Open questions on the formation of binaries containing black holes

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The “No-Hair” theorem

Every astrophysical black hole is fully characterized by two quantities:

\[ M = \text{mass}, \]

\[ a = \text{spin}. \]

Black holes are as simple as elementary particles (in a sense).
Black Hole X-ray Binaries
Dynamically confirmed black holes

- **Cyg X-1**: the first BH candidate  
  Bolton (1972), Webster & Mardin (1972)

- **21 BHs with dynamical mass measurement**  
  McClintock & Remillard 2006, Casares & Jonker 2014

- **18 Galactic, 3 in nearby galaxies**

- **33 more BH candidates**
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LMXBs: $M_{\text{BH, current}} \sim 7.8\pm1.2 \, M_{\odot}$

HMXBs: $M_{\text{BH}} \sim 10-16 \, M_{\odot}$

*Farr et al. (2011)*
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**Özel et al. (2011)**

LMXBs: \( M_{\text{BH, current}} \approx 7.8 \pm 1.2 \ M_\odot \)

**Fragos & McClintock (2015)**

HMXBs: \( M_{\text{BH, natal}} \approx 6.3 \pm 1.1 \ M_\odot \)
Measuring the spin of Black Holes

Continuum-fitting and Reflection methods

McClintock et al. (2011, 2014)
The origin of black-hole spin

The spin of 9 stellar BHs measured with the continuum fitting method

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The spin of 9 stellar BHs measured with the **continuum fitting method**

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The real puzzle!
- Not enough mass accretion
  (cf. Moreno-Mendez 2011)
- Not enough AM in the progenitor
  (based on back of the envelope estimate)
- No spin up during core-collapse
  (Moreno-Mendez & Cantiello 2016; Fuller et al. 2015)
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The observed BH spin in LMXBs is an effect of mass accretion during the XRB phase.

Fragos & McClintock 2015; Podsiadlowski et al. 2003

The spin of 9 stellar BHs measured with the continuum fitting method

McClintock et al. (2011, 2013)
Coalescing Binary Black Holes
Binary BH mergers detected with LIGO

\[ M_{\text{chirp}} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} \]

\[ \chi_{\text{eff}} = \frac{M_1 \vec{a}_1 + M_2 \vec{a}_2}{M_1 + M_2} \hat{L} \]

\[ \mathbf{GW170104} \]

\[ \mathbf{GW150914} \]

\[ \mathbf{GW151226} \]

\[ \mathbf{LVT151012} \]

\[ \mathbf{GW151226} \]

\[ \mathbf{GW150914} \]

\[ \mathbf{GW170104} \]

\[ \mathbf{LVT151012} \]

\[ \mathbf{prior} \]

LIGO+VIRGO collaboration (2016a,d, 2017a,b)
Binary BH mergers detected with LIGO

The detection confirms that:

1) “heavy” black holes exist
2) binary black holes form in nature
3) binary black holes merge within a Hubble time (at a detectable rate)

LIGO+VIRGO collaboration (2016a,d, 2017a,b)
Predicted Masses for Single Black Holes

Belczynski et al. (2010)

Minimum metallicity: $Z < 0.003$

Indirect formations channels for “heavy” black holes have been suggested, but are unlikely: e.g. BH+star mergers (Mapelli & Zampieri 2014; Ziosi 2014) or star+star mergers (Portegies Zwart et al. 1999; c.f. Glebbeek et al. 2009)

Spera et al. (2015)
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- or star+star mergers (Portegies Zwart et al. 1999; c.f. Glebbeek et al. 2009)
Formation Channels of Binary BHs

- “Classical” Field Binary Evolution
- “Chemically Homogeneous” Field Binary Evolution
- Dynamical Black Hole Binary Formation
Sources of uncertainty:

(i) initial binary properties (masses, mass ratios, and orbital periods)
(ii) stellar evolution models including metallicity-dependent wind mass loss
(iii) mass and associated angular momentum transfer and loss from the systems
(iv) treatment of tidal evolution
(v) common-envelope evolution
(vi) BH natal kicks
Kicks in Neutron Stars

Hobbs et al. (2005)

Figure 1. The Galactic motions of the pulsars in our sample. A pulsar is currently at the position the last 1 Myr assuming no radial velocity.

What about black holes????
Supernova kick mechanisms

1) Asymmetries in the supernova ejecta
(large possible kicks ~100km/s, explosion required)

2) or Asymmetries in the neutrino emission
(small possible kicks ~10km/s, no explosion required)

Figure 1. Schematic visualization of SN mass ejection and compact remnant kicks. In the left-hand image the ejecta are spherically symmetric and no recoil is imparted to the central object. Asymmetric mass ejection must lead to compact remnant motion with the opposite linear momentum (middle panel). The momentum can be transferred by gravitational forces and by direct hydrodynamical forces in the case of accretion. The latter are crucial when the protoneutron star is accreting fallback matter to collapse to a BH (right-hand panel). (Image taken from Scheck et al. (2006); reproduced with permission ©ESO.)
Why do we care?

1) Significantly affect binary populations synthesis studies. E.g., prediction for BH mergers rates varies by two orders of magnitude! (Dominique at al., 2012)

2) Constraints core collapse physics.

Subkhold et al. (2015)
“Classical” Field Binary Evolution

Sources of uncertainty:

(i) initial binary properties (masses, mass ratios, and orbital periods)
(ii) stellar evolution models including metallicity-dependent wind mass loss
(iii) mass and associated angular momentum transfer and loss from the systems
(iv) treatment of tidal evolution
(v) common-envelope evolution
(vi) BH natal kicks

Belczynski et al. (2016a,b)
What is the Common Envelope?

Velocity differences between stellar components and CE cause drag forces.

Orbital angular momentum and energy is transferred to the CE.

Orbital shrinkage and CE ejection.
“Classical” Field Binary Evolution

Belczynski et al. (2016a,b)

Sources of uncertainty:

(i) initial binary properties (masses, mass ratios, and orbital periods)
(ii) stellar evolution models including metallicity-dependent wind mass loss
(iii) mass and associated angular momentum transfer and loss from the systems
(iv) treatment of tidal evolution
(v) common-envelope evolution
(vi) BH natal kicks
If rotationally induced chemical mixing during the main sequence occurs faster than the built-up of chemical gradients due to nuclear fusion the star evolves chemically homogeneous (Maeder, 1987)

\[
\frac{\tau_{ES}}{\tau_{MS}} < 1
\]

(Vega, a Fast rotating star - J.Aufdenberg)
“Chemically Homogeneous” Evolution

Sources of uncertainty:

(i) initial binary properties (masses, mass ratios, and orbital periods)
(ii) stellar evolution models including metallicity-dependent winds
(iii) mass and associated angular momentum transfer and loss from the systems
(iv) treatment of tidal evolution
(v) internal mixing processes
(vi) BH natal kicks

Marchant et al. (2016)

de Mink et al 2009; Song et al. (2015); Mandel & de Mink (2016)
Dynamical formation of binary BHs
Dynamical formation of binary BHs
consider a mass, $M$, moving through a uniform sea of stars. Stars in the wake are displaced inward.

This results in an enhanced region of density behind the mass, with a drag force, $F_d$, known as dynamical friction.
Dynamical formation of binary BHs
Dynamical formation of binary BHs

Sources of uncertainty:

(i) Initial GC properties
(ii) initial binary properties (masses, mass ratios, and orbital periods)
(iii) stellar evolution models including metallicity-dependent wind mass loss
(iv) BH natal kicks
(v) Computational cost - small number statistics
## Comparison of different channels

<table>
<thead>
<tr>
<th></th>
<th>Classical field binaries</th>
<th>Chemically homogeneous evolution</th>
<th>Dynamical Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Merger rate</strong></td>
<td>~200 Gpc$^{-3}$yr$^{-1}$</td>
<td>~10 Gpc$^{-3}$yr$^{-1}$</td>
<td>~2-20 Gpc$^{-3}$yr$^{-1}$</td>
</tr>
<tr>
<td><strong>01 detection rate</strong></td>
<td>2-470 yr$^{-1}$</td>
<td>~400 yr$^{-1}$</td>
<td>20-700 yr$^{-1}$</td>
</tr>
<tr>
<td><strong>Total BH mass</strong></td>
<td>20-80</td>
<td>57-103</td>
<td>32-64</td>
</tr>
<tr>
<td><strong>Mass ratio</strong></td>
<td>broad range</td>
<td>~1</td>
<td>close to ~1</td>
</tr>
<tr>
<td><strong>PISN BH mass gap</strong></td>
<td>yes</td>
<td>yes</td>
<td>maybe no…</td>
</tr>
<tr>
<td><strong>BH Spins</strong></td>
<td>Alligned</td>
<td>Alligned, high</td>
<td>Misalligned</td>
</tr>
<tr>
<td><strong>Observable Progenitors</strong></td>
<td>Ultraslumonous X-ray sources</td>
<td>Maybe… WR+BH HMXBs</td>
<td>NO</td>
</tr>
</tbody>
</table>

Empirically inferred merger rate: 2-400 Gpc$^{-3}$yr$^{-1}$
Currently observed properties: Donor’s position on the H-R (T_{eff} vs. L) diagram, BH and donor masses, orbital period, position in the galaxy and 3-D systemic velocity

**Step 1:** Model the mass-transfer phase (MESA; Paxton et al. 2011, 2013, 2015)

**Step 2:** Model the detached post-SN secular evolution

**Step 3:** Find the peculiar velocity post BH formation

**Step 4:** Compute the orbital dynamics involved in core collapse

Derive limits on immediate progenitor mass and natal kicks magnitude

**Step 5:** Compute priors based on population synthesis models and derive PDFs (BSE; Hurley et al. 2002)
### Results so far...

<table>
<thead>
<tr>
<th>System</th>
<th>Observed Current BH mass (M$_\odot$)</th>
<th>Post-SN BH mass (M$_\odot$)</th>
<th>Immediate Progenitor mass (M$_\odot$)</th>
<th>Natal Kick (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRO J1655-40</td>
<td>6.3 ± 0.5 (Greene et al. 2001)</td>
<td>5.5 – 6.3 (Willems et al. 2005)</td>
<td>5.5 – 11.0 (Willems et al. 2005)</td>
<td>30 – 160 (Willems et al. 2005)</td>
</tr>
<tr>
<td>LMC X-3</td>
<td>6.98 ± 0.56 (Orosz et al. 2014)</td>
<td>6.4 – 8.2 (Sorensen, TF et al. 2017)</td>
<td>11.1 – 18.0 (Sorensen, TF et al. 2017)</td>
<td>≤ 600 (Sorensen, TF et al. 2017)</td>
</tr>
<tr>
<td>GRS 1915+105</td>
<td>12.4 ± 2.0 (Reid et al. 2014)</td>
<td>6.5-13.5 (Kimball et al. 2017, in prep.)</td>
<td>13.0 – 18.0 (Kimball et al. 2017, in prep)</td>
<td>≤ 150 (Kimball et al. 2017, in prep)</td>
</tr>
<tr>
<td>V404 Cyg</td>
<td>9.0 ± 0.6 (Khargharia et al. 2010)</td>
<td>7.5-9.5 (Kimball, TF et al. 2017, in prep.)</td>
<td>COMING SOON</td>
<td>COMING SOON</td>
</tr>
<tr>
<td>Cygnus X-1</td>
<td>14.81 ± 0.98 (Orosz et al. 2011)</td>
<td>13.8 – 15.8 (Wong et al. 2012)</td>
<td>15.0 – 20.0 (Wong et al. 2012)</td>
<td>≤ 77 (Wong et al. 2012)</td>
</tr>
<tr>
<td>IC10 X-1</td>
<td>23.0 – 34.0 (Orosz et al. 2011)</td>
<td>23.0 – 34.0 (Wong et al. 2014)</td>
<td>&gt;31.0 (Wong et al. 2014)</td>
<td>≤ 130 (Wong et al. 2014)</td>
</tr>
</tbody>
</table>

Willems et al. (2005); Fragos et al (2009); Valsecchi et al. (2010); Wong et al. (2012); Wong et al. (2014); Sørensen, TF et al. (2017); Kimball, Sørensen, TF et al. (2017, in prep.)
The common envelope phase

The energy budget prescription

\[ \alpha_{CE} \left( \frac{GM_{\text{don,fin}} M_{\text{acc}}}{2A_{\text{fin}}} - \frac{GM_{\text{don,int}} M_{\text{acc}}}{2A_{\text{int}}} \right) = \frac{GM_{\text{don,int}} M_{\text{don,env}}}{\lambda R_{\text{don,lob}}} \]

The "muscle" approach

Ohlman et al. 2015; Ivanova et al. 2013
The common envelope phase

The 1D approach:

- Rich physics: Energy, radiation and angular momentum transport
- Computational efficient
- Applicable to progenitor of coalescing double compact objects

Fragos & Andrews 2017 (in prep)
Summary

- LIGO detections provide the first direct evidence for the existence of “heavy” BH and binary BHs.

- All three main formation channels predict merger rates and properties (marginally) consistent with LIGO detections so far. A population of 100s of binary BHs will be able to do this.

- BH spin and binary mass ratios will likely be the differentiating factors.

- Large BH kicks “kill” all three channels.

- Coalescing binary neutron star are believed to be formed via the “classical” channel. Advances in our understanding of the common envelope phase are badly needed!
The common envelope phase

common envelope outcomes: tightened binary or merger

Evolution to contact

Drag on surrounding gas tightens the orbit

envelope is ejected and orbit stabilizes

envelope is retained and binary merges

Diagram courtesy of Morgan MacLeod