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 $w_0 w_a$CDM across all the dataset combinations tested.

Suggestions for a vacuum correction

- The topological susceptibility $\chi = \frac{\partial^2 E}{\partial \theta^2}|_{\theta=0}$ 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.

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

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 $\overline{\rho_{\mathrm{DE}}} \equiv \varepsilon^{\mathrm{vac}}_{\mathrm{FLRW}} - \varepsilon^{\mathrm{vac}}_{\mathrm{Mink}} = c_H \Lambda^3_{\mathrm{QCD}} \overline{H}$.
- Where the time variation of H is small ($|\dot{H}/H| \ll \overline{H}$), one might expect a $\rho_{\mathrm{DE}}(t) \sim H(t)$.

Away from de Sitter

- 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:

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

- Since we are in an accelerating epoch today ($w_{\text{tot}} < -1/3$), 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.

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

- 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.

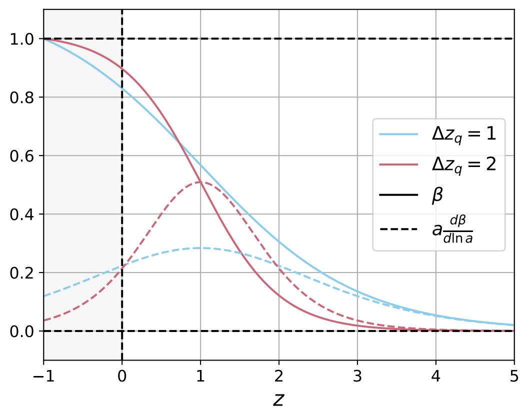

Figure 1: Plot of the switch functions and their derivatives for $z_q = \Delta z_q = 1$.

Properties of this DE

- The underlying physical motivation of this DE does not have any propagating degrees of freedom and therefore would not make sense to consider perturbations.
- 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.

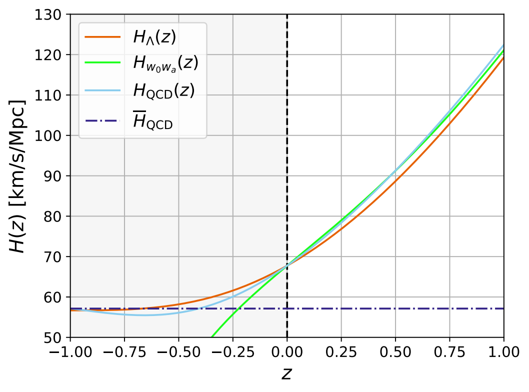

Figure 2: Plot of $H(z)$ for $z_q = \Delta z_q = 1$.

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)]
  - [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 used MCMC sampling implemented in Cobaya.
- We used harmonic [McEwen et al (2021)] to estimate the Bayesian evidence from the chains.

Constraints from observations

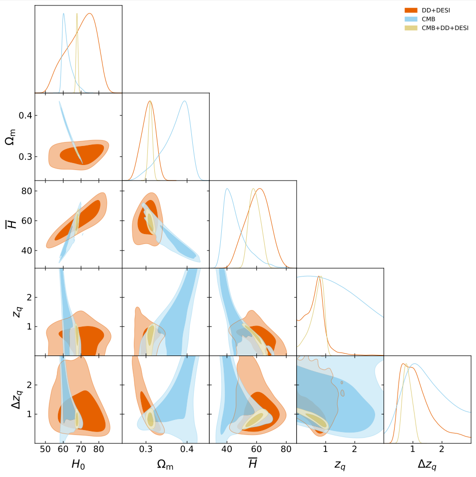

Figure 3: Constraints on the QCD-DE parameters and H_0, Ω_m from the cosmological datasets.

Constraints from observations

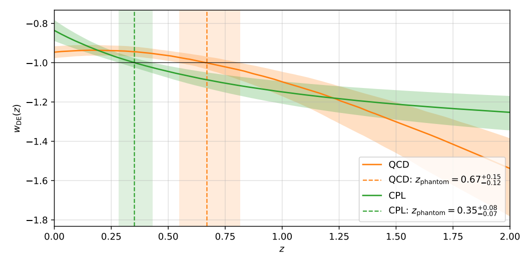

Figure 4: The effective DE EoS posterior functions for CPL and QCD-DE from the posteriors from CMB-SPA+DD+DESI.

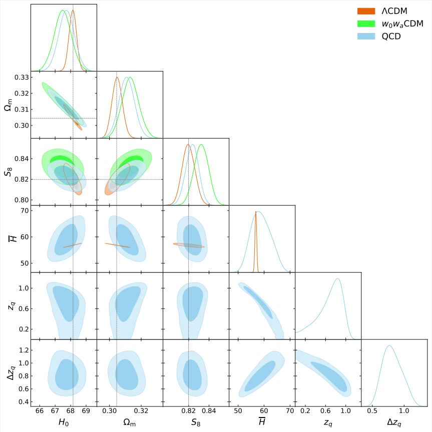

Figure 5: 2D posterior contour plot for CMB-SPA+DD+DESI.

χ^2 comparison

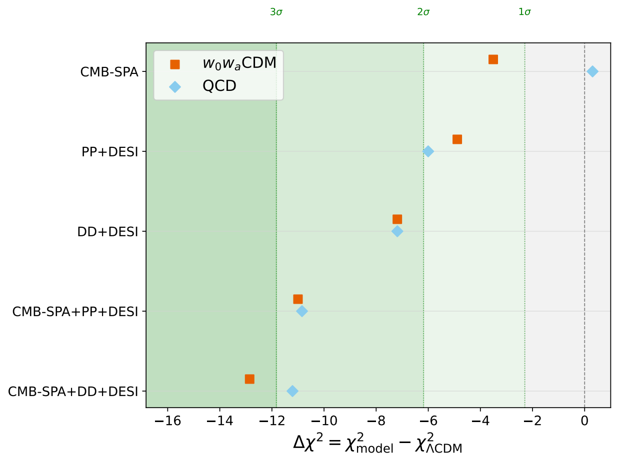

Figure 6: Plot of the difference in the MAP χ^2_{eff} with respect to the ΛCDM model. $\Delta\chi^2 > 0$ indicates a preference for ΛCDM (only possible for QCD-DE against ΛCDM).

Bayes factor

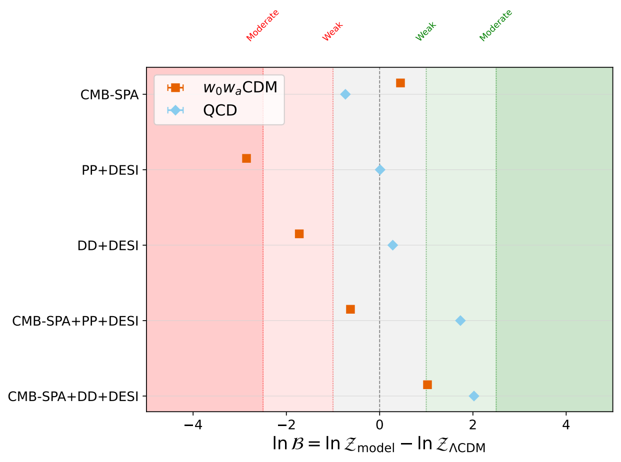

Figure 7: Plot of $\ln\mathcal{B}$. $\ln\mathcal{B} < 0$ indicates a preference for ΛCDM.

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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