Dark Energy Driven by the Cohen–Kaplan–Nelson Bound

[arXiv:2406.09964] and [arXiv:2504.15332]

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Outline

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2. Evolving Dark Energy
3. Analysis and Results
4. Summary and Outlook

Motivation

Blackhole Thermodynamics

A system with entropy S falls into a black hole
$\Rightarrow$ violation of 2nd law of thermodynamics, i.e. $\mathrm{d}S_{\text{universe}} < 0$

<u>Idea:</u>
Introduce the concept of a black hole entropy S_{BH} and generalise the 2nd law of thermodynamics, such that: [Bekenstein, '73]

The sum of the black hole entropy and the entropy exterior to the black hole never decreases.

$$\boxed{\Rightarrow S_{\text{BH}} \propto A}$$

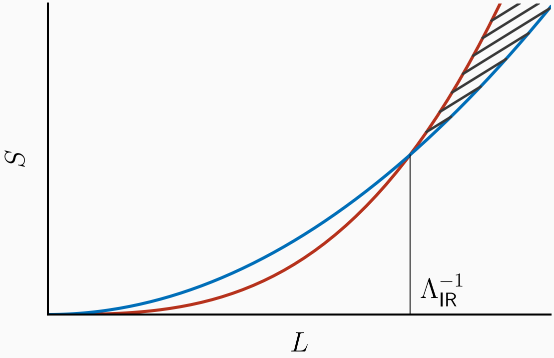
Bekenstein Bound

QFT

$S_{\text{QFT}} \propto \Lambda_{\text{UV}}^3 L^3$

Black Hole

$S_{\text{BH}} = \pi L^2 M_{\text{P}}^2$



$$\Lambda_{\text{UV}}^3 L^3 \lesssim \pi L^2 M_{\text{P}}^2 \quad \Rightarrow \quad \Lambda_{\text{IR}} \sim \Lambda_{\text{UV}}^3$$

['t Hooft, '93; Susskind, '94]

Cohen–Kaplan–Nelson Bound

Problem: Bekenstein bound contains states with $R_S \gg L_{\mathrm{IR}}$

$\rightarrow$ Low-energy states can turn into black hole

Cohen, Kaplan and Nelson propose stronger constraint excluding black hole states:

$$L_{\mathrm{IR}} \geq R_S = \frac{M}{M_{\mathrm{P}}^2} = \frac{\rho V}{M_{\mathrm{P}}^2} = \frac{\Lambda_{\mathrm{UV}}^4 L_{\mathrm{IR}}^3}{M_{\mathrm{P}}^2}$$

$$\boxed{\Rightarrow \quad \Lambda_{\mathrm{UV}}^2 \leq \frac{M_{\mathrm{P}}}{L_{\mathrm{IR}}}}$$

[Cohen, Kaplan, Nelson, '98]

Cohen–Kaplan–Nelson Bound

$(g-2)_{e,\mu}$

[Cohen, Kaplan, Nelson, '98]

hierarchy puzzle

[Kephart et al., '22]

$\int_0^\infty \to \int_{\Lambda_{\rm IR}}^{\Lambda_{\rm UV}}$

with $\Lambda_{\rm UV}^2 \leq M_{\rm P}\Lambda_{\rm IR}$

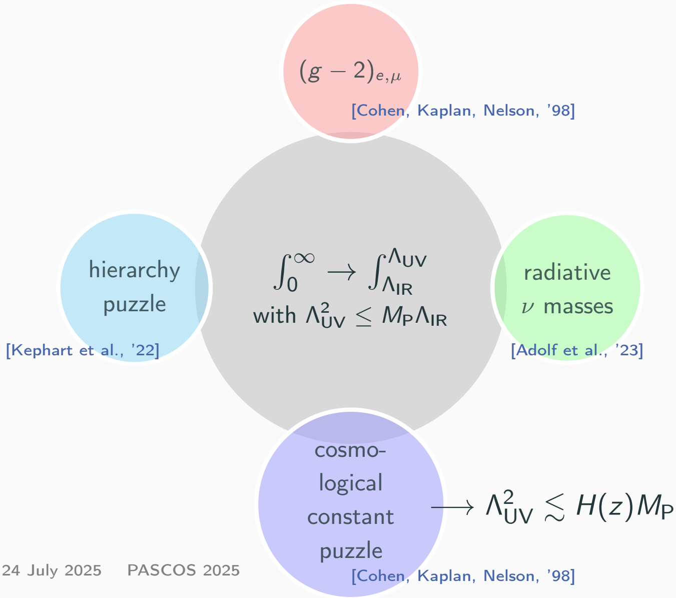
radiative ν masses

[Adolf et al., '23]

cosmo-logical constant puzzle $\longrightarrow \Lambda_{\rm UV}^2 \lesssim H_0 M_{\rm P}$

[Cohen, Kaplan, Nelson, '98]

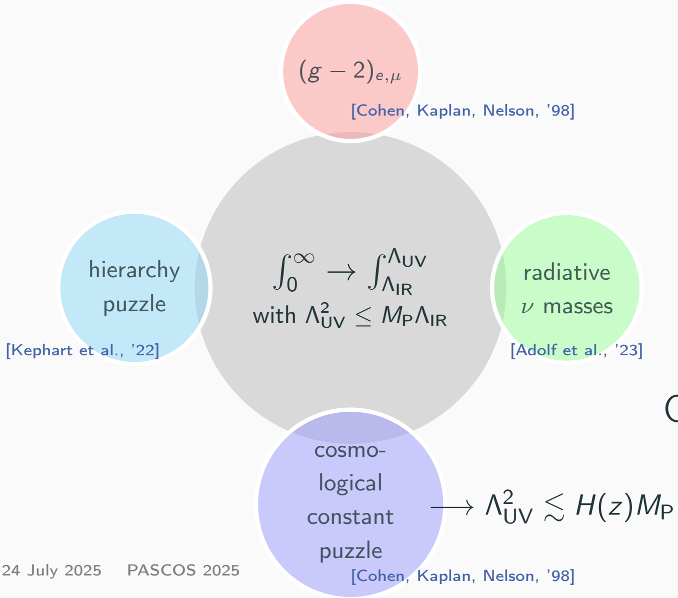
Cohen–Kaplan–Nelson Bound



Experiment

Recent measurements from the Dark Energy Spectroscopic Instrument (DESI) prefer time-dependent dark energy with up to $4.2\,\sigma$

Cohen–Kaplan–Nelson Bound



Experiment

Recent measurements from the Dark Energy Spectroscopic Instrument (DESI) prefer time-dependent dark energy with up to $4.2\,\sigma$

Cohen–Kaplan–Nelson bound?

Evolving Dark Energy

Evolving Dark Energy

$$\text{CKN-Bound: } \Lambda_{\text{UV}} \lesssim H^2(z) M_{\text{P}}^2$$

$$\rho_{\text{VED}}^{\text{1-loop}}(z) \simeq \frac{\Lambda_{\text{UV}}^4}{16\pi^2} \simeq \nu \frac{M_{\text{P}}^2 H^2(z)}{16\pi^2} \tag{1}$$

this yields:

$$T_{\text{tot}}^{\mu\nu} = T_{\text{classical}}^{\mu\nu} + \rho_{\text{VED}}^{\text{1-loop}} g^{\mu\nu} \quad \text{with} \quad \nabla_\mu T_{\text{tot}}^{\mu\nu} = 0 \tag{2}$$

$$H^2(t) = \frac{8\pi G}{3} \left(\rho_{\text{M}}(t) + \rho_{\text{DE}}(t)\right) \tag{3}$$

Evolving Dark Energy

CKN-Bound: $\Lambda_{\rm UV} \lesssim H^2(z) M_{\rm P}^2$

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$$\boxed{\begin{aligned} T^{\mu\nu}_{\rm tot} &= T^{\mu\nu}_{\rm classical} + \rho_{\rm VED}^{\text{1-loop}} g^{\mu\nu} \quad \text{with} \quad \nabla_\mu T^{\mu\nu}_{\rm tot} = 0 && (2) \\ H^2(t) &= \frac{8\pi G}{3}\left(\rho_{\rm M}(t) + \rho_{\rm DE}(t)\right) && (3) \end{aligned}}$$

$$\left.\begin{aligned} \rho_{\rm M} &\overset{(2)}{\sim} a^{-3+\frac{\nu}{2\pi}} \\ \rho_{\rm M} &\overset{(1),(3)}{\sim} H^2 \end{aligned}\right\} \Rightarrow \rho_{\rm DE} \overset{(1)}{\sim} \Omega_\Lambda^0 + \Omega_{\rm M}^0 \frac{\nu}{6\pi - \nu}\left[a^{-3+\frac{\nu}{2\pi}} - 1\right] \tag{4}$$

Analysis and Results

Analysis: Experimental Input and Statistical Procedure

DESI baryonic acoustic oscilations (BAO) DR1 and DR2 combined with late universe constraints:

[DESI, '24] and [DESI, '25]

- Supernova distance datasets
  - DES-SN5YR (DESY5) [DES, '24]
  - Pantheon+ [Brout et al., '22]
- Model-independent Hubble parameter measurements [Favale et al., '24]

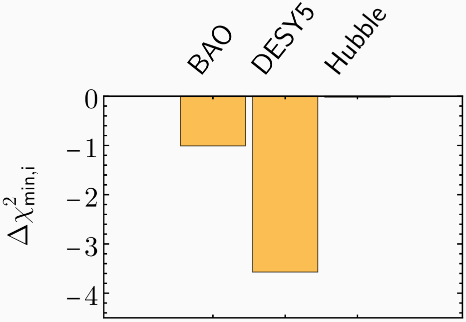
using χ^2-statistics:

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

Results: CKN $\leftrightarrow$ ΛCDM for DESI DR1

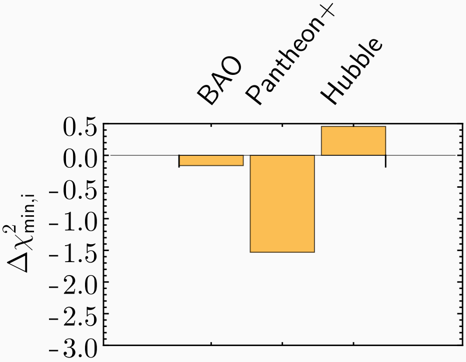
$$\chi^{2,\mathrm{CKN}}_{\mathrm{min}}/\mathrm{dof} = 1677/1871 \approx 0.90$$

$$\Delta\chi^2_{\mathrm{min}} = -4.6\,(2.1\sigma)$$



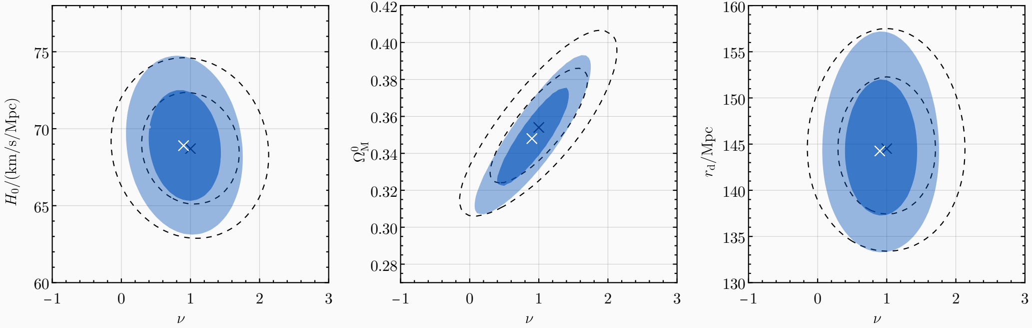
$$\chi^{2,\mathrm{CKN}}_{\mathrm{min}}/\mathrm{dof} = 1440/1632 \approx 0.88$$

$$\Delta\chi^2_{\mathrm{min}} = -1.1\,(1.1\sigma)$$

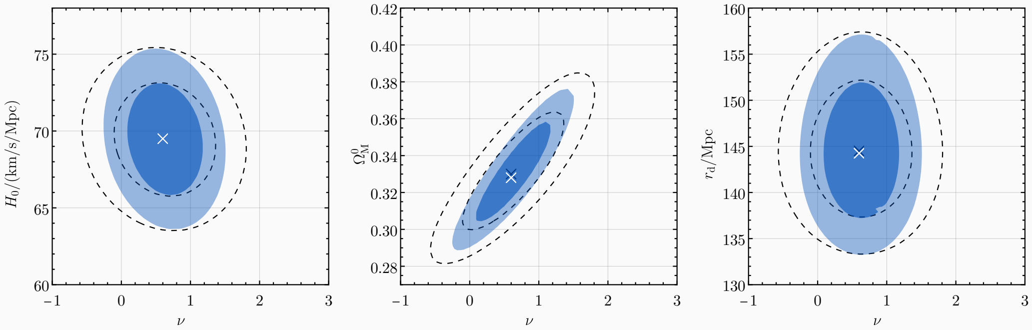


$$\Delta\chi^2_{\mathrm{min}} = \chi^{2,\mathrm{CKN}}_{\mathrm{min}} - \chi^{2,\Lambda\mathrm{CDM}}_{\mathrm{min}}$$

Results: Correlations for DESY5



Results: Correlations for Pantheon+



Results: Future Projection

- DESI running for another two years
- Euclid started measurements last year:
  - expected improvement on the uncertainties of cosmological model parameters up to factor 10
- Planned experiments: Large Synoptic Survey Telescope, ...

$\rightarrow$ Significantly better statistics, smaller uncertainties

$\rightarrow$ more significant discrimination between various cosmological models

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Models	DESI-5Y		Euclid		DESI-5Y + Euclid	
	Σ_{DESY5}	$\Sigma_{\mathrm{Pantheon+}}$	Σ_{DESY5}	$\Sigma_{\mathrm{Pantheon+}}$	Σ_{DESY5}	$\Sigma_{\mathrm{Pantheon+}}$
νCKN with						
ΛCDM	-1.9σ	-1.0σ	-4.3σ	-3.1σ	-6.6σ	-4.4σ
$\omega_0\omega_a$CDM	4.0σ	2.5σ	6.7σ	1.2σ	6.7σ	2.5σ

Summary and Outlook

Summary and Outlook

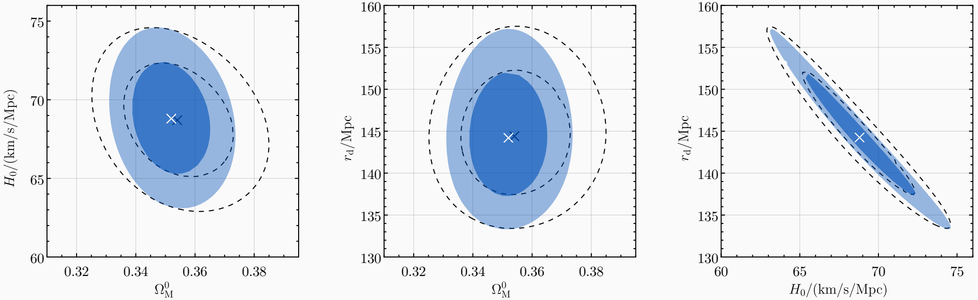
- Performed a global analysis of the CKN model taking into account the recent DESI BAO data DR2, supernova and Hubble data:
  - Preference over ΛCDM up to 2.6σ
  - Competes with other models of time-dependent dark energy
- Rough estimation of near future projections shows that one will already be able to distinguish between different models with the upcoming data releases

Outlook

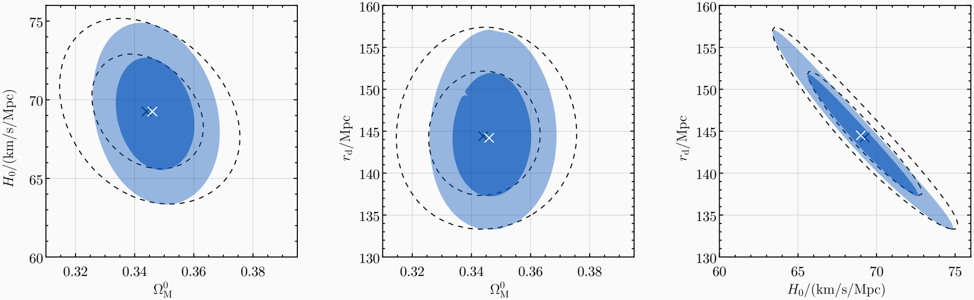
- Incorporate data from early universe, e.g. power spectra and lensing information from CMB measurements and big bang nucleosynthesis data

Backup

Results: Correlations II with DESY5



Results: Correlations II with Pantheon+



Results: Best-Fits for DESI BAO DR1

Model/Datasets	H_0/(km/s/Mpc)	Ω_M^0	r_d/Mpc	ν	χ^2_{min}/DOF
CKN					
+ DESY5	68.69 ± 2.39	0.354 ± 0.012	144.54 ± 4.89	–	1677/1871
+ Pantheon+	69.24 ± 2.41	0.344 ± 0.012	144.38 ± 4.89	–	1440/1632
νCKN					
+ DESY5	68.66 ± 2.38	0.354 ± 0.021	144.60 ± 4.87	1.00 ± 0.46	1677/1870
+ Pantheon+	67.94 ± 2.51	0.329 ± 0.021	147.76 ± 5.28	0.60 ± 0.49	1440/1631

Results: Best-Fits for DESI BAO DR2

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

Results: Significances for DESI BAO DR1

Models	$\Delta\chi^2_{\mathrm{DESY5}}$	Significance	ΔAIC	$\Delta\chi^2_{\mathrm{Pantheon+}}$	Significance	ΔAIC
CKN with						
ΛCDM	-4.6	–	-4.6	-1.1	–	-1.1
ωCDM	2.3	1.5σ	0.3	1.5	1.2σ	-0.2
$\omega_0\omega_a$CDM	5.3	1.8σ	1.3	2.1	1.0σ	-1.9
νCKN with						
ΛCDM	-4.6	-2.1σ	-2.5	-1.2	-1.1σ	0.8
ωCDM	2.3	–	2.3	1.4	–	1.4
$\omega_0\omega_a$CDM	5.3	2.3σ	3.4	2.0	1.4σ	0.0

Results: Significances for DESI BAO DR2

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

Results: Difference between the significances for DESI BAO DR1 and DR2

Models	$\Delta\chi^2_{\text{DR2}-\text{DR1}}$		$(\Delta\chi^2)^{\Lambda\text{CDM}}_{\text{DR2}} - (\Delta\chi^2)^{\Lambda\text{CDM}}_{\text{DR1}}$	
	DESY5	Pantheon+	DESY5	Pantheon+
CKN	-2.85	-2.84	-2.34	-0.90
νCKN	-2.91	-3.76	-2.39	-1.83
ΛCDM	-0.52	-1.93	–	–
ωCDM	-3.72	-3.59	-3.20	-1.66
$\omega_0\omega_a$CDM	-3.29	-3.13	-2.77	-1.20

Results: Best-Fits Alternative Models for DESI BAO DR1

Model /Datasets	H_0 in km/s/Mpc	Ω_M^0	r_d in Mpc	ω or ω_0	ω_a	χ^2_{min}/DOF
ΛCDM						
+ DESY5	69.15 ± 2.41	0.320 ± 0.011	144.55 ± 4.90	–	–	1681/1871
+ Pantheon+	69.79 ± 2.44	0.308 ± 0.011	144.41 ± 4.89	–	–	1441/1632
ωCDM						
+ DESY5	68.71 ± 2.39	0.296 ± 0.014	144.27 ± 4.89	-0.874 ± 0.046	–	1674/1870
+ Pantheon+	69.43 ± 2.43	0.296 ± 0.014	144.26 ± 4.88	-0.921 ± 0.048	–	1438/1631
$\omega_0\omega_a$CDM						
+ DESY5	66.93 ± 2.40	0.334 ± 0.016	147.57 ± 5.17	-0.716 ± 0.093	-1.36 ± 0.65	1671/1869
+ Pantheon+	69.65 ± 2.43	0.312 ± 0.018	143.79 ± 4.86	-0.873 ± 0.076	-0.51 ± 0.58	1438/1630

Results: Best-Fits Alternative Models for DESI BAO DR2

Model /Datasets	H_0 in km/s/Mpc	Ω_M^0	r_d in Mpc	ω or ω_0	ω_a	χ^2_{min}/DOF
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
ωCDM						
+ DESY5	68.71 ± 2.37	0.297 ± 0.009	144.11 ± 4.85	-0.88 ± 0.04	–	1670/1870
+ Pantheon+	69.32 ± 2.40	0.297 ± 0.008	144.10 ± 4.85	-0.92 ± 0.04	–	1435/1631
$\omega_0\omega_a$CDM						
+ DESY5	68.69 ± 2.50	0.321 ± 0.013	143.70 ± 5.01	-0.78 ± 0.07	-0.77 ± 0.39	1668/1869
+ Pantheon+	69.49 ± 2.28	0.302 ± 0.017	143.60 ± 4.58	-0.91 ± 0.06	-0.11 ± 0.43	1434/1630

Results: Future Projections

Models	DESI-5Y		Euclid		DESI-5Y + Euclid	
	$\Delta\chi^2_{\mathrm{DESY5}}$	$\Delta\chi^2_{\mathrm{Pantheon+}}$	$\Delta\chi^2_{\mathrm{DESY5}}$	$\Delta\chi^2_{\mathrm{Pantheon+}}$	$\Delta\chi^2_{\mathrm{DESY5}}$	$\Delta\chi^2_{\mathrm{Pantheon+}}$
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	-1.0	-18.1	-9.4	-43.2	-19.0
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