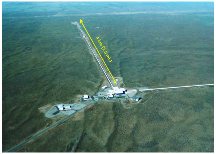
The ongoing LIGO search for gravitational-waves: BH-BH modeling



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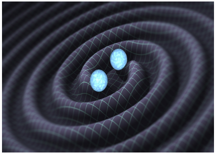


– BH mass: what to expect? (2010/2016)
– BH-BH from Pop III stars: not for LIGO... (2016)
– GW170104: from classical isolated binary evolution (2017)

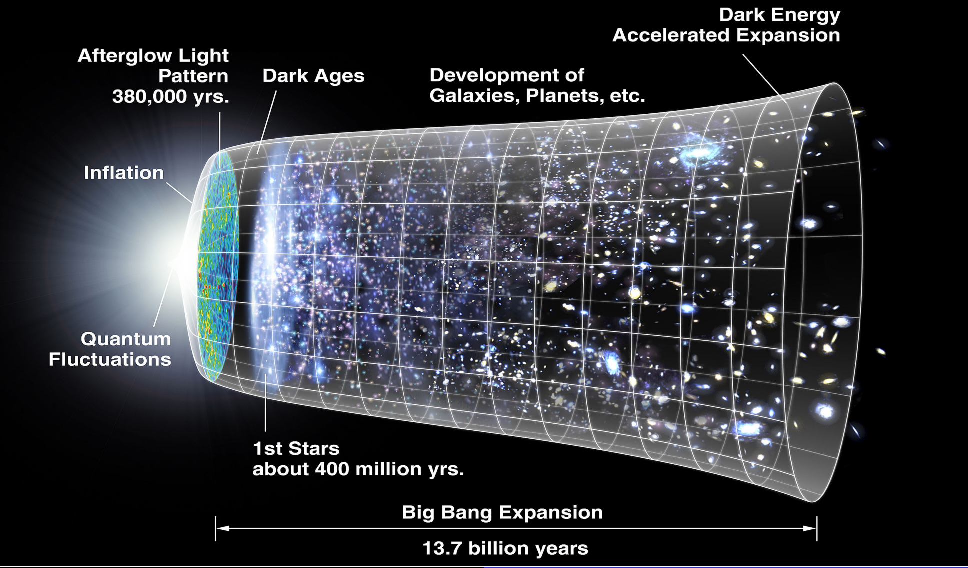
BH-BH formation: broad perspective

First astro-implication of LIGO detections: outbreak of models

- Primordial BH-BH: density fluctuations after Big Bang
- PopIII BH-BH: first massive stars ($\lesssim$ 1% of stars in Universe)
- PopII/I BH-BH: classical isolated binary evolution ($\sim$ 90%)
- PopII/I BH-BH: rapid rotation (homogeneous evol.) ($\sim$ 10%)
- PopII/I BH-BH: dynamics/globular clusters ($\sim$ 0.01–1%)
- exotic BH-BH: e.g., massive star formation in AGN disk (?)
  e.g., single star core splitting (?)

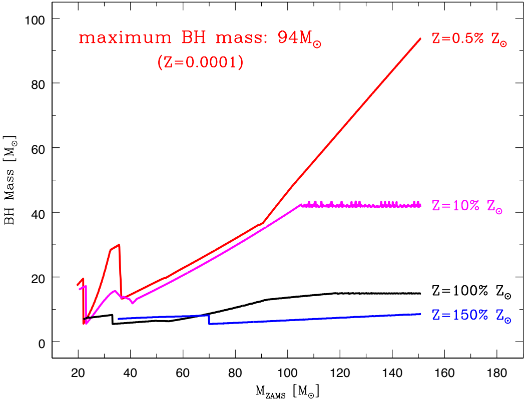
predictions before LIGO: NS-NS dominant source – a conceptual mistake

modeling: synthetic universe



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* $M_\odot$
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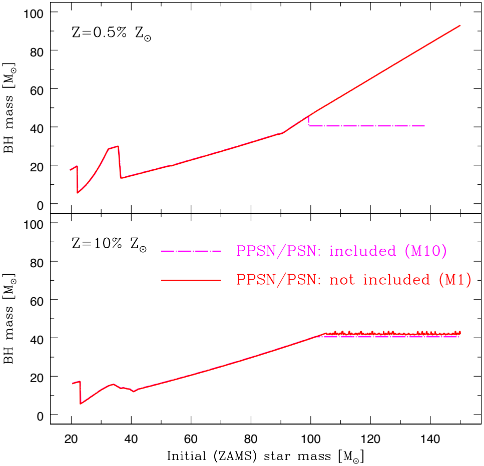
Pair instability: maximum BH mass $\sim 50 M_\odot$



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

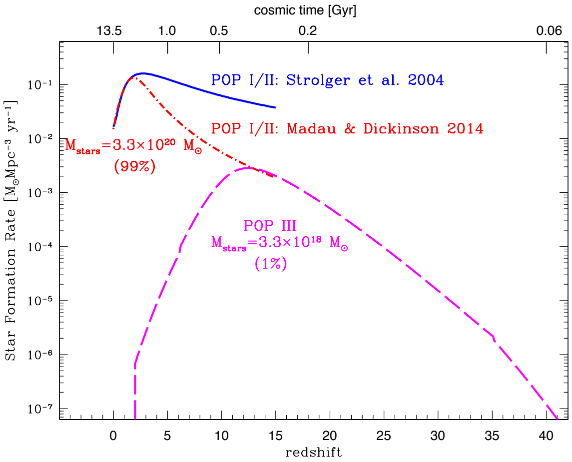
PPSN: Pair-instability Pulsation SN
($M_{\rm He} \sim$ 45–65 $M_\odot$)
black hole: and severe mass loss

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:	$130 - ???\ M_\odot$

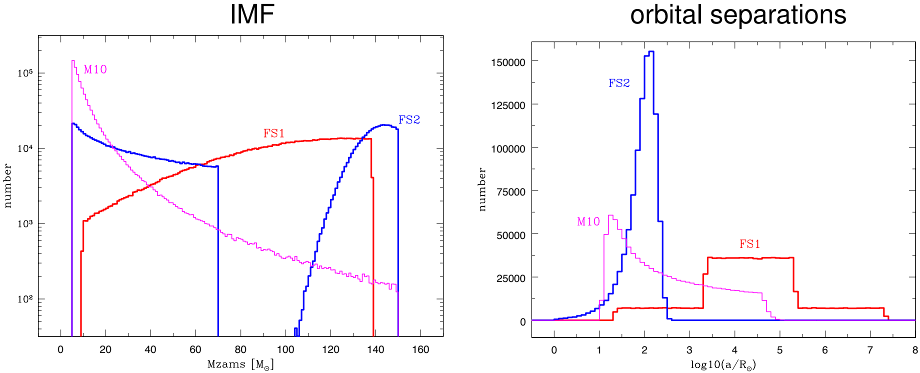
(Belczynski, Heger, Gladysz, Ruiter, Woosley, Wiktorowicz, Chen, Bulik, O'Shaughnessy, Holz, Fryer, Berti: A&A 2016)

Star formation history: Population III (first) stars



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

Population III binary initial conditions:



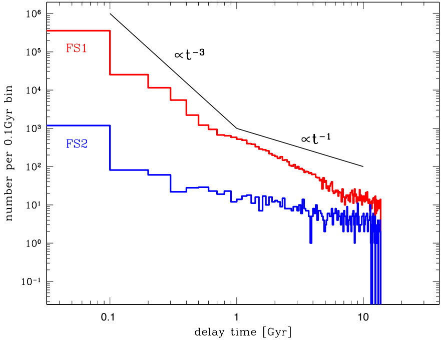
M10 – Pop I/II (Sana et al. 2012) $X_{\rm BHBH} \approx 10^{-5}$–$10^{-7}\ {\rm M}_\odot^{-1}$

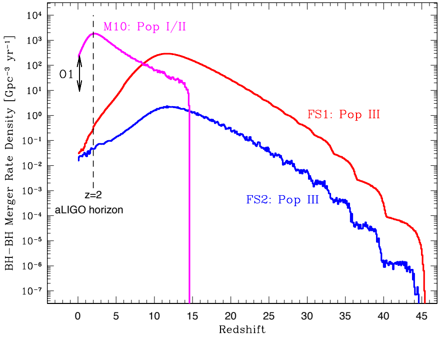
FS1 – Pop III: large dark matter halos (2000 AU) $X_{\rm BHBH} \approx 10^{-4}\ {\rm M}_\odot^{-1}$

FS2 – Pop III: small dark matter halos (10-20 AU) $X_{\rm BHBH} \approx 10^{-6}\ {\rm M}_\odot^{-1}$

Pop III: very different initial conditions than for PopI/II...

Pop III BH-BH merger rate history:

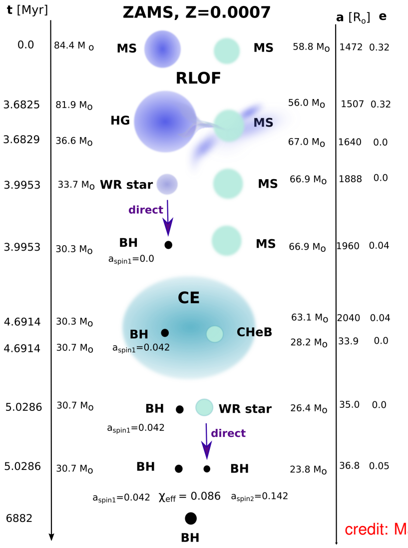




– delay time: $a^{-1}(da/dt)_{\rm GR} \propto t^{-1/4} d(t^{1/4})/dt \propto t^{-1}$
(initial separation distr.: $\sim a^{-1}$, $t_{\rm GR} \propto a^4$: Peters 1964)
– new O2 LIGO BH-BH merger rate: 12–213 $\rm Gpc^{-3}\ yr^{-1}$ (O1: 9–240)

Pop III BH-BH rates: 2.5 orders below LIGO, 4 orders below Pop I/II

Formation of massive BH-BH merger: Pop I/II

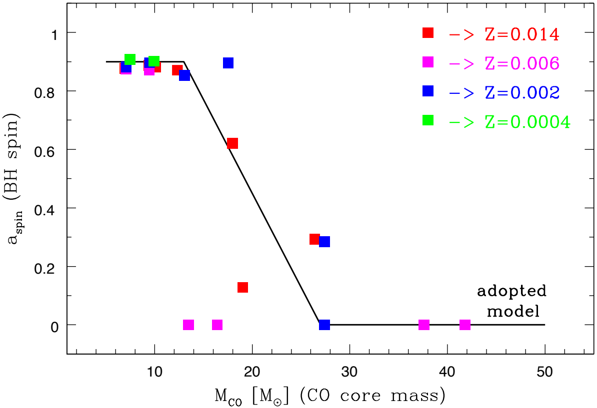


- low metallicity: $Z < 10\% Z_\odot$
- CE: during CHeB
- long delay: 5 Myr + 7 Gyr
- O1/O2 horizon: $z = 0.6$ (inspiral-merger-ringdown)
- total redshifted mass: 20–100 $M_\odot$
- aligned BH spins: tilt $= 0$ deg?
- BH spin: $a_1 = 0.0$ -> $a_1 = 0.04$
  $a_2 = 0.14$ -> $a_2 = 0.14$

$\chi_{\rm eff,max} = 0.086$ (<0.09: LIGO)

credit: Martyna Chruslinska (Warsaw)

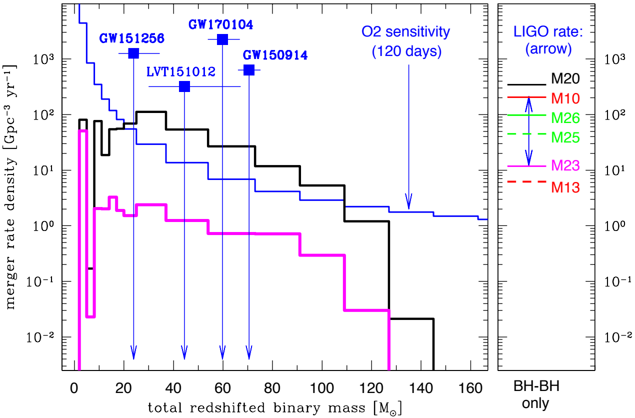
BH natal spin model: from the Geneva code



– low-mass BHs ($\lesssim 15\ M_\odot$): high natal spins ($a_{spin} \approx 0.9$)

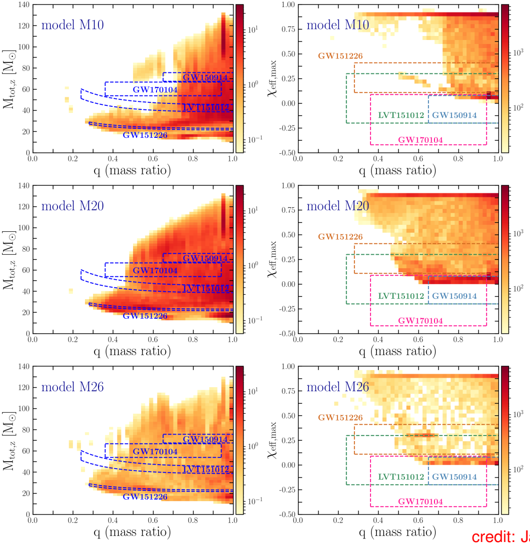
– high-mass BHs ($\gtrsim 30\ M_\odot$): low natal spins ($a_{spin} \approx 0.0$)

BH-BH mergers: LIGO 120 days of O2 (70 Mpc)



LIGO BH-BH merger rate (12–213 Gpc^{-3} yr^{-1}): GW151226: $14 + 8\ M_\odot$, LVT151012: $23 + 13\ M_\odot$, GW170104: $31 + 19\ M_\odot$, GW150914: $36 + 29\ M_\odot$

BH-BH properties: classical isolated binary evolution



- M10: no BH kicks, 50% RLOF
- M20: no BH kicks, 20% RLOF, rotation: $1.2 M_{CO}$
- M26: M20 + 70 km/s BH kicks
- q–$M_{tot,z}$:
  - – LIGO events within models
  - – M20/26 better than M10
- q–$\chi_{eff,max}$:
  - – models found for LIGO events
- GW170104: matches found: double conservative

credit: Jakub Klencki (Warsaw)

Conclusions

- origin of LIGO BH-BH mergers: still unknown
  - 4 LIGO events: isolated channel rates, masses, spins are OK
  - GW170104: could have formed in isolation or in dense cluster
- astro implications: doubly limited
  - implications: valid only within a given BH-BH origin model
  - within each model: multiple (untested) possibilities
- channel discrimination: will be very hard to do
  - GW170194, GW151226: seem not from homogeneous evol.
  - aligned spins and $M_{\rm BH} \lesssim 50\ {\rm M}_\odot$ or $M_{\rm BH} \gtrsim 130\ {\rm M}_\odot$-> -> -> -> isolated evolution (but reverse not true!)
  - uniform spin tilt distribution: not from globular clusters

*** no other origin statements seem to be true ***

BH-BH mergers: field + homogeneous + dynamical + PopIII + primordial ???