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Holographic Dark Energy in Light of Recent Data

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PASCOC, Sheffield, UK

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 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:
  - → $L^3 \Lambda_{\mathrm{UV}}^3 \lesssim \pi L^2 M_{\mathrm{P}}^2$
- 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}

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

Dark Energy 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

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

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

and assuming an interaction between matter and DE, yields

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

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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 χ^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

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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

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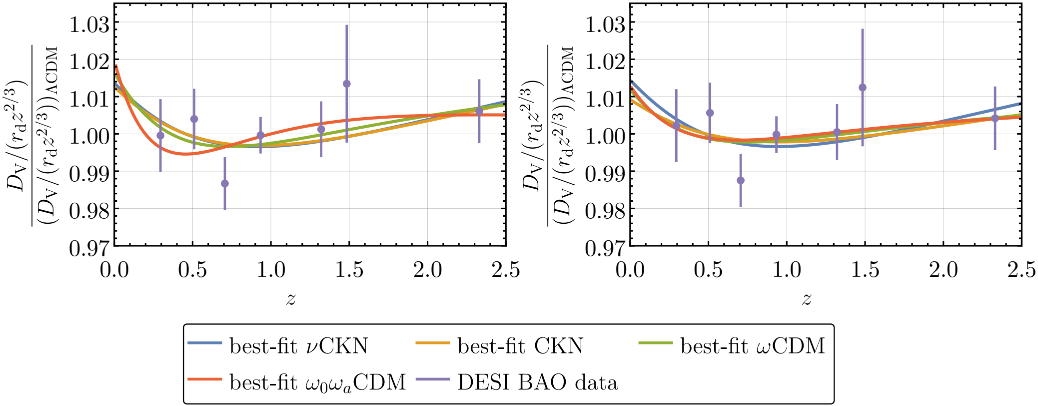
Results: Comparison to DESI measurements



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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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Extending to Early Universe

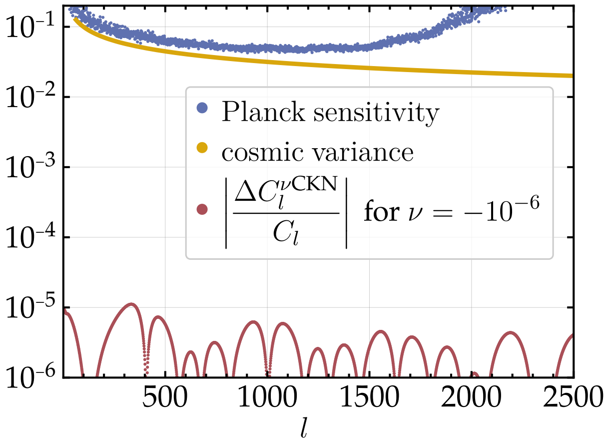
- Some assumptions made for the late-universe model do not hold in early universe
  - → Radiation cannot be neglected
- Additional model assumptions needed; as a minimal model:
  1. DE–DM interaction with source term $Q^{\mu}_{\mathrm{DE}} = \left(\bar{Q} + \delta Q\right) u^{\mu}$ and $\bar{Q} = \dot{\bar{\rho}}_{\mathrm{DE}} = \nu \frac{M_{\mathrm{Pl}}^2 \dot{H} H}{8\pi^2}$
  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:2607.xxxxx

Early Universe Model



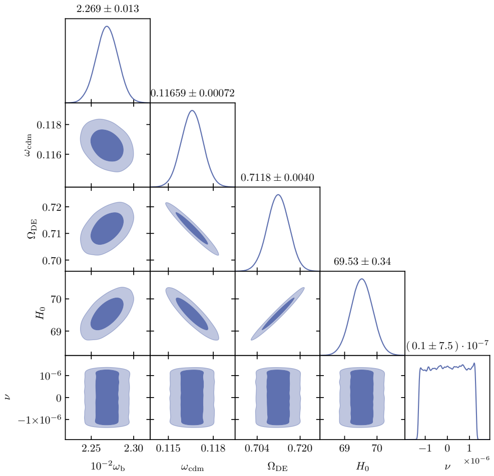
Sensitivity Estimation

- 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:2607.xxxxx

What now ?

Extend the minimal Model

- Allow for additional interaction
  - Dark radiation Berghaus et al., PRD'21
  - Fluid contribution of dark energy Grande et al., JCAP'06 + '07, Gómez-Valent, Sóla Peracaula, PLB'25

in preparation, arXiv:2607.xxxxx

Modify the minimal Model

- Time-dependent $\nu(z)$
  - Phase transition
    Kodama, Sasaki, PTPS'84, Salvatelli et al., PRL'14
  - Phenomenological parametrization
    Rezaei, Sóla Peracaula, EPJC'22
- Time-dependent EoS $\omega(z)$ Rezaei, Sóla Peracaula, EPJC'22
- Curved spacetime calculation
  Sóla Peracaula et al., Universe'23

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

Future Projection

- DESI results only from Year-1 measurements, will run in total 5 years
- New experiments are running...
  - Euclid expects improvement on uncertainties on cosmological model parameters at least by a factor of 4 Euclid collab., '24
- ... and planned
  - Large Synoptic Survey Telescope (LSST), ...

→ More data will lead to smaller uncertainties

Future Projection

Models	DESI-5Y		Euclid-Unc		DESI-5Y + Euclid-Unc	
	$\Delta\chi^2_{\mathrm{DESY5}}$	$\Delta\chi^2_{\mathrm{Pantheon+}}$	$\Delta\chi^2_{\mathrm{DESY5}}$	$\Delta\chi^2_{\mathrm{Pantheon+}}$	$\Delta\chi^2_{\mathrm{DESY5}}$	$\Delta\chi^2_{\mathrm{Pantheon+}}$
CKN with						
ΛCDM	−1.8	3.9	−16.5	−9.4	−42.4	−17.4
ωCDM	7.1	7.4	14.9	1.5	20.4	7.1
$\omega_0\omega_a$CDM	18.4	11.1	47.0	1.5	45.4	8.1
νCKN with						
ΛCDM	−3.7(−1.9σ)	−1.0(−1.0σ)	−18.1(−4.3σ)	−9.4(−3.1σ)	−43.2(−6.6σ)	−19.0(−4.4σ)
ωCDM	5.1	2.5	13.3	1.5	19.6	5.5
$\omega_0\omega_a$CDM	16.4	6.2	45.4	1.5	44.6	6.5

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