Dark Energy Driven by the Cohen–Kaplan–Nelson Bound

[arXiv:2406.09964]

Mustafa Tabet (TU Dortmund) in collaboration with
Patrick Adolf (TUD), Martin Hirsch (Valencia U.), Sara Krieg (TUD), Heinrich Päs (TUD)

9 July 2024 | PASCOS 2024

Outline

Motivation

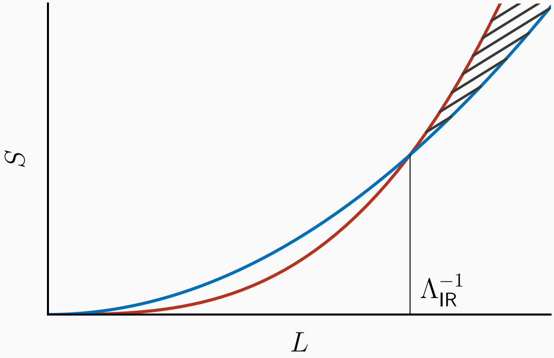
Bekenstein Bound

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:

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

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

[Cohen, Kaplan, Nelson, '98]

Cohen–Kaplan–Nelson Bound

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

[Cohen, Kaplan, Nelson, '98]

hierarchy puzzle

[Kephart et al., '22]

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

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

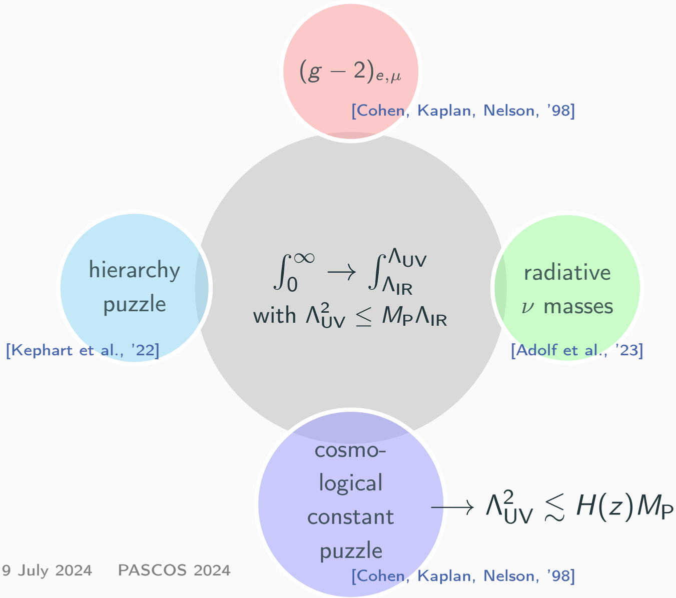
radiative ν masses

[Adolf et al., '23]

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

[Cohen, Kaplan, Nelson, '98]

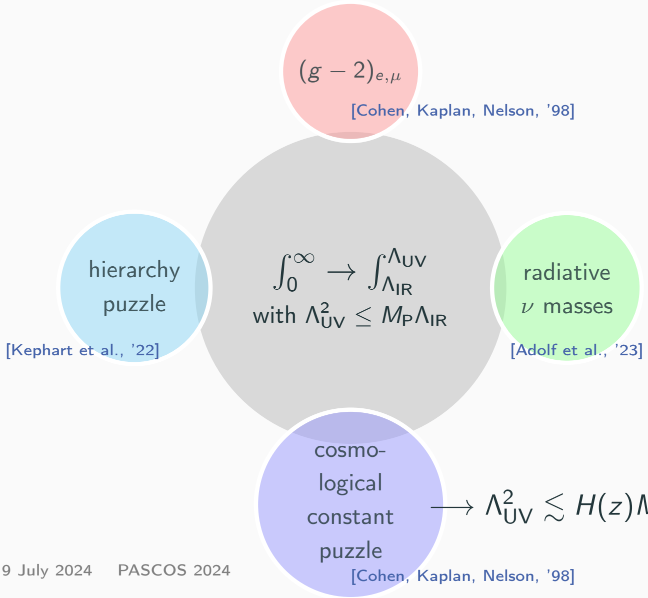
Cohen–Kaplan–Nelson Bound



Experiment

Recent measurements from the Dark Energy Spectroscopic Instrument (DESI) prefer time-dependent dark energy with up to $3.9\,\sigma$

Cohen–Kaplan–Nelson Bound



$\longrightarrow \Lambda_{\mathrm{UV}}^2 \lesssim H(z) M_{\mathrm{P}}$

Experiment

Recent measurements from the Dark Energy Spectroscopic Instrument (DESI) prefer time-dependent dark energy with up to $3.9\,\sigma$

Cohen–Kaplan–Nelson bound?

Evolving Dark Energy

Evolving Dark Energy

CKN-Bound: $\Lambda_{\text{UV}}^4 \lesssim H^2(z) M_{\text{P}}^2$

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

Evolving Dark Energy

CKN-Bound: $\Lambda_{\mathrm{UV}}^4 \lesssim H^2(z) M_{\mathrm{P}}^2$

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

this yields:

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

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

Evolving Dark Energy

$$\text{CKN-Bound: } \Lambda_{\text{UV}}^4 \lesssim H^2(z) M_{\text{P}}^2$$

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

this yields:

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

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

S. Hsu's no-go theorem [Hsu, '04]:

$$\left.\begin{aligned} \rho_{\text{M}} &\overset{(2)}{\sim} a^{-3} \\ \rho_{\text{M}} &\overset{(1),(3)}{\sim} H^2 \end{aligned}\right\} \Rightarrow \rho_{\text{DE}} \overset{(1)}{\sim} a^{-3} \tag{4}$$

Evolving Dark Energy

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

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

this yields:

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

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

~~S. Hsu's no-go theorem:~~

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

Analysis and Results

Analysis: Experimental Input and Statistical Procedure

DESI baryonic acoustic oscillations (BAO) combined with late universe constraints: [DESI, '24]

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

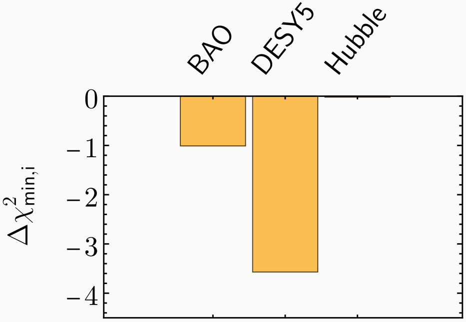
using χ^2-statistics:

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

Results: CKN $\leftrightarrow$ ΛCDM

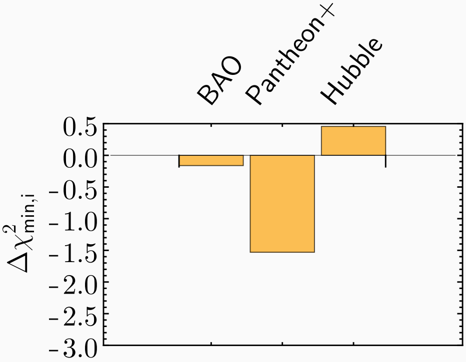
$$\chi^{2,\text{CKN}}_{\text{min}}/\text{dof} = 1677/1871 \approx 0.90$$

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



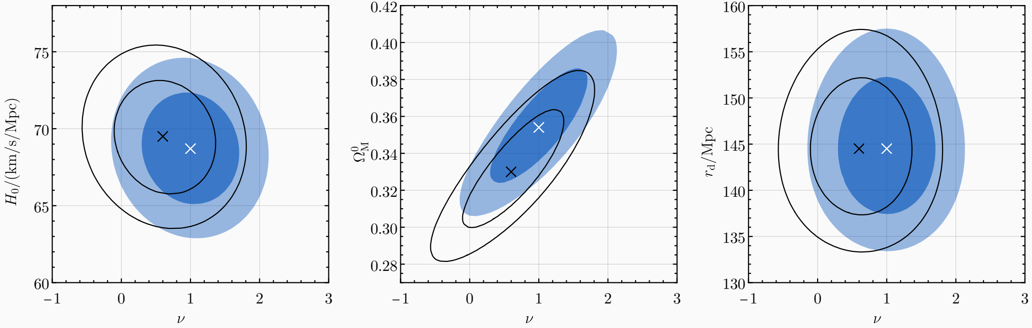
$$\chi^{2,\text{CKN}}_{\text{min}}/\text{dof} = 1440/1632 \approx 0.88$$

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



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

Results: Correlations



Results: Future Projection

- DESI running for another three 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

Results: Future Projection

- DESI running for another three 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

Models	DESI-5Y		Euclid		DESI-5Y + Euclid	
	Σ_{DESY5}	$\Sigma_{\text{Pantheon+}}$	Σ_{DESY5}	$\Sigma_{\text{Pantheon+}}$	Σ_{DESY5}	$\Sigma_{\text{Pantheon+}}$
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, supernova and Hubble data:
  - Preference over ΛCDM up to 2.1σ
  - 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