The Formation of Massive Black-Hole Binaries: Understanding the Advanced LIGO detections

Philipp Podsiadlowski, Lise du Boisson (Oxford)
Pablo Marchant, Norbert Langer, Thomas Tauris, Takashi Moriya (Bonn)
Ilya Mandel (Birmingham), Selma de Mink (Amsterdam)
Chiaki Kobayashi, Philip Taylor (Hertfordshire)

• the direct discovery of gravitational waves has started the era of gravitational-wave astronomy
• major surprise: the merger of two massive stellar black holes (BHs)

I. Gravitational Waves and the aLIGO Discoveries
II. Channels for Forming BH+BH Binaries
III. Cosmological Simulations in the MOB Scenario
IV. Implications for ULXs, PISNe, BH+NS Mergers, etc.
General Relativity and Gravitational Waves

Newton’s Gravity

Time is absolute: space and time are given apriori

Einstein’s General Relativity

Spacetime is a dynamic and elastic entity, influencing and influenced by mass-energy

\[ R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}, \]

\[ g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, \quad \rightarrow \quad \Box h_{\mu\nu} = -\frac{16\pi G}{c^4} T_{\mu\nu}. \]

- masses deform spacetime geometry → generate gravitational waves, propagating with the speed of light (Einstein 2016)

- GWs are very weak and need massive, compact bodies
Space Curvature

Double Neutron-Star Binaries as Gravitational-Wave Sources
Compact Binary Inspiral and Final Merger

Example Inspiral Gravitational Wave

Gravitational Wave Signal vs Time (sec)
Compact Binary Mergers (NS/BH+NS/BH)

- compact binaries are brought together by gravitational radiation in a Hubble time if their orbital period is $\lesssim 10\,\text{hr}$

Important as

- progenitors of short-duration gamma-ray bursts
  - different signatures for different mergers (NS+NS, NS+BH, BH+BH)
  - because of time delay can be far from star-forming regions (outside galaxy?)

- sources of r-process elements (rather than supernovae)
  - n-rich environment $\rightarrow$ can build up neutron-rich nuclei by successive n-rich captures onto iron-group seed elements (e.g. Au)

- candidates for the direction detection of gravitational waves with up-coming gravitational wave detectors (Advanced Ligo)
LIGO-India approved
Livingston/Hanford
First detection of gravitational waves passing through Earth

Abbott et al. (LIGO Scientific & Virgo Collaborations) 16

On Sep 14, 2015 at 09:50:45 UTC GW was detected!

\[ \Delta L = L h \sim 10^{-16} \text{ cm} \]

\[ L = 4 \text{ km} \Rightarrow h \sim 10^{-21} \]

(Credit: A. Buonanno 2016)
aLIGO Detection of Gravitational Waves

- **surprise:** merger of two massive ($\sim 30 \, M_\odot$) black holes (chirp-mass: $28 \, M_\odot$)
- $[M_1/M_2 \sim 0.8 \pm 0.2, \, D \sim 400 \, \text{Mpc}, \, \text{SNR} \gtrsim 20, \sim 5$-sigma detection]
Inspiral  Merger  Ringdown

Strain ($10^{-21}$)

-1.0  -0.5  0.0  0.5  1.0

Numerical relativity
Reconstructed (template)

Velocity (c)

-1.0  0.0  0.5  0.6

Black hole separation
Black hole relative velocity

Separation ($R_s$)

0  1  2  3  4

Time (s)

0.30  0.35  0.40  0.45

(Abbott et al. (LVC) 16)
Unveiling GW150914’s properties: sky location & distance

\[ (Abbott \textit{et al.} (LVC) 16) \]

- Face-off slightly favored with respect to face-on.

(Credit: A. Buonanno 2016)
Unveiling GW150914’s properties: masses & spins

(Abbott et al. (LVC) 16)

- Final black-hole mass and spin inferred from components posteriors and NR formulae.
- 3 solar masses emitted in GWs!

(Credit: A. Buonanno 2016)
Results: First Science Run

<table>
<thead>
<tr>
<th>Event</th>
<th>GW150914</th>
<th>GW151226</th>
<th>LVT151012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal-to-noise ratio $\rho$</td>
<td>23.7</td>
<td>13.0</td>
<td>9.7</td>
</tr>
<tr>
<td>False alarm rate FAR/yr^{-1}</td>
<td>$&lt; 6.0 \times 10^{-7}$</td>
<td>$&lt; 6.0 \times 10^{-7}$</td>
<td>0.37</td>
</tr>
<tr>
<td>p-value</td>
<td>7.5 \times 10^{-8}</td>
<td>7.5 \times 10^{-8}</td>
<td>0.045</td>
</tr>
<tr>
<td>Significance</td>
<td>$&gt; 5.3\sigma$</td>
<td>$&gt; 5.3\sigma$</td>
<td>1.7$\sigma$</td>
</tr>
<tr>
<td>Primary mass $m_1^{\text{source}}/\text{M}_\odot$</td>
<td>36.2$^{+5.2}_{-3.8}$</td>
<td>14.2$^{+8.3}_{-3.7}$</td>
<td>23$^{+18}_{-6}$</td>
</tr>
<tr>
<td>Secondary mass $m_2^{\text{source}}/\text{M}_\odot$</td>
<td>29.1$^{+4.4}_{-3.8}$</td>
<td>7.5$^{+2.3}_{-2.3}$</td>
<td>13$^{+4}_{-5}$</td>
</tr>
<tr>
<td>Chirp mass $M_\text{chirp}^{\text{source}}/\text{M}_\odot$</td>
<td>28.1$^{+1.8}_{-1.5}$</td>
<td>8.9$^{+0.3}_{-0.3}$</td>
<td>15.1$^{+1.4}_{-1.1}$</td>
</tr>
<tr>
<td>Total mass $M^{\text{source}}/\text{M}_\odot$</td>
<td>65.3$^{+6.4}_{-4.1}$</td>
<td>21.8$^{+5.9}_{-1.7}$</td>
<td>37$^{+13}_{-14}$</td>
</tr>
<tr>
<td>Effective inspiral spin $J_{\text{eff}}$</td>
<td>$-0.06^{+0.14}_{-0.14}$</td>
<td>$0.21^{+0.20}_{-0.10}$</td>
<td>0.0$^{+0.2}_{-0.1}$</td>
</tr>
<tr>
<td>Final mass $M_f/\text{M}_\odot$</td>
<td>62.3$^{+3.7}_{-3.1}$</td>
<td>20.8$^{+6.1}_{-1.7}$</td>
<td>35$^{+14}_{-1}$</td>
</tr>
<tr>
<td>Final spin $a_f$</td>
<td>0.68$^{+0.05}_{-0.04}$</td>
<td>0.74$^{+0.06}_{-0.06}$</td>
<td>0.66$^{+0.09}_{-0.10}$</td>
</tr>
<tr>
<td>Radiated energy $E_{\text{rad}}/(\text{M}_\odot c^2)$</td>
<td>3.0$^{+0.5}_{-0.4}$</td>
<td>1.0$^{+0.1}_{-0.2}$</td>
<td>1.5$^{+0.3}_{-0.4}$</td>
</tr>
<tr>
<td>Peak luminosity $\epsilon_{\text{peak}}/(\text{erg}\text{ s}^{-1})$</td>
<td>3.6$^{+0.5}_{-0.4} \times 10^{56}$</td>
<td>3.3$^{+0.8}_{-1.6} \times 10^{56}$</td>
<td>3.1$^{+0.8}_{-1.8} \times 10^{56}$</td>
</tr>
<tr>
<td>Luminosity distance $D_L/$Mpc</td>
<td>420$^{+150}_{-180}$</td>
<td>440$^{+190}_{-190}$</td>
<td>1000$^{+500}_{-500}$</td>
</tr>
<tr>
<td>Source redshift $z$</td>
<td>0.09$^{+0.03}_{-0.04}$</td>
<td>0.09$^{+0.03}_{-0.04}$</td>
<td>0.20$^{+0.09}_{-0.09}$</td>
</tr>
<tr>
<td>Sky localization $\Delta\Omega$/deg$^2$</td>
<td>230</td>
<td>850</td>
<td>1600</td>
</tr>
</tbody>
</table>
BH+BH Parameters

- $m^\text{source}_1 (M_\odot)$ vs. $m^\text{source}_2 (M_\odot)$
- $M^\text{source}_f (M_\odot)$ vs. $\alpha_f$
- $\chi_{\text{eff}}$ vs. $q$
- Posterior PDF (10$^{-3}$ Mpc$^{-1}$) vs. Distance (Mpc)
The Formation of Merging BH+BH Binaries

Note: high black-hole mass expected for low metallicity (stellar winds depend on metallicity)

I. Dynamical formation in dense clusters
   • in dense clusters: dynamical interactions $\rightarrow$ close BH+BH binaries

II. Non-dynamical formation
   • common-envelope scenarios: conversion of wide binary to close binary
   • homogeneous evolution scenarios: close binary from the beginning
Dynamical Formation in Stellar Clusters
(e.g. Banerjee, Baumgardt, Kroupa (2010), Rasio, Rodriguez, etc.)

- in dense clusters, BHs segregate quickly and can form sub-clusters of BHs (Spitzer instability)
- three-body encounters $\rightarrow$ BH+BH binaries
- most are ejected, but some harden sufficiently to ultimately merge
- aLIGO detection rates (e.g. Banerjee 2016): $10 - 300 \text{ yr}^{-1}$
Dynamical ways of BBH merger

Merger of eccentric binary

Triple

Kozai oscillation

Merger of eccentric inner binary

(Credit: Banerjee 2016)
The Formation of BH+BH Binaries through Common-Envelope Evolution

- the progenitors of black holes are big stars
- need to get them into a close orbit to merge
- possible solution: common-envelope evolution
- standard scenario to produce compact NS+NS binaries (Hulse-Taylor pulsar, PSR J0737-3039)
- problem with black holes:
  - difficult to form two black holes (requires late mass transfer)
  - but possible with some fine-tuning
  - rates highly uncertain (Belczynski et al. [2016] vs. Kruckow, et al. [2016])
Belczynski (2016)
The Massive Overcontact Binary (MOB) Model
(Marchant et al. 2016; also de Mink & Mandel 2016a,b)

- initial homogeneous evolution is enforced by tidal locking in a very close massive binary (de Mink et al. 2009)
- needs to avoid binary widening by stellar wind mass loss → requires low metallicity
- most systems pass through contact phase on main sequence
→ evolution drives systems towards mass ratio of 1

Model Description

- uses latest MESA code (Paxton et al. 2015)
- with binary evolution fully implemented (Marchant)
- mass loss:
  - Vink (2001) $\times 1/3$ (H-rich), Hamann (1995) (no H)
  - $\dot{M} \propto Z^{0.85}$
Marchant et al. (2016)
Yoon (2005/6)

Maeder (1987)
Marchant et al. (2016) depends on metallicity-dependent stellar winds.
Final BH spins and LGRBs

Marchant et al. (2016)
Cosmological Simulations of BH+BH Mergers in the MOB Scenario
Lise du Boisson, Podsiadlowski

- use full cosmological simulations to simulate rates of GW sources as a function of $z$ and $Z$ (plus LGRBs, PISNe)
- simulations by Taylor & Kobayashi (2014)
  - self-consistent hydrodynamical simulations with star formation, SN and AGN feedback, and chemical enrichment
  - fit key observables, such as the galaxy mass-metallicity relations, metallicity gradients, etc.

1: plus Kobayashi, Taylor, Marchant, Langer, Tauris, Mandel, de Mink

Based on Taylor & Kobayashi (2014)
• form massive BH+BH systems ($\gtrsim 25 M_\odot$)

• at very low metallicity ($Z_\odot/50$): bimodal mass distribution with systems below and above pair-instability supernova (PISN) gap (no BH formation)

• very massive BH+BH mergers can be detected with aLIGO throughout the Universe (prediction: $140 \text{yr}^{-1}$ below and $14 \text{yr}^{-1}$ above PISN gap)

$\rightarrow$ probe massive stellar evolution throughout the Universe

• known observational counterparts (e.g. double He-star binary (SMC) with $M_1 = 66 M_1, M_2 = 61 M_2, P_{\text{orb}} = 19.3 \text{d}$)
Ultraluminous X-ray sources (ULXs) from chemically homogeneous evolution (Marchant+ 2017)

- ULXs have luminosities $> 10^{39}$ erg/s
- probably stellar BH binaries (not intermediate-mass BHs) with super-Eddington radiation (plus beaming?)
- optical counterpart problem: massive optical counterparts require more massive black holes ($\sim 50 \, M_\odot$) (Madhusudhan et al. 2008)
- for mass ratios $q \simeq 0.1 - 0.4$
  - massive black holes with massive companion
  - rate: up to $\sim 2$ (per SFR $[M_\odot/\text{yr}]$)
  - metallicity dependent
  - lead to the formation of NS+BH binaries

Marchant, Langer, Podsiadlowski+ (2017)
Advanced LIGO roadmap until 2019

Detection rates @ design sensitivity:
- **NS-NS**: 0.2 - 200 per year
- **BH-BHs**: tens to hundreds per year!

(Credit: A. Buonanno 2016)
Sesana 2016

![Graph showing characteristic amplitude vs frequency with frequency [Hz] on the x-axis and characteristic amplitude on the y-axis. The graph includes various lines and markers for different systems such as eLISA and aLIGO. The y-axis ranges from $10^{-22}$ to $10^{-18}$ and the x-axis ranges from 0.001 to 1000 Hz.](image)
Conclusions and Future Outlook

- present aLIGO rate: 1 every 2 weeks (?) ; future rate: 1 every day or 2 (?)
- all three channels may be at work (interesting rates)
- distinguish between different models based on
  - BH+BH chirp mass distribution
  - mass ratios
  - spins and their alignments
  - ratio of NS+NS to BH+BH mergers
  - host galaxies
- MOB Prediction: aLIGO should discover mergers of intermediate-mass black holes \( (M_{\text{tot}} \sim 200 - 300 M_\odot) \)
  - already detectable in the ring-down phase

→ The Era of GW Astronomy has Really Arrived
1. Gravitational waves from supermassive black-hole mergers in distant galaxies subtly shift the position of Earth.

2. Telescopes on Earth measure tiny differences in the arrival times of the radio bursts caused by the jostling.

3. Measuring the effect on an array of pulsars enhances the chance of detecting the gravitational waves.

NEW MILLISECOND PULSARS
An all-sky map as seen by the Fermi Gamma-ray Space Telescope in its first year.
- massive red-supergiant ($88 \, M_\odot$, $3530 \, R_\odot$)
- issue for BPS: location of core boundary → very different binding energy

**Kruckow et al. (2016)**
- for massive companions form wide non-merging binaries ($> 50 \, R_\odot$)
- further spiral-in due to envelope expansion? (not modelled in $\alpha$ formalism)
- can form systems like GW150914 with fine-tuning, but rate estimates very uncertain
Spinning precessing waveform models

(Pan et al. 14, Babak et al. (in prep))

- **Single effective-spin precessing** waveform model in **frequency domain** (IMR phenomenological, 13-independent parameters) (Hannam et al. 14)

- **Double-spin precessing** waveform model in **time domain** (EOBNR, 15-independent parameters) (Pan et al. 14, Babak et al. (in prep)).
  [Analysis is ongoing.]

(Credit: A. Buonanno 2016)