The Integrated Sachs-Wolfe Effect in 4D Einstein-Gauss-Bonnet Gravity

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Abstract

A novel 4-dimensional Einstein-Gauss-Bonnet (4D EGB) gravity has been proposed that asserts to bypass Lovelock's theorem and result in a non-trivial contribution to the gravitational dynamics in four-dimensional spacetime [1]. Although inconsistencies have been raised for this theory in nonlinear perturbation limits, the results of the consistent 4D EGB model indicate that the background equations and the linear scalar modes are in good agreement with the initial 4D EGB model. In this work, we study the integrated Sachs–Wolfe (ISW) effect, as a linear phenomenon, in the 4D EGB model. For this purpose, we calculate the evolution of the gravitational potential, the linear growth factor as a function of redshift, the ISW-auto and cross power spectrum as a function of cosmic microwave background (CMB) multipoles for the 4D EGB model and compare those with the one obtained from the ΛCDM model. The results exhibit that the ISW effect in the 4D EGB model is higher than the one obtained from the ΛCDM model. Correspondingly, we indicate that the deviation from the ΛCDM model is directly proportional to the value of the dimensionless coupling parameter β.

Theoretical Framework

The Gauss-Bonnet (GB) action in D-dimensional spacetime is

$$S_{\rm GB} = \int d^D x \sqrt{-g}\alpha \mathcal{G}, \tag{1}$$

where α is the GB coupling parameter. In this action, $\mathcal{G}$ is the GB invariant and has the following form:

$$\mathcal{G} = R^{\mu\nu\rho\sigma}R_{\mu\nu\rho\sigma} - 4R^{\mu\nu}R_{\mu\nu} + R^2, \tag{2}$$

where $R_{\mu\nu\rho\sigma}$ is the Riemann curvature tensor, $R_{\mu\nu}$ is the Ricci curvature tensor and R^2 is the squared of the scalar curvature. In 4-dimensional spacetime, the GB invariant is a total derivative and does not alter the dynamics of the gravitational system.
4D EGB has been proposed to rescale GB coupling parameter as $\alpha \to \alpha/(D-4)$ in a way that it cancels the factor of $(D-4)$ in the GB action. With these considerations, the total action can be specified as:

$$S = \int d^D x \sqrt{-g}\{\kappa^2(R - 2\Lambda) + \frac{\alpha}{D-4}\mathcal{G} + \mathcal{L}_m\}, \tag{3}$$

The ISW effect

As the CMB photons travel from the last scattering surface to us, they move through gravitational potentials e.g., the galaxy clusters. So, the photons become blueshifted when they move into potential wells and will be redshifted as they move out of the gravitational potential wells. Accordingly, these shifts will be accumulated along the line of sight of the observer.
The ISW-auto spectrum and the ISW-cross spectrum can be calculated respectively as follows [2]:

$$C_{\rm TT}^{ISW}(l) = \int_0^{\chi_{\rm H}} d\chi \frac{W_{\rm T}^2(\chi)}{\chi^2}\frac{H_0^4 P(k = l/\chi)}{k^4}, \tag{4}$$

$$C_{\rm Tg}(l) = \int_0^{\chi_{\rm H}} d\chi \frac{W_T(\chi)W_{\rm g}(\chi)}{\chi^2}\frac{H_0^2 P(k = l/\chi)}{k^2}, \tag{5}$$

where $P(k)$ is the present power spectrum, χ is the comoving distance, k is the wave number, and $W_{\rm T}$ and $W_{\rm g}$ are the window functions.
The ISW window function in the case of a spatially flat Universe with non-clustering dark energy is

$$W_{\rm T}(\chi) = \frac{1}{2c^3}\, a\, \mathcal{H}(a)\frac{d\mathcal{V}}{da}, \tag{6}$$

where $\mathcal{V}(a)$ is a function of scale factor and has been defined as:

$$\mathcal{V}(a) \equiv \frac{a^4(4\alpha\dot{\mathcal{H}} - \mathcal{Q}(a))}{\mathcal{P}^2(a)} \left(\frac{2\kappa^2(3\mathcal{H}^2 - a^2\Lambda)}{a^2} + \frac{6\alpha\mathcal{H}^4}{a^4}\right)\Omega_{\rm m}(a)D_+(a). \tag{7}$$

And the Galaxy window function is:

$$W_{\rm g}(\chi) = \frac{\mathcal{H}(a)}{a\, c} b(z)\frac{dN}{dz}D_+(a), \tag{8}$$

that $b(z)$ is the redshift-dependent bias which relates the baryonic matter to the dark matter, and dN/dz is the redshift distribution of the survey.

Results 1

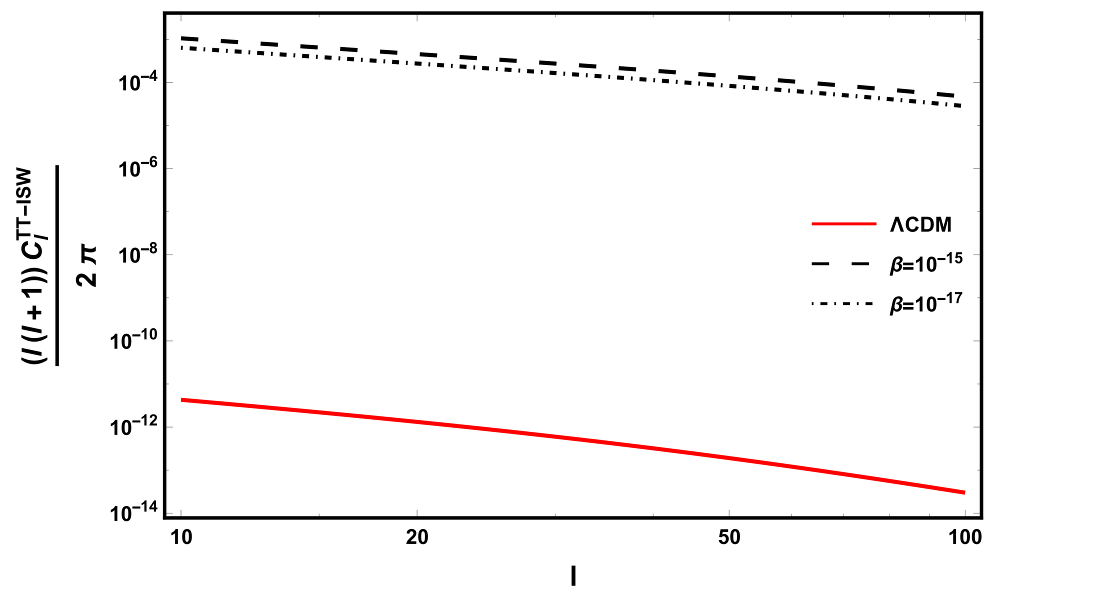

Figure 1: The ISW auto-power-spectrum are shown for ΛCDM (solid-red), $\beta = 10^{-15}$ (dashed) and $\beta = 10^{-17}$ (dot-dashed), respectively

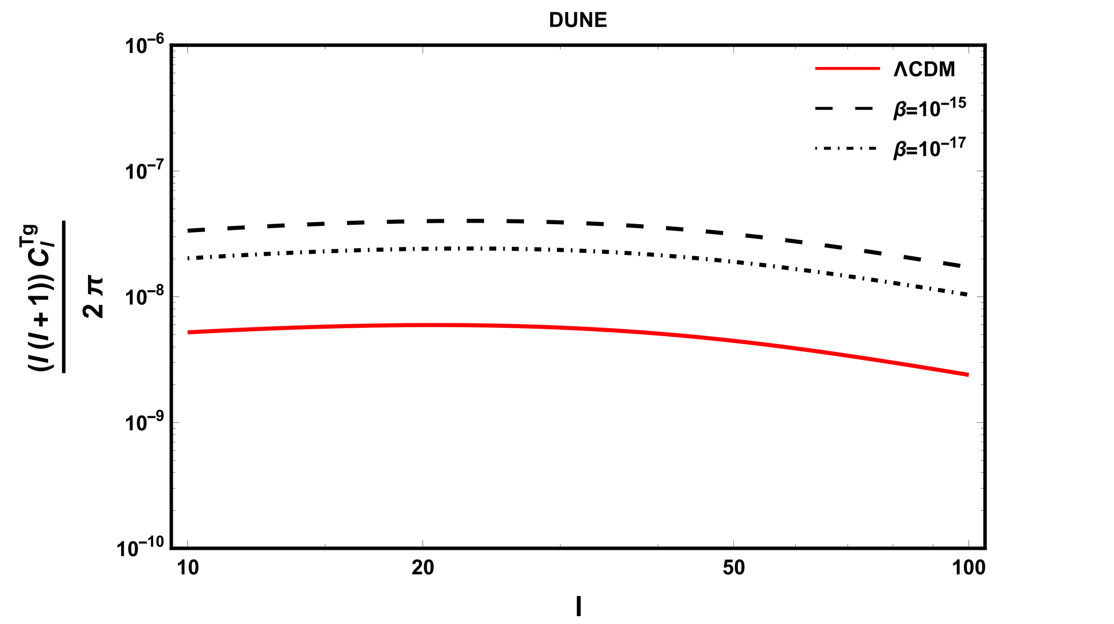

Figure 2: The ISW cross-power-spectrum are shown for ΛCDM (solid-red), $\beta = 10^{-15}$ (dashed) and $\beta = 10^{-17}$ (dot-dashed), respectively for the DUNE sample

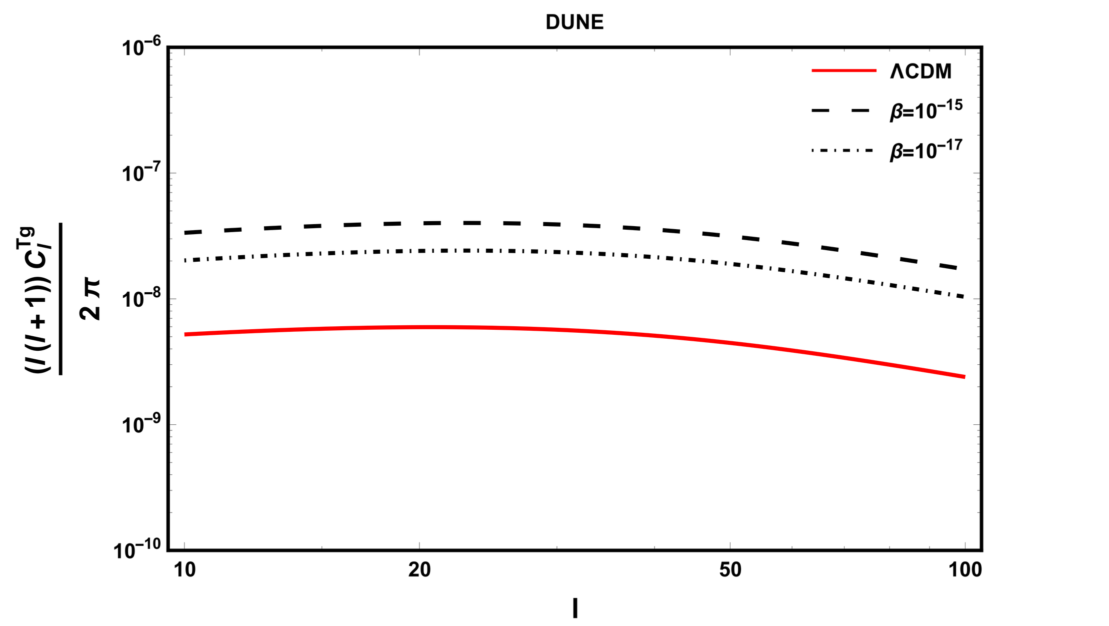

Figure 3: The ISW cross-power-spectrum are shown for ΛCDM (solid-red), $\beta = 10^{-15}$ (dashed) and $\beta = 10^{-17}$ (dot-dashed), respectively for the SDSS-MphG sample.

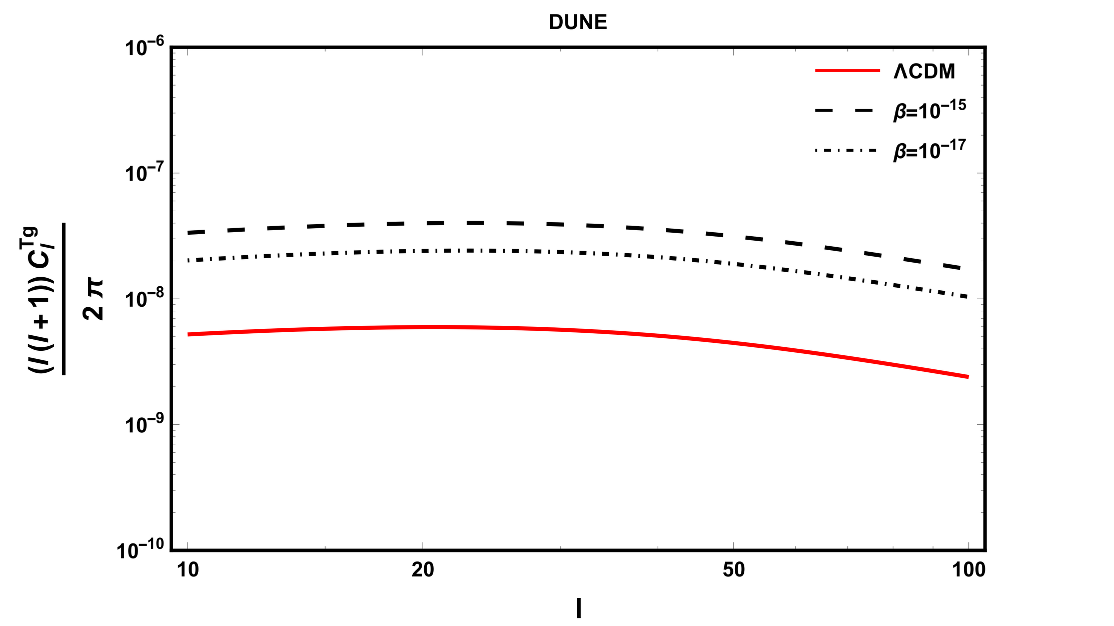

Figure 4: The ISW cross-power-spectrum are shown for ΛCDM (solid-red), $\beta = 10^{-15}$ (dashed) and $\beta = 10^{-17}$ (dot-dashed), respectively for the SDSS-MphG sample.

Conclusion

- The amplitude of the ISW-auto power spectrum for the 4D EGB model displays a major difference that is not consistent with observations. Based on this, it may be necessary to strengthen observational constraints on the coupling parameter of the model β.
- By employing three different surveys, we showed that the 4D EGB model can amplify the ISW-cross power spectrum.

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