Dynamical Dark Energy from the QCD Vacuum

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Summary

- We consider a parametrisation of effective dark energy as described in [Van Waerbeke & Zhitnitsky (2025)] of the form:

$$\rho_{\mathrm{DE}} = \varepsilon^{\mathrm{vac}}_{\mathrm{FLRW}} - \varepsilon^{\mathrm{vac}}_{\mathrm{Mink}}. \tag{1}$$

- We consider a parametrisation of the model and obtain constraints on combinations of the CMB, BAO and SN datasets.
- We consider $\Delta\chi^2$ and $\ln\mathcal{B}$ with respect to ΛCDM and find that the model remains competitive with ΛCDM and w_0w_aCDM across all the dataset combinations tested.

Suggestions for a vacuum correction

- The topological susceptibility $\chi = \frac{\partial^2 E}{\partial \theta^2}\big|_{\theta=0}$ in QCD requires non-dispersive contributions which is often modelled as an auxiliary, non-dynamical field.
- These contributions are generated by tunnelling between topologically distinct vacuum states, mediated by configurations with non-trivial holonomy.
- The vacuum energy density on $\mathbb{R}^3 \times \mathbb{S}^1$ can be computed to be $\varepsilon^{\mathrm{vac}}_{\mathrm{Mink}} = -\Lambda^4_{\mathrm{QCD}}$.
- It was shown in [Zhitnitsky (2015)] that for $\mathbb{H}^3_\kappa \times \mathbb{S}^1_{\kappa^{-1}}$, the vacuum energy picks up a correction linear in κ.

$$\varepsilon^{\mathrm{vac}}_{\mathrm{hyp}} = -\Lambda^4_{\mathrm{QCD}} \left(1 - \frac{c_\kappa \kappa}{\Lambda_{\mathrm{QCD}}}\right) \qquad (2)$$

de Sitter vacuum

- We observe similar behaviour in deformed QCD (weakly coupled gauge theory) defined on a box size $\mathbb{L}$ where the vacuum energy corrections scale as $\sim \mathbb{L}^{-1}$. [Thomas & Zhitnitsky (2012)]
- Moreover, Lattice QCD simulations in de Sitter with an imaginary $\overline{H}$ show that particle generation is linear in $\overline{H}$ [Yamamoto (2014)].
- Proposed in [Zhitnitsky (2015)] that $\overline{\rho_{\mathrm{DE}}} \equiv \varepsilon_{\mathrm{FLRW}}^{\mathrm{vac}} - \varepsilon_{\mathrm{Mink}}^{\mathrm{vac}} = c_H \Lambda_{\mathrm{QCD}}^3 \overline{H}$.
- The scale of this DE is governed then by $\overline{H} = \frac{8\pi G}{3} c_H \Lambda_{\mathrm{QCD}}^3$ when $\overline{H}/\Lambda_{\mathrm{QCD}} \ll 1$

Away from de Sitter

- Where the time variation of H is small ($|\dot{H}/H| \ll \overline{H}$), one might expect a $\rho_{\rm DE}(t) \sim H(t)$.
- When away from this adiabatic approximation, we expect additional suppression $\propto (H\overline{H}/|\dot{H}|)$ [Van Waerbeke & Zhitnitsky (2025)].
- We can recast the adiabatic condition as:

$$\frac{3}{2}\frac{H}{\overline{\overline{H}}}(1 + w_{\rm tot}) \ll 1 \tag{3}$$

- Since we are in an accelerating epoch today ($w_{\rm tot} < -1/3$), this would equate to marginally satisfying the condition.
- In the asymptotic de Sitter limit, we recover the exact $\rho \propto \overline{H}$.
- Otherwise, we have an additional, time dependent suppression factor β.

$$H^2(t) = \frac{8\pi G}{3}\left[\rho_t(t) + [c_H \beta(t)]\Lambda^3_{\rm QCD} H(t)\right] \tag{4}$$

- where $\beta \in (0, 1)$ and ρ_t is the density of species contributing to the stress-energy tensor.

Parametrisation of the model

- We consider a parametrisation of the suppression factor β as a function of z:

$$\beta(z) = \frac{A_q}{1 + \exp\left(\frac{z-z_q}{\Delta z_q}\right)} \tag{5}$$

- The parametrisation contains two free parameters $\{z_q, \Delta z_q\}$ with A_q being a normalisation parameter to fix the de Sitter limit to 1.

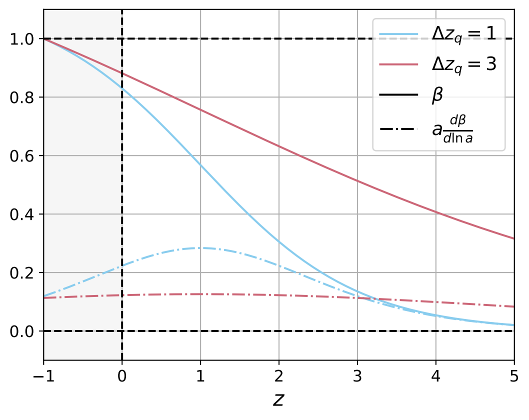

Figure 1: Plot of the switch functions and their derivatives for $z_q = \Delta z_q = 1$.

Properties of this DE

- The vacuum energy does not cluster and therefore is a purely background effect.
- Since this is not a physical, local field, the effective equation of state of dark energy is able cross the phantom divide.
- The physical concept of this vacuum energy correction may be testable in the form of the Topological Casimir Effect.

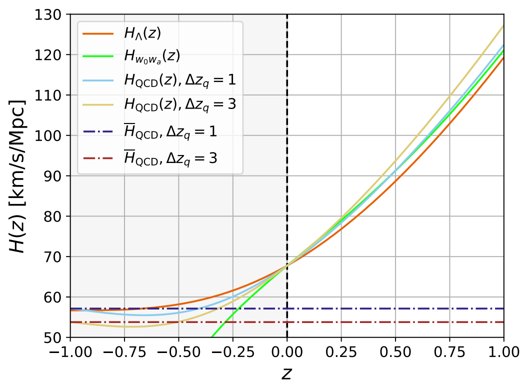

Figure 2: Plot of $H(z)$ for $z_q = \Delta z_q = 1$.

Cosmological datasets

- Datasets:
  - Primary CMB from [Planck PR3 (2020)], [ACT DR6 (2025)] and [SPT-3G D1].
  - CMB lensing reconstruction from [Planck PR4 (2022)], [ACT DR6 (2024)] and [SPT-3G MUSE (2025)]
  - BAO from [DESI DR2 (2025)]
  - SNe type Ia from [Pantheon+ (2022)] or [DES Dovekie (2025)]
- We consider CMB-SPA, combinations of the BAO and SN and triplet combinations.
- We implemented this cosmology in Class [Blas, Lesgourgues & Tram (2011)].
- We used MCMC sampling implemented in Cobaya [Torrado & Lewis (2021)].
- We used harmonic [McEwen et al (2021)] to estimate the Bayesian evidence from the chains.

Constraints from observations

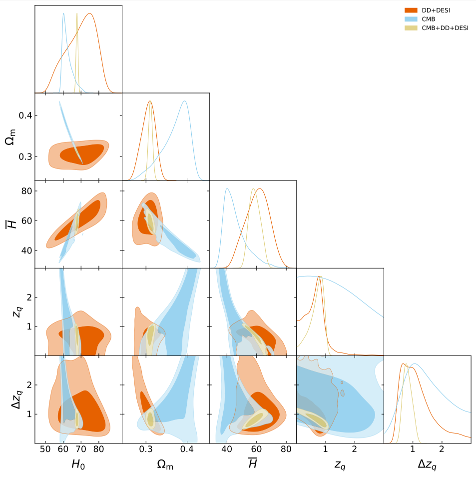

Figure 3: Constraints on the QCD-DE parameters and H_0, Ω_m from the cosmological datasets.

Constraints from observations

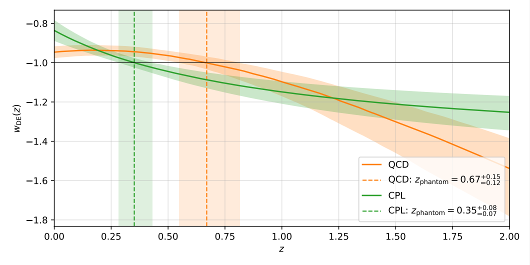

Figure 4: The effective DE EoS posterior functions for CPL and QCD-DE from the posteriors from CMB-SPA+DD+DESI.

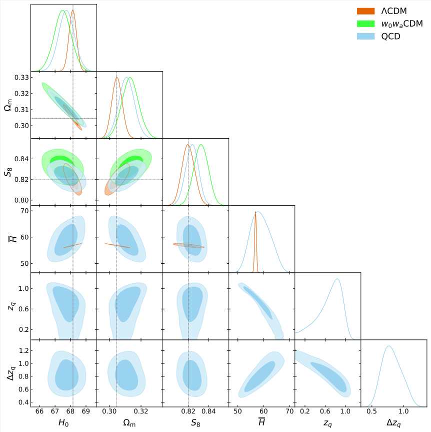

Figure 5: 2D posterior contour plot for CMB-SPA+DD+DESI.

χ^2 comparison

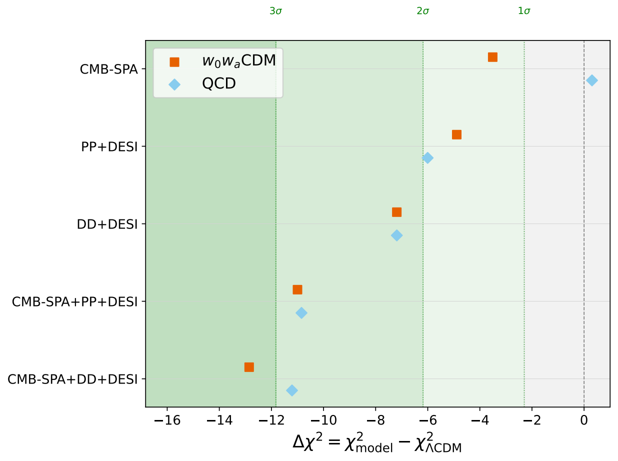

Figure 6: Plot of the difference in the MAP χ^2_{eff} with respect to the ΛCDM model. $\Delta\chi^2 > 0$ indicates a preference for ΛCDM (only possible for QCD-DE against ΛCDM).

Bayes factor

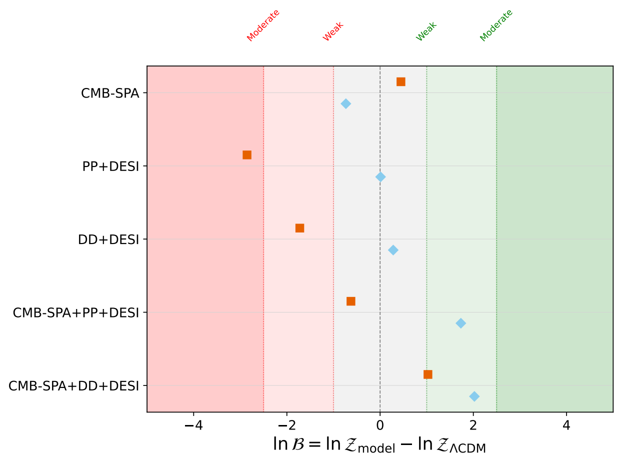

Figure 7: Plot of $\ln \mathcal{B}$. $\ln \mathcal{B} < 0$ indicates a preference for ΛCDM.

Conclusion

- We developed a model for DE motivated from QCD vacuum calculations.
- We obtained constraints on cosmological parameters of this model using the latest dataset combinations for the CMB, BAO and SN.
- The performance of the QCD-DE model was measured against ΛCDM and $w_0 w_a$CDM and was shown to be competitive across the datasets used.
- We wrote a wrapper to make running harmonic on Cobaya MCMC chains easier.
- The parametrisation shown, is an attempt at trying to capture the phenomenology of the QCD vacuum DE.

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Additional Slides 1: ΔAIC

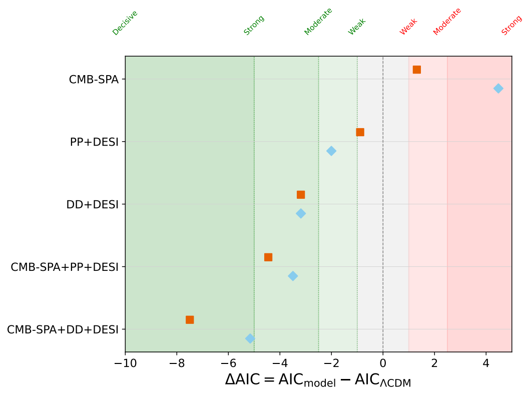

Figure 8: ΔAIC with respect to ΛCDM. Positive values indicate a preference for ΛCDM.

Additional Slides 2: ΔDIC

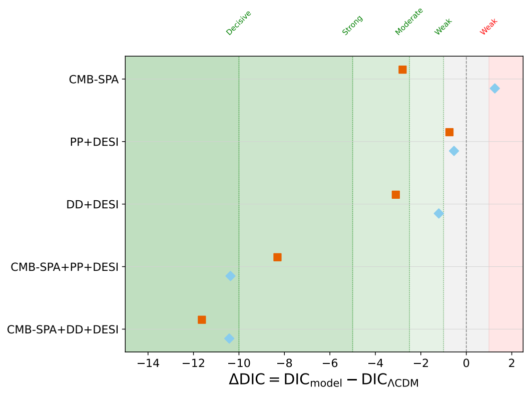

Figure 9: ΔDIC with respect to ΛCDM. Positive values indicate a preference for ΛCDM.

Additional Slides 3: Constraints

Parameters	PP+DESI	DD+DESI	CMB-SPA	CMB-SPA+PP+DESI	CMB-SPA+DD+DESI
H_0	70^{+10}_{-6}	70^{+10}_{-6}	$62.24^{+0.93}_{-3.2}$	67.74 ± 0.58	67.74 ± 0.52
$\Omega_b h^2$	$0.0264^{+0.013}_{-0.0052}$	$0.0263^{+0.013}_{-0.0052}$	0.022390 ± 0.000096	0.022428 ± 0.000094	0.022423 ± 0.000093
$\Omega_c h^2$	$0.123^{+0.025}_{-0.032}$	$0.125^{+0.026}_{-0.033}$	0.1206 ± 0.0010	0.11955 ± 0.00078	0.11957 ± 0.00078
$\ln(10^{10} A_s)$	$---$	$---$	3.052 ± 0.011	3.050 ± 0.010	3.049 ± 0.010
n_s	$---$	$---$	0.9683 ± 0.0035	0.9710 ± 0.0030	0.9710 ± 0.0031
$\tau_{\rm reio}$	0.06 (fixed)	0.06 (fixed)	0.0552 ± 0.0057	0.0553 ± 0.0054	0.0552 ± 0.0055
z_q	$0.64^{+0.29}_{-0.42}$	$0.64^{+0.30}_{-0.37}$	< 1.77	$0.66^{+0.32}_{-0.16}$	$0.68^{+0.31}_{-0.14}$
Δz_q	$1.24^{+0.25}_{-0.73}$	$1.17^{+0.23}_{-0.70}$	$1.50^{+0.66}_{-0.95}$	$0.83^{+0.14}_{-0.18}$	$0.82^{+0.13}_{-0.18}$
$\overline{H}$	61^{+9}_{-8}	61^{+9}_{-7}	$45.4^{+2.8}_{-8.9}$	$59.1^{+3.8}_{-4.4}$	$58.8^{+3.5}_{-4.3}$
A_q	$1.26^{+0.10}_{-0.24}$	$1.241^{+0.097}_{-0.23}$	$1.23^{+0.13}_{-0.24}$	$1.147^{+0.040}_{-0.12}$	$1.140^{+0.035}_{-0.11}$
Ω_m	$0.304^{+0.018}_{-0.015}$	$0.306^{+0.019}_{-0.015}$	$0.373^{+0.040}_{-0.016}$	0.3109 ± 0.0054	0.3109 ± 0.0049
σ_8	$0.74^{+0.16}_{-0.36}$	$0.74^{+0.17}_{-0.35}$	$0.7795^{+0.0067}_{-0.019}$	0.8091 ± 0.0060	0.8090 ± 0.0056
S_8	$0.75^{+0.16}_{-0.36}$	$0.75^{+0.17}_{-0.36}$	$0.868^{+0.029}_{-0.014}$	0.8235 ± 0.0064	0.8235 ± 0.0063
$r_{\rm drag}$	$144.5^{+8.5}_{-22}$	$144.3^{+8.8}_{-22}$	146.85 ± 0.25	147.09 ± 0.21	147.09 ± 0.21
$r_{\rm drag} h$	99.49 ± 0.87	99.53 ± 0.79	$91.4^{+1.4}_{-4.8}$	99.64 ± 0.85	99.64 ± 0.76

Figure 10: Constraints on Cosmological parameters of the QCD-DE model across different combinations of cosmological datasets.