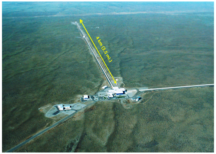
Binary Models versus LIGO/Virgo data



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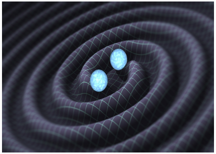
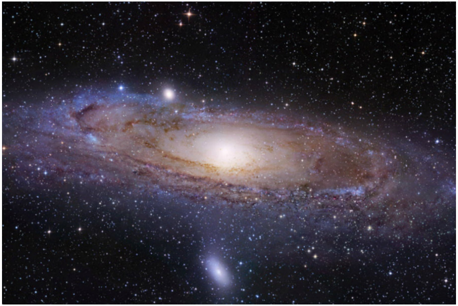


– modeling: formation channels, input physics
– BH-BH: merger rate, masses, effective spins
– NS-NS: merger rate and host galaxy

major formation scenarios: stars

isolated binaries:



– spirals, ellipticals, dwarf galaxies
– stellar/binary evolution
– 99% of stars
– formation efficiency: $X_{\rm BHBH} \approx 10^{-6}$

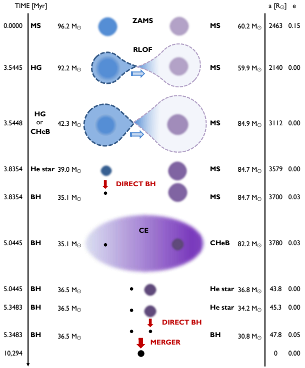
dynamical interactions:

– globular, nuclear, open clusters
– dynamics + stellar/binary evolution
– 0.1% of stars
– formation efficiency: $X_{\rm BHBH} \approx 10^{-4}$

+ some exotica: triple stars, single stars, binaries in AGN disks, PBHs...

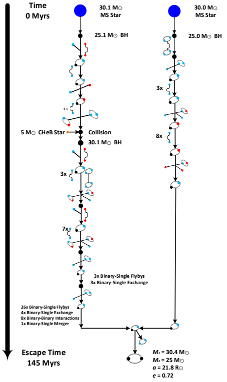
GW150914: 30 + 30 $M_\odot$ massive BH-BH merger

binary evolution



credit: W.Gladysz – StarTrack simulation

dynamics/globular clusters

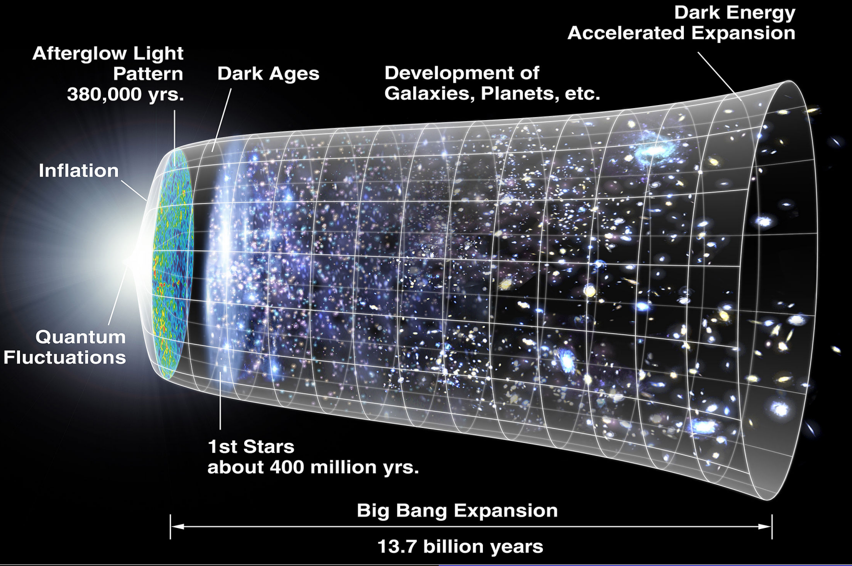


credit: A.Askar – MOCCA simulation

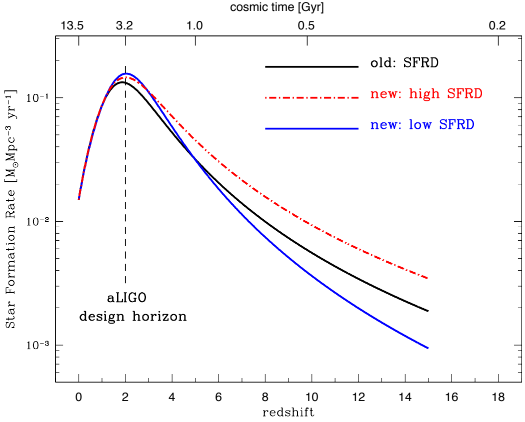
1) binary evolution and dynamics: can produce massive BH-BH mergers

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

modeling: synthetic universe



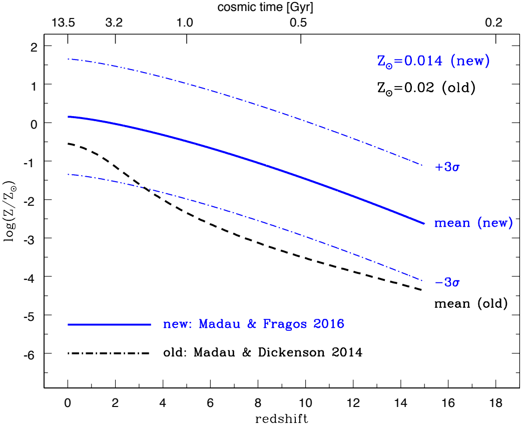
Cosmic Star Formation Rate SFR (z): Pop I/II



– 2 new SFRs: low and high (uncertainty range: Piero Madau)

– old versus new: not much change (until $z = 2$)

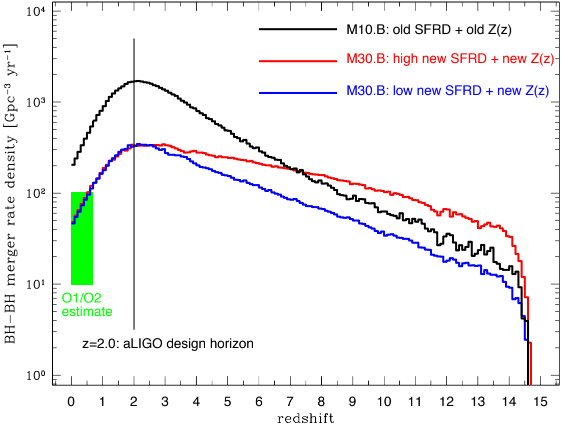
Cosmic Metallicity Evolution Z(z): Pop I/II



– new Z(z): high metallicity of star forming gas at a given z

– old Z(z): low metallicity of star forming gas at a given z

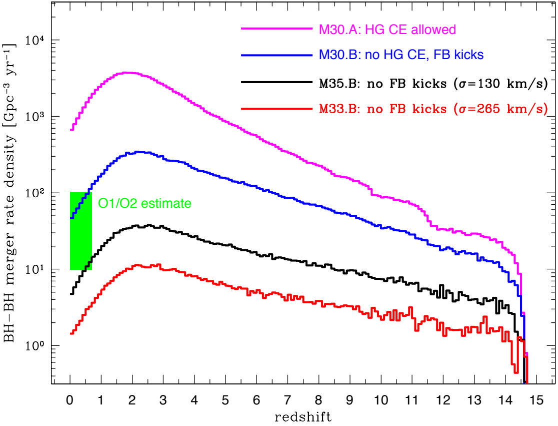
BH-BH merger rate: effect of SFR(z) and Z(z)



– SFR(z): almost no impact on merger rates ($z < 2$)

– Z(z): significant impact on merger rates (BH-BH/BH-NS)

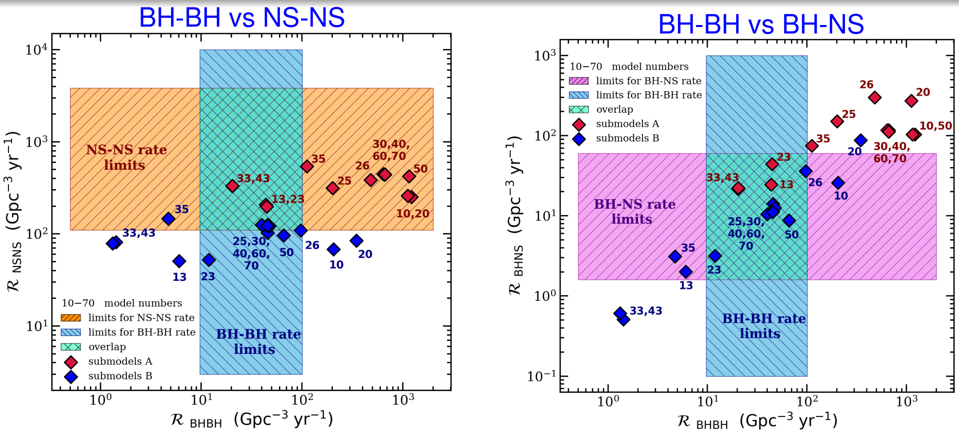
BH-BH merger rate: effect of CE and SNe kicks



– Common Envelope: $\sim$ 1 order of mag. change of merger rates

– Natal Kicks: $\sim$ 1 order of mag. change of merger rates

Models of BH-BH/BH-NS/NS-NS with new physics:

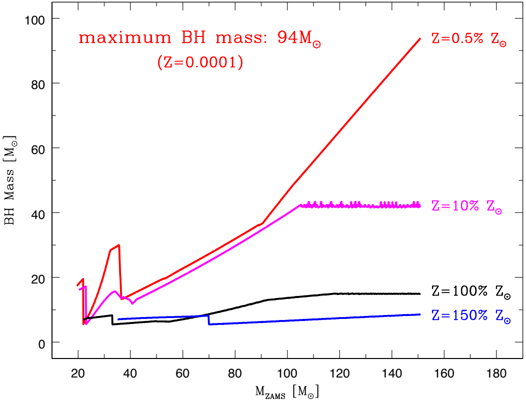


1) some models: fit all rates (e.g., M30.B or M33.A)

2) all models: available at www.syntheticuniverse.org

BH mass spectrum: maximum BH mass

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



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

– past updates:

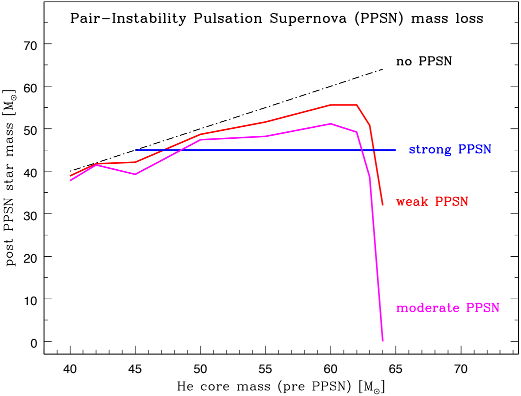
stellar models: $\sim 130\ M_\odot$
(Spera et al. 2015)

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

– present update (2019):

BH mass: $\lesssim 40 - 60\ M_\odot$
(pair-instability pulsations)

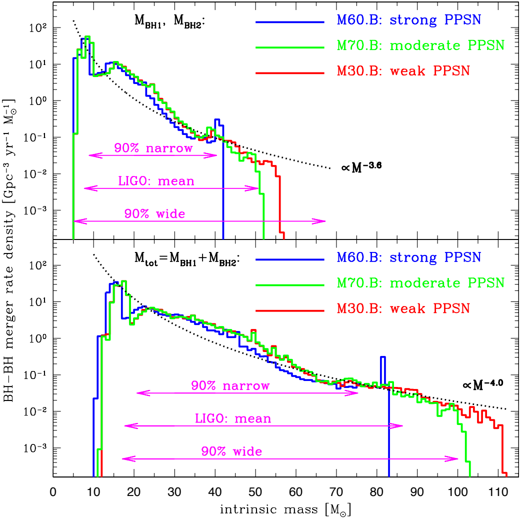
Pair-instability Pulsation Supernovae: PPSN



– no PPSN/PSN: any BH mass allowed (limits from: IMF, winds, SN)

– PPSN/PSN: second mass gap (no close binary BHs with $M_{\rm BH} \sim 60 - 130\ {\rm M}_{\odot}$)

Maximum stellar-origin BH mass: $\sim 60 M_\odot$



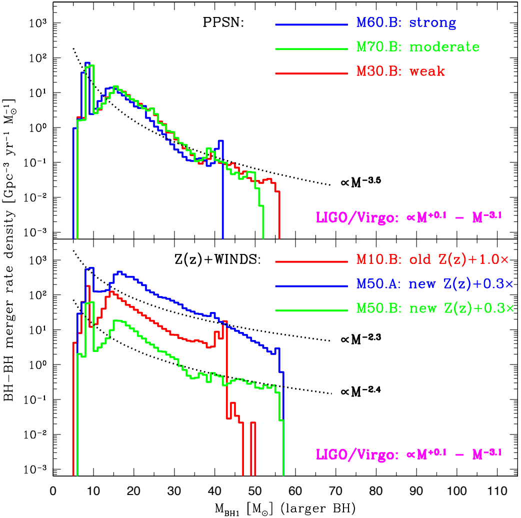
new NS/BH mass spectrum:

neutron stars:	$1 - 2\ M_\odot$
first mass gap:	$2 - 5\ M_\odot$
black holes:	$5 - 60\ M_\odot$
second mass gap:	$60 - 130\ M_\odot$
black holes:	$130 - ???\ M_\odot$

BH masses:

- LIGO/Virgo will test PPSN/PSN
- all our PPSN/PSN models: are OK so far

Predicted primary BH mass vs LIGO estimates



primary BH mass:

LIGO/Virgo: $\propto M^{-1.6}$

$(\propto M^{+0.1} - M^{-3.1})$

Models: $\propto M^{-2} - M^{-4}$

laying out the problem....

- LIGO/Virgo detected 10 BH-BH mergers: all with $\chi_{\rm eff} \approx 0$
  $\chi_{\rm eff} \equiv (M_1 a_1 \cos\theta_1 + M_2 a_2 \cos\theta_2)/(M_1 + M_2), \quad a \equiv cJ_{\rm BH}/(GM_{\rm BH}^2)$

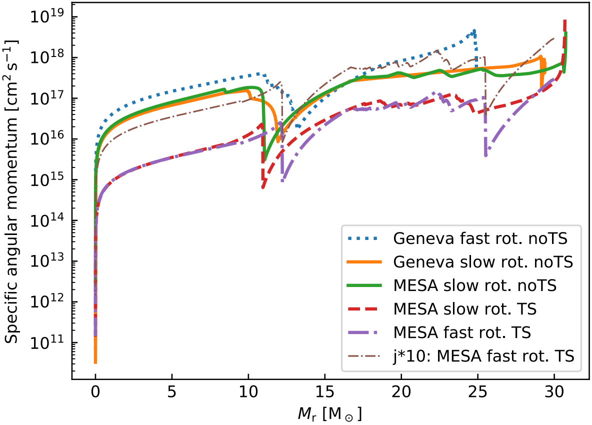
  (1) BH spins in opposite direction ($a_1 \approx a_2 \approx 1$): $\chi_{\rm eff} \approx 0$
  (2) both BH spins in orbital plane ($a_1 \approx a_2 \approx 1$): $\chi_{\rm eff} \approx 0$
  (3) both BH spins very small ($a_1 \approx a_2 \approx 0$): $\chi_{\rm eff} \approx 0$

- EM observations: high BH spins in high mass X-ray binaries
  (M33 X-7: a=0.84, LMC X-1: a=0.92, Cyg X-1: a>0.98)

- what do stellar evolution models predict for BH-BH mergers?

  (1) initial rotation of a massive star
  (2) angular momentum transport through a star
  (3) mass loss that removes angular momentum from a star
  (4) core collapse (supernova?) mass/ang. momentum loss

$M_{zams} = 32\ M_\odot$ at $Z = 0.002$: angular momentum

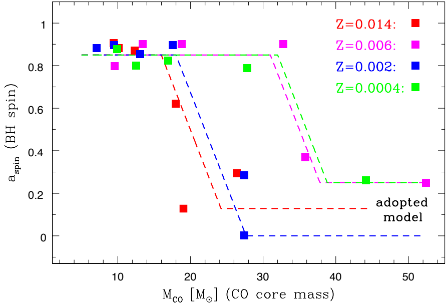


no TS: meridional currents (mild ang. momentum transport)

TS: Tyler-Spruit magnetic dynamo (efficient ang. momentum transport)

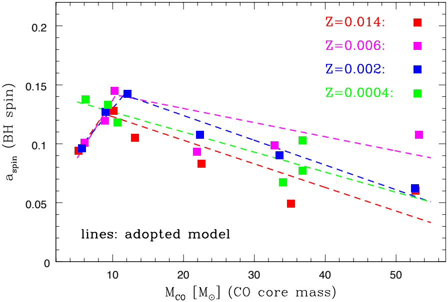
Angular momentum transport in massive stars

Geneva model



Gorges Meynet, Sylvia Ekstrom, Cyril Gregory

MESA model

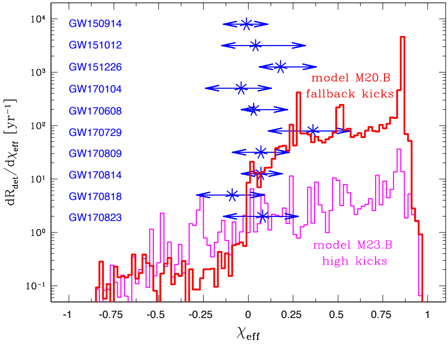


Carl Fields, Sam Jones, Raphael Hirschi

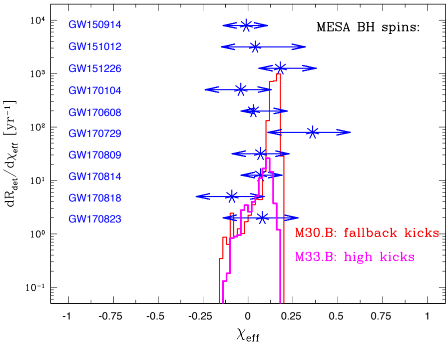
1) Geneva: mild ang. momentum transport (meridional currents)
2) MESA: effective ang. momentum transport (magnetic fields)
3) Fuller: very effective ang. momentum transport ($a_{spin} = 0.01$)

BH-BH effective spins parameter: $\chi_{\rm eff}$

Geneva model



MESA model

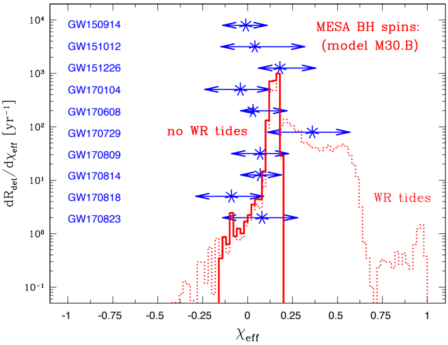


1) Geneva: effective spins too high ($\chi_{\rm eff} \sim$ 0.8 -> 0.7)

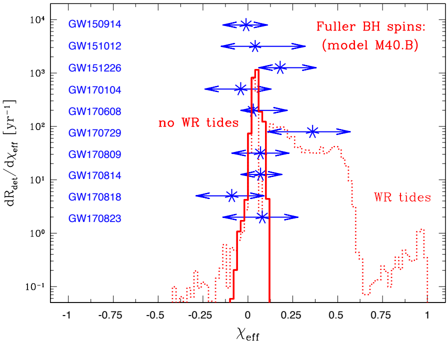
$$\chi_{\rm eff} = (M_1 a_1 \cos\theta_1 + M_2 a_2 \cos\theta_2)/(M_1 + M_2)$$

BH-BH effective spins: tides

MESA model



Fuller model



1) MESA: tides not needed

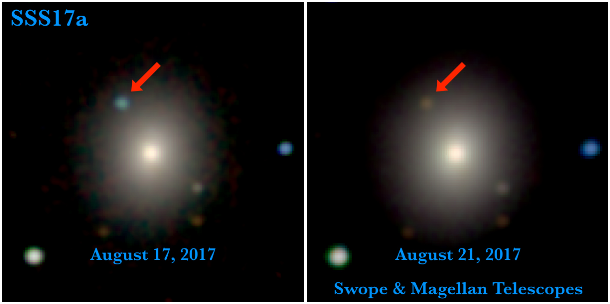
2) Fuller: tides (marginally) needed

but, 2 low p-astro IAS detections with high positive χ_{eff}: may require tides...

Conclusions: BH-BH

- origin of BH-BH mergers: still unknown
  - – isolated binaries: $\sim$ 90%?
  - – globular clusters: $\sim$ 10%?
- LIGO/Virgo BH-BH mergers: if from isolated binary evolution
  - – merger rate density: OK
  - – BH masses: OK
  - – effective spins: OK
- astro implications: from just several models
  - – efficient angular momentum transport
  - – PPSN mass loss required
  - – tidal spin-up possibly detected?

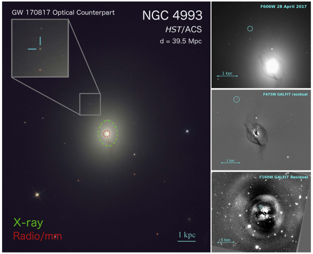
GW170817: first NS-NS merger in gravitational waves



- LIGO/Virgo inspiral detection of: $1.4 - 1.6\ M_\odot$ and $1.2 - 1.4\ M_\odot$ (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)

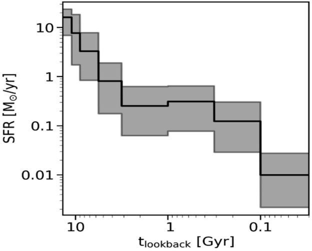
NGC 4993: GW170817 host galaxy star formation

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



NGC 4993:

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

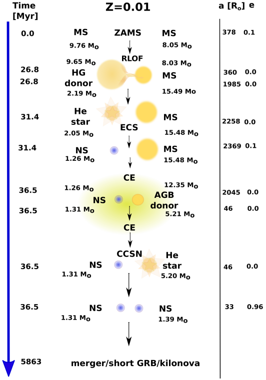


almost no current/recent star formation...

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

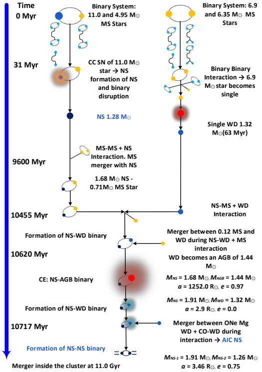
NS-NS merger: in old host galaxies (NGC4993-like)

binary stars:



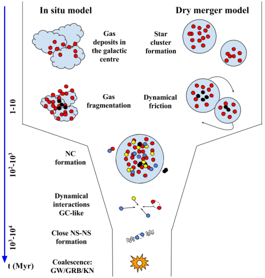
rate: 1×10^{-2} yr^{-1}

globular clusters:



rate: 5×10^{-5} yr^{-1}

nuclear clusters:

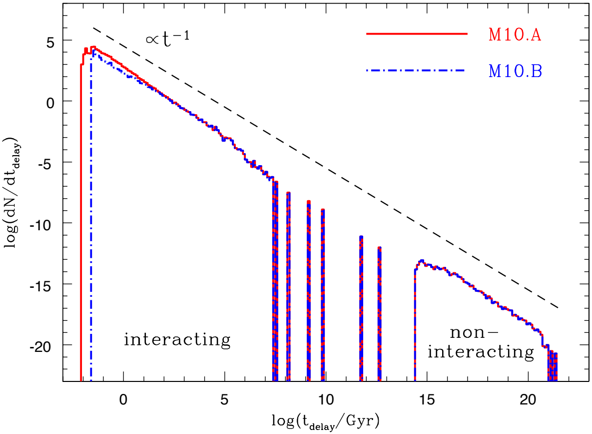


rate: 1×10^{-5} yr^{-1}

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 mergers: delay time distribution



typically short delays: most mergers expected in star forming regions

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

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

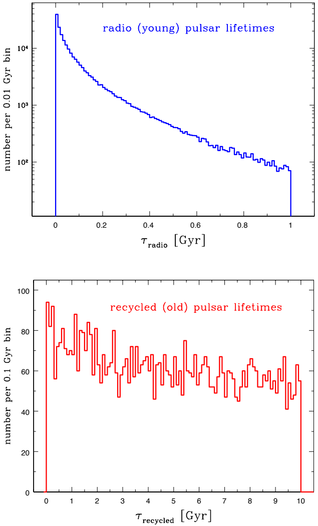
(Belczynski, Bulik, Olejak et al. 12/2018: arXiv:1812.10065)

Galactic NS-NS: merger rate in MW

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

1st estimate: 28–72 Myr^{-1}

2nd estimate: 6.6–190 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)

NS-NS models: merger rate predictions

Population synthesis calculations
(the StarTrack code)

$\sim$ 20 models:

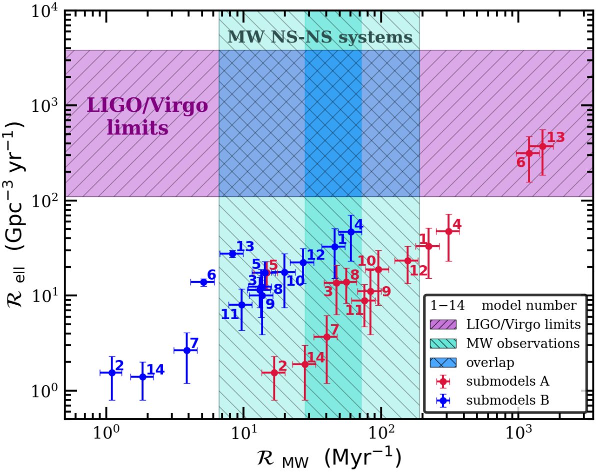
- NS natal kicks
  (Hobbs, ECS, Bray&Eldridge)
- CE effciency
  (0.1–1.0-10)
- RLOF mass loss
  (50%–80%)

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

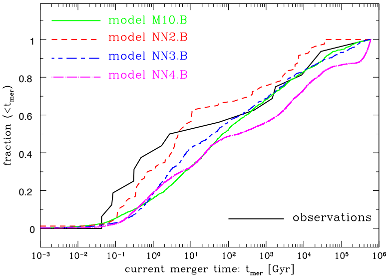
(Belczynski, Bulik, Olejak et al. 12/2018: arXiv:1812.10065)

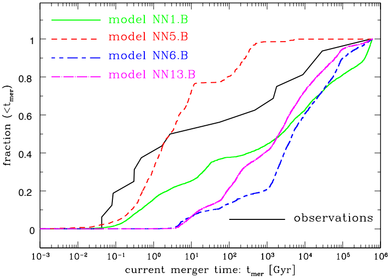
NS-NS models: Milky Way vs Elliptical galaxies



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

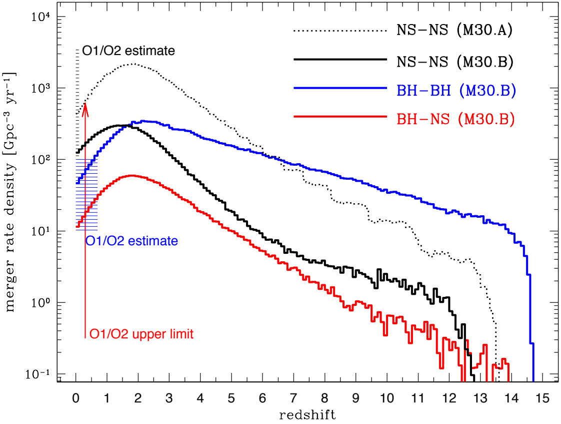
NS-NS: conclusions

- 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 formation process must be at work...

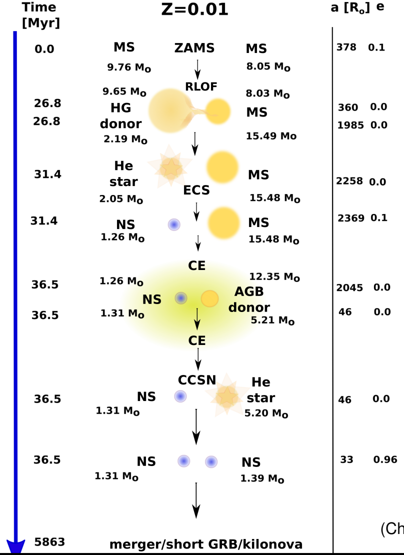
DCO merger rates: comaprison with LIGO/Virgo



– NS-NS: OK match to LIGO/Virgo (but host galaxy issue)

– BH-NS: rate within upper limit (first detection in O3?)

NS-NS merger: stellar/binary evolution



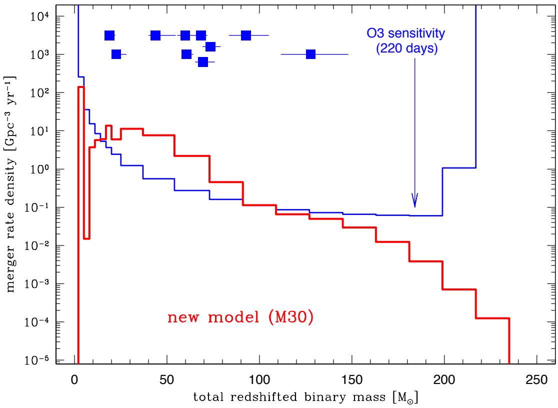
NS-NS merger rate: $\sim 1,000$ Gpc^{-3} yr^{-1}
LIGO/Virgo range: 110–3,840 Gpc^{-3} yr^{-1}

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

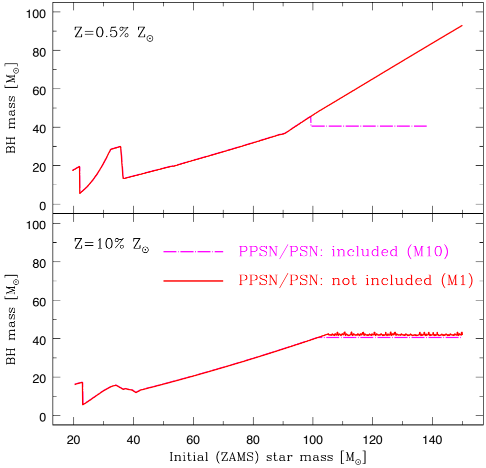
- narrow mass range: $M_{\rm ZAMS} \sim 10$–20 M$_\odot$
- common envelope: 50% binary mergers
- first SNa: $\gtrsim 90\%$ binary disruptions
- common envelope: 20% binary mergers
- short delay: 30 Myr + $\lesssim 1$ Gyr –>
  –> not expected in old ellipticals!

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

BH-BH masses: Pop I/II



Maximum stellar-origin 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

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neutron stars:	$1 - 2\ M_\odot$
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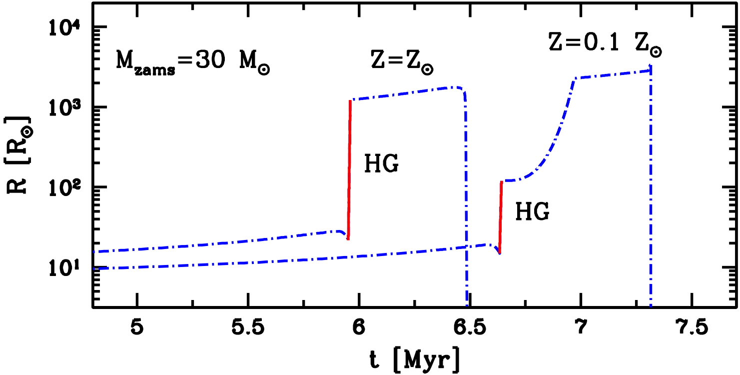
black holes:	$130 - ???\ M_\odot$

(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

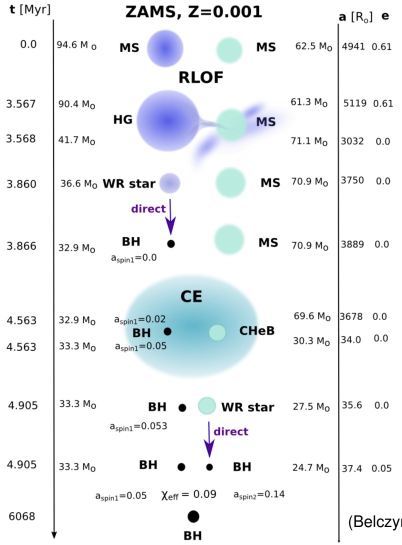
BH-BH progenitors go through CE: at low Z rates up by 50 times ($Z_\odot$ -> 0.1 $Z_\odot$)

BH-BH 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%)
  $X_{\rm BHBH} \approx 10^{-5}$–$10^{-7}$ $M_\odot^{-1}$ (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 (?)

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



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

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

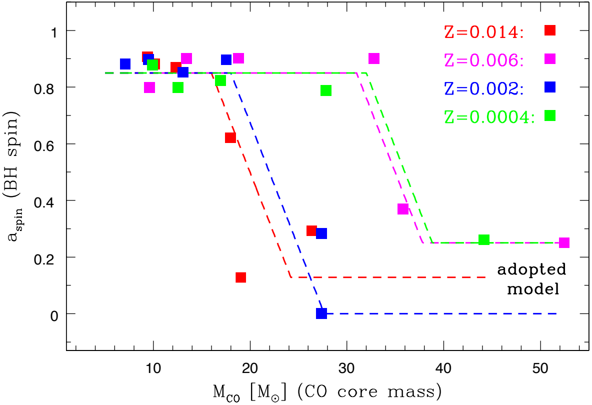
binary evolution can explain GW170104:

- 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)

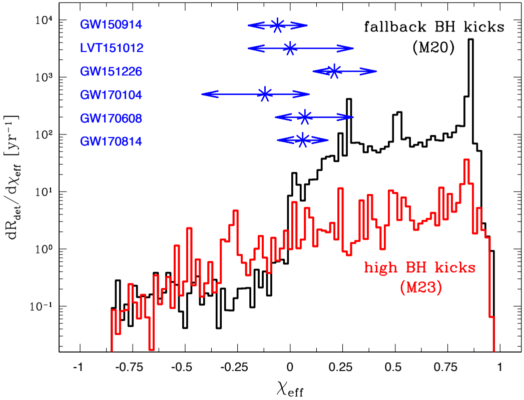
BH natal spin model: from the Geneva code



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

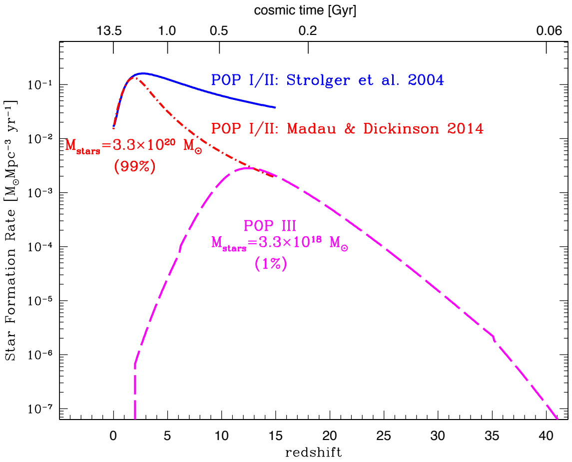
– high-mass BHs ($\gtrsim$ 30 $M_\odot$, strong winds): low natal spins ($a_{spin} \approx 0.1$)

Predictions vs LIGO/Virgo effective spins



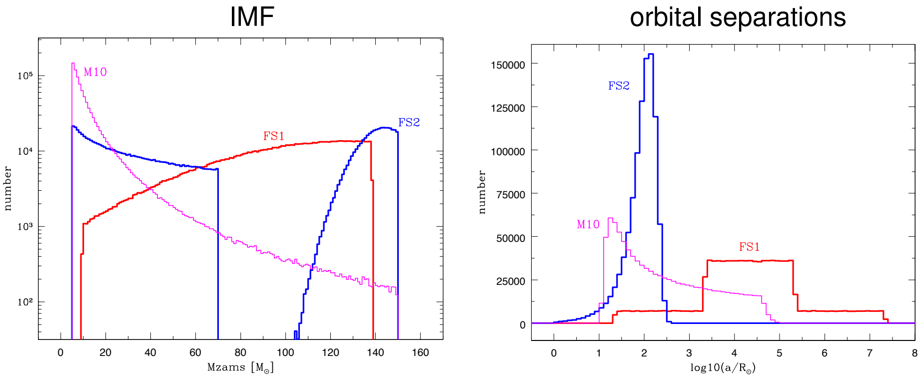
– if LIGO/Virgo effective spins continue at low values:
then even BHs with $M_{\rm BH} < 30\ {\rm M}_\odot$ are born with low spins
–> efficient angular momentum transport in stellar interiors

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:



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

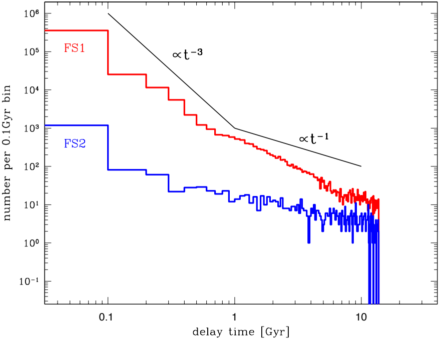
FS1 – Pop III: large dark matter halos (2000 AU) $X_{\rm BHBH} \approx 10^{-4}$ M$_\odot^{-1}$

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

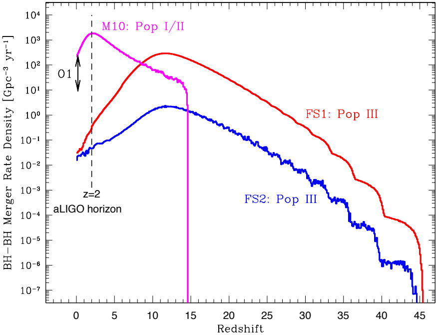
Pop III: potentially very different initial conditions than for PopI/II...

Pop III BH-BH merger rate history:

delay time



merger rate



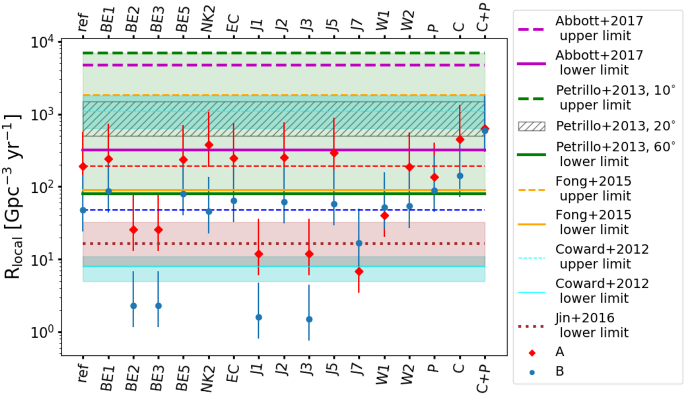
– delay time: $a^{-1}(da/dt)_{\rm GR} \propto t^{-1/4}d(t^{1/4})/dt \propto t^{-1}$
(initial separation distr.: $\sim a^{-1}$, $t_{\rm GR} \propto a^4$: Peters 1964)
– O1/O2 LIGO BH-BH merger rate: 12–213 $\rm Gpc^{-3}\ yr^{-1}$

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

Conclusions

- LIGO/Virgo NS-NS merger: will guide evolutionary physics...
- origin of LIGO/Virgo BH-BH mergers: still unknown
  - binary channel: high rates; but masses OK (spins not OK)
  - dynamical channel: low rates; but masses OK (spins not OK)
- 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

NS-NS merger rates: observations vs predictions

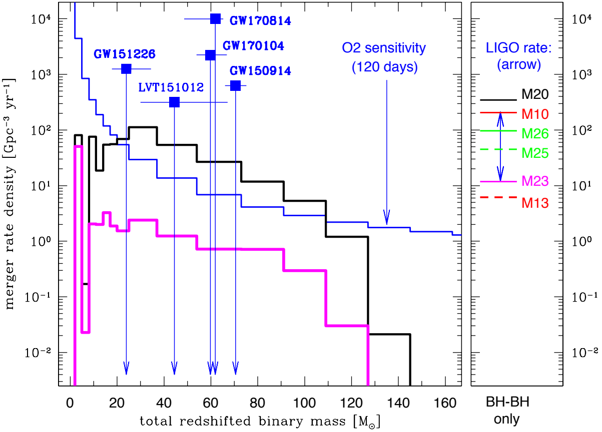


– NS-NS upto 1000 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$: but over-production of BH-BH mergers...

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

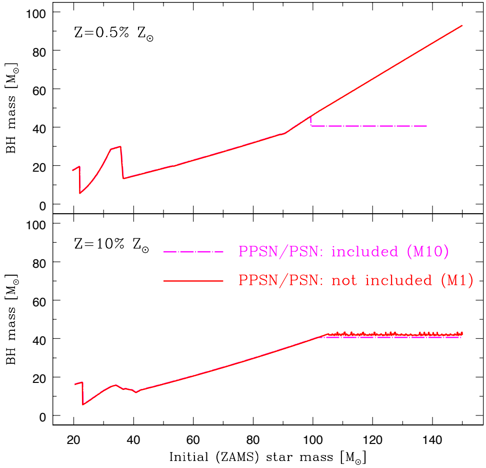
do BH-BH progenitors evolve through a different CE than NS-NS systems?

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



LIGO/Virgo BH-BH mergers: GW151226: $14 + 8\ M_\odot$, LVT151012: $23 + 13\ M_\odot$, GW170104: $31 + 19\ M_\odot$, GW170814: $31 + 25\ M_\odot$, GW150914: $36 + 29\ M_\odot$

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



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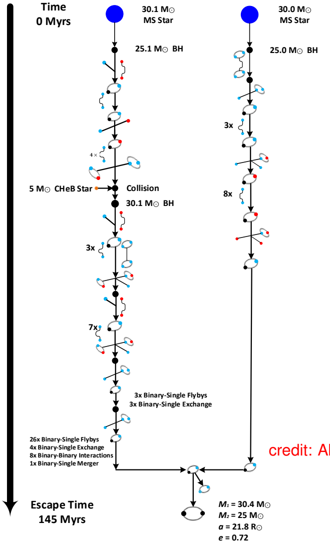
(Belczynski, Heger, Gladysz, Ruiter, Woosley, Wiktorowicz, Chen, Bulik, O'Shaughnessy, Holz, Fryer, Berti: A&A 2016)

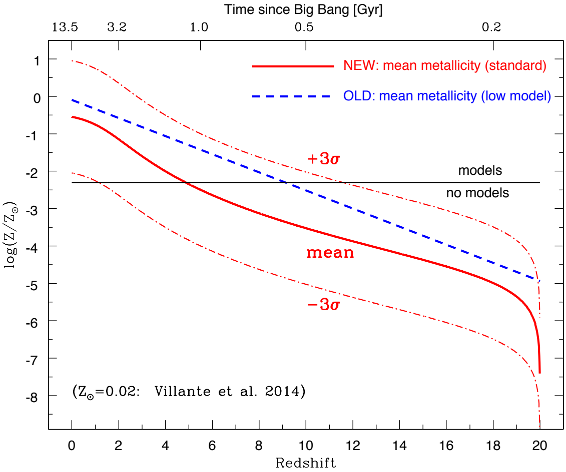
Formation of BH-BH merger: dynamics



- 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

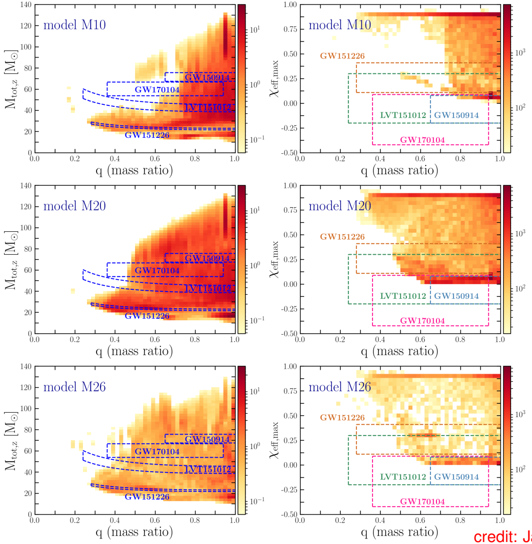
credit: Abbas Askar (Warsaw): MOCCA simulation

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)