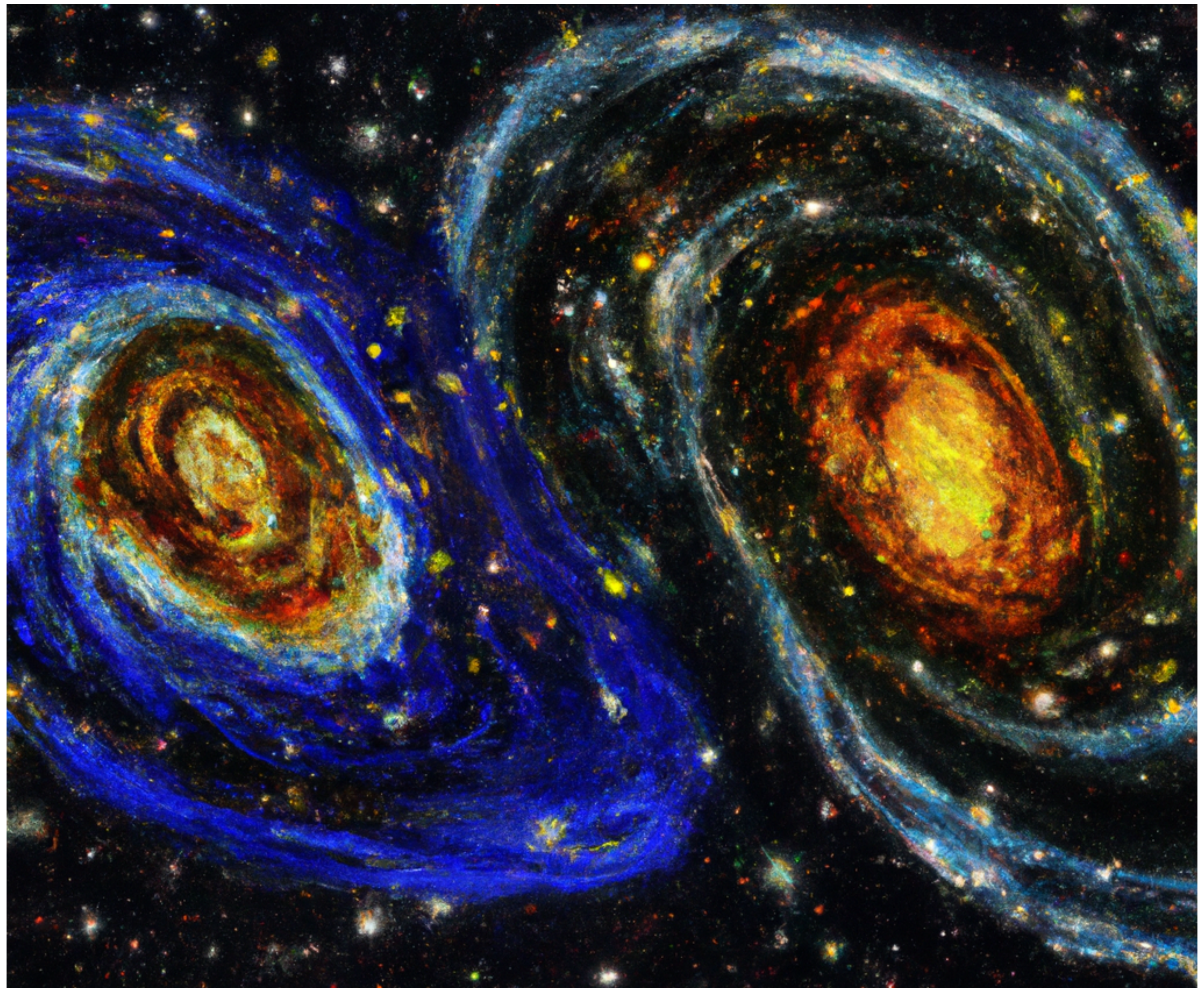
THE EVOLUTION OF COMPACT OBJECTS AND THEIR HOST GALAXIES ACROSS COSMIC TIME

Ph.D. candidate: **Filippo Santoliquido**

Supervisor: **Prof. Michela Mapelli**
Co-supervisor: **Prof. M. Celeste Artale**



OpenAI. (2023). "Two stellar-mass black holes merging inside a spiral galaxy in Van Gogh's style." [Digital image]. Retrieved from https://openai.com/dall-e/

University of Padova

PhD Thesis Defence - XXV cycle
03/04/2023

outline

1. *Introduction:*

    1.1. The inferred **merger rate density** from **gravitational-wave detections**

    1.2. Main **physical processes** of gravitational-wave **sources** formation

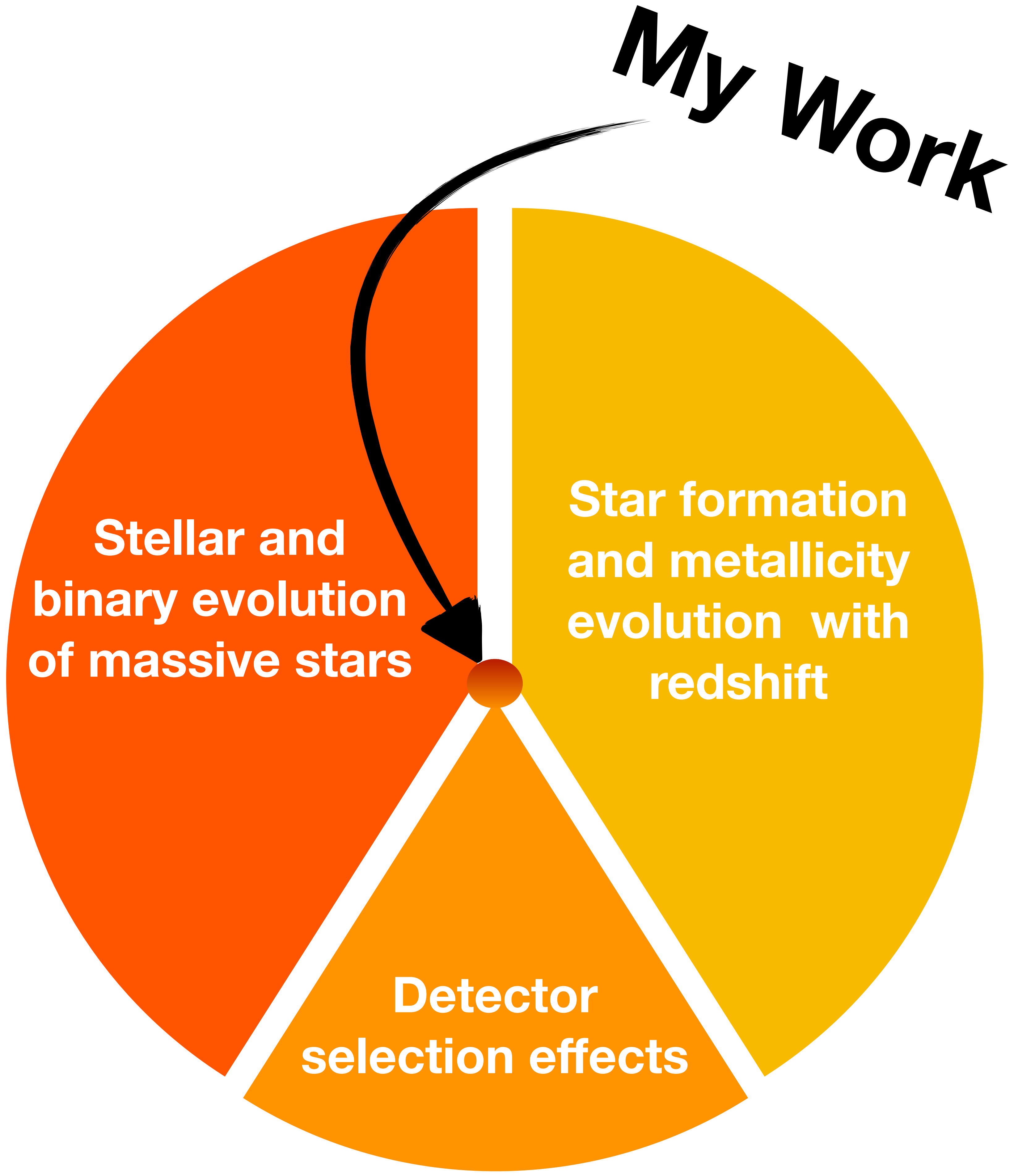
2. *Original results:*

    2.1. `cosmoRate:` uncertainties on **merger rate density**

    2.2. `galaxyRate:` **host galaxies** of compact object mergers

    2.3. A look to the future: **Population III BBHs** and the Einstein Telescope

3. *Conclusions*



gravitational-wave astrophysics

- Current operating **gravitational-wave detectors**: **LIGO, Virgo, KAGRA (LVK)**
- **Gravitational waves** detected with LVK are likely associated with **mergers of compact objects** in binary systems:
  - Binary black holes **(BBHs)**
  - Black hole - neutron star binaries **(BHNSs)**
  - Binary neutron stars **(BNSs)**
- Collecting **confirmed detections** allows us to **reconstruct a demography** of BBHs, BHNSs and BNSs:
  - *What is their mass distribution?*
  - *How many of these objects we observe? How many of them merge across cosmic time?*

https://www.ligo.caltech.edu/news/ligo20191004

the inferred merger rate density

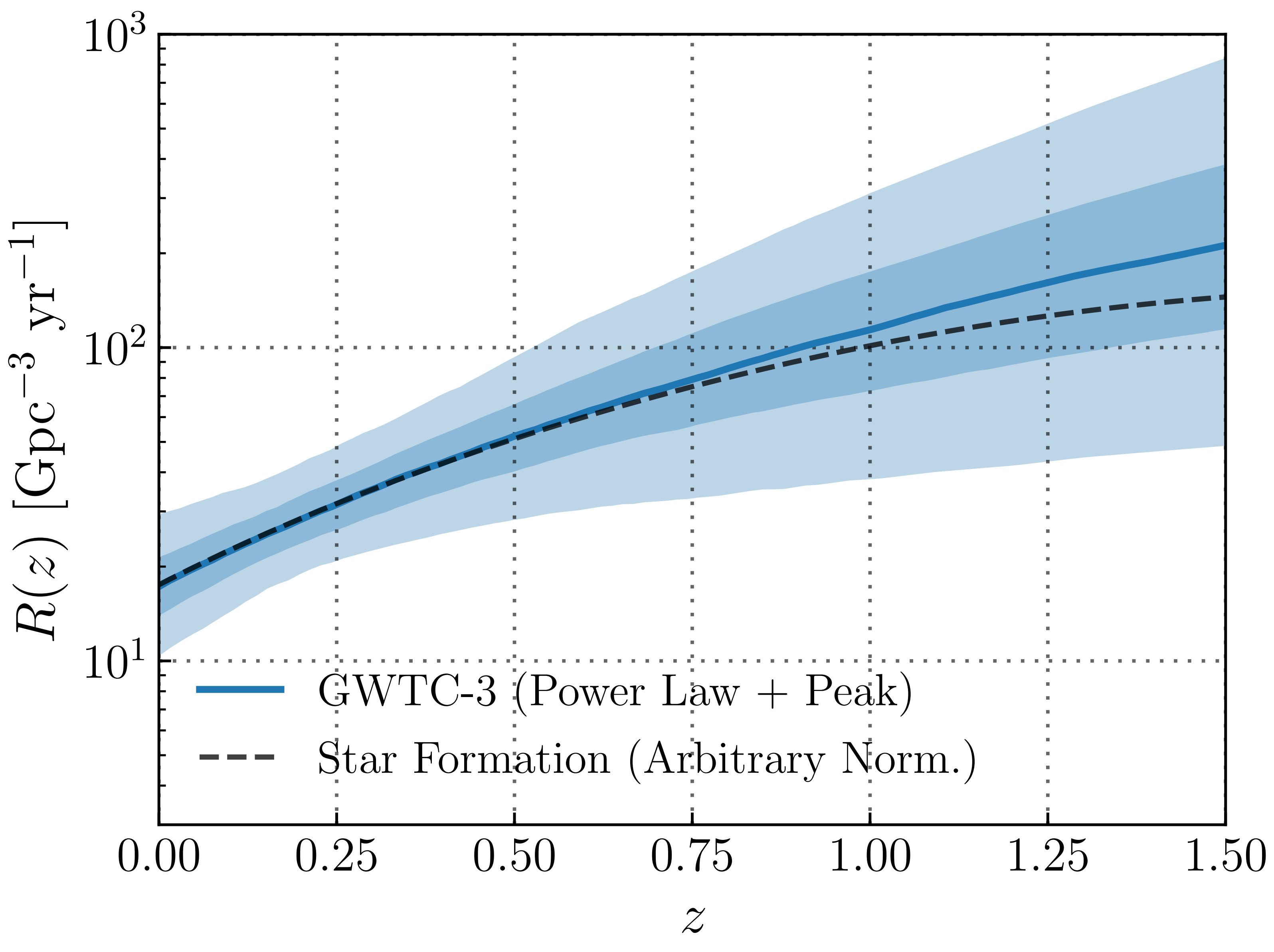
90% credible intervals

$\mathscr{R}^0_{\mathrm{BBH}}$	[16 - 61] $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$
$\mathscr{R}^0_{\mathrm{BHNS}}$	[7.8 - 140] $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$
$\mathscr{R}^0_{\mathrm{BNS}}$	[10 - 1700] $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$

https://arxiv.org/abs/2111.03634

redshift evolution of the merger rate density

- high-mass **BBH**, LVK sensitivity allows for a **cosmologically significant reach**
- It is thus possibile to infer the **evolution of merger rate density with redshift**
- LVK collaboration assumes the rate to evolve as: $\mathscr{R}(z) = \mathscr{R}^0(1+z)^\kappa$
- $\kappa > 0$ at 99% credibility



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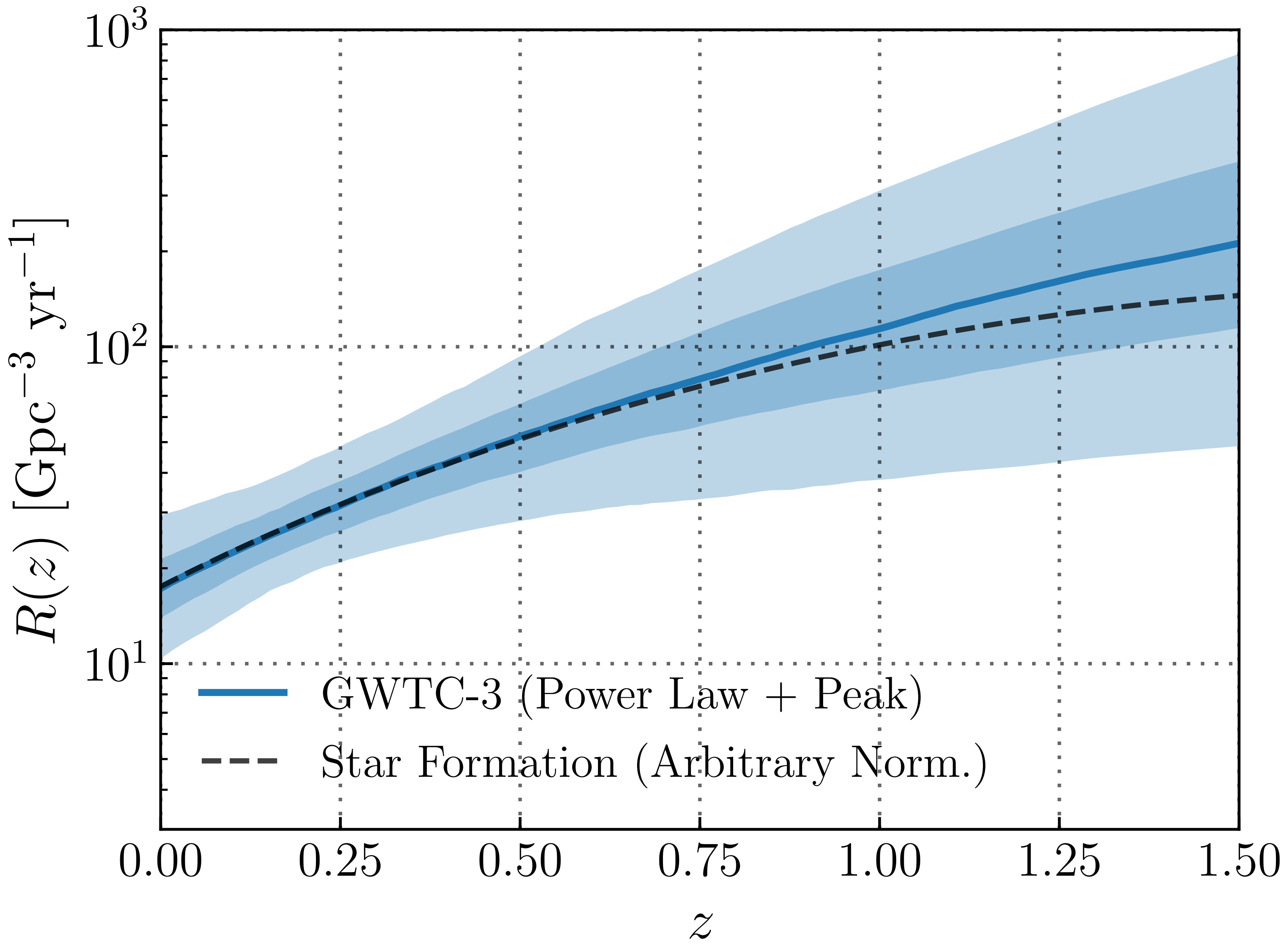
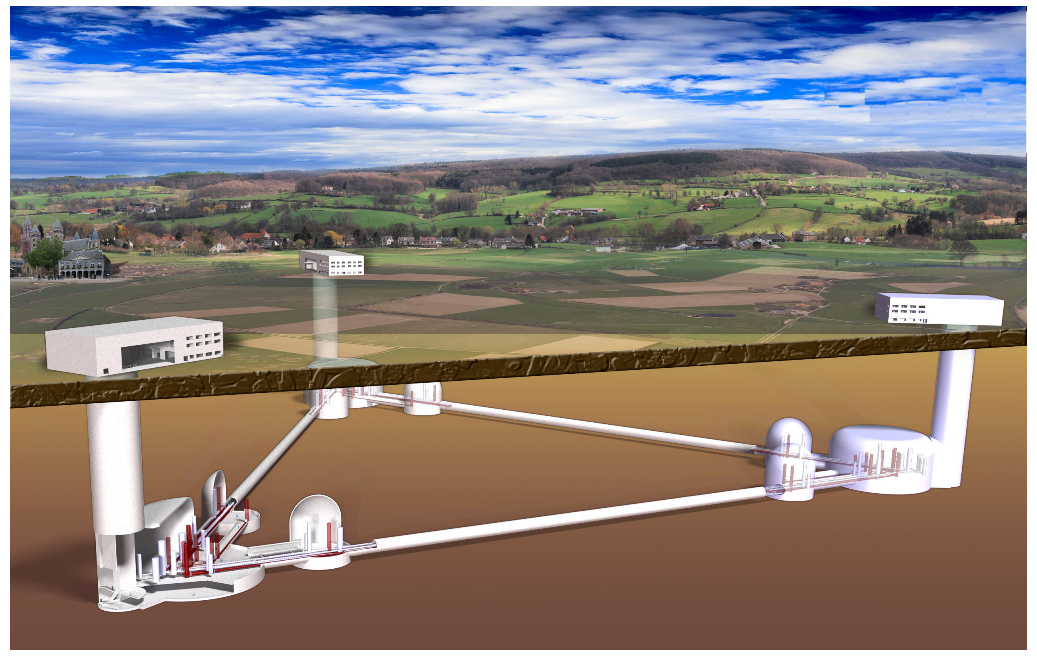


https://arxiv.org/pdf/2111.03634.pdf

Objective of my PhD Thesis

- My Thesis **interprets** from a model-based perspective the **merger rate** in the **local Universe** and **as a function of redshift**
- This is fundamental to get **new insights on our models**
- I contribute to the **science case of third-generation detectors**

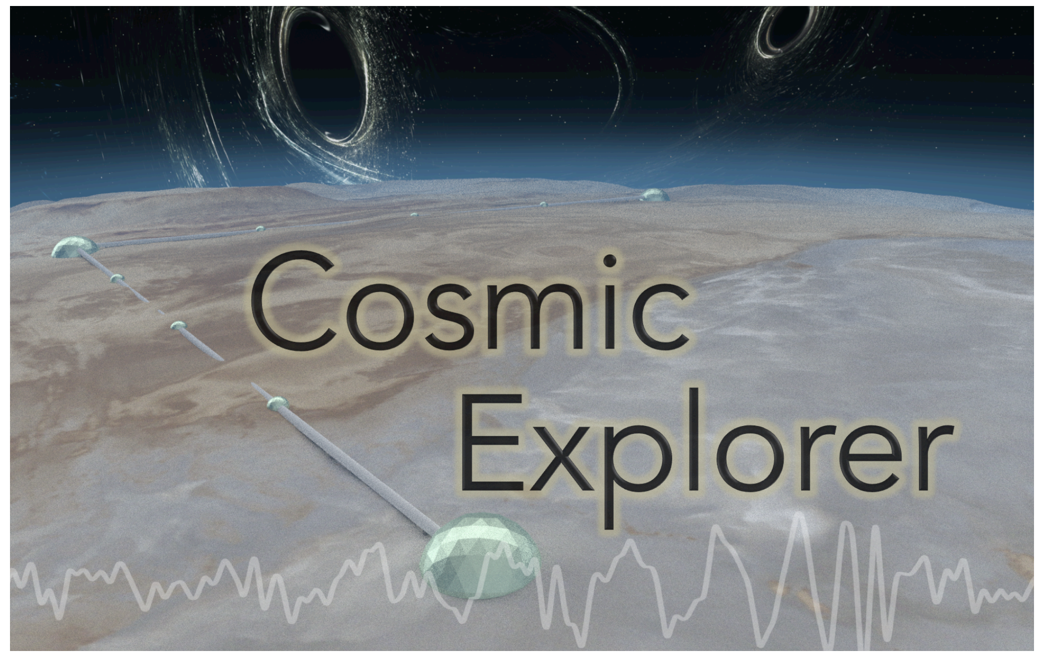
third-generation detectors



https://www.ncbj.gov.pl/en/bp4/einstein-telescope-0

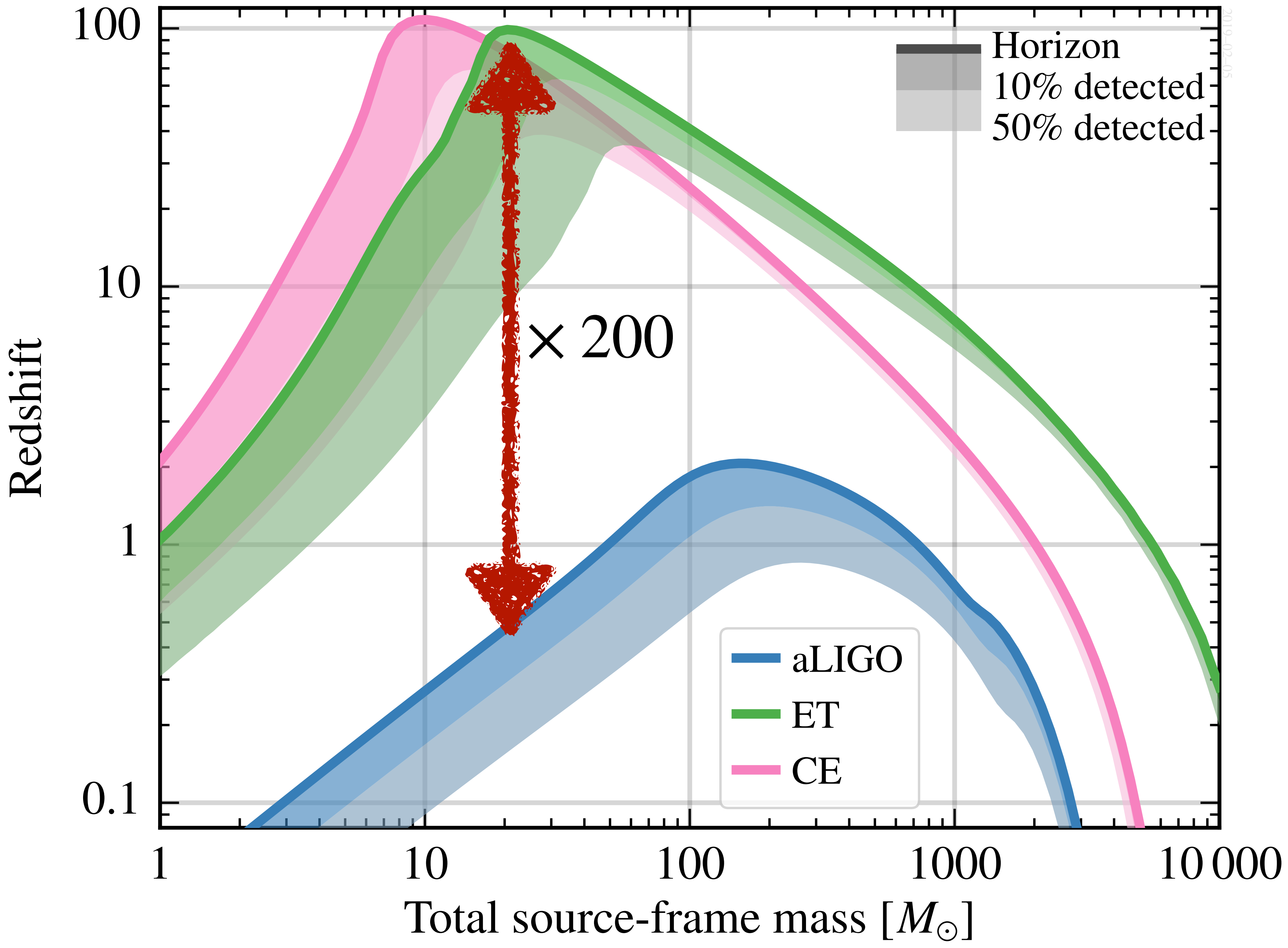
Credits: Ego Collaboration

Cosmic Explorer



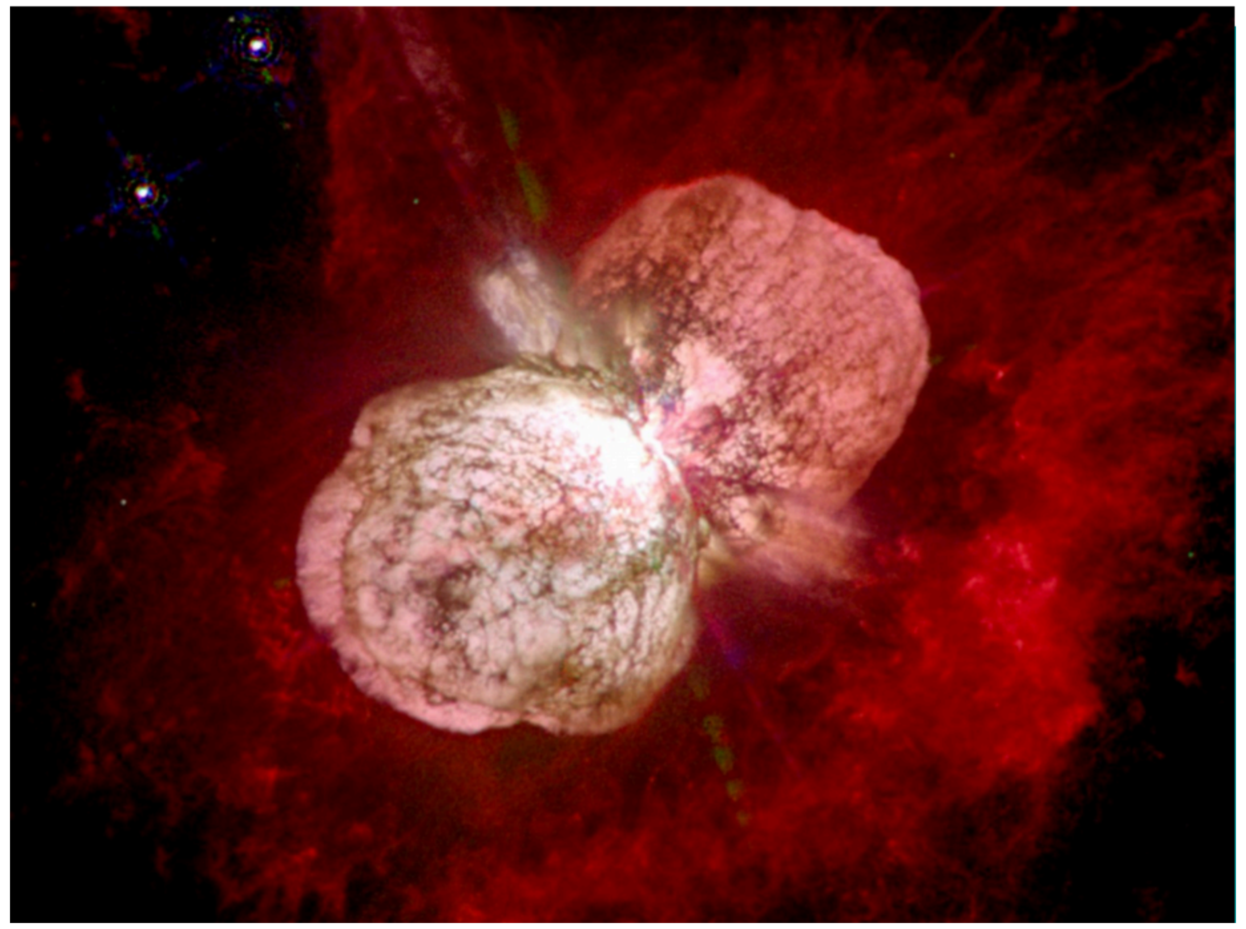
https://cosmicexplorer.org/

https://arxiv.org/pdf/2111.06990.pdf



To extend the redshift range, we need to rely on 3G detectors, capable to detect mergers of BBHs at $z \sim 100$

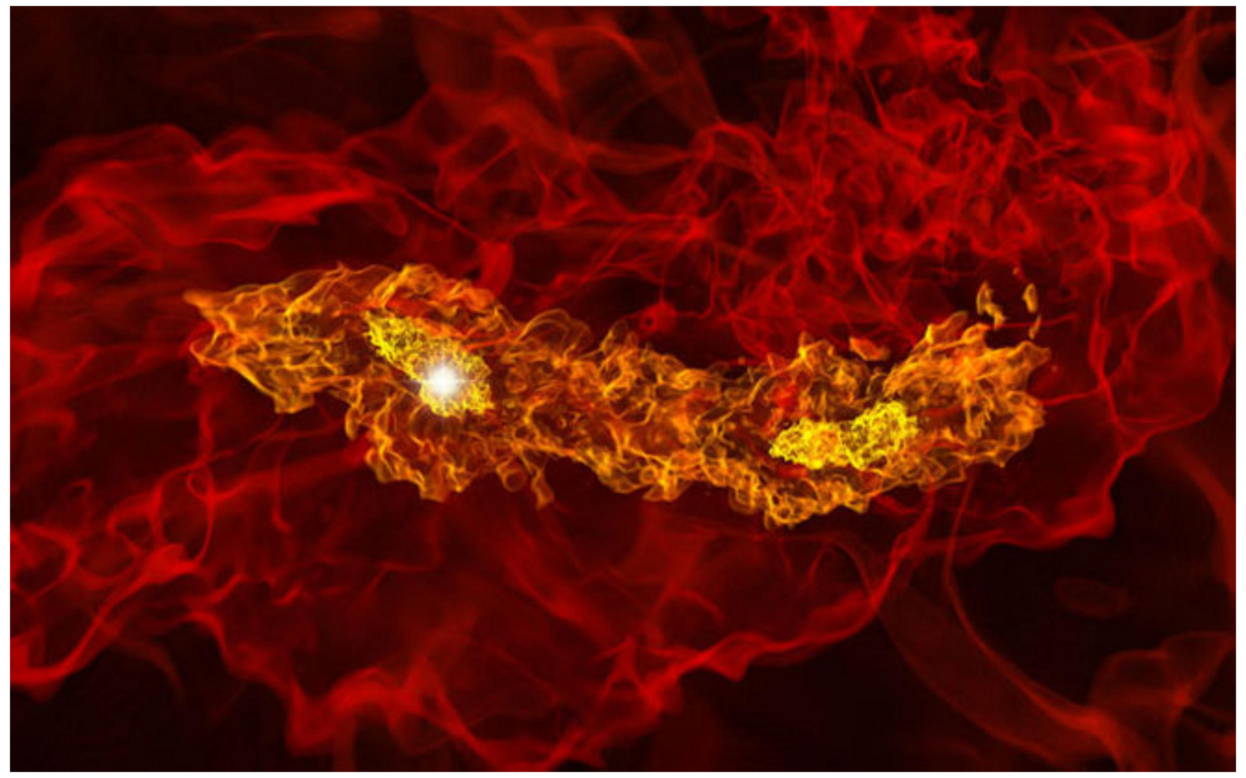
how gravitational-wave sources form?



Credit: NASA

Single stellar evolution:
Neutron stars and astrophysical black holes are believed to form from massive stars

Isolated formation channel:
two stars in a binary system evolve into two compact objects that eventually might merge within an Hubble time

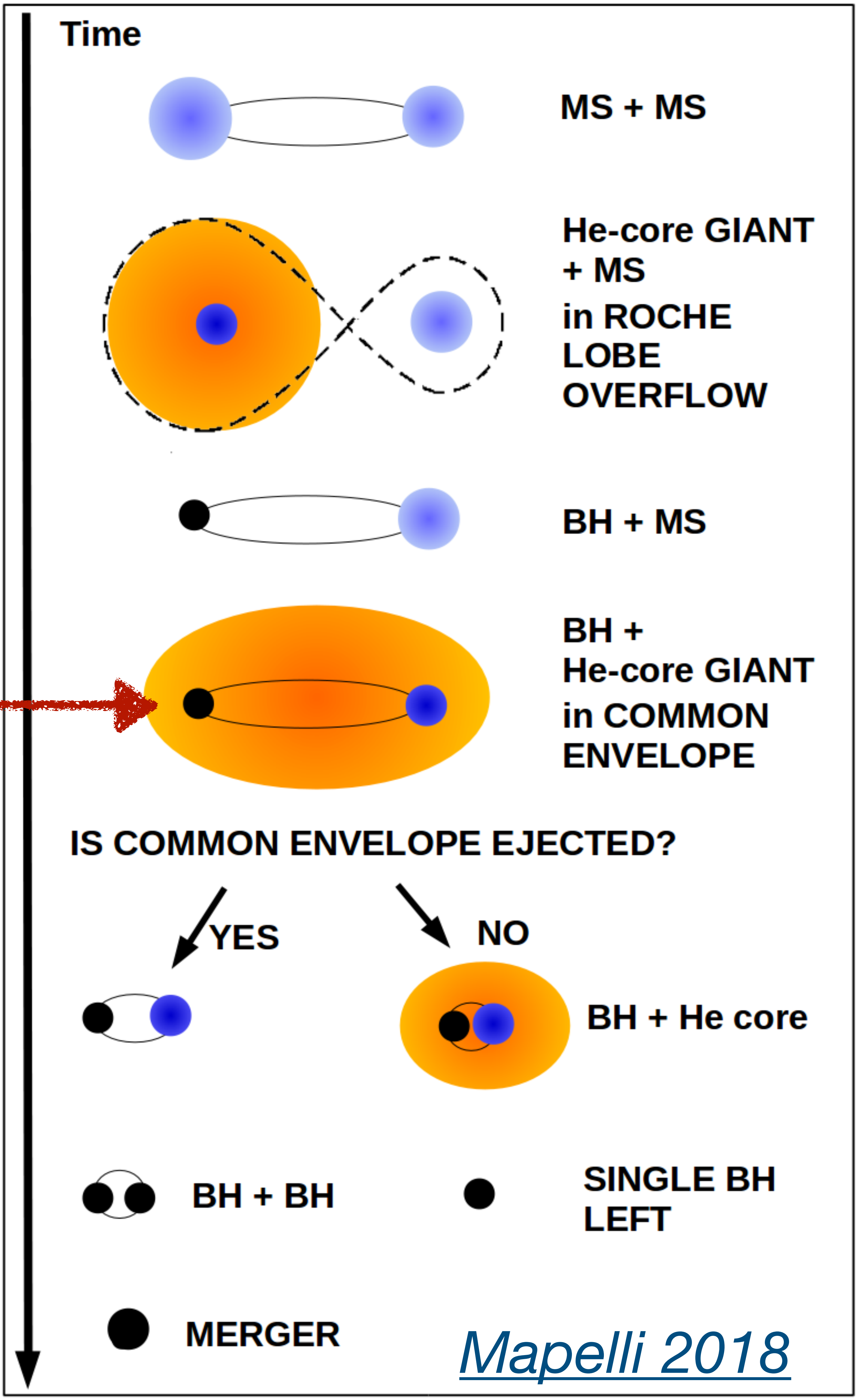


Credit: NASA

isolated formation channel: main physical processes

- **mass transfer** during Roche lobe overflow can be
  - *Stable* mass transfer (accretion efficiency $f_{\rm MT}$ [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** ($\Delta E = E_{\rm env}$)
    - α measures the fraction of the removed orbital energy transferred to the envelope

Example



Mapelli 2018

compact object mergers through population-synthesis

Very large statistical samples of merging compact binaries.

By using approximate models for stellar and binary evolution

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

Input/Output of population-synthesis simulations

Initial conditions: IMF, period and eccentricity distribution, progenitor metallicity, free parameters (such as α of the common envelope)

Catalogs of merging compact objects, defined by intrinsic parameters: primary mass, secondary mass, **delay time,** etc…

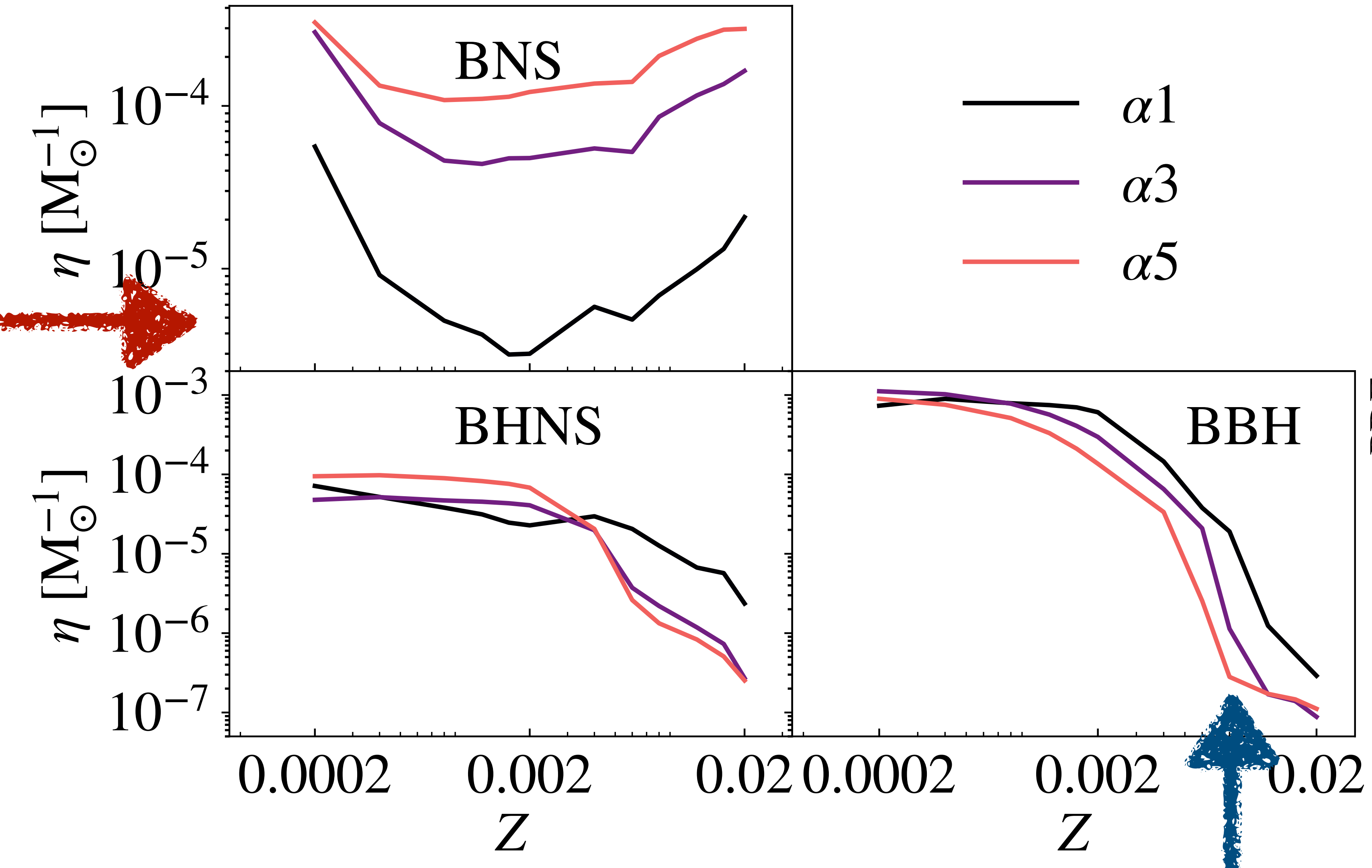
catalogs from population-synthesis

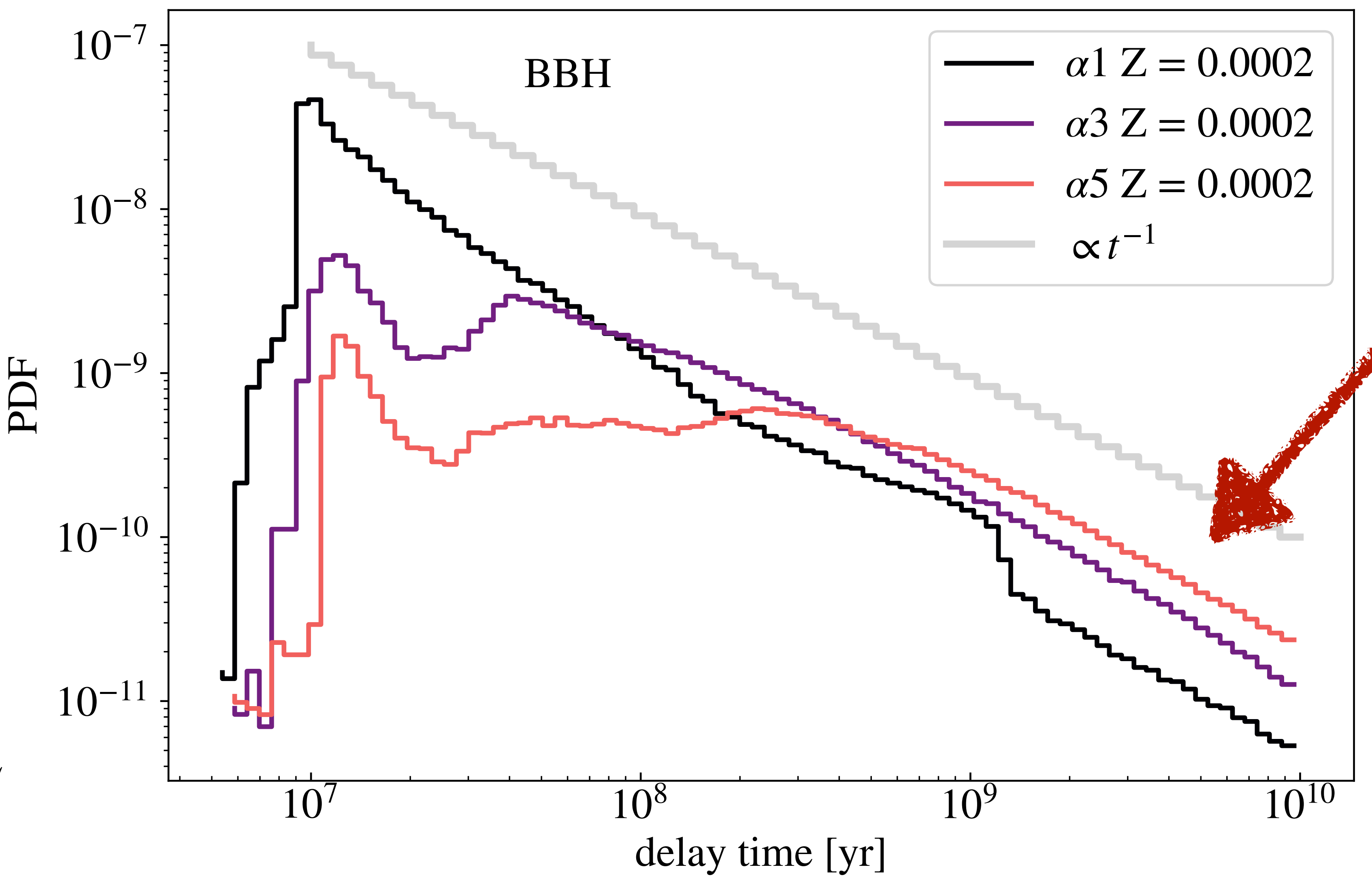
Santoliquido et al. 2022:
https://arxiv.org/pdf/2205.05099.pdf

merger efficiency

delay time

Effect of common envelope



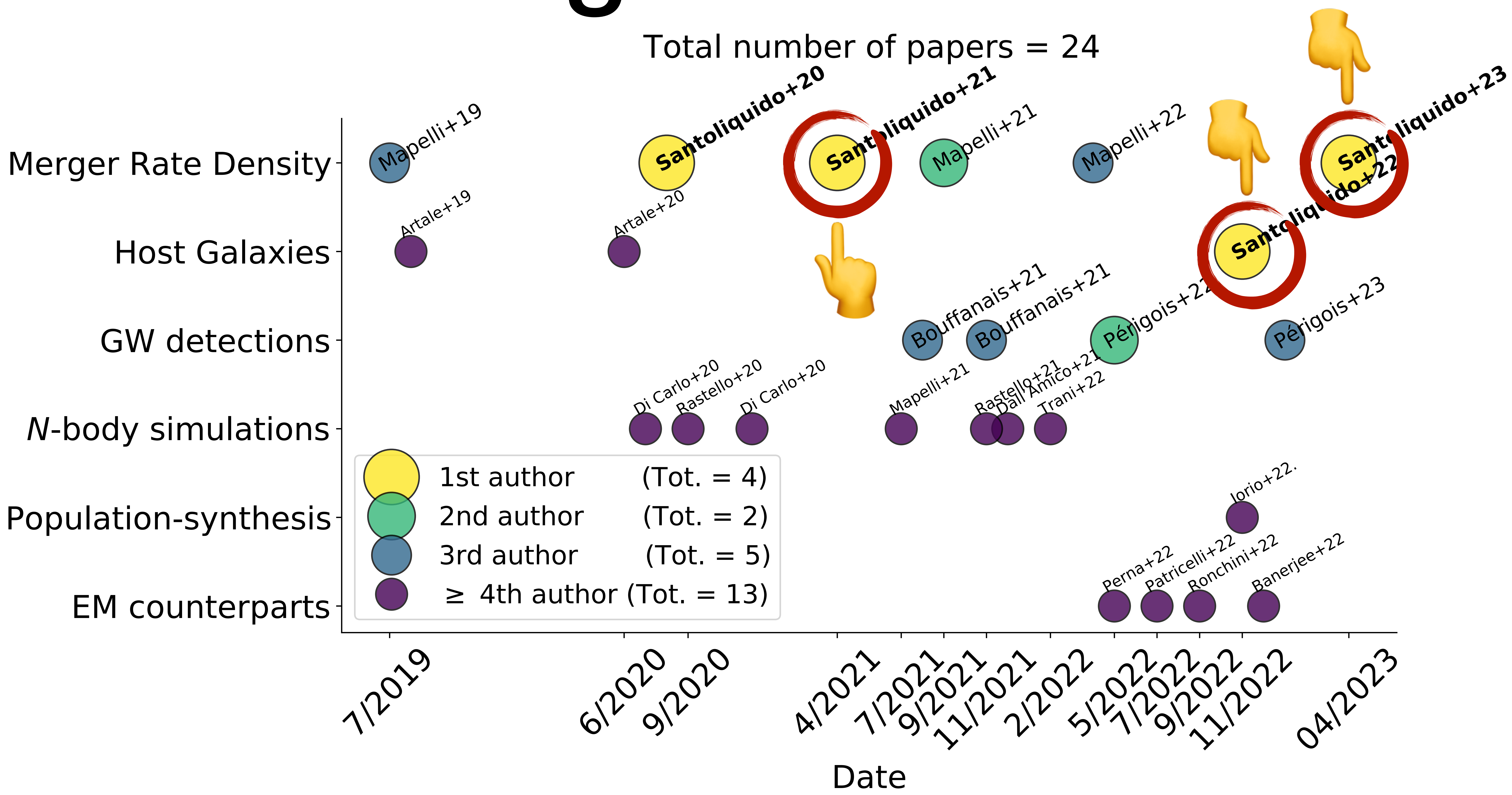


Effect of common envelope

Effect of progenitor metallicity

These catalogs lack the information on redshift and host galaxies: this is my goal

original work



COSMORATE

$$\mathcal{R}(z) = \int_{z_{\max}}^{z} \left[\int_{Z_{\min}}^{Z_{\max}} \boxed{\mathrm{SFRD}(z', Z)} \boxed{\mathcal{F}(z', z, Z)} \mathrm{d}Z \right] \frac{\mathrm{d}t(z')}{\mathrm{d}z'} \mathrm{d}z'$$

Santoliquido et al. 2020:
https://arxiv.org/pdf/2004.09533.pdf

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Evaluated from our population-synthesis catalogs:

$$\mathcal{F}(z', z, Z) = \frac{1}{\mathcal{M}_{\mathrm{TOT}}(Z)} \frac{\mathrm{d}\mathcal{N}(z', z, Z)}{\mathrm{d}t(z)}$$

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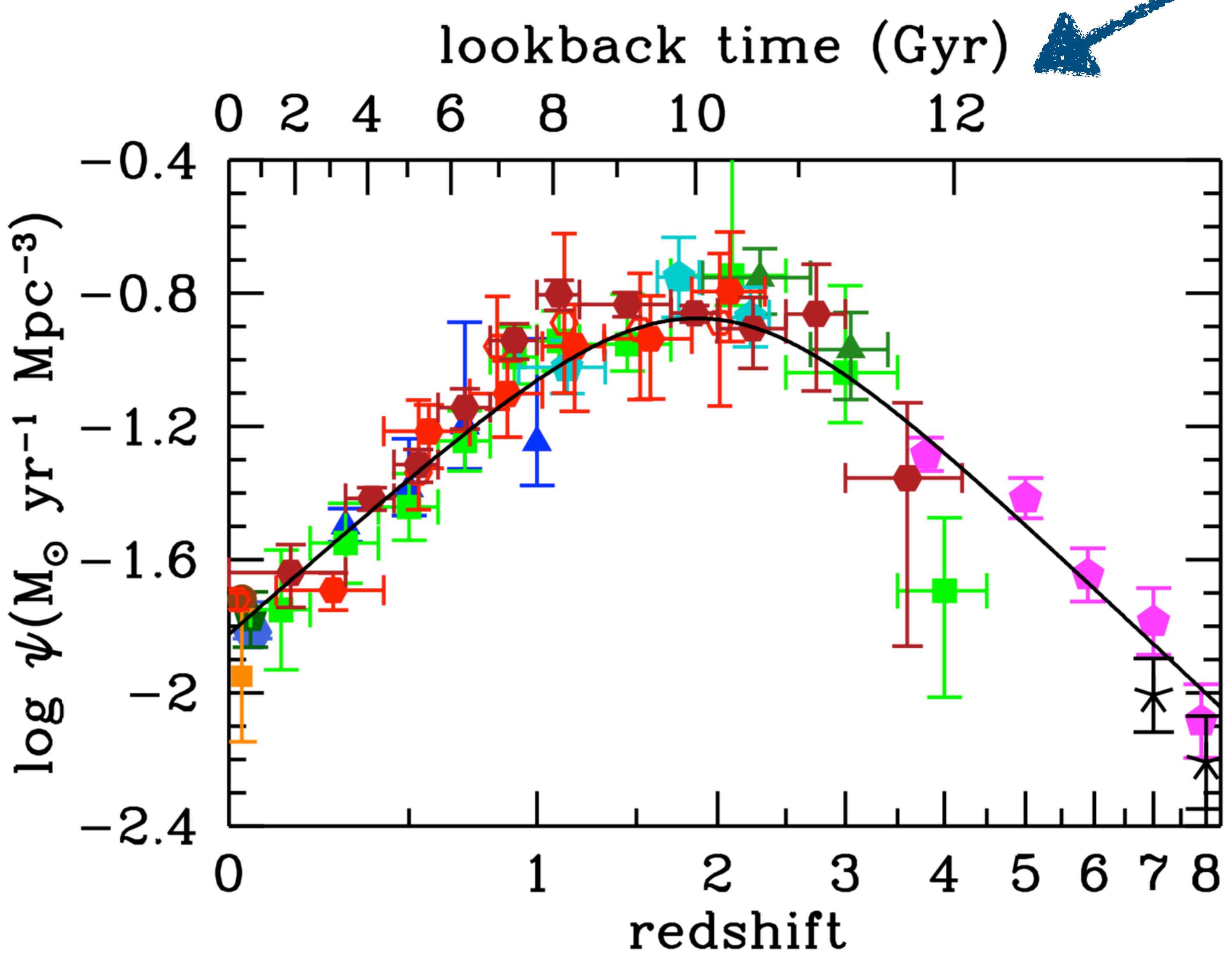

Madau & Dickinson 2014, Madau & Fargos 2017

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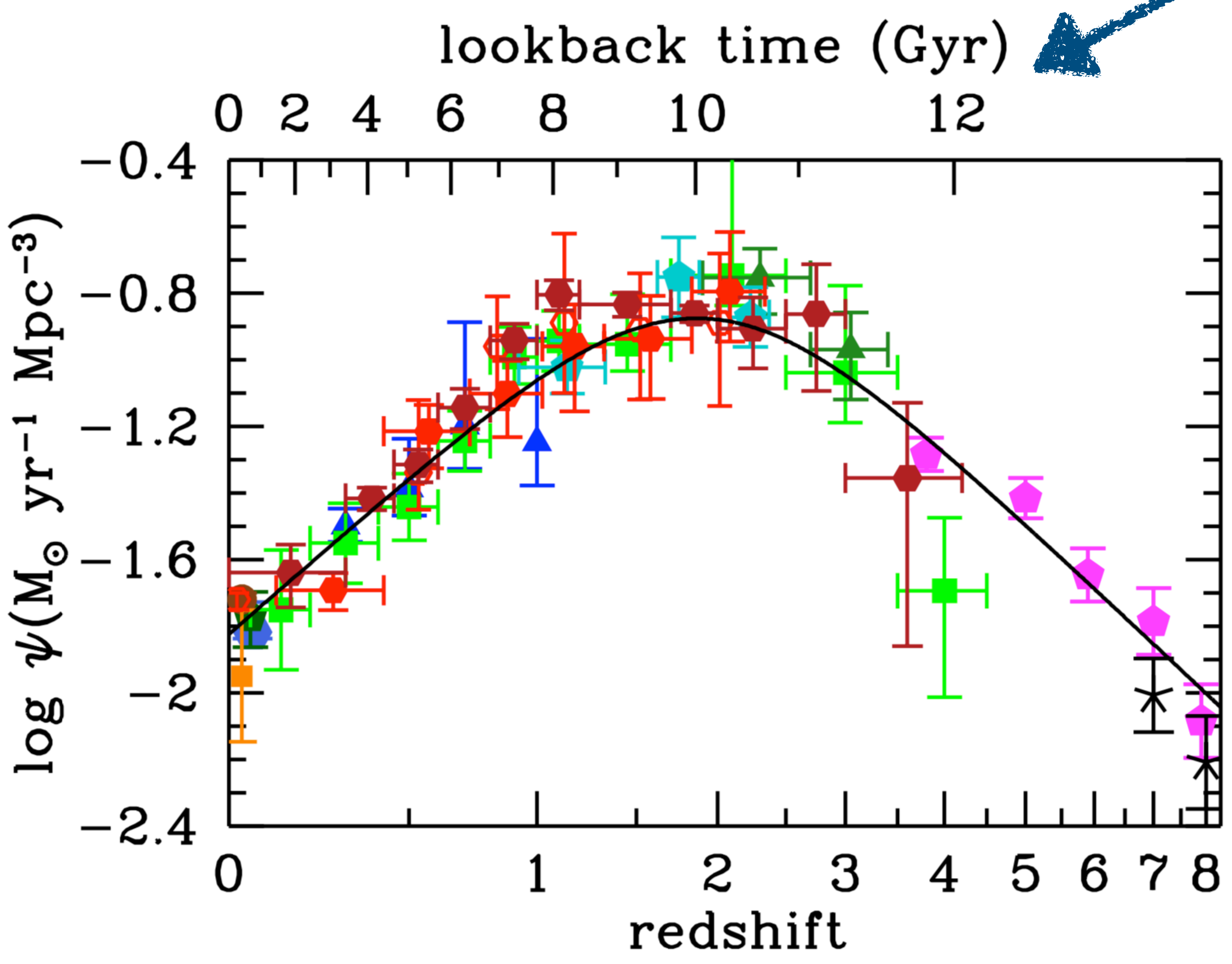

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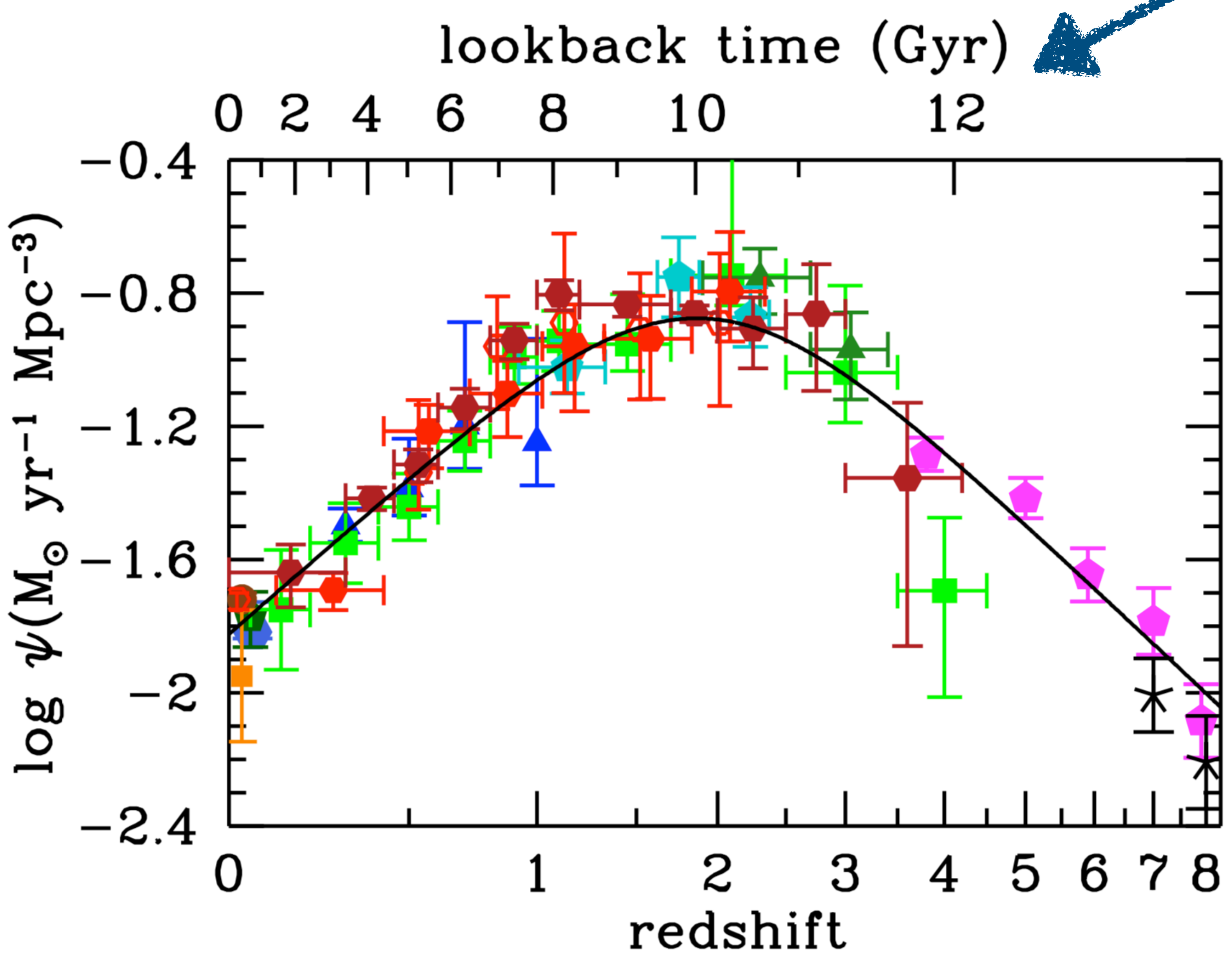

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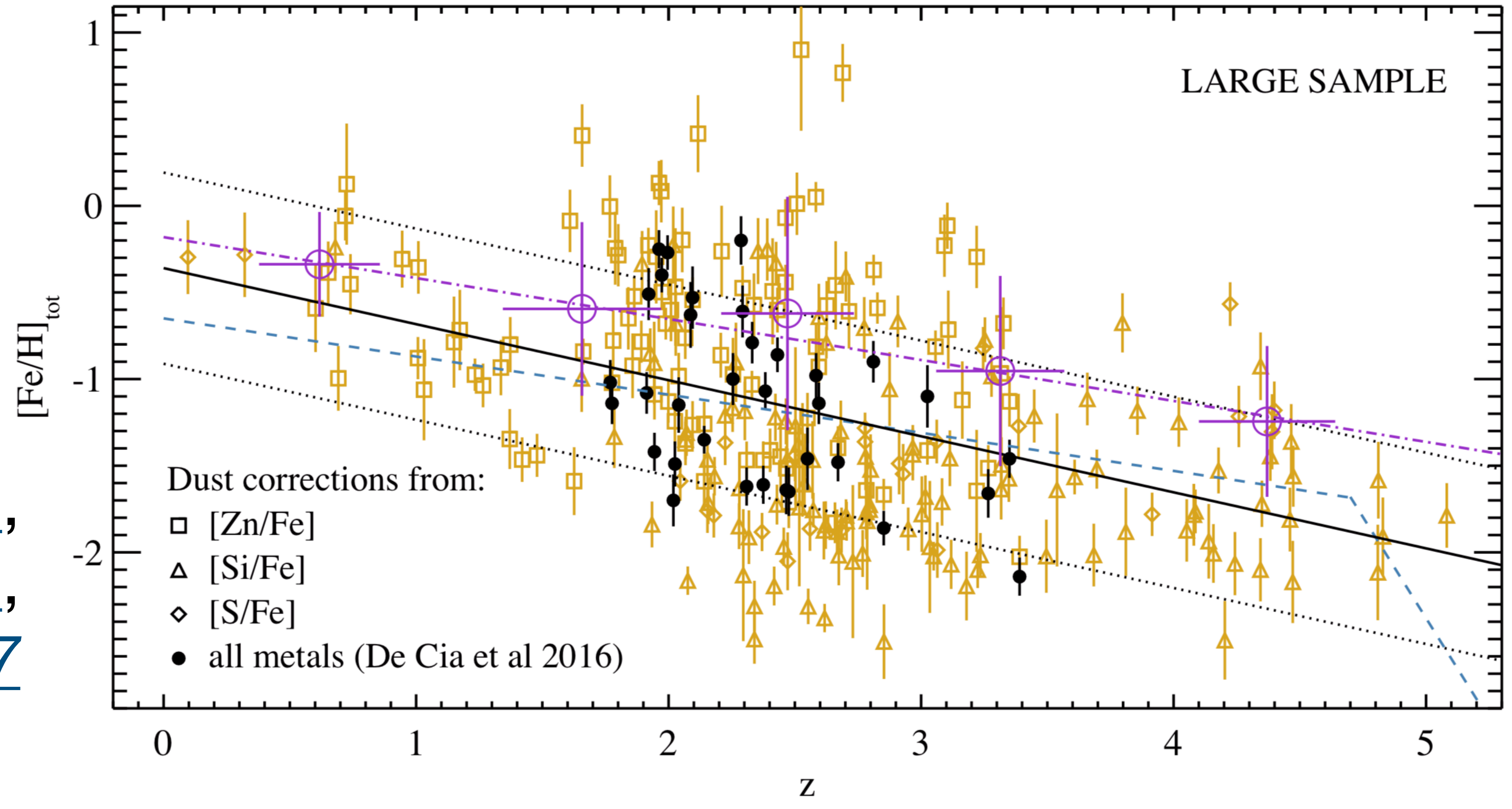


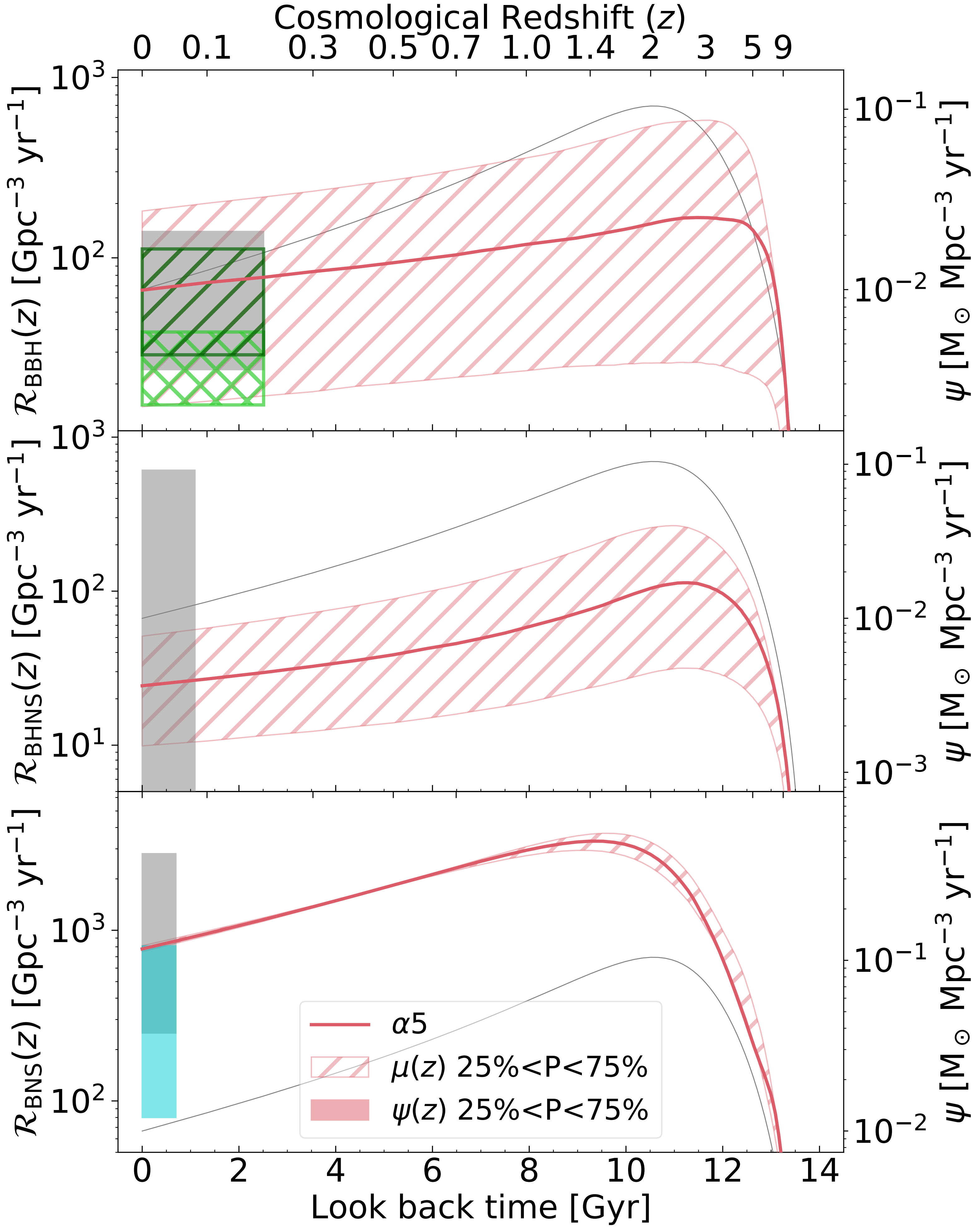
De Cia et al. 2018, Gallazzi et al. 2008, Madau & Fragos 2017

The cosmic merger rate density of compact objects: impact of star formation, metallicity, initial mass function and binary evolution

$\boxed{\mathrm{SFRD}(z', Z)}$

Filippo Santoliquido,[1,2★] Michela Mapelli,[1,2,3] Nicola Giacobbo,[1,2,3]
Yann Bouffanais,[1,2] M. Celeste Artale[4]

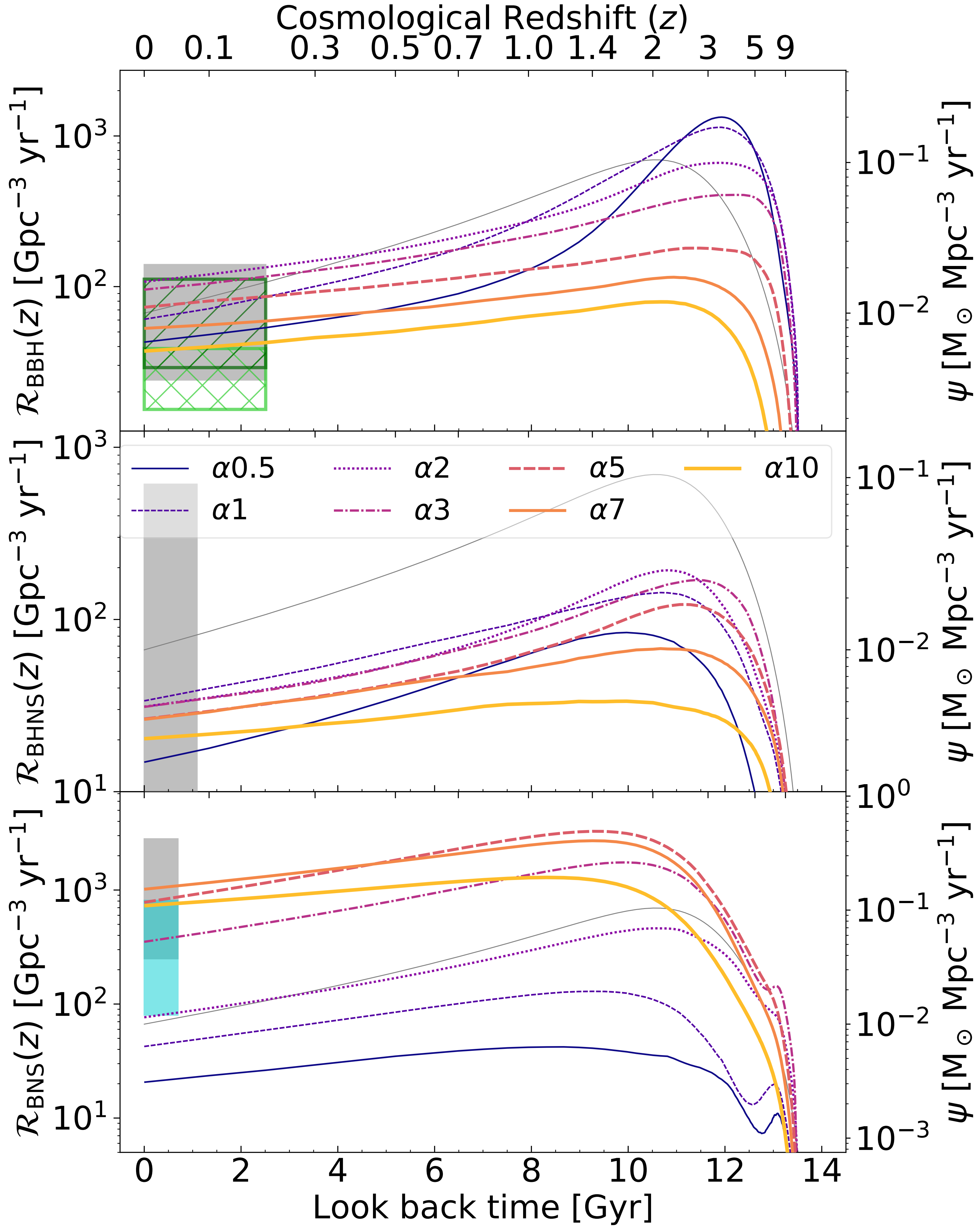
$\boxed{\mathcal{F}(z', z, Z)}$



Santoliquido et al. 2021:
https://arxiv.org/pdf/2009.03911.pdf

main source of uncertainty for the BBH merger rate density is the uncertainty in stellar **metallicity evolution**

main source of uncertainty for BNS merger rate density is the uncertainty on α **common-envelope**



galaxyRate

- `galaxyRate` is a unique approach, featuring unprecedented speed
- **Why did we need to introduce this new method?**
    - To have a more **realistic model** for $\mathrm{SFRD}(z, Z)$
    - To reconstruct the **properties of host galaxies** of compact object mergers:
        - **characterisation of host galaxies is crucial** to identify likely formation mechanisms
        - **Theoretical models** might be **required** to further increase the chances to identify host galaxies. Unique detection of a BNS merger with its host galaxy (**GW170817**, *Abbott et al. 2017*).

general scheme of galaxyRate

Formation galaxies → Merging compact objects → Host galaxies

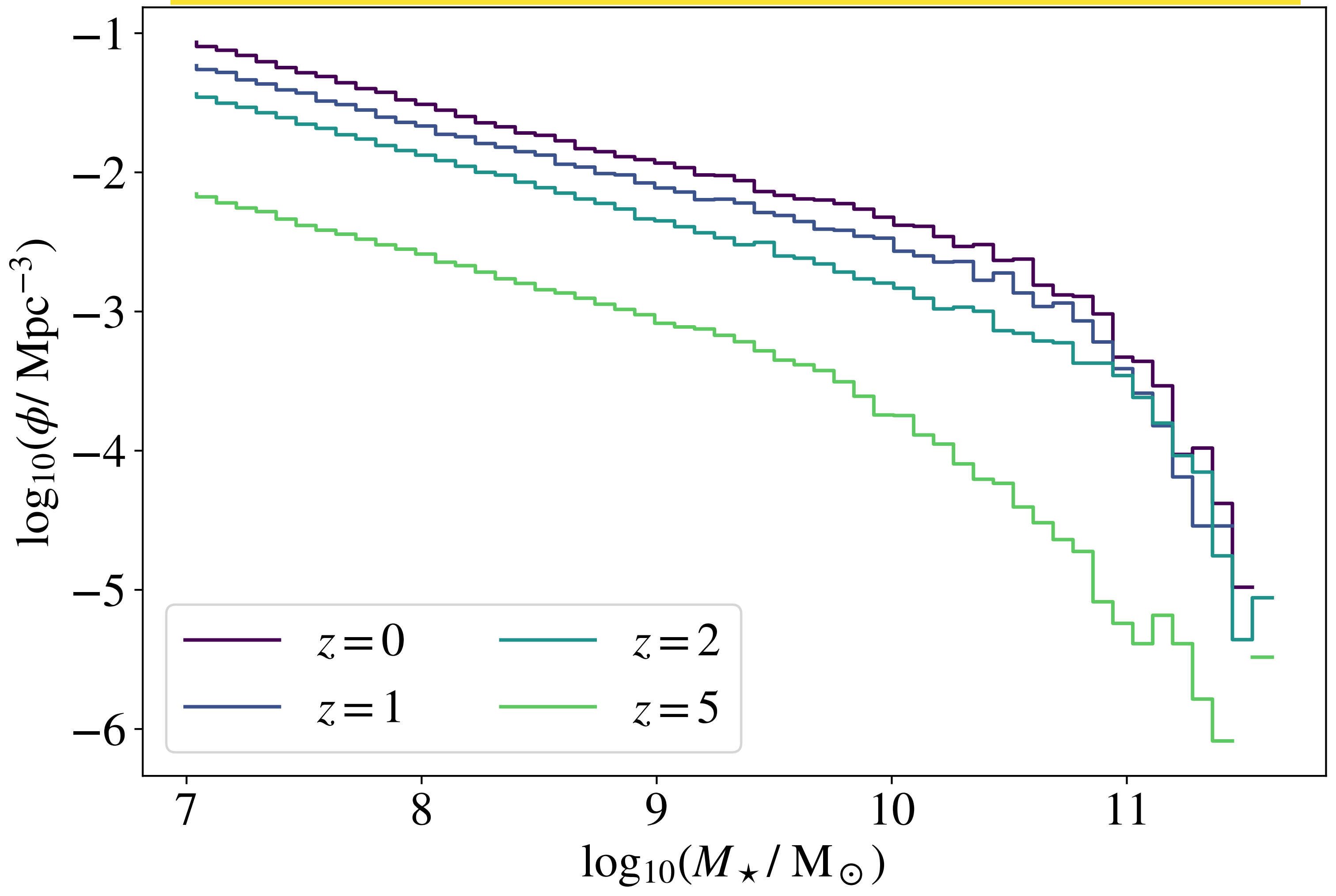
general scheme of galaxyRate

Formation galaxies → Merging compact objects → Host galaxies

↑

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

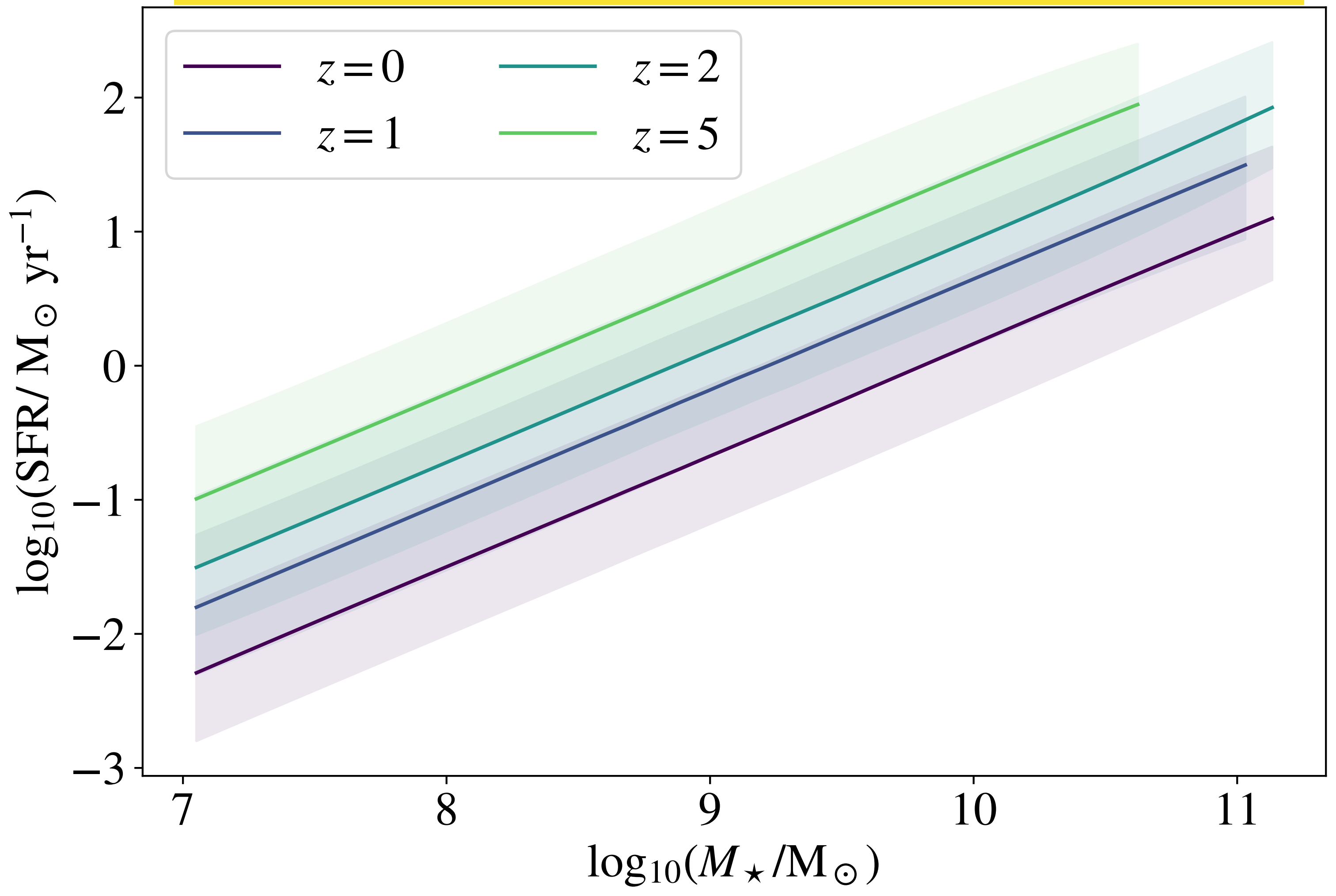
Stellar mass



[Chruslinska et al. 2019]

⊗

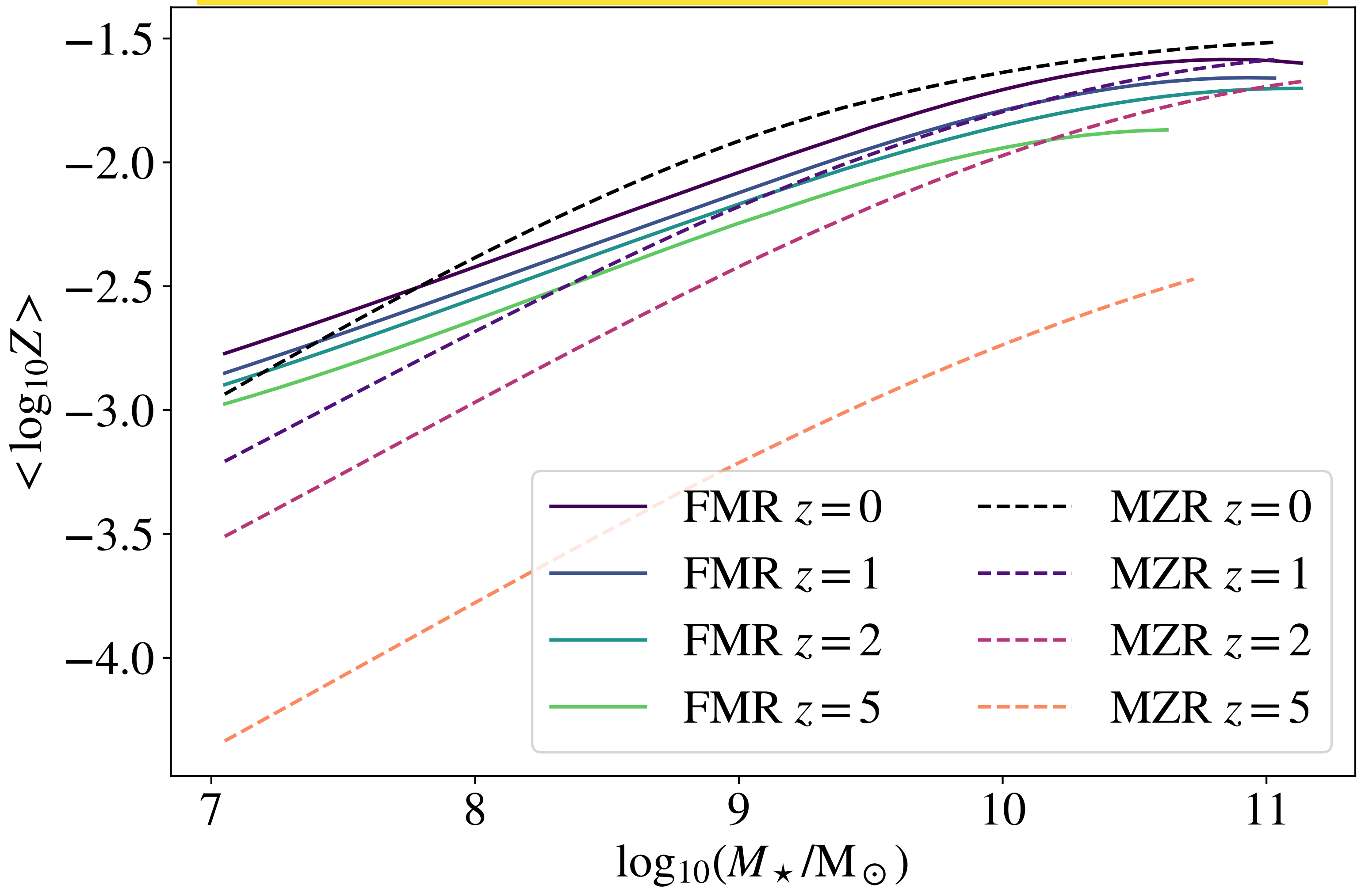
Star-formation rate



[Speagle et al. 2014, Boogaard et al. 2018]

⊗

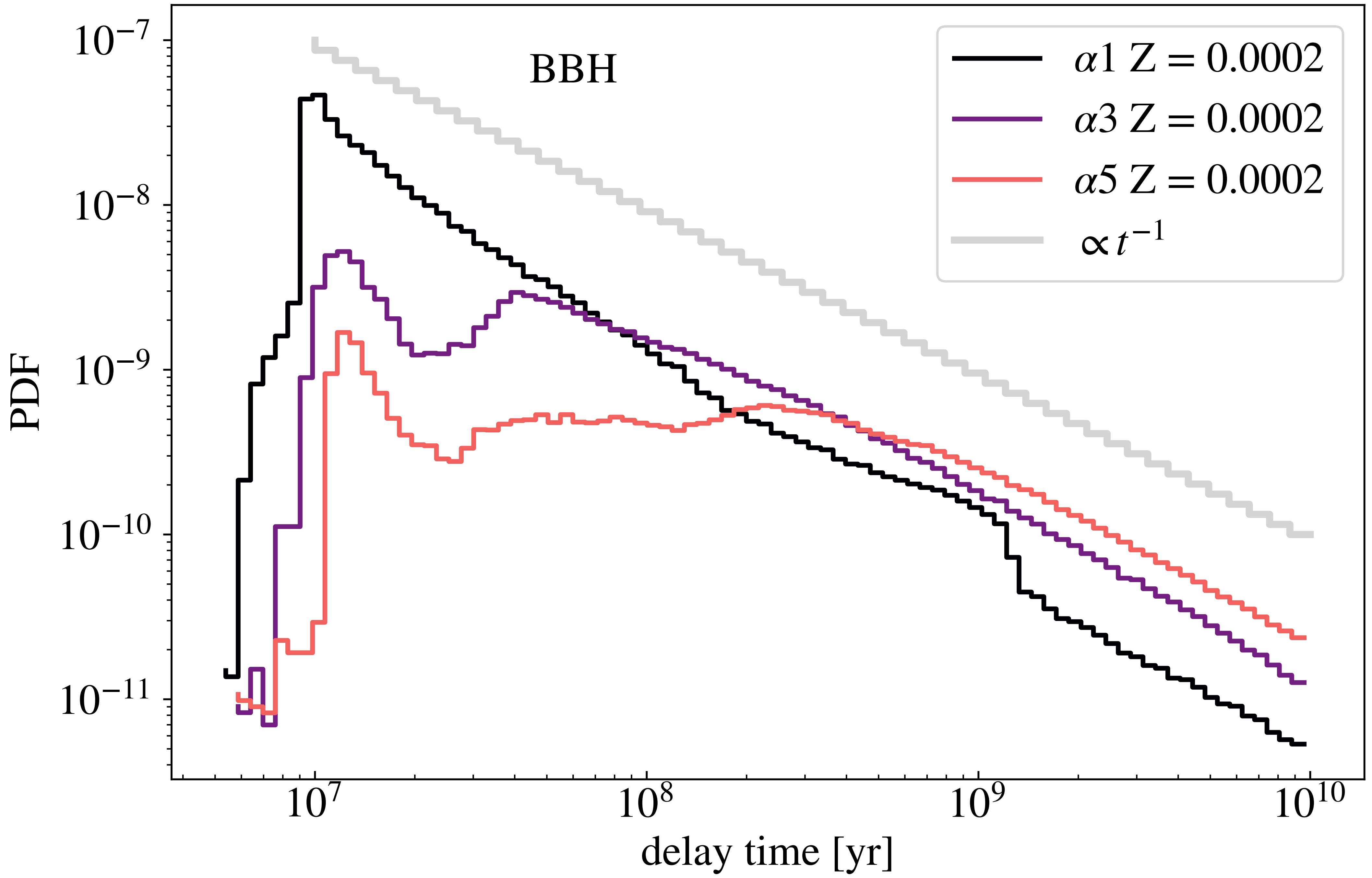
Metallicity



[Mannucci et al. 2009, Mannucci et al. 2011]

general scheme of galaxyRate

Formation galaxies → Merging compact objects → Host galaxies



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

Effect of common envelope

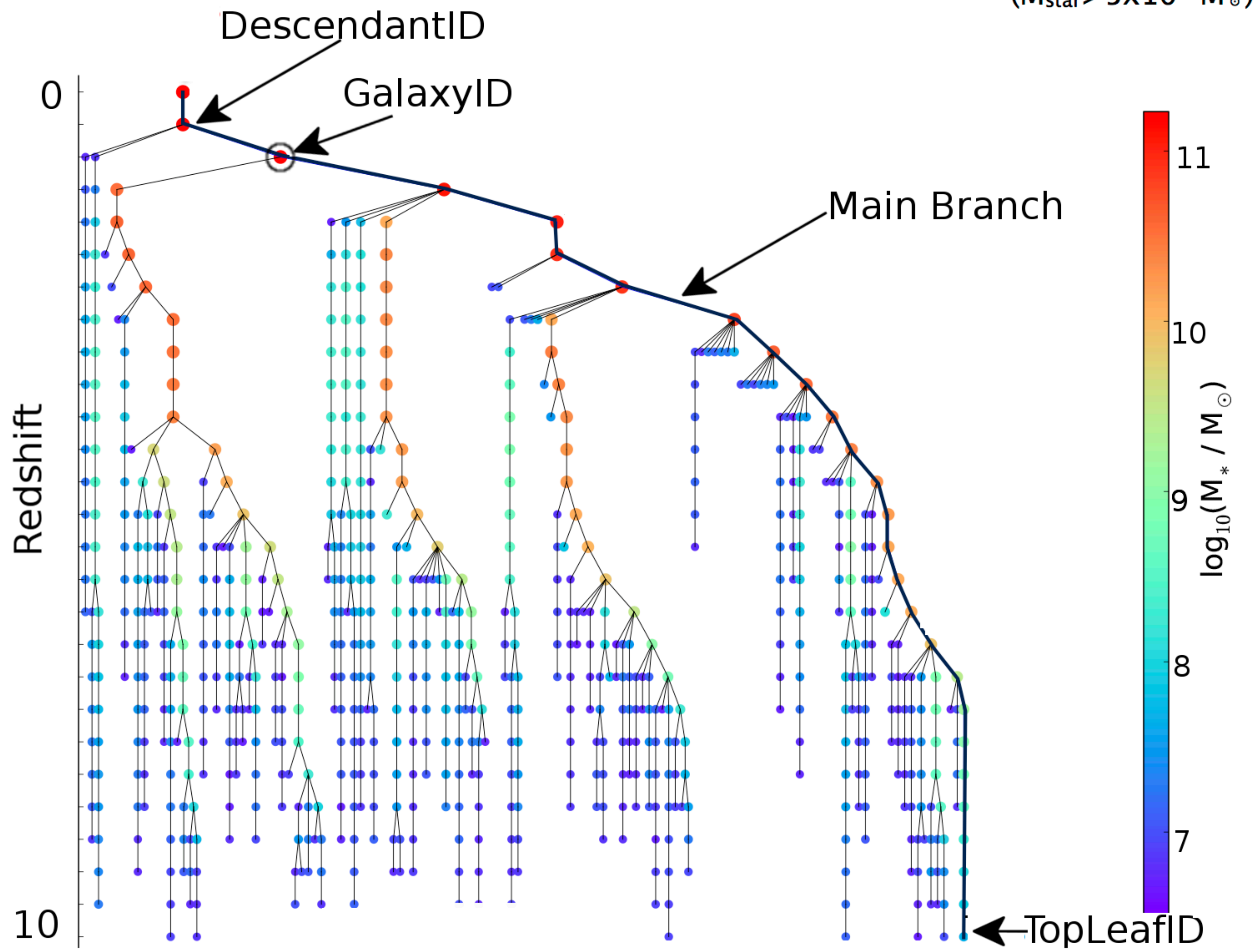
general scheme of galaxyRate

Formation galaxies → Merging compact objects → Host galaxies

subhalo merger tree
($M_{star} > 5\times10^6\ M_\odot$)

The **merger trees** of cosmological simulations encode the entire **assembly history** and **property evolution** of each single galaxy across cosmic time

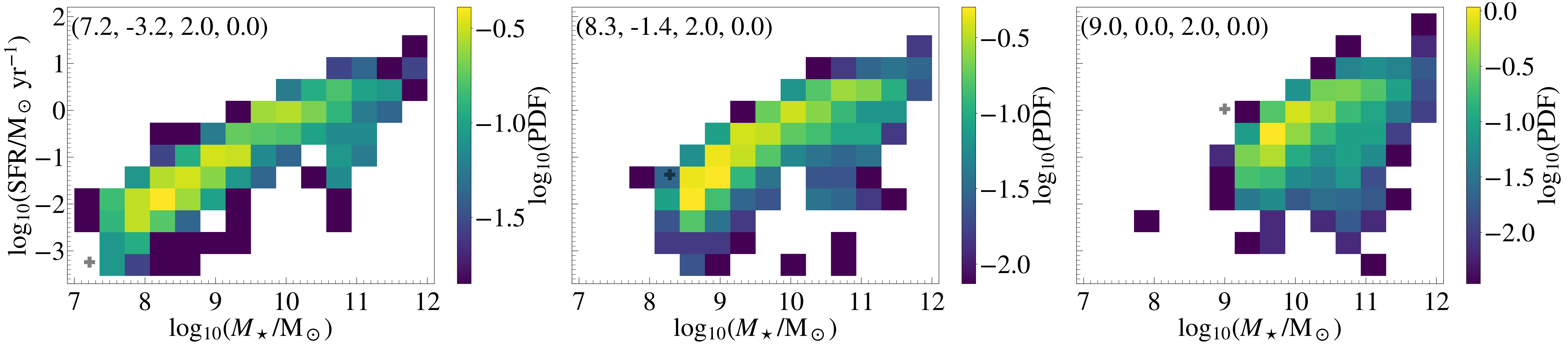
https://arxiv.org/pdf/1510.01320.pdf



general scheme of galaxy$\mathcal{R}$ate

Formation galaxies → Merging compact objects → Host galaxies

From the **merger trees** of the EAGLE cosmological simulation (Schaye et al. 2015), I compute a **conditional probability** $p(\mathrm{M}_{host}, \mathrm{SFR}_{host} \,|\, \mathrm{M}_{form}, \mathrm{SFR}_{form}, z_{form}, z_{merg})$, from which I **sample** the **properties** of the **host galaxy** for each compact object merger.



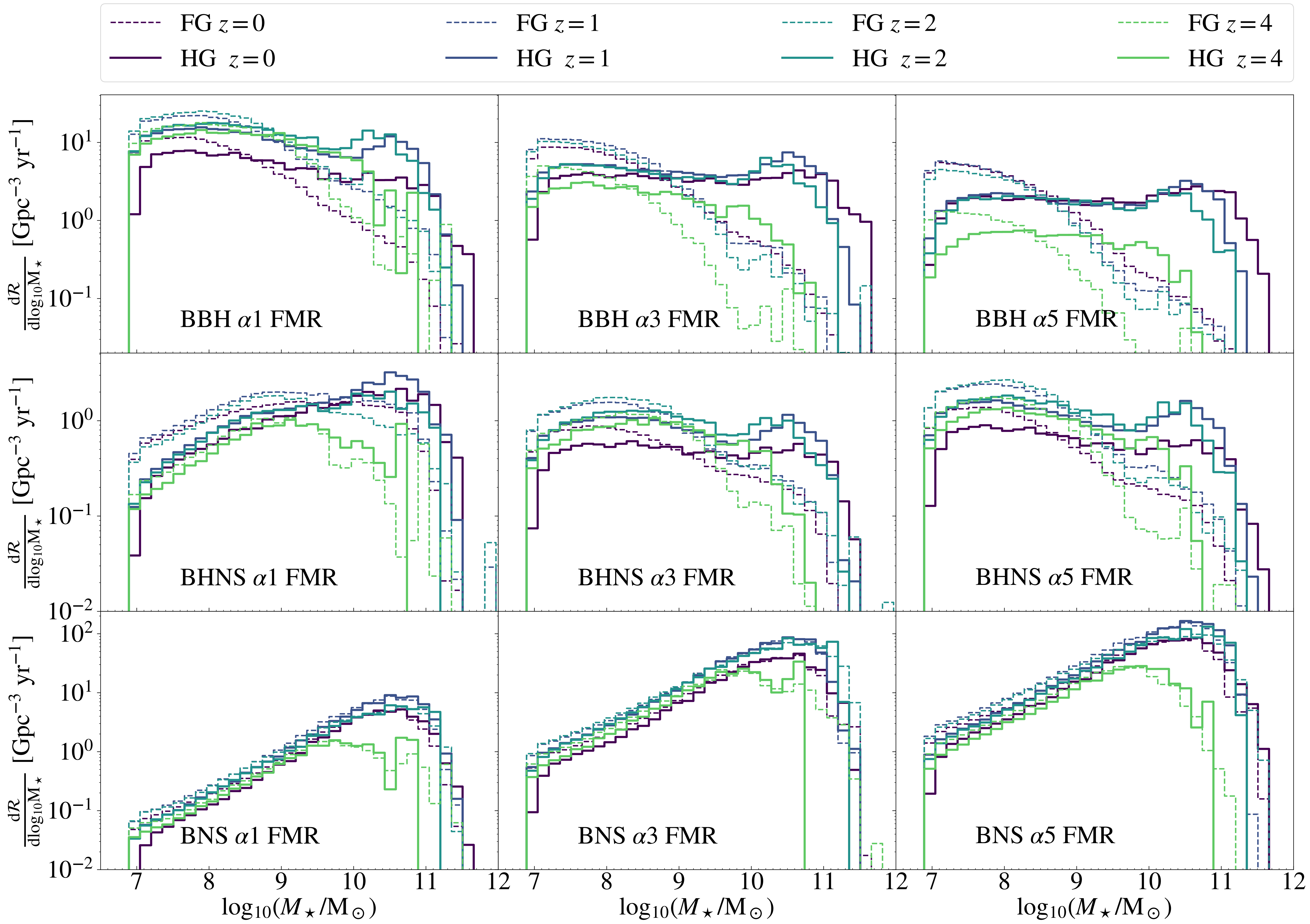
Santoliquido et al. 2022: https://arxiv.org/pdf/2205.05099.pdf

Modelling the host galaxies of binary compact object mergers with observational scaling relations

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

Filippo Santoliquido,[1,2★] Michela Mapelli,[1,2,3†] M. Celeste Artale,[1,2,4,5] and Lumen Boco[6,7,8]

- The Formation Galaxy (**FG**) and Host Galaxy (**HG**) **can be different**
- Large fraction of **BBHs** is **hosted** in **low-mass galaxies**
- **Contribution of high-mass galaxies** increases with **increasing** α



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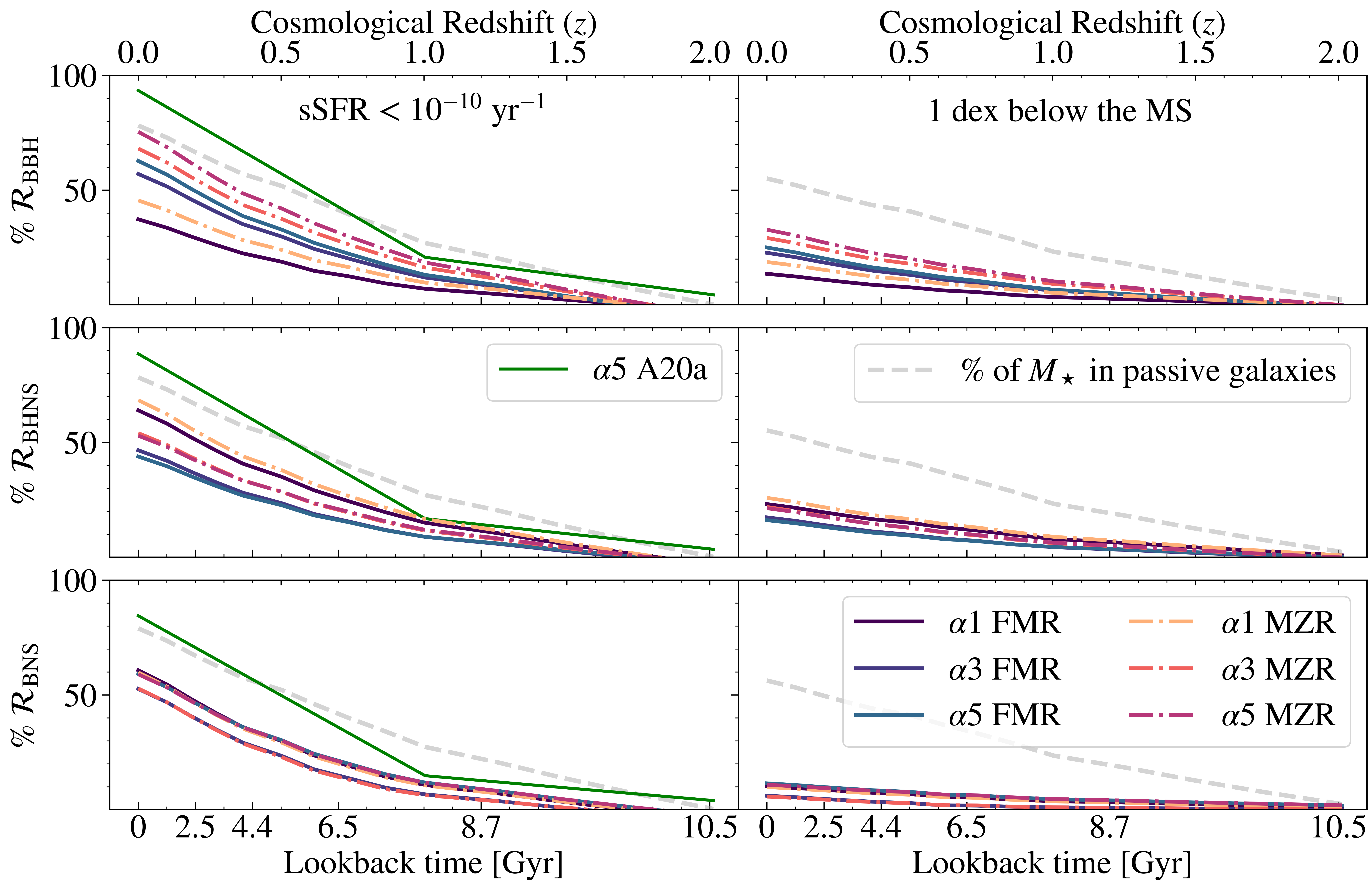
- Passive galaxies can only be host galaxies in `galaxyRate`
- Percentage of mergers hosted by passive galaxies **increases at decreasing redshift**
- the percentage of BBH mergers hosted in passive galaxies can changed by a **factor of ~2 depending on the considered model**



population III BBHs

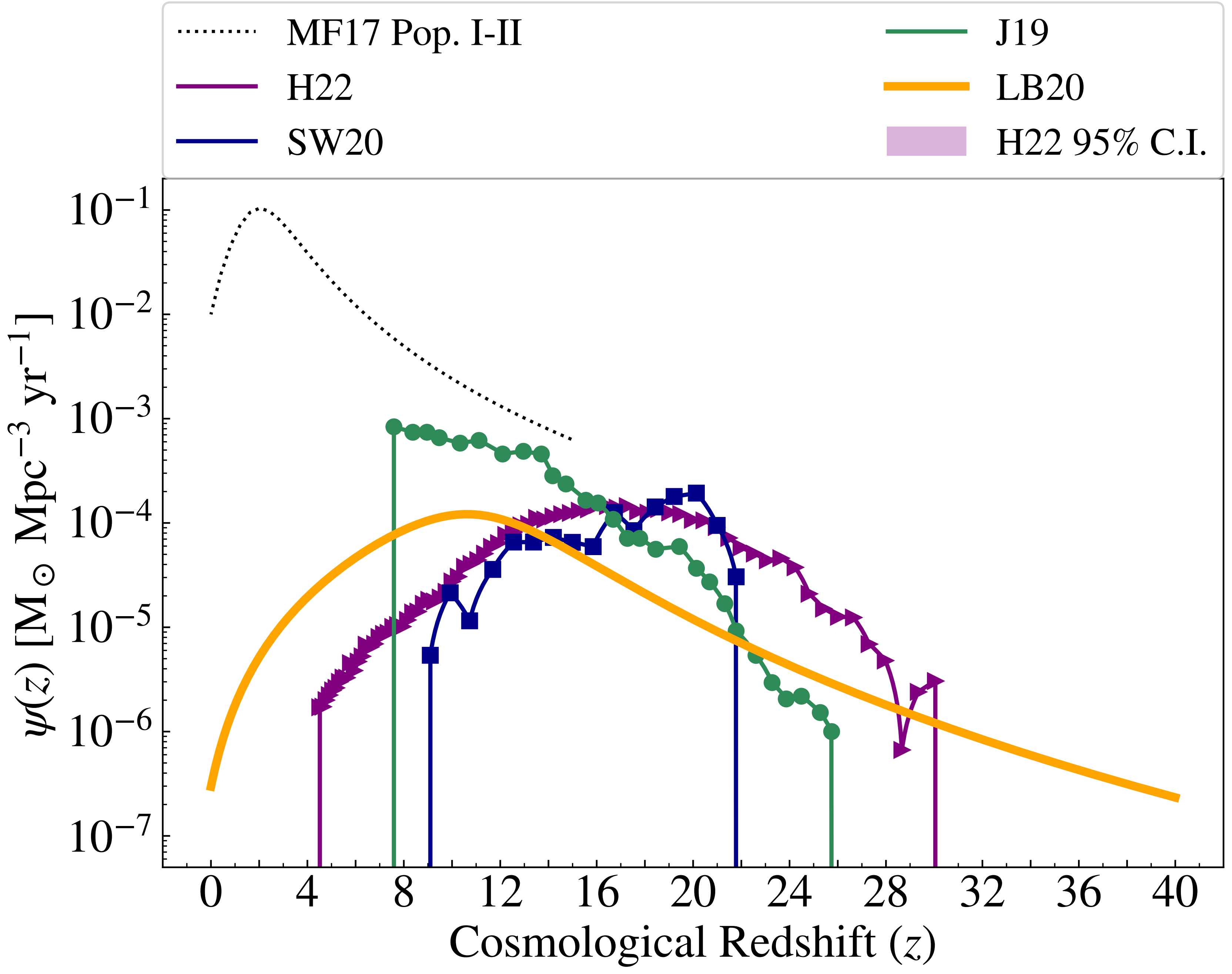
Credit: ESO
https://supernova.eso.org/exhibition/images/1120_pop3-CC/

- Population III (**Pop. III**) binary stars likely produced the **first stellar-born BBH mergers** in the Universe
- The **third-generation** ground-based gravitational-wave (GW) **detectors** (e.g. the Einstein Telescope) will capture BBH mergers up to a **redshift** $z \leq 100$ (*Maggiore et al. 2020*; *Ng et al. 2021*)

Pop. III BBHs

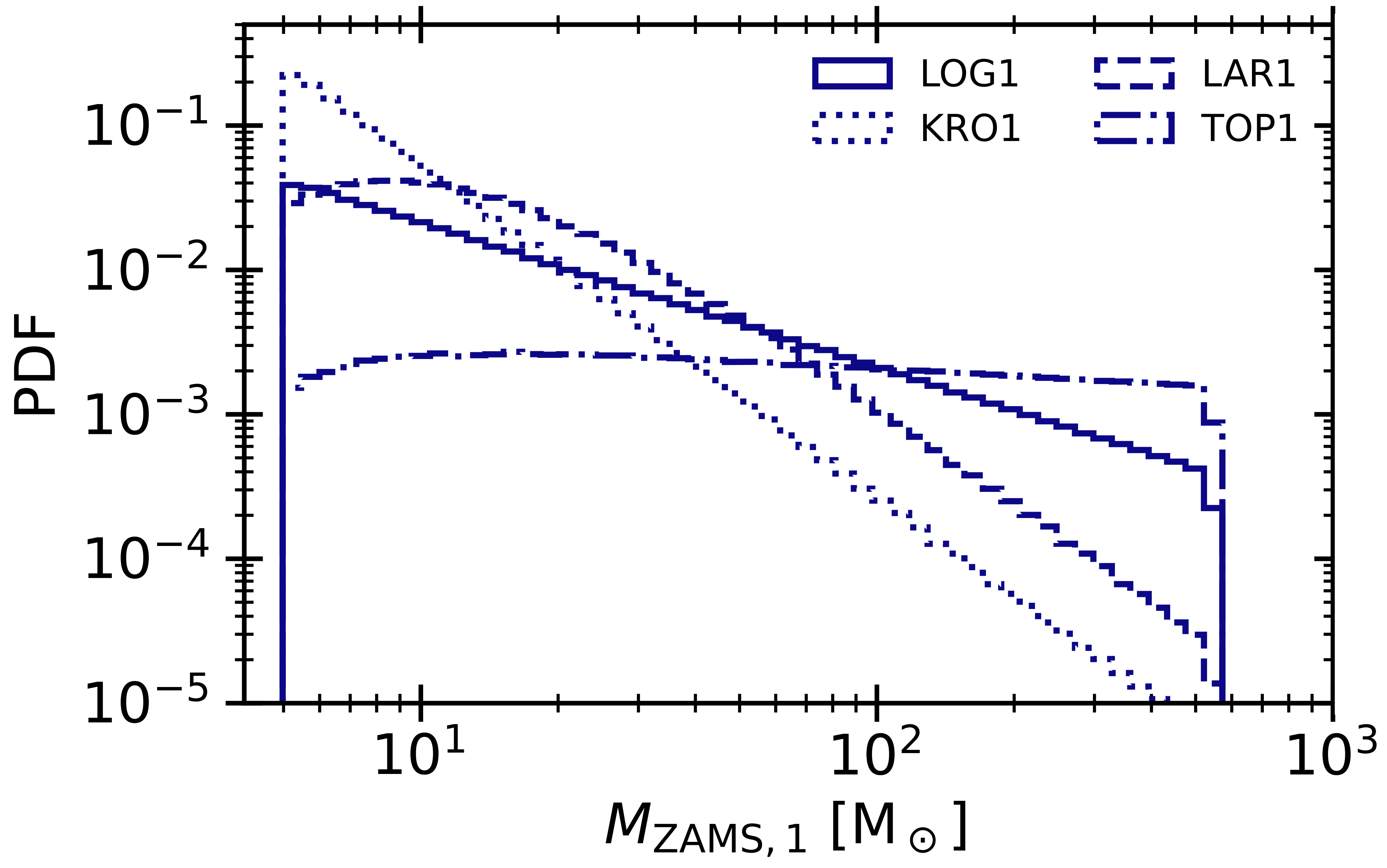
I used **`cosmoRate`** to predict the **merger rate density** of **BBHs** born from **Pop. III** stars for a set of different models

star formation histories



Santoliquido et al. 2023:
https://arxiv.org/pdf/2303.15515.pdf

initial conditions (e.g. IMF)



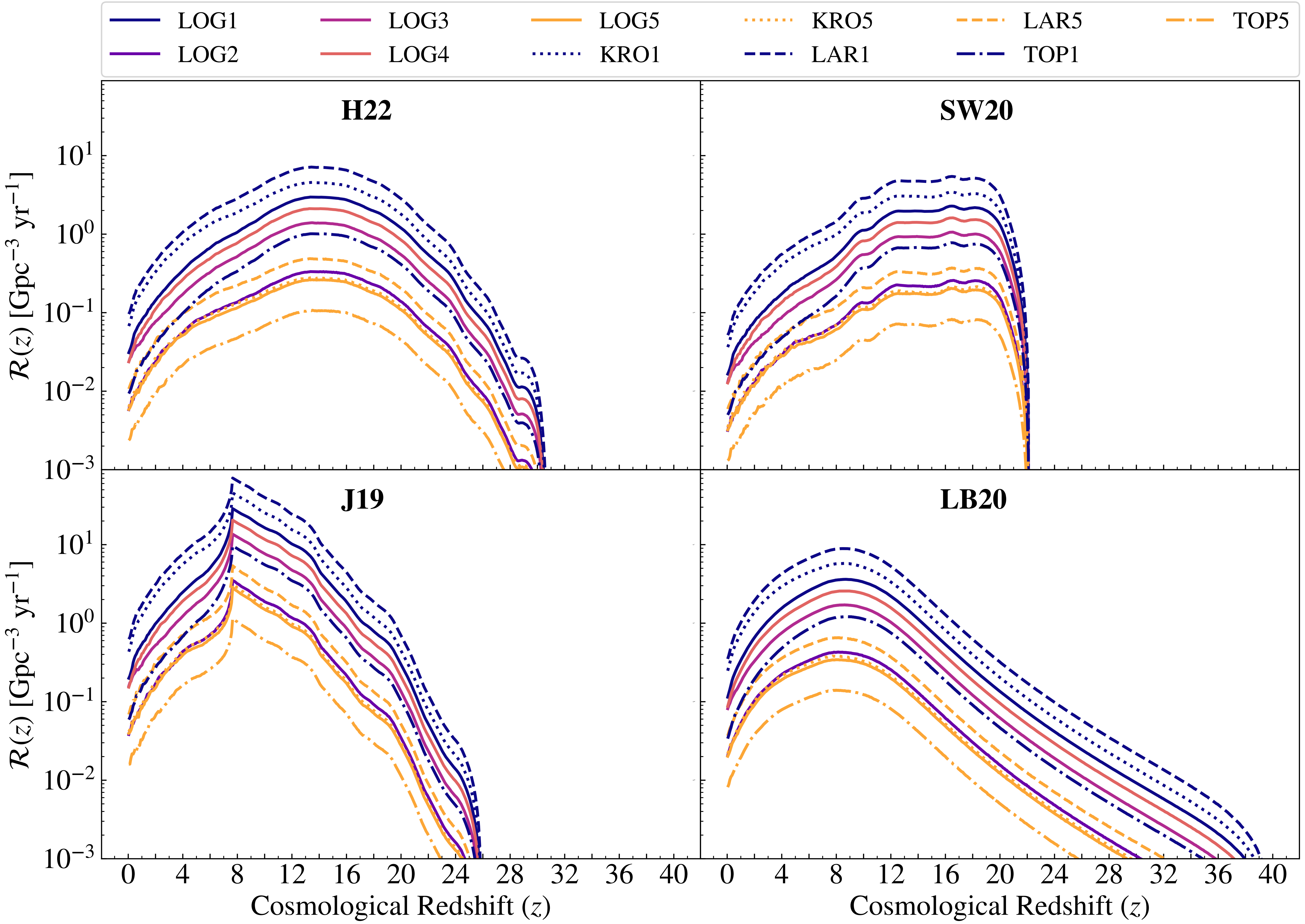
Costa et al. 2023

Binary black hole mergers from Population III stars: uncertainties from star formation and binary star properties

Filippo Santoliquido [1,2★] Michela Mapelli [1,2,3†] Giuliano Iorio [1,2,3‡] Guglielmo Costa [1,2,3,4]
Simon C. O. Glover [5] Tilman Hartwig [6,7,8] Ralf Klessen [5] and Lorenzo Merli [1]

Santoliquido et al. 2023:
https://arxiv.org/pdf/2303.15515.pdf

- The **uncertainty on the star formation history** impacts both the **shape and the normalisation**
- the **peak** of the merger rate density **shifts** from $z \sim 8$ (J19) up to $z \sim 16$ (SW20)



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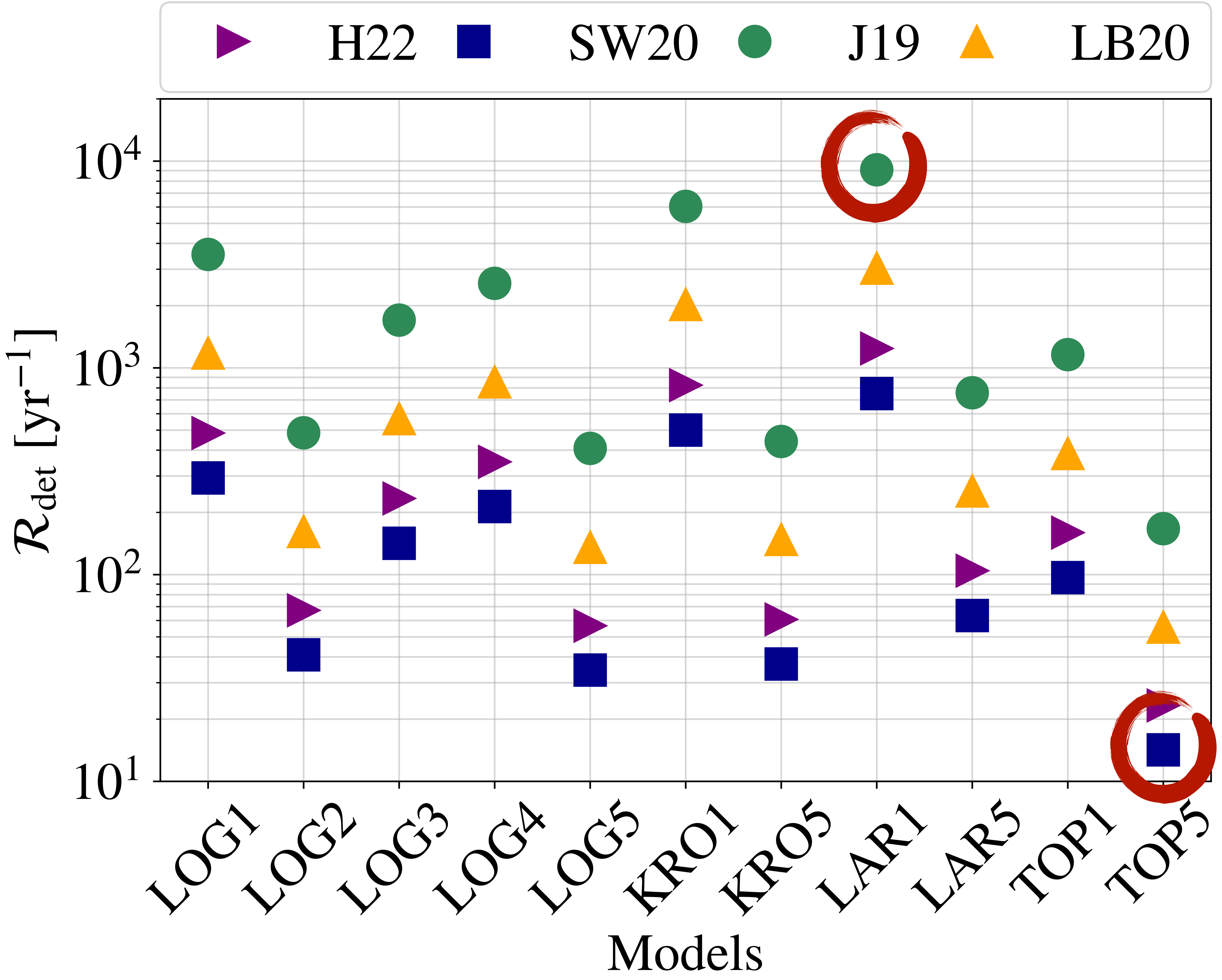
Santoliquido et al. 2023:
https://arxiv.org/pdf/2303.15515.pdf

- **Einstein Telescope will detect 10 – 10^4** Pop. III BBH mergers per year
- I expect **62% of detections** from BBH mergers occurring at redshift z **> 8** for H22 LOG1.
- such **high-redshift detections** will be **crucial to characterise the population of Pop. III BBHs.**



Conclusions

- I evaluated the **merger rate density** of compact objects and explored the properties of their **host galaxies** by means of two codes I developed: **`cosmoRate`** and **`galaxyRate`**

- **BBH** merger rate density is **highly depended** on star-formation rate at **sub-solar metallicity.** **BNS** are mostly **affected** by **binary evolution** (common envelope phase)
- A **large fraction of BBHs can merge in low-mass host galaxies** and this depends on the delay time distribution.
- All compact objects have more chances to be hosted in **passive galaxies** if their **delay time** distribution is **longer**

- **Einstein Telescope** will detect **10 – 10^4** Pop. III **BBH mergers** per year, depending on the model

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- I evaluated the **merger rate density** of compact objects and explored the properties of their **host galaxies** by means of two codes I developed: **`cosmoRate`** and **`galaxyRate`**

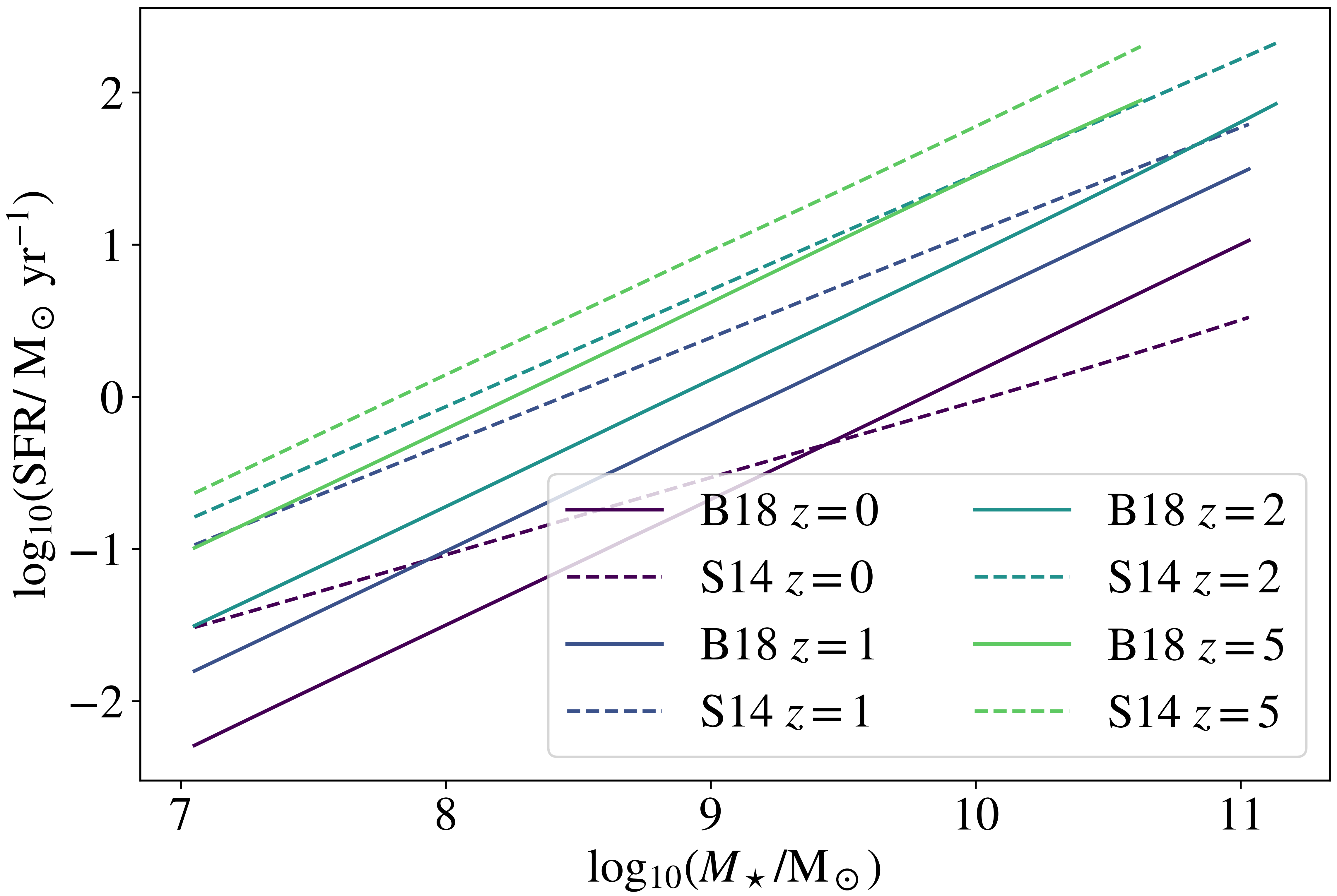
- **BBH** merger rate density is **highly depended** on star-formation rate at **sub-solar metallicity. BNS** are mostly **affected** by **binary evolution** (common envelope phase)
- A **large fraction of BBHs can merge in low-mass host galaxies** and this depends on the delay time distribution.
- All compact objects have more chances to be hosted in **passive galaxies** if their **delay time** distribution is **longer**

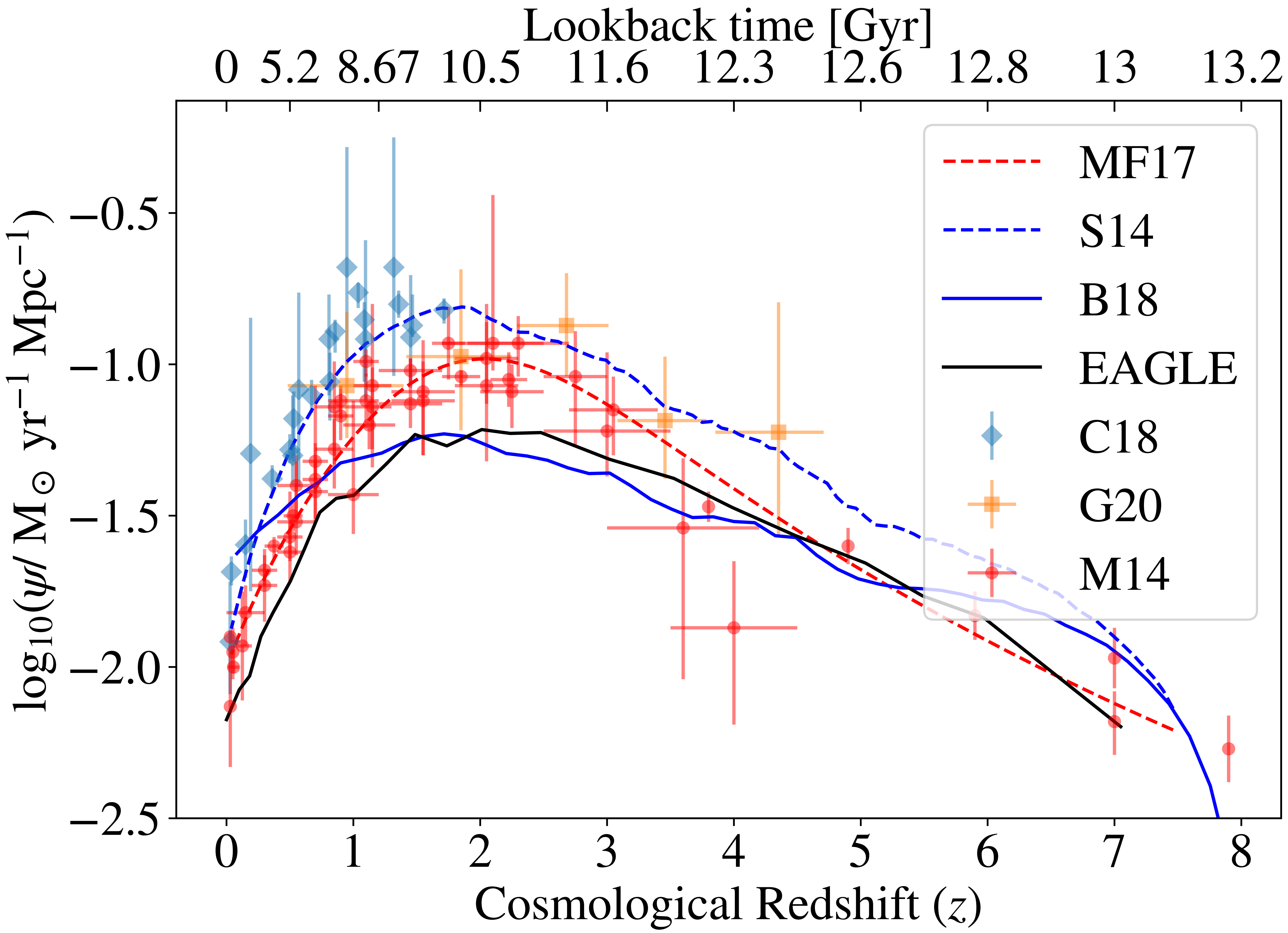
- **Einstein Telescope** will detect **10 – 10^4** Pop. III **BBH mergers** per year, depending on the model

Thank you

Backup slides

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

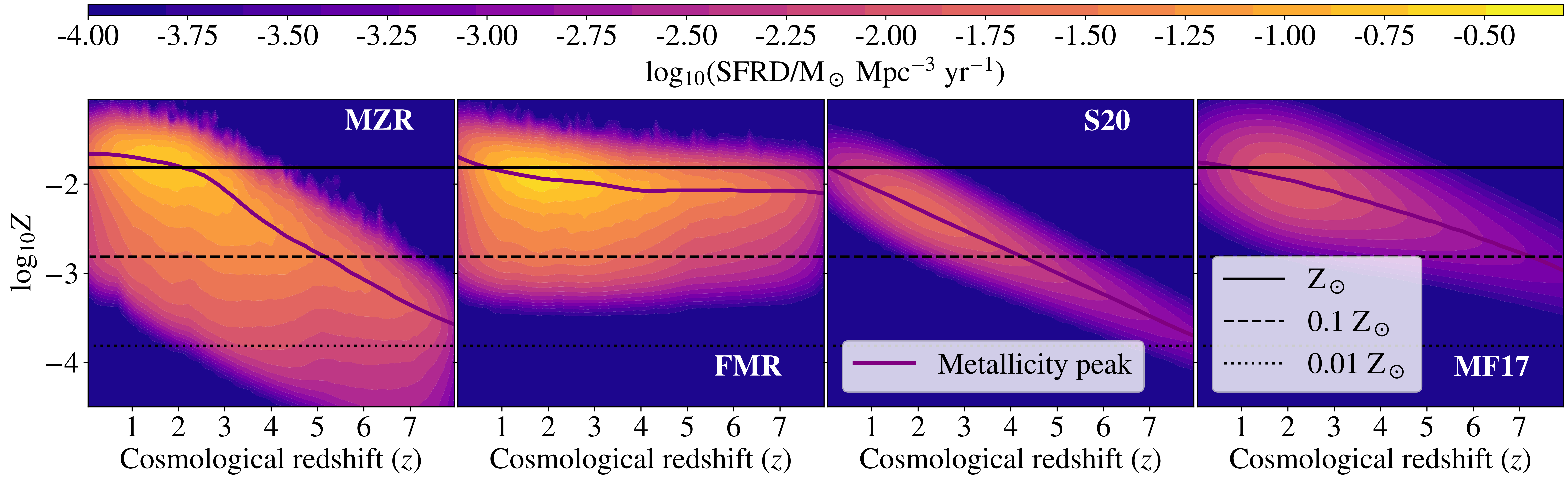




Santoliquido et al. 2022:
https://arxiv.org/pdf/2205.05099.pdf

SFRD(*z*,*Z*) distributions

Formation galaxies → Merging compact objects → Host galaxies

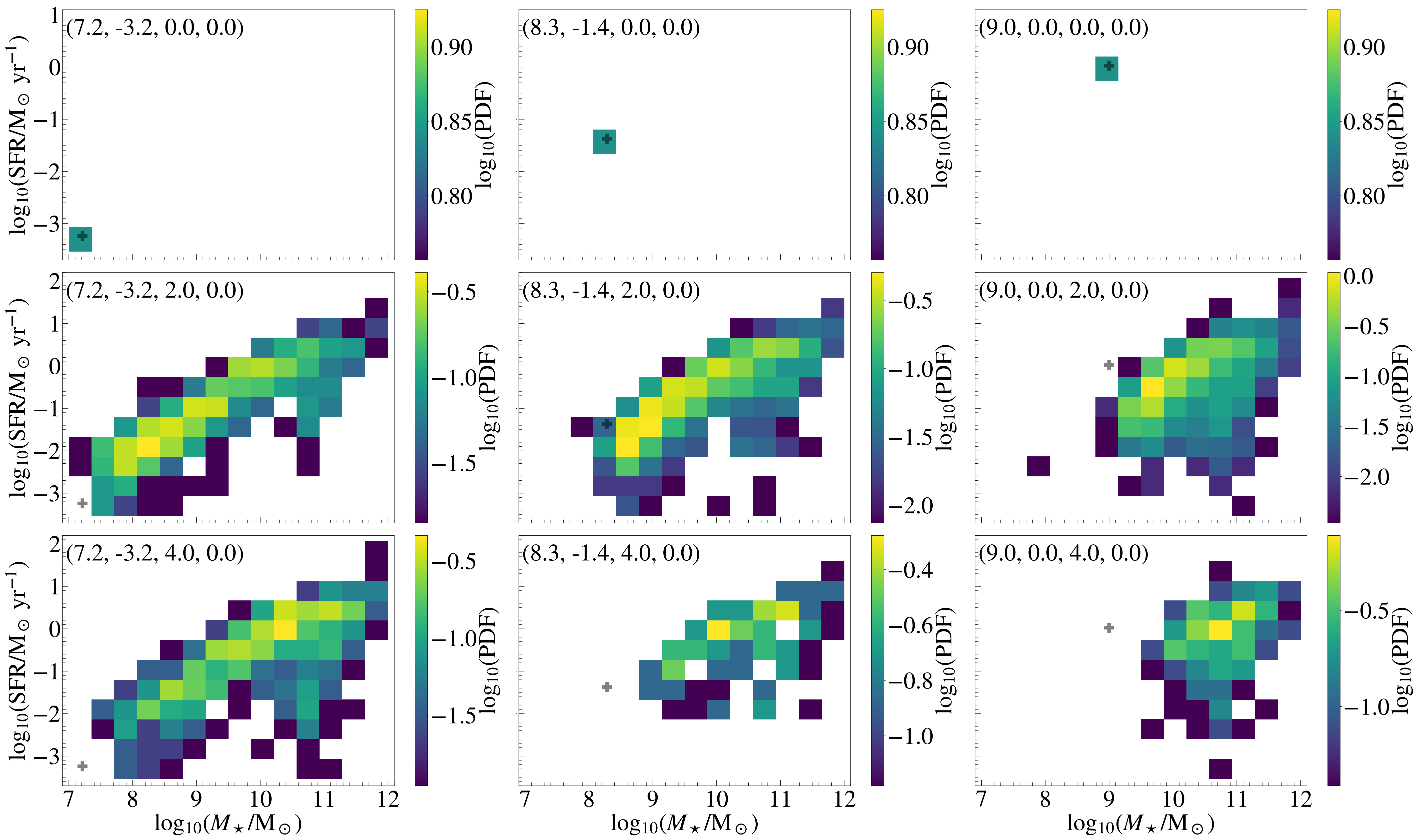


`galaxyRate` `cosmoRate`

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

conditional probability

The figure shows some examples of the conditional probability, for various properties of the formation galaxies, annotated at the top of each panel following the order $(\log_{10}(M_{form}/M_\odot),\ \log_{10}(SFR_{form}/M_\odot yr^{-1}),\ z_{form})$



If the formation galaxy has no time to evolve (short delay time), the properties of the host galaxy remain the same (first row) as those of the formation galaxy, while if the formation galaxy has more time to evolve (long delay time) then the host galaxy can be very different from the formation galaxy.

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

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