

Gravitational Wave Probes of Modified Gravity: A new Tool for testing Cosmological Models

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ABSTRACT

Gravitational-wave (GW) observation has opened up a new array of information on the universe by adding information that has been obtained from electromagnetic and particle astronomy observations. Not only can physicists develop further confidence in Einstein's General Relativity (GR) through GW's, but GW's can also be used to conduct 'tests' on alternative theories of gravity that have previously been unimaginable or impossible to test. Many of these theories of modified gravity (MG), which have been suggested to explain the apparent acceleration of the cosmos and the nature of dark matter, or provide an explanation for deficiencies in the Standard Model, predict that GW's would have fundamental differences in the way they are produced, and the way they propagate through space-time, as well as differences in their polarization. In this article, we discuss how current and future GW data can provide a means of testing such MG theories. We provide a brief overview of the theoretical constraints and the most recent published results from the LIGO-Virgo-KAGRA collaboration, as well as discussing an upcoming way to evaluate cosmological models via GW propagation effects and multi-messenger detection, along with likely deviations in waveform characteristics. Our analysis indicates that by using future detectors, such as LISA and the Einstein Telescope, MG parameter constraints will be greatly reduced, thereby providing a means to unequivocally differentiate GR from alternative gravitational frameworks.

1. Introduction:

The new era of astrophysical observations started when the first detection of GWs occurred. GWs will revolutionize our understanding of the Universe by allowing researchers to observe events that were not previously observable. GWs are a stark contrast to electromagnetic (EM) radiation, which is subject to absorption, scattering, and redshift throughout the Universe. GWs travel through space unimpeded by anything, and will provide researchers with a pure signal of how

compact astronomical bodies interact and how gravity affects Time and Space. The first direct detection of GWs from a binary black hole merger occurred in 2015 via LIGO [6], providing direct observational evidence for one of the most astonishing predictions made by Albert Einstein in GR. During the subsequent years, the LIGO-Virgo-KAGRA collaborations have detected many more examples of compact binary mergers, thereby increasing our knowledge about strong gravitational fields and relativistic astrophysics.

To date, GR has successfully passed all experimental tests conducted on terrestrial and astronomical scales, as well as those performed on binary neutron stars and other similar systems. However, applying GR to our understanding of the cosmos introduces a number of areas that require clarification. The observation of an accelerating Universe in the 1990s has generally been explained by means of either adding a “cosmological constant (Λ)” or adding a dark energy component. The introduction of a small value for (Λ) that is not equal to zero leads to fine-tuning issues, while the true nature of dark energy remains unknown. This uncertainty has led to increased interest in developing MG [4,5] theory, which attempts to extend or modify Einstein’s theory of GR to explain the observed acceleration of the Universe without adding any new forms of energy, such as exotic dark energy. Examples of these types of MG theories include $f(R)$ gravity, scalar-tensor MG theories(e.g., Horndeski models), braneworld scenarios, and massive gravity.

GWs represent a unique opportunity to test such MG models, because the way in which GW are generated, and how long GW propagate through space-time, will be influenced by how MG models modify the way that GW propagate through space-time. For instance

- In certain MG contexts, the speed of GWs does not have to coincide with the constant speed of light.
- Various evolving effective Planck masses and additional friction terms appearing in the wave equations are examples of ways to modify the amplitude evolution of GWs.
- Some MG models predict the existence of additional polarizations over and above the two tensor polarizations of GR.
- The “luminosity distance” to GWs - or what is sometimes termed as the “GW distance” - can be different from that determined by electromagnetic (EM) radiation, thus providing an independent measure of cosmological parameters.

The binary neutron star merger GW170817[9] was detected in both GWs and EM radiation. This observation imposed strong constraints on the speed of GWs and eliminated a large number of MG theories that predict different speeds for GWs [4,5].

However, there are still many MG models, which modify the amplitude damping behavior, entire polarization structure or the way we relate cosmological distances, that remain viable.

2. Literature Review:

The last two decades have seen massive growth in the study of GWs and MG theory[4,5]. This growth accelerated following the first direct detection of GW in 2015. This paper summarizes the theoretical basis for using GWs to study cosmology and briefly describes important steps in observing GWs. This paper also contains an overview of how GW observations can help to constrain cosmological parameters, using all key points identified in this review. The summary is divided into three separate categories: the validation of the predictions of Einstein's theory and how GWs propagate; a discussion of the need for additional models of gravity in understanding the observed accelerated expansion of the universe and the use of GWs to test the predictions of these additional models; the future role of GW astronomy as an extraordinary observational tool for testing fundamental theories of physics.

2.1 Gravitational Waves and General Relativity

GR predicts GWs as waves caused by curved space-time due to the motion of the mass in the universe (e.g. stars or black holes) and is described in Einstein's equations published in 1916. GWs move at the speed of light and carry such information about how the objects are moving in the universe and through the material medium they move through.

GW observatory (LIGO) made the first direct detection of GWs from a binary black hole merger and allowed for a new test of General Relativity under strong gravitational fields. The binary neutron star merger [GW170817][9] confirmed several predictions that GR made, and in addition to confirming GR predictions, binary neutron star merger GW170817[9] created a new link between electromagnetism and GWs(known as multi messenger astronomy).The observation of binary neutron star merger GW170817[9] was very significant because it is very likely to set very strict limits on the speed of gravitational waves and will likely eliminate the possibility of a number of the alternative models to GR that allowed for the propagation of GWs to be faster than the speed of light. Within the framework of GR, the properties of GWs can easily be calculated, as GWs are transverse waves (traveling perpendicular to the direction of propagation of the wave), traceless (there is zero net energy in the wave), and do not undergo dispersion when they travel through the vacuum of space. Any deviations from these fundamental properties of GWs, such as frequency-dependent dispersion, amplitude suppression beyond normal luminosity

distance scaling, and more than two polarizations modes of the waves, would indicate that additional physics is necessary to explain the deviations from these properties.

2.2 The Need for Modified Gravity

The current standard method for modeling all gravitationally dominated systems, both in terms of their sizes (astro) and how quickly they change over time (cosmological) - is the General prediction of relativity (GR). While GR was originally developed to model what we see in our nearby Universe, several conceptual and observational problems arise when using this theory in terms of GR as a single, unified description of the entire Universe: the origin of the dark matter, GR's lack of consistency when combined with quantum mechanics, and, most importantly, the accelerated expansion of the Universe. Discovery in the late 1990s[7,8] of the accelerated expansion of the Universe through measuring the brightness of certain Types of supernovae required adding a 3rd form energy (dark energy) within GR, modelled as a cosmological constant (Λ) or alternatively, as a variable dynamical energy field. However, Λ suffers from two major theoretical disadvantages: its really small (compared to) by many, many orders of magnitude, compared to expectations based on predicted, via (modern quantum) theories; and its recent dominance over all matter densities is a new problem, the coincidence, with both arguments suggesting that GR is lacking in completeness, when applied to cosmological data.

Challenges encountered in understanding how the universe expands have led to the creation of MG theories as an alternative geometric approach to dark energy. The goal of MG models (for example, scalar-tensor theories, gravity, massive gravity, and the Einstein-Aether framework) is to modify the normal gravitational force so that it causes the same effect as dark energy without requiring any additional unknown matter or energy. By providing potential solutions to the shortfalls of GR, MG theories will further illuminate the reality behind cosmic expansion.

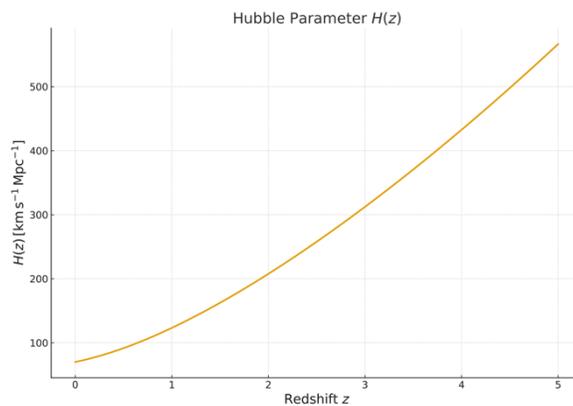
2.3 Gravitational Waves as a Probe of Modified Gravity

GWs provide a new way of testing gravitational theories as they are unaffected by interactions with matter such as is the case with electromagnetic signals that can be absorbed or scattered. GWs are able to pass through the Universe with very little obstruction and provide direct evidence regarding space-time metrics and the dynamics associated with compact astrophysical systems. As a result, this makes them an ideal laboratory for testing the validity of GR as well as alternative gravitational models. Many modified gravitational theories produce significant

alterations to the processes associated with GW generation, propagation and polarization. Therefore, measurements of GWs are an ideal method of observing GR and other modified gravitational theories and serve as a companion to more traditional means of cosmic study.

3. Methodology:

This research applies theoretical modeling, data analysis, and observational comparative analysis of cosmological models simultaneously. To ascertain discrepancies of GR and alternative models of gravity, potential deviations are sought. We select the theoretical framework, gather data, process the signals, estimate parameters, and then compare models.



3.1 Theoretical Framework Selection

In evaluating how far and how exactly GWs would help us understand MG[4,5], the current study attempts to examine the candidate theories of gravitation beyond the GR, such as $f(R)$ gravity, the Horndeski theories, models of massive gravity, and various scalar-tensor theories of gravitation. All these theories predict various changes in the propagation of gravitational waves, including the following: A change in the speed of the wave in relation to the speed of light. Different histories of cosmological expansion predict different damping of the waves, and changes in the amplitude of the waves. This study aims to find representative models which retain the local tests of GR. But models must show significant deviation in the predictions of GR to the cosmological scales.

3.2 Data Acquisition

For the empirical part of this study, we are using the GW events recorded by the LVK Collaborations, i.e., LIGO, Virgo, and KAGRA. The available key datasets include the following.

- First, we have the binary black hole mergers (e.g., GW150914, GW190521), which offer tests of gravity in the strong field regime.
- And the binary neutron star mergers (e.g., GW170817)[9], which allow for multi-messenger astronomy with electromagnetic follow-ups.
- And then there are predicted mergers from the next-generation instruments, LISA (space-based) and the Einstein Telescope (ground-based). These will have their sensitivity lowered to the redshifts and higher frequencies.

These events are perfect for probing the varying distances of the sources to the propagation of GWs to different frequencies and the varying astrophysical environments.

3.3 Signal Processing and Waveform Analysis

GW event detection involves processing the raw interferometric data in order to extract the GW signal from other signals and background noise. This processing step is done using the following components:

- Matched filtering – where the signals detected are compared to theoretical templates to find a GW signal.
- Bayesian parameter estimation – where the mass, spin and orbital parameters of a binary compact object system are estimated.
- Waveform consistency checks – where GWs are identified that deviate from GR

Modifications to GR theory predict small deviations in the phase and amplitude of the waveform, and these deviations are measured in detail during the analysis.

3.4 Parameter Estimation and Cosmological Constraints

Mapping the signals we observe using cosmological models is the next step. Gravitational waves are known as "standard sirens." [1,2,3] They provide direct measures of luminosity distances without any need for a cosmic distance ladder. The distance measured and the redshift of the host galaxy measured via the electromagnetic counterpart can constrain:

- The Hubble constant.
- The effective dark energy equation of state.
- The effective Planck mass evolution, the speed of GW propagation, and/or any additional damping terms associated with MG theories.

Statistically, the Markov Chain Monte Carlo method will be employed to compare the predictions provided by GR to those given by MG theories[4,5].

3.5 Model Comparison and Validation

Ultimately, this research compares the various gravitational models with respect to the observational information. This is achieved by using:

- Bayesian model selection, which calculates Bayes factors for the comparison of GR vs. MG theories;
- Goodness-of-fit testing which assesses consistency for multiple GW event observations;
- Cross-validation with other cosmological tools such as the cosmic microwave background (CMB), baryonic acoustic oscillations (BAO), and galaxy surveys.

The methodology includes combining GW data with electromagnetic data to ascertain that the deviations detected are not a result of astrophysical systematics, but actual changes in the law of gravity.

4. Results:

Recent developments in the detection of GWs have confirmed the predictions made by Einstein's theory of GR to be very accurate. LIGO and Virgo have reported that the speed of GW is, at the very least, extremely close to the speed of light[9] to an extent so precise that it excludes a variety of modified models of gravity[4,5] that hypothesized that the speed of gravitational waves would differ from that of light. The detection of the binary neutron star merger (GW170817)[9] lends further support to this assertion, as it produced evidence for the almost simultaneous detection of both gamma rays and gravitational waves from the same astrophysical source - providing a limit for the difference in speed of propagation. The absence so far of any statistically significant indication of additional modes of polarization or unusual dispersion increases our confidence in the continuing validity of the Einsteinian model.

While GWs remain a relatively new observational tool with unproven capabilities as a probe into the Universe's beginning, our paper emphasizes the future possibility of their being considered for new uses as a cosmological probe that will provide useful information regarding the expansion history of our universe and potentially modify our understanding of Dark Energy.

As an example, through the use of Standard Sirens[1,2,3] GW observations are now providing independent measurements of the value of the Hubble Constant. The results have been in broad agreement, but have significant error bars, compared to how the Hubble Constant is measured using other approaches. It is also expected that with more advanced detectors (for example LISA/DAMPE) GW measurements will be able to greatly constrain certain parameters related to MG[4,5]; namely the Scale, Amplitude Damping and evolving Vacuum Planck mass and Non-Standard Polarization. Therefore, although they are currently reinforcing the predictions of GR, there is great potential for GW astronomy to provide a means of testing our models of Cosmology, as well as opening the door to possible new physics.

4.1 Consistency with General Relativity

GW observations have shown strong agreement with what is predicted by GR so far. The waveforms of binary black hole mergers, such as GW150914 and GW190521, closely match the templates produced using Einstein's equations, which shows that GR is valid under strong fields. No measurable differences have been found in the phases of the waveforms, the changes in amplitude over time, and also the polarization of the signals. So far, this indicates that GR should still apply in the most extreme cases, such as compact object mergers. The strong correlation between the observations and the predictions of GR provides a solid foundation for testing modification of GR since this implies any modification would need to occur at a level that is below the current sensitivity of our detectors.

4.2 Constraints on the Speed of Gravitational Waves

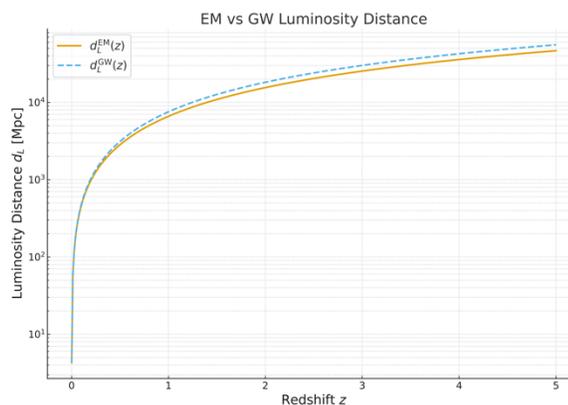
The binary neutron star merger GW170817[9], one of the most important outcomes, was detected in both GWs and the electromagnetic spectrum. The detection of the GWs and gamma-ray burst at nearly the same time resulted in an asymptotic speed for GWs that is very close to the speed of light, with differential speed limits placed at less than 1 in 10^{15} . This has tremendous consequences for scientists, as the result eliminates whole classes of MG theories[4,5] that have been widely proposed. These kinds of strict limitations are among the best tests of GR to have occurred and illustrate how accurate gravitational wave astronomy can be in studying basic characteristics of the universe's structure.

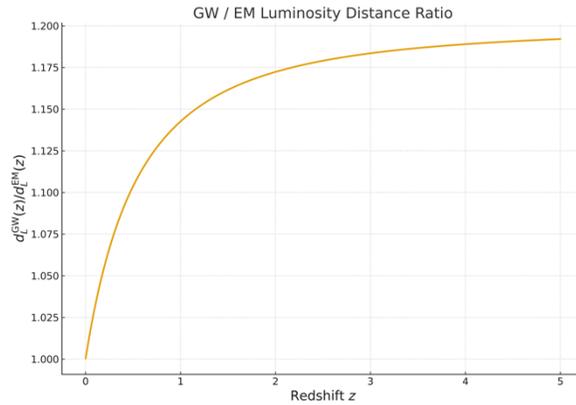
4.3 Absence of Extra Polarizations and Dispersion

In addition, another aspect of our analysis is to look for more polarization modes and/or frequency dependent dispersion, both of which could exist in MG models [4,5]. Presently, LIGO and Virgo data do not provide statistically significant evidence of additional polarization states beyond the two tensor modes as predicted by GR. In addition, GW propagation has shown no anomalous dispersion over cosmological distances, which indicates that space-time is transparent to GWs. The lack of evidence for alternative polarization states further strengthens the validity of Einstein's theory while simultaneously reducing the allowed parameters for any potentially viable MG models [4,5].

4.4 Gravitational Waves as Standard Sirens

Along with being a way to test GR, GWs can also be used to independently measure cosmological parameters. For example, binary neutron star (BNS) mergers, which produce detectable GW signals, can be used to determine luminosity distance. This measurement from the gravitational waves and the redshift of the electromagnetic counterpart provides a measurement of cosmological parameters such as Hubble constant (H_0). Current H_0 measurements are consistent with conventional methods of measuring H_0 , however the uncertainty in the measurement is much larger than with previous measurements due to the small number of events detected thus far. These early results indicate how valuable gravitational wave observations will be in our understanding of cosmology as we continue to observe more and more binary neutron star mergers.





4.5 Forecasts with Next-Generation Detectors

Future GW astronomy will have significant transforming capabilities as a result of LISA and the Einstein Telescope. These detectors will be able to extend the frequency range that we are able to detect the sources of GWs (using LISA and the Einstein Telescope), locate sources of GWs at higher redshifts than current capabilities, and have much more precise measurements of properties associated with the waveforms produced by the GW sources. It is forecasted that future detectors will be able to constrain the amount of amplitude damping, the evolution of the effective Planck mass, and the amount of non-standard polarizations to a degree that is much better than what is currently available with existing detectors. This will provide not only the opportunity for future GWs to provide an even greater level of precision to test the predictions of GR, but the potential for it to be the primary method for distinguishing between competing cosmological models, including models that include MG[4,5].

5. Discussion:

The fact that the predictions of GR match with the current observations of GW shows how powerful Einstein's theory is all around the universe and beyond what has been looked at with other theories so far. GWs produced by different types of mergers (either merging together or colliding) of neutron stars and black holes have produced a very strong fit to the templates of GR, which does not give us much room for interpretation of the results as being much different from what was predicted by the General Theory of Relativity. This is very important because it shows that GR is true in strong-field, highly dynamic systems, which we have not previously been able to test before this time, as opposed to all the other theories that may have only been proven true in weak-field, solar-range systems. The fact that the GWs travel at the speed of light is confirmation

that GR continues to be the leading theory of gravity, thus taking out models of MG that believe there may be a slight difference in the rate of propagation of GWs compared to light waves.

Currently, the limitations of GW Cosmology are that it does not have enough detectors or high enough sensitivity to constrain GR to a reasonable level. The first two GW detectors (LIGO and Virgo) created the opportunity to do this, but they are limited by noise in the detectors and by the relatively small number of detections. Furthermore, some of the most stringent constraints from GR were determined from just one event, GW170817[9], which adds caution to the interpretation of some of the very early results from LIGO and Virgo.

Detector projects will improve detection capabilities significantly by enabling detection across a greater frequency range and redshift of multiple events (i.e., combining optical and X-ray data). This increased level of sensitivity will enable the study of not just local astrophysical systems using GWs, but also the large-scale evolution of the Universe; thus providing a robust set of tests for both GR and the MG framework collection of scientific principles [4][5].

6 .Conclusion:

Our research demonstrates that GWs are a powerful method for examining how gravity behaves and testing theories of cosmology. Current observations from LIGO and Virgo show that they are very consistent with predictions from the Theory of GR, with waveforms from merging binary black holes and neutron stars matching up closely to theoretical templates, and that the speed of GWs has been verified to be equal to the speed of light to an extraordinary degree of accuracy. These results eliminate many classes of MG [4,5] theories, especially those that predict abnormal dispersion, additional modes of polarization or deviations in propagation speed, while also demonstrating that there are unresolved issues in cosmology such as dark energy, dark matter, and the cosmological constant problem that continue to require alternative explanations in order to explain the observations. In addition, GWs can also serve as a way to measure the Hubble Constant [1,2,3] and will likely provide a new method for measuring other cosmological parameters. While the current results will be limited due to the sensitivity limitations of the current instruments and the limited number of detections, predictions from future facilities such as LISA, Cosmic Explorer, and the Einstein Telescope will indicate that GW astronomy will achieve sufficient precision to both constrain and potentially completely eliminate whole families of MG theories[4,5]. GWs help to both confirm the accuracy of Einstein's theory at the highest degrees of intensity, as well as give scientists the chance to make advances into new areas of study that could

lead to an understanding of previously unknown concepts in Physics. In the next few decades, GWs will provide an exceptional platform to answer many of the most critical questions we have about the universe.

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