Implications of the Neutron Star Merger GW170817 for Cosmological Scalar-Tensor Theories

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The LIGO and VIRGO Collaborations have recently announced the detection of gravitational waves from a neutron star–neutron star merger (GW170817) and the simultaneous measurement of an optical counterpart (the γ-ray burst GRB 170817A). The close arrival time of the gravitational and electromagnetic waves limits the difference in speed of photons and gravitons to be less than about 1 part in 10^{15}. This has three important implications for cosmological scalar-tensor gravity theories that are often touted as dark energy candidates and alternatives to the Λ cold dark matter model. First, for the most general scalar-tensor theories—beyond Horndeski models—three of the five parameters appearing in the effective theory of dark energy can now be severely constrained on astrophysical scales; we present the results of combining the new gravity wave results with galaxy cluster observations. Second, the combination with the lack of strong equivalence principle violations exhibited by the supermassive black hole in M87 constrains the quartic galileon model to be cosmologically irrelevant. Finally, we derive a new bound on the disformal coupling to photons that implies that such couplings are irrelevant for the cosmic evolution of the field.

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The terms dark energy and modified gravity are closely connected at the most general level; all but the simplest alternatives to the Λ cold dark matter (ΛCDM) model typically invoke some modification of general relativity (GR) (see [1–5] for reviews). The most widely studied of these are scalar-tensor theories where a new scalar ϕ mediates an additional gravitational interaction between matter that is suppressed in the solar system by screening mechanisms (see [6–9] for reviews) but that becomes relevant on cosmological scales. This has motivated an intense theoretical effort towards finding the most general scalar-tensor theory that is pathology free, and the modern approach to dark energy model building can be epitomized by the class of models called beyond Horndeski (BH) [10,11]. BH theories are a complete and general framework for constructing dark energy and modified gravity models (including commonly studied paragons for modified gravity such as chameleons [12] and galileons [13]), many of which can accelerate without a cosmological constant (self-accelerate). They are therefore viewed as alternatives to the ΛCDM cosmological model and there is much effort focused on how well upcoming cosmological surveys will constrain them [14].

BH theories make a striking prediction: the speed of gravitational waves in the cosmological background differs in general from the speed of light [15–18]. Recently, the LIGO and VIRGO consortium has announced the observation of neutron star merger GW170817 [19], a neutron star–neutron star merger that has been localized to the galaxy NGC 4993, about 40 Mpc from the Milky Way. The simultaneous observation of an optical counterpart (the γ-ray burst GRB 170817A) by the Fermi γ-ray telescope [20] and several optical telescopes [21] implies that the two speeds can differ by at most 1 part in 10^{15}, more specifically $|c_T^2 - c^2|/c^2 \leq 6\times 10^{-15}$, where c_T is the speed of gravitational waves and c is the speed of light. (This limit comes from the time lag between the LIGO and Fermi detections; note that the sign is unknown due to uncertainties in the photon generation mechanism during the merger [20].) Previously, the lack of any observed gravi-Čerenkov radiation at Large Electron Positron (LEP) collider constrained this ratio to be $> 10^{-15}$ [22,23] and the LIGO-*Fermi* observation has closed this window from the other side with the same precision. This has severe implications for cosmological scalar-tensor theories that we delineate in this Letter.

Cosmologically, deviations for ΛCDM that fall into the BH class of models can be parameterized by five free functions of time $\{\alpha_M, \alpha_K, \alpha_B, \alpha_H, \alpha_T\}$ [16,24]. These are typically referred to as the effective theory of dark energy [25–27], and constraining both their values and their cosmological time dependence is one of the goals of upcoming dark energy missions such as Dark Energy Spectroscopic Instrument, Large Synoptic Survey Telescope, *Euclid*, and the Wide Field Infrared Survey Telescope (see [14] for example). The first describes the running of the Planck mass and the second the kinetic term for the scalar; we will not discuss these here. The third, α_B, describes the kinetic mixing of the scalar and graviton, and the fourth, α_H, describes the so-called disformal properties of the theory [28–32]. The fifth, $\alpha_T = (c_T^2 - c^2)/c^2$, is none other than the fractional difference between the speed of gravitons and photons.

The observation of optical counterparts therefore implies that this is now known, $\alpha_T \approx 0$.

An interesting property of BH theories we will consider [33] is that they satisfy solar system tests of gravity perfectly using the Vainshtein screening mechanism (note that the Vainshtein mechanism does not screen deviations in the speed of photons and gravitons [34]), but they predict new and novel deviations from GR inside astrophysical bodies of the form [35–37]

$$\frac{d\Phi}{dr} = -\frac{GM(r)}{r^2} - \frac{\Upsilon_1 G}{4}\frac{d^2M(r)}{dr^2}, \tag{1}$$

$$\frac{d\Psi}{dr} = -\frac{GM(r)}{r^2} + \frac{5\Upsilon_2 G}{4r}\frac{dM(r)}{dr}, \tag{2}$$

where

$$\Upsilon_1 = \frac{4\alpha_H^2}{(1+\alpha_T)(1+\alpha_B)-\alpha_H-1} \quad \text{and} \tag{3}$$

$$\Upsilon_2 = \frac{4\alpha_H(\alpha_H-\alpha_B)}{5[(1+\alpha_T)(1+\alpha_B)-\alpha_H-1]}, \tag{4}$$

and Φ and Ψ are the Newtonian potential and the ij component of the metric. This novel Vainshtein breaking led to several suggestions for small-scale tests of Υ_i [36,38–45], which could be used either as priors for cosmological searches or as consistency checks. Note that Eqs. (1) and (2) contain three unknown functions, so until now there was a degeneracy even allowing for the left-hand side to be constrained observationally (as described below). With α_T known to be negligible these constraints translate uniquely into bounds on α_B and α_H at late times. We present these in Fig. 1.

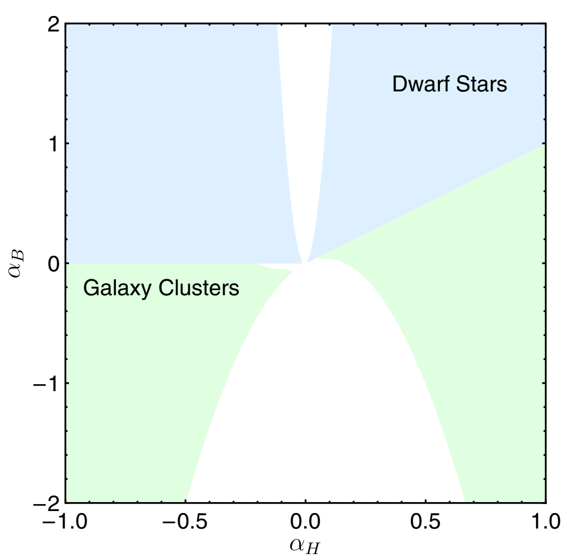

FIG. 1. The excluded regions in the $\alpha_H - \alpha_B$ plane now that c_T is known to be unity with very high precision. The regions excluded by cluster tests and dwarf stars are labeled accordingly.

We have used two sets of constraints to obtain these bounds. The first comes from dwarf stars [38,39]. There is a minimum mass for the onset of hydrogen burning (MMHB) in stars (see [46] for a review); stars lighter than this are brown dwarfs, while heavier stars are red dwarfs. When $\Upsilon_1 > 0$, nonrelativistic stars are typically less compact so that their cores are cooler and less dense, and therefore this MMHB is larger than the GR value of $0.08\, M_\odot$. Demanding that the lightest observed red dwarf is at least as heavy as the MMHB sets the bound $\Upsilon_1 < 0.027$. The second constraint come from galaxy clusters. The equivalence of Φ and Ψ in GR implies that the mass measured by weak lensing (lensing mass, sensitive to $\Phi + \Psi$) and x-ray data (the surface brightness measured in x-ray data is a probe of the hydrostatic mass, sensitive to Φ) should agree. In BH, this equivalence is broken and so any deviation (or lack thereof) constrains the parameters Υ_1 and Υ_2. Reference [42] has performed such a test using weak lensing data from CFHTLenS and x-ray data from XMM-Newton, including measurement errors and systematic uncertainty due to nonthermal pressure (see [47–49] for studies on the consistency of x-ray and lensing masses). They obtain the constraints $\Upsilon_1 = -0.11^{+0.93}_{-0.67}$ and $\Upsilon_2 = -0.22^{+1.22}_{-1.19}$. (There is a stronger bound than the lower bound on Υ_1, $\Upsilon_1 > -2/3$ that we include in Fig. 1; one cannot form stable stars if this is violated [37].)

Figure 1 shows that a large region of the $\alpha_B - \alpha_H$ plane is ruled out [50]. The allowed region can be further constrained by data on galaxy clusters with forthcoming surveys. Modified gravity models that can explain dark energy typically predict $\alpha_i \sim O(1)$ so our results are severely constraining for these models. Stage IV cosmological surveys could constrain α_i to levels of $O(10^{-1})$ but these make several assumptions about the evolution of these parameters and the amount of screening [14]. Our results are independent of these assumptions and are completely general.. Note that there are two other parameters, α_M and α_K, that are completely unconstrained on small scales (although one may be able to constrain α_M using tests of the time variation of Newton's constant). It is also worth noting that the line $\alpha_H = 0$ is completely unconstrained, as it should be given Eqs. (3) and (4). This line corresponds to a large subset of models known as Horndeski theories [51,56,57]. These theories can still be constrained using gravitational waves, but one needs a second probe since Vainshtein screening works inside objects for these theories. This probe comes in the form of strong equivalence principle (SEP) violations, which we describe next.

The entire class of Horndeski theories is vast, and one typically focuses on specific models that encapsulate the relevant physics in order to provide a concrete realization of their cosmological consequences. The quintessential paradigm is the covariant quartic galileon [58] with Lagrangian

$$\frac{\mathcal{L}}{\sqrt{g}} = K(X) + G_4(X)R + G_{4,X}((\Box\phi)^2 - \nabla_\mu\nabla_\nu\phi\nabla^\mu\nabla^\nu\phi), \tag{5}$$

where $X = -(\partial\phi)^2/2$, $K(X) = X$, and

$$G_4(X) = \frac{M_{\rm pl}{}^2}{2} + 2c_0\frac{\phi}{M_{\rm pl}} + 2\frac{c_4}{\Lambda_4^6}X^2. \tag{6}$$

(We have chosen the notation to match that commonly used in the literature.) The free parameters c_0 (often called α or β elsewhere in the literature) and c_4 parameterize the strength of the coupling to matter and the strength of the new interaction, respectively. The speed of gravitational waves in this theory is given by [59]

$$\left|\frac{c_T^2 - c^2}{c^2}\right| = \left|\frac{4c_4x^2}{1-3c_4x^2}\right| < 6\times10^{-15} \tag{7}$$

imposing the LIGO-VIRGO-*Fermi* bound. The parameter $x = \dot{\phi}/(HM_{\rm pl})$ where $\dot{\phi}$ is the time derivative of the scalar (using cosmic time) encodes information about the cosmology of the galileon. Indeed, one has [60]

$$\Omega_\phi = c_0x^2 + \frac{x^2}{6} + \frac{15c_4x^2}{2}. \tag{8}$$

where Ω_ϕ is the density parameter for galileons. The speed of gravitational waves therefore constrains a combination of c_4 and the cosmology of the galileon.

On smaller scales, Ref. [61] has recently obtained new bounds on the parameters c_0 and c_4 using the lack of SEP violations predicted in these theories [62,63]. Black holes in galileon theories have no scalar hair and therefore do not couple to external fields. Nonrelativistic baryons do couple to galileon fields, and therefore black holes and baryons fall at different rates in external gravitational fields, signifying a violation of the SEP. The acceleration of a satellite galaxy infalling towards the center of a cluster would have a subdominant galileon component not felt by its central supermassive black hole (SMBH). This would cause the SMBH to lag behind the rest of the galaxy and become offset from the center by an observable amount [O(kpc)] given by the distance where the missing galileon component is balanced by the restoring force from the baryons left at the center. Using the techniques of [64] applied to the galaxy M87 (located in the Virgo cluster), Ref. [61] was able to place strong constraints on c_0 [65] and c_4.

Taken together, the SMBH and LIGO-VIRGO-*Fermi* constraints allow one to constrain the cosmological contribution of the quartic galileon to the Universe's energy budget using Eq. (8). In Fig. 2 we show the corresponding constraints in the c_4-Ω_ϕ plane for representative values of $c_0 \sim O(1)$ [68]. The LIGO-VIRGO-*Fermi* bounds constrain large values of c_4, which correspond to large

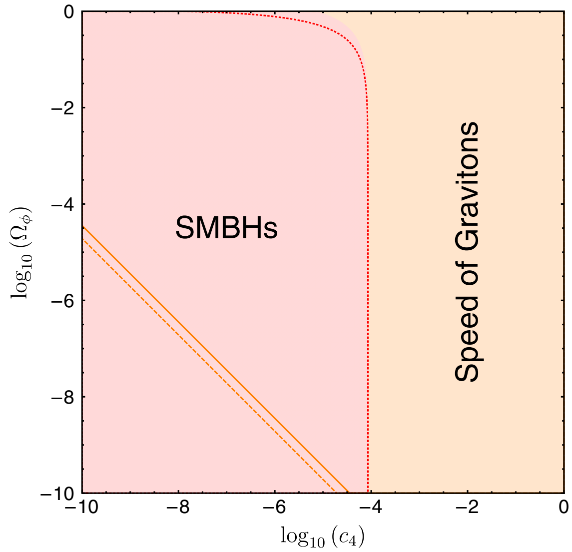

FIG. 2. Constraints in the c_4-Ω_ϕ plane coming from the near equivalence of the speed of gravitons and photons (orange) and the lack of an offset supermassive black hole in M87 (red). The shaded regions correspond to $c_0 = 1$, and we indicate the extent of the graviton speed constraint using the solid orange line. Also shown using the dashed and dotted lines are the equivalent regions for $c_0 = 3$ from the LIGO-*Fermi* and SMBH bounds respectively.

differences in the speed of photons and gravitons as well as strong screening, whereas SMBH constrains small c_4, where galaxy clusters are less screened and the speed of photons and gravitons are similar. The speed of gravitons therefore rules out larger values of Ω_ϕ at large c_4 while SMBH constraints rule out lower values at low c_4. The two constraints are therefore complementary, and the combination rules out all galileon cosmologies except those where $\Omega_\phi \ll 1$. In particular, the combination of SMBH and LIGO-VIRGO-*Fermi* constraints rules out regions where the galileon is more important than radiation in the late-time Universe. Clearly, the galileon can have little to nothing to say about dark energy. One could potentially avoid these harsh restrictions by adding other terms such as a cubic galileon (which itself is heavily constrained by a prediction of a too-large integrated Sachs-Wolfe effect [74,75]) or a quintic galileon (which typically destabilizes Vainshtein screening [66,67]). We will not do so here because, ultimately, one is simply adding more parameters to the theory, in which case there are bound to be tunings that can circumvent constraints.

An alternative to the covariant quartic galileon is the beyond-Horndeski quartic galileon [76]. This model gives an identical cosmology to the model studied above and has an identical expression for c_T^2 [77]. Therefore, this model is also tightly constrained. Going beyond this, a large portion of Horndeski and BH models are now excluded as dark energy candidates, as are several more complicated theories such as vector-tensor and degenerate higher-order scalar-tensor theories [78–80]. We emphasize that models such as Einstein-dilaton-Gauss-Bonnet that do not lead an accelerating universe, of interest for example for deviations detectable via black hole tests [81], are still allowed.

Finally, we consider one additional quantity that can be bounded by the LIGO-VIRGO-*Fermi* observation: the disformal coupling to photons. Disformal couplings refer to derivative couplings of the scalar to a matter species i via the metric

$$\tilde{g}^{(i)}_{\mu\nu} = g_{\mu\nu} + \frac{\partial_\mu\phi\partial_\nu\phi}{\mathcal{M}_i^4}. \quad (9)$$

If $\mathcal{M}_i = \mathcal{M}$ then the field couples to all species universally and there is no violation of the equivalence principle. But there is no *a priori* reason for one to expect this to be the case and, in particular, Ref. [82] has investigated the effects of having different disformal couplings to photons and baryons. In the simplest case where there is no disformal coupling to matter [83], the speed of photons is given by

$$\frac{c_\gamma^2}{c^2} = 1 - \frac{\dot{\phi}^2}{\mathcal{M}_\gamma^4}, \quad (10)$$

and so the LIGO-VIRGO-*Fermi* bound implies that $\dot{\phi}^2/\mathcal{M}_\gamma^4 \lesssim 6 \times 10^{-15}$. Dark energy scalars typically have $\dot{\phi} \sim H_0 M_{\rm pl}$ [85], which implies that $\mathcal{M}_\gamma \gtrsim 10$ MeV. This is stronger than the constraint inferred from the absence of any vacuum Ćerenkov radiation observed at LEP [23] and is comparable with the bound from constraints on energy loss by the Primakov process in the Sun. It is superseded by the same constraints coming from horizontal branch stars, which give $M_\gamma \gtrsim 100$ MeV [86], although our bound is free from the degeneracies of stellar physics (such as metallicity). At this level, the disformal coupling to photons can have no significant effect on the cosmic evolution of the scalar [32].

To summarize, in this Letter we have highlighted three important consequences of the observation of gravitational waves and an optical counterpart from the binary neutron star merger GW170817 [19–21] for cosmological scalar-tensor theories. The close arrival time (less than a minute) constrains the speed of gravitons and photons to differ by at most 1 part in 10^{-15}. For beyond-Horndeski theories, a very general framework for constructing pathology-free dark energy models, one of the five functions that describes the cosmology of these theories ($\alpha_T = c_T^2/c^2 - 1$) is now known to be negligible. Furthermore, this implies that two of the other functions, α_B and α_H, can be constrained using astrophysical tests. We have presented these constraints here for the first time. Second, combining the LIGO-VIRGO-*Fermi* bound with separate bounds coming from the lack of any strong equivalence principle violations by the central supermassive black hole in M87, we have shown that the covariant quartic galileon, a common paradigm for modified gravity as dark energy, must be cosmologically irrelevant. Finally, we have constrained the disformal coupling to photons, and shown that this can play no significant role in the cosmological evolution of scalar fields.

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