

The trouble with spatial curvature

Sunny Vagnozzi

Newton-Kavli Fellow @ KICC, University of Cambridge

✉ sunny.vagnozzi@ast.cam.ac.uk

🏠 www.sunnyvagnozzi.com

👤 [sunnyvagnozzi](https://github.com/sunnyvagnozzi)

🐦 [@SunnyVagnozzi](https://twitter.com/SunnyVagnozzi)

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IGIT Sarang, 6 November 2020



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What is the shape of the Universe?

*What is the shape of the Universe?
What is the sign of the spatial
curvature parameter Ω_K ?*

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What is the sign of the spatial
curvature parameter Ω_K ?*

- It is true that *Planck* CMB temperature and polarization data appears to prefer a spatially closed Universe ($\Omega_K < 0$)
- However, to learn more we must combine *Planck* data with other external datasets to break the *geometrical degeneracy*...
- ...and doing so teaches us that the Universe is very likely spatially flat to the $|\Omega_K| \sim \mathcal{O}(10^{-2})$ level

Based on arXiv:2010.02230 and upcoming paper

arXiv:2010.02230v2 [astro-ph.CO] 14 Oct 2020

Listening to the BOSS: the galaxy power spectrum take on spatial curvature and cosmic concordance

Sunny Vagnozzi,^a Eleonora Di Valentino,^b Stefano Gariazzo,^{c,d} Alessandro Melchiorri,^e Olga Mena,^f and Joseph Silk^{g,h}

^aKavli Institute for Cosmology (KICoC) and Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom

^bJodrell Bank Center for Astrophysics, School of Physics and Astronomy, University of Manchester, Oxford Road, Manchester M13 9PL, United Kingdom

^cInstituto de Física Corpuscular (IFIC), University of Valencia-CSIC, Parc Científic UV, c/ Catedrático José Beltrán 2, E-46100 Paterna, Spain

^dIstituto Nazionale di Fisica Nucleare (INFN), Sezione di Torino, Via P. Giuria 1, I-10125 Torino, Italy

^eDepartment of Physics and Instituto Nazionale di Fisica Nucleare (INFN), University of Rome "La Sapienza", Piazzale Aldo Moro 2, I-00185 Rome, Italy

^fInstitut d'Astrophysique de Paris (IAP), UMR 7095, CNRS/UPMC Université Paris 6, Sorbonne Universités, 98bis Boulevard Arago, F-75014, Paris, France

^gDepartment of Physics and Astronomy, The Johns Hopkins University, 3400 N. Charles Street, Baltimore, MD 21218, USA

^hKeck Institute for Particle Astrophysics and Cosmology (KIPAC), Department of Physics, University of Oxford, Keble Road, Oxford OX1 3RH, United Kingdom

E-mail: sunny.vagnozzi@ast.cam.ac.uk, eleonora.di.valentino@manchester.ac.uk, gariazzo@to.infn.it, alessandro.melchiorri@infn.it, omens@ific.uv.es, joseph.silk@physics.ox.ac.uk

Abstract. The concordance of the Λ CDM cosmological model in light of current observations has been the subject of an intense debate in recent months. The 2018 *Planck* Cosmic Microwave Background (CMB) temperature anisotropy power spectrum measurements appear at face value to favour a spatially closed Universe with curvature parameter $\Omega_K < 0$. This preference disappears if Baryon Acoustic Oscillation (BAO) measurements are combined with *Planck* data to break the geometrical degeneracy, although the reliability of this combination has been questioned due to the strong tension present between the two datasets when assuming a curved Universe. Here, we address this issue from yet another point of view, using measurements of the full-shape (FS) galaxy power spectrum, $P(k)$, from the Baryon Oscillation Spectroscopic Survey DR12 CMASS sample. By combining *Planck* data with FS measurements, we break the geometrical degeneracy and find $\Omega_K = 0.0023 \pm 0.0028$. This constrains the Universe to be spatially flat to sub-percent precision, in excellent agreement with results obtained using BAO measurements. However, as with BAO, the overall increase in the best-fit χ^2 suggests a similar level of tension between *Planck* and $P(k)$ under the assumption of a curved Universe. While the debate on spatial curvature and the concordance between cosmological datasets remains open, our results provide new perspectives on the issue, highlighting the crucial role of FS measurements in the era of precision cosmology.



Eleonora Di Valentino
(Manchester → Durham)



Stefano Gariazzo
(Valencia → Turin)



Alessandro Melchiorri
(Rome)



Olga Mena
(Valencia)



Joe Silk
(Oxford/IAP/Johns Hopkins)



Avi Loeb
(Harvard)

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Eppur è piatto?

The cosmic chronometer take on spatial curvature and cosmic concordance

SUNNY VAGNOZZI^a AND ABRAHAM LOEB^b

^aKavli Institute for Cosmology, University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom

^bDepartment of Astronomy, Harvard University, 60 Garden Street, Cambridge, MA 02138, USA

ABSTRACT

The question of whether Cosmic Microwave Background (CMB) temperature and polarization data from *Planck* favor a spatially closed Universe with curvature parameter $\Omega_K < 0$ has been the subject of recent intense discussions. Attempts to break the geometrical degeneracy combining *Planck* data with external datasets such as Baryon Acoustic Oscillation (BAO) measurements all point towards a spatially flat Universe, at the cost of significant tensions with *Planck*, which make the resulting dataset combination problematic. Settling this issue would require identifying a dataset which can break the geometrical degeneracy while not incurring in these tensions. In this work we argue that cosmic chronometers (CC), measurements of the expansion rate $H(z)$ from the relative ages of passively evolving galaxies, are the dataset we are after, and come with the additional advantage of being virtually free of cosmological model assumptions. Combining *Planck* with CC data, we find $\Omega_K = -0.0054 \pm 0.0055$, consistent with a spatially flat Universe and competitive with the *Planck*+BAO constraint. We find the result to be stable against minimal parameter space extensions, as well as systematics affecting the cosmic chronometer measurements. We find no substantial tension between *Planck* and CC data within a non-flat Universe, making the resulting combination reliable. This allows us to assert with confidence that the Universe is indeed spatially flat to the $\mathcal{O}(10^{-2})$ level, possibly settling the ongoing spatial curvature debate and lending even more support to the already very successful inflationary paradigm.

Keywords: cosmic background radiation — cosmological parameters — cosmology: observations — distance scale — galaxies: general

1. INTRODUCTION

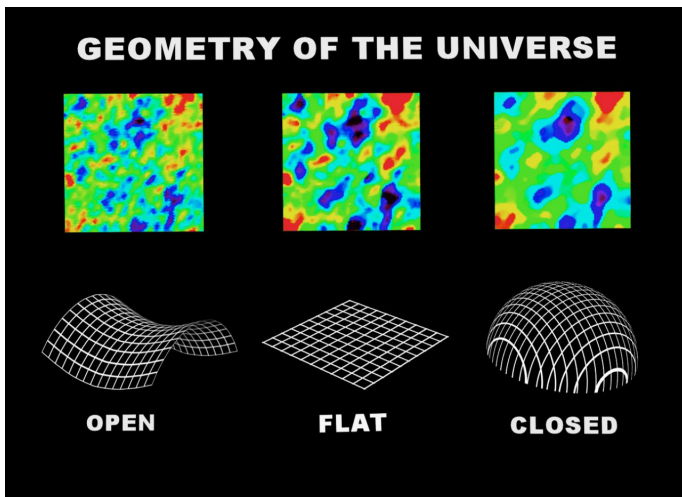
The question concerning what is the shape of the Universe, or more precisely the local geometry of the observable Universe, is one of central importance in cosmology. This question can be addressed by determining the spatial curvature of the Universe (henceforth simply curvature), a quantity which specifies how much the Universe's local geometry differs from flat space geometry. In practice, this

sunny.vagnozzi@ast.cam.ac.uk
aloeb@cfp.harvard.edu

What is the shape of the Universe?



What is the ~~shape~~ local geometry of the observable Universe?



Credits: NASA/GSFC

The curvature parameter

$$H^2 = \frac{8\pi G(\rho_m + \rho_\gamma + \rho_\nu)}{3} + \frac{\Lambda}{3} - \frac{k}{R_0^2 a^2}$$

↓

$$H^2 = H_0^2 \sqrt{\Omega_m a^{-3} + \Omega_\gamma a^{-4} + \Omega_\nu(a) + \Omega_\Lambda + \Omega_K a^{-2}}$$

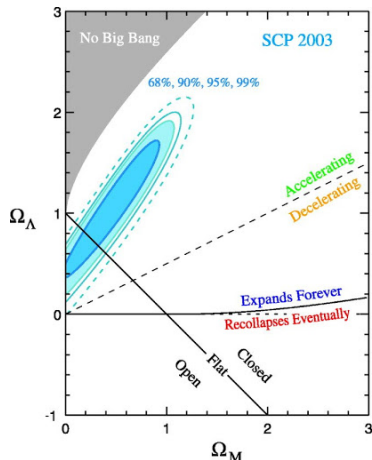
$$\Omega_K \equiv -\frac{k}{H_0^2 R_0^2}$$

Ω_K and k come (confusingly) with opposite signs:

$$k = \begin{cases} -1 & \text{spatially open Universe} & \Omega_K > 0 \\ +1 & \text{spatially closed Universe} & \Omega_K < 0 \\ 0 & \text{spatially flat Universe} & \Omega_K = 0 \end{cases}$$

The importance of spatial curvature

Late Universe: sign and value of Ω_K plays a key role in determining the future evolution of the Universe

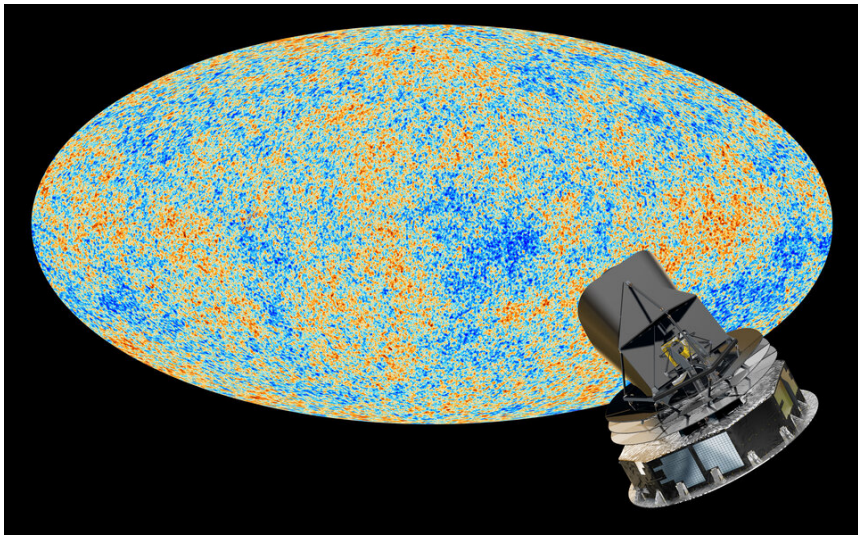


Early Universe: many inflation models predict (constructed to give) $\Omega_K \sim 0$

Measurement of $|\Omega_K| \gtrsim \mathcal{O}(10^{-4})$ would be a problem for many inflationary models

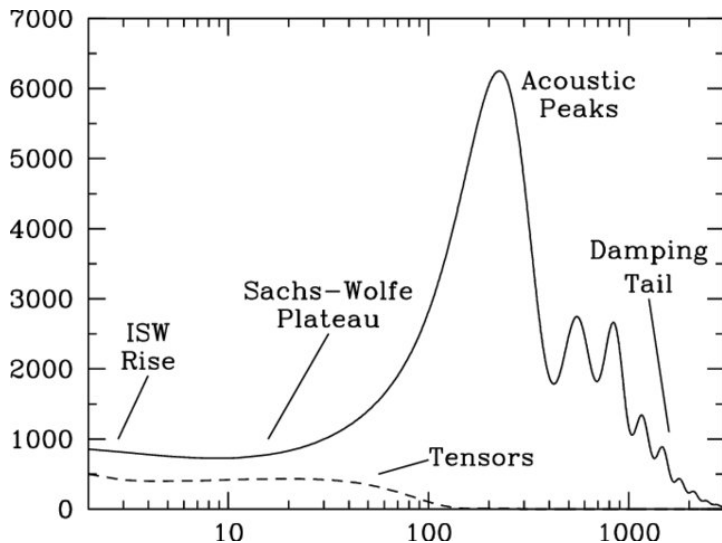
Generally easier to accommodate open rather than closed Universe from inflation

The *Planck* satellite

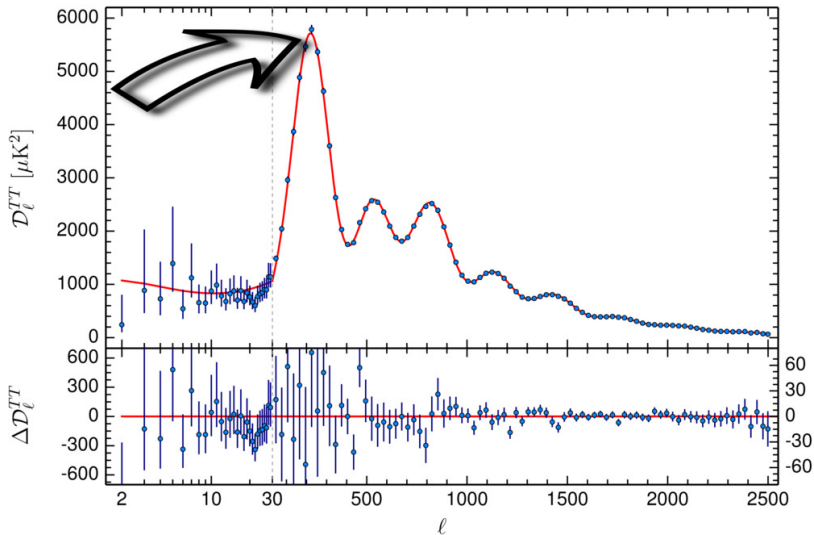


Credits: *Planck* collaboration and ESA

CMB power spectrum



Planck 2018 temperature power spectrum



The geometrical degeneracy

Key angular scale:

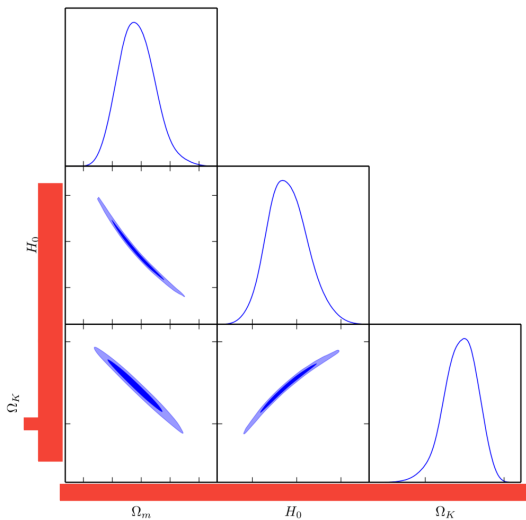
$$\theta_s = \frac{r_s(z_{\text{LS}})}{D_A(z_{\text{LS}})} = \frac{\int_{z_{\text{LS}}}^{\infty} \frac{dz'}{H(z')}}{\int_0^{z_{\text{LS}}} \frac{dz''}{H(z'')}}$$

Geometrical degeneracy notably affects Ω_K , H_0 , and Ω_m (equivalently Ω_Λ)

Is the Universe:

- young (high H_0) with a large amount of vacuum energy and negative spatial curvature?
- spatially flat?
- old (low H_0) with little vacuum energy and positive spatial curvature?
- ...

The geometrical degeneracy



How to break the geometrical degeneracy?

Need to pin down post-recombination expansion rate: $\Omega_m, H_0, H(z), \dots$

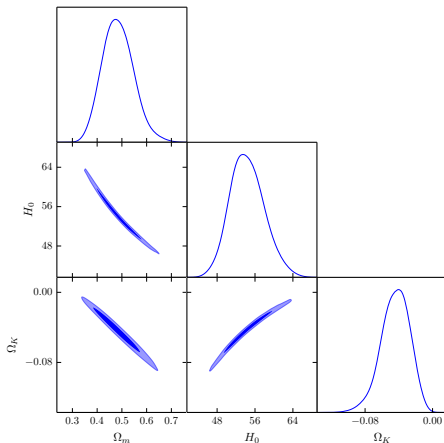
$$D_A(z) = \int_0^z \frac{dz'}{H(z')} \simeq \int_0^z \frac{dz'}{H_0 \sqrt{\Omega_m(1+z')^3 + \Omega_K(1+z')^2 + (1 - \Omega_m - \Omega_K)}}$$

Examples:

- BAO ($D_V/r_s, D_A/r_s, Hr_s \rightarrow$ help stabilizing Ω_m and H_0)
- CMB lensing (helps stabilizing Ω_m)
- Uncalibrated SNeIa (*Pantheon*, help stabilizing Ω_m)
- Local Cepheid- or TRGB-calibrated SNeIa measurements of H_0
- This talk: full-shape (FS) galaxy power spectrum
- This talk: cosmic chronometers (CC)
- ++

Planck 2018 results

Planck TTTEEE+lowE: $\Omega_K = -0.044_{-0.015}^{+0.018}$ \rightarrow apparent detection of $\Omega_K \neq 0$ at the $\mathcal{O}(10^{-2} - 10^{-1})$ level?



	Dataset
Parameters	<i>Planck</i>
Ω_K	$-0.044_{-0.015}^{+0.018}$
H_0 [km/s/Mpc]	$54.36_{-3.96}^{+3.25}$
Ω_m	$0.485_{-0.068}^{+0.058}$

Credits: Planck public chains

Planck 2018 results

Rather implausible (to say the least) values of H_0 and Ω_m within Λ CDM+ Ω_K 7-parameter model ($K\Lambda$ CDM)

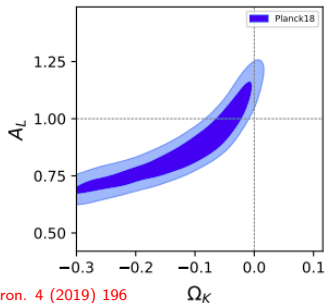
Parameters \ Dataset	Planck
Ω_K	$-0.044^{+0.018}_{-0.015}$
H_0 [km/s/Mpc]	$54.36^{+3.25}_{-3.96}$
Ω_m	$0.485^{+0.058}_{-0.068}$

H_0 in strong tension with whatever local measurement you can think about (Cepheid- and TRGB-calibrated SNeIa, megamasers, H0LiCOW strong lensing,...)

Ω_m also in strong tension with late-time measurements (cosmic shear, cluster counts,...)

Where does this come from?

Partly (but not entirely) from the lensing/ A_{lens} anomaly



Credits: Di Valentino *et al.*, *Nat. Astron.* 4 (2019) 196

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.

Efstathiou, *MNRAS* 343 (2003) L95

Is this a fluke?

Significance of anomalies appears to decrease with more data (=access to higher sky fraction - using 12.5HMC1 CamSpec likelihood)...

A Detailed Description of the CamSpec Likelihood Pipeline and a Reanalysis of the Planck High Frequency Maps

George Efstathiou, Steven Gratton

This paper presents a detailed description of the CamSpec likelihood which has been used to analyse Planck temperature and polarization maps of the cosmic microwave background since the first Planck data release. We have created a number of likelihoods using a range of Galactic sky masks and different methods of temperature foreground cleaning. Our most powerful likelihood uses 80 percent of the sky in temperature and polarization. Our results show that the six-parameter LCDM cosmology provides an excellent fit to the Planck data. There is no evidence for statistically significant internal tensions in the Planck TT, TE and EE spectra computed for different frequency combinations. We present evidence that the tendencies for the Planck temperature power spectra to favour a lensing amplitude $A_L > 1$ and positive spatial curvature are caused by statistical fluctuations in the temperature power spectra. Using our statistically most powerful likelihood, we find that the A_L parameter differs from unity at no more than the 2.2 sigma level. We find no evidence for anomalous shifts in cosmological parameters with multipole range. In fact, we show that the combined TTTEE likelihood over the restricted multipole range 2-800 gives cosmological parameters for the base LCDM cosmology that are very close to those derived from the full multipole range 2-2500. We present revised constraints on a few extensions of the base LCDM cosmology, focussing on the sum of neutrino masses, number of relativistic species and the tensor-scalar ratio. The results presented here show that the Planck data are remarkably consistent between detector-sets, frequencies and sky area. We find no evidence in our analysis that cosmological parameters determined from the CamSpec likelihood are affected to any significant degree by systematic errors in the Planck data (abridged).

Efstathiou & Gratton, [arXiv:1910.00483](https://arxiv.org/abs/1910.00483)

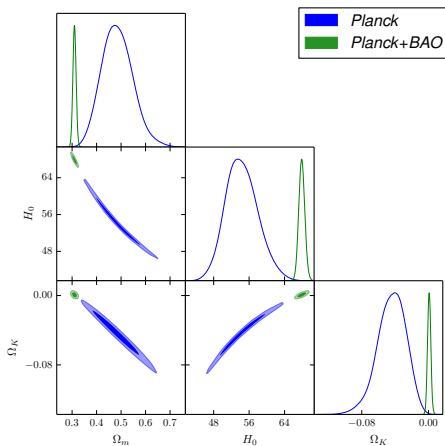
...as one would expect if this were a fluke!

ACT DR4 (+WMAP) results consistent with $A_L = 1$ and $\Omega_K = 0$, no sign of lensing anomaly, support fluke interpretation [Aiola et al., arXiv:2007.07288](https://arxiv.org/abs/2007.07288)

Breaking the geometrical degeneracy

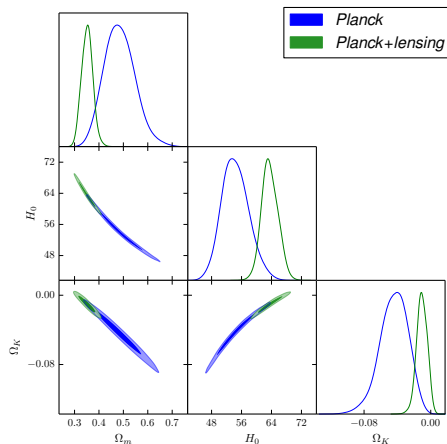
Examples: *Planck* TTTEEE+lowl+lowE

+BAO



Credits: *Planck* public chains

+CMB lensing



Credits: *Planck* public chains

Lots of subsequent discussion

Curvature tension: evidence for a closed universe

Will Handley

The curvature parameter tension between Planck 2018, cosmic microwave background lensing, and baryon acoustic oscillation data is measured using the suspiciousness statistic to be 2.5 to 3 σ . Conclusions regarding the spatial curvature of the universe which stem from the combination of these data should therefore be viewed with suspicion. Without CMB lensing or BAO, Planck 2018 has a moderate preference for closed universes, with Bayesian betting odds of over $50:1$ against a flat universe, and over $2000:1$ against an open universe.

Handley, [arXiv:1908.09139](https://arxiv.org/abs/1908.09139)

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

Eleonora Di Valentino, Alessandro Melchiorri, Joseph Silk

The recent Planck Legacy 2018 release has confirmed the presence of an enhanced lensing amplitude in CMB power spectra compared to that predicted in the standard Λ CDM model. A closed universe can provide a physical explanation for this effect, with the Planck CMB spectra now preferring a positive curvature at more than 99% C.L. 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 within the Planck data set 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 BAO. 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.

Di Valentino *et al.*, *Nat. Astron.* 4 (2019) 196

The evidence for a spatially flat Universe

George Efstathiou, Steven Gratton

We revisit the observational constraints on spatial curvature following recent claims that the Planck data favour a closed Universe. We use a new and statistically powerful Planck likelihood to show that the Planck temperature and polarization spectra are consistent with a spatially flat Universe, though because of a geometrical degeneracy cosmic microwave background spectra on their own do not lead to tight constraints on the curvature density parameter Ω_K . When combined with other astrophysical data, particularly geometrical measurements of baryon acoustic oscillations, the Universe is constrained to be spatially flat to extremely high precision, with $\Omega_K = 0.0004 \pm 0.0018$ in agreement with the 2018 results of the Planck team. In the context of inflationary cosmology, the observations offer strong support for models of inflation with a large number of e-foldings and disfavour models of incomplete inflation.

Efstathiou & Gratton, *MNRAS* 496 (2020) L91

Lots of media attention

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

Eleonora Di Valentino, Alessandro Melchiorri  & Joseph Silk

Nature Astronomy 4, 196–203(2020) | Cite this article

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Lots of media attention

ABSTRACTIONS BLOG

What Shape Is the Universe? A New Study Suggests We've Got It All Wrong

🔥 64 | 📖

When researchers reanalyzed the gold-standard data set of the early universe, they concluded that the cosmos must be "closed," or curled up like a ball. Most others remain unconvinced.

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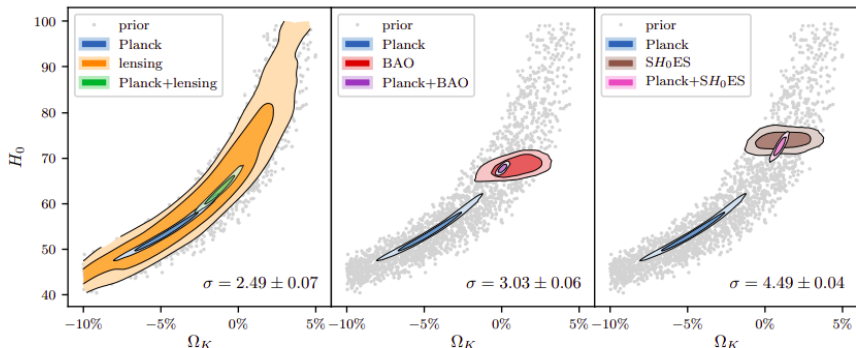
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SPACE

Is the Universe a Giant Loop?

A new study suggests the cosmos may be curved in upon itself like a ball—but many experts remain unconvinced

Credits: Scientific American

Tensions with external datasets?

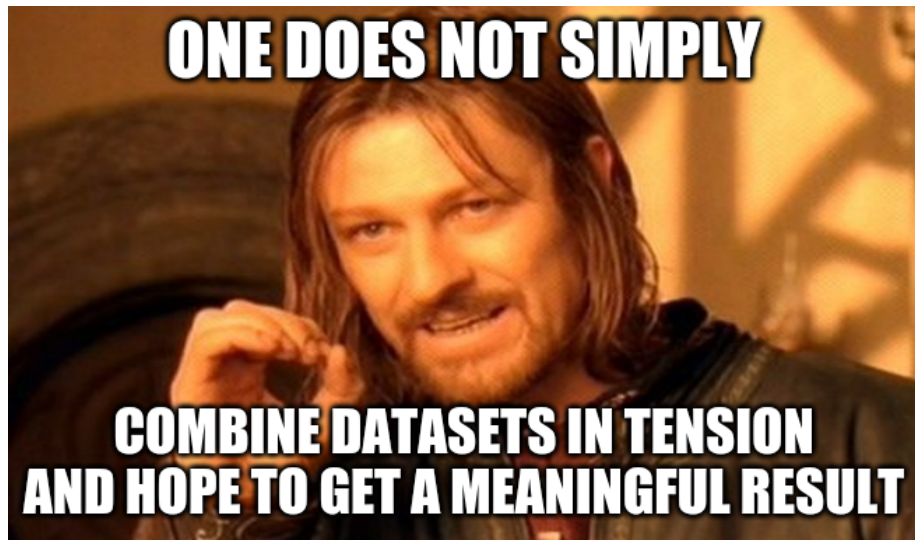


Credits: Handley, arXiv:1908.09139

Should we believe results coming from the combination of datasets in tension *within a given model*?

Can we break the geometrical degeneracy in a different way?

Tensions with external datasets



Breaking the geometrical degeneracy with full-shape galaxy power spectrum data

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[Submitted on 5 Oct 2020 (v1), last revised 14 Oct 2020 (this version, v2)]

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Comments: 33 pages, 1 figure (busy readers should skip to the key plot on Page 12). This is an agnostic paper, but if you've enjoyed reading it we'd love to hear your interpretation of our results, and whether you think the Universe is flat or not - please participate in this poll at this [http URL](#) (it's anonymous)! v2: references added

Subjects: **Cosmology and Nongalactic Astrophysics (astro-ph.CO)**; General Relativity and Quantum Cosmology (gr-qc)

Cite as: [arXiv:2010.02230](#) [[astro-ph.CO](#)]

(or [arXiv:2010.02230v2](#) [[astro-ph.CO](#)] for this version)

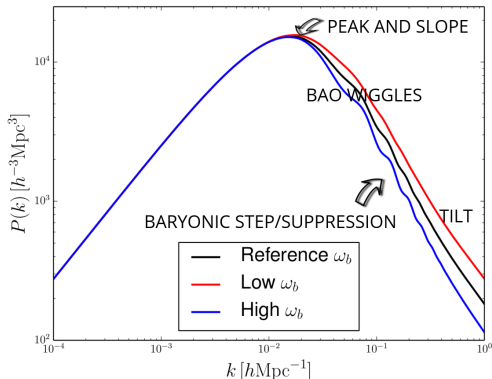
Submission history

From: Sunny Vagnozzi [[view email](#)]

[v1] Mon, 5 Oct 2020 18:00:03 UTC (734 KB)

[v2] Wed, 14 Oct 2020 15:01:14 UTC (734 KB)

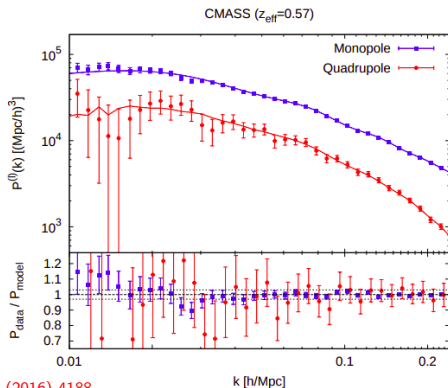
How can FS break the geometrical degeneracy?



- Position of BAO wiggles in k space $\rightarrow D_V \rightarrow H_0$
- k_{eq} turnaround in $P(k)$ \rightarrow shape parameter $\Gamma \equiv \Omega_m h$
- Baryonic step/suppression $\rightarrow \Omega_b h^2$ (hard to measure)
- The CMB already gives us $\Omega_m h^2 \rightarrow$ disentangle Ω_m and H_0

FS data

Monopole of BOSS DR12 CMASS power spectrum measured by Gil-Marín *et al.*¹ (conservative $k_{\max} = 0.135 h \text{ Mpc}^{-1}$ cutoff)

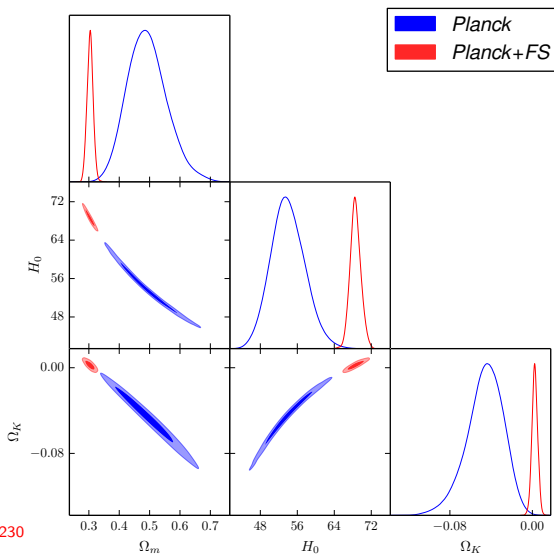


Gil-Marín *et al.*, MNRAS 460 (2016) 4188

¹Note: 1) not the same $P(k)$ quoted in “consensus” BOSS results (but gives consistent results); 2) not the same $P(k)$ used by recent EFTofLSS analyses

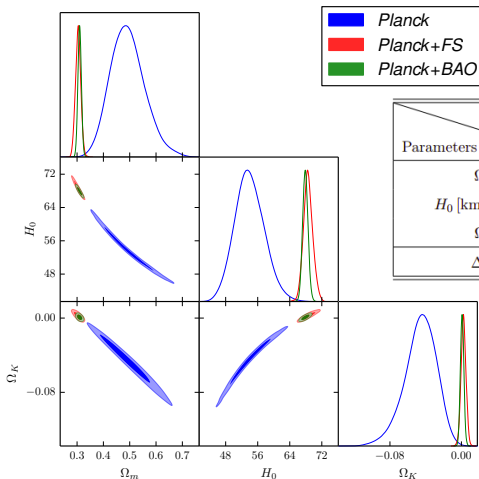
Combining *Planck* and FS data

Planck+FS: $\Omega_K = 0.0023 \pm 0.0028 \rightarrow$ consistent with $\Omega_K = 0 @ < 1\sigma$



Compare FS and BAO

- 1 Consistent results across the two \rightarrow good sanity check!
- 2 Sensible values for H_0 and Ω_m (also a good sanity check)
- 3 Much smaller $\Delta\chi^2$ (additional Ω_k parameter not preferred)

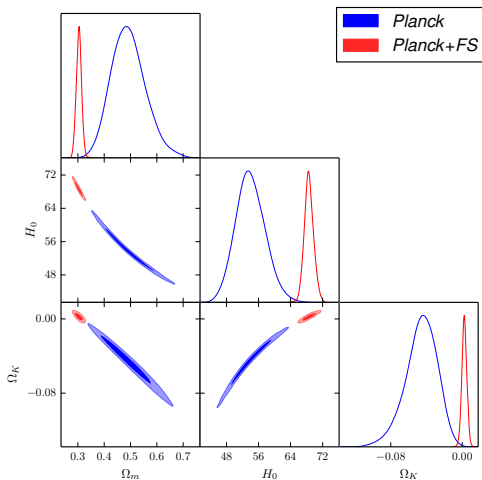


Dataset \ Parameters	Planck	Planck+BAO	Planck+FS
Ω_K	$-0.044^{+0.018}_{-0.015}$	0.0008 ± 0.0019	0.0023 ± 0.0028
H_0 [km/s/Mpc]	$54.36^{+3.25}_{-3.96}$	67.88 ± 0.66	$68.59^{+1.08}_{-1.20}$
Ω_m	$0.485^{+0.058}_{-0.068}$	0.310 ± 0.007	0.304 ± 0.010
$\Delta\chi^2$	-10.9	-0.6	-1.0

SV et al., arXiv:2010.02230

Tensions between *Planck* and FS?

We all see a 3σ ish tension by eye...



SV *et al.*, arXiv:2010.02230

Tensions between *Planck* and FS?

We use a deviance information criterion (DIC)-based tension metric:

Used in KiDS and CFHTLenS, see e.g. Hildebrandt *et al.*, MNRAS 465 (2017) 1454; Joudaki *et al.*

$$\mathcal{I}(D_1, D_2) = \exp \left[-\frac{\text{DIC}(D_1 \cup D_2) - \text{DIC}(D_1) - \text{DIC}(D_2)}{2} \right]$$

If datasets concordant then $\log \mathcal{I} > 0$, else $\log \mathcal{I} < 0$ if discordant

With $D_1 = \textit{Planck}$, $D_2 = \textit{FS} \rightarrow \log \mathcal{I} \approx -2.5$

strong tension on a Jeffreys-like scale \rightarrow see this by eye (and from χ^2 s)

Model \ Dataset	Dataset	
	<i>Planck</i> +BAO	<i>Planck</i> +FS
Λ CDM	+6.1	+22.0
K Λ CDM	+16.8	+31.9

An impasse?

- We want to break the geometrical degeneracy with external datasets (“ext”) to stabilize *Planck* constraints on Ω_K ...
- ...but always run into tensions when doing so within $K\Lambda$ CDM...
- ...including when using FS to break the geometrical degeneracy!
- *Planck*+ext always points towards $\Omega_K = 0$, including “ext”=FS
- Another problem: most of these external datasets (e.g. BAO and FS) carry some amount of model-dependence in the form of fiducial cosmological assumptions during data reduction process

How to exit this impasse?

Need a “golden dataset” which:

- helps to break the geometrical degeneracy once combined with *Planck* CMB temperature and polarization data
- is not in strong tension with *Planck* data when working within a non-flat Universe
- is as model-independent as possible

Breaking the geometrical degeneracy with cosmic chronometer data

Eppur è piatto?

The cosmic chronometer take on spatial curvature and cosmic concordance

SUNNY VAGNOZZI ¹ AND ABRAHAM LOEB ²

¹*Kavli Institute for Cosmology, University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom*

²*Department of Astronomy, Harvard University, 60 Garden Street, Cambridge, MA 02138, USA*

ABSTRACT

The question of whether Cosmic Microwave Background (CMB) temperature and polarization data from *Planck* favor a spatially closed Universe with curvature parameter $\Omega_K < 0$ has been the subject of recent intense discussions. Attempts to break the geometrical degeneracy combining *Planck* data with external datasets such as Baryon Acoustic Oscillation (BAO) measurements all point towards a spatially flat Universe, at the cost of significant tensions with *Planck*, which make the resulting dataset combination problematic. Settling this issue would require identifying a dataset which can break the geometrical degeneracy while not incurring in these tensions. In this work we argue that cosmic chronometers (CC), measurements of the expansion rate $H(z)$ from the relative ages of passively evolving galaxies, are the dataset we are after, and come with the additional advantage of being virtually free of cosmological model assumptions. Combining *Planck* with CC data, we find $\Omega_K = -0.0054 \pm 0.0055$, consistent with a spatially flat Universe and competitive with the *Planck*+BAO constraint. We find the result to be stable against minimal parameter space extensions, as well as systematics affecting the cosmic chronometer measurements. We find no substantial tension between *Planck* and CC data within a non-flat Universe, making the resulting combination reliable. This allows us to assert with confidence that the Universe is indeed spatially flat to the $\mathcal{O}(10^{-2})$ level, possibly settling the ongoing spatial curvature debate and lending even more support to the already very successful inflationary paradigm.

Cosmic chronometers

Age-redshift relation:

$$\frac{dt}{dz} = -\frac{1}{(1+z)H(z)}$$

Take two ensembles of passively evolving galaxies that formed at the same time and are separated by a small redshift interval Δz around z_{eff} :

$$H(z_{\text{eff}}) = -\frac{1}{1+z_{\text{eff}}} \frac{\Delta z}{\Delta t}$$

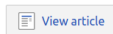
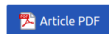
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Constraining Cosmological Parameters Based on Relative Galaxy Ages

Raul Jimenez¹ and Abraham Loeb²

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[The Astrophysical Journal, Volume 573, Number 1](#)



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Advantages with respect to distance measurements

Luminosity/angular diameter distance:

$$D_L = (1+z) \int_0^z \frac{dz'}{H(z')} \quad D_A = \frac{1}{1+z} \int_0^z \frac{dz'}{H(z')}$$

Distances suffer from integral sensitivity to expansion history and parameters such as the dark energy equation of state

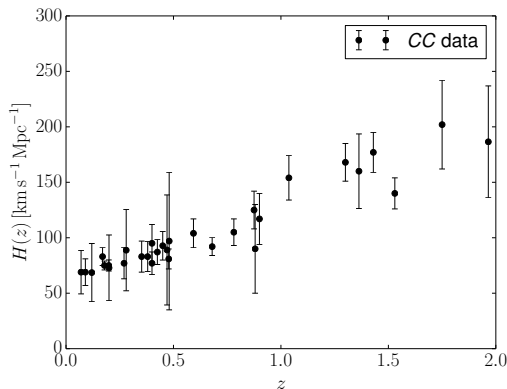
CMB acoustic scale:

$$\theta_s = \frac{r_s(z_{\text{LS}})}{D_A(z_{\text{LS}})} = \frac{\int_{z_{\text{LS}}}^{\infty} \frac{dz'}{H(z')}}{\int_0^{z_{\text{LS}}} \frac{dz''}{H(z'')}}$$

Most of the contribution to $D_A(z_{\text{LS}})$ comes from $H(z)$ at $0 < z \lesssim 2$

Cosmic chronometer measurements

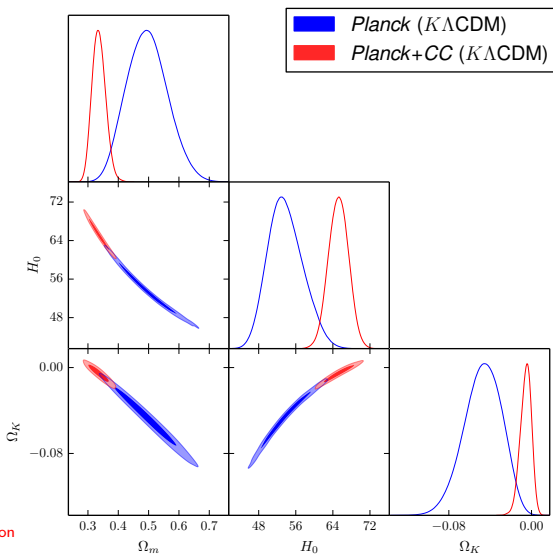
Using massive, passively-evolving galaxies



Compiled across the last 20 years in: Jiménez *et al.*, ApJ 593 (2003) 622; Simon *et al.*, PRD 71 (2005) 123001; Stern *et al.*, JCAP 1002 (2010) 008; Moresco *et al.*, JCAP 1207 (2012) 053; Zhang *et al.*, Res. Astron. Astrophys. 14 (2014) 1221; Moresco, MNRAS 450 (2015) L16; Moresco *et al.*, JCAP 1605 (2016) 014; Ratsimbazafy *et al.*, MNRAS 467 (2017) 3239

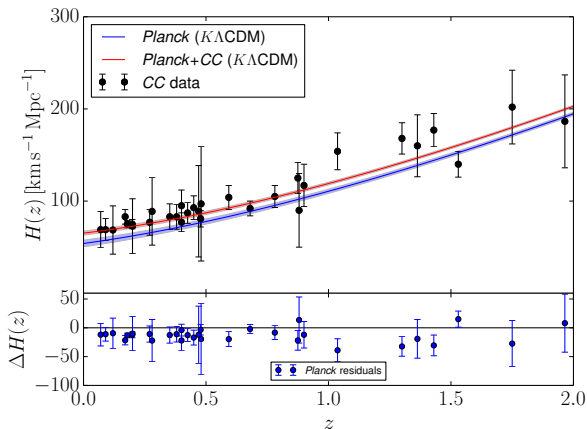
Combining *Planck* and CC data

Planck+CC: $\Omega_K = -0.0054 \pm 0.0055 \rightarrow$ consistent with $\Omega_K = 0 @ < 1\sigma$



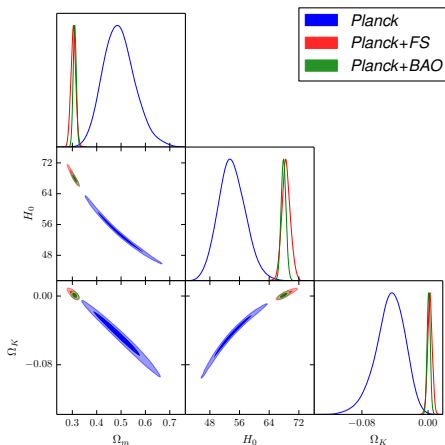
Tensions between *Planck* and CC?

$\log \mathcal{I} \approx -0.43 \rightarrow$ no strong tension \rightarrow we may trust the *Planck*+CC dataset combination even within a non-flat Universe!

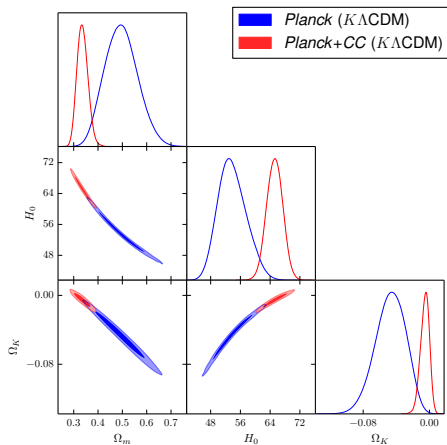


Compare *Planck*+CC to *Planck*+BAO/FS

By eye much less tension, yet results still go towards $\Omega_K = 0$



SV *et al.*, arXiv:2010.02230



SV & Loeb, in preparation

Are cosmic chronometers our “golden dataset”?

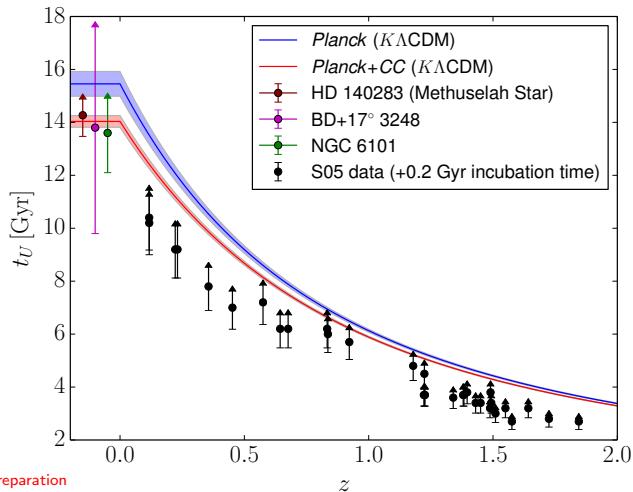
Golden dataset characteristics:

- helps to break the geometrical degeneracy once combined with *Planck* CMB temperature and polarization data ✓
- is not in strong tension with *Planck* data when working within a non-flat Universe ✓
- is as model-independent as possible ✓

Two additional advantages:

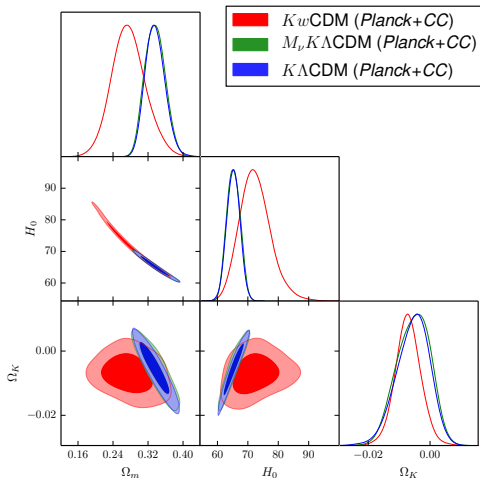
- requires no cosmological calibration (compare with measurements which require r_s/ω_b prior/calibration)
- directly measuring expansion rate more helpful than measuring distances to break geometrical degeneracy

Age of the Universe and the oldest known objects



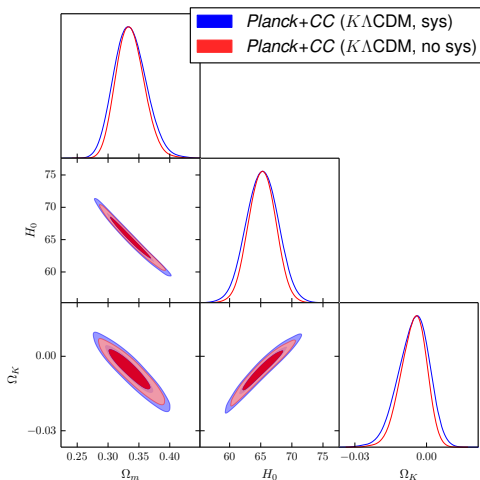
Are these results stable against an enlarged parameter space?

Yes (at least when varying w or M_ν)!



How much are these results affected by CC systematics?

Very little ($\lesssim 10\%$)!



Conclusions

- Curvature parameter Ω_K is a key quantity in cosmology
- *Planck* CMB temperature and polarization data prefers $\Omega_K < 0...$
- but for a reliable result need to break geometrical degeneracy!
- Attempts to break the geometrical degeneracy incur in tensions...
- ...example: *Planck*+full-shape galaxy power spectrum data
→ $\Omega_K = 0.0023 \pm 0.0028$ at the cost of a $\sim 3\sigma$ tension
- Cosmic chronometer data can break the geometrical degeneracy without incurring in strong tensions → $\Omega_K = -0.0054 \pm 0.0055$
- **Universe is spatially flat to the $\mathcal{O}(10^{-2})$ level**