

Optical follow-up observation with Subaru/Hyper Suprime-Cam

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On behalf of J-GEM collaboration



3rd Aug 2017

Observational Signatures of r-process Nucleosynthesis in Neutron Star Mergers

Outline

- Subaru/Hyper Suprime-Cam
- Japanese collaboration for Gravitational wave ElectroMagnetic follow-up (J-GEM)
- J-GEM follow-up observations of GW alerts
 - GW150914
 - GW151226 (incl. HSC observations)
- Contaminations in 24mag observations

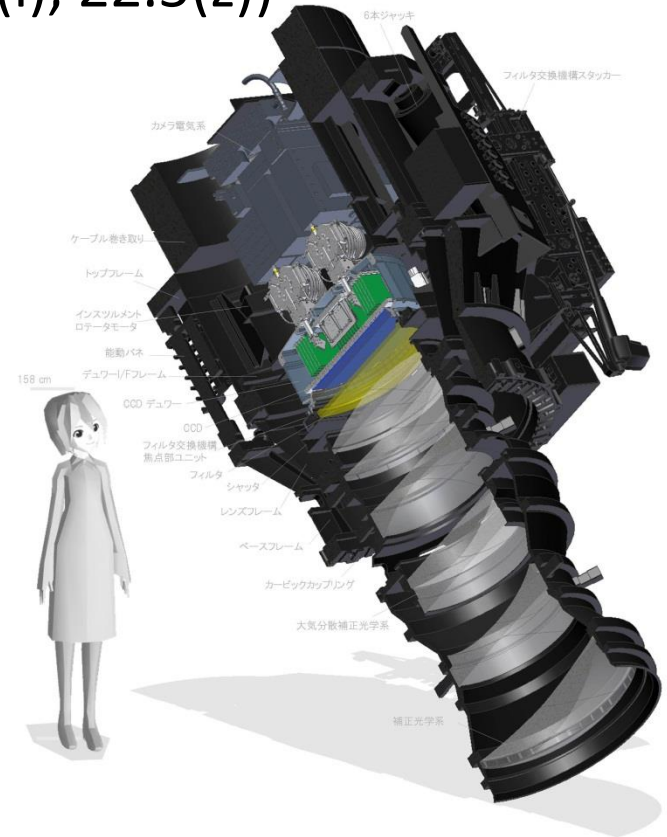
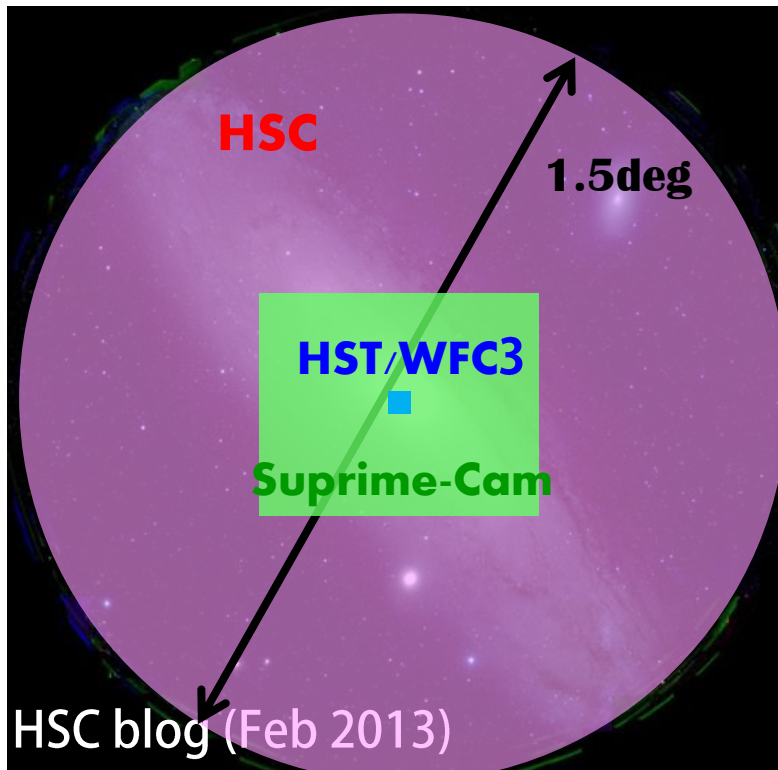
Morokuma, ..., NT et al. 2016 PASJ 68 L9

Yoshida, Utsumi, NT et al. 2017 PASJ 69 9

Utsumi, NT et al. in prep.

Subaru/Hyper Suprime Cam

- Hyper Suprime-Cam (HSC)
 - Diameter: 8.2m, FoV: 1.77deg², ~900M pixels
 - m_{lim} (5 σ) w/ 1min: **24.5**(i), **23.8**(z)
(CTIO/DECam 1min: 23.3(i), 22.5(z))



Etendue of telescopes/cameras

Survey	Diameter [m]	FoV [deg ²]	Etendue (AΩ, roughly) [m ² deg ²]
ROTSE-III	0.45	3.42	0.54
CRTS	0.7	8	3.1
KWFC/KISS	1.05	4	3.5
PTF	1.26	7.8	9.7
Sk	Currently, Subaru/HSC is the instrument with the highest survey power.		
Pa			
SDSS	2.5	1.5	7.4
CFHT/SNLS	3.6	1	10.2
HST/GOODS	2.5	0.003	0.015
DECam	4	3.0	38
Subaru/HSC	8.2	1.75	92
2022- LSST	8.4	9.62	319

Japanese collaboration for
Gravitational wave ElectroMagnetic
follow-up (J-GEM)

J-GEM (Japanese collaboration for Gravitational-wave Electro-Magnetic follow-up)

A part of the project “Multi-messenger Observations of GW sources”

* collaborating with the KAGRA data analysis team

Main features:

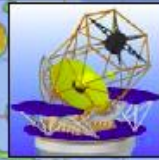
5 deg² opt. imaging w/ 1m
1 deg² NIR imaging w/ 1m
opt-NIR spectroscopy w/ 1–8m
opt-NIR polarimetry



- 1m Kiso Schmidt telescope
- 6 deg² camera → 36 deg²
- 1.5m Kanata telescope
- 2m Nayuta telescope
- 50cm MITSuME
- 91cm OAO-WFC of NAOJ
- Yamaguchi 32m radio telescope



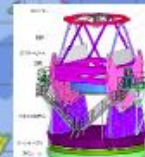
50cm telescope
(Hiroshima Univ. 2016)



3.8m telescope
(Kyoto Univ. 2017)



HSC, Subaru @Hawaii



TAO 6.5m (Tokyo Univ. 2018)



IRSF (Nagoya Univ.)
@ South Africa



MOA-II, B&C (Nagoya Univ.)
@ New Zealand

miniTAO (Tokyo Univ.)
ASTE (NAOJ) @ Chile



Telescopes/Cameras in J-GEM

Site (telescope)*	Diam. [m]*	Place (long., lat., hgt.)	Instrument [†]	FoV	Pixel scale	Note [‡]
Mt. Johns (B&C 61 cm) ★	0.61	170°47 E, 43°40 S, 1029 m	Tripole5	4'2 × 6'2	0''17	(1)
Mt. Johns (MOA-II) ★	1.8	170°47 E, 43°40 S, 1029 m	MOA-cam3 [1]	1°31 × 1°64	0''58	(3)
Akeno (MITSuME) ★	0.5	138°48 E, 35°79 N, 900 m	(g, R _C , I _C imager)	27'8 × 27'8	1''63	(1)
Kiso (Kiso Schmidt) ★	1.05	137°63 E, 35°79 N, 1130 m	KWFC [2]	2°2 × 2°2	0''946	(3)
Nishi-Harima (Nayuta) ★	2.0	134°34 E, 35°03 N, 449 m	MINT	10'9 × 10'9	0''32	(1)
Okayama, OAO (Kyoto 3.8 m ^[a]) ★	3.8	133°60 E, 34°58 N, 343 m	KOOLS-IFU	14'' φ	1''14	(2)
Okayama, OAO (OAO 188 cm) ★	1.88	133°59 E, 34°58 N, 371 m	KOOLS-IFU	30'' φ	2''34	(2)
Okayama, OAO (OAO 91 cm) ★	0.9	133°59 E, 34°58 N, 364 m	OAO-WFC [3]	28'4 × 28'4	1''67	(1)
Okayama, OAO (MITSuME) ★	0.5	133°59 E, 34°58 N, 358 m	(g, R _C , I _C imager) [4],[5]	26'9 × 26'9	1''52	(1)
Higashi-Hiroshima (Kanata) ★	1.5	132°78 E, 34°38 N, 511 m	HOWPol [6]	15' φ	0''30	(1)
Higashi-Hiroshima (Kanata) ★	1.5	132°78 E, 34°38 N, 511 m	HONIR [7],[8]	10' × 10'	0''30	(1)
Yamaguchi (Yamaguchi ^[b]) ★	32 × 2	131°56 E, 34°22 N, 166 m	6–8 GHz Receiver	–	4'–5'	(1)
Tibet (HinOTORI ^[a]) ★	0.5	80°03 E, 32°31 N, 5130 m	(u, R _C , I _C imager)	24' × 24'	0''68	(1)
Sutherland, SAAO (IRSF) ★	1.4	20°81 E, 32°38 S, 1761 m	SIRIUS [9],[10]	7'7 × 7'7	0''45	(1)
Pampa la Bola (ASTE ^[c]) ★	10	67°70 W, 22°97 S, 4862 m	ASTECAM [11]	8'1 φ	20''–30''	(1)
Chajnantor, TAO (miniTAO) ★	1.04	67°74 W, 22°99 S, 5640 m	ANIR [12]	5'1 × 5'1	0''298	(1)
Mauna Kea, MKO (Subaru) ★	8.2	155°48 W, 19°83 N, 4139 m	HSC [13]	1°5 φ	0''168	(3)

(1) Optical, (2) Optical wide-field(>1deg²), (3) NIR, and (4) Radio

3 wide-field cameras

- Kiso/KWFC (**North**)

- 1.05m/4.3deg²

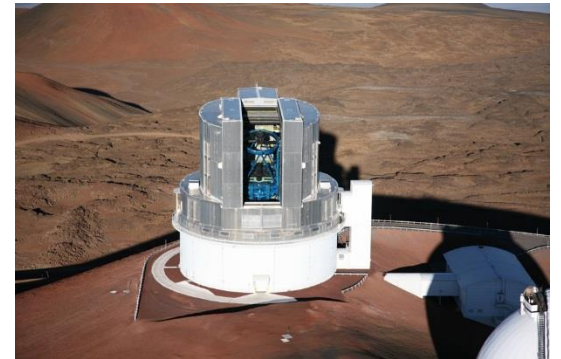
→ Tomo-e (CMOS, 20deg², in 2018)

- MOA-II/MOA-Cam (**South**)

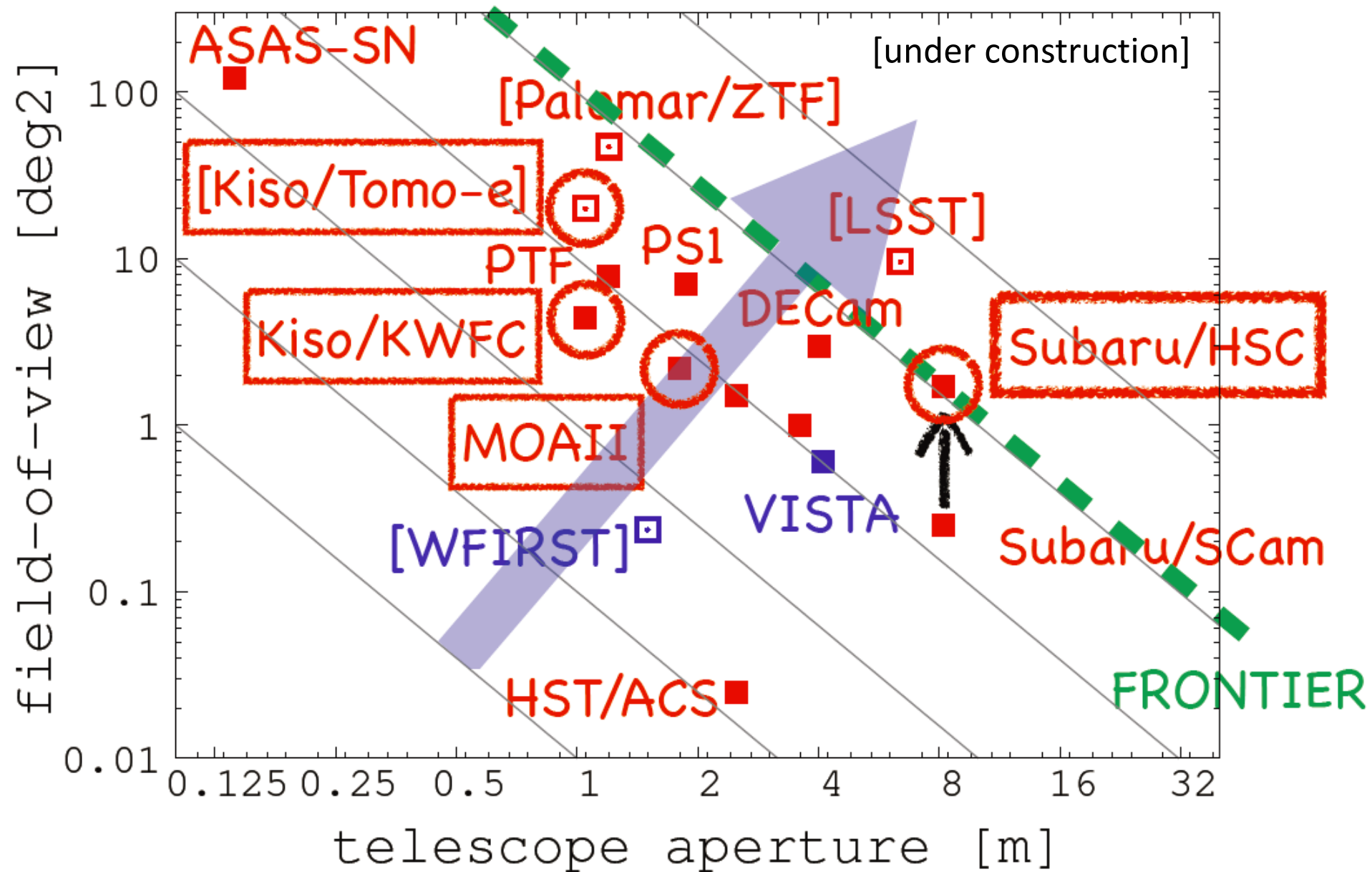
- 1.8m/2.2deg²

- Subaru/HSC (**North**)

- 8.2m/1.77deg²



Survey power in optical/NIR



J-GEM
follow-up observations
of GW alerts

First detection: GW150914

Selected for a **Viewpoint** in *Physics*
PHYSICAL REVIEW LETTERS

week ending
12 FEBRUARY 2016

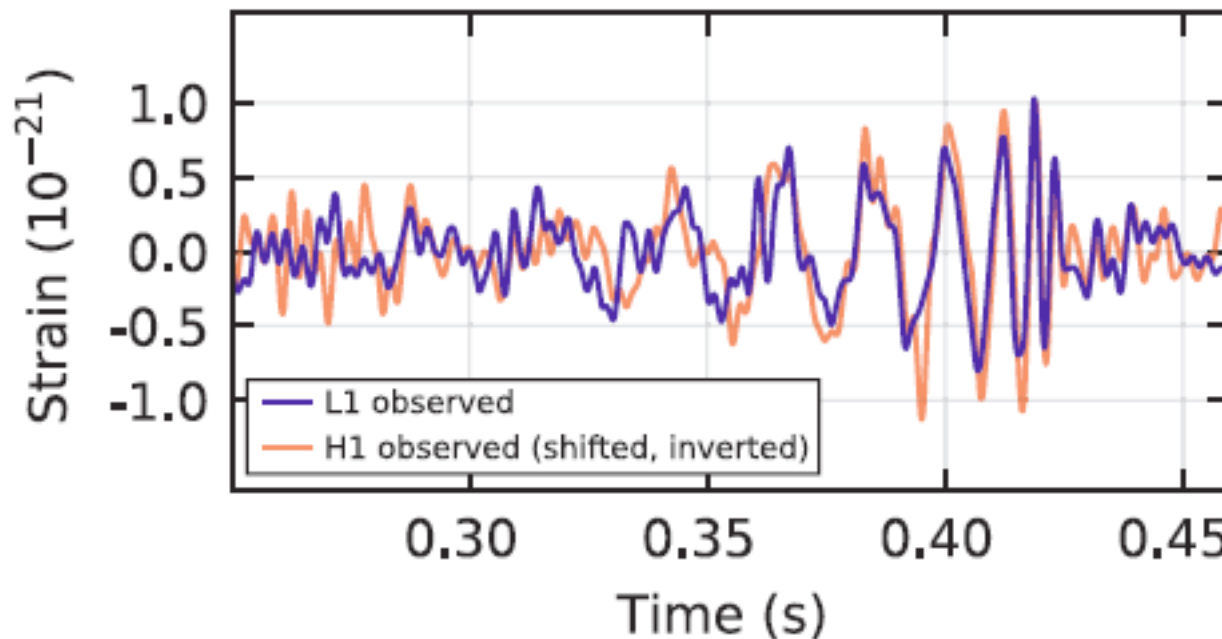


Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)



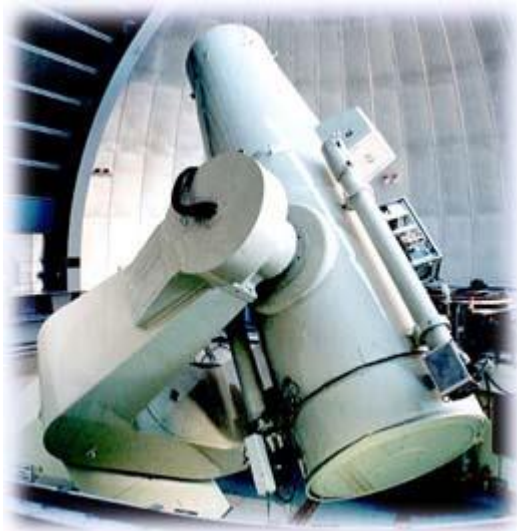
$36^{+5}_{-4} M_{\odot}$ and $29^{+4}_{-4} M_{\odot}$ BHs merged at 410^{+160}_{-180} Mpc

“J-GEM follow-up observations to search for an
optical counterpart of the first gravitational wave
source GW150914”
PASJ, 68, L9 (2016)

Morokuma, T., Tanaka, M., Asakura, Y., ..., NT et al.

J-GEM follow-ups of GW150914

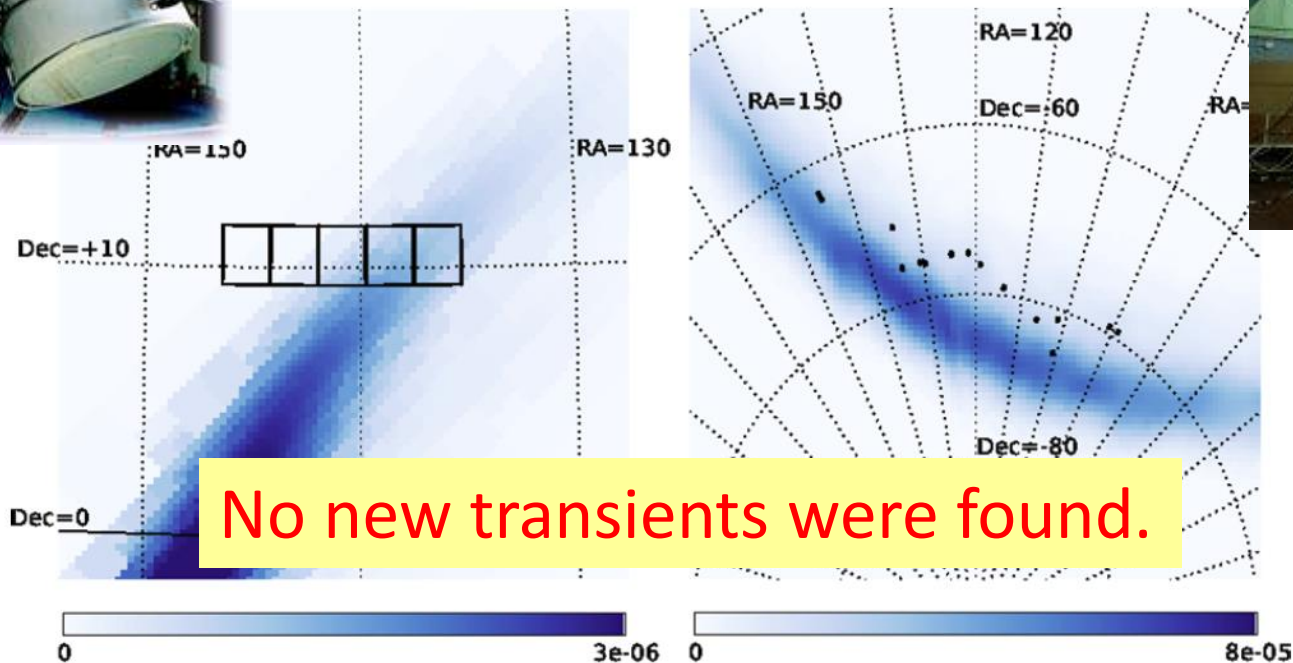
- Kiso/KWFC (North)



$t_{\text{obs}} = 4.4$ days
Wide-field
(24deg^2 , $i \sim 19$)
survey

- B&C/Tripole5 (South)

$t_{\text{obs}} = 6.3\text{-}12$ days
observation
of targeted
nearby 18 gals.



Subaru/HSC was not available

Schedule for September 2015

Schedule for October 2015

Sun	Mon	Tue	Wed	Thu	Fri	Sat
		Sep 01	Sep 02	Sep 03	Sep 04	Sep 05 ☉
		Obs SCEXAO+AO188		Obs FOCAS	Service FOCAS	UH-18B1 Stockton FOCAS
Sep 06	Sep 07	Sep 08	Sep 09	Sep 10	Sep 11	Sep 12 ●
UH-18B1 Stockton FOCAS	Service FOCAS	S15B-055 Maeda FOCAS	S15B-017 Uchiyama S-Cam		Gemini Dawson S-Cam	S15B-050 Utsumi S-Cam
Sep 13	Sep 14	Sep 15	Sep 16	Sep 17	Sep 18	Sep 19
GW150914		Alert UH-09A S-Cam		Obs IRCS+AO188	S15A-002 Imanishi IRCS+AO188	S15A-105 Helminiak IRCS+AO188
Sep 20 ☉	Sep 21	Sep 22	Sep 23	Sep 24	Sep 25	Sep 26
Obs IRCS+AO188	S15B-139	Service FOCAS	Eng Kyoto3DII+AO188	S15B-045	Obs Kyoto3DII+AO188	
Eng IRCS+AO188	COMICS		Obs Kyoto3DII+AO188			
Sep 27 ☉	Sep 28	Sep 29	Sep 30			
Obs Kyoto3DII+AO188	COMICS	IRCS+AO188	IRCS+AO188			

Sun	Mon	Tue	Wed	Thu	Fri	Sat
				Oct 01	Oct 02	Oct 03
				Obs IRCS+AO188		
Oct 04 ☉	Oct 05	Oct 06	Oct 07	Oct 08	Oct 09	Oct 10
Obs IRCS+AO188	StrObs HSC	GTO HSC	S15B-061I Chiba HSC		StrObs HSC	S15B-061I Chiba HSC
Oct 11	Oct 12 ●	Oct 13	Oct 14	Oct 15	Oct 16	Oct 17
S15B-061I Chiba HSC	UH-14B1 Tholen HSC	HSC observing run				S15B-061I Chiba HSC
Oct 18	Oct 19 ☉	Oct 20	Oct 21	Oct 22	Oct 23	Oct 24
Keck Cohen HSC	StrObs HSC	Eng HSC	S15B-154 Arai HDS	S15B-154 Arai HDS	S15B-128 Takagi HDS	
			S15B-078 Tsujiimoto HDS	S15B-078 Tsujiimoto HDS		
Oct 25	Oct 26	Oct 27 ☉	Oct 28	Oct 29	Oct 30	Oct 31
S15B-090 Kawahara HDS	S15B-154 Arai HDS	Obs HDS	Eng SCEXAO+AO188		S15B-111 Currie SCEXAO+AO188	UH-17A Hagelberg SCEXAO+AO188
	Service HDS	Service HDS			S15B-160 Kotani SCEXAO+AO188	

HSC is only available at **>+21days** after GW150914.
 The **visibility** of GW150914 from Mauna Kea was poor.

Second detection: GW151226

PRL 116, 241103 (2016)

PHYSICAL REVIEW LETTERS

week ending
17 JUNE 2016

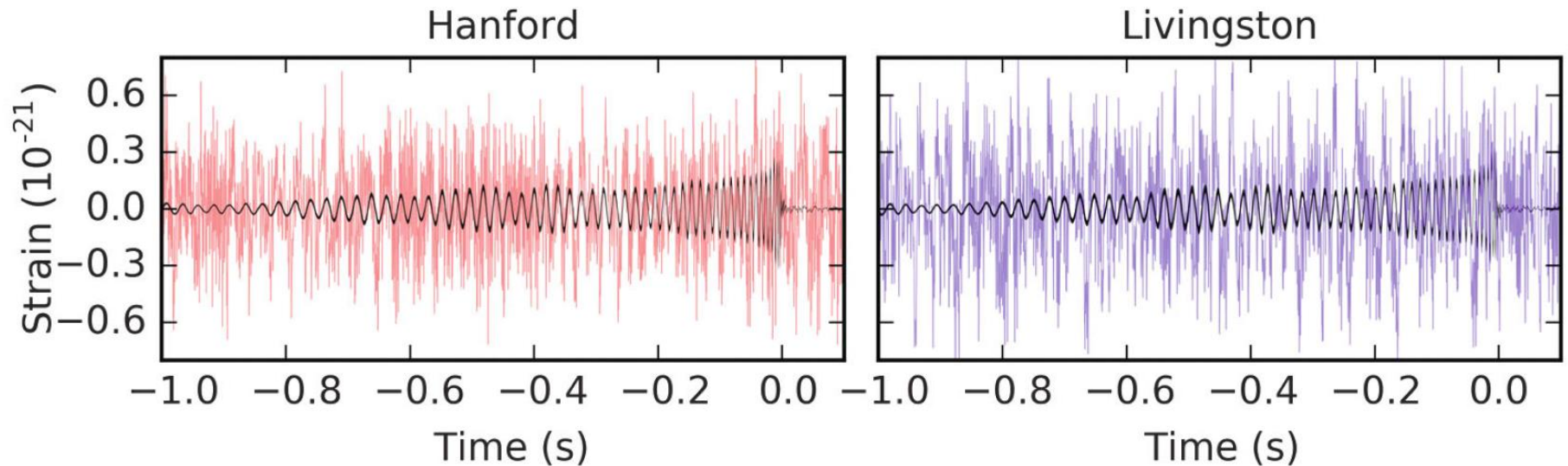


GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 31 May 2016; published 15 June 2016)



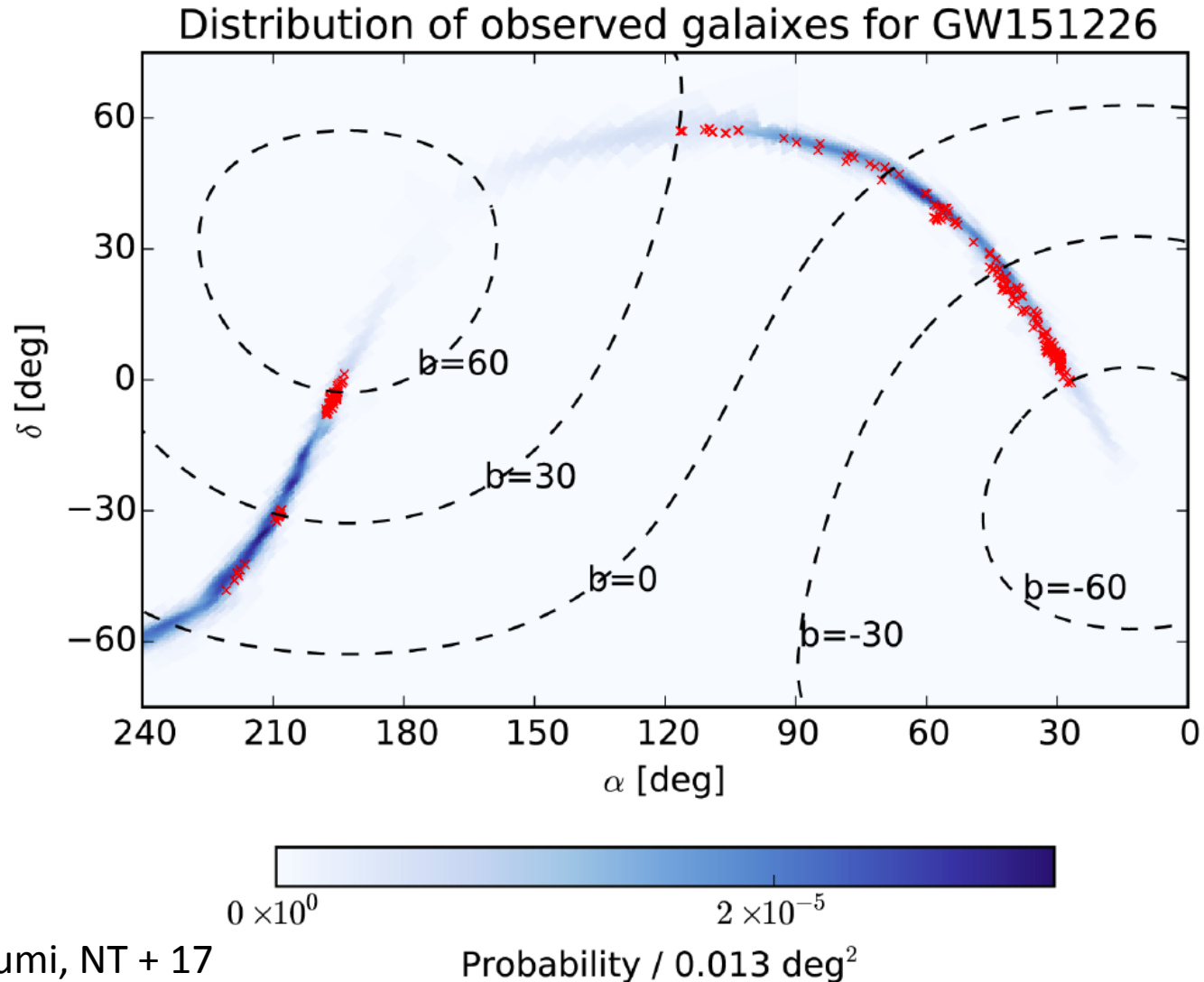
$14.2^{+8.3}_{-3.7} M_{\odot}$ and $7.5^{+2.3}_{-2.3} M_{\odot}$ BHs merged at 440^{+180}_{-190} Mpc

“J-GEM follow-up observations of the
gravitational wave source GW151226”
PASJ, 69, 9 (2017)

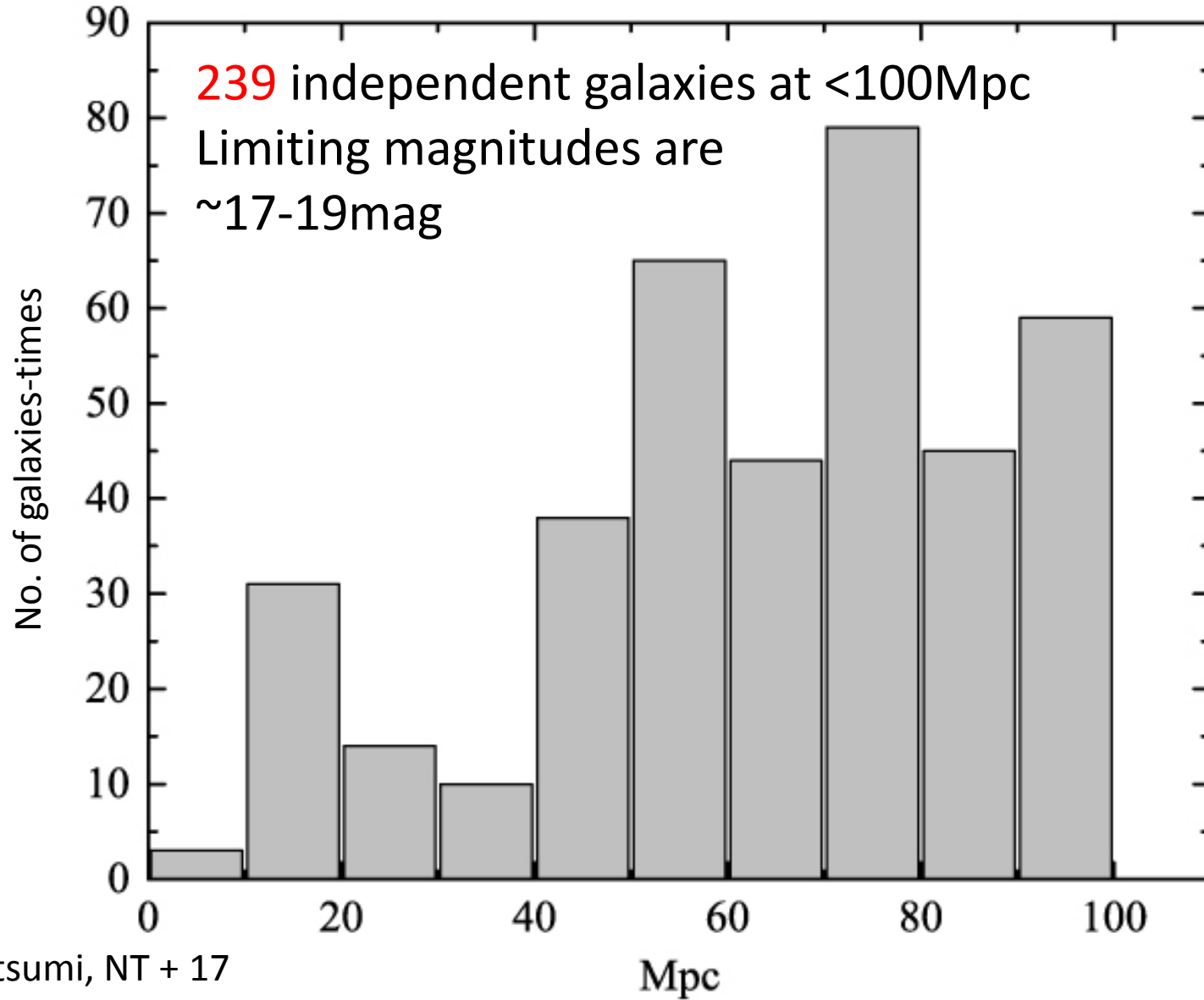
Yoshida, M., Utsumi, Y., NT, et al.

J-GEM nearby galaxies observation

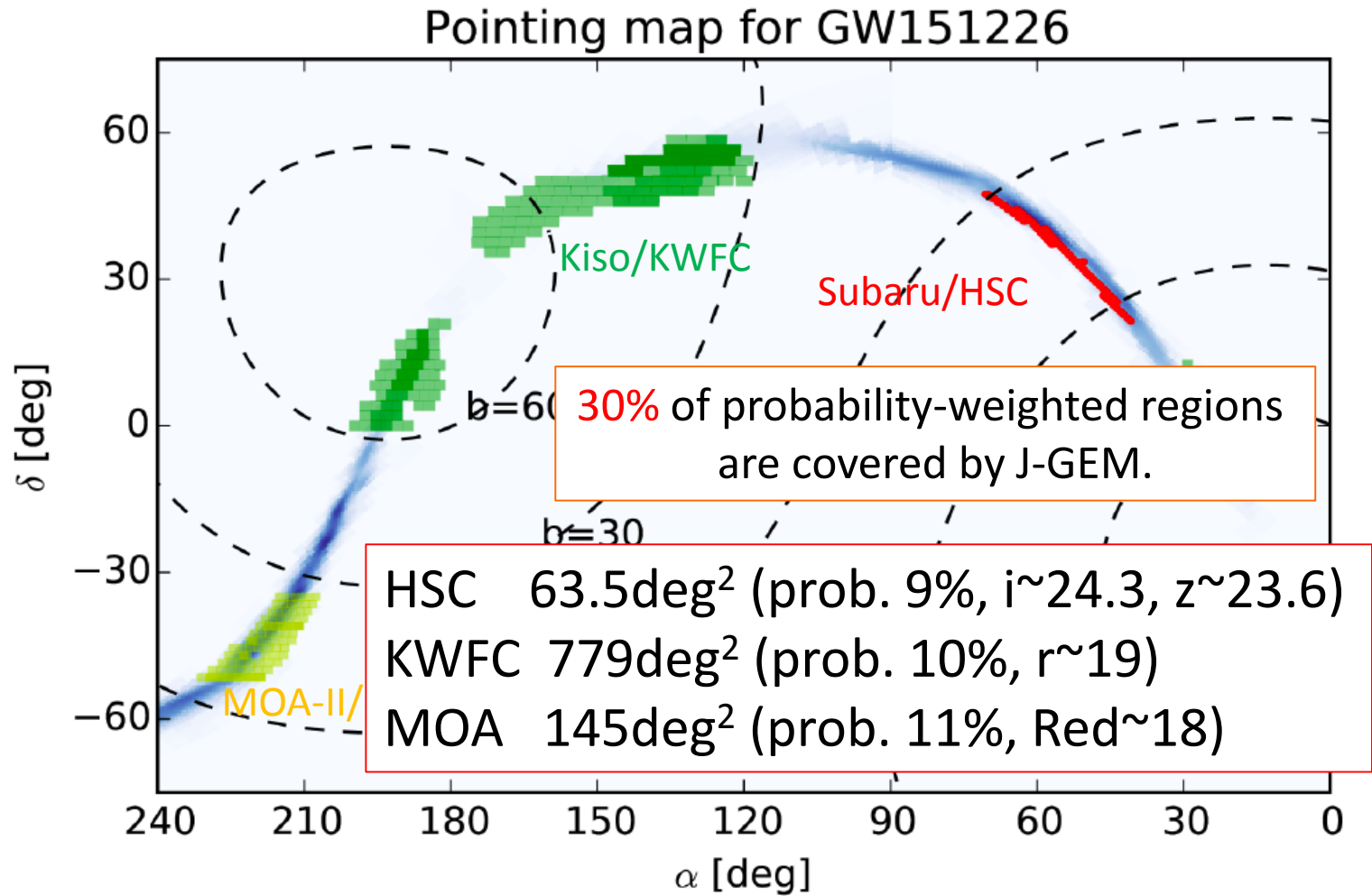
Nayuta/MINT, Kanata/HONIR, OAO91cm/OAO-WFC,
TIT-OAO50cm/MITSuME, IRSF/SIRIUS



Observed galaxies



Wide-field survey

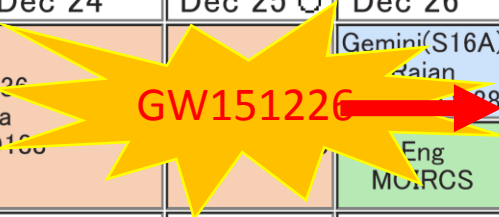




0×10^0

2×10^{-5}

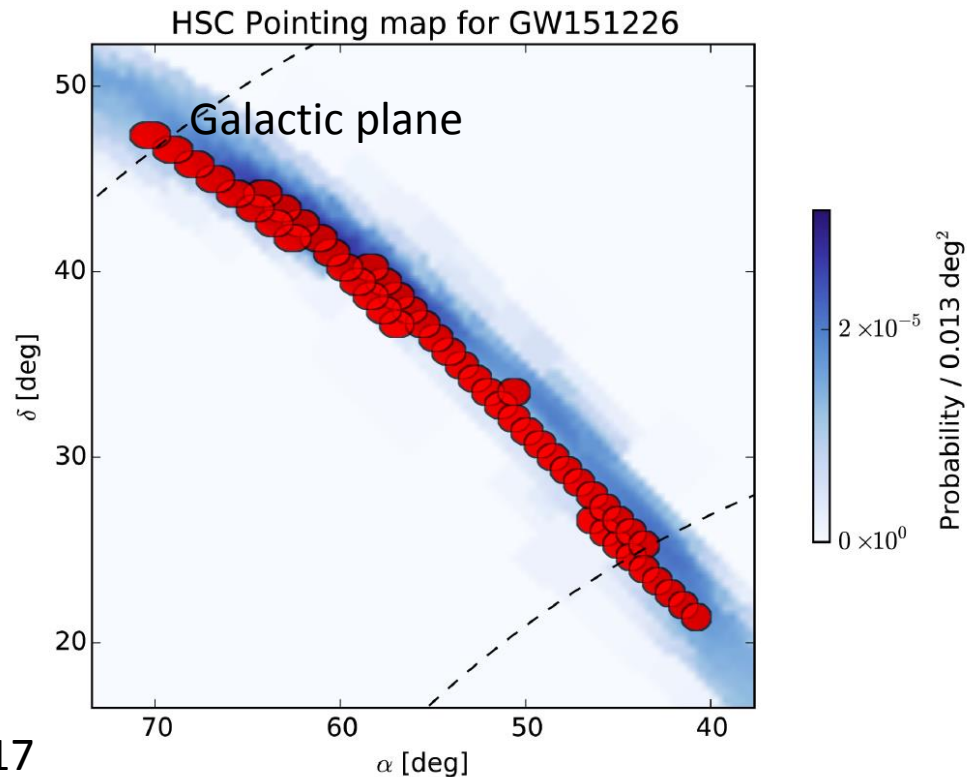
Probability / 0.013 deg²

Schedule of Subaru telescope

Dec 20	Dec 21	Dec 22	Dec 23	Dec 24	Dec 25 ☉	Dec 26
UH-10A Hasinger FMOS			S15B-026 Minowa IRCS+AO188		Gemini(S16A) Rajan IRCS+AO188 Eng MOIRCS	
						
Dec 27	Dec 28	Dec 29	Dec 30	Dec 31		
Gemini(S16A) Rajan IRCS+AO188	S14B-097 Kuzuhara HiCIAO+AO188	S15B-022 Kudo HiCIAO+AO188	S15B-119 Kudo HiCIAO+AO188	S15B-119 Kudo HiCIAO+AO188		
Eng MOIRCS	S15A-133 Kuzuhara HiCIAO+AO188	HiCIAO+AO188	S15B-085 Hirano HiCIAO+AO188	HiCIAO+AO188		
						
					Jan 01 ☉	Jan 02
					Obs HiCIAO+AO188	Obs HiCIAO+AO188
					S15B-088 Shinnaka HDS	S15B-088 Shinnaka HDS
Jan 03	Jan 04	Jan 05	Jan 06	Jan 07	Jan 08 ●	Jan 09
Obs HiCIAO+AO188	UH-31A1 Jedicke HSC	UH-31A2 Jedicke HSC	S15B-137 Yoshida HSC	Keck Wittman HSC	StrObs HSC	GTO HSC
			S15B-009 Totani HSC			S15B-009 Totani HSC
Jan 10	Jan 11	Jan 12	Jan 13	Jan 14	Jan 15	Jan 16 ☉
StrObs HSC	StrObs HSC	S15B-137 Yoshida HSC	S15B-073 Okamoto HSC	StrObs HSC	S15A-134I Silverman FMOS	
S15B-056 Okabe HSC	S15B-056 Okabe HSC	S15B-009 Totani HSC				

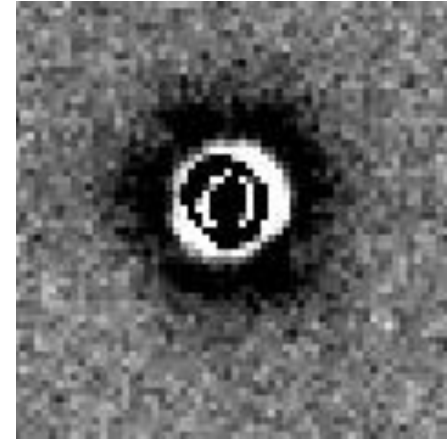
Observation summary -Subaru/HSC-

- Date: Jan 7 (+12days), 13, and Feb 6, 2016 (half nights)
- Filter: i, z \sim 50sec exp. (34sec overhead)
- Survey fields: 50 pointing \sim 60deg²
- Limiting magnitude: i \sim 24.3 and z \sim 23.6



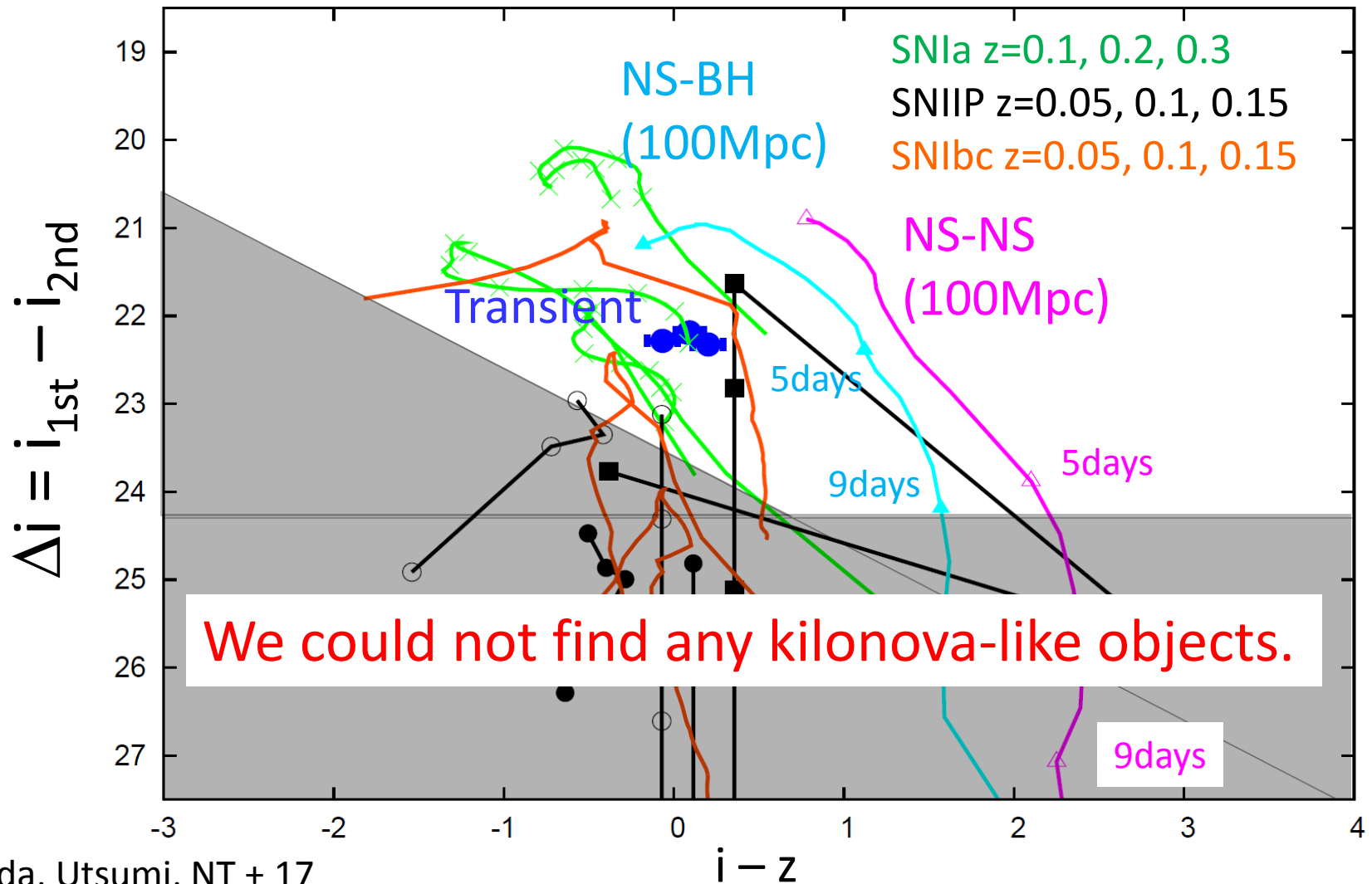
Candidate detection

- Reference frame: Feb 6, 2016
- Science frames: Jan 7, 13, 2016
- **Detection criteria** to exclude bogus and cosmic rays
 - Significance
 - $|S/N(\text{PSF})| > 5$ in the difference images
 - $S/N(1.5'') > 5$ in the pre-differenced image
 - Shape
 - $\text{Elongation}/\text{Elongation}_{\text{PSF}} > 0.8$
 - $0.8 < \text{FWHM}/\text{FWHM}_{\text{PSF}} < 1.3$
 - PSF subtracted residual < 3 sigma in the difference image
 - Number of detection
 - ≥ 2 detections



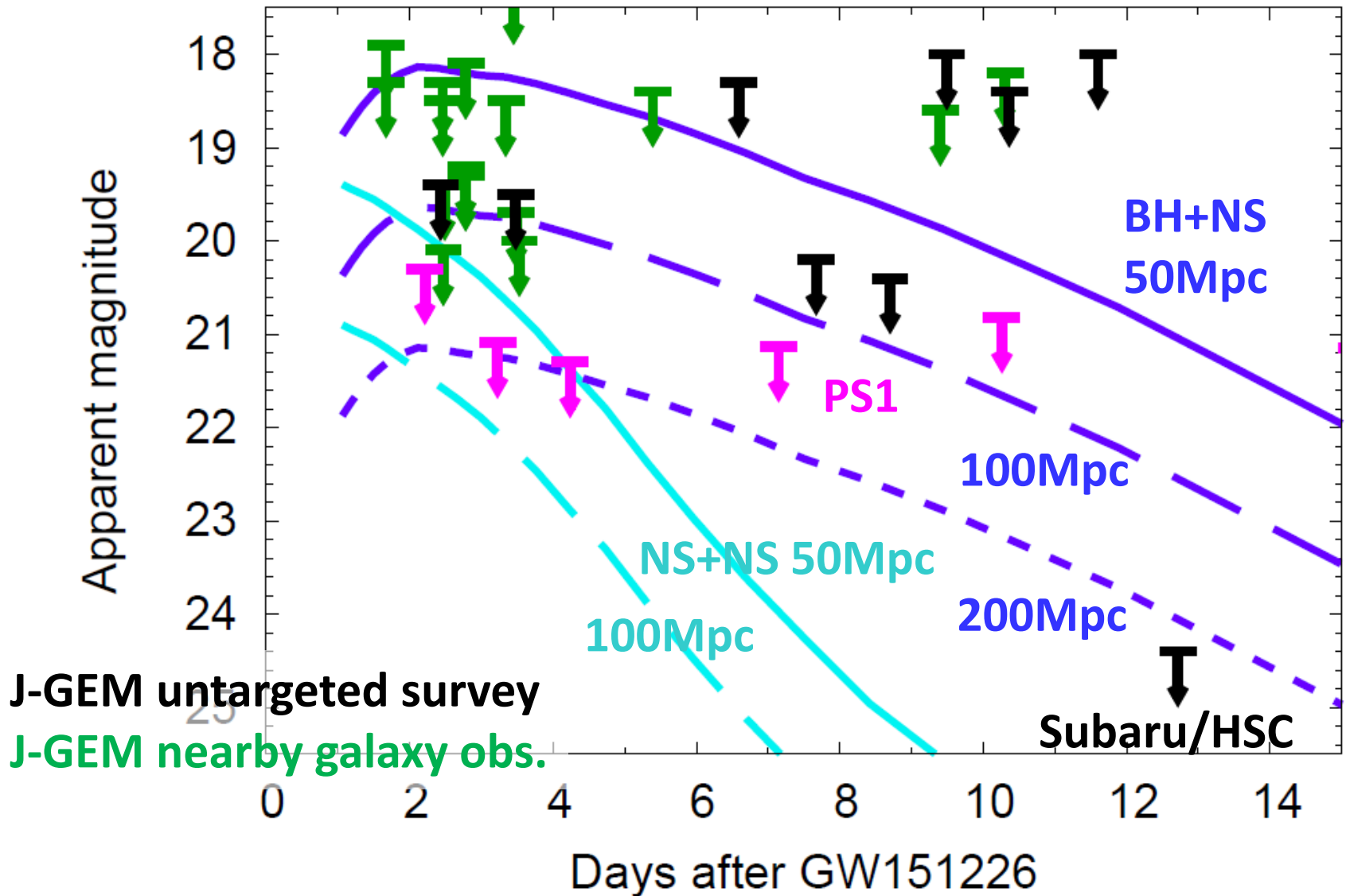
Candidates from Subaru/HSC

- Color-magnitude diagram in difference magnitudes



If GW151226 was a nearby NS-NS or BH-NS merger,

or BH-NS merger,



“A Challenge to the Optical Counterpart of the
Gravitational Wave with Hyper Suprime-Cam:
GW151226”
in preparation

Utsumi, Y., NT, Tanaka, M., et al.

Summary

- **Subaru/HSC** is the best instrument for optical wide-field follow-up observation (**24mag, ~60deg², half night, 2color**) but unfortunately not always available.
- J-GEM follow-up observations were performed for GW150914 and GW151226. Especially, GW151226 was followed by Subaru/HSC.
- Majority of contaminations in 24mag images are supernovae, Galactic variable stars, and AGNs.
- **Time variability, color evolution, association with a nearby galaxy, and properties of a object in the reference** are keys to identify kilonovae from other transients.