Characterizing the EM Counterparts of Advanced LIGO sources

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Advanced LIGO/Virgo Network

Hanford + Livingston (aLIGO), Cascina (Virgo), KAGRA (Japan), IndIGO (India?)
By TMT era, binary neutron star mergers out to ~ 200 Mpc
Expect tens of binary neutron star (BNS) detections per year in TMT era (but large uncertainties)!

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Estimated Run Duration</th>
<th>$E_{GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc)</th>
<th>BNS Range (Mpc)</th>
<th>Number of BNS Detections</th>
<th>% BNS Localized within 5 deg$^2$</th>
<th>% BNS Localized within 20 deg$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>3 months</td>
<td>40 – 60</td>
<td>40 – 80</td>
<td>0.0004 – 3</td>
<td>2</td>
<td>–</td>
</tr>
<tr>
<td>2016–17</td>
<td>6 months</td>
<td>60 – 75</td>
<td>80 – 120</td>
<td>0.006 – 20</td>
<td>5 – 12</td>
<td>–</td>
</tr>
<tr>
<td>2017–18</td>
<td>9 months (per year)</td>
<td>75 – 90</td>
<td>120 – 170</td>
<td>0.04 – 100</td>
<td>10 – 12</td>
<td>–</td>
</tr>
<tr>
<td>2019+</td>
<td></td>
<td>105</td>
<td>200</td>
<td>0.2 – 200</td>
<td>8 – 28</td>
<td>–</td>
</tr>
<tr>
<td>2022+ (India) (per year)</td>
<td></td>
<td>105</td>
<td>80</td>
<td>0.4 – 400</td>
<td>17</td>
<td>48</td>
</tr>
</tbody>
</table>
Why Electromagnetic Counterparts?

- GW detectors provide chirp mass, luminosity distance, (crude) inclination angle
- EM counterpart provides:
  - redshift ($H_0$?)
  - Astrophysical context (host, offset)
  - Composition (r-process nucleosynthesis)
  - Inclination

Rosswog et al., 2012
What will an EM counterpart look like?

On-axis: Short Gamma-ray Burst; Off-axis: Kilonova

Metzger & Berger, 2012
On-Axis Events: Bright but Rare

Bright high-energy emission, but only ~ 1/50 events within ultra-relativistic jet opening angle

Kanner et al., 2012
Kilonovae: r-process sites

~ 0.01 $M_{\text{sun}}$ ejecta of neutron-rich material with $v \sim 0.2c$

Rosswog et al., 2012
Kilonovae: r-process sites

Possibly dominant site of r-process material in Universe!
**Kilonovae: Predicted Light Curves**

- **Time scale:**
  - 2 days in B-band
  - 2 weeks in NIR
- **Peak magnitude (@ 200 Mpc):**
  - B ~ 25 mag
  - R ~ 24 mag
  - H ~ 21 mag

Kasen & Barnes, 2013
Do Kilonovae Exist?

- GRB130603B: Short-hard GRB at $z = 0.36$.
- Late-time (~ 1 week) “bump” in NIR light curve, with no corresponding optical signal.
- Still waiting for confirmation from additional nearby short-hard GRBs.

Tanvir et al., 2013
TMT GW Follow-up: Timeline

Localizations (~ 10 deg²) much too crude for TMT observations

Aasi et al., 2013
TMT GW Follow-up: Timeline

- \( t_0 \): GW trigger
- \( t_0 + 2 \) min: Localization and parameter estimation
- \( t_0 + 5 \) min: Wide-field counterpart searches

Wide-field surveys (ZTF, HSC, LSST) will tile error regions to search for candidate counterparts
Fermi GRBs: A Trial Run with PTF

Routinely identify optical afterglows in ~ 100 deg² Fermi-GBM localizations

Singer et al., 2012
Distinguishing Kilonovae

Modest number of “fast” contaminants. More “slow” transients (supernovae, AGN), but could be distinguished by light curve, color, etc.

Table 1

<table>
<thead>
<tr>
<th>Object</th>
<th>$R_{\text{vol}}$ (Mpc$^{-3}$ yr$^{-1}$)</th>
<th>$z_{\text{max}}$</th>
<th>$R_{\text{area}}$ (deg$^{-2}$ yr$^{-1}$)</th>
<th>$N$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type Ia</td>
<td>10$^{-6}$</td>
<td>0.5</td>
<td>0.7</td>
<td>1.4</td>
<td>Bildsten et al. 2007</td>
</tr>
<tr>
<td>WD-NS mergers</td>
<td>10$^{-5}$</td>
<td>0.06</td>
<td>2 × 10$^{-2}$</td>
<td>3 × 10$^{-2}$</td>
<td>Thompson 2009</td>
</tr>
<tr>
<td>WD-BH mergers</td>
<td>10$^{-5}$</td>
<td>0.06</td>
<td>2 × 10$^{-2}$</td>
<td>3 × 10$^{-2}$</td>
<td>Fryer et al. 1999</td>
</tr>
<tr>
<td>AIC</td>
<td>10$^{-6}$</td>
<td>0.06</td>
<td>2 × 10$^{-3}$</td>
<td>3 × 10$^{-3}$</td>
<td>Darbha et al. 2010</td>
</tr>
<tr>
<td>ELDD</td>
<td>3 × 10$^{-7}$</td>
<td>0.14</td>
<td>6 × 10$^{-3}$</td>
<td>1 × 10$^{-2}$</td>
<td>...</td>
</tr>
<tr>
<td>Pan-STARRS fast</td>
<td>5 × 10$^{-6}$</td>
<td>0.5</td>
<td>3.5</td>
<td>7</td>
<td>Drout et al. 2014</td>
</tr>
</tbody>
</table>

NOTE. — Expected rates for the various contaminants considered in Section 2. $R_{\text{area}}$ is computed assuming an isotropic distribution of sources in a volume defined by the comoving volume at $z_{\text{max}}$. The column $N$ refers to the number of events expected during a search covering 100 deg$^2$ for 7 days. See § 2.10 for details.

Cowperthwaite & Berger, 2015
TMT GW Follow-up: Timeline

$t_0$: GW trigger
$t_0 + 2$ min: Localization and parameter estimation
$t_0 + 5$ min: Wide-field counterpart searches
$t_0 + 1$ hr: TMT spectroscopy of $\sim 10$ candidates

Synthetic spectra show contributions from both Ni and r-process nucleosynthesis. As a result, they are clearly distinguishable from other (known) transients.

Kasen & Barnes, 2013
TMT SNR Estimates

- $t_0$: GW trigger
- $t_0 + 2$ min: Localization and parameter estimation
- $t_0 + 5$ min: Wide-field counterpart searches
- $t_0 + 1$ hr: TMT spectroscopy of $\sim 10$ candidates

- Time to reach SNR $\sim 10$ per resolution element:
  - MOBIE: 10 min
  - IRMS/IRIS: 5 min
TMT Requirements for GW Follow-Up

- Response Time: 1 hr to days (standard queue mode)
- Instrument availability: Continuous
- Bandpass: Optical + NIR
- Resolution: Low to moderate ($v \sim 0.3c$)