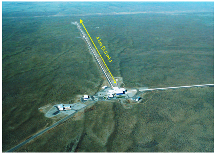
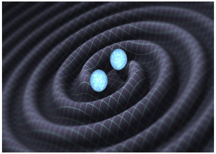
# BH-BH effective spins and masses



Chris Belczynski[1]
T.Bulik, D.Holz, P.Madau
R.O'Shaughnessy, E.Berti
C.Fryer, J.Klencki, G.Meynet
C.Fields, N.Singh, K.Nomoto, D.Brown, M.Chruslinska, A.Olejak
S.Jones, S.Leung, N.Pol, S.Mondal, P.Drozda, D.Wysocki, S.Ekstrom
R.Hirschi, L.Zdunik, C.Georgy, M.Giersz, A.Askar, J.P.Lasota
M.McLaughlin, D.Lorimer, O.Korobkin, M.Davies, E. van den Heuvel, ...
[1] Copernicus Center (Warsaw), Polish Academy of Sciences

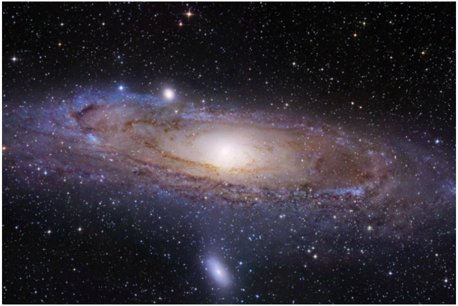


– BH-BH: effective spins

– BH-BH: masses

# major formation scenarios: stars

isolated binaries:



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

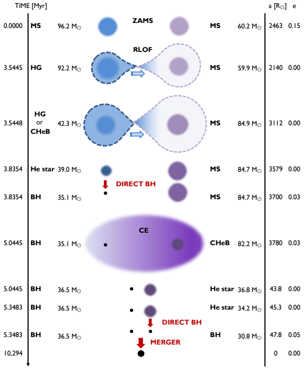
dynamical interactions:

- – globular, nuclear, open clusters
- – dynamics + stellar/binary evolution
- – 0.1 – 1% of stars
- – formation effciency: $X_{\rm BHBH} \approx 10^{-4}$

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

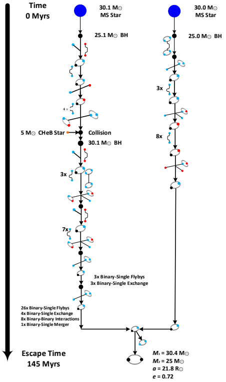
# GW150914: 30 + 30 $\mathrm{M}_{\odot}$ massive BH-BH merger

## binary evolution



credit: W.Gladysz – StarTrack simulation

## dynamics/globular clusters

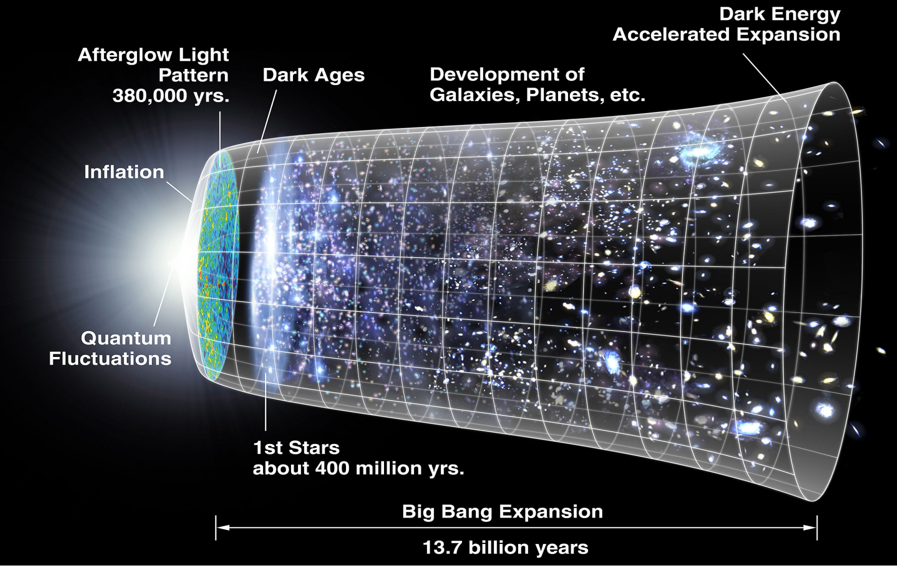


credit: A.Askar – MOCCA simulation

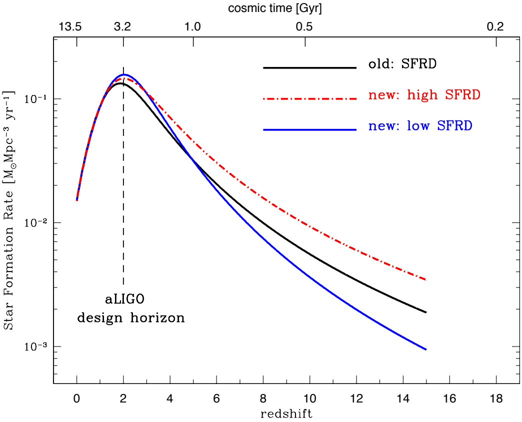
1) binary evolution and dynamics: can produce massive BH-BH mergers

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

# modeling: synthetic universe



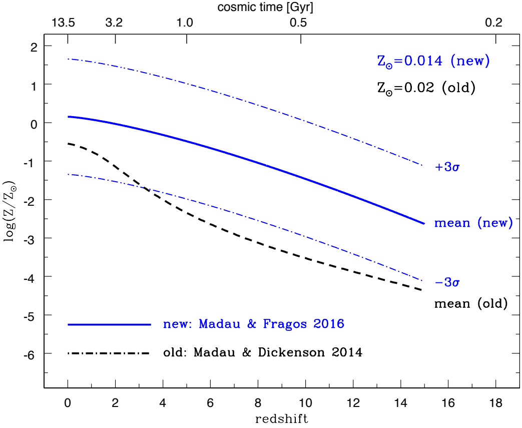
# Cosmic Star Formation Rate SFR (z): Pop I/II



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

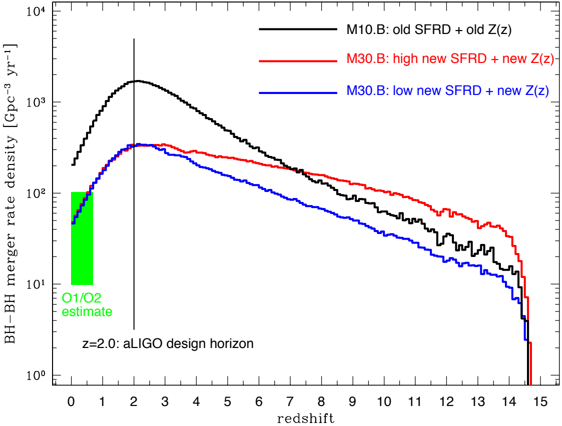
– old versus new: not much change (until $z = 2$)

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



- – new Z(z): metallicity of (star forming) gas at a given *z* (high)
- – old Z(z): metallicity of gas/stars at a given *z* (low)

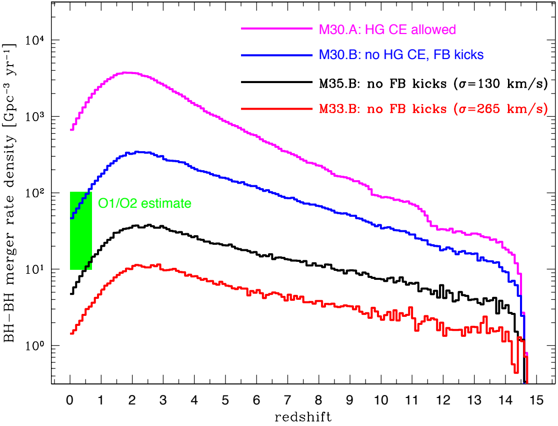
# BH-BH merger rate: effect of SFR(z) and Z(z)



– old models: (too) high rates – low Z(z): star forming gas

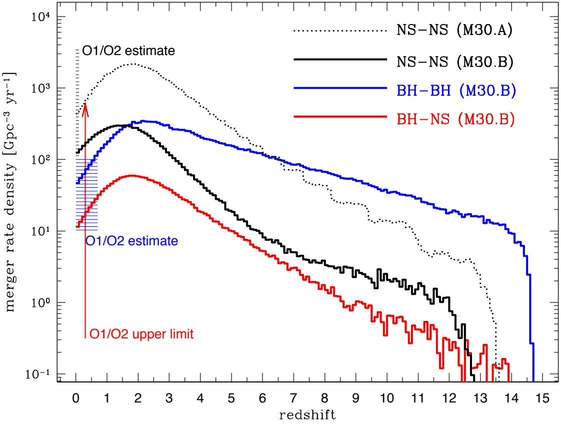
– new models: (nicely) low rates – high Z(z): gas/stars

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



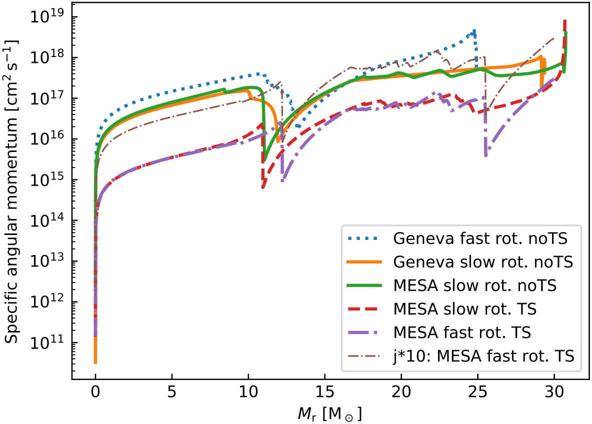
- **Common Envelope:** ∼ 1 order of mag. change of rates
- **Natal Kicks:** ∼ 1 order of mag. change of rates

# 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?)

# $M_{\rm zams} = 32\ {\rm M}_\odot$ at $Z = 0.002$: angular momentum

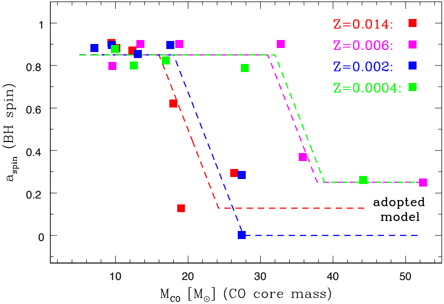


TS: Tyler-Spruit magnetic dynamo (efficient ang. momentum transport)

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

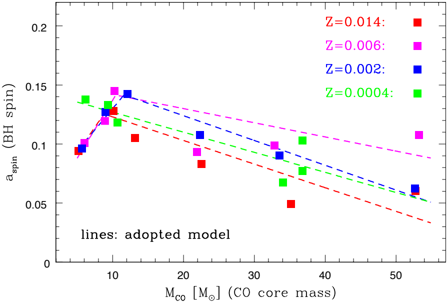
# Angular momentum transport in massive stars

Geneva model



Gorges Meynet, Sylvia Ekstrom, Cyril Gregory

MESA model



Carl Fields, Sam Jones, Raphael Hirschi

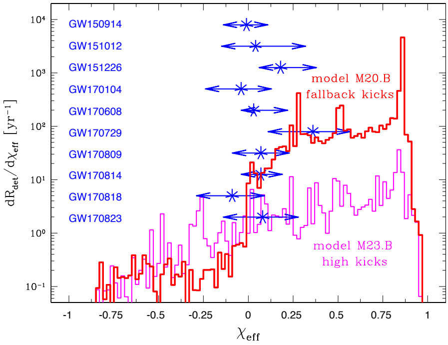
1) Geneva: mild ang. momentum transport (meridional currents)

2) MESA: effective ang. momentum transport (magnetic fields)

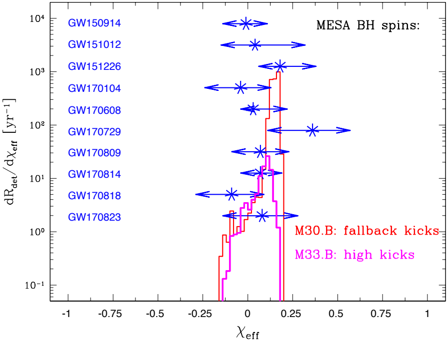
2) Fuller: very effective ang. momentum transport ($a_{\rm spin} = 0.01$)

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

Geneva model



MESA model

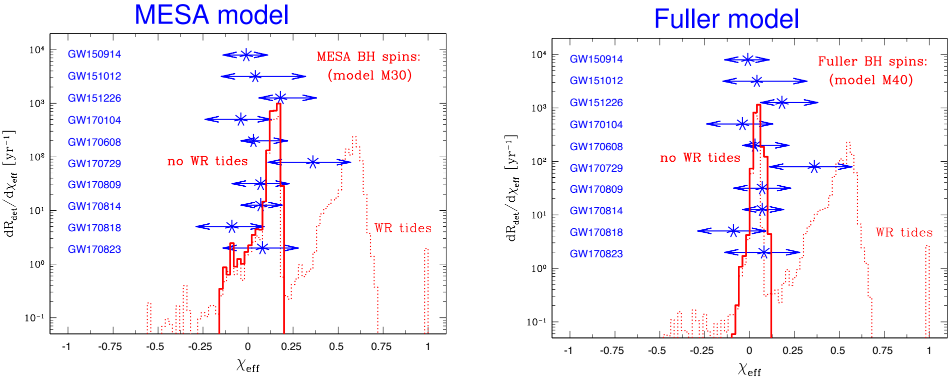


1) Geneva: effective spins too high ($\chi_{\rm eff} \sim$ 0.8 -> 0.7)

2) MESA: effective spins OK ($\chi_{\rm eff} \sim$ 0.15 -> 0.08)

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

# BH-BH effective spins: tides



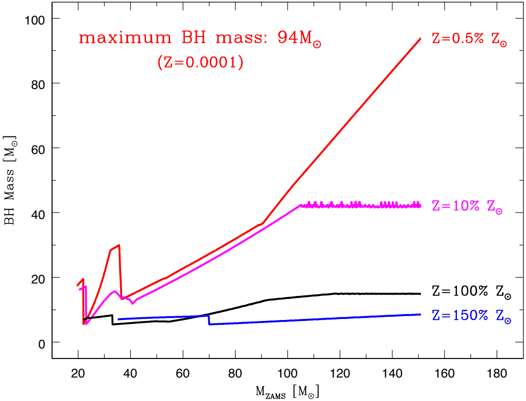
1) MESA: tides not needed

2) Fuller: tides (marginally) needed

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

# BH mass spectrum: maximum BH mass

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



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

– past updates:

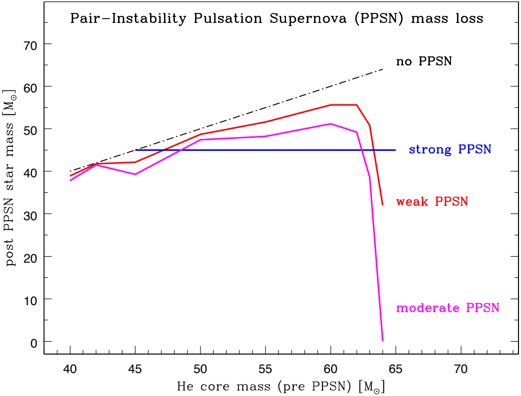
stellar models: $\sim 130\ \mathrm{M}_\odot$
(Spera et al. 2015)

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

– present update (2019):

BH mass down: $\lesssim 55\ \mathrm{M}_\odot$
(pair-instability pulsations)

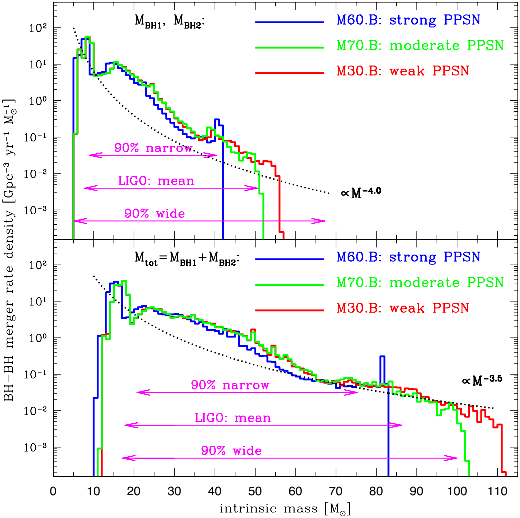
# Pair-instability Pulsation Supernovae: PPSN



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

– PPSN/PSN: second mass gap (no BHs with $M_{\rm BH} \sim 55 - 130\ {\rm M}_\odot$)

# Maximum stellar-origin BH mass: $\sim 55 M_\odot$



new NS/BH mass spectrum:

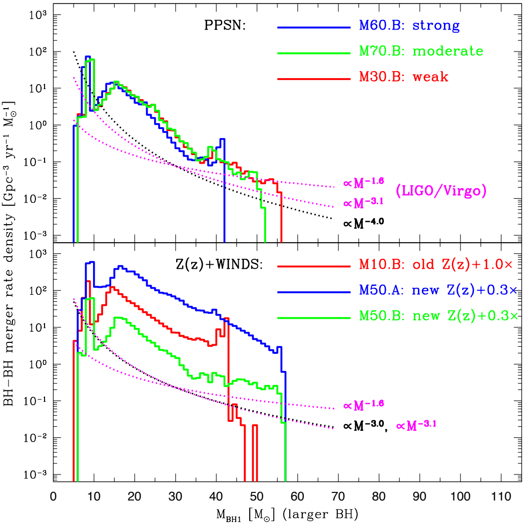
| | |
|---|---|
| neutron stars: | $1 - 2\ M_\odot$ |
| first mass gap: | $2 - 5\ M_\odot$ |
| black holes: | $5 - 55\ M_\odot$ |
| second mass gap: | $55 - 130\ M_\odot$ |
| black holes: | $130 - ???\ M_\odot$ |

BH masses:

– LIGO/Virgo will test PPSN/PSN

– so far: all PPSN/PSN are OK

# Predicted $BH_1$ mass vs LIGO/Virgo estimates



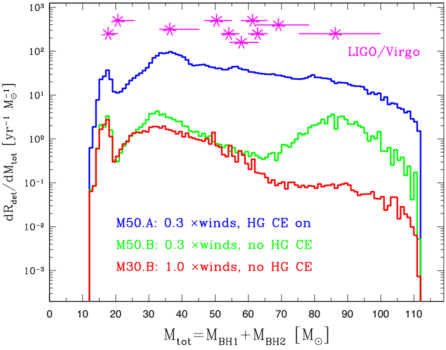
primary BH mass:

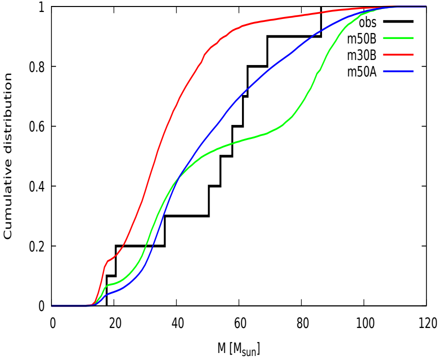
LIGO/Virgo: $\propto M^{-1.6}$

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

Models: $\propto M^{-3} - M^{-4}$

# Predicted BH-BH mass vs LIGO/Virgo observations





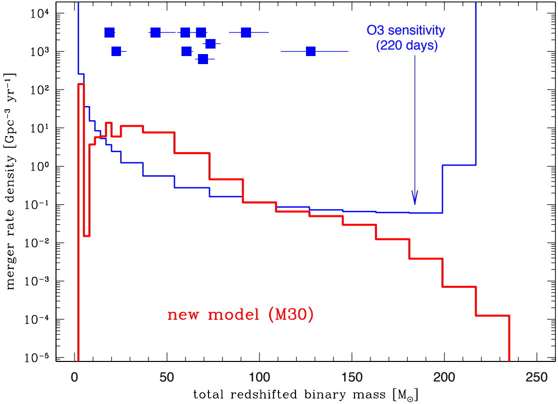
Observations: overaboundance of $M_{\text{tot}} \sim 60\ \mathrm{M}_\odot$ BH-BH meregrs?

KS test: 10% – 50% chance that observations are from these models

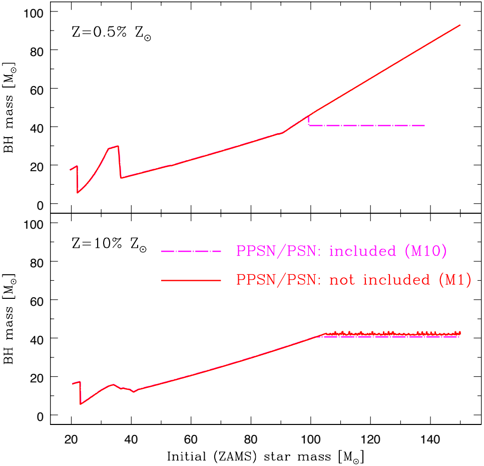
# Conclusions: BH-BH

- evolution of stars: new updates/revisions available
- 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
  - rapid cosmic chemical evolution
  - weak PPSN mass loss
  - efficient angular momentum transport

# 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 $\rm M_\odot$)
no remnant: entire star disruption

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

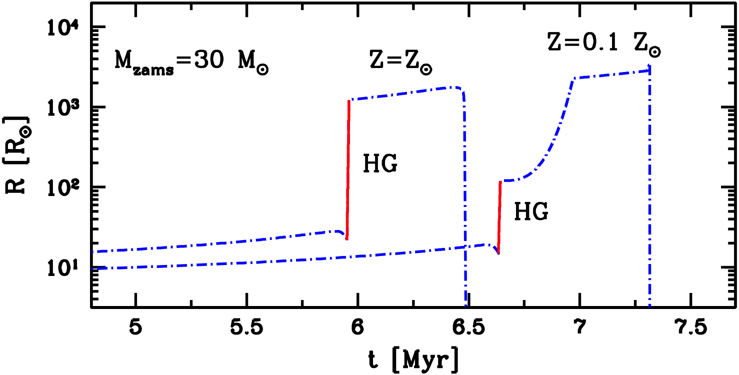
NS/BH mass spectrum:

| | |
|---|---|
| neutron stars: | $1 - 2\ \rm M_\odot$ |
| first mass gap: | $2 - 5\ \rm M_\odot$ |
| black holes: | $5 - 50\ \rm M_\odot$ |
| second mass gap: | $50 - 130\ \rm M_\odot$ |
| black holes: | $130 - ???\ \rm M_\odot$ |

(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

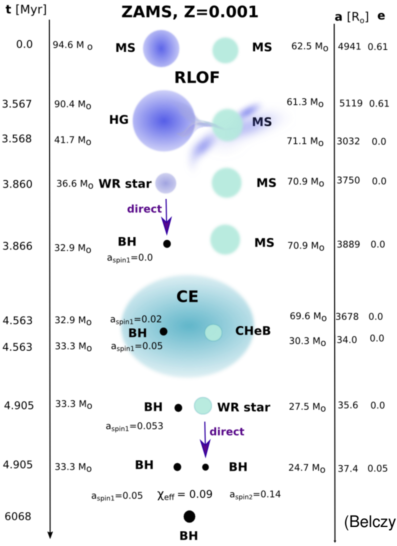
BH-BH progenitors go through CE: at low Z rates up by 50 times ($Z_\odot$ -> 0.1 $Z_\odot$)

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

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



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

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

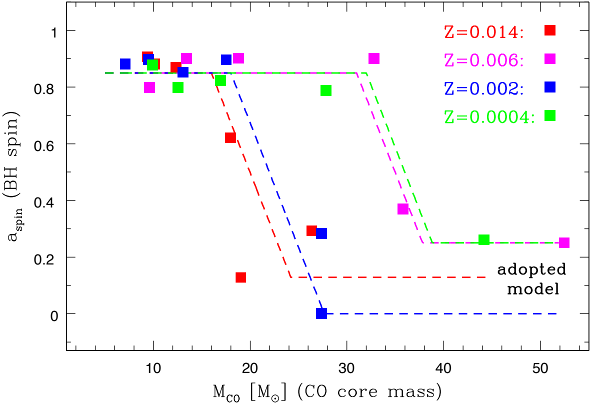
binary evolution can explain GW170104:

- 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)

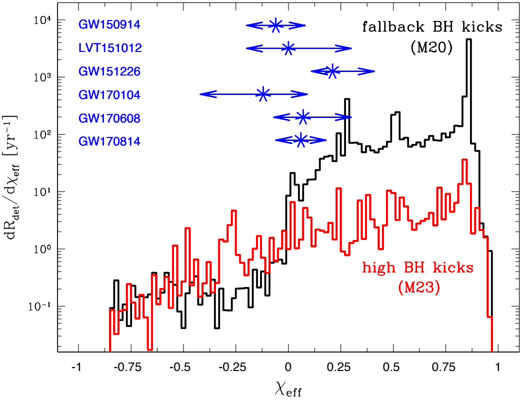
(Belczynski, Klencki, Meynet, Fryer, Brown, et al. 2018, submitted)

# BH natal spin model: from the `Geneva` code



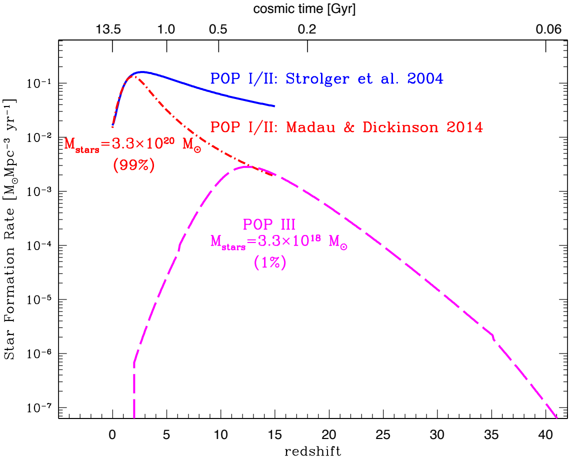
- low-mass BHs ($\lesssim 15\ M_\odot$, weak winds): high natal spins ($a_{spin} \approx 0.9$)
- high-mass BHs ($\gtrsim 30\ M_\odot$, strong winds): low natal spins ($a_{spin} \approx 0.1$)

# Predictions vs LIGO/Virgo effective spins



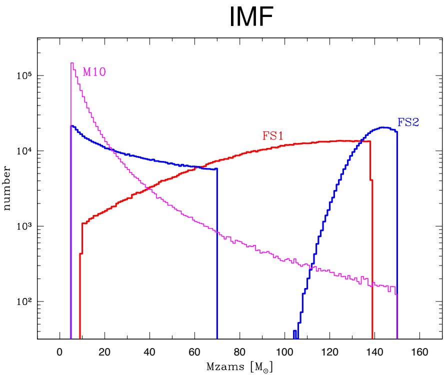
– if LIGO/Virgo effective spins continue at low values:
then even BHs with $M_{\rm BH} < 30\ \rm M_{\odot}$ are born with low spins
–> efficient angular momentum transport in stellar interiors

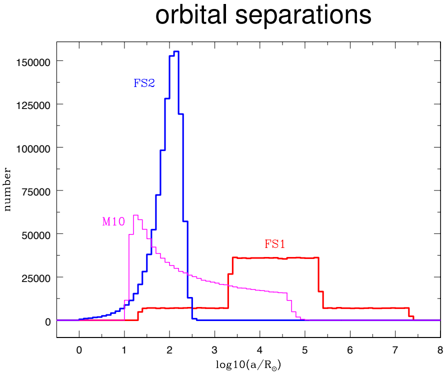
# Star formation history: Pop I/II vs Pop III stars



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

# Population III binary initial conditions:


IMF


orbital separations

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

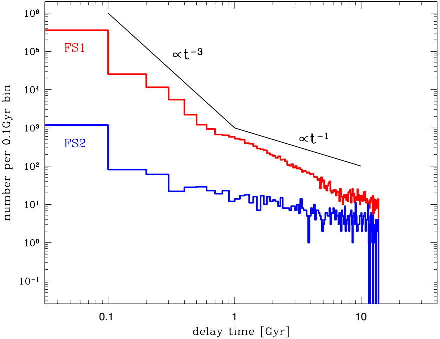
FS1 – Pop III: large dark matter halos (2000 AU) $X_{\rm BHBH} \approx 10^{-4}$ $M_\odot^{-1}$

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

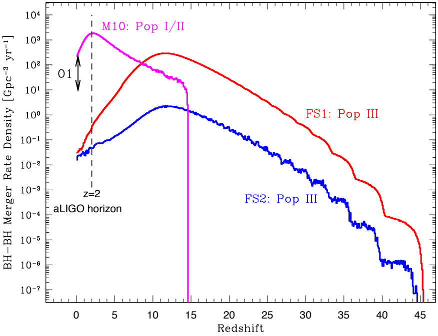
Pop III: potentially very different initial conditions than for PopI/II...

# Pop III BH-BH merger rate history:

delay time



merger rate



– delay time: $a^{-1}(da/dt)_{\mathrm{GR}} \propto t^{-1/4} d(t^{1/4})/dt \propto t^{-1}$
(initial separation distr.: $\sim a^{-1}$, $t_{\mathrm{GR}} \propto a^{4}$: Peters 1964)

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

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...

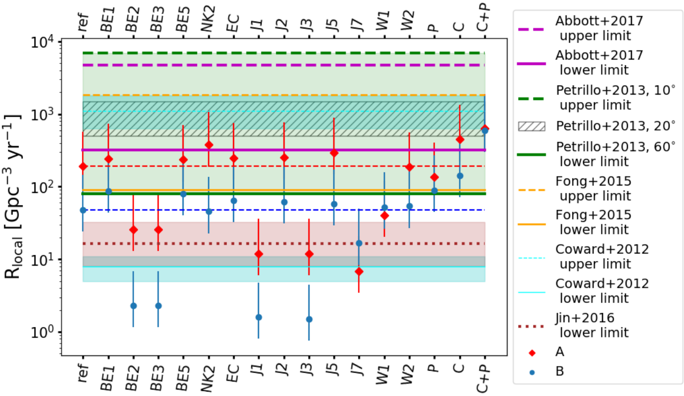
- origin of LIGO/Virgo BH-BH mergers: still unknown
  - binary channel: high rates; but masses OK (spins not OK)
  - dynamical channel: low rates; but masses OK (spins not OK)

- 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

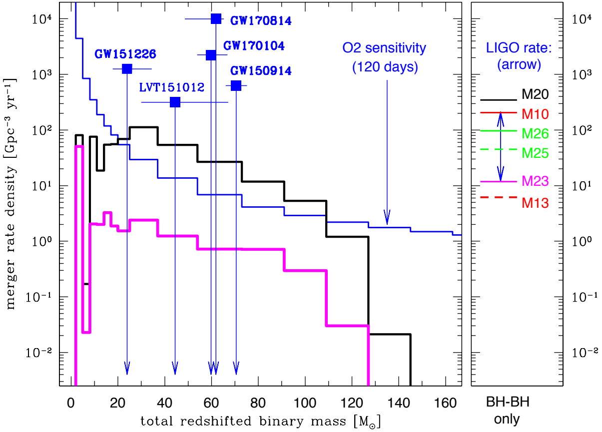
# NS-NS merger rates: observations vs predictions



- 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

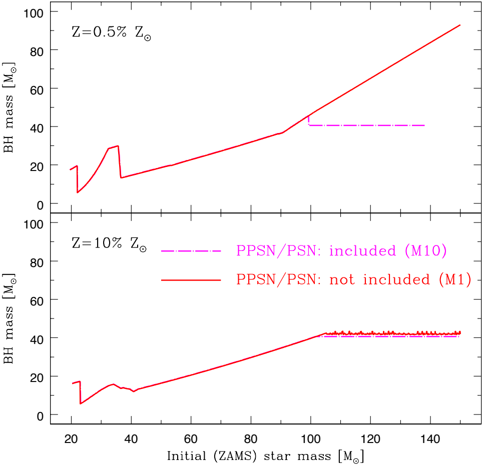
do BH-BH progenitors evolve through a different CE than NS-NS systems?

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



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

# 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

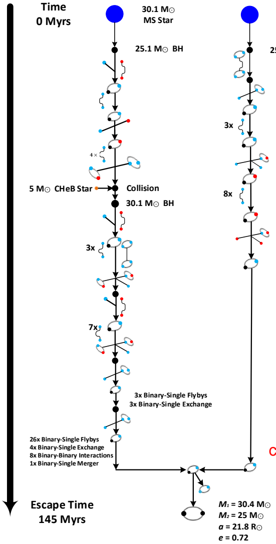
PPSN: Pair-instability Pulsation SN
($M_{\rm He} \sim$ 45–65 $M_\odot$)
black hole: and severe mass loss

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)

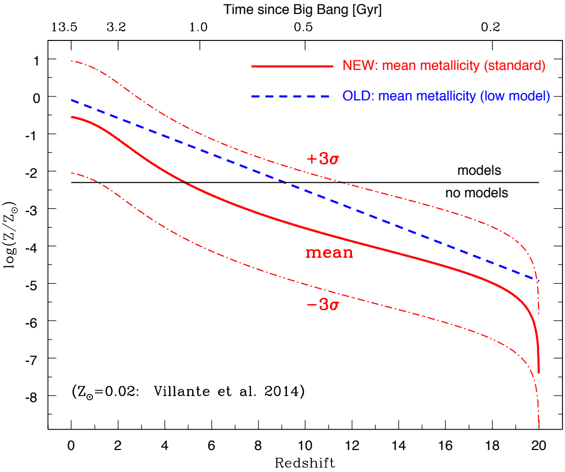
# Formation of BH-BH merger: dynamics



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

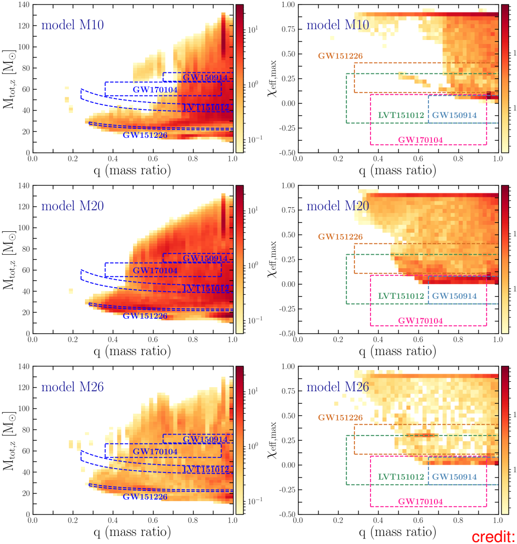
credit: Abbas Askar (Warsaw): MOCCA simulation

# 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: $1.2 M_{\rm CO}$
- **M26:** M20 + 70 km/s BH kicks
- $q$–$M_{\rm tot,z}$:
  - – LIGO events within models
  - – M20/26 better than M10
- $q$–$\chi_{\rm eff,max}$:
  - – models found for LIGO events
- **GW170104:** matches found: doubly conservative

credit: Jakub Klencki (Warsaw)