Current and future constraints on f(Q) cosmology with Λ CDM background

 $D\Lambda rk$ Energy: from Fundamental Theories to Observations (and back)

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Fundação para a Ciência e a Tecnologia

Introduction

Gravity as Geometry

- Spacetime is described with two (in principle independent) objects: the metric $g_{\mu\nu}$, and the, affine connection $\Gamma^{\lambda}_{\mu\nu}$
- Metric defines distances, lengths and angles

 $ds^{2} = g_{\mu\nu}dx^{\mu}dx^{\nu}, \qquad \cos(V,U) = \frac{g_{\mu\nu}V^{\mu}U^{\nu}}{\sqrt{g_{\mu\nu}V^{\mu}V^{\nu}g_{\rho\sigma}U^{\rho}U^{\sigma}}}$

• The affine connection relates two nearby tangent spaces

$$V^{\mu}(x) - \tilde{V}^{\mu}(x + \delta x) = \Gamma^{\mu}{}_{\alpha\beta}V^{\alpha}(x)\delta x^{\beta}$$

defines the covariant derivative

$$\nabla_{\mu}V^{\nu} \equiv \partial_{\mu}V^{\nu} + \Gamma^{\nu}{}_{\alpha\mu}V^{\alpha}$$

and the Riemann tensor

$$R^{\sigma}{}_{\rho\mu\nu} \equiv \partial_{\mu}\Gamma^{\sigma}{}_{\nu\rho} - \partial_{\nu}\Gamma^{\sigma}{}_{\mu\rho} + \Gamma^{\alpha}{}_{\nu\rho}\Gamma^{\sigma}{}_{\mu\alpha} - \Gamma^{\alpha}{}_{\mu\rho}\Gamma^{\sigma}{}_{\nu\alpha}$$

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Decomposition of the affine connection

$$\Gamma^{\lambda}{}_{\mu\nu} = \left\{{}^{\lambda}{}_{\mu\nu}\right\} + K^{\lambda}{}_{\mu\nu} + L^{\lambda}{}_{\mu\nu}$$

$$\left\{{}^{\lambda}_{\mu\nu}\right\} \equiv \frac{1}{2}g^{\lambda\beta}\left(\partial_{\mu}g_{\beta\nu} + \partial_{\nu}g_{\beta\mu} - \partial_{\beta}g_{\mu\nu}\right)$$

• Contortion and tortion

$$K^{\lambda}{}_{\mu\nu} \equiv \frac{1}{2}g^{\lambda\beta} \left(T_{\mu\beta\nu} + T_{\nu\beta\mu} + T_{\beta\mu\nu} \right) , \qquad T^{\lambda}{}_{\mu\nu} \equiv \Gamma^{\lambda}{}_{\mu\nu} - \Gamma^{\lambda}{}_{\nu\mu}$$

• Disformation and non-metricity

$$L^{\lambda}{}_{\mu\nu} \equiv \frac{1}{2} g^{\lambda\beta} \left(-Q_{\mu\beta\nu} - Q_{\nu\beta\mu} + Q_{\beta\mu\nu} \right) , \qquad Q_{\alpha\mu\nu} \equiv \nabla_{\alpha} g_{\mu\nu}$$

Interpretation of curvature, torsion and non-metricity



By Laur Järv, from Bahamonde 2021.

Construction of GR equivalent theories



Trinity of Gravity as in Beltrán Jiménez, Heisenberg, Koivisto 2019

Extending GR equivalent theories



Symmetric Teleparallel Gravity (STG)

$$S = \int \sqrt{-g} \left[-\frac{1}{16\pi G} F(Q) + \mathcal{L}_m \right] d^4 x$$
$$Q \equiv -\frac{1}{4} Q_{\alpha\beta\gamma} Q^{\alpha\beta\gamma} + \frac{1}{2} Q_{\alpha\beta\gamma} Q^{\gamma\beta\alpha} + \frac{1}{4} Q_\alpha Q^\alpha - \frac{1}{2} Q_\alpha \tilde{Q}^\alpha,$$
$$Q_\mu \equiv Q_\mu{}^\alpha{}_\alpha, \qquad \tilde{Q}^\mu \equiv Q_\alpha{}^{\alpha\mu}.$$

For a flat FLRW, the non-metricity scalar is

 $Q=6H^2$

and the Friedmann equations are

$$6F_QH^2 - \frac{1}{2}F = 8\pi G\rho$$

$$(12H^2F_{QQ} + F_Q)\dot{H} = -4\pi G\left(\rho + p\right)$$

The evolution of the matter contrast in the small scales

$$\ddot{\delta} + 2H\dot{\delta} - \frac{4\pi G}{F_Q}\,\rho_m\,\delta = 0$$

Beltrán Jiménez, Heisenberg, Koivisto, Pekar 2020

The propagation of the tensorial perturbations $g_{\mu
u}=\eta_{\mu
u}+h_{\mu
u}$

 $\bar{h}_A^{\prime\prime} + 2\mathcal{H}(1+2\delta(z))\bar{h}_A^\prime + k^2\bar{h}_A = 0$

where for an $f(\boldsymbol{Q})$ model

$$\delta(z) = \frac{d\ln F_Q}{2\mathcal{H}d\eta}$$

which leads to modification in the luminosity distance for GW

$$d_L^{(\text{GW})}(z) = \exp\left(\int_0^z \frac{\delta(z)}{1+z} dz\right) d_L(z) = \sqrt{\frac{F_Q^{(0)}}{F_Q}} d_L(z)$$

Belgacem 2018.

STG with a ΛCDM background

Imposing a $\Lambda {\rm CDM}$ background in the Friedmann equation, the general solution for F(Q) is

 $F = Q + M\sqrt{Q} + C$

then the evolution of matter contrast is

$$\delta^{\prime\prime}+\delta^{\prime}\left(2+\frac{H^{\prime}}{H}\right)-\frac{3\sqrt{6}H}{2\sqrt{6}H+M}\Omega_{m}\delta=0$$

and the relation between d_L and $d_L^{(GW)}$

$$d_L^{(GW)}(z) = \sqrt{\frac{2\sqrt{6} + M}{2\sqrt{6} + M/E(z)}} \, d_L(z)$$

where we take

$$E^{2}(z) \equiv \frac{H^{2}}{H_{0}^{2}} = \Omega_{m}(1+z)^{3} + 1 - \Omega_{m}$$

Constraints with Redshift Space Distortions data

Dataset

RSD data constrain the combination

$$f\sigma_8(N) = \sigma_8 \frac{\delta'(N)}{\delta(0)}$$

Use RSD data from Sagredo 2018.



Likelihood analysis results



Barros, Barreiro, Koivisto, NJN 2020

Likelihood analysis results



Possible alleviation of the σ_8 tension with the 3rd model?

Model	M	σ_8	$\chi^2/\operatorname{dof}$	ΔAIC_c
ΛCDM	0	0.75	0.62	0.60
$F(Q) = Q + M\sqrt{Q}$	2.03	0.83	0.60	1.90
$F(Q) = Q + \sqrt{8\Lambda Q} + 2\Lambda$	4.05	0.90	0.60	0

- Model with fixed M has a best fit value of σ_8 beyond the Planck value and also in tension;
- Best fit for M is non-zero;
- For the model with free M, the best fit σ_8 includes the Planck value;
- Both the χ^2 and AIC_c tests favour the model with fixed M.
- As the values for the AIC_c are all relatively close, there is no strong evidence for a preferred model.

Forecasts for GW interferometers





Since 2002

2030 - 2040?

From 2035

Standard sirens: Astrophysics events measured in both the electromagnetic spectrum and in gravitational waves.

Examples such as binary neutron star mergers (BNS), black hole binaries with accretion disks (BHB); extreme mass ratio inspirals (EMRI).

- LIGO: we generated 15 catalogs, each with 50 events (Macarena 2019, Baker 2020);
- LISA: we generated 15 different catalogs, each with 15 events, and picked the best, median and worst catalogs (Speri 2021);
- ET: we generated 5 different catalogs, each with 1000 events (Belgacem 2018);
- ... and we used **Snla** data from the Pantheon compilation.

Making a mock catalog



LISA



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EΤ



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LISA vs ET



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Yes. A good catalog can improve LISA's constraints.

Catalog	σ_{lpha}	Relative Size
ET	0.25	1
LISA (best)	0.37	1.5
LISA (worst) + LIGO-Virgo (best)	0.44	1.8
LISA (median)	0.49	2
LISA (worst)	1.70	6.8

- The Einstein Telescope will perform better than LISA;
- LISA will perform better than LIGO;
- LIGO alone will not be able to constrain this model;
- We obtain different catalogs for LISA and LIGO, but the Einstein Telescope catalogs are all very similar;
- If we obtain a bad LISA catalog, we can use LIGO as a complement to obtain better constrains;
- The optimal region is $z\sim 0.6$ for LISA and $z\sim 1$ for the Einstein Telescope.

Beyond the ΛCDM background assumption

A model with only one free parameter λ ,

 $F(Q) = Q \, e^{\lambda Q_0/Q}$

 \ll one of the first alternatives to the concordance model that apart from the fact that it might be preferred by the data [...] it does not face the cosmological constant problem since it does not include a "hidden" cosmological constant inside the F(Q) form \gg

Anagnostopoulos, Basilakos, Saridakis 2021

$$(E^2 - 2\lambda)e^{\lambda/E^2} = \Omega_m (1+z)^3 + \Omega_r (1+z)^4$$

with

$$\lambda = \frac{1}{2} + W_0 \left(-\frac{\Omega_m + \Omega_r}{2e^{1/2}} \right)$$

Given that

$$(E^2 - 2\lambda)e^{\lambda/E^2} = \Omega_m (1+z)^3 + \Omega_r (1+z)^4$$

In the limit of low redshifts

$$E^2 \approx e^{-\lambda} \Omega_m (1+z)^3 + e^{-\lambda} \Omega_r (1+z)^4 + 2\lambda$$

For high redshifts one recovers ΛCDM

$$E^2 \approx \Omega_m (1+z)^3 + \Omega_r (1+z)^4 + \lambda$$

Supernovae + CMB + standard sirens constraints



Actually ... CMB already rules out this model as is!