Alleviating both H_0 and σ_8 tensions through Tsallis entropy

(arXiv:2308.01200, S.Basilakos, A.Lymperis, M.Petronikolou, E.N.Saridakis)

Petronikolou Maria

Physics Department, National Technical University of Athens
National Observatory of Athens

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Introduction

- Motivation: The need to incorporate tensions such as the H_0 and σ_8

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- Motivation: The need to incorporate tensions such as the H_0 and σ_8

  $\rightarrow$ Extensions/modifications of the concordance cosmology

- Alter the universe content and interactions while maintaining GR as the gravitational theory or Modify gravity.

Modified cosmology through Tsallis entropy

- Tsallis non-additive entropy generalizes the standard thermodynamics to non-extensive one (possess standard Boltzmann-Gibbs statistics as a limit)
- Tsallis entropy

$$S_T = \frac{\tilde{\alpha}}{4G} A^{\delta} \tag{1}$$

where $A \propto L^2$ (the area of the system with characteristic length L)
$\tilde{\alpha} > 0$: constant with dimensions $[L^{2(1-\delta)}]$
δ: is the non-additivity parameter.

- Tsallis entropy $\rightarrow$ standard Bekenstein-Hawking additive entropy for: $\delta = 1$ and $\tilde{\alpha} = 1$

Modified cosmology through Tsallis entropy

Imposing a Friedmann-Robertson-Walker (FRW) metric of the form

$$ds^2 = -dt^2 + a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right), \qquad (2)$$

where $a(t) \rightarrow$ the scale factor.

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- We substitute Tsallis entropy (1) into $-dE = TdS$ (1st law of thermodynamics)
- We consider the boundary of the system to be the Universe apparent horizon: $\tilde{r}_a = (H^2 + \frac{k}{a^2})^{-1}$, with temperature $T = 1/(2\pi\tilde{r}_a)$

  (filled by the universe matter fluid, with energy density ρ_m and pressure p_m)

[arXiv:1806.04614]

Modified cosmology through Tsallis entropy

Friedmann equations for the non-extensive scenario with Tsallis entropy:

$$-\frac{(4\pi)^{2-\delta}G}{\tilde{\alpha}}(\rho_m + p_m) = \delta\frac{\dot{H} - \frac{k}{a^2}}{\left(H^2 + \frac{k}{a^2}\right)^{\delta-1}}, \qquad (3)$$

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$$\frac{2(4\pi)^{2-\delta}G}{3\tilde{\alpha}}\rho_m = \frac{\delta}{2-\delta}\left(H^2 + \frac{k}{a^2}\right)^{2-\delta} - \frac{\tilde{\Lambda}}{3\tilde{\alpha}}, \tag{4}$$

$\tilde{\Lambda} \rightarrow$ integration constant, which can be considered as the cosmological constant
$H = \dot{a}/a \rightarrow$ Hubble parameter

Modified cosmology through Tsallis entropy

Assuming flat geometry, i.e. $k = 0$, we can re-write them into the standard form

$$H^2 = \frac{8\pi G}{3}\left(\rho_m + \rho_{DE}\right) \quad (5)$$

$$\dot{H} = -4\pi G\left(\rho_m + p_m + \rho_{DE} + p_{DE}\right), \quad (6)$$

with effective dark energy density

$$\rho_{DE} = \frac{3}{8\pi G}\left\{\frac{\Lambda}{3} + H^2\left[1 - \alpha\frac{\delta}{2-\delta}H^{2(1-\delta)}\right]\right\} \quad (7)$$

and pressure

$$p_{DE} = -\frac{1}{8\pi G}\left\{\Lambda + 2\dot{H}\left[1 - \alpha\delta H^{2(1-\delta)}\right] + 3H^2\left[1 - \alpha\frac{\delta}{2-\delta}H^{2(1-\delta)}\right]\right\} \quad (8)$$

new constants: $\Lambda \equiv (4\pi)^{\delta-1}\tilde{\Lambda}$ and $\alpha \equiv (4\pi)^{\delta-1}\tilde{\alpha}$

Modified cosmology through Tsallis entropy

We define

- Dust matter: $p_m = 0$
- Cosmological redshift: $z = -1 + a_0/a$, $a_0 = 1$
- Density parameters:

$$\Omega_m = \frac{8\pi G}{3H^2}\rho_m \tag{9}$$

$$\Omega_{DE} = \frac{8\pi G}{3H^2}\rho_{DE} \tag{10}$$

So the Hubble parameter can be written as

$$H = \frac{\sqrt{\Omega_{m0}}H_0}{\sqrt{(z+1)^{-3}(1-\Omega_{DE})}} \tag{11}$$

Modified cosmology through Tsallis entropy

Additionally, we define the w_{DE} equation-of-state parameter:

$$w_{DE} \equiv \frac{p_{DE}}{\rho_{DE}} = -1 - \frac{2\dot{H}\left[1 - \alpha\delta H^{2(1-\delta)}\right]}{\Lambda + 3H^2\left[1 - \frac{\alpha\delta}{2-\delta}H^{2(1-\delta)}\right]} \qquad (12)$$

Substituting (7) into (10) and taking into account (11) we acquire

$$\Omega_{DE}(z) = 1 - H_0^2\Omega_{m0}(1+z)^3\left\{\frac{(2-\delta)}{\alpha\delta}\left[H_0^2\Omega_{m0}(1+z)^3 + \frac{\Lambda}{3}\right]\right\}^{\frac{1}{\delta-2}} \qquad (13)$$

applying for $z = 0$ we obtain

$$\Lambda = \frac{3\alpha\delta}{2-\delta}H_0^{2(2-\delta)} - 3H_0^2\Omega_{m0} \qquad (14)$$

→ our model has two extra free parameters: α and δ.

Modified cosmology through Tsallis entropy

At the perturbative level:

- We introduce the matter overdensity $\delta_m := \delta\rho_m/\rho_m$
- and setting $\alpha = 1$, its evolution equation is given by

$$\delta_m'' + \frac{2\,(4-2\delta) - \left(9-6\delta+8\pi G\Lambda H^{2\delta-4}\right)}{(4-2\delta)\,(1+z)}\delta_m' + \frac{3^{\frac{1}{\delta-2}}\left[(1-2\delta)\,\rho_m^{\frac{1}{2-\delta}} - 9\,(1-\delta)\,\Lambda\rho_m^{\frac{\delta-1}{2-\delta}}\right]8\pi G}{2\,(2-\delta)^2\,H^2(1+z)^2}\delta_m = 0, \quad (15)$$

with Λ given by (14)

- Case $\delta = 1$: we recover the standard result, (for $\Omega_m \approx 1$) gives

$$\delta_m'' + \frac{1}{2(1+z)}\delta_m' - \frac{3}{2(1+z)^2}\delta_m = 0 \qquad (16)$$

Alleviating H_0 and σ_8 tensions in Tsallis cosmology

H_0 tension

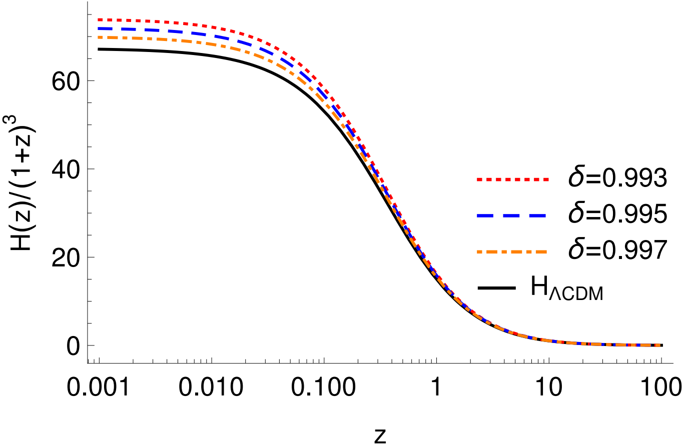
- We choose the model parameters in order to obtain $H(z_{CMB}) = H_{\Lambda CDM}(z_{CMB})$ and $\Omega_{m_0} = 0.31$, but give $H(z \to 0) > H_{\Lambda \mathrm{CDM}}(z \to 0)$.
- We also obtain the sequence of matter and dark-energy epochs, according to observations.
- In ΛCDM cosmology the Hubble function is given by

$$H_{\Lambda CDM}(z) \equiv H_0 \sqrt{\Omega_{m0}(1+z)^3 + 1 - \Omega_{m0}} \qquad (17)$$

with $H_{0\Lambda CDM} = 67.27 \pm 0.6$ km/s/Mpc.

We depict the normalized $H(z)/(1+z)^3$ as a function of z, for ΛCDM and Tsallis (eq.(11), (13)) models :

Results

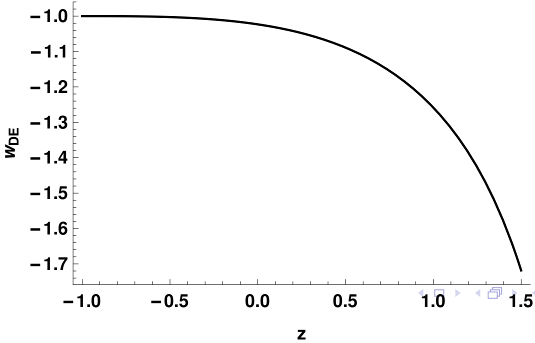


Dependence of H_0 on δ.

$\rightarrow H_0 \approx 74$ km/s/Mpc for $\delta = 0.993$.

The mechanism behind H_0 alleviation

- In Tsallis cosmology, as we mentioned w_{DE} is given by (12) (and eq.(11), (13)).
- In the case where $\{\delta, \alpha, \Omega_{m0}\}=\{0.993, 1, 0.31\}$, w_{DE} lies in the phantom regime $\rightarrow$ one of the sufficient ways to alleviate the H_0 tension!



Alleviating H_0 and σ_8 tensions in Tsallis cosmology

σ_8 tension

Obtaining the solution for $\delta_m(z)$ by eq.(15), we can calculate the physically interesting observational quantity

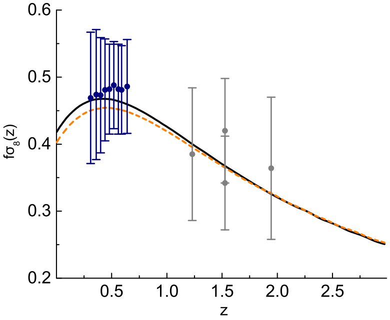
$$f\sigma_8(z) = f(z)\,\sigma(z), \tag{18}$$

with

- $f(z) := -\frac{d\ln\delta_m(z)}{d\ln z}$
- $\sigma(z) := \sigma_8\frac{\delta_m(z)}{\delta_m(0)}$

and present the evolution of $f\sigma_8(z)$ for both ΛCDM and Tsallis cosmology, on top of observational data:

Results: Evolution of $f\sigma_8(z)$ in ΛCDM scenario and in Tsallis cosmology



ΛCDM scenario and Tsallis cosmology with $\{\alpha, \delta\} = \{1, 0.993\}$ (data points: BAO observations in SDSS-III DR12, data points: from SDSS-IV DR14)

The mechanism behind σ_8 alleviation

As we observe from the evolution equation (15):

- The scenario at hand has a different friction term as well as an effective Newton's constant.
- Under the above parameter choice: we obtain an increased friction term and an effective Newton's constant smaller than the usual one.

One of the sufficient mechanisms to alleviate σ_8 tension!

Conclusions-Prospects

- By choosing particular values of the model parameters we were able to reproduce the observed Hubble and $f\sigma_8$ functions evolution and at late times potentially alleviate the H_0 and σ_8 tensions, implying also the viability of the examined model.
- The mechanisms behind the alleviation of H_0 and σ_8 tensions, were the $w_{DE} < -1$ (phantom regime) and an increased friction term or/and a smaller effective Newton's constant in the evolution equation of $\delta_m(z)$, respectively.
- A detailed verification of viability for the proposed model and its results is necessary using observational data sets of SNIa, BAO, CMB (etc.) samples.
- Finally, if the tensions aren't a result of unknown systematics, then one should indeed seek for alleviation in extensions of the standard lore of cosmology.

(Helmos Observatory)

THANK YOU!