Einstein-Gauss-Bonnet gravity: constraining with current cosmological observations

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Einstein-Gauss-Bonnet (EGB) model is recently restudied in order to analyze new consequences in gravitation, modifying appropriately the Einstein-Hilbert action. The consequences in EGB cosmology are mainly geometric, with higher order values in the Hubble parameter. In this vein this paper is devoted to constrain the characteristic parameter, $\alpha$, of the EGB model when a cosmological constant as the catalyst for the acceleration is considered. The constrictions are developed at the background cosmology using Observational Hubble Data, Baryon Acoustic Oscillations, Supernovae of the Ia type, Strong Lensing Systems and the recent compilation of HII Galaxies. Additionally, we implement a statefinder analysis where we found not only a late acceleration but also an early Universe acceleration which is associated with the parameter $\alpha$. Based on our results of the lensing systems, the Universe evolution never reaches a non accelerated phase, instead it is always presented in an accelerated state.

Keywords: cosmology, universe acceleration, Einstein-Gauss-Bonnet gravity.

I. INTRODUCTION

Several theories of gravity have emerged in order to solve the profound conundrums of the Universe evolution like the dark matter (DM) and the dark energy (DE) problems. Centered in the DE problem, the first evidence comes from observations of Supernova of the Ia type (SNIa) [1] and confirmed by the acoustic peaks of Cosmic Microwave Background Radiation (CMB) [2], that the Universe is in an accelerated stage and possibly driven by a DE fluid or by a modification to General Theory of Relativity (GR). Among the most accepted candidates are for example the Chaplygin fluids, the cosmological constant, phantom fluids, phenomenological emergent dark energy models, viscous fluids, among other (see the following references [3-5] for a compilation). On the other hand geometrical extensions to GR are also comprehensive candidates, being the extra dimensional theories [6-9], $f(R)$ theories [10-11], and unimodular gravity [12-15], some of the most important contenders. It is worth notice that in literature, the cosmological constant (CC) which together cold dark matter (DM), baryons and relativistic species, make up the well known standard cosmological model or also called Λ-Cold Dark Matter model (ΛCDM), being the CC the preferred component to describe the Universe acceleration. Despite its success, the CC afflicts with severe problems when it is assumed that the CC is caused by quantum vacuum fluctuations, indeed, its theoretical value differs $\sim 120$ orders of magnitude [16, 17] in comparison with the value obtained by the most precise cosmological observations [2].

Recently, the Einstein-Gauss-Bonnet (EGB) gravity [18] has surged, predicting non-trivial contributions to gravitational dynamics and preserving the same number of degrees of freedom for the graviton as GR (other previous studies of EGB can be tracked since the Refs. [19, 20]). In cosmology, the EGB framework adds higher order terms in the Hubble parameter to the Friedmann equations which have important consequences mainly in the early epoch of the Universe. Moreover, the continuity equation does not suffer with modification despite the extra terms considered in EGB theory. Matter density perturbations are also studied in EGB context, presenting differences with ΛCDM in parameter $\sigma_8$ [21]. Furthermore, they are tuned with an extra free parameter named $\alpha$ which is expected to be negligible mainly in the late Universe. For instance in [21], the dimensionless value $\alpha$ of $\alpha \to \bar{\alpha}$ is expected to be of the order $10^{-2}$, with the aim to fit with the expected dynamics of Hubble parameter $H$ and the deceleration parameter $q$ (see also [22]). Recently, the authors in [23] propose a constriction given by $0 \lesssim \alpha \lesssim 10^8 m^2$ based on observations of

\[ \alpha \equiv 3 \alpha H_0^2 \]

$\bar{\alpha}$ will be discussed hereafter.
binary black holes. Other bounds for $\alpha$ from several astrophysical and cosmological phenomena can be checked in\textsuperscript{23} [23].

Another consequences of EGB gravity are for example, in a robust analysis through dynamical systems applied to cosmology developed in\textsuperscript{29} or in studies based on black holes and stellar dynamics in EGB framework, studied in\textsuperscript{24} [28], which present functional forms of how elucidate the differences among the standard knowledge based in GR and in EGB paradigm. Additionally, studies on strong gravitational systems have been done recently in\textsuperscript{30} [31] where they studied several parameters and its correlation with EGB parameter that causes differences with the standard GR for the gravitational lensing by Schwarzschild and charged black holes. Regarding gravitational waves (GW) authors in\textsuperscript{32} find a bound for the EGB parameter as $\tilde{\alpha} \lesssim O(1)$eV$^{-2}$, obtaining one of the first constrictions of $\tilde{\alpha}$ in the EGB model, in addition, Refs. [28] presents therein the bound $\alpha \approx 10^{49}$eV$^{-2}$, using the velocity propagation of GW.

As far as we know, there is no literature where EGB model has been constrained at cosmological background with the recent cosmological samples. In this sense, this paper is devoted to revisit the EGB gravity and constrain its main free parameters through the current cosmological observations, like SN1a\textsuperscript{33}, Strong Gravitational Lensing (SLS)\textsuperscript{34}, Observational Hubble Data (OHD)\textsuperscript{35}, Baryon Acoustic Oscillations (BAO)\textsuperscript{36}, HII starburst galaxy (HIIG)\textsuperscript{37}, together with a joint analysis combining the mentioned observations. We compute an appropriate equation of $H^2$, that emerge from the EGB cosmology in order to present the constrictions of the free parameters. Deceleration and jerk parameters are also presented together with a statefinder analysis that discriminate details of EGB dynamics.

The outline of the paper is as follows. Section II \textsuperscript{11} is dedicated to present the theoretical framework of the EGB models, focusing in Hubble, deceleration and jerk parameters. Sec. II \textsuperscript{11} presents the details of the samples and the methodology to obtain the EGB constraints. Sec. IV \textsuperscript{11} shows the results obtained together with the comparison to the standard $\Lambda$CDM model. Finally in Sec. V \textsuperscript{11} we develop the conclusions and outlooks. In what follows we will use units in which $\hbar = c = k = 1$, unless we indicate otherwise.

II. THEORETICAL FRAMEWORK

The action of the EGB gravity can be written in the form\textsuperscript{18} [18]

$$S_{\text{EGB}}[g_{\mu\nu}] = \int d^{d+1}x \sqrt{-g} \left[ \frac{1}{2k^2} (R - 2\Lambda) + \mathcal{L}_m + \frac{\alpha}{d - 3} \mathcal{G} \right],$$  

where $\kappa^2 \equiv 8\pi G$, $G$ is the Newton constant, $\Lambda$ is an effective cosmological constant, $R$ is the Ricci scalar, $\mathcal{L}_m$ is the matter Lagrangian, $\alpha$ is an appropriate free parameter, $\mathcal{G} = 6R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma} - 4R_{\mu\nu}R^{\mu\nu} - 8R^2$ is the Gauss-Bonnet contribution to the Einstein-Hilbert action and $d + 1$ is considered in the limit when $\lim_{d \to 3} d + 1$ as presented in\textsuperscript{18} [18]. Minimizing the action, the field equation can be written as

$$G_{\mu\nu} + \Lambda g_{\mu\nu} + \frac{\alpha}{(d - 3)} (4R_{\mu\nu} - 8R_{\mu\alpha}R^\alpha_\nu - 8R^\rho_{\mu\rho\nu}) - 8R_{\mu\rho\nu\beta}R^{\rho\sigma\beta\alpha} - g_{\mu\nu}G) = \kappa^2 T_{\mu\nu}. \quad (2)$$

Notice that when $\alpha = 0$, the standard Einstein field equation with a $\mathcal{C}$ is recovered.

In order to study the background cosmology, we assume a flat Friedman-Lemaître-Robertson-Walker (FLRW) line element, which form is $ds^2 = -dt^2 + a(t)^2 (dr^2 + r^2 d\Omega^2)$ where $d\Omega^2 = d\theta^2 + \sin^2 \theta d\varphi^2$ is the solid angle and $a(t)$ is the scale factor. The energy-momentum tensor is the usual, described by the following tensor equation

$$T_{\mu\nu} = pg_{\mu\nu} + (\rho + p)u_\mu u_\nu, \quad (3)$$

where $p$ and $\rho$ represent the pressure and energy density of the fluid respectively and $u_\mu$ is the fluid four-velocity and assumed in a comoving coordinate system. After some manipulations of the previous expressions, the Friedmann equation for EGB reads

$$H^2 + 3\alpha H^4 = \frac{\kappa^2}{3} \sum \rho_i + \Lambda \frac{3}{3}, \quad (4)$$

where we assume a perfect fluid for the energy-momentum tensor and $H \equiv \dot{a}/a$, being the dot a temporal derivative. Moreover, the continuity equation takes its traditional form as

$$\sum \dot{\rho}_i + 3H (\rho_i + p_i) = 0. \quad (5)$$

In terms of the dimensionless variables, Eq. (4) is rewritten as

$$E(z)^2 + \bar{\alpha} E(z)^4 = \Omega_m (z + 1)^3 + \Omega_{r0} (z + 1)^4 + \Omega_{\Lambda0}, \quad (6)$$

where $\bar{\alpha} \equiv 3\alpha H_0^2$, $\Omega_{r0} \equiv \kappa^2 \rho_r / 3H_0^2$ and $\Omega_{\Lambda0} \equiv \Lambda / 3H_0^2$, being $H_0$ the Hubble parameter at today and it is considered the matter (baryons and dark matter) and relativistic particles (photons and neutrinos), where radiation can be constrained with the expression $\Omega_{r0} = 2.409 \times 10^{-5} \bar{h}^{-2}(1 + 0.2271N_{\text{eff}})$, where $N_{\text{eff}} = 3.04$ is the standard number of relativistic particles\textsuperscript{35}. Another important consideration is that $\bar{\alpha}$ is a positive value as inflation demands (see Ref. [23] for details).

In order to constrain the $\bar{\alpha}$ parameter, we divide the problem in two branches through Eq. (6). Therefore, if we only consider the branch where we have a real value of $E(z)$, then we have

$$E(z)^2 = \frac{1}{2\bar{\alpha}} [\sqrt{1 + 4\bar{\alpha} \Omega(z)_{\text{std}} - 1}], \quad (7)$$
where
\[ \Omega(z)_{\text{std}} \equiv \Omega_m(z+1)^3 + \Omega_r(z+1)^4 + \Omega_{\Lambda 0}. \] (8)
is the standard cosmological model. Eq. (7) is constrained to the condition \( E(0) = 1 \), having the following relation
\[ \Omega_{\Lambda 0} = \frac{(2\bar{a} + 1)^2 - 1}{4\bar{a}} - \Omega_m - \Omega_r. \] (9)
Notice that when \( \bar{a} \rightarrow 0 \), in (7) the standard Friedmann equation is recovered. In addition, the deceleration can be computed through the \( q(z) \) formula, resulting in
\[ q(z) = \frac{1}{2E(z)^2} \left[ \frac{3\Omega_m(z+1)^3 + 4\Omega_r(z+1)^4}{\sqrt{1 + 4\bar{a} \Omega(z)_{\text{std}}}} \right] - 1. \] (10)
Moreover the jerk parameter can be constructed through the \( j \equiv \ddot{a}/aH^3 \) function, having
\[ j(z) = q(z)^2 + \frac{(z+1)^2}{2E(z)^2} \frac{d^2E(z)^2}{dz^2} - \frac{(z+1)^2}{4E(z)^4} \times \left( \frac{dE(z)^2}{dz} \right)^2, \] (11)
where
\[ \frac{dE(z)^2}{dz} = \frac{3\Omega_m(z+1)^2 + 4\Omega_r(z+1)^3}{\sqrt{1 + 4\bar{a} \Omega(z)_{\text{std}}}}, \] (12)
\[ \frac{d^2E(z)^2}{dz^2} = -\frac{2\bar{a}[3\Omega_m(z+1)^2 + 4\Omega_r(z+1)^3]^2}{[1 + 4\bar{a} \Omega(z)_{\text{std}}]^{3/2}} + \frac{6\Omega_m(z+1) + 12\Omega_r(z+1)^2}{\sqrt{1 + 4\bar{a} \Omega(z)_{\text{std}}}}. \] (13)
Finally, a statefinder analysis is based in a study in the \( \{s, r\} \)-plane \[39,40\]. The main parameters are defined by the following geometric variables
\[ r \equiv j = \frac{\ddot{a}}{aH^3}, \] (14)
\[ s = \frac{r - 1}{3(q - 1/2)}, \] (15)
where \( r \equiv j \) is also the jerk parameter but written in the statefinder notation. We remark that the \( \Lambda \)CDM is located at \( (s, r) = (0, 1) \) in the statefinder space-phase.

III. OBSERVATIONAL CONSTRAINTS

In order to constrain the free parameters we employ the SNIa, BAO, OHD, SLS and HIIG samples (see \[33–37\]). To constrain the EGB parameters, we perform a Markov Chain Monte Carlo (MCMC) analysis, based on the emcee Python module \[41\], by setting 2500 chains with 250 steps each one. The burn phase is stopped up to obtain a value of 1.1 on each free parameter in the Gelman-Rubin criteria \[42\]. Then, we build a Gaussian log-likelihood as the merit-of-function to minimize
\[ -2 \log(\mathcal{L}_{\text{data}}) \propto \chi^2_{\text{data}}, \] (16)
for each dataset mentioned previously. Additionally, a joint analysis can be constructed through the sum of them, i.e.,
\[ \chi^2_{\text{joint}} = \chi^2_{\text{SN Ia}} + \chi^2_{\text{BAO}} + \chi^2_{\text{OHD}} + \chi^2_{\text{SLS}} + \chi^2_{\text{HIIG}}, \] (17)
where subscripts indicate the observational measurements under consideration. The rest of the section is devoted to describe the different cosmological observations.

A. Supernovas of Ia Type

The most recent and largest compilation provided by \[33\], contains the observations of the luminosity modulus from 1048 SNIa located in the redshift region \( 0.01 < z < 2.3 \). The merit of function is constructed as
\[ \chi^2_{\text{SN Ia}} = (m_{\text{th}} - m_{\text{obs}}) \cdot \text{Cov}^{-1} \cdot (m_{\text{th}} - m_{\text{obs}})^T, \] (18)
where \( m_{\text{th}} - m_{\text{obs}} \) is the difference between the theoretical and observational bolometric apparent magnitude and \( \text{Cov}^{-1} \) is the inverse of the covariance matrix. The theoretical counterpart is estimated by
\[ m_{\text{th}} = M + 5 \log_{10}[d_L(z)/10 \text{pc}], \] (19)
where \( M \) is a nuisance parameter and \( d_L(z) \) is the dimensionless luminosity distance given by
\[ d_L(z) = (1 + z)c \int_0^z \frac{dz'}{H(z')}, \] (20)
where \( c \) is the light velocity, recovered in order to maintain the correct units.

B. Baryon Acoustic Oscillations

BAO are standard rulers, being primordial signatures of the interaction of baryons and photons in a hot plasma on the matter power spectrum in the pre-recombination epoch. Recently, the authors in \[43\] collected 15 transversal BAO scale measurements, obtained from luminous red galaxies located in the region \( 0.110 < z < 2.225 \). To confront cosmological models to these data, it is useful to build the \( \chi^2 \)-function as
\[ \chi^2_{\text{BAO}} = \frac{1}{\sigma^2_{\theta_{\text{BAO}}}} \sum_{i=1}^{15} \left( \frac{\theta^i_{\text{BAO}} - \theta_{\text{th}}(z_i)}{\sigma_{\theta_{\text{BAO}}}} \right)^2, \] (21)
where \( \theta^i_{\text{BAO}} \) is the BAO angular scale and its uncertainty \( \sigma_{\theta_{\text{BAO}}} \) is measured at \( z_i \). The theoretical counterpart, \( \theta_{\text{th}}(z) \), is estimated as
\[ \theta_{\text{th}}(z) = \frac{r_{\text{drag}}}{(1 + z)D_A(z)} \] (22)
In the latter, $r_{\text{drag}}$ is the sound horizon at baryon drag epoch and $D_A = d_L(z)/(1 + z)^2$ is the angular diameter distance at $z$, with $d_L(z)$ defined in \cite{20}. Finally, we use the $r_{\text{drag}} = 147.21 \pm 0.23$ reported by \cite{2}.

C. Observational Hubble Data

The Observational Hubble Data (OHD) are a cosmological model independent measurements of the Hubble parameter $H(z)$. We consider the OHD compilation provided by \cite{35} which contains 51 points given by the differential age (DA) tool and BAO measurements, within the redshift region $0 < z < 2.36$. Hence, the chi square function for OHD can be written as

$$\chi^2_{\text{OHD}} = \sum_{i}^{51} \left( \frac{H_{\text{th}}(z_i) - H_{\text{obs}}}{\sigma^i_{\text{obs}}} \right)^2,$$

where $H_{\text{th}}(z)$ and $H_{\text{obs}}(z) \pm \sigma^i_{\text{obs}}$, are the theoretical and observational Hubble parameter at the redshift $z_i$.

D. Strong Lensing Systems

The Einstein radius of a lens described by the Singular Isothermal Sphere (SIS), is defined by

$$\theta_E = 4\pi \frac{\sigma^2_{\text{SIS}} D_{ls}}{c^2 D_s},$$

where $\sigma_{\text{SIS}}$ is the velocity dispersion of the lens galaxy, $D_s$ is the angular diameter distance to the source, and $D_{ls}$ is the angular diameter distance from the lens to the source. While the first one is obtained by $D_s = d_L(z)/(1 + z)^2$, the latter is estimated by

$$D_{ls}(z) = \frac{c}{1 + z} \int_{z_l}^{z_s} \frac{dz'}{H(z')} = \frac{c}{1 + z} \int_{z_l}^{z_s} \frac{dz'}{H(z')},$$

where $z_l$ ($z_s$) is the redshift of the lens (source). Hence, it is possible to define a theoretical distance ratio $D^{th} = D_{ls}/D_s$ and the observable counterpart as $D^{obs} = c^2\theta_E/4\pi\sigma^2$. Therefore, the merit of function for SLS is

$$\chi^2_{\text{SLS}} = \sum_{i}^{205} \left[ \frac{D^{th}(z_i, z_s) - D^{obs}(\theta_E, \sigma^2)}{(\delta D^{obs})^2} \right]^2,$$

where

$$\delta D^{obs} = D^{obs} \left[ \left( \frac{\delta \theta_E}{\theta_E} \right)^2 + 4 \left( \frac{\delta \sigma}{\sigma} \right)^2 \right]^{1/2},$$

being $\delta \theta_E$ and $\delta \sigma$ the uncertainties of the Einstein radius and velocity dispersion respectively.

E. HII Galaxies

As it is discussed in \cite{37}, the HIIG can be used as an alternative form to constrain diverse cosmological models due to the correlation between the observed luminosity and the velocity dispersion of the ionized gas. This mentioned correlation can be written as

$$\log L = \beta \log \sigma + \gamma,$$

where $L$ is the luminosity, $\sigma$ the velocity dispersion, $\gamma$ and $\beta$ are the intercept and slope functions respectively. Therefore, the distance modulus takes the form

$$\mu_{\text{obs}} = 2.5 \log L - 2.5 \log f - 100.2,$$

where $f$ is the flux emitted by the HIIG. On the other hand, the theoretical distance modulus is

$$\mu_{\text{th}}(z) = 5 \log d_L(z) + 25,$$

being $d_L(z)$ the luminosity distance defined in \cite{20}. Hence, motivated by the recent collection provided by \cite{37} containing a total of 153 HIIG measurements, we constrain the parameter phase-space $\Theta = (h, \Omega_{\text{m}0}, \bar{\alpha})$ of EGB model by building the following figure-of-merit

$$\chi^2_{\text{HIIG}} = \sum_{i}^{153} \left[ \frac{\mu_{\text{th}}(\Theta, z_i) - \mu_{\text{obs}}(z_i)}{\epsilon^i} \right]^2,$$

where $\epsilon_i$ is the uncertainty of the $i_{th}$ measurement.

IV. RESULTS

Our cosmological constriction applied to EGB model are presented in Figure 2 which the 2D regions correspond to 68% CL (1$\sigma$) and 99.7% CL (1$\sigma$) for darker and lighter contours respectively for each data sample. Furthermore, the central values of the free model parameters with their uncertainties at 1$\sigma$ are summarized in Table I according to each data and the combined data (joint analysis). The joint analysis give us a value of $\bar{\alpha}$ of the order $\sim 10^{-3}$, which is the most restricted bound on $\bar{\alpha}$ through cosmological observables and competitive with those obtained by \cite{21}. These confidence contours also remark that there is not a tension with cosmological data at the background level, but it is needed a CC at least to obtain the expected Universe dynamics. However the mystery of the origin of the CC is still an open question. Moreover, it is presented in Fig. 1 the best fits for the evolution of the Hubble parameter in terms of the red shift for the four cosmological samples and joint; a comparison with the standard cosmological model it is shown, together with the $H(z)$ data. In addition, we show in Figs. 3 the deceleration and jerk parameters and their comparison with ΛCDM. As it is interesting to observe from the jerk reconstruction, the EGB model has as upper limit the ΛCDM in the past ($z > 0$),
having a convergence to this model at $z = 0$. Therefore a possible conclusion is due to the correction terms to $\Lambda$CDM caused by EGB gravity, CC mimics dynamical characteristics instead to have $\Lambda^{ACDM} = 1$ for times $z < 2.5$. Additionally, we estimate a yield value of the deceleration-acceleration transition at $z_t = 0.612^{+0.012}_{-0.012}$. At current epochs, we obtain $q_0 = -0.513^{+0.007}_{-0.007}$ and $j_0 = 0.999^{+0.004}_{-0.004}$ for the deceleration and jerk parameters, respectively. In case of $\Lambda$CDM, the transition redshift is estimated at $z^{ACDM}_{\Lambda} = 0.642^{+0.014}_{-0.014}$, which corresponds a deviation of 0.92$\sigma$, while the deceleration parameter today is $q_0^{ACDM} = -0.63^{+0.02}_{-0.02}$ for $\Lambda$CDM obtaining a deviation of 3.11$\sigma$. Additionally, another useful comparison is with cosmological viscous models like those studied in [14], where $q_0^{CVM} = -0.568^{+0.018}_{-0.021}$, $j_0^{CVM} = 1.058^{+0.039}_{-0.033}$, $q_0^{PVM} = -0.472^{+0.056}_{-0.056}$ and $j_0^{PVM} = 0.444^{+0.344}_{-0.394}$ for the constant (CVM) and polynomial viscous models (PVM) respectively. In comparison, we obtain a deviations up to 1.61$\sigma$ (0.91$\sigma$) between CVM (PVM) and EGB model.

Regarding statefinder analysis, we show in Figs. 4 the phase-state for r-s and r-q respectively. Notice the convergence to the $\Lambda$CDM attractor point for lower values of $\alpha$, as it is expected. Furthermore, it is important to remark that this kind of models predicts an early accelerated phase –not only the accelerated phase at $z \sim 0.6$– (see Figs. 4), which could generate problems for the established knowledge of cosmology, in particular, for important phases of the Universe like structure formation, nucleosynthesis, reionization, among others. Based on our joint analysis, the earlier acceleration-deceleration transition happens around $z_t \approx 17.2$ which coincides with reionization epoch. Notice also that for values of $\bar{\alpha} \sim 10^{-9}$, this transition is moved to the photon decoupling era ($z \approx 1300$). Moreover, lower values for $\bar{\alpha}$ imply a no so long early accelerated phase, which could have important consequences, notice however that through cosmological constrictions always exist this early acceleration (see Figs. 4). Other complementary constrictions developed by astrophysical events could reduce the presence of $\bar{\alpha}$ avoiding the early Universe accelerations predicted by our cosmological constrictions.

V. CONCLUSIONS AND OUTLOOKS

In this paper, we present the constraints for EGB free parameters through the most recent cosmological observation. Our results from the Joint analysis, show that the EGB free parameter $\bar{\alpha}$, must be of the order $0.001^{+0.002}_{-0.001}$, therefore we have that $\alpha \approx 10^{-3}/3H_0^2 = (1.604^{+0.017}_{-0.018}) \times 10^5 \text{eV}^{-2}$, which is the best constrictions up to now using cosmological data at the background level. Our results complement also to those collected in [23], where they found the bound $0 \leq \alpha \lesssim 2.57 \times 10^{51} \text{eV}^{-2}$, from binary black holes systems and $\alpha \approx 10^{49} \text{eV}^{-2}$, from velocity propagation of gravitational waves [24, 25].

In addition, the different cosmological observations are not in tension with the cosmological EGB model, but it is necessary to include a CC to drive the late accelerated expansion phase of the Universe. When the deceleration and jerk parameters were analyzed, we found there is a deceleration-acceleration transition at $z_t = 0.612^{+0.012}_{-0.012}$ which is in agreement with the standard cosmological

\[ \text{FIG. 1: Best fits for each data sample and joint, together with the comparison with the standard } \Lambda \text{CDM model.} \]

\[ \text{FIG. 2: 1D posteriors distributions and 2D contours of the free parameters for EGB model at } 1\sigma \text{ and } 3\sigma \text{ CL (from darker to lighter respectively).} \]
TABLE I: Best fitting values of the free parameters for the EGB model with the different samples used in this paper.

| Sample | $\chi^2$ | $h$    | $\Omega_{m0}$ | $\alpha$ | $\Lambda$ |
|--------|---------|--------|---------------|----------|-----------|
| OHD    | 25.8    | 0.677$^{+0.004}_{-0.004}$ | 0.312$^{+0.005}_{-0.005}$ | 0.011$^{+0.007}_{-0.005}$ | –         |
| BAO    | 40.7    | 0.688$^{+0.004}_{-0.004}$ | 0.315$^{+0.006}_{-0.006}$ | 0.008$^{+0.014}_{-0.006}$ | –         |
| SNla   | 39.8    | 0.677$^{+0.004}_{-0.004}$ | 0.312$^{+0.005}_{-0.005}$ | 0.025$^{+0.028}_{-0.018}$ | $-19.400^{+0.016}_{-0.016}$ |
| SLS    | 577.8   | 0.676$^{+0.004}_{-0.004}$ | 0.311$^{+0.006}_{-0.006}$ | 0.281$^{+0.218}_{-0.143}$ | –         |
| HIIG   | 2269.5  | 0.677$^{+0.004}_{-0.004}$ | 0.331$^{+0.005}_{-0.005}$ | 0.000$^{+0.011}_{-0.005}$ | –         |
| Joint  | 6181.9  | 0.676$^{+0.004}_{-0.004}$ | 0.326$^{+0.005}_{-0.005}$ | 0.001$^{+0.002}_{-0.001}$ | $-19.400^{+0.012}_{-0.012}$ |

FIG. 3: Reconstruction of deceleration and jerk parameters (red solid line) using the joint analysis. Inner (outer) bands represent the uncertainties at 1σ (3σ) CL. Magenta star markers represent $\Lambda$CDM model.

FIG. 4: Top panel: Evolution of EGB model in the statefinder phase-space. At the future, EGB model converges to $\Lambda$CDM. Bottom panel: jerk vs deceleration parameter, showing a division between an accelerated and decelerated Universe. Both panels correspond to the redshift range $-1 < z < 1000$.

model. On the other hand, the analysis of the jerk parameter show us that the CC can mimic a dynamical evolution under the EGB formalism, without adding complexity in the EoS equation associated to DE.

Moreover, the statefinder analysis remarks an accelerated Universe phase in early epochs, which could have affectations in nucleosynthesis or reionization epochs. In particular for the joint analysis results, we have a tran-
sition to an accelerated Universe at $z_t \approx 17.2$, which is into the reionization epoch. As it is possible to observe, large values of $\bar{\alpha}$ generate that the early universe acceleration stay long time, even, never disappears from the scenario evolution like in the case of SLS constrictions. We observe that for values $\bar{\alpha} \sim 10^{-9}$, the acceler-
ated phase happens approximately at photon decoupling epoch, modifying its physics. On the other hand, such earlier acceleration phased may play an important role to explain the inflationary cosmology that could be explored in future works. In this sense, further studies through astrophysical events, such as black holes or neutron stars, are needed to obtain strong constrictions of the parameter $\alpha$ and allow a small range for the early acceleration or rule it out. We remark that models with the presence of a early dark energy, mainly in the recombination epoch, are considered by several authors as solution to the $H_0$ tension between CMB and Supernovae measurements. Finally, to confirm the EGB cosmology predictions it is necessary a perturbative analysis, which will be also studied in future and presented elsewhere.

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