Progenitors of low-mass binary BH mergers in the isolated binary evolution scenario

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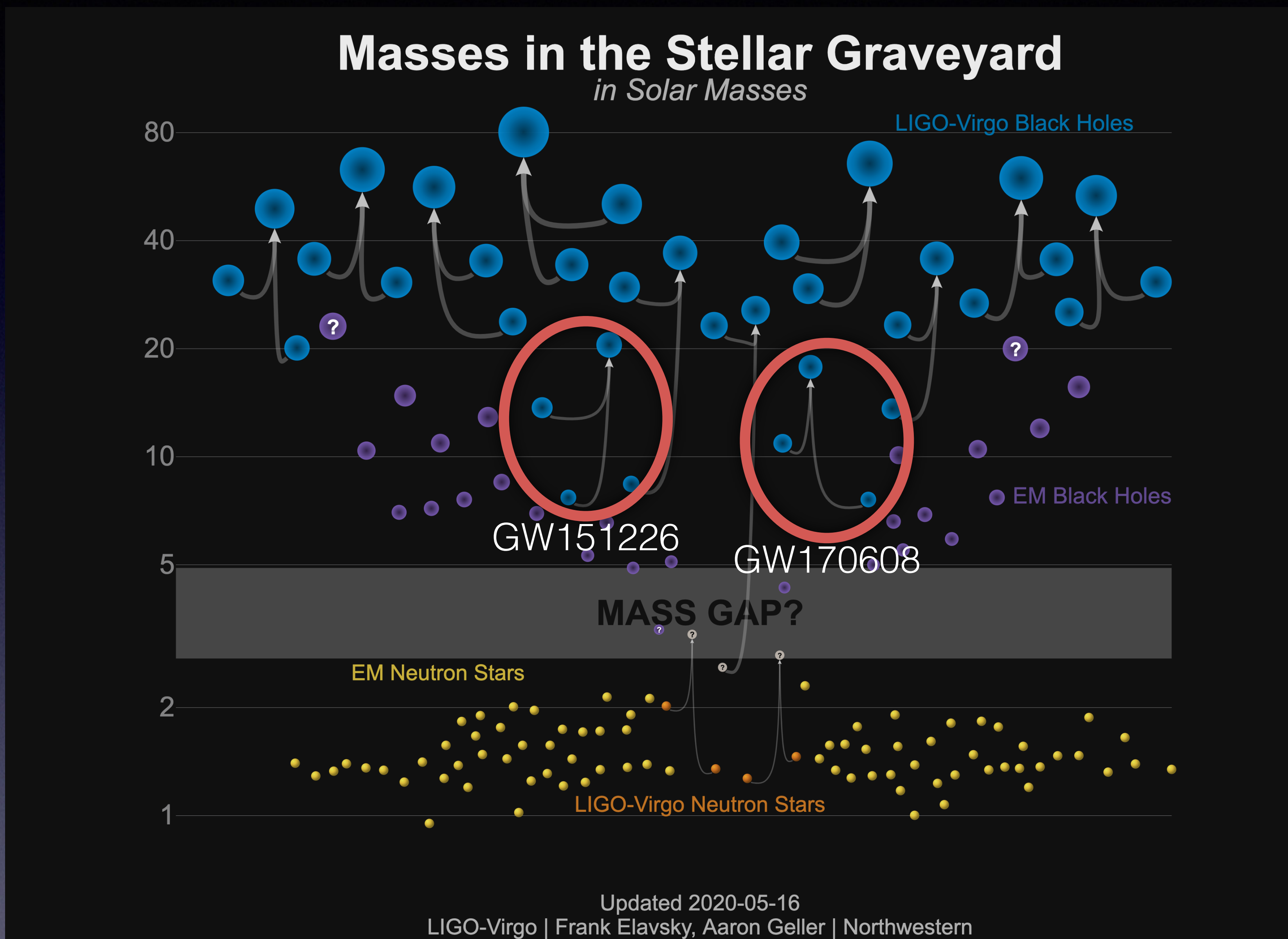
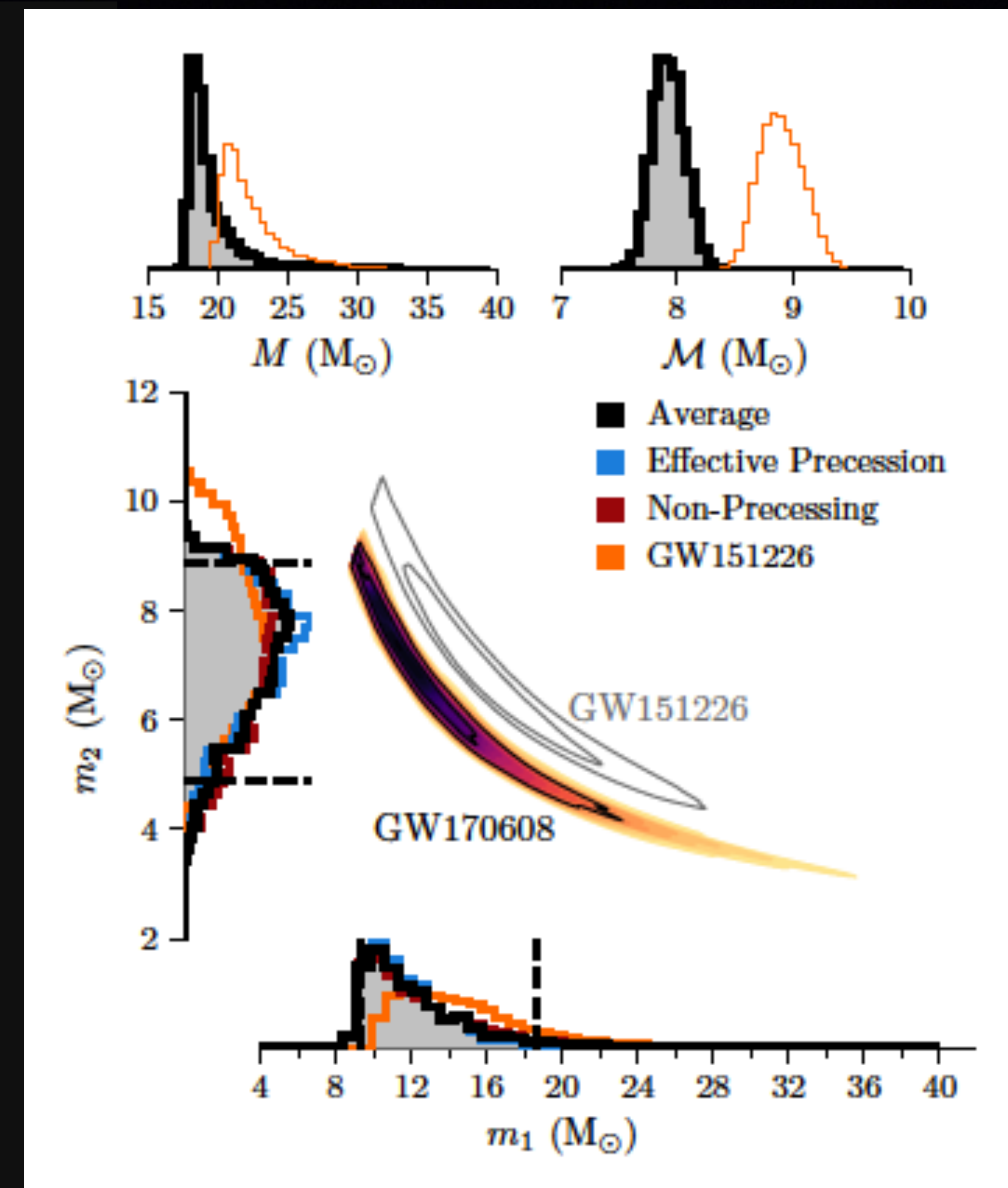
GW151226 & GW170608: the lightest binary BH mergers in O1/O2 runs

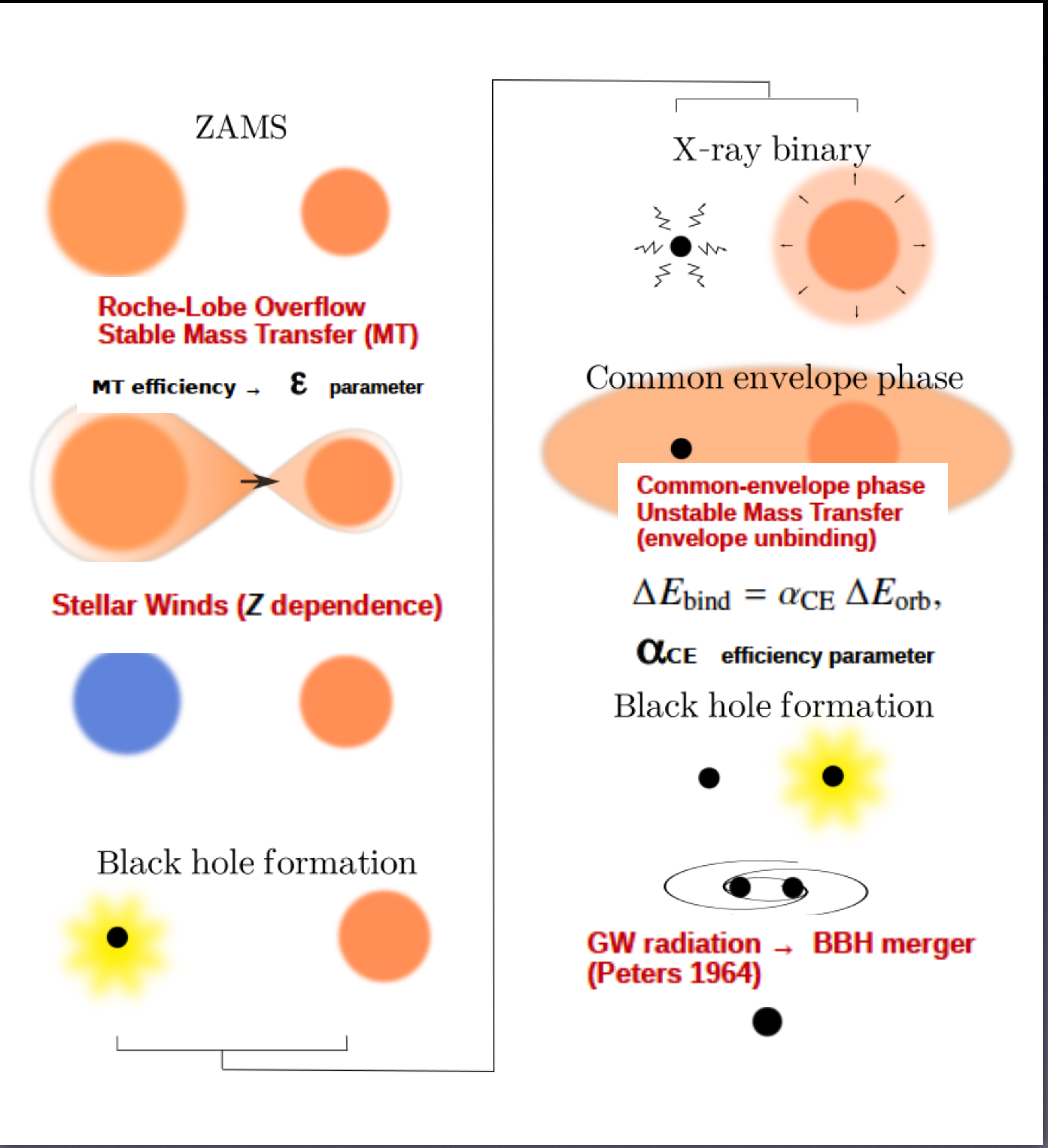




- **Aims:** study the formation history, progenitor properties and expected rates of the lightest BBH mergers detected during O1/O2 runs, with **BH masses compatible with Galactic X-ray binaries** ($M < 18\ M_\odot$)

Isolated binary evolution scenario

- **Method**: simulations using **MESA**[1] (1D-hydrodynamic stellar code) including binary evolution (interacting through stable MT) [***MESAbinary***]
- **To model binary evolution, we incorporated in MESA**:
  - **BH formation**: delayed core-collapse prescription (Fryer+2012)
  - **Common envelope** (CE) phase: unstable mass transfer (1D)
  - we compile in one run the full binary evolution, **from ZAMS to BBH merger**
- [1]http://mesa.sourceforge.net

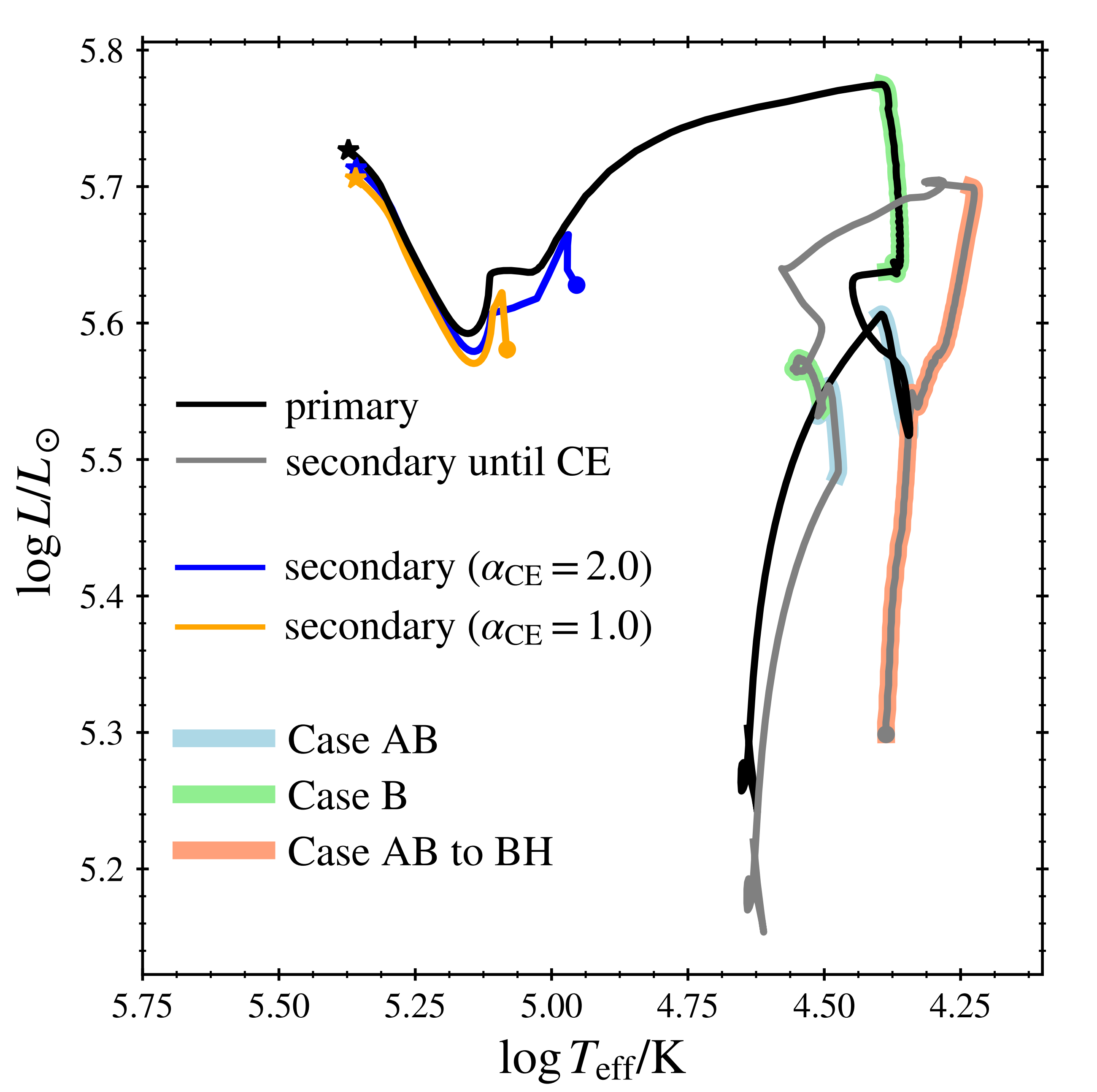


Non-rotating stars, circular orbits and no asymmetric kicks

Binary stellar-evolution simulations

- **Explore a wide parameter space (66 632 simulations):**
  - initial stellar masses [20-24/30-34 $M_\odot$]
  - orbital separations [40-200 $R_\odot$]
  - 4 metallicities [Z = 0.1, 1, 4, 7, 15] x 10^{-3}
  - 4 stable MT efficiencies [ε = 0.0, 0.2, 0.4, 0.6]
  - 2 unstable MT efficiencies [α_{CE} = 1.0, 2.0]
- **Results**: binary progenitors leading to BBHs with chirp mass & merger-time delay compatible with detected GW events
- **compare** local merger-rate densities with detected GW events

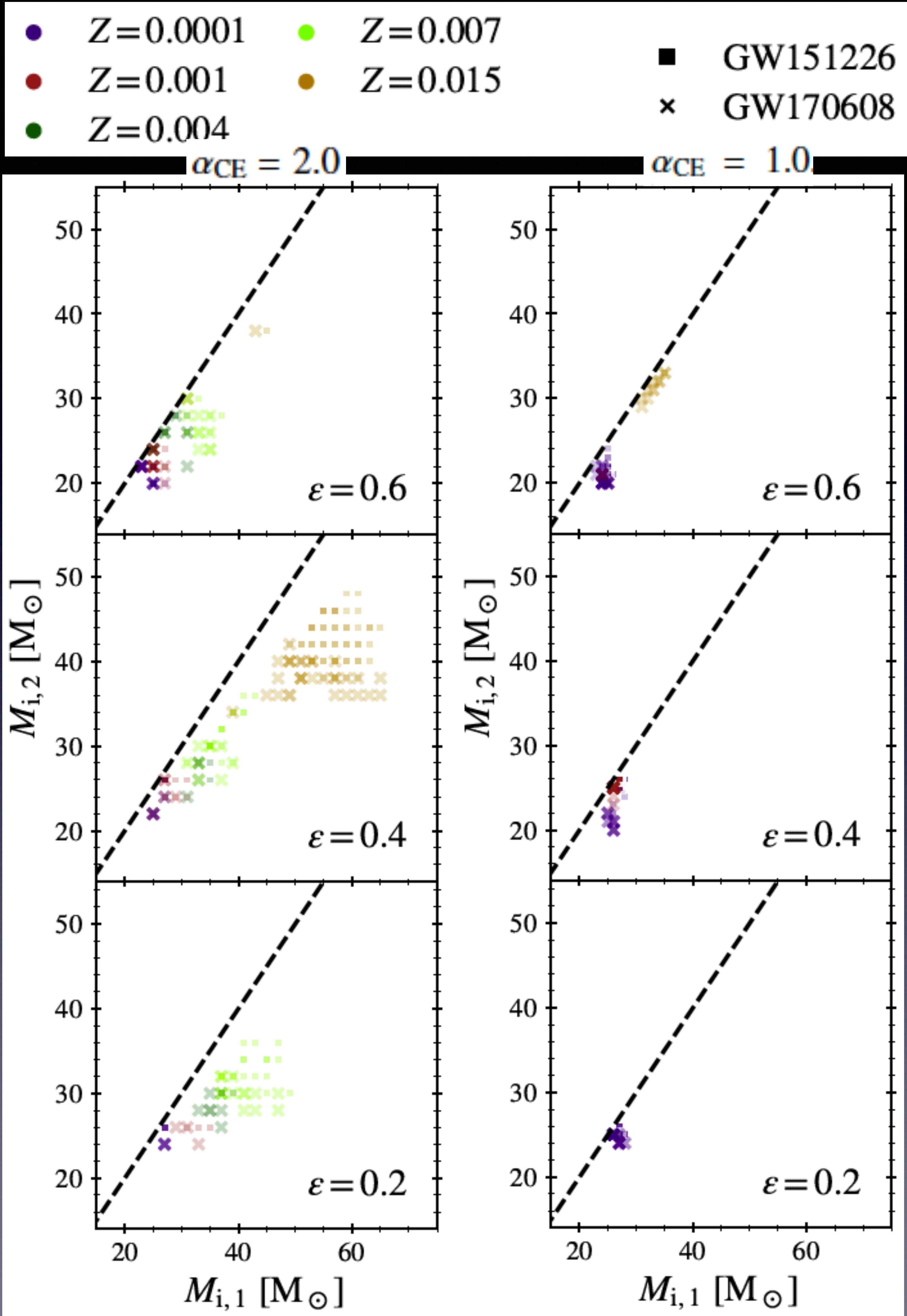
[$Z_\odot$ = 12x10^{-3}]



Full binary evolution simulation leading to the formation of a BBH

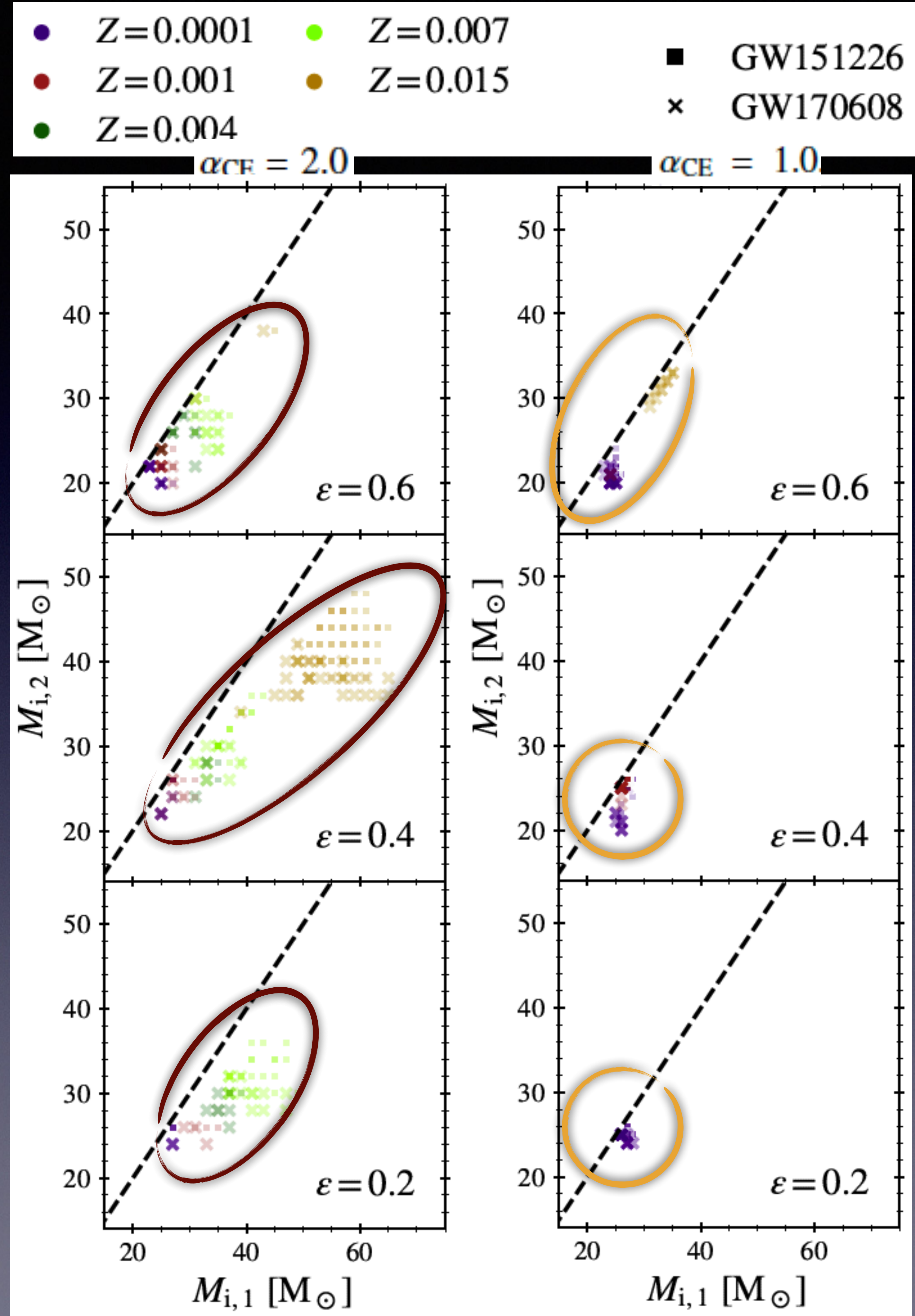
Properties of binary progenitors

- **We obtain >1000s binary progenitors** distributed for metallicities (Z), MT (ε) & CE (α_{CE}) efficiencies**:**
  - **Stellar progenitors** of GW151226 **more massive** than GW170608
  - **All progenitors experience a CE** shrinking their orbital separation, leading to BBH merging in $t < t_{Hubble}$
  - **No progenitor** found for fully-inefficient MT scenario (ε = 0)



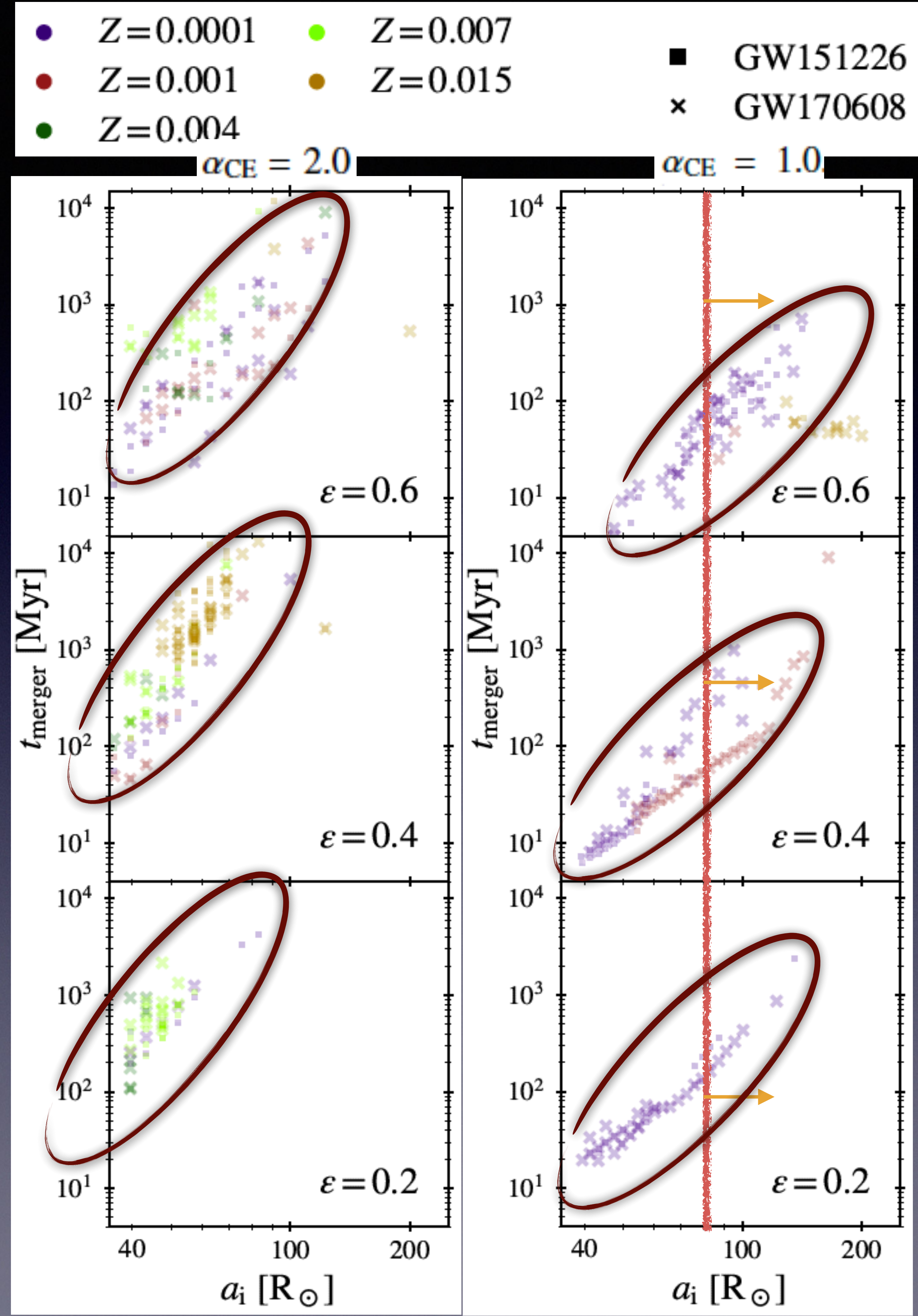
Properties of binary progenitors ($M_{i,1}$ vs $M_{i,2}$)

- **High CE** efficiencies (α_{CE}) favored to eject CE, avoiding a *merger* during CE
- **Higher Z** lead to more massive progenitors (mass loss stellar winds)
- **Higher MT** (ε = 0.6) efficiencies allow for wider range (Z) of progenitors
- **For α_{CE} =1.0 :**
    - **Low Z** progenitors preferred in all cases (except for ε=0.6)
    - **progenitors** have mass ratio ~1 ($q \neq 1$ *merge* during CE, -> no BBH)

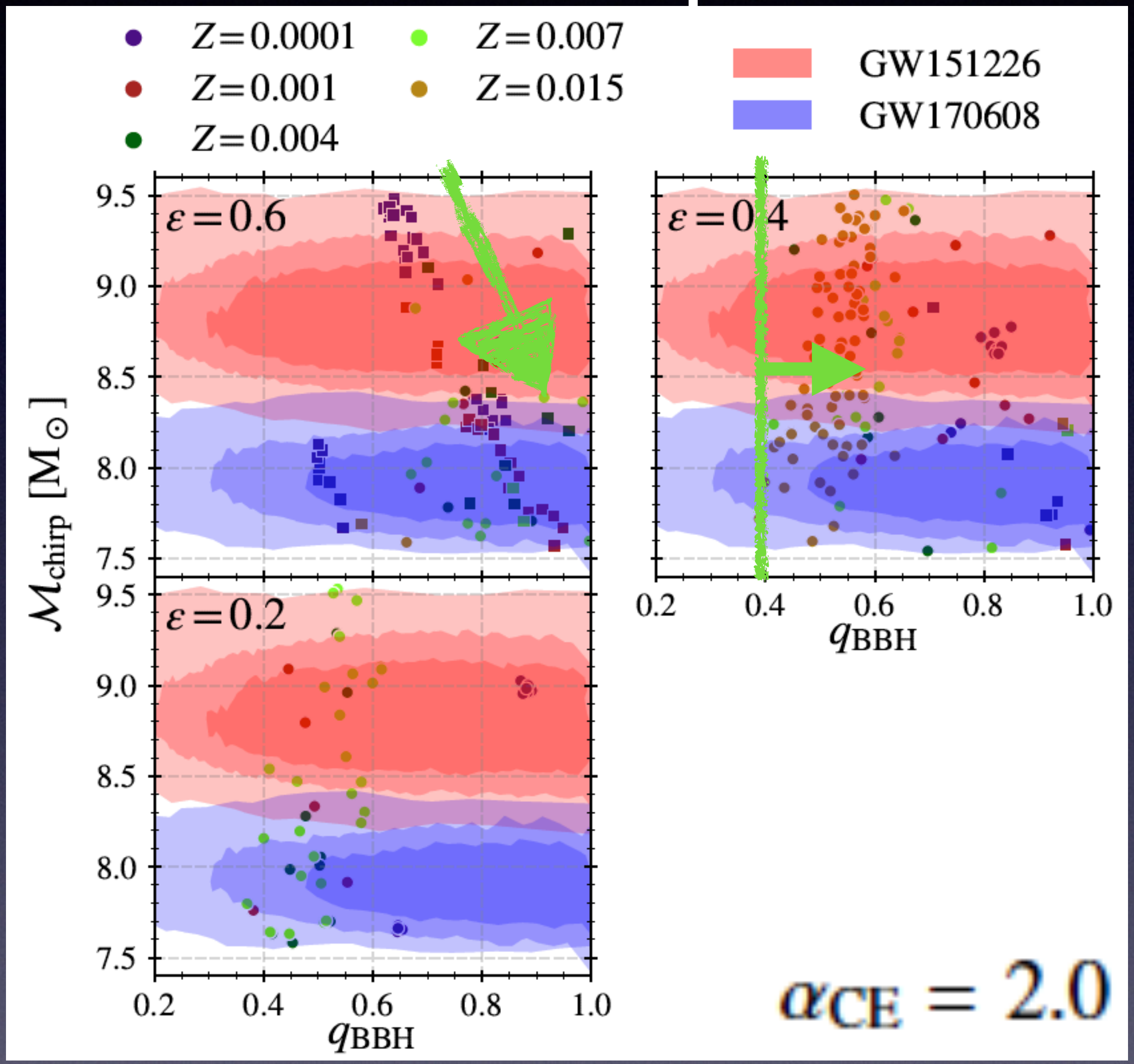


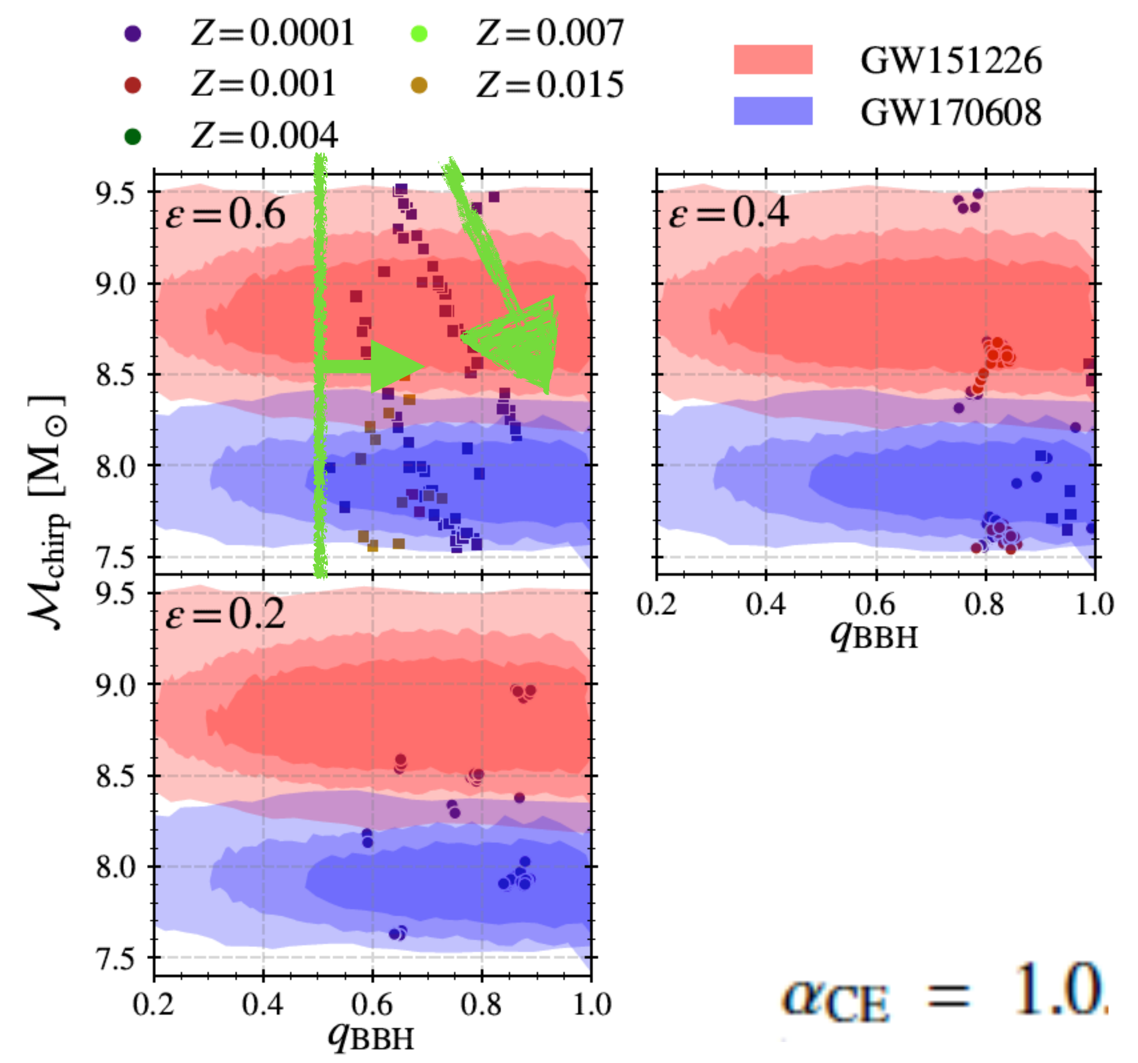
Properties of binary progenitors (a_i vs t_{merger})

- **Higher orbital** separation a_i leads to longer t_{merger} delay
- **t_{merger}** reduced for $\alpha_{CE} = 1.0$ compared to $\alpha_{CE} = 2.0$: **a slow CE ejection reduces a_i**
- **No high Z** progenitors with $a_i < 80\ R_\odot$ (***merge* during CE**)



Properties of formed BBH:
chirp mass vs mass ratio





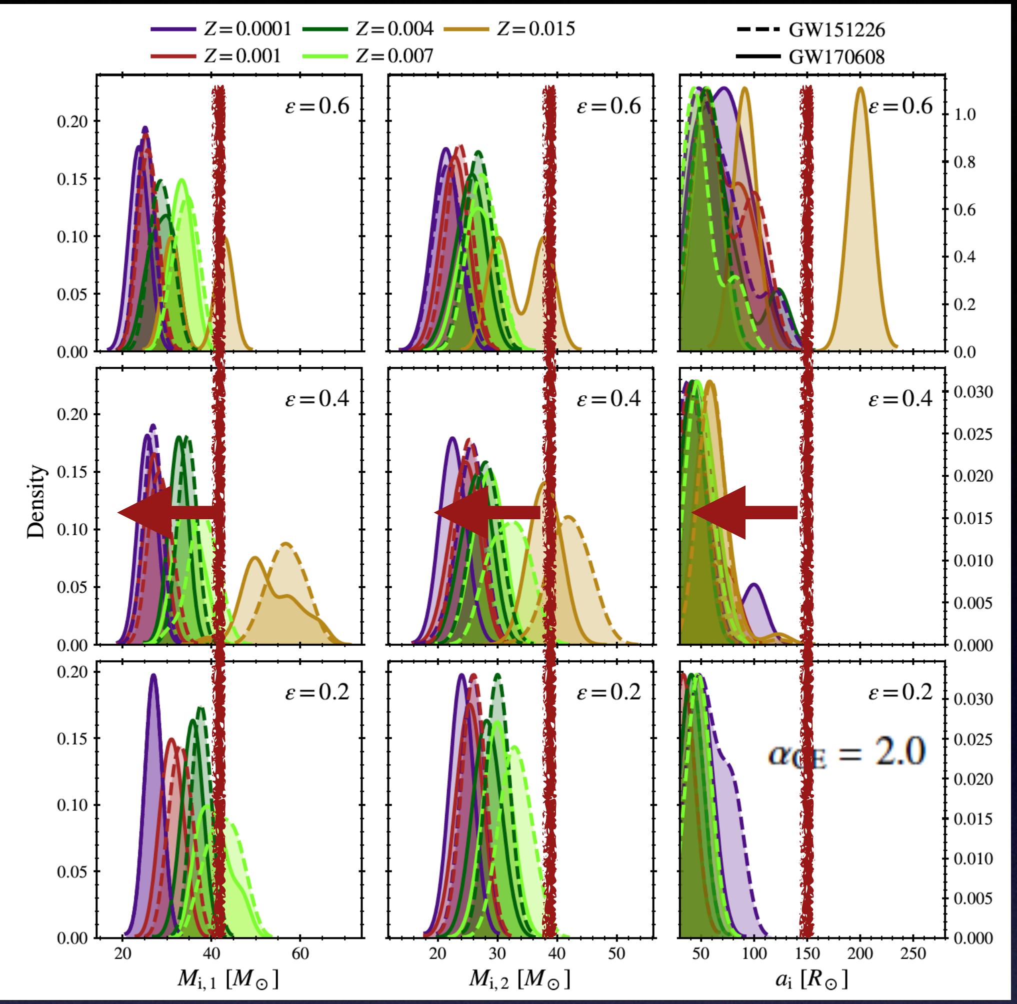
- **BBH are formed with mass ratios q > 0.4** (for α_{CE}=2.0, and q > 0.5 for α_{CE}=1.0)
- For α_{CE}=1.0: BBH of q~0.6-0.8 are preferred at high MT
- High ε=0.6 form BBH with q increasing up to 1: **rejuvenation process** (second-formed BH becomes more massive than first)

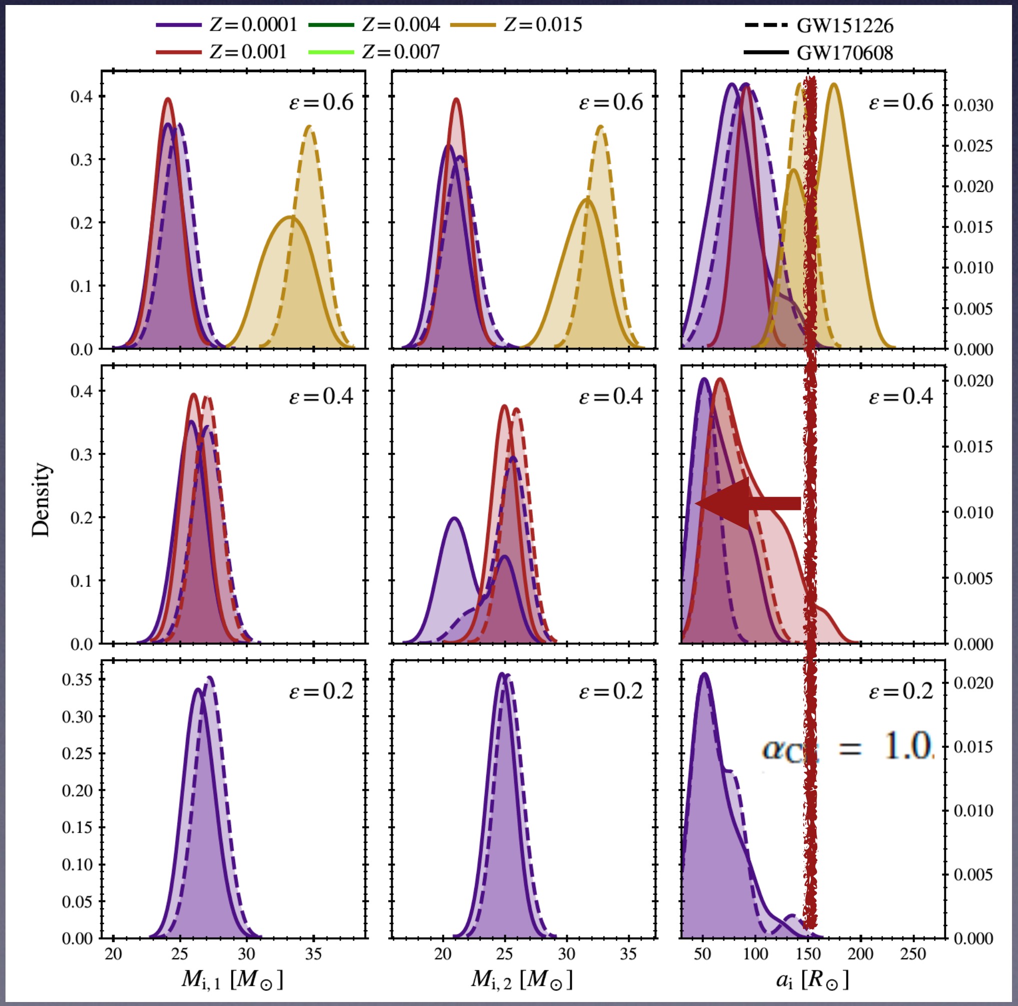
Population-weighted results:
mass and separation

- We use **uniform grids to estimate relative contributions of progenitors**:
  Initial Mass Function [Kroupa+2001]; Mass-ratio [0.1-1.0]; Separation/period [Sana+2012] (log P æ -0.55)

- **Progenitors:** M [20-40 $M_\odot$] and a_i < 150 $R_\odot$
  (except for α_{CE}=2.0/high Z: M->70 $M_\odot$ / a_i -> 250 $R_\odot$)

- **Strong dependence on MT efficiency:**
  interplay between stellar wind mass loss and initial binary separation

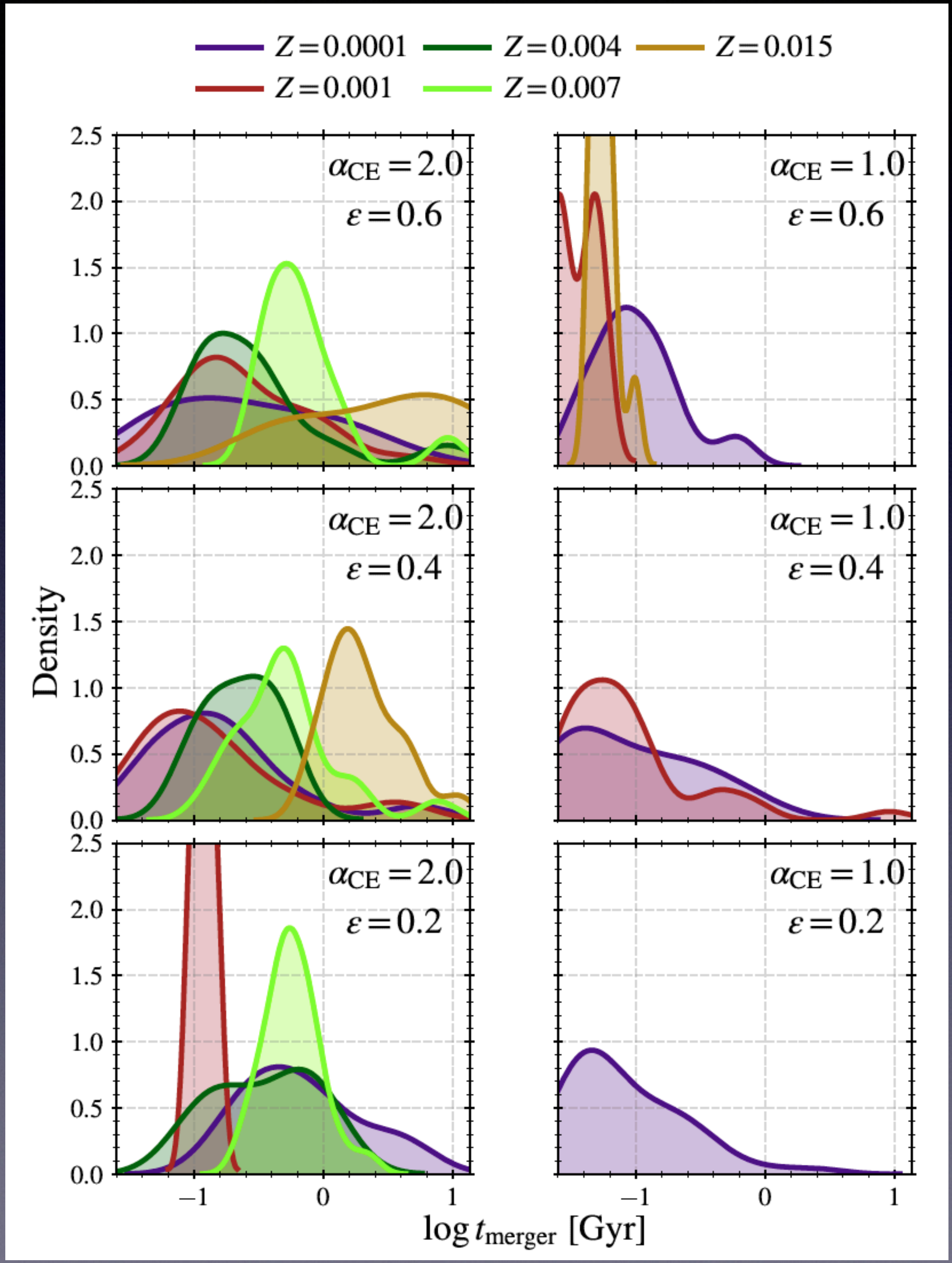




Population-weighted results:

merger time delay

- **Merger time delay strongly influenced by metallicity Z and CE α_{CE} efficiency:**
  - For **α_{CE} = 2.0: long time delay 1 Gyr** [0.1-8 Gyr] (due to **fast CE ejection**): old population with high Z
  - For **α_{CE} = 1.0**: **short time delay 100 Myr** [0.01-1 Gyr] (**slow CE ejection**): young population with low Z
  - **competition effect** between both populations: high Z progenitors are not expected at high z



Merger-rate density estimates

- **Density of GW events at redshift z obtained by Monte-Carlo integration:**

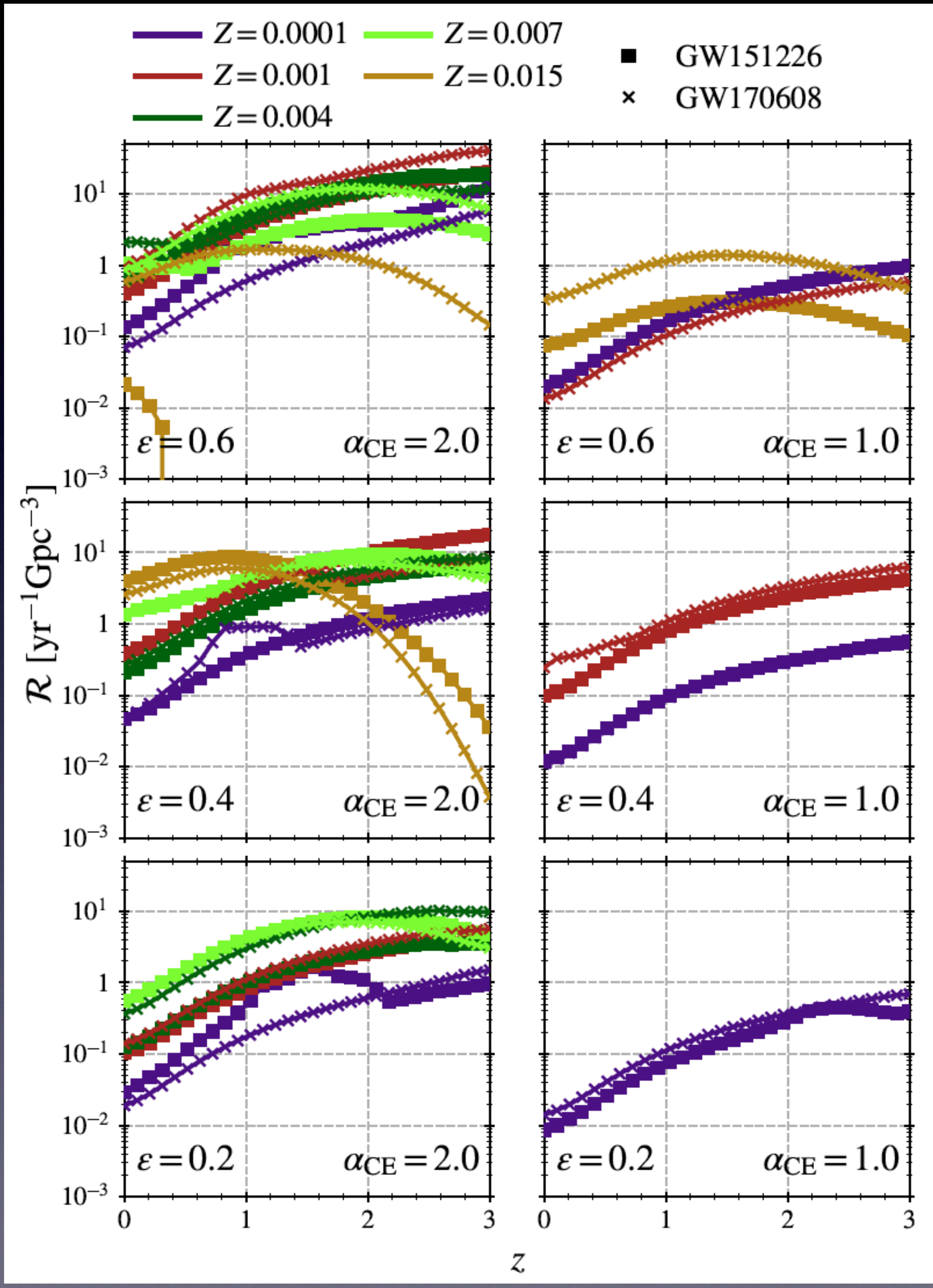
$$\mathcal{R}(Z, z(t)) = \mathcal{N}_{\mathrm{corr}} \int_0^{t(z)} \int_{M_{\mathrm{i},1}} \int_{M_{\mathrm{i},2}} \int_{a_{\mathrm{i}}} \int_0^{t(z)} \frac{\mathrm{d}N}{\mathrm{d}M_{\mathrm{i},1}\,\mathrm{d}M_{\mathrm{i},2}\,\mathrm{d}a_{\mathrm{i}}\,\mathrm{d}t_{\mathrm{m}}} \widehat{\mathrm{SFR}}(t'; Z)\,\delta\left[t(z) - (t_{\mathrm{m}} + t')\right] \mathrm{d}t_{\mathrm{m}}\,\mathrm{d}a_{\mathrm{i}}\,\mathrm{d}M_{\mathrm{i},2}\,\mathrm{d}M_{\mathrm{i},1}\,\mathrm{d}t'$$

  - SFR: star formation rate (Strolger+2004); ψ: metallicity evolution (Langer+2006)

- **Rate evolution shaped by the SFR across z:** rapid decay found for z < 1

- **Chemical evolution has an impact on the rates**: high Z drops at z > 1

- **Local merger rate densities are larger for high CE phase and MT efficiency**: R>0.1 for α_{CE}=2.0 & ε=0.6 (Z-independent)



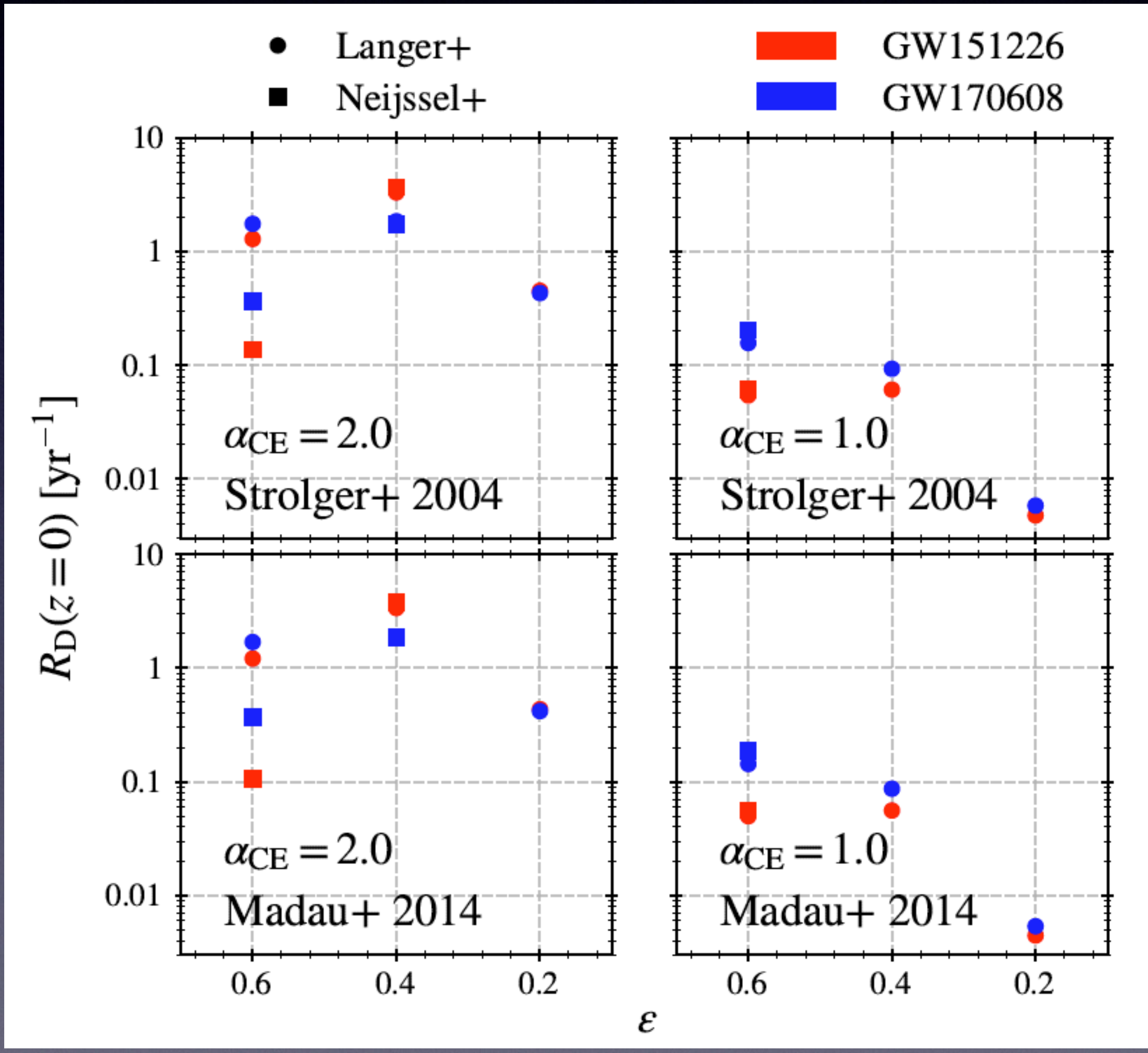
Total merger detection rates for O1/O2 runs

- **To estimate the local detection rate, we consider the detector sensitivity of LIGO/Virgo and the local merger rate densities (at z=0):**

$$R_{\rm D} = \frac{4\pi}{3} D_{\rm h}^3 \langle w^3 \rangle \langle (\mathcal{M}_{\rm c} \, / \, 1.2 \, M_{\odot})^{15/6} \rangle \mathcal{R}(z = 0)$$

- We obtain highest detection rate of light BBH of **0.5-3.0 Gpc^{-3} yr^{-1}**

- compare to **9.7-101 Gpc^{-3} yr^{-1}** for full BBH population (Abbott+2019)



Rate dependence vs MT/CE efficiency

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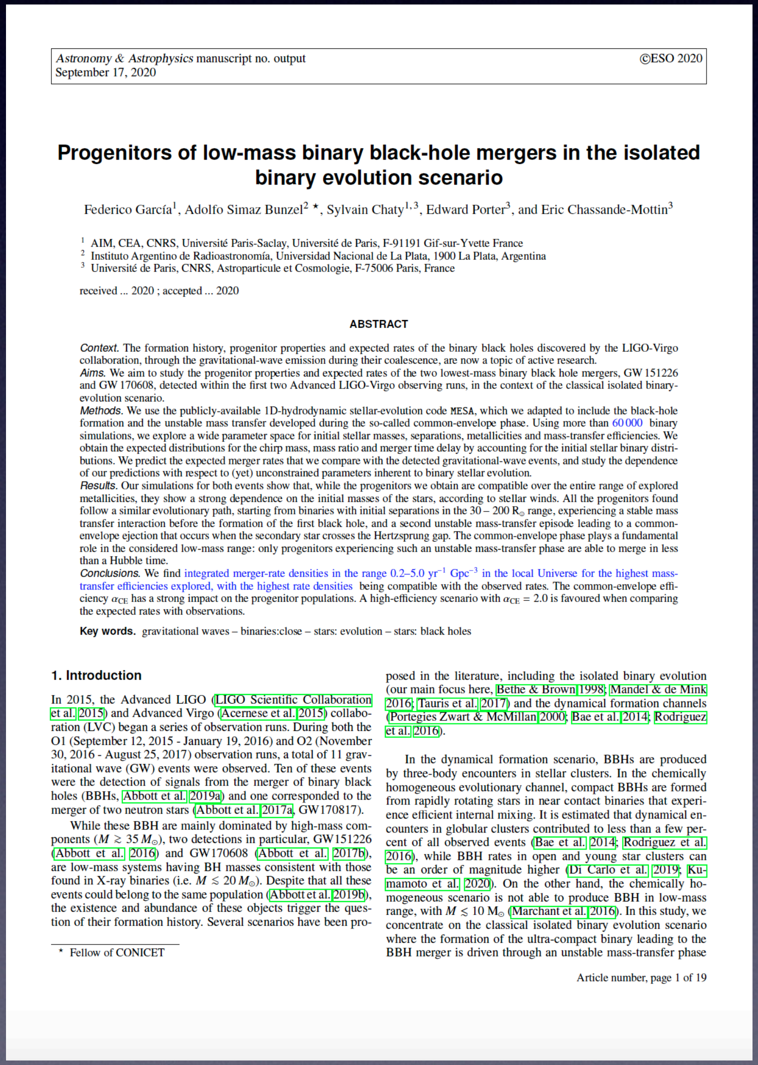
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Progenitors of low-mass binary black-hole mergers in the isolated binary evolution scenario

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ABSTRACT

Context. The formation history, progenitor properties and expected rates of the binary black holes discovered by the LIGO-Virgo collaboration, through the gravitational-wave emission during their coalescence, are now a topic of active research.
Aims. We aim to study the progenitor properties and expected rates of the two lowest-mass binary black hole mergers, GW 151226 and GW 170608, detected within the first two Advanced LIGO-Virgo observing runs, in the context of the classical isolated binary-evolution scenario.
Methods. We use the publicly-available 1D-hydrodynamic stellar-evolution code `MESA`, which we adapted to include the black-hole formation and the unstable mass transfer developed during the so-called common-envelope phase. Using more than 60 000 binary simulations, we explore a wide parameter space for initial stellar masses, separations, metallicities and mass-transfer efficiencies. We obtain the expected distributions for the chirp mass, mass ratio and merger time delay by accounting for the initial stellar binary distributions. We predict the expected merger rates that we compare with the detected gravitational-wave events, and study the dependence of our predictions with respect to (yet) unconstrained parameters inherent to binary stellar evolution.
Results. Our simulations for both events show that, while the progenitors we obtain are compatible over the entire range of explored metallicities, they show a strong dependence on the initial masses of the stars, according to stellar winds. All the progenitors found follow a similar evolutionary path, starting from binaries with initial separations in the 30 – 200 $R_{\odot}$ range, experiencing a stable mass transfer interaction before the formation of the first black hole, and a second unstable mass-transfer episode leading to a common-envelope ejection that occurs when the secondary star crosses the Hertzsprung gap. The common-envelope phase plays a fundamental role in the considered low-mass range: only progenitors experiencing such an unstable mass-transfer phase are able to merge in less than a Hubble time.
Conclusions. We find integrated merger-rate densities in the range 0.2–5.0 yr^{-1} Gpc^{-3} in the local Universe for the highest mass-transfer efficiencies explored, with the highest rate densities being compatible with the observed rates. The common-envelope efficiency α_{CE} has a strong impact on the progenitor populations. A high-efficiency scenario with $\alpha_{CE} = 2.0$ is favoured when comparing the expected rates with observations.

Key words. gravitational waves – binaries:close – stars: evolution – stars: black holes

1. Introduction

In 2015, the Advanced LIGO (LIGO Scientific Collaboration et al. 2015) and Advanced Virgo (Acernese et al. 2015) collaboration (LVC) began a series of observation runs. During both the O1 (September 12, 2015 - January 19, 2016) and O2 (November 30, 2016 - August 25, 2017) observation runs, a total of 11 gravitational wave (GW) events were observed. Ten of these events were the detection of signals from the merger of binary black holes (BBHs, Abbott et al. 2019a) and one corresponded to the merger of two neutron stars (Abbott et al. 2017a, GW170817).

While these BBH are mainly dominated by high-mass components ($M \gtrsim 35\,M_{\odot}$), two detections in particular, GW151226 (Abbott et al. 2016) and GW170608 (Abbott et al. 2017b), are low-mass systems having BH masses consistent with those found in X-ray binaries (i.e. $M \lesssim 20\,M_{\odot}$). Despite that all these events could belong to the same population (Abbott et al. 2019b), the existence and abundance of these objects trigger the question of their formation history. Several scenarios have been proposed in the literature, including the isolated binary evolution (our main focus here, Bethe & Brown 1998; Mandel & de Mink 2016; Tauris et al. 2017) and the dynamical formation channels (Portegies Zwart & McMillan 2000; Bae et al. 2014; Rodriguez et al. 2016).

In the dynamical formation scenario, BBHs are produced by three-body encounters in stellar clusters. In the chemically homogeneous evolutionary channel, compact BBHs are formed from rapidly rotating stars in near contact binaries that experience efficient internal mixing. It is estimated that dynamical encounters in globular clusters contributed to less than a few percent of all observed events (Bae et al. 2014; Rodriguez et al. 2016), while BBH rates in open and young star clusters can be an order of magnitude higher (Di Carlo et al. 2019; Kumamoto et al. 2020). On the other hand, the chemically homogeneous scenario is not able to produce BBH in low-mass range, with $M \lesssim 10\,M_{\odot}$ (Marchant et al. 2016). In this study, we concentrate on the classical isolated binary evolution scenario where the formation of the ultra-compact binary leading to the BBH merger is driven through an unstable mass-transfer phase

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