Progenitors of low-mass binary black hole mergers

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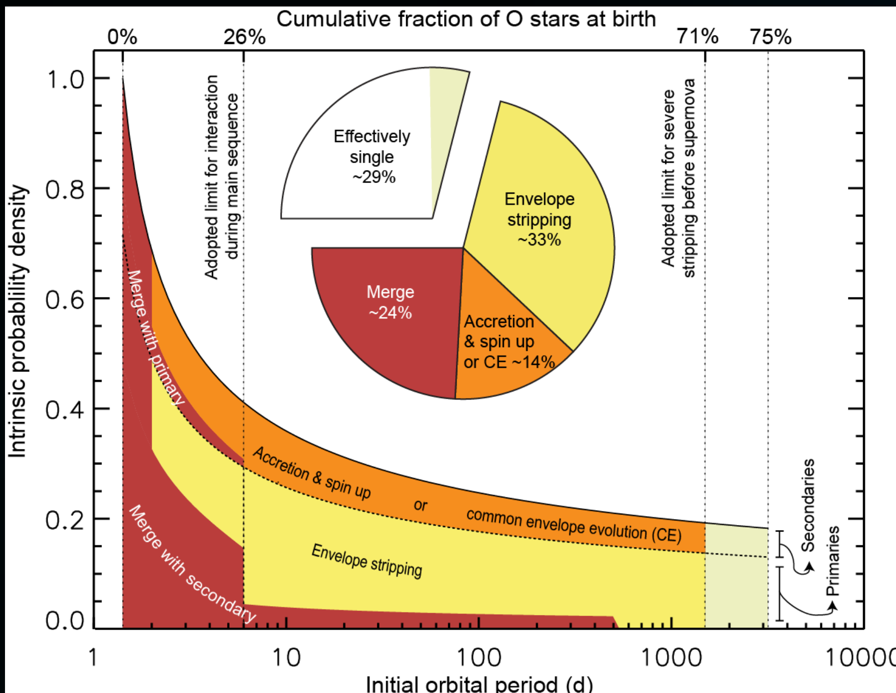
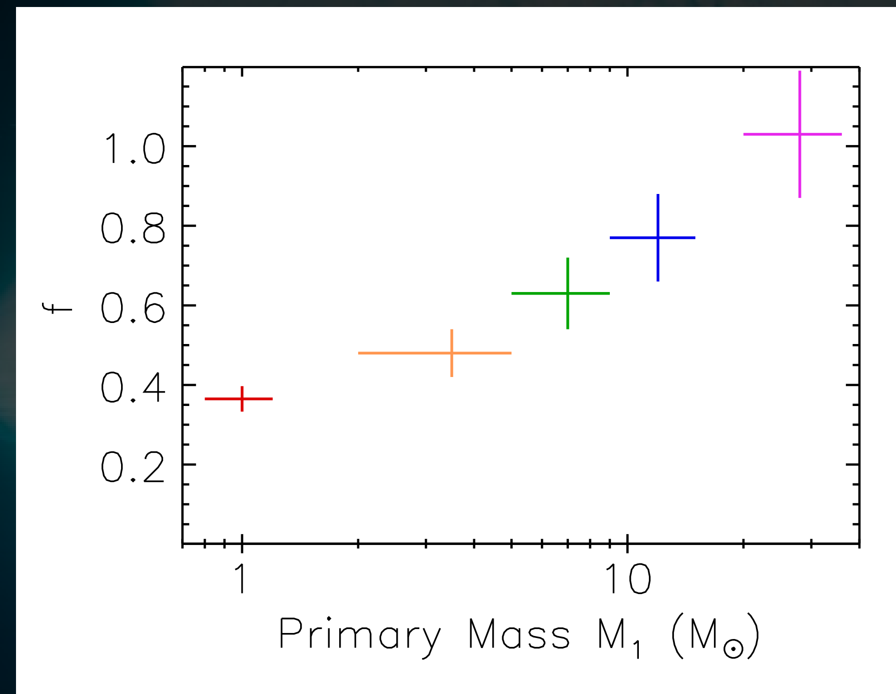
How common are they?

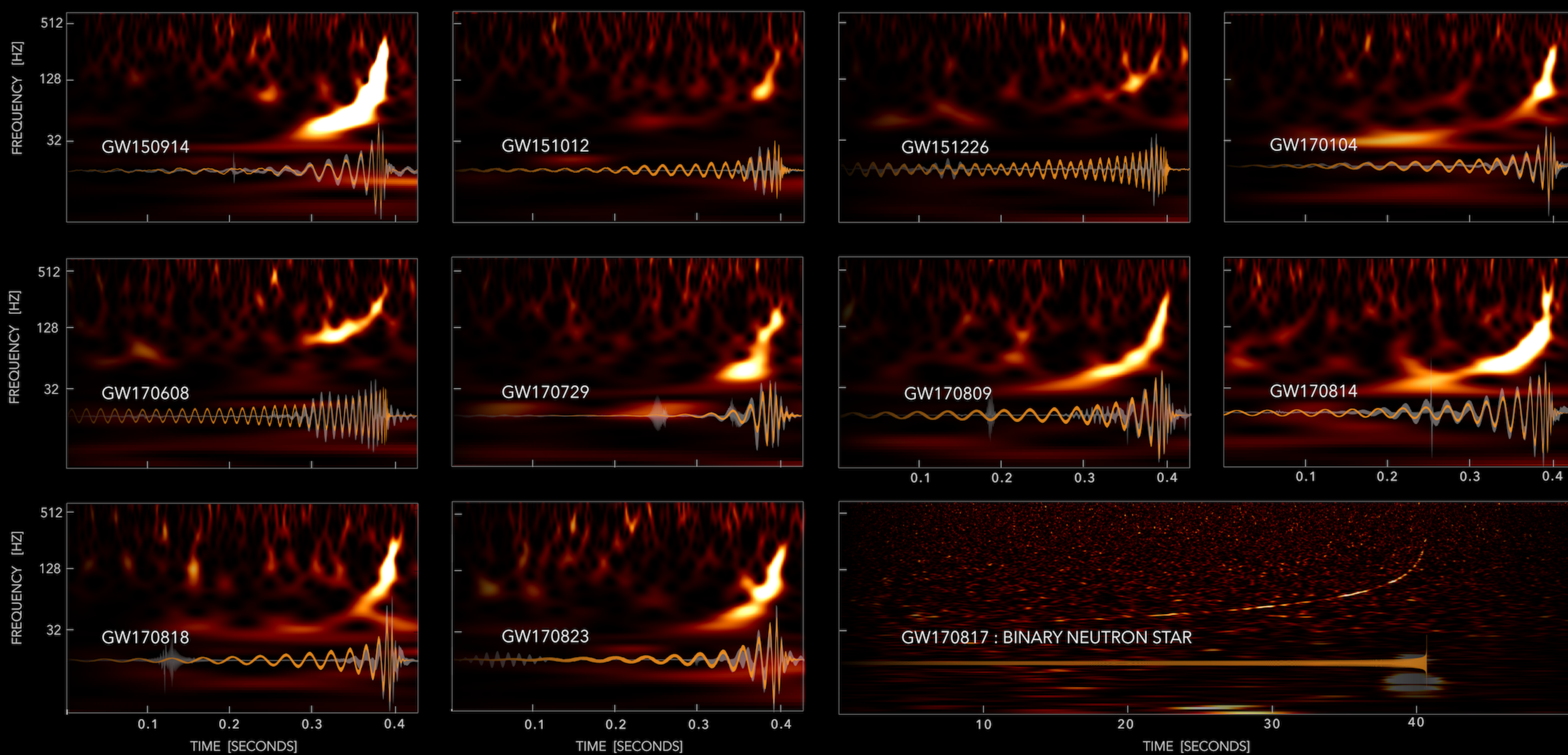




Fractions estimated for all stars with initial masses above 15 $M_\odot$ (from Sana et al., 2012)

Larger sample of binary systems (adapted from Moe & di Stefano, 2017)

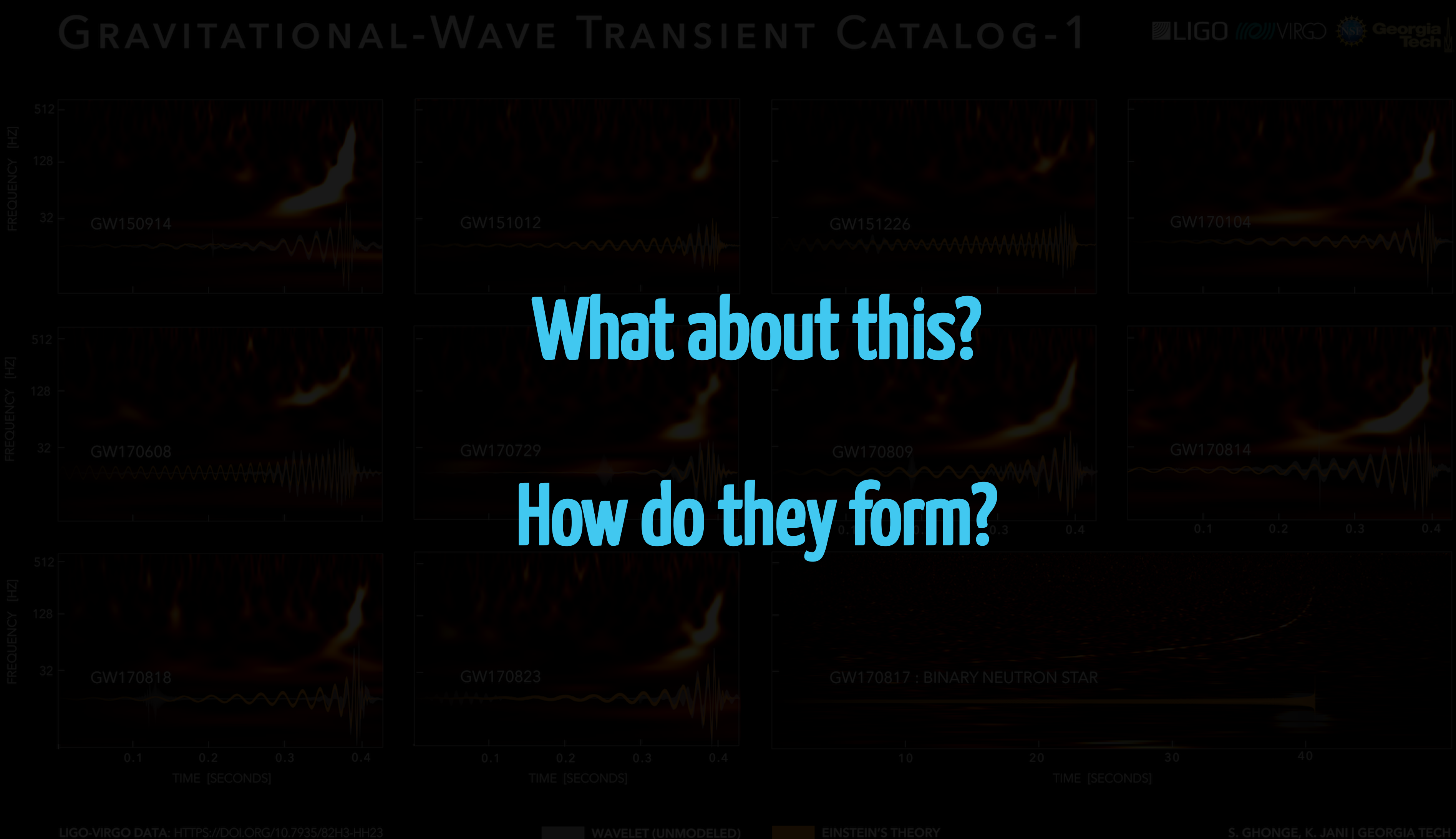
GRAVITATIONAL-WAVE TRANSIENT CATALOG-1



LIGO-VIRGO DATA: HTTPS://DOI.ORG/10.7935/82H3-HH23

WAVELET (UNMODELED) EINSTEIN'S THEORY

S. GHONGE, K. JANI | GEORGIA TECH



What about this?

How do they form?

Dynamical interaction channel

Key aspect: **dense stellar cluster** such that there are several interactions before binary black hole formation

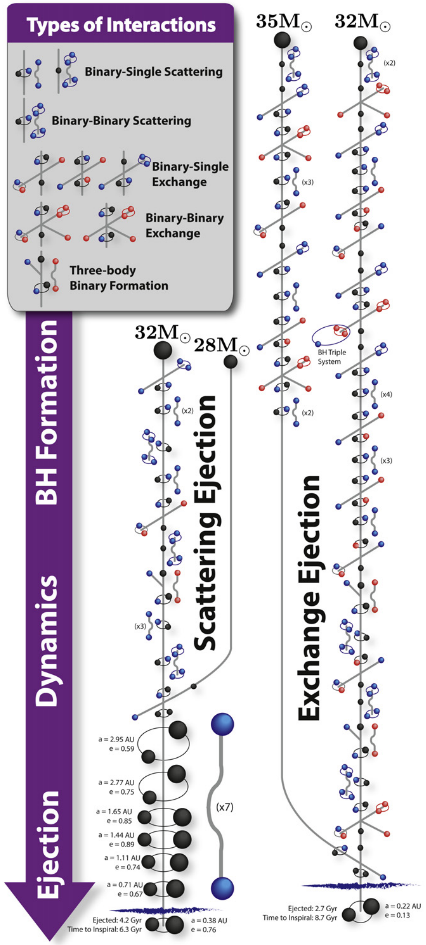


image from Rodriguez et al. 2016

Isolated evolutionary channel (I)

Key aspect: stars need to evolve **chemical homogeneously** their entire life

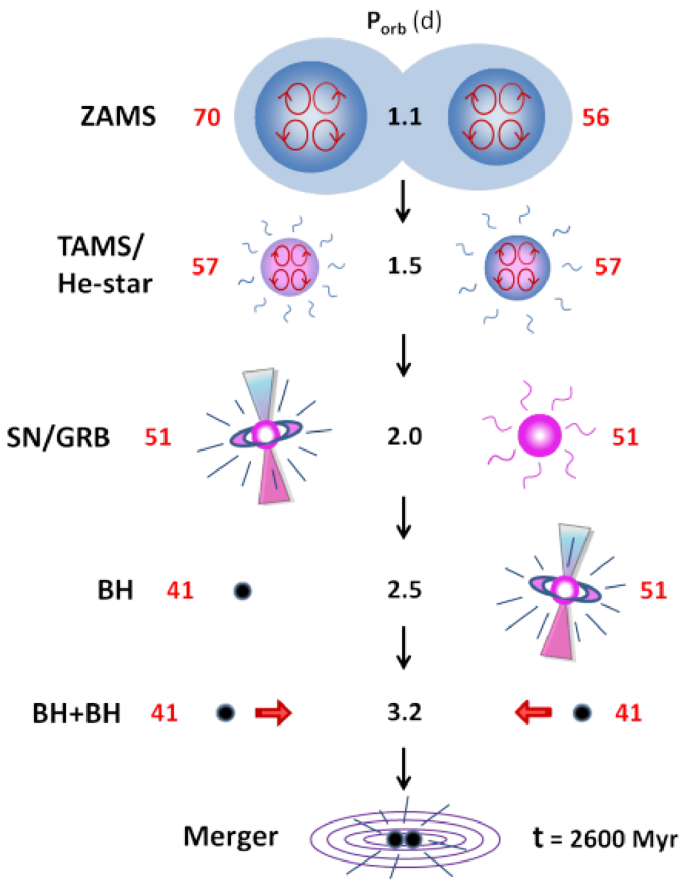


image from Marchant et al. 2016

Isolated evolutionary channel (II)

Key aspect: need a **common-envelope phase** (CE)

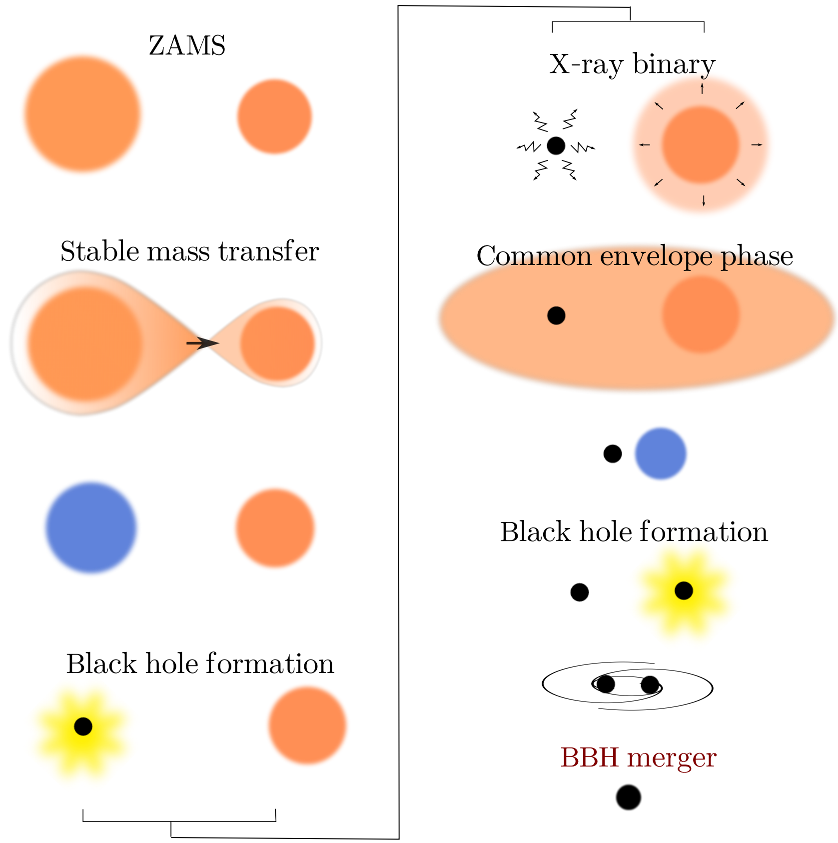
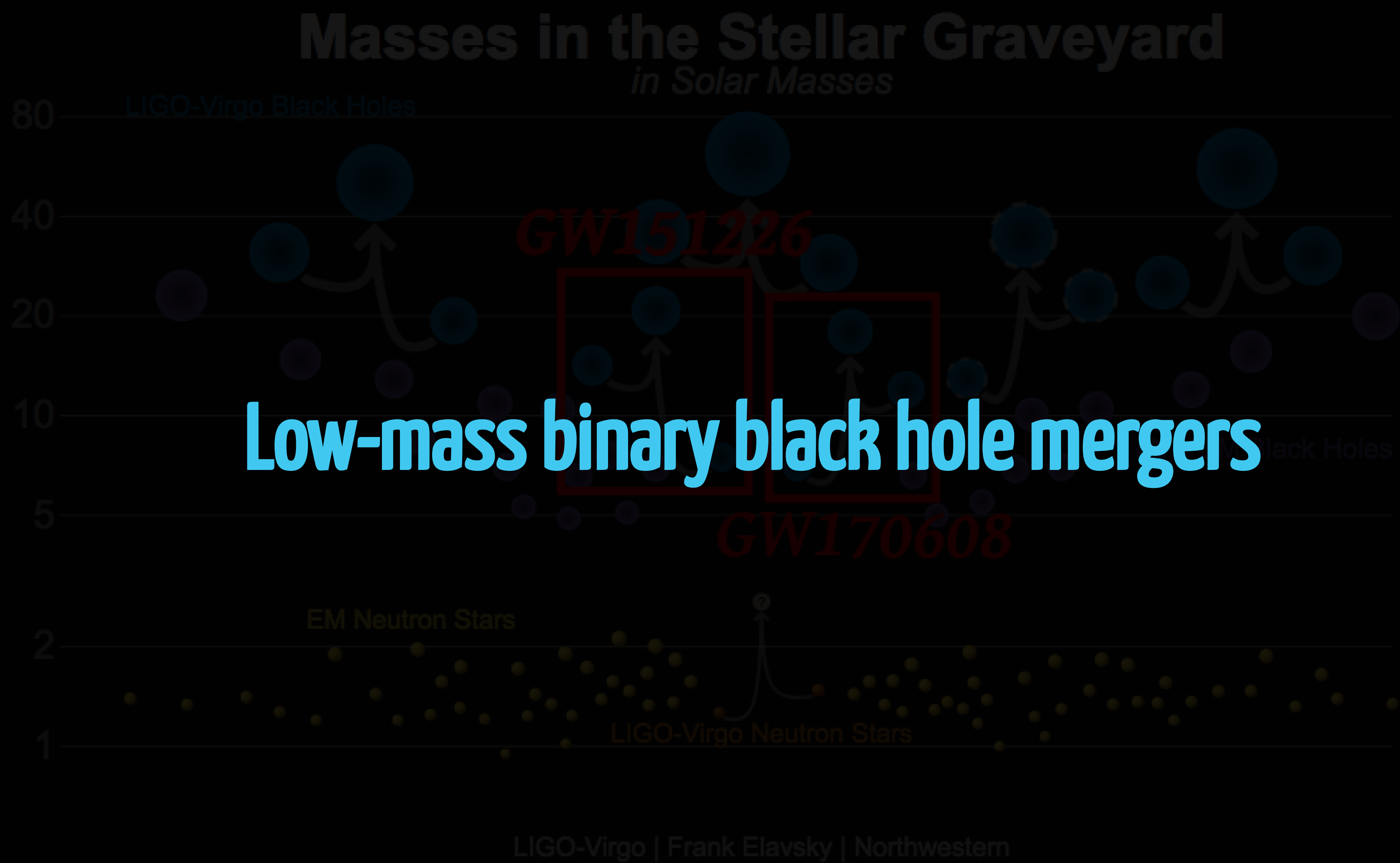
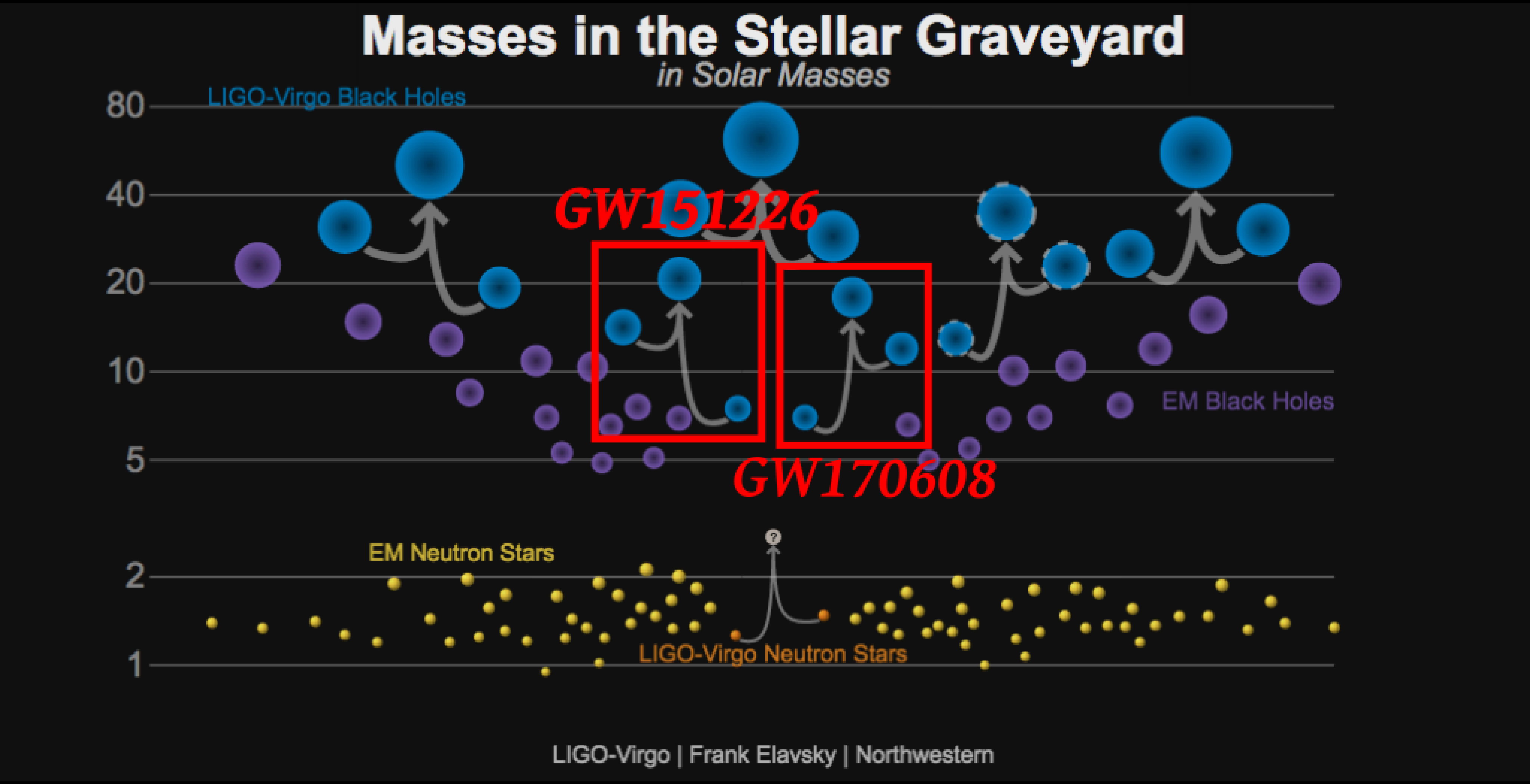


image from García et al., in prep.

Low-mass binary black hole mergers

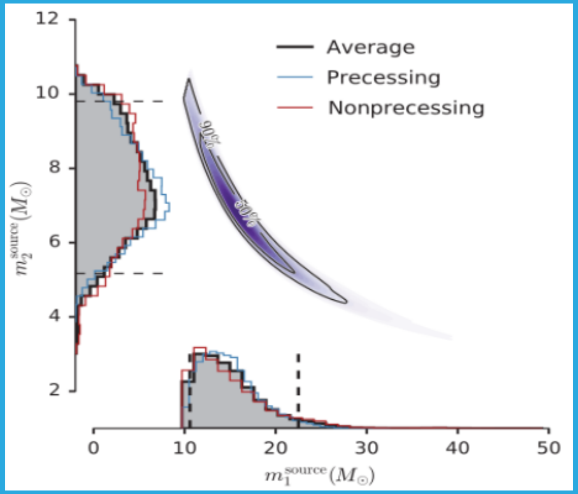




Masses in the Stellar Graveyard
in Solar Masses
LIGO-Virgo Black Holes
80
40
20
10
5
2
1
GW151226
GW170608
EM Black Holes
EM Neutron Stars
?
LIGO-Virgo Neutron Stars
LIGO-Virgo | Frank Elavsky | Northwestern

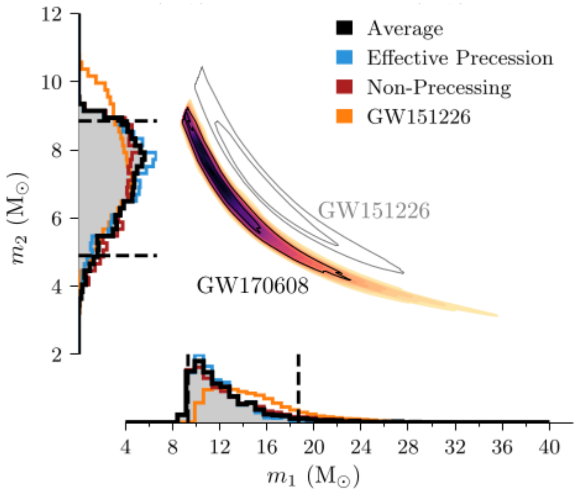
GW151226

- Discovery date: December 26, 2015
- Hanford SNR of 10.5, Livingston SNR of 7.9
- $M_{\mathrm{BH},1} = 14.2^{+8.3}_{-3.7}\, M_\odot ; M_{\mathrm{BH},2} = 7.5^{+2.3}_{-2.3}\, M_\odot$
- $M_{\mathrm{chirp}} = 8.9^{+0.3}_{-0.3}\, M_\odot ; M_{\mathrm{merged-BH}} = 20.8^{+6.1}_{-1.7}\, M_\odot$
- redshift: $z = 0.09^{+0.03}_{-0.04}$



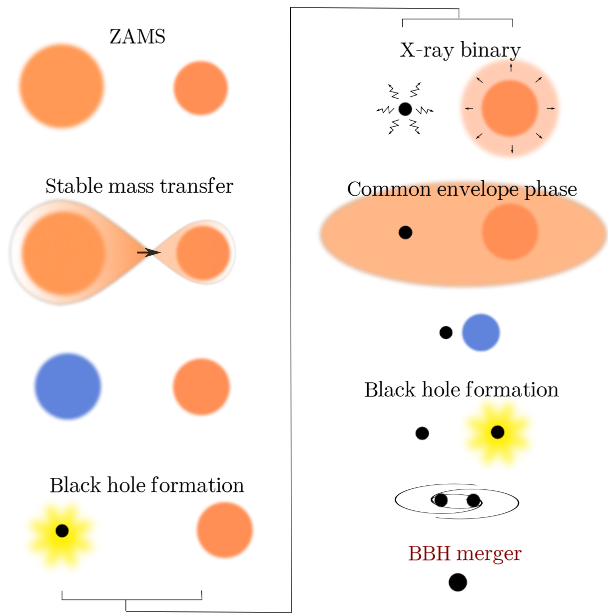
GW170608

- Discovery date: June 8, 2017
- Hanford SNR of 10.5, Livingston SNR of 7.9
- $M_{\mathrm{BH},1} = 12^{+7}_{-2}\, M_\odot ; M_{\mathrm{BH},2} = 7^{+2}_{-2}\, M_\odot$
- $M_{\mathrm{chirp}} = 7.9^{+0.2}_{-0.2}\, M_\odot ; M_{\mathrm{merged-BH}} = 18^{+4.8}_{-0.9}\, M_\odot$
- redshift: $z = 0.07^{+0.03}_{-0.03}$



Aims

First part: study the progenitor properties for these two GW events in the isolated binary evolutionary scenario



For that, we follow the complete evolution of the binary: from two non-degenerate stars up to the formation of the two black holes. We used a detailed evolutionary code, publicly available, **MESA**, which we modified to include the common-envelope phase and a compact object formation

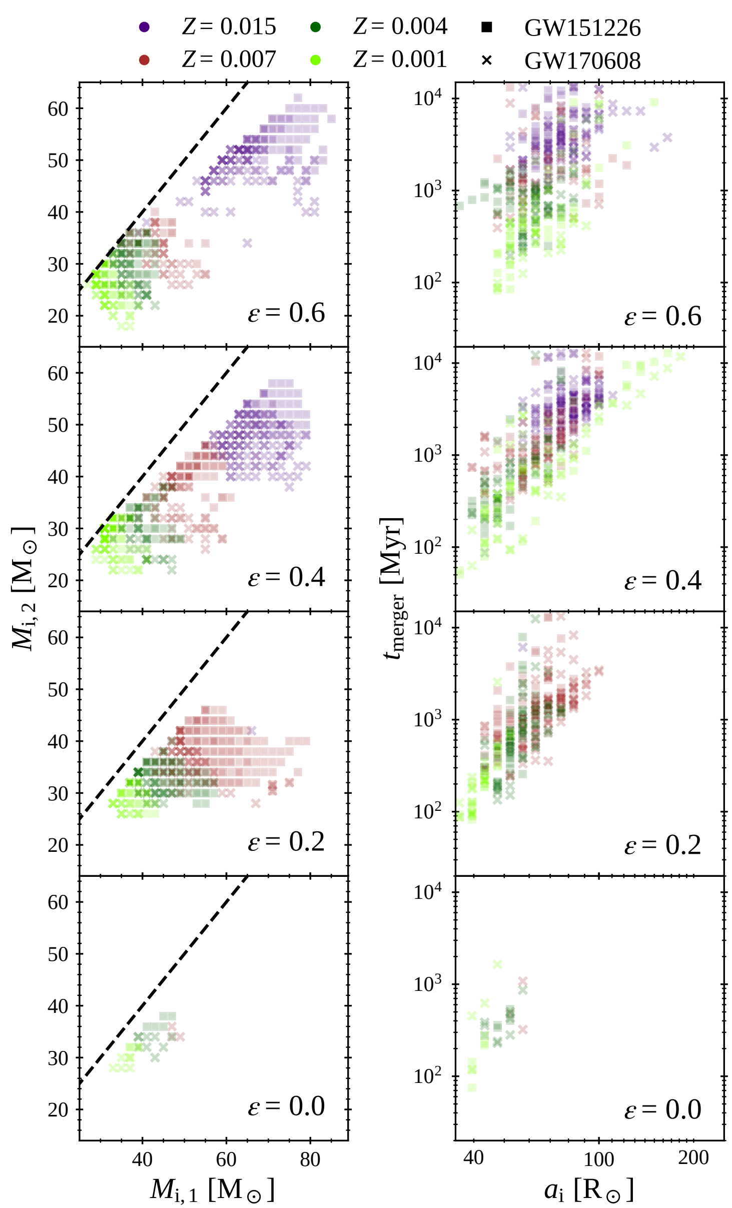
Second part: obtain merger rates for them in O1, O2 and expected ones in O3

Methods:

First part

Free parameters in simulations
Metallicity of the population, (Z)
Accretion efficiency during the stable mass-transfer phase, (f_{MT})
Efficiency for the removal of a star envelope during and unstable mass-transfer phase, i.e, common-envelope (CE) phase, (α_{CE})

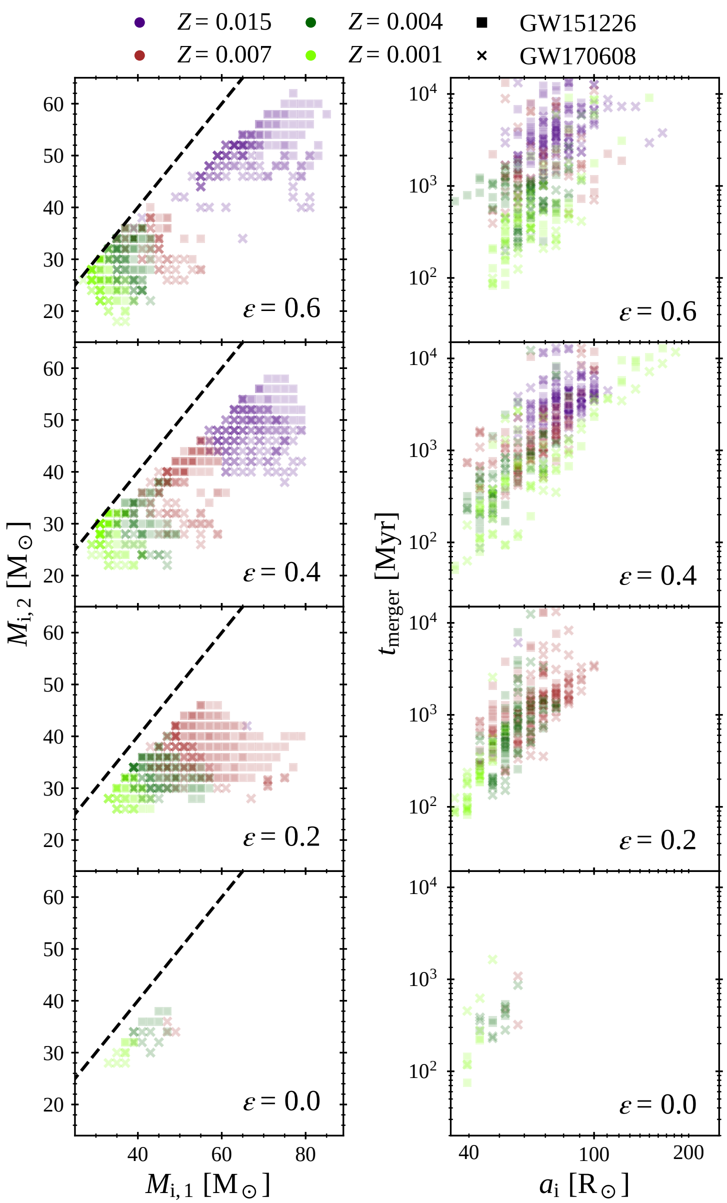
3D grids of initial masses and binary separations were created for each of the above parameters, giving a total number of simulations of more than 50 000



Initial binary parameters

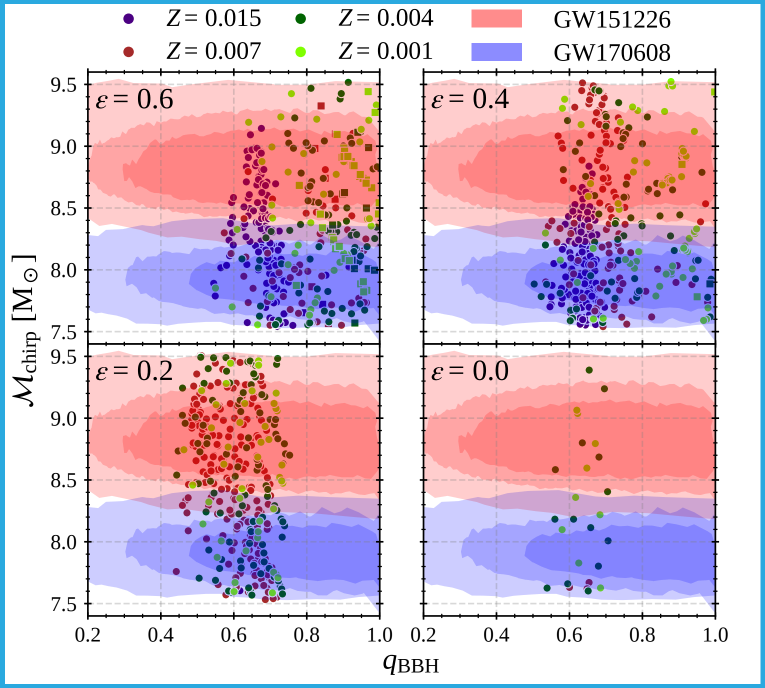
$\alpha_{CE} = 2$

- Higher metallicities requires increasingly massive stars: directly related to winds
- In the low mass-accretion regime, only low metallicity binaries are progenitors. High metallicity ones produce low chirp masses
- For $\epsilon > 0.2$, binaries with similar initial masses are also progenitors



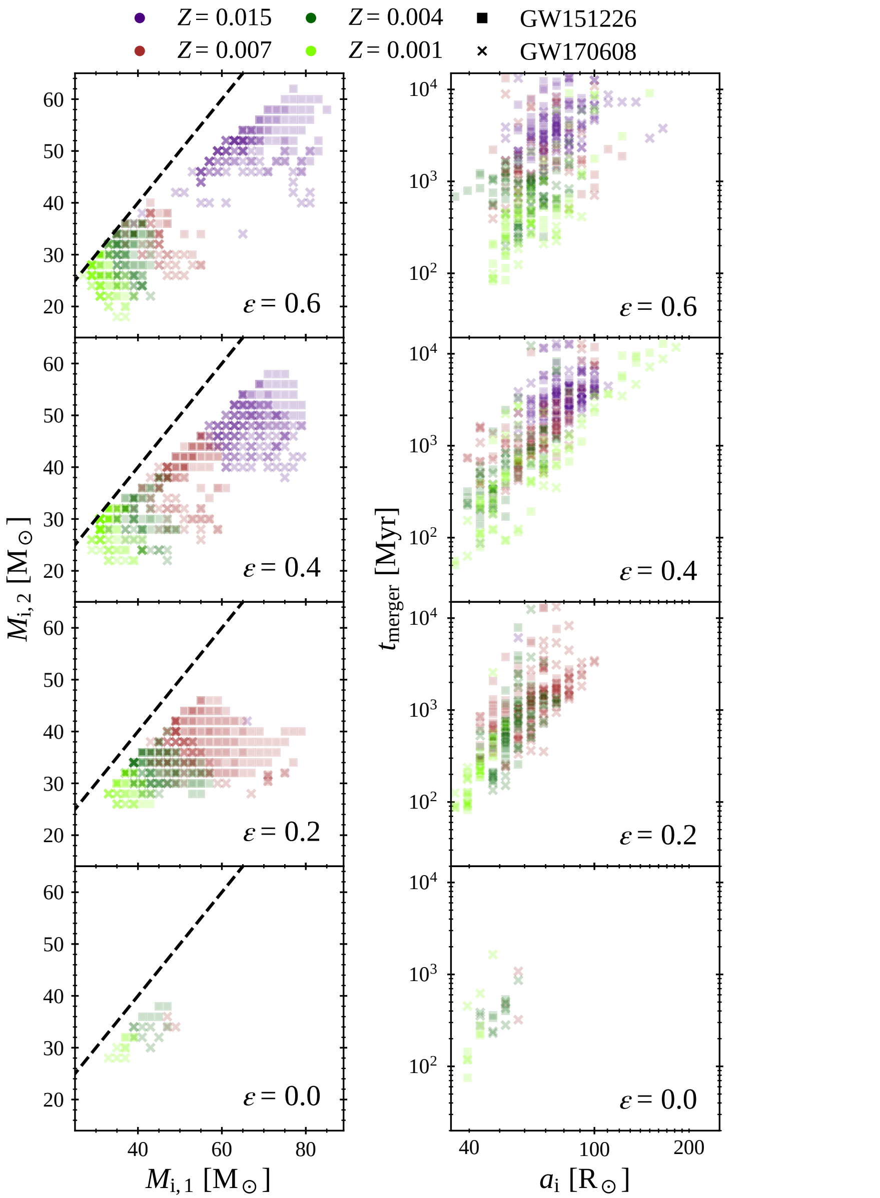
Map with BBH properties

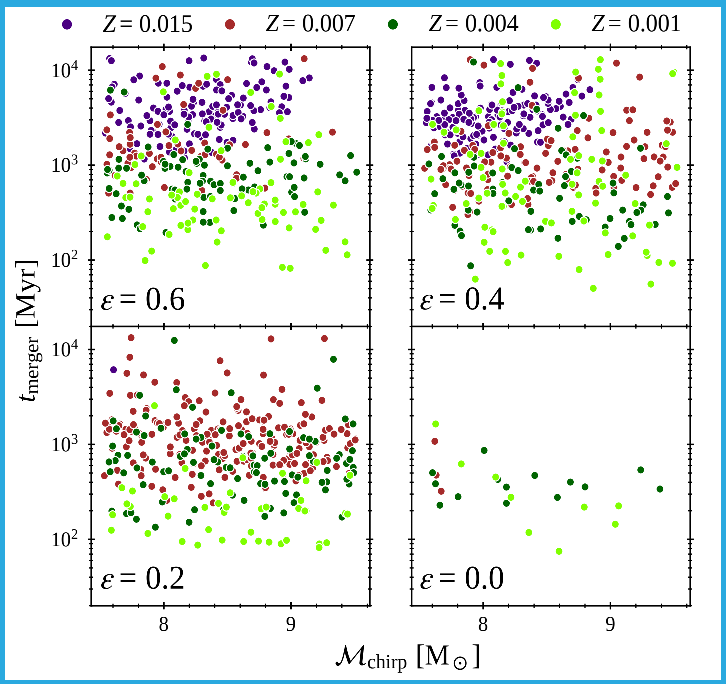
$\alpha_{\rm CE} = 2$

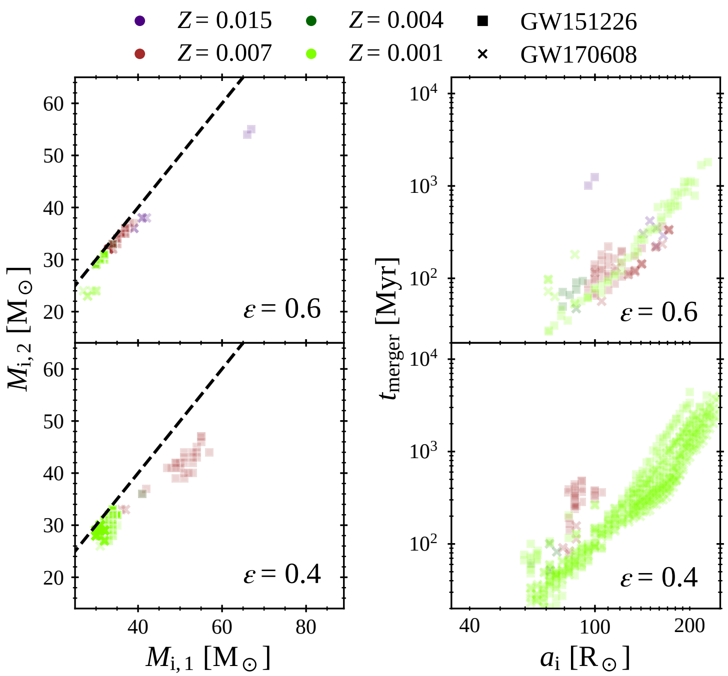


Map with BBH properties

$\alpha_{\mathrm{CE}} = 2$







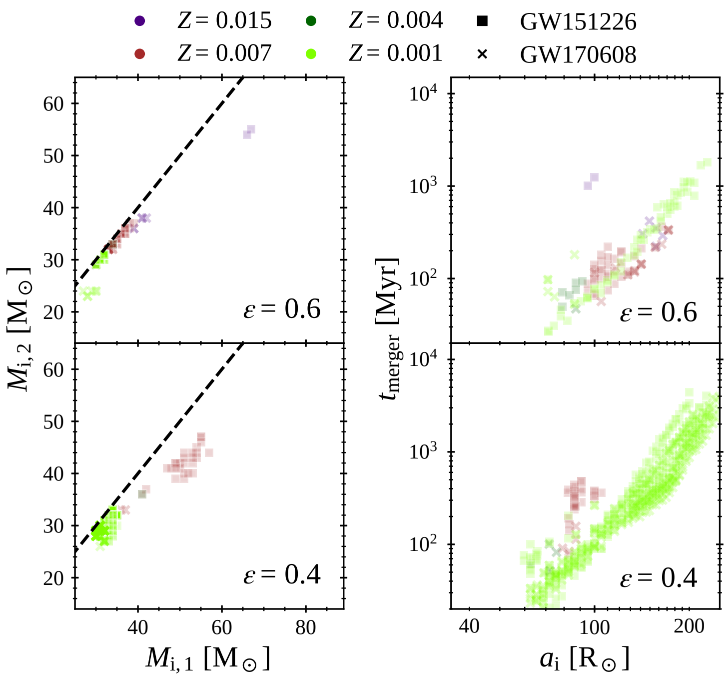
Initial binary parameters

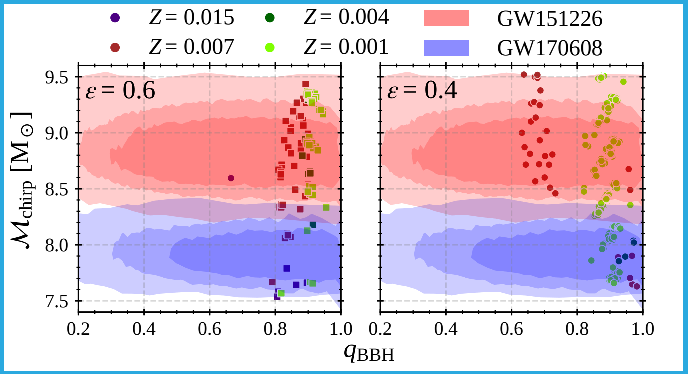
$\alpha_{CE} = 1$

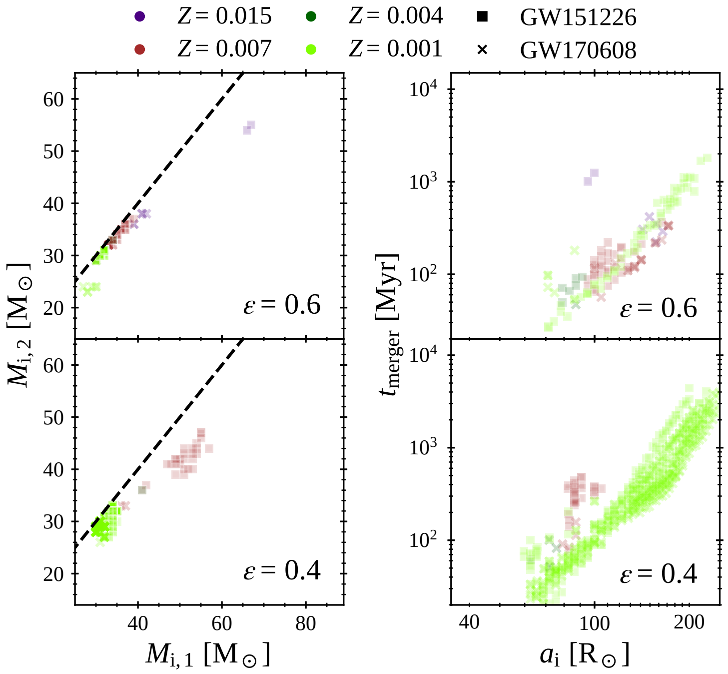
- Initial mass ratios of progenitors are closer to unity (similar initial masses)
- No solutions were found for mass-accretion efficiencies that are below 0.2
- Binaries with separations lower than 60 $R_\odot$ merge during the CE phase as a consequence of having a lower efficiency for the CE ejection
- Merger times are also lowered wrt the ones from high CE ejection efficiencies

Map with BBH properties

$\alpha_{CE} = 1$

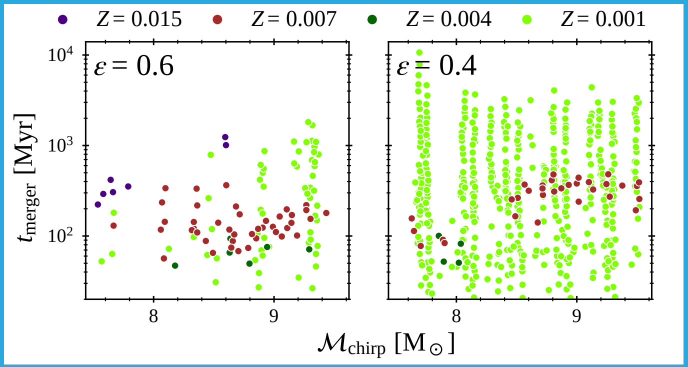






Map with BBH properties

$\alpha_{\mathrm{CE}} = 1$



Methods:

Second part

To estimate expected properties, detailed stellar models were rescaled by empirical **initial mass functions** (IMF, e.g., Kroupa et al., 1993) for the primary and secondary stars (flat distribution in mass-ratio) and by an **initial separation distribution** from the observed binary orbital period distribution (Sana et al., 2012)

Methods:

Second part

For a number density of binaries in the multidimensional space of initial masses, separations and delay times,

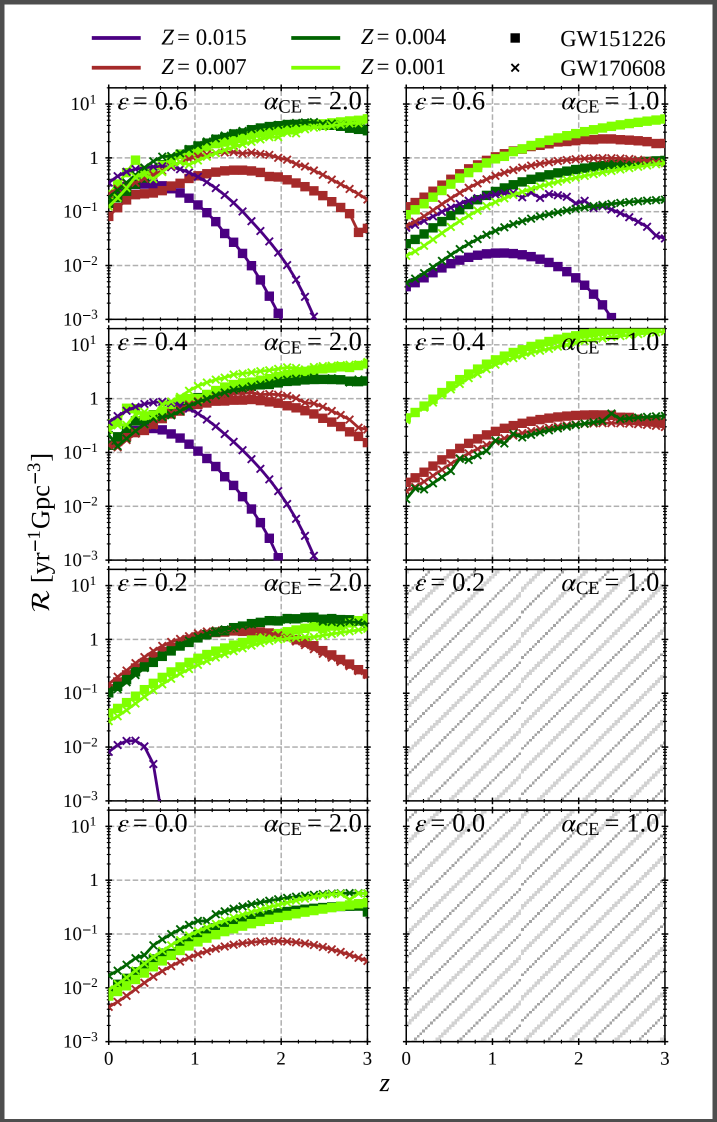
$$\frac{\mathrm{dN}}{\mathrm{dM_{i,1}\,dM_{i,2}\,da_i\,dt_m}}(\mathrm{M_{i,1}, M_{i,2}, a_i; t_m}) = \mathrm{P_{GW-event}}\ \mathrm{f_{M_{i,1}}}\ \mathrm{f_{M_{i,2}}}\ \mathrm{f_{a_i}}$$

And assuming a cosmology that relates redshift to cosmic time, and a given metallicity-dependent star formation rate,

$$\mathrm{SFR(t'; Z) = SFR(t')\psi(Z, z'(t'))}$$

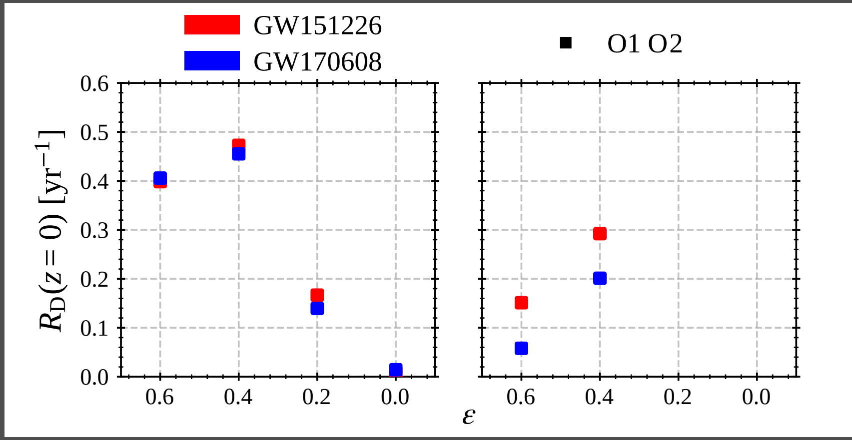
The intrinsic merger rate for a GW event is:

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



Merger rate density history

- The expected local merger rate densities are all larger for the highest value of CE removal efficiency. Something that is related to the 'size' of the parameter space
- For high metallicities, rates decay with redshift because of the chemical evolution
- For the low CE efficiency, rates are largely dominated by low metallicities



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

Detectable merger rate at zero redshift

- The highest rate is obtained for a mass-accretion efficiency of 0.4 for both CE efficiencies
- However, expected rates obtained are within a factor of 2, thus we are not able to distinguish a preferred value for the mass-accretion efficiency

Conclusions

With current and future campaings of observing GW, more we will now about their progenitors

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Giving the rising power of computers, having a large grid of detailed binary calculations is possible. Even to calculate complete populations of progenitors

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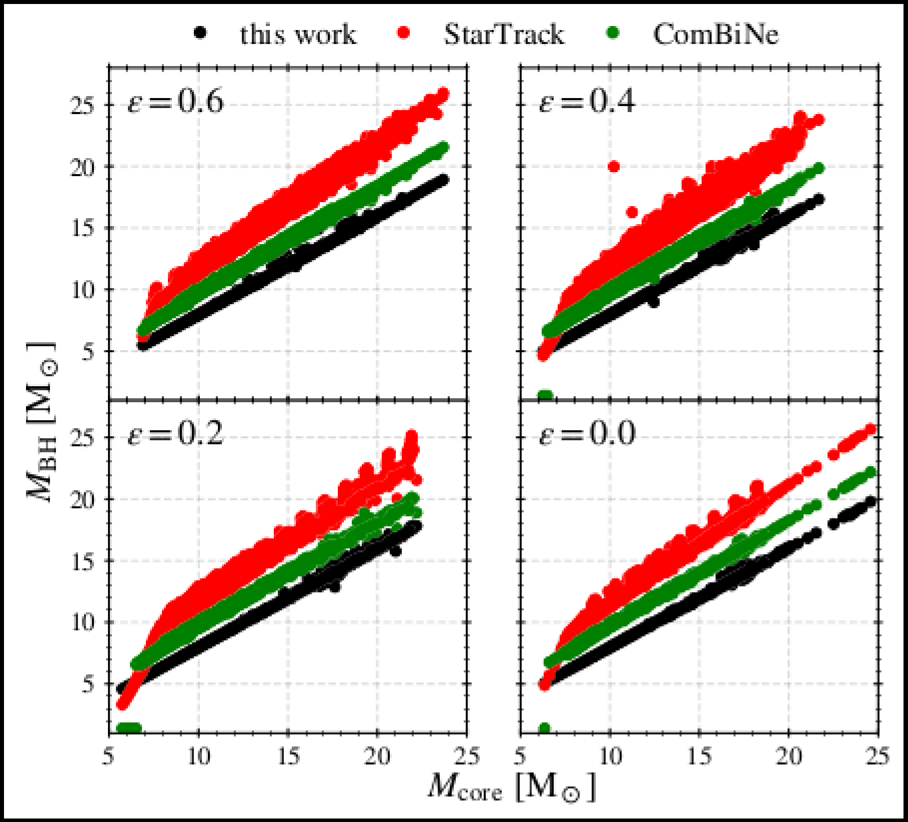
Several uncertainties are still present in nowadays calculations, so estimates like rates can vary by order of magnitude when changing input physical parameters

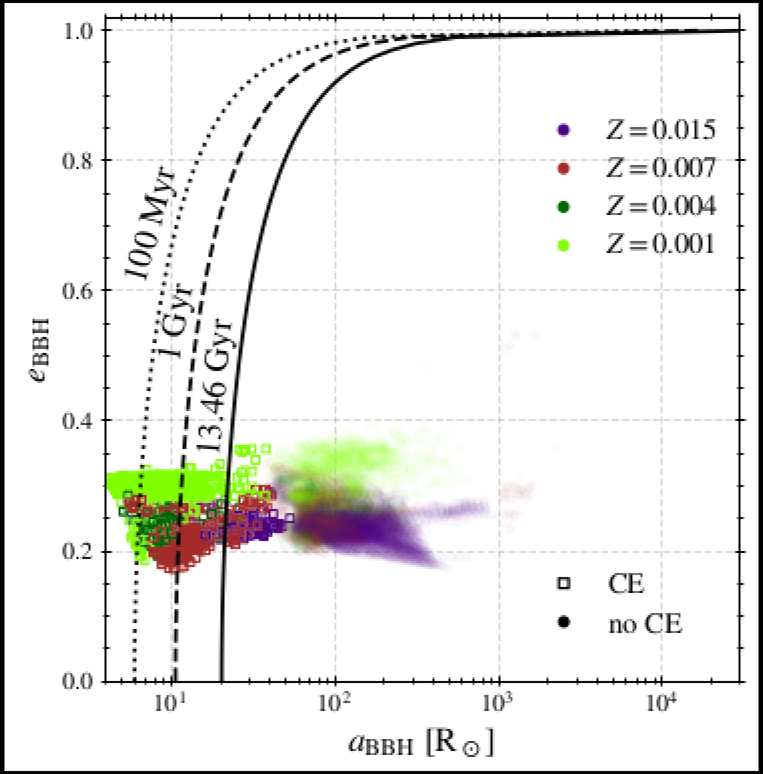
THANK YOU!

Backup

Different prescriptions for BH masses



Importance of CE phase



Importance of evolution through cosmic time