16th Marcel Grossman - 2021, CM3 Session

Alleviating H_0 and σ_8 tensions with $f(T)$ gravity, using the effective field theory approach

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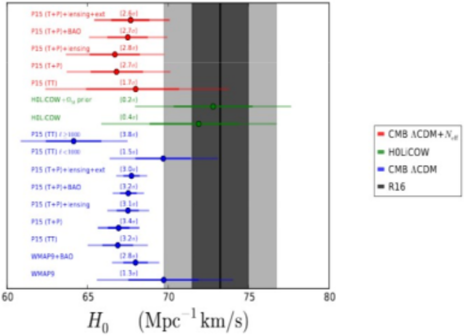
Goal and Motivation

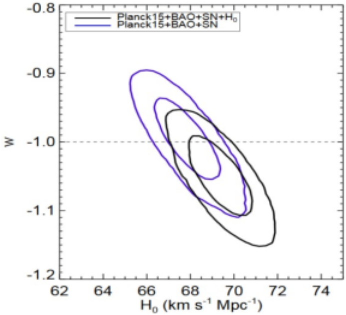
- Goal: we report how to alleviate both the H_0 and σ_8 tensions simultaneously within torsional gravity from the perspective of effective field theory (EFT).
- S-F. Yan, Pierre Zhang, J-W. Chen, X-Z. Zhang, Y-F. Cai, E. N. Saridakis Phys.Rev.D 101 (2020) 12, 121301

H_0 tensions

- Tension between the data (direct measurements) and Planck/ΛCDM (indirect measurements). The data indicate a lack of "gravitational power".



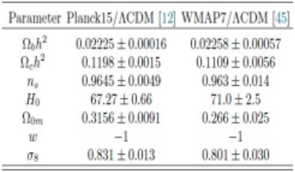
[Bernal, Verde, Riess, JCAP1610]



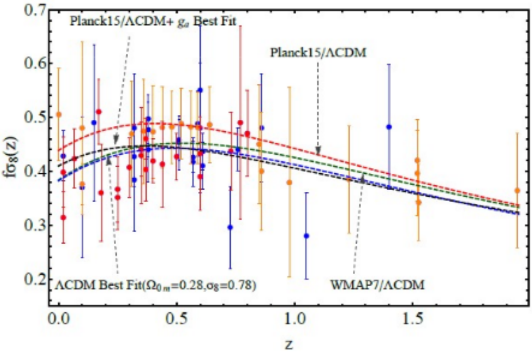
[Riess et al, Astrophys.J 826]

σ_8 tensions

- Tension between the data and Planck/ΛCDM. The data indicate a lack of "gravitational power" in structures on intermediate-small cosmological scales.



Parameter	Planck15/ΛCDM [12]	WMAP7/ΛCDM [45]
$\Omega_b h^2$	0.02225 ± 0.00016	0.02258 ± 0.00057
$\Omega_c h^2$	0.1198 ± 0.0015	0.1109 ± 0.0056
n_s	0.9645 ± 0.0049	0.963 ± 0.014
H_0	67.27 ± 0.66	71.0 ± 2.5
Ω_{0m}	0.3156 ± 0.0091	0.266 ± 0.025
w	-1	-1
σ_8	0.831 ± 0.013	0.801 ± 0.030



[Kazantzidis, Perivolaropoulos, PRD97]

- The H_0 tension can be alleviated in specific theoretical models, such as early DE, interacting DE, dark radiation, improved big bang nucleosynthesis (BBN), or modified gravity.
- The σ_8 tension may be addressed by sterile neutrinos, running vacuum models, a dark matter (DM) sector that clusters differently at small and large scales, or by modified gravity.
- There were attempts from the nonconventional matter sector to address both tensions simultaneously, such as DM-neutrino interactions.

[Eleonora Di Valentino et. al, Class.Quant.Grav. (2021]

Model independent analysis

- In general, to avoid the H_0 tension one needs a positive correction to the first Friedmann equation at late times that could yield an increase in H_0 compared to the ΛCDM scenario.

Model independent analysis

- For the σ_8 tension, we recall that in any cosmological model, at sub-Hubble scales and through matter epoch, the equation that governs the evolution of matter perturbations in the linear regime is

  $$\ddot{\delta} + 2H\dot{\delta} = 4\pi G_{\rm eff}\rho_m \delta \ , \tag{1}$$

  where $G_{\rm eff}$ is the effective gravitational coupling given by a generalized Poisson equation.
- Solving for $\delta(a)$ provides the observable quantity $f\sigma_8(a)$, following the definitions $f(a) \equiv d\ln\delta(a)/d\ln a$ and $\sigma(a) = \sigma_8\delta(1)/\delta(a=1)$. Hence, alleviation of the σ_8 tension may be obtained if $G_{\rm eff}$ becomes smaller than G_N during the growth of matter perturbations and/or if the “friction” term in (1) increases.

Model independent analysis

We consider a correction in the first Friedmann equation of the form

$$H(z) = -\frac{d(z)}{4} + \sqrt{\frac{d^2(z)}{16} + H^2_{\Lambda\mathrm{CDM}}(z)}\,, \qquad (2)$$

where $H_{\Lambda\mathrm{CDM}}(z) \equiv H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}$ is the Hubble rate in ΛCDM, with $\Omega_m = \rho_m/(3M_p^2 H^2)$ the matter density parameter and primes denote derivatives with respect to z.

Model independent analysis

- Îf $d < 0$ and is suitably chosen, one can have $H(z \to z_{\mathrm{CMB}}) \approx H_{\Lambda\mathrm{CDM}}(z \to z_{\mathrm{CMB}})$ but $H(z \to 0) > H_{\Lambda\mathrm{CDM}}(z \to 0)$; i.e., the H_0 tension is solved [one should choose $|d(z)| < H(z)$, and thus, since $H(z)$ decreases for smaller z, the deviation from ΛCDM will be significant only at low redshift].
- Since the friction term in (1) increases, the growth of structure gets damped, and therefore, the σ_8 tension is also solved.

$f(T)$ gravity and cosmology

In torsional formulation we use the vierbeins fields $\mathbf{e}_A(x^\mu)$ as dynamical variables, which at a manifold point x^μ form an orthonormal basis ($\mathbf{e}_A \cdot \mathbf{e}_B = \eta_{AB}$ with $\eta_{AB} = \mathrm{diag}(1, -1, -1, -1)$).
In a coordinate basis they read as $\mathbf{e}_A = e^\mu_A \partial_\mu$ and the metric is given by

$$g_{\mu\nu}(x) = \eta_{AB}\, e^A_\mu(x)\, e^B_\nu(x), \tag{3}$$

with Greek and Latin indices used for the coordinate and tangent space respectively.
[Y-F. Cai, S. Capozziello, M. De Laurentis, E. N. Saridakis, Rept.Prog.Phys. 79 (2016) 10, 106901]

$f(T)$ gravity and cosmology

- Concerning the connection one introduces the Weitzenböck one, namely $\overset{\mathbf{w}}{\Gamma}{}^{\lambda}_{\nu\mu} \equiv e^{\lambda}_{A}\, \partial_{\mu} e^{A}_{\nu}$, and thus the corresponding torsion tensor becomes

$$T^{\lambda}_{\mu\nu} \equiv \overset{\mathbf{w}}{\Gamma}{}^{\lambda}_{\nu\mu} - \overset{\mathbf{w}}{\Gamma}{}^{\lambda}_{\mu\nu} = e^{\lambda}_{A}\, (\partial_{\mu} e^{A}_{\nu} - \partial_{\nu} e^{A}_{\mu}). \qquad (4)$$

- The torsion tensor contains all information of the gravitational field, and its contraction provides the torsion scalar

$$T \equiv \frac{1}{4} T^{\rho\mu\nu} T_{\rho\mu\nu} + \frac{1}{2} T^{\rho\mu\nu} T_{\nu\mu\rho} - T_{\rho\mu}{}^{\rho} T^{\nu\mu}{}_{\nu}, \qquad (5)$$

which forms the Lagrangian of teleparallel gravity (in similar lines to the fact that the Ricci scalar forms the Lagrangian of general relativity).

$f(T)$ gravity and cosmology

- One can use TEGR as the starting point of gravitational modifications. The simplest direction is to generalize T to a function $T + f(T)$ in the action:

$$S = \frac{1}{16\pi G} \int d^4 x e \left[T + f(T) + L_m \right], \tag{6}$$

- Hence, we extract the Friedmann equations for $f(T)$ cosmology as

$$H^2 = \frac{8\pi G}{3}(\rho_m + \rho_r) - \frac{f}{6} + \frac{T f_T}{3} \tag{7}$$

$$\dot{H} = -\frac{4\pi G(\rho_m + P_m + \rho_r + P_r)}{1 + f_T + 2T f_{TT}}, \tag{8}$$

Alleviating the tensions

- We consider the following ansatz:

$$f(T) = -[T + 6H_0^2(1 - \Omega_{m0}) + F(T)], \tag{9}$$

where $F(T)$ describes the deviation from GR
The first Friedmann equation becomes

$$T(z) + 2\frac{F'(z)}{T'(z)}T(z) - F(z) = 6H^2_{\Lambda CDM}(z)\ . \tag{10}$$

- In order to solve the H_0 tension, we need $T(0) = 6H_0^2 \simeq 6(H_0^{CC})^2$, with $H_0^{CC} = 74.03\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$, while in the early era of $z \gtrsim 1100$ we require the Universe expansion to evolve as in ΛCDM, namely
$H(z \gtrsim 1100) \simeq H_{\Lambda CDM}(z \gtrsim 1100)$
This implies $F(z)|_{z \gtrsim 1100} \simeq cT^{1/2}(z)$ (the value $c = 0$ corresponds to standard GR, while for $c \neq 0$ we obtain ΛCDM too).

Alleviating the tensions

The effective gravitational coupling is given by

$$G_{\text{eff}} = \frac{G_N}{1+F_T} \, . \tag{11}$$

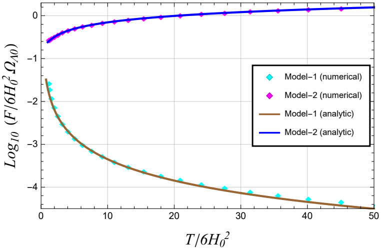
Therefore, the perturbation equation becomes

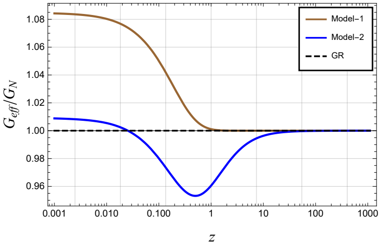
$$\delta'' + \left[\frac{T'(z)}{2T(z)} - \frac{1}{1+z}\right]\delta' = \frac{9H_0^2\Omega_{m0}(1+z)}{[1+F'(z)/T'(z)]T(z)}\delta \, . \tag{12}$$

Since around the last scattering moment $z \gtrsim 1100$ the Universe should be matter-dominated, we impose $\delta'(z)|_{z\gtrsim 1100} \simeq -\frac{1}{1+z}\delta(z)$, while at late times we look for $\delta(z)$ that leads to an $f\sigma_8$ in agreement with redshift survey observations.

Alleviating the tensions

By solving (10) and (12) with initial and boundary conditions at $z \sim 0$ and $z \sim 1100$, we can find the functional forms for the free functions of the $f(T)$ gravity that we consider, namely, $T(z)$ and $F(z)$, that can alleviate both H_0 and σ_8 tensions.

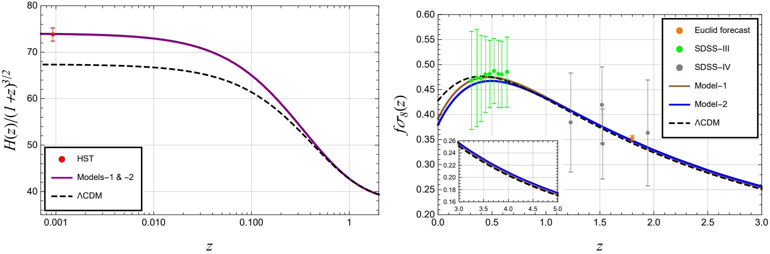




$$\text{Model-1: } F(T) \approx 375.47\left(\frac{T}{6H_0^2}\right)^{-1.65}$$

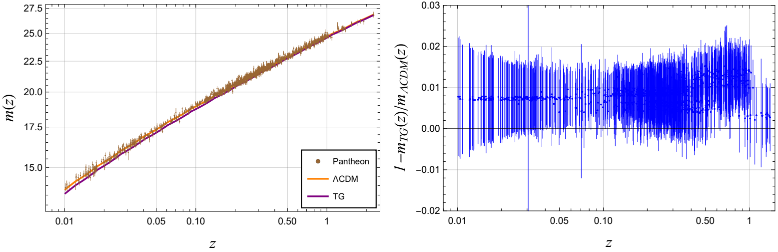
$$\text{Model-2: } F(T) \approx 375.47\left(\frac{T}{6H_0^2}\right)^{-1.65} + 25T^{1/2}.$$

Alleviating the tensions



Left panel: Evolution of the Hubble parameter $H(z)$ in the two $f(T)$ models (purple solid line) and in ΛCDM cosmology (black dashed line). The red point represents the latest data from Cepheid-based local measurement. Right panel: Evolution of $f\sigma_8$ in Model-1 (brown solid line) and Model-2 (blue solid line) of $f(T)$ gravity and in ΛCDM cosmology (black dashed line). The green data points are from BAO observations in SDSS-III DR12, the gray data points at higher redshift are from SDSS-IV DR14, while the red point around ~ 1.8 is the forecast from Euclid. The subgraph in the left bottom displays $f\sigma_8$ at high redshift $z = 3 \sim 5$, which shows that the curve of Model-2 is above the one of Model-1 and ΛCDM scenario and hence approaches ΛCDM slower than Model-1.

Alleviating the tensions



Left panel: Distance modulus magnitude $m = 5\log_{10} D_L(z) + 25 + M$ in TG and ΛCDM with Planck close to best fit H_0 and $M = -19.45$ (Pantheon close to best fit) vs Pantheon SN data. Right panel: Ratio of modulus distances in TG and ΛCDM vs Pantheon SN error bars divided by the data. The difference between Model-1 (labeled as TG in plots) and ΛCDM is well within the error bars, as well as the residuals are consistent with zero. Note that in a real fit to Pantheon, there are even more room with free varying M and Ω_m: the residuals between Model-1 and data will be smaller.

Alleviating the tensions

- We conclude that the class of $f(T)$ gravity: $f(T) = -T - 2\Lambda/M_P^2 + \alpha T^{\beta}$, where only two out of the three parameters Λ, α, and β are independent (the third one is eliminated using Ω_{m0}), can alleviate both H_0 and σ_8 tensions with suitable parameter choices.
- Such kinds of models in $f(T)$ gravity could also be examined through galaxy-galaxy lensing effects [Z. Chen, W. Luo, Y.F. Cai and E.N. Saridakis, Phys.Rev.D 102 (2020) 10, 104044], strong lensing effects around black holes [S. Yan et. al, Phys.Rev.Res. 2 (2020) 2, 023164] and gravitational wave experiments [Y-F. Cai, C. Li, E.N. Saridakis and L. Xue, Phys. Rev. D 97, no. 10, 103513 (2018)].

Conclusions

- We reported how theories of torsional gravity can alleviate both H_0 and σ_8 tensions simultaneously.
- Imposing initial conditions at the last scattering that reproduce the ΛCDM scenario, and imposing the late-time values preferred by local measurements, we reconstructed two particular forms of $f(T)$.
- These models are well described by the parametrization: $f(T) = -T - 2\Lambda/M_P^2 + \alpha T^\beta$.
- This is one of the few constructions where both H_0 and σ_8 tensions are simultaneously alleviated by a modified gravity theory.
- Models beyond the $f(T)$ class could also solve both tensions simultaneously, such as the $f(T, B)$ extensions, symmetric teleparallel gravity, $f(T, T_G)$ gravity,

THANK YOU!

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