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

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Outline

Bekenstein Bound

- QFT: Box with size L and energy cutoff Λ_{UV}, entropy $S_{\mathrm{QFT}} \sim \Lambda_{\mathrm{UV}}^3 L^3$
- Black hole: Entropy $S_{\mathrm{BH}} \equiv \pi L^2 M_{\mathrm{P}}^2$
- For any fixed energy 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:
  - → $L^3 \Lambda_{\mathrm{UV}}^3 \lesssim \pi L^2 M_{\mathrm{P}}^2$
- New (IR) cutoff L
  - → L is not independent of Λ_{UV}, since it has to scale as $L \sim \Lambda_{\mathrm{UV}}^{-3}$

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}

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Applications in the Literature

- 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, Bramante, Gould, PRD '20, ...
  - → 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 $\sim \Lambda_{UV}^4$ Weinberg, RMP '89
  - → taking M_P as Λ_{UV} → many orders of magnitude larger than measurements
- CKN propose Hubble length as IR cutoff:

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

  - → matches dark energy density today
- Interesting consequence: $H = H(z) \rightarrow \rho_{DE} = \rho_{DE}(z)$
- 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

Dark Energy Model from the CKN Bound

- 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:

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

Dark Energy Model from the CKN Bound

- Friedmann equation for the CKN parametrization:

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

- Conservation of 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:

$$H^2(z) = H_0^2\left(\Omega_M(z) + \Omega_{DE}(z)\right), \qquad \Omega_i = \rho_i/\rho_{crit,0}, \qquad \rho_{crit,0} = 3H_0^2/(8\pi G),$$

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

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
***ν*CKN**					
+ 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

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Results

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

Models	$\Delta\chi^2_{\text{DESY5}}$	$\Delta\text{AIC}_{\text{DESY5}}$	$\Delta\chi^2_{\text{Pantheon+}}$	$\Delta\text{AIC}_{\text{Pantheon+}}$
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

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Comparing DR1 with DR2

Models	$\Delta\chi^2_{\mathrm{DR2-DR1}}$	
	DESY5	Pantheon+
CKN	−2.85	−2.84
νCKN	−2.91	−3.76
ΛCDM	−0.52	−1.93
ωCDM	−3.72	−3.59
$\omega_0\omega_a$CDM	−3.29	−3.13

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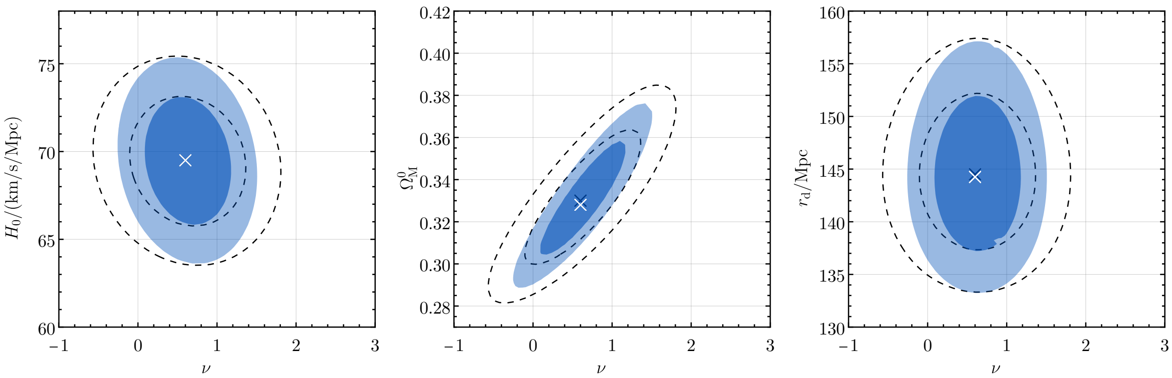
Summary

- 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 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 shows that new data will soon be able to distinguish between different models

Stay Tuned!

Results: Correlations νCKN model for Pantheon+ data



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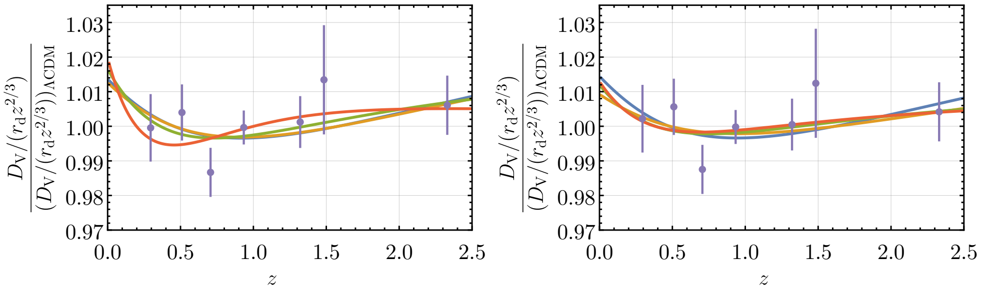
Results: Comparison to DESI measurements

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



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