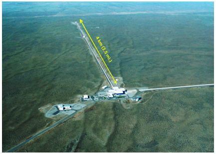
Binary neutron star formation and the origin of GW170817



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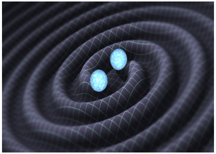


– Milky Way data: 18 NS-NS systems
– LIGO/Virgo data: 1 system (GW170817)
– evolutionary models: can we fit all the data?

Galactic NS-NS: 18 known systems

Name	type	M_{psr}[b] [$M_\odot$]	M_{com} [$M_\odot$]	P_{orb} [day]	a [$R_\odot$]	e	t_{mer}[c] [Gyr]	reference[e]
field:								
1) J1946+2052	recycled	1.25	1.25	0.076	1.028	0.06	0.042	[1]
2) J1757-1854	recycled	1.34	1.39	0.183	1.897	0.6	0.079	[2]
3) J0737-3039	young	1.338	1.249	0.102	1.261	0.088	0.085	[3,4,5]
4) B1913+16	recycled	1.440	1.389	0.323	2.801	0.617	0.301	[6,7]
5) J1906+0746	young	1.291	1.322	0.166	1.750	0.085	0.308	[8,9]
6) J1913+1102	recycled	1.64	1.25	0.206	2.090	0.08	0.473	[10,11]
7) J1756-2251	recycled	1.341	1.230	0.320	2.696	0.181	1.660	[12,13]
8) B1534+12	recycled	1.333	1.346	0.421	3.282	0.274	2.736	[14]
9) J1829+2456	recycled	1.295	1.295	1.176	6.436	0.139	55.36	[15]
10) J1411+2551	recycled	1.265	1.265	2.61	10.9	0.16	471.3	[16]
11) J0453+1559	recycled	1.559	1.174	4.072	15.0	0.113	1,452	[17]
12) J1811-1736	recycled	1.285	1.285	18.779	40.7	0.828	1,794	[18]
13) J1518+4904	recycled	1.359	1.359	8.634	24.7	0.249	8,853	[19]
14) J1755-2550	young	1.3	1.3	9.696	26.3	0.089	15,917	[20,21]
15) J1753-2240	recycled	1.3	1.3	13.638	33.0	0.304	28,646	[22]
16) J1930-1852	recycled	1.295	1.295	45.060	73.1	0.399	531,294	[23]
globular clusters:								
17) B2127+11C	recycled	1.358	1.354	0.335	2.830	0.681	0.217	[24,25]
18) J1807-2500B[d]	recycled	1.366	1.206	9.957	26.7	0.747	1,044	[26]

current merger times: 50%–50% short vs long merger time systems

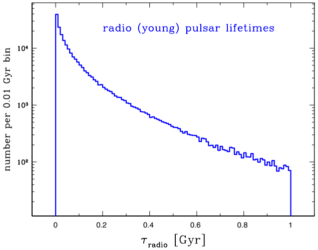
(Belczynski, Bulik, Olejak et al. 12/2018: arXiv:1812.10065)

Galactic NS-NS: merger rate in MW

peak value: $\mathcal{R}_{\rm MW} \sim 40\ {\rm Myr}^{-1}$

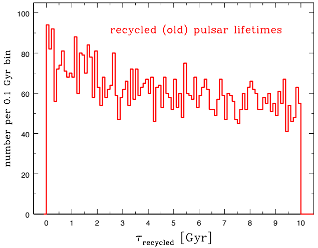
1st estimate: $28\text{–}72\ {\rm Myr}^{-1}$

2nd estimate: $6.6\text{–}190\ {\rm Myr}^{-1}$



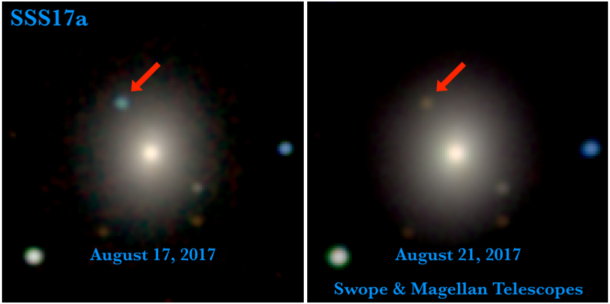
merger rate estimates:

- adopt MW star formation model
- adopt radio and recycled pulsar lifetimes
- radio detctability model (beaming, luminosity)
- extrapolate from 8 close NS-NS MW systems



– Pol, McLaughlin, Lorimer 11/2018, arXiv:1811.04086)
– O'Shaughnessy 2019)

GW170817: first NS-NS merger in gravitational waves



– LIGO/Virgo inspiral detection of: $1.4 - 1.6\ \mathrm{M}_\odot$ and $1.2 - 1.4\ \mathrm{M}_\odot$ (NS-NS?)

– LIGO/Virgo merger rate: $\sim 1,000\ (110 - 3,840)\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ (1st surprise)

– EM: optical kilonova + off-axis short GRB

– Host galaxy: massive elliptical at 40 Mpc (2nd surprise)

NGC 4993: GW170817 host galaxy star formation

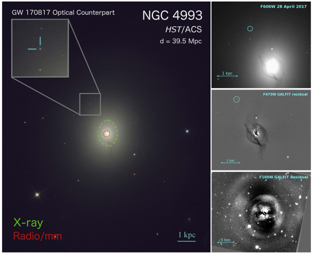
observations: photometry, spectra, images (radio, IR, optical, UV, X-rays, gamma-rays)

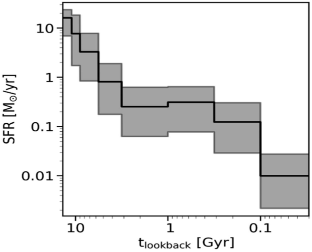
NGC 4993:

- medium elliptical galaxy: 40 Mpc away
- stars at near-solar metallicity: $Z \approx 0.02$
- total star forming mass: $7.9 \times 10^{10}\ \mathrm{M}_{\odot}$
- peak of star formation rate: 11 Gyr ago
- extra (?) episode of SFR: 0.5-1 Gyr ago (but only $< 1\%$ of total SFR)

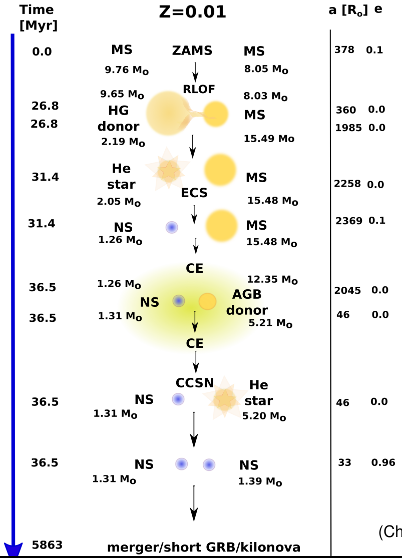
almost no current/recent star formation...

Blanchard, Berger et al. 2017, ApJ 848, L22 –> (see also Troja et al. 2017, Palmese et al. 2017)





NS-NS merger: stellar/binary evolution



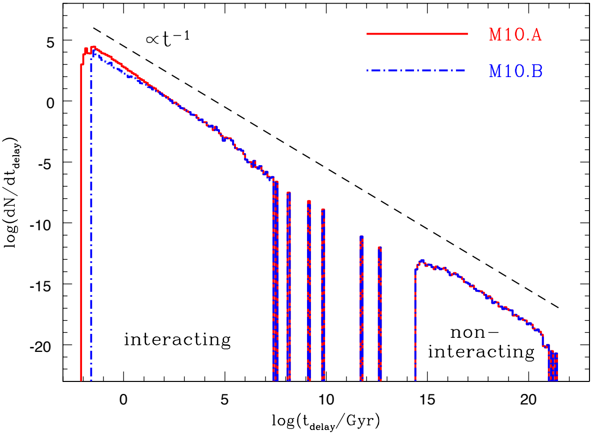
NS-NS merger rate: $\sim 1,000$ Gpc^{-3} yr^{-1}
LIGO/Virgo range: 110–3,840 Gpc^{-3} yr^{-1}

predictions: ~ 100 Gpc^{-3} yr^{-1}, because:

- narrow mass range: $M_{\rm ZAMS} \sim 10$–20 M$_\odot$
- common envelope: 50% binary mergers
- first SNa: $\gtrsim 90\%$ binary disruptions
- common envelope: 20% binary mergers
- short delay: 30 Myr + $\lesssim 1$ Gyr –>
  –> not expected in old ellipticals!

(Chruslinska et al. 2018, MRAS 474, 2937)

NS-NS mergers: delay time distribution

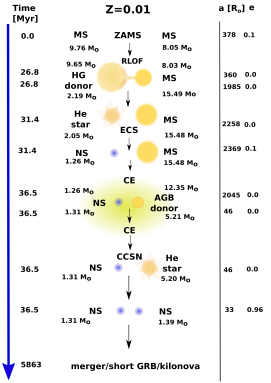


typically short delays: most mergers expected in star forming regions

(this is a generic result and very hard to change...)

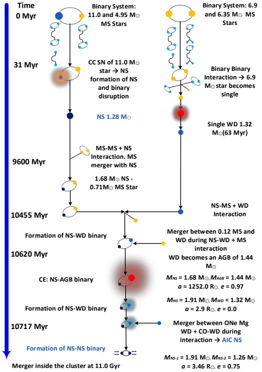
NS-NS merger: in old host galaxies (NGC4993-like)

binary stars:



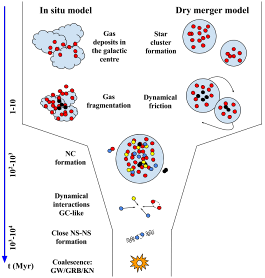
rate: 1×10^{-2} yr^{-1}

globular clusters:



rate: 5×10^{-5} yr^{-1}

nuclear clusters:



rate: 1×10^{-5} yr^{-1}

LIGO rate: ~ 1 yr^{-1} – so how did GW170817 formed?

(Belczynski, Askar, Arca-Sedda, Chruslinska, Donnari, Giersz, Benacquista, Spurzem, Jin, Wiktorowicz, Belloni 2018, A&A, 615, 91)

NS-NS models: merger rate predictions

Population synthesis calculations
(the StarTrack code)

$\sim$ 20 models:

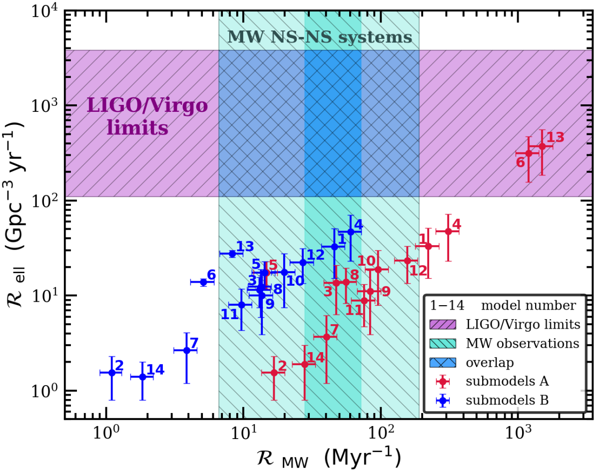
- NS natal kicks
  (Hobbs, ECS, Bray&Eldridge)
- CE effciency
  (0.1–1.0-10)
- RLOF mass loss
  (50%–80%)

we calculate NS-NS merger rate:
– in Milky Way
– in all local Elliptical galaxies
we compare both with observations...

Name	CC kick[a]	ECS kick[b]	α_{CE}[c]	(acc/eje)$_{RLOF}$[d]	$\mathcal{R}_{MW}$ [Myr^{-1}][e]	$\mathcal{R}_{ell}$ [Gpc^{-3} yr^{-1}][f]
observations					28–72[g] 6.6–190[h]	110–3840[i]
NN2.A	Hobbs: 265 km s^{-1}	OFF: –	1.0	0.2/0.8	13.5–20.0	0.8–2.3
NN2.B	Hobbs: 265 km s^{-1}	OFF: –	1.0	0.2/0.8	0.9–1.3	0.8–2.3
NN14.A	HobbsFB: 265 km s^{-1}	OFF: –	1.0	0.2/0.8	22.6–33.4	0.8–3.0
NN14.B	HobbsFB: 265 km s^{-1}	OFF: –	1.0	0.2/0.8	1.5–2.2	0.8–2.0
NN7.A	Hobbs: 133 km s^{-1}	ON: 66 km s^{-1}	1.0	0.2/0.8	32.4–48.0	1.2–6.2
NN7.B	Hobbs: 133 km s^{-1}	ON: 66 km s^{-1}	1.0	0.2/0.8	3.1–4.6	1.2–4.1
NN3.A	HobbsFB: 265 km s^{-1}	ON: 0 km s^{-1}	1.0	0.2/0.8	38.4–56.8	6.3–21.0
NN3.B	HobbsFB: 265 km s^{-1}	ON: 0 km s^{-1}	1.0	0.2/0.8	10.8–16.0	5.9–18.9
NN8.A	Hobbs: 133 km s^{-1}	ON: 0 km s^{-1}	1.0	0.2/0.8	45.0–66.6	8.3–19.6
NN8.B	Hobbs: 133 km s^{-1}	ON: 0 km s^{-1}	1.0	0.2/0.8	10.6–15.7	7.5–15.6
M10.A	HobbsFB: 265 km s^{-1}	ON: 0 km s^{-1}	1.0	0.5/0.5	53.6–79.3	11.4–51.4
M10.B	HobbsFB: 265 km s^{-1}	ON: 0 km s^{-1}	1.0	0.5/0.5	17.4–25.8	18.5–22.1
NN11.A	Hobbs: 66 km s^{-1}	OFF: –	1.0	0.2/0.8	61.1–90.4	4.7–13.1
NN11.B	Hobbs: 66 km s^{-1}	OFF: –	1.0	0.2/0.8	7.8–11.5	4.3–11.8
NN9.A	Hobbs: 66 km s^{-1}	ON: 33 km s^{-1}	1.0	0.2/0.8	67.6–100	3.9–18.4
NN9.B	Hobbs: 66 km s^{-1}	ON: 33 km s^{-1}	1.0	0.2/0.8	11.0–16.3	3.9–16.3
NN10.A	Hobbs: 66 km s^{-1}	ON: 0 km s^{-1}	1.0	0.2/0.8	76.9–114	7.9–29.9
NN10.B	Hobbs: 66 km s^{-1}	ON: 0 km s^{-1}	1.0	0.2/0.8	16.0–23.7	7.5–27.7
NN12.A	Hobbs: 33 km s^{-1}	OFF: –	1.0	0.2/0.8	126–186	13.4–33.1
NN12.B	Hobbs: 33 km s^{-1}	OFF: –	1.0	0.2/0.8	21.8–32.3	13.4–31.5
NN4.A	Hobbs: 0 km s^{-1}	OFF: –	1.0	0.2/0.8	251–371	23.2–72.1
NN4.B	Hobbs: 0 km s^{-1}	OFF: –	1.0	0.2/0.8	48.9–72.4	23.2–70.8
NN13.A	Hobbs: 0 km s^{-1}	OFF: –	10	0.2/0.8	1208–1788	186–561
NN13.B	Hobbs: 0 km s^{-1}	OFF: –	10	0.2/0.8	6.7–9.9	29.9–25.2
NN5.A	BE18: 100/ – 170 km s^{-1}	OFF: –	0.1	0.2/0.8	11.9–17.6	11.8–22.9
NN5.B	BE18: 100/ – 170 km s^{-1}	OFF: –	0.1	0.2/0.8	11.5–17.0	11.8–22.9
NN1.A	BE18: 100/ – 170 km s^{-1}	OFF: –	1.0	0.2/0.8	179–265	15.3–51.2
NN1.B	BE18: 100/ – 170 km s^{-1}	OFF: –	1.0	0.2/0.8	37.0–54.8	15.3–50.6
NN6.A	BE18: 100/ – 170 km s^{-1}	OFF: –	10	0.2/0.8	961–1422	156–471
NN6.B	BE18: 100/ – 170 km s^{-1}	OFF: –	10	0.2/0.8	4.1–6.1	12.6–15.1

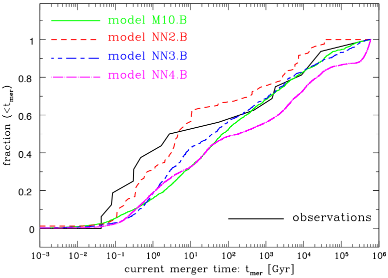
(Belczynski, Bulik, Olejak et al. 12/2018: arXiv:1812.10065)

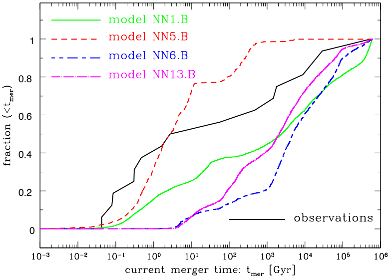
NS-NS models: Milky Way vs Elliptical galaxies



Milky Way vs LIGO/Virgo: no tested models overalp with both constraints...

Predicted merger times for NS-NS in Milky Way





- models with Hobbs/ECS kicks
- with normal CE effciency
- reproduce Galactic merger rates
- are good match to merger times

they don’t produce LIGO/Virgo rate

- models with Eldridge/zero kicks
- with high CE effciency
- don’t reproduce Galactic rates
- no good match to merger times

but they produce LIGO/Virgo rate

Conclusions

- Milky Way: many evolutionary models...
  (agreement: rates, merger times)
- LIGO/Virgo: very few (unphysical?) models...
  (but these models in disagreement with Milky Way observations)

LIGO/Virgo NS-NS merger: formation mechanism unknown... unless:

1. detection of NS-NS merger in elliptical was a statistical fluke
2. if above not true: solution in untested part of parameter space
3. if above not true: classical binary evolution model needs revision
4. if above not true: different model must be at work...

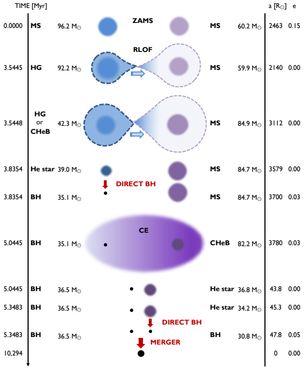
BH-BH formation: broad perspective

LIGO detections: outbreak of models

- PopII/I BH-BH: isolated binary evolution (90% stars in cosmos)
- PopII/I BH-BH: dynamics/globular clusters (0.1%)
  $X_{\rm BHBH} \approx 10^{-5}$–$10^{-7}$ $\rm M_\odot^{-1}$ (binary) vs $X_{\rm BHBH} \approx 10^{-4}$ (dynamics)
  rate_binary / rate_dynamics $\approx$ 10–100
- Primordial BH-BH: density fluctuations after Big Bang
- PopIII BH-BH: first massive stars ($\lesssim$ 1%)
- PopII/I BH-BH: rapid rotation (homogeneous evol.) (10%)
- exotic BH-BH: e.g., nuclear star clusters: dynamics (?)
  e.g., massive star formation in AGN disk (?)
  e.g., single star core splitting (?)

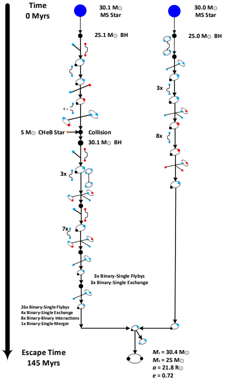
GW150914: 30 + 30 $M_\odot$ massive BH-BH merger

binary evolution



credit: W.Gladysz – StarTrack simulation

dynamics/globular clusters

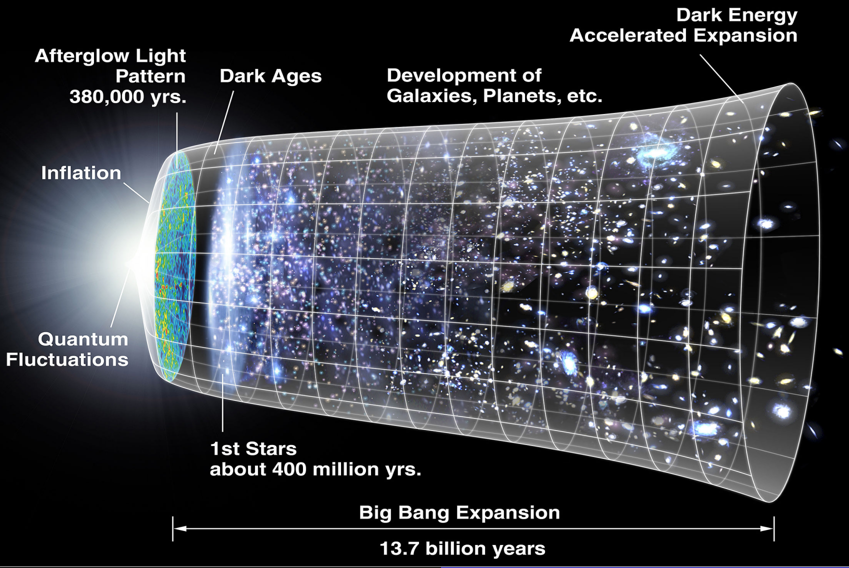


credit: A.Askar – MOCCA simulation

1) binary evolution and dynamics: can produce massive BH-BH mergers

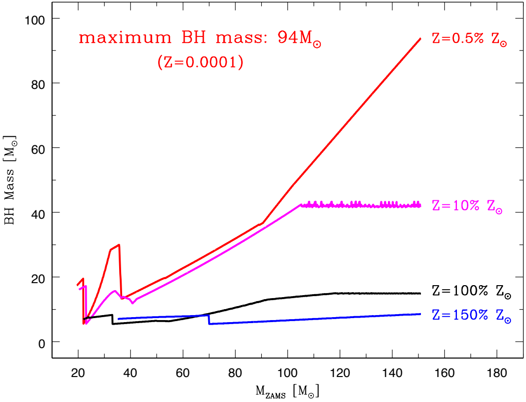
2) because of (1): the origin of BH-BH mergers unknown...

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:

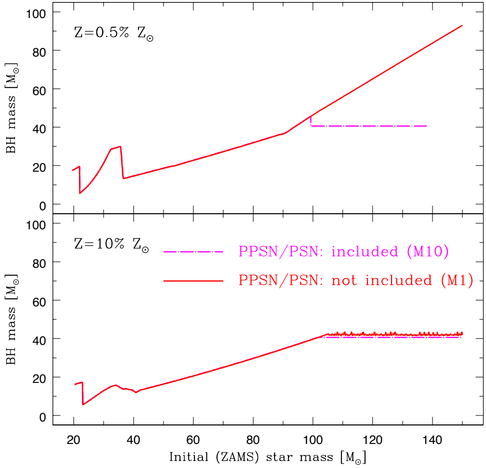
stellar models: $\sim 130\ M_\odot$
(Spera et al. 2015)

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

– present update (2016):

BH mass down: $\lesssim 50\ M_\odot$
(pair-instability pulsations)

Maximum stellar-origin BH mass: $\sim 50 M_\odot$



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

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

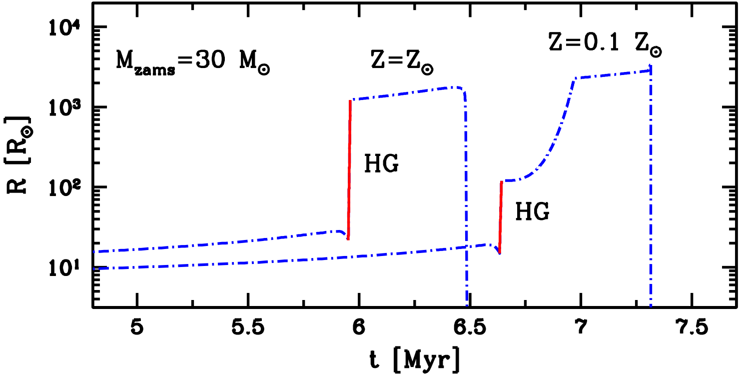
NS/BH mass spectrum:

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)

Common envelope: orbital decay at low Z

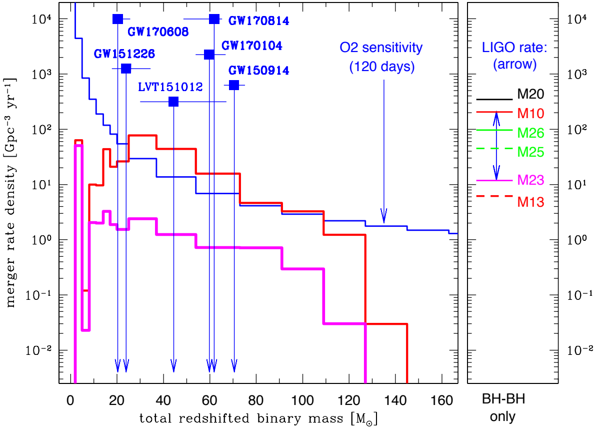
(Belczynski et al. 2010, ApJ 715, L138; Pavlovskii et al. 2017, MNRAS 465, 2092)



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 50 times ($Z_\odot$ -> 0.1 $Z_\odot$)

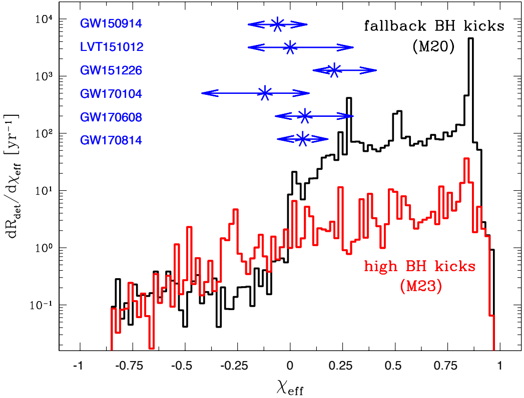
BH-BH mergers: LIGO 120 days of O2 (70 Mpc)



LIGO: GW170608: $12 + 7\ M_\odot$, GW151226: $14 + 8\ M_\odot$, LVT151012: $23 + 13\ M_\odot$
GW170104: $31 + 19\ M_\odot$, GW170814: $31 + 25\ M_\odot$, GW150914: $36 + 29\ M_\odot$

Predictions vs LIGO/Virgo effective spins

$$\chi_{\rm eff} = (M_1 a_1 \cos\theta_1 + M_2 a_2 \cos\theta_2)/(M_1 + M_2)$$



if LIGO/Virgo effective spins continue at low values:

–> efficient angular momentum transport in stellar interiors

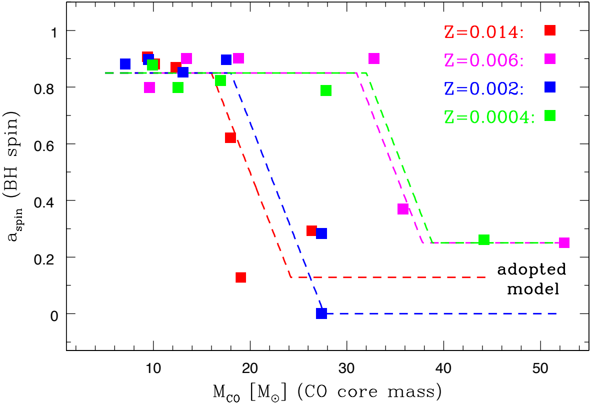
BH HMXBs with estimated BH spins

1. Cyg X-1: 15 $M_\odot$ BH + 19 $M_\odot$ O star, $a_{\rm BH} > 0.98$
   fate: RLOF -> SN Ib/c -> NS formation:
   70% disruption, 29% wide BH-NS, 1% merging BH-NS
2. LMC X-1: 11 $M_\odot$ BH + 32 $M_\odot$ O star, $a_{\rm BH} = 0.92$
   fate: short orbital period; CE during MS -> CE merger
3. M33 X-7: 16 $M_\odot$ BH + 70 $M_\odot$ O star, $a_{\rm BH} = 0.84$
   fate: short orbital period; CE during MS -> CE merger

BH HMXBs with high spins: not likely progenitors of BH-BH mergers...

If LIGO/Virgo BH spins low: then LIGO/Virgo BHs are formed in different way than Galactic HMXB BHs...

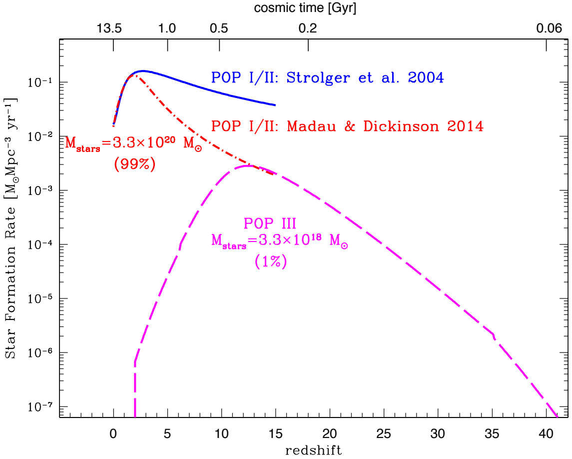
BH natal spin model: from the Geneva code



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

– high-mass BHs ($\gtrsim$ 30 $M_\odot$, strong winds): low natal spins ($a_{spin} \approx 0.1$)

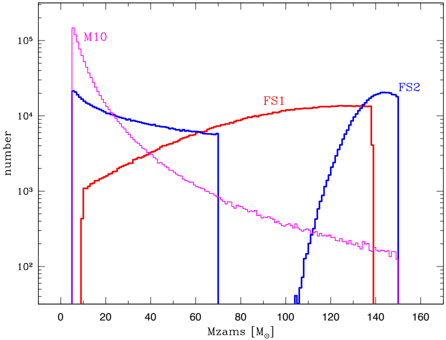
Star formation history: Pop I/II vs Pop III stars



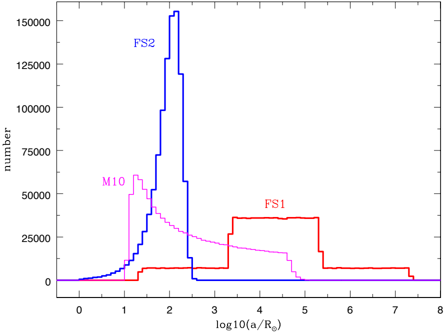
Pop I/II: uncertain for z>2, Pop III: much smaller contribution

Population III binary initial conditions:

IMF



orbital separations



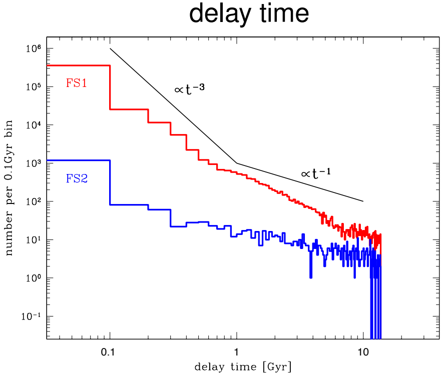
M10 – Pop I/II (Sana et al. 2012) $X_{\rm BHBH} \approx 10^{-5}$–$10^{-7}$ $M_\odot^{-1}$

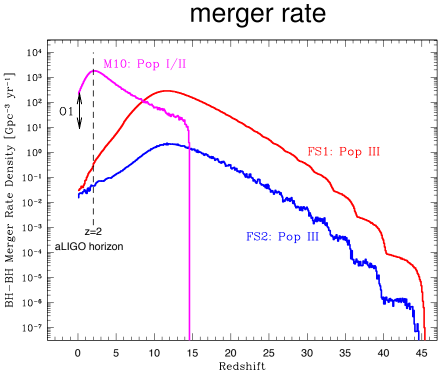
FS1 – Pop III: large dark matter halos (2000 AU) $X_{\rm BHBH} \approx 10^{-4}$ $M_\odot^{-1}$

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

Pop III: potentially 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)

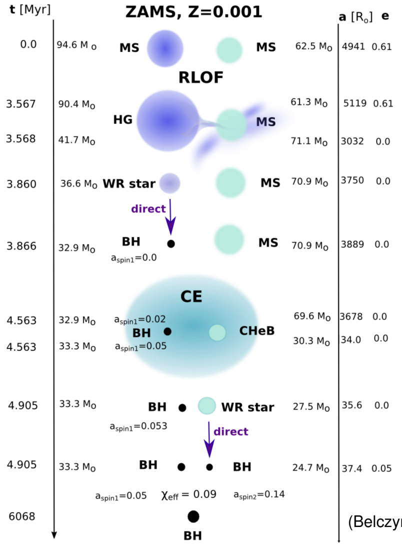
– O1/O2 LIGO BH-BH merger rate: 12–213 $\rm Gpc^{-3}\ yr^{-1}$

Pop III BH-BH rates: 3 orders below LIGO, 4 orders below Pop I/II

Conclusions

- LIGO/Virgo NS-NS merger: formation mechanism unknown...
- LIGO/Virgo BH-BH mergers: many formation channels...
  - binary channel: high rates, masses OK, spins not OK
  - dynamical channel: low rates, masses OK, spins?
- astro implications: doubly limited
  - implications: valid only within a given BH-BH origin model
  - within each model: multiple (untested) possibilities
- channel discrimination: may be very hard to do, but
  - BH spins: semi-aligned/random? (binary/dynamical)
  - BH mass: $M_{\rm BH} \approx 50$–$130\ {\rm M}_{\odot}$ and $a_{\rm BH} \sim 0.6$? (dynamical)
  - BH-BH rate: $\gtrsim 100\ {\rm Gpc}^{-3}\ {\rm yr}^{-1}$? (binary)
- Pop III BH-BH mergers: not likely as LIGO/Virgo sources

GW170104: claimed to originate from dynamics, but...



LIGO: $-0.42 < \chi_{\rm eff} < 0.09$ (90% credible)

$$\chi_{\rm eff} = (M_1 a_1 \cos\theta_1 + M_2 a_2 \cos\theta_2)/(M_1 + M_2)$$

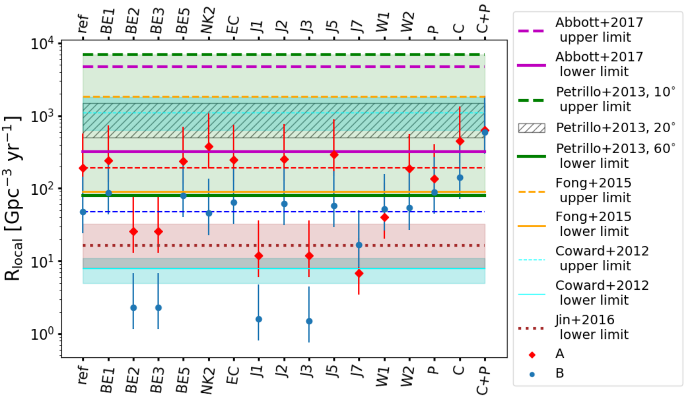
binary evolution can explain GW170104:

- low metallicity: $Z < 10\%\, Z_\odot$
- CE: during CHeB
- long delay: 5 Myr + 6 Gyr
- aligned BH spins: tilt $= 0$ deg?
- BH spin: $a_1 = 0.0$ -> $a_1 = 0.05$
  $a_2 = 0.14$ -> $a_2 = 0.14$

$\chi_{\rm eff,max} = 0.09$ (OK with observations)

(Belczynski, Klencki, Meynet, Fryer, Brown, et al. 2018, submitted)

NS-NS merger rates: observations vs predictions

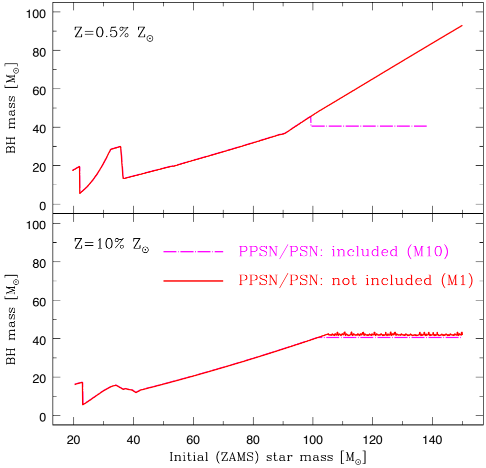


– NS-NS upto 1000 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$: but over-production of BH-BH mergers...

– Diamonds/Circles: pop. synthesis models with different Common Envelope

do BH-BH progenitors evolve through a different CE than NS-NS systems?

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

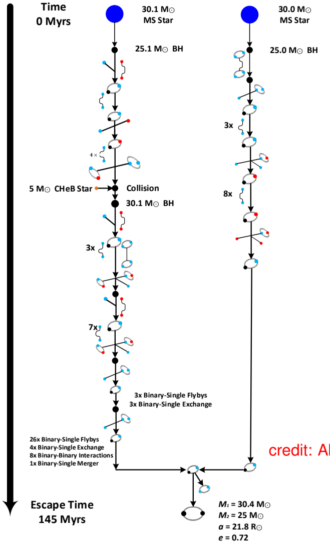
PPSN: Pair-instability Pulsation SN
($M_{\rm He} \sim$ 45–65 $M_\odot$)
black hole: and severe mass loss

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)

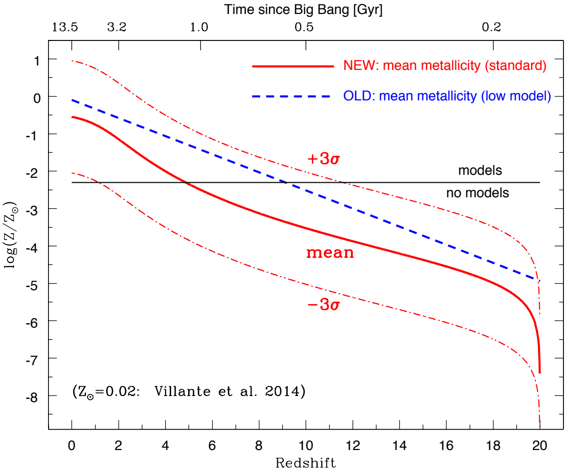
Formation of BH-BH merger: dynamics



- globular cluster: 1.2×10^6 stars
- low metallicity: $Z < 10\% \, Z_\odot$
- dynamical interactions: 40!
- BH-BH system: kicked out of the cluster
- BH spin direction: isotropic distribution

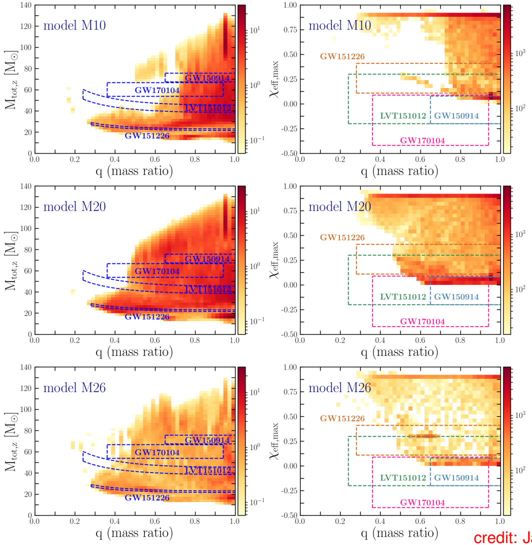
credit: Abbas Askar (Warsaw): MOCCA simulation

Metallicity evolution:



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

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: doubly conservative

credit: Jakub Klencki (Warsaw)