Neutron Star Astrophysics at the Crossroads: Magnetars and the Multimessenger Revolution
Proceedings IAU Symposium No. 363, 2023
E. Troja & M. G. Baring, eds.
doi:10.1017/S1743921322000503

Gravitational-wave EM Counterpart Korean Observatory (GECKO)

Myungshin Im, Gregory S. H. Paek, Joonho Kim, Gu Lim
and the GECKO Team

SNU Astronomy Research Center, Astronomy Program, Dept. of Physics & Astronomy,
Seoul National University, Seoul 08826, Republic of Korea
email: `myungshin.im@gmail.com`

Abstract. Identification of the electromagnetic-wave (EM) counterparts of gravitational-wave (GW) sources can significantly broaden the research scope of GW astronomy, by pinpointing the exact locations of GW events and their environments, and using GW sources as standard sirens for cosmology. Yet, only one GW event has been found to be associated with an EM counterpart so far. Here, we outline the challenges of identifying EM counterparts of GW events, and describe our global network of telescopes that has been used to uncover GW EM counterparts. We also introduce a new facility in construction, the 7-dimensional telescope (7DT). Our GECKO observations have demonstrated that we can cover 50 deg^2 within one hour to find kilonovae at a few hundred Mpc away. Furthermore, 7DT will produce a low resolution spectral map of the GW localization area, facilitating the EM counterpart search.

Keywords. gravitational waves, black hole physics, telescopes, stars: neutron, galaxies: general

1. Introduction

The identification of the EM counterpart of the GW event, GW170817, in 2017 signaled the start of multi-messenger astronomy (MMA, Abbott et al. 2017a). The event was caused by a binary neutron star (BNS) merger, and it produced an optical counterpart, kilonova, which was intensively observed by astronomers around the world (Abbott et al. 2017a). The studies of GW170817 demonstrate the great potential of MMA through a number of key findings such as the accurate determination of GW event position (e.g., Abbott et al. 2017a; Im et al. 2017), a convincing proof for the link between short gamma-ray bursts and BNS mergers (Abbott et al. 2017b; Goldstein et al. 2017; Troja et al. 2017; Sachenko et al. 2017), the environment of BNS merger (e.g., Im et al. 2017), and the standard siren constraint on the Hubble constant (e.g., Abbott et al. 2017c).

To follow up the great success of the GW170817 studies, intensive efforts have been made during the Advanced LIGO and Advanced Virgo (LIGO/Virgo) O3 run in 2019 – 2020, to uncover more kilonovae in the GW localization areas. However, the efforts have not yet revealed any promising EM counterparts, although useful constraints have been obtained on kilonovae signals on various GW events (e.g., Kim et al. 2021).

With the expected improvements in GW detection sensitivities in the near future, the anticipation is very high for MMA to revolutionize our understanding of the universe. Future LIGO/Virgo runs could detect tens of EM signal producing GW events, and hence, preparations are under way to capture kilonovae associated with GW events.

Since the first detection of the GW event, our group has been organizing efforts in Korea to detect EM counterparts by expanding the existing transient search telescope network (Im et al. 2019). In this contribution, we first outline the challenges that we are facing in finding kilonovae from GW events, then describe our network of telescopes, and finally introduce a new facility in construction, the 7-dimensional telescope (7DT), that is designed to efficiently find kilonovae during future GW observing runs.

2. Challenges for EM Counterpart Identification

The challenges for identifying GW EM counterparts can be summarized in three-holds.

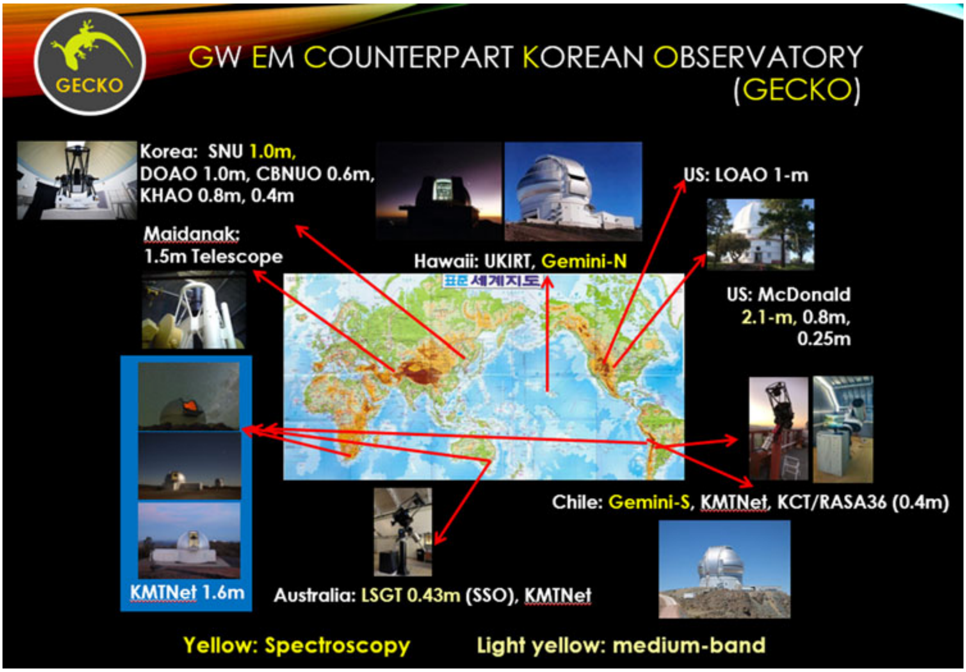
(1) The area to search for GW EM counterparts is too wide. The localization accuracy of GW events is still too poor, at 10's deg^2 to 1000's deg^2, with a typical area of a few hundreds deg^2 (Abbott et al. 2021). For example, the localization area at 90% confidence for the BNS event during the GW O3 run, GW190425, was about 7,000 deg^2. This requires about 2.5 million pointings for the Hubble Space Telescope to cover the whole area. Consequently, no EM counterpart was identified during the O3 run, despite the fact that there were at least a few potentially EM-producing events.

(2) The EM counterparts are faint and fade quickly. BNS mergers produce kilonovae, but they are more than 10 times fainter at peak luminosity than supernovae, with $R = 22 - 24$ mag at 400 Mpc (Kim et al. 2021). They quickly reach their peak luminosity in hours to 0.5 days since the merger event, and fade rapidly in optical (a few days). Therefore, finding such a faint, fast-fading object in a very wide area is not trivial.

(3) There are many other signals that could be confused as kilonovae. The expected number of transients can be over 1000 or more over about 100 deg^2 area (Kim et al. 2021), and about 7000 variable sources are also expected in the same area (Sesar et al. 2007) to the depths of potential kilonovae in future GW run. On top of that, there are numerous artificial signals that look like transient. Therefore, the confirmation of kilonovae requires selecting promising candidates among many sources and taking spectra, which requires multiple step observing campaigns and therefore is very time-consuming.

3. GW EM Counterpart Korean Observatory, GECKO

As a way to alleviate the difficulty of EM counterpart identification, we assembled a global network of telescopes, the GW EM Counterpart Korean Observatory (GECKO). GECKO is made of more than a dozen 1-m class optical telescopes, with a few additional 4- to 8-m class telescopes for extensive follow-up observations (Figure 1). Most of these telescopes are owned by Korean institutions and belong to the Small Telescope Network of Korea (SomangNet, Im et al. 2021), with 5 of them having a wide-field of view of more than 1 deg^2. One notable facility is the Korean Microlensing Telescope Network (KMTNet) which is made of three 1.6-m telescopes that can cover a field of view of 4 deg^2. The KMTNet telescopes are located in Australia, South Africa, and Chile, so that it can follow up GW events in the southern hemisphere sky any time. The limiting magnitude of the KMTNet telescopes is 23 AB mag for the point source detection at 5-σ in 6 minutes of integration in R-band, making it possible to detect an EM counterpart for a GW170817-like event out to 400 Mpc (Kim et al. 2021). Figure 2 shows AT2017gfo (the EM counterpart of GW170817) observed by KMTNet (Troja et al. 2017), demonstrating the capability of KMTNet to trace time evolution of the kilonova signal in time and color. During the LIGO/Virgo O3 run, we followed up 11 GW event with GECKO, but without detecting any kilonovae. However, the observations proved that we can start the follow-up observation within 30 minutes of GW alerts, and can cover the localization area of about 50 deg^2 (expected median 90 % confidence area during the O4 run) within about one hour, to detect kilonovae as far as a few hundred Mpc (Kim et al. 2021). To speed up the transient identification process, we are now implementing artificial intelligence techniques in our transient search process.



GECKO

GW EM COUNTERPART KOREAN OBSERVATORY (GECKO)

Korea: SNU 1.0m, DOAO 1.0m, CBNUO 0.6m, KHAO 0.8m, 0.4m

Maidanak: 1.5m Telescope

Hawaii: UKIRT, Gemini-N

US: LOAO 1-m

US: McDonald 2.1-m, 0.8m, 0.25m

Chile: Gemini-S, KMTNet, KCT/RASA36 (0.4m)

KMTNet 1.6m

Australia: LSGT 0.43m (SSO), KMTNet

Yellow: Spectroscopy Light yellow: medium-band

Figure 1. GECKO telescopes. Telescopes with spectroscopic capabilities are marked in thick yellow (moderate resolution spectroscopy) or light yellow (medium-band spectroscopy).

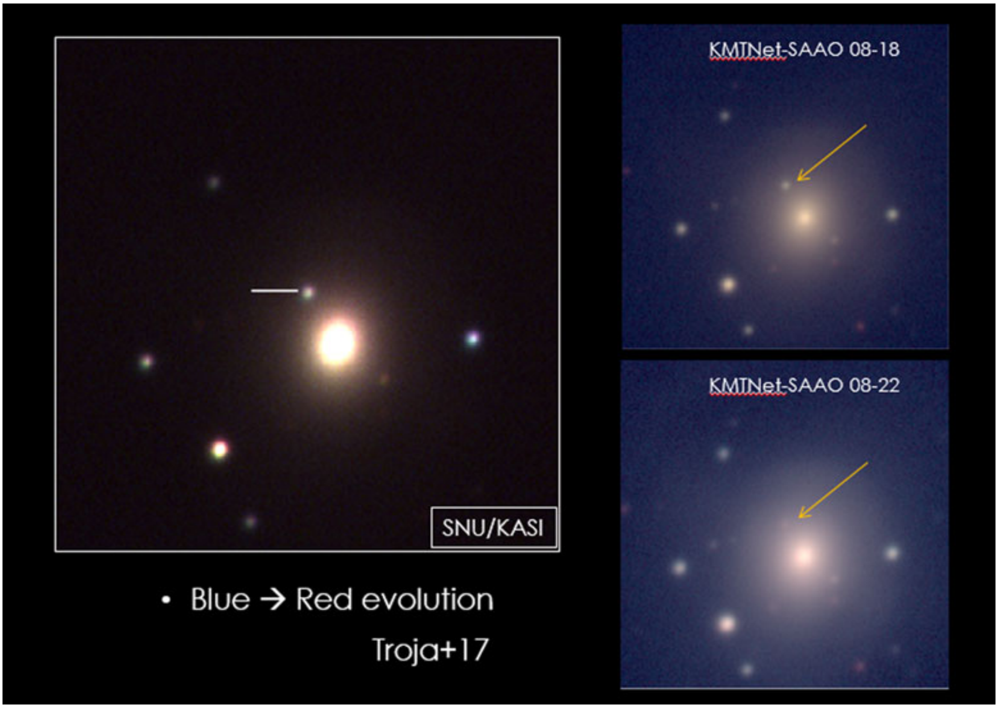


Figure 2. The optical counterpart (arrows) of GW170817 (AT2017gfo) in the galaxy NGC 4993, taken by KMTNet. The right figures show the time evolution of AT2017gfo which becomes redder as it fades.

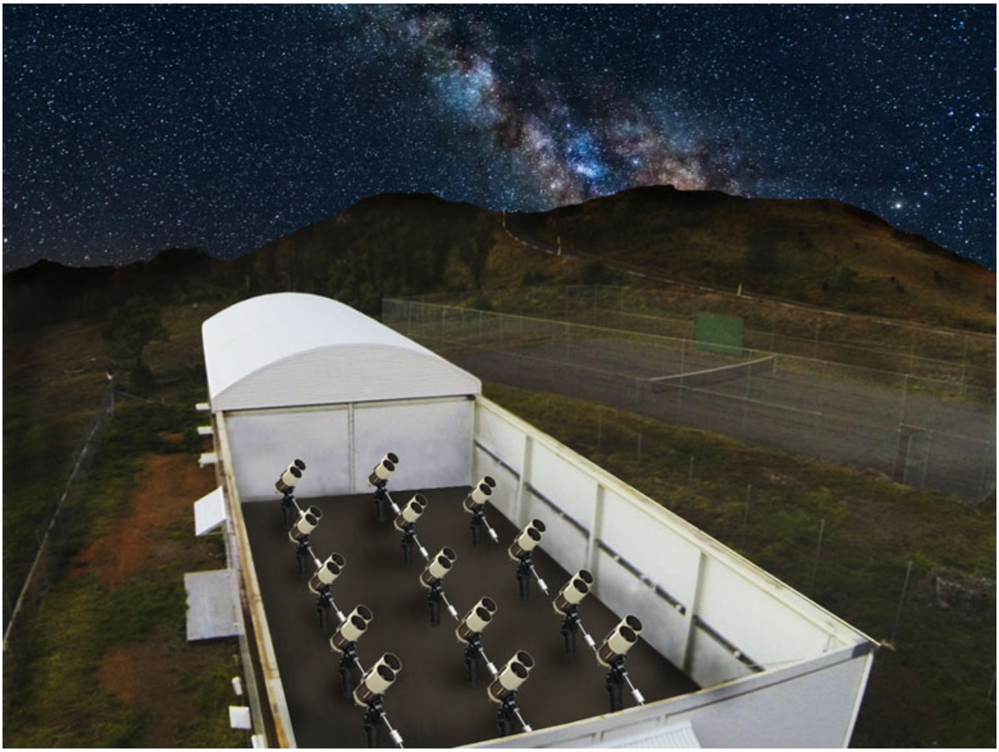


Figure 3. Conceptual drawing of 7DT, which will be installed in Chile.

4. 7-Dimensional Telescope, 7DT

As a new initiative to rapidly discover GW EM counterparts, we are constructing a new telescope, 7DT. 7DT is a multiple telescope system made of twenty, wide-field 0.5-m optical telescopes (Figure 3), with an expected completion by the end of 2023. Each of the 20 telescopes will image the sky with medium-band filters centered at two different wavelengths, providing 40 wavelength element spectral image with a single observation. 7DT can obtain low resolution spectra at $R \sim 30$ of every pixel in the entire field of view (about 1.4 $\deg^2$) to a depth of about 20 AB mag for a point source detection at 5-σ with a few minutes of exposure. Alternatively, with a single filter, it can cover 28 $\deg^2$ of the sky by having each telescope to observe different parts of the sky, or we can have the telescopes view the same region of the sky so that the entire system works as an equivalent of a wide-field, 2.3-m telescope. By obtaining spectra of all objects in a single observation, we expect that 7DT will expedite the whole process of the kilonovae identification.

References

Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017a, *ApJL*, 848, 12
Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017b, *ApJL*, 848, 13
Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017c, *Nature*, 551, 85
Abbott, R., Abbott, T. D., Abraham, S., et al. 2021, *PhRvX*, 11, 021053
Goldstein, A., Veres, P., Burns, E., et al. 2017, *ApJL*, 848, 14
Im, M., Yoon, Y., Lee, S.-K., et al. 2017, *ApJL*, 849, 16
Im, M., Choi, C., Hwang, S., et al. 2019, *JKAS*, 52, 11
Im, M., Kim, Y., Lee, C.-U., et al. 2021, *JKAS*, 54, 89
Kim, J., Im, M., Paek, G. S. H., et al. 2021, *ApJ*, 916, 47
Savchenko, V., Ferrigno, C., Kuulkers, E., et al. 2017, *ApJL*, 848, 15
Sesar, B., Ivezic, Z., Lupton, R. H., et al. 2007, *AJ*, 134, 2236
Troja, E., Piro, L., van Eerten, H., et al. 2017, *Nature*, 551, 71