Astrophysical Rates of Gravitational-Wave Compact Binary Sources in O3

Chris Pankow (CIERA/Northwestern) for the LIGO and Virgo Collaborations

DCC: LIGO-G1800370
Strain sensitivity for LIGO and Virgo
Values are projected and representative, but not official
Actual strain sensitivity may be different in O3

BNS ranges quoted for a 1.4+1.4 M☉ face-on system at SNR 8 in a single instrument, averaged over binary orientations and sky location for O3...

Expected LIGO BNS range: 120 Mpc
Expected Virgo BNS range: 65 Mpc

GW170817 is at 1/3 (LIGO) of the sky/orientation averaged range for O3
Calculating event rates and significance

Model comparison of noise background and signal distributions of ranking statistic

\[ V = \int f(z, M_c, \cdots) \frac{1}{1 + \frac{dV}{dz} dz} \]

\[ \rightarrow R \sim N/<VT> \]

Moving pieces

VT is dependent on instrument duty cycle and SNR threshold
alerts could have smaller SNRs than “gold plated” events
all binary physics is not encoded in searches: assumed SNR loss is small
Basic Pop. Modeling: Assume $p(m_1) \propto m_1^{-\alpha}$ and fit observations to model.

After GW170104 ($N_{BBH}=3.9$)

- Uniform in log mass: $12 - 65 \text{ Gpc}^{-3} \text{yr}^{-1}$
- Power law ($\alpha=-2.35$) only: $40 - 213 \text{ Gpc}^{-3} \text{yr}^{-1}$
- Unified interval: $12 - 213 \text{ Gpc}^{-3} \text{yr}^{-1}$
Towards Pop. Distributions:
Constraints on the primary mass distribution from current observations (assumes power law from previous slide)

After GW170104 ($N_{BBH}=3.9$)
- Uniform in log mass: $12 - 65 \text{ Gpc}^{-3} \text{yr}^{-1}$
- Power law ($\alpha=-2.35$) only: $40 - 213 \text{ Gpc}^{-3} \text{yr}^{-1}$
- Unified interval: $12 - 213 \text{ Gpc}^{-3} \text{yr}^{-1}$
if the detector noise is Gaussian and stationary and if there are two detector is sensitive to CBCs above a fiducial signal-to-noise ratio (coherent search) (see, e.g., [24]). A full treatment of these e

---

### Table IV: Compact binary coalescence rates per Mpc$^3$ per Myr.$^a$

<table>
<thead>
<tr>
<th>Source</th>
<th>$R_{low}$</th>
<th>$R_{re}$</th>
<th>$R_{high}$</th>
<th>$R_{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS-NS (Mpc$^{-3}$ Myr$^{-1}$)</td>
<td>0.01 [1]</td>
<td>1 [1]</td>
<td>10 [1]</td>
<td>50 [16]</td>
</tr>
<tr>
<td>NS-BH (Mpc$^{-3}$ Myr$^{-1}$)</td>
<td>$6 \times 10^{-4}$ [18]</td>
<td>0.03 [18]</td>
<td>1 [18]</td>
<td></td>
</tr>
<tr>
<td>BH-BH (Mpc$^{-3}$ Myr$^{-1}$)</td>
<td>$1 \times 10^{-4}$ [14]</td>
<td>0.005 [14]</td>
<td>0.3 [14]</td>
<td></td>
</tr>
</tbody>
</table>

---

*Class. Quantum Grav. 27 (2010) 173001*
BNS/NSBH rate distributions at end of O1

TABLE IV: Compact binary coalescence rates per Mpc$^3$ per Myr.$^a$

<table>
<thead>
<tr>
<th>Source</th>
<th>$R_{\text{low}}$</th>
<th>$R_{\text{re}}$</th>
<th>$R_{\text{high}}$</th>
<th>$R_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS-NS (Mpc$^{-3}$ Myr$^{-1}$)</td>
<td>0.01 [1]</td>
<td>1 [1]</td>
<td>10 [1]</td>
<td>50 [16]</td>
</tr>
<tr>
<td>NS-BH (Mpc$^{-3}$ Myr$^{-1}$)</td>
<td>$6 \times 10^{-4}$ [18]</td>
<td>0.03 [18]</td>
<td>1 [18]</td>
<td></td>
</tr>
<tr>
<td>BH-BH (Mpc$^{-3}$ Myr$^{-1}$)</td>
<td>$1 \times 10^{-4}$ [14]</td>
<td>0.005 [14]</td>
<td>0.3 [14]</td>
<td></td>
</tr>
</tbody>
</table>

Class. Quantum Grav. 27 (2010) 173001
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Planned run duration</td>
<td>4 months</td>
<td>9 months</td>
<td>12 months</td>
<td>(per year)</td>
<td>(per year)</td>
</tr>
<tr>
<td>LIGO</td>
<td>40 – 60</td>
<td>60 – 75</td>
<td>75 – 90</td>
<td>105</td>
<td>105</td>
</tr>
<tr>
<td>Virgo</td>
<td>—</td>
<td>20 – 40</td>
<td>40 – 50</td>
<td>40 – 70</td>
<td>80</td>
</tr>
<tr>
<td>KAGRA</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>100</td>
</tr>
<tr>
<td>Expected burst range/Mpc</td>
<td>40 – 80</td>
<td>80 – 120</td>
<td>120 – 170</td>
<td>190</td>
<td>190</td>
</tr>
<tr>
<td>LIGO</td>
<td>—</td>
<td>20 – 65</td>
<td>65 – 85</td>
<td>65 – 115</td>
<td>125</td>
</tr>
<tr>
<td>Virgo</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>140</td>
</tr>
<tr>
<td>KAGRA</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Achieved BNS range/Mpc</td>
<td>60 – 80</td>
<td>60 – 100</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>LIGO</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Virgo</td>
<td>—</td>
<td>25 – 30</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>KAGRA</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Estimated BNS detections</td>
<td>0.05 – 1</td>
<td>0.2 – 4.5</td>
<td>1 – 50</td>
<td>4 – 80</td>
<td>11 – 180</td>
</tr>
<tr>
<td>Actual BNS detections</td>
<td>0</td>
<td>1</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>90% CR % within 5 deg²</td>
<td>&lt; 1</td>
<td>1 – 5</td>
<td>1 – 4</td>
<td>3 – 7</td>
<td>23 – 30</td>
</tr>
<tr>
<td>20 deg²</td>
<td>&lt; 1</td>
<td>7 – 14</td>
<td>12 – 21</td>
<td>14 – 22</td>
<td>65 – 73</td>
</tr>
<tr>
<td>median/deg²</td>
<td>460 – 530</td>
<td>230 – 320</td>
<td>120 – 180</td>
<td>110 – 180</td>
<td>9 – 12</td>
</tr>
<tr>
<td>Searched area % within 5 deg²</td>
<td>4 – 6</td>
<td>15 – 21</td>
<td>20 – 26</td>
<td>23 – 29</td>
<td>62 – 67</td>
</tr>
<tr>
<td>20 deg²</td>
<td>14 – 17</td>
<td>33 – 41</td>
<td>42 – 50</td>
<td>44 – 52</td>
<td>87 – 90</td>
</tr>
</tbody>
</table>
### Estimated BNS detections

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Planned run duration</td>
<td>4 months</td>
<td>9 months</td>
<td>12 months</td>
<td>(per year)</td>
<td>(per year)</td>
</tr>
<tr>
<td>LIGO</td>
<td>40 – 60</td>
<td>60 – 75</td>
<td>75 – 90</td>
<td>105</td>
<td>105</td>
</tr>
<tr>
<td>Virgo</td>
<td>—</td>
<td>20 – 40</td>
<td>40 – 50</td>
<td>40 – 70</td>
<td>80</td>
</tr>
<tr>
<td>KAGRA</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>100</td>
</tr>
<tr>
<td>Expected burst range/Mpc</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>LIGO</td>
<td>40 – 80</td>
<td>80 – 120</td>
<td>120 – 170</td>
<td>190</td>
<td>190</td>
</tr>
<tr>
<td>Virgo</td>
<td>—</td>
<td>20 – 65</td>
<td>65 – 85</td>
<td>65 – 115</td>
<td>125</td>
</tr>
<tr>
<td>KAGRA</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>140</td>
</tr>
<tr>
<td>Expected BNS range/Mpc</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>LIGO</td>
<td>60 – 80</td>
<td>60 – 100</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Virgo</td>
<td>—</td>
<td>25 – 30</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>KAGRA</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Achieved BNS range/Mpc</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>Estimated BNS detections</td>
<td>0.05 – 1</td>
<td>0.2 – 4.5</td>
<td>1 – 50</td>
<td>4 – 80</td>
<td>11 – 180</td>
</tr>
</tbody>
</table>

### Actual BNS detections

- **LIGO**: 0 detections
- **Virgo**: 1 detection
- **KAGRA**: —

### 90% CR

- **5 deg²**:
  - LIGO: < 1
  - Virgo: 1 – 5
  - KAGRA: 1 – 4
- **20 deg²**:
  - LIGO: < 1
  - Virgo: 7 – 14
  - KAGRA: 12 – 21
- **Median/deg²**:
  - LIGO: 460 – 530
  - Virgo: 230 – 320
  - KAGRA: 120 – 180

### Searched area

- **5 deg²**:
  - LIGO: 4 – 6
  - Virgo: 15 – 21
  - KAGRA: 20 – 26
- **20 deg²**:
  - LIGO: 14 – 17
  - Virgo: 33 – 41
  - KAGRA: 42 – 50

---

**post-GW170817**:

\[ R_{\text{BNS}} \sim 3.2 \times 10^{-7} – 4 \times 10^{-6} \text{ Mpc}^{-3}\text{yr}^{-1} \]
This rate distribution…

\[ R_{BBH} \sim 1.2 \times 10^{-8} - 2.1 \times 10^{-6} \text{ Mpc}^{-3}\text{yr}^{-1} \]
Assumptions:
\( \rho_{\text{net}} > 12 \)
\( T_{\text{obs}}: \) 1 yr with 50% duty cycle

log-uniform: \( p(m_1) \sim m^{-1} \) (5 < \( m_1 \) < 100 \( M\odot \))

…with O3 surveyed space-time volume:
\( V_{T_{\text{BBH}}} \sim 7 \times 10^8 \text{ Mpc}^{-3} \text{yr}^{-1} \)

This rate distribution…
\( R_{\text{BBH}} \sim 1.2 \times 10^{-8} - 2.1 \times 10^{-6} \text{ Mpc}^{-3} \text{yr}^{-1} \)
This rate distribution…
$R_{\text{BBH}} \sim 1.2 \times 10^{-8} - 2.1 \times 10^{-6} \text{ Mpc}^{-3} \text{yr}^{-1}$

…gives this distribution of detected events.
**median** $p(N) \sim 34$

Assumptions:
$\rho_{\text{net}} > 12$
$T_{\text{obs}}$: 1 yr with 50% duty cycle

log-uniform: $p(m_1) \sim m^{-1} (5 < m_1 < 100 \text{ M}^{\odot})$

…with O3 surveyed space-time volume:
$V_{T_{\text{BBH}}} \sim 7 \times 10^8 \text{ Mpc}^{-3} \text{yr}^{-1}$

Binary Black Hole Rates (post-GW170104)
This rate distribution…
\[ R_{BBH} \sim 1.2 \times 10^{-8} - 2.1 \times 10^{-6} \text{ Mpc}^{-3}\text{yr}^{-1} \]

…gives this distribution of detected events.
\[ \text{median } p(N) \sim 34 \]

Caveats

Uncertain cut off at higher masses from pair-instability SN, future analyses to measure this

Only beginning to pin down crude mass distributions, handles on spin magnitude distribution and putative alignment in nascence

Assumptions:
\[ \rho_{\text{net}} > 12 \]
\[ T_{\text{obs}}: 1 \text{ yr with 50% duty cycle} \]

log-uniform: \( p(m_1) \sim m^{-1} (5 < m_1 < 100 \text{ M}_\odot) \)

This rate distribution…
\[ R_{BBH} \sim 1.2 \times 10^{-8} - 2.1 \times 10^{-6} \text{ Mpc}^{-3}\text{yr}^{-1} \]
Binary Neutron Star Rates (post-GW170817)

This rate distribution...

\[ R_{\text{BNS}} \sim 3.2 \times 10^{-7} - 4 \times 10^{-6} \text{ Mpc}^{-3} \text{yr}^{-1} \]
Binary Neutron Star Rates (post-GW170817)

This rate distribution…
\[ R_{\text{BNS}} \sim 3.2 \times 10^{-7} - 4 \times 10^{-6} \text{ Mpc}^{-3}\text{yr}^{-1} \]

Assumptions:
- \( \rho_{\text{net}} > 12 \)
- \( T_{\text{obs}}: 1 \text{ yr with 50\% duty cycle} \)

Broad (uniform): 1-3 M\( \odot \)

‘Milky Way-like’: 1.33 ± 0.09 M\( \odot \)

…with O3 surveyed space-time volume:
\[ V_{\text{BNS}} \sim 2-4 \times 10^7 \text{ Mpc}^{-3}\text{yr}^{-1} \]
This rate distribution...

\[ R_{\text{BNS}} \sim 3.2 \times 10^{-7} - 4 \times 10^{-6} \text{ Mpc}^{-3} \text{yr}^{-1} \]

...gives this distribution of detected events.

**median** \( p(N) / \text{MW} \sim 4 \\
**median** \( p(N) / \text{broad} \sim 9 \\

**Assumptions:**
- \( \rho_{\text{net}} > 12 \)
- \( T_{\text{obs}}: 1 \text{ yr with 50\% duty cycle} \)

**Broad (uniform): 1-3 M\odot**

‘Milky Way-like’: \( 1.33 \pm 0.09 \text{ M}\odot \)

...with O3 surveyed space-time volume:

\[ V_{\text{BNS}} \sim 2 - 4 \times 10^7 \text{ Mpc}^{-3} \text{yr}^{-1} \]
Binary Neutron Star Rates (post-GW170817)

This rate distribution…
\[ R_{BNS} \sim 3.2 \times 10^{-7} - 4 \times 10^{-6} \text{ Mpc}^{-3} \text{yr}^{-1} \]

Caveats

No inclusion of finite-size or equation of state induced systematics

Mass ranges and distribution still uncertain, 1-3 uniform is probably optimistic and gaussian may be conservative

...gives this distribution of detected events.

\textbf{median} \( p(N) / \text{MW} \ N \sim 4 \)

\textbf{median} \( p(N) / \text{broad} \ N \sim 9 \)
NSBH Rates (much uncertainty)
p(R) limits taken from Abbott+, 2010, assumes log-normal peaked away from zero

This rate distribution…
\[ R_{\text{NSBH}} \sim 6 \times 10^{-10} - 1 \times 10^{-6} \text{ Mpc}^{-3}\text{yr}^{-1} \]
This rate distribution...

$R_{\text{NSBH}} \sim 6 \times 10^{-10} - 1 \times 10^{-6} \text{ Mpc}^{-3}\text{yr}^{-1}$

NSBH Rates (much uncertainty)

$p(R)$ limits taken from Abbott+, 2010, assumes log-normal peaked away from zero

Assumptions:

$\rho_{\text{net}} > 12$

$T_{\text{obs}}$: 1 yr with 50% duty cycle

log-uniform: $p(m_1) \sim m^{-1}$ ($5 < m_1 < 100 \, M_\odot$)

With O3 surveyed space-time volume

$V_{T_{\text{NSBH}}} \sim 0.8-2 \times 10^8 \text{ Mpc}^{-3}\text{yr}^{-1}$
NSBH Rates (much uncertainty)

\[ p(R) \text{ limits taken from Abbott+}, 2010, \text{ assumes log-normal peaked away from zero} \]

Assumptions:
\[ \rho_{\text{net}} > 12 \]
\[ T_{\text{obs}}: 1 \text{ yr with 50% duty cycle} \]

log-uniform: \( p(m_1) \sim m^{-1} \) (5 < \( m_1 \) < 100 M\( \odot \))

With O3 surveyed space-time volume
\[ V_{\text{NSBH}} \sim 0.8-2 \times 10^8 \text{ Mpc}^{-3}\text{yr}^{-1} \]

This rate distribution...
\[ R_{\text{NSBH}} \sim 6 \times 10^{-10} - 1 \times 10^{-6} \text{ Mpc}^{-3}\text{yr}^{-1} \]

...gives this distribution of detected events. **median** \( p(N) \sim 1 \)
NSBH Rates (much uncertainty)

p(R) limits taken from Abbott+, 2010, assumes log-normal peaked away from zero

This rate distribution...
R_{NSBH} \sim 6 \times 10^{-10} \text{ to } 1 \times 10^{-6} \text{ Mpc}^{-3}\text{yr}^{-1}

...gives this distribution of detected events. **median** p(N) \sim 1

Assumptions:
ρ_{net} > 12
T_{obs}: 1 yr with 50% duty cycle

Caveats

Widest potential variation in mass ratio, no reliable models for high mass ratio events

Physics encoded in waveforms (e.g. precession) which is not completely captured by online searches

Uncertain mass and spin distributions
Uncertainty of about width (or even existence) of ccSN induced mass gap and/or upper limit on NS mass
**Take Aways**

**BBH** rate will **dominate**, possibly by more than an order of magnitude, up to $\sim$few/wk., at least $\sim$few/mo.

**1-10 BNS**, possibly up to $\sim$1/mo.

VT has **strong mass dependence** but **very mild dependence** on assumed spin distribution

**NSBH: N=0 not ruled out** in any scenario, most give $\sim$50% N>0

---

**Source Summary**

<table>
<thead>
<tr>
<th>source category</th>
<th>full year VT</th>
<th>$N_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BBH / bbh_astrophysical_aligned</td>
<td>$6.8 \times 10^8$ Mpc$^3$ yr</td>
<td>$34_{-25}^{+79}$</td>
</tr>
<tr>
<td>BNS / bns_astrophysical</td>
<td>$3.2 \times 10^6$ Mpc$^3$ yr</td>
<td>$4_{-4}^{+9}$</td>
</tr>
<tr>
<td>BNS / bns_broad</td>
<td>$7.3 \times 10^6$ Mpc$^3$ yr</td>
<td>$9_{-7}^{+19}$</td>
</tr>
<tr>
<td>NSBH / nsbh_broad_aligned</td>
<td>$5.0 \times 10^7$ Mpc$^3$ yr</td>
<td>$1_{-1}^{+24}$</td>
</tr>
<tr>
<td>NSBH / nsbh_broad_isotropic</td>
<td>$5.7 \times 10^7$ Mpc$^3$ yr</td>
<td>$1_{-1}^{+28}$</td>
</tr>
</tbody>
</table>