GECKO Optical Follow-up Observation of Three Binary Black Hole Merger Events

Joonho Kim[1,2], Myungshin Im[1,2], Gregory S. H. Paek[1,2], Chung-Uk Lee[3], Seung-Lee Kim[3], Seo-Won Chang[1,2], Changsu Choi[1,2], Sungyong Hwang[1,2], Wonseok Kang[4], Sophia Kim[1,2], Taewoo Kim[4], Hyung Mok Lee[1,2], Gu Lim[1,2], Jinguk Seo[1,2], and Hyun-il Sung[3]

[1]Astronomy Program, Department of Physics and Astronomy, Seoul National University, Seoul 08826, Korea
[2]SNU Astronomy Research Center, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 08826, Korea
[3]Korea Astronomy and Space Science Institute, Daejeon 34055, Korea.
[4]Deokheung Optical Astronomical Observatory, National Youth Space Center, Goheung 59567, Korea

Abstract

We present optical follow-up observation results of three binary black hole merger (BBH) events, GW190408, GW190412, and GW190503, which were detected by the Advanced Ligo and Virgo gravitational wave (GW) detectors. Electromagnetic (EM) counterparts are generally not expected for BBH merger events. However, some theoretical models suggest that EM counterparts of BBH can possibly arise in special environments, prompting motivation to search for EM counterparts for such events. To identify EM counterparts of the three BBH merger events, we observed high-credibility regions of the sky with telescopes of the Gravitational-wave EM Counterpart Korean Observatory (GECKO), including the Korea Microlensing Telescope Network (KMTNet). Our observation started as soon as 100 minutes after the GW event alert and covered roughly 29 - 63 deg^2. No plausible EM counterparts were found for these events, but from no detection in the GW190503 event, for which we covered 69% credibility region, we place the BBH merger EM counterpart signal to be M_g > 18.0 AB mag within about 1 day of the GW event. The comparison of our detection limits with light curves of several kilonova model suggests that a kilonova event could have been identified within hours from GW alert with GECKO observations if the compact merger happened at < 400 Mpc and the localization accuracy was of order of 50 deg^2. Our result gives a great promise for the GECKO facilities to find EM counterparts within few hours from GW detection in future GW observation runs.

Introduction

- First GW detection, GW150914
  - BBH merger
- First EM counterpart of GW source, GW170817
  - Binary neutron stars (BNS) merger
  - Discovery of kilonova at NGC4993 (KMTNet & LSGT follow-up)
- BBH merger detections so far
  - 1 for O1 run, 3 for O2 run, 20 for O3a run
- EM counterpart of BBH merger
  - Not expected in general and no EM counterpart detection so far
  - Possible to have EM emission in special environment (e.q., AGN)

→ Optical follow-up of three BBH merger events with GECKO telescopes

Observation

Event	Distance	90% area	Telescope	Coverage
GW190408	1580 Mpc	140 deg^2	KMTNet, WIT	0.14%
GW190412	740 Mpc	21 deg^2	KMTNet, WIT, DOAO, SAO, LOAO	2.3%
GW190503	1520 Mpc	94 deg^2	KMTNet	33%

- We used GWTC-2 catalog (Abbott et al. 2020) for distance and 90% area
- Information about telescopes can be found in Im et al. (2019) and Kim et al. (2016)
- Tiling observation coverage is shown in Figure 1

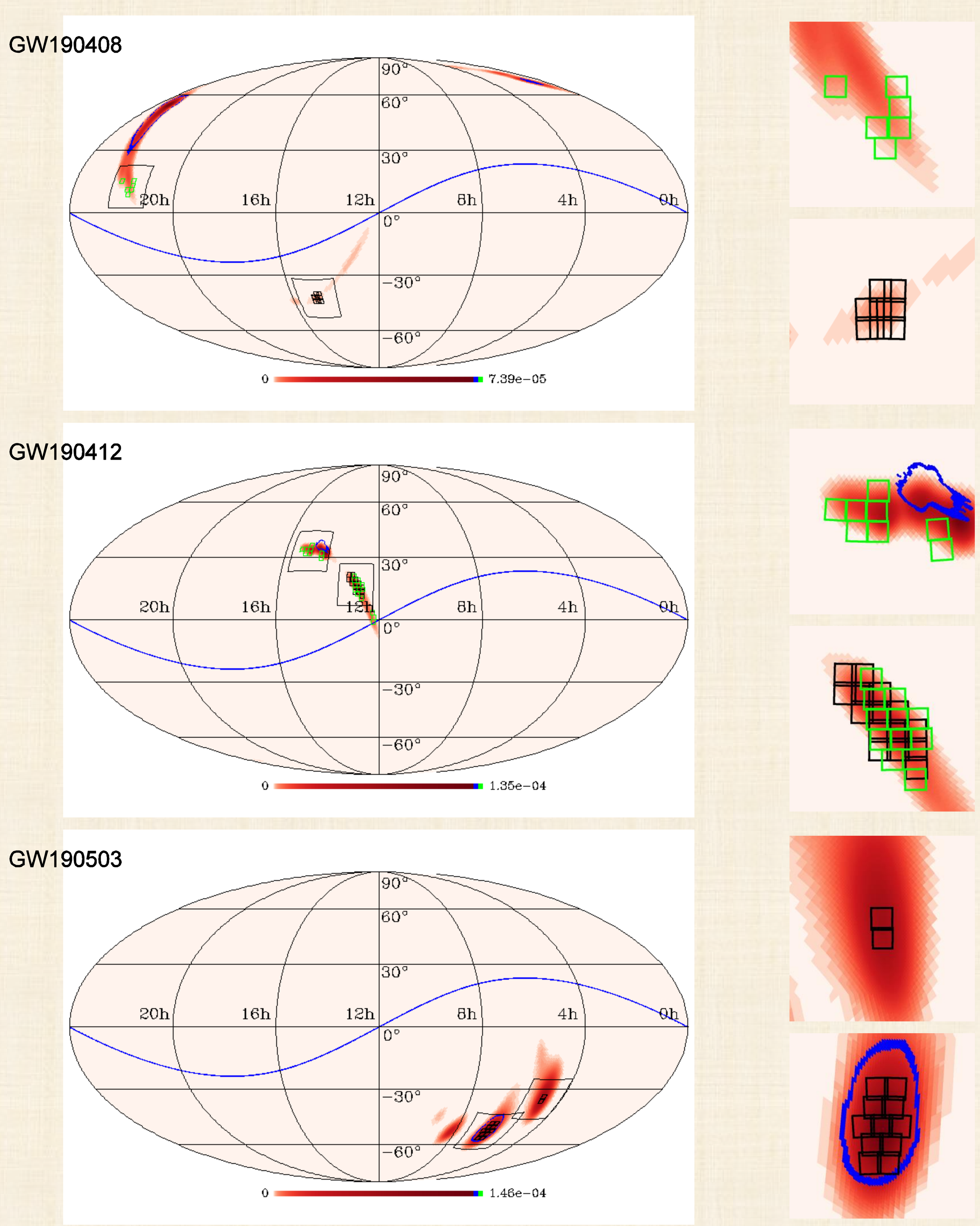

Figure 1. The GW localization and the coverage of our EM follow-up tiling observation for three GW events. Here, we used the GW localization map of the initial alerts, while the blue contours show boundary of the 90% localization area in the GWTC-2 catalog. The large black boxes in the sky map on the left are expanded in the right panels. The small black and green boxes are field coverages of the KMTNet and WIT pointings, respectively. The blue lines indicate the ecliptic plane.

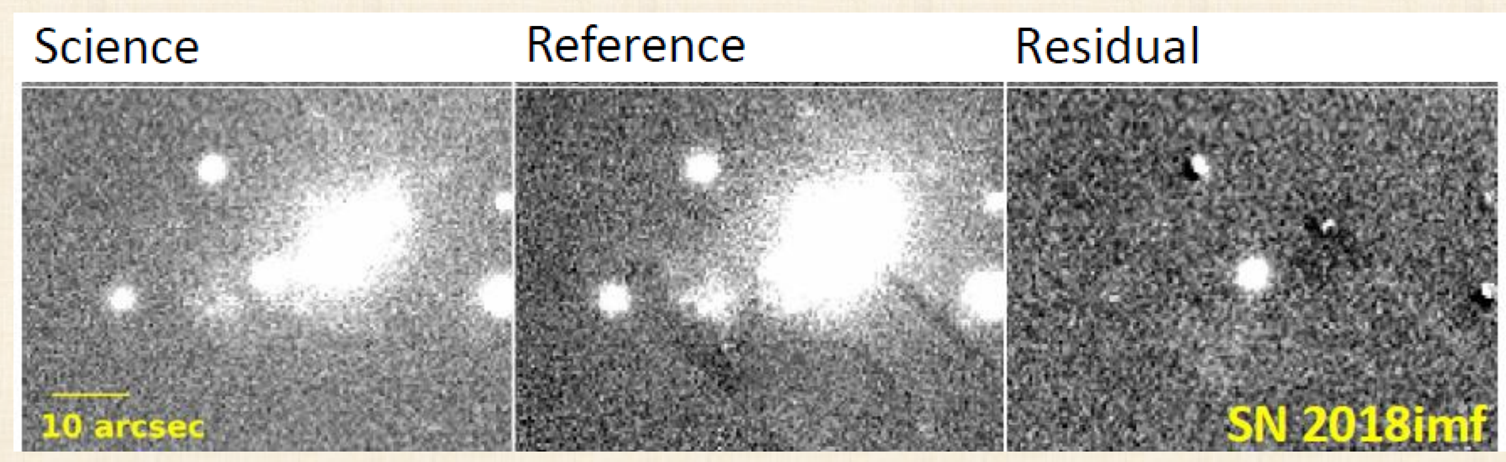

Figure 2. One of the three known transients found in the follow-up observation of GW190412 event, SN 2018imf. From left to right, each panel represents the object (science) image, the reference image, and the residual image after subtracting the reference image from the object image.

Transient search

- Image subtraction using HOTPANTS software (Becker 2015)
- Find possible transients with SExtractor (Bertin&Arnouts1996) parameters
- Matching with SkyBoT (Berthier et al. 2006) to remove solar system objects
- No transient candidate for GW190408 and GW190503
- 17 transient candidates for GW190412 (But, no plausible EM counterparts)
  - One fast proper motion star
  - 3 unknown moving objects and 10 moving object candidates
  - 3 known transients (Figure 2)

Discussion

- Constrain BBH EM counterpart brightness as M_g > 18.0 AB mag
- Comparison with kilonova light curve models (Figure 3)
- Prospects for rapid (within 1 hour) follow-up observation
- Need for reference images (KMTNet Synoptic Survey of Southern Sky)

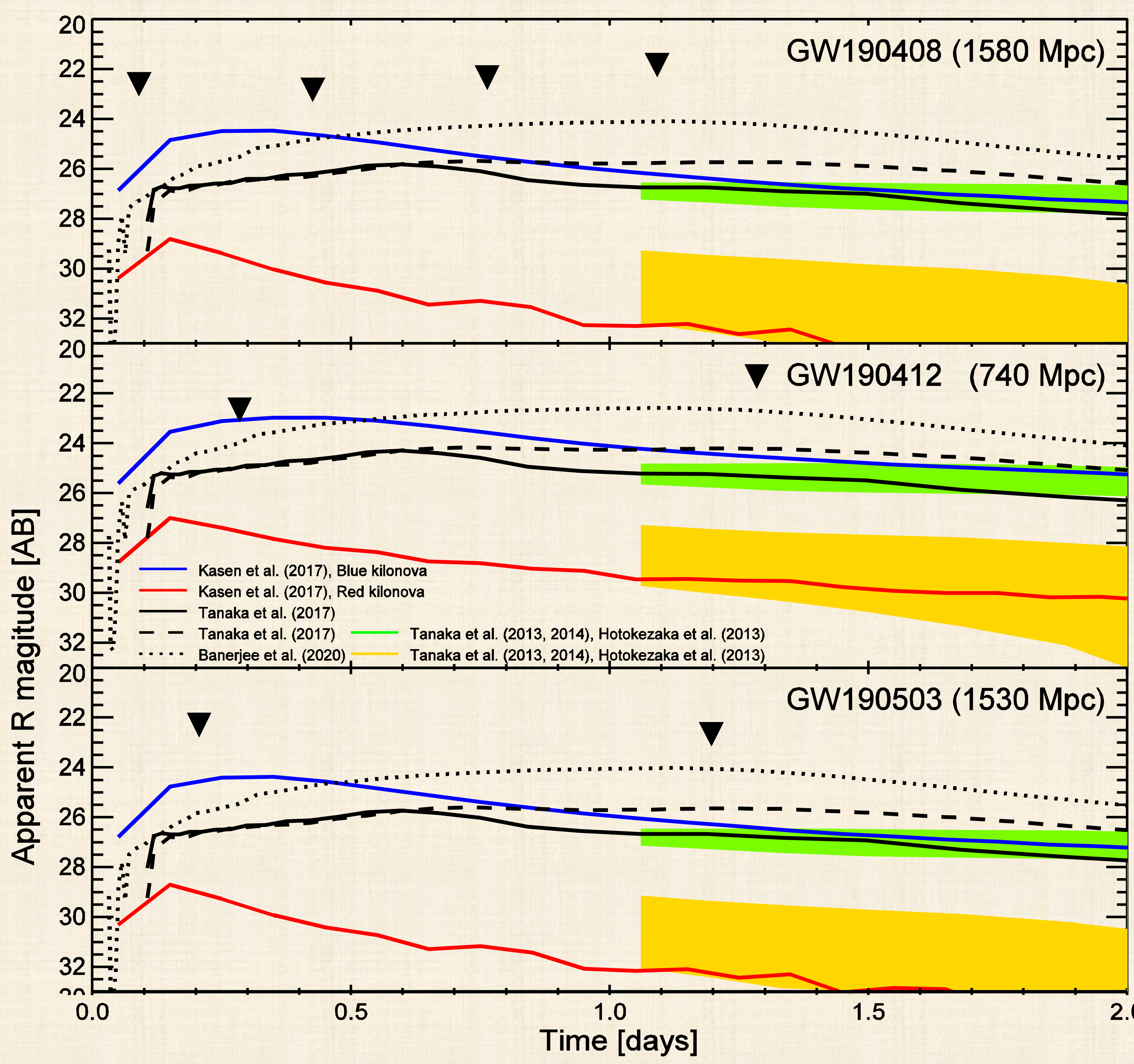

Figure 3. Comparison of different model light curves of kilonova and the KMTNet image depths (black triangles) of three events in top three panels. The blue and red solid lines indicate the blue and red components of the GW170817-like kilonova model light curves of Kasen et al. (2017). The black solid, dashed, and dotted lines are the GW170817-like kilonova model of Tanaka et al. (2017), and Banerjee et al. (2020). These models assume ejecta masses of 0.03 Msun, 0.03 Msun, and 0.05 Msun and electron fractions of 0.1 - 0.4, 0.25, and 0.3 - 0.4, respectively. The green and yellow regions are the range of four NSBH and five BNS model light curves, respectively, from Tanaka et al. (2013, 2014); Hotokezaka et al. (2013).