An early Planck mass transition and its effect on cosmological tensions

An exploration of an early gravity transition in light of cosmological tensions

Giampaolo Benevento,[1] Joshua A. Kable,[1] Graeme E. Addison,[1] and Charles L. Bennett[1]

APJ, 935:156 (15), 2022
arXiv:2202.09356

Cosmological Tensions and the Transitional Planck Mass Model

Joshua A. Kable,[1] Giampaolo Benevento,[2,3,4,5] Graeme E. Addison,[5] and Charles L. Bennett[5]

arXiv:2307.12174

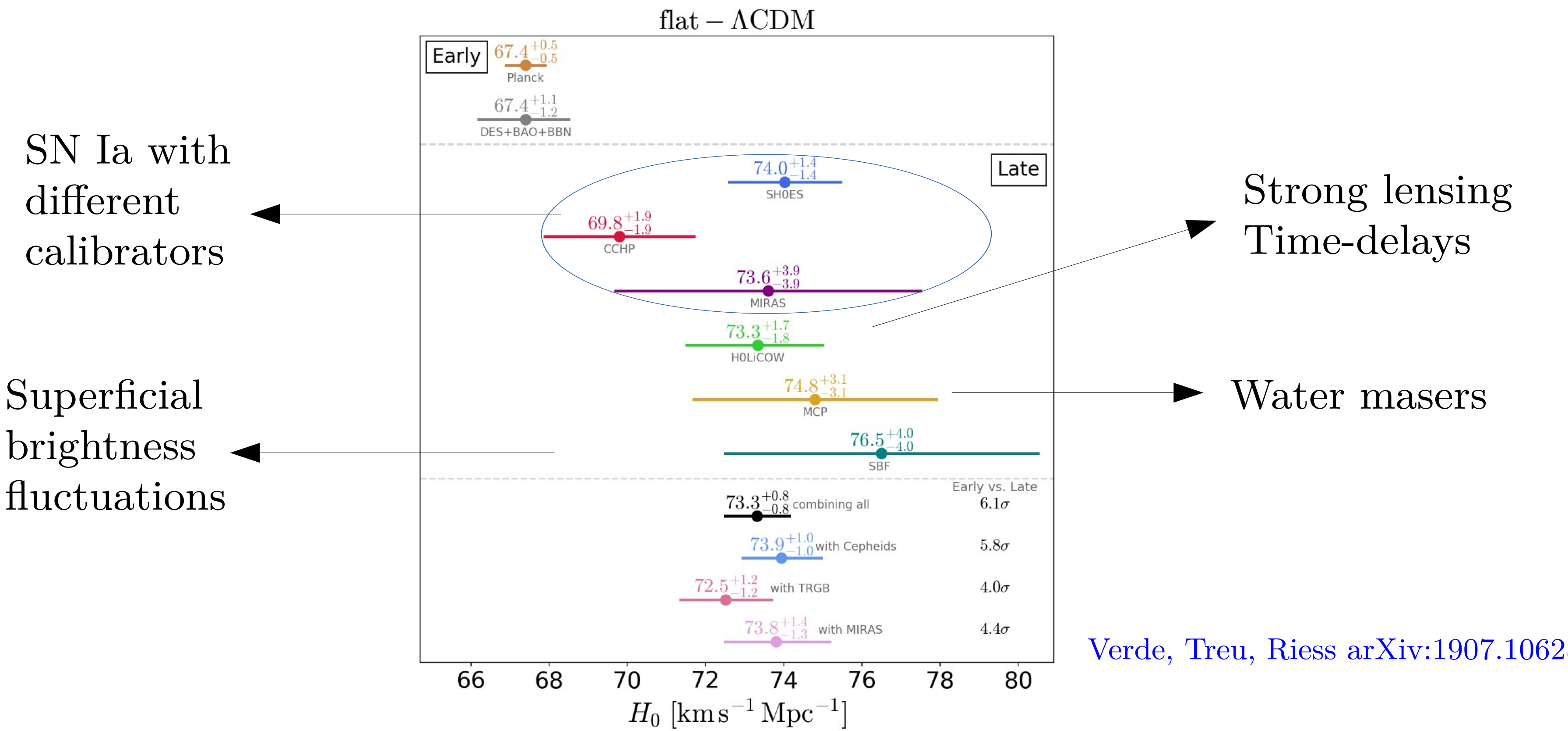
Also check out: Testing gravity with CMB and LSS cross-correlations

Guglielmo Frittoli, Giampaolo Benevento, Marina Migliaccio, Nicola Bartolo

Giampaolo Benevento

INFN Tor Vergata

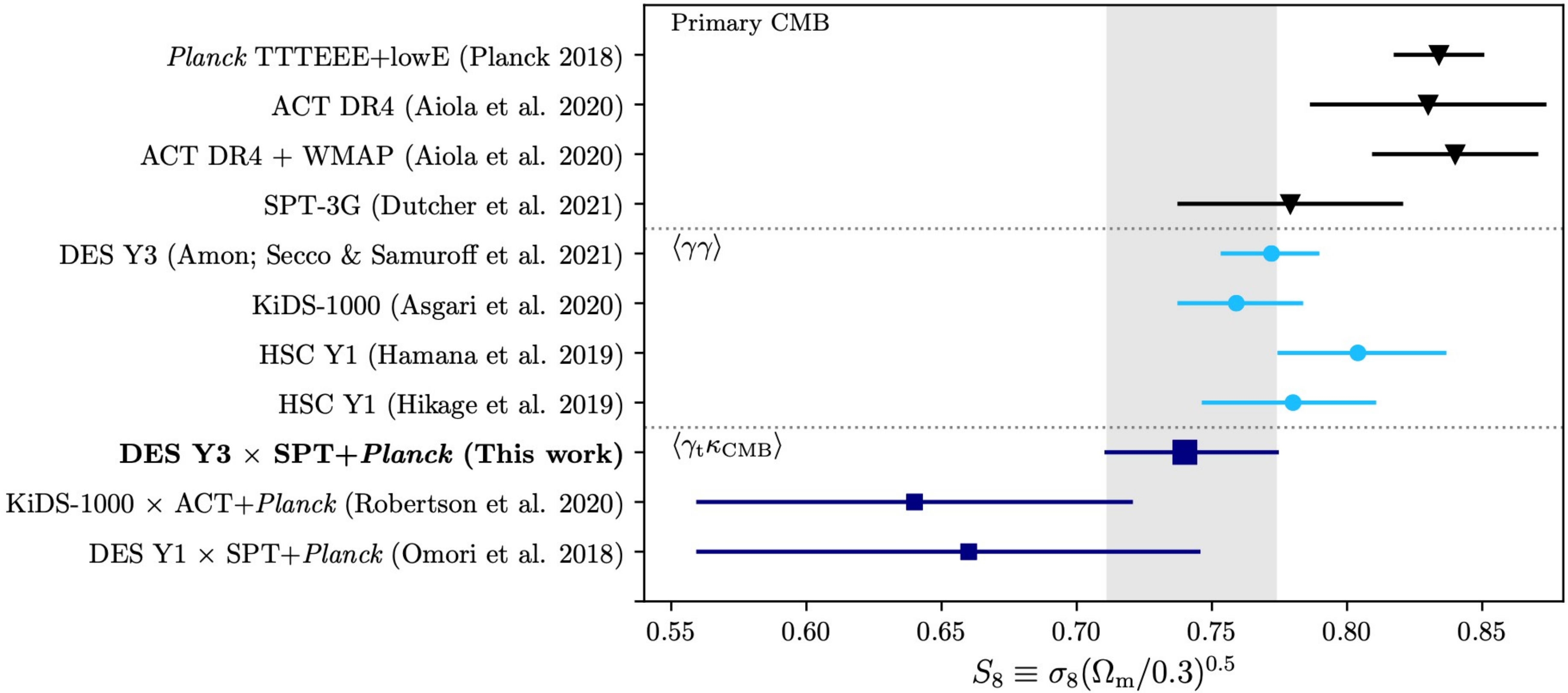
H0: Early time VS late time probes



Verde, Treu, Riess arXiv:1907.10625

The current tension between Planck and a combination of independent local measurements is > 5 σ

The S8 tension

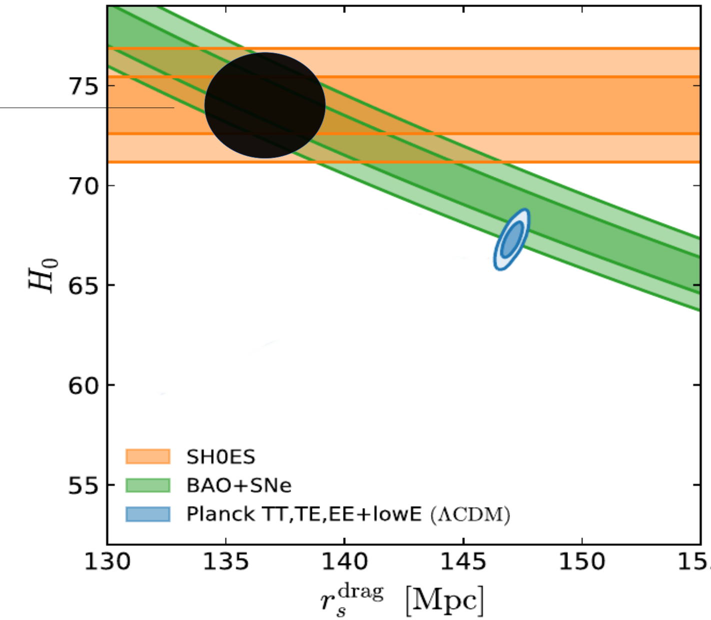


Chang et al arXiv:2203.12440

Weak lensing surveys prefer a value of S8 lower than what infered by CMB (discrepancy around 2.5 σ)

Early DE in a nutshell

Any solution of the tension needs to reduce **rs** by 7% while preserving a good fit to CMB data



Adapted from Knox & Millea 2019

Modifications to rs require to change in the expansion history before recombination

$$r_s \equiv \int_{\infty}^{z_{rec}} \mathrm{d}z \frac{c_s(z)}{H(z)}$$

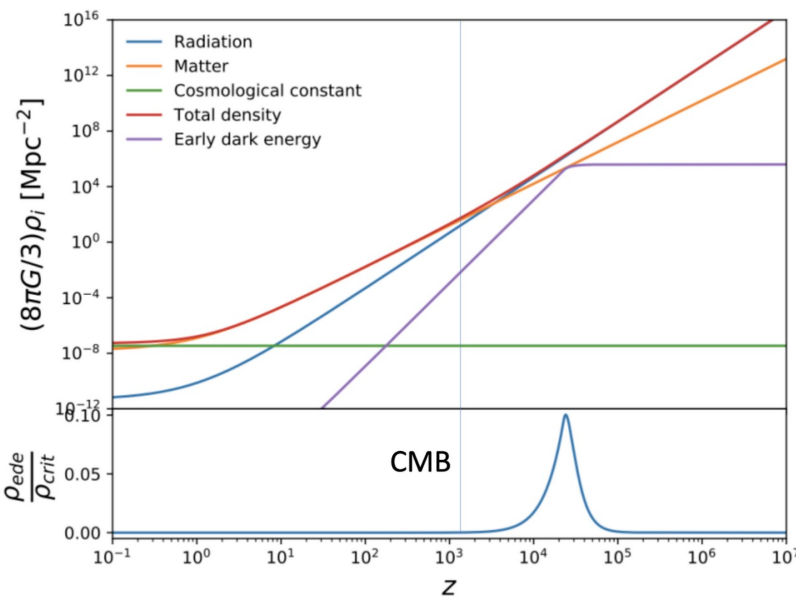


Figure courtesy of Tanvi Karwal

The idea of EDE (and many EDE-like models) is to introduce a transient dark energy component before recombination

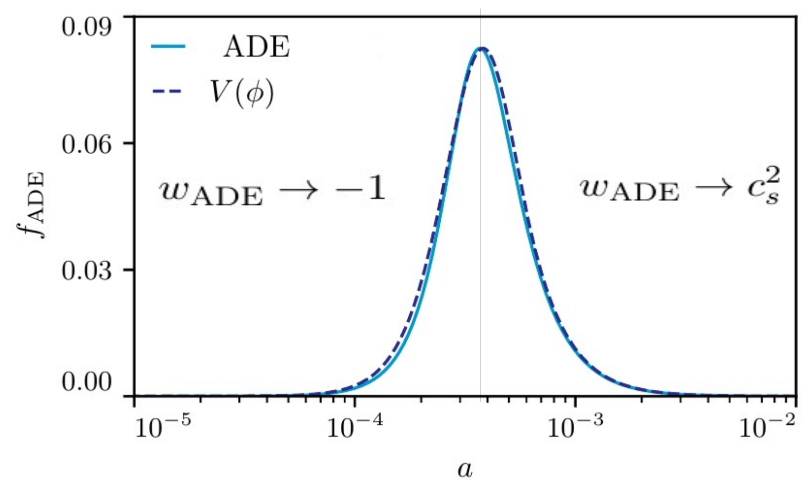
Acoustic Dark Energy (ADE)

Lin M.X., **GB**, Hu W., Raveri M. arXiv:1905.12618

Transient Dark Energy before recombination can increse H(a) and reduce r_s consistently with cosmological probes. We parametrize the e.o.s. as a step function:

$$1 + w_{\rm ADE}(a) = \frac{1 + w_{\rm f}}{[1 + (a_c/a)^{3(1+w_{\rm f})}\ \ ]}$$

$$f_{\rm ADE}(a) = \frac{\rho_{\rm ADE}(a)}{\rho_{\rm tot}(a)}$$



This scenario is very general and can be realized e.g. by a simple K-essence lagrangian:

$$P(X, \phi) = \left(\frac{X}{A}\right)^{\frac{1-c_s^2}{2c_s^2}} X - V(\phi) \qquad X = -\nabla^\mu\phi\nabla_\mu\phi/2$$

$a<a_c$: Potential domination

$$w_{\rm ADE} \to -1$$

$a>a_c$: Kinetic domination

$$w_{\rm ADE} \to c_s^2$$

Preference for ADE found using ACT CMB data

In a more recent analysis (Lin M.X., Hu W., Raveri M. arXiv:2009.08974) ADE has been tested using Planck+ACT+SH0ES+BAO+Pantheon data. ADE is still detected at 2.8 σ

cADE	All	-ACT	-P18Pol	-H0
f_c	$0.072(0.068^{+0.025}_{-0.022})$	$0.081(0.070^{+0.027}_{-0.024})$	$0.105(0.110\pm0.030)$	$0.050(0.027^{+0.008}_{-0.027})$
$\log_{10} a_c$	$-3.42(-3.43^{+0.05}_{-0.07})$	$-3.50(-3.50^{+0.07}_{-0.06})$	$-3.41(-3.39^{+0.03}_{-0.10})$	$-3.42(-3.47^{+0.24}_{-0.11})$
H_0	$70.25(70.14\pm0.82)$	$70.60(70.19\pm0.86)$	$71.38(71.54\pm1.07)$	$69.19(68.50^{+0.55}_{-0.93})$
S_8	$0.841(0.839\pm0.013)$	$0.841(0.839\pm0.013)$	$0.846(0.845^{+0.018}_{-0.015})$	$0.842(0.833^{+0.011}_{-0.012})$
$\Delta\chi^2_{\rm P}$	-0.2	-1.5	-4.3	-1.7
$\Delta\chi^2_{\rm ACT}$	-1.8	–	-4.3	-1.0
$\Delta\chi^2_{\rm tot}$	-11.5	-10.7	-19.4	-1.6
$H_0^{\Lambda\rm CDM}$	$68.23(68.17\pm0.38)$	$68.29(68.22\pm0.40)$	$68.30(68.32\pm0.42)$	$67.80(67.73\pm0.39)$
$S_8^{\Lambda\rm CDM}$	$0.815(0.818\pm0.010)$	$0.812(0.814\pm0.010)$	$0.814(0.813\pm0.011)$	$0.826(0.827\pm0.010)$

ADE (as well as other early dark energy models) worsen the S8 tension

Beyond Early Dark Energy?

- The Hubble tension can be effectively relieved by a transient Dark Energy before recombination

- This phenomenology is provided by a scalar field converting its potential energy into kinetic

- The shift in other cosmological parameters (mainly the matter density) leads to worsening of the S8 tension

- Can we find a different mechanism to reduce both the Hubble tension and S8 tension?

Effective Field Theory of DE and MG

Most general single scalar field models invariant under spatial diffeos.

$$S = \int d^4x \sqrt{-g} \Big\{ \frac{m_0^2}{2} \Omega(t) R + \Lambda(t) - c(t) \delta g^{00} + \frac{M_2^4(t)}{2} (\delta g^{00})^2 - \frac{\bar{M}_1^3(t)}{2} \delta g^{00} \delta K^i{}_i - \frac{\bar{M}_2^2(t)}{2} \delta K^i{}_i{}^2 - \frac{\bar{M}_3^2(t)}{2} \delta K^i{}_j \delta K^j{}_i + \frac{\hat{M}^2(t)}{2} \delta g^{00} \delta R^{(3)} + h^{ij} \partial_i \delta g^{00} \partial_j \delta g^{00} + \dots \Big\} + S_{matter}[g_{\mu\nu}]$$

EFT functions c and Λ modify the e.o.s. of the scalar field,
Ω modifies the effective value of the Planck mass: $M_\star^2 = m_0^2 (1 + \Omega)$

The remaining functions affect perturbation evolution only

We select models within this class assuming:
- **Second order equation of motion**
- **Standard tensor speed of propagation**
- **No ghost or gradient instabilities.**

Transitional Planck Mass model

astro-ph.CO/2202.09356

The TPM model features a step-like Ω (described by 3 parameters)

$$\Omega(x) = \frac{\Omega_0}{2}\left(1 - ERF\left(\frac{(x_T - x)}{\sqrt{2\pi}\sigma}\right)\right)$$

$$\Omega'(x) = \Omega_0 \frac{\exp \frac{-(x-x_T)^2}{2\sigma^2}}{\sqrt{2\pi}\sigma}$$

The EFT function c is assumed to be constant and Λ is determined by solving the Friedmann eqs.

$$\frac{c}{3H_0^2 m_0^2} = c_0$$

The remaining EFT functions are fixed as:

$$\frac{M_2^4}{3H_0^2 m_0^2} = -c_0$$

$$\frac{\bar{M}_1^3}{3H_0^2 m_0^2} = \frac{2c_0}{H}$$

Stability conditions are met if:

$$\Omega_0 < 0 \text{ and } c_0 < 0$$

Connection to Horndenski

The TPM model can be obtained as a sub-class of Horndenski theories.
Horndenski alpha-functions are switched on:

$$\alpha_M = \frac{\Omega'}{1+\Omega} \qquad \alpha_K = -\frac{2c_0}{H^2(1+\Omega)} \qquad \alpha_B = \frac{\Omega'}{2(1+\Omega)} + \frac{c_0}{H^2(1+\Omega)}$$

An interesting sub-case is given by $c_0 = 0$

Leading to an f(R) model with $\Lambda = f(R) - R\frac{df}{dR}, \;\; \Omega = \frac{df}{dR}$

$$\alpha_M = 2\alpha_B \;, \alpha_K = 0$$

This is a good approximation when: $\Omega' \gg c_0/H^2$

Phenomenology of TPM

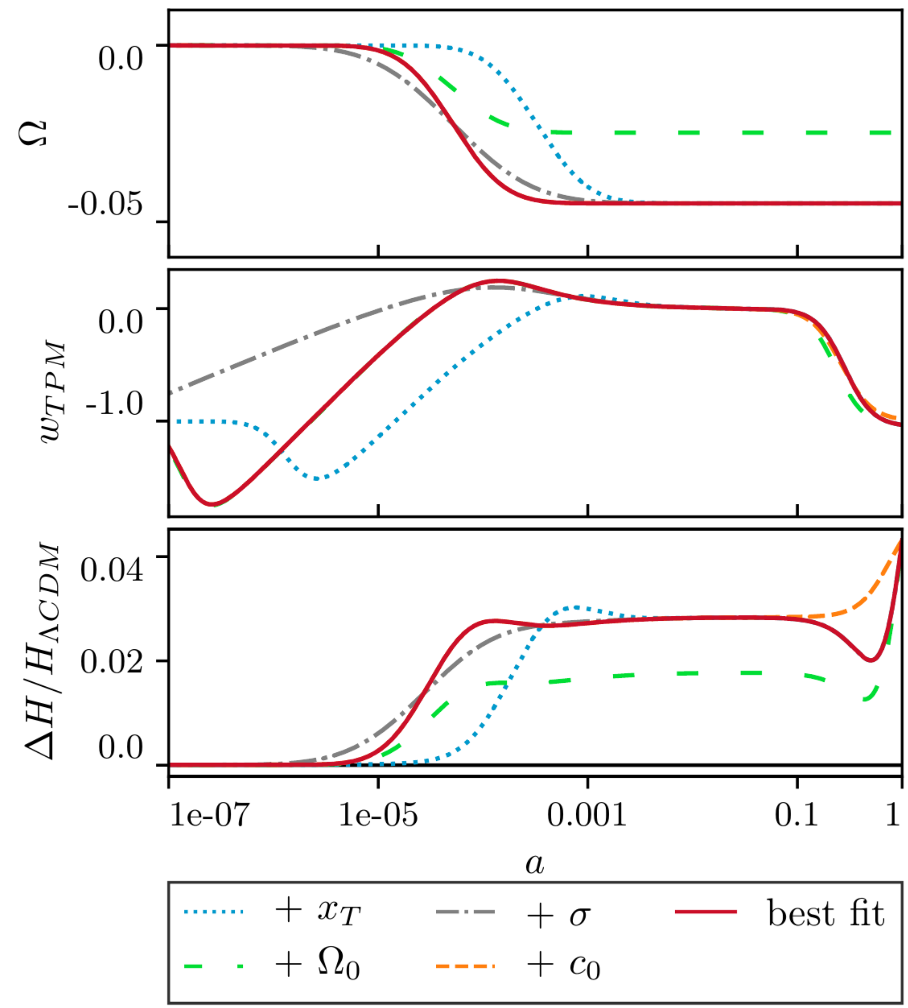
- **Step downwards in the Planck mass**
- **Increase in H(a)**

$$H^2 = \frac{1}{1+\Omega+\Omega'}\left(\frac{\rho_{m,rad}}{3m_0^2} - \frac{\Lambda}{3m_0^2} + \frac{2c}{3m_0^2}\right)$$

- **Tracks the dominant energy component of the universe once the scalar field kicks in**

$$w_{\mathrm{TPM}} = \frac{\Lambda - \Omega_0 P_{m,rad}}{2c - \Lambda - \Omega_0 \rho_{m,rad}}$$

- **Different parameters affect different epochs of cosmological evolution**



Phenomenology of TPM: perturbations

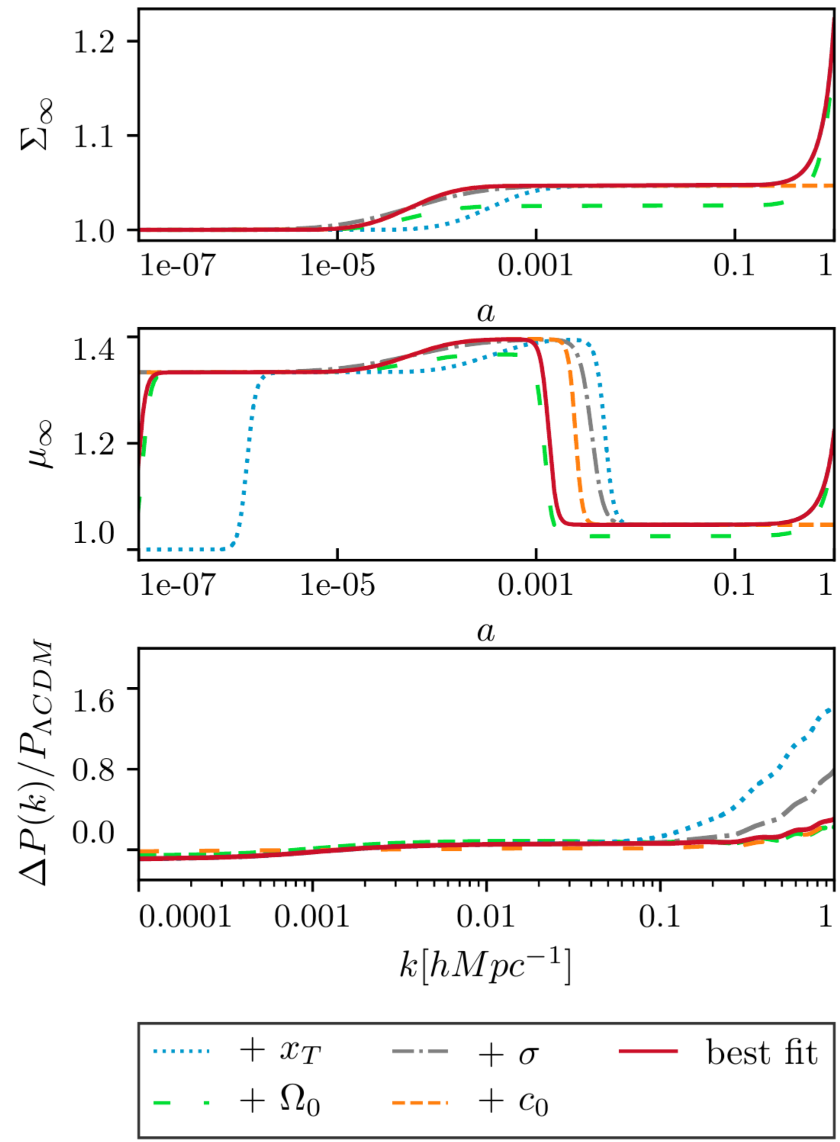
Departures from general relativity manifest as changes to the Poisson and lensing equations:

$$\mu(k,a) \equiv \frac{-k^2\Phi}{4\pi G a^2 \bar{\rho}_m \Delta_m} \quad \Sigma(k,a) \equiv \frac{-k^2(\Phi+\Psi)}{8\pi G a^2 \bar{\rho}_m \Delta_m}$$

- **In the f(R) regime μ=4/3 and we have a clear sign that gravity is modified**

- **The c_0 parameter is important in setting the late-time behavior**

- **On small scales the P(k) is enhanced relative to ΛCDM**



Data analysis of TPM

- **We run MCMC (EFTCosmoMC) with different data configurations:**

Baseline dataset: BAO (BOSS DR 12 + SDSS main galaxy sample + 6dFGS), SNe Ia (Pantheon), Planck CMB lensing (in the $8 \leq L \leq 400$ multipole range).

+Planck: Plik Lite 2018 TTTEEE, Planck TT $L \leq 30$, and Planck Low L EE

+ H0 from local measurements: We added a gaussian H0 prior from local independent measurements 72.61 ± 0.89 (SHOES + Masers + Surface Brightness Fluctuations)

arXiv:2202.09356

+SPT: TE and EE power spectra from SPT 3G over the multipole range $300 \leq L < 3000$

+ DES: DES Y1 cosmic shear, galaxy-galaxy lensing, and galaxy clustering, where non-linear scales are removed following arXiv:1810.02499

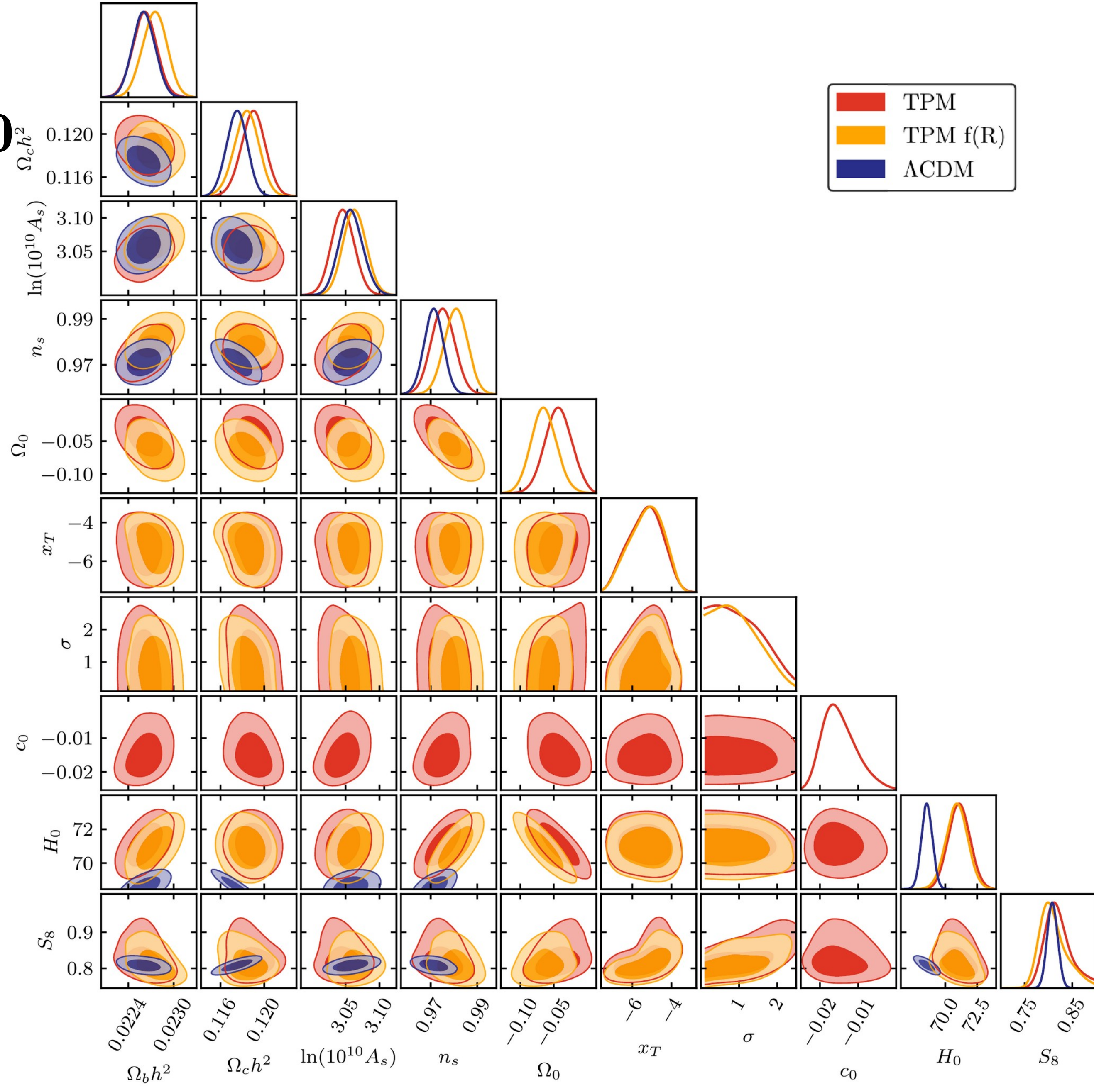
+ $f\sigma_8$: Boss DR 12 measurements of redshift space distortions

arXiv:2307.12174

- **We compare results for the TPM, TPM f(R) and for** ΛCDM

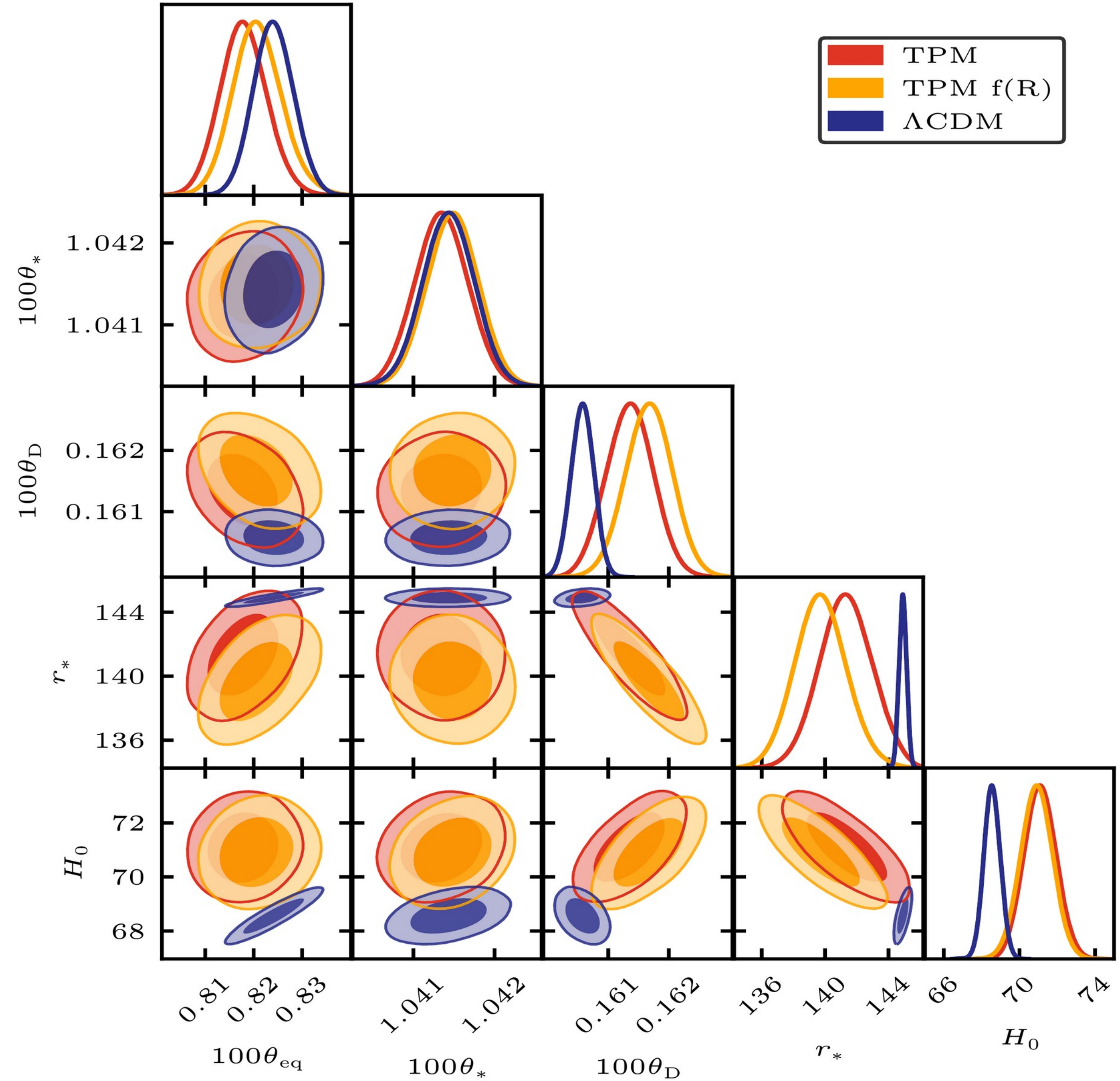
TPM results
Baseline+Planck+H0

- **Baseline+Planck+H0 data prefer ~5% shift in the Effective Planck Mass**
- **The transition is free to occur over multiple decades of scale factor during radiation domination (no coincidence)**
- **Shape (duration) of the transition is unconstrained**
- **The negative c_0 parameter allows for phantom w and a late-universe bump in H**

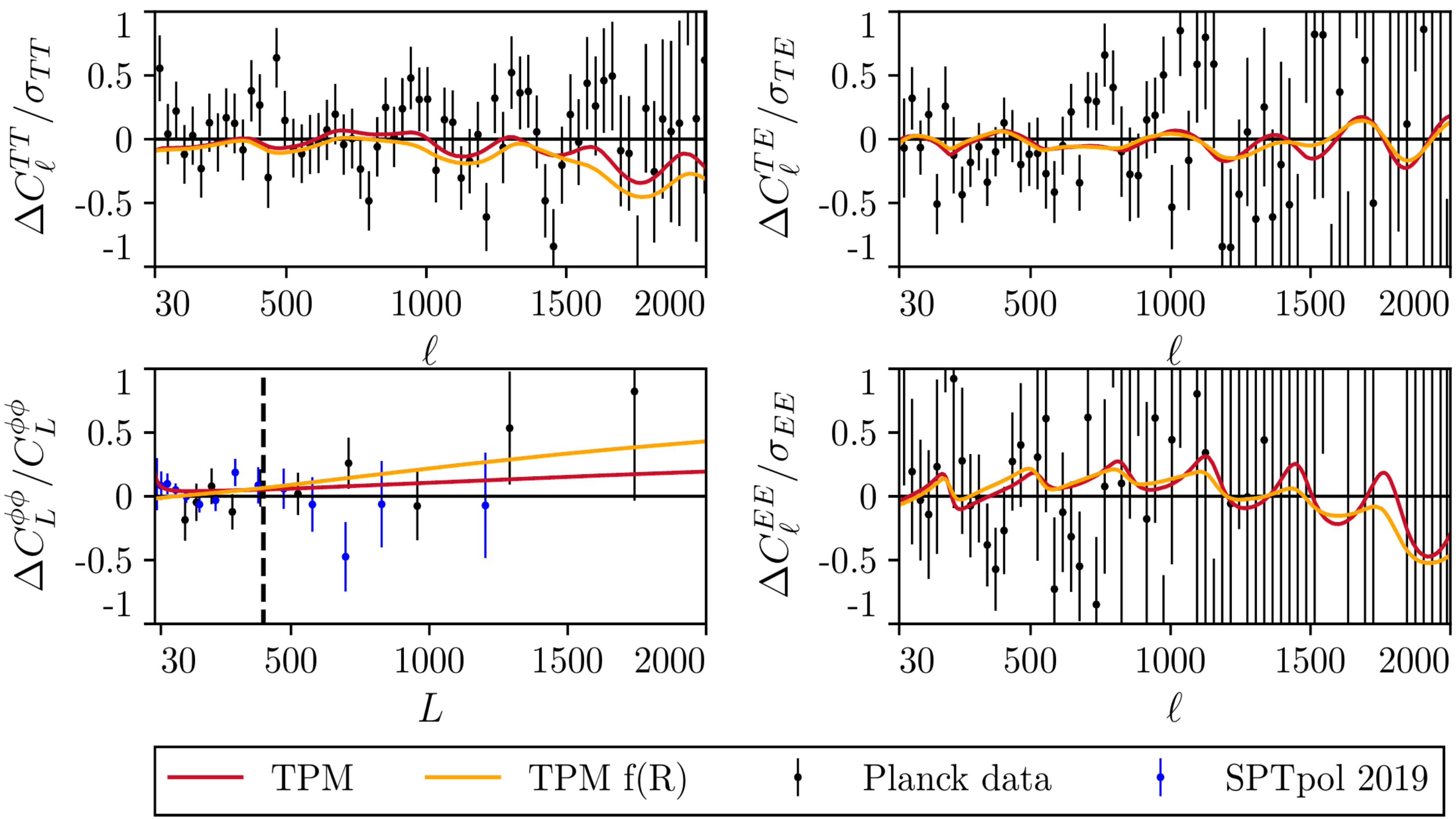


EDE-like effect in TPM

- **The transition in Ω allows for larger H0 by decreasing rs**
- **TPM f(R) model must have larger shift in effective Planck mass to achieve similar values of H0 as TPM model**
- **The damping scale increase is a limiting factor for TPM performances**



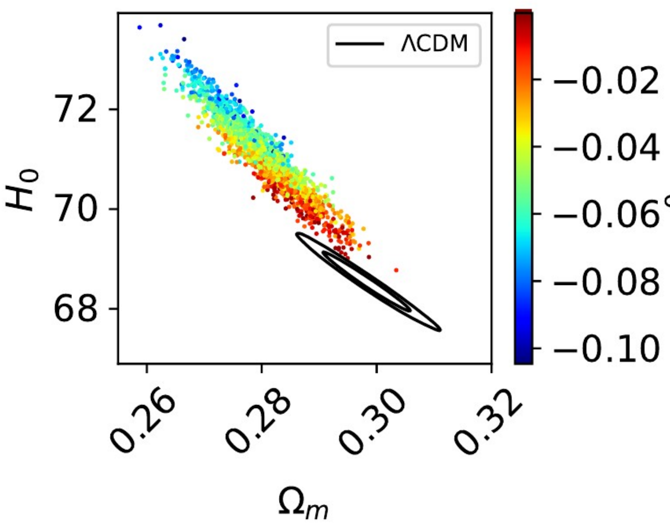
CMB data constrain TPM well



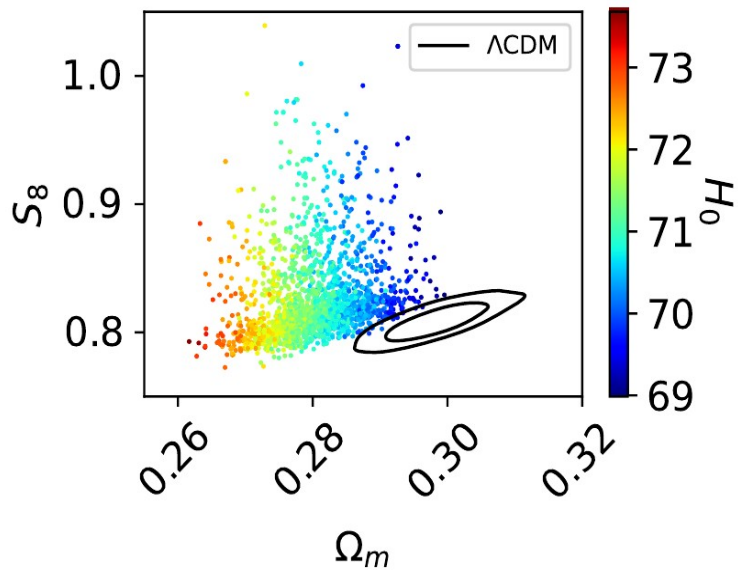
Good fit to L < 1500 TT, damping effect dominant at higher L

Incresed CMB lensing amplitude, but still compatible with measurements.

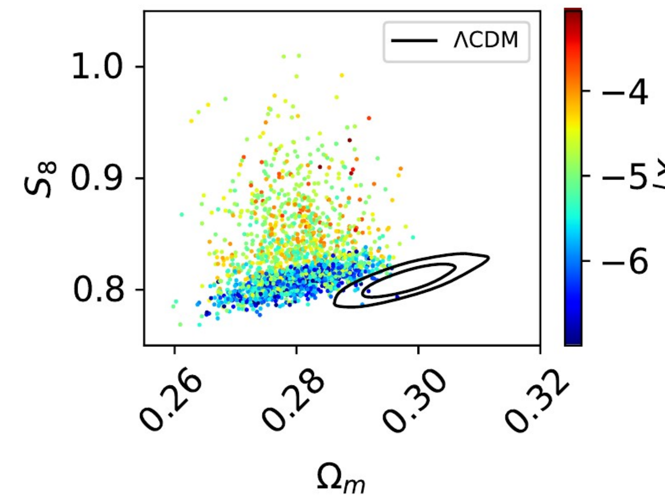
Cosmological tensions in TPM



No shift in the physical matter density for TPM. Leads to a reduced fractional matter density



Higher values of H0 are correlated with lower values of S8



Restricting to early transitions removes the high values of S8

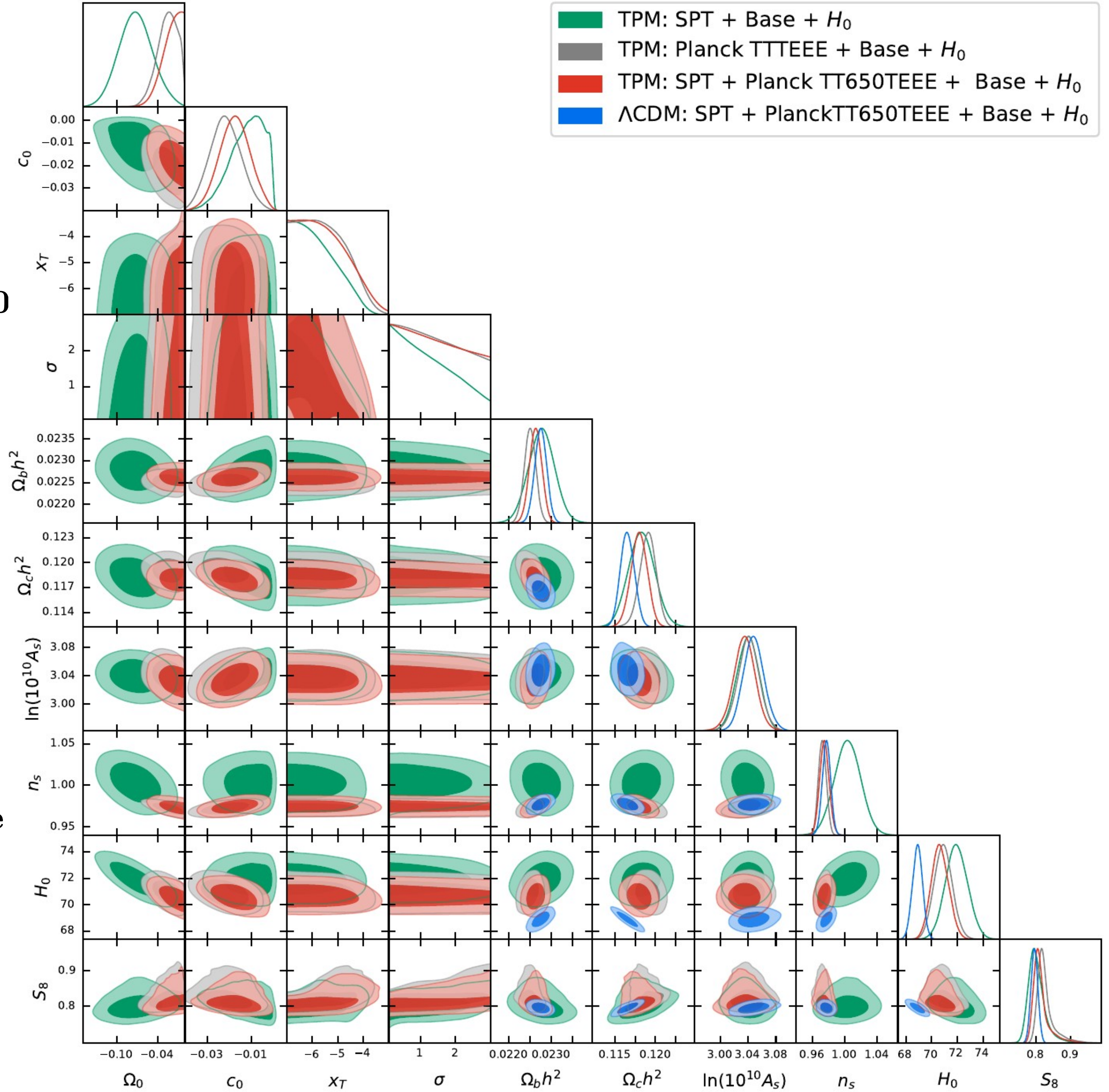
TPM allows for both H0>70 and S8<0.8

Testing TPM with CMB data

In the TPM fit to SPT + Base + H0 data the shift in ns, ns=1.003 ± 0.016 allows to compensate for the small-scale suppression of power.

Planck data constrain the variation of Planck Mass tighter than SPT

The combination SPT + Base + H0 prefers Ω0 = −0.072 ± 0.025, which corresponds to a nonzero shift in the Planck mass at 2.9σ, the constraint on H0 shifts to H0 = 71.94± 0.85



Results: CMB+ Baseline+H0 prior

	ΛCDM: Planck TTTEEE + Base + H_0	*TPM*: Planck TTTEEE + Base + H_0	ΛCDM: SPT + Base + H_0	*TPM*: SPT + Base+ H_0
$100\theta_{MC}$	$1.0413\ (1.04127^{+0.00029}_{-0.00030})$	$1.04139\ (1.04135 \pm 0.00036)$	$1.03992\ (1.03984^{+0.00064}_{-0.00065})$	$1.04039\ (1.04042^{+0.00071}_{-0.00072})$
$\Omega_b h^2$	$0.02261\ (0.02261 \pm 0.00013)$	$0.022505\ (0.022498 \pm 0.00013)$	$0.02288\ (0.02290 \pm 0.00029)$	$0.02271\ (0.02277 \pm 0.00030)$
$\Omega_c h^2$	$0.11748\ (0.11748 \pm 0.00086)$	$0.11934\ (0.11906 \pm 0.00099)$	$0.1148\ (0.1147 \pm 0.0012)$	$0.1182\ (0.1183 \pm 0.0016)$
τ	$0.0615\ (0.0633^{+0.0080}_{-0.0079})$	$0.0532\ (0.0528 \pm 0.0074)$	$0.0556\ (0.0563 \pm 0.0070)$	$0.0610\ (0.0543 \pm 0.071)$
$\ln(10^{10}A_s)$	$3.054\ (3.058^{+0.016}_{-0.015})$	$3.043\ (3.040 \pm 0.015)$	$3.047\ (3.049 \pm 0.014)$	$3.049\ (3.039 \pm 0.016)$
n_s	$0.9712\ (0.9713 \pm 0.0036)$	$0.9715\ (0.9721 \pm 0.0048)$	$0.978\ (0.978 \pm 0.014)$	$1.008\ (1.003 \pm 0.016)$
Ω_0	-	-0.025 (> -0.058 at 95%)	-	$-0.073\ (-0.072 \pm 0.025)$
x_T	-	$-5.33\ (-5.58 \pm 0.99)$	-	$-5.06\ (-5.81^{+0.91}_{-0.86})$
σ	-	$0.82\ (1.42^{+0.98}_{-0.93})$	-	$1.35\ (1.23^{+0.90}_{-0.84})$
c_0	-	$-0.02293\ (-0.02174 \pm 0.0071)$	-	-0.0111 (> -0.0287 at 95%)
H_0	$68.56\ (68.57 \pm 0.39)$	$70.94\ (70.90^{+0.69}_{-0.70})$	$69.32\ (69.34^{+0.48}_{-0.47})$	$71.87\ (71.94^{+0.86}_{-0.85})$
σ_8	$0.8076\ (0.8091 \pm 0.0064)$	$0.839\ (0.853^{+0.020}_{-0.021})$	$0.7948\ (0.7952^{+0.0076}_{-0.0077})$	$0.830\ (0.840^{+0.020}_{-0.021})$
S_8	$0.8068\ (0.8083^{+0.0098}_{-0.0099})$	$0.815\ (0.828^{+0.020}_{-0.021})$	$0.778\ (0.779 \pm 0.013)$	$0.794\ (0.802^{+0.022}_{-0.023})$
$\chi^2_{\rm PlanckTTTEEE}$	589.78	585.69	-	-
$\chi^2_{\rm PlancklowTT}$	22.41	21.41	-	-
$\chi^2_{\rm PlancklowE}$	397.70	395.83	-	-
$\chi^2_{\rm SPT}$	-	-	1120.67	1120.67
$\chi^2_{\rm CMB\ lensing}$	9.575	8.82	8.95	9.17
$\chi^2_{\rm BAO}$	5.55	7.74	8.27	6.32
$\chi^2_{\rm Pantheon}$	1034.73	1037.08	1035.00	1035.23
$\chi^2_{\rm H_0}$	20.68	3.52	13.66	0.69
$\chi^2_{\rm prior}$	0.22	0.09	0.66	0.41
$\chi^2_{\rm tot}$	2081.39	2060.19	2187.20	2172.48

Results: Planck + Baseline

-The preference for a Transitional Planck Mass is driven by the H0 prior

- When no prior from local measurement is included the H0 tension reduced to 2.8 σ

Fit To Baseline Likelihood

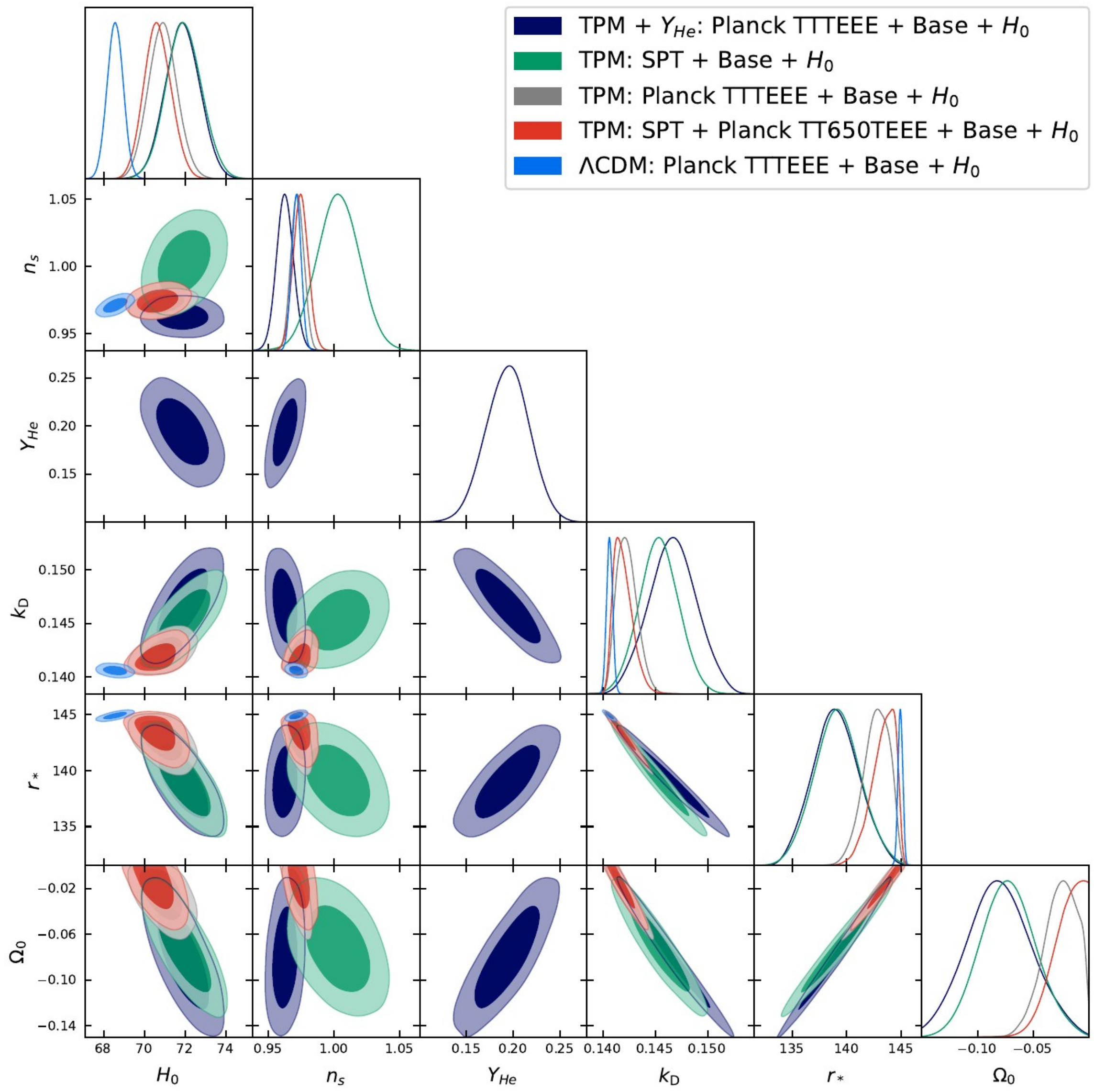
model	ΛCDM	TPM f(R)	*TPM*
$100\theta_{\rm MC}$	1.04107 (1.04099 ± 0.00029)	1.04116 ($1.04122^{+0.00032}_{-0.00037}$)	1.04111 (1.04114 ± 0.00034)
$\Omega_b h^2$	0.02242 (0.02241 ± 0.00013)	0.02243 (0.02249 ± 0.00015)	0.02247 (0.02245 ± 0.00014)
$\Omega_c h^2$	0.11919 (0.11933 ± 0.00091)	0.11896 (0.1189 ± 0.0010)	0.1185 (0.1195 ± 0.0011)
τ	0.0592 (0.0574 ± 0.0073)	0.0575 (0.0566 ± 0.0077)	0.0484 (0.0528 ± 0.0075)
$\ln(10^{10}A_s)$	3.052 (3.049 ± 0.014)	3.051 (3.048 ± 0.016)	3.029 (3.041 ± 0.015)
n_s	0.9677 (0.9666 ± 0.0036)	0.9692 (0.9704 ± 0.0046)	0.9681 ($0.9685^{+0.0041}_{-0.0046}$)
Ω_0		-0.014 ($-0.0153^{+0.015}_{-0.0037}$)	-0.027 ($-0.0140^{+0.014}_{-0.0031}$)
x_T	-	-4.09 ($-4.90^{+1.1}_{-0.66}$)	-3.59 ($-5.05^{+1.1}_{-0.87}$)
x_T (95% CL)		$-4.9^{+1.5}_{-1.9}$	$-5.1^{+1.5}_{-1.9}$
σ	-	0.873 ($1.50^{+0.66}_{-0.97}$)	2.71 (< 1.85)
c_0	-	0 (fixed)	-0.0216 ($-0.0119^{+0.0046}_{-0.0064}$)
c_0 (95% CL)			$-0.0119^{+0.0099}_{-0.0090}$
$w_{TPM,0}$	-	-0.9945 ($-0.9932^{+0.0037}_{-0.0083}$)	-1.05 ($-1.028^{+0.017}_{-0.020}$)
H_0	67.72 (67.65 ± 0.41)	68.27 ($68.43^{+0.51}_{-0.83}$)	69.19 ($69.22^{+0.67}_{-0.86}$)
σ_8	0.812 (0.8110 ± 0.0060)	0.850 ($0.873^{+0.023}_{-0.071}$)	0.9099 ($0.8530^{+0.0051}_{-0.040}$)
S_8	0.826 (0.826 ± 0.010)	0.857 ($0.877^{+0.046}_{-0.078}$)	0.903 ($0.8494^{+0.0089}_{-0.043}$)
$\Delta\chi^2_{\rm CMB}$	0	0.5	-5.88
$\Delta\chi^2_{\rm CMB\ lensing}$	0	-0.05	-0.05
$\Delta\chi^2_{\rm BAO}$	0	-0.23	0.77
$\Delta\chi^2_{\rm Pantheon}$	0	-0.05	0.26
$\Delta\chi^2_{\rm tot}$	0	0.18	- 4.8
$\Delta \log_{10} B$	0	**-3.60**	**-3.85**

TPM model with less Helium

The main effect of varying the helium fraction conflicts with BBN constraints.

Allowing the helium fraction to vary within opens up the degeneracy between r_*, and H0 to match the degeneracy allowing the transition amplitude Ω_0 to further deviate from 0.

The resulting value of the helium fraction conflicts with BBN constraints.

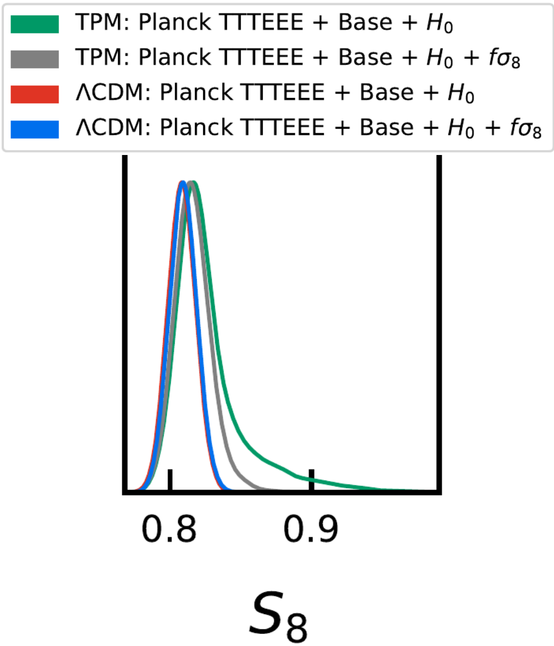


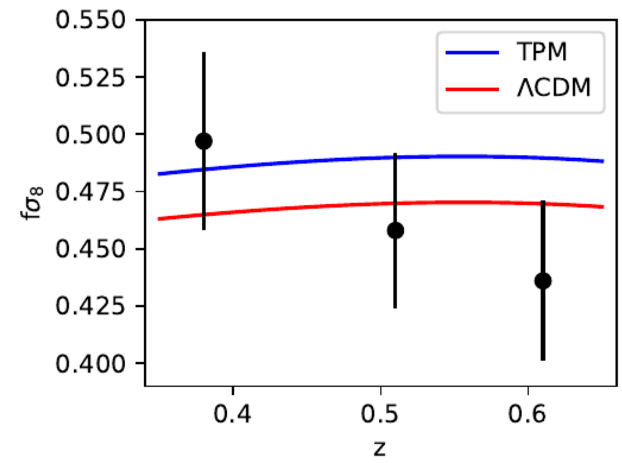
Testing TPM with Large Scale Structure

The TPM model predicts a slightly higher value of f$\boldsymbol{\sigma}_8$ than ΛCDM

The addition of BOSS RSD measurements significatly limit the non-gaussian tail in the S8 posterior, by disfavoring transitions that happen at later epochs

DES Y1 data with the linear cut are not sufficiently constraining to significantly affect the TPM model parameter space allowed by Planck, BAO, and Supernova

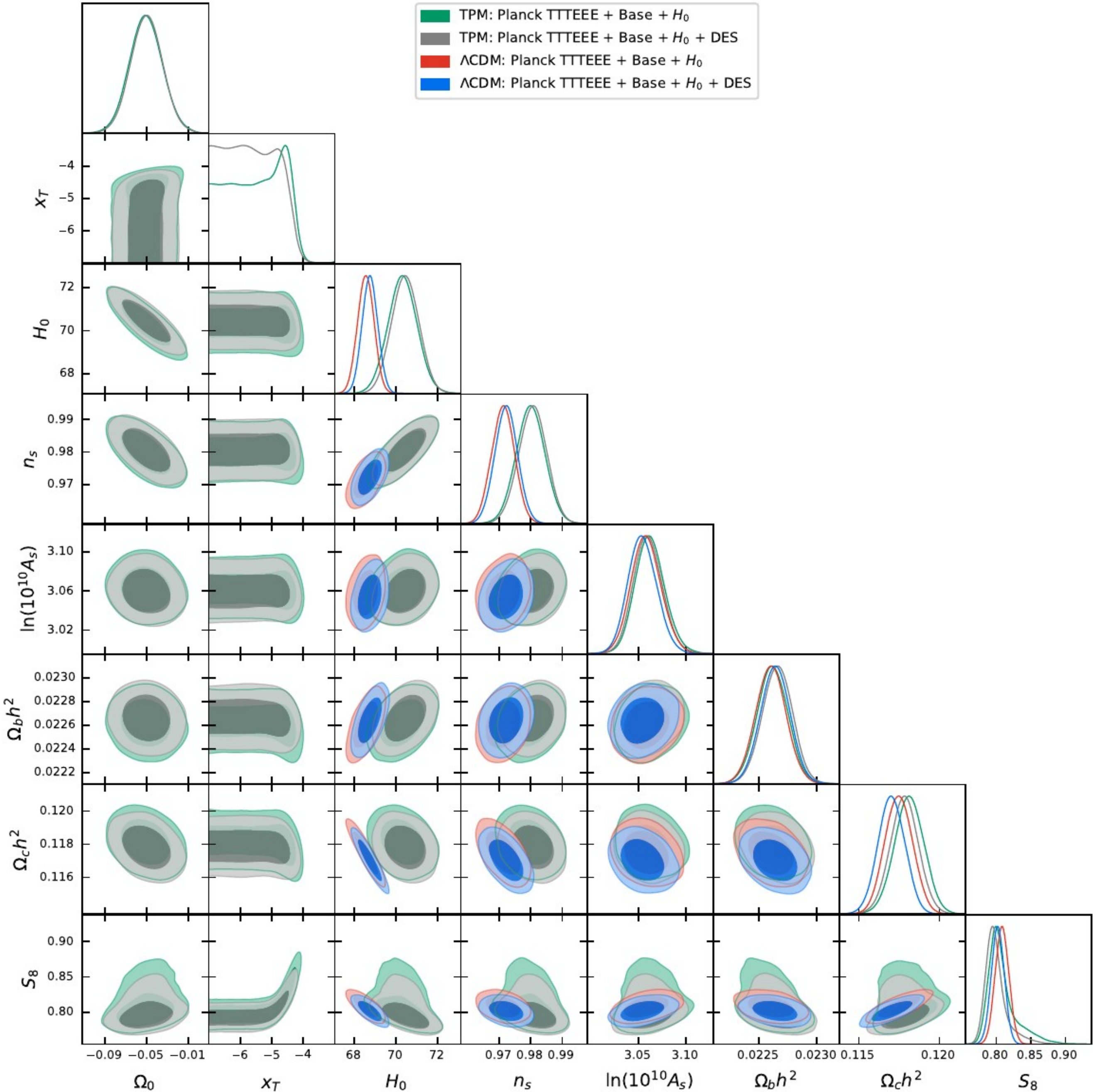




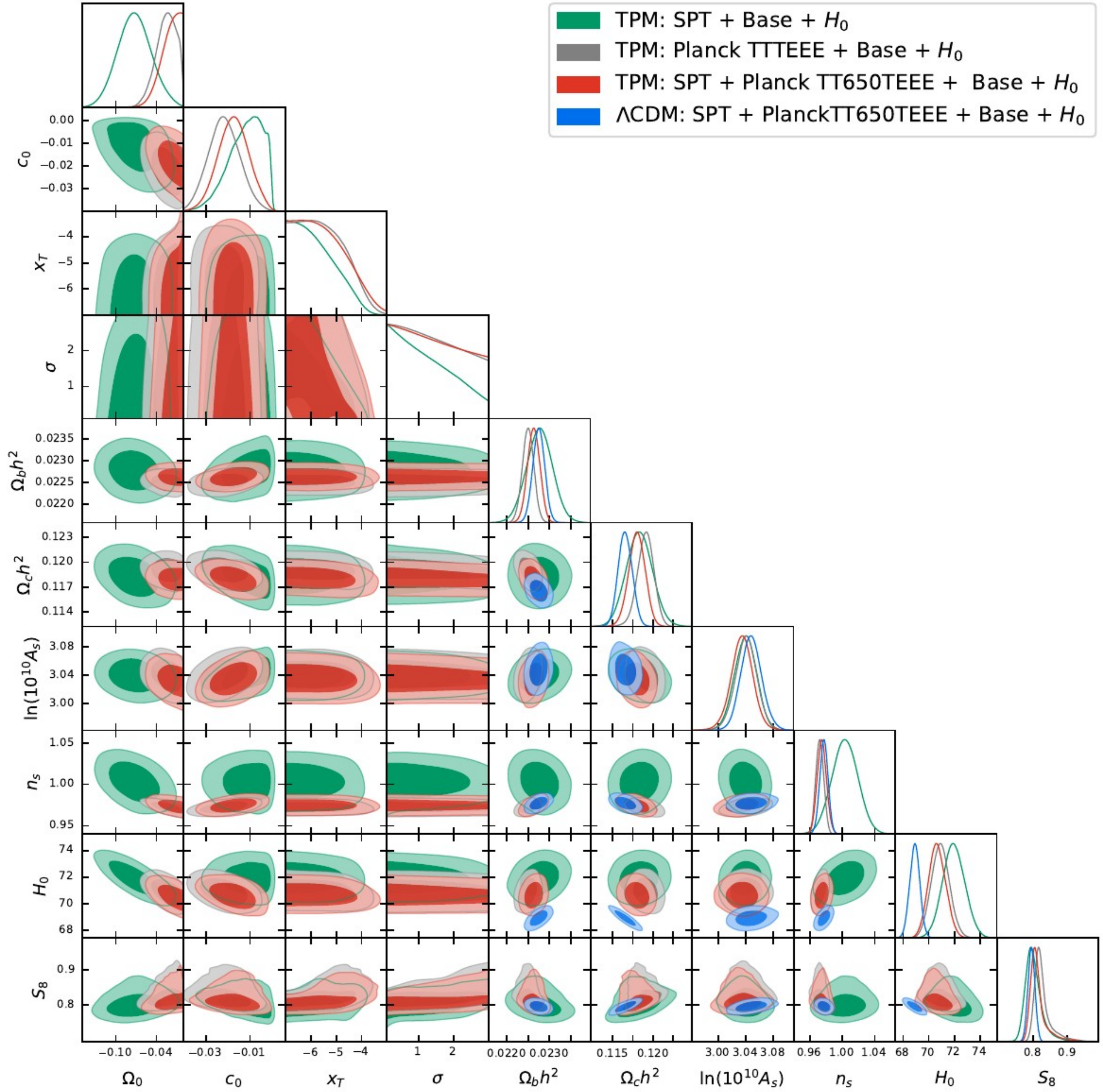
Conclusions

- **The TPM model includes a scalar field that is non-minimally coupled to gravity and induces a step-like transition in the effective Planck mass**
- **CMB, BAO, SNIa data are able to precisely constrain the TPM model finding a preference for a shift in the effective Planck mass when an H0 prior is included**
- **There exists a sizable parameter space with $H_0 > 70$ and $S8 < 0.8$, which are allowed by a reduction in matter fraction**
- **The main limiting factor of TPM in the fit to CMB data is the increased damping effect**
- **The inclusion of DES data does not disfavor the model but further tests are needed, with a proper treatment of non-linear scales**

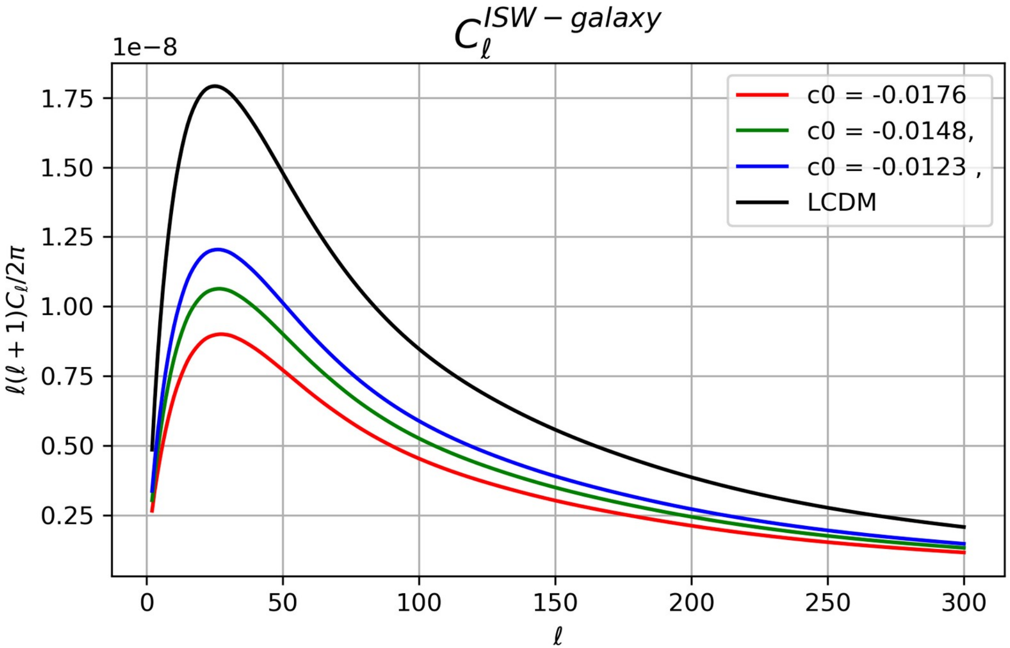
Results for TPM with DES likelihood

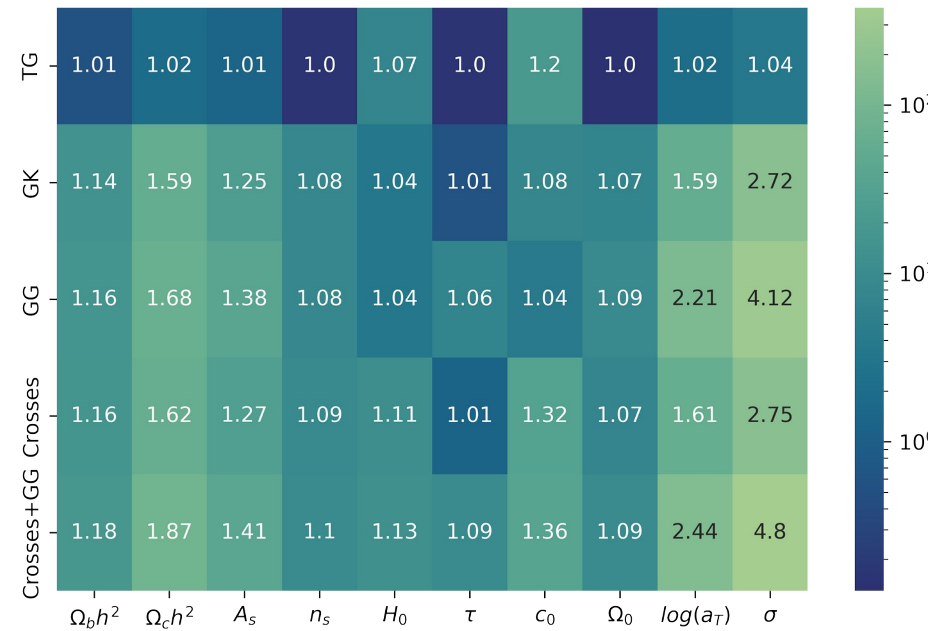


Combination of Planck and SPT



Testing TPM with CMB-galaxy cross-correlation





Results summary: Baseline +Planck+ H0 dataset

-Positive evidence for TPM and TPM f(R)in this configuration

- H0 tension reduced to less than 1.2 σ

- S8 tension slightly worst than ΛCDM

- TPM needs a lower change in Ω to get a higher H0 compared to TPM f(R)

Fit To Baseline $+H_0$ Likelihood

model	ΛCDM	$TPM\ f(R)$	TPM
$100\theta_{MC}$	1.04131 (1.04126± 0.00029)	1.04195 (1.04201 ± 0.00035)	1.04154 (1.04163 ± 0.00037)
$\Omega_b h^2$	0.02257 (0.02260± 0.00013)	0.02267 (0.02275 ± 0.00015)	0.022649 (0.02261 ± 0.00015)
$\Omega_c h^2$	0.11777 (0.11752± 0.00087)	0.1181 ($0.1184^{+0.0011}_{-0.00095}$)	0.1191 (0.1190 ± 0.0010)
τ	0.0621 ($0.0631^{+0.0070}_{-0.0084}$)	0.0602 ($0.0616^{+0.0072}_{-0.0082}$)	0.054 (0.0542 ± 0.0076)
$\ln(10^{10}A_s)$	3.058 ($3.058^{+0.014}_{-0.016}$)	3.060 (3.063 ± 0.016)	3.049 (3.046 ± 0.016)
n_s	0.9698 (0.9712 ± 0.0037)	0.9805 (0.9808 ± 0.0046)	0.9772 (0.9751 ± 0.0047)
Ω_0	-	-0.063 (−0.065 ± 0.018)	-0.045 (−0.050 ± 0.019)
x_T	-	-4.26 ($-5.30^{+1.0}_{-0.59}$)	-4.29 ($-5.32^{+0.96}_{-0.72}$)
x_T (95% CL)		$-5.30^{+1.2}_{-1.5}$	$-5.3^{+1.3}_{-1.6}$
σ	-	0.82 ($0.97^{+0.27}_{-0.83}$)	0.88 ($1.04^{+0.34}_{-0.88}$)
σ (95% CL)		< 1.95	< 2.12
c_0	-	0 (fixed)	-0.0176 ($-0.0148^{+0.0025}_{-0.0050}$)
c_0 (95% CL)			$-0.0148^{+0.0085}_{-0.0066}$
$w_{TPM,0}$	-	-0.9735 (−0.9728 ± 0.0072)	-1.0249($-1.025^{+0.013}_{-0.020}$)
H_0	68.44 (68.54 ± 0.40)	70.80 (70.90 ± 0.76)	71.38 (71.09 ± 0.75)
σ_8	0.810 ($0.8090^{+0.0059}_{-0.0066}$)	0.868 ($0.8386^{+0.0068}_{-0.032}$)	0.854 ($0.8531^{+0.0029}_{-0.033}$)
S_8	0.811 (0.8086 ± 0.0099)	0.842 ($0.813^{+0.010}_{-0.033}$)	0.825 ($0.8264^{+0.0065}_{-0.034}$)
$\Delta\chi^2_{\rm CMB}$	0	1.8	- 6.29
$\Delta\chi^2_{\rm CMB\ lensing}$	0	0.01	-0.57
$\Delta\chi^2_{\rm BAO}$	0	- 0.07	1.67
$\Delta\chi^2_{\rm Pantheon}$	0	0.0	1.35
$\Delta\chi^2_{\rm H_0}$	0	-17.8	-20.06
$\Delta\chi^2_{\rm tot}$	0	- 16.68	-23.72
$\Delta\log_{10}B$	0	**5.69**	**4.93**