technische universität
dortmund

Fitting the DESI BAO Data with Dark Energy Driven by the Cohen—Kaplan—Nelson Bound

Patrick Adolf

based on JCAP 08 (2024) 048 + Addendum JCAP 07 (2025) A01 and work in progress 2511.xxxxx
in collaboration with M. Hirsch (IFIC, Valencia), H. Päs, S. Krieg and M. Tabet (TU Dortmund)

04.11.2025

TeV Particle Astrophysics 2025, Valencia

Outline

Bekenstein Bound

- QFT: Box with size L and energy cutoff Λ_{UV}, entropy $S_{\text{QFT}} \sim \Lambda_{\text{UV}}^3 L^3$
- Black hole: Entropy $S_{\text{BH}} \equiv \pi L^2 M_{\text{P}}^2$
- For any given scale Λ_{UV}, S_{QFT} outruns S_{BH} by increasing L
  - → Over-count degrees of freedom 't Hooft '93, Susskind '94
- Take Bekenstein bound as fixed limit:
  - → $L^3 \Lambda_{\text{UV}}^3 \lesssim \pi L^2 M_{\text{P}}^2$
- New (IR) cutoff L
  - → L is not independent of Λ_{UV}, since it has to scale as $L \sim \Lambda_{\text{UV}}^{-3}$

A. Cohen, D. Kaplan, A. Nelson, PRL (1999), arxiv: hep-th/9803132

Cohen–Kaplan–Nelson Bound

- Problem: Bekenstein bound contains states with $R_S \gg L$
  - → Also low-energy states can turn into black holes
- Cohen, Kaplan, Nelson propose stronger constraint excluding black hole states

$$R_S \leq L$$
$$\rightarrow L \leq \frac{M_P}{\Lambda_{UV}^2}$$

- Always satisfies Bekenstein bound as $S_{max} \simeq S_{BH}^{3/4}$
- Possible energy range of EFTs from $\Lambda_{IR} = 1/L$ to Λ_{UV}

A. Cohen, D. Kaplan, A. Nelson, PRL (1999), arxiv: hep-th/9803132

Phenomenological Consequences

- CKN bound introduces momentum cutoffs:

$$\int_0^\infty \mathrm{d}l \frac{l^3}{(l^2+\Delta)^3} \to \int_{\frac{1}{L}}^{\Lambda_{\mathrm{UV}}} \mathrm{d}l \frac{l^3}{(l^2+\Delta)^3}$$

- Magnetic moment of the electron and muon Cohen, Kaplan, Nelson, PRL ’99, Cohen, Kaplan ’21, ...
  → Minimal expected correction to electron magnetic moment is just one order of magnitude smaller than experimental uncertainties
- Hierarchy problem and causal diamonds Kephart, Päs, MPLA ’22
- Radiative neutrino masses Adolf, Hirsch, Päs, JHEP ’23
- Cosmological constant problem Cohen, Kaplan, Nelson, PRL ’99, ...

Dark Energy Model from the CKN Bound

- Quantum corrections to the dark energy density scale as $\sim \Lambda_{\mathrm{UV}}^4$ Weinberg, RMP ’89
  - → Taking M_{P} as Λ_{UV} → many orders of magnitude larger than measurements
- CKN propose Hubble length as IR cutoff:

$$L = 1/H \rightarrow \rho_{\mathrm{DE}} \sim (10^{-3}\,\mathrm{eV})^4$$

  - → Matches dark energy density today
- Interesting consequence: $H = H(z) \rightarrow \rho_{\mathrm{DE}} = \rho_{\mathrm{DE}}(z)$
- DESI collaboration finds up to 3.9σ preference for time-dependent dark energy model over the ΛCDM, 4.2σ for DR2 DESI collab. ’24 + ’25

Late Universe Model

- 1-loop contribution to vacuum energy from QFT:

$$\Rightarrow \rho_{\mathrm{VED}}^{\text{1-loop}}(z) \simeq \int_{\Lambda_{\mathrm{IR}}}^{\Lambda_{\mathrm{UV}}} \mathrm{d}k \frac{4\pi k^2}{(2\pi)^3}\sqrt{k^2 + m^2} \simeq \frac{\Lambda_{\mathrm{UV}}^4}{16\pi^2} \simeq \nu \frac{H^2(z) M_{\mathrm{P}}^2}{16\pi^2}$$

- Adding this contribution Lorentz invariant to the energy-momentum tensor

$$T_{\mathrm{tot}}^{\mu\nu} = T_{\mathrm{classical}}^{\mu\nu} + \rho_{\mathrm{VED}}^{\text{1-loop}} g^{\mu\nu}$$

- Note: matter and dark energy densities are no longer conserved separately, otherwise:

$$\nabla_\mu T^{\mu\nu} = 0 \rightarrow \dot{\rho}_{\mathrm{VED}}^{1-loop} = 0$$

Late Universe Model

- Friedmann equation for the CKN parametrization:

$$H^2(t) = \frac{8\pi G}{3}(\rho_M(t) + \rho_{DE}(t))$$

- Conservation of total energy-momentum tensor $\nabla_\mu T^\mu_0 = 0$ with EoS of matter $\omega_M = 0$ leads to

$$\dot{\rho}_{DE}(t) + \dot{\rho}_M(t) = -3H(t)\rho_M(t)$$

- Solution to the above equations:

$$\Omega_M(z) = \Omega_M^0 (1+z)^{3-\frac{v}{2\pi}} , \qquad \Omega_{DE}(z) = \Omega_{DE}^0 + \Omega_M^0 \frac{v}{6\pi - v}\left[(1+z)^{3-\frac{v}{2\pi}} - 1\right]$$

P. Adolf, M. Hirsch, S. Krieg, H. Päs, M. Tabet, JCAP ’24

Data and Methodology

Late Universe Data:

- Baryonic acoustic oscillations (BAO) from DESI DESI collab. '24 + '25
  - Extracted from galaxy, quasar and Lyman-α forest tracers
- Supernova distance datasets from DES-SN5YR (DESY5) DES collab., '24 and Pantheon+ Brout et al., '22
  - Typ Ia supernovae as standard candles
- Model-independent Hubble parameter measurements Favale et al., '24
  - Based on cosmic chronometers

Methodology:

- Using X^2-statistics:

$$\chi^2 = \left(\vec{O}_{\text{th}}(\xi) - \vec{O}_{\text{exp}}\right)^T C^{-1} \left(\vec{O}_{\text{th}}(\xi) - \vec{O}_{\text{exp}}\right)$$

Results

Model / Datasets	H_0 /(km/s/Mpc)	Ω_M^0	r_d /Mpc	ν	χ^2_{min} /DOF
CKN					
+ DESY5	68.83 ± 2.35	0.352 ± 0.009	144.27 ± 4.85	–	1674/1871
+ Pantheon+	69.09 ± 2.36	0.347 ± 0.009	144.23 ± 4.85	–	1437/1632
νCKN					
+ DESY5	68.90 ± 2.38	0.348 ± 0.018	144.26 ± 4.85	0.92 ± 0.35	1674/1870
+ Pantheon+	69.46 ± 2.40	0.330 ± 0.018	144.21 ± 4.85	0.64 ± 0.36	1436/1631
ΛCDM					
+ DESY5	69.77 ± 2.38	0.309 ± 0.008	144.28 ± 4.85	–	1681/1871
+ Pantheon+	70.10 ± 2.39	0.303 ± 0.008	144.21 ± 4.85	–	1439/1632

P. Adolf, M. Hirsch, S. Krieg, H. Päs, M. Tabet, JCAP ’25

Results

$$\mathrm{AIC} = \chi^2_{\mathrm{min}} + 2k$$

Models	$\Delta\chi^2_{\mathrm{DESY5}}$	$\Delta\mathrm{AIC}_{\mathrm{DESY5}}$	$\Delta\chi^2_{\mathrm{Pantheon+}}$	$\Delta\mathrm{AIC}_{\mathrm{Pantheon+}}$
CKN with				
ΛCDM	−6.90	−6.90	−2.05	−2.05
ωCDM	3.14	1.14	2.26	0.26
$\omega_0\omega_a$CDM	5.74	1.74	2.43	−1.57
νCKN with				
ΛCDM	−6.94	−4.94	−3.07	−1.07
ωCDM	3.09	3.09	1.24	1.24
$\omega_0\omega_a$CDM	5.69	3.69	1.41	−0.59

P. Adolf, M. Hirsch, S. Krieg, H. Päs, M. Tabet, JCAP ’25

Early Universe Model

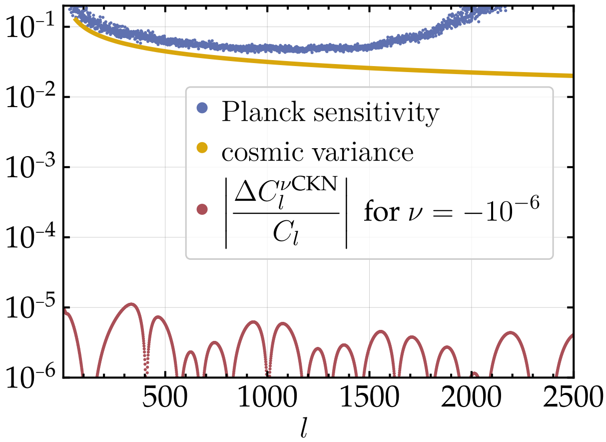
- Some assumptions made for the late-universe model do not hold in early universe
  → Radiation cannot be neglected
- Additional model assumptions needed; as a minimal model:
  1. DE–DM interaction with source term $Q^{\mu}_{\mathrm{DE}} = \left(\bar{Q} + \delta Q\right) u^{\mu}$ and $\bar{Q} = \dot{\bar{\rho}}_{\mathrm{DE}} = \nu \frac{M^2_{\mathrm{Pl}} \dot{H} H}{8\pi^2}$
  2. $\delta\rho_{\mathrm{DE}} = 0$

→ $\rho_{\mathrm{DM}}(a) \sim \rho_{\mathrm{DM},0} a^{-3} - \frac{2}{3\pi} \nu \rho_{\mathrm{R},0} a^{-4}$

- Initial-condition analysis reveals that model suffers from instabilities when a^{-4} term is the leading order contribution → strict bound: for $a_{\mathrm{ini}} \sim 10^{-10}$ we obtain $|\nu| \lesssim 10^{-6}$

  in preparation, arXiv:2511.xxxxx

Early Universe Model



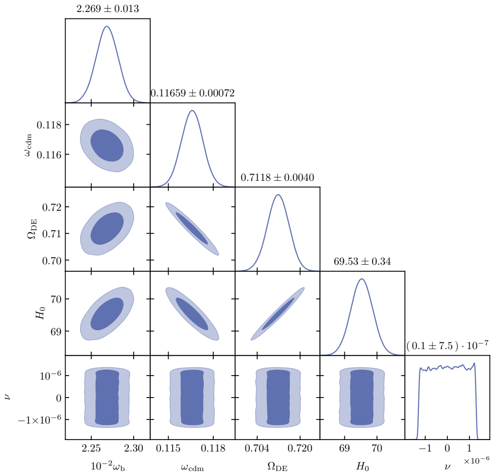
Sensitivity Estimation

- Relative difference to ΛCDM model is below Planck sensitivity
- Limited throught cosmic variance

in preparation, arXiv:2511.xxxxx

sensitivity taken from Planck '19

Early Universe Model



Numerical Verification

- MCMC analysis using `CLASS` within `MontePython` with late universe data + CMB (Planck '18) and Weak Lensing (KiDS '20)
- Result verifies sensitivity analysis

in preparation, arXiv:2511.xxxxx

Summary

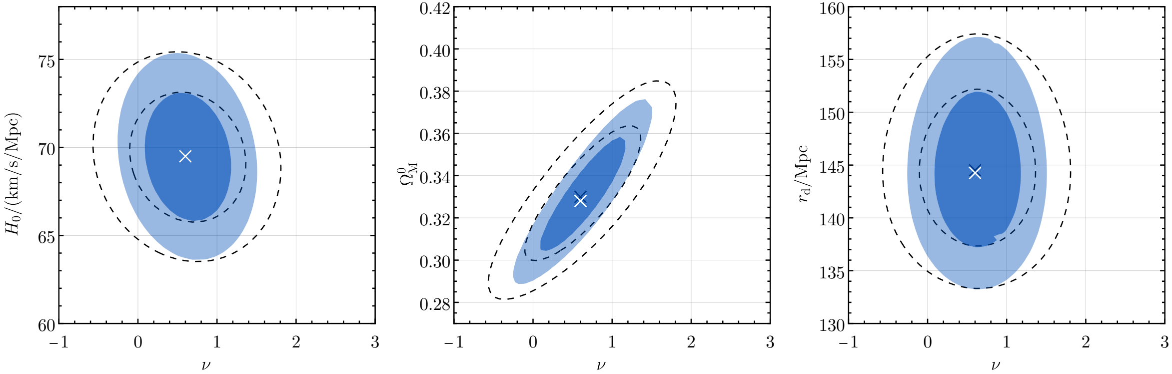
Summary

- CKN bound imposes momentum cutoffs relevant for loop calculations
- Using the Hubble length as IR cutoff a time-dependent dark energy model can be constructed
- Performing a global analysis of the late-universe model with DESI BAO, Supernova and Hubble measurements shows a preference over the ΛCDM model of up to 2.6σ and can compete with alternative, time-dependent dark energy models
  - Future projection indicates that new data can soon be able to distinguish between different models
- Current data is not able to distinguish between ΛCDM and the early-universe model
  - Some model assumptions can be changed to avoid the strict theoretical bound on ν

technische universität
dortmund

Backup

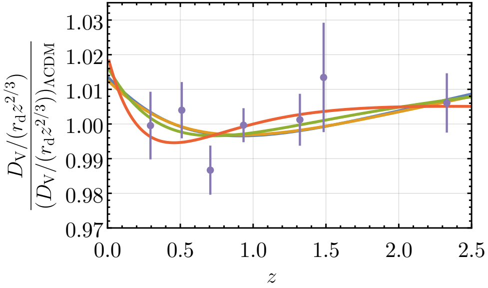
Results: Correlations νCKN model for Pantheon+ data

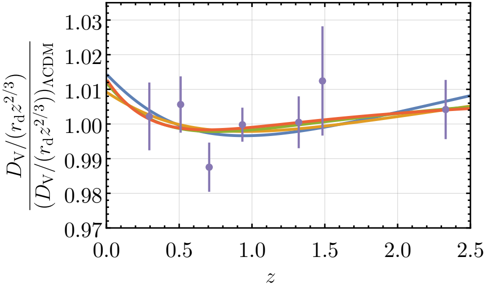


P. Adolf, M. Hirsch, S. Krieg, H. Päs, M. Tabet, arXiv:2504.15332

Results: Comparison to DESI measurements

- Angle-averaged distance quantity at best-fit point together with DESI measurement (left: DESY5; right: Pantheon+)





P. Adolf, M. Hirsch, S. Krieg, H. Päs, M. Tabet, arXiv:2504.15332