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Measuring Gravitational-Wave Propagation Speed with Multimessenger Observations

Atsushi Nishizawa[1*] **and Takashi Nakamura**[2]

[1] Theoretical Astrophysics 350-17, California Institute of Technology, Pasadena, California 91125, USA

[2] Department of Physics, Kyoto University, Kyoto 606-8502, Japan

E-mail: *anishi@caltech.edu

Abstract. A measurement of gravitational wave (GW) propagation speed is one of important tests of gravity in a dynamical regime. We report a method to measure the GW propagation speed by directly comparing arrival times of GWs, neutrinos from supernovae (SN), and photons from short gamma-ray bursts (SGRB). We found that the future multimessenger observations can test the GW propagation speed with the precision of $\sim 10^{-16}$-10^{-15}, improving the previous suggestions by $9 - 10$ orders of magnitude. We also propose a novel method that distinguishes the true signal due to the deviation of GW speed from the speed of light and the intrinsic time delay with compact binaries at cosmological distances.

1. Introduction

The GW observations enable us to test gravity theory in strong and dynamical regimes of gravity (for reviews, [1–3]). There have been the suggestions of model-independent method to test gravity by searching for anomalous phase deviation from general relativity [4–6] and with GW polarizations [7–9]. The other test is measuring the propagation speed of a GW. In general relativity, a GW propagates with the speed of light, while in the alternative gravity theories the propagation speed could deviate from the speed of light [10–12]. Also the modification of spacetime structure due to quantum gravity effects may affect the propagation of a GW [13].

GW propagation speed has been constrained from ultra-high energy cosmic rays. Assuming the cosmic rays originate in our Galaxy, the absence of gravitational Cherenkov radiation leads to the limit, $c - v_g < 2 \times 10^{-15} c$ [14]. However, this constraint is applied to only subluminal case. So far there have been a few proposals to directly measure the GW speed. One method is comparing the phases of a GW and its electromagnetic counterpart from a periodic binary source [15, 16]. A similar method (the GW Rømer time delay) that does not rely on any EM observation was suggested recently [17]. A GW signal from a periodic GW source is modulated in phase due to the Earth revolution. In these methods, the sensitivities are limited by the baseline of the solar system and results in the measurement precision of the order of 10^{-6}.

This article is a short summary of our previous work [18], in which we have reported a simple but powerful method to measure the propagation speed of a GW by directly comparing the arrival times between GWs, and neutrinos or photons from SGRB and SN. To this end, we presuppose that SGRB is associated with a NS-NS or NS-BH binary merger [19], where NS and BH mean neutron star and black hole, respectively.

2. Method

Let us start with the comparison of the propagation speeds of a GW and a neutrino. We write the lightest neutrino mass among three mass eigenstates as m_ν and the neutrino energy as E_ν, and define the fastest propagation speed of neutrinos as v_ν. A GW is emitted at the time $t = t_e$ and is detected on the Earth at $t = t_e + T_g$, where T_g is the GW propagation time from the source to the Earth. While a neutrino is emitted at $t = t_e + \tau_{\rm int}$ with some intrinsic time delay $\tau_{\rm int}$ and is detected at $t = t_e + \tau_{\rm int} + T_\nu$, where T_ν is the neutrino propagation time. The observable is the difference of the arrival times between the GW and the neutrino. Defining $\Delta T \equiv T_\nu - T_g$, we write it $\tau_{\rm obs} = \Delta T + \tau_{\rm int}$. The first term contains the time lags due to the possible deviation of the GW propagation speed from the speed of light and the contribution of non-zero neutrino mass. The second term comes from the intrinsically delayed emission time of neutrinos at a source.

In order that the finite time lag due to the GW propagation speed different from the speed of light and neutrino mass is detectable, ΔT has to exceed uncertainties in the intrinsic time lag,

$$\Delta\tau_{\rm int} < |\Delta T| \approx T_0 |\delta_\nu - \delta_g| \,, \tag{1}$$

with $\Delta\tau_{\rm int} \equiv \tau_{\rm int,max} - \tau_{\rm int,min}$ and $\delta_\nu = m_\nu^2 c^4/(2E_\nu^2)$. At the right equality, we defined $\delta_g \equiv (c - v_g)/c$ and $\delta_\nu \equiv (c - v_\nu)/c$, and expressed ΔT in terms of δ_g and δ_ν using distance to a source L[1] and the propagation times, $T_g \equiv L/v_g$, $T_\nu \equiv L/v_\nu$, and $T_0 \equiv L/c$. For the comparison between a GW and a photon, the detectable range of δ_g is obtained by merely setting $\delta_\nu = 0$ in Eq. (1). In the derivation of Eq. (1), we have not considered the instrumental timing errors of a GW, neutrinos, and photons. However, as discussed in [18], they can be ignored because the intrinsic time delays are typically much larger.

3. Constraint on GW propagation speed

First let us focus on a SN GW-neutrino multimessenger observation. Most numerical simulations of SN with rotating progenitors [20,21] predict that GWs are mainly radiated sharply at the time of the core bounce and neutrinos are emitted within 10 msec after the core bounce. However, this is not always true for non-rotating collapses [21, 22]. However, the GW waveform of the non-rotating core-collapse could easily be distinguished from that in a rotating case because of characteristic GW spikes. From this reason, we consider only the SN with rotating progenitors, in which the intrinsic time delay of neutrino emission is at most 10 msec. To find the detectable ranges of δ_g from Eqs. (1), one also need to consider an uncertainty in the neutrino mass. However, it is shown in [18] that since the neutrino mass has been constrained tightly from the cosmological observations [23], the neutrino mass can set to zero in constraining δ_g within interesting parameter ranges.

Next let us consider the intrinsic time delay of SGRB photon emission. Concentrating on the prompt emission of SGRB, high energy photons can be radiated in advance or behind the GW emission time, but this time window (of intense emission) would be less than 10 sec since the duration of the SGRB is typically less than ~ 2 sec. Thus, we use $\Delta\tau_{\rm int} = 10$ sec hereafter.

From a SN GW-neutrino event at $L = 100$ kpc, assuming $\Delta\tau_{\rm int} = 10$ msec, we have the constraint, $|\delta_g| < 9.7 \times 10^{-16}$. As for a SGRB GW-photon event, with $\Delta\tau_{\rm int} = 10$ sec and $L = 200$ Mpc, we obtain $|\delta_g| < 4.9 \times 10^{-16}$. Since the constraint on δ_g is inversely proportional to L, if SGRB is associated with NS-BH binary of mass $1.4M_\odot$ and $10M_\odot$, the distance range is ~ 3.4 times larger [24] so that the constraint would be improved by a factor ~ 3. Comparing with the previous proposals [15–17] based on direct measurements of GW propagation speed, our constraints are about 9-10 orders of magnitude tighter. We also should compare with the

[1] For cosmological sources we consider later, we must use the exact formula of the distance that takes into account the cosmic expansion.

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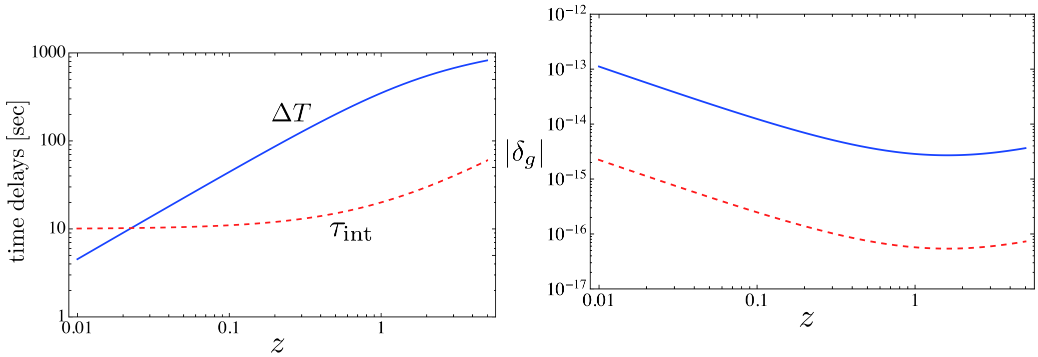

Figure 1. (left): Arrival time lag between a GW and a photon (blue, solid) and the intrinsic time delay (red, dashed) of a cosmological SGRB at redshift z when $\delta_g = 10^{-15}$ and $\tau_{\rm int}^{(e)} = 10\,{\rm sec}$. (right): Constraint on δ_g from a source at redshift z, assuming $\Delta\tau_{\rm int} = 10\,{\rm sec}$ (red, dashed) and conservatively $\Delta\tau_{\rm int} = 500\,{\rm sec}$ (blue, solid). Taken from [18].

indirect constraint on δ_g obtained so far. From the measurement of ultra-high energy cosmic rays, the constraint $0 \leq \delta_g < 2\times 10^{-15}$ has been obtained [14]. This bound can be applied only to subluminal propagation. In this case, our method gives a stronger constraint by a factor of a few. The advantage of our method is that it is also applied to a superluminal case as well.

We comment on the event rate of coincidence detection with GW detectors such as aLIGO and neutrino detectors such as Super-KAMIOKANDE. In SN GW-neutrino observations, the coincident event rate is roughly a few events per a century [25]. In SGRB GW-γ-ray observations, the coincident event rate that has recently been estimated in [24] using BATSE data is $\sim 0.08\,{\rm yr}^{-1}$ and $\sim 3.6\,{\rm yr}^{-1}$ for NS-NS and NS-BH cases, respectively. Therefore, we can expect at least one SGRB coincident event after from a few to several years observation.

4. Using multiple cosmological SGRB

The future ground-based GW detector, Einstein Telescope (ET), extends the detection range by more than ten times and enables us to observe a million of NS-NS binaries up to $z \sim 2$ and NS-BH binaries up to $z \sim 4$ [26]. From the consideration of the beaming angle of SGRB, the number of coincidence events between GWs and SGRB photons would be more than 100 in a realistic observation time. In this section, we discuss how the time delay is affected by the cosmic expansion and how we can distinguish the time delay due to δ_g from the intrinsic time delay with multiple SGRB at cosmological distances.

The time delay induced by nonzero δ_g is given by $\Delta T = \delta_g \int_0^z H^{-1}(z')dz'$ [18], where a flat ΛCDM universe is assumed. $H(z)$ is the Hubble parameter at z. On the other hand, the intrinsic time delay at the source $\tau_{\rm int}^{(e)}$ is redshifted and is observed on the Earth as $\tau_{\rm int} = (1+z)\,\tau_{\rm int}^{(e)}$. In Fig. 1, ΔT and $\tau_{\rm int}$ are illustrated for $\delta_g = 10^{-15}$ and $\tau_{\rm int}^{(e)} = 10\,{\rm sec}$. ΔT increases at low z, proportional to the distance to the source. While, $\tau_{\rm int}$ is almost constant at low z and increases proportional to z at high z.The possible constraint on δ_g from a cosmological SGRB event becomes the tightest around $z = 1$, where the constraint is $|\delta_g| < 5.7\times 10^{-17}$ for $\Delta\tau_{\rm int}^{(e)} = 10\,{\rm sec}$.

If multiple SGRB events observed coincidentally by GW and γ-ray detectors are available, the true signal due to δ_g can be distinguished from the intrinsic time delay at the time of emission by looking at the redshift dependence. For the data analysis, we propose a new statistics:

$$\Delta\tau_{\mathrm{obs}}(z_i, z_j) \equiv \frac{\tau_{\mathrm{obs}}(z_i)}{1+z_i} - \frac{\tau_{\mathrm{obs}}(z_j)}{1+z_j} = \frac{\Delta T(z_i)}{1+z_i} - \frac{\Delta T(z_j)}{1+z_j} + \tau_{\mathrm{int}}^{(\mathrm{e})}(z_i) - \tau_{\mathrm{int}}^{(\mathrm{e})}(z_j)\ . \quad (2)$$

Since $\tau_{\mathrm{int}}^{(\mathrm{e})}$ is expected to be distributed about its average, depending on a specific model of SGRB emission, the third and fourth terms would be a stochastic noise and vanishes on average. On the other hand, the first and the second terms has almost always the same signs only if signal summation is taken over the redshifts $z_j < z_i$. Therefore, this statistic effectively distinguishes the signal and the noise in our purpose detecting δ_g.

5. Conclusion

We have proposed the method to measure the propagation speed of a GW by directly comparing the arrival time lags between a GW and, neutrinos from SN or photons from SGRB. We have found that the constraint on δ_g would be 10^{-16}-10^{-15}, improving the sensitivity of the previous studies by 9-10 orders of magnitude. We also have shown that with ET one can distinguish the true signal due to the deviation of GW propagation speed and the intrinsic time delay at a source by looking at the redshift dependence.

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