Evolutionary predictions in the advanced LIGO/Virgo era

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– BH-BH binaries: modeling (field)
– BH-BH mergers: formation (field)
– BH-BH detection: astrophysical implications of LIGO detections
BH-BH formation: broad perspective

First astro-implication of LIGO detections: outbreak of models

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

Before LIGO detections: NS-NS dominant source – a conceptual mistake
modeling: synthetic universe

1st Stars about 400 million yrs.

Big Bang Expansion
13.7 billion years

Afterglow Light Pattern 380,000 yrs.

Dark Ages

Development of Galaxies, Planets, etc.

Dark Energy
Accelerated Expansion

Inflation

Quantum Fluctuations

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

POP I/II: uncertain for z>2, POP III: much smaller contribution
BH mass spectrum: maximum BH mass


Maximum BH mass: $94M_\odot$
(Z=0.0001)

$Z=0.5\%\ Z_\odot$

$Z=10\%\ Z_\odot$

$Z=100\%\ Z_\odot$

$Z=150\%\ Z_\odot$

stellar origin BH can reach: $\sim 100\ M_\odot$
(Zamperni & 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: $\ll XX\ M_\odot$

\rightarrow \rightarrow \rightarrow
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: $130 – ?? M_\odot$

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

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! ($Z_\odot$ -> 0.1 $Z_\odot$)
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
BH-BH mergers: LIGO 44 days of O1 (70 Mpc)

LIGO BH-BH merger rate: $9–240 \text{ Gpc}^{-3} \text{ yr}^{-1}$

GW150914: $36 + 29 \, M_\odot$, LVT151012: $23 + 13 \, M_\odot$, GW151226: $14 + 8 \, M_\odot$
# of BH-BH detections: $66$ (M1), $64$ (M10), $2$ (M3) in 60 days of LIGO O2
Astro implications: from BH-BH merger detection

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

- **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

Redshift

10

3.0

0.5

0

$\propto t^{-1}$

$F_Z(<10\%Z_\odot)$

$F_Z \times sfr$

(star formation with $Z<10\%Z_\odot$)

final birth times:

high-$z$ peak

low-$z$ peak

Cosmic time [Gyr]

1

10

100

Number
Metallicity evolution:

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

(\(Z_\odot=0.02\): Villante et al. 2014)
Predictions: population synthesis

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 ->
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 ~30 solar masses
- Compact objects – ~ 20-30 solar masses (but see later)
- Orbital period ~ 1.25 days
- Future evolution: mass transfer, mass loss, formation of 2nd BH
- Formation of BH-BH with the coalescence time ~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
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
Advanced LIGO/Virgo upper limits: OLD OLD OLD OLD

Dominik et al. 2013, 2015 \rightarrow Belczynski et al. 2015 (arXiv:1510.04615)

- Expected Advanced LIGO/VIRGO upper limits
- Most likely detection: BH-BH merger with total redshifted mass $25-73 \, M_\odot$

Chris Belczynski
The Astrophysics of BH-BH Mergers (LISA Symposium 2016)
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 -> 20 millions) (now)
BH-BH progenitors: chemical composition

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