Massive stars as progenitors of merging black hole binaries

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Introduction

Open question:

→ What are **the formation mechanisms of binary black holes?**

Purpose:

→ to study the **demography** of **compact object binaries** in **different environments**.

Issue:

→ most of current **population-synthesis codes do not use recent stellar evolution models**.

MOBSE (Massive Objects in Binary Stellar Evolution)

Updated version of the **most popular** and **used population synthesis code** (Hurley+ 2002).

BSE: includes **obsolete stellar-evolution models**:

- **Tout+ 1997** for the **stellar winds**;
- **Hurley+ 2000** for the **supernova explosions** (SNe).

MOBSE: major updates:

- **recent stellar winds** Vink+ 2001 and Gränefer+ 2011;
- **new SNe** Fryer+ 2012, **Pulsation-Pair-Instability** (PPISN) and **Pair-Instability** (PISN) Woosley 2017.

Upgrades: stellar winds

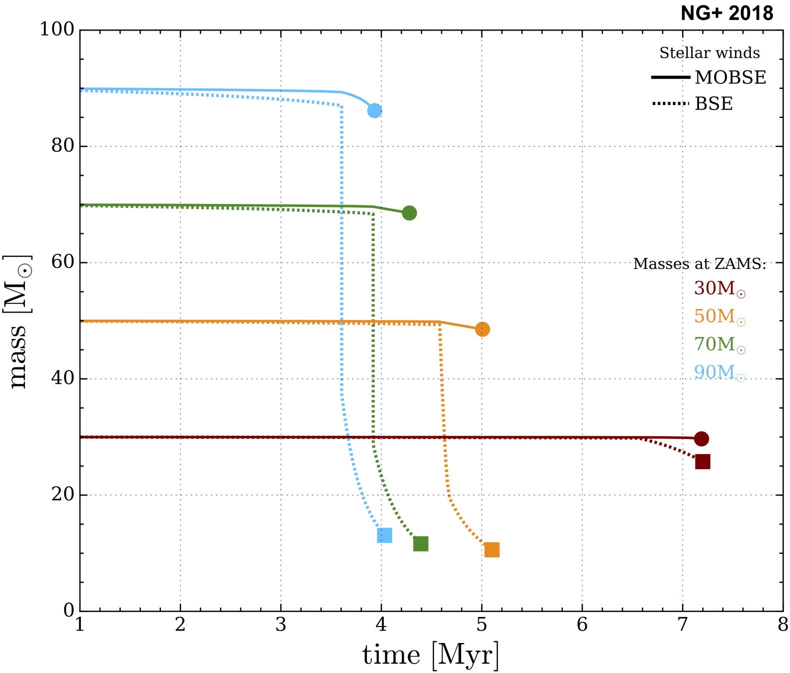
The **main differences** with respect to the **old recipes** for the stellar winds are:

Dependence on metallicity Z during **Wolf-Rayet** phase and **Luminous Blue Varible** stars:

$$\dot{M} \propto Z^{\alpha} \ \mathrm{M}_{\odot}\ \mathrm{yr}^{-1}$$

Effect of the electron - scattering **Eddington factor** on mass loss: (Chen+ 2015)

$$\begin{cases} \alpha = 0.85 & \Gamma_{\mathrm{e}} < \frac{2}{3} \\ \alpha = 2.45 - 2.4\,\Gamma_{\mathrm{e}} & \frac{2}{3} \leq \Gamma_{\mathrm{e}} \leq 1 \end{cases}$$

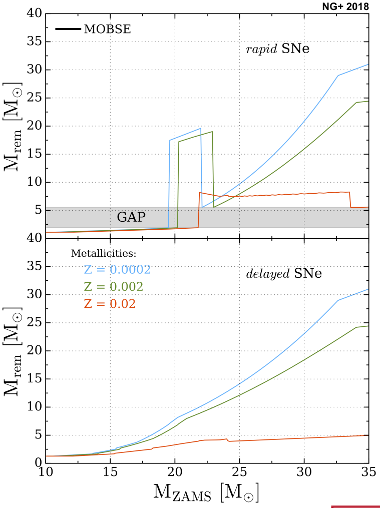

NG+ 2018
Stellar winds
MOBSE
BSE
Masses at ZAMS:
$30M_\odot$
$50M_\odot$
$70M_\odot$
$90M_\odot$
mass $[M_\odot]$
time [Myr]
100
80
60
40
20
0
1
2
3
4
5
6
7
8

Upgrades: SNe models

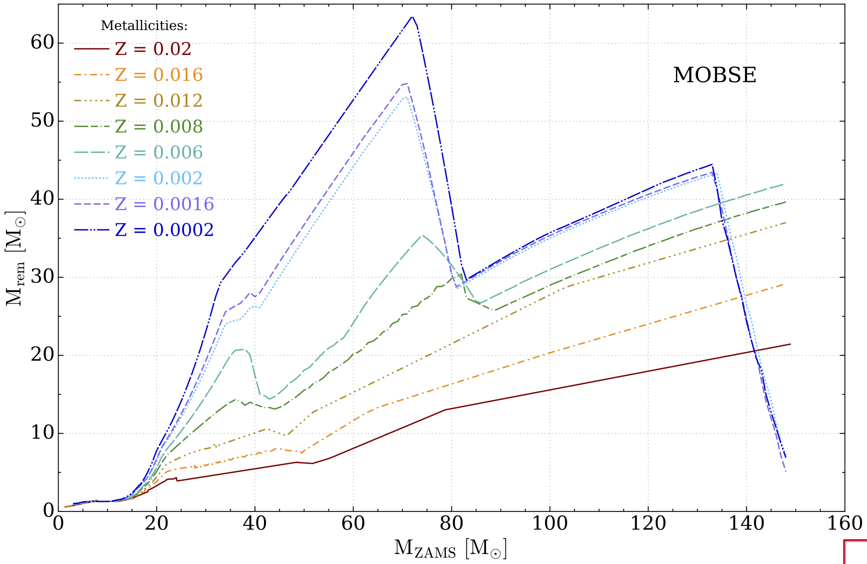
Implementation of two new **SNe models** described in **Fryer+ (2012)**.

Rapid SNe:
explosion occurs at $t \lesssim 250$ ms after the bounce.

Delayed SNe:
explosion occurs after $t \gtrsim 0.5$ s from the bounce.



Mass spectrum



BHBs Demography with MOBSE

Grid of initial conditions:

Z → 12 metallicity $\in [0.02 - 0.0002]$;

systems → 10^7 for each metallicity;

Distributions proposed by Sana+ 2012:

M_1 → **IMF** of Kroupa+ 2001 in $M_1 \in [5 - 150]\mathrm{M}_\odot$;

M_2 → uniform distribution of $M_2 \in [0.1 - 1.0] M_1$;

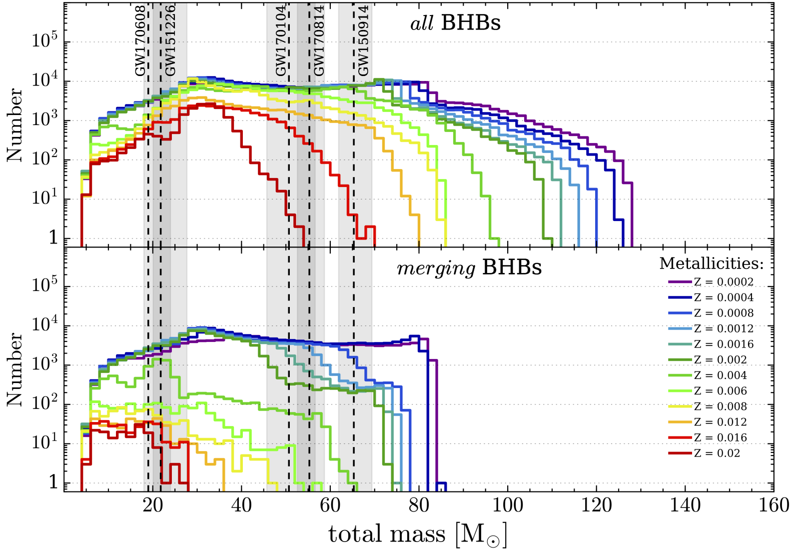
e → uniform distribution of $e^{-0.42} \in [0.0 - 1.0]$;

P → uniform distribution of $\log_{10}(P/\mathrm{day})^{-0.55} \in [0.15 - 5.5]$.

NG, M. Mapelli & M.Spera, **2018, MNRAS, 474, 2959**

Mass BHBs

NG+ 2018



Common-Envelope

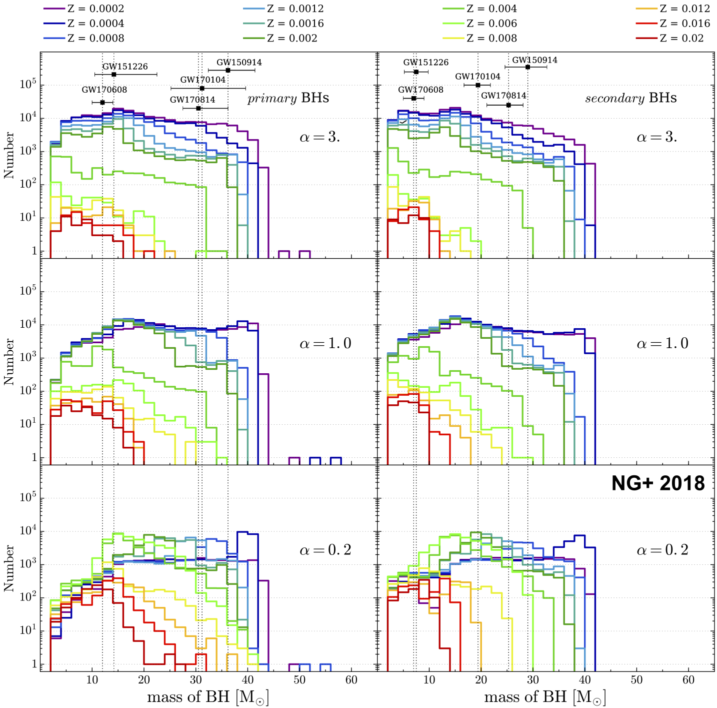
CE critical phase for the **formation of compact object binaries**.

Energy conservation formalism: $\alpha\lambda$

$$\boldsymbol{\alpha}\left(\frac{Gm_1 m_2}{2a_{\rm i}} - \frac{Gm_{1,\rm core} m_2}{2a_{\rm f}}\right) = -\frac{Gm_1 m_{1,\rm env}}{\boldsymbol{\lambda} R_1}$$

$\boldsymbol{\alpha}$ $\longrightarrow$ efficiency transfer of orbital energy to the common envelope.

$\boldsymbol{\lambda}$ $\longrightarrow$ describes the binding energy of the common envelope.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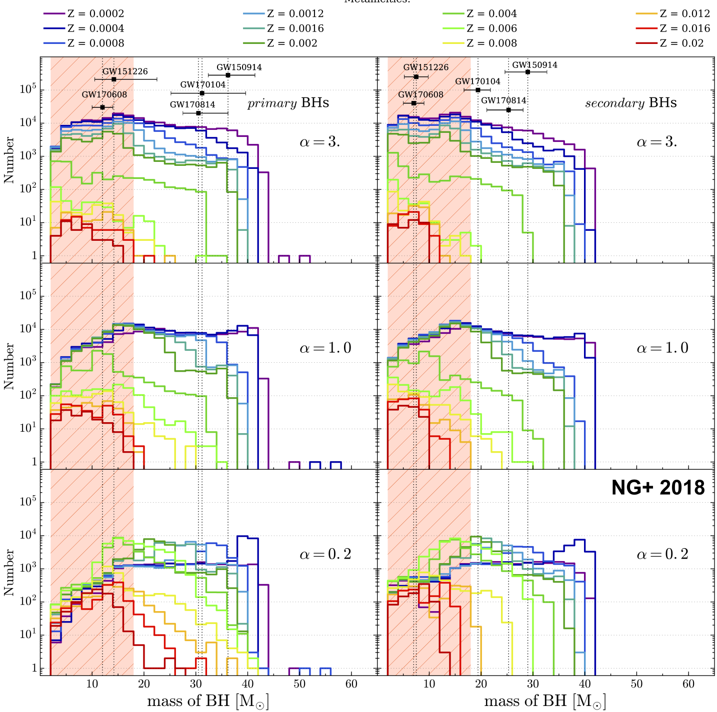
Z = 0.0004
Z = 0.0008
Z = 0.0012
Z = 0.0016
Z = 0.002
Z = 0.004
Z = 0.006
Z = 0.008
Z = 0.012
Z = 0.016
Z = 0.02
GW151226
GW150914
GW170104
GW170608
GW170814
primary BHs
secondary BHs
α = 3.
α = 1.0
α = 0.2
NG+ 2018
Number
mass of BH [M⊙]


Metallicities:
Z = 0.0002
Z = 0.0004
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Z = 0.0012
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NG+ 2018
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Merger per unit mass

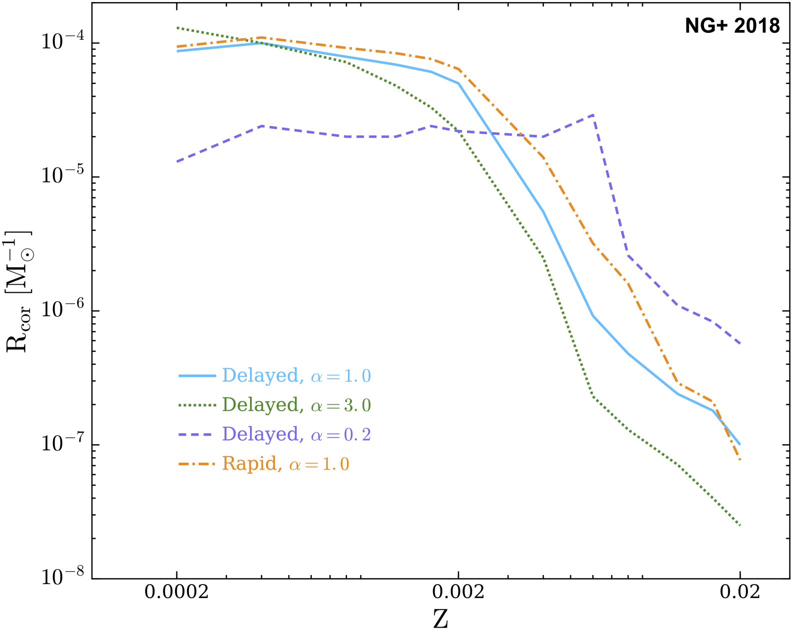
$$R = \frac{N_{\rm merger}}{M_{\rm tot,sim}}$$

$$R_{\rm cor} = {\rm f_{bin}}\,{\rm f_{IMF}}\,R$$

$\mathbf{f_{bin} = 0.5}$ $\rightarrow$ we assume 50 per cent of binary

$\mathbf{f_{IMF} = 0.285}$ $\rightarrow$ we simulate only $M_1 \geq 5$ $M_\odot$

Merger per unit mass



Conclusions

1. → the **heaviest BHs (**~ 60 **$\mathbf{M_\odot}$)** formed at $Z \lesssim$ **0.002**;

2. → the most **massive BHBs (**$\gtrsim 85$ **$\mathbf{M_\odot}$) do not merge**;

3. → the masses of **our merging BHBs match** those of the five reported **GW events**;

4. → **merging BHBs** form much **more efficiently** from **metal-poor** ($R_{\rm cor} \sim 10^{-4}$ $\mathrm{M}_\odot^{-1}$) than from metal-rich ($R_{\rm cor} \sim 10^{-7}$ $\mathrm{M}_\odot^{-1}$) binaries.