# 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

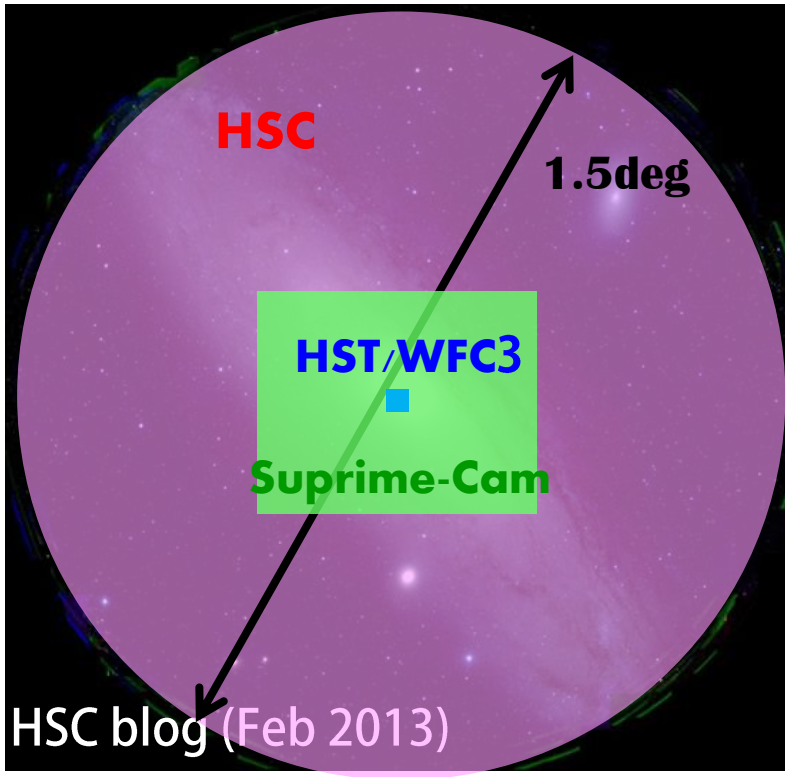
- Subaru/Hyper Suprime-Cam
- Japanese collaboration for Gravitational wave ElectroMagnetic follow-up (J-GEM)
- J-GEM follow-up observations of GW alerts
  - GW150914
  - GW151226 (incl. HSC observations)
- Contaminations in 24mag observations

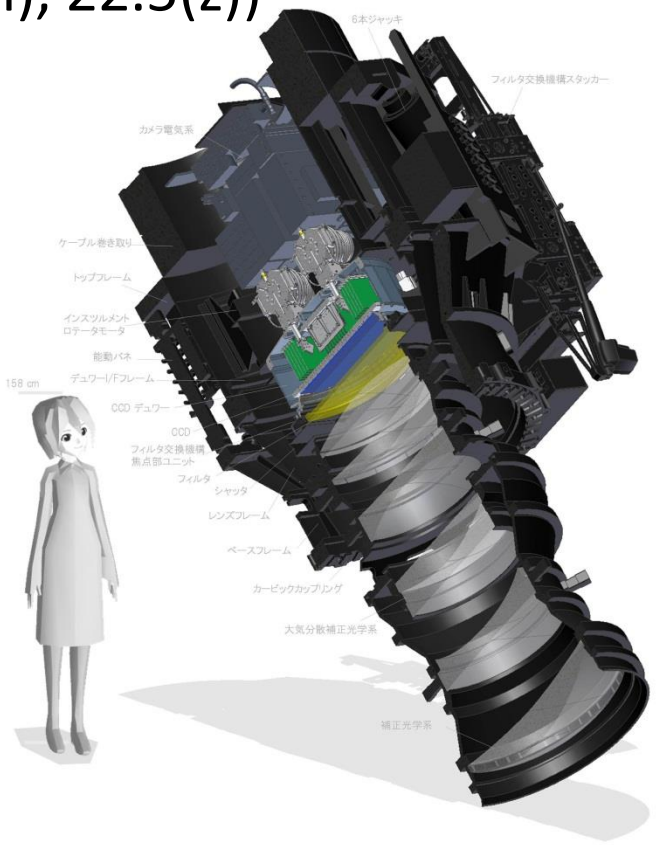
Morokuma, …, NT et al. 2016 PASJ 68 L9
Yoshida, Utsumi, NT et al. 2017 PASJ 69 9
Utsumi, NT et al. in prep.

# Subaru/Hyper Suprime Cam

- Hyper Suprime-Cam (HSC)
  - Diameter: 8.2m, FoV: 1.77deg$^2$, ~900M pixels
  - $m_{lim}$ (5$\sigma$) 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 | | | |
| 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 |
| LSST | 8.4 | 9.62 | 319 |

Currently, Subaru/HSC is the instrument with the highest survey power.

2022-

Rau+09

# 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

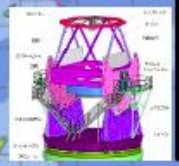
Main features:
- 5 deg$^2$ opt. imaging w/ 1m
- 1 deg$^2$ NIR imaging w/ 1m
- opt-NIR spectroscopy w/ 1–8m
- opt-NIR polarimetry

- **1m Kiso Schmidt telescope**
  **6 deg$^2$ camera ➔ 36 deg$^2$**
- **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)

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

**IRSF (Nagoya Univ.) @ South Africa**

**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 Schimidt) ★ | 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″ $\phi$ | 1″.14 | (2) |
| Okayama, OAO (OAO 188 cm) ★ | 1.88 | 133°.59 E, 34°.58 N, 371 m | KOOLS-IFU | 30″ $\phi$ | 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′ $\phi$ | 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 $\phi$ | 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 $\phi$ | 0″.168 | (3) |

(1) Optical, (2) Optical wide-field(>1deg$^2$), (3) NIR, and (4) Radio

Morokuma + 16

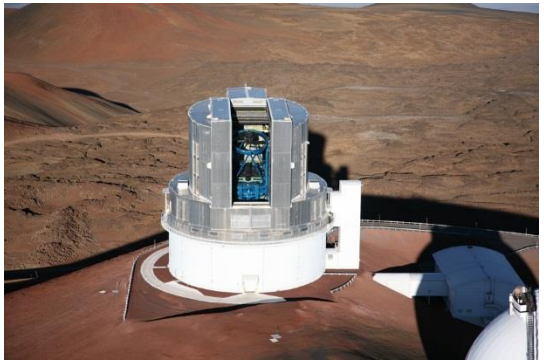
# 3 wide-field cameras

- Kiso/KWFC (North)
  - 1.05m/4.3deg$^2$

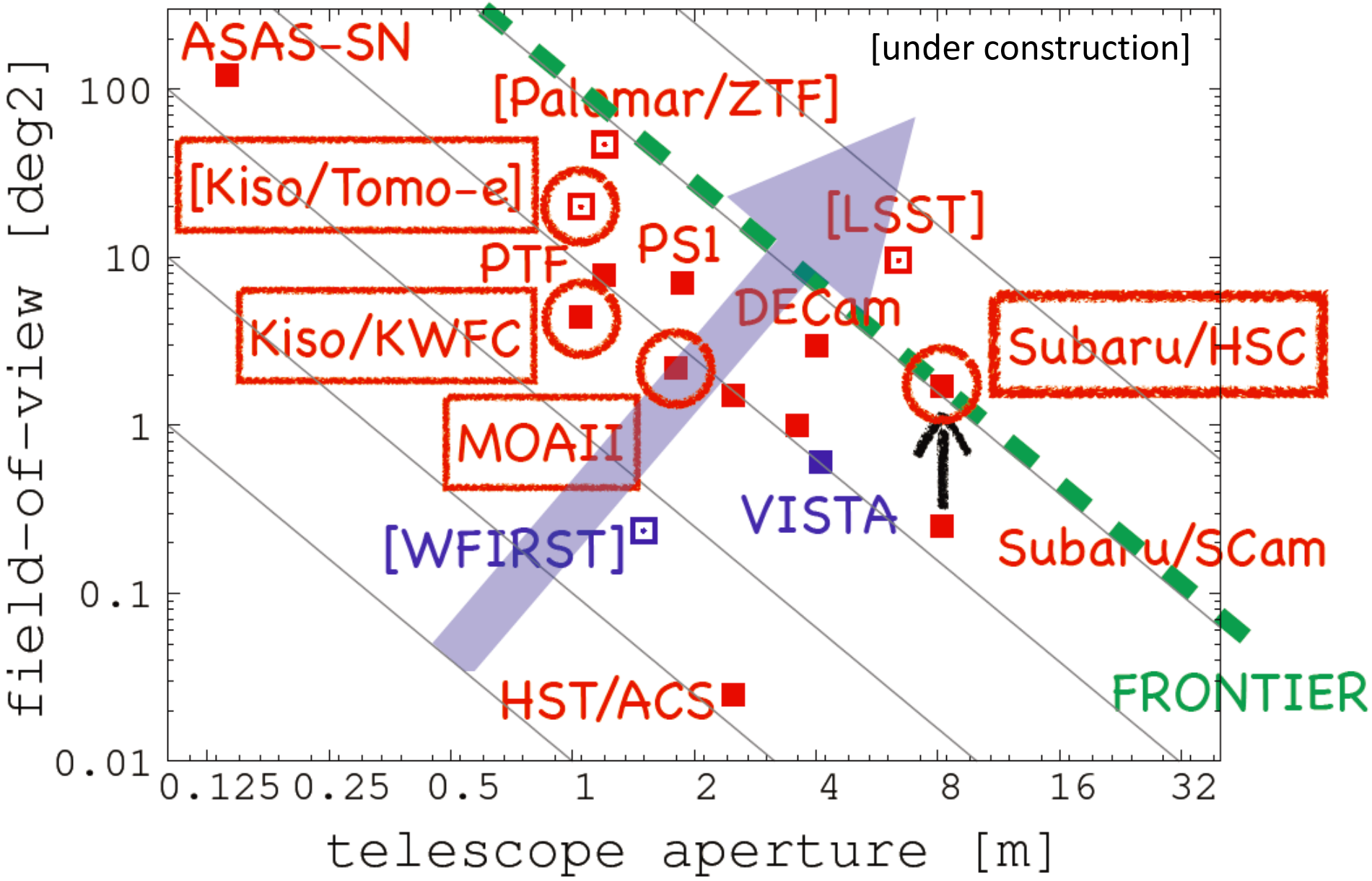
→ Tomo-e (CMOS, 20deg$^2$, in 2018)

- MOA-II/MOA-Cam (South)
  - 1.8m/2.2deg$^2$

- Subaru/HSC (North)
  - 8.2m/1.77deg$^2$



# Survey power in optical/NIR



# J-GEM
# follow-up observations of GW alerts

# First detection: GW150914

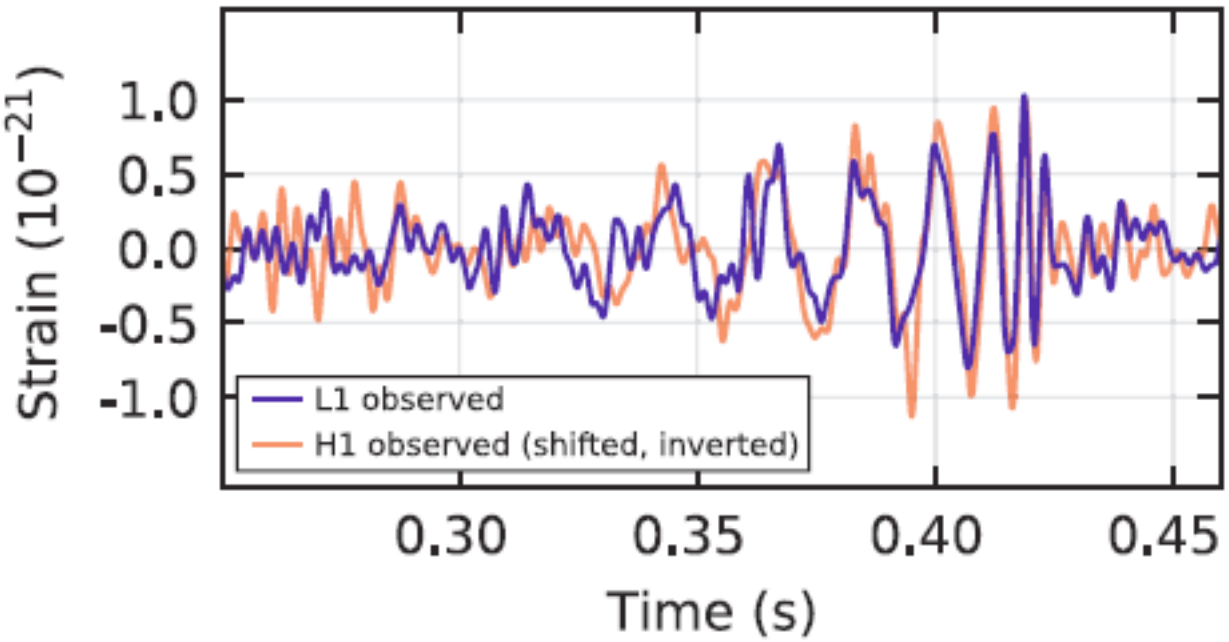
PRL 116, 061102 (2016)

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

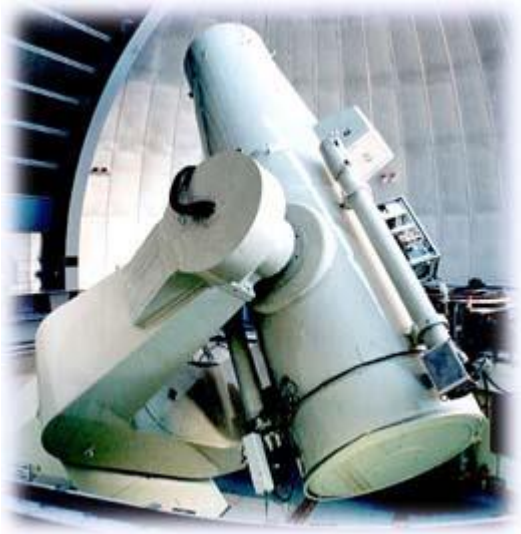
# “J-GEM follow-up observations to search for an optical counterpart of the first gravitational wave source GW150914”

PASJ, 68, L9 (2016)

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

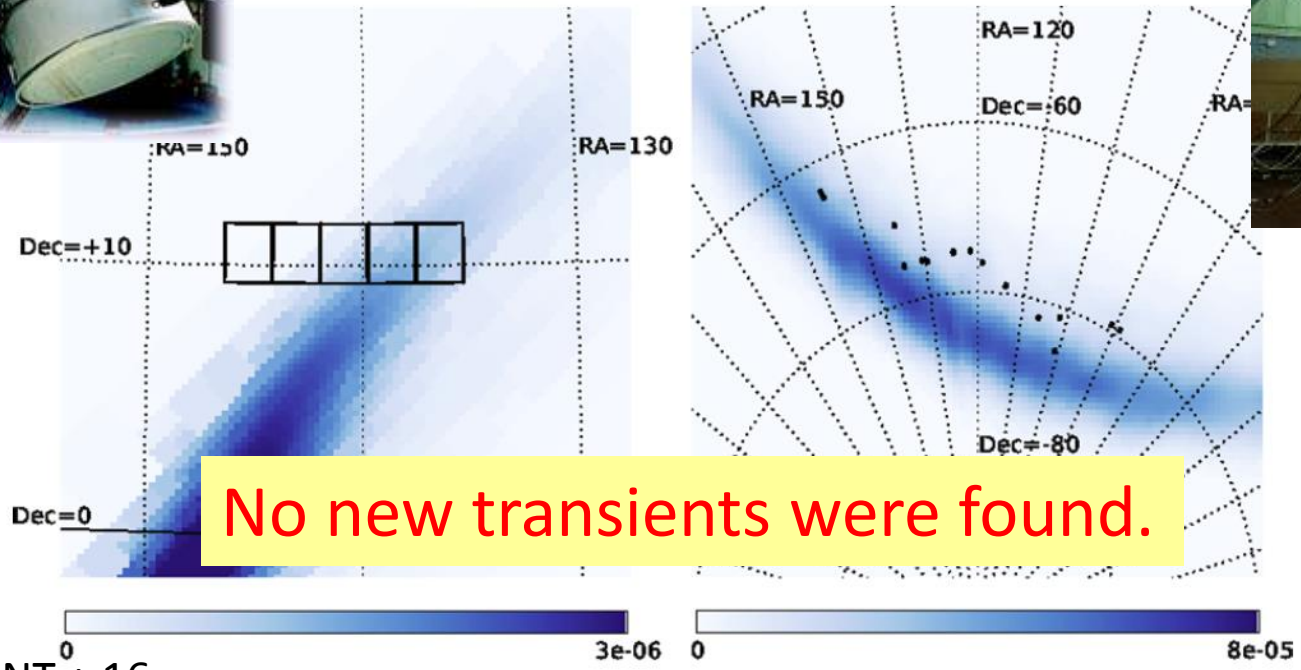
# J-GEM follow-ups of GW150914

- Kiso/KWFC (North)
- B&C/Tripole5 (South)



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

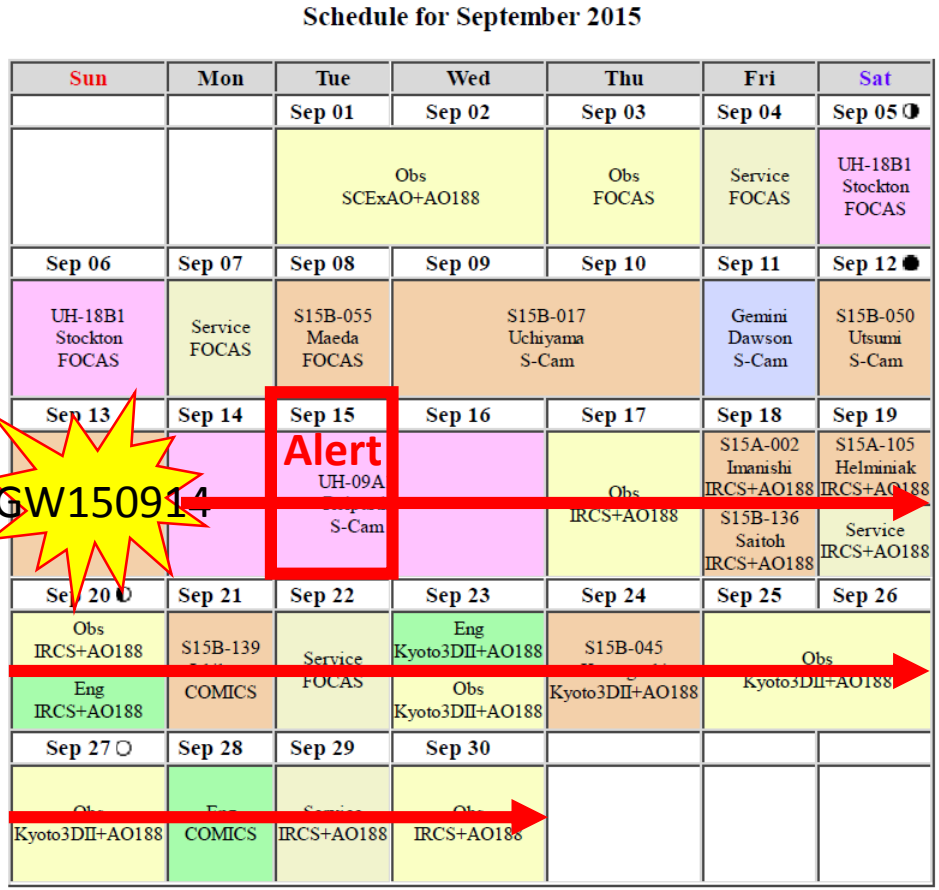
$t_{obs}$=6.3-12 days
observation
of targeted
nearby 18 gals.

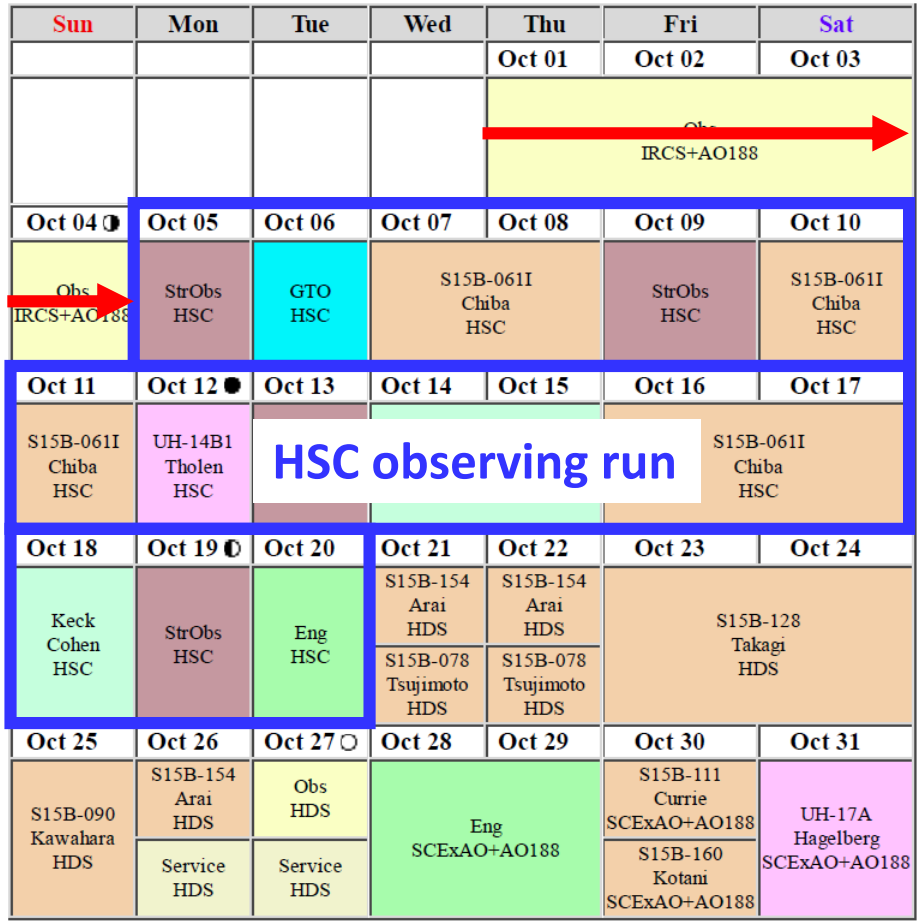



No new transients were found.

Morokuma, …, NT + 16

# Subaru/HSC was not available




**HSC is only available at >+21days after GW150914.**

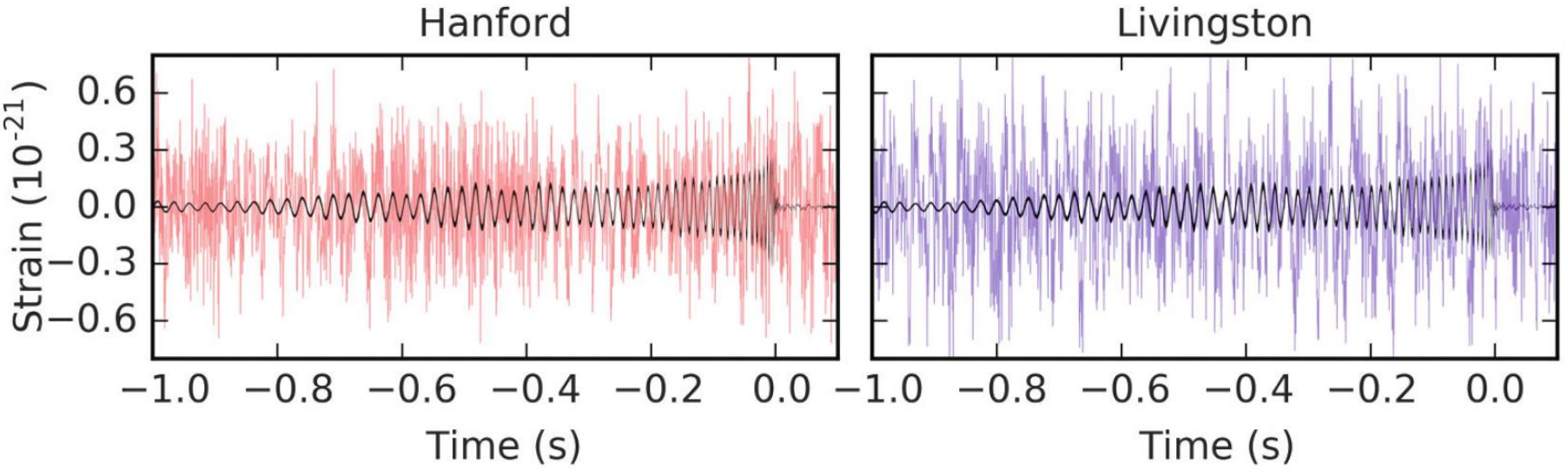
**The visibility of GW150914 from Mauna Kea was poor.**

# 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)



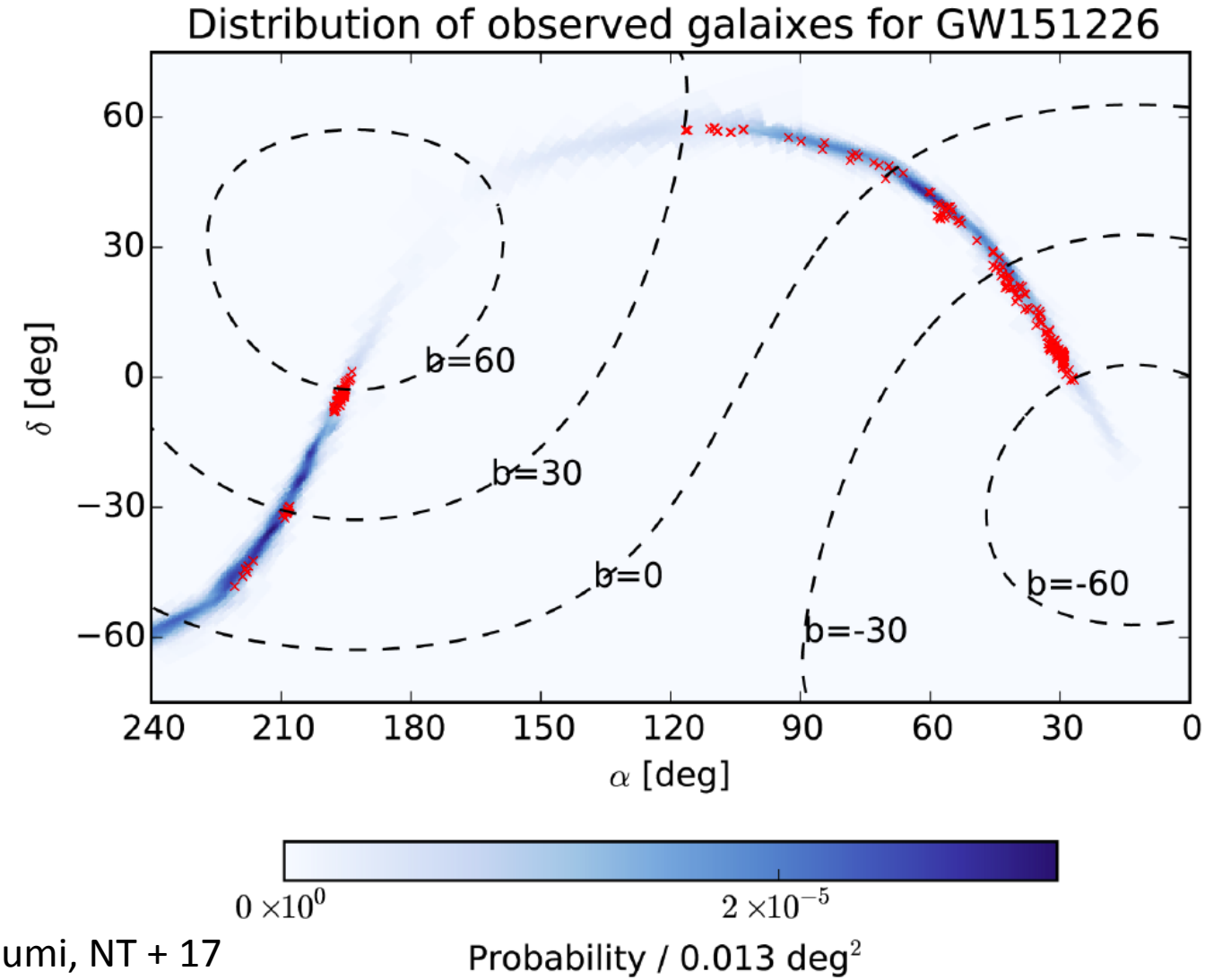

$14.2^{+8.3}_{-3.7}M_{\odot}$ and $7.5^{+2.3}_{-2.3}M_{\odot}$ BHs merged at $440^{+180}_{-190}$Mpc

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

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

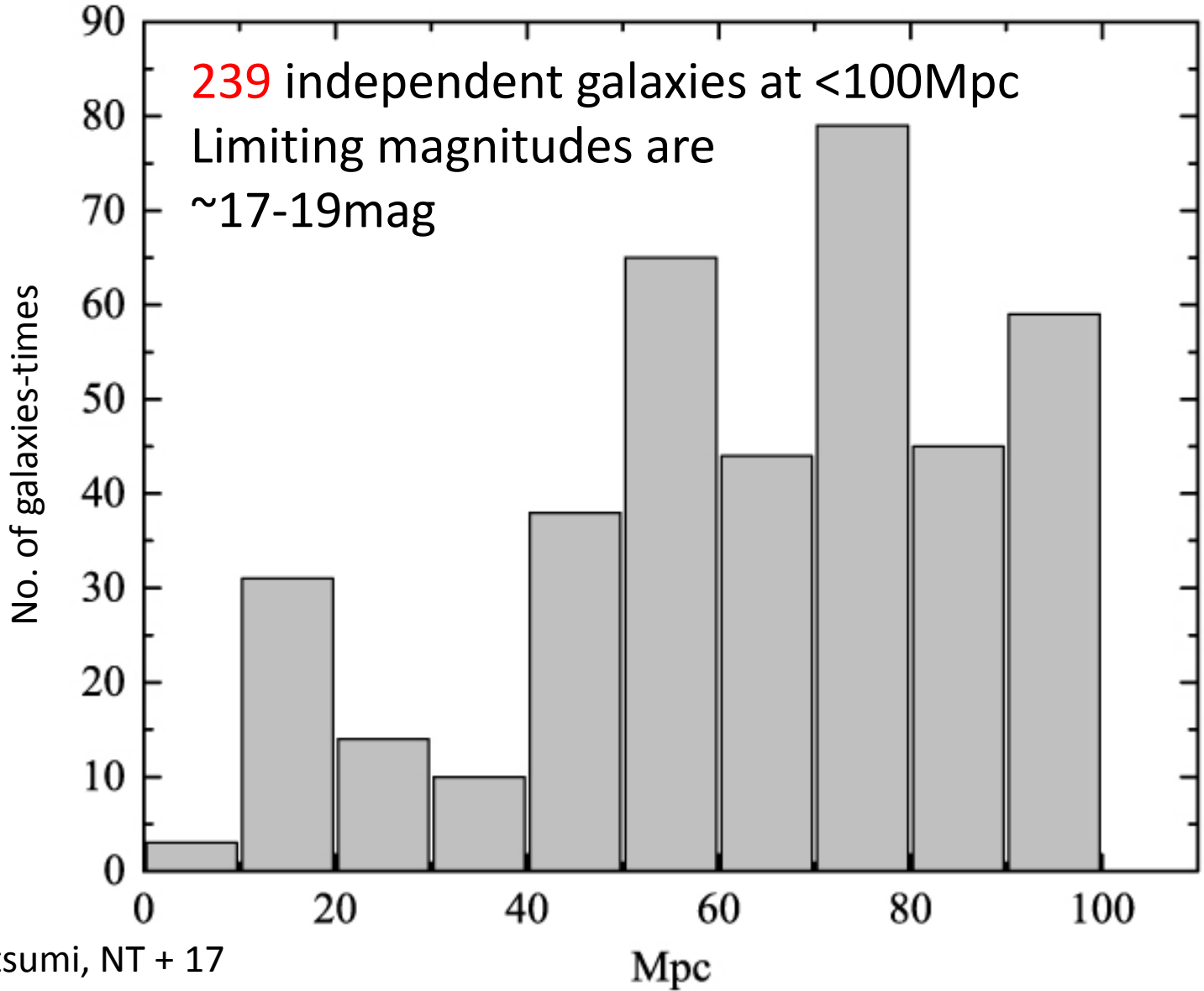
# J-GEM nearby galaxies observation

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



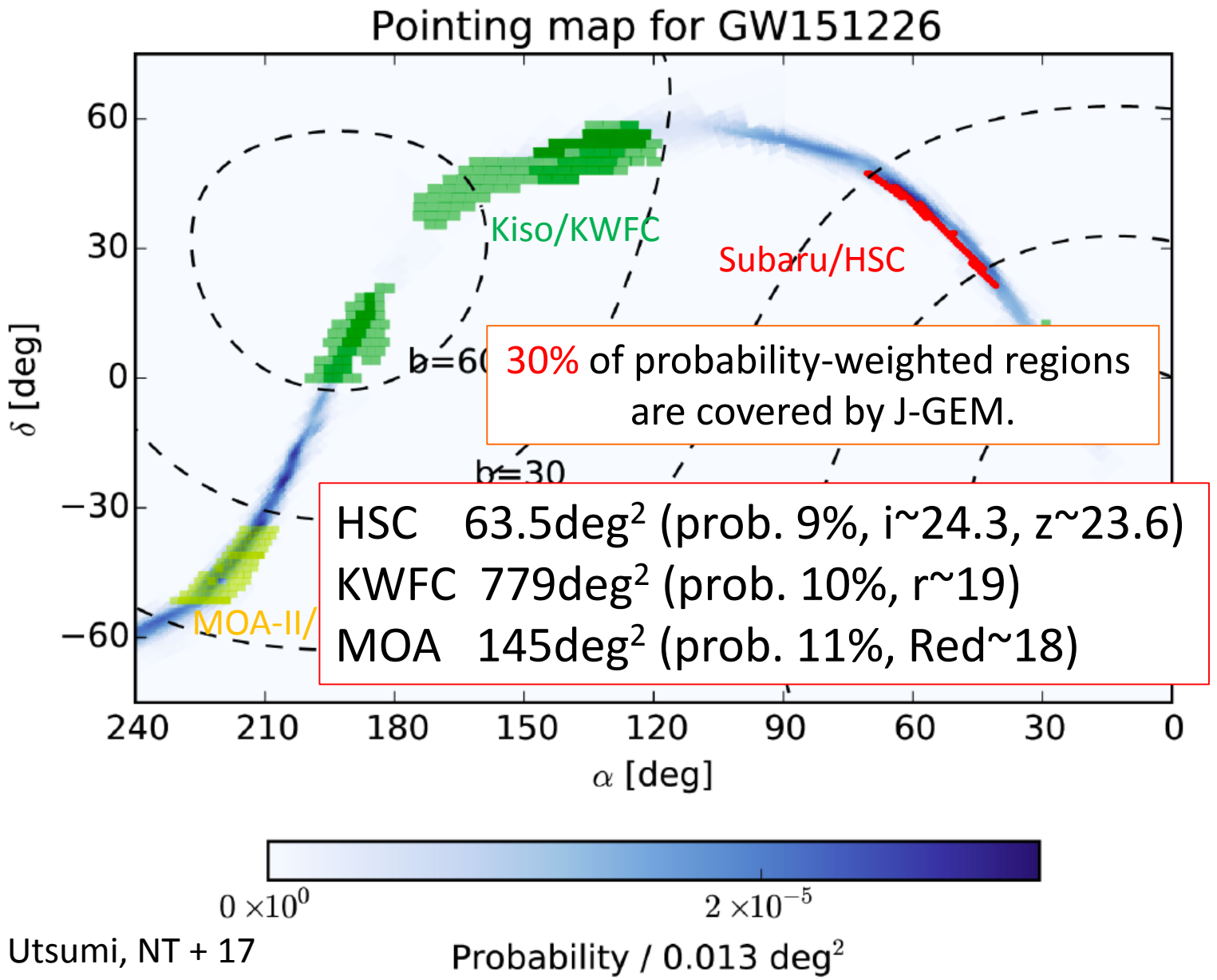

Yoshida, Utsumi, NT + 17

# Observed galaxies




Yoshida, Utsumi, NT + 17

# Wide-field survey

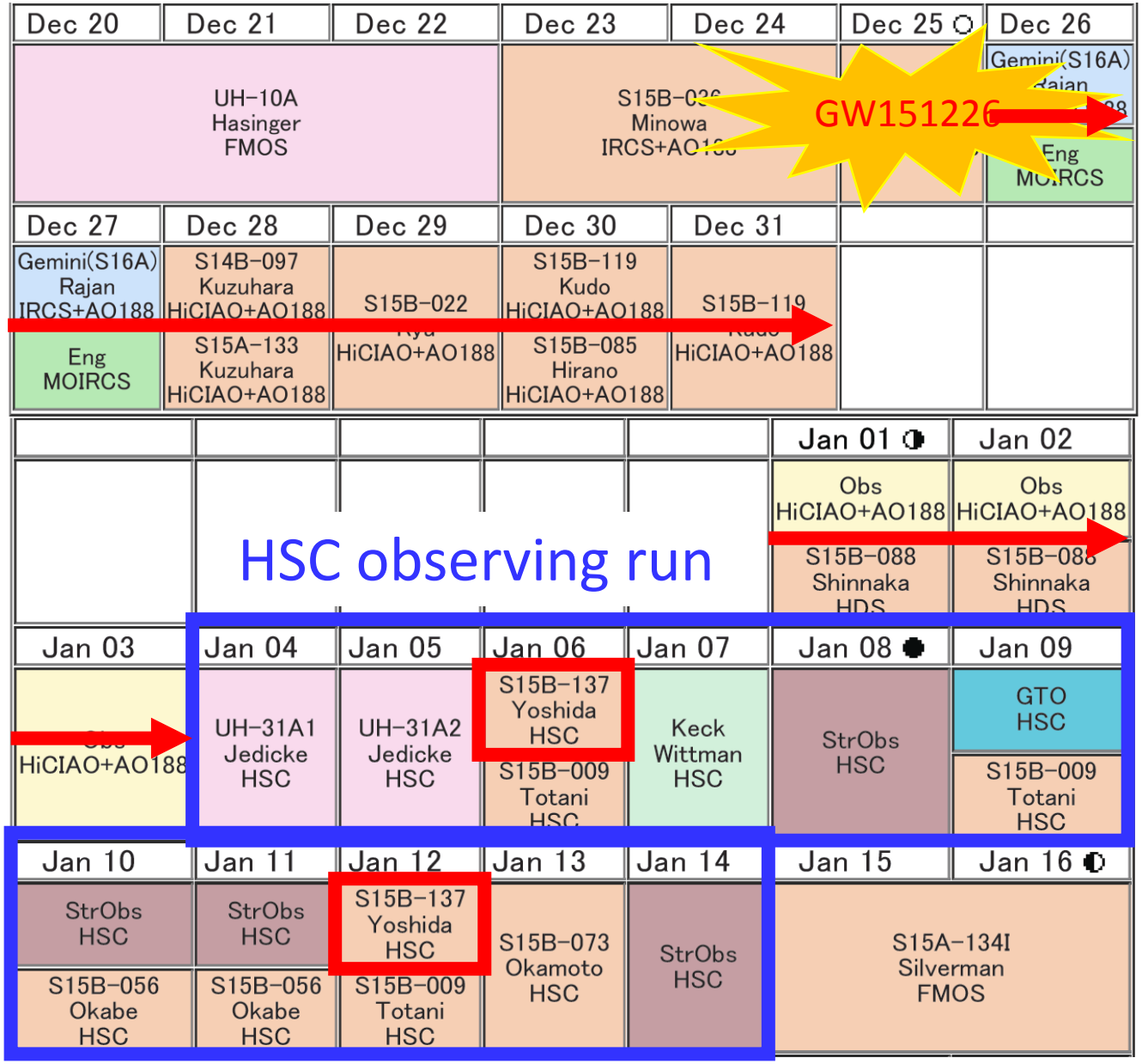



30% of probability-weighted regions are covered by J-GEM.

HSC 63.5deg$^2$ (prob. 9%, i~24.3, z~23.6)
KWFC 779deg$^2$ (prob. 10%, r~19)
MOA 145deg$^2$ (prob. 11%, Red~18)

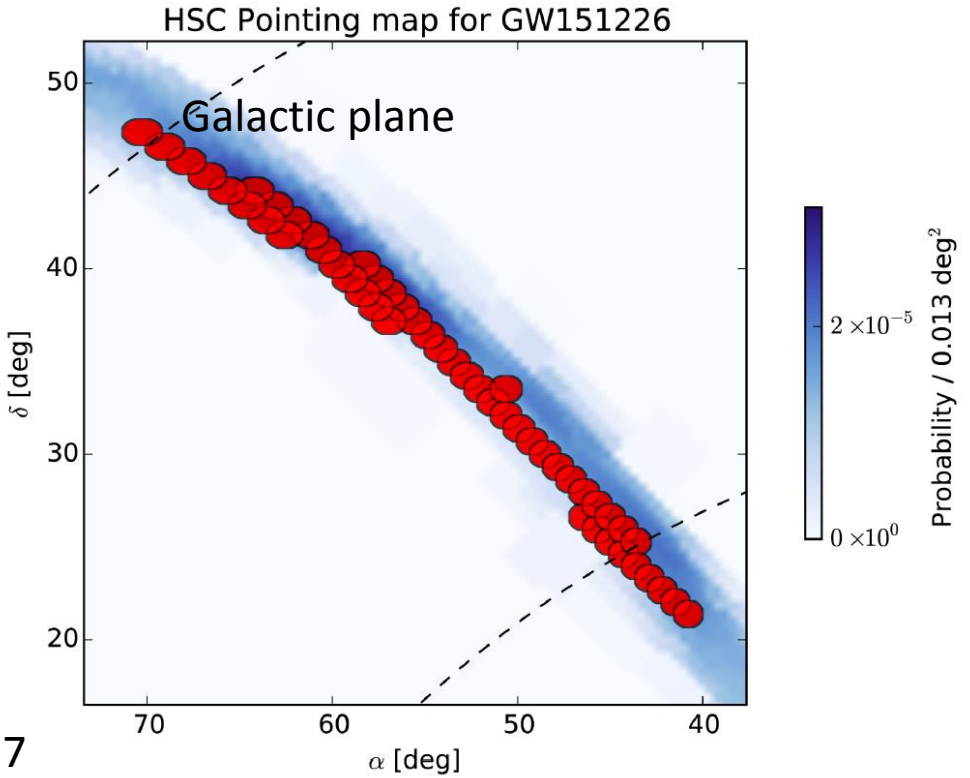
Yoshida, Utsumi, NT + 17

# Schedule of Subaru telescope



# Observation summary -Subaru/HSC-

- Date: Jan 7 (+12days), 13, and Feb 6, 2016 (half nights)
- Filter: i, z ~50sec exp. (34sec overhead)
- Survey fields: 50 pointing ~ 60deg$^2$
- Limiting magnitude: i~24.3 and z~23.6

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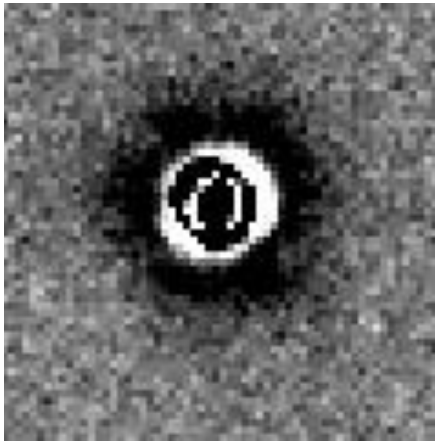
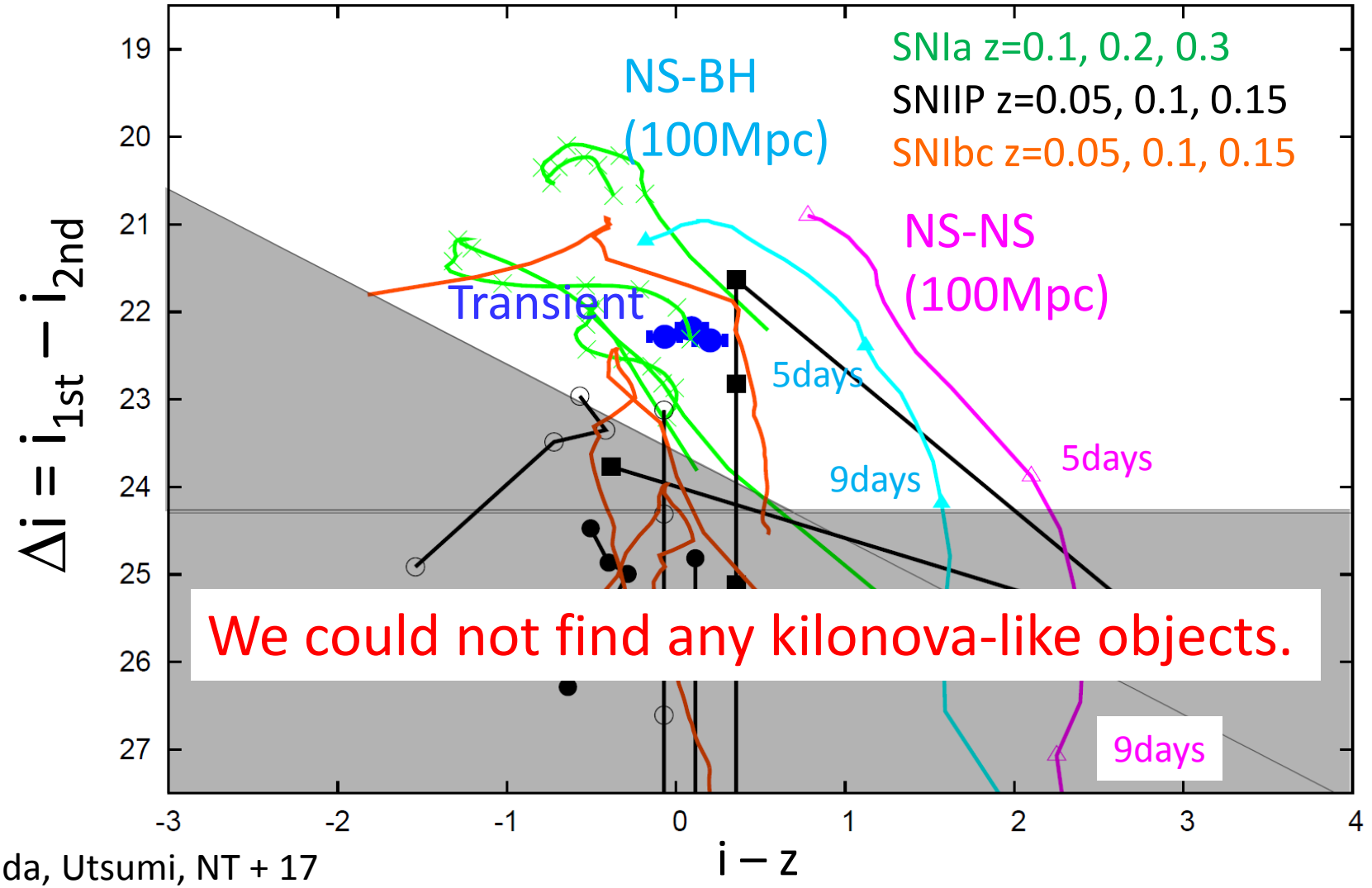
# Candidate detection



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

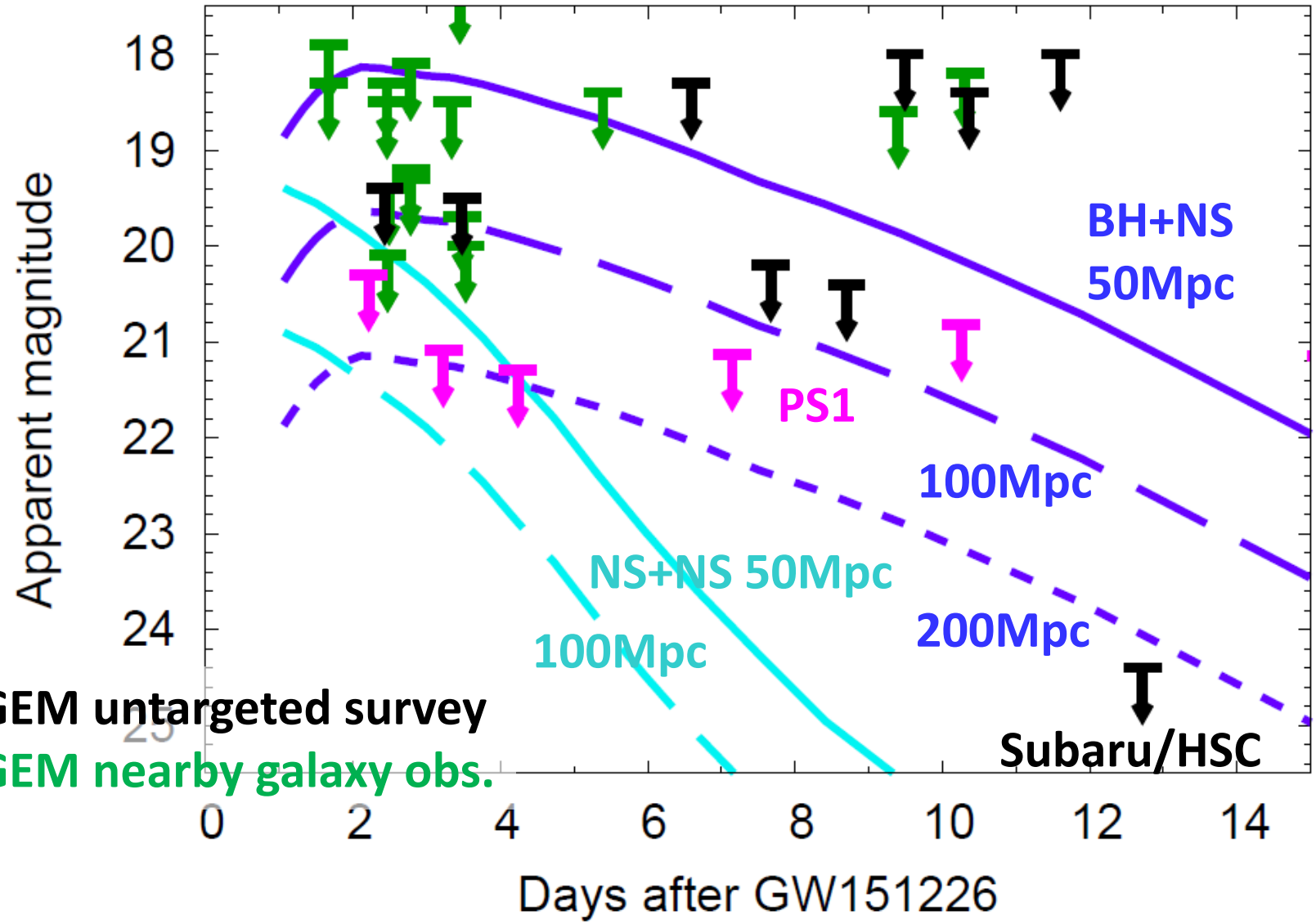
# Candidates from Subaru/HSC

- Color-magnitude diagram in difference magnitudes




Yoshida, Utsumi, NT + 17

# If GW151226 was a nearby NS-NS 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, ~60deg$^2$, 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.