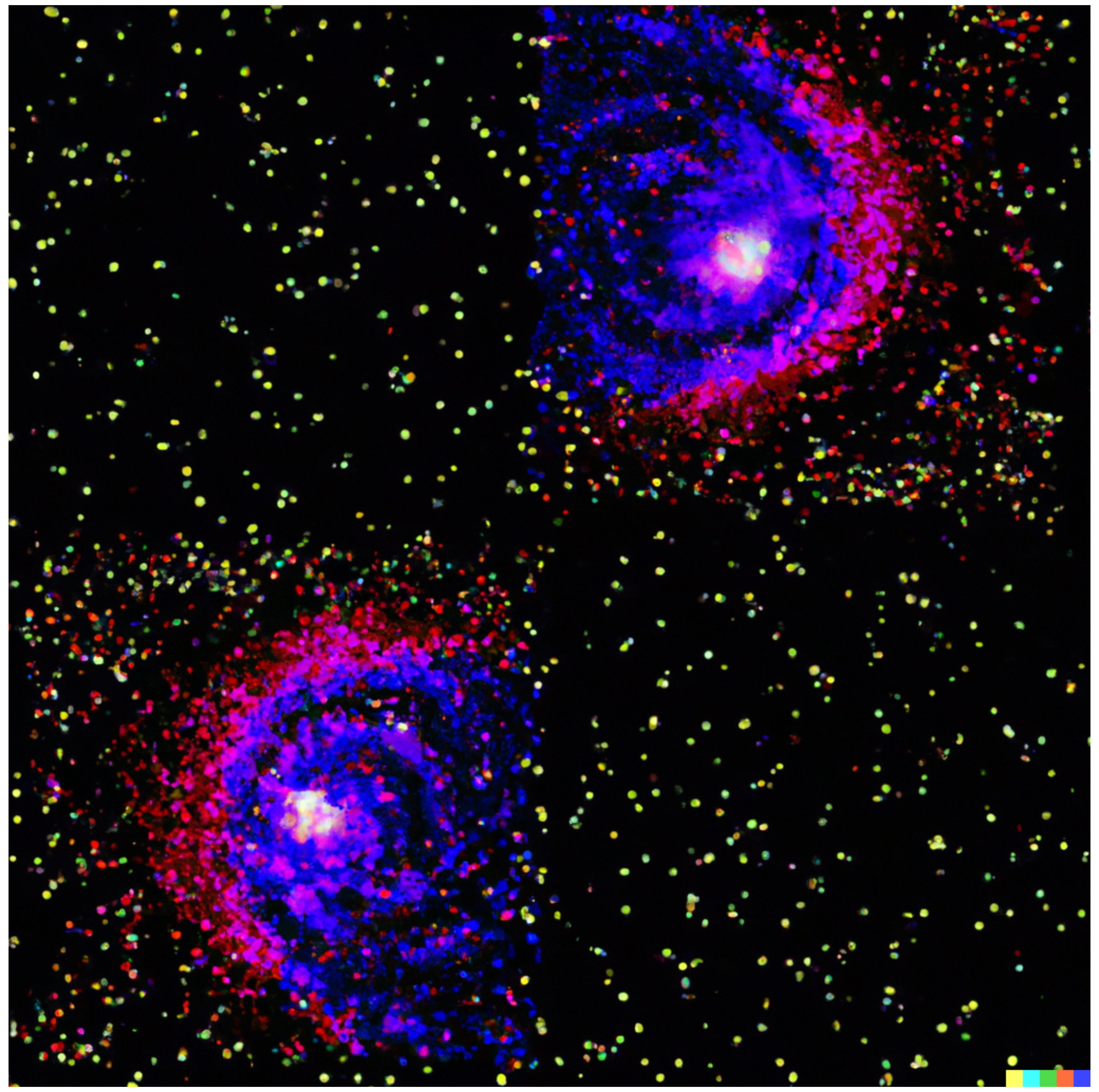
The host galaxies of binary compact objects



OpenAI. (2023). "The host galaxies of binary black hole mergers in pixel art" [Digital image]. Retrieved from https://openai.com/dall-e/

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L'Aquila, *Gravi-Gamma-Nu workshop*, October 4-6, 2023 galaxyRate

- **Why we need to study the host galaxies of compact objects?**
  - crucial **to explore** likely **formation mechanisms**
  - increase the chances to **identify host galaxies.**
- **How we did it?**
  - `galaxyRate` is a unique approach, featuring unprecedented speed
  - a **realistic model** of **star formation**

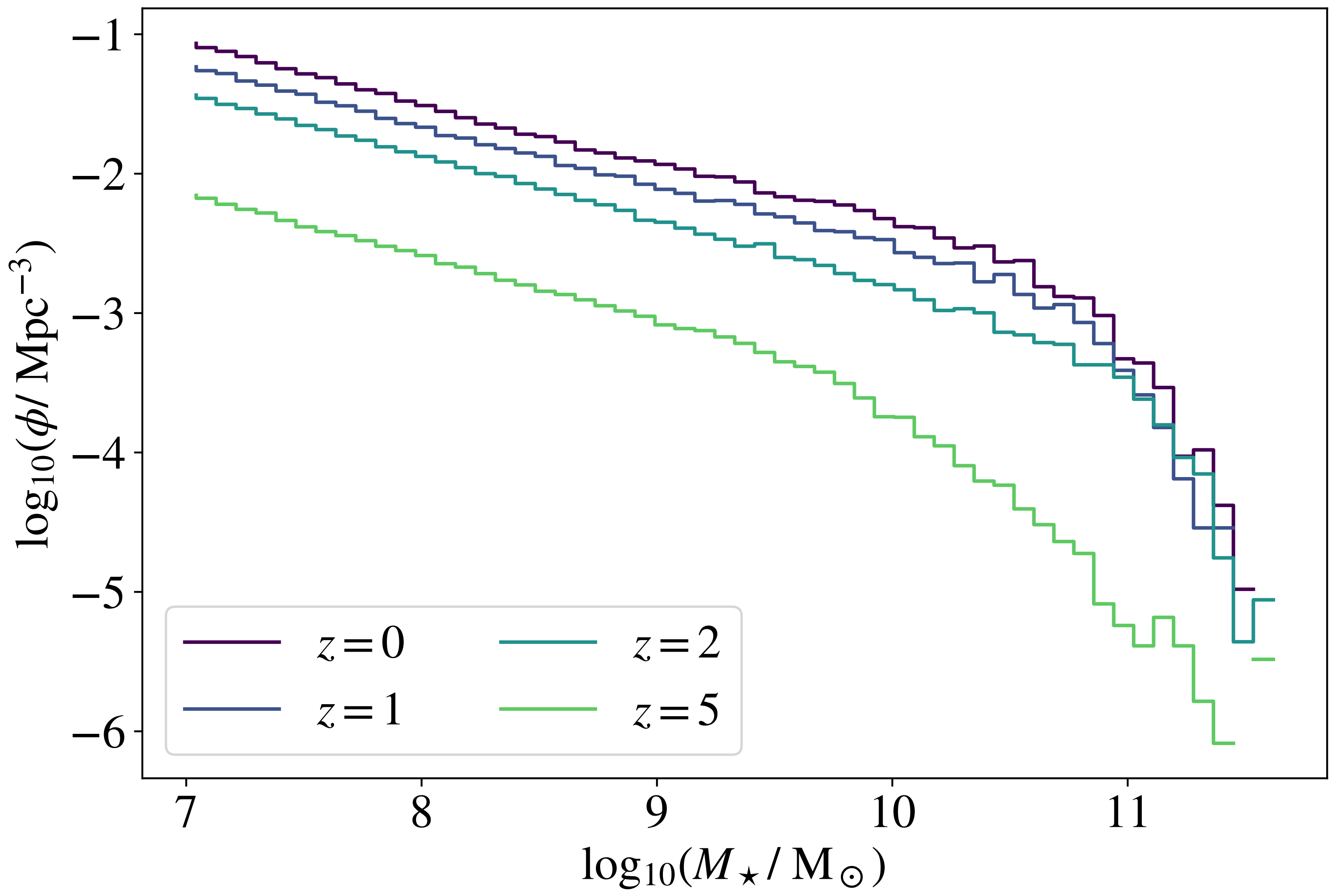
How galaxyRate works

Formation galaxies → Merging compact objects → Host galaxies

↑

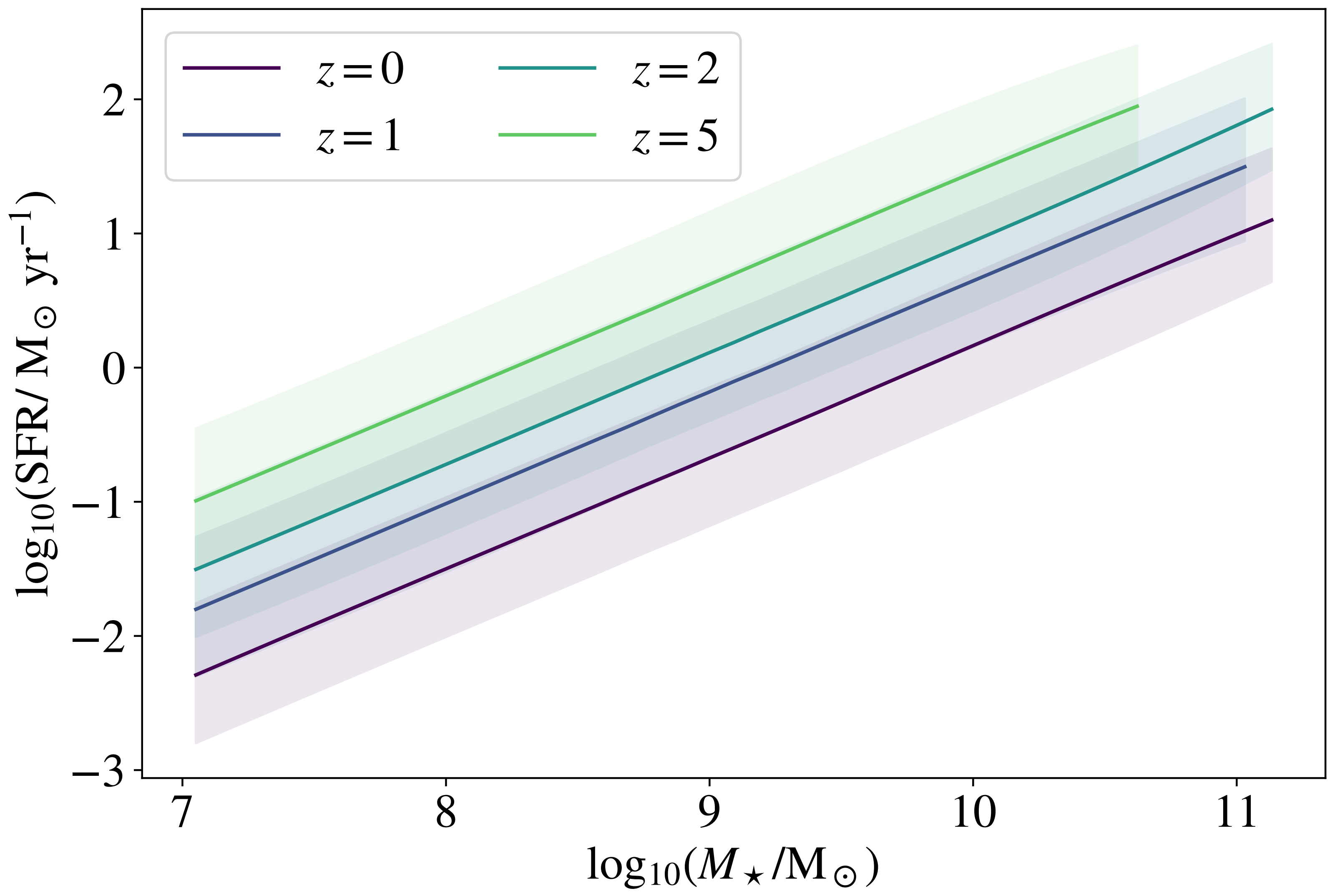
Population of star-forming galaxies from **observational scaling relations**

Stellar mass



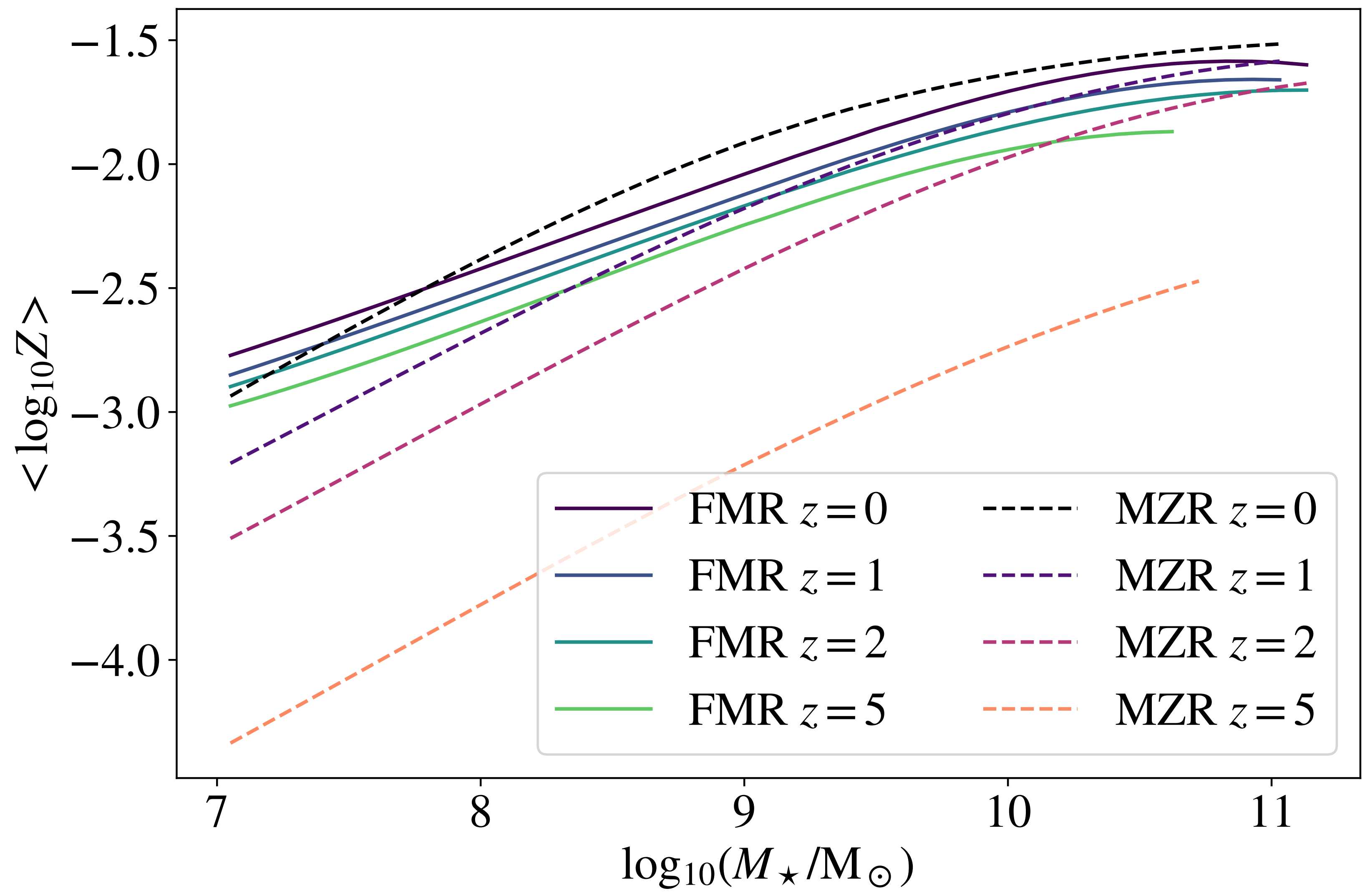
Chruslinska et al. 2019

Star-formation rate



Speagle et al. 2014, Boogaard et al. 2018

Metallicity



Mannucci et al. 2009, Mannucci et al. 2011

Formation galaxies → Merging compact objects → Host galaxies

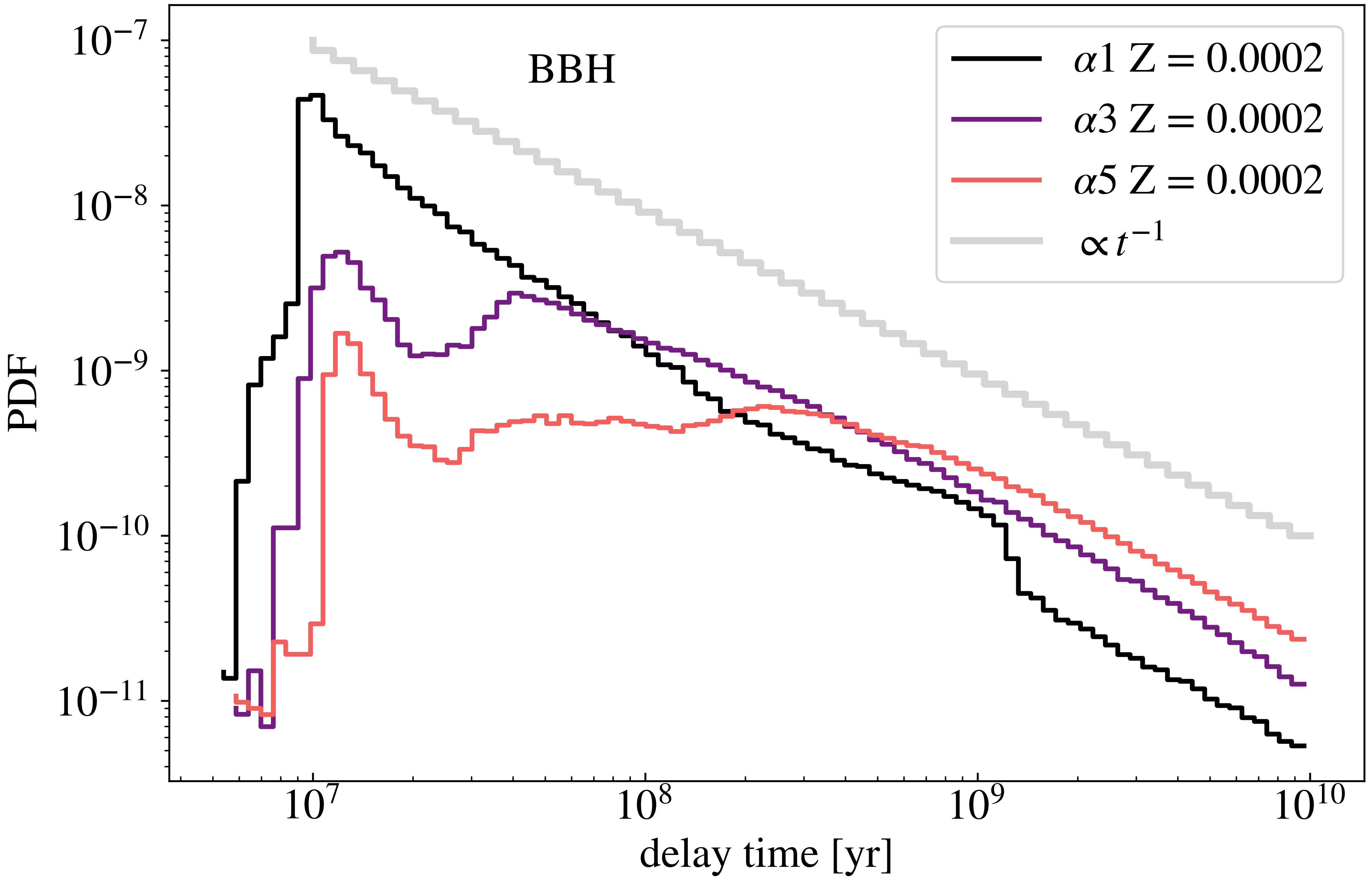
We evolved binary stars with **population-synthesis code** SEVN

Input VS **Output**

Initial conditions and **free parameters** of binary evolution → **Catalogs of merging BBHs** (primary mass, secondary mass, **delay time**, etc.)

SEVN is available at https://gitlab.com/sevncodes/sevn (*Iorio et al. 2022*)

Formation galaxies → Merging compact objects → Host galaxies

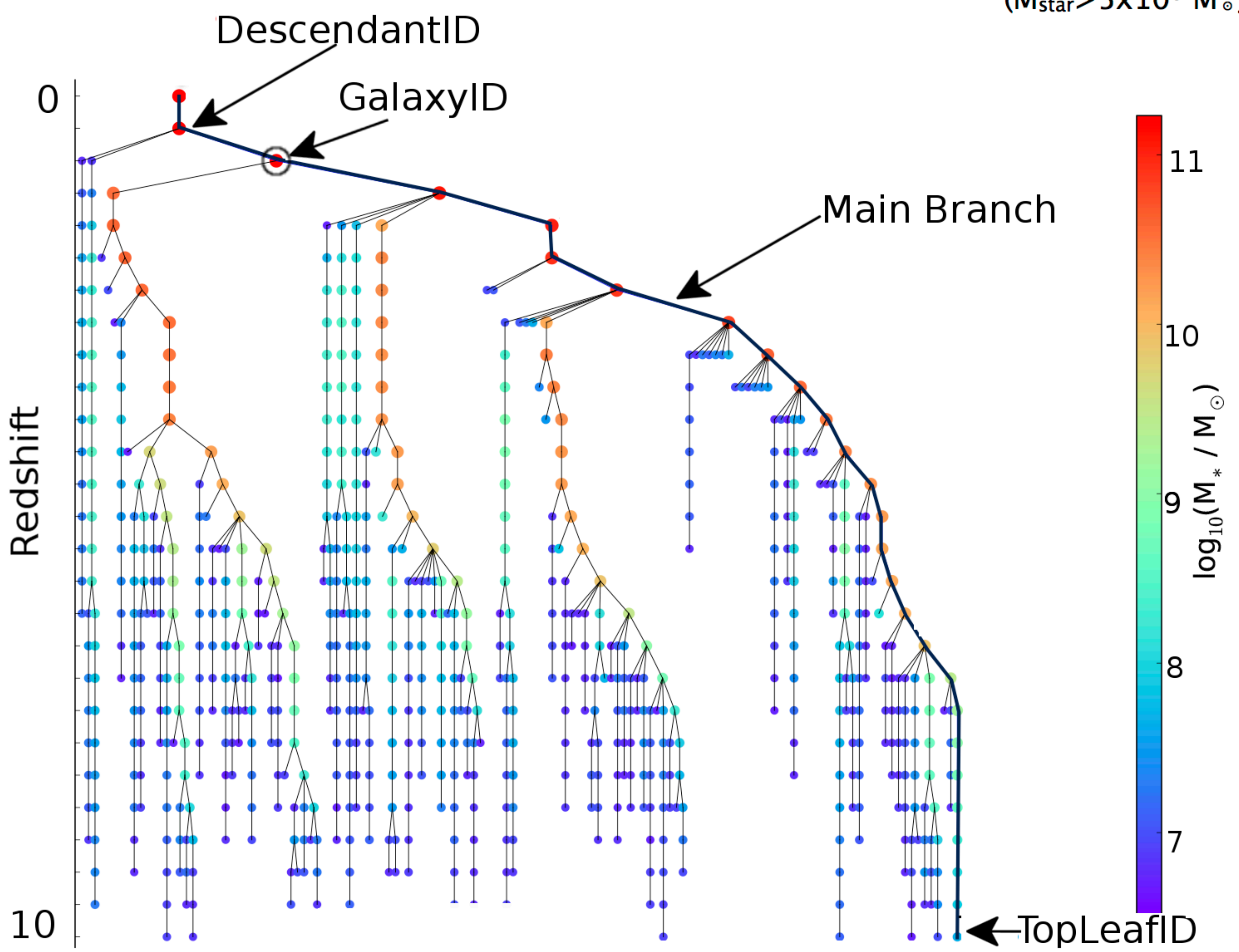


Santoliquido et al. 2022:
https://arxiv.org/pdf/2205.05099.pdf

Effect of common envelope

Formation galaxies → Merging compact objects → Host galaxies

subhalo merger tree
($M_{star} > 5x10^6$ $M_\odot$)

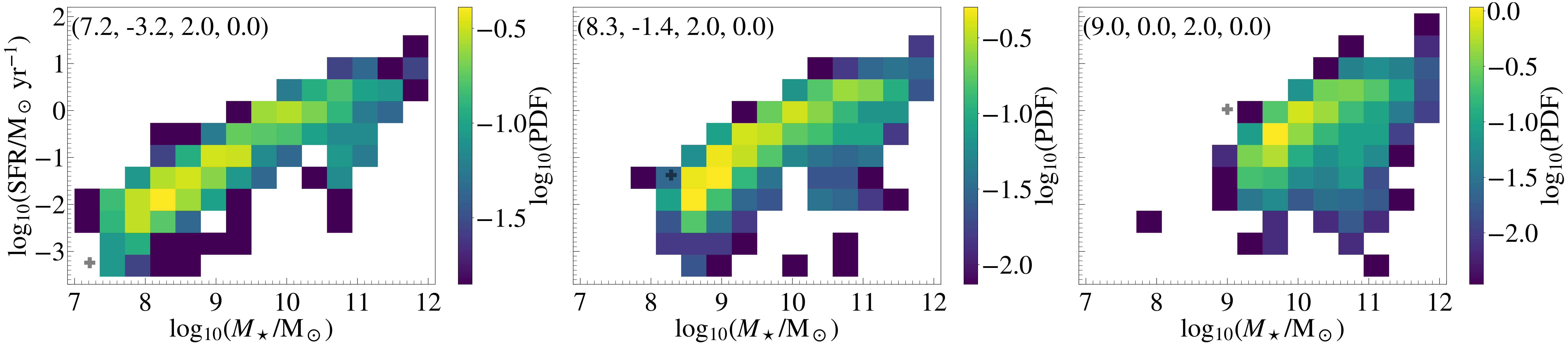


Schaye et al. 2015, McAlpine et al. 2016

Formation galaxies → Merging compact objects → Host galaxies

From the **merger trees**, I compute a **conditional probability**

I **sample** the **properties** of the **host galaxy**



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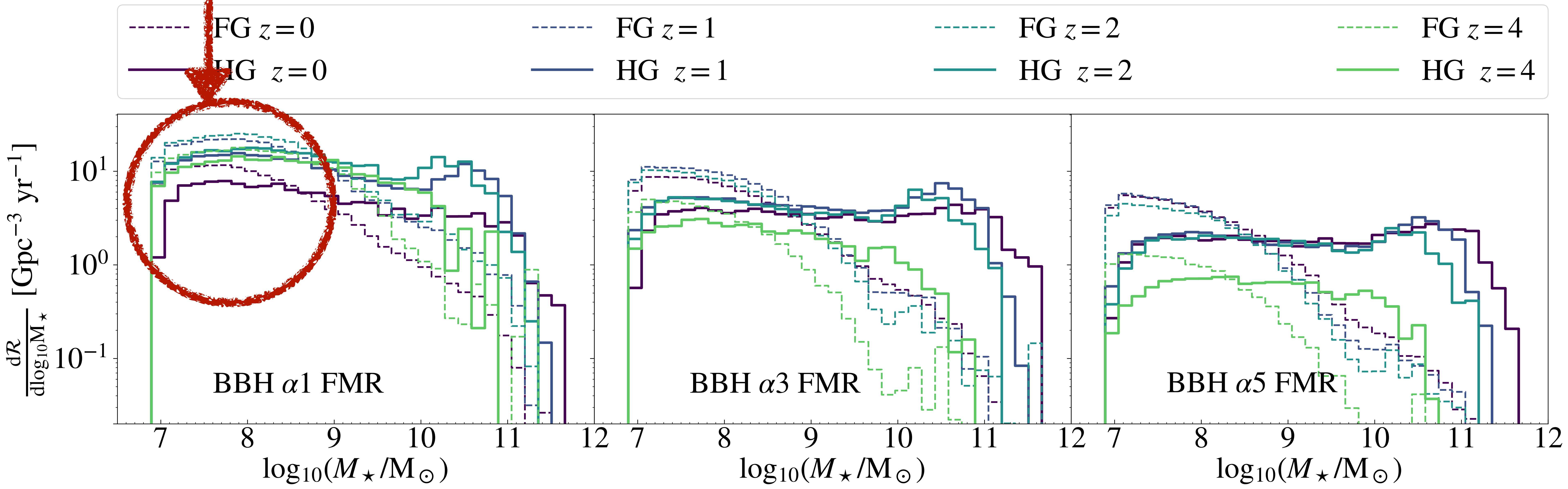
Host galaxy stellar mass

Santoliquido et al. 2022:
https://arxiv.org/pdf/2205.05099.pdf

1) BBHs form in low-mass galaxies and merge in low-mass galaxies



Host galaxy stellar mass

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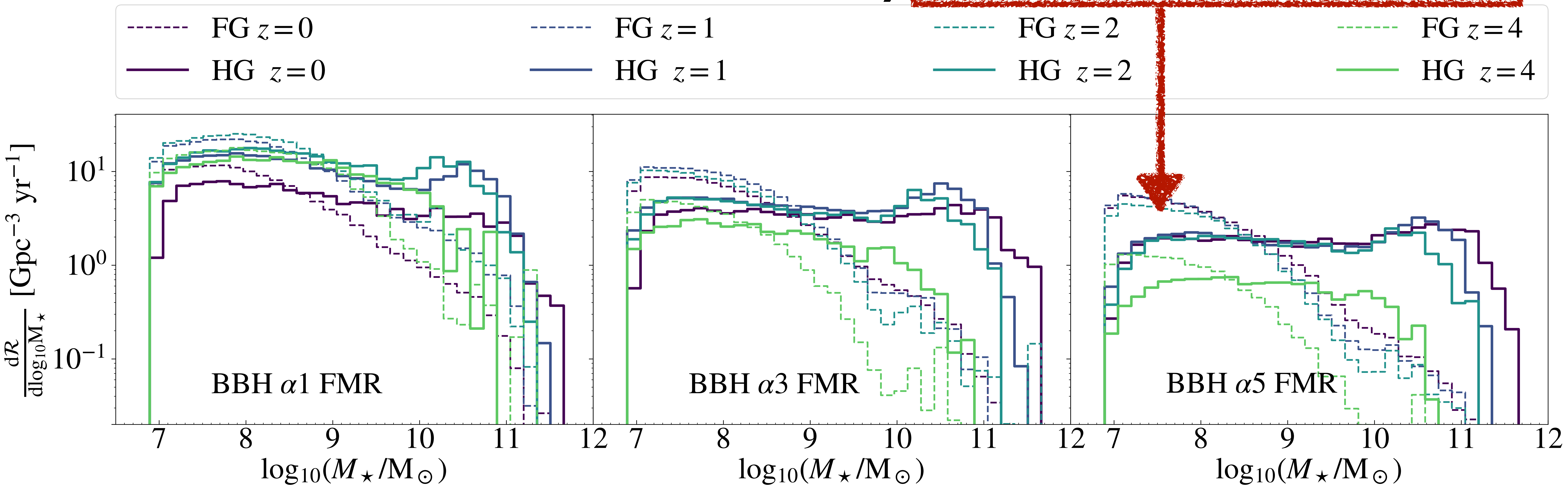
The fraction of merging in low-mass galaxies decreases with increasing α

2)

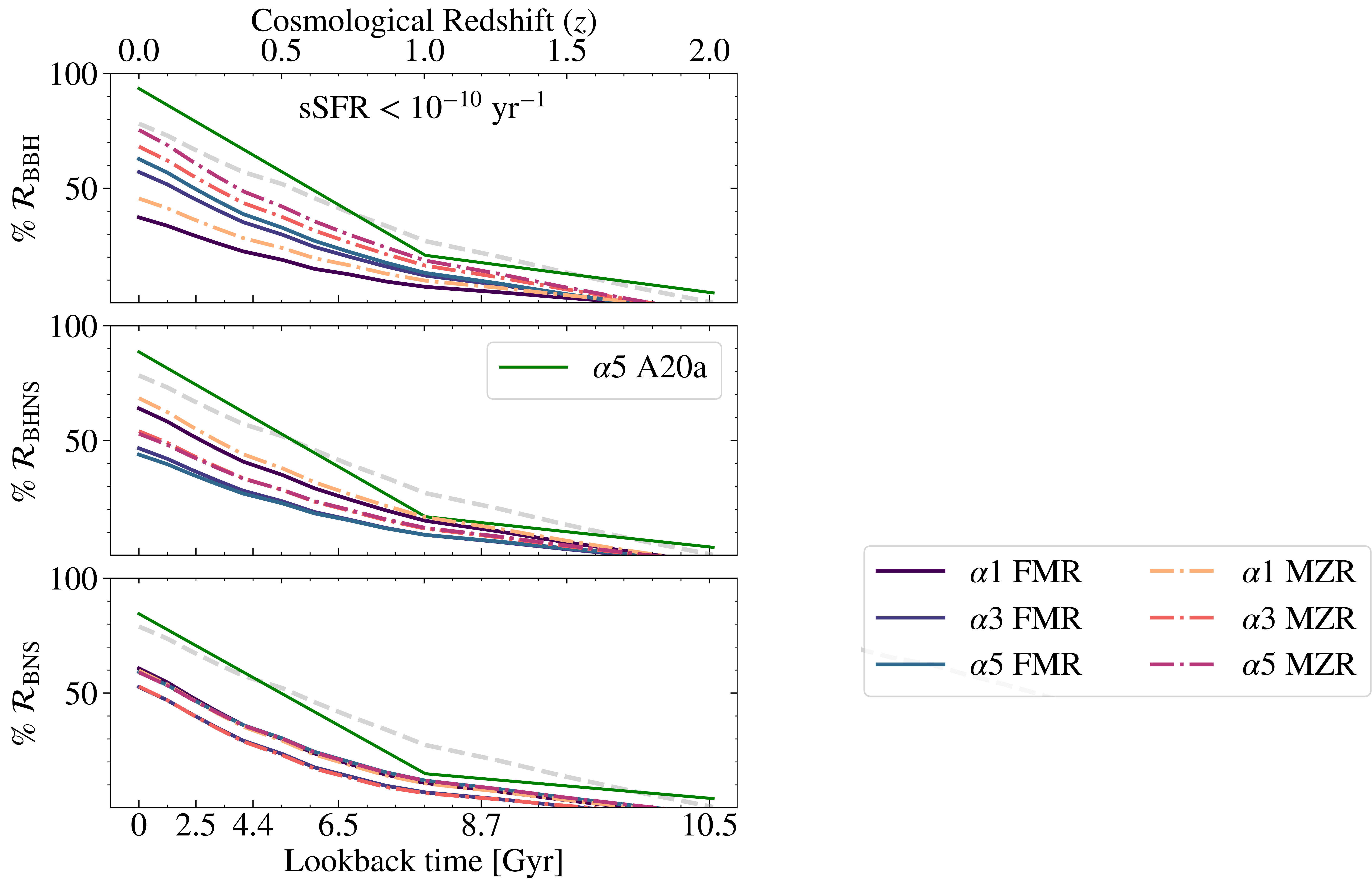


Passive galaxies

Santoliquido et al. 2022:
https://arxiv.org/pdf/2205.05099.pdf

1)

Percentage of mergers hosted in passive galaxies **increases at decreasing redshift**



Passive galaxies

Santoliquido et al. 2022:
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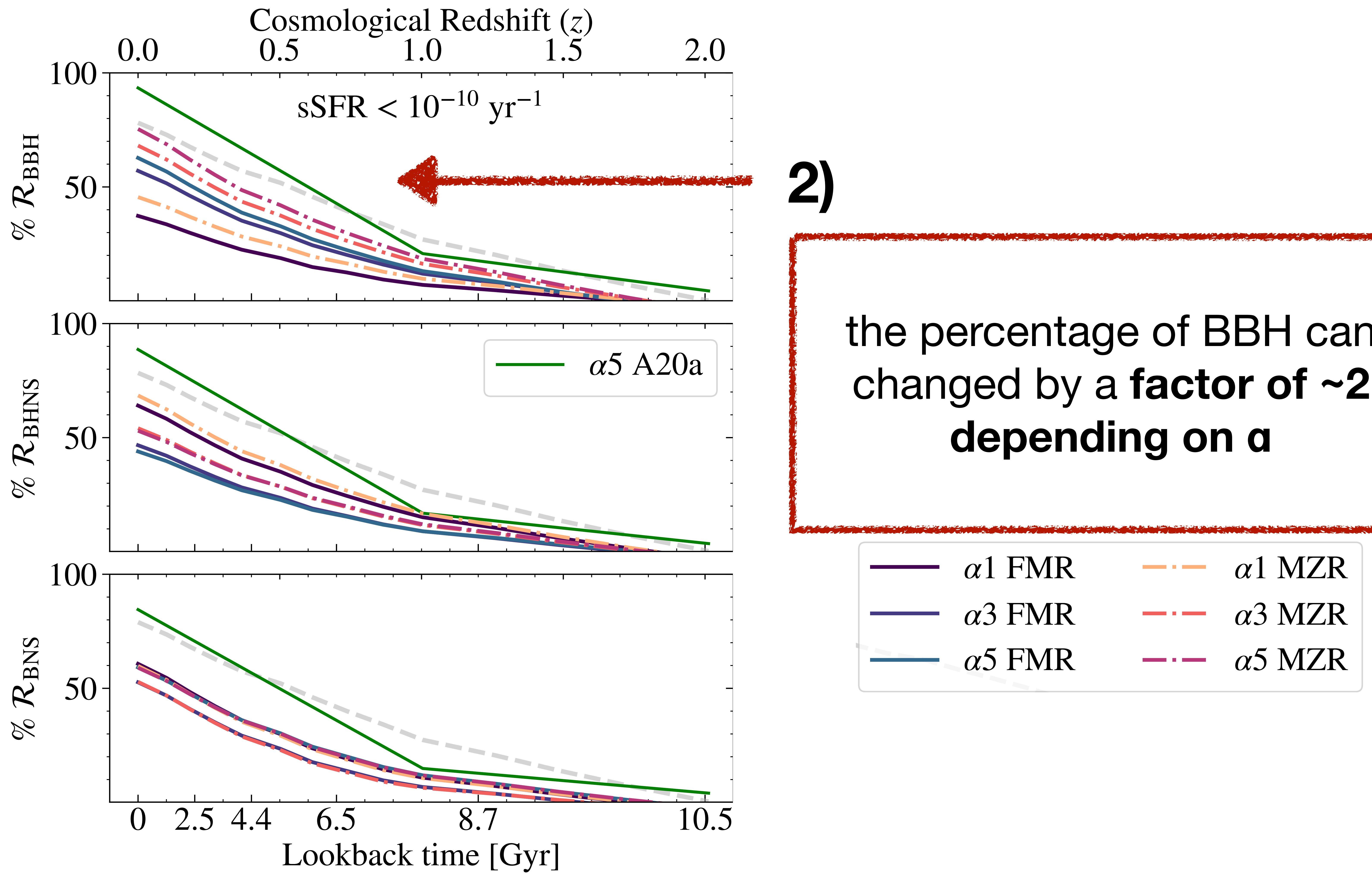


2)

the percentage of BBH can changed by a **factor of ~2 depending on α**

Conclusions

- I explore the properties of **host galaxies** with **`galaxyRate`**
- **BBHs** can merge in **low-mass host galaxies**
- All compact objects have more chances to be hosted in **passive galaxies**

Download `galaxyRate`
at https://filippo-santoliquido.github.io/software/

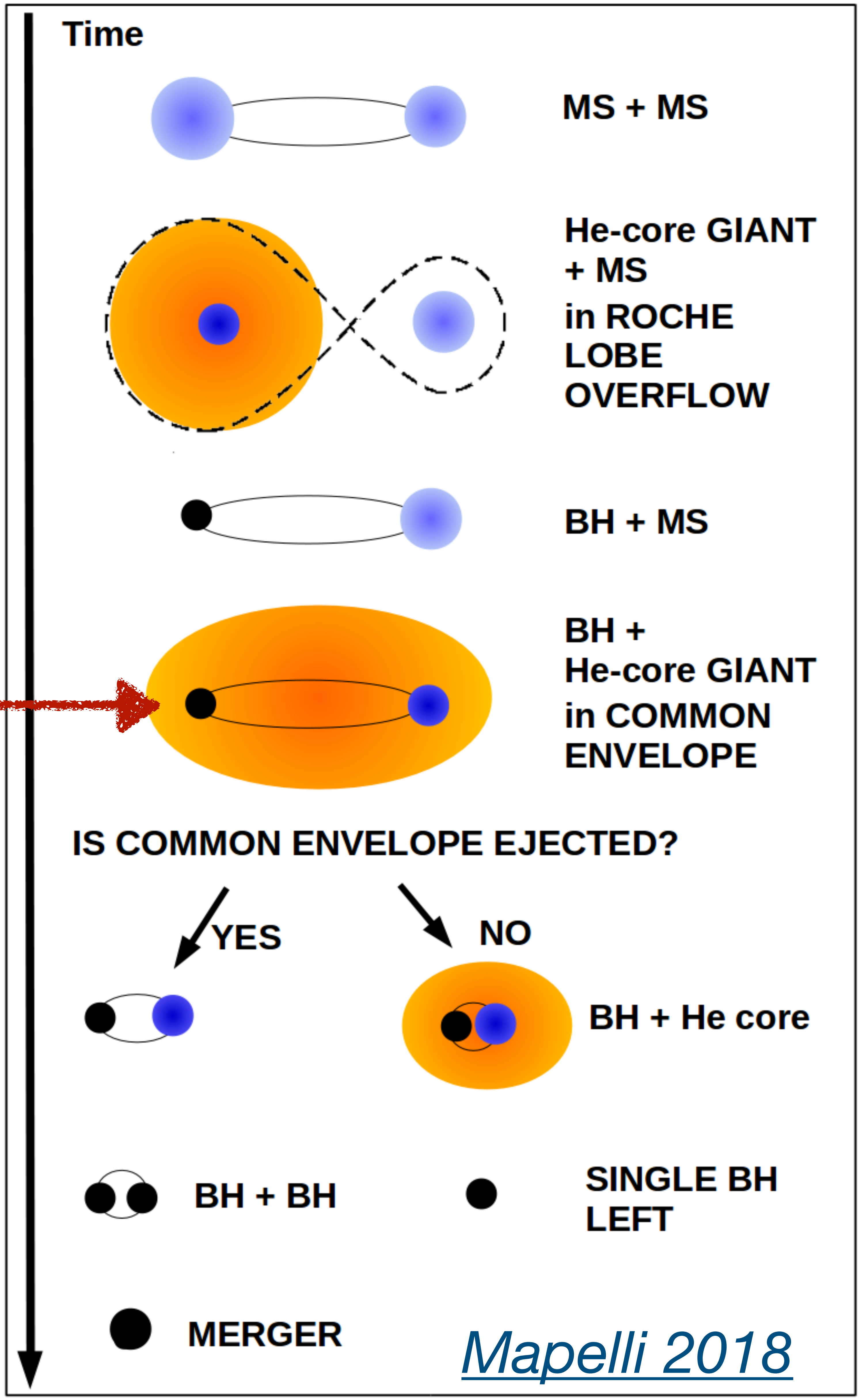
Backup slides

Population-synthesis

isolated formation channel: main physical processes

- **mass transfer** during Roche lobe overflow can be
  - *Stable* mass transfer (accretion efficiency f_{MT} *Mapelli 2018*)
  - *Unstable* mass transfer leads to the **common envelope** phase ($\alpha\lambda$-formalism, *Webbink 1984*):
    - *basic idea:* the energy needed to **unbind the envelope** comes from the **loss of orbital energy** ($\Delta E = E_{\mathrm{env}}$)
    - α measures the fraction of the removed orbital energy transferred to the envelope

Example



single stellar evolution: stellar winds

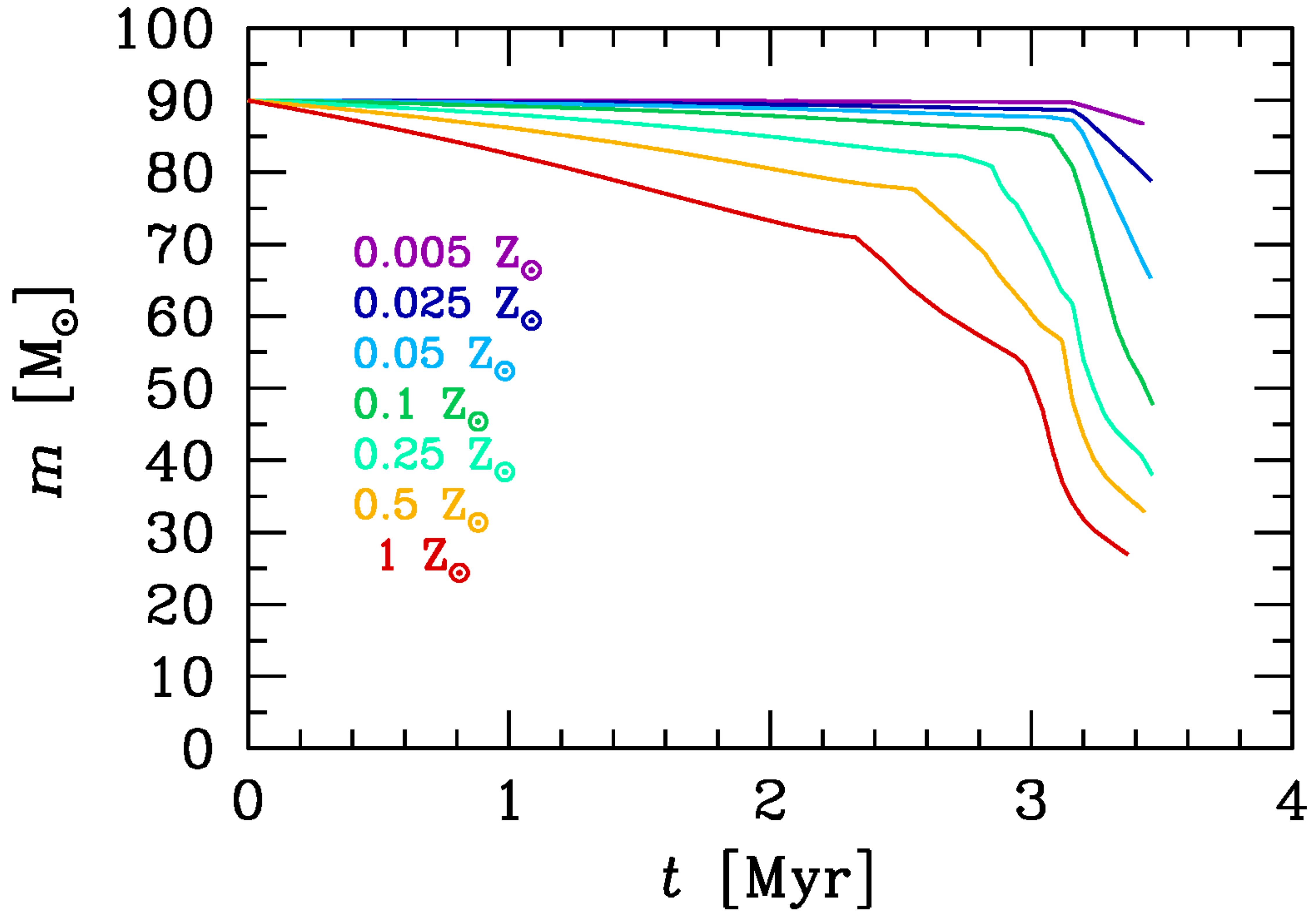
- Massive stars lose mass by **stellar winds** which depend on **metallicity** and **Eddington ratio** (e.g. *Vink et al. 2011*)

- $\dot{M} \propto Z^{\beta}$ (*Chen et al. 2015*)

- This mass loss has also consequences during binary evolution:

  - **metal-rich stars** tend to interact less during binary evolution, because they are more compact

  - thus, common envelope phase is less effective for metal-rich stars



Mapelli 2018

αλ formalism for modelling the common envelope

- $\Delta E = \alpha(E_{\mathrm{b,f}} - E_{\mathrm{b,i}}) = \alpha \frac{G m_{\mathrm{c1}} m_{\mathrm{c2}}}{2} \left(\frac{1}{a_{\mathrm{f}}} - \frac{1}{a_{\mathrm{i}}} \right)$ This is the orbital energy before and after the common envelope phase
- $E_{\mathrm{env}} = \frac{G}{\lambda} \left[\frac{m_{\mathrm{env,1}} m_1}{R_1} + \frac{m_{\mathrm{env,2}} m_2}{R_2} \right]$ This is the binding energy of the envelope
- By imposing $\Delta E = E_{\mathrm{env}}$, $\frac{1}{a_{\mathrm{f}}} = \frac{1}{\alpha\lambda} \frac{2}{m_{\mathrm{c1}} m_{\mathrm{c2}}} \left[\frac{m_{\mathrm{env,1}} m_1}{R_1} + \frac{m_{\mathrm{env,2}} m_2}{R_2} \right] + \frac{1}{a_i}$
- Where λ is the parameter which measures the concentration of the envelope (the smaller λ is, the more concentrated is the envelope).
- The $\alpha\lambda$ formalism is a simplified prescription. When $\alpha > 1$, we account for other sources of energy that make the envelope less bind, for instance recombination energy. Recent works (e.g. *Fragos et al. 2019*) suggest that $\alpha > 1$ is necessary to reproduce the final orbital separation obtained with hydrodynamical simulations.

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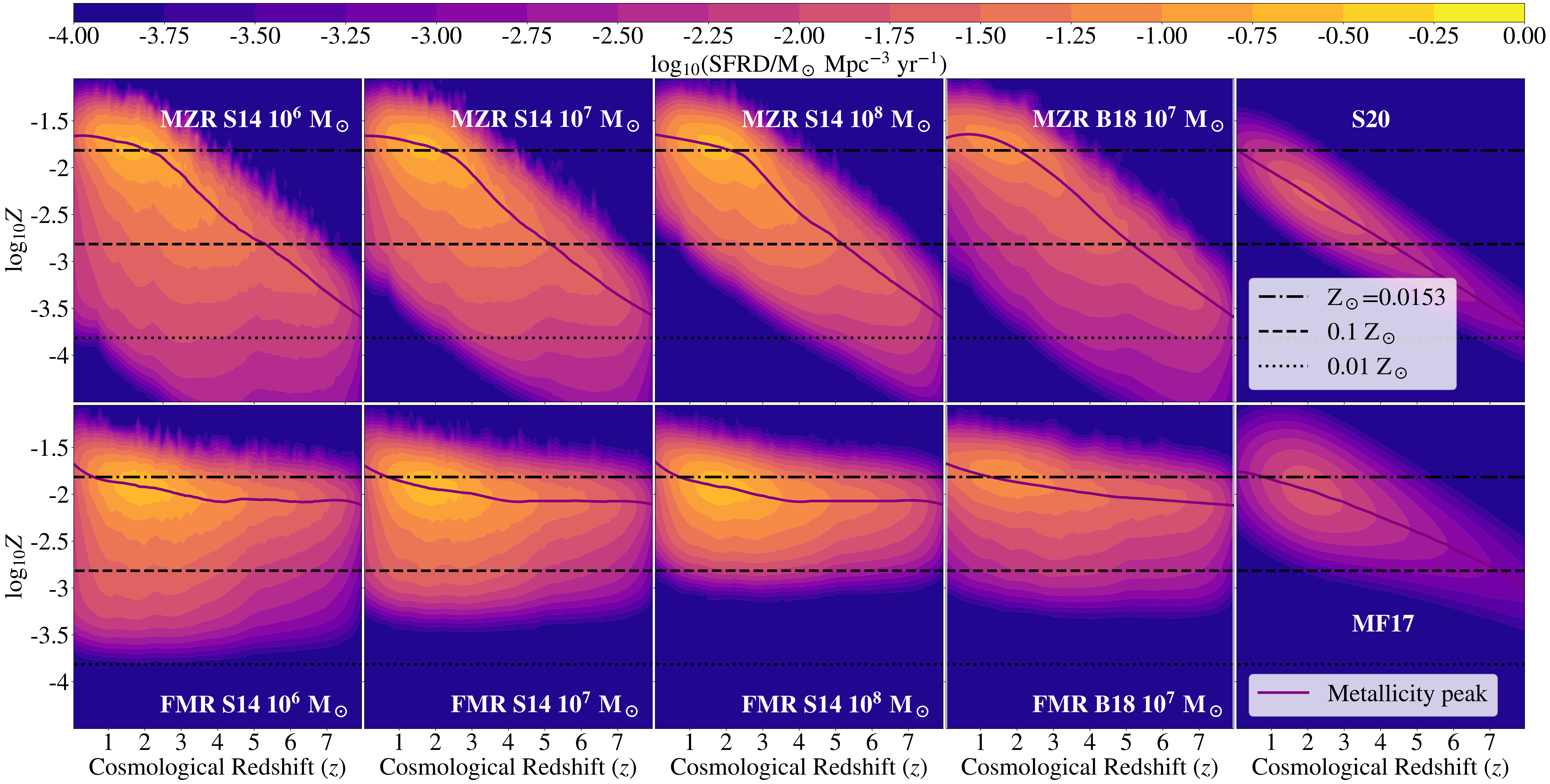
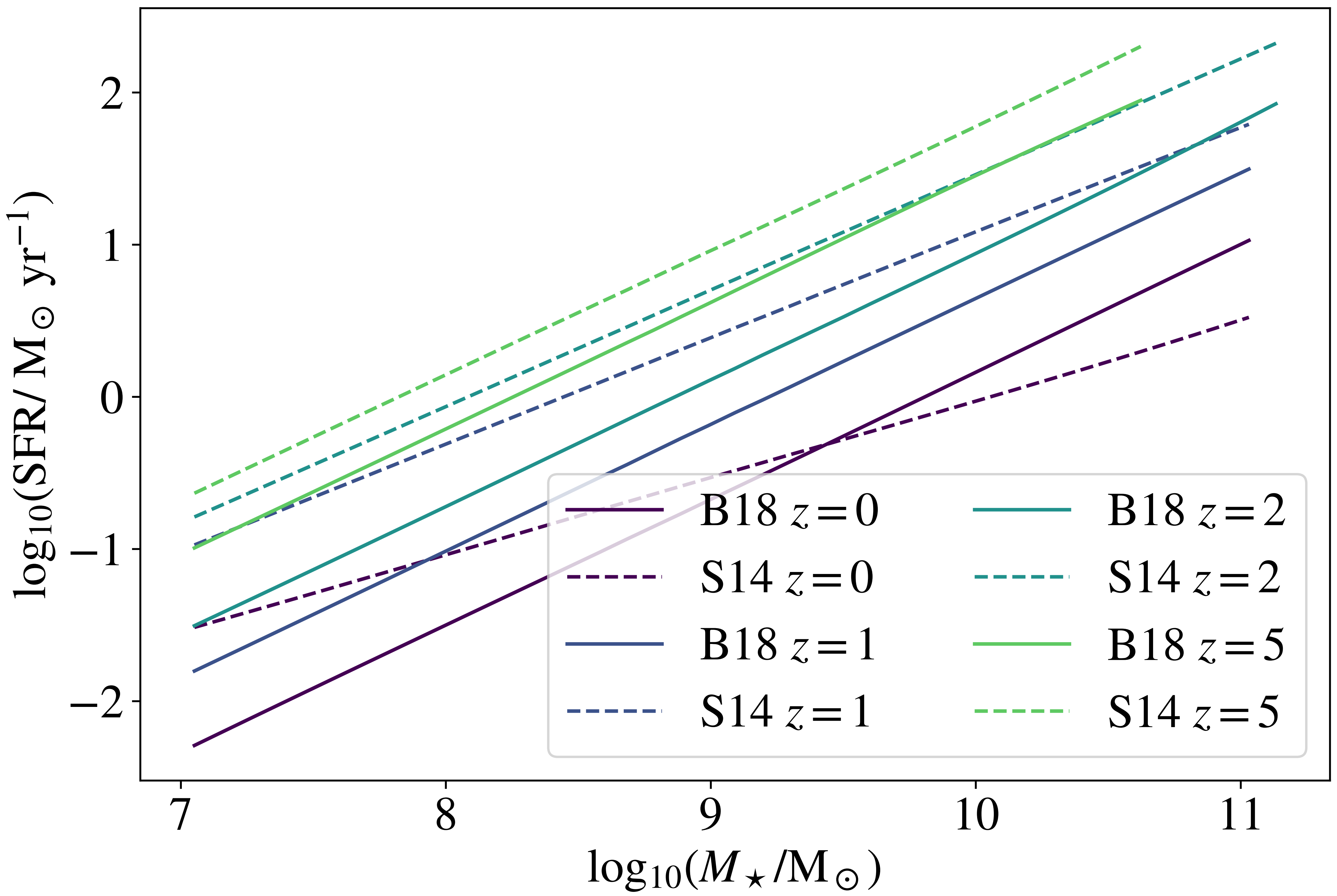
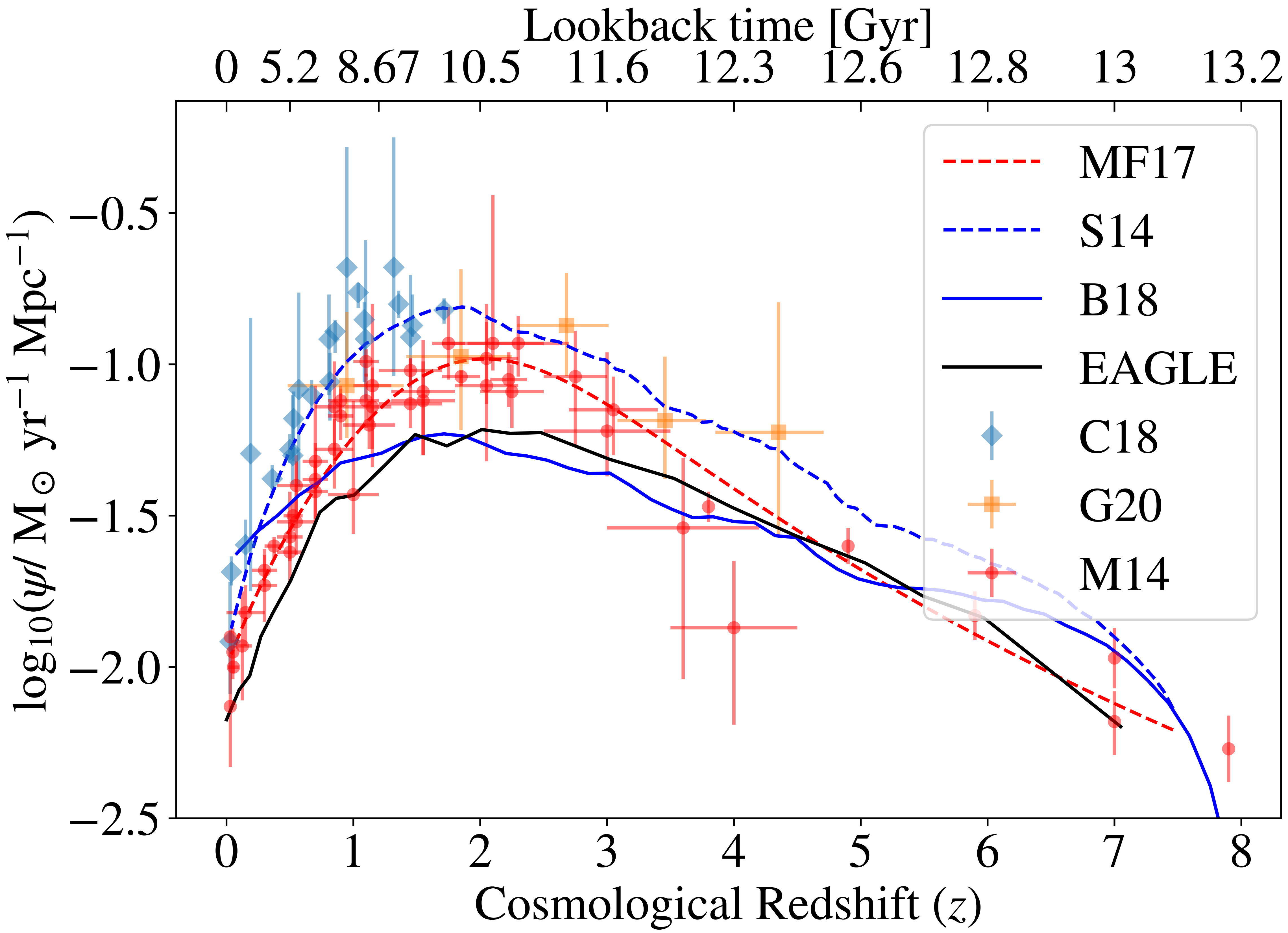


different main sequence of star-forming galaxies → SFRD = GSMF x MS





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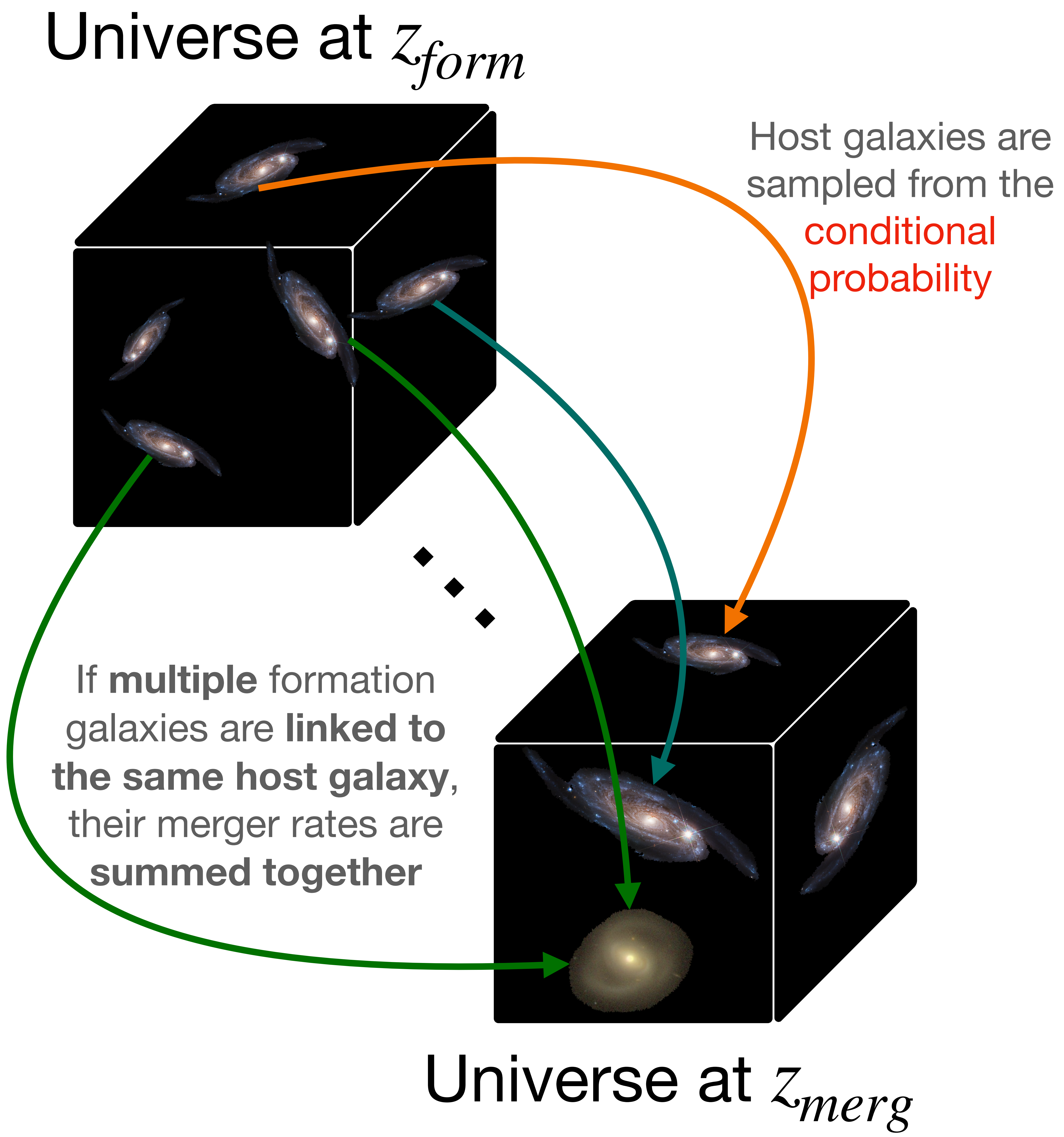
host galaxies through a probabilistic approach

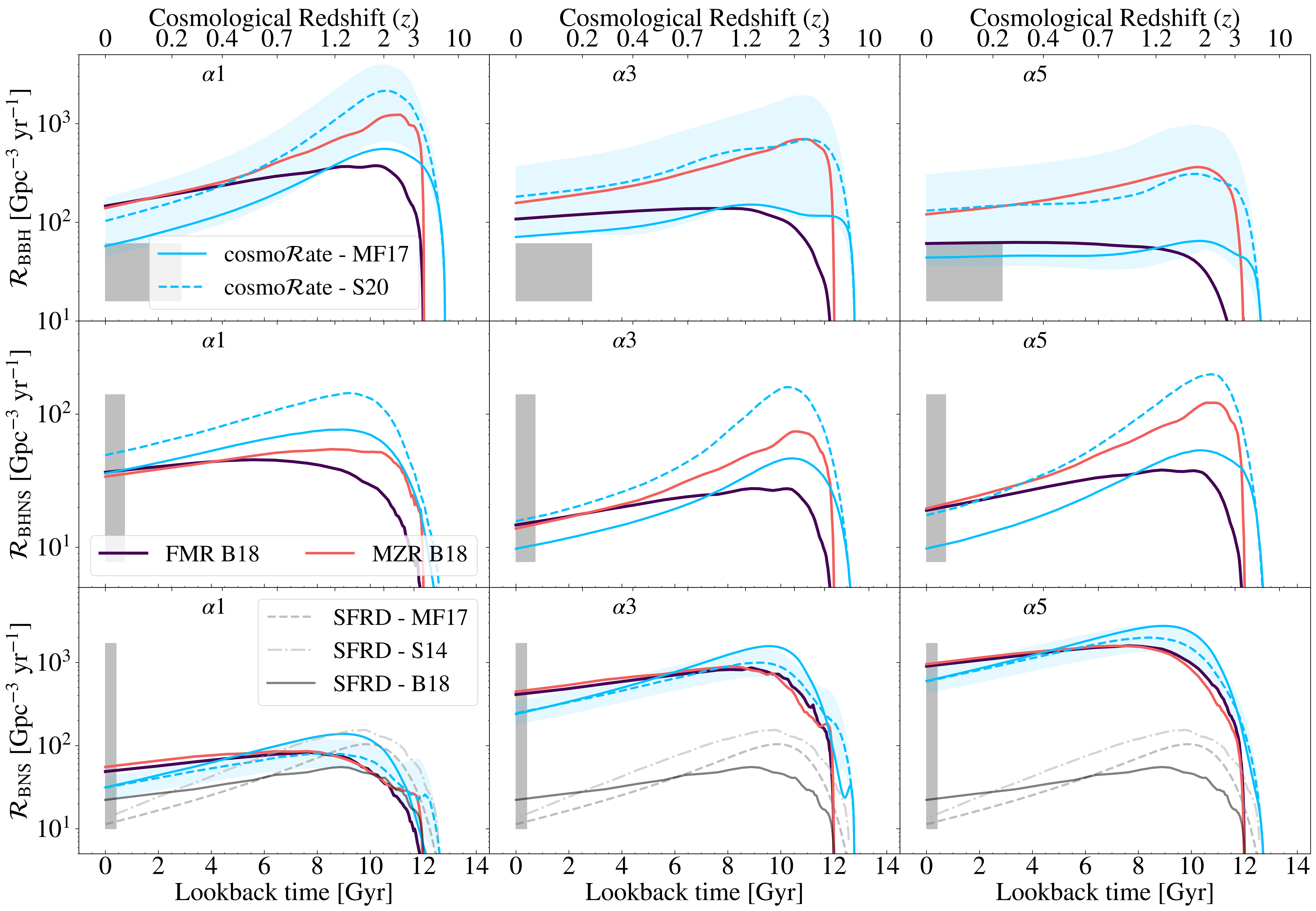
In order to study the **host galaxies** of compact objects, we have to **link** the properties of the formation galaxies *(that we know)* to the properties of host galaxies. To do so, I implemented a new method, based on two steps:

1. **Sampling.** I estimated from the galaxy catalogs from the EAGLE cosmological simulation the following conditional probability $p(\mathrm{M}_{host}, \mathrm{SFR}_{host}\;\; \mathrm{M}_{form}, \mathrm{SFR}_{form}, z_{form}, z_{merg})$. In this way, each sampled galaxy formed at $z_{form} \geq z_{merg}$ is associated with one and only one galaxy at z_{merg}.

2. **Merger trees.** In order to reproduce the galaxy hierarchical assembly, I sum together the merger rates that end up in the same host galaxy



merger rate density with galaxy$\mathcal{R}$ate



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- **different evolution** of BBH merger rate density with either **MZR or FMR.**
- The merger rate density of BHNS and BNS is inside the 90% credible interval inferred from O3b
- **BNS merger rate density** is dominated by **SFRD evolution** and it is extremely sensitive to the **Common Envelope** evolution

merger rate per galaxy

Santoliquido et al. 2022:
https://arxiv.org/pdf/2205.05099.pdf

- Here I am showing the **merger rate per galaxy** as function of **stellar mass**
- I compare it with results obtained with EAGLE **cosmological simulation** (*Artale et al. 2020*)
- correlation of $n_{\rm GW}$ with stellar mass depends on **redshift** and **metallicity evolution** model for BBHs