# Gravitational Wave Astrophysics

## Lecture 3

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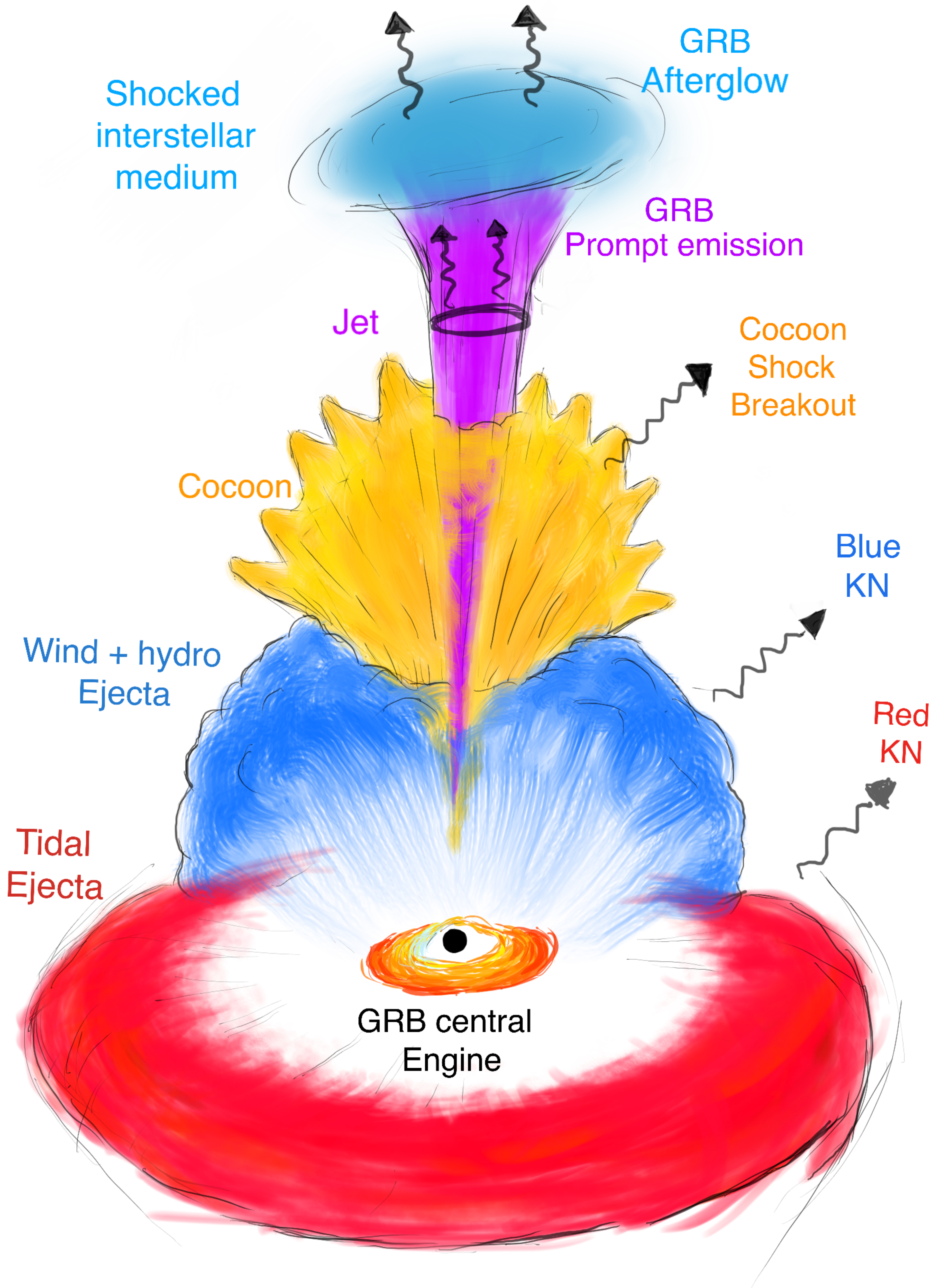
# In this lecture, you will learn

- Multimessenger astrophysics
- Host galaxies and how to model them
- GWs and cosmology

# The Kilonova

- A Kilonova (KN) is an emission of electromagnetic radiation due to the radioactive decay of heavy elements that are ejected fairly isotropically during the merger.

- Profound impact on many research areas




Credits: Ascenzi et al. 2020

# The Kilonova

- $L_{\rm peak} = 2.5 \times 10^{40} \; \frac{\rm erg}{\rm s} \left( \frac{v_{\rm ej}}{0.1 \; c} \frac{10 \; {\rm cm^2/g}}{k} \right)^{0.65} \left( \frac{m_{\rm ej}}{0.01 \; {\rm M_\odot}} \right)^{0.35} \left( \frac{\dot{e}_0}{5 \times 10^{16} \; {\rm erg \; s^{-1} \; g^{-1}}} \right)$

- $m_{\rm ej}$ *and* $v_{\rm ej}$ ➡️ ***Astrophysics***

- $k$ (opacity) ➡️ ***Atomic Physics***

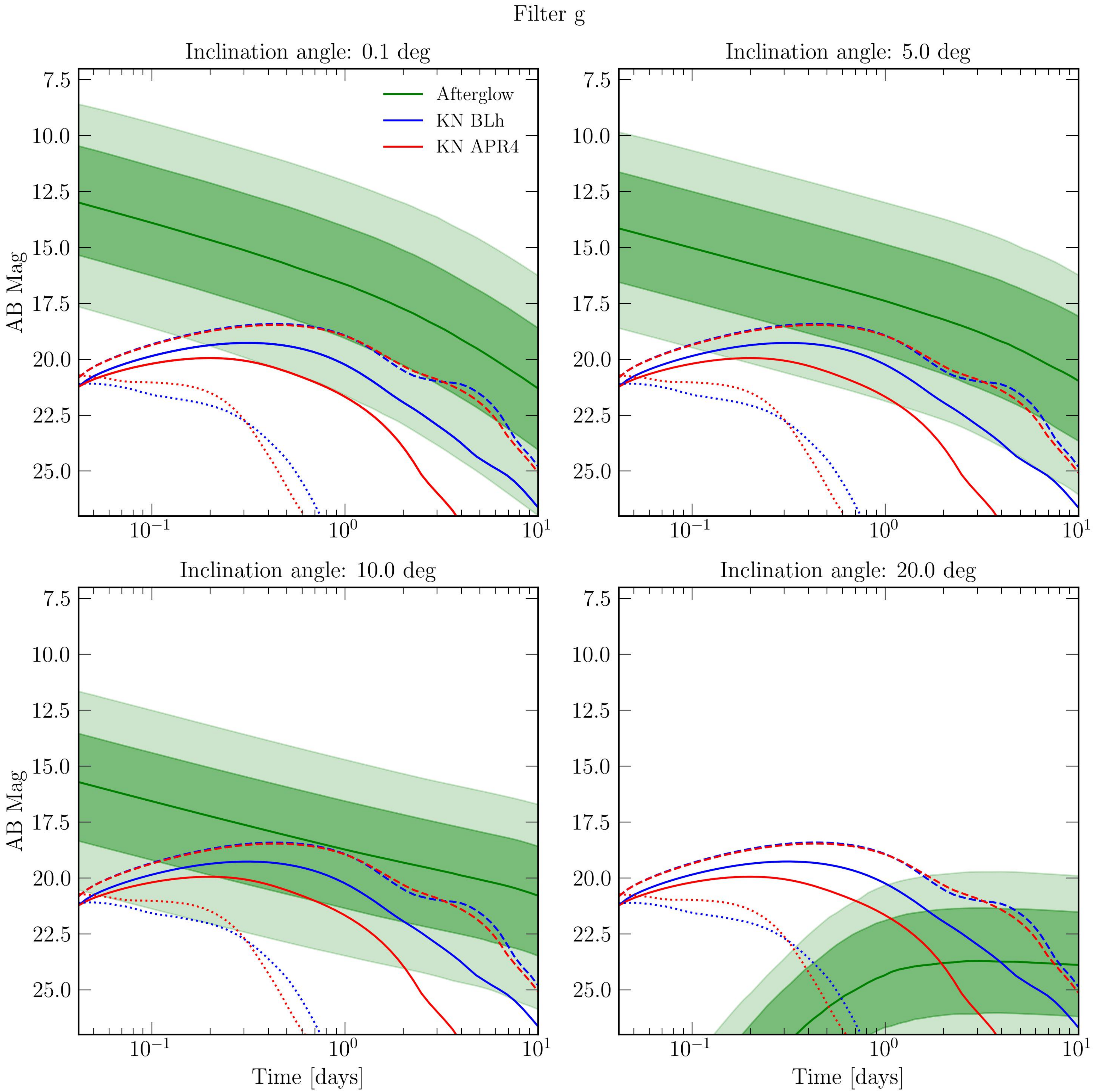
- $\dot{e}_0$ (radioactive heating rate) ➡️ ***Nuclear Physics***



Refs: Metzger 2019, Perego et al. 2021,

# Kilonova VS GRB

- Light curves at varying inclination angles
- KN mostly outshined by Afterglow
- Line styles correspond to different NS masses
- **Take-home message:** boost observations of KNs with GWs



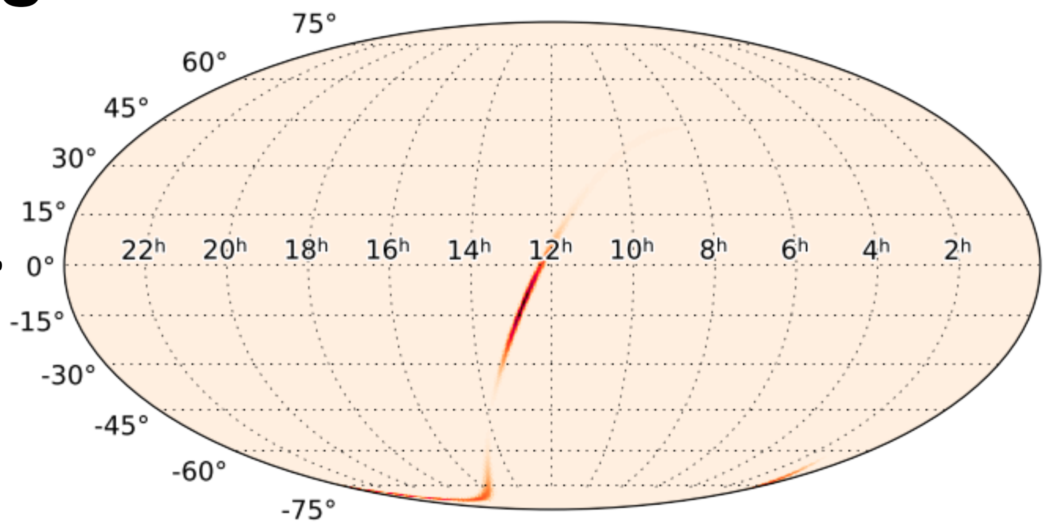

Credits: Loffredo et al. in preparation

# Low latency

**Detectors**

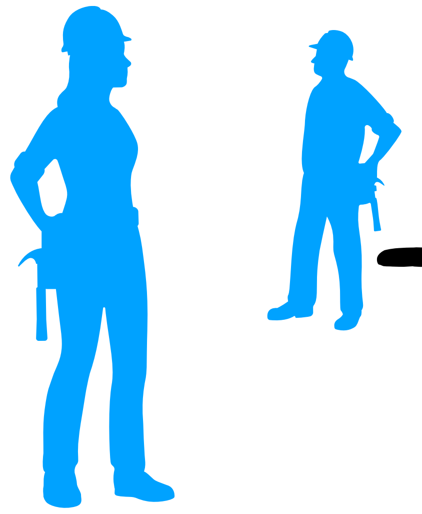
**Automatic searches**

**Sky localisation**

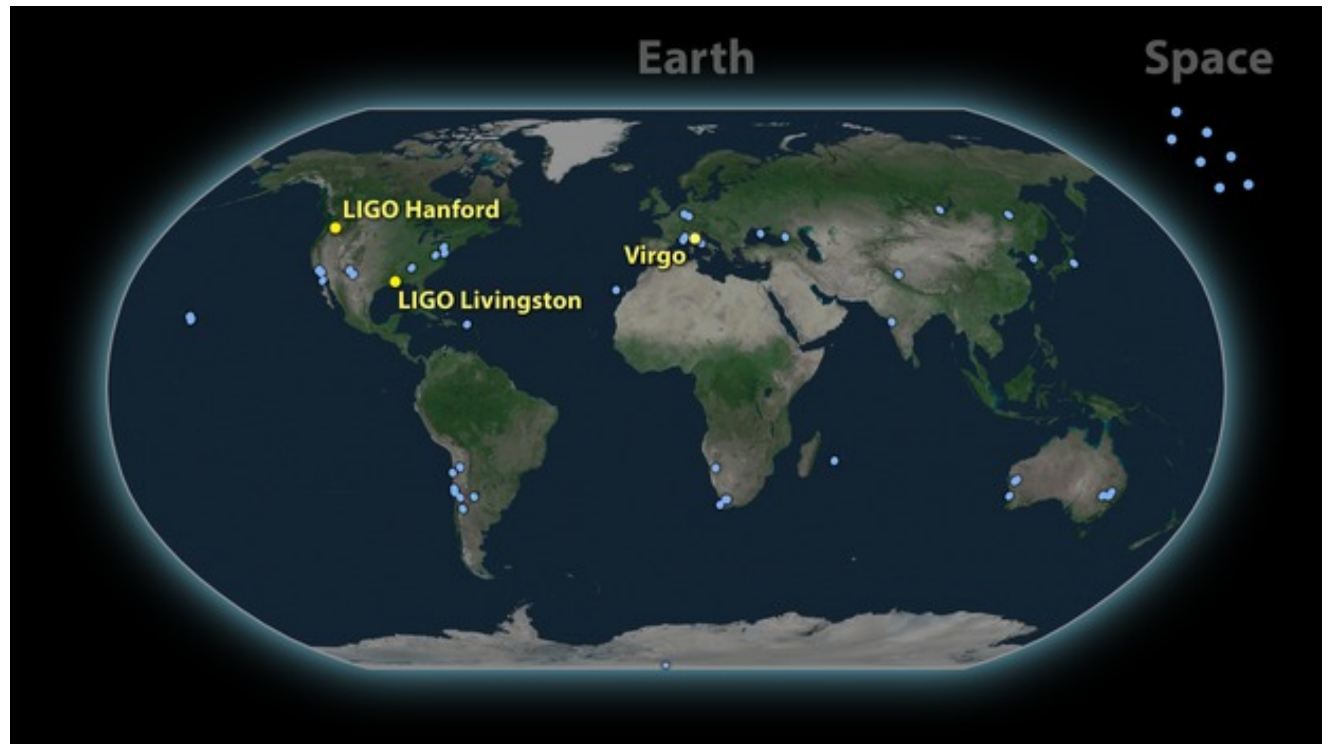



Credits: The LIGO-Virgo-KAGRA collaboration

**Human validation**



**EM facilities**

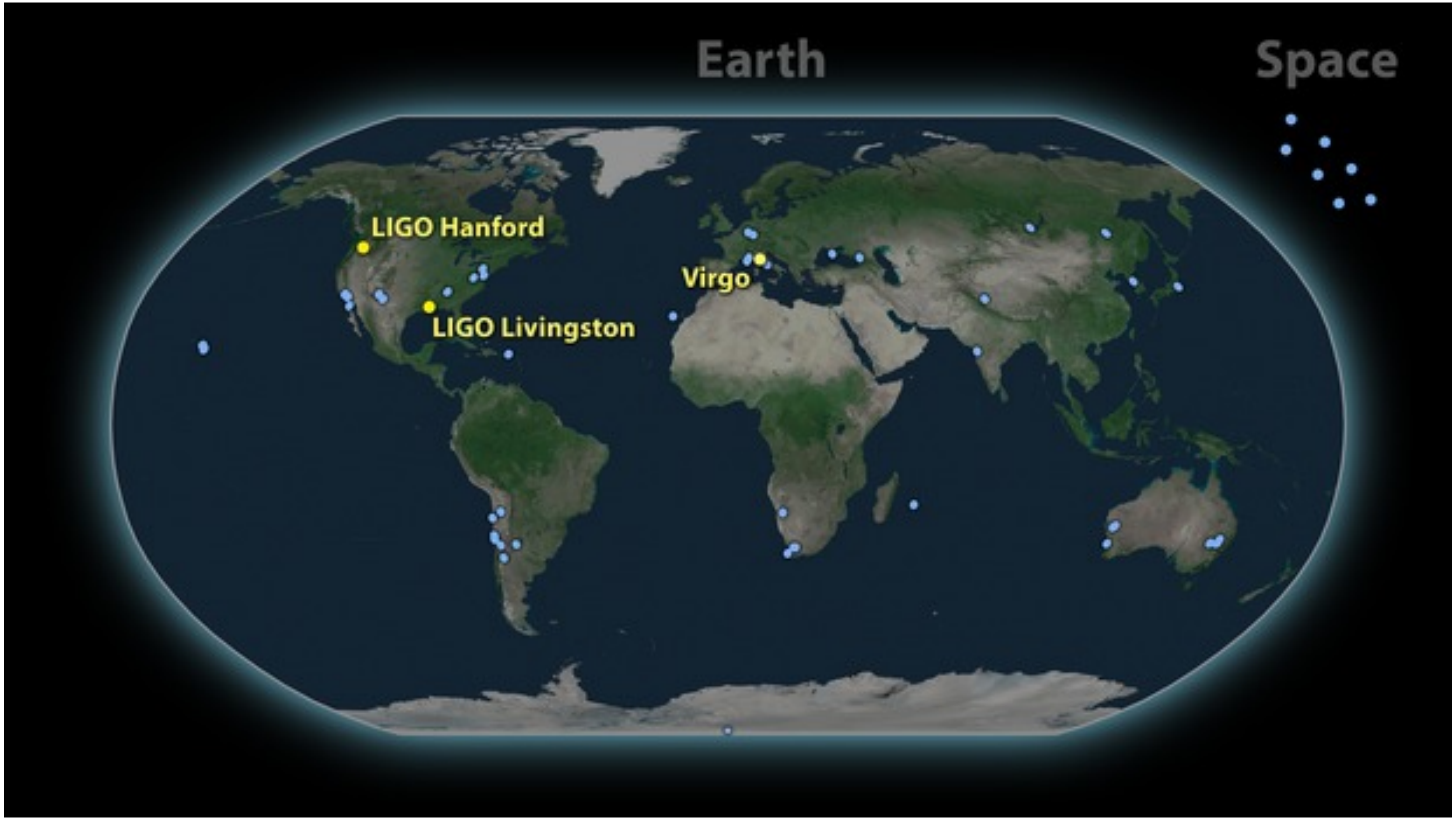



Credits: The LIGO-Virgo-KAGRA collaboration

**~ few minutes**

**~ 30 minutes**

# Low latency: EM facilities



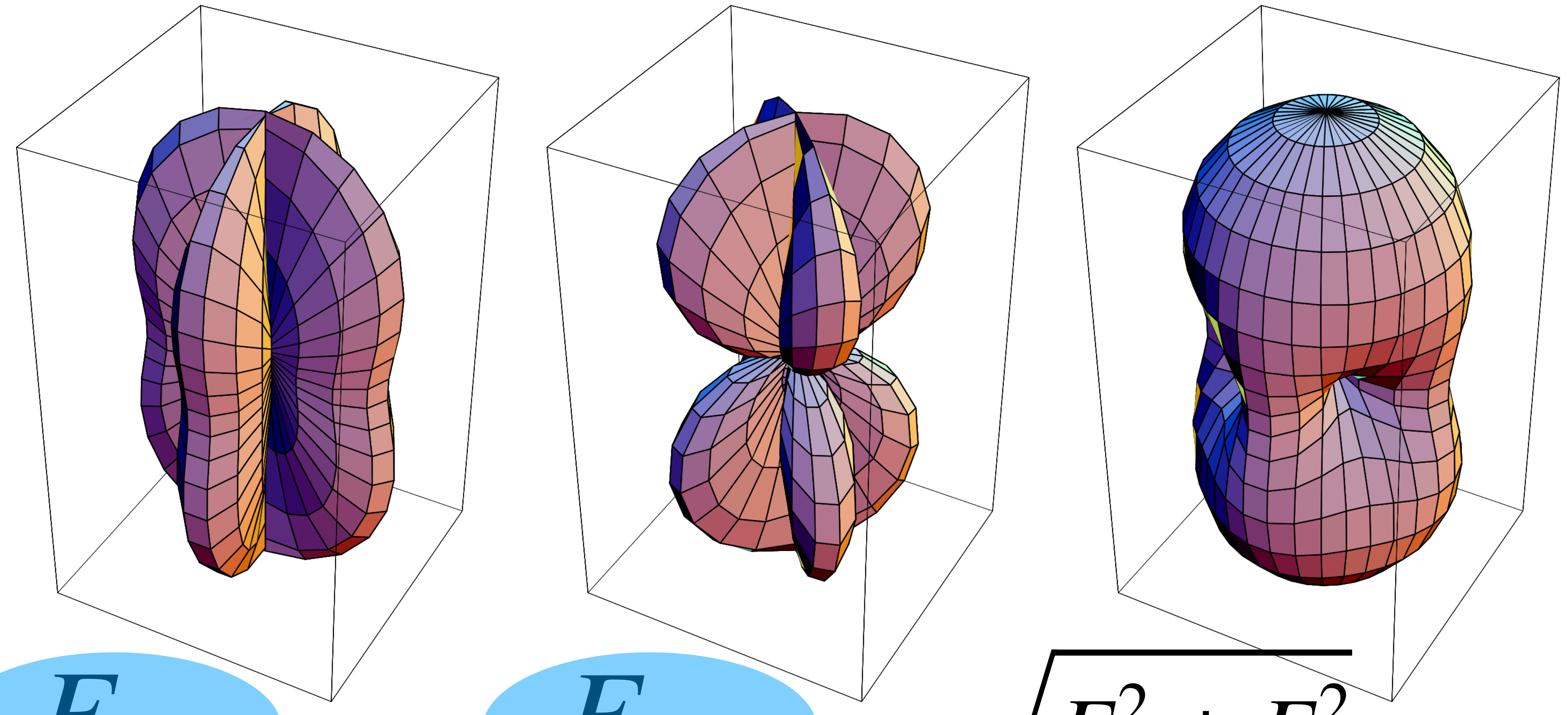



Credits: The LIGO-Virgo-KAGRA collaboration

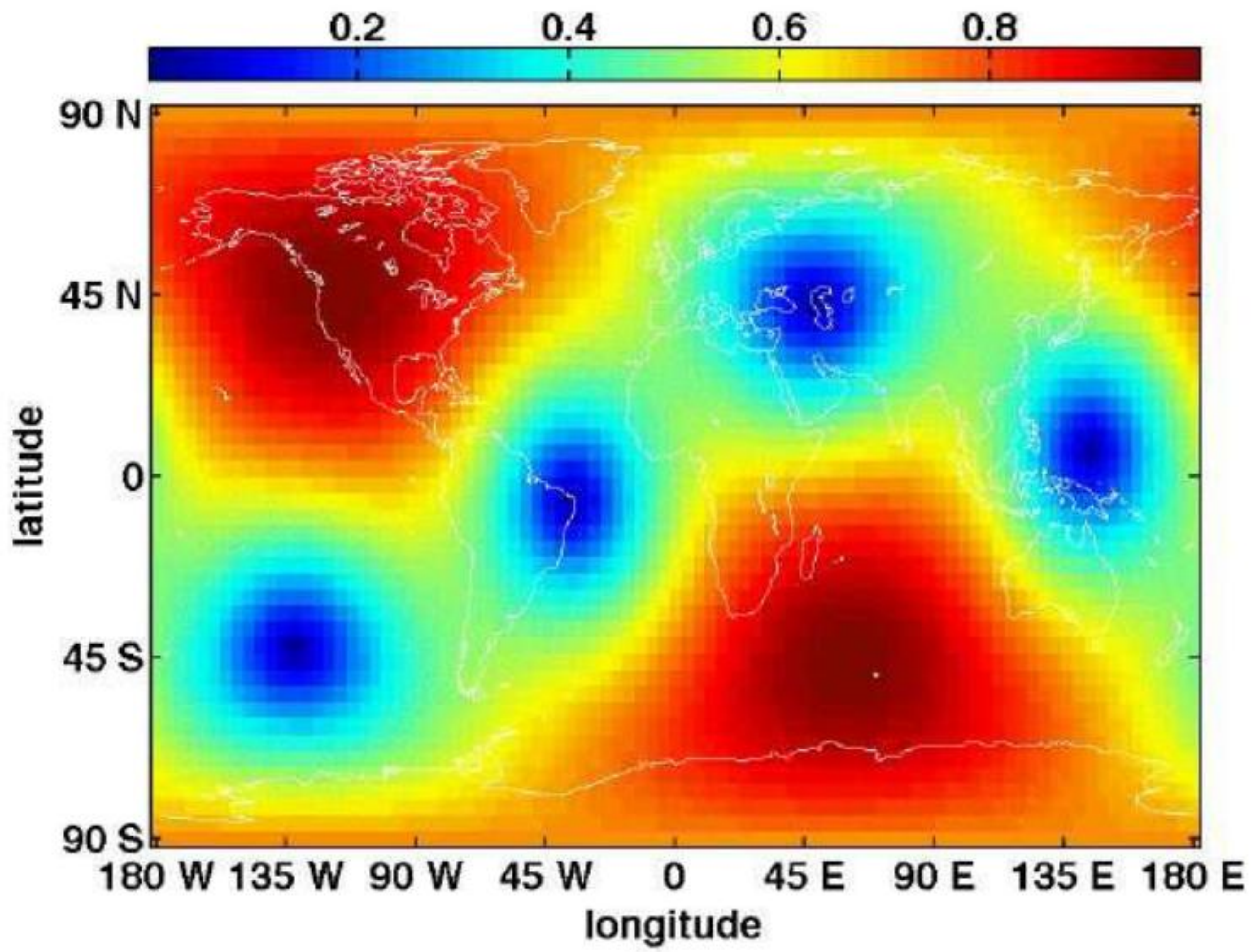
# Sky localisation

- $\frac{\Delta L}{L} \propto h_{\text{measured}}(t) = F_{+}(\theta, \phi) h_{+}(t) + F_{\times}(\theta, \phi) h_{\times}(t)$
- GW detector is an **all-sky monitor** with varying sensitivity
- No directional sensitivity

Credits: the LIGO-Virgo-KAGRA collaboration



$F_{+}$ $F_{\times}$ $\sqrt{F_{+}^{2} + F_{\times}^{2}}$

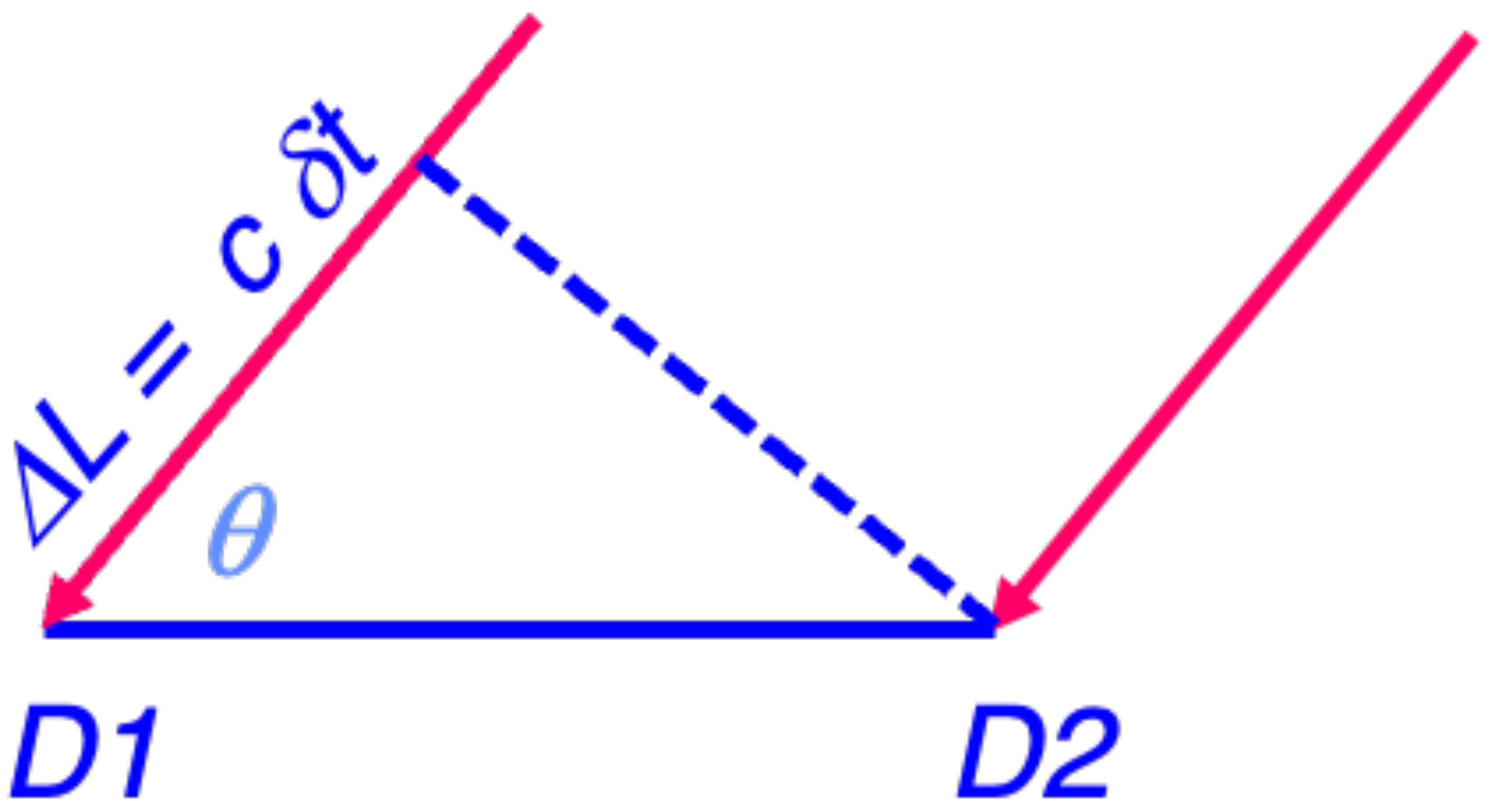


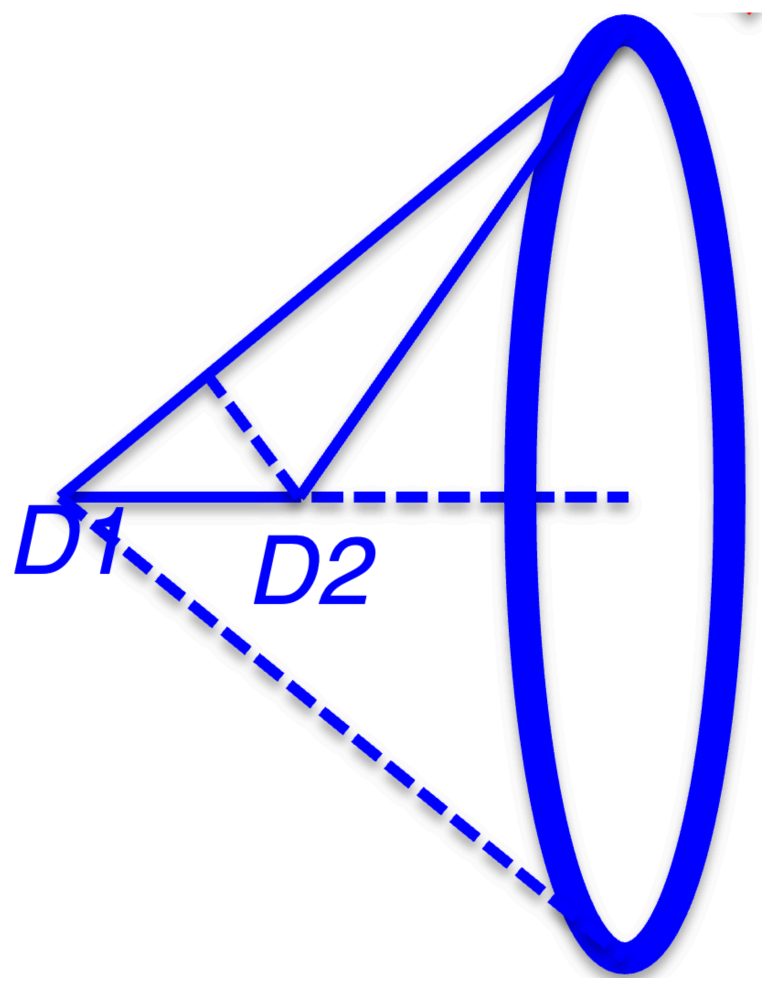

Credits: Hayama et al. 2012

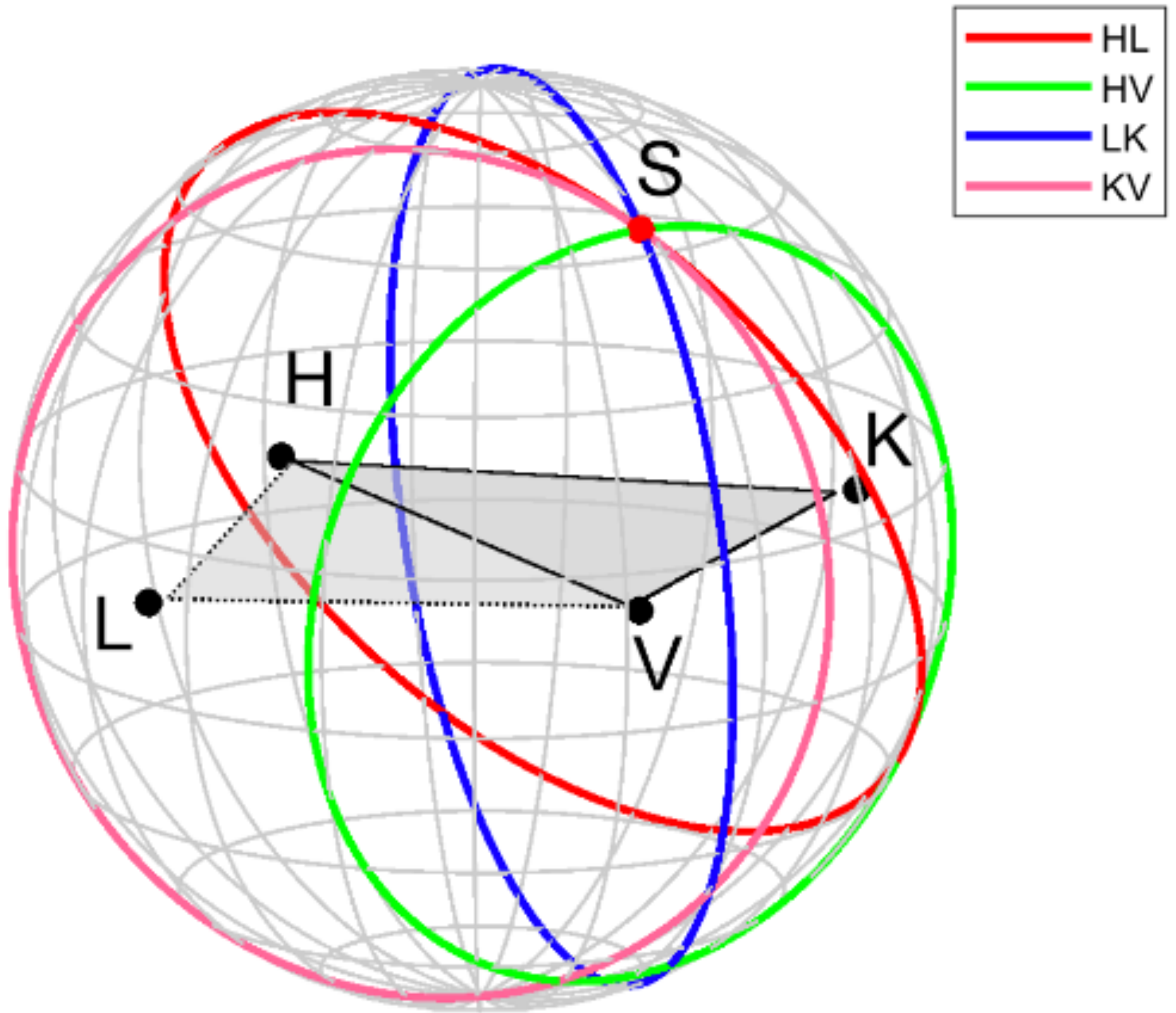
# Triangulation

- Sky position of GW sources is evaluated with triangulation
- Difference in the arrival time at the detectors
- $\Delta\Omega \propto SNR^{-2}$

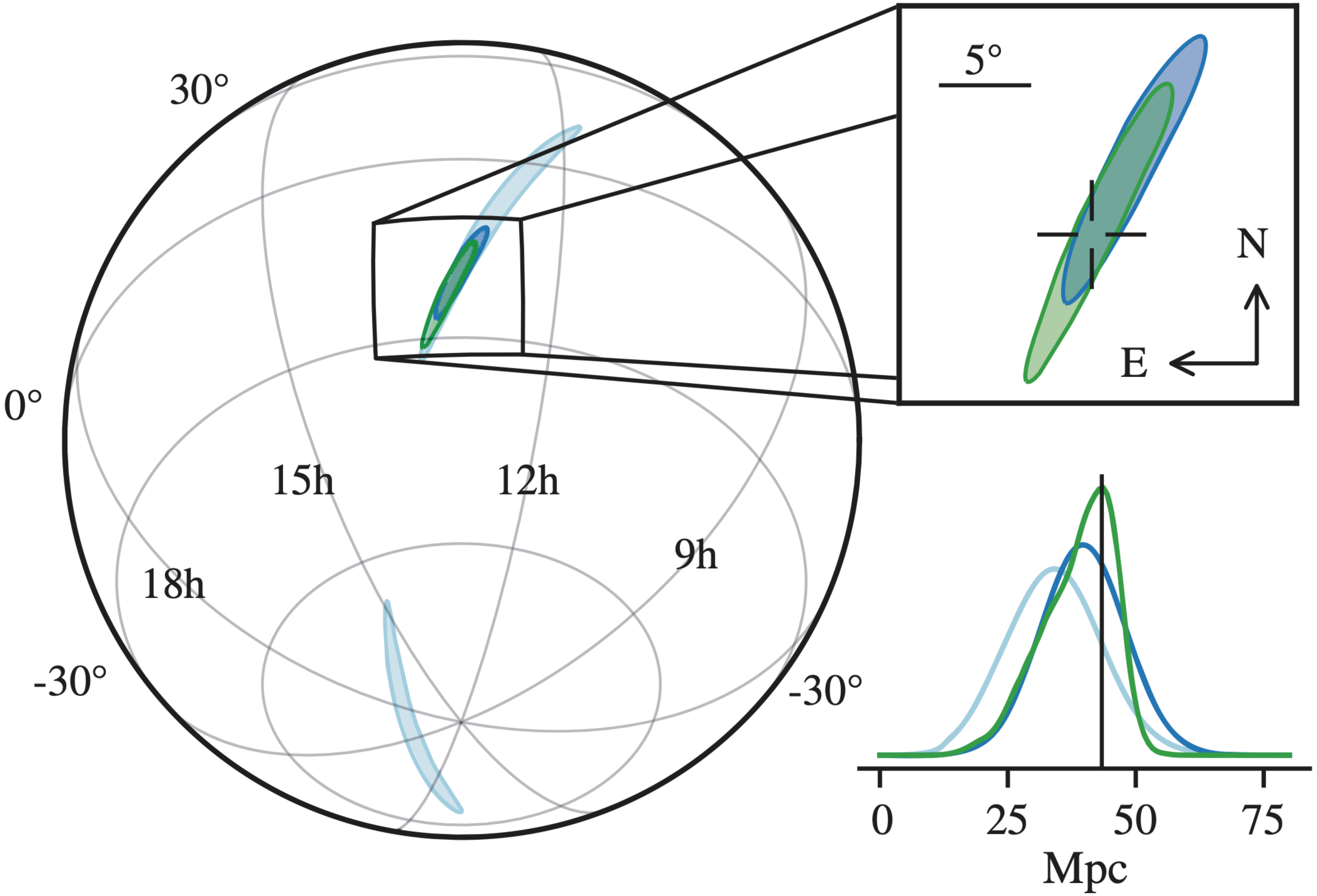
Credits: The LVK collaboration



# GW170817

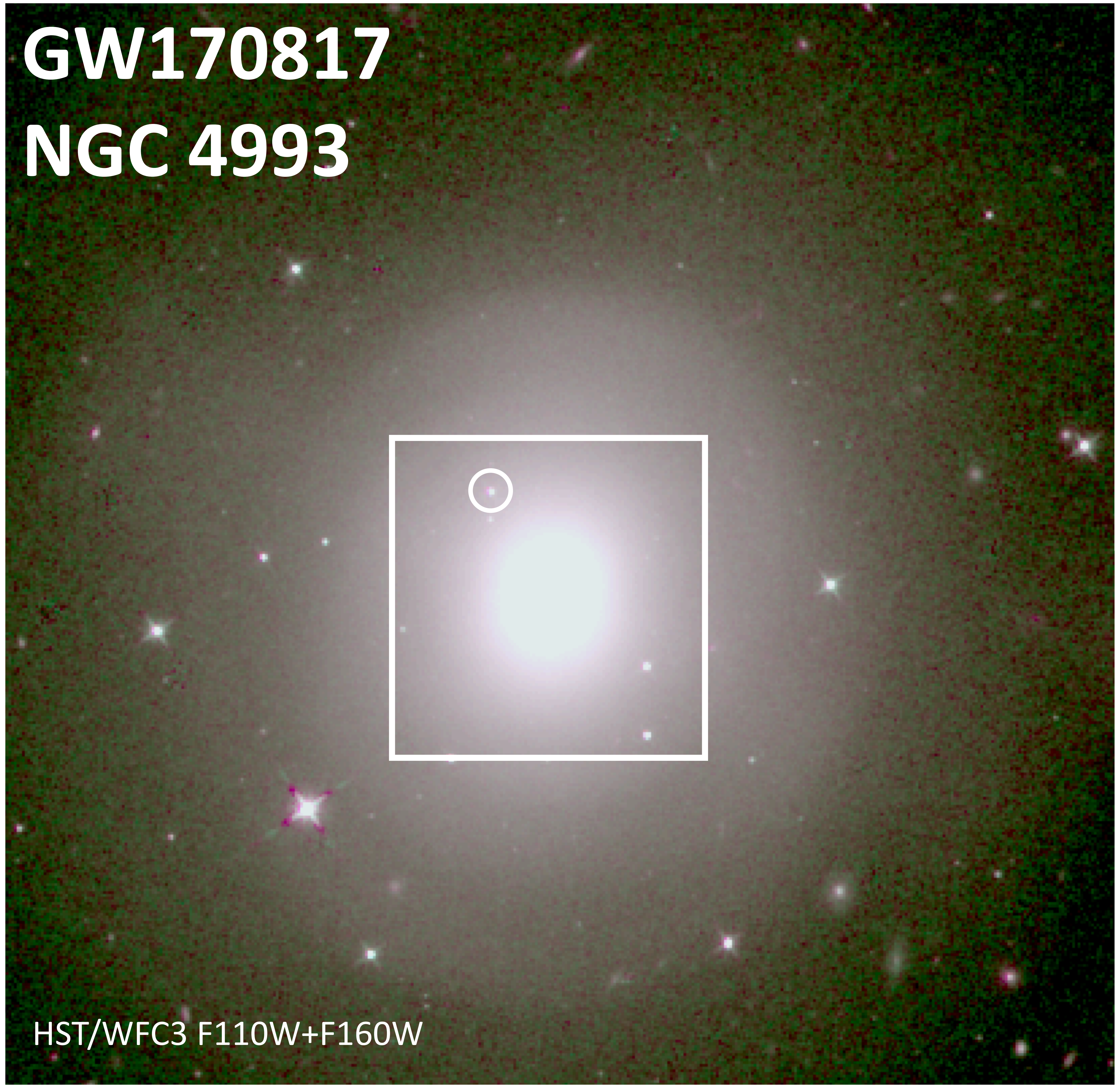





Credits: The LVK collaboration

# GW170817 host galaxy

- NGC4993, S0 galaxy
- $M_* \sim 10^{10.65}\ \mathrm{M}_\odot$
- $\mathrm{SFR} \sim 0.01\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$
- $z = 0.009783$
- Small natal kick velocity, no GC or YSC





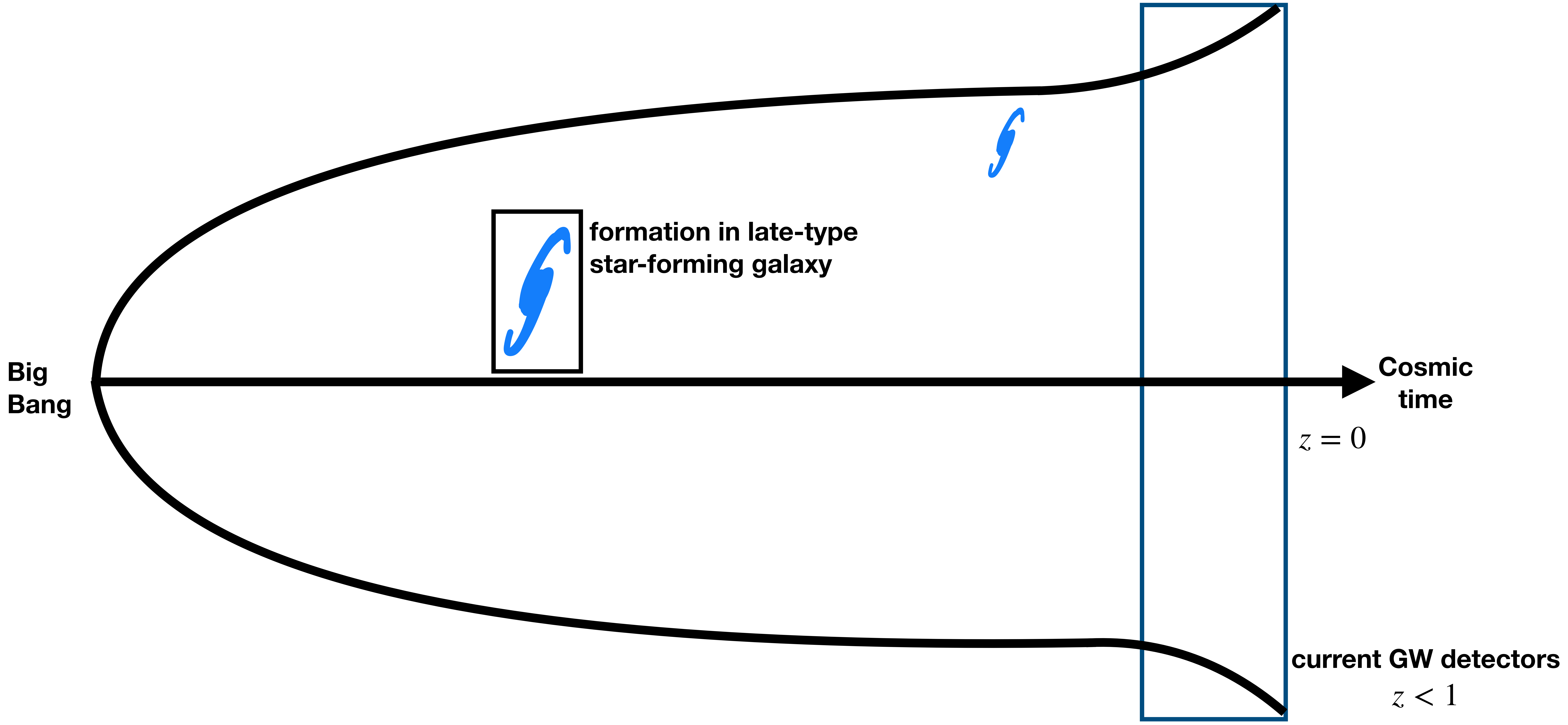

Refs: Levan et al. 2017, Blanchard et al. 2017

# How to model host galaxies

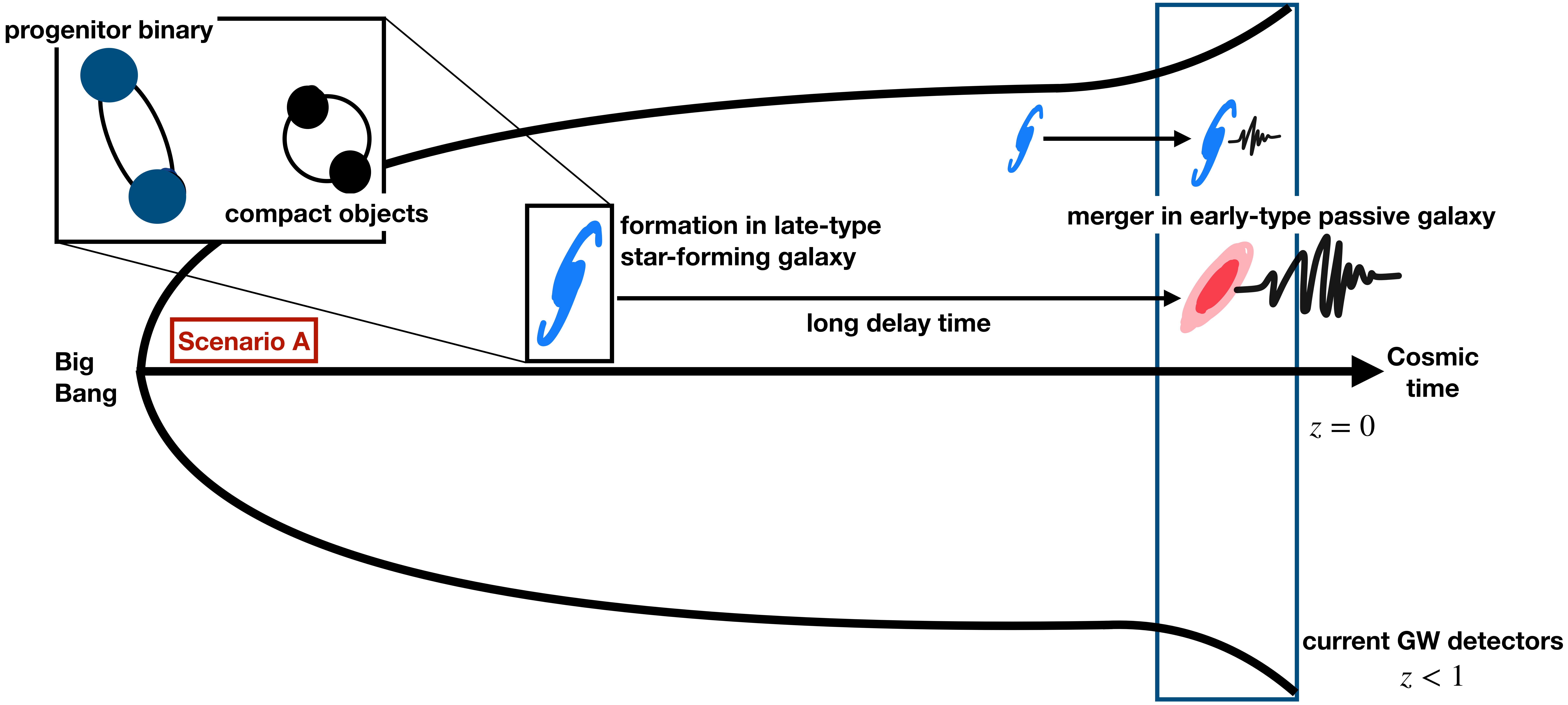
- **Challenge:** interfacing Physics at scales spanning orders of magnitude
    - Evolution of galaxies across history of the Universe and formation of compact object mergers at binary system level
- **Solution:** galaxy catalogs from cosmological simulations

Refs: Mapelli et al. 2017, Artale et al. 2019, Toffano et al. 2019, Artale et al. 2020, Chu et al. 2022, Perna et al. 2022

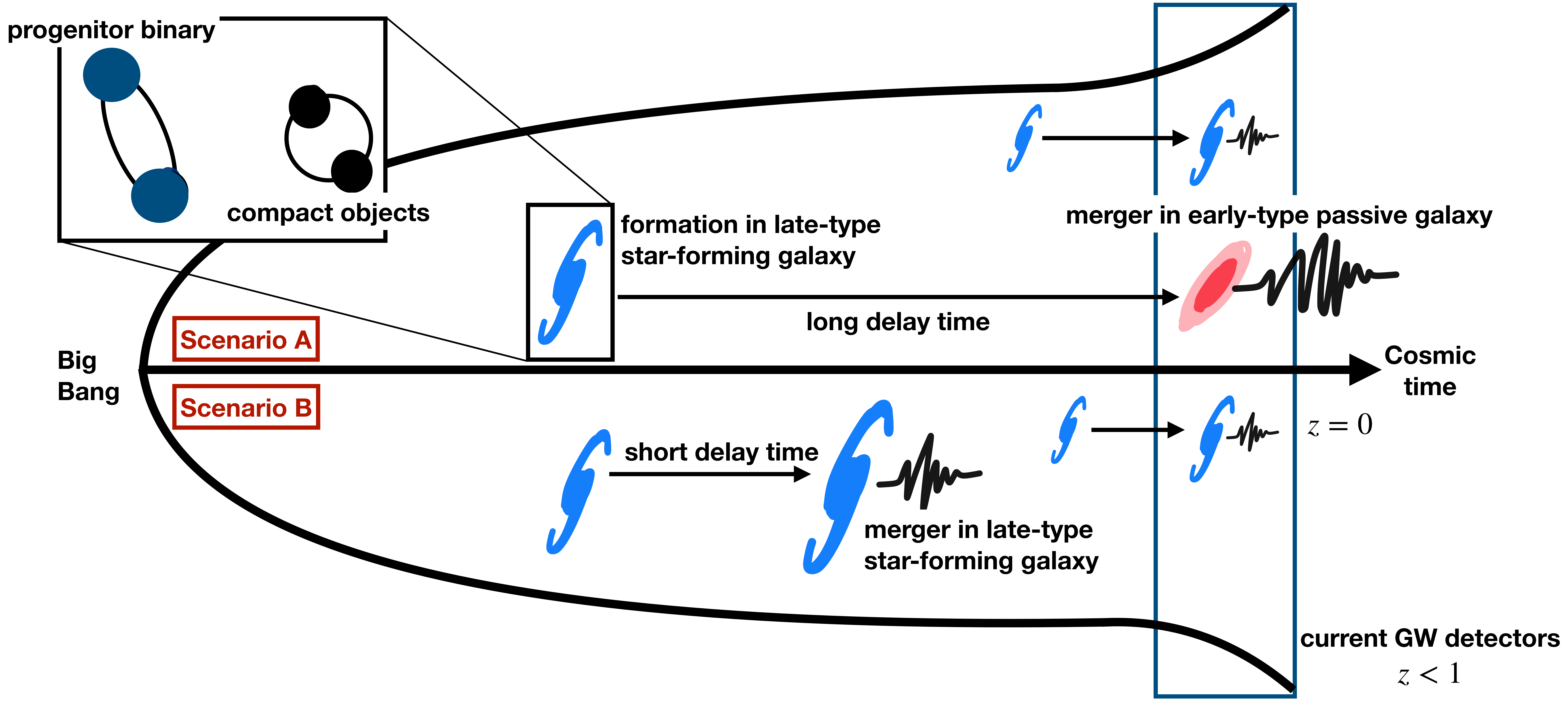
# How to model host galaxies



# How to model host galaxies



# How to model host galaxies



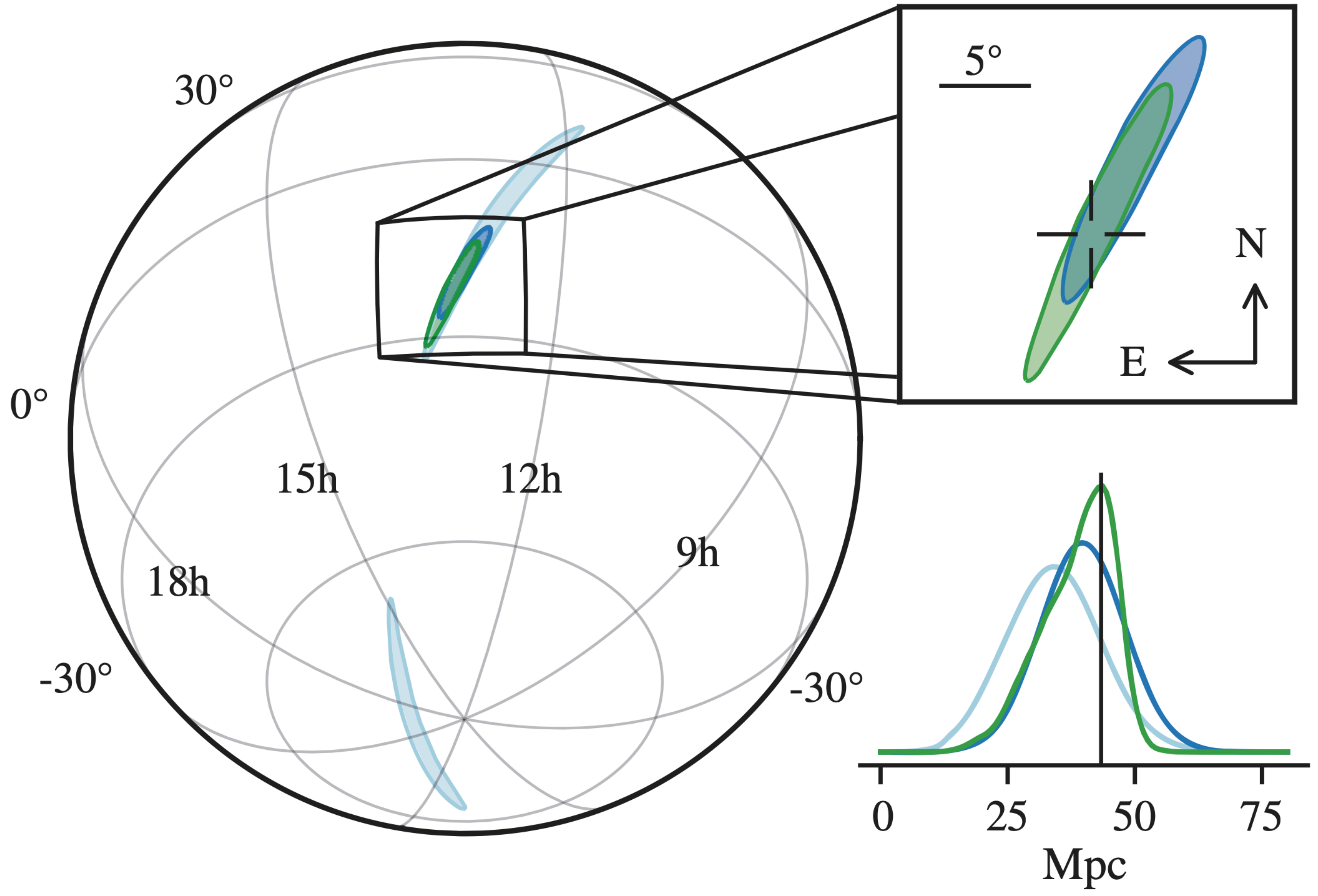
# Model to rank host galaxies

- $p(\text{galaxy}) \propto p(M, \text{SFR})\, p_{\text{loc}}(\text{galaxy})$
- $p(M, \text{SFR}) \propto N_{GW}/N_{\text{galaxies}}$
- $N_{GW}$ total number of mergers and $N_{\text{galaxies}}$ total number of galaxies at $(M, \text{SFR})$

Refs: Artale et al. 2020

# Model to rank host galaxies

- $p(\text{galaxy}) \propto p(M, \text{SFR})\, p_{\text{loc}}(\text{galaxy})$




- $p(M, \text{SFR}) \propto N_{GW}/N_{\text{galaxies}}$
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Refs: Artale et al. 2020



Credits: The LVK collaboration

# Model to rank host galaxies

- $p(\text{galaxy}) \propto p(M, \text{SFR})\, p_{\text{loc}}(\text{galaxy})$ →
- $p(M, \text{SFR}) \propto N_{GW}/N_{\text{galaxies}}$
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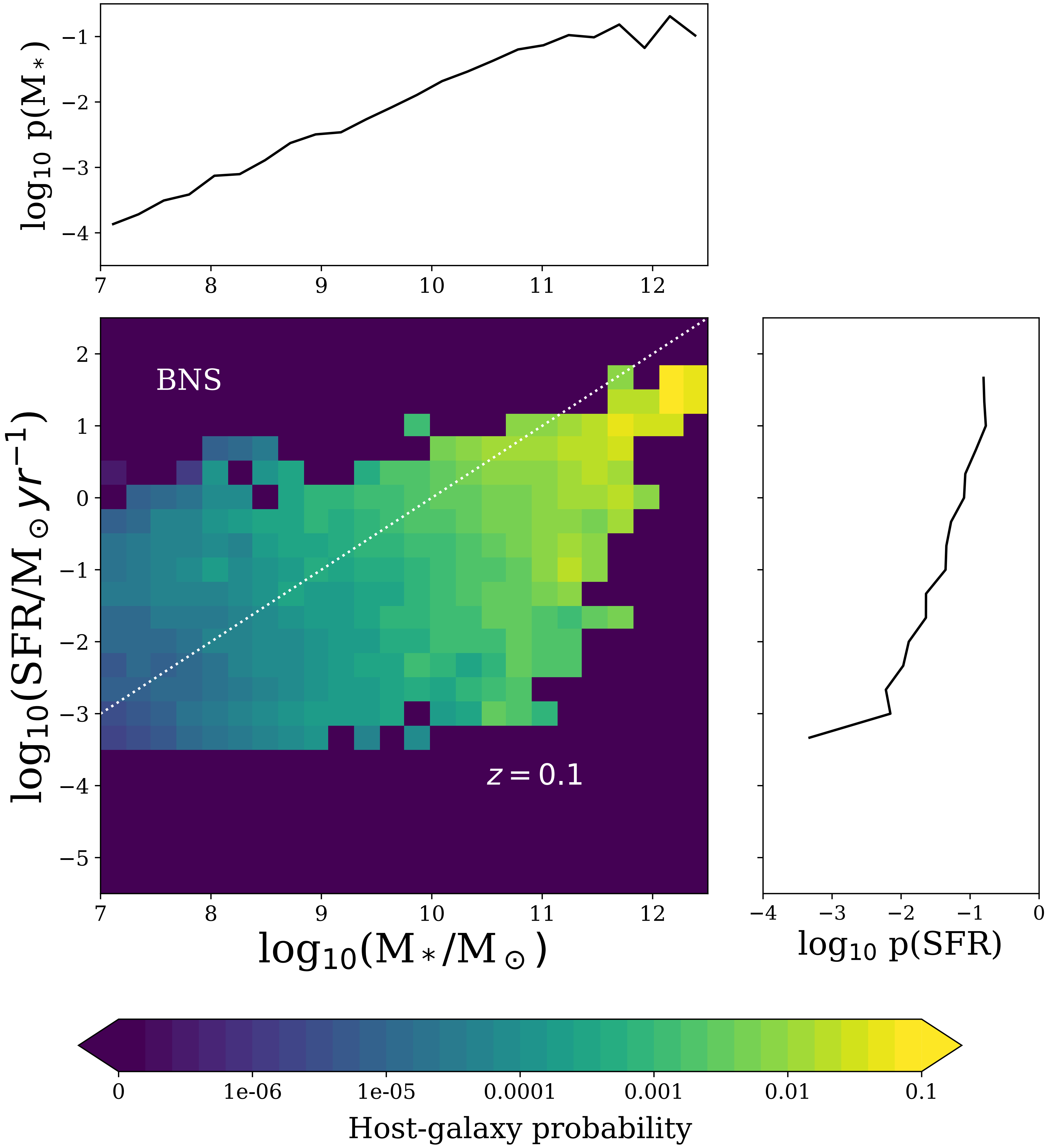



**Do you see a strong correlation in $p(M, \text{SFR})$?**

Refs: Artale et al. 2020

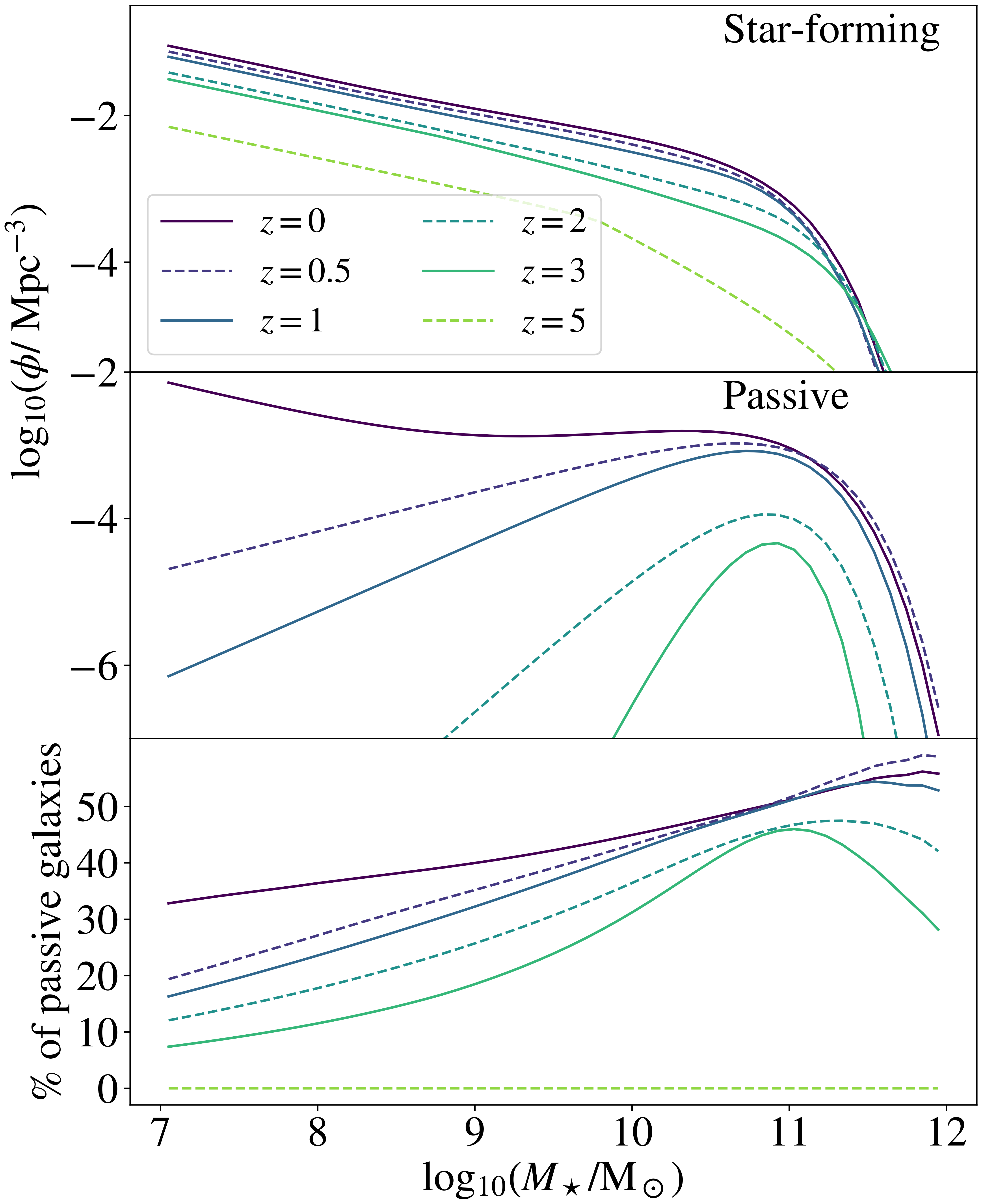
# Uncertainties

- alternative approach: **`galaxyRate`**
- We explore the **parameter space** to look for the **key physical processes** shaping host galaxy properties:
  - Stellar mass
  - Star formation rate
  - Metallicity



Refs: Santoliquido et al. 2022

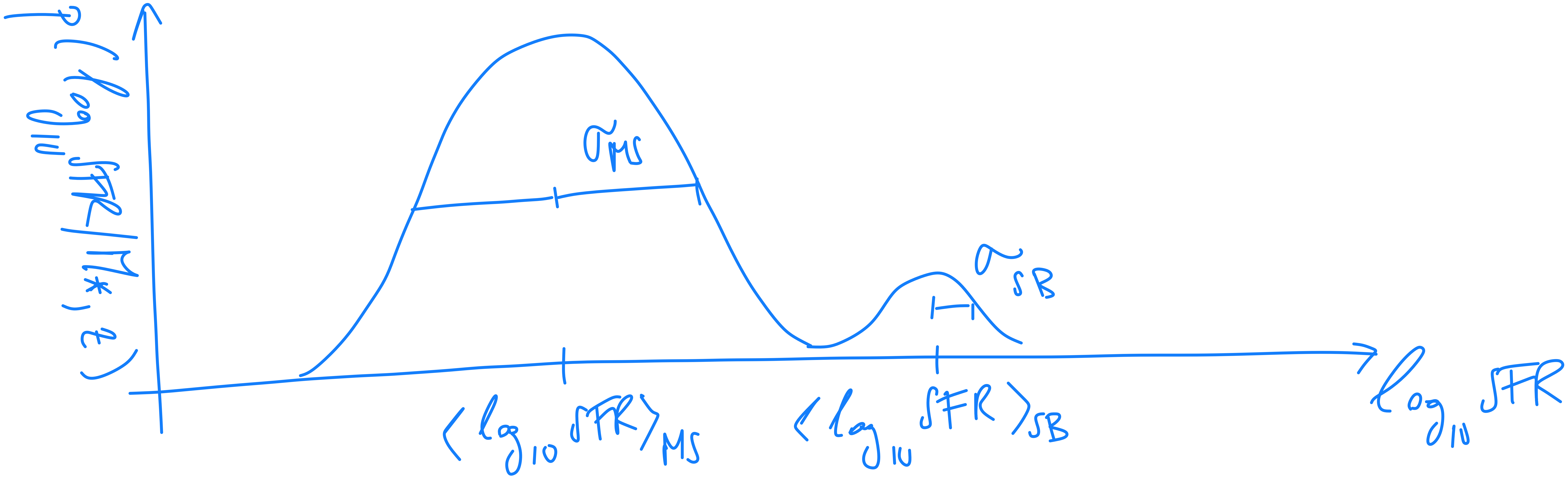
# Galaxy Stellar Mass Function




Refs: Chruslinska & Nelemans 2019, Ilbert et al. 2013, Santoliquido et al. 2022

# SFR main sequence

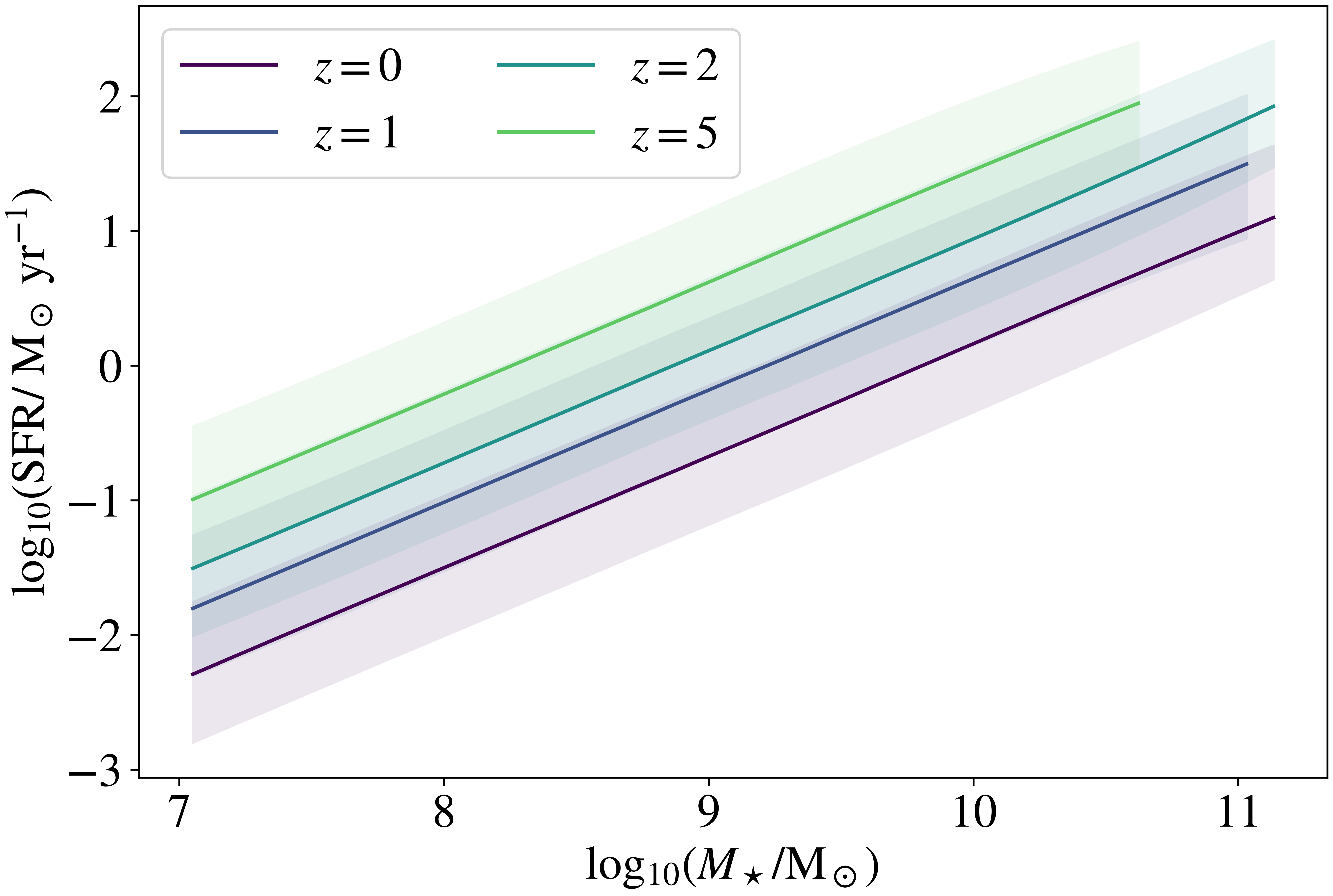
- $p(\log_{10}\mathrm{SFR}\,|\,M_*, z) = A_{\mathrm{MS}} \exp - \dfrac{(\log_{10}\mathrm{SFR} - \langle \log_{10}\mathrm{SFR}\rangle_{\mathrm{MS}})^2}{2\sigma_{\mathrm{MS}}^2} + A_{\mathrm{SB}} \exp - \dfrac{(\log_{10}\mathrm{SFR} - \langle \log_{10}\mathrm{SFR}\rangle_{\mathrm{SB}})^2}{2\sigma_{\mathrm{SB}}^2}$
- $\langle \log_{10}\mathrm{SFR}\rangle_{MS} = 0.83 \log_{10}\left(\dfrac{M_*}{M_0}\right) - 0.83 + 1.74\left(\dfrac{1+z}{1+z_0}\right)$





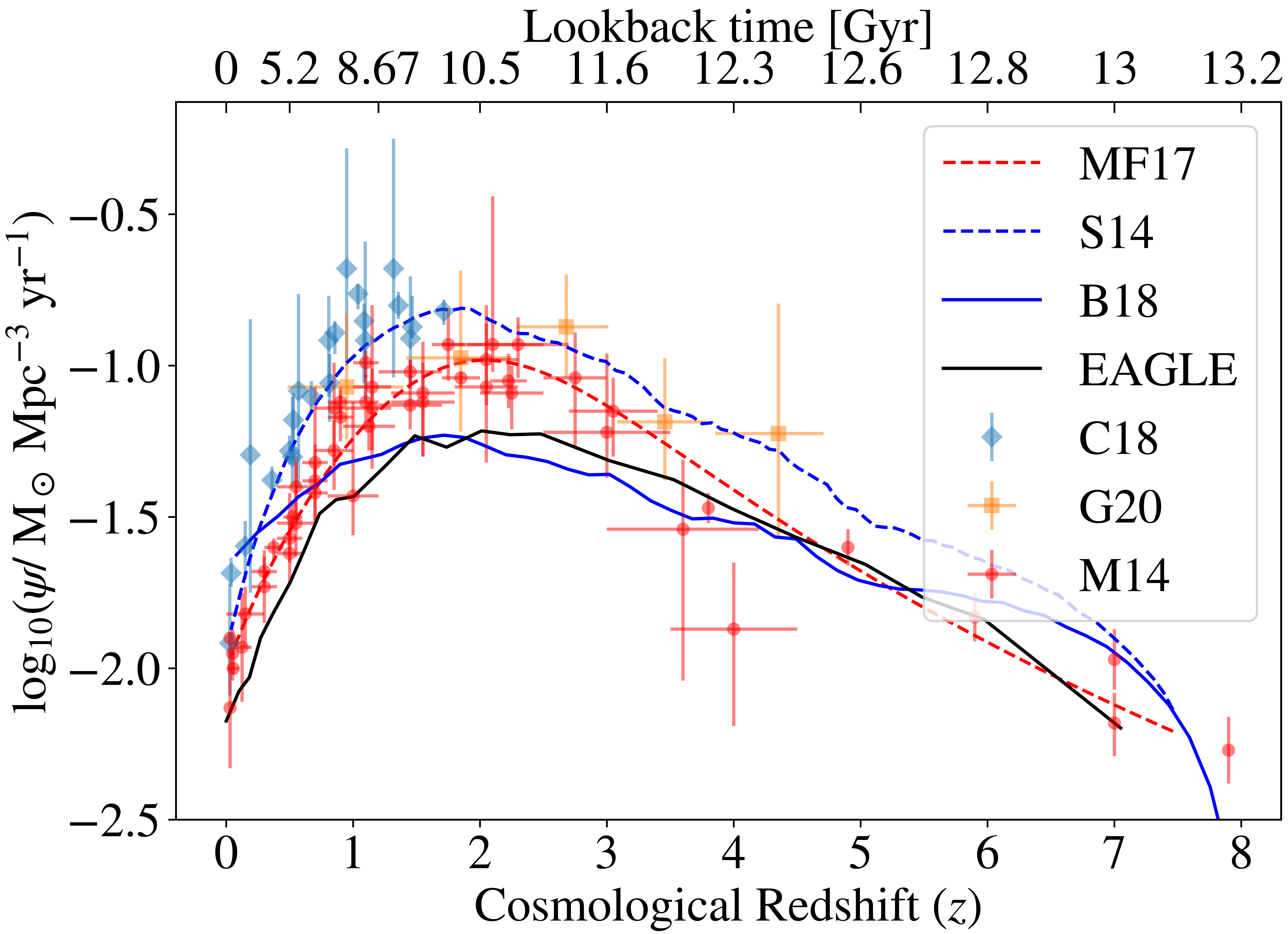

Refs: Boco et al. 2021, Boogaard et al. 2018

# SFR main sequence




Refs: Boco et al. 2021, Boogaard et al. 2018

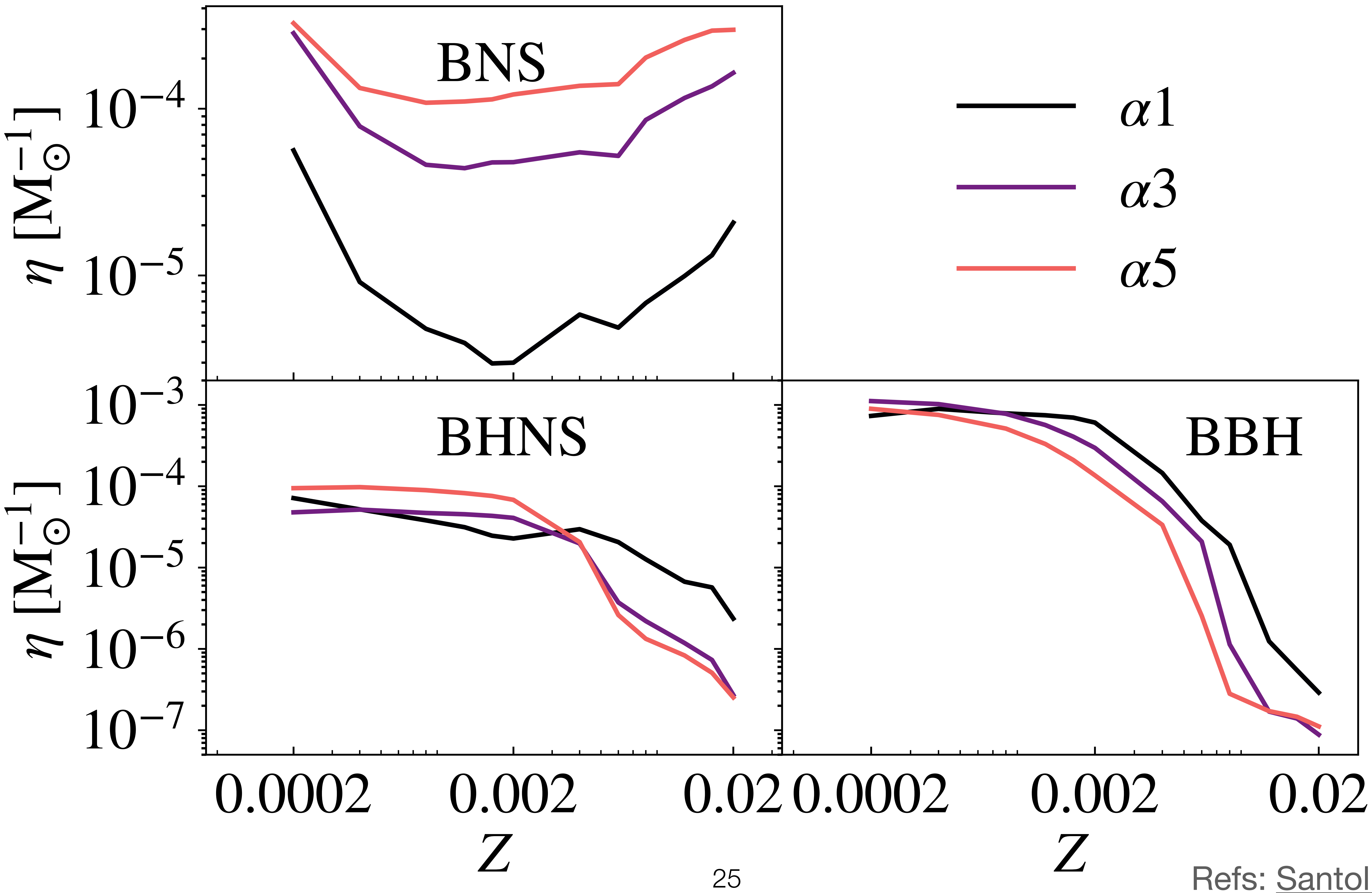
# SFR($z$)




Refs: Speagle et al. 2014, Boogaard et al. 2018, Madau and Fragos 2017, Schaye et al 2015

# Do you remember metallicity impact on compact object formation?

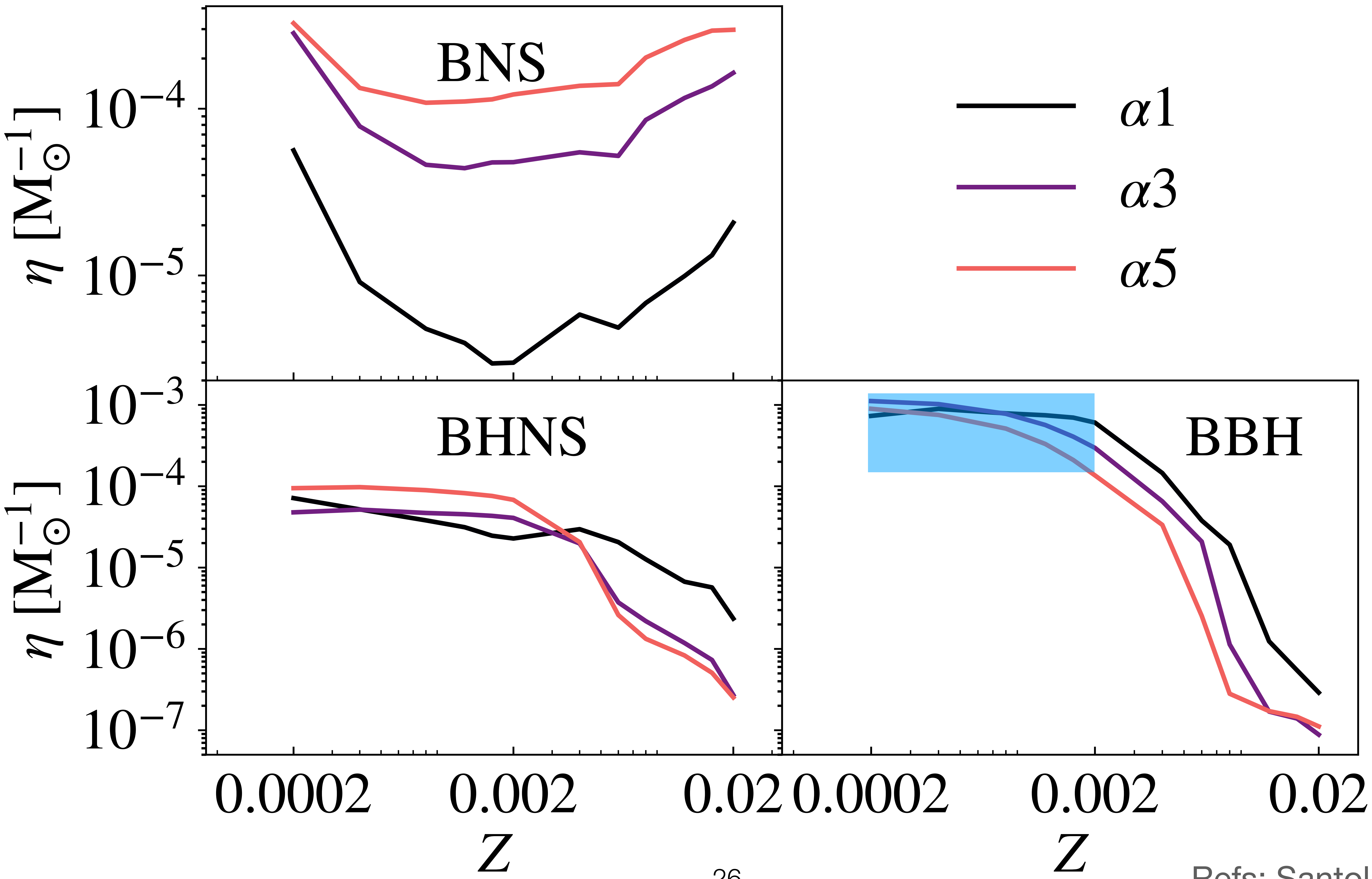
# Merger efficiency





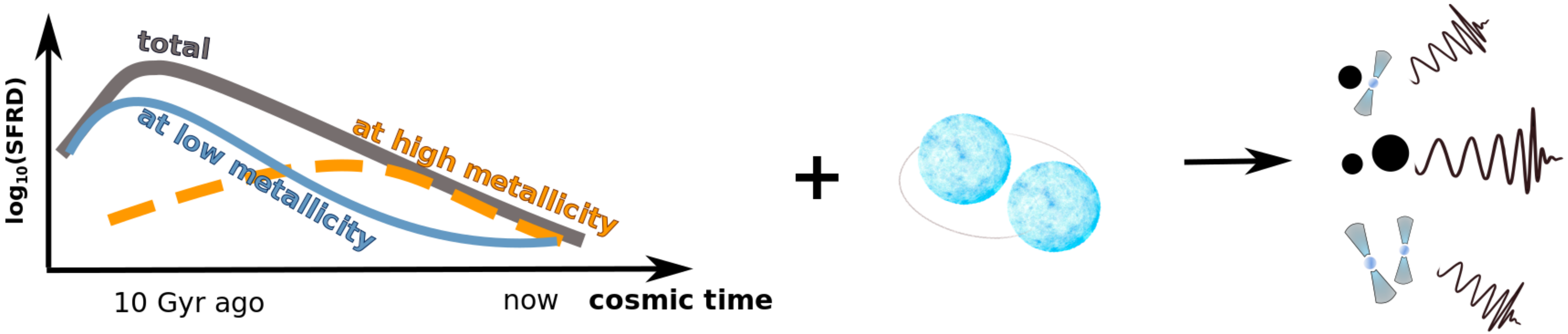

Refs: Santoliquido et al. 2022

# Merger efficiency




Refs: Santoliquido et al. 2022

# Impact of metallicity




number and metallicity of stars formed at different times

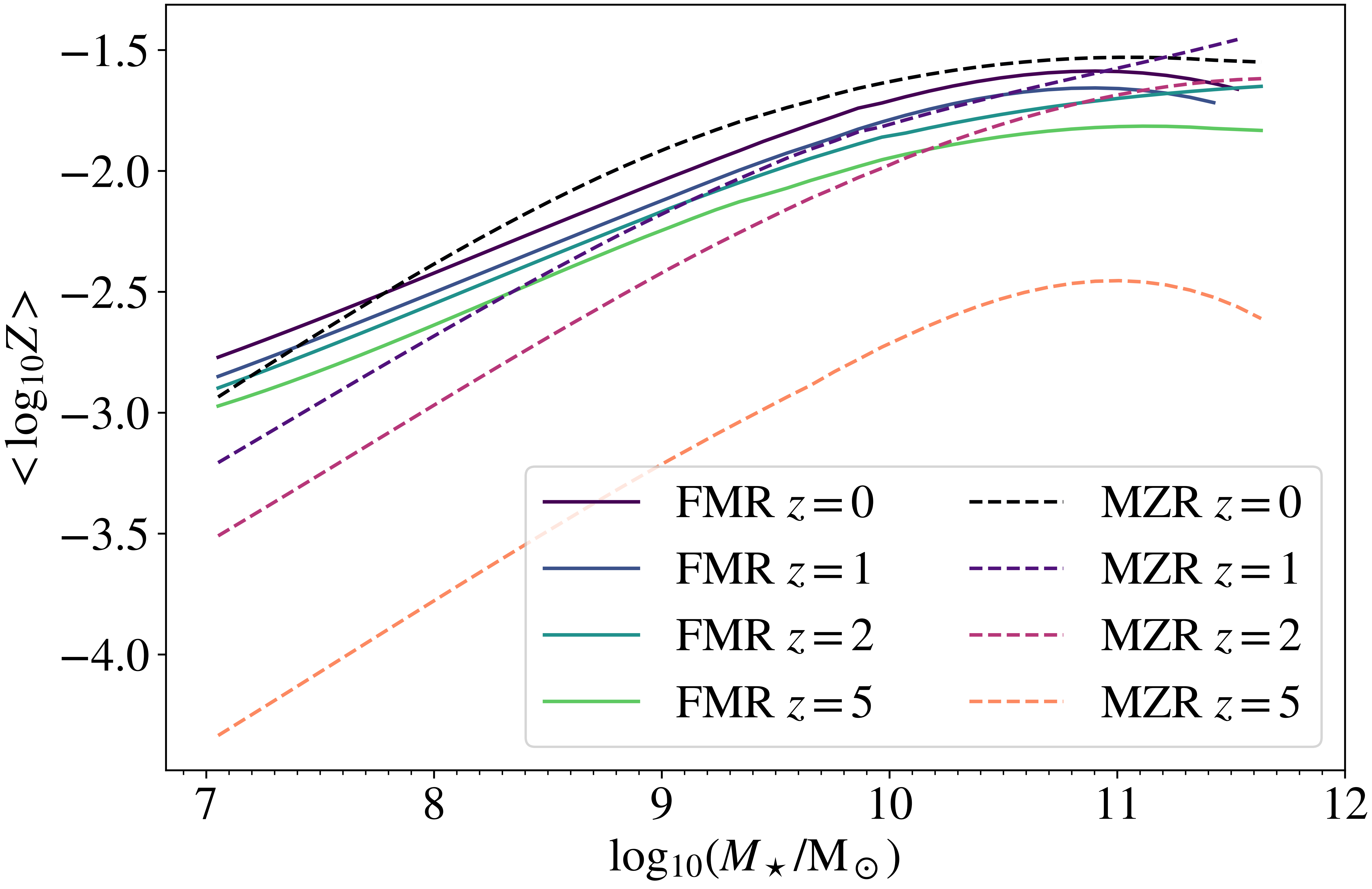
evolution of massive stars and binaries

population of GW sources



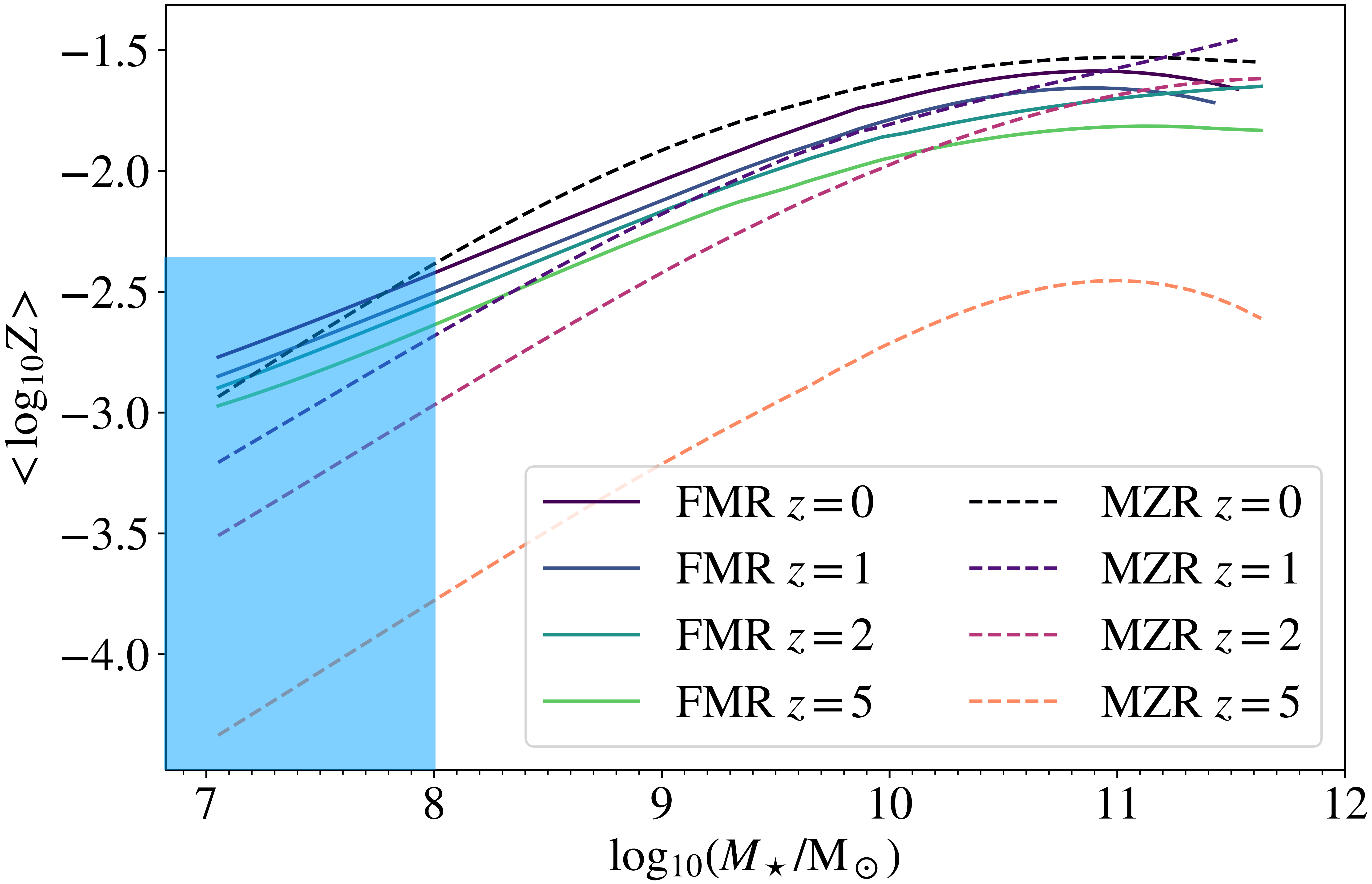
Credits: Chruślinska 2022

# Metallicity distribution



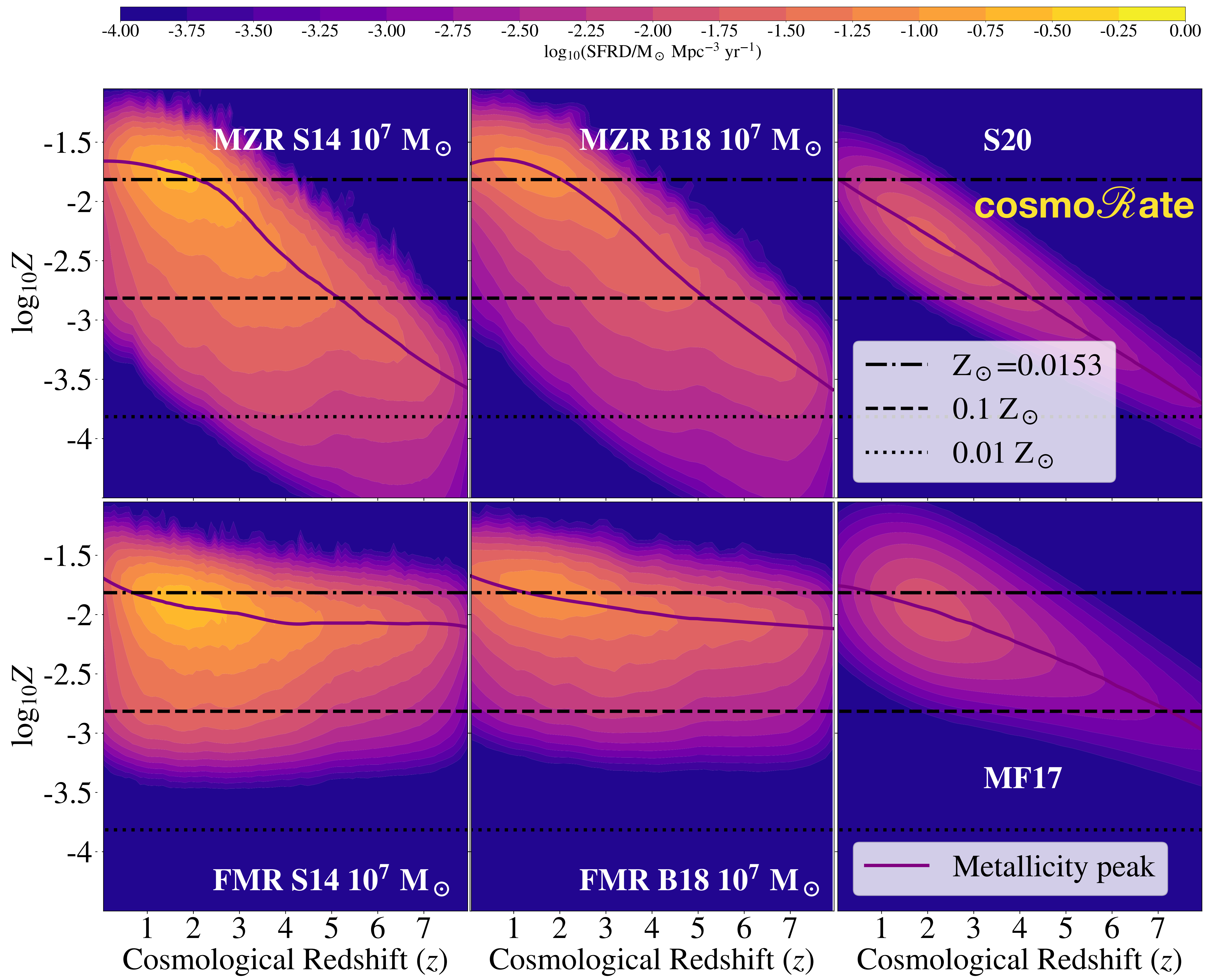

Refs: Mannucci et al. 2011, Chruslinska & Nelemans 2019, Curti et al. 2020,

# Metallicity distribution




Refs: Mannucci et al. 2011, Chruslinska & Nelemans 2019, Curti et al. 2020,

# SFRD$(z, Z)$

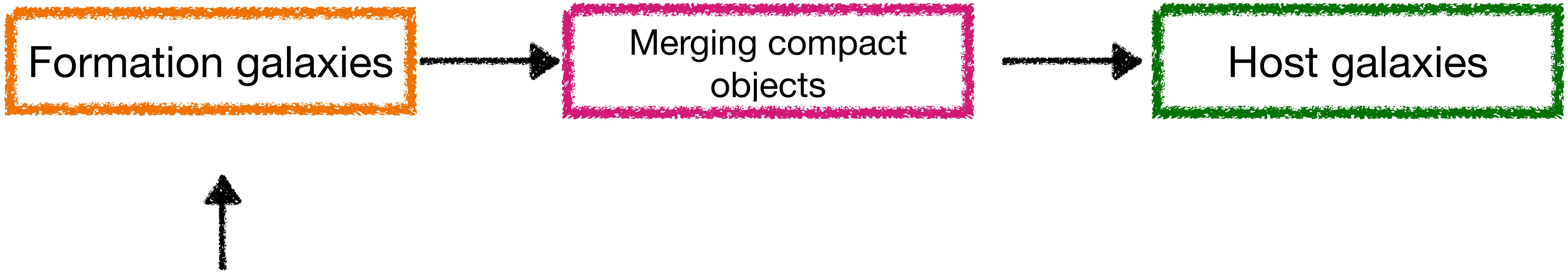





Refs: Santoliquido et al. 2022

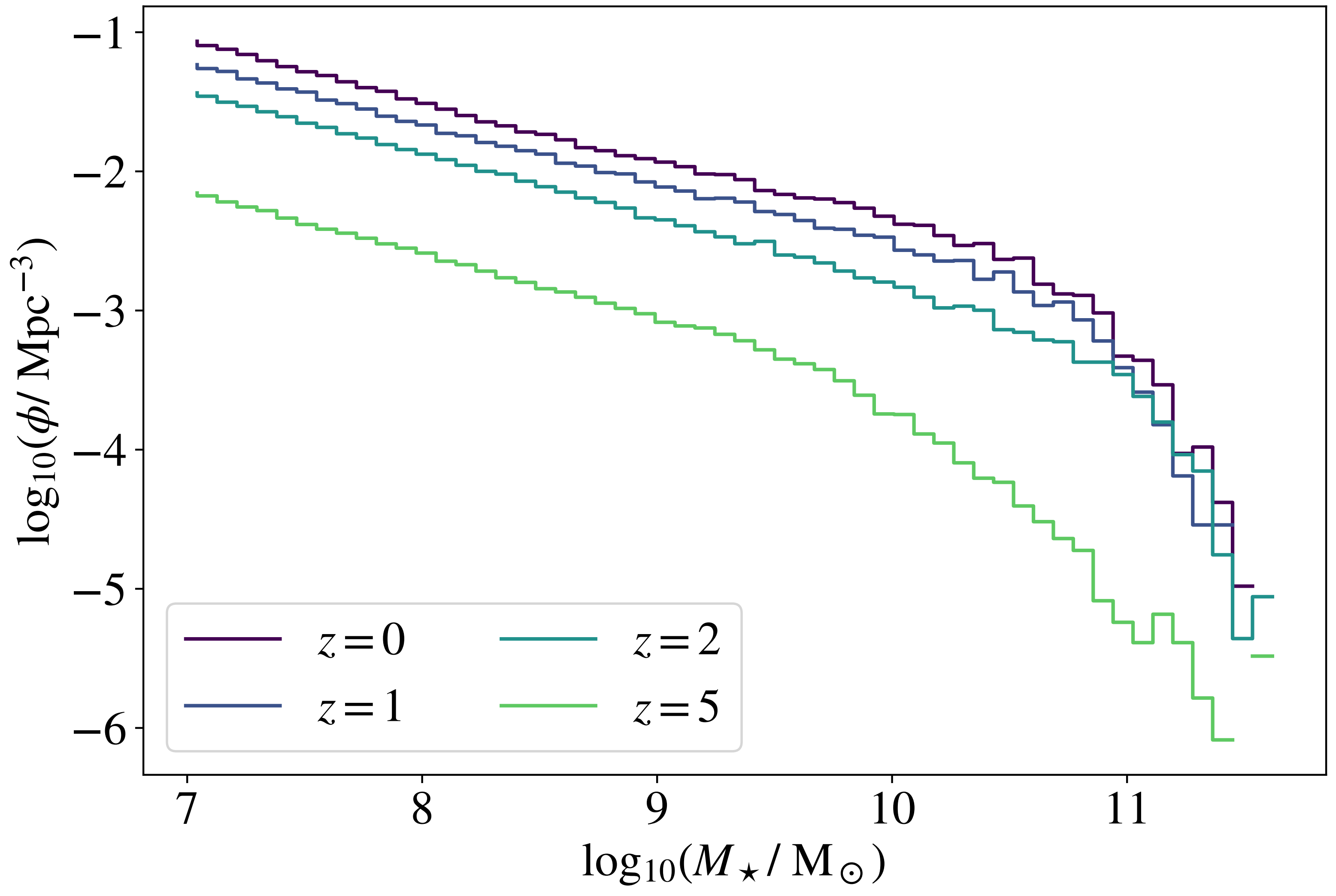
# galaxyRate


Formation galaxies
Merging compact objects
Host galaxies

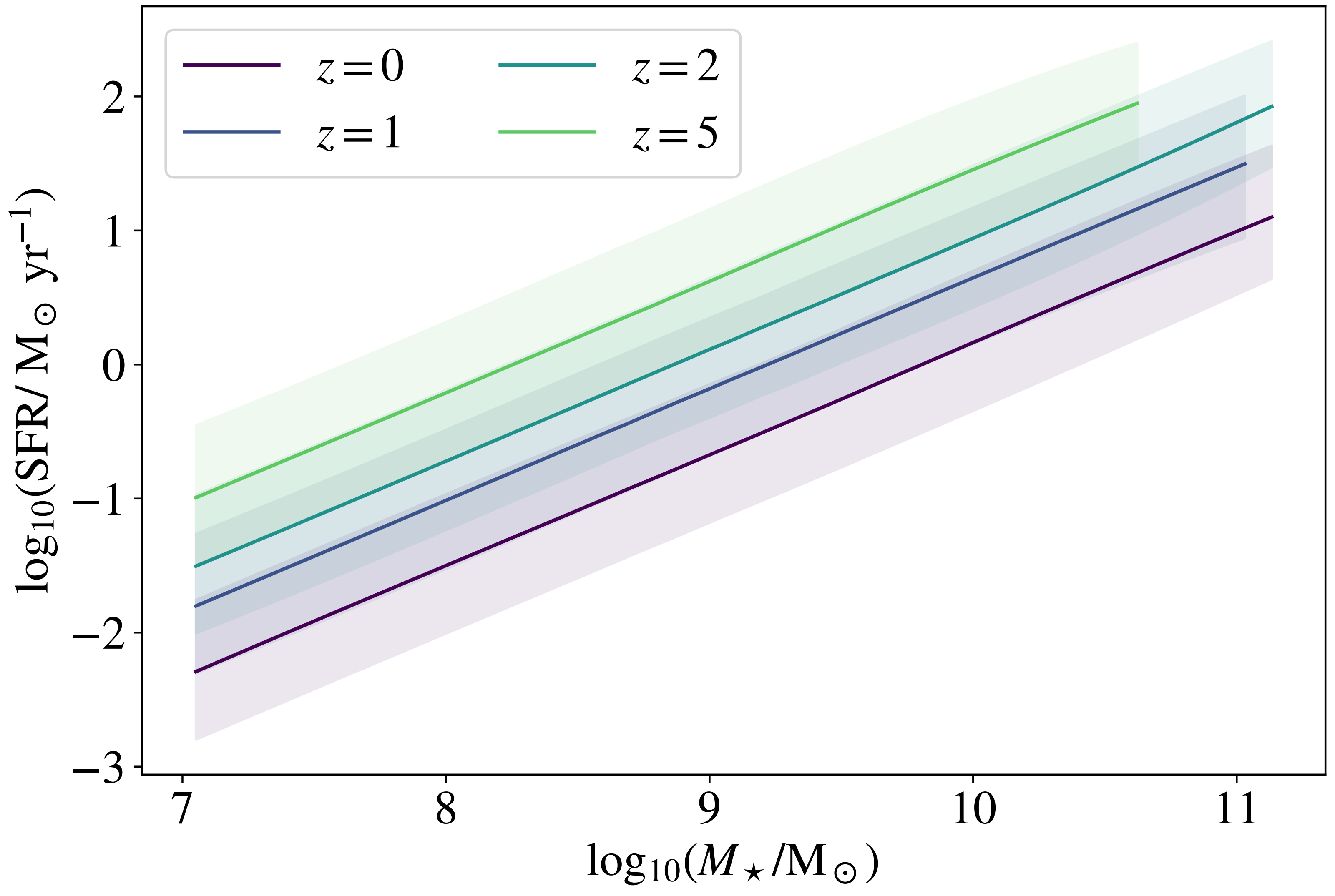



Population of star-forming galaxies from **observational scaling relations**

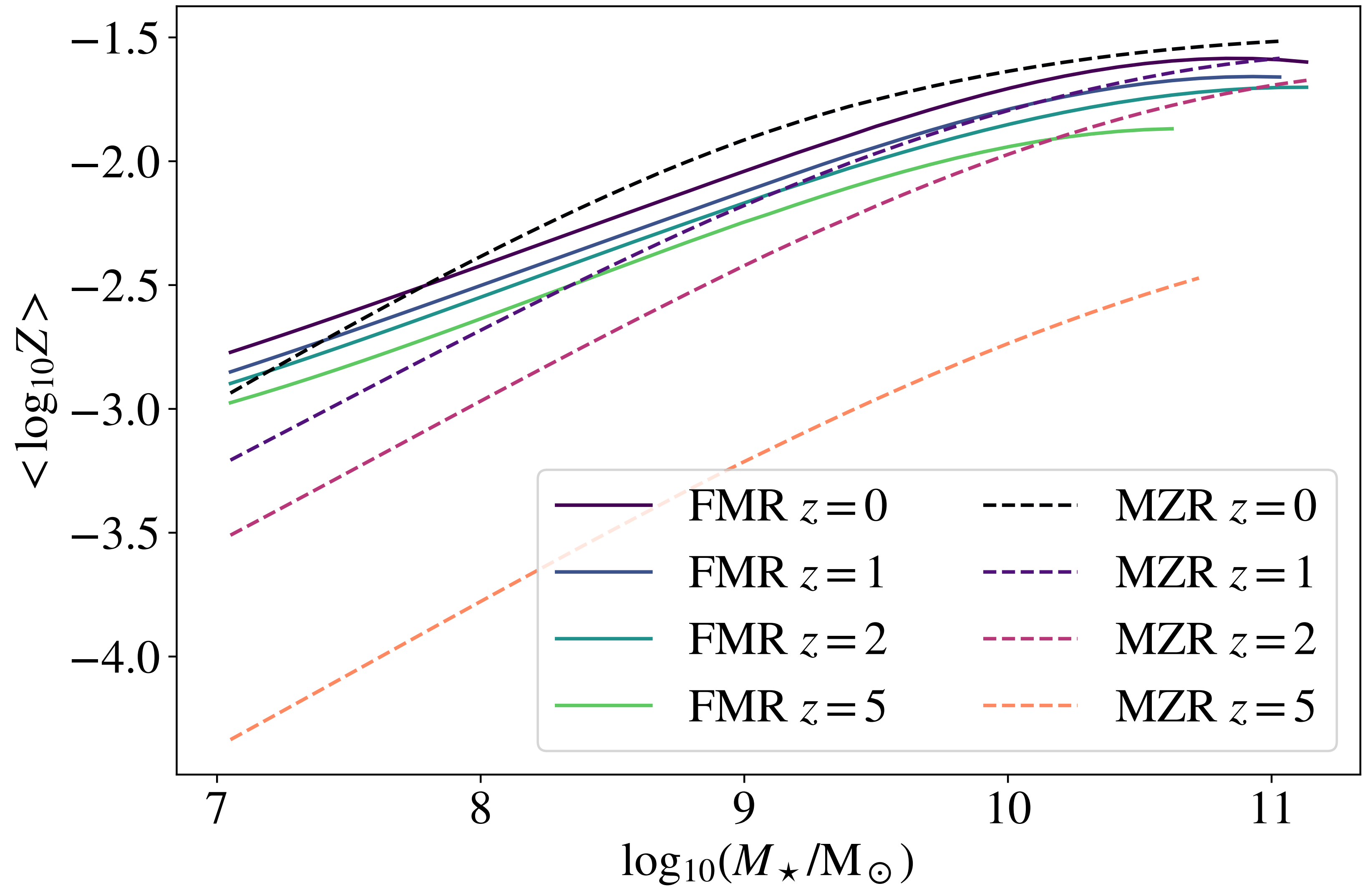
## Stellar mass



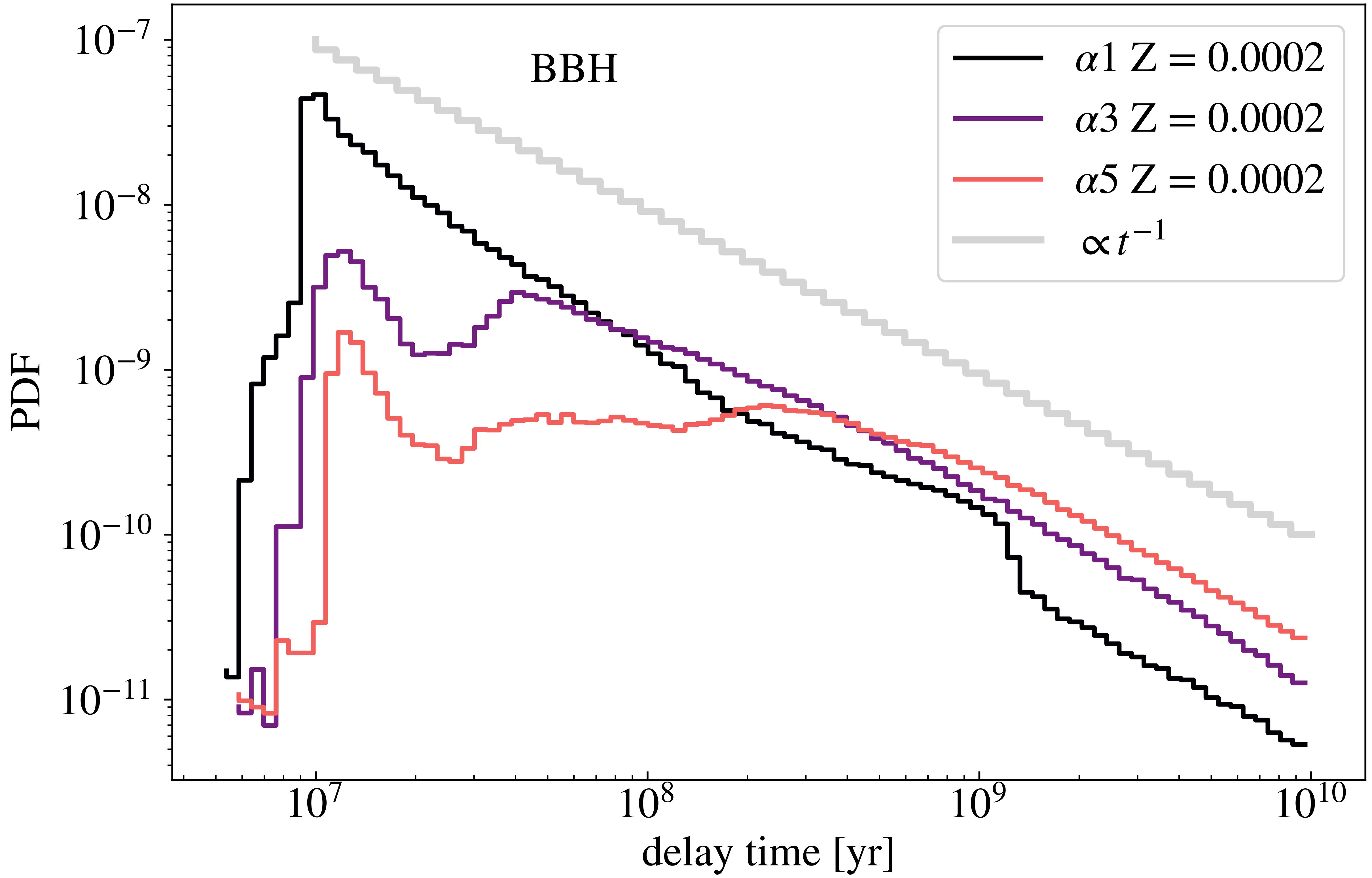

## Star-formation rate




## Metallicity

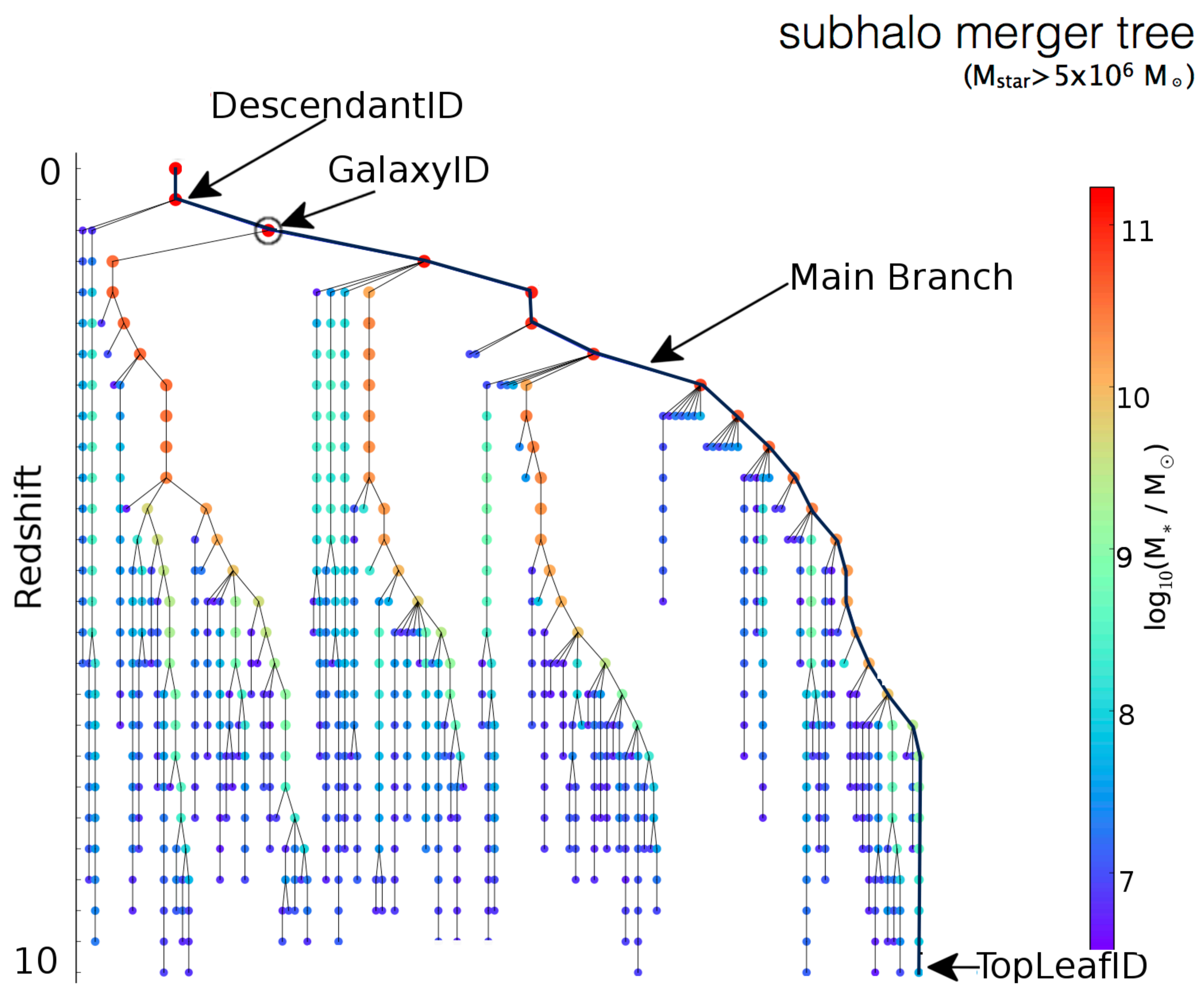


Formation galaxies → Merging compact objects → Host galaxies



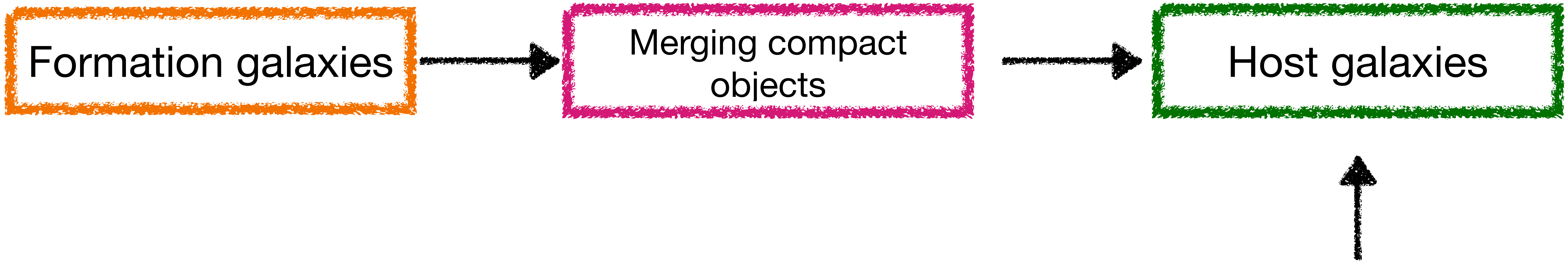

Effect of common envelope on delay time

Formation galaxies → Merging compact objects → Host galaxies



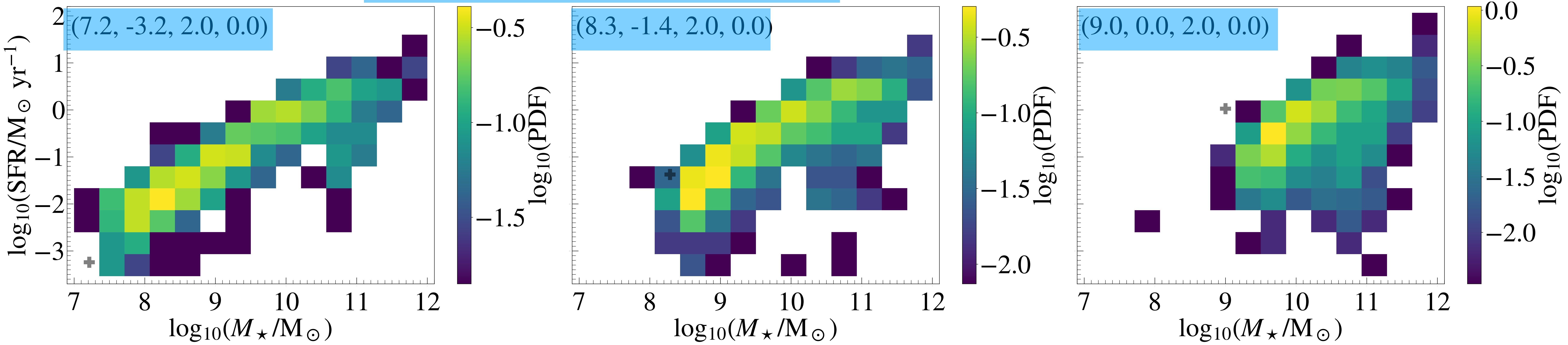


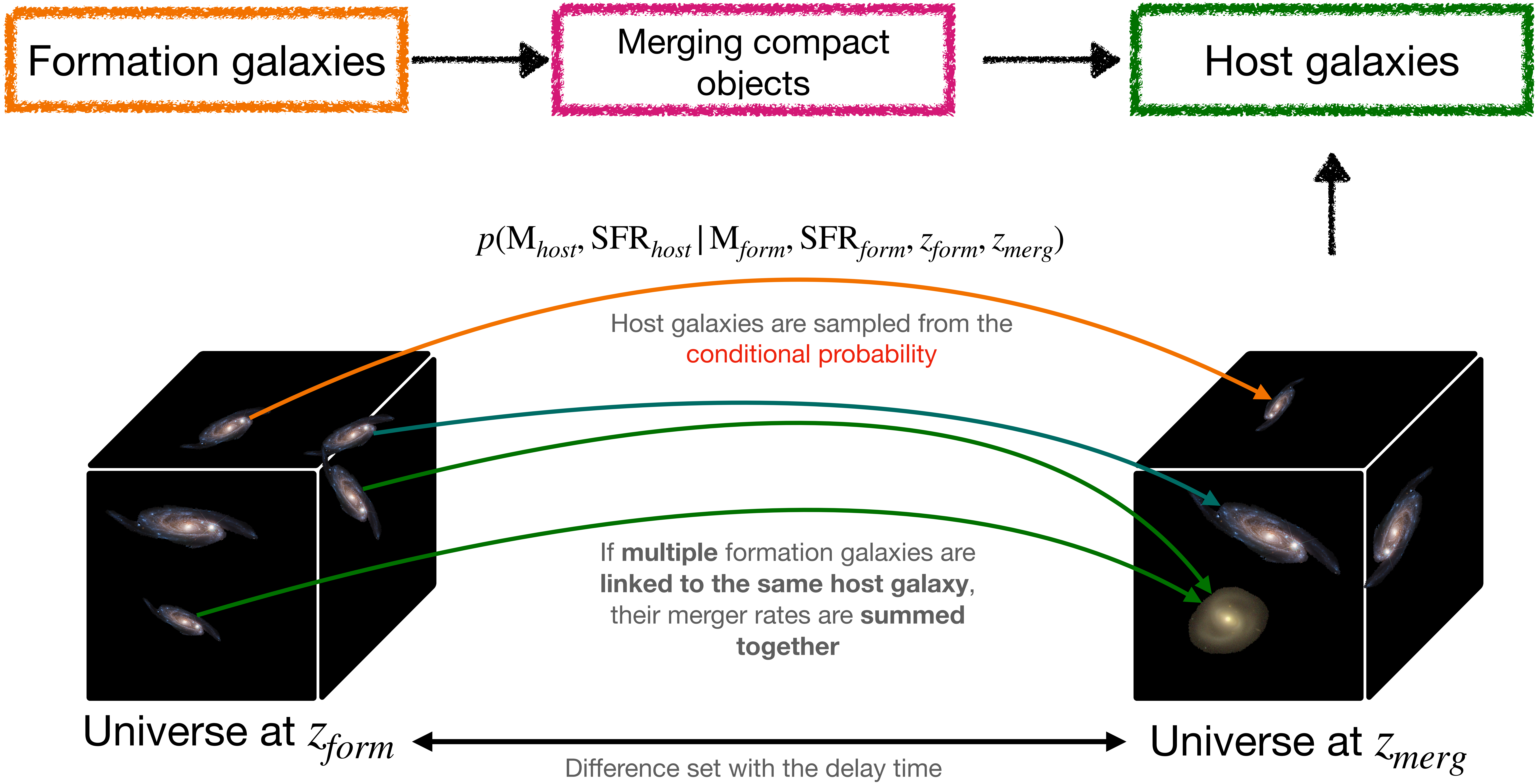

Refs: Schaye et al. 2015, McAlpine et al. 2016




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

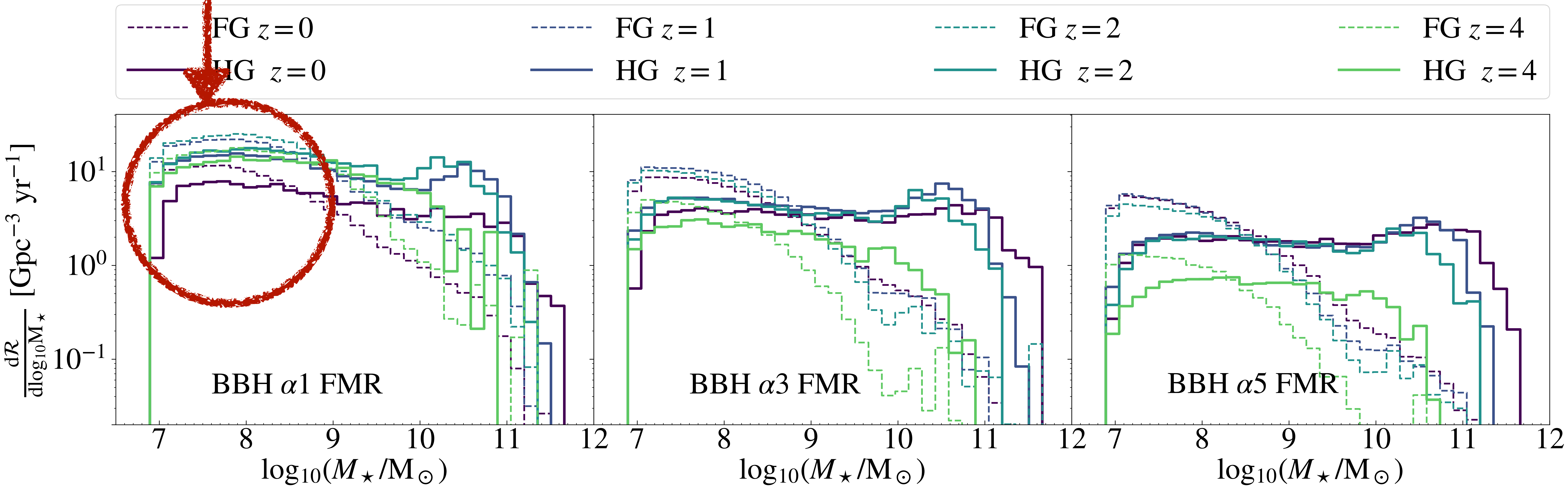
$$p(\mathrm{M}_{host}, \mathrm{SFR}_{host} \,|\, \mathrm{M}_{form}, \mathrm{SFR}_{form}, z_{form}, z_{merg})$$




Formation galaxies
Merging compact objects
Host galaxies
$p(\mathrm{M}_{host}, \mathrm{SFR}_{host} \mid \mathrm{M}_{form}, \mathrm{SFR}_{form}, z_{form}, z_{merg})$
Host galaxies are sampled from the conditional probability
If **multiple** formation galaxies are **linked to the same host galaxy**, their merger rates are **summed together**
Universe at $z_{form}$
Universe at $z_{merg}$
Difference set with the delay time

# `galaxyRate`: host galaxy stellar mass

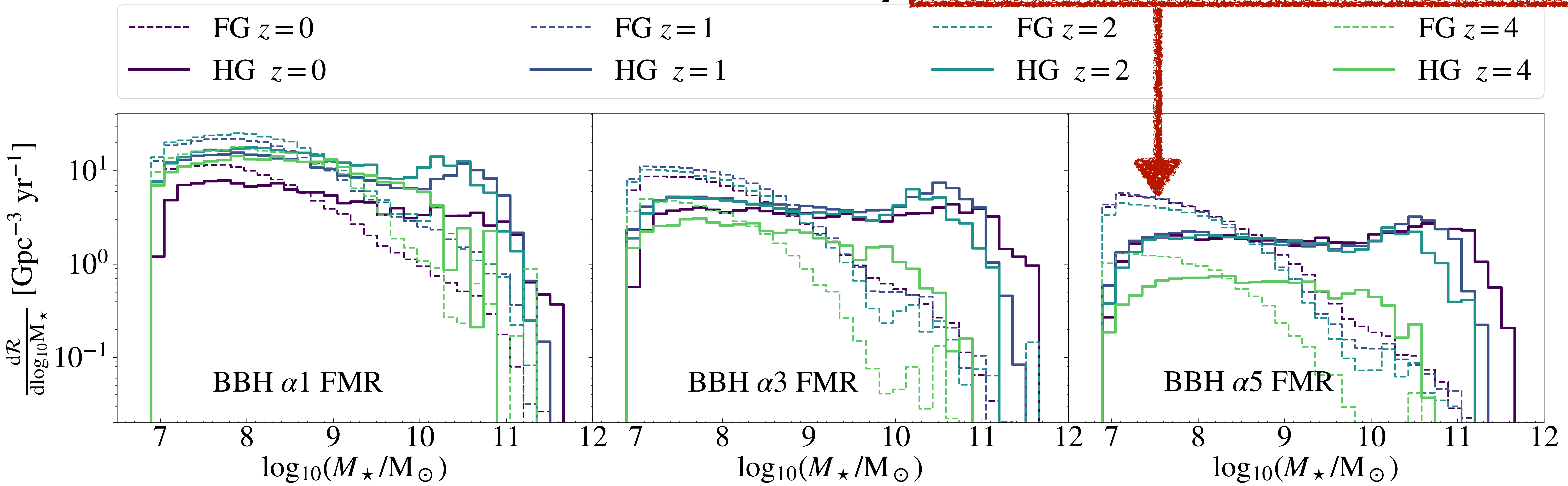
1) BBHs **form** in low-mass galaxies and **merge** in low-mass galaxies



# `galaxyRate`: host galaxy stellar mass

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

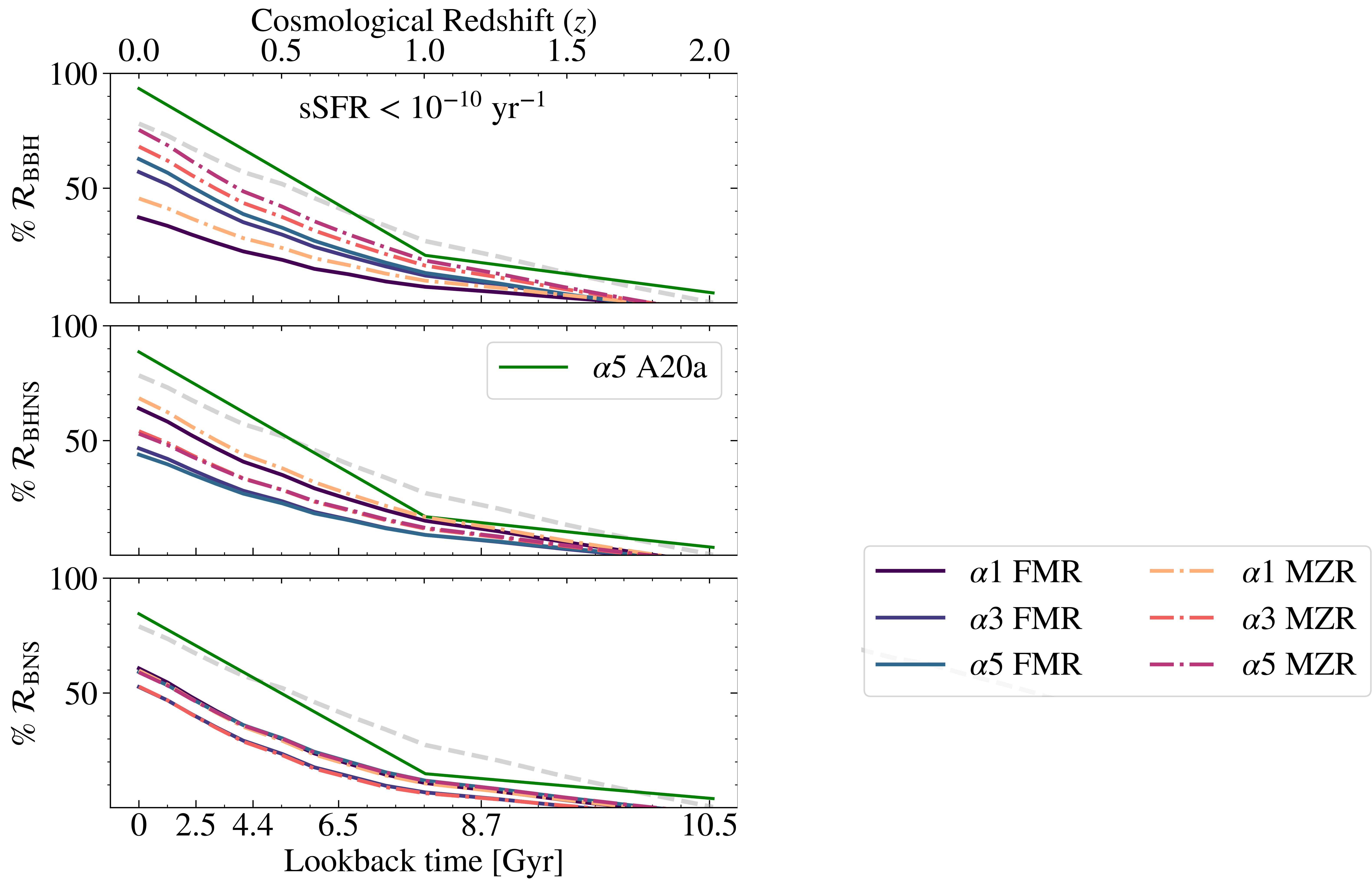
**2)**



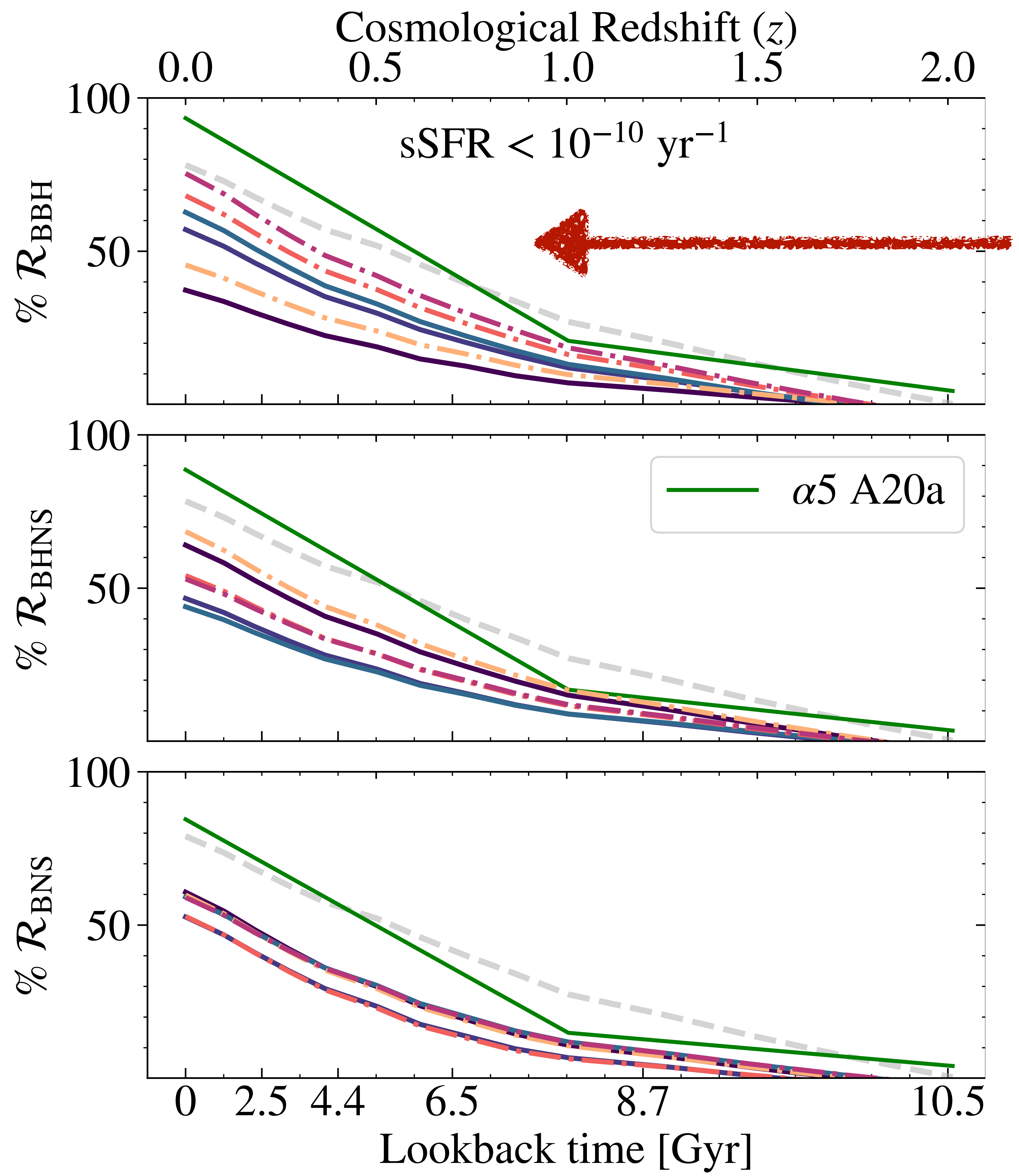
# `galaxyRate`: **passive galaxies**

**1)**

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



# galaxyRate: **passive galaxies**




2)

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

# Can host galaxies be useful in other ways?

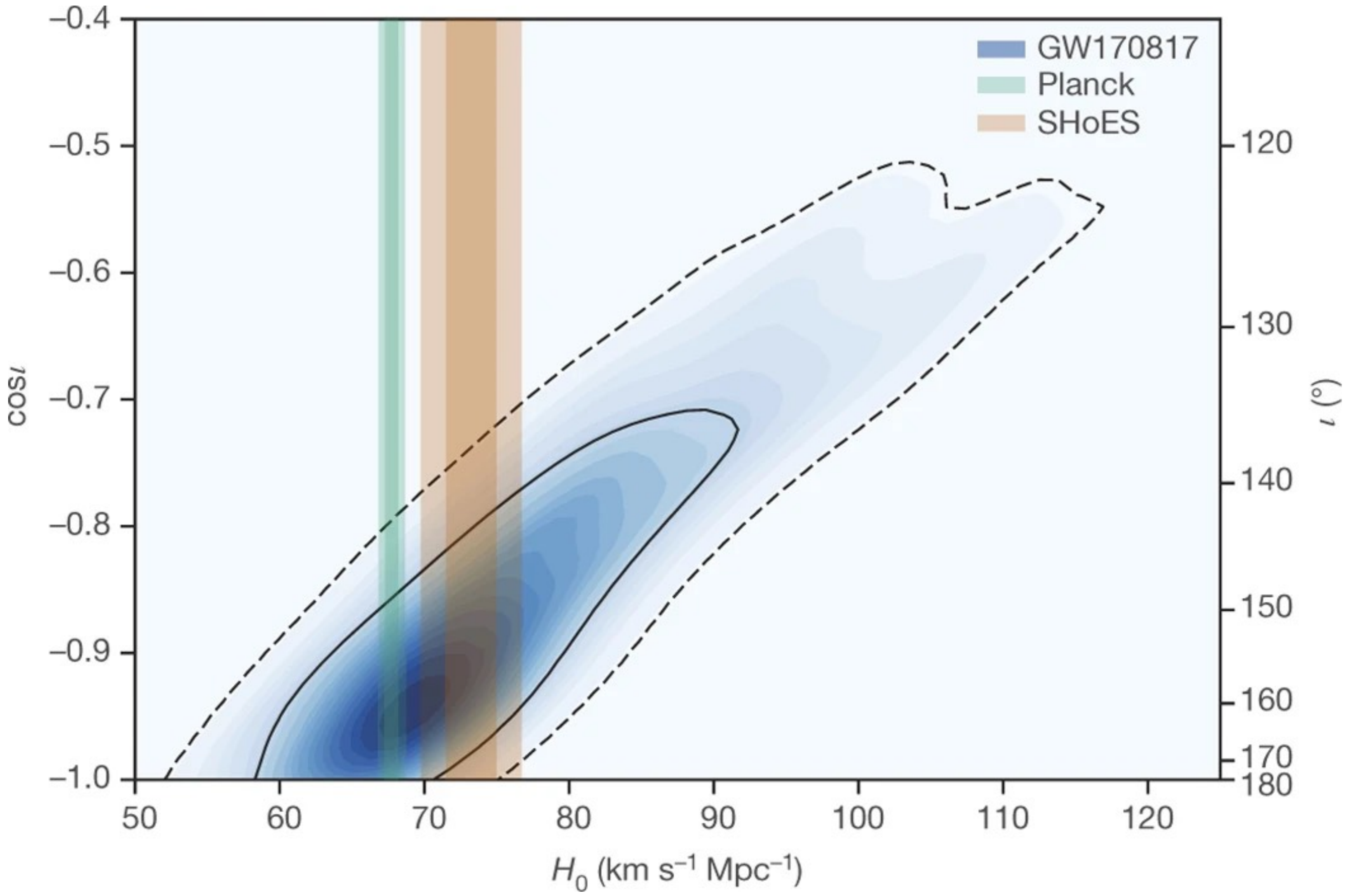
# GW and cosmology

- GW are **standard sirens**
- $h_+ = \frac{2(1+z)\mathcal{M}}{d_L}(\pi(1+z)\mathcal{M}f)^{2/3}(1+\cos^2\iota)\cos 2\phi_N(t)$
- $h_\times = -\frac{4(1+z)\mathcal{M}}{d_L}(\pi(1+z)\mathcal{M}f)^{2/3}\cos\iota)\sin 2\phi_N(t)$
- Chirp mass $\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$


Refs: Mastrogiovanni et al. 2021, Gray et al. 2022

# GW and cosmology

- $v_{\mathrm{H}} = H_0 d_L$
- Recession velocity from NGC 4993: $v_H = 3017 \pm 166 \text{ km s}^{-1}$
- $d_L = 43.8^{+2.9}_{-6.9} \text{ Mpc}$
- $H_0 = 70.0^{+12.0}_{-8.0} \text{ km s}^{-1} \text{ Mpc}^{-1}$ 68% C.I.
- SHoES: Cepheids and type Ia SN

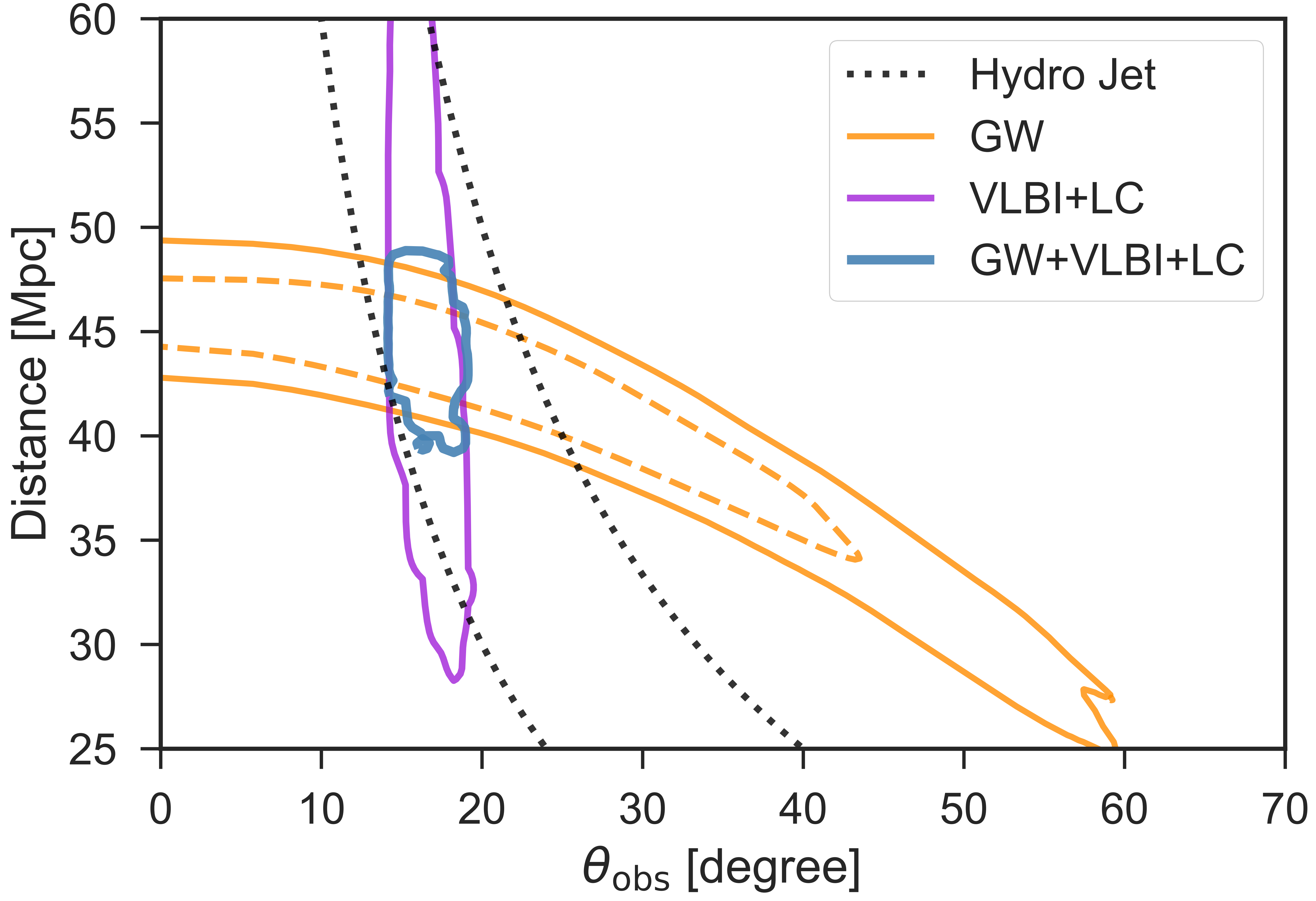





Refs: Abbott et al. 2017

# GW and cosmology

- **Bright sirens:** EM counterpart breaks the inclination angle/ luminosity distance degeneracy ➡️ inclination angle from KN and afterglow models

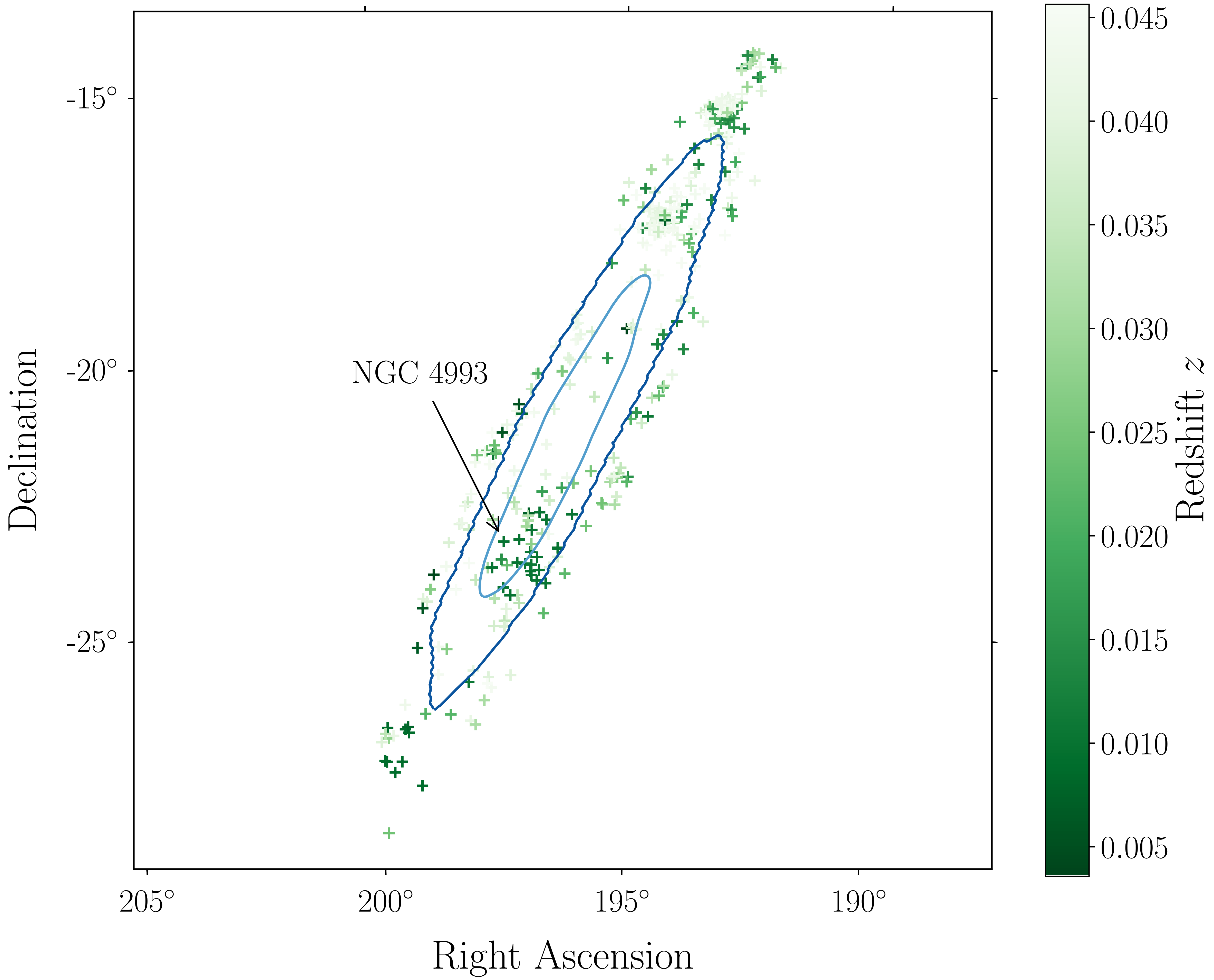



Credits: Hotokezaka et al. 2019

# GW and cosmology

- **Dark sirens:** cross-correlation with potential host galaxies within localisation volumes

- GW event well localised (*only one host galaxy*), the statistical method (dark sirens) reduces to the counterpart method (bright sirens)




Credits: Fishbach et al. 2019

# What you did (not) learn today

- Multimessenger astrophysics and host galaxies
- Modelling the host galaxies and cosmology

**Tomorrow**

- Population-synthesis simulation
- Population III stars and black holes
- Einstein Telescope and the future of GW astrophysics

# Further reading:

- This is based on lecture materials of Marica Branchesi, Jan Harms, Tito Dal Canton, Michela Mapelli, Eleonora Loffredo, Giuliano Iorio and Gaston Escobar

- References:

  - **Chemical evolution of the Universe:** Chruślinska 2022

  - **Dark sirens:** Dal Pozzo 2012, Chen and Holz 2016, Chen et al. 2018, Borghi et al. 2024

- **See you this afternoon!**