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P. Serra

University of California, Irvine

A. Cooray

University of California, Irvine

S. F. Daniel

Dartmouth College

R. R. Caldwell

Dartmouth College

A. Melchiorri

Sapienza University of Rome

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Serra, P.; Cooray, A.; Daniel, S. F.; Caldwell, R. R.; and Melchiorri, A., "Lensed Cosmic Microwave Background Constraints on Post-General Relativity Parameters" (2009). *Dartmouth Scholarship*. 1970. <https://digitalcommons.dartmouth.edu/facoa/1970>

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Lensed Cosmic Microwave Background Constraints on Post-General Relativity Parameters

Paolo Serra¹, Asantha Cooray¹, Scott F. Daniel², Robert Caldwell², Alessandro Melchiorri³

¹*Center for Cosmology, Department of Physics and Astronomy, University of California, Irvine, CA 92697*

²*Department of Physics and Astronomy, Dartmouth College, Hanover, NH 03755 USA and*

³*Physics Department and Sezione INFN, University of Rome,*

“La Sapienza,” P.le Aldo Moro 2, 00185 Rome, Italy

(Dated: January 1, 2018)

The constraints on departures from general relativity (GR) at cosmological length scales due to cosmic microwave background (CMB) data are discussed. The departure from GR is measured by the ratio, parameterized as $1 + \varpi_0(1+z)^{-S}$, between the gravitational potentials conventionally appearing in the geodesic equation and the Poisson equation. Current CMB data indicate $\varpi_0 = 1.67^{+3.07}_{-1.87}$ at the 2σ confidence level, while S remains unconstrained. The departure from GR affects the lensing conversion of E-mode into B-mode polarization. Hence, the lensing measurements from a future CMBpol experiment should be able to improve the constraints to $\varpi_0 < 0.30$ for a fiducial $\varpi_0 = 0$ model and independent of S .

Introduction—The quest for the source of the cosmic acceleration has led to speculation that the proper theory for gravitation departs from general relativity (GR) on cosmological length scales (e.g. Ref. [1]). There are numerous theoretical examples that introduce new gravitational degrees of freedom and that are capable of producing a late-time acceleration, with wide-ranging implications for observable phenomena (e.g. Refs. [2, 3]). Given this possible abundance in new physics, it is important to identify tests that can distinguish between the effects of dark energy and those of modified gravity. Though late-time accelerated cosmic expansion is the principal indicator that a new “dark” physics is needed, it is not the only test such physics must satisfy. A successful cosmology must also agree with measurements related to the behavior of inhomogeneities as probed by the cosmic microwave background and large-scale structure.

To understand the extent to which cosmological data support GR, we make use of an approach motivated by the post-Newtonian parameterization of the gravitational field within the Solar system and introduce a post-GR parameterization for cosmological perturbations. Such a parameterization is also motivated by the common feature within a broad range of gravity theories of a decoupling of the perturbed Newtonian-gauge gravitational potentials ϕ and ψ , defined by the perturbed Robertson-Walker line-element

$$ds^2 = a^2 [-(1 + 2\psi) d\tau^2 + (1 - 2\phi) d\vec{x}^2], \quad (1)$$

using the notation and convention of Ref. [4].

Whereas GR predicts $\psi = \phi$ in the presence of non-relativistic matter, a *gravitational slip*, defined as $\psi \neq \phi$, occurs in modified gravity theories. For example, this inequality means that the gravitational potential of a galaxy cluster is not the same potential traced by the geodesic motion of the constituent galaxies. Hence, a new relation between these potentials is a launching point for investigations of cosmological manifestations of modified gravity [6, 7]. For primordial cosmological perturbations, the potentials

are not completely free, however, as there exists a constraint equation in the long-wavelength limit [5].

We consider an alternative theory of gravitation that predicts an expansion history indistinguishable from Λ CDM, accompanied by post-GR effects whereby

$$\psi(\tau, \vec{x}) = [1 + \varpi(\tau, x)] \phi(\tau, \vec{x}), \quad (2)$$

following Refs. [8, 9]. If the new gravitational phenomena is to mimic the effects of Λ by changing the amount of spacetime curvature produced by the cosmic matter density, then we expect ϖ to grow to order unity at late times on large scales. Looking for clues to such a scenario, CMB temperature anisotropies alone provide a weak constraint to ϖ as the departure from GR is primarily manifest in the integrated Sachs-Wolfe effect [10, 11], as illustrated in Fig. 1. However, CMB lensing is also sensitive to ϖ because the lensing deflection of CMB photons by foreground large-scale structure depends on the sum of the potentials $\psi + \phi$ [12, 13, 14, 15]. In this *Letter*, we show that the expected conversion of E-mode to B-mode polarization through lensing [16], shown in Fig. 1, allows a new probe of departures from GR that will be accessible to future CMB B-mode polarization experiments.

The lensing of the CMB affects temperature perturbations at the level of a few percent at arcminute angular scales, which is on the damping tail of CMB anisotropies [17]. Using temperature anisotropy data from WMAP [18] and ACBAR [19] we can only put weak constraints on the post-GR parameterization at present. On the other hand, B-modes at tens of arcminute angular scales are mainly due to the lensing conversion from E-modes. Using the combination of E- and B-modes one can reconstruct the lensing signal in CMB data by using quadratic statistics [20, 21, 22] and likelihood methods [23]. The projected lensing potential power spectrum out to the last scattering surface can then be used to extract ϖ . As we find, upcoming high sensitivity CMB polarization experiments, such as CMBpol [24, 25] of NASA’s Beyond

Einstein program, have a significant role to play in constraining GR at cosmological length scales.

Calculational Method—The treatment of cosmological perturbations under modified GR follows from Ref. [9]. The metric perturbation variables in the synchronous and conformal Newtonian gauges are related as $\psi = \dot{\alpha} + \mathcal{H}\alpha$, $\phi = \eta - \mathcal{H}\alpha$, where $\alpha \equiv (\dot{h} + 6\dot{\eta})/2k^2$, h , η are synchronous-gauge metric variables, and the dot indicates the derivative with respect to the conformal time [4]. In GR ($\varpi = 0$), the perturbed Einstein equations,

$$k^2\eta - \frac{1}{2}\mathcal{H}\dot{h} = 4\pi Ga^2\delta T_0^0 \quad (3)$$

$$k^2\dot{\eta} = 4\pi Ga^2(\bar{\rho} + \bar{p})\theta \quad (4)$$

$$\ddot{h} + 2\mathcal{H}\dot{h} - 2k^2\eta = -8\pi Ga^2\delta T_i^i, \quad (5)$$

are used to evolve the metric variables, where $(\bar{\rho} + \bar{p})\theta \equiv ik^j\delta T_j^0$ [4].

In our post-GR description, we assume the stress-energy tensor is conserved and that there is no preferred reference frame introduced by the new gravitational effects. Consequently, Eq. (4) remains valid but Eqns. (3, 5) do not. Because gravitational slip is degenerate with a cosmological fluid component with shear, Eq. (2) becomes

$$\dot{\alpha} = -(2 + \varpi)\mathcal{H}\alpha + (1 + \varpi)\eta - 12\pi Ga^2(\bar{\rho} + \bar{p})\sigma/k^2. \quad (6)$$

This modification preserves the consistency condition for long wavelength cosmological perturbations [5, 9].

In our study we restrict attention to a homogeneous model of gravitational slip,

$$\varpi = \varpi_0(1 + z)^{-S}, \quad (7)$$

and seek to constrain the post-GR parameters ϖ_0 and S . By allowing the redshift dependence of the modified gravity parameter ϖ to be a free parameter, this relationship is more general than the one introduced in Ref. [8]. (Note that we have also removed a prefactor Ω_Λ/Ω_m .)

The lensing deflection of CMB photons by foreground large-scale structure depends upon gradients in the total gravitational potential $\phi + \psi$ transverse to the line of sight to the last scattering surface [17]. The evolution of the lensing potential is separated from the primordial curvature perturbation $R(\vec{k})$ using a transfer function $T_\phi(\vec{k}, \tau)$, whereby $\phi(\vec{k}, \tau) = T_\phi(k, \tau)R(\vec{k})$. Hence, the power spectrum of the lensing potential is

$$C_\ell^\phi = 4\pi \int \frac{dk}{k} P_R(k) \left[\int_0^{\chi_*} d\chi S_\phi(k; \tau_0 - \chi) j_\ell(k\chi) \right]^2. \quad (8)$$

Here $P_R(k)$ is the primordial power spectrum, $\tau_0 - \chi$ is the conformal time at which a given photon was at the position $\chi\hat{n}$, and the lensing source is given by:

$$S_\phi(k, \tau_0 - \chi) = (2 + \varpi)T_\phi(k, \tau_0 - \chi)j_\ell(k\chi) \left(\frac{\chi_* - \chi}{\chi_*\chi} \right), \quad (9)$$

where we have made use of the post-GR relation between ϕ and ψ to simplify the expression in terms of the transfer function of ϕ . To evaluate the lensing source and angular power spectrum, we use Eqns. (4, 6) to evolve η and α , from which ϕ is obtained. The lensing potential for different values of the post-GR parameters is shown in Fig. 1. In the case of temperature, lensing modifies the damping tail. The B-mode polarization signal due to lensing that peak at tens of arcminute angular scales is directly proportional to the lensing power spectrum. We ignore non-linear corrections to the lensing calculation as non-linearities are responsible for less than a 6% change to the B-modes [17] and we only consider parameter constraints out to $l < 700$ when using C_ℓ^ϕ .

The E- to B-conversion is on an angular scale where it is not contaminated by primordial gravitational wave signal in the B-modes, which are relevant at larger angular scales, if at all. And although the implicitly assumed theory of gravitation should introduce new degrees of freedom, the scalar-vector-tensor decomposition of perturbations in linear theory ensures us that no further sources of B-mode polarization should arise. We further caution that viable models must satisfy $|\varpi| \lesssim 10^{-5}$ within the Solar System, with a transition taking place near the outskirts of the galaxy. Rather than implying a scale-dependence for post-GR effects, this suggests that a viable model for ϖ must display a nonlocal or environmental dependence on the density field, with ϖ vanishing within a few tens of kpc of a galactic core. CMB photons are weakly lensed by Mpc-scale density perturbations, but should not experience post-GR effects while passing so near to galactic cores. On the celestial sphere, kpc radii subtend angular scales well below the angular scales of interest for next-generation polarization experiments. Thus, we tentatively ignore the position-dependence of the post-GR effects introduced by Eq. 2.

In the case of temperature anisotropies, at small angular scales where the lensing effect is present, confusion from other secondary signals, most notably the Sunyaev-Zel'dovich effect [26, 27] and clustering of unresolved extragalactic point sources [28], must also be considered. When fitting to WMAP and ACBAR data, we take into account the contribution from clustered point sources on the angular power spectrum in order to avoid a bias in the determination of the cosmological parameters. We do this by writing the total CMB anisotropy spectrum as $C_\ell^{\text{tot}} = C_\ell^{\text{CMB}} + C_\ell^{\text{PS}} + C_\ell^{\text{SZ}}$ and allowing the amplitudes of both the SZ contribution (A_{sz}) and clustered point sources (with varying amplitudes for the two different experiments [28]) to vary as free parameters when fitting for the combined cosmological and post-GR parameters.

We make use of the publicly available Markov Chain Monte Carlo (MCMC) package CosmoMC [29] with a convergence diagnostic based on the Gelman and Ru-

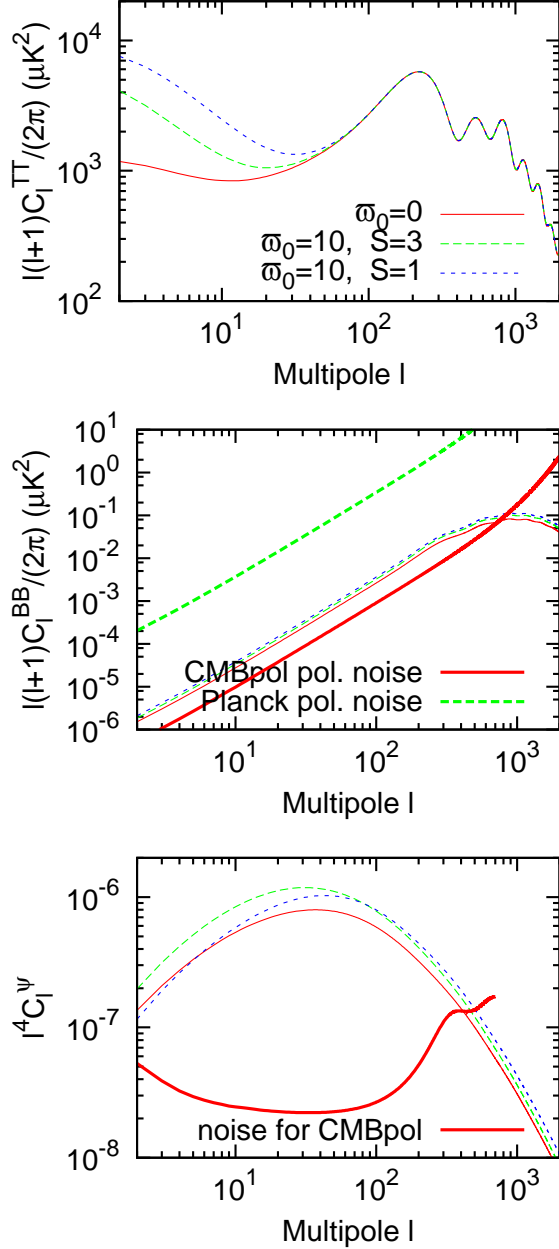


FIG. 1: The effect of the modified gravity parameters on the temperature, B-mode polarization, and lensing potential power spectra for the best fit Λ CDM model from WMAP5+ACBAR [18]; we also show the measurement error for B-mode polarization measurements with Planck and CMBpol and the CMBpol noise for lensing reconstruction (up to $l = 700$).

bin statistic [30] to model fit the data. The post-GR parameters are allowed to take values $-5 < \varpi_0 < 10$ and $0 < S < 10$. In addition, we implement the flat Λ CDM cosmological model with six standard parameters: baryon density $\Omega_b h^2$; dark matter density $\Omega_c h^2$; reionization optical depth τ ; ratio of the sound horizon to the angular diameter distance at the decoupling

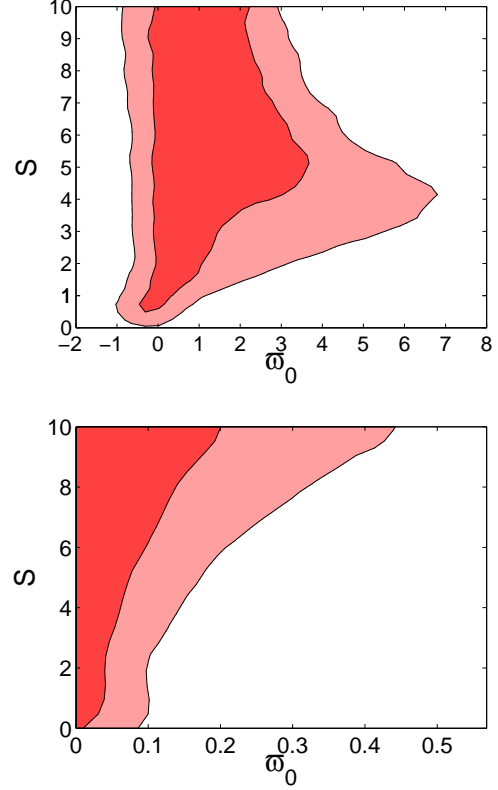


FIG. 2: Two-dimensional contours at 1σ (dark) and 2σ (light) in the plane ϖ_0 - S for WMAP+ACBAR (top panel) and CMBpol (bottom panel).

measured by θ ; amplitude of the curvature perturbation A_s (with flat prior on $\log(A_s)$; spectral index n_s . These two last parameters are defined with respect to a pivot scale at 0.002 h/Mpc , as in Ref. [31].

Results—We first use the combination of WMAP 5-year [18] and ACBAR data [19] (both temperature and temperature-polarization cross-correlation). To avoid complications due to overlapping of the datasets, we use WMAP data out to $\ell < 900$ and then ACBAR data in the range $900 < \ell < 2000$. The constraint on ϖ_0 is $\varpi_0 = 1.67^{+3.07}_{-1.87}$ at the 2σ confidence level, but S remains unconstrained. As shown in the upper panel of Fig. 2, there is a clear correlation between S and ϖ_0 : when S goes to 0 only very small values of ϖ_0 are allowed and when $S \sim 5$, values of $\varpi_0 \sim 6$ are allowed at the 2σ confidence level.

By including the post-GR parameterization, we find that cosmological parameters from WMAP+ACBAR change by less than 1σ ; for example, with post-GR effects, $\sigma_8 = 0.814 \pm 0.044$ and $n_s = 0.954 \pm 0.014$ while $\sigma_8 = 0.803 \pm 0.034$ and $n_s = 0.964 \pm 0.014$ [18] without post-GR effects.

To study the extent to which future CMB data improve these constraints, we create mock datasets for both Planck and CMBpol. For Planck we create a mock temperature and polarization dataset with noise

properties consistent with a combination of Planck at 100, 143, and 217 GHz channels of HFI [32]. We assume the best fit WMAP5+ACBAR parameters without modified gravity [18] as the underlying cosmological model. We use the full-sky likelihood function given in Ref. [33] when fitting the data. The upper and lower limits with Planck don't show improvement compared to the case with WMAP and ACBAR; S is still unconstrained and $\varpi_0 < 5.08$ (2σ), mostly due to degeneracies with other cosmological parameters. While we include polarization information, Planck does not probe the lensed B-mode spectrum with adequate signal-to-noise ratio, as seen in the middle panel of Fig. 1.

To study how improved polarization measurements, and thereby a measurement of the lensing potential power spectrum, improve the parameter constraints, we also make mock datasets for CMBpol using 70 GHz to 220 GHz for the 2-meter version of the EPIC concept study [25]. We also make a mock dataset of the lensing potential power spectrum under the same cosmological model by creating the noise spectrum for the lensing construction with using same experimental noise as above concept with the reconstruction calculated using quadratic statistics [20]. To avoid any biases from non-linearities, we consider only multipoles out to $l < 700$ probed by CMBpol. The projected

upper limit with CMBpol is $\varpi_0 < 0.30$ (2σ), showing significant improvement compared to the present-day CMB constraints; the parameter S remains unconstrained as we find the same strong correlation with the amplitude ϖ_0 .

Previous studies have shown that the combination of Planck and a probe of the large-scale structure weak lensing such as from NASA/DOE JDEM or the ESA-based Euclid can improve constraints of modified gravity. With $S = 3$ fixed, the Planck and future weak lensing combination constrains $\varpi_0 = -0.07^{+0.13}_{-0.16}$ at the 95% confidence level [34]. In comparison with an experiment such as CMBpol using lensing information from B-modes, we have considered the constraints on both the amplitude and the redshift-dependence of the post-GR effects. If we fix $S = 3$, then for CMBpol we find $\varpi_0 < 0.11$ (2σ), which is comparable to the projections for Planck and a half-sky space-based weak lensing survey with Euclid. While competitive, the advantage with the CMB constraint is that it comes from a single dataset and avoids issues related to systematics that can impact weak lensing observations.

AC and PS acknowledge support from NSF CAREER AST-0645427. PS thanks Alex Amblard for useful discussions. RC and SD are supported by NSF AST-0349213 at Dartmouth.

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