Planck constraints on the non-flat ΛCDM inflation model

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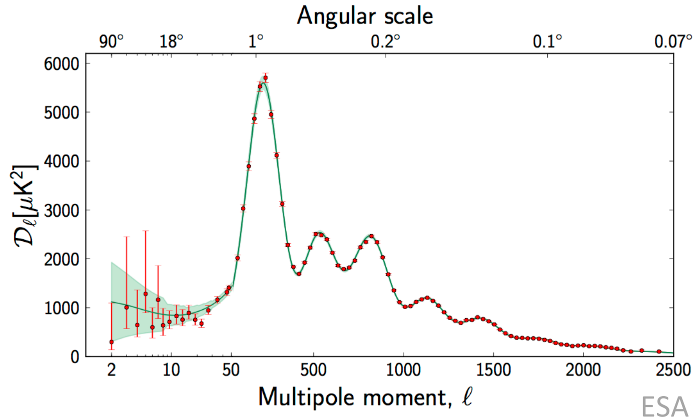
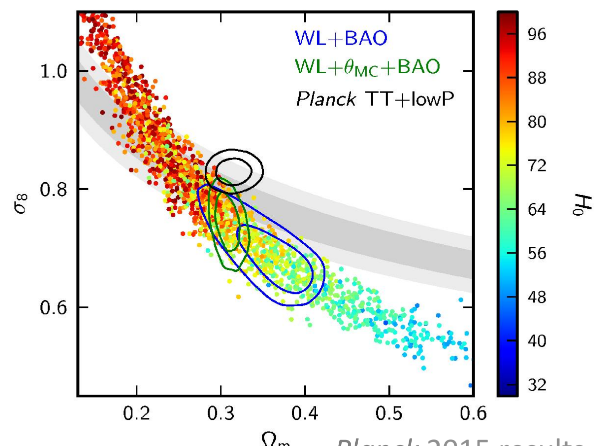
Contents

Introduction

- Planck mission put strong constraint on the cosmological parameters.
- Flat ΛCDM model is consistent with data.
- However there are some deviations.
  - deficit in power of the low-ℓ C_ℓ^{TT} data
  - higher σ_8 prediction than weak lensing observation
- These deviations might be a possibility of some extended theories.
  - here we focus on the non-flat model.



ESA

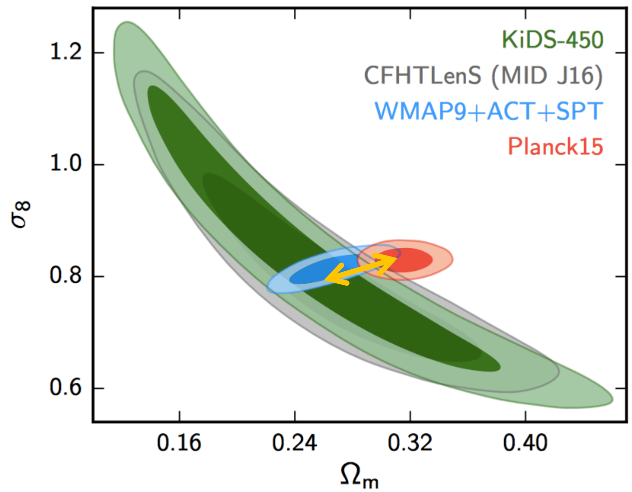


Planck 2015 results. XIII.

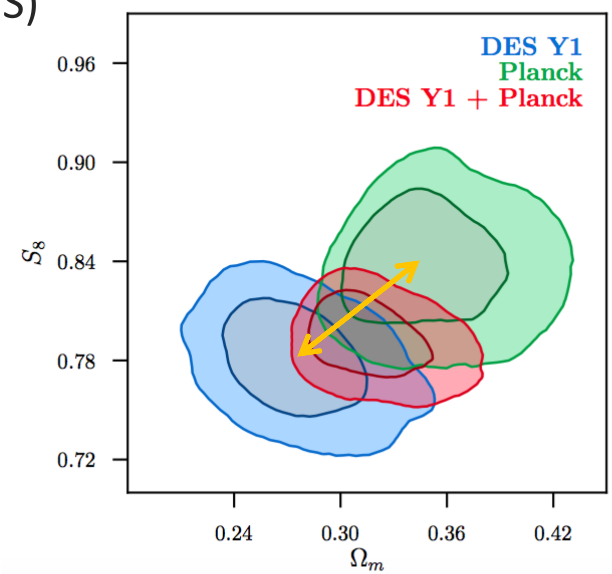
Introduction

- New results of constraints on the σ_8 also show the tension.
  - left: Kilo Degree Survey (KiDS)
  - right: Dark Energy Survey (DES)

$$S_8 \equiv \sigma_8 \left(\frac{\Omega_\mathrm{m}}{0.3}\right)^{0.5}$$



Hildebrandt+ (2016)



DES collaboration (2017)

Non-flat inflation model

- The metric with a spatial curvature is

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

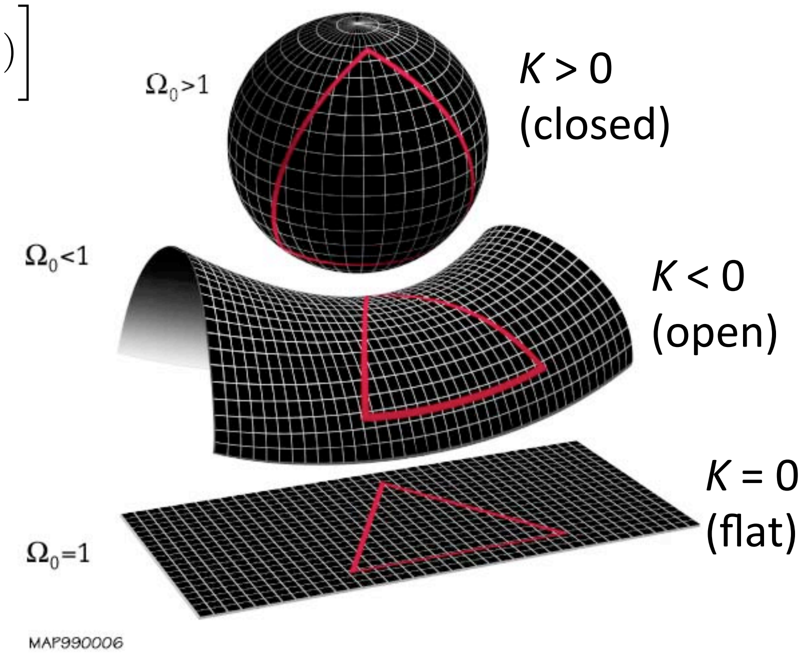
- Friedmann eq is

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

- In terms of density parameters,

$$1 = \Omega_0 + \Omega_{K0}$$

  - Here, $\Omega_{K0} = -\frac{K}{H_0^2}$



wikipedia

Non-flat inflation model

- The energy density inhomogeneity power spectrum generated by quantum fluctuations during an early epoch of inflation in the spatially non-flat universe is

$$P(q) \propto \frac{(q^2 - 4K)^2}{q(q^2 - K)}$$

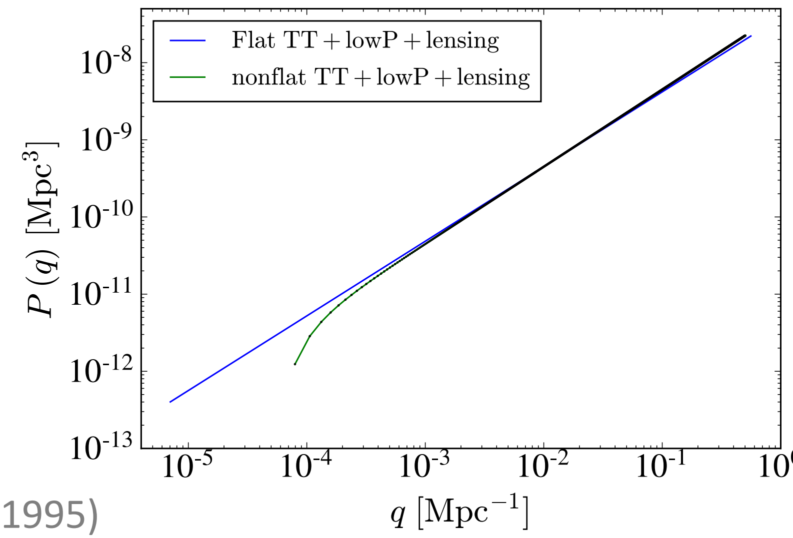
Ratra & Peebles (1995)
Ratra (2017)

- Here, $q^2 = k^2 + K$

- From Ratra's papers, there is no simple tilt option, so n_s is no longer a free parameter and replaced by Ω_{K0} which results in a non-flat ΛCDM inflation model.

Non-flat inflation model

- This is a generalization of the flat-space scale invariant spectrum.
- On large scales, the fractional energy density inhomogeneity power spectrum for the best-fit closed ΛCDM model is suppressed relative to that of flat ΛCDM model.
- Open case, q runs from 0 to ∞. Ratra & Peebles (1995)
- Closed case, $q/\mathrm{sqrt}(K)$ runs 3, 4, 5, … . Ratra (2017)
  - It takes discrete values because the universe is spatially closed.

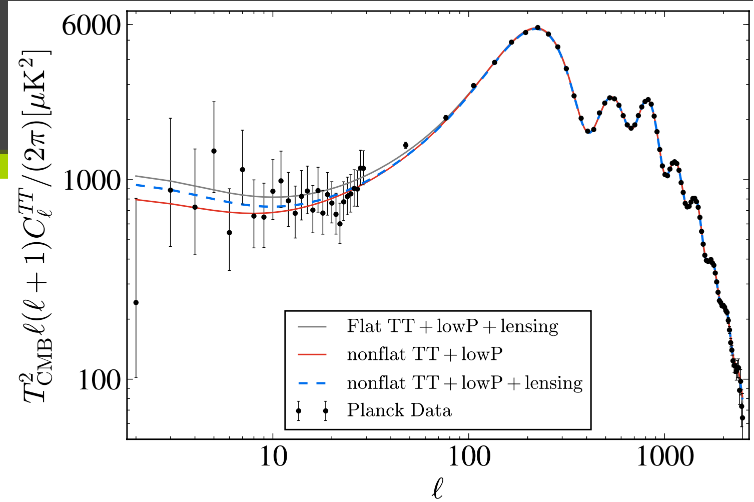


$$P(q) \propto \frac{(q^2 - 4K)^2}{q(q^2 - K)}$$

Result

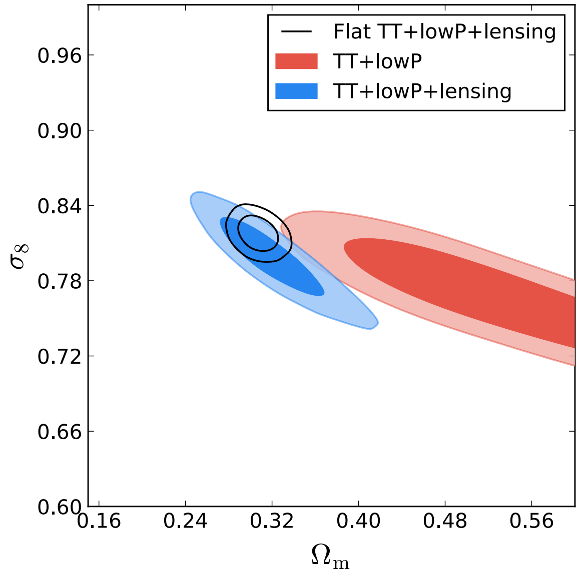
- CLASS (class-code.net)
  - To compute the fluctuations in the CMB.
- Monte python (montepython.net)
  - To analyze data by using the Markov chain Monte Carlo (MCMC) method.
- Data
  - Planck 2015: *TT, lowP*, lensing
  - BAO: 6dF, BOSS (LOWZ and CMASS), SDSS

Result: Planck only

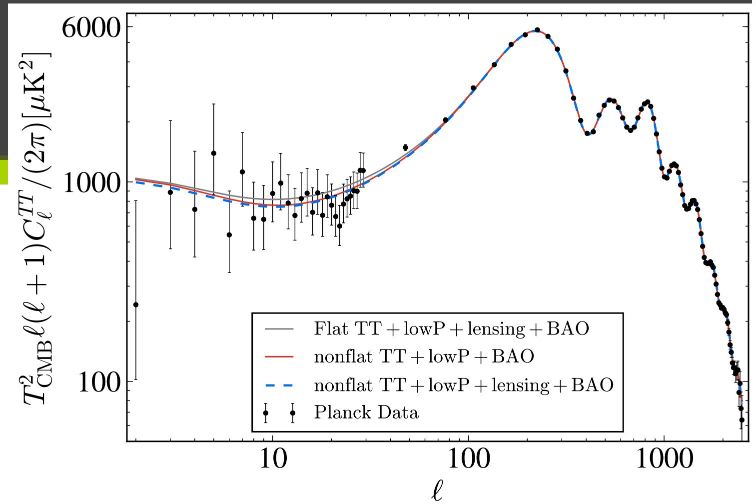


- We found that non-flat models fit the low-ℓ C_ℓ better than the flat case.
- When CMB lensing is included, we found that our non-flat model weakens the tension in the σ_8–Ω_m constraint.
  - lower σ_8 values are preferred.
- The spatial curvature density parameter is constrained as,

$$\Omega_{\rm k} = -0.018^{+0.018}_{-0.020} \quad (95.45\%,\ {\rm TT + lowP + lensing}).$$



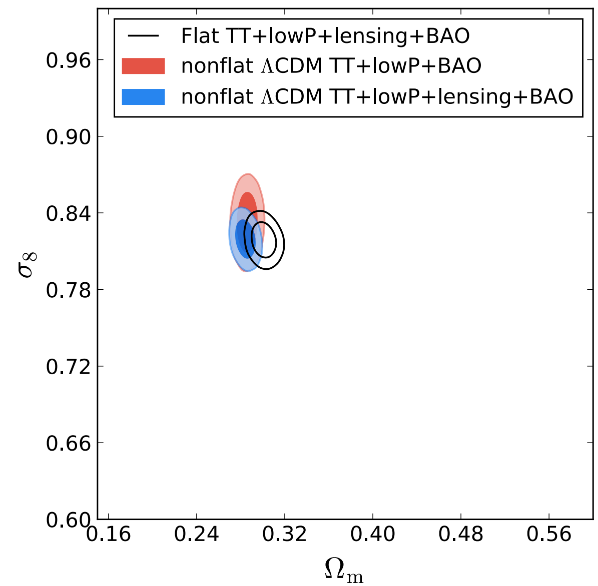
Result: + BAO



- Including the BAO data does somewhat degrade the fit in the low-ℓ region.
- Including the BAO data also degrades the tension in the σ_8–Ω_m constraint.
- The spatial curvature density parameter is constrained as,

$$\Omega_k = -0.008 \pm 0.004 \quad (95.45\%,\ \mathrm{TT+lowP+lensing+BAO}).$$

This case is about 4 σ away from flat.



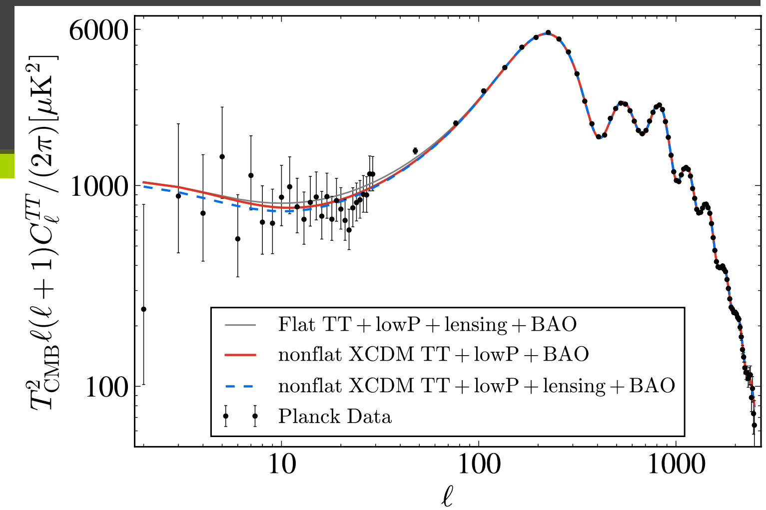
Result: non-flat XCDM model

- XCDM model in which dark energy is parameterized in terms of the EoS parameter of a fluid.
- Here the dark energy fluid pressure and energy density are related via,

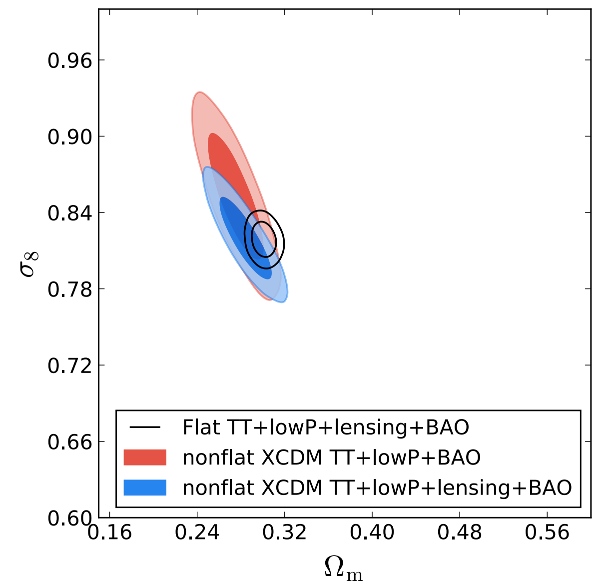
$$p_X = w_0 \rho_X$$

- It is a simple parameterization of the dynamical dark energy that is relatively straightforward to use in a computation.
  - additional parameter w_0

Result: XCDM



- It does not change the fit in the low-ℓ region significantly.
  - similar to the ΛCDM case.
- In the σ_8–Ω_m contour, there is a region that weaken the tension, lower σ_8.



- This case is about 3 σ away from flat

$$\Omega_{\rm k} = -0.008 \pm 0.006 \quad (95.45\%,\ {\rm TT + lowP + lensing + BAO}).$$

$$w_0 = -1.00 \pm 0.10 \quad (68.27\%,\ {\rm TT + lowP + lensing + BAO}).$$

Result: non-flat ϕCDM model

- ϕCDM model is physically consistent dynamical dark energy model.
- ϕ is the scalar field with a potential

$$V(\phi) = \kappa m_P^2 \phi^{-\alpha}$$

Ratra & Peebles (1988)

- Equations of motion of the non-flat ϕCDM model are

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3m_P^2}(\rho + \rho_\phi) - \frac{K}{a^2}$$

$$\rho_\phi = \frac{m_P^2}{32\pi}\left(\dot{\phi}^2 + 2\kappa m_P^2 \phi^{-\alpha}\right)$$

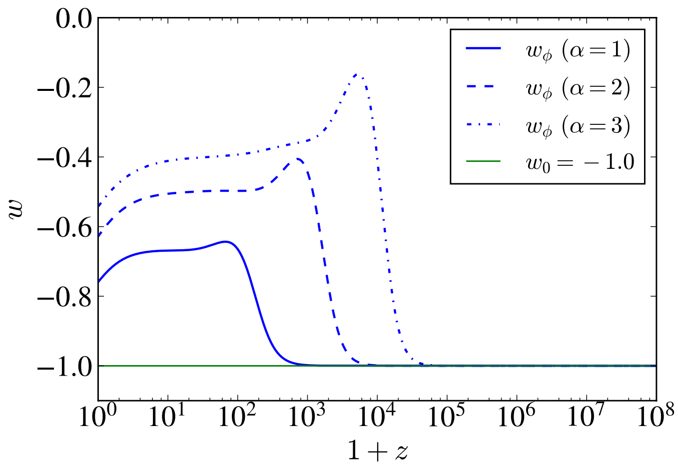
$$\ddot{\phi} + 3\frac{\dot{a}}{a}\dot{\phi} - \kappa\alpha m_P^2 \phi^{-(\alpha+1)} = 0$$

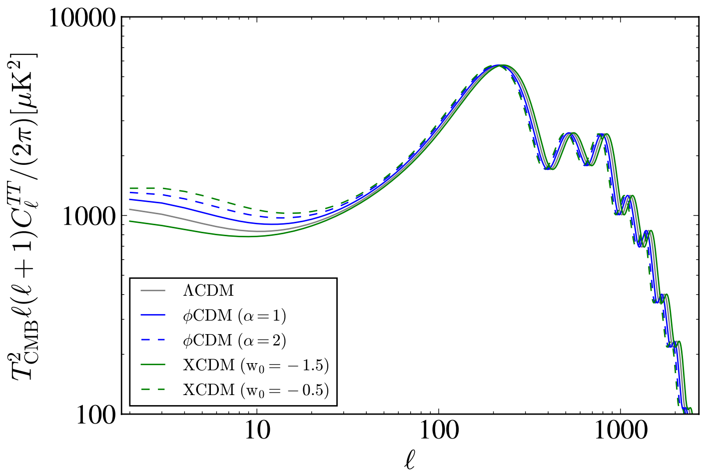
Result: non-flat ϕCDM model

- ϕCDM model is physically consistent dynamical dark energy model.
- ϕ is the scalar field with potential

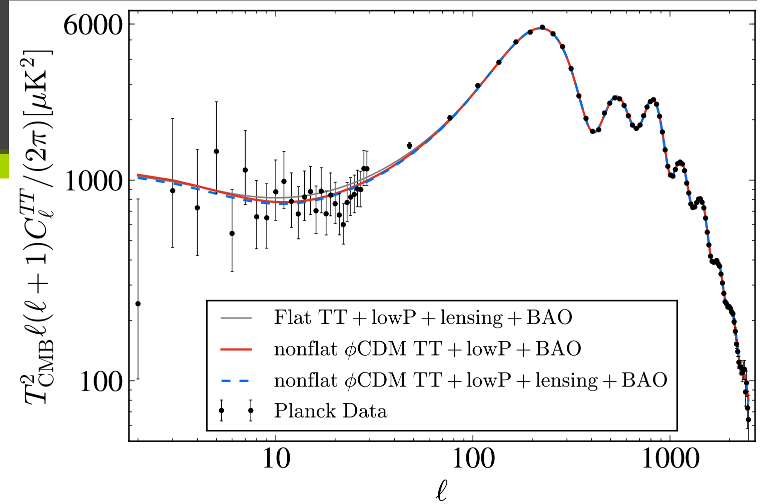
$$V(\phi) = \kappa m_P^2 \phi^{-\alpha}$$

Ratra & Peebles (1988)





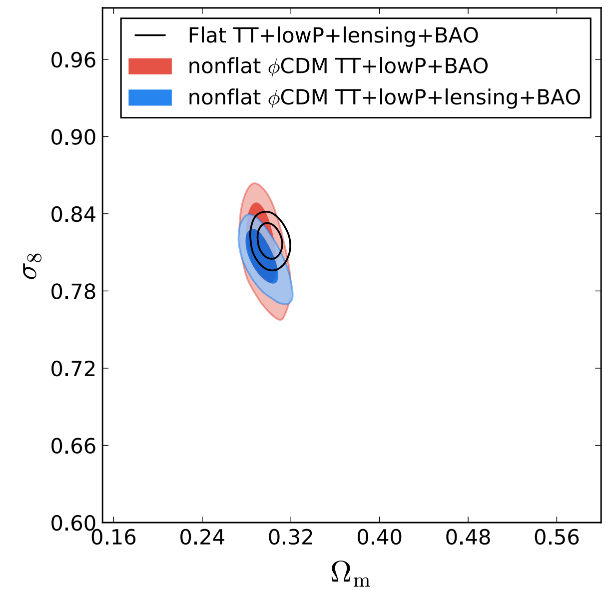
Result: ϕCDM



- Including the BAO data does not improve the fit in the low-ℓ region.
  - similar to non-flat ΛCDM & XCDM cases.
- The tension is weakened in the σ_8–Ω_m contour.
  - more consistent with weak lensing.
- Ω_K and α are constrained as follows.

$$\Omega_{\rm k} = -0.006 \pm 0.005 \quad (95.45\%,\ {\rm TT + lowP + lensing + BAO}).$$

$$\alpha < 0.304 \quad (95.45\%,\ {\rm TT + lowP + lensing + BAO}).$$



Summary

arXiv:1707.03452

- We study the non-flat inflation model which realize a reduced power in the large scale region of the energy density inhomogeneity power spectrum.
- This model is interesting and might be useful for the tensions in the current CMB observation.
  - low-ℓ C_ℓ deficit, weak lensing σ_8
- We also did additional works
  - non-flat XCDM, ϕCDM models arXiv:1710.03271 arXiv:1712.08617

Backup

Result

Table 1. 68.27% confidence limits on cosmological parameters of the non-flat ΛCDM model from CMB data.

Parameter	TT+lowP	TT+lowP+lensing	TT,TE,EE+lowP	TT,TE,EE+lowP+lensing
$\Omega_b h^2$	0.02333 ± 0.00022	0.02304 ± 0.00020	0.02304 ± 0.00015	0.02289 ± 0.00015
$\Omega_c h^2$	0.1092 ± 0.0011	0.1091 ± 0.0011	0.1108 ± 0.0010	0.1111 ± 0.0009
100θ	1.04300 ± 0.00041	1.04306 ± 0.00041	1.04256 ± 0.00030	1.04259 ± 0.00029
τ	0.089 ± 0.028	0.101 ± 0.021	0.089 ± 0.026	0.100 ± 0.019
$\ln(10^{10} A_s)$	3.088 ± 0.057	3.108 ± 0.042	3.091 ± 0.053	3.112 ± 0.039
Ω_k	-0.093 ± 0.037	-0.018 ± 0.008	-0.071 ± 0.028	-0.014 ± 0.008
H_0 [km/s/Mpc]	48.38 ± 5.77	64.33 ± 3.34	51.14 ± 5.08	65.13 ± 3.14
Ω_m	0.59 ± 0.13	0.32 ± 0.03	0.53 ± 0.10	0.31 ± 0.03
σ_8	0.751 ± 0.039	0.797 ± 0.022	0.768 ± 0.034	0.808 ± 0.020

Table 2. 68.27% confidence limits on cosmological parameters of the non-flat ΛCDM model from CMB and BAO data.

Parameter	TT+lowP+BAO	TT+lowP+lensing+BAO	TT,TE,EE+lowP+BAO	TT,TE,EE+lowP+lensing+BAO
$\Omega_b h^2$	0.02305 ± 0.00021	0.02302 ± 0.00020	0.02290 ± 0.00015	0.02288 ± 0.00015
$\Omega_c h^2$	0.1096 ± 0.0011	0.1093 ± 0.0011	0.1114 ± 0.0009	0.1112 ± 0.0009
100θ	1.04293 ± 0.00041	1.04302 ± 0.00041	1.04251 ± 0.00029	1.04257 ± 0.00029
τ	0.135 ± 0.017	0.120 ± 0.012	0.138 ± 0.016	0.117 ± 0.011
$\ln(10^{10} A_s)$	3.181 ± 0.035	3.150 ± 0.023	3.190 ± 0.033	3.146 ± 0.022
Ω_k	-0.008 ± 0.002	-0.008 ± 0.002	-0.006 ± 0.002	-0.006 ± 0.002
H_0 [km/s/Mpc]	68.12 ± 0.75	68.23 ± 0.74	68.05 ± 0.74	68.28 ± 0.74
Ω_m	0.28 ± 0.01	0.28 ± 0.01	0.29 ± 0.01	0.29 ± 0.01
σ_8	0.819 ± 0.010	0.819 ± 0.010	0.845 ± 0.015	0.826 ± 0.009

Result: ϕCDM model

- ϕCDM model is physically consistent dynamical dark energy model.
  - an analogy with the inflation.
- Because there are two big problems in the ΛCDM.
  - cosmological coincidence problem. Velten+ (2014)
  - cosmological constant problem. Weinberg (1989)

$$\frac{\rho_{\Lambda 0}}{\rho_{\mathrm{m}0}} \sim \mathcal{O}(1)$$

$$\rho_{\Lambda 0} \sim 10^{-47} \mathrm{GeV}^4$$

- Also,
  - recent works (in flat case!): Solà+ (2017), Zhang+ (2017)
  - in which they claim the ϕCDM is more favored than ΛCDM.