Physics Letters B 742 (2015) 353–357

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Friction in gravitational waves: A test for early-time modified gravity

Valeria Pettorino *, Luca Amendola

Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 16, D-69120 Heidelberg, Germany

ARTICLE INFO

Article history:
Received 30 August 2014
Received in revised form 3 December 2014
Accepted 2 February 2015
Available online 4 February 2015
Editor: M. Trodden

ABSTRACT

Modified gravity theories predict in general a non-standard equation for the propagation of gravitational waves. Here we discuss the impact of modified friction and speed of tensor modes on cosmic microwave polarization B modes. We show that the non-standard friction term, parametrized by α_M, is degenerate with the tensor-to-scalar ratio r, so that small values of r can be compensated by negative constant values of α_M. We quantify this degeneracy and its dependence on the epoch at which α_M is different from the standard, zero, value and on the speed of gravitational waves c_T. In the particular case of scalar-tensor theories, α_M is constant and strongly constrained by background and scalar perturbations, $0 \le \alpha_M < 0.01$ and the degeneracy with r is removed. In more general cases however such tight bounds are weakened and the B modes can provide useful constraints on early-time modified gravity.

In modified gravity models, the equation for the tensor metric perturbations (gravitational waves) is affected in several ways. First, the speed c_T of the gravitational waves can be different from the speed of light [3,24]. A second effect is instead related to a modification of the friction term in the tensor equation that depends on the evolution rate of the effective Planck mass or equivalently on the effective universal gravitational interaction of the cosmological model [5]. In more general modifications of gravity, for instance in bimetric models [10], two coupled tensor equations are present, corresponding to the two metrics of the theory and additional changes are possible [25]. Considering only the first two possible modifications, gravitational wave speed and friction, the linear generalized tensor equation for the amplitude h in vacuum can be written in a Friedmann–Robertson–Walker (FRW) metric as [8,5]:

$$\ddot{h} + (3+\alpha_M)H\dot{h} + c_T^2 \frac{k^2}{a^2} h = 0, \qquad (1)$$

where the dot represents derivative with respect to cosmic time, α_M, c_T are time-dependent functions that vary with the specific model, k is the wavenumber, a is the scale factor and H the Hubble function. In the standard case one has $\alpha_M = 0$ and the speed of gravitational waves c_T equals the speed of light, $c_T = 1$. General models belonging to the so-called Horndeski Lagrangian [11] produce both effects, i.e. $\alpha_M \neq 0$ and $c_T \neq 1$. When anisotropic stress is present [9], a source term in (1) is also included, although it is typically negligible.

Any modification of the tensor wave equation can potentially lead to observable effects on the Cosmic Microwave Background (CMB), on both the temperature and the polarization spectra. The recent measurement of the B-modes at multipoles around $\ell = 100$ reported by the BICEP2 experiment [2], as well as follow up analysis on foreground contributions such as dust emission [6,16,23,21], has motivated a great interest in the information contained in the polarization B-mode signal, especially for as concerns the inflationary dynamics. As it is well known, in absence of vector sources, the primordial B-mode spectrum is generated exclusively by tensor waves and affects small to intermediate multipoles. Larger multipoles $\ell \gtrsim 100$ are mainly affected by CMB-lensing. In [3,24] it has been shown that the gravitational wave speed at the epoch of decoupling or before affects the position of the inflationary and of the reionization peak in the polarization B-modes so that a measurement of B-modes at $\ell \approx 100$ can be employed to set limits on the early-time speed of gravitational waves.

In many cases, the effects of these changes on the CMB can be safely neglected if one assumes that gravity deviates from the Einsteinian form only recently, as in several models proposed to explain the recent epoch of cosmic acceleration by non-standard gravity. In general, however, modification of gravity can occur at any time in the past; in some models, e.g. Brans–Dicke theories or some bimetric models [14], gravity is modified at all times. In this Letter we wish to study the impact and limits that the current observations of B-modes can set on the two modified gravity tensor

* Corresponding author.
E-mail address: v.pettorino@thphys.uni-heidelberg.de (V. Pettorino).

http://dx.doi.org/10.1016/j.physletb.2015.02.007

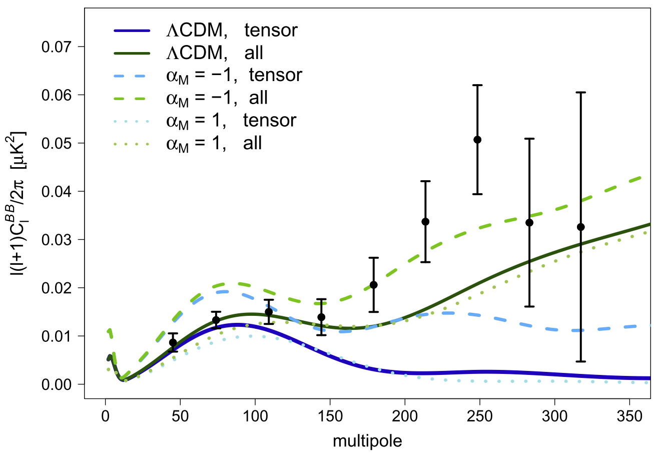

Fig. 1. CMB BB spectra for two values of α_M and for ΛCDM. We plot both tensor contribution only (blue lines) and the total spectra (green lines), including lensing. The data points are from BICEP2. The case $\alpha_M = 0$ coincides with ΛCDM. For this plot, $c_T^2 = 1$ and $r_{0.05} = 0.2$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

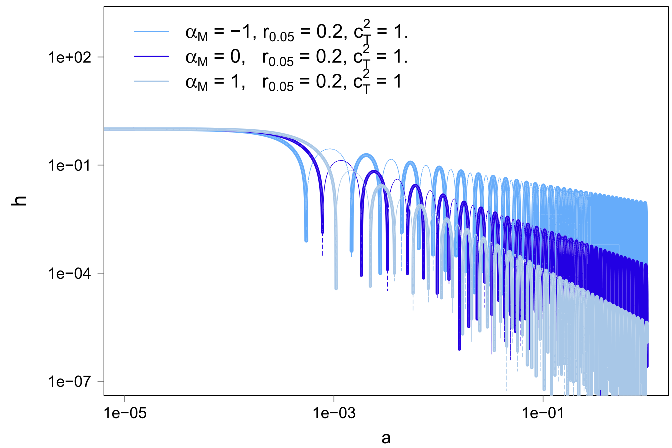

Fig. 2. Tensor perturbation evolution for $k \sim 0.01$ for two values of α_M and for ΛCDM. Thin dashed lines show the absolute value.

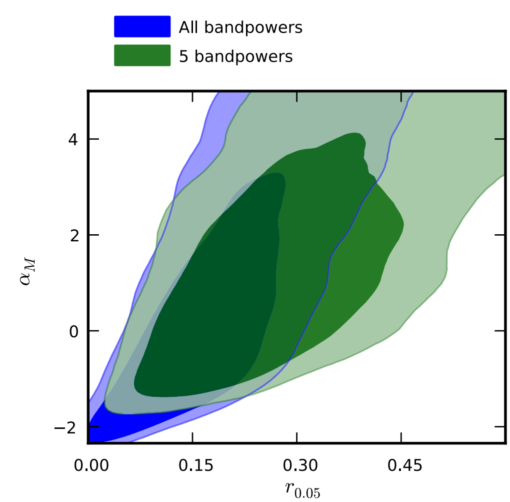

Fig. 3. Posterior likelihood for α_M and $r_{0.05}$. Blue contours are obtained using all nine bandpowers from BICEP2 while green (top) contours include only the first five bandpowers. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

parameters, α_M and c_T. Although they are both in general time-dependent quantities, we assume here for simplicity that they are constant or that they deviate from the standard case only at early time, i.e. before some epoch z_d.

We have modified the tensor equation in CAMB[1] and combined it within CosmoMC [15] to include the α_M, c_T parameters. We first consider the case in which $c_T = 1$ but α_M is arbitrary and constant. All the other parameters are as in standard ΛCDM. In Fig. 1 we show the effect of α_M on the BB spectrum of the CMB both on the tensor modes only and on the total spectrum. As expected, a positive α_M increases the friction term and therefore reduces the wave amplitude, while a negative α_M has the opposite effect.

From Fig. 1 we can expect a degeneracy between the tensor-to-scalar ratio r and α_M, as they both regulate the amplitude of the primordial peak. Comparing only with the BICEP2 data and fixing the optical depth to the Planck best fit value ($\tau = 0.09$ for Planck + WMAP polarization [22]), we obtain the allowed region for (α_M, r), shown in Fig. 3, which clearly shows the degeneracy. Values of r close to zero can be reconciled with the BICEP2 data if α_M is close to -2. This is the central result of this paper. In the same figure we also compare the results obtained when including all nine band powers of BICEP2 with the case in which only the first five are included. As expected from Fig. 1, a negative value of α_M also increases tensor modes at large multipoles, therefore smaller values of α_M are favored if also the last four (higher multipole) band powers of BICEP2 are included. The corresponding evolution of tensor perturbations is shown in Fig. 2.

Before drawing any conclusion from Fig. 3, one should consider however that the term α_M, as already mentioned, is proportional to the time derivative of $G_{\rm eff}$. It enters, therefore, into the scalar perturbation equations and contributes to the Sachs–Wolfe, Integrated Sachs–Wolfe and lensing signal, affecting both the temperature and the polarization spectra. In principle, one should therefore consider all the spectra at the same time, and also the background evolution which in general will be different from ΛCDM. However to a large extent the low-ℓ B modes are independent of all the other signals (T and E spectra, and high-ℓ B modes) since they depend uniquely on the tensor modes; on the other hand, tensor modes affect only marginally the other CMB spectra. Therefore, to a first approximation, we can just use the already available constraints on α_M in some specific model to see which fraction of the parameters space of Fig. 3 is allowed.

Let us consider for instance one of the simplest cases of modified gravity, the scalar-tensor theory. Perturbation equations for scalar-tensor theories with a scalar field ϕ have been calculated for example in [4,12] including tensor equations for the metric. For a model with Lagrangian

$$L = \sqrt{-g}\left[f(\psi)R - 2\kappa^2\left(\frac{1}{2}\psi_{;\mu}\psi^{;\mu} + V(\psi)\right)\right] \tag{2}$$

where $\kappa^2 = 8\pi G$ and R is Ricci's scalar, the gravitational wave equation turns out to be

$$\ddot{h} + \left(3H + \frac{\dot{\phi}}{\phi}\right)\dot{h} + \frac{k^2}{a^2}h = 0 \tag{3}$$

if we introduce the rescaled field $\phi = f(\psi)$. Therefore in scalar-tensor theories we can readily identify

$$\alpha_M = \frac{\dot{\phi}}{\phi H} = \frac{d\log\phi}{d\log a}. \tag{4}$$

[1] http://camb.info/.

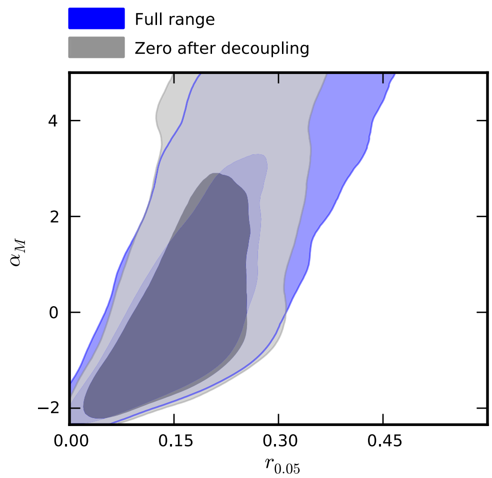

Fig. 4. Posterior likelihood for α_M and $r_{0.05}$. Blue (top) contours are obtained using all nine bandpowers from BICEP2 and modifying α_M in the full z range (same as previous figures). Gray contours correspond to the case in which α_M is only modified up to decoupling. We fix $c_T = 1$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In the simplest form of scalar-tensor model, the original Brans–Dicke model

$$L = \sqrt{-g}\left[\phi R - \kappa^2 \frac{\omega}{\phi}\phi_{;\mu}\phi^{;\mu}\right] \tag{5}$$

the evolution is controlled by the single observable parameter ω. As long as the matter density is dominated by a component with constant equation of state w_m the background expansion has a simple analytical solution [19],

$$\phi \sim t^{\frac{2-6w_m}{4+3\omega-3\omega w_m^2}}, \quad a \sim t^{\frac{2+2\omega-2\omega w_m}{4+3\omega-3\omega w_m^2}}. \tag{6}$$

In this case, we can relate the α_M parameter to ω, so that:

$$\alpha_M = \frac{2-6w_m}{2+2\omega-2\omega w_m}. \tag{7}$$

During the matter dominated era, this becomes simply $\alpha_M = 1/(1+\omega)$. The local gravity constraints on ω are extremely tight, $\omega > 25{,}000$ [20], but they could be escaped if the scalar couples to dark matter only. In order to obtain more general constraints one can use cosmological observations, as e.g. CMB or large-scale structure. In this case one has typically $\omega > 100$ (see e.g. [1]), so we get $0 \le \alpha_M < 0.01$. Taking this constraint at face value, we should conclude that the effect of α_M on the tensor modes is practically negligible. However, this is only true for the particular case in which $\alpha_M = \text{const}$ at all times. If α_M varies in time (as expected in general) and in particular if α_M is very small after decoupling, the scalar effects can become arbitrarily weak since they are mostly due to post-decoupling physics (except of course for the inflationary initial conditions, that we are assuming to be independent of the gravity modifications we are considering here). On the other hand, B modes depend on the evolution of gravitational waves before decoupling. To give an example, if we have an extreme case in which α_M suddenly decreases to zero just after decoupling then the B modes would be practically the same as if α_M were constant at all times (see Fig. 4), while the scalar perturbations would be the same as in ΛCDM. In this case, α_M has effect on B modes up to decoupling, while it has no impact on secondary anisotropies such as integrated Sachs–Wolfe and CMB lensing. As a consequence, the constraints we obtain on α_M from B modes are also valid for all those models in which the modified gravity effects are due to an α_M that is a non-zero constant only until the epoch of decoupling. Needless to say, assuming α_M to be exactly zero immediately after the decoupling serves merely as an illustrative example and should not be taken as a realistic model.

A larger friction term has two competing effects: on one side, it delays the horizon reenter and the subsequent damping, therefore momentarily enhancing the tensor amplitude; on the other, it increases the damping itself, quenching the "acoustic" oscillations more than in the standard case. This implies that if the epoch at which α_M goes to zero moves from the decoupling to an earlier epoch, e.g. $z_d = 2000$, the BB spectra change in a non-trivial way. High multipoles, e.g. $\ell \gg 100$, which correspond to wavelengths that are well within the horizon at decoupling, move monotonically closer to the ΛCDM spectrum the higher is z_d, as expected since α_M vanishes during a longer part of the evolution. Modes that are crossing the horizon at decoupling, however, have a more complicate behavior since they are just beginning their oscillations: for these scales the trend is not monotonic with z_d when z_d is close to the decoupling epoch. Only for z_d larger than 10,000 are they back to the ΛCDM amplitude. Since r is related to the primordial peak in the BB spectrum, which changes non-monotonically if α_M is set to zero before decoupling, this also means that the direction of the degeneracy between r and α_M is not necessarily the one in Fig. 3 if α_M is not constant at all times until decoupling. In particular, even for negative $\alpha_M = -1$, the primordial B spectrum becomes smaller than ΛCDM if $z_d \approx 1500$. The degeneracy becomes then inverted (larger r corresponding to smaller α_M if z_d is larger than 1500, for instance fixed to matter-radiation equality). The degeneracy between $r_{0.05}$ and n_s shown in [3] is weakened when α_M is free to vary.

Since α_M is related to $G_{\rm eff}$, another caveat is that $G_{\rm eff}$ influences the growth of scalar perturbations before decoupling. As a consequence, r can also change indirectly through the Poisson equation and the modification of scalar perturbations, even if tensor spectra stay the same. This effect will have to be investigated more systematically implementing also the full set of scalar equations, which is beyond the scope of this paper. However we note that it will mainly play a role only after perturbations have entered the horizon, affecting scalar perturbations only for $\ell \gtrsim 100$ through a change in the Sachs–Wolfe effect, given by the different gravitational potential. Moreover, a change in $G_{\rm eff}$ could be compensated with a change in Ω_m. If z_d is set to a redshift before the equality, the effect should be negligible as matter perturbations only start growing when α_M is already zero.

We can now consider simultaneously both parameters, α_M and c_T. In this case, marginalizing over c_T, we obtain the contours in Fig. 5, which appear to be very similar to the case in which we fix $c_T = 1$. The contours of α_M, c_T and r, c_T are in Fig. 6. We find a mean and standard deviation for $c_T^2 = 1.3 \pm 0.5$ with a best-fit of $c_T^2(\text{best fit}) = 0.8$ which is compatible with ΛCDM and, most of all, the same value found in [3,24] using also the temperature power spectra besides BICEP2. This confirms that the relevant epoch during which the tensor equation is affected mainly by B modes is the one before decoupling.

We remark that the speed of gravitational waves can be constrained also with the gravi-Cherenkov effect (see e.g. [7,13,18]), which gives a tight lower limit but no upper limit. However, this methods applies only locally (or at most within the distance scale of cosmic rays) and/or at the present time; therefore, they are complementary to the observation of B-modes.

Finally, we note that the theoretical BB spectrum shows another peak at $\ell \approx 5$, still to be detected, due to the effects of tensor modes on the scattering during reionization. A non-zero α_M changes the amplitude of the reionization peak, similarly to what happens when c_T is modified [3]. Its detection, for instance with

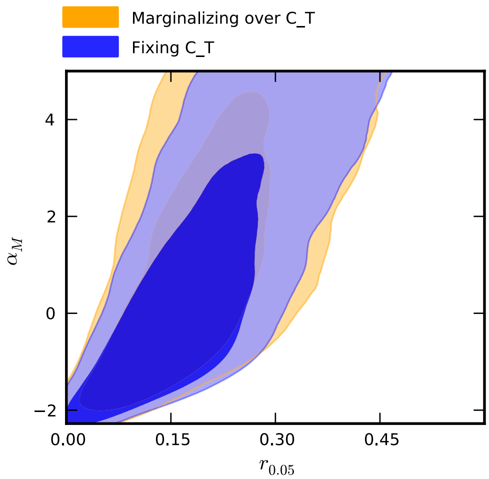

Fig. 5. Posterior likelihood for α_M and $r_{0.05}$. Blue (top) contours are obtained using all nine bandpowers from BICEP2 and fixing c_T while orange contours marginalize over c_T. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

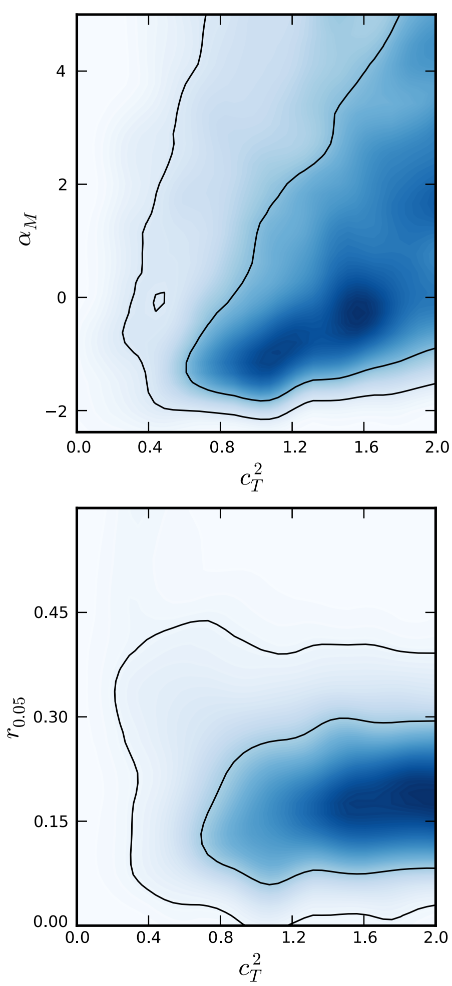

Fig. 6. Posterior likelihood for α_M and $r_{0.05}$ vs c_T^2.

the proposed satellite mission LiteBIRD [17],[2] could therefore put constraints on the friction and gravitational wave speed before and during reionization.

[2] http://litebird.jp/.

In conclusion, we have studied the impact on B modes of a modified gravity tensor equation taking into account both the friction and the speed term. We have shown that a low value of the tensor-to-scalar ratio r can be reconciled with the BICEP2 recent data if α_M is close to -2. In the case in which all signal will turn out to be mainly due to dust [21], the BICEP2 measurements would mainly give a bound on the B mode primordial signal, that can still be used to constrain modifications of gravity. The lensing part of the B mode signal is also degenerate with modifications of gravity, as shown in Fig. 1. In specific models, such as Brans–Dicke scalar-tensor theories, the α_M parameter is already strongly constrained by the temperature spectra and the degeneracy with r is removed. We argue however that in general this is not the case and therefore the BB spectrum is a useful test of early time modifications of gravity.

Acknowledgements

The authors acknowledge the DFG TransRegio TRR33 grant on 'The Dark Universe'. The authors thank Guillermo Ballesteros, Francesco Montanari and Marco Raveri for fruitful discussion.

References

[1] V. Acquaviva, C. Baccigalupi, S.M. Leach, A.R. Liddle, F. Perrotta, Structure formation constraints on the Jordan–Brans–Dicke theory, Phys. Rev. D 71 (10) (May 2005) 104025.
[2] P.A.R. Ade, et al., BICEP2 Collaboration, Detection of *B*-mode polarization at degree angular scales by BICEP2, Phys. Rev. Lett. 112 (2014) 241101.
[3] L. Amendola, G. Ballesteros, V. Pettorino, Effects of modified gravity on B-mode polarization, Phys. Rev. D 90 (2014) 043009.
[4] L. Amendola, M. Litterio, F. Occhionero, Very large angular scales and very high-energy physics, Phys. Lett. B 231 (1989) 43–48.
[5] Emilio Bellini, Ignacy Sawicki, Maximal freedom at minimum cost: linear large-scale structure in general modifications of gravity, J. Cosmol. Astropart. Phys. 2014 (07) (2014) 050.
[6] C.L. Bennett, D. Larson, J.L. Weiland, N. Jarosik, G. Hinshaw, N. Odegard, K.M. Smith, R.S. Hill, B. Gold, M. Halpern, E. Komatsu, M.R. Nolta, L. Page, D.N. Spergel, E. Wollack, J. Dunkley, A. Kogut, M. Limon, S.S. Meyer, G.S. Tucker, E.L. Wright, Nine-year Wilkinson Microwave Anisotropy Probe (WMAP) observations: final maps and results, arXiv:1212.5225 [astro-ph.CO], December 2012.
[7] C.M. Caves, Gravitational radiation and the ultimate speed in Rosen's bimetric theory of gravity, Ann. Phys. 125 (March 1980) 35–52.
[8] Antonio De Felice, Shinji Tsujikawa, Conditions for the cosmological viability of the most general scalar-tensor theories and their applications to extended Galileon dark energy models, J. Cosmol. Astropart. Phys. 1202 (2012) 007.
[9] J.B. Dent, L.M. Krauss, S. Sabharwal, T. Vachaspati, Damping of primordial gravitational waves from generalized sources, Phys. Rev. D 88 (8) (October 2013) 084008.
[10] S.F. Hassan, Rachel A. Rosen, On non-linear actions for massive gravity, J. High Energy Phys. 1107 (2011) 009.
[11] Gregory Walter Horndeski, Second-order scalar-tensor field equations in a four-dimensional space, Int. J. Theor. Phys. 10 (1974) 363–384.
[12] J.C. Hwang, Cosmological perturbations in generalized gravity theories: formulation, Class. Quantum Gravity 7 (1990) 1613–1631.
[13] R. Kimura, K. Yamamoto, Constraints on general second-order scalar-tensor models from gravitational Cherenkov radiation, J. Cosmol. Astropart. Phys. 7 (July 2012) 50.
[14] Frank Könnig, Yashar Akrami, Luca Amendola, Mariele Motta, Adam R. Solomon, Stable and unstable cosmological models in bimetric massive gravity, Phys. Rev. D 90 (2014) 124014.
[15] A. Lewis, S. Bridle, Cosmological parameters from CMB and other data: a Monte Carlo approach, Phys. Rev. D 66 (10) (November 2002) 103511.
[16] Hao Liu, Philipp Mertsch, Subir Sarkar, Fingerprints of galactic loop I on the cosmic microwave background, Astrophys. J. 789 (2014) L29.
[17] T. Matsumura, Y. Akiba, J. Borrill, Y. Chinone, M. Dobbs, H. Fuke, A. Ghribi, M. Hasegawa, K. Hattori, M. Hattori, M. Hazumi, W. Holzapfel, Y. Inoue, K. Ishidoshiro, H. Ishino, H. Ishitsuka, K. Karatsu, N. Katayama, I. Kawano, A. Kibayashi, Y. Kibe, K. Kimura, N. Kimura, K. Koga, M. Kozu, E. Komatsu, A. Lee, H. Matsuhara, S. Mima, K. Mitsuda, K. Mizukami, H. Morii, T. Morishima, S. Murayama, M. Nagai, R. Nagata, S. Nakamura, M. Naruse, K. Natsume, T. Nishibori, H. Nishino, A. Noda, T. Noguchi, H. Ogawa, S. Oguri, I. Ohta, C. Otani, P. Richards, S. Sakai, N. Sato, Y. Sato, Y. Sekimoto, A. Shimizu, K. Shinozaki, H. Sugita, T. Suzuki, A. Suzuki, O. Tajima, S. Takada, S. Takakura, Y. Takei, T.

Tomaru, Y. Uzawa, T. Wada, H. Watanabe, N. Yamasaki, M. Yoshida, T. Yoshida, K. Yotsumoto, Mission design of LiteBIRD, J. Low Temp. Phys. 176 (5–6) (2014) 733–740.

[18] Guy D. Moore, Ann E. Nelson, Lower bound on the propagation speed of gravity from gravitational Cherenkov radiation, J. High Energy Phys. 0109 (2001) 023.

[19] H. Nariai, Gravitational instability in the Brans-Dicke cosmology, Prog. Theor. Phys. 42 (September 1969) 544–554.

[20] K.A. Olive, et al., Review of particle physics, Chin. Phys. C 38 (2014) 090001.

[21] Planck Collaboration, R. Adam, P.A.R. Ade, N. Aghanim, M. Arnaud, J. Aumont, C. Baccigalupi, A.J. Banday, R.B. Barreiro, J.G. Bartlett, et al., Planck intermediate results. XXX. The angular power spectrum of polarized dust emission at intermediate and high Galactic latitudes, arXiv:1409.5738 [astro-ph.CO], September 2014.

[22] Planck Collaboration, P.A.R. Ade, N. Aghanim, C. Armitage-Caplan, M. Arnaud, M. Ashdown, F. Atrio-Barandela, J. Aumont, C. Baccigalupi, A.J. Banday, et al., Planck 2013 results. XVI. Cosmological parameters, arXiv:1303.5076 [astro-ph.CO], March 2013.

[23] Planck Collaboration, P.A.R. Ade, M.I.R. Alves, G. Aniano, C. Armitage-Caplan, M. Arnaud, F. Atrio-Barandela, J. Aumont, C. Baccigalupi, A.J. Banday, R.B. Barreiro, E. Battaner, K. Benabed, A. Benoit-Lévy, J.-P. Bernard, M. Bersanelli, P. Bielewicz, J.J. Bock, J.R. Bond, J. Borrill, F.R. Bouchet, F. Boulanger, C. Burigana, J.-F. Cardoso, A. Catalano, A. Chamballu, H.C. Chiang, L.P.L. Colombo, C. Combet, F. Couchot, A. Coulais, B.P. Crill, A. Curto, F. Cuttaia, L. Danese, R.D. Davies, R.J. Davis, P. de Bernardis, G. de Zotti, J. Delabrouille, F.-X. Désert, C. Dickinson, J.M. Diego, S. Donzelli, O. Doré, M. Douspis, J. Dunkley, X. Dupac, T.A. Enßlin, H.K. Eriksen, E. Falgarone, L. Fanciullo, F. Finelli, O. Forni, M. Frailis, A.A. Fraisse, E. Franceschi, S. Galeotta, K. Ganga, T. Ghosh, M. Giard , J. González-Nuevo, K.M. Górski, A. Gregorio, A. Gruppuso, V. Guillet, F.K. Hansen, D.L. Harrison, G. Helou, C. Hernández-Monteagudo, S.R. Hildebrandt, E. Hivon, M. Hobson, W.A. Holmes, A. Hornstrup, A.H. Jaffe, T.R. Jaffe, W.C. Jones, E. Keihänen, R. Keskitalo, T.S. Kisner, R. Kneissl, J. Knoche, M. Kunz, H. Kurki-Suonio, G. Lagache, J.-M. Lamarre, A. Lasenby, C.R. Lawrence, J.P. Leahy, R. Leonardi, F. Levrier, M. Liguori, P.B. Lilje, M. Linden-Vørnle, M. López-Caniego, P.M. Lubin, J.F. Macías-Pérez, B. Maffei, A.M. Magalhães, D. Maino, N. Mandolesi, M. Maris, D.J. Marshall, P.G. Martin, E. Martínez-González, S. Masi, S. Matarrese, P. Mazzotta, A. Melchiorri, L. Mendes, A. Mennella, M. Migliaccio, M.-A. Miville-Deschênes, A. Moneti, L. Montier, G. Morgante, D. Mortlock, D. Munshi, J.A. Murphy, P. Naselsky, F. Nati, P. Natoli, C.B. Netterfield, F. Noviello, D. Novikov, I. Novikov, N. Oppermann, C.A. Oxborrow, L. Pagano, F. Pajot, D. Paoletti, F. Pasian, O. Perdereau, L. Perotto, F. Perrotta, F. Piacentini, D. Pietrobon, S. Plaszczynski, E. Pointecouteau, G. Polenta, L. Popa, G.W. Pratt, J.P. Rachen, W.T. Reach, M. Reinecke, M. Remazeilles, C. Renault, S. Ricciardi, T. Riller, I. Ristorcelli, G. Rocha, C. Rosset, G. Roudier, J.A. Rubiño-Martín, B. Rusholme, E. Salerno, M. Sandri, G. Savini, D. Scott, L.D. Spencer, V. Stolyarov, R. Stompor, R. Sudiwala, D. Sutton, A.-S. Suur-Uski, J.-F. Sygnet, J.A. Tauber, L. Terenzi, L. Toffolatti, M. Tomasi, M. Tristram, M. Tucci, L. Valenziano, J. Valiviita, B. Van Tent, P. Vielva, F. Villa, B.D. Wandelt, A. Zacchei, A. Zonca, Planck intermediate results. XXII. Frequency dependence of thermal emission from Galactic dust in intensity and polarization, arXiv:1405.0874 [astro-ph.GA], May 2014.

[24] M. Raveri, C. Baccigalupi, A. Silvestri, S.-Y. Zhou, Measuring the speed of cosmological gravitational waves, arXiv:1405.7974 [astro-ph.CO], May 2014.

[25] Ippocratis D. Saltas, Ignacy Sawicki, Luca Amendola, Martin Kunz, Scalar anisotropic stress as signature of correction to gravitational waves, Phys. Rev. Lett. 113 (2014) 191101.