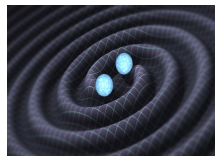


Massive Stellar Black Hole Binaries and Gravitational Waves



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Tomek Bulik¹
Daniel Holz
Richard O'Shaughnessy

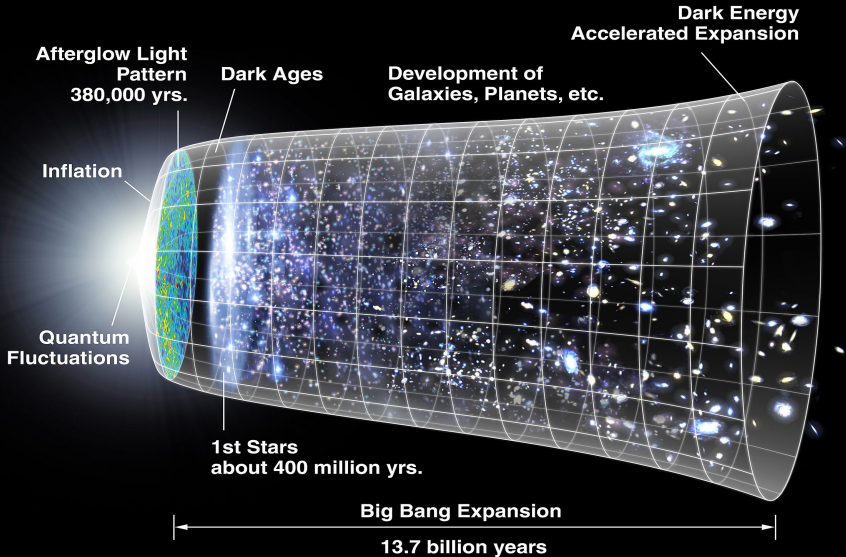


Wojciech Gladysz¹ and Grzegorz Wiktorowicz¹

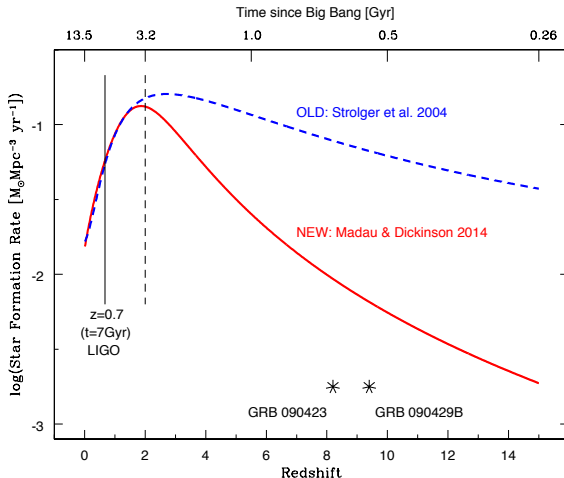
¹ **Astronomical Observatory, Warsaw University**

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

modeling: synthetic universe

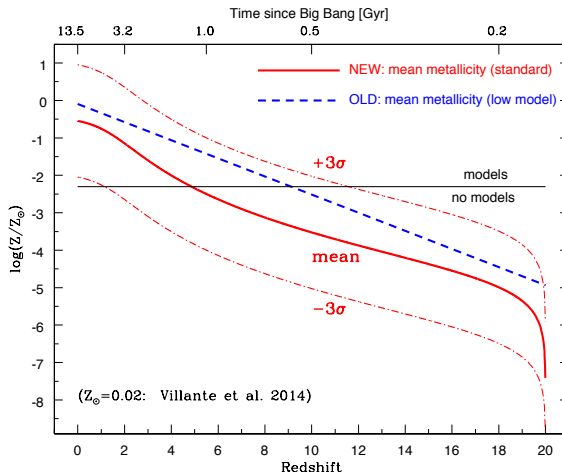


Star formation rate update



revised SFR: merger rate decrease

Metallicity evolution update



revised metallicity: merger rate increase

Predictions: BH-BH merger rates and masses

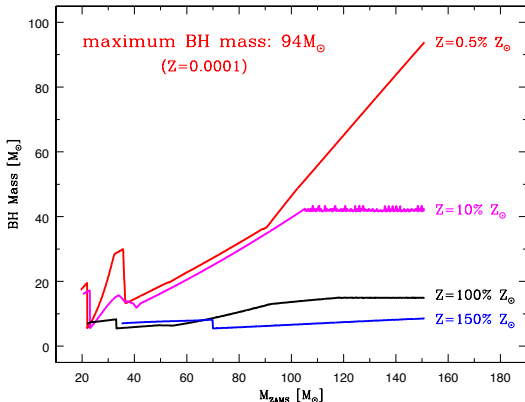
Evolutionary assumptions and uncertainties:

- **global properties:** cosmology, $\text{SFR}(z)$, $Z(z)$, f_{binary} —fraction
- **initial conditions:** IMF, q , a_{orbit} , e , V_{rotation}
- **single star evolution:** winds + mixing \rightarrow radius & BH mass?
- **binary CE evolution:** development criteria + survival?
- **BH formation:** SN or Direct BH \rightarrow BH mass?
- **BH formation:** BH natal kicks \rightarrow low or high?

population synthesis calculations \rightarrow

Maximum BH mass: first breakthrough

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



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

– two existing updates:

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

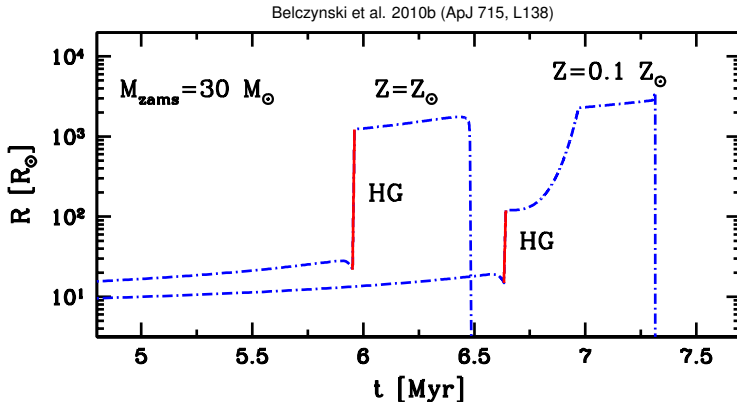
IMF extension: $\sim 300 M_{\odot}$
(Belczynski et al. 2014)

– two upcoming updates:

Pair-instability SNe: $\lesssim 100 M_{\odot}$
(Mapelli et al. 2016)

Pair-instability SNe: $\lesssim 50 M_{\odot}$
(Belczynski et al. 2016)

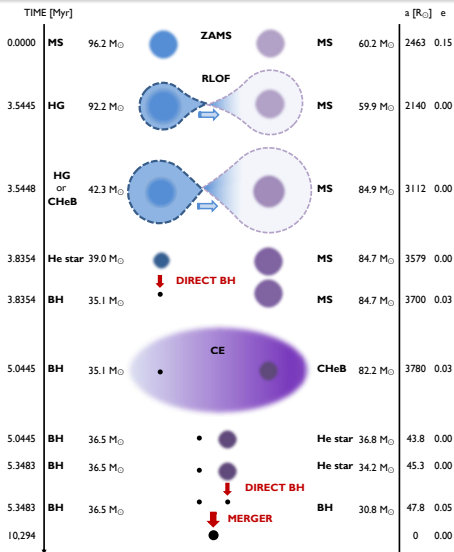
Common envelop at low Z: second breakthrough



BH-BH progenitors survive CE at low Z: rates up by 70 times!!! ($Z_{\odot} \rightarrow 0.1 Z_{\odot}$)

(low-Z stars: RLOF beyond HG \rightarrow convective envelope \rightarrow CE & orbit decay)

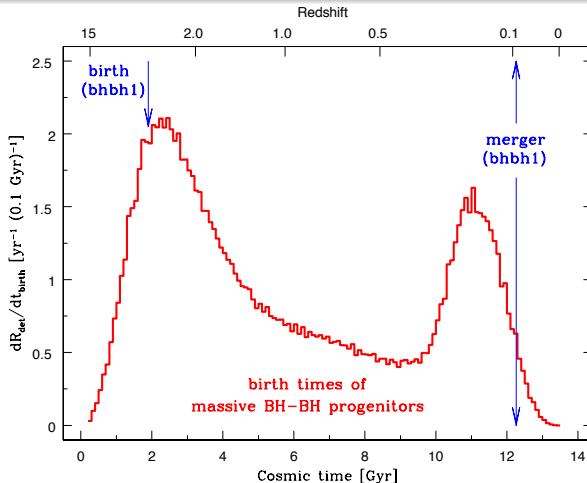
Formation of massive BH-BH merger



- 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: $a = 0.0 \rightarrow a = 0.126$
 $a = 0.5 \rightarrow a = 0.572$
 $a = 0.9 \rightarrow a = 0.920$

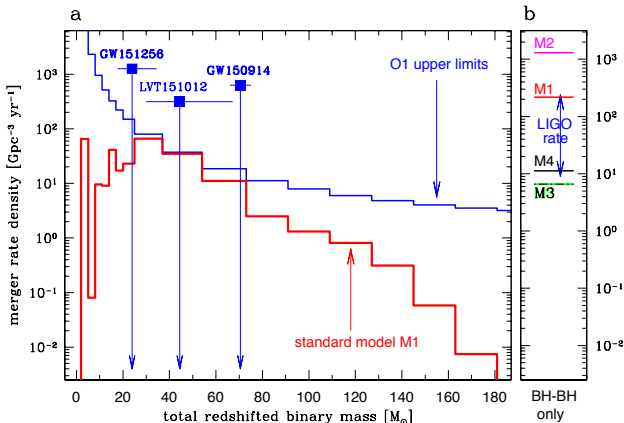
credit: Wojciech Gladysz (Warsaw)

BH-BH progenitors: birth times



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

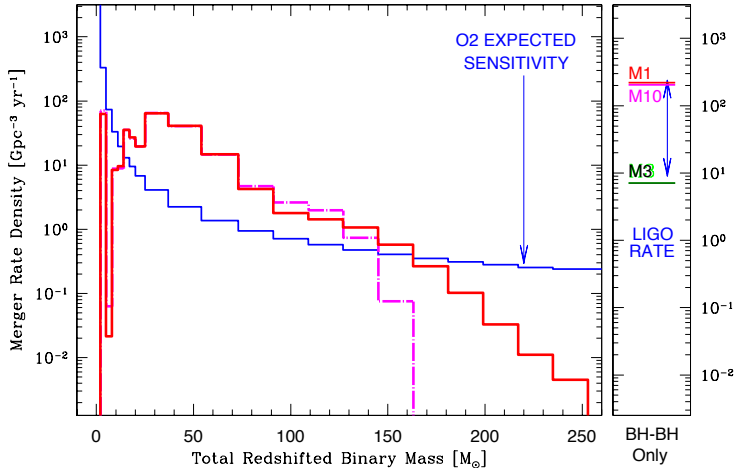
LIGO detections: all BH-BH mergers (44 days)



BH-BH mergers:

GW150914: $36 + 29 M_{\odot}$, LVT151012: $23 + 13 M_{\odot}$, GW151226: $8 + 14 M_{\odot}$

BH-BH mergers: LIGO 60 days of O2

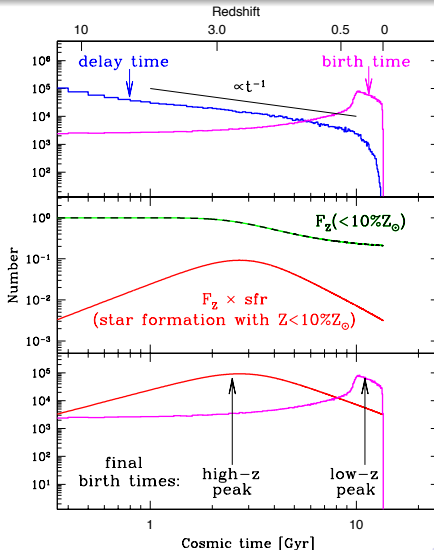


of BH-BH detections: 64 (M1), 62 (M10), 2 (M3) in 60 days of LIGO O2

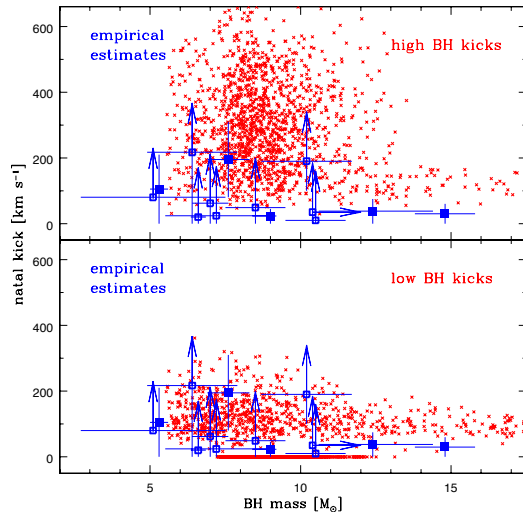
Astro implications: from BH-BH merger detection

- **massive BH-BH merger:** dominant GW source (field evolution)
(1000 \times 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 detection rates:** 40 times higher than for dynamical BH-BH!
(Belczynski et al. 2016 versus Rodriguez et al. 2016)

Birth time distribution for BH-BH progenitors



BH natal kicks: extras 1/4



EM observations:
no good information

if BH kicks decrease with M_{BH} :

- asymmetric mass ejection
- asymmetric neutrino emission

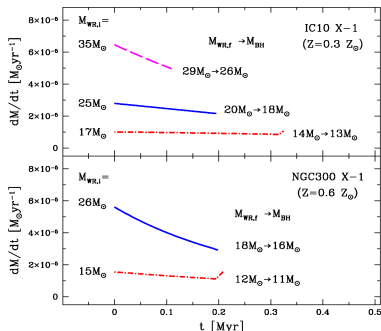
both mechanisms: OK!

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 \sim a few Gyrs
- Low metallicity host galaxies

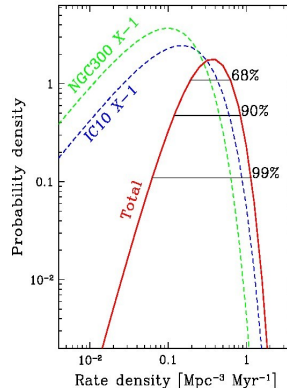


Bulik, Belczynski, Prestwich 2011

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 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

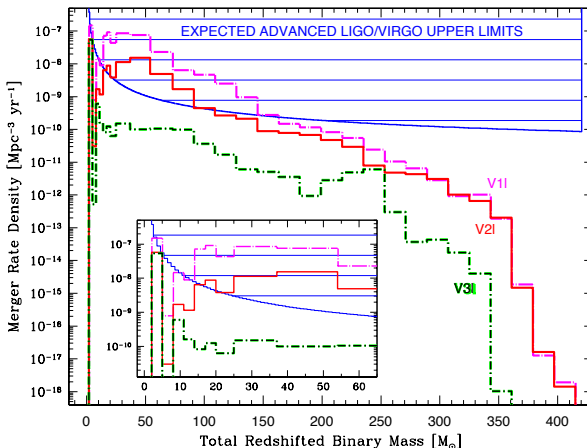
Mass transfer: if wind, then the X-ray luminosity (10^{38} erg/s) is unusually high (too large by 2-3 orders of magnitude)

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

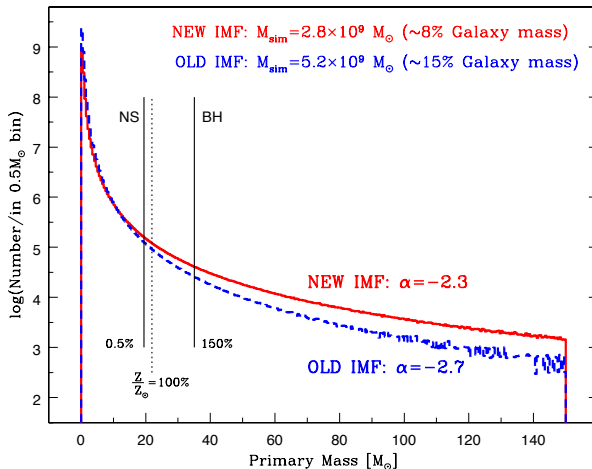
Advanced LIGO/Virgo upper limits: OLD OLD OLD

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



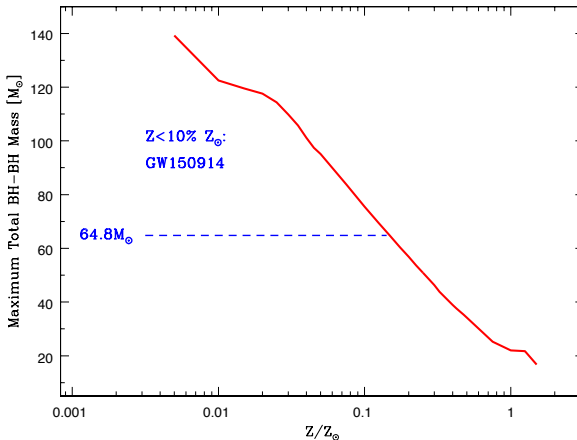
revised IMF: merger rate increase (de Mink & Belczynski 2015)

Overall updates (2010-2015):

Most important recent model updates:

- low metallicity introduced: $Z_{\odot} \rightarrow 10\% Z_{\odot} \rightarrow 1\% Z_{\odot}$ (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_{orb} , e , f_{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 $Z < 10\% Z_{\odot}$