Formation of Black Hole — Black Hole Binaries in the Field

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– BH-BH binaries: modeling (field)
– BH-BH mergers: formation (field)
– BH-BH detection: astrophysical implications of LIGO detections
First astro-implication of LIGO detections: outbreak of models

- **Primordial BH-BH**: density fluctuations after Big Bang
- **PopIII BH-BH**: first massive stars (≈ 1% of stars in Universe)
- **PopII/I BH-BH**: dynamics/globular clusters (≈ 0.1%)
- **PopII/I BH-BH**: rapid rotation (homogeneous evol.) (≈ 10%)
- **exotic BH-BH**: single star core splitting (≈ 0%)
- **POPII/I BH-BH**: classic field binary evolution (≈ 90%)

before LIGO detections: NS-NS dominant source – a conceptual mistake
BH-BH binaries: modeling
BH-BH mergers: formation
BH-BH detection: astrophysical implications

modeling: synthetic universe

Afterglow Light Pattern
380,000 yrs.

Inflation

Dark Ages

Development of Galaxies, Planets, etc.

Quantum Fluctuations

1st Stars about 400 million yrs.

Big Bang Expansion
13.7 billion years

Chris Belczynski
The Astrophysics of BH-BH Mergers (Cambridge 2016)
Star formation history:

\[ \text{Star Formation Rate [M}_\odot\text{Mpc}^{-3} \text{ yr}^{-1}] \]

- POP I/II: Strolger et al. 2004
- POP I/II: Madau & Dickinson 2014
- POP III

**POP I/II:** uncertain for \( z > 2 \), **POP III:** much smaller contribution

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Metallicity evolution:

Metallicity model: Madau & Dickinson 2014 with SNe and GRB calibration
Evolutionary assumptions and uncertainties:

- **global properties**: cosmology, SFR\((z)\), \(Z(z)\)
- **initial conditions**: IMF, \(q\), \(a_{\text{orbit}}\), \(e\), \(f_{\text{binary}}\) (Sana et al. 2012)
- **single star evolution**: modified Hurley et al. 2000
- **winds**: Vink et al. 2001 + LBV
- **binary CE evolution**: Pavlovskii et al. 2016 or more optimistic
- **BH formation**: SN or Direct BH (Fryer et al. 2012)
- **BH formation**: BH natal kicks (agnostic: low — to — high)

major factor setting BH-BH rates/properties: metallicity ->
The stellar origin BH can reach: $\sim 100 \, M_\odot$

(Zamperi & Roberts 2009; Mapelli et al. 2009)

- **past updates:**
  - **stellar models:** $\sim 130 \, M_\odot$  
    (Spera et al. 2015)
  - **IMF extension:** $\sim 300 \, M_\odot$  
    (Belczynski et al. 2014)

- **present update (2016):**
  - **BH mass down:** $\lesssim XX \, M_\odot$
Pair instability: maximum BH mass $\sim 50M_\odot$

PSN: Pair-instability SN
($M_{\text{He}} \sim 65-130 M_\odot$)
no remnant: entire star disruption

PPSN: Pair-instability Pulsation SN
($M_{\text{He}} \sim 45-65 M_\odot$)
black hole: and severe mass loss

NS/BH mass spectrum:
neutron stars: $1 - 2 M_\odot$
first mass gap: $2 - 5 M_\odot$
black holes: $5 - 50 M_\odot$
second mass gap: $50 - 130 M_\odot$
black holes: $130 - ??? M_\odot$


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Common envelope: orbital decay at low Z


high-Z: RLOF at HG -> radiative envelope -> stable MT & no orbit decay

low-Z: RLOF at CHeB -> convective envelope -> CE & orbit decay

BH-BH progenitors go through CE at low Z: rates up by 70 times! (Z⊙ -> 0.1 Z⊙)
Formation of massive BH-BH merger

- low metallicity: $Z < 10\% Z_\odot$
- CE: during CHeB
- delay: 10 Gyr or 2 Gyr
- O1 horizon: $z = 0.7$
  (inspiral-merger-ringdown)
- total merger mass: $20–80 M_\odot$
- aligned BH spins: tilt = 0 deg
- BH spin: $a = 0.0 \rightarrow a = 0.126$
  $a = 0.5 \rightarrow a = 0.572$
  $a = 0.9 \rightarrow a = 0.920$

credit: Wojciech Gladysz (Warsaw)
BH-BH progenitors: birth times

typical BH-BH progenitors: very old (10 Gyr) or young (2 Gyr) systems
LIGO BH-BH merger rate: 9–240 Gpc$^{-3}$ yr$^{-1}$

GW150914: 36 + 29 M$_\odot$, LVT151012: 23 + 13 M$_\odot$, GW151226: 14 + 8 M$_\odot$
BH-BH mergers: LIGO 60 days of O2 (120 Mpc)

# of BH-BH detections: 66 (M1), 64 (M10), 2 (M3) in 60 days of LIGO O2

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The Astrophysics of BH-BH Mergers (Cambridge 2016)
Astro implications: from BH-BH merger detection

- **massive BH-BH merger**: dominant GW source (field evolution) 
  \(1000 \times\) over NS-NS, \(200 \times\) over BH-NS

- **BH-BH merger**: comparable masses, aligned (?) birth spins

- **BH-BH progenitor**: either very old or young and low-Z environ

- **easy common envelope**: (case B) excluded

- **high BH kicks**: most likely excluded (more detections?)

- **field merger rates**: 40 times higher than for dynamical BH-BH

At the moment: origin not distinguishable:

BH-BH mergers: field + homogeneous + dynamical + popIII – sci-fi channels
Birth time distribution for BH-BH progenitors

- BH-BH binaries: modeling
- BH-BH mergers: formation
- BH-BH detection: astrophysical implications

**Redshift**

- 0
- 0.5
- 3.0
- 10

**Number**

- $F_\nu(<10\%Z_\odot)$
- $F_\nu \times sfr$ (star formation with $Z<10\%Z_\odot$)

**Cosmic time [Gyr]**

- 1
- 10

**Delay time**

- $\propto t^{-1}$

**Birth time**

- Final birth times: high-z peak, low-z peak

*The Astrophysics of BH-BH Mergers (Cambridge 2016)*
BH natal kicks: extras 1/4

EM observations:
no good information

if BH kicks decrease with $M_{\text{BH}}$:
- asymmetric mass ejection
- asymmetric neutrino emission
both mechanisms: OK!

Belczynski et al. 2015 (arXiv:1510.04615)
The interesting case of IC10 X-1 and NGC300X-1

- WR stars – mass $\sim$30 solar masses
- Compact objects – $\sim$ 20-30 solar masses (but see later)
- Orbital period $\sim$ 1.25 days
- Future evolution: mass transfer, mass loss, formation of 2\textsuperscript{nd} BH
- Formation of BH-BH with the coalescence time $\sim$ a few Gyrs
- Low metallicity host galaxies

Bulik, Belczynski, Prestwich 2011
Rate density estimate

- Estimate of the observability volume and object density
- Estimate of the time to coalescence
- Just two objects – low statistic leads to high uncertainty
- Rate density very high
- Expected to be close to detection even with Initial LIGO/VIRGO
- Expected component mass range:
  \(~20-40\) solar mass
- Expected total mass:
  \(~60\) solar masses

Bulik, Belczynski, Prestwich 2011
Observations (Tomek Bulik): 3/3

Potential problem with mass estimate

- Recent measurement of the X-ray eclipse over the optical lightcurve (Laycock et al. 2015)
- Offset of 0.25 in phase
- The radial velocity has a contribution from ionized wind velocity
- Imply a possibility that the companion is a low mass BH or a NS
- Model of Kerkwijk et al. (1996)

Potential problems:

- Evolution: it is very difficult to form a massive WR star in a binary with a low mass compact object
- Mass transfer: if wind, then the X-ray luminosity ($10^{38}$ erg/s) is unusually high (too large by 2-3 orders of magnitude)
- Mass transfer: if RLOF, then the system should not be stable.

It is still quite likely that the companions in IC10 X-1 and NGC300 X-1 are ~20 solar mass BHs
BH-BH binaries: modeling
BH-BH mergers: formation
BH-BH detection: astrophysical implications

Dominik et al. 2013, 2015 -> Belczynski et al. 2015 (arXiv:1510.04615)

most likely detection: BH-BH merger with total redshifted mass 25–73 $M_{\odot}$
Initial mass function update: 2/5

NEW IMF: $M_{\text{sim}} = 2.8 \times 10^9 \ M_\odot$ ($\sim 8\%$ Galaxy mass)

OLD IMF: $M_{\text{sim}} = 5.2 \times 10^9 \ M_\odot$ ($\sim 15\%$ Galaxy mass)

revised IMF: merger rate increase (de Mink & Belczynski 2015)
Overall updates (2010-2015):

Most important recent model updates:

- low metallicity introduced: \( Z_\odot \rightarrow 10\% Z_\odot \rightarrow 1\% Z_\odot \) (2010)
- binary CE evolution: more physical (2012)
- NS/BH formation: updated models (2012)
- first metallicity grid: 11 grid points (150\% \( Z_\odot \)–0.5\% \( Z_\odot \)) (2013)
- BH natal kicks: low and high (2015)
- initial conditions: \( a_{\text{orb}}, e, f_{\text{binary}} \) (2015, now)
- global properties: IMF, SFR(z), Z(z) (now)
- metallicity grid: 32 grid points (150\% \( Z_\odot \)–0.5\% \( Z_\odot \)) (now)
- statistics: Monte Carlo (2 millions \( \rightarrow \) 20 millions) (now)
BH-BH progenitors: chemical composition

Typical BH-BH progenitors: low metallicity stars \( Z < 10\% Z_\odot \)