On the microphysics of Dark Energy

-Topological Dark Energy-

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Structure of this talk

Introduction

Topological Dark Energy

Observational Aspects

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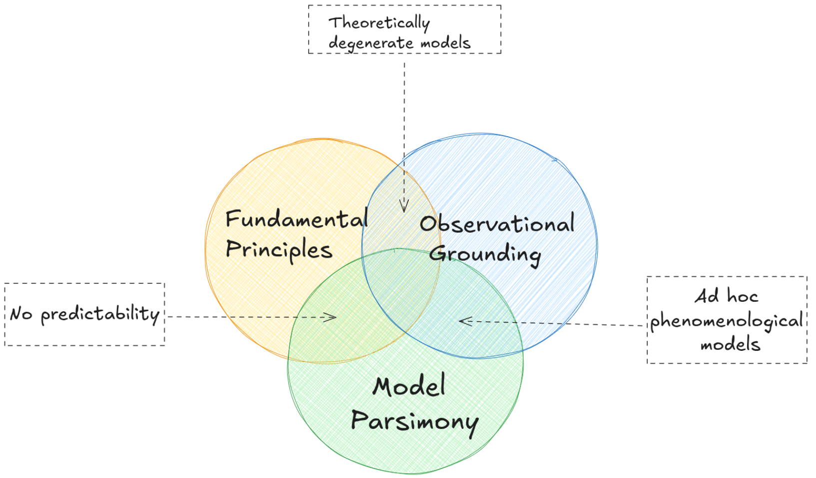
Introduction

Going beyond ΛCDM...



Well-motivated, testable & predictive models

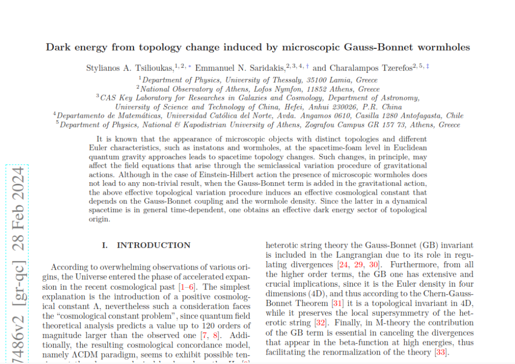
The idea

Assuming[a]

- Spacetime foam
- Addition of Gauss-Bonnet term
- Wormholes

Generate an effective cosmological constant

Topological Dark Energy



Dark energy from topology change induced by microscopic Gauss-Bonnet wormholes

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It is known that the appearance of microscopic objects with distinct topologies and different Euler characteristics, such as instatons and wormholes, at the spacetime-foam level in Euclidean quantum gravity approaches leads to spacetime topology changes. Such changes, in principle, may affect the field equations that arise through the semiclassical variation procedure of gravitational actions. Although in the case of Einstein-Hilbert action the presence of microscopic wormholes does not lead to any non-trivial result, when the Gauss-Bonnet term is added in the gravitational action, the above effective topological variation procedure induces an effective cosmological constant that depends on the Gauss-Bonnet coupling and the wormhole density. Since the latter in a dynamical spacetime is in general time-dependent, one obtains an effective dark energy sector of topological origin.

I. INTRODUCTION

According to overwhelming observations of various origins, the Universe entered the phase of accelerated expansion in the recent cosmological past [1–6]. The simplest explanation is the introduction of a positive cosmological constant Λ, nevertheless such a consideration faces the "cosmological constant problem", since quantum field theoretical analysis predicts a value up to 120 orders of magnitude larger than the observed one [7, 8]. Additionally, the resulting cosmological concordance model, namely ΛCDM paradigm, seems to exhibit possible ten-

heterotic string theory the Gauss-Bonnet (GB) invariant is included in the Langrangian due to its role in regulating divergences [24, 29, 30]. Furthermore, from all the higher order terms, the GB one has extensive and crucial implications, since it is the Euler density in four dimensions (4D), and thus according to the Chern-Gauss-Bonnet Theorem [31] it is a topological invariant in 4D, while it preserves the local supersymmetry of the heterotic string [32]. Finally, in M-theory the contribution of the GB term is essential in canceling the divergences that appear in the beta-function at high energies, thus facilitating the renormalization of the theory [33].

[a] Tsilioukas, Saridakis & Tzerefos (2024), Phys. Rev. D, arxiv:2312.07486

Topological Dark Energy

TDE - starting point

Previous work found*:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda_{\text{eff}} g_{\mu\nu} = \kappa^2 T_{\mu\nu}, \tag{1}$$

where

$$\Lambda_{\text{eff}} = -16\pi^2 \alpha \frac{\partial \chi}{\partial V}, \tag{2}$$

Q: How we calculate $\frac{\partial \chi}{\partial V}$?

$$\frac{\partial \chi}{\partial V} = \sum_i \delta\chi_i n_i$$

$\delta\chi_i,\ n_i$ - Euler characteristic change, numerical density for instatons type i.

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*Tsilioukas, Saridakis & Tzerefos (2024), Phys. Rev. D, arxiv:2312.07486

TDE - instatons

$$\Lambda_{\rm eff} = -16\pi^2\alpha\frac{\partial\chi}{\partial V}, \quad \frac{\partial\chi}{\partial V} = \sum_i \delta\chi_i n_i$$

Examples:

- Black Holes - $\delta\chi = 0$
- Euclidean Wormhole - $\delta\chi = -2$
- Nariai - $\delta\chi = 2$

We can have positive/negative/zero $\Lambda_{\rm eff}$
Q: How we calculate n?†

$$n_i = Aexp(-\Delta S) \tag{3}$$

where

$$\Delta S = S_{\rm inst} - S_{\rm back}$$

† Coleman (1977), Phys. Rev. D 15, 2929.

Thus we have

$$\Lambda_{\text{eff}} = -16\pi^2\alpha \sum_i \delta\chi_i A_i exp\left(-\frac{2\pi\alpha\chi_i}{G}\right)$$
$$exp\left[\frac{1}{12G}\int_0^t dt \frac{a^3}{H^3}\left(12H^2 + 6\dot{H} + 6\frac{k}{a^2} - 4\Lambda_{\text{eff}}\right)\right] \tag{4}$$

Q:How we continue?

$$\frac{d\Lambda_{\text{eff}}}{dt} = \frac{1}{12G}\frac{a^3}{H^3}\left(12H^2 + 6\frac{dH}{dt} + 6\frac{k}{a^2} - 4\Lambda_{\text{eff}}\right)\Lambda_{\text{eff}}. \tag{5}$$

TDE - Concrete scenario

Standard definitions:

$$\Omega_{\Lambda_{\text{eff}}} = \frac{\Lambda_{\text{eff}}}{3H^2}, \quad E(z) = \frac{H(z)}{H_0}, \quad h = H_0/100$$

The model

$$E(z) = \left[\frac{\Omega_{r0}(1+z)^4 + \Omega_{m0}(1+z)^3 + \Omega_{k0}(1+z)^2}{1 - \Omega_{\Lambda_{\text{eff}}}(z)} \right]^{1/2},$$

$$\frac{d\Omega_{\Lambda_{\text{eff}}}(z)}{dz} = g(z, \Omega_{\Lambda_{\text{eff}}}(z), \Omega_{m0}, \Omega_{k0}, \Omega_{r0}, h)$$

Initial condition:

$$\Omega_{\Lambda_{\text{eff}}}(z=0) = 1 - \Omega_{k0} - \Omega_{m0} - \Omega_{r0}$$

Observational Aspects

Cosmological observables & data

- Cosmic Chronometers (CC)[‡]: probe H(z)
- Supernovae Type Ia + calibrators (Pantheon+/SH0ES): probe d_L
- Baryonic Acoustic Oscillations (BAOs) data: probe combinations of $d_L, H(z)$

$$d_L(z) = c(1+z)\frac{1}{\sqrt{|\Omega_{k0}|}}\Phi\left(\sqrt{|\Omega_{k0}|}\int_0^z \frac{1}{H(\omega,\phi^\nu)}d\omega\right), \qquad (6)$$

where

$$\Phi(x) = \begin{cases} \sinh(x), & \Omega_{k0} > 0 \\ x, & \Omega_{k0} = 0 \\ \sin(x), & \Omega_{k0} < 0 \end{cases} \qquad (7)$$

[‡] Anagnostopoulos & Saridakis (2024), JCAP 2024(04), 051.

Likelihood analysis

Q: Which are the most probable values for the free parameters given the data?

$$\mathcal{L}(\phi^\mu) \sim exp\left[-\chi^2_{tot}(\phi^\mu)\right]$$

$$\chi^2_{\rm tot}(\phi^\mu) = \sum_{p=1}^{\mathcal{P}} \chi^2_p, \quad \chi^2_p = \sum_{i=1}^{N_p} \left(\frac{\mathrm{Obs}_i - \mathrm{Theor}(z_i, \phi^\mu)}{\sigma_i} \right)^2$$

- $\phi^\mu = \{\Omega_{m0}, h, \mathcal{M}\}$ and $\mathcal{P} = \{CC, SNIa + SH0ES\}$.
- $\phi^\mu = \{\Omega_{m0}, h, \mathcal{M}, r_d\}$ and $\mathcal{P} = \{CC, SNIa + SH0ES, BAOs\}$.
- $\phi^\mu = \{\Omega_{m0}, h, \mathcal{M}, r_d\}$ and $\mathcal{P} = \{SNIa + SH0ES, BAOs\}$.

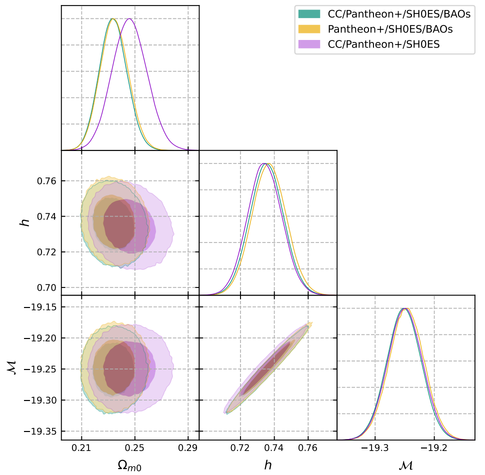
We sample the likelihood using emcee[§]

[§] Many technical details here - see Anagnostopoulos, Basilakos & Saridakis (2019), Phys. Rev. D 100, 083517.

Results: Flat TDE parameter values

- r_d value much smaller than CMB + ΛCDM - as expected[a]
- SH0ES data dominate on the H_0 value
- Less Ω_{m0} than ΛCDM.

[a] Favale, Gómez-Valent & Migliaccio (2024), arXiv:2405.17643.



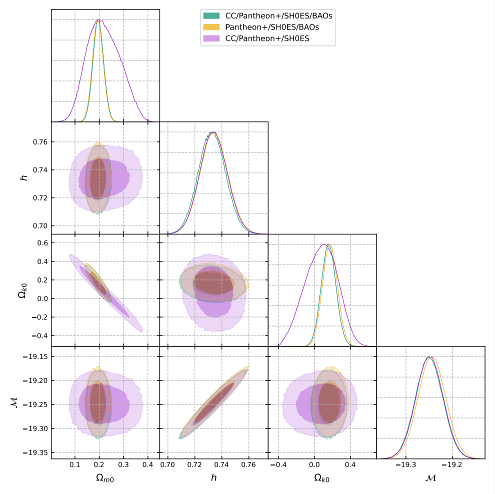
Posterior parameter plots: flat TDE model[a]

[a] Anagnostopoulos, Tsilioukas, Saridakis, (2025), to appear

Results: non - flat TDE parameter values

- r_d value much smaller than CMB + ΛCDM - as expected[a]
- SH0ES data governs H_0 value.
- Even less Ω_{m0} than ΛCDM.
- Flat Universe within 2σ.

[a]Favale, Gómez-Valent & Migliaccio (2024), arXiv:2405.17643.



Posterior parameter distribution: non-flat TDE model [a]

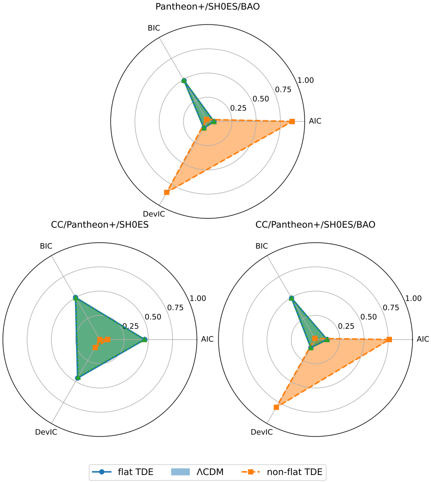
[a] Anagnostopoulos, Tsilioukas, Saridakis, (2025), to appear

Results: Model Selection Criteria

Q: How we quantify the relative model adequacy?

- Akaike IC (AIC), Bayesian IC (BIC) & Deviance IC (DevIC)[a]
- **The difference is important:** $\Delta IC = IC_{model} - IC_{minimum}$
- Degree of belief :

$$P = \frac{e^{-\Delta IC}}{\sum_{i=1}^{N_{\rm m}} e^{-\Delta IC_i}}$$



[a] Liddle, Mukherjee & Parkinson (2006), arXiv:astro-ph/0608184.

Results: Big Bang Nucleosynthesis

Q1: Does the TDE scenario spoils the thermal history?

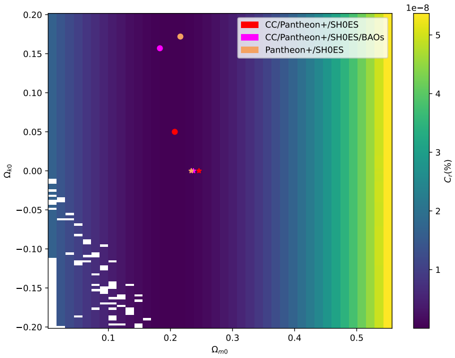
Criterion[a]:

$C_r < 10\%$, $C_r = \left|\frac{H_{TDE} - H_{\Lambda CDM}}{H_{\Lambda CDM}}\right|^2$

at $z \sim 10^9$

Q2: Does curvature produce extra effects in BBN era?

[a] Uzan, J.-P. (2011), Living Rev. Relativity

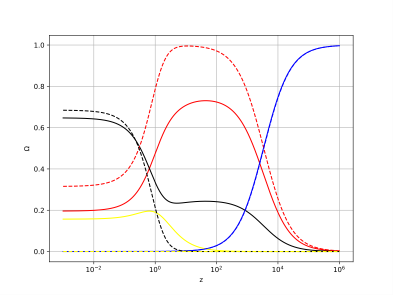


$C_r[\%]$ as a function of curvature and matter energy densities[a]

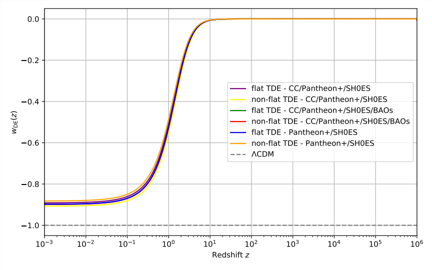
[a] Anagnostopoulos, Tsilioukas, Saridakis, (2025), to appear

Cosmic Evolution

Q1: How do the cosmic densities evolve?



Q2: What about the equation-of-state parameter $w_{\mathrm{DE}}(z)$?



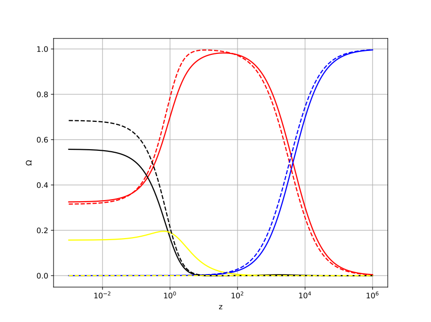
DM transition to DE

Assume two components of the *DE*

- "pure" Λ-like $w_\Lambda = -1$.
- a component with $w_{\Lambda_{eff}}$

Calculate the effective DM

- $\Omega_{\Lambda_{\text{eff}}} = \Omega_\Lambda + \Omega_{\text{DM}_{\text{eff}}}$
- $\Omega_{\text{DM}_{\text{eff}}} = \left(1 - \frac{w_{\Lambda_{\text{eff}}}}{w_\Lambda}\right) \Omega_{\Lambda_{\text{eff}}}$



Notes:

- $\Omega_{\text{DM}_{\text{eff}}} \simeq 0.1$ today, $\sim 12\%$ of DE behaves as DM today.
- Non-flat TDE is very similar with ΛCDM for $z > 100$

Conclusions

Main Results: Topological Dark Energy (TDE)

Key Properties

- *Statistically significant* preference for non-flat TDE from current data.
- Flat TDE is statistically equivalent to ΛCDM.
- TDE exhibits Dark Matter to Dark Energy transition.
- Consistent with Big Bang Nucleosynthesis (BBN).
- Allows for changing Λ sign.
- TDE has the same number of free parameters with ΛCDM.

Outlook

A new cosmological scenario has introduced - TDE

- It is motivated by quantum gravity considerations.
- Exhibits strong phenomenological performance.

Future work

Q1: What about σ_8, H_0 tensions in the TDE context?[¶]

- Calculate perturbations on FRWL.
- Check CMB and fσ_8 datasets.

Q2: Can we upgrade on the assumptions of the scenario?
Q3: Are there possible imprints of spacetime foam?

[¶]A previous speaker described a mechanism in which σ_8 values are related to photometric redshift errors of LSS surveys...