DESI results and time dependent Dark Energy from the QCD topological sectors

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Dynamical de Sitter phase and nontrivial holonomy in strongly coupled gauge theories in expanding Universe.

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Theoretical foundation: how the vacuum energy can be generated in strongly coupled QCD for pure de Sitter state when $H = \text{constant}$

DESI results and Dark Energy from QCD topological sectors

Ludovic Van Waerbeke[1] and Ariel Zhitnitsky[1]

arxiv 2506.14182

How these results can be generalized to a time dependent background $\overline{H} \to H(t)$

Evolving Dark Energy Is Vacuum Energy After All

Dong Ha Lee,[1] Carsten van de Bruck,[1] Eleonora Di Valentino,[1] Ludovic Van Waerbeke,[2] and Ariel Zhitnitsky[2]

arxiv 2606.20036

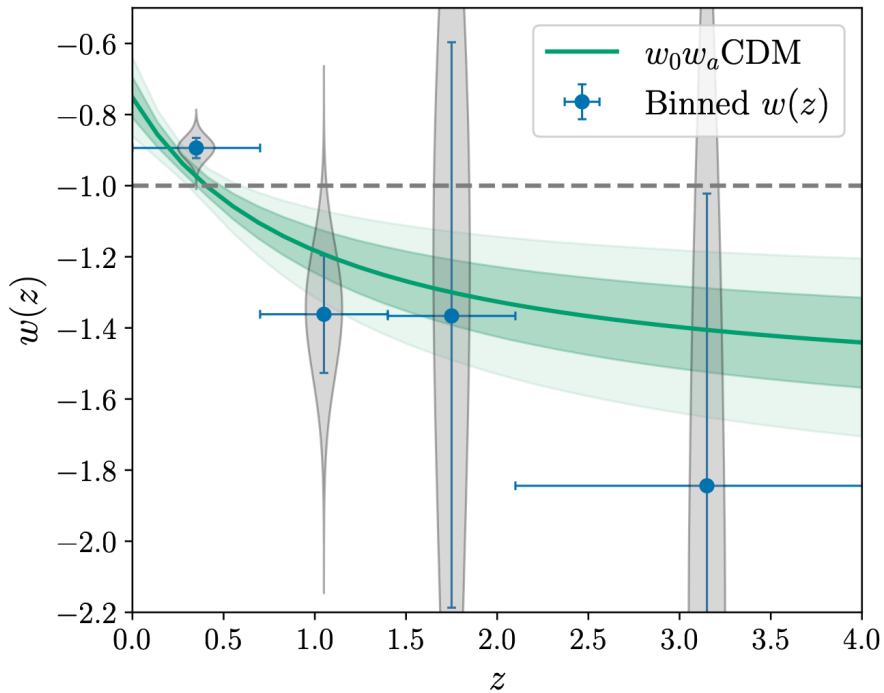
Confronting the QCD-induced vacuum energy with current observations:Planck, DESI DR2, Type Ia supernova from Patheon+, DES-Dovekie

Motivation: Recent observations from Dark Energy Spectroscopic Instrument (DESI)

- DESI observed a time evolving EoS

- Furthermore, the EoS shows

$$w \equiv \frac{p}{\rho} = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)} < (-1)$$



- From QFT viewpoint such a behaviour is complete disaster: it contradicts Unitarity, causality, and other fundamental features of QFT

- Previously data had been fitted as a cosmological constant with $w = -1$ DESI results suggest t-dependence.

- Our proposal is that the source of the observed Dark Energy (DE) is the QCD vacuum energy and tunnelling processes between the topological $|k\rangle$ sectors.

- The variation of the transition rate between $|k\rangle$ sectors in expanding Universe will result in variation of the DE with time (DESI results).

- No any new degrees of freedom such as ϕ with potential $V(\phi)$ are present in the system. Nevertheless there is a nontrivial dynamics of the system

- How a theory with a gap $\Lambda_{\rm QCD} = 100{\rm MeV}$ could be ever sensitive to arbitrary large distances?

1. Energy in non-perturbative QCD

- We want to argue that there is a novel type of energy in strongly coupled QCD. This energy has "non-dispersive" nature, and can not be expressed in terms of conventional scattering amplitudes.

- This physics is hidden in contact term which is saturated by IR (large distances), not UV physics

- All these novel effects are due to the nontrivial topological sectors $|k\rangle$ in the gauge systems and tunnelling transitions between them.

- The effect is non-local in nature, and can not be expressed in terms of local curvature in gradient expansion. It is expressed in terms of a non-local characteristics of the system -**the holonomy.**

2. Definition of the Gravitating Energy

- We assume that the relevant (gravitating) energy which enters the Friedman's equation is the difference $\Delta E = (E_{\mathrm{FLRW}}(H) - E_{\mathrm{Mink}})$ similar to computations of the Casimir energy, when the difference ΔE is observed. This assumption was, in fact, originally formulated by Zeldovich in 1967.

- We can not (by technical reasons) to perform the computations in FLRW background. However, we can proceed with computations in a toy model formulated on hyperbolic space $\mathbb{H}^3_\kappa \times \mathbb{S}^1_{\kappa^{-1}}$ when role of $H \sim 10^{-33}\ eV$ plays parameter $\kappa \to 0$

- We want to argue that a nontrivial holonomy generates a linear correction $\Delta E(\kappa) \sim \kappa$ in contrast with conventional expectation $\Delta E \sim R\,[\mathbb{H}^3_\kappa] \sim \kappa^2$

- Technically, we want to see a linear (rather than very small quadratic κ^2) correction in the ratio

$$\frac{E_{\rm vac}[\mathbb{H}^3_\kappa \times \mathbb{S}^1_{\kappa^{-1}}]}{E_{\rm vac}[\mathbb{R}^3 \times \mathbb{S}^1]} \simeq 1 + \mathcal{O}\left(\frac{\kappa}{\Lambda_{QCD}}\right).$$

- If the same pattern persists in real FLRW Universe one could replace $\kappa \to H$ (Hubble) :

- In other words, we interpret the observed Dark Energy as a **leftover** between expanding Universe and flat Minkowski space-time

$$\rho_{\rm DE} \equiv \Delta E \equiv E_{\rm deSitter} - E_{\rm Mink}$$

- It has the same non-dispersive nature (can not be expressed in terms of propagating dof), it is non-local in nature (not expressible in terms of the local curvature, local scalar field ϕ), and it has a positive sign.

- If one assumes that the same effect to persist in our FLRW Universe one should replace $\kappa \to \overline{H}$ to arrive (amazingly close to the observed values):

$$\rho_{\rm DE} \equiv (E_{\rm deSitter} - E_{\rm Mink}) = -\Lambda_{QCD}^4 \left(1 - c_H \frac{\overline{H}}{\Lambda_{QCD}}\right) + \Lambda_{QCD}^4$$

$$\overline{H} = c_H \frac{8\pi\Lambda_{QCD}^3}{3M_{PL}^2} \approx \bar{c}_H \cdot 2.8 \cdot 10^{-33} eV, \quad t_0 \equiv \overline{H}^{-1} = \frac{7.3}{\bar{c}_H} \text{Gyr}$$

$$\rho_{\rm DE} = c_H \Lambda_{QCD}^3 \overline{H} \approx \bar{c}_H^2 \left(3.4 \cdot 10^{-3} \text{eV}\right)^4, \quad \bar{c}_H \sim 1$$

- The driving force for the deSitter behaviour is <u>not a local dynamical DE field</u> ϕ . Rather, the driving force should be thought as a Casimir type vacuum energy generated by tunnelling transitions between different topological sectors.

- There is a single dimensional parameter of the problem, it is $\Lambda_{\rm QCD} \simeq 100 \text{MeV}$. No any new parameters in the system. It is the SM physics

- *Q: How a system with a gap could be ever sensitive to arbitrary large distances?*

- A1: The long range order in gapped QCD is similar to Aharonov -Casher effect. If one inserts an external charge into superconductor when electric field is screened $\exp(-r/\lambda)$ a neutral magnetic fluxon will be still sensitive to external charge at arbitrary large distances. This is the so-called "non-dispersive" contribution. Topological insulator in CM system is another analog

- A2: it can be tested in exactly solvable models such as 2d QED, or "deformed QCD". It can be also tested in a tabletop experiment (measurements of the so-called Topological Casimir Effect).

3. Time dependent DE and adiabatic condition

- There is a number of hints that DE is NOT a cosmological constant, it may cross the phantom line $w = -1$

- In our framework it is anticipated: when the system deviates from exact de Sitter ($\overline{H} = \text{constant}$) the vacuum energy also starts to depend on time

- The formula for DE $\rho_{\rm DE} \propto \Lambda^3_{QCD} H$, holds only when the adiabatic condition is satisfied

$$\frac{|\dot{H}|}{H} \ll \overline{H} \quad \rightarrow z \lesssim 0.5$$

- It implies that DE can be effectively generated only now. It solves the question `` why it is now?''

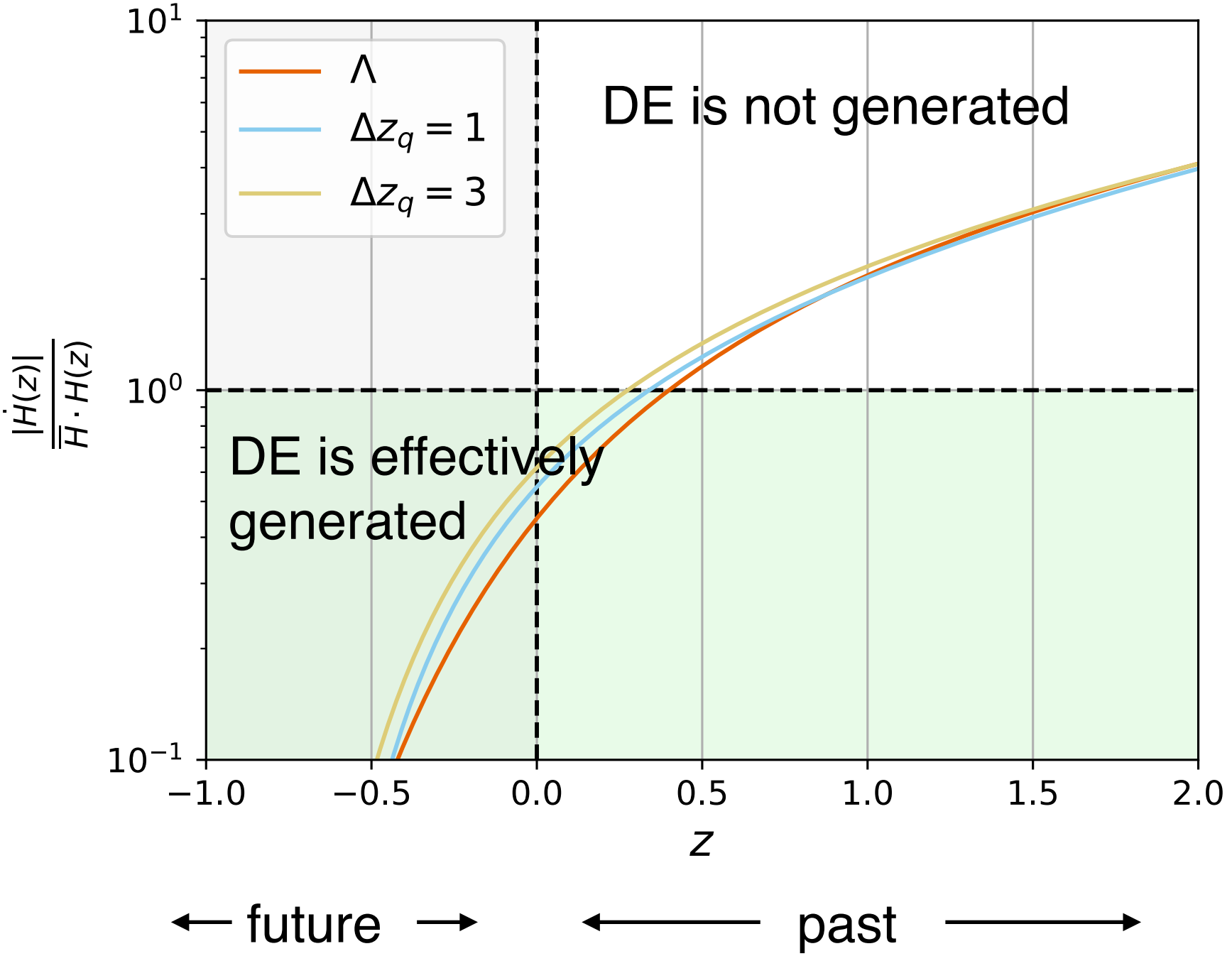
- In principle the DE can be computed from the first principles (e.g. using the lattice QCD). However, it is not feasible today and we parameterize DE as

$$\rho_{\rm DE} \approx \beta(t)[\Lambda^3_{QCD} H], \quad \beta(t) \in (0,1)$$

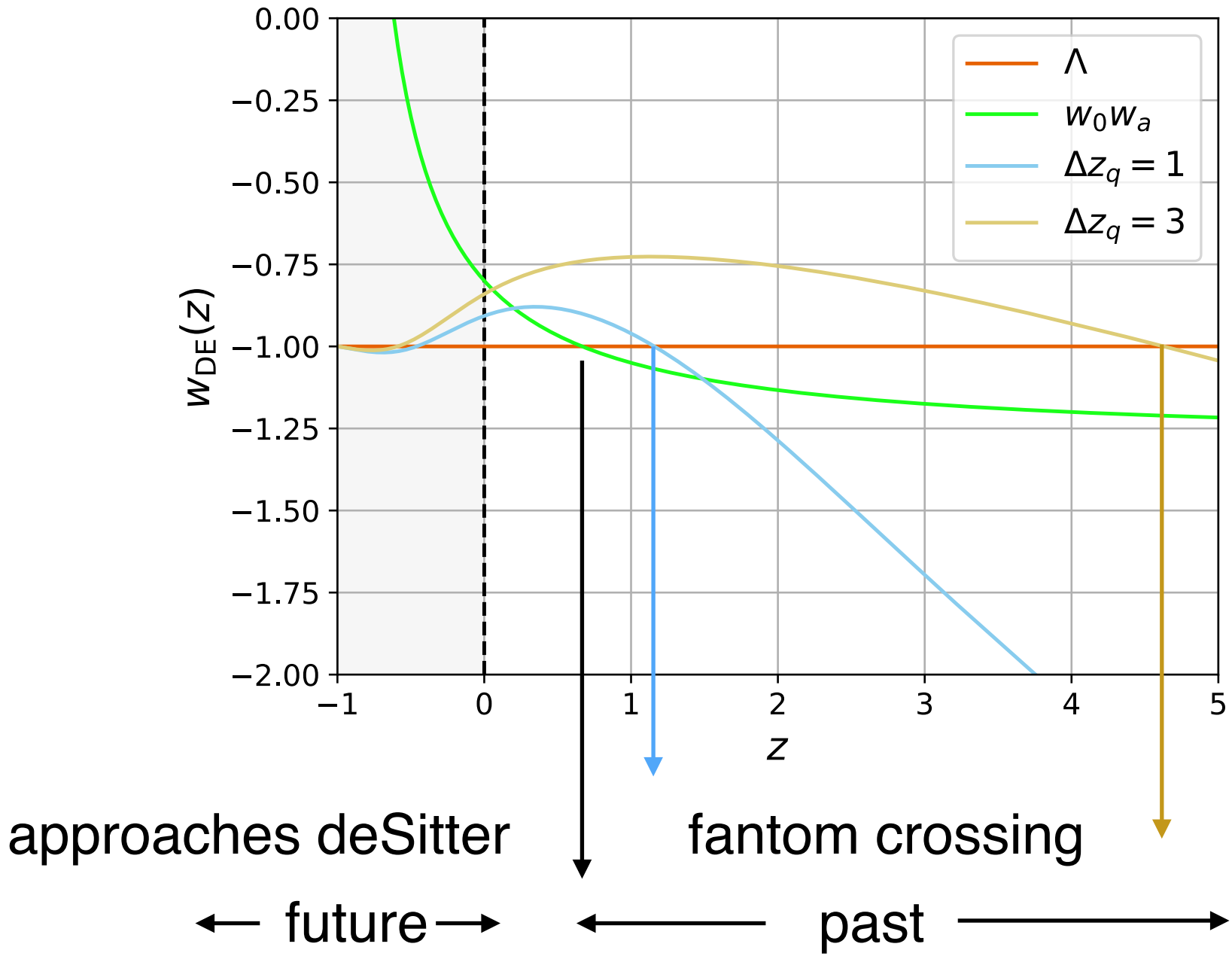
- The $\beta(t)$ is a **switch function** which describes transition z~1 when adiabatic approximation is marginally justified (strongly deviates from de Sitter).

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

- The EoS typically goes to phantom regime without violating any fundamental principles of QFT as this crossing is not related to dynamical fields

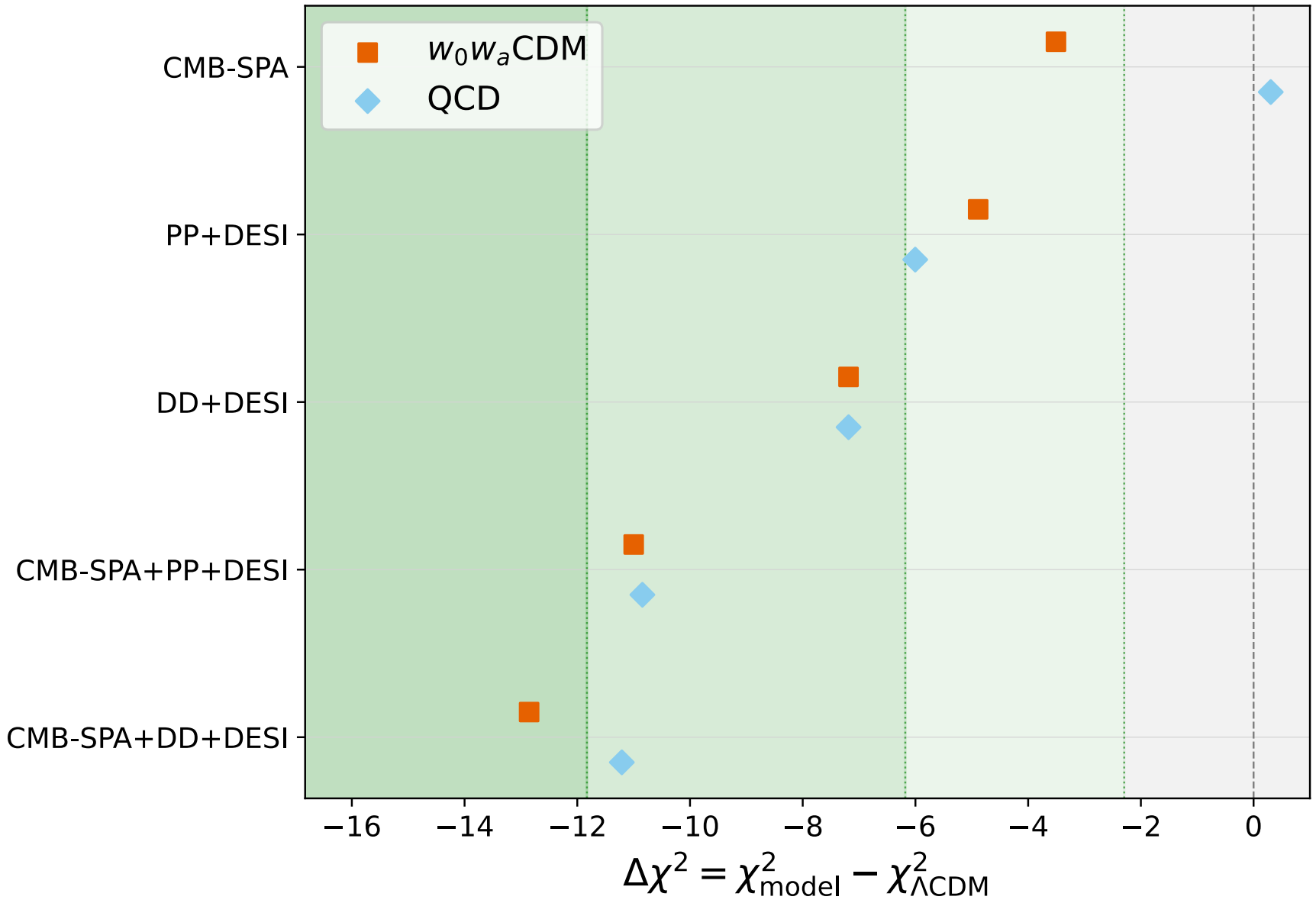

10^1
10^0
10^{-1}
$\frac{|\dot{H}(z)|}{\overline{H} \cdot H(z)}$
Λ
$\Delta z_q = 1$
$\Delta z_q = 3$
DE is not generated
DE is effectively generated
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
z
future
past

Equation of state $w_{\mathrm{DE}}(z)$ for typical parameters



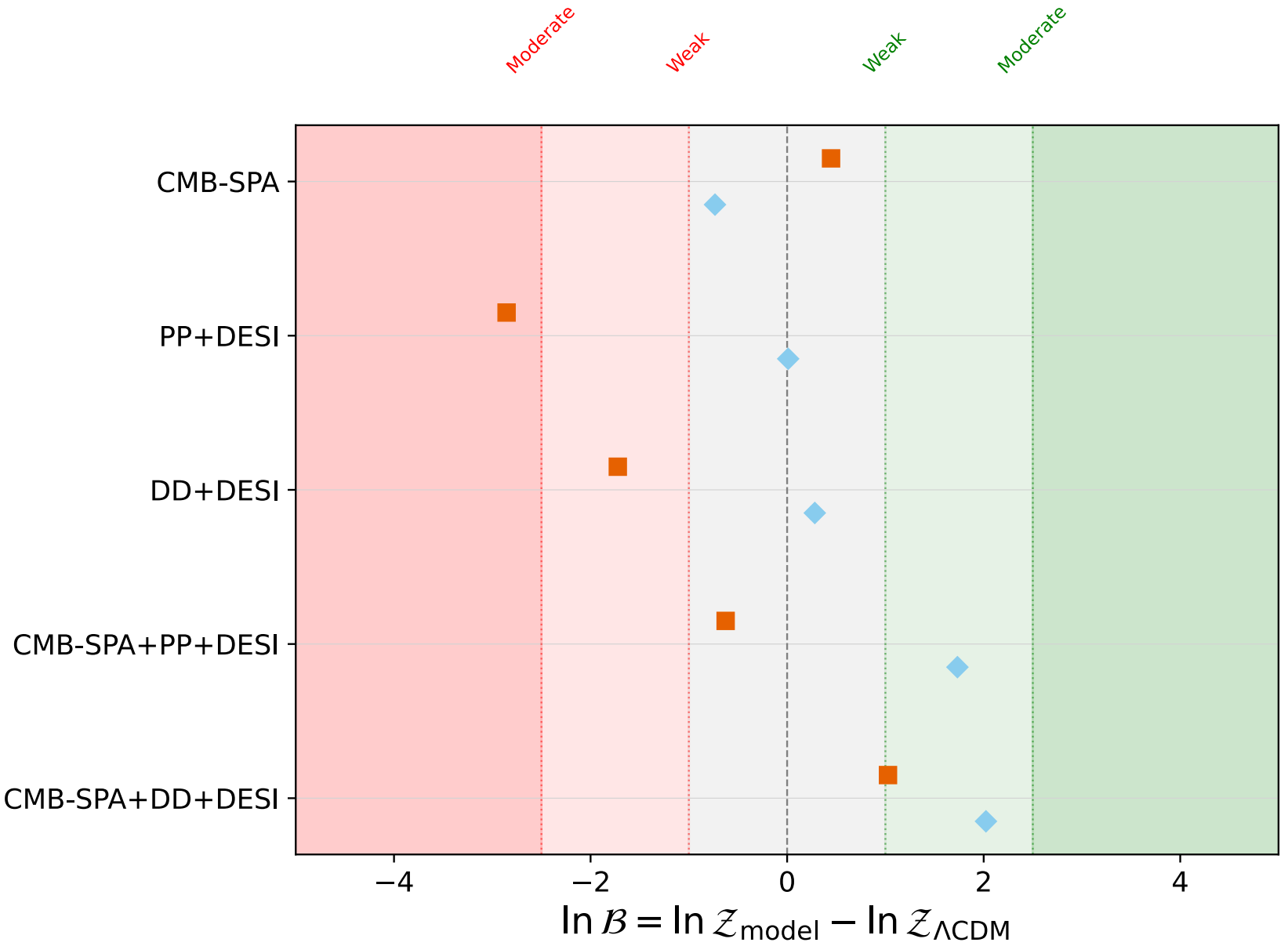
4. Cosmological datasets and analysis

- We use CMB data (Planck, ACT, SPT)-labeled "CMB"
- We use Baryon Acoustic Oscillations-DR2 "DESI"
- We use Supernovae-DES-Y5 Dovekie, Pantheon+ labeled as "PP" and "DD"
- We show the Bayesian evidence relative to ΛCDM
- We show χ^2 relative to ΛCDM
- We also show the effective QCD-DE EoS in comparison with conventional CPL $(w_0 w_a)$ parametrization

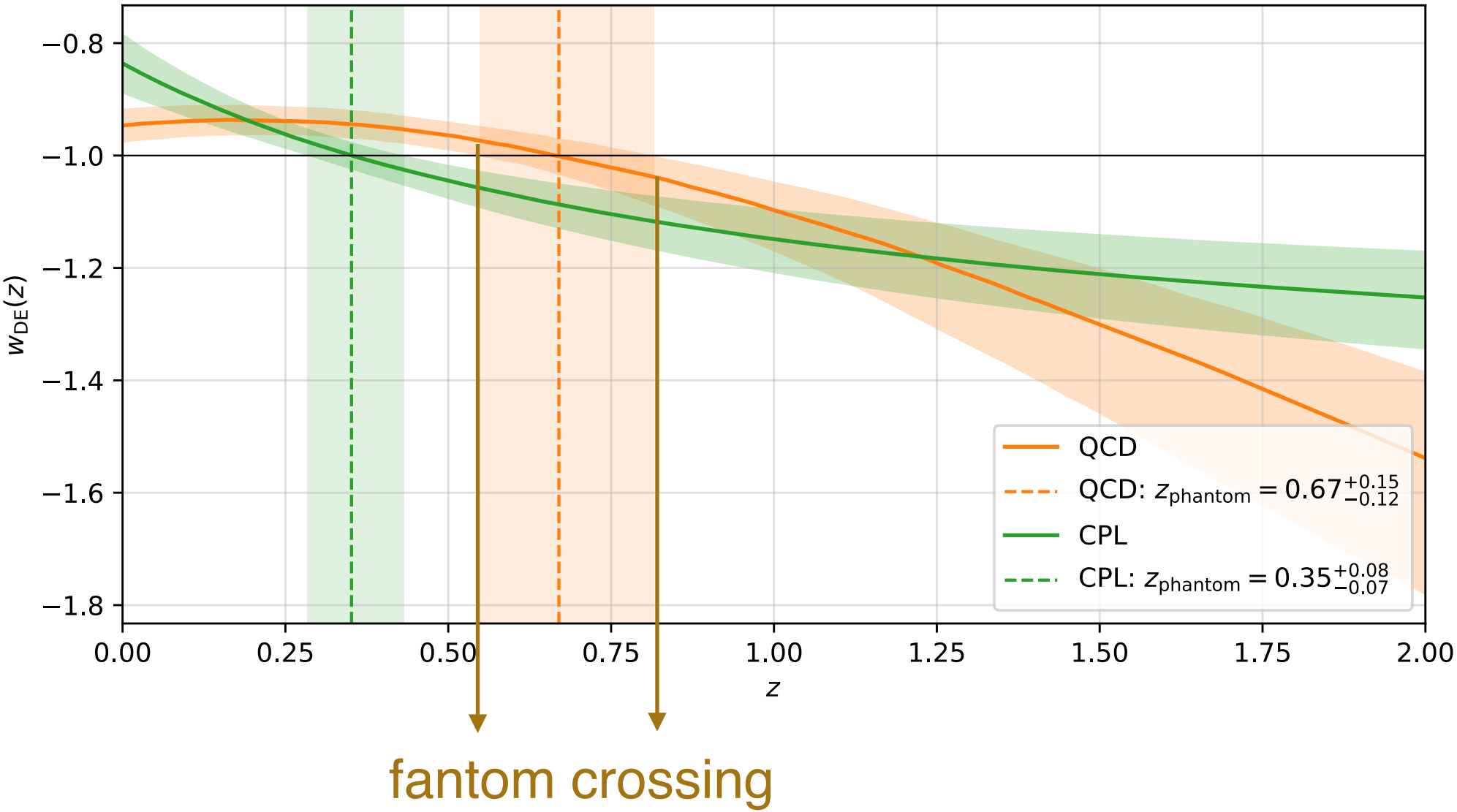


Plot of the difference in the MAP χ^2_{eff} with respect to the ΛCDM

$\Delta\chi^2 < 0$ indicates a preference for the alternative model



Plot of the Bayesian factors with respect to ΛCDM evidence. $\ln \mathcal{B} > 0$ indicates a preference for the alternative model. The QCD-DE does not fluctuate much for different data-sets



The effective DE EoS posterior functions for CPL $(w_0 w_a)$ and QCD-DE from the posteriors from CMB-SPA+DD+DESI

Conclusion (theoretical foundation)

- Lesson 1: There is a fundamentally new type of the vacuum energy in SM physics which cannot be expressed in terms of any local propagating field

- Lesson 2: We identify this new type of energy with cosmological vacuum dark energy (DE) we observe today (coined as QCD-DE)

- Lesson 3: A similar type of new vacuum energy could be realized during inflation (must be a different gauge theory with a different scale). It could be formulated in terms of non-dynamical auxiliary fields (axion, dilaton) which is a common tool in CM system such as topological insulator

- Lessons 4: The new type of vacuum energy can be tested in tabletop experiments (Casimir type exp)

Conclusion (practical consequences)

- Why is DE-QCD interesting and fundamentally different from any other DE models? It is based on SM physics. It provides a physical motivation for:

- 1. Why $\Omega_{\rm DE} \sim 1$ and why it started at z~1 without any fitting parameters, only $\Lambda_{\rm QCD}$ matters

- 2 There is no any new dynamical fields ϕ as DE in this framework is similar to auxiliary topological fields in CM systems (e.g. topological insulator).

- 3. The EoS crosses w=-1 without violating any fundamental principles of QFT. Only future observations have final verdict