Search for optical counterparts of gravitational waves

Nozomu Tominaga
(Konan Univ./Kavli IPMU)
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• Electromagnetic wave counterparts of GW sources
• Japanese collaboration for Gravitational wave ElectroMagnetic follow-up (J-GEM)

• GW150914
  • LV-EM observations
  • J-GEM observations

• GW151226
  • LV-EM observations
  • J-GEM observations

• Future prospects for LIGO O2
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  • J-GEM observations
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  • J-GEM observations
• Future prospects for LIGO O2
EM counterparts of GW sources

See also Tanaka-san’s talk
Origins of GWs

- Supernovae
- Pulsar
- Black hole
- Binary merger

**Binary merger**
- NS-NS
- BH-NS
- BH-BH

**Merger rate**
- \(<12600 \text{ Gpc}^{-3} \text{ yr}^{-1}\)
- \(<3600 \text{ Gpc}^{-3} \text{ yr}^{-1}\)
- 9-240 Gpc\(^{-3}\) yr\(^{-1}\)

Abbott+16a,b

KAGRA homepage
EM counterparts of NS-NS/NS-BH mergers

Short timescale (<week)
- Short GRBs
  - relativistic beaming
- Kilonova/Macronova
  - r-process nova/wind
  - neutron powered precursor

Long timescale (~year)
- GRB afterglow
- ISM interaction

Metzger & Berger 12
Theoretical LCs of kilonova

In the current understanding, kilonovae are red and bright in IR.

Barnes & Kasen 13; Kasen +13; 15; Tanaka & Hotokezaka 13; Tanaka +14
IR excess of short GRB AG

Recent nearby short GRB 160821B at z=0.16 (Levan+16) will add constraints.

But, see also, e.g., dust formation (Takami+14)

Recent nearby short GRB 160821B at z=0.16 (Levan+16) will add constraints.
IR excess of short GRB AG

Kilonovae could be the EM counterpart of GW signals.

But, see also, e.g., dust formation (Takami+14)

@200Mpc

Berger+13

@z=0.356

Tanvir+13
Follow-up observations of GWs
GW alerts are sent to observers having signed MoU via GCN Notice

Shawhan+12 (Swift image credit: NASA E/PO, Sonoma State University, Aurore Simonnet)

See also Nissanke-san’s talk
84 teams in LV-EM follow-up (O2)

AAO GW Candidate Obs.  GRA SAO RAS  PESSTO
AGILE  HAWC  Pi of the Sky project
Apertif-EVN  H.E.S.S.  PIRATE
ARAE  HETGS  RAPTOR
Astrophys. Research Inst., Liverpool  HXMT  RATIR
AROMA  HTRU  RIMAS
ATLAS  Huntsman  RoboPol
AZTEC  INAF-GRAWITA  SAAO
Berger Time-Domain Research Group  IPN  SkyMapper
BlackGEM  ISDC INTEGRAL Science Data Centre  SRO7
CALET  IUCAA  SVOM
Caltech-NRAO Radio Transient Group  J-GEM  Swift Mission
COSI  KU Korea-Uzbekistan Consortium  Terskol-GW follow-up
CRTS  LCOGT  TLC X-ray Imaging
CTA  LGT Lulin  TLS
CZTI-IUCAA  LOFAR-TKSP  TTU LSC group
DLT40  LSQ  TTU Observatory
DES  LV Swift MIT EM Follow-up  TOROS
DWF  MAGIC  TZAC
EWE follow-ups at Nanshan  MASTER  Leicester transient science team
Fast Spectroscopy with LBT  MAXI  UNC-LFP
FAST  MeerKAT  USO
Fermi GBM and LAT  MWA Murchison Widefield Array  VAST
FIGARO  NenuFAR  VERITAS
FLEAS  NTE  Wise-GECO
FRBSG  OGWARTS  XMM-Newton Science Ops Centre team
GOTO  OVRO  XMM ToO
GROND  Pan-STARRS  ZTF
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)

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

IRSF (Nagoya Univ.) @ South Africa

MOA–II, B&C (Nagoya Univ.) @ New Zeeland
# Telescopes/Cameras in J-GEM

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

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

Morokuma + 16
Immediate & automated follow-up obs. w/ small telescopes after GCN Notice

TITLE: GCN CIRCULAR
NUMBER: 20039
SUBJECT: GRB 161014A: Kanata optical observation
DATE: 16/10/14 16:56:59 GMT
FROM: Michitoshi Yoshida at HASC, Hiroshima U <yoshidam@hiroshima-u.ac.jp>
(abbreviated)
# T0+ MID-UT T-EXP R mag. R err R limit

86sec 12:32:48 30 15.1 0.2 17.0

TITLE: GCN CIRCULAR
NUMBER: 20036
SUBJECT: GRB 161014A: MITSuME-Akeno optical observation
DATE: 16/10/14 13:14:41 GMT
FROM: Yoichi Yatsu at Tokyo Tech. <yatsu@hp.phys.titech.ac.jp>
(abbreviated)
T0+[sec] MID-UT T-EXP[sec] Rc Rc_err

46sec 12:32:23 30 ~14.52 0.06
3 wide-field cameras

• Kiso/KWFC (North)
  • 1.05m/4.3deg²

• MOA-II/MOA-Cam (South)
  • 1.8m/2.2deg²

• Subaru/HSC (North)
  • 8.2m/1.77deg²
Survey power in optical/NIR

Field-of-view [deg²] vs. telescope aperture [m]
Subaru/Hyper Suprime Cam

- Hyper Suprime-Cam (HSC)
  - Diameter: 8.2m, FoV: 1.77deg$^2$, ~900M pixels
  - $m_{\text{lim}} (5\sigma)$ w/ 1min: 24.5(i), 23.8(z)
    (DECam 1min: 23.3(i), 22.5(z))
Detection of GWs
First detection: GW150914

**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)
  - 2 days before scheduled O1 run
- False alarm rate (FAR)
  - $< \sim 1$/month (alert)
  - $< 1/100$yrs (Jan 2016)
  - $< 1/203,000$yrs (Feb 2016)

Skymap of GW150914

See also Nissanke-san’s talk
LV-EM follow-ups of GW150914

- 25 of 63 observing teams
- Broad band tiled observation
- Observation of nearby galaxies
- Spectroscopic follow-up observations
- Optical: $\sim 900\text{deg}^2$ (50% of LIB)
- NIR: $\sim 70\text{deg}^2$ (8% of final map)

See also Nissanke-san’s talk
Initial responses of J-GEM

- Sat, 12 Sep 2015
  - LIGO O1 started

- Mon, 14 Sep 2015 18:59:45
  - Detection of GW150914 but no GCN Notice was sent.

- Wed, 16 Sep 2015 14:39:44 (L. Singer)
  - GCN circular was sent via e-mail.

- Wed, 16 Sep 2015 15:07 (M. Yoshida)
  - List of nearby galaxies prepared.
  - Observations are asked to IRSF (South Africa) and MOA (NZ)

  - Observation with KWFC (wide-field) started

- Sun, 20 Sep 2015 (Y. Asakura+)
  - Observation with B&C61cm (nearby galaxies) started
J-GEM follow-ups of GW150914

- Kiso/KWFC (North)
  \[ t_{\text{obs}} = 4.4 \text{ days} \]
  Wide-field (24deg^2, i~19) survey

- B&C/Tripole5 (South)
  \[ t_{\text{obs}} = 6.3-12 \text{ days} \]
  observation of targeted nearby 18 gals.

No new transients were found.

Morokuma, ..., NT + 16
Subaru/HSC was not available

HSC is only available at +21 days after GW150914. The visibility of GW150914 from Mauna Kea was poor.
Second (2.5\textsuperscript{th}) detection: GW151226

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

B. P. Abbott \textit{et al.}*

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 31 May 2016; published 15 June 2016)

14.2\textsuperscript{+8.3}_{-3.7} M_{\odot} and 7.5\textsuperscript{+2.3}_{-2.3} M_{\odot} BHs merged at 440\textsuperscript{+180}_{-190} Mpc
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: ~1300deg² (90%)
Optical WF follow-ups of GW151226

- **DECam** $28.8\,\text{deg}^2$ (Cowperthwaite + 16 ApJL)
  - 3 AGNs and 1 SNIIP ($i\sim21.7$ and $z\sim21.5$)
- **PS1** $290\,\text{deg}^2$ (Smartt+16 MNRAS)
  - 20 SNe from 49 OTs ($i\sim20.5$)
- **iPTF** $952\,\text{deg}^2$ (Cenko+16 GCN)
  - 2 SNe from 20 OTs ($R\sim20$)
- **MASTER** 99% of North (Lipunov+16 GCN)
  - 1 PSN from 7 OTs
- **VST** $72\,\text{deg}^2$ (Grado+16 GCN)
- **Skymapper** $110\,\text{deg}^2$ (Yuan+16 GCN)
  - 1 OT ($i\sim18.6$)
- **J-GEM collaboration** (Yoshida, Utsumi, NT+ PASJ submitted)

No plausible optical counterparts
Initial responses of J-GEM

• Sat, 26 Dec 2015 12:38:53.648 (JST)
  • Detection of GW151226 but no GCN Notice was sent.

• Mon, 28 Dec 2015 02:28:13 (L. Singer)
  • GCN circular was sent via E-mail.

• Mon, 28 Dec 2015 03:14:22 (Y. Utsumi)
  • List of nearby galaxy prepared

• Mon, 28 Dec 2015 06:45:18 (R. Itoh+)
  • 18 galaxies are observed by Kanata/HOWPol

• Mon, 28 Dec 2015 13:30:23 (M. Yoshida)
  • Nearby galaxies to be followed-up are assigned to telescopes.

• From 28 Dec 2015
  • Observations started with Nayuta/MINT, Kanata/HONIR, OAO91cm/OAO-WFC, TITOA050cm/MITSuME, Kiso/KWFC

• From 29 Dec 2015
  • Observations started with MOA-II/MOA-Red, IRSF/SIRIUS, OAO188cm/KOOLS-IFU (spec)
How about Subaru/HSC?

We have no access to HSC.

Original schedule of Subaru

<table>
<thead>
<tr>
<th>Dec 20</th>
<th>Dec 21</th>
<th>Dec 22</th>
<th>Dec 23</th>
<th>Dec 24</th>
<th>Dec 25</th>
<th>Dec 26</th>
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<td>Dec 27</td>
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<td>Dec 31</td>
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<tr>
<td>Gemini(S16A) Rajan IRCS+AO188</td>
<td>S14B-097 Kuzuhara HiCIAO+AO188</td>
<td>S15B-022</td>
<td>S15B-119 Kudo HiCIAO+AO188</td>
<td>S15B-119</td>
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<tr>
<td>Eng MO</td>
<td>S15A-133 Kuzuhara HiCIAO+AO188</td>
<td>HiCIAO+AO188</td>
<td>S15B-085 HiCIAO+AO188</td>
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<th>Jan 02</th>
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<tbody>
<tr>
<td>Obs HiCIAO+AO188</td>
<td>Obs HiCIAO+AO188</td>
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<tr>
<td>S15B-088 Shinnaka HDS</td>
<td>S15B-092 Shinnaka HDS</td>
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<tr>
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<td>UH-31A1 Lulin HSC</td>
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<td>StrObs HSC</td>
<td>Keck Wittman HSC</td>
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<td>S15B-073 Okamoto HSC</td>
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<td>S15A-134I Silverman FMOS</td>
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| S15B-056 Okabe HSC | S15B-056 Okabe HSC | S15B-065 Okabe HSC | S15B-073 Okamoto HSC | StrObs HSC | StrObs HSC | S15A-134I Silverman FMOS |
How about Subaru/HSC?

Updated schedule of Subaru

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<td>S15B-009 Totani HSC</td>
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GW151226
How can we discover transients?

-Image subtraction-
How can we discover transients?

- Image subtraction -
How can we discover transients?  
-Image subtraction-
Candidate selection

• Reference frame: Feb 6, 2016
• Science frames: Jan 7 1\textsuperscript{st}, 2\textsuperscript{nd}, 13, 2016

• Detection criteria:
  • To remove \textit{bogus and cosmic rays}
    • 2 detections with \textit{z} on Jan 7 \textcolor{red}{\leftarrow 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 \textit{minor planets}
    • No detection with \textit{i} on Jan 7 at 0.5-45arcsec
    • No registered minor planets at <0.5arcsec
  • To exclude \textit{brightening sources} \textcolor{red}{\leftarrow short time scale}
    • Positive sources on difference image (Jan 7 - Feb 6)
Candidates from Subaru/HSC

• **1256** candidates remain and visually inspected.
<table>
<thead>
<tr>
<th>GW</th>
<th>GW150914</th>
<th>GW151226</th>
</tr>
</thead>
<tbody>
<tr>
<td>Localization (90%)</td>
<td>~600deg(^2)</td>
<td>~1400deg(^2)</td>
</tr>
<tr>
<td>Area &amp; prob. by LV-EM</td>
<td>~900deg(^2), ~50%</td>
<td>&gt;1000deg(^2), ~90%?</td>
</tr>
<tr>
<td>Wide-field survey by J-GEM</td>
<td>24deg(^2), 0.1%</td>
<td>985deg(^2), 29%</td>
</tr>
<tr>
<td>Nearby galaxies by J-GEM</td>
<td>18 galaxies</td>
<td>239 galaxies</td>
</tr>
<tr>
<td>Number of telescopes</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>Subaru/HSC</td>
<td>Not available</td>
<td>i<del>24.6, z</del>23.8 (60deg(^2))</td>
</tr>
<tr>
<td>Reference</td>
<td>Morokuma+16</td>
<td>Yoshida, Utsumi, NT+ Utsumi, NT+</td>
</tr>
</tbody>
</table>
Improvements in LIGO O2

1. Alerts will be sent via GCN Notice.
   • Immediate and automated follow-up obs. is possible.

2. 3D probability map will be provided.
   • Efficiency of wide-field survey is doubled.
   • Efficiency of galaxy-targeted obs. is tripled.

3. Virgo will join in next Spring!!
   • Localization is largely improved.
   • 600deg$^2$ -> 100deg$^2$
     <-> 60deg$^2$ (GW151226, HSC)

4. 3 Subaru ToO nights are approved until Jan.
   <-> 1 ToO nights (S15B)
Summary

• Binary mergers involving at least a neutron star could accompany kilonovae being visible in electromagnetic wave, especially optical/NIR over ~1 week.

• LV-EM (including J-GEM) follow-up observations were performed for GW150914 and GW151226.

• No candidates of EM counterparts have been found.

• Subaru/HSC is the best instrument for optical wide-field follow-up observation (but not always available).

• Time variability, color evolution, and location are keys to identify kilonovae from other transients.

• Huge improvements are expected in LIGO/Virgo O2.

Hope a merger with (a) NS takes place near future!