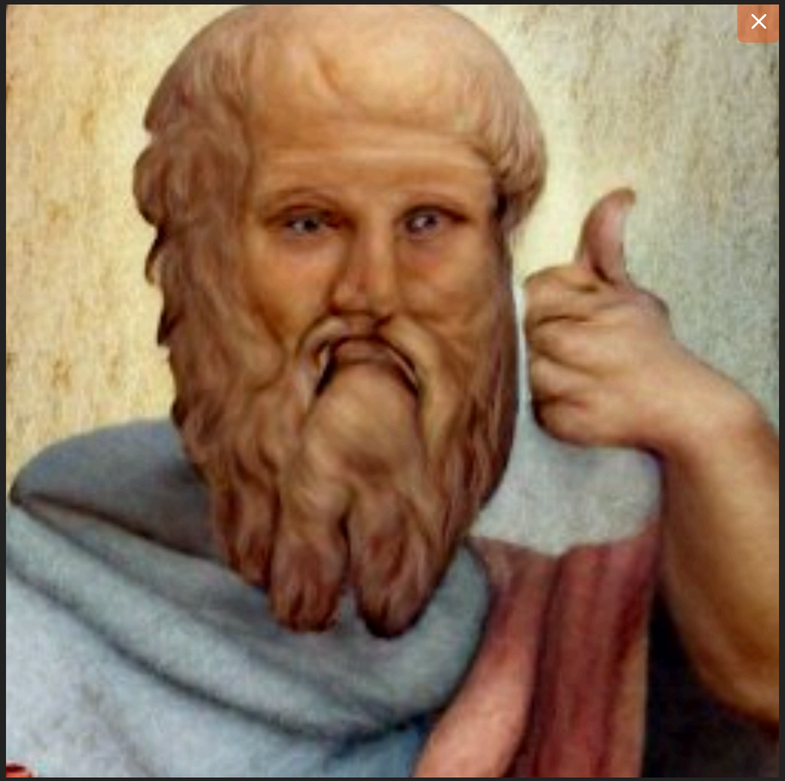
[a] Planck alone results (TTTEEE with the same τ prior) are reported for reference.



PLATO'S WAY: IS JUST A SYSTEMATIC OR A STATISTICAL FLUCTUATION IN PLANCK DATA

… let's assume you don't like BAO, we have plenty of other datasets (like SN-Ia or matter PS) that, when combined with Planck, prefer a flat universe.



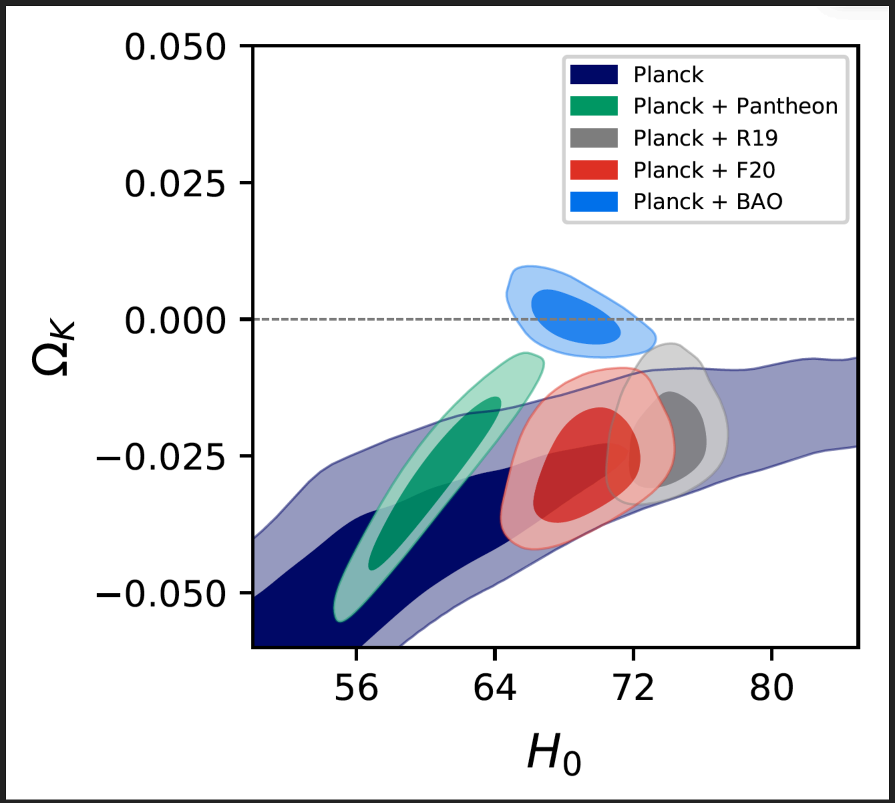


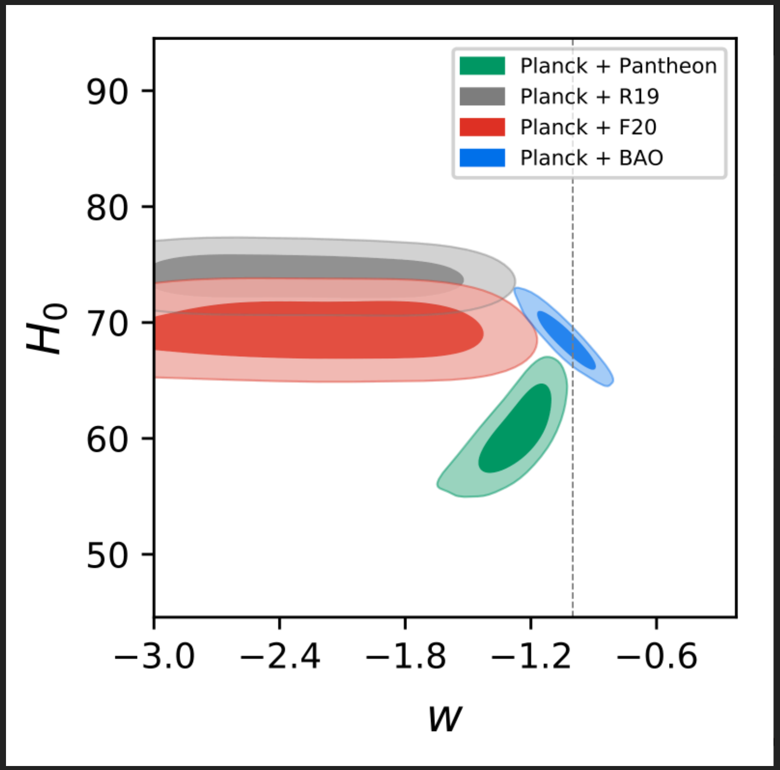
Efsthathiou, Gratton MNRAS 2020

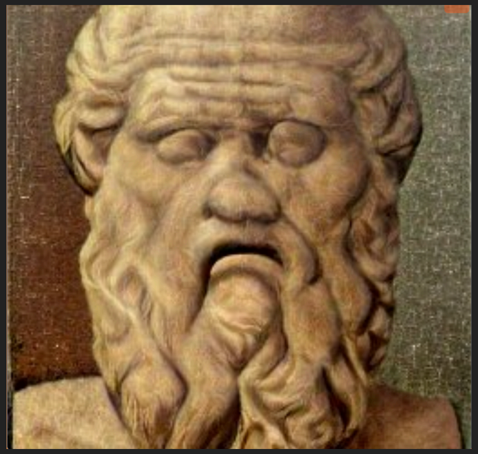
PLATO'S WAY: IS JUST A SYSTEMATIC OR A STATISTICAL FLUCTUATION IN PLANCK DATA

… but this is true only if you assume a cosmological constant. If you just include a constant equation of state

several datasets prefer a closed universe with w<-1:



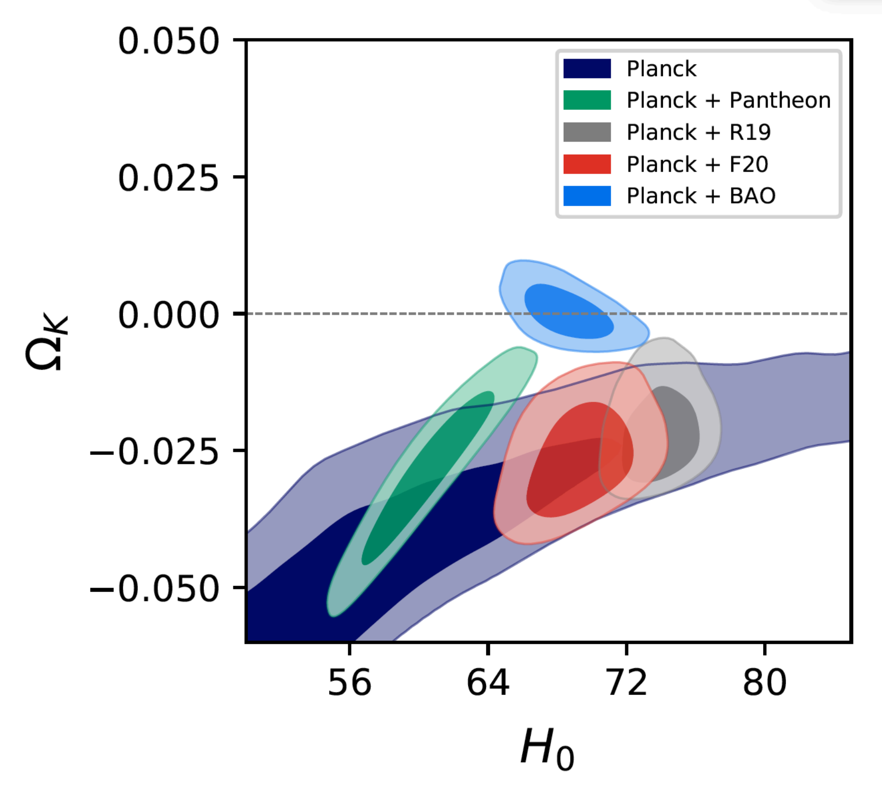


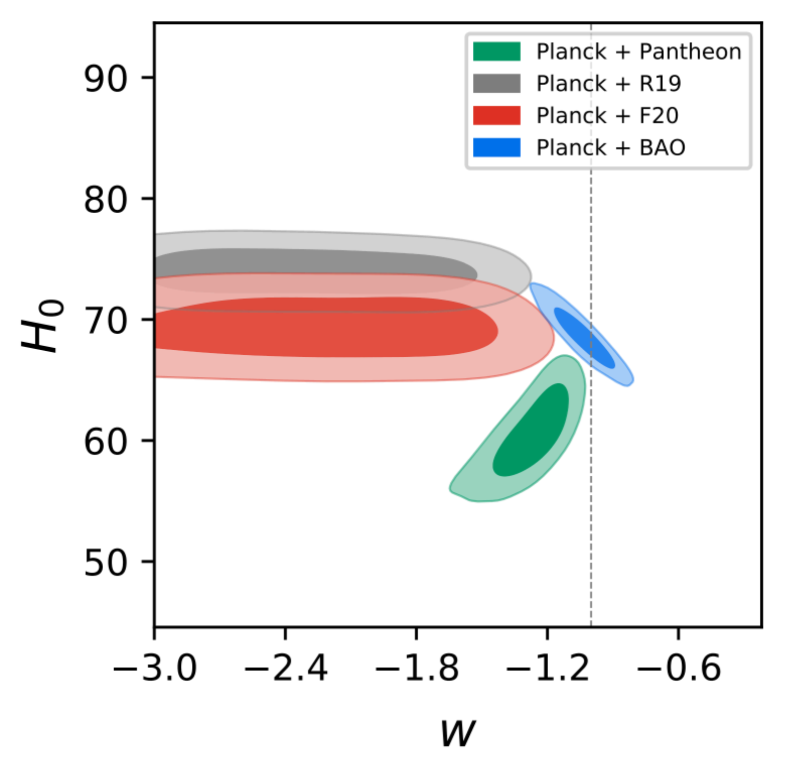


Di Valentino, Melchiorri, Silk, ApJ letters 2021

ARISTOTLE'S WAY: TRUST THE DATA AND LOOK FOR A NEW MODEL

if so many datasets are in agreement with a closed universe and w<-1 maybe this is the way?



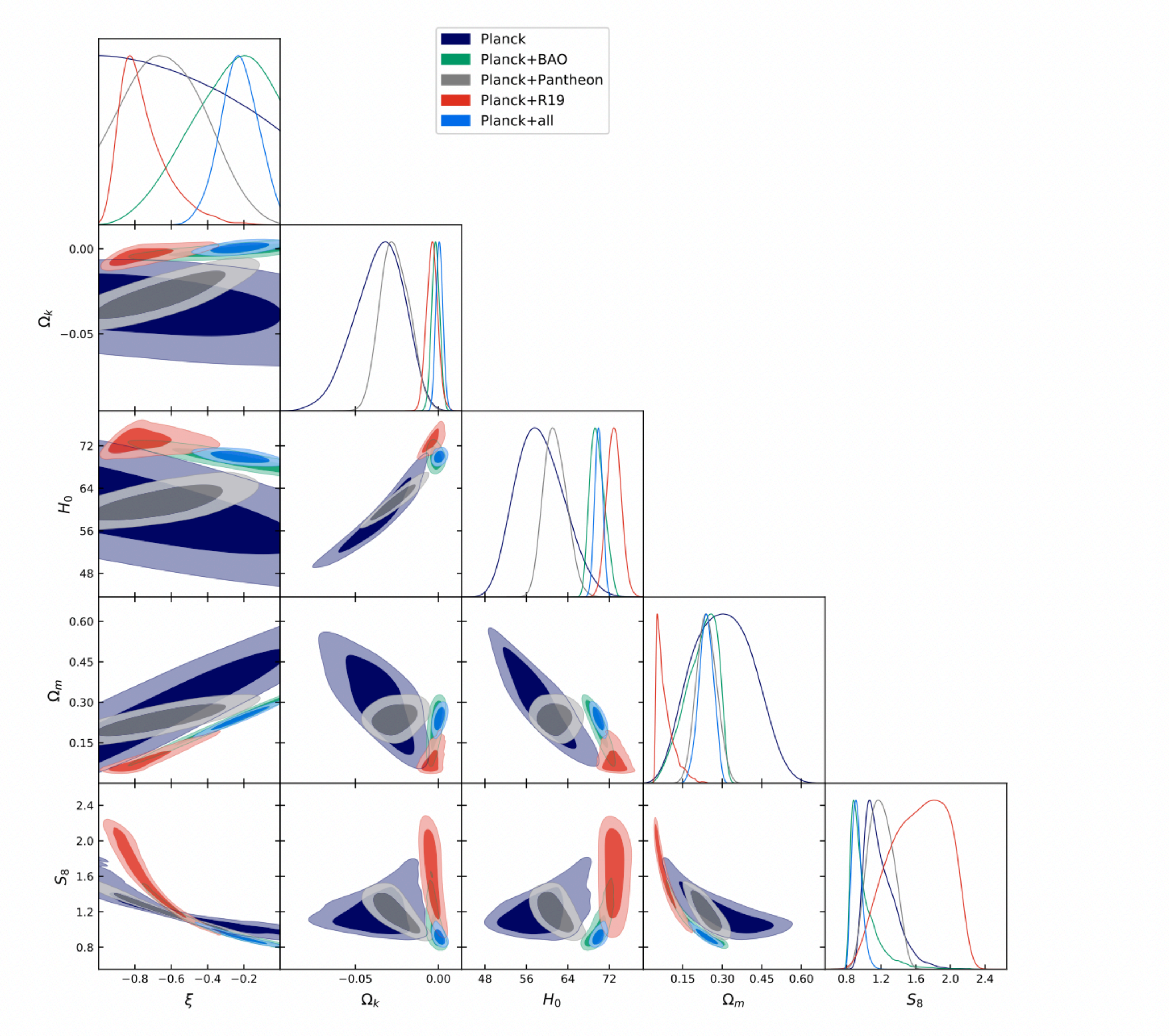


Di Valentino, Melchiorri, Silk, ApJ letters 2021

ARISTOTLE'S WAY: THIS IS A CLEAR INDICATION FOR A NEW MODEL.

The easiest way to have $w<-1$ is to consider interacting dark energy. Does a simple model of interacting dark energy helps in recoinciling the datasets? yes and no…

(Di Valentino et al, MNRAS letters 2021)

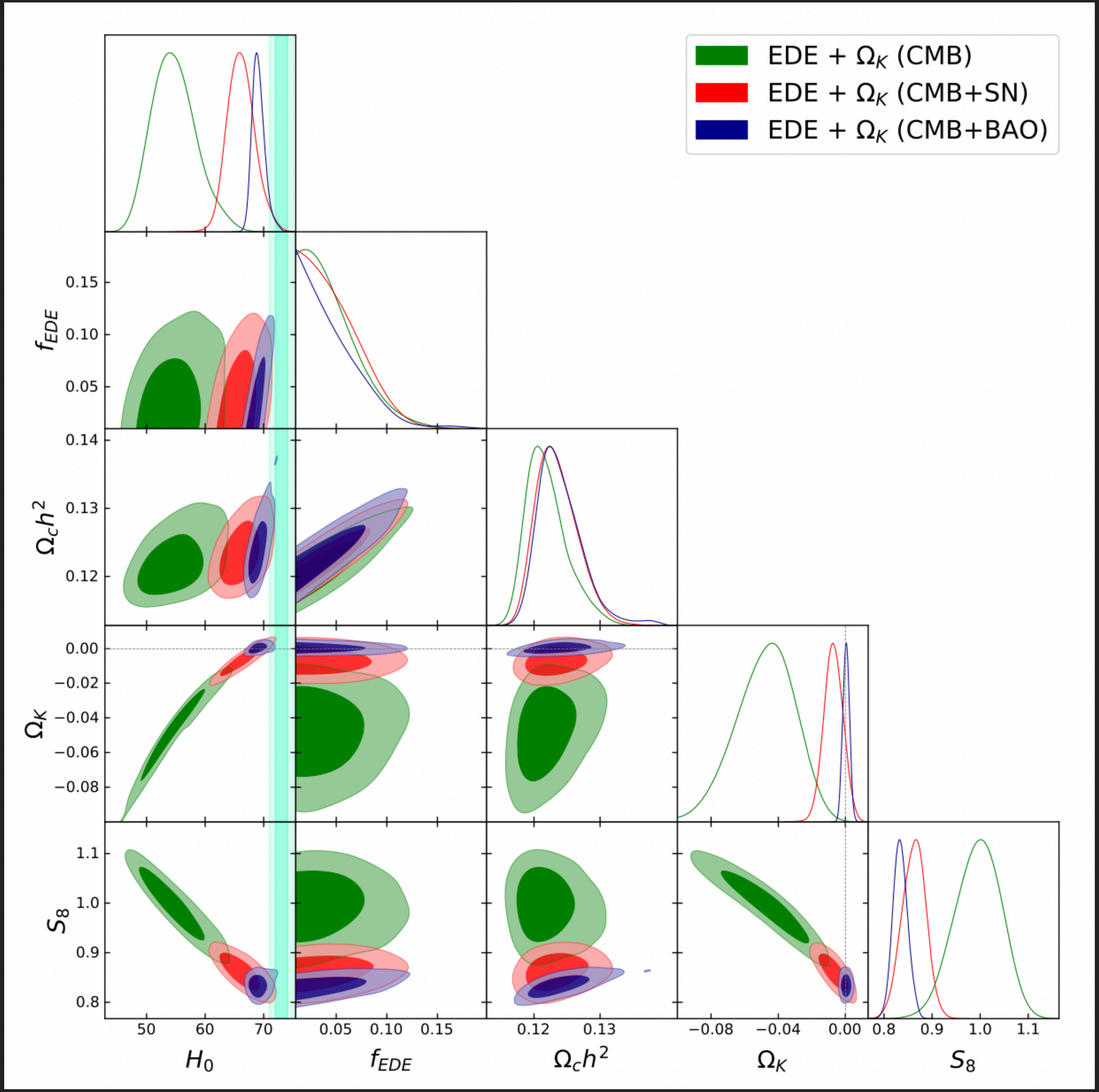


ARISTOTLE'S WAY: THIS IS A CLEAR INDICATION FOR A NEW MODEL.

What about Early Dark Energy?

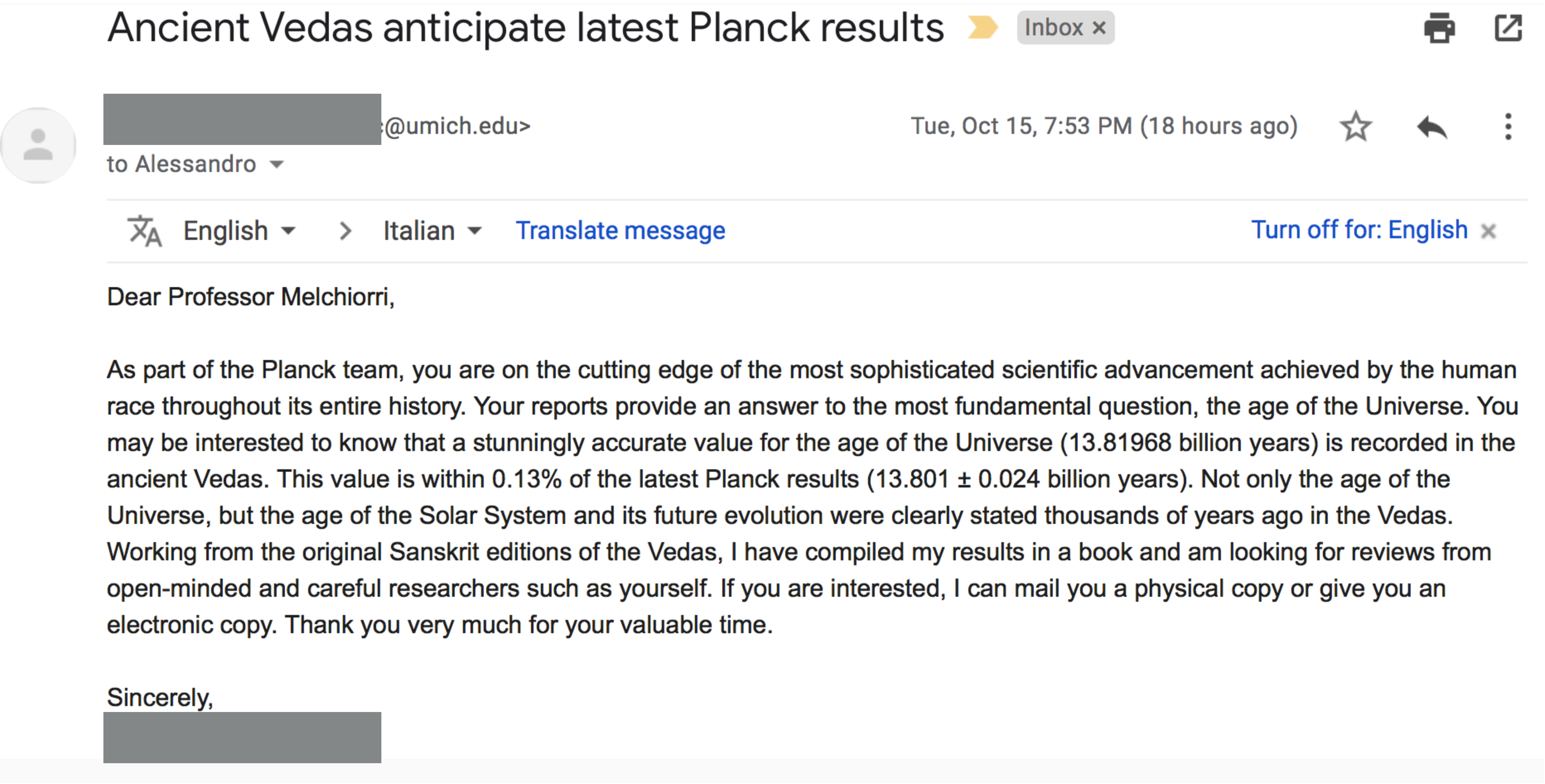
no correlation between EDE and curvature…

(Fondi et al, 2022)



CONCLUSIONS

- Tensions with LCDM are now present at 3-5 sigmas level. Curvature in the Planck data is one of them.
- If we consider curvature all current anomalies increase in statistical significance (and curvature is preferred by Planck).
- Can all of this be due to multiple systematics ? there is no reason to be conservative with LCDM since is not based on known physics!
- However, at the moment, there is no ‘new concordance model’ that could explain most of the anomalies at the same time…



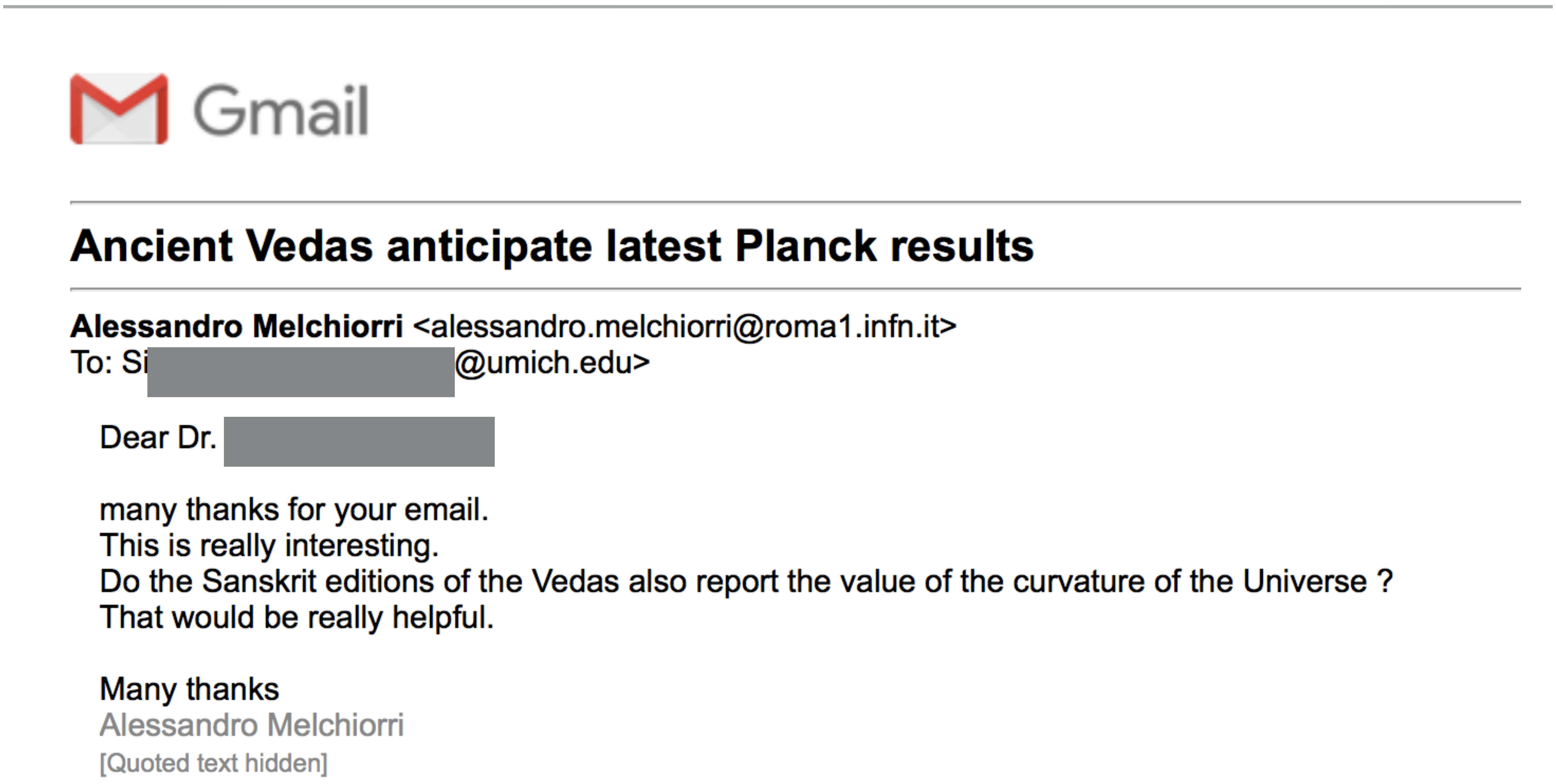
Ancient Vedas anticipate latest Planck results

[redacted]@umich.edu>
Tue, Oct 15, 7:53 PM (18 hours ago)
to Alessandro

Dear Professor Melchiorri,

As part of the Planck team, you are on the cutting edge of the most sophisticated scientific advancement achieved by the human race throughout its entire history. Your reports provide an answer to the most fundamental question, the age of the Universe. You may be interested to know that a stunningly accurate value for the age of the Universe (13.81968 billion years) is recorded in the ancient Vedas. This value is within 0.13% of the latest Planck results (13.801 ± 0.024 billion years). Not only the age of the Universe, but the age of the Solar System and its future evolution were clearly stated thousands of years ago in the Vedas. Working from the original Sanskrit editions of the Vedas, I have compiled my results in a book and am looking for reviews from open-minded and careful researchers such as yourself. If you are interested, I can mail you a physical copy or give you an electronic copy. Thank you very much for your valuable time.

Sincerely,
[redacted]



Gmail

Ancient Vedas anticipate latest Planck results

Alessandro Melchiorri <alessandro.melchiorri@roma1.infn.it>
To: Si[redacted]@umich.edu>

Dear Dr. [redacted]

many thanks for your email.
This is really interesting.
Do the Sanskrit editions of the Vedas also report the value of the curvature of the Universe ?
That would be really helpful.

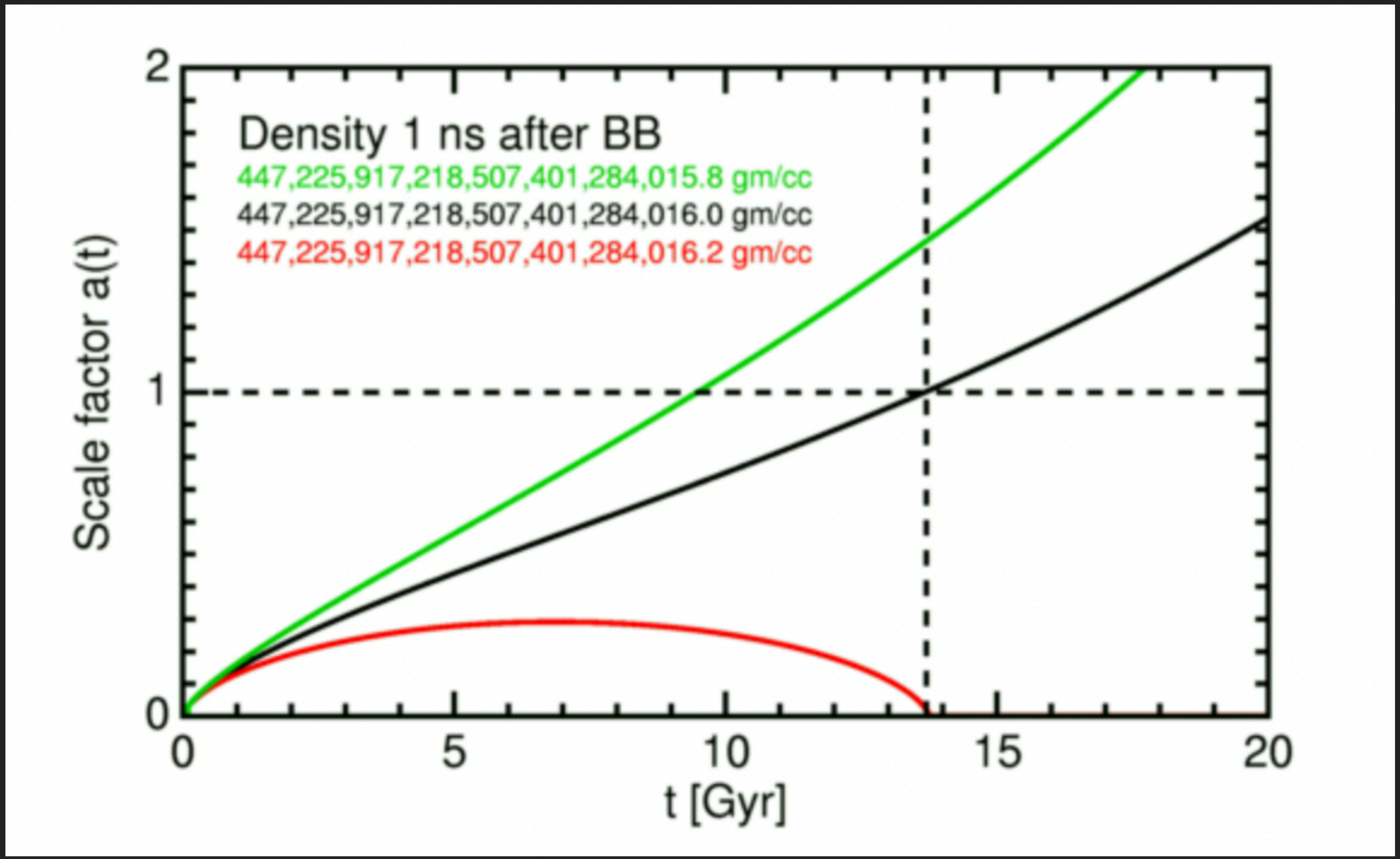
Many thanks
Alessandro Melchiorri
[Quoted text hidden]

FINE TUNING…

Curvature must be close to zero with a precision of 10^-24 1 ns after the Big Bang in order to have approximately flatness today.

This is clearly a fine tuning but still less than the 10^-123 fine tuning with the cosmological constant!

If we learned how to live with Lambda we may well live with curvature…



Ned Wright Cosmology Tutorial