A (DOUBLE) TAKE ON THE γ_L INDEX

EXPLORING LINEAR GROWTH WITH CMB DATA

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CMB and the ΛCDM Model

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- COBE, launched in 1989, was the first mission entirely dedicated to the study of CMB.
- It measured CMB radiation's temperature directly [Mather *et al.*, 1998]:

$$T_{CMB,0} = 2.725 \pm 0.002\mathrm{K}.$$

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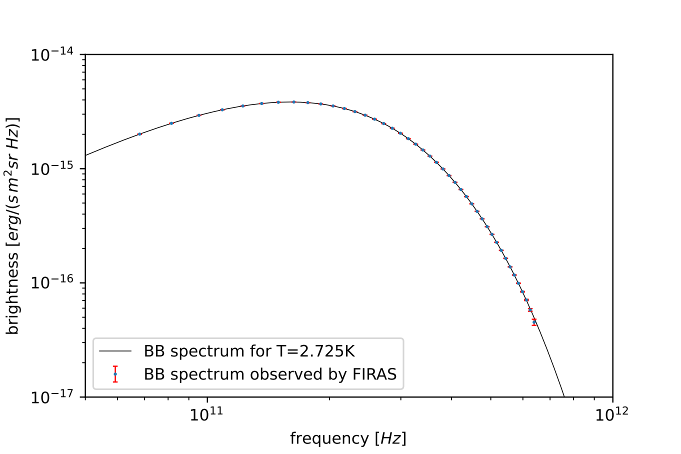

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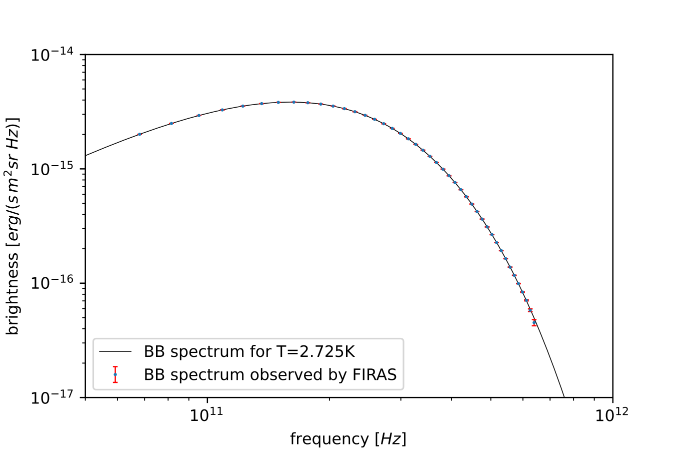

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- Pretty neat! (50-parts-in-10^6 neat to be precise)

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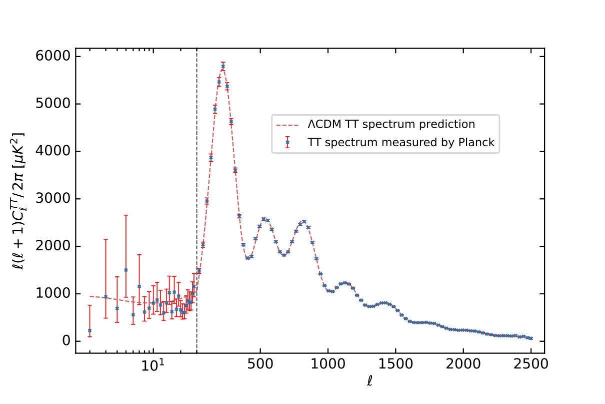

Data from [Aghanim *et al.*, 2020]

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  - [Heymans *et al.*, 2022]:

$$S_8 = 0.766^{+0.020}_{-0.014} \,(\sim 3\sigma \text{ away})$$

Planck and Tensions - A_L

- The lensing of CMB can be quantified by the A_L parameter, which changes the ΛCDM lensing potential spectrum $C_L^{\phi\phi}$ [Calabrese *et al.*, 2008]:

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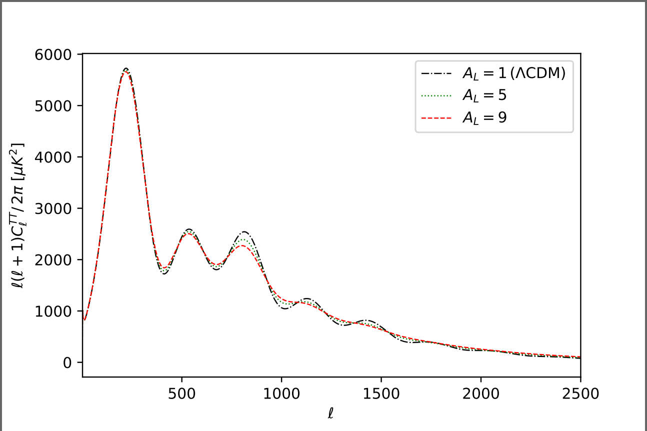

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- One way to tackle these tensions is to stretch beyond ΛCDM by modifying GR.

Modifying perturbations with μ, η

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- Given our uncertainty on a fundamental mechanism that can describe expansion and growth consistently, we can choose to modify ΛCDM in a general, model-independent way.
- An example of this modification is the μ, η *parametrisation* [Kunz+Sapone, 2007][Wang *et al.*, 2023]:

$$\Phi = \Psi \to \Phi = \mu(a, k)\Psi,$$
$$G_N \to \eta(a, k) G_N.$$

Modifying perturbations with γ_L

- [Linder, 2005] proposed that matter density growth, identified with the *growth rate* $f(a) = \frac{d\ln(D)}{d\ln(a)}$, can be parametrised at linear scales as:

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- In a MG model like DGP cosmology (i.e., the *Dvali-Gabadadze-Porrati* MG model, [Dvali *et al.*, 2000]), we accurately obtain: $\gamma_L \approx 0.68$.
- This substantial difference shows γ_L to be a powerful tool to detect departures from ΛCDM in the data.

Comparing Two γ_L Codes ([Specogna *et al.*, 2023])

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- MGCAMB [Wang *et al.*, 2023]:
  - this Boltzmann code modifies the perturbation equations of ΛCDM using the μ, η parametrisation mentioned above;

$$\mu = \frac{2}{3}\Omega_{\mathrm{m}}^{\gamma_L - 1}\left[\Omega_{\mathrm{m}}^{\gamma_L} + 2 + \frac{H'}{H} + \gamma_L \frac{\Omega_{\mathrm{m}}'}{\Omega_{\mathrm{m}}} + \gamma_L' \ln(\Omega_{\mathrm{m}})\right];$$

  - in the sub-horizon limit ($k \gtrsim 0.0003\,\mathrm{h\,Mpc^{-1}}$), γ_L can be mapped onto μ [Zucca *et al.*, 2019], which in turn affects the shape of the CMB anisotropies spectrum.

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  - in the sub-horizon limit ($k \gtrsim 0.0003\,\mathrm{h\,Mpc^{-1}}$), γ_L can be mapped onto μ [Zucca *et al.*, 2019], which in turn affects the shape of the CMB anisotropies spectrum.
- CAMB_GammaPrime_Growth [Nguyen *et al.*, 2023]:
  - the matter power spectrum in ΛCDM is modified *directly* by γ_L

$$P(\gamma_L, k, a) = P(k, a = 1)\, D^2(\gamma_L, a);$$

  - this choice modifies the part of the CMB spectrum affected by sub-horizon physics *only* i.e., the lensing potential spectrum $C_L^{\phi\phi}$.

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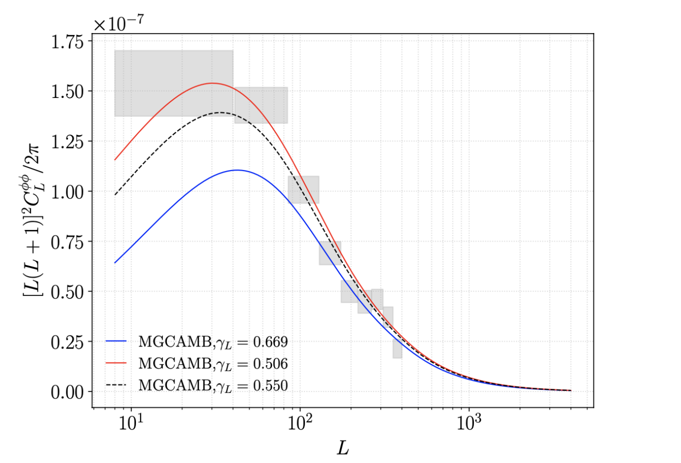

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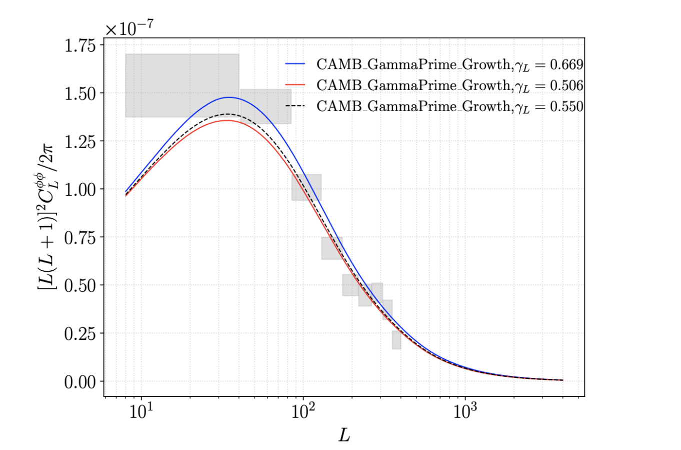


`CAMB_GammaPrime_Growth` – [Specogna *et al.*, 2023]

Constraining Two γ_L Codes ([Specogna *et al.*, 2023])

Parameter	Planck	Planck+BAO	Planck+lensing	Planck+BAO+lensing
$\Omega_b h^2$	0.02253 ± 0.00016	0.02250 ± 0.00016	0.02249 ± 0.00016	0.02246 ± 0.00015
$\Omega_c h^2$	0.1187 ± 0.0015	0.1190 ± 0.0013	0.1186 ± 0.0014	0.1189 ± 0.0012
$100\theta_{MC}$	1.04110 ± 0.00032	1.04106 ± 0.00032	1.04107 ± 0.00032	1.04103 ± 0.00030
τ_{reio}	0.0510 ± 0.0085	0.0507 ± 0.0082	$0.0496^{+0.0087}_{-0.0073}$	$0.0490^{+0.0083}_{-0.0073}$
n_s	0.9688 ± 0.0047	0.9681 ± 0.0045	0.9684 ± 0.0046	0.9675 ± 0.0042
$\log(10^{10} A_s)$	3.034 ± 0.018	3.034 ± 0.017	$3.030^{+0.018}_{-0.015}$	3.030 ± 0.017
γ_L	$0.467^{+0.018}_{-0.029}$	$0.469^{+0.017}_{-0.029}$	0.506 ± 0.022	$0.509^{+0.022}_{-0.020}$
H_0	68.02 ± 0.66	67.86 ± 0.60	68.00 ± 0.64	67.84 ± 0.57
S_8	0.839 ± 0.015	0.842 ± 0.015	0.824 ± 0.013	0.827 ± 0.012

Constraints at 68% CL for `MGCAMB` with Planck

Constraining Two γ_L Codes ([Specogna *et al.*, 2023])

Parameter	Planck	Planck+BAO	Planck+lensing	Planck+BAO+lensing
$\Omega_b h^2$	0.02258 ± 0.00016	0.02255 ± 0.00016	0.02251 ± 0.00017	0.02248 ± 0.00016
$\Omega_c h^2$	0.1181 ± 0.0015	0.1186 ± 0.0013	0.1183 ± 0.0015	0.1188 ± 0.0013
$100\theta_{MC}$	1.04113 ± 0.00032	1.04108 ± 0.00031	1.04109 ± 0.00032	1.04103 ± 0.00032
τ_{reio}	$0.0496^{+0.0087}_{-0.0074}$	0.0495 ± 0.0084	$0.0493^{+0.0087}_{-0.0074}$	$0.0488^{+0.0086}_{-0.0075}$
n_s	0.9709 ± 0.0047	0.9696 ± 0.0045	0.9696 ± 0.0048	0.9683 ± 0.0044
$\log(10^{10} A_s)$	3.030 ± 0.017	3.031 ± 0.018	$3.029^{+0.018}_{-0.016}$	$3.029^{+0.018}_{-0.016}$
γ_L	$0.841^{+0.11}_{-0.074}$	$0.831^{+0.11}_{-0.080}$	0.669 ± 0.069	0.658 ± 0.063
H_0	68.27 ± 0.69	68.06 ± 0.61	68.14 ± 0.70	67.92 ± 0.61
S_8	0.805 ± 0.018	0.810 ± 0.017	0.807 ± 0.019	0.812 ± 0.017

Constraints at 68% CL for `CAMB_GammaPrime_Growth` with Planck

Constraining Two γ_L Codes ([Specogna *et al.*, 2023])

Parameter	SPT	SPT+BAO	SPT+WMAP	SPT+WMAP+BAO
$\Omega_b h^2$	0.02238 ± 0.00033	0.02237 ± 0.00032	0.02264 ± 0.00023	0.02259 ± 0.00021
$\Omega_c h^2$	0.1175 ± 0.0057	0.1186 ± 0.0026	0.1153 ± 0.0028	0.1171 ± 0.0020
$100\theta_{\rm MC}$	1.03945 ± 0.00081	1.03933 ± 0.00069	1.03973 ± 0.00066	1.03954 ± 0.00064
τ_{reio}	0.065 ± 0.015	0.066 ± 0.015	0.060 ± 0.013	0.058 ± 0.013
n_s	0.991 ± 0.025	0.987 ± 0.019	0.9733 ± 0.0075	0.9709 ± 0.0067
$\log(10^{10} A_s)$	3.040 ± 0.039	3.043 ± 0.038	3.041 ± 0.025	3.042 ± 0.026
γ_L	$0.622^{+0.075}_{-0.11}$	$0.635^{+0.063}_{-0.084}$	$0.556^{+0.023}_{-0.018}$	$0.558^{+0.024}_{-0.018}$
H_0	67.8 ± 2.3	67.3 ± 1.0	68.9 ± 1.2	68.11 ± 0.83
S_8	0.796 ± 0.048	0.804 ± 0.028	0.782 ± 0.032	0.801 ± 0.025

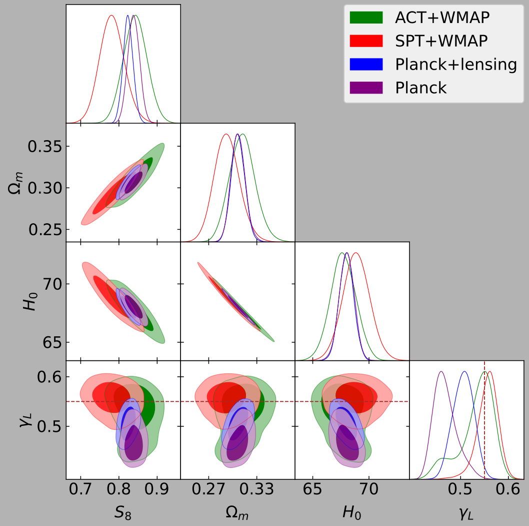
Constraints at 68% CL for MGCAMB with SPT

Constraining Two γ_L Codes ([Specogna *et al.*, 2023])

Parameter	SPT	SPT+BAO	SPT+WMAP	SPT+WMAP+BAO
$\Omega_b h^2$	0.02241 ± 0.00033	0.02238 ± 0.00031	0.02259 ± 0.00024	0.02253 ± 0.00022
$\Omega_c h^2$	0.1164 ± 0.0056	0.1183 ± 0.0026	0.1167 ± 0.0032	0.1178 ± 0.0021
$100\theta_{MC}$	1.03953 ± 0.00081	1.03935 ± 0.00067	1.03955 ± 0.00071	1.03942 ± 0.00064
τ_{reio}	0.065 ± 0.015	0.065 ± 0.015	0.062 ± 0.013	0.061 ± 0.013
n_s	0.994 ± 0.024	0.989 ± 0.019	0.9709 ± 0.0080	0.9687 ± 0.0068
$\log(10^{10} A_s)$	3.035 ± 0.039	3.040 ± 0.035	3.049 ± 0.027	3.051 ± 0.027
γ_L	0.46 ± 0.19	0.41 ± 0.15	0.43 ± 0.14	0.41 ± 0.13
H_0	$68.3^{+2.1}_{-2.4}$	67.4 ± 1.0	68.3 ± 1.4	67.77 ± 0.89
S_8	0.803 ± 0.064	0.824 ± 0.032	0.802 ± 0.039	0.815 ± 0.027

Constraints at 68% CL for `CAMB_GammaPrime_Growth` with SPT

Constraining Two γ_L Codes ([Specogna *et al.*, 2023])



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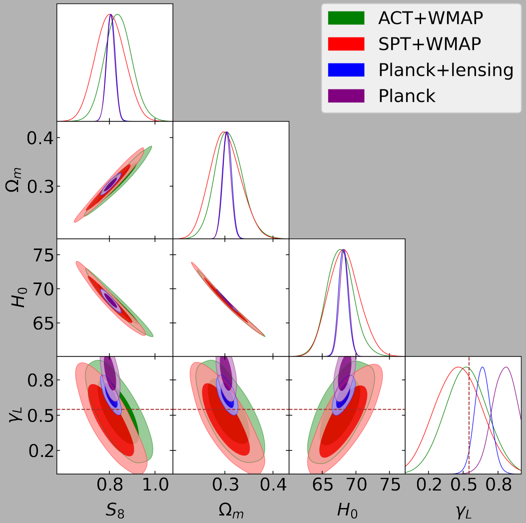

CAMB_GammaPrime_Growth

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- While this model represented a simple modification, it does not represent a solution to the cosmological tensions.
- γ_L was assumed to be constant, but it does not have to be (could be extended to include, for instance, redshift dependence).

Thank You For Your Attention

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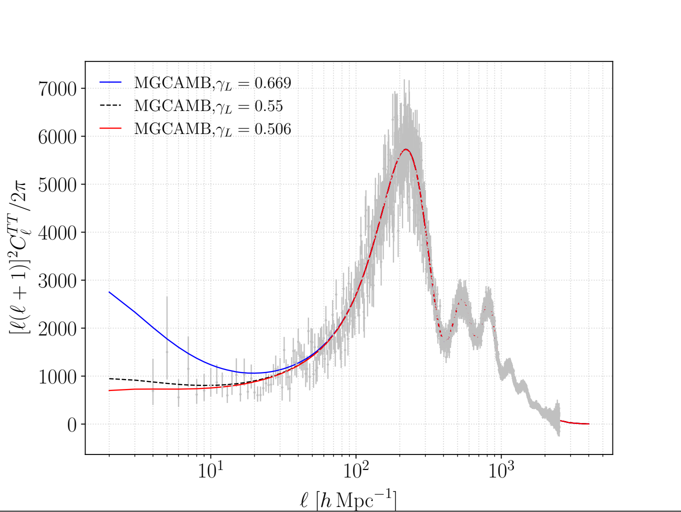
Comparing Two γ_L Codes (extra)



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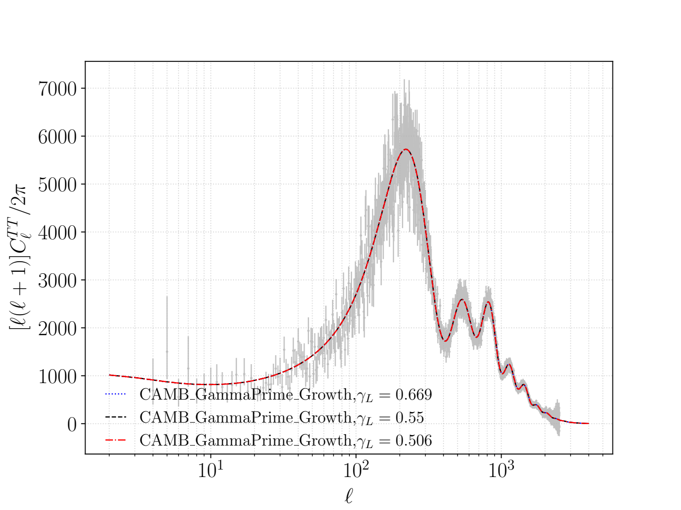

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