Remnants of First Stars for Gravitational wave sources

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Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott et al.*
(LIGO Scientific Collaboration and Virgo Collaboration)
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On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of $1.0 \times 10^{-21}$. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203,000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of $410^{+160}_{-180}$ Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

- $36 M_\odot + 29 M_\odot$
Masses of GW events

• GW events show that there are many massive BHs (≥30 Msun).

• On the other hand, the typical mass of BHs in X-ray binaries is ~10 Msun.

<table>
<thead>
<tr>
<th>Event</th>
<th>$m_1/M_\odot$</th>
<th>$m_2/M_\odot$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GW150914</td>
<td>35.6$^{+4.8}_{-3.0}$</td>
<td>30.6$^{+3.0}_{-4.4}$</td>
</tr>
<tr>
<td>GW151012</td>
<td>23.3$^{+14.0}_{-5.5}$</td>
<td>13.6$^{+4.1}_{-4.8}$</td>
</tr>
<tr>
<td>GW151226</td>
<td>13.7$^{+8.8}_{-3.2}$</td>
<td>7.7$^{+2.2}_{-2.6}$</td>
</tr>
<tr>
<td>GW170104</td>
<td>31.0$^{+7.2}_{-5.6}$</td>
<td>20.1$^{+4.9}_{-4.5}$</td>
</tr>
<tr>
<td>GW170608</td>
<td>10.9$^{+5.3}_{-1.7}$</td>
<td>7.6$^{+1.3}_{-2.1}$</td>
</tr>
<tr>
<td>GW170729</td>
<td>50.6$^{+16.6}_{-10.2}$</td>
<td>34.3$^{+9.1}_{-10.1}$</td>
</tr>
<tr>
<td>GW170809</td>
<td>35.2$^{+8.3}_{-6.0}$</td>
<td>23.8$^{+5.2}_{-5.1}$</td>
</tr>
<tr>
<td>GW170814</td>
<td>30.7$^{+5.7}_{-3.0}$</td>
<td>25.3$^{+2.9}_{-4.1}$</td>
</tr>
<tr>
<td>GW170817</td>
<td>1.46$^{+0.12}_{-0.10}$</td>
<td>1.27$^{+0.09}_{-0.09}$</td>
</tr>
<tr>
<td>GW170818</td>
<td>35.5$^{+7.5}_{-4.7}$</td>
<td>26.8$^{+4.3}_{-5.2}$</td>
</tr>
<tr>
<td>GW170823</td>
<td>39.6$^{+10.0}_{-6.6}$</td>
<td>29.4$^{+6.3}_{-7.1}$</td>
</tr>
</tbody>
</table>

The LIGO scientific collaboration 2018
Origin of massive BBHs

Many theories exist such as

- 1) Pop II BBH
- 2) Pop III BBH  
  - Low metal field binaries
- 3) Primordial Binary BH (PBBH)
- 4) N body origin from Globular Cluster

........................
Why field binaries?

• There are many massive close binaries

Example

Milky way young open clusters

71 O stars fbinary=69+/−9% (P<3200days)
Sana et al. 2012

30 Doradus (Tarantula Nebula)

362 O stars fbinary=51+/−4%(P<3200days)
Sana et al. 2013
Why low metal?

• If the progenitor of BH is Pop I (=Solar metal stars)
• Typical mass is small (IMF $\propto M^{-2.35}$, $0.1\text{Msun}<M<100\text{Msun}$)
• Stars lose a lot of mass due to the strong stellar wind

• The orbit become wide due to stellar wind mass loss
Why low metal?

- If the progenitor is low metal,
- Pop II (Metal<0.1SolarMetal)
  Typical mass is same as Pop I
  But, week wind mass loss
- Pop III (No metal)
  Pop III stars are **the first stars** after the Big Bang.
  Typical mass is more massive than Pop I, II
  $M_{\text{popIII}} \sim 10-100\text{M}_{\odot}$
  No wind mass loss due to no metal.

Minitial: $8\text{M}_{\odot} < M < 150\text{M}_{\odot}$

Single stellar evolution with 2 stellar wind models.
(Belczynski et al. 2010, Abbot et al. 2016)
Pop III binary population synthesis

We simulate $10^6$ Pop III-binary evolutions and estimate how many binaries become compact binary which merges within Hubble time. × 84 models (Kinugawa et al. 2014, 2016)

Initial stellar parameters are decided by Monte Carlo method with initial distribution functions

- Initial parameter $(M_1, M_2, a, e)$ distribution in our standard model
  - $M_1$ : Flat ($10 M_\odot < M < 100 M_\odot$)
  - $q = M_2 / M_1$ : $P(q) = \text{const.} (10 M_{\odot}/M_1 < q < 1)$
  - $a$ : $P(a) \propto 1/a$ ($a_{\text{min}} < a < 10^6 R_\odot$)
  - $e$ : $P(e) \propto e$ ($0 < e < 1$)

The same distribution functions adopted for Pop I population synthesis
Typical total mass
$M \sim 60 M_\odot$

$(30 M_\odot + 30 M_\odot)$

**TK et al. 2014, 2016**

IMF: Flat

$10 M_\odot < M < 140 M_\odot$

Total mass distribution of BBH which merge within the Hubble time
What do determine the BH-BH mass?

• Steller wind mass loss
• Binary interactions
  (Mass transfer, Common envelope)

Mass transfer

Common envelope

Red Giants tend to become CE

Close binary or merge
Z = Z_\odot (=Pop I)

Z = 1/20Z_\odot (=Pop II)

All star evolve via a red giant
Almost all binaries evolve via a similar evolution pass

Figure 1. Selected OVS evolution tracks for Z = 0.02, for masses 0.64, 1.0, 1.6, 2.5, 4.0, 6.35, 10, 16, 25 and 40 M_\odot.

Figure 2. Same as Fig. 1 for Z = 0.001. The 1.0 M_\odot post He flash track has been omitted for clarity.
Why Pop III binaries become 30M_{\odot} BH-BH

- M>50M_{\odot} red giant
  - Mass transfer is unstable
  - common envelope
  - 1/3~1/2 of initial mass (~25-30M_{\odot})

- M<50M_{\odot} blue giant
  - Mass transfer is stable
  - mass loss is not so effective
  - 2/3~1 of initial mass (25-30M_{\odot})
Total mass distribution of BBH which merge within the Hubble time

This shape reflects the influence of Pop III stellar evolution.
These shapes have the influence of IMF and the influence of stellar wind mass loss.
Pop III BBH remnants for gravitational wave

- Pop III stars were born and died at $z \geq 20$.
- The typical merger time of compact binaries is $\sim 10^{8-10}$ yr.
- We might see Pop III BBH at the present day.

Massive BBHs = the fossil of Pop III?
Pop III BBH?

ASTROPHYSICAL IMPLICATIONS OF THE BINARY BLACK-HOLE MERGER GW150914


(2014; Dominik et al. 2013).

On the extreme low-metallicity end, it has been proposed that BBH formation is also possible in the case of stellar binaries at zero metallicity (Population III [PopIII] stars; see Belczynski et al. 2004; Kinugawa et al. 2014). The predictions from these studies are even more uncertain, since we have no observational constraints on the properties of first-generation stellar binaries (e.g., mass function, mass ratios, orbital separations). However, if one assumes that the properties of PopIII massive binaries are not very different from binary populations in the local universe (admittedly a considerable extrapolation), then recently predicted BBH total masses agree astonishingly well with GW150914 and can have sufficiently long merger times to occur in the nearby universe (Kinugawa et al. 2014). This is in contrast to the predicted mass properties
Results

The numbers of the compact binaries which merge within Hubble time for $10^6$ binaries (Kinugawa et al. 2014,2016)

Our standard model

| BHBH | 115056 |

• A lot of Pop III BH-BH binaries form and merge within Hubble time
In order to calculate merger rate, we need to know

- When were Pop III stars born?
- How many were Pop III stars born?

⇒ Star formation rate

We adopt the Pop III SFR by de Souza et al. 2011

\[ SFR_{peak} \sim 10^{-2.5} \ \text{[}\text{M}_\odot \ \text{yr}^{-1} \ \text{Mpc}^{-3}\text{]} \]
The Pop III BH-BH merger rate density

Pop III BHBH merger rate at the present day
In our standard model
\[ R \sim 25 \left( \frac{SFR_{\text{peak}}}{10^{-2.5}} \right) \left( \frac{f_b}{(1+f_b)} \right) \text{Err}_{\text{sys}} \text{ [yr}^{-1} \text{ Gpc}^{-3}] \]  
(Kinugawa et al. 2014, 2016)

BBH merger rate estimated by LIGO
\[ R=9.7-10^1 \text{ [yr}^{-1} \text{ Gpc}^{-3}] \]  
(1811.12907)
Detection range of KAGRA and Adv. LIGO

- SNR=8
- Luminosity distance \( \sim 1.5 \text{ Gpc} \)
- Redshift \( z \sim 0.28 \)
- BH mass \( M_{\text{BH}} \sim 30M_\odot \)
Detection rate of Pop III BH-BH

• Detection rate of Pop III BBH (GW150914 like BBH) in our standard model (aLIGO design sensitivity)

\[ R \sim 180 \left( \frac{SFR_{\text{peak}}}{10^{-2.5}} \right) \left( \frac{f_b/(1+f_b)}{0.33} \right) \text{Err}_{\text{sys}} \text{ [yr}^{-1}] (S/N>8) \]

(Kinugawa et al. 2014, 2016)

• Typical mass

\[ M \sim 30 \, M_\odot \]
Other Pop III SFRs

• simulation
e.g. Johnson et al. 2013
SFR$_p$ ~ $10^{-3}$-$10^{-4}$ Msun/yr/Mpc$^3$

• Constraints by Planck $\tau_e$
e.g. Visbal et al.2015, Hartwig et al.2016, Inayoshi et al.2016
→The merger rate decrease to 1/3-1/10?
## Errsys (Example)

<table>
<thead>
<tr>
<th>Standard</th>
<th>Errsys</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass range: ((10 , M_\odot &lt; M &lt; 100 , M_\odot \text{ or } 140 , M_\odot))</td>
<td>1 ((180 , /\text{yr}))</td>
</tr>
<tr>
<td>IMF: Flat, (M^{-1}), Salpeter</td>
<td>1~3.4</td>
</tr>
<tr>
<td>IEF: (f(e) \propto e, \text{const.}, e^{-0.5})</td>
<td>0.42~1</td>
</tr>
<tr>
<td>BH natal kick: (\sigma_V = 0, 100, 300 , \text{km/s})</td>
<td>0.2~1</td>
</tr>
<tr>
<td>CE: (\alpha \lambda = 0.01, 0.1, 1, 10)</td>
<td>0.21~1</td>
</tr>
<tr>
<td>Mass transfer (mass loss fraction): (\beta = 0, 0.5, 1)</td>
<td>0.67~1.3</td>
</tr>
</tbody>
</table>

- The typical mass is **not changed** (~30 Msun).
Mass distributions of observable BBHs (KAGRA)

- The mass distribution might distinguish Pop III from Pop I, Pop II
  → The evidence of Pop III

If it cannot distinguish
  → redshift dependence

\[ M = (1 + z) \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}} \quad \text{if } 30+30 \text{ BBH} \quad \rightarrow M \sim 26 \]

(Miyamoto et al. 2017)

Pop I/II BBH (Dominik et al. 2012)
Pop III BBH (Kinugawa et al. 2016)
Cumulative BBH merger rate

Saturated at $z \geq 10$
Pop III BBH ($\sim 30$ Msun)

Saturated at $z \leq 5$
Pop I and II BBH ($\approx 5$ Msun)
(Belczynski et al. 2016)
(2 metallicity evolution models)
Future plan of GW observer: ET, CE, B-DECIGO and DECIGO

- Einstein telescope (ET): the next generation GW observatory of Europe
- Cosmic explorer (CE): the next generation GW observatory of US.
- DECIGO: Japanese space gravitational wave observatory project
- B-DECIGO: test version of DECIGO

ET, CE, B-DECIGO: $z \sim 10$ (30 Msun BH-BH)\n
$\sim 10^5$ events/yr

DECIGO can see Pop III BH-BHs\nwhen Pop III stars were born ($z \sim 20$)!\n(Nakamura, Ando, Kinugawa et al. 2016)
Summary

• Pop III binaries tend to become 30M_{sun}+30M_{sun} BH-BH

• Pop III BBH detection rate of aLIGO in our standard model

\[ R \sim 180 \left( \frac{SFR_{peak}}{10^{-2.5}} \right) \left( \frac{f_b/(1+f_b)}{0.33} \right) \text{Errsys [yr}^{-1}] (S/N>8) \]

• The mass distribution or the redshift dependence might distinguish Pop III from Pop I,II.

• DECIGO can see Pop III BH-BH merger when they were born