Follow-up observation with Subaru/Hyper Suprime-Cam

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Subaru/Hyper Suprime Cam

- Hyper Suprime-Cam (HSC)
  - Diameter: 8.2m, FoV: 1.77deg$^2$, ~900M pixels
Etendue of optical telescopes

**Aperture**
- LA SILLA 1m: 7.4 m²·deg²
- SKYMAPPER 1.3m: 7.9 m²·deg²
- PTF 1.2m: 9.7 m²·deg²
- CFHT 3.6m: 10.2 m²·deg²
- PS1 1.8m: 17.8 m²·deg²
- DECAM 4m: 38 m²·deg²
- HSC 8.2m: 92 m²·deg²
- LSST 6.4m: 319 m²·deg²

**Future Aperture**
- LSST 2023+: 6.4m
Usage of Subaru/HSC

• HSC-SSP
  • Transient survey in COSMOS and SXDS

• Openuse proposals
  • High-cadence transient survey
    • Supernovae in the early phase
  • Target-of-opportunity follow-up observation
    • Gravitational wave sources
    • Fast radio bursts
    • High-energy neutrinos
J-GEM activity in LVC O3 observation

- S190408an (BBH, 387deg\(^2\))
  - GCN 24064
- S190412m (BBH, 156deg\(^2\))
  - GCN 24113, 24350
- S190425z (BNS, 7461deg\(^2\))
  - GCN 24192, 24219, 24230, 24238
- S190426c (BNS[49\%], NSBH[13\%], 1131deg\(^2\))
  - GCN 24299
- S190510g (BNS[98\%] -> Terrestrial[58\%], BNS[42\%], 1166deg\(^2\))
  - GCN 24450, 24464
Latency of Subaru telescope

- S190510g (LVC alert)
  - Preliminary alert: 13:03 May 10, 2019 (JST)
  - Initial alert: 14:24 May 10, 2019 (JST)
  - HSC observation start: 14:46 May 10, 2019 (JST)
  - GCN 24450
    LIGO/Virgo S190510g: HSC Y-band follow-up observation
Survey pointings with Subaru/HSC

HSC-Y, $120\text{deg}^2$, 2 epochs

![Survey pointings with Subaru/HSC](image)
ToO observations of GW151226

- $63.5 \text{deg}^2$, $i=24.5$, $z=23.8$, 3 epochs (Jan 7, 13 and Feb 6, 2015)

**Table 3. Numbers of surviving candidates with different criteria.**

<table>
<thead>
<tr>
<th>Condition</th>
<th>No cut</th>
<th>$\Delta i &gt; 0.0$</th>
<th>$\Delta i &gt; 0.5$</th>
<th>$\Delta i &gt; 1.0$</th>
<th>$\Delta i &gt; 1.5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>1744(1729)</td>
<td>829(814)</td>
<td>236(221)</td>
<td>154(139)</td>
<td>118(109)</td>
</tr>
<tr>
<td>Fadeout only</td>
<td>430(415)</td>
<td>218(203)</td>
<td>92(77)</td>
<td>45(30)</td>
<td>24(15)</td>
</tr>
<tr>
<td>$i-z_{1st} &gt; 0.0$</td>
<td>294(279)</td>
<td>135(120)</td>
<td>55(40)</td>
<td>29(14)</td>
<td>17(8)</td>
</tr>
<tr>
<td>$i-z_{1st} &gt; 0.5$</td>
<td>185(170)</td>
<td>72(57)</td>
<td>29(14)</td>
<td>16(1)</td>
<td>9(0)</td>
</tr>
<tr>
<td>$i-z_{1st} &gt; 1.0$</td>
<td>75(71)</td>
<td>22(18)</td>
<td>8(4)</td>
<td>4(0)</td>
<td>2(0)</td>
</tr>
</tbody>
</table>

*This table corresponds to the result of steps 4a and b. The number of candidates with no stellar-like counterpart in the reference frame is shown in parentheses (step 4c).

<table>
<thead>
<tr>
<th>Condition</th>
<th>No cut</th>
<th>$\Delta i &gt; 0.0$</th>
<th>$\Delta i &gt; 0.5$</th>
<th>$\Delta i &gt; 1.0$</th>
<th>$\Delta i &gt; 1.5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>132(130)</td>
<td>67(63)</td>
<td>16(14)</td>
<td>15(11)</td>
<td>8(7)</td>
</tr>
<tr>
<td>Fadeout only</td>
<td>43(41)</td>
<td>23(21)</td>
<td>8(6)</td>
<td>7(5)</td>
<td>3(2)</td>
</tr>
<tr>
<td>$i-z_{1st} &gt; 0.0$</td>
<td>32(30)</td>
<td>16(14)</td>
<td>6(4)</td>
<td>5(3)</td>
<td>1(0)</td>
</tr>
<tr>
<td>$i-z_{1st} &gt; 0.5$</td>
<td>21(19)</td>
<td>9(7)</td>
<td>2(0)</td>
<td>2(0)</td>
<td>1(0)</td>
</tr>
<tr>
<td>$i-z_{1st} &gt; 1.0$</td>
<td>13(11)</td>
<td>5(3)</td>
<td>2(0)</td>
<td>2(0)</td>
<td>1(0)</td>
</tr>
</tbody>
</table>

*This table is the same as table 3 but is associated with GLADE galaxies and corresponds to the results of step 5.

GW170817-associated AT2017gfo had $\Delta z \sim 2$ $i-z \sim +0.4$

The time variability and color can narrow down the candidates.

Utsumi, NT, Tanaka+18
ToO observations of GW170817

- 23.6$\text{deg}^2$, $z=21.0$, 2 epochs (Aug 18 and 19, 2017)

\begin{itemize}
  \item \textbf{Sources} 1551
    \begin{itemize}
      \item \textbf{Negative} 461
      \item \textbf{Positive} 1090
    \end{itemize}
  \item \textbf{Positive detection on Aug 18 and 19}
    \begin{itemize}
      \item \textbf{Associated object in PS1 catalog}
        \begin{itemize}
          \item \textbf{Non-extended} 706
          \item \textbf{Extended or no close object} 384
        \end{itemize}
      \item \textbf{Transient location in PS1 catalog}
        \begin{itemize}
          \item \textbf{Center of extended object} 322
          \item \textbf{Off-center transient} 62
        \end{itemize}
    \end{itemize}
  \item \textbf{Location in 3D skymap (distance)}
    \begin{itemize}
      \item \textbf{Outside} 98
      \item \textbf{No information} 224
      \item \textbf{No information} 58
      \item \textbf{Inside} 1
      \item \textbf{Outside} 1
    \end{itemize}
  \item \textbf{Visual inspection}
    \begin{itemize}
      \item 58
      \item 1
      \item 1
    \end{itemize}
\end{itemize}

\textasciitilde85 astronomical variable objects in 23.6 $\text{deg}^2$ w/o distance information

\Rightarrow 3.6 \text{ variable objects/deg}^2 \text{ in images with limmag} = 21.0

NT, Tanaka, Morokuma+18a
ToO observations of GW170817

We calculate the possibility $P_{3D}$ that the host galaxy is located in the 3D skymap, where $\phi$ is the luminosity function.

$$P_{3D}(\lambda_j, m_j) = \frac{\int_{D_{\text{mean}} - 3\sigma_D}^{D_{\text{mean}} + 3\sigma_D} \phi(\lambda[\lambda_j, D], M[m_j, D]) A(D) dD}{\int_0^\infty \phi(\lambda[\lambda_j, D], M[m_j, D]) A(D) dD}$$

$P_{3D}$ can be significantly small for distant galaxy if $D_{\text{mean}} + 3\sigma_D$ is small (40$^{+8}_{-14}$ Mpc for GW170817).

For example,

- $P_{3D}$ of AT2017gfo is 64%.
- $P_{3D}$ of the other candidates are 0.0093-0.21%.

The distance information is quite useful.
ToO observations of FRB151230

• 0.2deg\(^2\) (1.77deg\(^2\))
• g=26.5, r=26.3, i=26.5
• 3 epochs (Jan 7, 10, and 13, 2016)

Detection with an alternative image subtraction method
Visual inspection
Template fitting w/ photo-z
Off-center transient

Sources 1196
Inside 118
Outside 1078
0.2deg\(^2\)
1.57deg\(^2\)

Location

13 astronomical variable objects in 0.2deg\(^2\) with time variability in 1 week
=> 65 variable objects/deg\(^2\) in images with limmag = 26.5

NT, Niino, Totani+18b
Redshift information constrains the association with SN Ia

- SN Ia: Q < 4 \times 10^{-8}

The association of SNe Ia with $t_{\text{exp}} = 0$ at $z \leq 0.6$ with FRB 151230 is excluded.

$z < \sim 0.8$ from the DM of FRB 151230

Two possible explanations
- SNe Ia association with FRB 151230 is allowed for $z \sim 0.6–0.8$.
- The DM of the host galaxy of FRB 151230 < 300 pc cm$^{-3}$.

NT, Niino, Totani+18b
Lessons from previous ToO observations

There are so many contamination in deep images taken, e.g., with Subaru/HSC.

• GW151226
  • The time variability (incl. constraint on the date of event) and color can reduce the number of candidates.
  • The distance information is also important.

• GW170817
  • 3.6 variable objects/deg² in images with limmag = 21.0
  • The distance information is critical to narrow down the candidates and pick up AT2017gfo.

• FRB151230
  • 65 variable objects/deg² in images with a variability of limmag = 26.5
  • The multi-color light curves and photo-z of host galaxies help to reduce the number of candidates.
  • Assuming the date of event, the redshift constraints from radio and optical observation restrict the association with SNe Ia.
Additional information is important in deep follow-up observations. What is additional information?

- Distance (redshift)
- Time variability
- Color
- Date of event