Optical follow-up observation for GW event with Subaru/HSC

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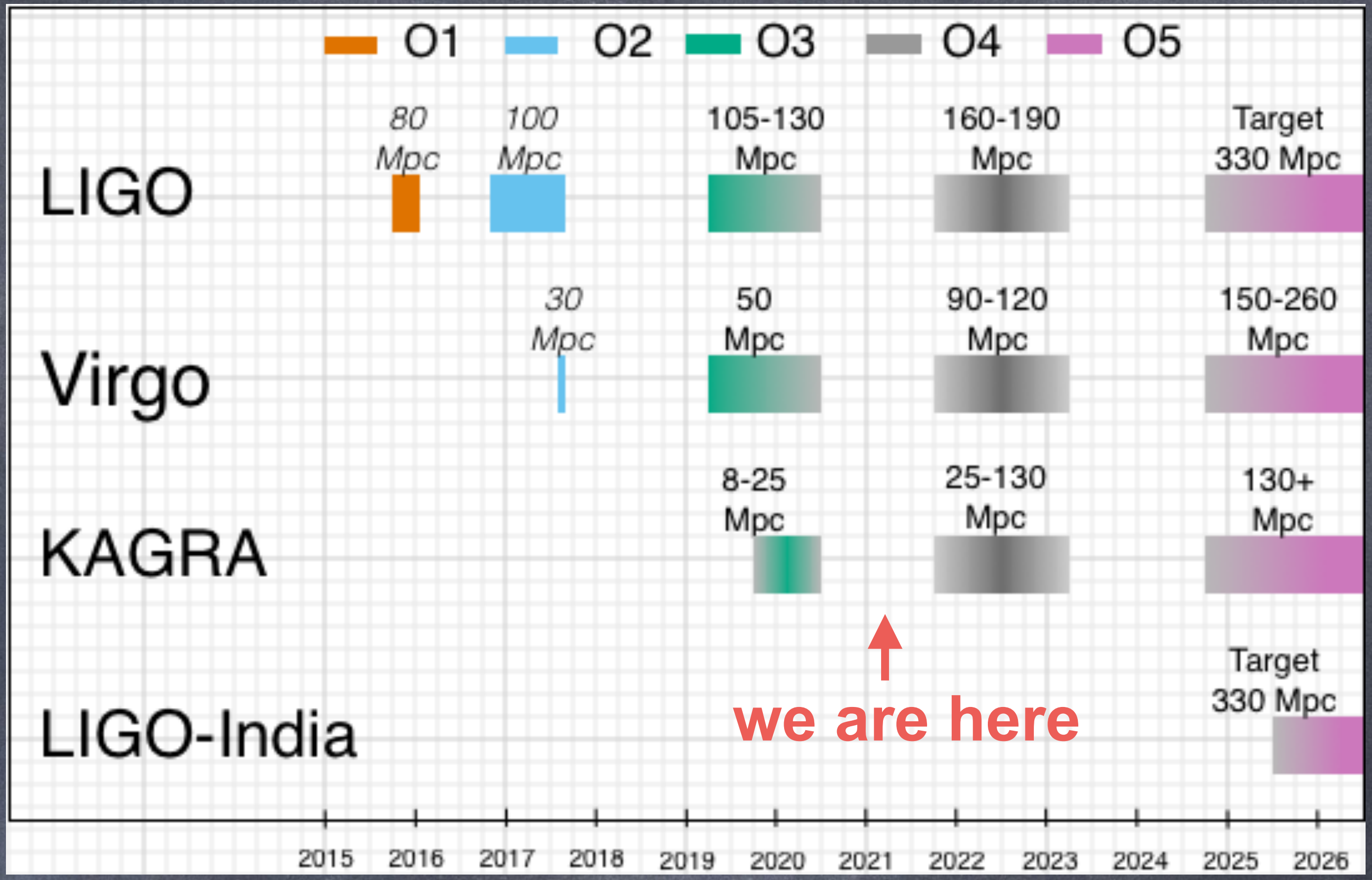
Current GW interferometers are aiming at compact object mergers as a GW source. If the system includes NS, it should be accompanied with EM emissions.



https://wiki.gw-astronomy.org/OpenLVEM/Telecon20190815

J-GEM

Japanese collaboration for Gravitational-wave Electro-Magnetic follow-up

Introduction

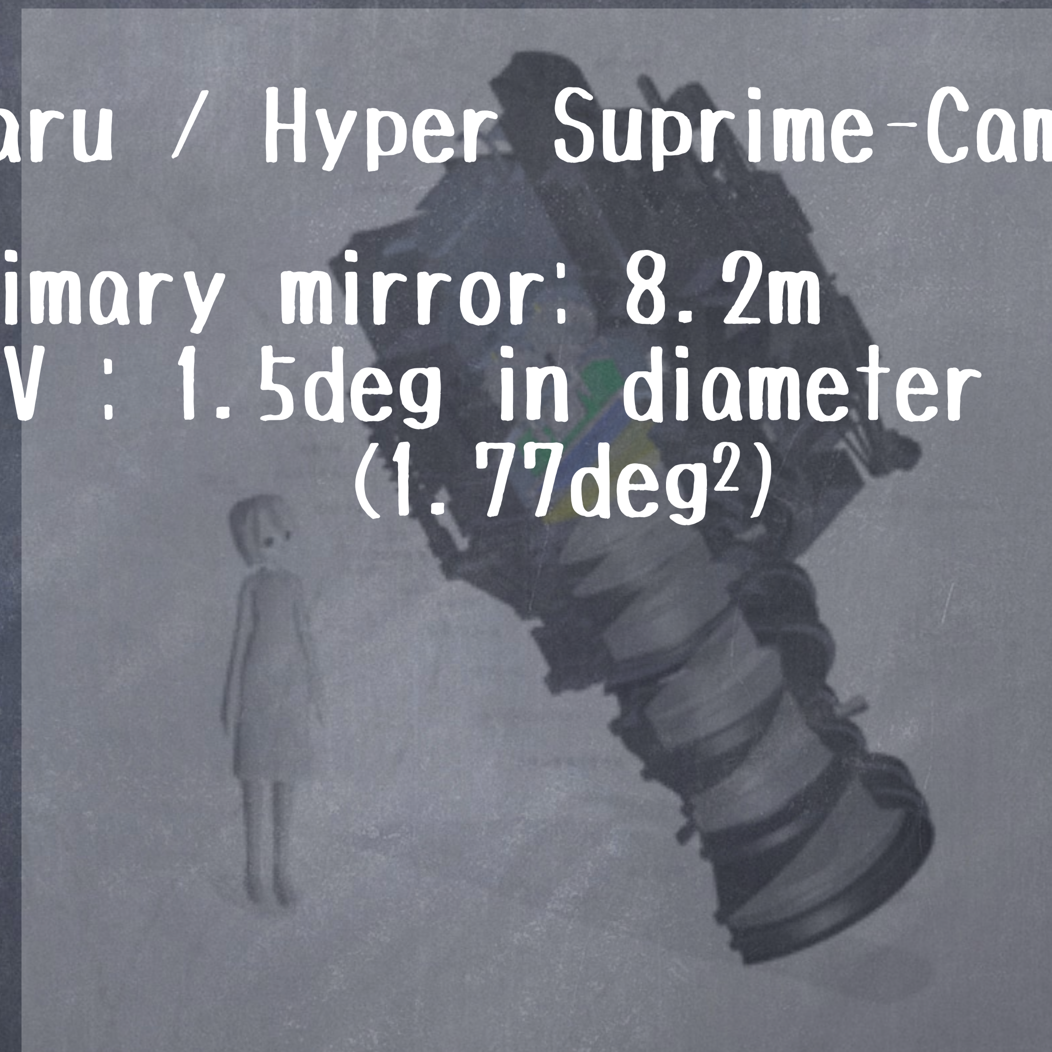
Several events of interest

Event	Source category	90% credible region	Luminosity distance
GW190412	BBH [>99%]	21 deg^2	734 Mpc
GW190425	BNS [>99%]	7461 deg^2	156 Mpc
GW190521	BBH [97%], Terrestrial [3%]	936 deg^2	4567 Mpc
GW190814	NSBH [99%]	23 deg^2	267 Mpc
GW170817	BNS	28 deg^2	40 Mpc

very far and very wide

Because the localizations are spread reaching to ~1000 deg^2 or more, it is very important to perform a survey with large telescopes with a wide FoV.

Introduction



Subaru / Hyper Suprime-Cam

Primary mirror: 8.2m
FoV : 1.5deg in diameter
($1.77\mathrm{deg}^2$)

Because Subaru telescope has one of the powerful cameras in the world, Hyper Suprime-Cam, it has very important role for the transient survey.

This work takes on a role of wide-field survey in the J-GEM activities (targeted or wide-field).

Follow-up observations with Subaru/HSC

- S190510g (Published in PASJ): BNS (85%) -> Terrestrial (58%)

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Optical follow-up observation for GW event S190510g using Subaru/Hyper Suprime-Cam

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Abstract

A gravitational wave event, S190510g, which was classified as a binary-neutron-star coalescence at the time of preliminary alert, was detected by LIGO/Virgo collaboration on 2019 May 10. At 1.7 hours after the issue of its preliminary alert, we started a target-of-opportunity imaging observation in the *Y* band to search for its optical counterpart using the Hyper Suprime-Cam (HSC) on the Subaru Telescope. The observation covers a 118.8 deg^2 sky area corresponding to 11.6% confidence in the localization skymap released in the preliminary alert and 1.2% in the updated skymap. We divided the observed area into two fields based on the availability of HSC reference images. For the fields with the HSC reference images, we applied an image subtraction technique; for the fields without the HSC reference images, we sought individual HSC images by matching a catalog of observed objects with the PS1 catalog. The search depth is 22.28 mag in the former method and the limit of search depth is 21.3 mag in the latter method. Subsequently, we performed visual inspection and obtained 83 candidates using the former method and 50 candidates using the latter method. Since we only have the one-day photometric data, we evaluated the probability of candidates being located inside the 3D skymap by estimating their distances with photometry of associated extended objects. We found three candidates are likely located inside the 3D skymap and concluded they could be a counterpart of S190510g, while most of the 133 candidates were likely to be supernovae because the number density of candidates was consistent with the expected number of supernova detections. By comparing our observational depth with a light-curve model of such a kilonova reproducing AT2017gfo, we show that early deep observations with the Subaru/HSC can capture the rising phase of the blue component of a kilonova at the estimated distance of S190510g (∼230 Mpc).

Key words: gravitational waves — nuclear reactions, nucleosynthesis, abundances — stars: neutron — surveys

1 Introduction

A multi-messenger observation with gravitational waves (GW) and electromagnetic (EM) waves is crucial for understanding the physical processes of compact star coalescence. Neutron-star (NS) mergers are expected to be accompanied by EM emissions called "kilonova" (or "macronova") powered by radioactive decays of *r*-process nuclei (Li & Paczyński 1998; Kulkarni 2005; Metzger et al. 2010); therefore, the EM emission from binary neutron star (BNS)-merger events aids in understanding the origin of heavy elements produced by the *r*-process (Metzger et al. 2010; Kasen et al. 2013, 2015; Barnes & Kasen 2013; Tanaka & Hotokezaka 2013; Tanaka et al. 2014).

The localization area of GW observations can be an order of 10 deg^2 for the best case, but can be as large as 1000 deg^2. It has been quite large for locating a galaxy hosting a system that caused the GW event. Therefore, EM follow-up observations had been expected to play a key role in identifying the counterpart. The first identification of an EM counterpart to GW was achieved in the event of the first detection of GW from a neutron star merger (GW170817). GW170817 was localized with three interferometers in the second observing run (O2) of the LIGO/Virgo collaboration (Abbott et al. 2017). The identification of the EM counterpart was made by several observatories including space telescope from radio to gamma-ray (Arcavi et al. 2017; Coulter et al. 2017; Díaz et al. 2017; Evans et al. 2017; Lipunov et al. 2017; Soares-Santos et al. 2017; Tanvir et al. 2017; Tominaga et al. 2018; Valenti et al. 2017).

Untargeted wide-field surveys are important for identifying the uniqueness of the counterpart. The Japanese collaboration for Gravitational wave ElectroMagnetic follow-up (J-GEM; Morokuma et al. 2016) conducted coordinated observations (Utsumi et al. 2017) and deep blind *z*-band imaging surveys to identify an EM counterpart using the Hyper Suprime-Cam (HSC) on the Subaru Telescope (Miyazaki et al. 2018; Kawanomoto et al. 2018; Komiyama et al. 2018; Furusawa et al. 2018). They succeeded in independently identifying the counterpart (AT2017gfo; Tominaga et al. 2018). HSC is a $1\overset{\circ}{.}5$ ϕ wide-field optical imager, which is the largest among the current existing telescopes with an aperture larger than 8 m. While galaxy-targeted and untargeted wide-field surveys identified AT2017gfo, wide-field survey observations with the Subaru/HSC and Blanco/Dark Energy Camera (DECam) succeeded in identifying the uniqueness of AT2017gfo with a high completeness by ruling out the other candidates including transients which are not associated with galaxy.

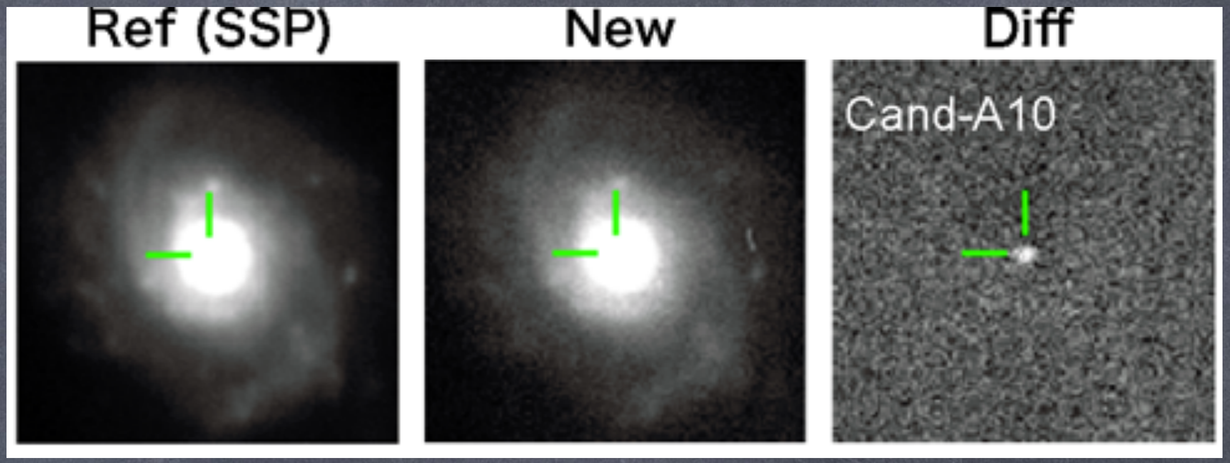
Kilonova models can broadly reproduce the time evolution of optical and near-infrared emissions of AT2017gfo (Shibata et al. 2017; Tanaka et al. 2017; Kasen et al. 2017; Perego et al. 2017; Kawaguchi et al. 2018; Rosswog et al. 2018). However, the observed emissions display blue components in the early-phase spectra, and the origin of the emission is unclear. Two models for the early blue component are proposed: a radioactive heating model (a kilonova model having higher electron fraction; Tanaka et al.

Ohgami et al. 2021

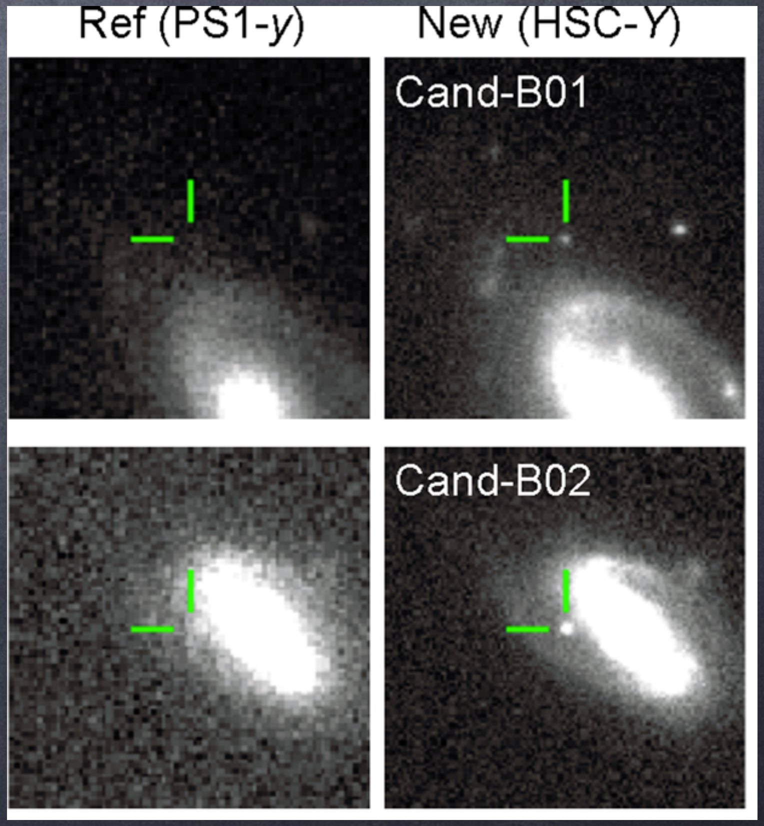
S190510g

- Results of candidate selection

We concluded that 3 sources are final candidates (P_{3D} > 50%). And we could not rule out the possibility that 44 candidates are related to the GW event because their distance cannot be estimated.



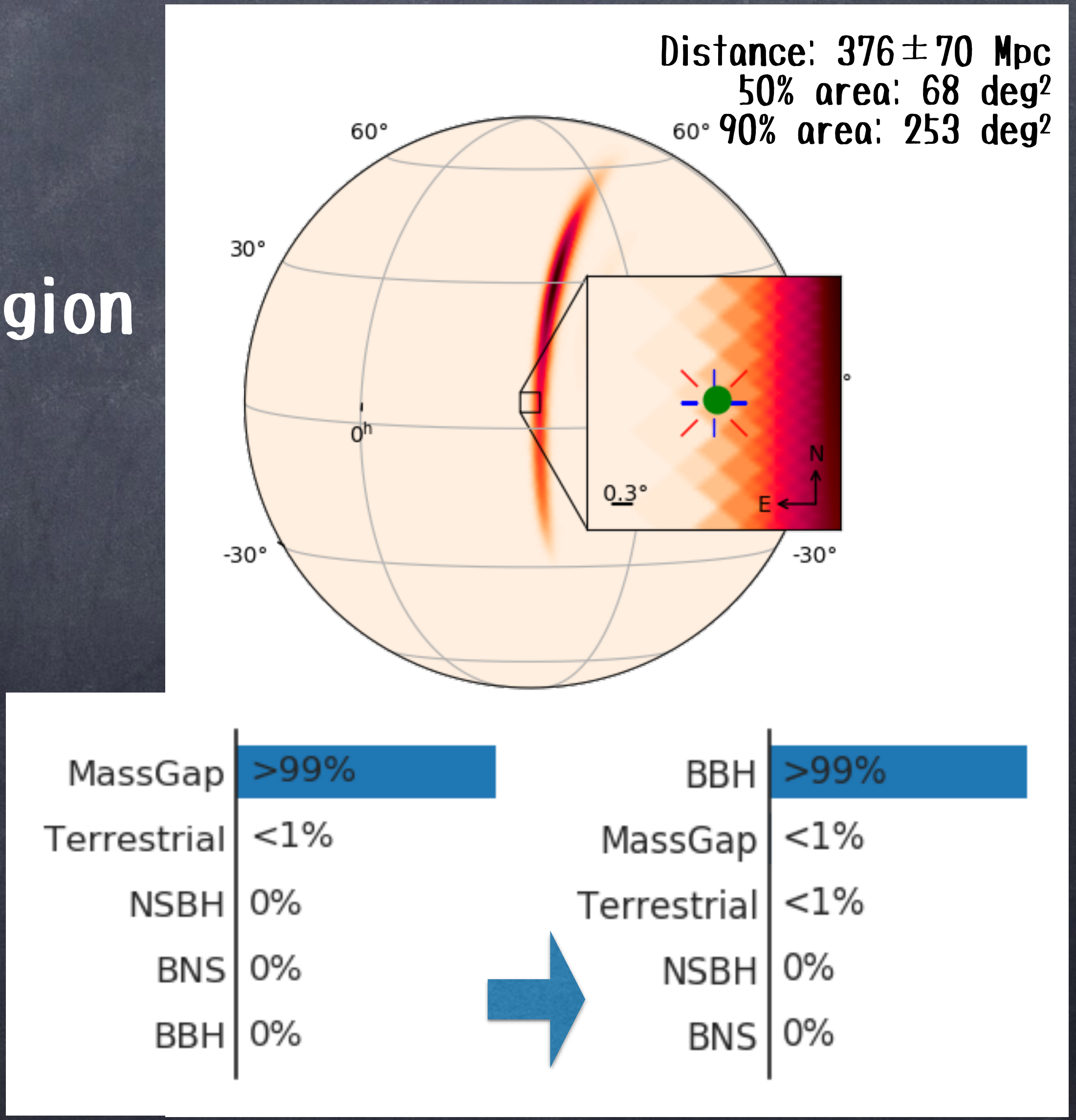
Name	RA	Dec	Mag (AB)	P_{3D}
fields with HSC-SSP reference				
Cand-A10	13h29m50s.37	-01d25’44”.5	21.11	65.0%
fields without HSC-SSP reference				
Cand-B01	13h46m52s.14	+03d45’01”.4	21.24	84.8%
Cand-B02	13h44m36s.38	+03d17’19”.6	20.56	73.3%



See Ohgami et al. 2021 for the details.

Follow-up observations with Subaru/HSC

- S191216ap
  - MassGap -> BBH
  - GCN 26509 (LIGO/Virgo S191216ap: Subaru/Hyper Suprime-Cam observations of GW+IceCube+HAWC error region)
  - started 2019-12-20 05:06 UT
  - observation area: 2.3 deg^2
    - main target: GL213356+051647
    - covers the HAWC's 68% credible region
  - z-band (2730 sec)
  - limiting magnitude: 25.2 mag

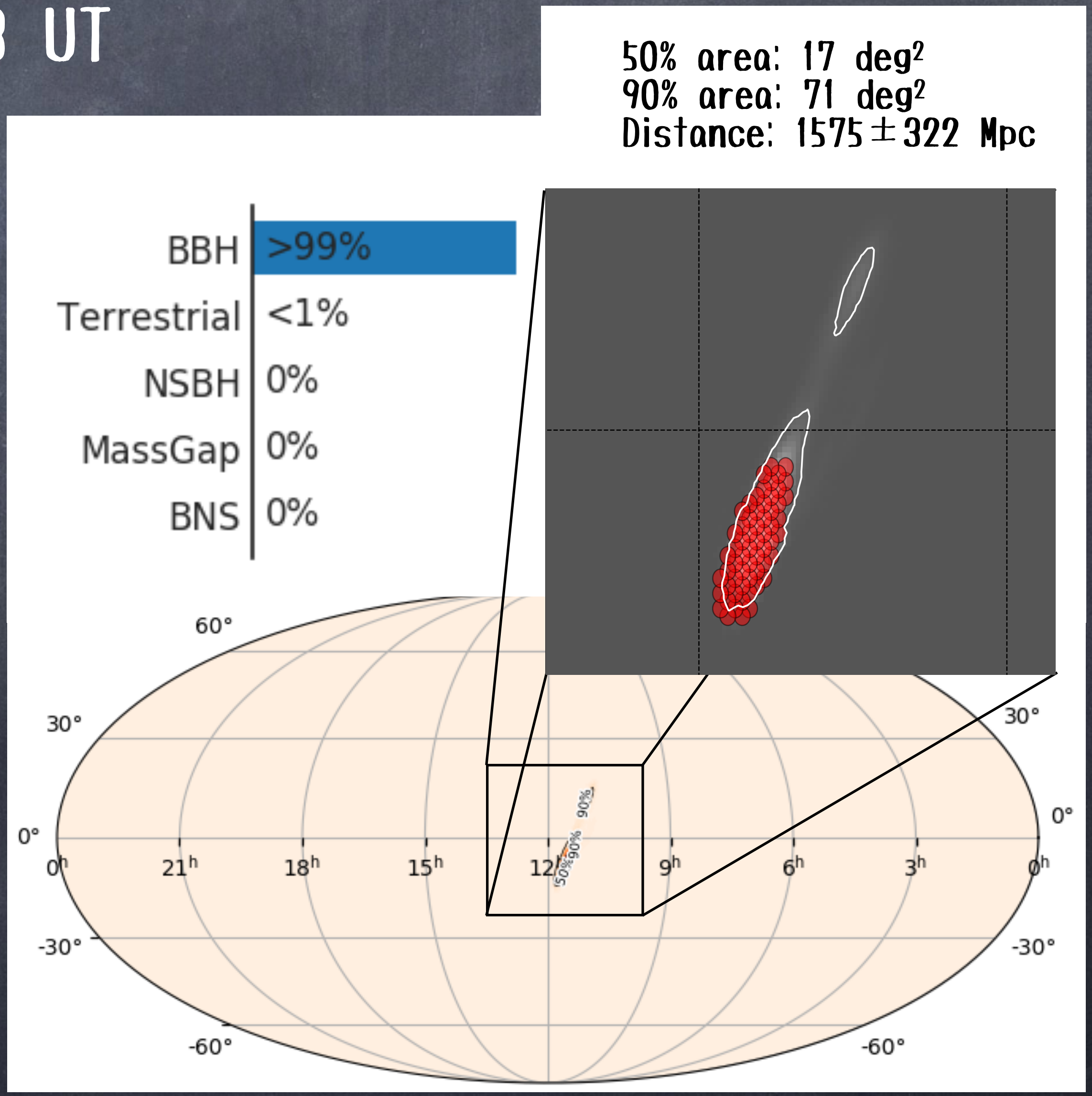


No additional observation because the estimated origin changed from MassGap to BBH.

Follow-up observations with Subaru/HSC

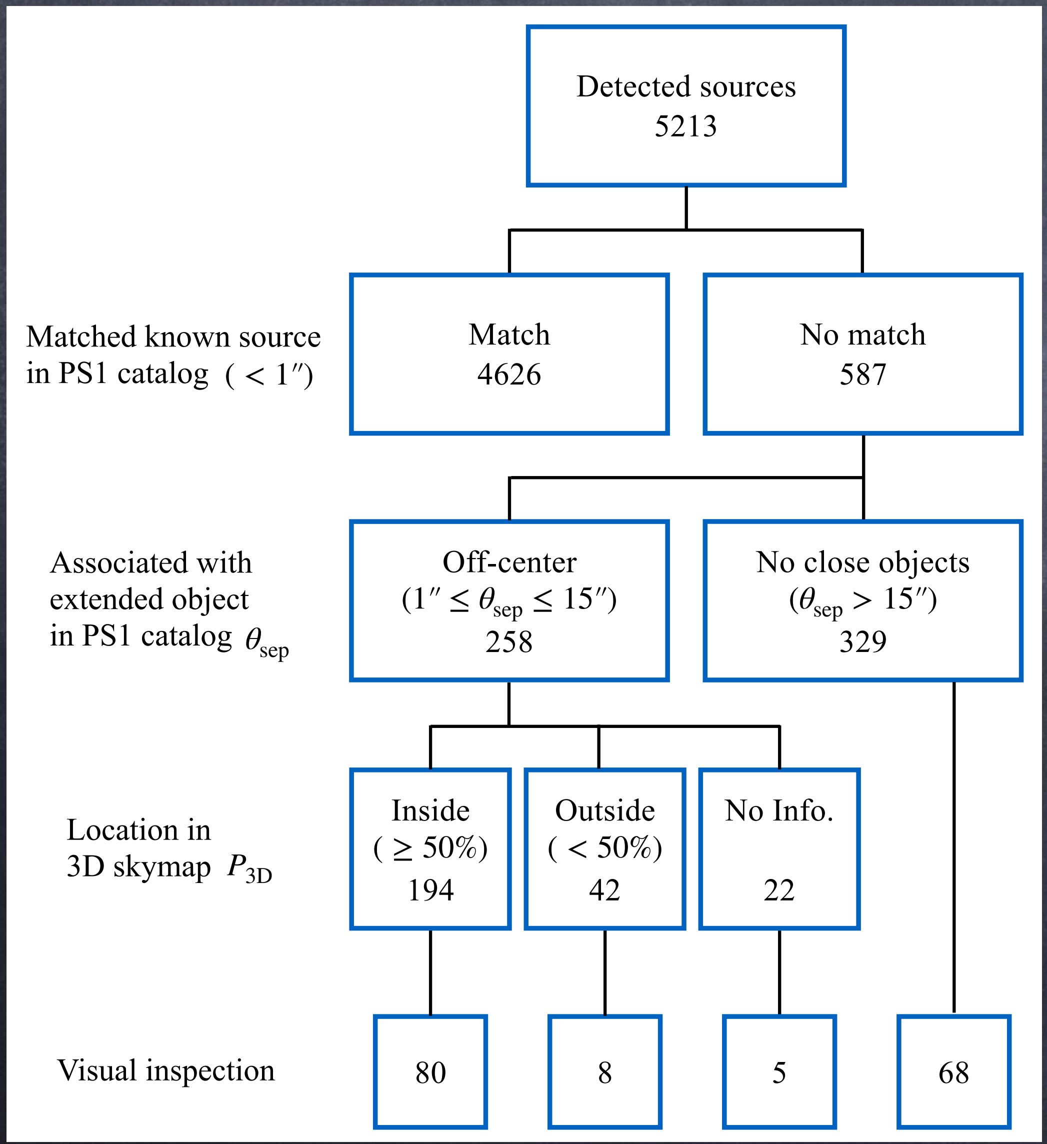
- S200224ca
  - BBH event
  - GCN 27205 (LIGO/Virgo S200224ca: Subaru/Hyper Suprime-Cam follow-up observations)
  - 2020-02-25, 2020-02-28, 2020-03-23 UT
  - observation area: 57.8 deg^2
    - 60 pointings
    - integrated probability: 80.8%
  - $r2$- and z-band

Date (Day after event)	Filter	Exposure time	Limiting magnitude (AB)
2020-02-25 UT	$r2$	30 sec x 2	24.51 - 25.71
(Day 1)	z	30 sec x 2	22.84 - 24.14
2020-02-28 UT	$r2$	30 sec x 2	23.98 - 25.13
(Day 4)	z	30 sec x 2	22.54 - 23.76
2020-03-23	$r2$	50 or 70 sec	24.64 - 26.25
(Day 28)	z	35 sec x 2	22.85 - 24.64



S200224ca

- Source detection and screening
  - image subtraction (ref 03-23)
  - selection criteria
    - identified point sources
    - detected at least twice in 4 difference images



- MCMC fitting with light curve templates
  - Type Ia SN
  - Core-collapse SNe (Type Ibc, IIL, IIP, IIn)
  - Rapid transients (PS1-10ah, 10bjp, 11bbq, 11qr, 12bb, 12bv, 12brf, 13ess, 13duy)
  - threshold: Q-value(χ^2) > 10^{-4}

- 29 candidates inconsistent with the transient templates
  - 18 Inside 3D skymap
  - 3 Outside 3D skymap
  - 2 No Information
  - 6 No close objects

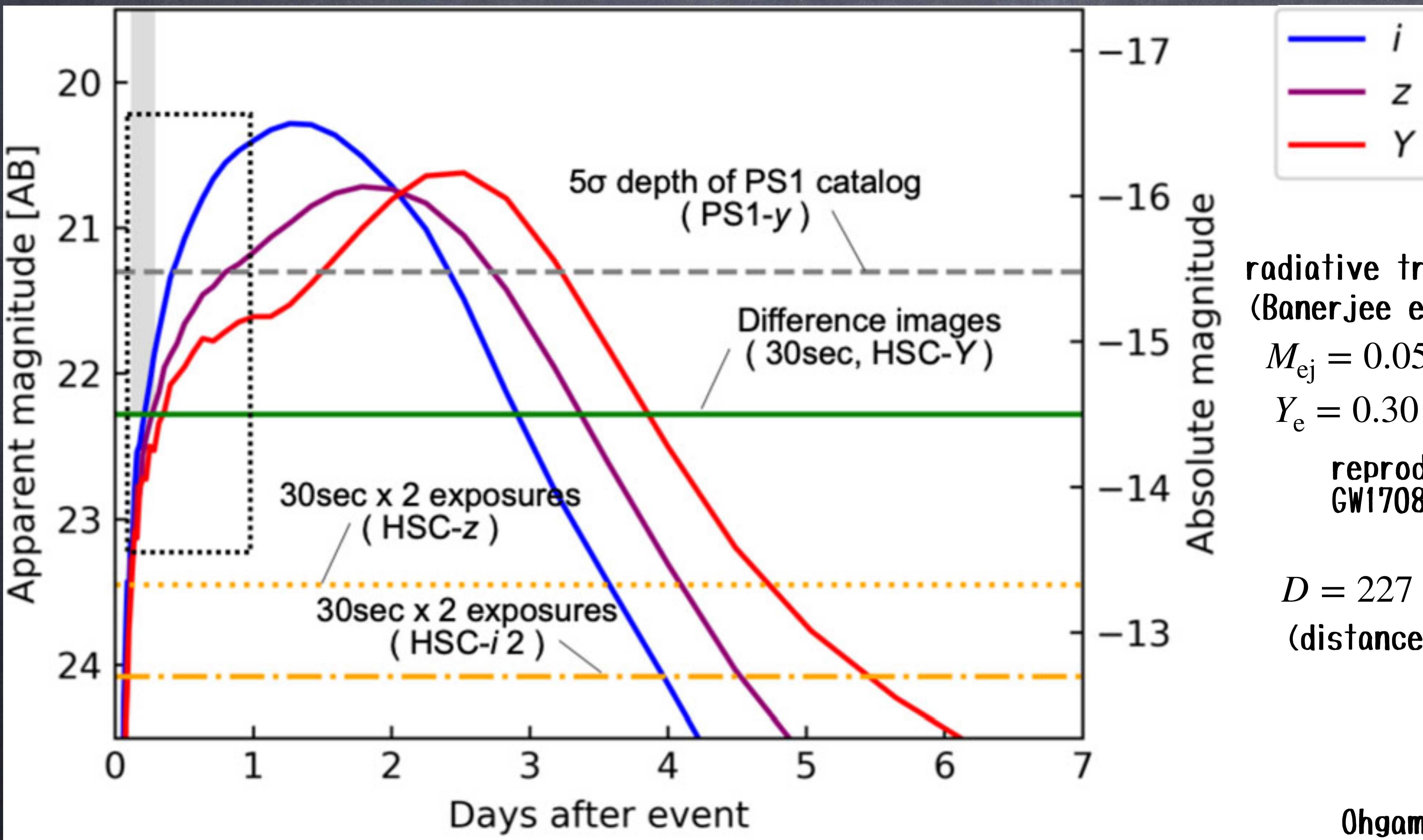
cannot be ruled out

5 of 18 candidates probably inside 3D skymap were observed with GTC (10m Opt/IR telescope)/OSIRIS to be measured its redshift (spec-z).

-> analysis ongoing

Future prospects

Comparison with a kilonova model



radiative transfer model
(Banerjee et al. 2020)

$M_{\rm ej} = 0.05 M_\odot$

$Y_{\rm e} = 0.30 - 0.40$

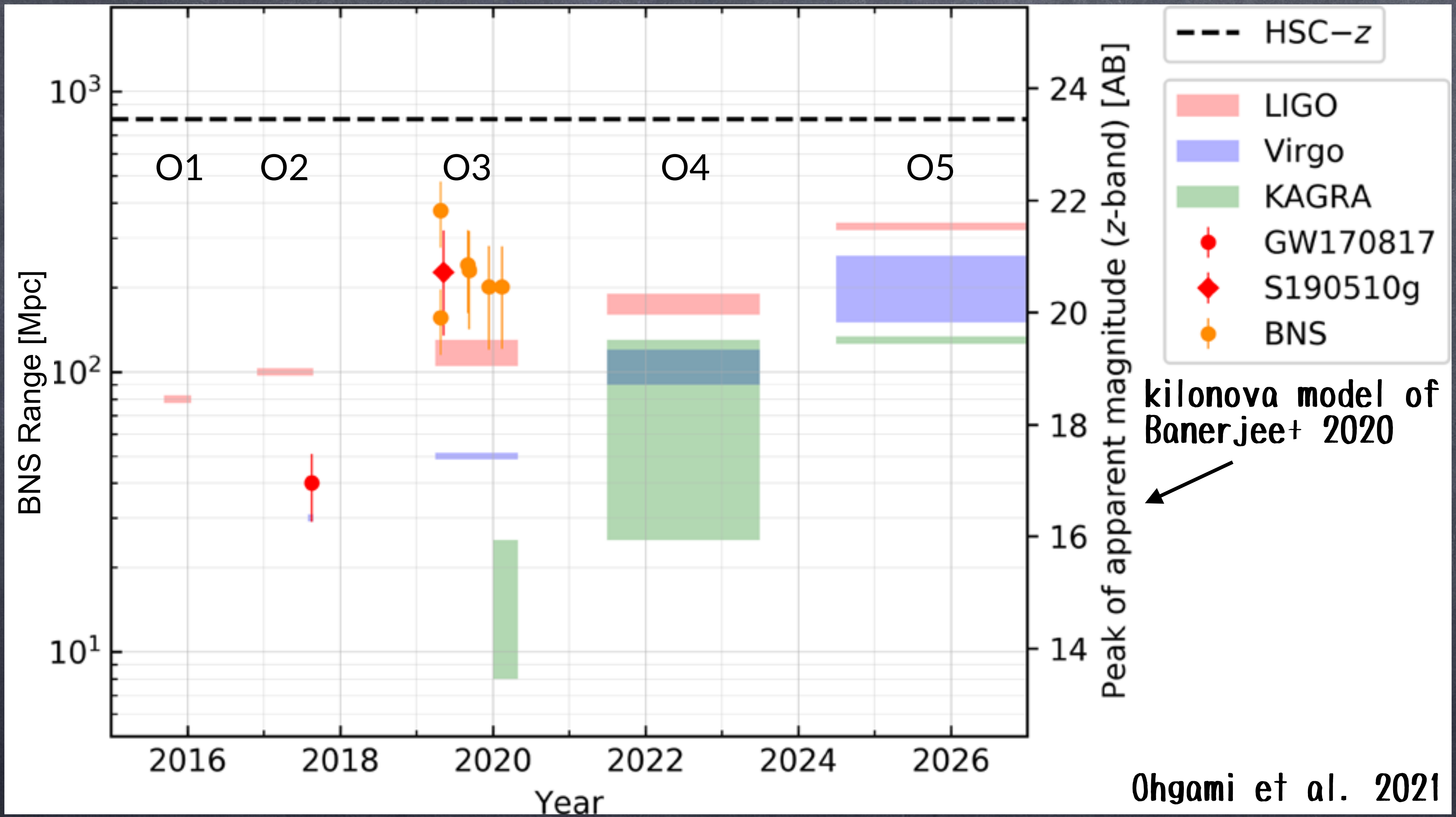
reproducing
GW170817/AT2017gfo

$D = 227$ [Mpc]
(distance of S190510g)

Ohgami et al. 2021

Future prospects

Comparison with detecter's BNS range



The chance we can trigger a ToO observation will be 9% (8hr/1day & availability rate of 30%).
0.4-15.2 BNS events might be observed with Subaru/HSC in O4.
(BNS event rate 110-3840 $Gpc^{-3}yr^{-1}$; Abbott et al. 2019)

Summary & Conclusion

- We performed ToO observation with Subaru/HSC at 3 events; S190510g, S191216ap and S200224ca.
  - S190510g (BNS -> Terrestrial)
    - 3 candidates
    - 44 sources are not ruled out
  - S191216ap (MassGap -> BBH)
    - not found apparent transient associated with GL213356+051647
    - estimated origin changed MassGap to BBH
  - S200224ca (BBH)
    - 18 candidates are likely inside of 3D skymap
    - 5 of them were observed by GTC/OSIRIS to be measure its redshift (spec-z)
    - 8 candidates cannot be ruled out
- Future prospects
  - Subau/HSC has a chance to contribute to 0.4 - 15 BNS events in O4.