Multimessenger tests of the weak equivalence principle from GW170817 and its electromagnetic counterparts

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Abstract. The coincident detection of a gravitational-wave (GW) event GW170817 with electromagnetic (EM) signals (e.g., a short gamma-ray burst SGRB 170817A or a macronova) from a binary neutron star merger within the nearby galaxy NGC 4933 provides a new, multimessenger test of the weak equivalence principle (WEP), extending the WEP test with GWs and photons. Assuming that the arrival time delay between the GW signals from GW170817 and the photons from SGRB 170817A or the macronova is mainly attributed to the gravitational potential of the Milky Way, we demonstrate that the strict upper limits on the deviation from the WEP are $\Delta \gamma < 1.4 \times 10^{-3}$ for GW170817/macronova and $\Delta \gamma < 5.9 \times 10^{-8}$ for GW170817/SGRB 170817A. A much more severe constraint on the WEP accuracy can be achieved ($\sim 0.9 \times 10^{-10}$) for GW170817/SGRB 170817A when we consider the gravitational potential of the Virgo Cluster, rather than the Milky Way’s gravity. This provides the tightest limit to date on the WEP through the relative differential variations of the $\gamma$ parameter for two different species of particles. Compared with other multimessenger (photons and neutrinos) results, our limit is 7 orders of magnitude tighter than that placed by the neutrinos and photons from supernova 1987A, and is almost as good as or is an improvement of 6 orders of magnitude over the limits obtained by the low-significance neutrinos correlated with GRBs and a blazar flare.

Keywords: gravity, gamma ray burst experiments, gravitational waves / experiments

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1 Introduction

The Laser Interferometer Gravitational-Wave Observatory (LIGO) has previously identified four gravitational wave (GW) sources with high statistical significance, GW150914 [1], GW151226 [2], GW170104 [3], and GW170814 [4], as well as a less significant candidate LVT151012 [5]. All of them are produced by the collisions of binary black holes (BHs). No statistically significant electromagnetic (EM) counterparts of these GW signals have so far been confirmed by follow-up observations. Note that a suspected association between GW150914 and a weak gamma-ray transient was reported by the Fermi Gamma-Ray Monitor (GBM) team [6], despite the lack of a common consensus for a production mechanism of such counterpart to a BH-BH merger [7–10]. Besides BH-BH mergers, it was taken to be just a matter of time before GW signals from binary neutron stars (NSs) and/or BH-NS mergers would be detected as well [11]. Merging BH-NS and NS-NS are not only important GW sources, but also promising candidates for coincident EM counterparts. These systems are expected to be accompanied by a variety of detectable EM transients, including short Gamma-Ray Bursts (SGRBs) [12–15], on-beam SGRB afterglows [16], and macronovae/kilonovae [17–20].

On 17 August 2017 at 12:41:04 UTC, a new kind of gravitational-wave event (GW170817) from a merger of binary NSs was discovered with high significance by the two Advanced LIGO detectors and the Advanced Virgo detector [21]. A network of three detectors significantly improves the sky localization of GW170814, resulting in a small probability region of only 28 deg^2 (90% credibility). This source had a luminosity distance of 40+8−14 Mpc. Meanwhile, a short Gamma-Ray Burst (SGRB 170817A) triggered GBM on board the Fermi satellite at $T_0 = 12:41:06$ UTC, about 1.7 s after the merger time [22–25]. SGRB 170817A was also detected by the International Gamma-Ray Astrophysics Laboratory (INTEGRAL) [26]. The temporal and spatial coincidence between GW170817 and SGRB 170817A appears to confirm the long-held hypothesis that NS-NS mergers are linked to SGRBs. Even more encouragingly, optical follow-ups of the sky localization of GW170817 identified a bright optical counterpart (SSS17a, now with the IAU identification of AT2017gfo) in NGC 4993 (at 40 Mpc) less than 11 hours after the merger time, consistent with the localization and distance inferred from gravitational-wave data [27].

The same optical transient was independently confirmed by several teams [28–34], which is believed to be powered by the radioactive decay of heavy elements formed by neutron capture called a macronova/kilonova. These multimessenger data provide the first firm evidence that GW170817, SGRB 170817A, and macronova originate from the NS-NS merger. NGC 4993, the host galaxy of the optical transient, is an elliptical galaxy in the constellation Hydra, with coordinates (J2000) R.A.=13h09m47.7s and Dec.=−23°23′02″ [35]. In this work, we adopt the more precise location of NGC 4993 as the locations of SGRB 170817A and the
associated macronova, and take its distance as $d = 40$ Mpc (corresponding to a redshift of $z = 0.009787$) for the SGRB 170817A and the macronova accordingly.

With the physical association between gravitational and EM waves, the flight time differences between these multimessenger signals can in principle be used to give important constraints on the validity of Einstein’s weak equivalence principle (WEP). The WEP is the foundation of general relativity as well as of many other metric theories of gravity [36, 37]. In the parametrized post-Newtonian (PPN) formalism, each gravity theory incorporating the WEP is specified by a set of PPN parameters (e.g., the parameter $\gamma$ which denotes the level of space curvature by unit rest mass), which predicts that the parameter $\gamma$ should be the same for any two different species of massless (or negligible rest mass) neutral particles, or any two particles of the same species with different frequencies (i.e., $\gamma_1 = \gamma_2 \equiv \gamma$, where the subscripts stand for two different particles) [36, 37]. Hence, the WEP accuracy can be described by constraints on the differences of the $\gamma$ values for different particles.

In the multimessenger era, the arrival time delays of the same species of particles (e.g., photons, neutrinos, or GWs) but with varying energies have been widely adopted to test the WEP through the relative differential variations of the $\gamma$ values, such as the particle emissions from supernova SN 1987A [40], GRBs [41, 42], fast radio bursts [43, 44], TeV blazars [45], the Crab pulsar [46–48], and GW sources [49–51]. However, there are only a few WEP tests with different species of messenger particles, and moreover the tests have been limited so far to the photon and neutrino sectors. For example, the flight time differences between MeV neutrinos and photons from SN 1987A have been used to test the WEP accuracy, and the results showed that the $\gamma$ value for photons is the same as that for neutrinos to within 0.2–0.5% [40, 52]. With the assumption that the arrival time delay between a PeV neutrino and gamma-ray photons from a blazar flare is caused dominantly by the gravitational potential of Virgo Cluster, ref. [53] set a stricter limit on the $\gamma$ differences of $\Delta \gamma < 3.4 \times 10^{-4}$. Based on the associations between the TeV neutrinos and gamma-ray photons from five GRBs, ref. [54] tightened the constraint on the WEP to $\Delta \gamma \sim 10^{-11}–10^{-13}$ when taking into account the gravitational potential of the Laniakea supercluster of galaxies. However, except for the SN neutrinos with SN 1987A, the significance of these TeV neutrinos (or the PeV neutrino) being associated with GRBs (or the blazar flare) is low. A 5% probability for a chance coincidence between the blazar flare and the PeV neutrino remains [55], and the coincidences between the TeV neutrinos and GRBs only yielded a combined p-value of 0.32 [56]. In sum, except for the WEP test from SN neutrinos, all the other multimessenger tests have relied on using low-significance neutrino events correlated with photons, which are not very reliable. New multimessenger signals exploiting different emission channels with high significance (e.g., GWs and photons/neutrinos) are essential for further testing the WEP to a higher accuracy level.

Recently, ref. [49] proposed that more tests of the WEP between GWs and photons would be possible with future coincident detection of GWs with EM counterparts from binary NSs and NS-BH mergers, and they provided estimates of the resulting constraints on the WEP from various detectable EM counterparts. Based on the first claimed EM counterpart of GW150914 [6], ref. [49] also showed how this GW/EM association could be used to test the WEP (see also [57]). However, BH-BH mergers are not expected to have enough surrounding material to power bright EM counterparts [7–10], it is still unclear whether the sub-threshold transient event was associated with GW150914 or a chance coincidence. Our

\footnote{Note that the arrival time delays of photons with different polarizations from astrophysical events have also been used to constrain the differences of the $\gamma$ values [38, 39].}
interest in the possibility of using GWs to test the WEP has recently been revived by the observations of a new kind of gravitational-wave signal (GW170817) which comes from a binary NSs merger. Since GW170817 is confirmed to be accompanied by SGRB 170817A and a macronova with high significance, we now use this true GW/EM association (i.e., GW170817/SGRB 170817A and GW170817/macronova) to provide robust constraints on the WEP, thus extending significantly the WEP test with GWs and photons.

2 WEP tests with GW170817 and its EM counterparts

In the presence of a gravitational potential \( U(r) \), the time interval required for particles to traverse a given distance is expected to be longer, by the so-called Shapiro (gravitational) time delay \[ t_{\text{gra}} = -\frac{1 + \gamma}{c^3} \int_{r_e}^{r_o} U(r) dr , \tag{2.1} \]

where the integration is along the path of the particle emitted at \( r_e \) and observed at \( r_o \). If the WEP fails, the \( \gamma \) values of different particles will be different, leading to arrival-time differences of the two particles arising from the same transient source. The relative Shapiro time delay is therefore expressed as \[ \Delta t_{\text{gra}} = \frac{\gamma_1 - \gamma_2}{c^3} \int_{r_e}^{r_o} U(r) dr , \tag{2.2} \]

where the difference of the \( \gamma \) values \( \Delta \gamma = \gamma_1 - \gamma_2 \) can be characterized as a measure of a possible deviation from the WEP.

To calculate the relative Shapiro time delay with eq. (2.2), we need to figure out the gravitational potential \( U(r) \) along the propagation path. In principle, \( U(r) \) consists of three parts: the gravitational potentials of the Milky Way \( U_{\text{MW}}(r) \), the intergalactic space \( U_{\text{IG}}(r) \), and the transient host galaxy \( U_{\text{host}}(r) \). Since the potential function of \( U_{\text{host}}(r) \) and \( U_{\text{IG}}(r) \) is hard to model, we first consider only the potential of the Milky Way \( U_{\text{MW}}(r) \). Assuming that the observed time delay (\( \Delta t_{\text{obs}} \)) between correlated particles is dominated by the relative Shapiro time delay, and adopting a Keplerian potential \( U_{\text{MW}}(r) = -GM/r \) for the Milky Way,\(^2\) a conservative upper limit on \( \Delta \gamma \) can be estimated to be \[ \Delta t_{\text{obs}} > \Delta t_{\text{gra}} = \Delta \gamma \frac{GM_c}{c^3} \ln \left\{ \frac{d + (d^2 - b^2)^{1/2}}{b^2} \left[ r_c + (r_c^2 - b^2)^{1/2} \right] \right\} , \tag{2.3} \]

where \( M_c \simeq 6 \times 10^{11} M_\odot \) is the total mass of the gravitational field source (the Milky Way) \([59, 60]\), \( d \) is the distance from the particle transient (GW170817) to the center of the gravitational source (for an extragalactic or cosmic transient, \( d \) is approximated as the distance from the Earth to the particle transient), \( r_c \simeq 8.3 \) kpc represents the distance from the Milky Way center to Earth, and \( b \) corresponds to the impact parameter (see figure 1 in ref. [40]). The location of the Milky Way center is R.A. = 17\(^{h}\) 45\(^{m}\) 40\(^{s}\) 04 and Dec. = \(-29^\circ 00' 28''\) 1 [61].

Note that Insight-HXMT did not detect any significant gamma-rays between 200 keV and 5 MeV during the SGRB 170817A episode [62]. Upper limits for SGRB 170817A are

\(^2\)Although the gravitational potential of our galaxy is still unknown, ref. [52] examined two popular potential models, i.e., the Keplerian potential and the isothermal potential. They suggested that different potential models do not have a strong influence on the resulting constraints on the WEP. Here we adopt the Keplerian potential for the Milky Way.
reported in ref. [63]. However, Insight-HXMT was monitoring GW170817 before and after the GW event, and thus excludes a classical short/hard GRB during this period (upper limits also given) [63]. Consequently, it is justified to use the time-delay of 1.7 s between GW170817 and SGRB 170817A to test the WEP. Since the first detection of the optical counterpart (macronova) was carried out in less than 11 hours after the merger time [27], we adopt 11 hours as the conservative limit of the observed time delay between GW170817 and macronova. With these time delays and considering the gravitational potential of the Milky Way, a stringent limit on the WEP from eq. (2.3) is

$$|\gamma_g - \gamma_\gamma| < 1.4 \times 10^{-3}$$

(2.4)

for GW170817/macronova, and

$$|\gamma_g - \gamma_\gamma| < 5.9 \times 10^{-8}$$

(2.5)

for GW170817/SGRB 170817A.\(^3\)

On the other hand, it has been shown that considering the large-scale gravitational potential in the intergalactic space would improve the constraints on the WEP accuracy by a few orders of magnitude, rather than the Milky Way’s gravity [65–67]. That is, for the cosmic transients, the Shapiro delay due to nearby clusters and/or superclusters is more important than the Milky Way and the transient host galaxy. Thus, we here also consider the gravitational potential of the Virgo Cluster. The Virgo Cluster is the nearest cluster to the Milky Way, whose center lies at a distance of \( r_c \simeq 16.5 \) Mpc at a position of R.A.\( =186.8^\circ \) and Dec.\( =12.7^\circ \) (or R.A.\( =12^h27^m12^s \) and Dec.\( =12^\circ42'00'' \)) [68]. Its mass is estimated to be \( 1.2 \times 10^{15} M_\odot \) out to 8 degrees from the center of the cluster or a radius of about 2.2 Mpc [69]. Since the distance of GW170817 is far beyond the scale of the Virgo Cluster, the gravitational potential of the particle paths from GW170817 to us can be treated as a point mass potential for which the Virgo Cluster’s total mass is assumed at the center of the mass. Considering the Virgo Cluster’s gravity, a stronger limit on the WEP from eq. (2.3) is

$$|\gamma_g - \gamma_\gamma| < 2.1 \times 10^{-6}$$

(2.6)

for GW170817/macronova, and

$$|\gamma_g - \gamma_\gamma| < 9.2 \times 10^{-11}$$

(2.7)

for GW170817/SGRB 170817A, which is about 6 orders of magnitude tighter than the previous limit obtained with the PeV neutrino from a blazar flare (\( |\gamma_\nu - \gamma_\gamma| < 3.4 \times 10^{-4} \)) [53], and is almost as good as the results with TeV neutrinos from GRBs (\( |\gamma_\nu - \gamma_\gamma| < 10^{-11} - 10^{-13} \)) [54].

### 3 Summary and discussion

Very recently, the LIGO-Virgo team reported the first detection of a new kind of gravitational-wave event (GW170817), which arises from a binary NSs merger [21]. Moreover, the EM counterparts of GW170817, such as the SGRB 170817A and a macronova within the nearby galaxy NGC 4933, are firmly detected by the follow-up observations [22–34]. This is the

\(^3\)Two independent works were simultaneously carried out by refs. [24, 64], who tested the WEP by using only the observed time delay between GW170817 and SGRB 170817A, and by considering only the effect of the Milky Way’s gravity.
first time in history that gravitational and EM waves from a single astrophysical source have been identified. Based on this first truly GW/EM association, we demonstrate that new, multimessenger WEP tests can be carried out by using the arrival time delays between the GW signals from GW170817 and the photons from SGRB 170817A or the macronova. Attributing the time delays to the gravitational potential of the Milky Way, we set stringent limits on the differences of the PPN $\gamma$ parameter values for two cases, i.e., $\Delta \gamma < 1.4 \times 10^{-5}$ for the GW170817/macronova, and $\Delta \gamma < 5.9 \times 10^{-8}$ for the GW170817/SGRB 170817A. If the time delays are mainly caused by the gravitational potential of the Virgo Cluster, much more severe constraints can be achieved, implying $\Delta \gamma < 2.1 \times 10^{-6}$ for GW170817/macronova, and $\Delta \gamma < 9.2 \times 10^{-11}$ for GW170817/SGRB 170817A.

To date, only three WEP tests with different species of messenger particles have been obtained, and moreover these tests were limited to the photon and neutrino sectors. Note that, except for the WEP test from SN neutrinos [40, 52], the other two multimessenger tests have relied on using the low-significance neutrino events correlated with photons [53, 54], which are not very reliable. It is highly desirable to develop more accurate tests that include new multimessenger signals with higher significance (e.g., GWs and photons/neutrinos). In the present work, we have extended the particle sector over which the WEP is tested to the GWs and photons, at comparable or higher levels of accuracy. The results from GW170817/SGRB 170817A that we discussed here provide the hitherto most stringent constraint on the WEP through the relative differential variations of the $\gamma$ parameter for two different species of particles, namely $\sim 10^{-10}$, which is 7 orders of magnitudes tighter than that placed by the neutrinos and photons firmly detected from SN 1987A [40, 52], and is as good as or is an improvement of 6 orders of magnitude over the results set by the low-significance neutrinos correlated with GRBs and a blazar flare [53, 54]. In conclusion, the coincident detection of GWs with EM signals from compact binary mergers containing NSs can provide attractive candidates for constraining the WEP, extending the tests to the GW and photon sectors. If in the future more robust GW/EM associations are detected by the GW detectors and the conventional EM telescopes, better limits on the accuracy of the WEP might be achieved.

The LIGO detection of GWs from binary BH mergers triggered a large number of follow-up searches for coincident EM emission [70] as well as coincident neutrinos [71–73], but no neutrino emission was found. Since in general little or no matter is expected to be present in the binary BH environment, no significant neutrino emission is expected from such mergers. However, it will be possible to detect neutrino emission from other source classes, such as NS-NS and BH-NS mergers, where one does expect neutrino emission, e.g. [74]. In view of the onset of the multimessenger era, a neutrino detection of a GW source would shine a unique light on testing the WEP with GWs and neutrinos.

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