# HSC Transient Survey

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マルチメッセンジャー天文学研究会

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- HSC follow-up survey
  - Gravitational waves
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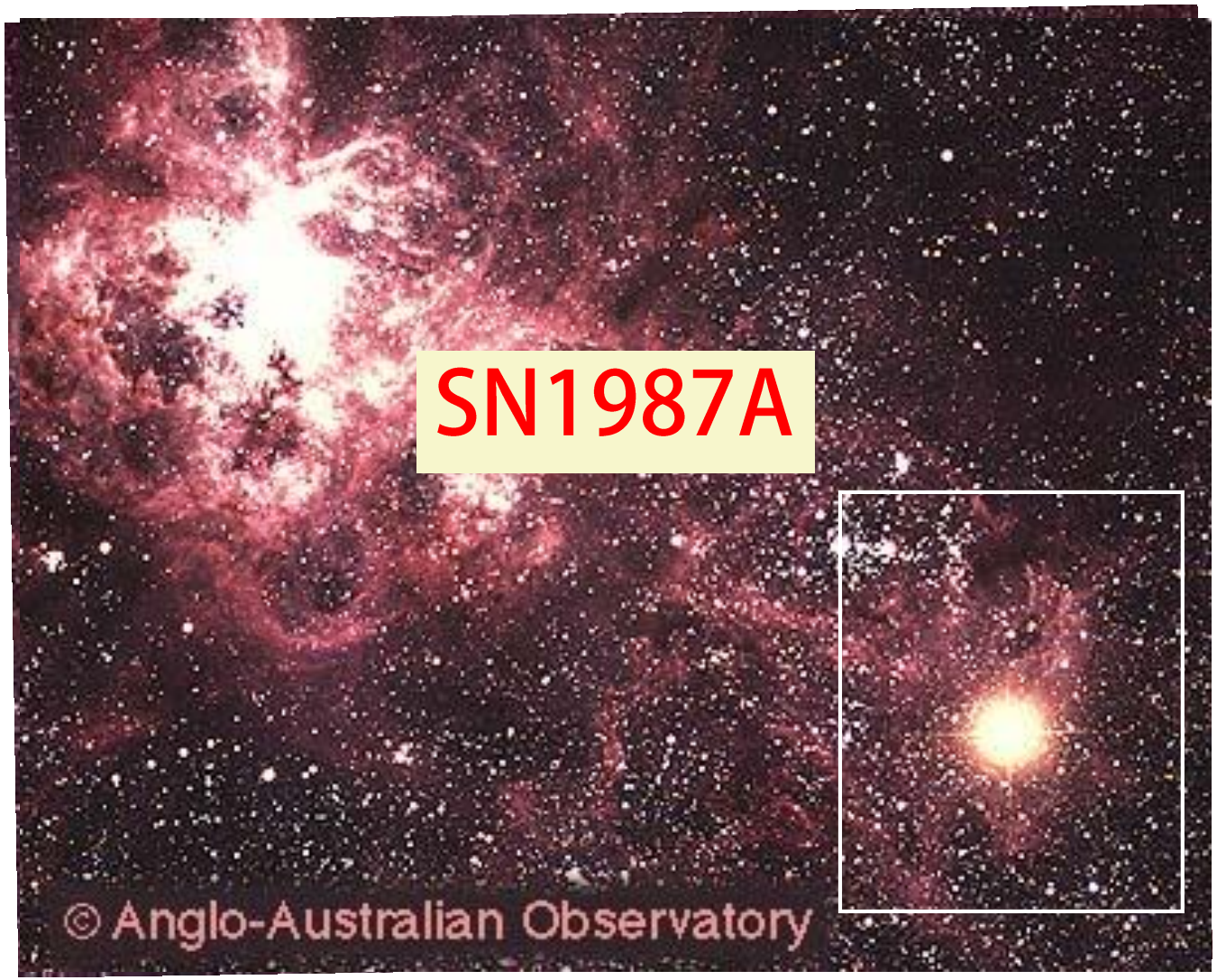
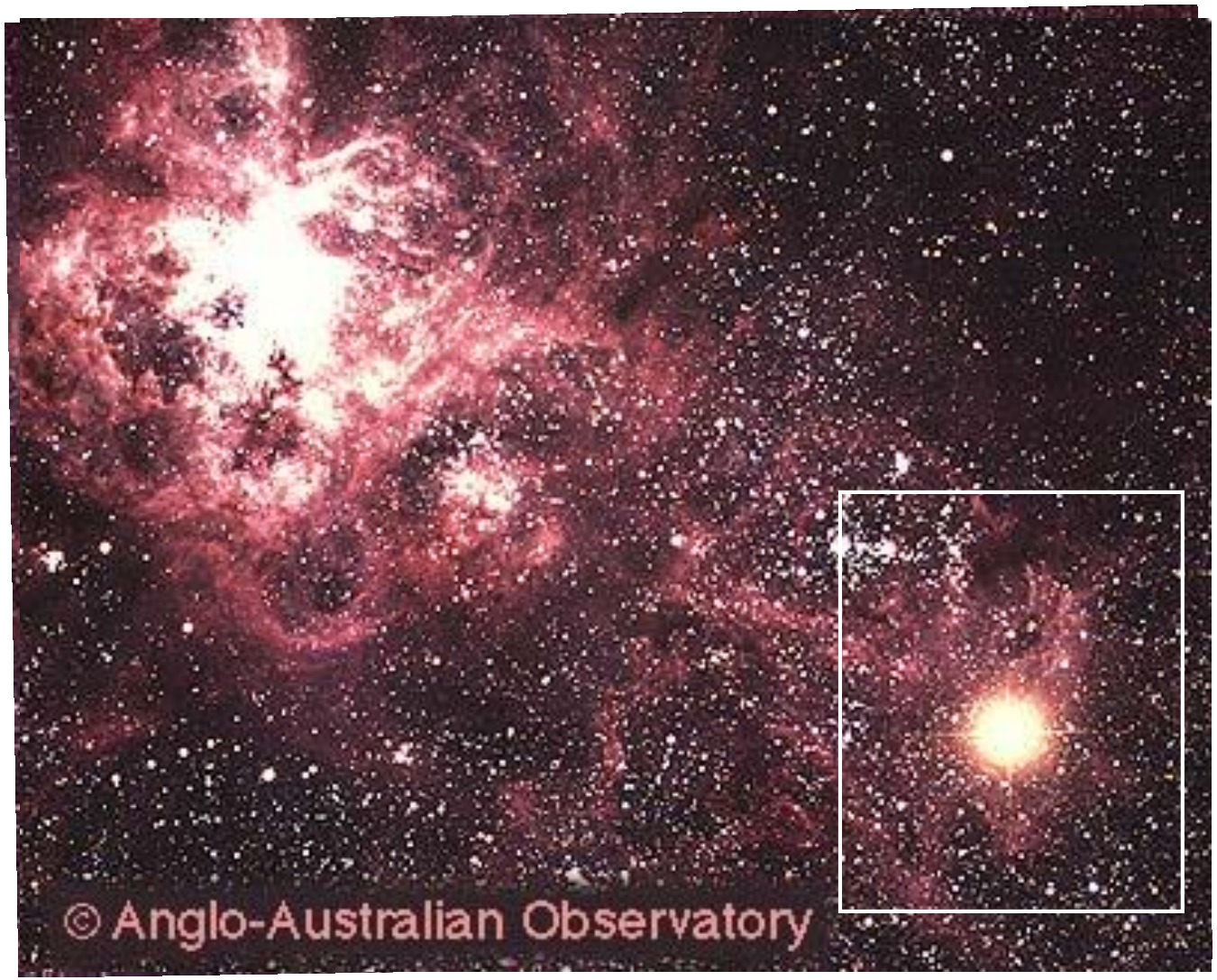
# Optical transient survey



# Optical transient survey
# ~ Supenova survey



# Amateur & traditional supernova survey

- Targeted nearby galaxies

http://www.dailymail.co.uk/sciencetech/article-2074145/Supernova-SN-2011fe-spotted-just-11-hours-exploded.html

# Untargeted optical transient surveys since 1995

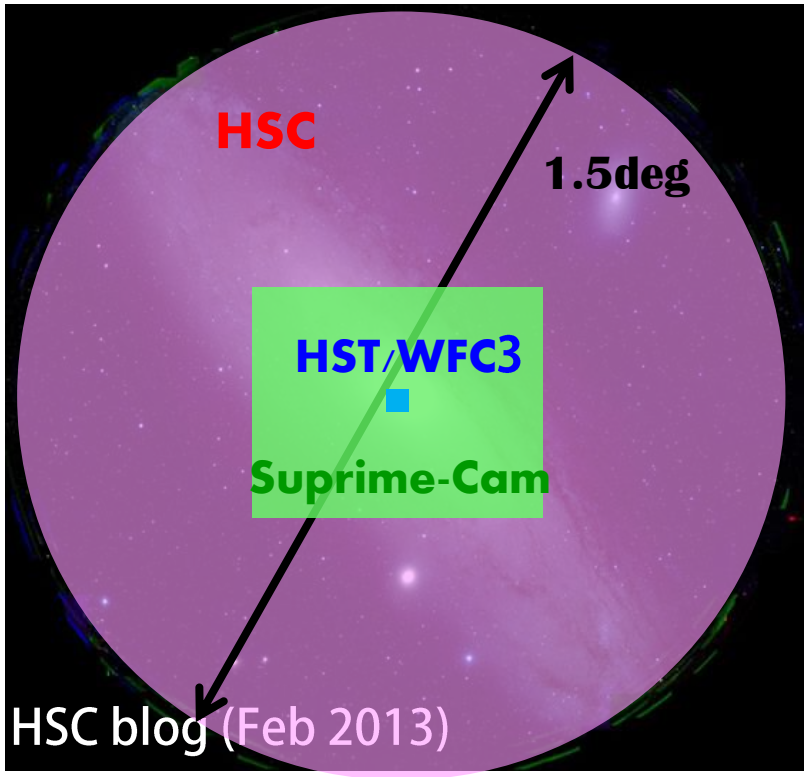
| Survey | Diameter [m] | FoV [deg$^2$] | Depth [mag] | Area [deg$^2$/day] |
|---|---|---|---|---|
| ASAS-SN | 0.14 | 20 | 17 | 20000 |
| ROTSE-III | 0.45 | 3.42 | 18.5 | 450 |
| CRTS | 0.7 | 8 | 19.5 | 1200 |
| KISS | 1.05 | 4 | 21 | 100 |
| PTF | 1.26 | 7.8 | 21 | 1000 |
| Skymapper | 1.33 | 5.7 | 19 | 1000 |
| Pan-STARRS | 1.8 | 7 | 21.5 | 6000 |
| SDSS | 2.5 | 1.5 | 22.6 | 150 |
| SNLS | 3.6 | 1 | 24.3 | 2 |
| HST/GOODS | 2.5 | 0.003 | 26 | 0.04 |
| Subaru/HSC | 8.2 | 1.75 | 26.5 | 3.5 (SSP) |
| LSST | 8.4 | 9.62 | 24.5 | 3300 |

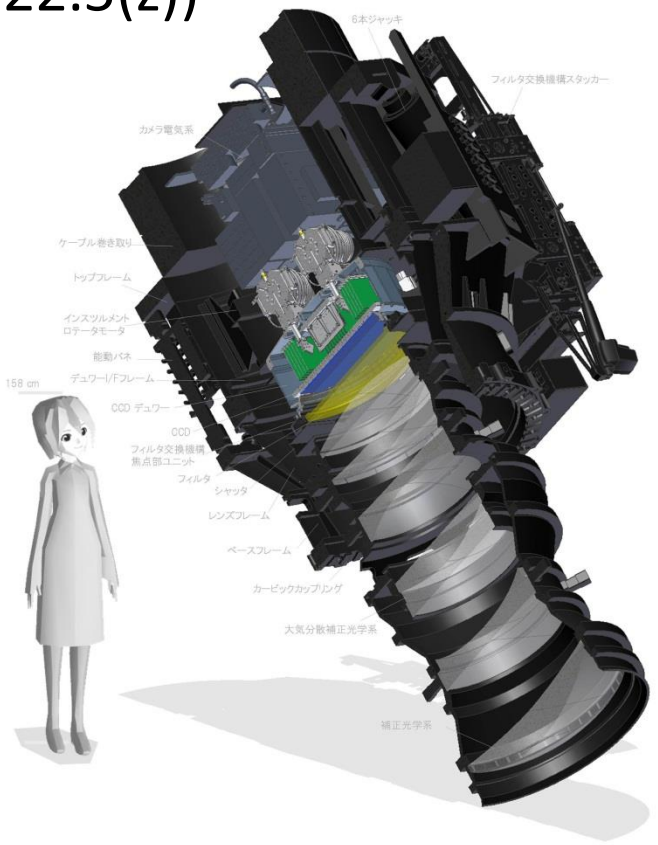
Rau+09

# 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)

    (DECam 1min: 23.3(i), 22.5(z))



# Survey power “Etendue” of telescopes/cameras

| Survey | Diameter [m] | FoV [deg$^2$] | Etendue (AΩ, roughly) [m$^2$deg$^2$] |
|---|---|---|---|
| ASAS-SN | 0.14 | 20 | 22 (8 cameras) |
| ROTSE-III | 0.45 | 3.42 | 0.54 |
| CRTS | 0.7 | 8 | 3.1 |
| KISS | 1.05 | 4 | 3.5 |
| PTF | 1.26 | 7.8 | 9.7 |
| Sk | | | |
| Pa | | | |
| SDSS | 2.5 | 1.5 | 7.4 |
| 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.

2023-

# HUGE data is provided by HSC

- 104 science CCD chips ~ 900M pixels
- hscPipe (HSC data analysis pipeline) is available.
  http://hsc.mtk.nao.ac.jp/pipedoc_e/index.html

## Environment

We present a typical envoroment to reduce 300 shots of HSC data.

| | Spec | Comments |
|---|---|---|
| CPU | x86_64 | |
| Core | 12 | |
| Memory | 64 GB | Data analysis for HSC data observed in large area requries additional memory. |
| HDD Storage | 10 TB | In case of 300 shots for objects. |

These are required for stationary objects.
The data analysis probably takes >1 week.

# How about transient surveys?

- data flow: ~4TB/night (strategy-dependent)
  - 200-300 exposures/nights
  - raw data: ~2GB/exposure
  - processed data: ~26GB/exposure
  - final data: ~36GB/epoch/field
- hscPipe is designed for stationary objects. Some modifications are required.

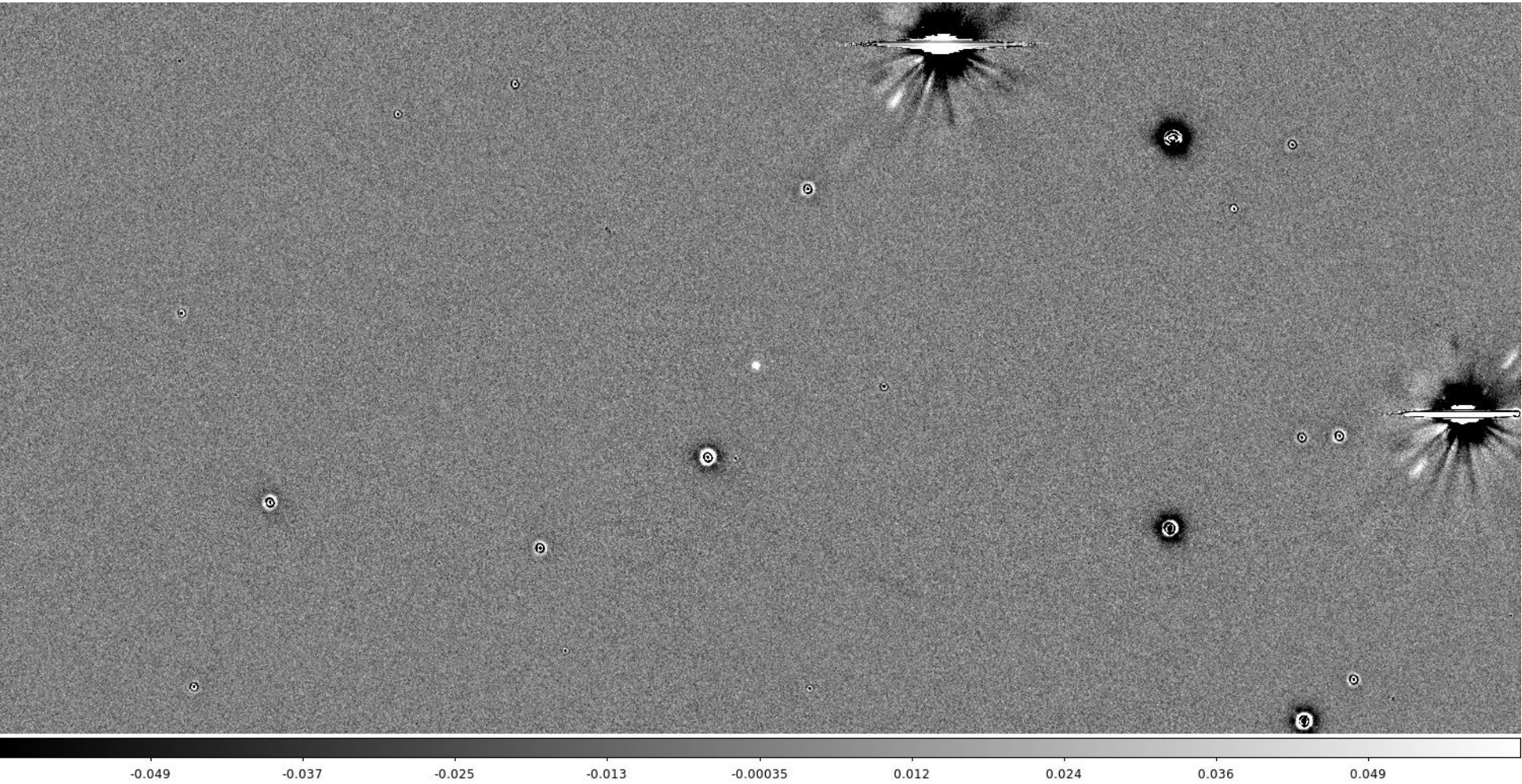
**Realtime data analysis required for immediate detection and follow-up observation is challenging.**

# Real-time transient detection system

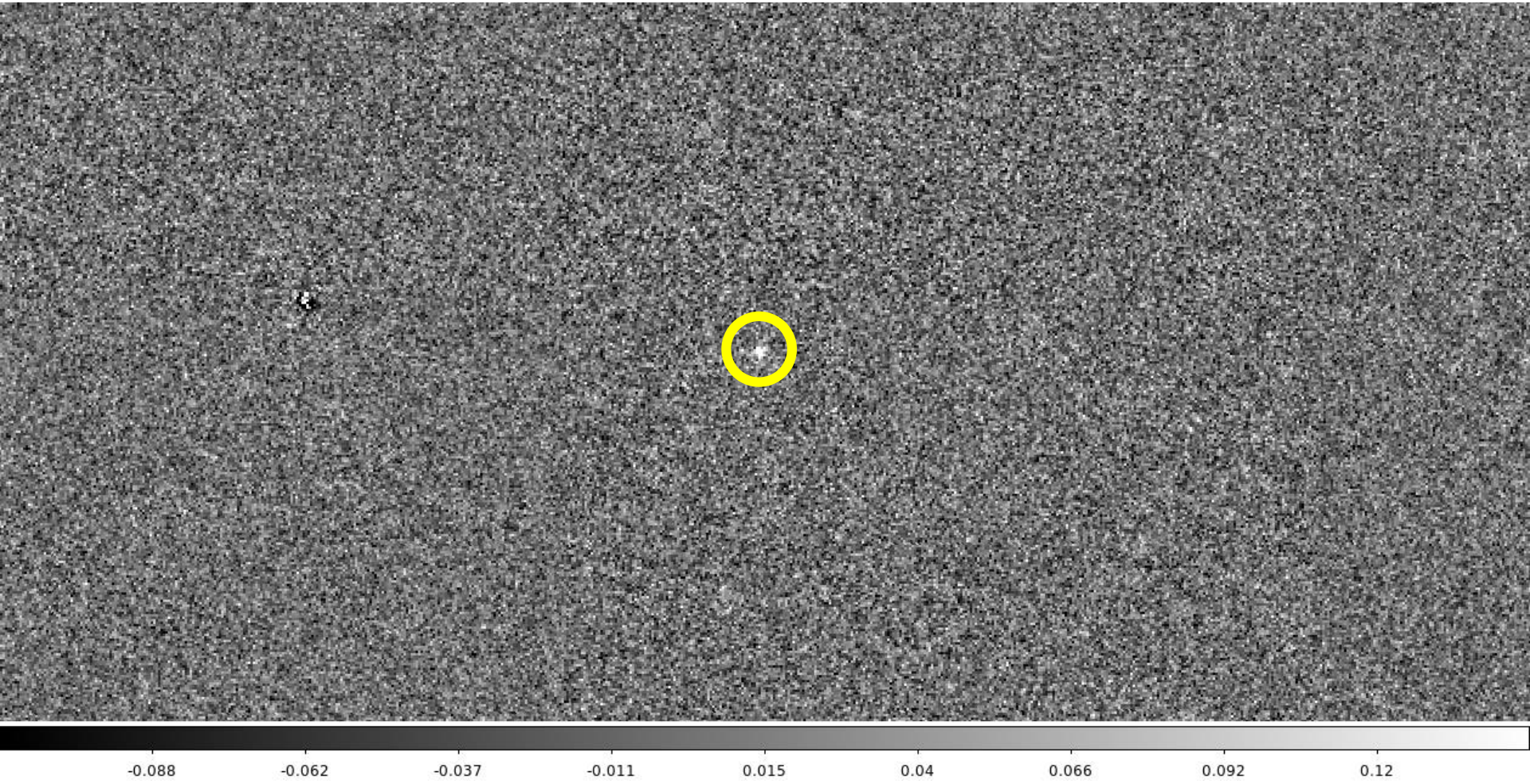
We developed a real-time data analysis system.

I stayed Subaru observatory ~1 week for the initial setup.

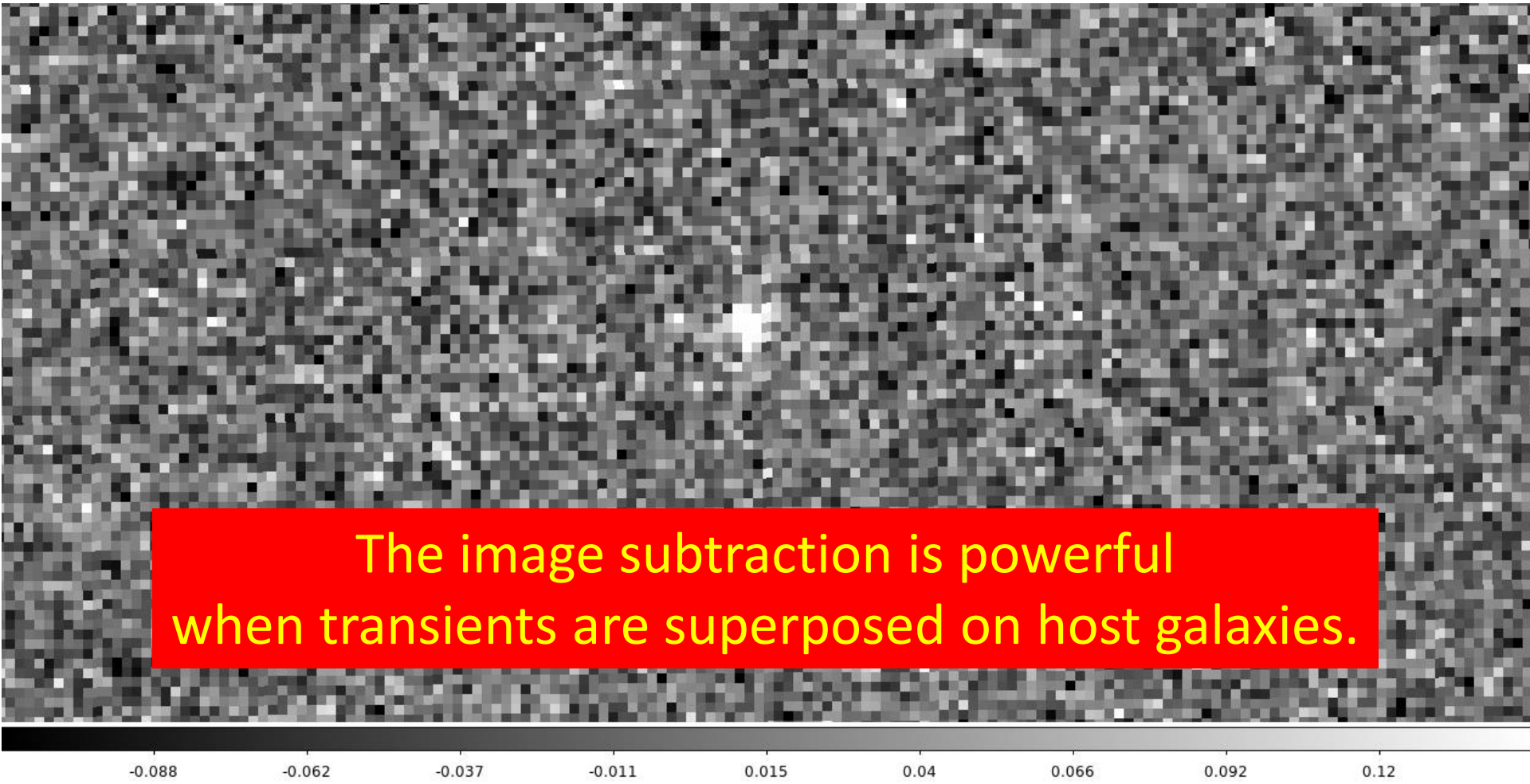
# How can we discover transients?
# -Image subtraction-



# How can we discover transients?
# -Image subtraction-



# How can we discover transients? -Image subtraction-



# Real-time detection and quick alert

## First supernova candidates discovered with Subaru/Hyper Suprime-Cam

The Astronomer's Telegram

ATel #6291; *Nozomu Tominaga (Konan U./Kavli IPMU, U. Tokyo), Tomoki Morokuma (U. Tokyo), Masaomi Tanaka (NAOJ), Naoki Yasuda (Kavli IPMU, U. Tokyo), Hisanori Furusawa (NAOJ), Jian Jiang (U. Tokyo), Satoshi Miyazaki (NAOJ), Takashi J. Moriya (U. Bonn), Junichi Noumaru (NAOJ), Kiaina Schubert (NAOJ), and Tadafumi Takata (NAOJ)*
*on 4 Jul 2014; 15:51 UT* (Obs.: 02 and 03 Jul 2014)

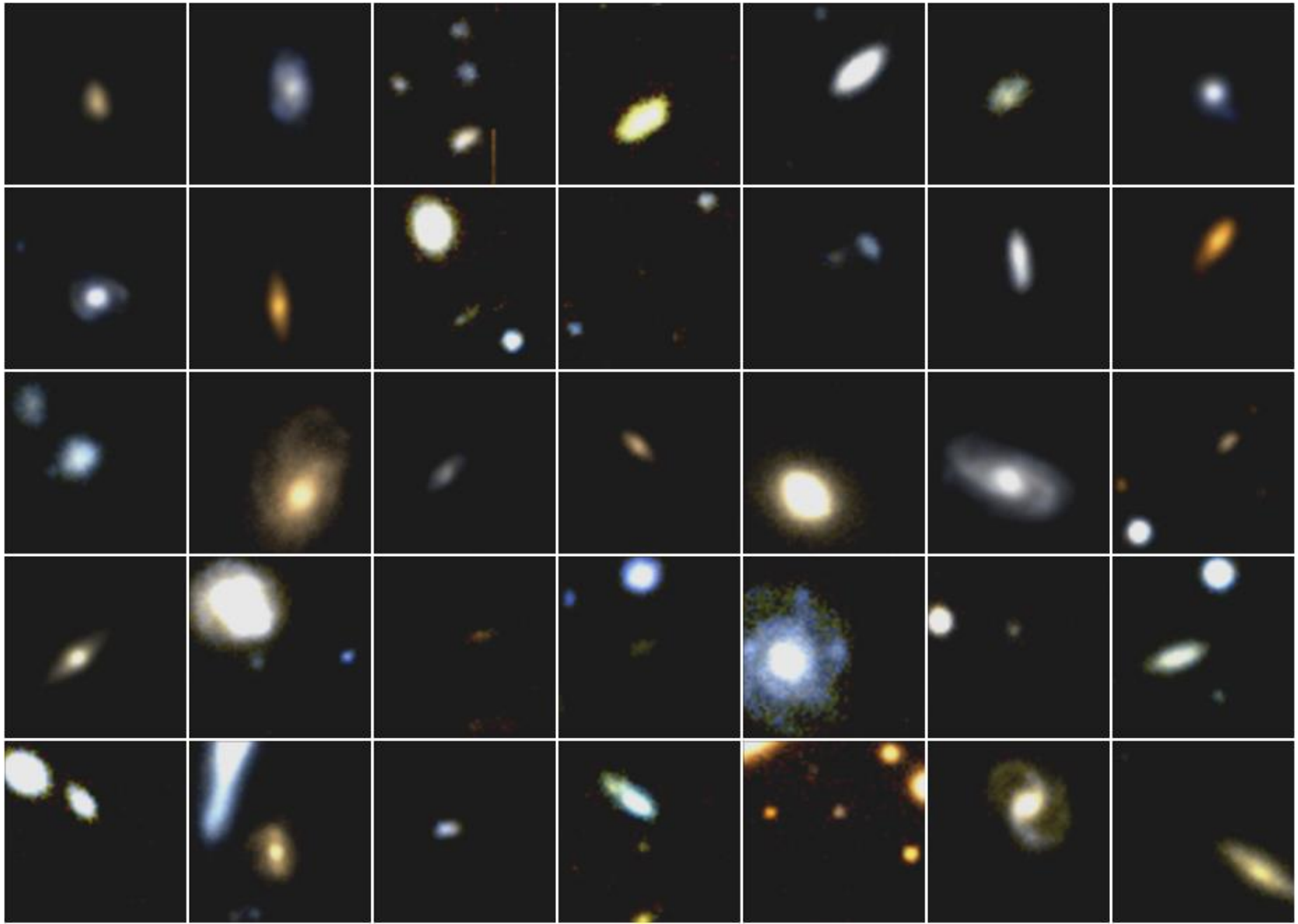
ATel #6763; *+N. Okabe, T.Futamase on 27 Nov 2014; 18:03 UT* (Obs.: 26 and 27 Nov 2014)

## Fifty supernova candidates discovered with Subaru/Hyper Suprime-Cam

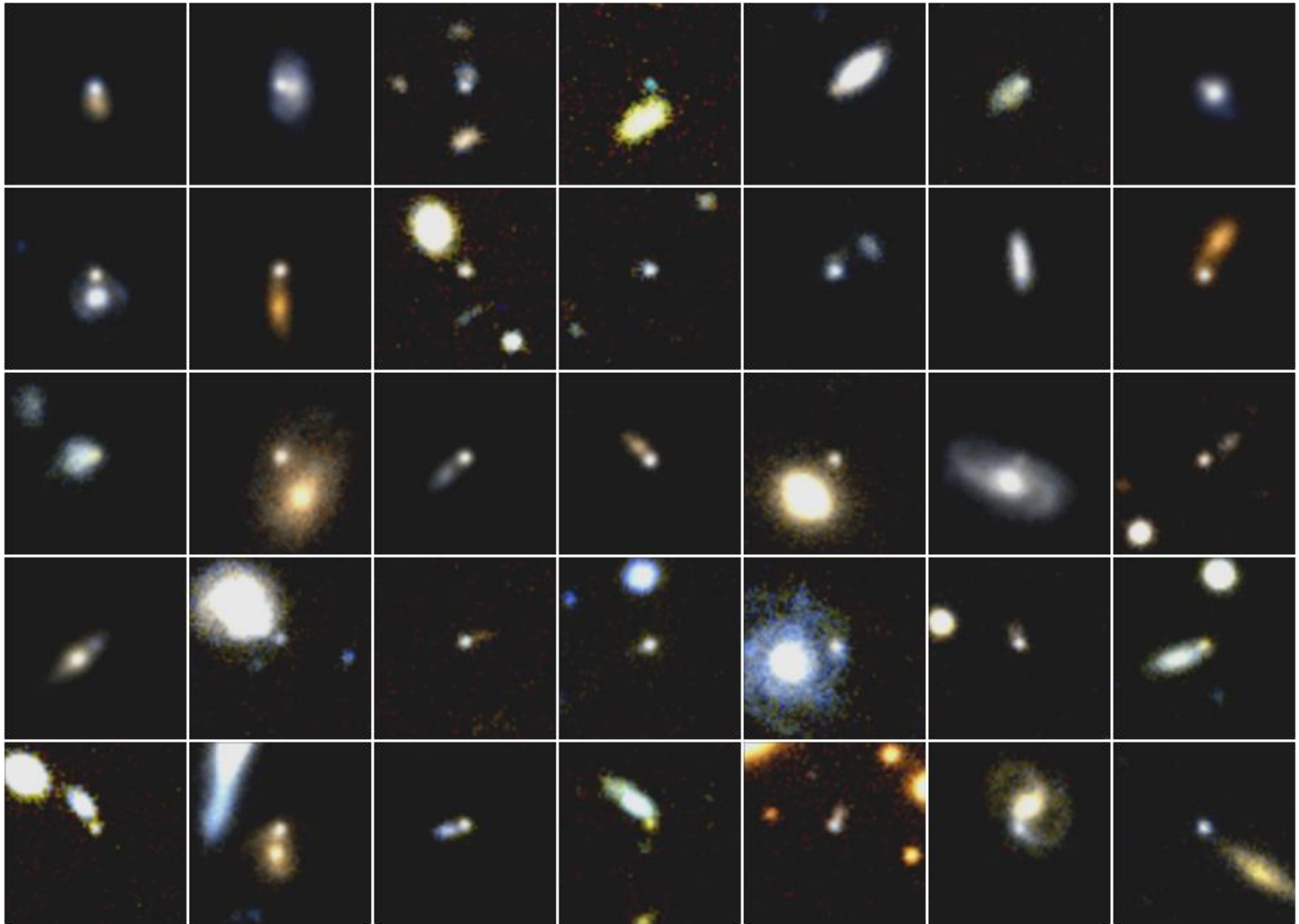
ATel #7565 ; *Nozomu Tominaga (Konan U./Kavli IPMU, U. Tokyo), Tomoki Morokuma (IoA, U. Tokyo/Kavli IPMU, U. Tokyo), Masaomi Tanaka (NAOJ/Kavli IPMU, U. Tokyo), Ji-an Jiang (U. Tokyo), Takahiro Kato (U. Tokyo), Yuki Taniguchi (U. Tokyo), Naoki Yasuda (Kavli IPMU, U. Tokyo), Hisanori Furusawa (NAOJ), Nobuhiro Okabe (Hiroshima Univ.), Toshifumi Futamase (Tohoku Univ.), Satoshi Miyazaki (NAOJ), Takashi J. Moriya (AIfA, U. Bonn), Junichi Noumaru (NAOJ), Kiaina Schubert (NAOJ), and Tadafumi Takata (NAOJ)*
*on 26 May 2015; 15:23 UT* (Obs.: 24 May 2015)

http://tpweb2.phys.konan-u.ac.jp/~tominaga/HSC-SN/

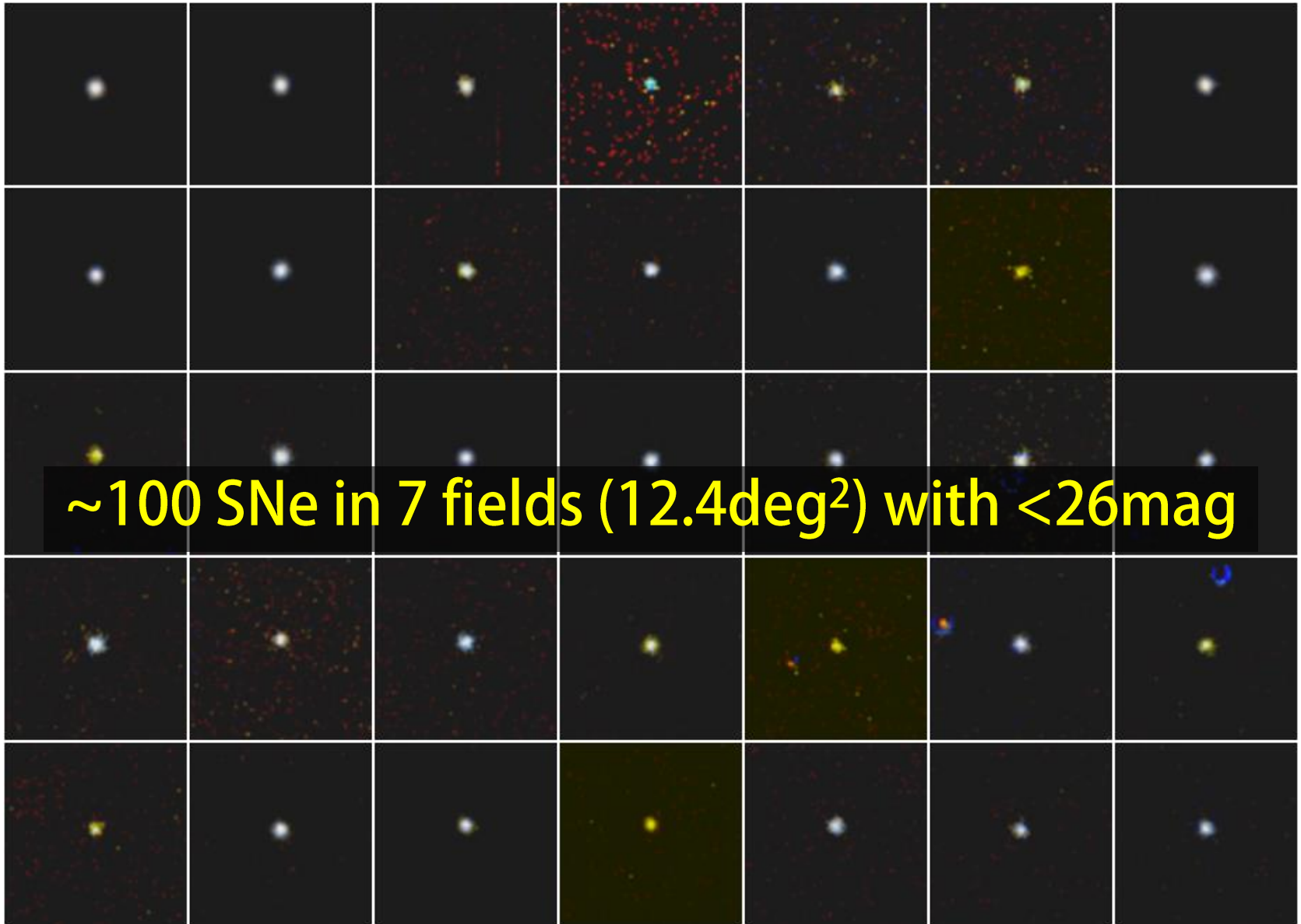
# SN candidates -Jul 2014-



# SN candidates -May 2015-



# SN candidates -subtracted-



# HSC follow-up survey
# -Gravitational wave-

特集：重力波電磁波対応天体追観測

## Subaru/Hyper Suprime-Cam を用いた重力波可視光対応天体探査観測

冨　永　　望

天文月報2017年1月号

# First detection: GW150914

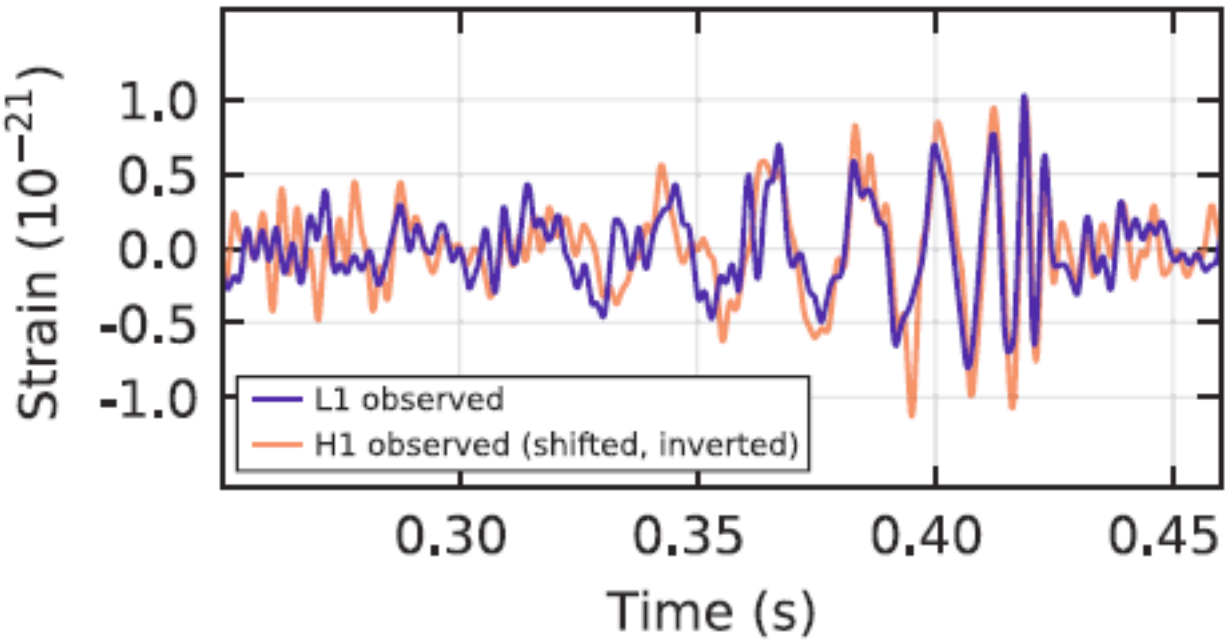
PRL 116, 061102 (2016)

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)

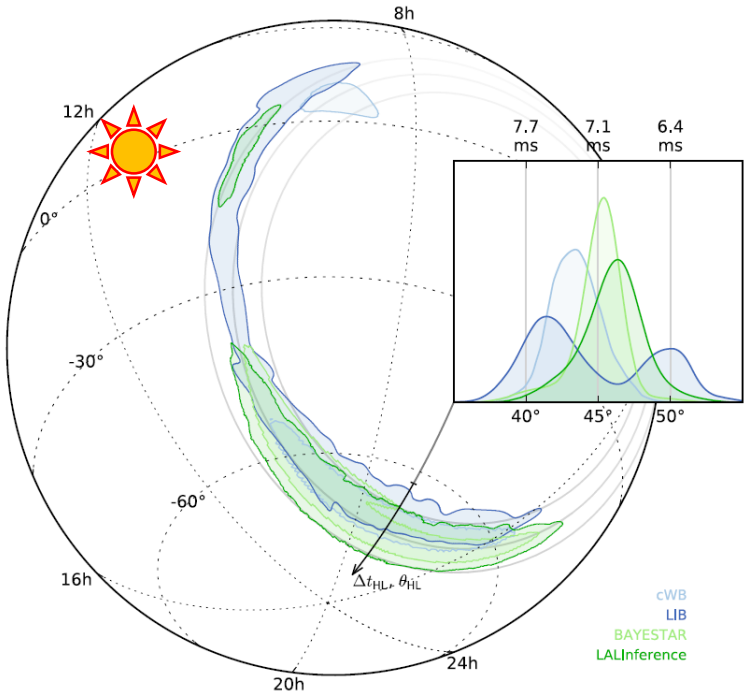



$36^{+5}_{-4}M_{\odot}$ and $29^{+4}_{-4}M_{\odot}$ BHs merged at $410^{+160}_{-180}$Mpc

# Unscheduled discovery of GW150914

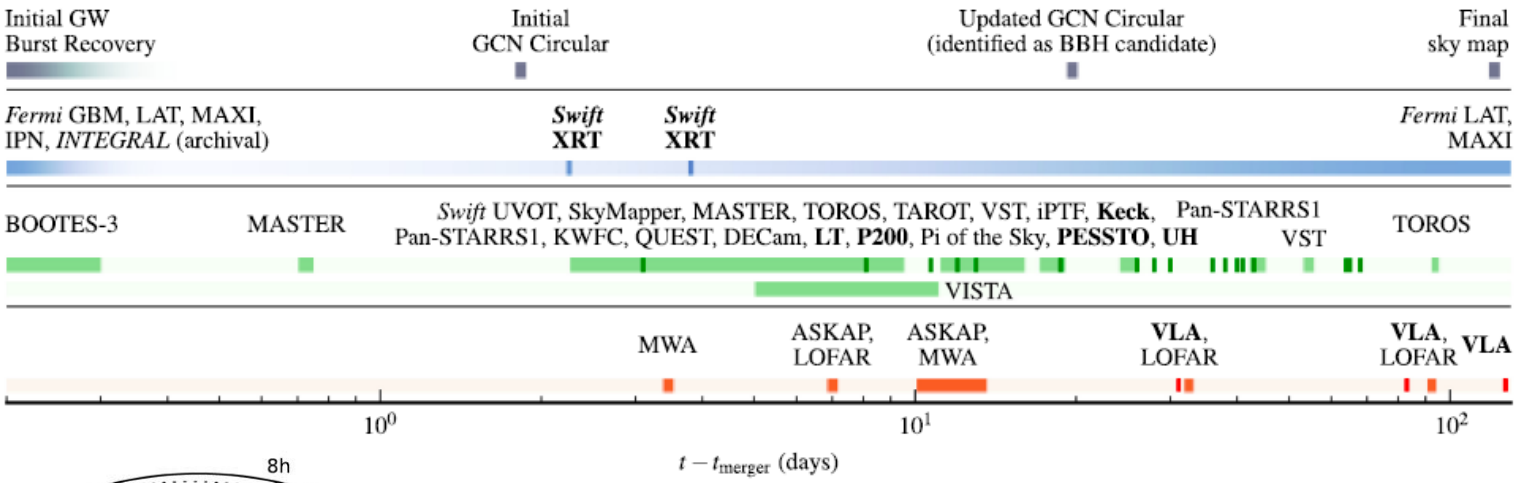
- Signal detection
  - Sep 14, 2015, 09:50:45 (UT)
  - during engineering run (ER8)
- Alert announced
  - Sep 16, 2015 (+2days)
  - 2days before scheduled O1 run
- False alarm rate (FAR)
  - <~ 1/month (alert)
  - < 1/100yrs (Jan 2016)
  - < 1/203,000yrs (Feb 2016)

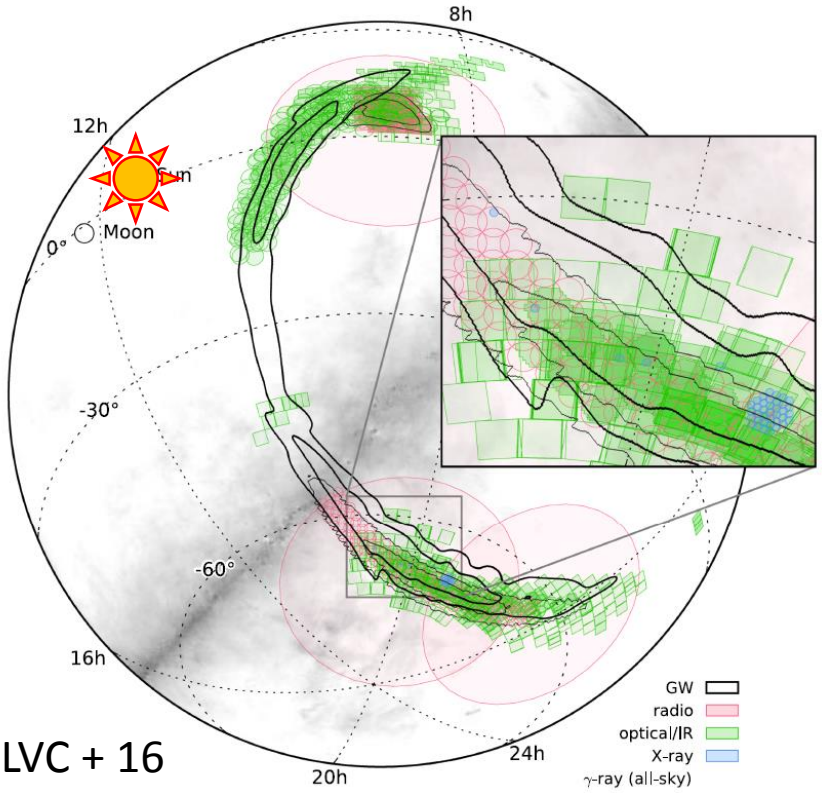
Skymap of GW150914




LVC + 16

# LV-EM follow-ups of GW150914



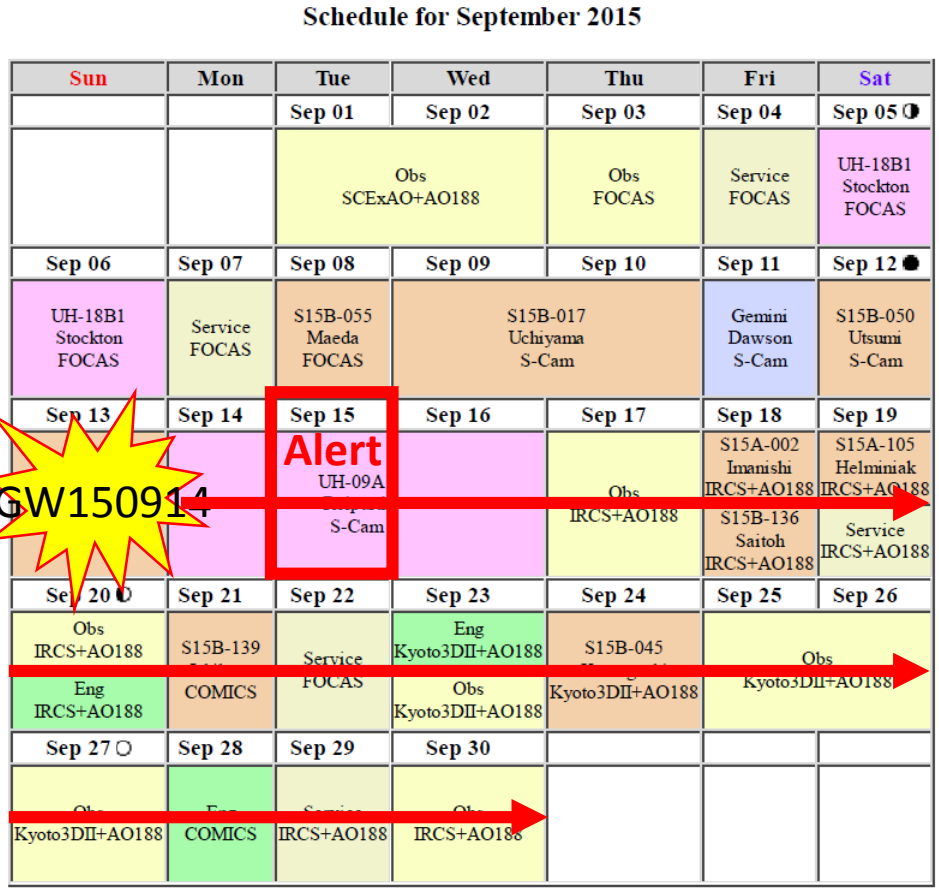




LVC + 16

- 25 of 63 observing teams **J-GEM**
  - Broad band tiled observation
  - Observation of nearby galaxies
  - Spectroscopic follow-up observations
- Optical: ~900deg$^2$ (50% of LIB)
- NIR: ~70deg$^2$ (8% of final map)

See also Nissanke-san's talk

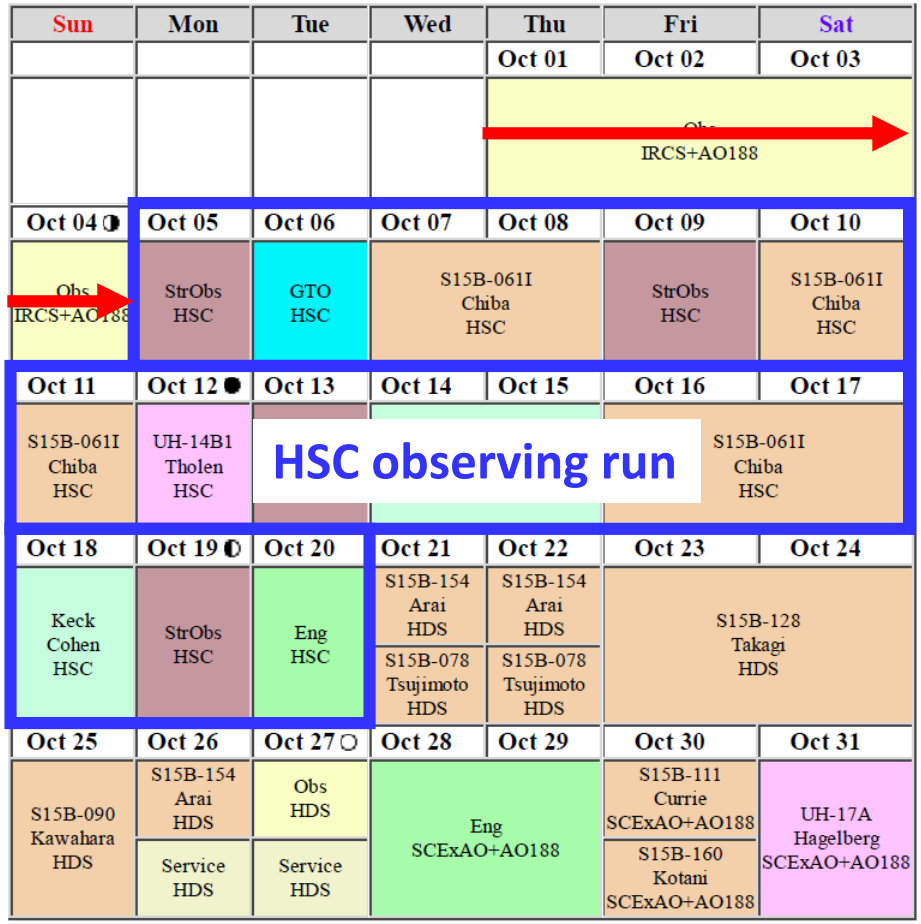
# Subaru/HSC was not available



Schedule for September 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 |
| | | Alert UH-09A [illegible] S-Cam | | Obs IRCS+AO188 | S15A-002 Imanishi IRCS+AO188 / S15B-136 Saitoh IRCS+AO188 | S15A-105 Helminiak IRCS+AO188 / Service IRCS+AO188 |
| Sep 20 ◐ | Sep 21 | Sep 22 | Sep 23 | Sep 24 | Sep 25 | Sep 26 |
| Obs IRCS+AO188 / Eng IRCS+AO188 | S15B-139 [illegible] / COMICS | Service FOCAS | Eng Kyoto3DII+AO188 / Obs Kyoto3DII+AO188 | S15B-045 [illegible] Kyoto3DII+AO188 | Obs Kyoto3DII+AO188 | |
| Sep 27 ○ | Sep 28 | Sep 29 | Sep 30 | | | |
| Obs Kyoto3DII+AO188 | Eng COMICS | Service IRCS+AO188 | Obs IRCS+AO188 | | | |

GW150914



Schedule for October 2015

| 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-078 Tsujimoto HDS | S15B-154 Arai HDS / S15B-078 Tsujimoto HDS | S15B-128 Takagi HDS | |
| Oct 25 | Oct 26 | Oct 27 ○ | Oct 28 | Oct 29 | Oct 30 | Oct 31 |
| S15B-090 Kawahara HDS | S15B-154 Arai HDS / Service HDS | Obs HDS / Service HDS | Eng SCExAO+AO188 | | S15B-111 Currie SCExAO+AO188 / S15B-160 Kotani SCExAO+AO188 | UH-17A Hagelberg SCExAO+AO188 |

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

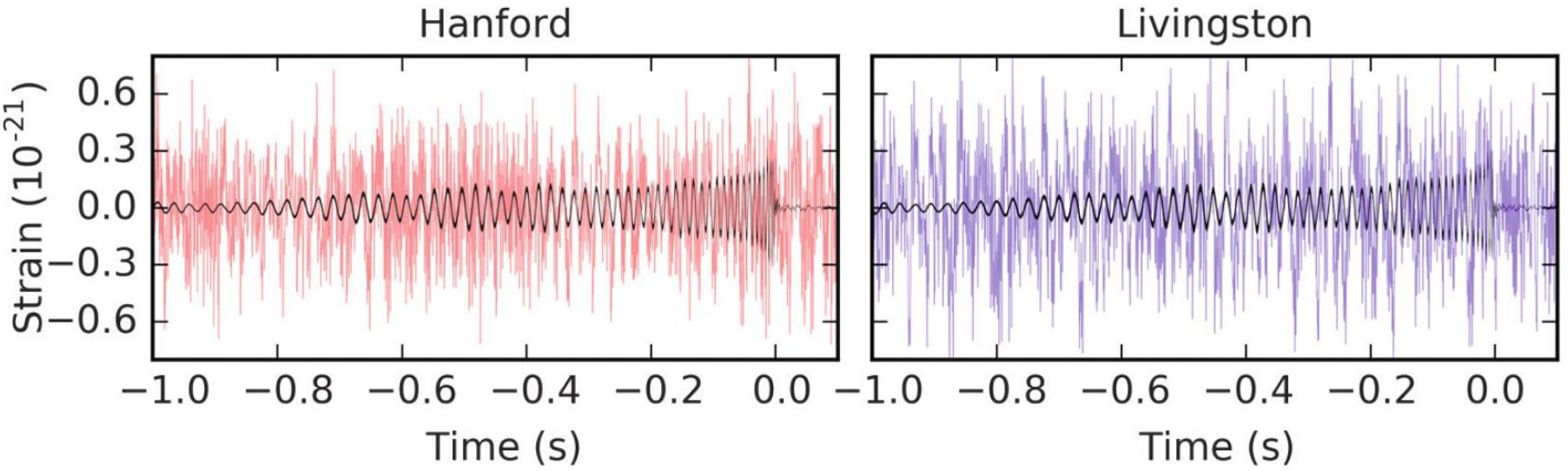
**The visibility of GW150914 from Mauna Kea was poor.**

# 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

# 2015-12-27 16:28:13 (UT) (+1.6days) GCN/LVC_INITIAL_SKYMAP

TITLE: GCN/LVC NOTICE

NOTICE_DATE: Sun 27 Dec 15 16:28:13 UT

NOTICE_TYPE: LVC Initial Skymap

TRIGGER_NUM: G211117

TRIGGER_DATE: 17382 TJD; 360 DOY; 2015/12/26 (yy/mm/dd)

TRIGGER_TIME: 13133.647758 SOD {03:38:53.647758} UT

GROUP_TYPE: 1 = CBC (= compact binary coalescence)

SEARCH_TYPE: 3 = HighMass (including BH)

PIPELINE_TYPE: 4 = GSTLAL

FAR: 6.340e-09 [Hz] (one per 1825.5 days)

CHIRP_MASS: -1.0000 [M_solar]

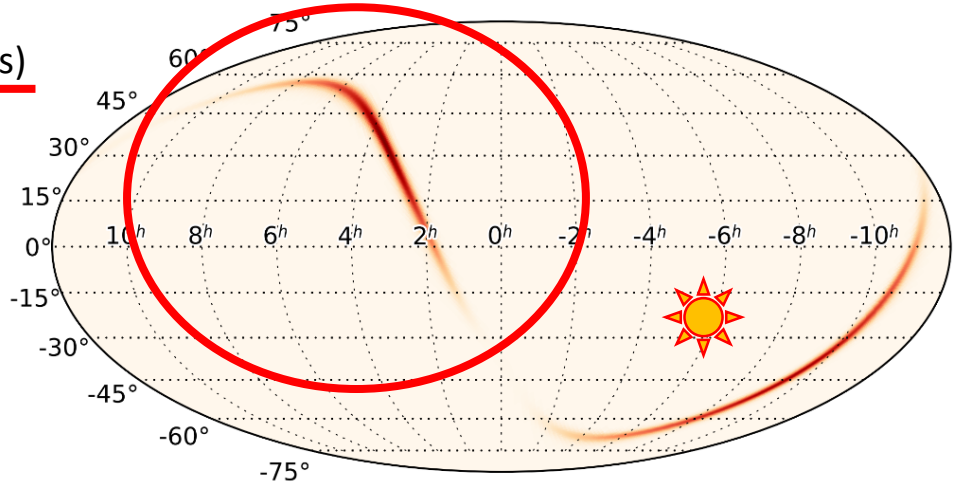
ETA: -1.000

MAX_DIST: -1.00 [Mpc]

TRIGGER_ID: 0x0

MISC: 0x2100003

error region: ~1300deg$^2$ (90%)



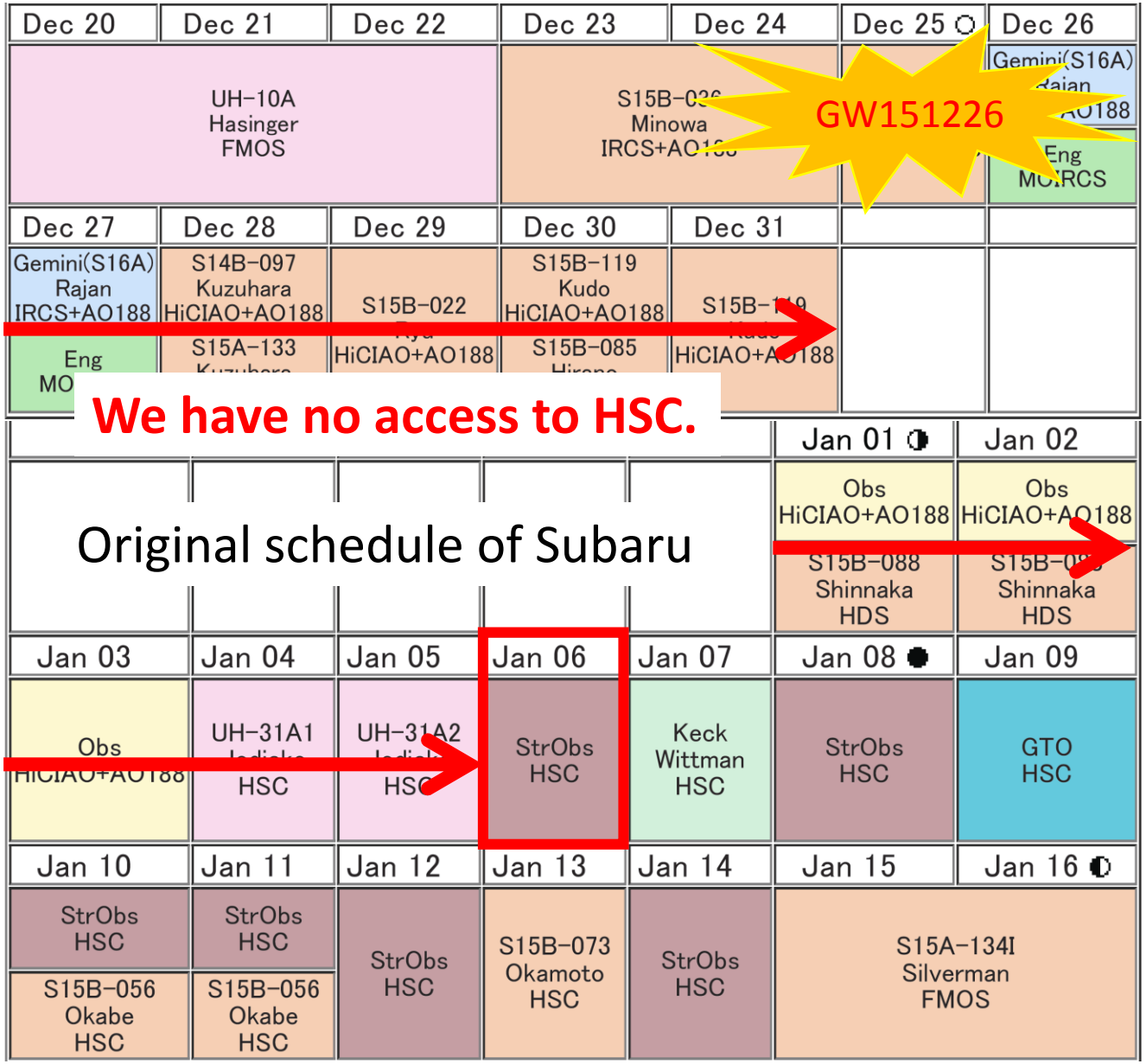
# Optical WF follow-ups of GW151226

- DECam 28.8deg$^2$ (Cowperthwaite + 16 ApJL)
  - 3 AGNs and 1 SNIIP (i~21.7 and z~21.5)
- PS1 290deg$^2$ (Smartt+16 MNRAS)
  - 20 SNe from 49 OTs (i~20.5)
- iPTF 952deg$^2$ (Cenko+16 GCN)
  - 2 SNe from 20 OTs (R~20)
- MASTER 99% of North (Lipunov+16 GCN)
  - 1 PSN from 7 OTs
- VST 72deg$^2$ (Grado+16 GCN)
- Skymapper 110deg$^2$ (Yuan+16 GCN)
  - 1 OT (i~18.6)
- J-GEM collaboration (Yoshida, Utsumi, NT+ 16 PASJ)

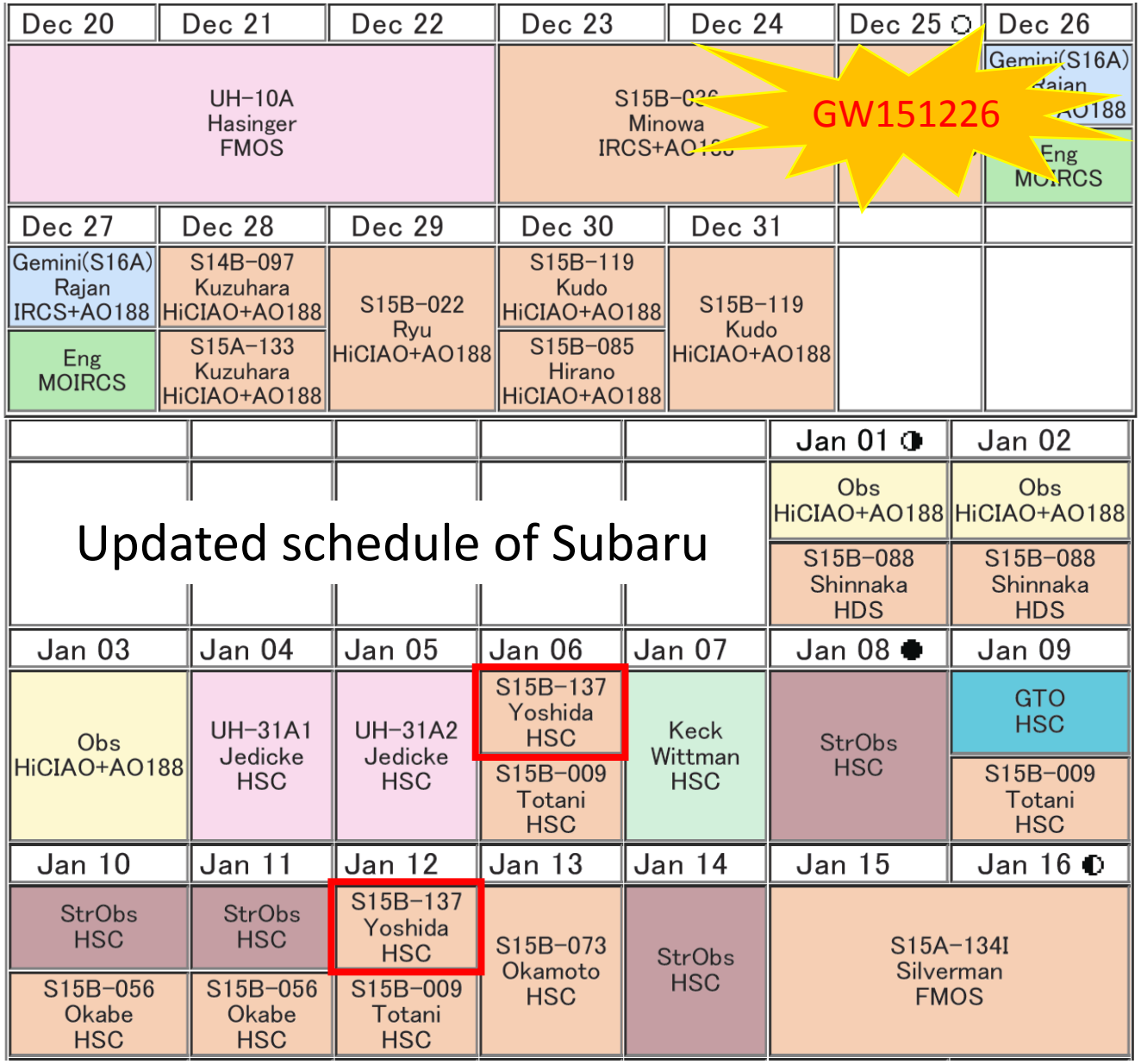
No plausible optical counterpart

→ Yoshida-san's talk

# Availability of Subaru/HSC

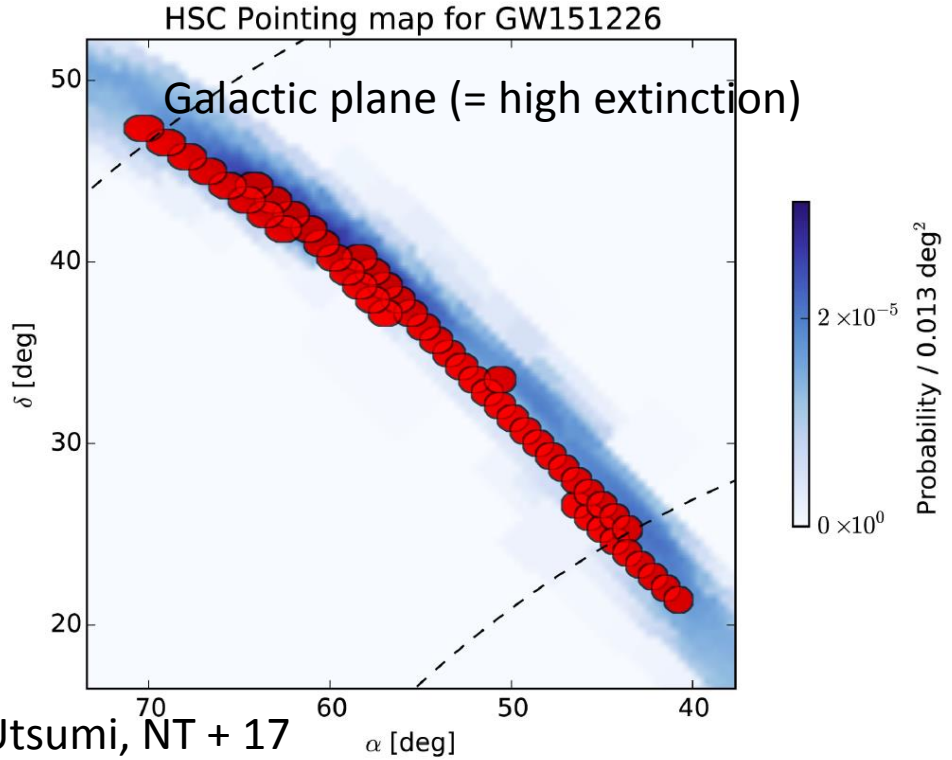


# Availability of Subaru/HSC



# Observation summary -Subaru/HSC-

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




Yoshida, Utsumi, NT + 17

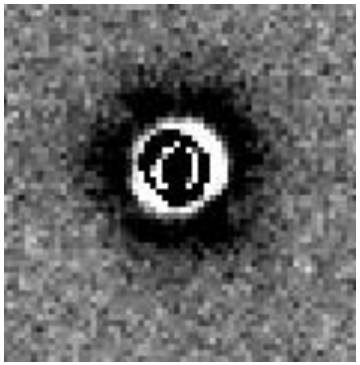
50 pointing ~
(5hr - 30min)
/ 1.4min
/ 2 color
/ 2 times

Total time -
filter exchange
Exposure +
overhead
i, z
# of exposure
per pointing

Regions with the highest probability were observed.

# Candidate selection

- Reference frame: Feb 6, 2016
- Science frames: Jan 7 1st, 2nd, 13, 2016
- Detection criteria:
  - To remove bogus and cosmic rays
    - 2 detections with z on Jan 7 ← red color
    - Signal-to-noise ratio > 5 $\sigma$
    - Elongation > 0.8 of point spread function (psf)
    - FWHM 0.8-1.3 of psf
    - Residual after psf subtraction < 3 $\sigma$
  - To exclude minor planets
    - No detection with i on Jan 7 at 0.5-45arcsec
    - No registered minor planets at <0.5arcsec
  - To exclude brightening sources ← short time scale
    - Positive sources on difference image (Jan 7 - Feb 6)



# Candidates from Subaru/HSC

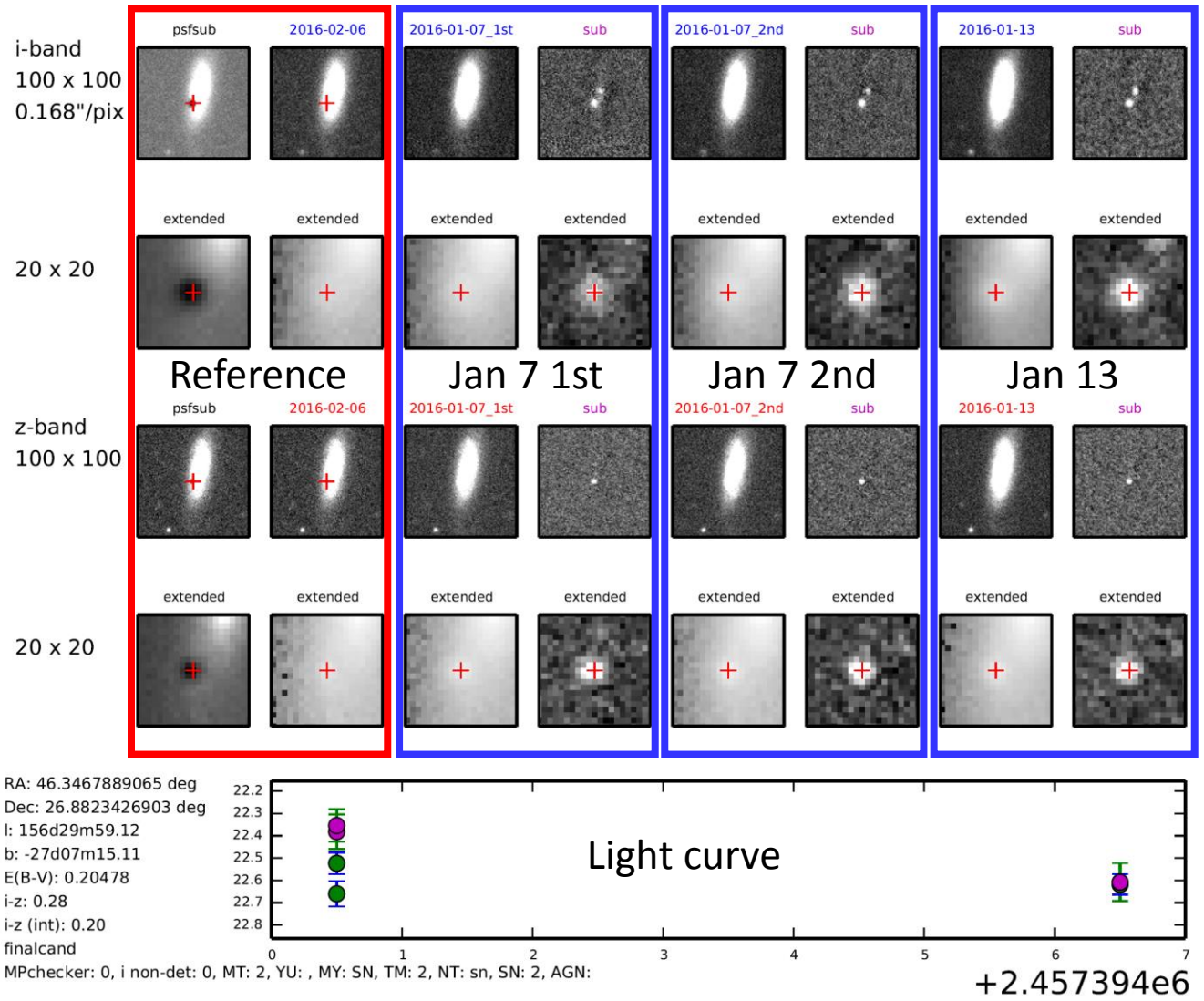
- 1256 candidates remain and visually inspected.

16.8”x16.8”

i-band

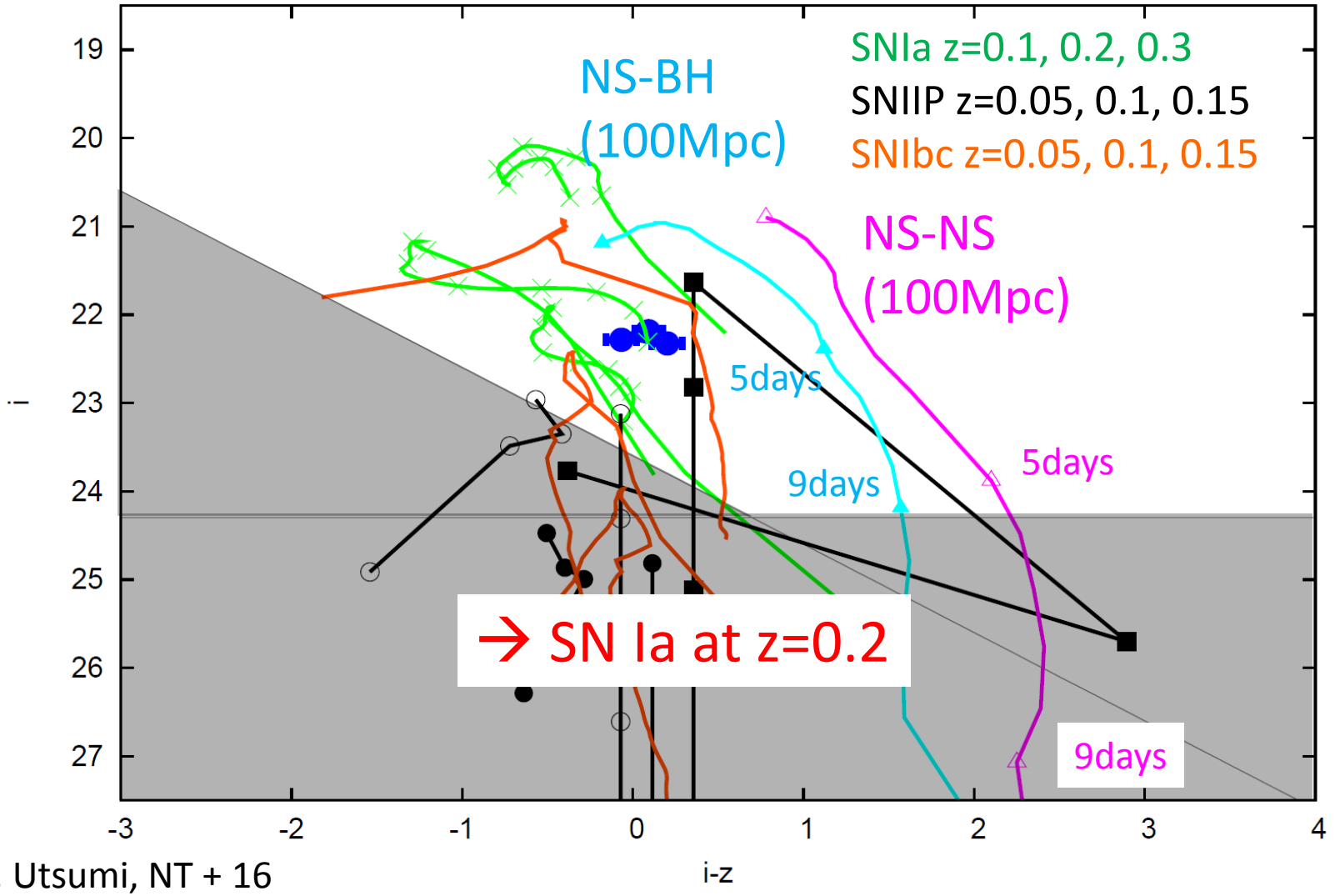
3.4”x3.4”

z-band



# Candidates from Subaru/HSC

- Color-magnitude diagram in difference images




Yoshida, Utsumi, NT + 16

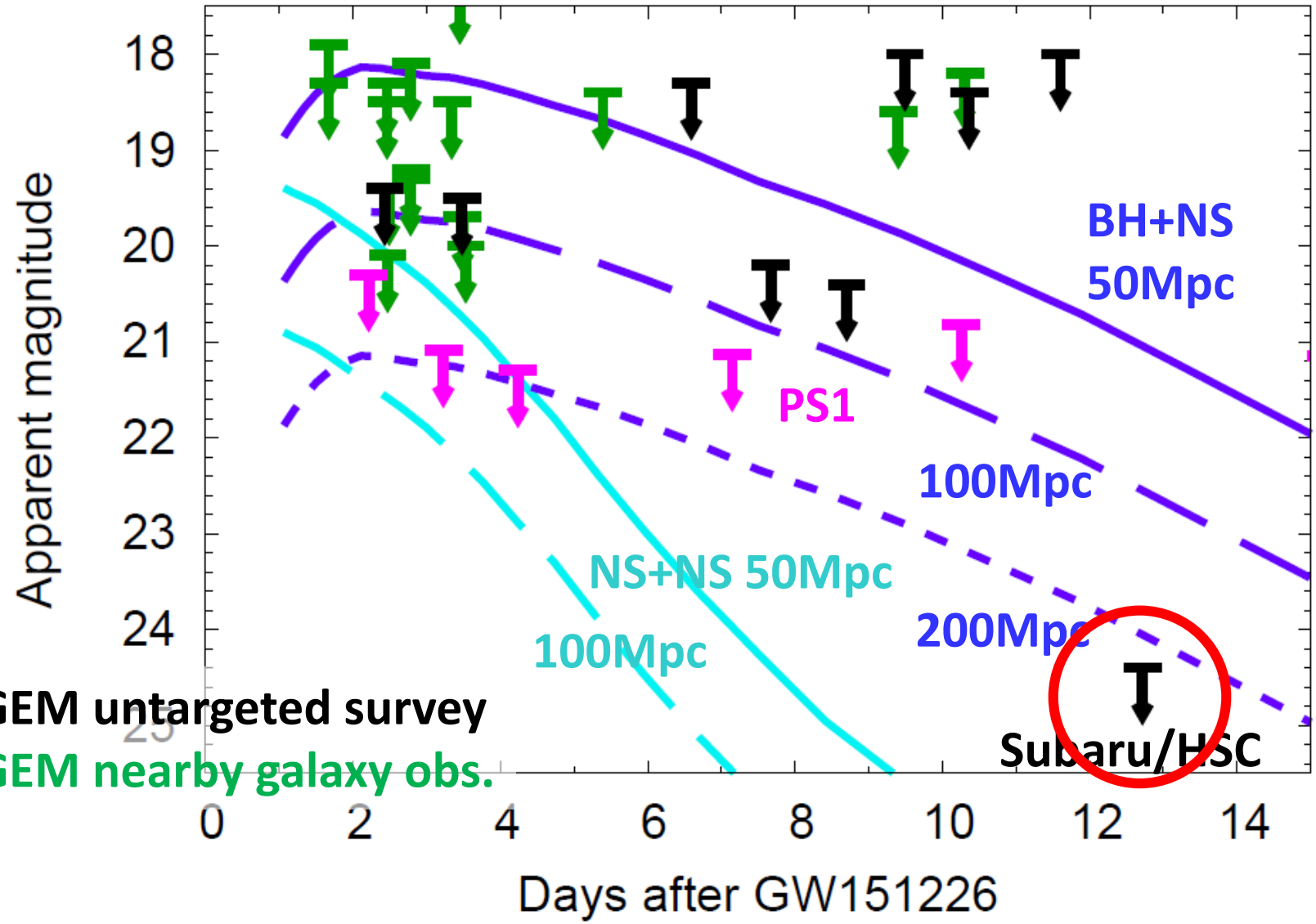
# Candidates from Subaru/HSC

- 60 candidates are likely to be astronomical objects.
  - 20 AGN
  - 40 SNe
    - SNe Ia at $z<0.3$ are dominant
- No candidate for an optical counterpart of GW151226

**This is consistent with the fact that GW151226 was a BH-BH merger at ~440Mpc.**

Yoshida, Utsumi, NT + 17

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



# Summary

- Subaru/HSC is the most powerful instrument for transient searches. However, we should keep in mind that HSC is not always available and that data analysis is quite tough.
- Realtime data analysis system works well (with some troubles) for designed strategies, i.e., SN survey.
- Follow-up obs. with HSC is performed for GW151226.
- Time variability, color evolution, and location are keys to identify kilonovae from other transients.

**Conceivable preparations with trial-and-errors are strongly recommended for the full use of HSC survey with, especially, realtime data analysis (I can help you).**

A (pilot) survey with Kiso Schmidt telescope is worth considering for bright sources. (HSC is extremely competitive.)