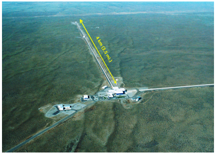
Evolutionary predictions in the advanced LIGO/Virgo era



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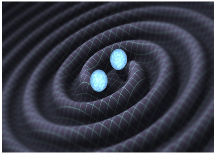


- BH-BH binaries: modeling (field)
- BH-BH mergers: formation (field)
- BH-BH detection: astrophysical implications of LIGO detections

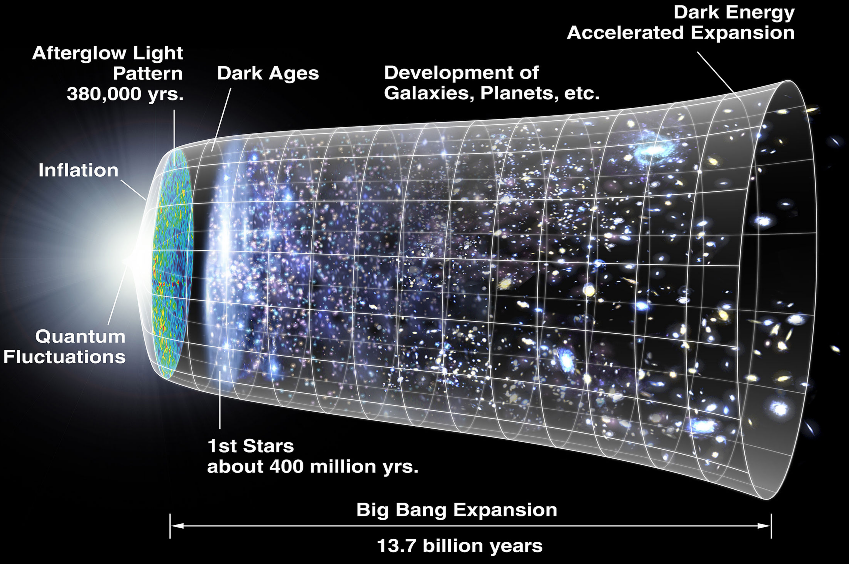
BH-BH formation: broad perspective

First astro-implication of LIGO detections: outbreak of models

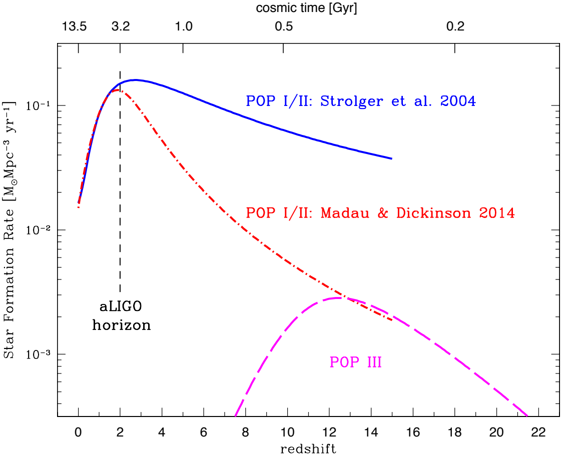
- Primordial BH-BH: density fluctuations after Big Bang
- PopIII BH-BH: first massive stars ($\sim$ 1% of stars in Universe)
- PopII/I BH-BH: dynamics/globular clusters ($\sim$ 0.1%)
- PopII/I BH-BH: rapid rotation (homogeneous evol.) ($\sim$ 10%)
- exotic BH-BH: single star core splitting ($\sim$ 0%)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

before LIGO detections: NS-NS dominant source – a conceptual mistake

modeling: synthetic universe



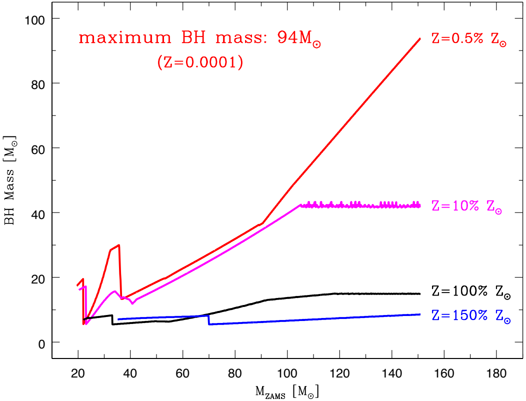
Star formation history:



POP I/II: uncertain for z>2, POP III: much smaller contribution

BH mass spectrum: maximum BH mass

Belczynski et al. 2010a (ApJ 714, 1217)



stellar origin BH can reach: $\sim 100\ M_\odot$
(Zamperi & Roberts 2009; Mapelli et al. 2009)

– past updates:

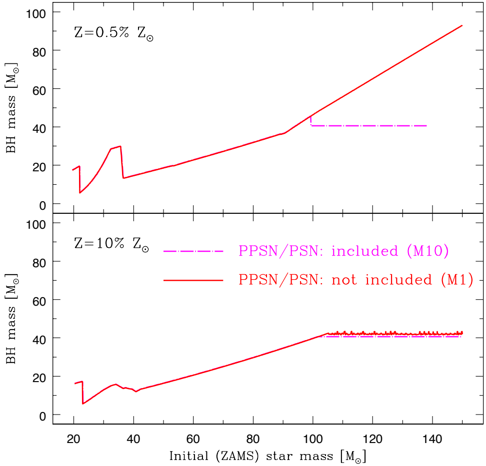
stellar models: $\sim 130\ M_\odot$
(Spera et al. 2015)

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 $\sim 50 M_\odot$



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

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

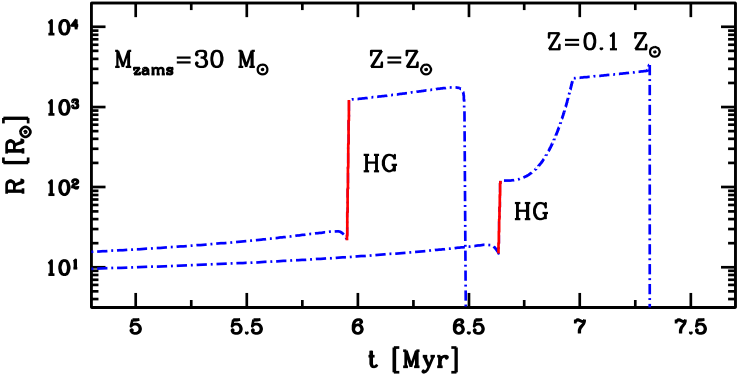
NS/BH mass spectrum:

neutron stars:	$1 - 2\ \mathrm{M}_\odot$
first mass gap:	$2 - 5\ \mathrm{M}_\odot$
black holes:	$5 - 50\ \mathrm{M}_\odot$
second mass gap:	$50 - 130\ \mathrm{M}_\odot$
black holes:	$130 - ???\ \mathrm{M}_\odot$

(Belczynski, Heger, Gladysz, Ruiter, Woosley, Wiktorowicz, Chen, Bulik, O'Shaughnessy, Holz, Fryer, Berti: A&A 2016)

Common envelope: orbital decay at low Z

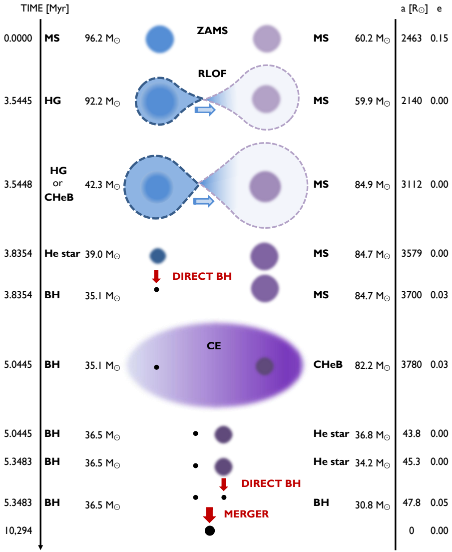
Belczynski et al. 2010 (ApJ 715, L138), Pavlovskii et al. 2016



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

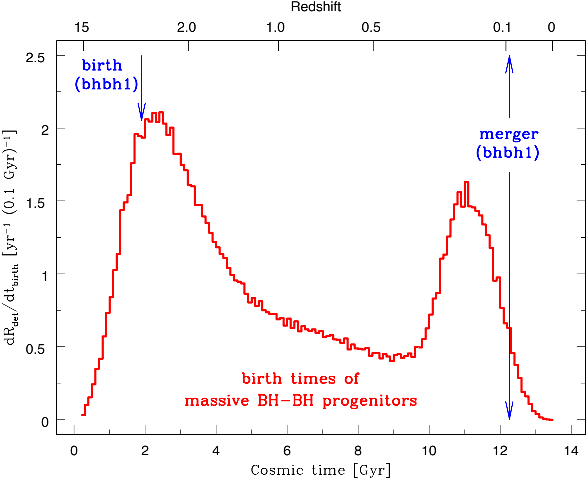


TIME [Myr]						a [R⊙]	e
0.0000	MS	96.2 M⊙	ZAMS	MS	60.2 M⊙	2463	0.15
3.5445	HG	92.2 M⊙	RLOF	MS	59.9 M⊙	2140	0.00
3.5448	HG or CHeB	42.3 M⊙		MS	84.9 M⊙	3112	0.00
3.8354	He star	39.0 M⊙	DIRECT BH	MS	84.7 M⊙	3579	0.00
3.8354	BH	35.1 M⊙		MS	84.7 M⊙	3700	0.03
5.0445	BH	35.1 M⊙	CE	CHeB	82.2 M⊙	3780	0.03
5.0445	BH	36.5 M⊙		He star	36.8 M⊙	43.8	0.00
5.3483	BH	36.5 M⊙	DIRECT BH	He star	34.2 M⊙	45.3	0.00
5.3483	BH	36.5 M⊙	MERGER	BH	30.8 M⊙	47.8	0.05
10,294						0	0.00

- 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 $\mathrm{M}_\odot$
- aligned BH spins: tilt$=$ 0 deg
- BH spin: $a = 0.0$ -> $a = 0.126$
  $a = 0.5$ -> $a = 0.572$
  $a = 0.9$ -> $a = 0.920$

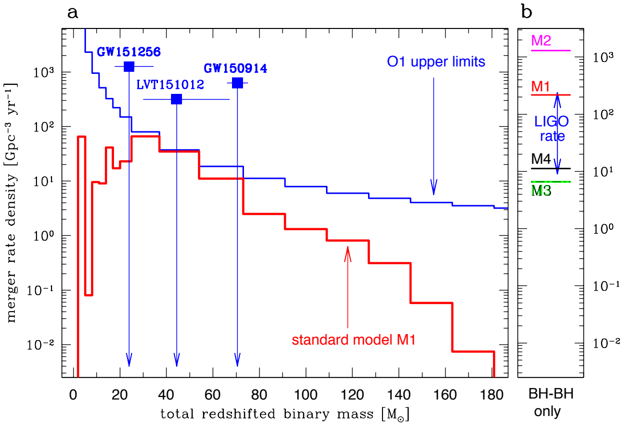
credit: Wojciech Gladysz (Warsaw)

BH-BH progenitors: birth times



typical BH-BH progenitors: very old (10 Gyr) or young (2 Gyr) systems

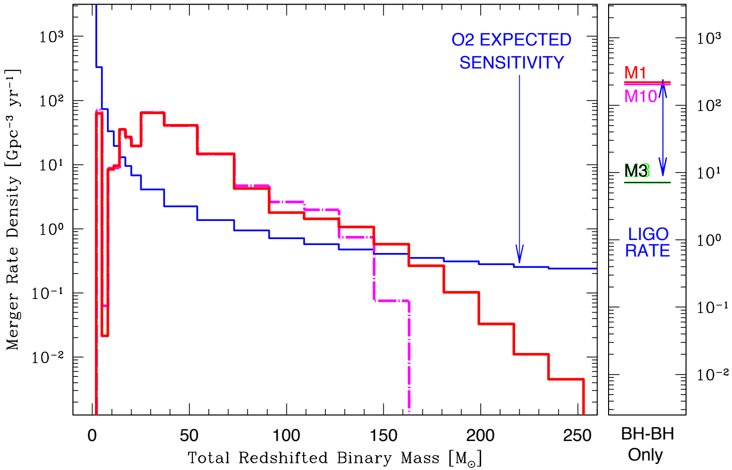
BH-BH mergers: LIGO 44 days of O1 (70 Mpc)



LIGO BH-BH merger rate: 9–240 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

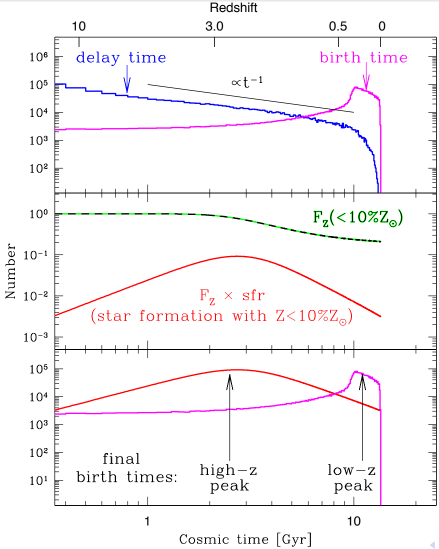
Astro implications: from BH-BH merger detection

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

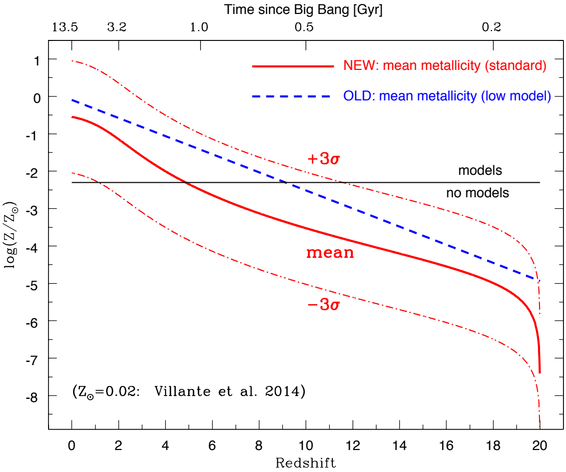
at the moment: origin not distinguishable:

BH-BH mergers: field + homogeneous + dynamical + popIII – sci-fi channels

Birth time distribution for BH-BH progenitors



Metallicity evolution:



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

Predictions: population synthesis

Evolutionary assumptions and uncertainties:

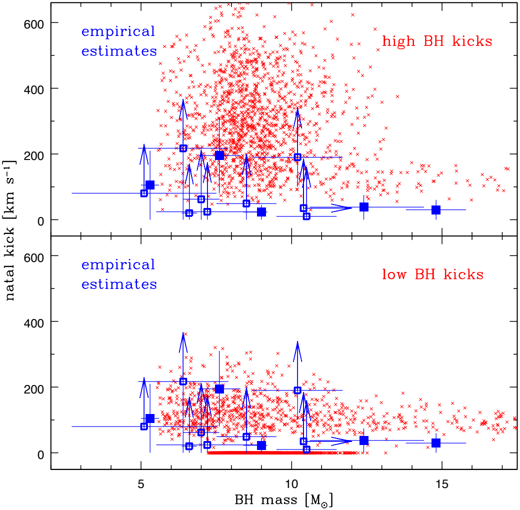
- global properties: cosmology, SFR(z), $Z(z)$
- initial conditions: IMF, q, $a_{\rm orbit}$, e, $f_{\rm binary}$ (Sana et al. 2012)

- 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 $M_{\rm BH}$:

- asymmetric mass ejection
- asymmetric neutrino emission

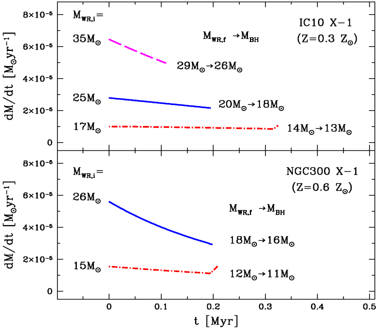
both mechanisms: OK!

Belczynski et al. 2015 (arXiv:1510.04615)

Observations (Tomek Bulik): 1/3

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

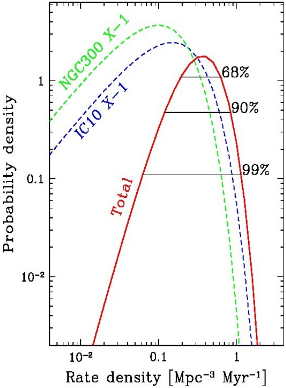
Observations (Tomek Bulik): 2/3

Rate density estimate

- Estimate of the observability volume and object density
- Estimate of the time to coalescence
- Just two objects – low stastistic 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 mesurement 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 possibilty 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

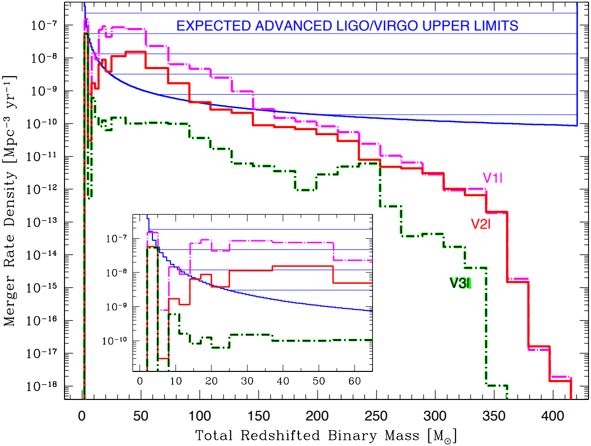
Mass transfer: if wind, then the X-ray luminosity (10^{38} erg/s) is unusually high (too large by 2-3 orders of magnitude)

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

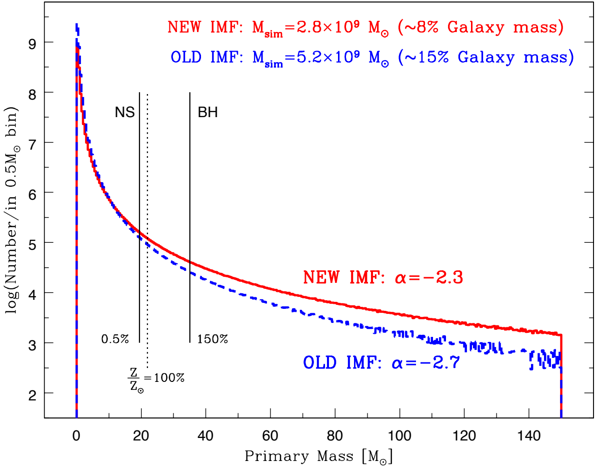
Advanced LIGO/Virgo upper limits: OLD OLD OLD

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



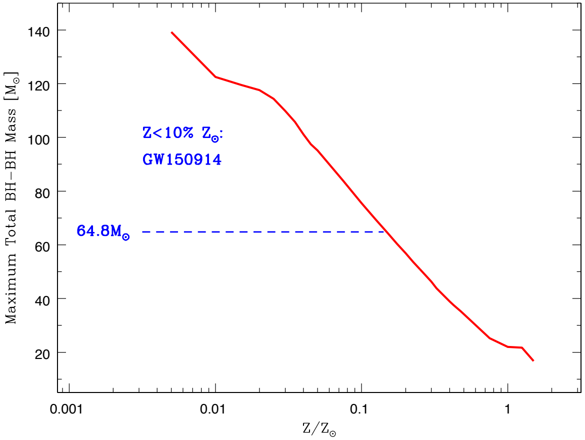
revised IMF: merger rate increase (de Mink & Belczynski 2015)

Overall updates (2010-2015):

Most important recent model updates:

- low metallicity introduced: $Z_\odot$ -> 10% $Z_\odot$ -> 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: $a_{\rm orb}$, e, $f_{\rm binary}$ (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 $Z < 10\% Z_\odot$