Gravitational Wave Astrophysics

Lecture 3

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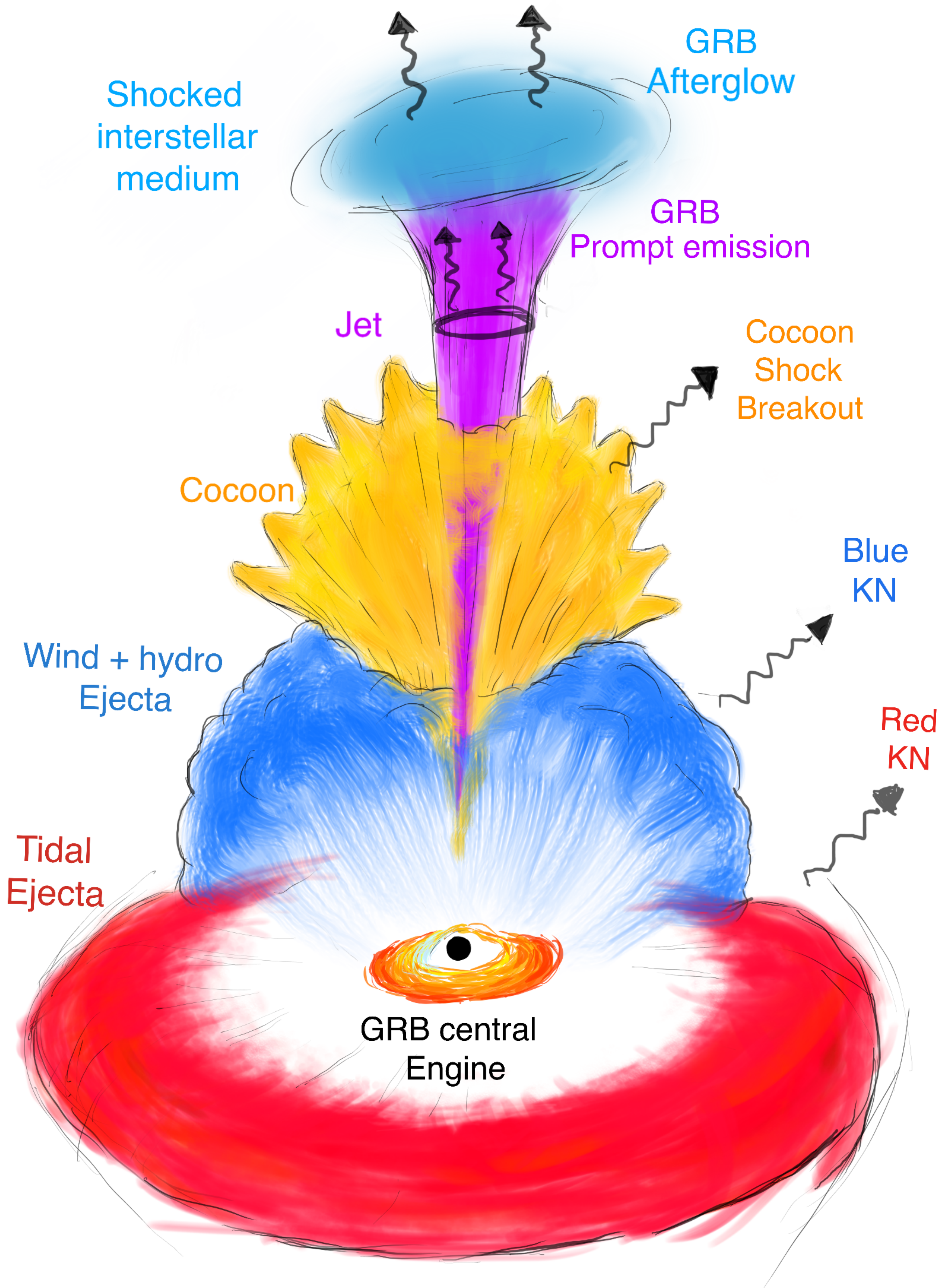
In this lecture, you will learn

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

Multimessenger astronomy

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***

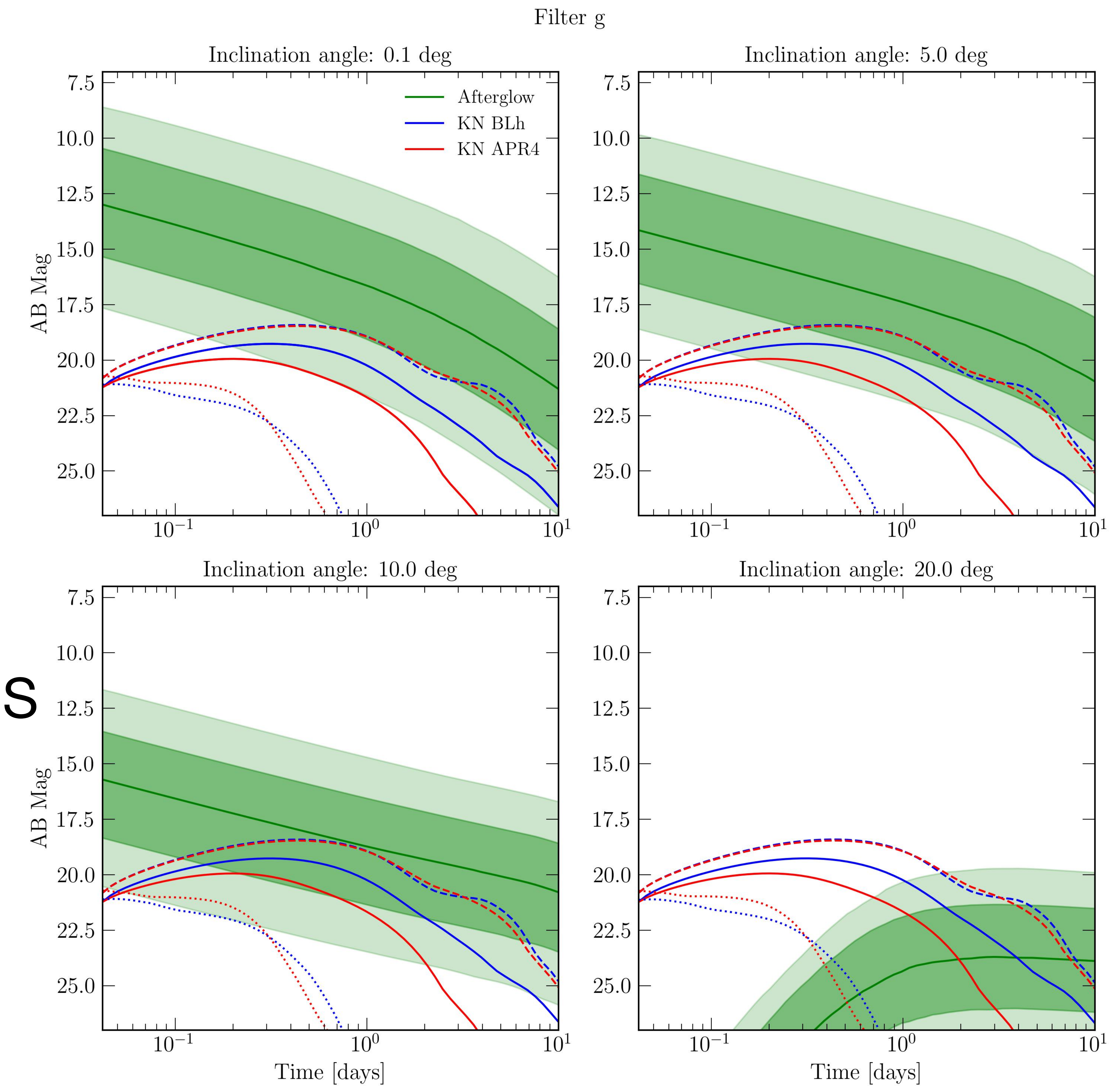
- k (opacity) ➡️ ***Atomic Physics***

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

Credits: Ascenzi et al. 2020

Kilonova VS GRB

- Light curves
- Varying inclination angle
- KN mostly outshined by Afterglow
- Line styles correspond to varying NS masses
- **Take-home message:** boost observations of KN with GW



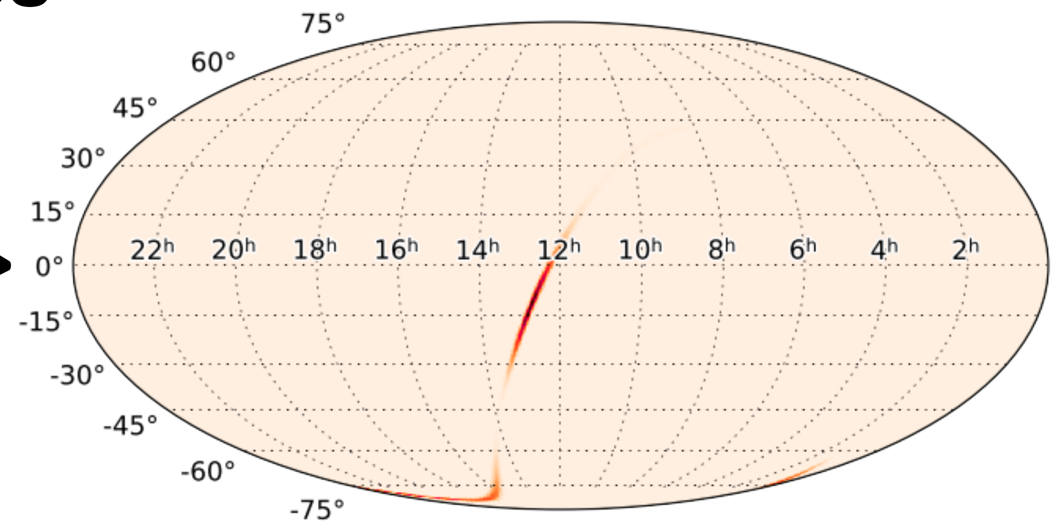
Credits: Loffredo et al. in preparation

Low latency

Detectors

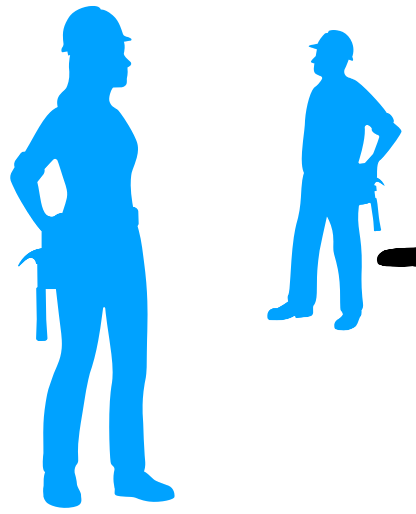
Automatic searches

Sky localisation

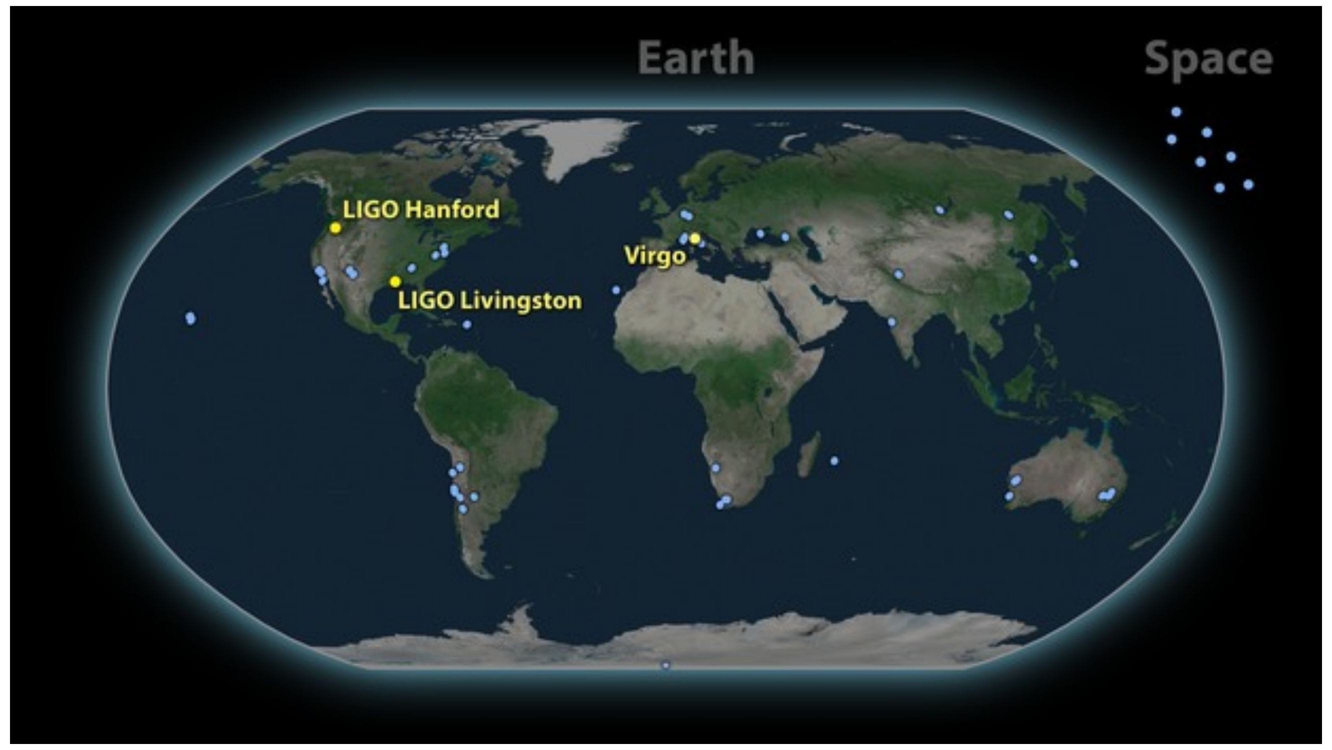


Credits: The LIGO-Virgo-KAGRA collaboration

Human validation



EM facilities



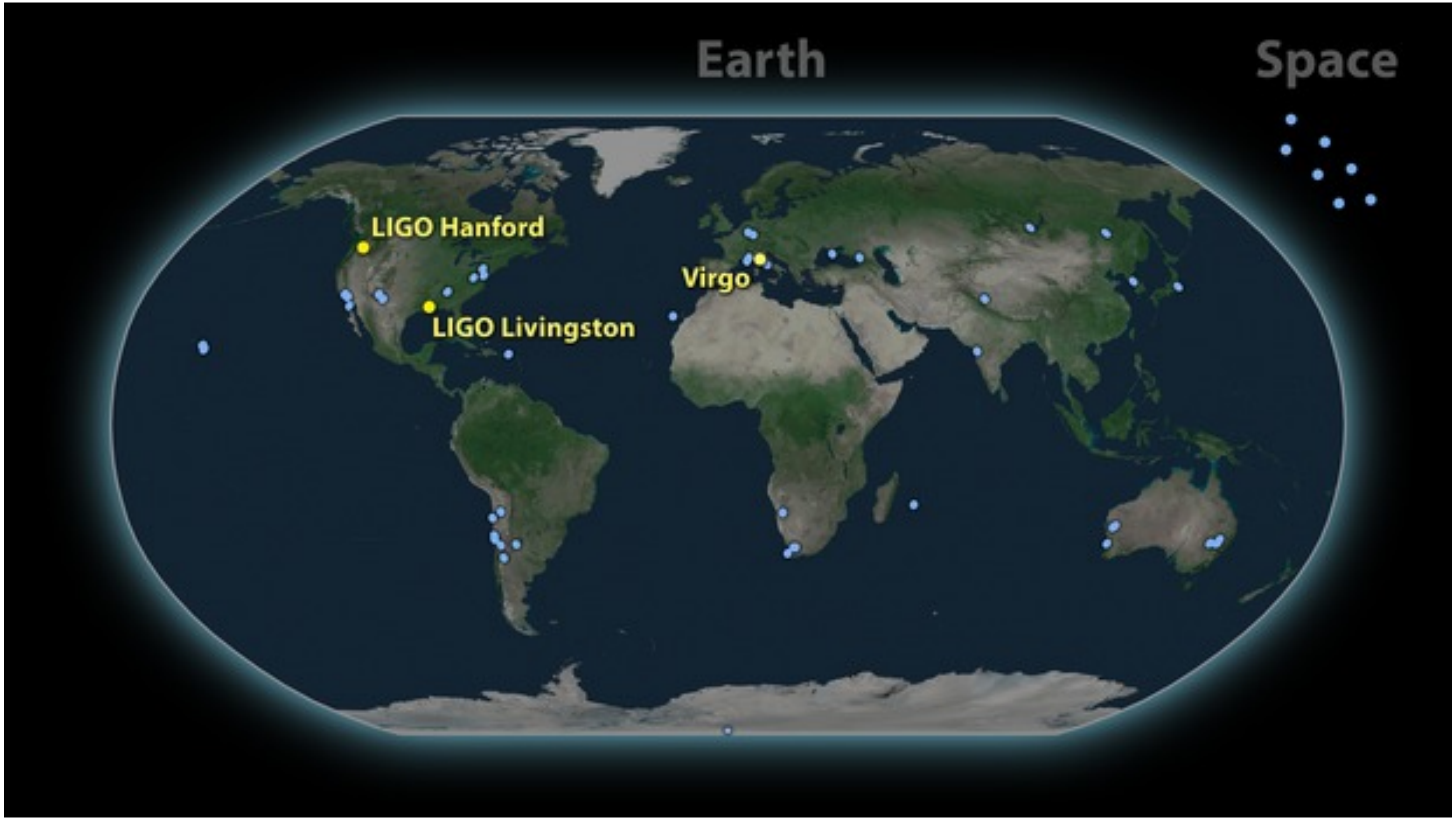
Credits: The LIGO-Virgo-KAGRA collaboration

~ few minutes

~ 30 minutes

Low latency

EM facilities



Credits: The LIGO-Virgo-KAGRA collaboration

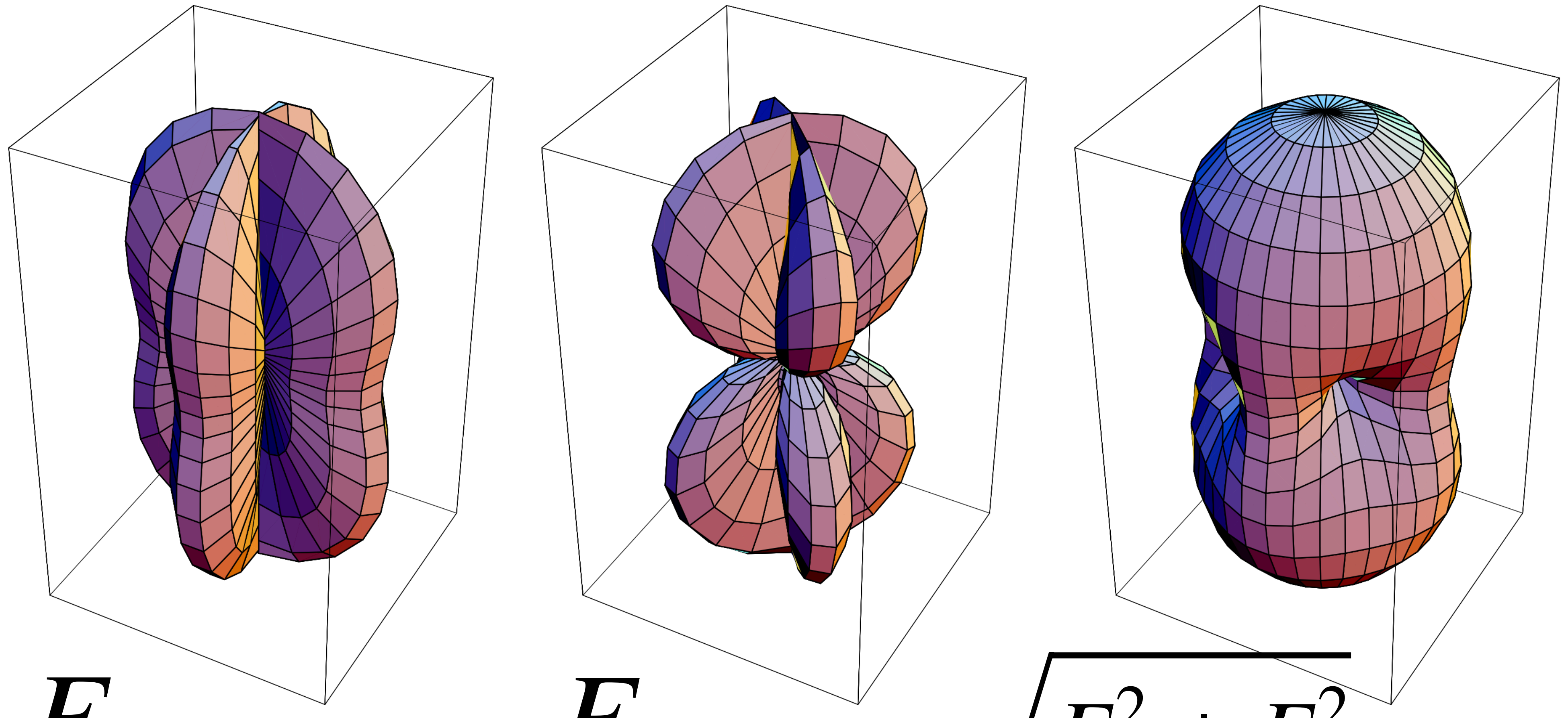
Sky localisation

- $\frac{\Delta L}{L} \propto h_{\mathrm{det}}(t) = F_+(\theta,\phi)h_+(t) + F_\times(\theta,\phi)h_\times(t)$

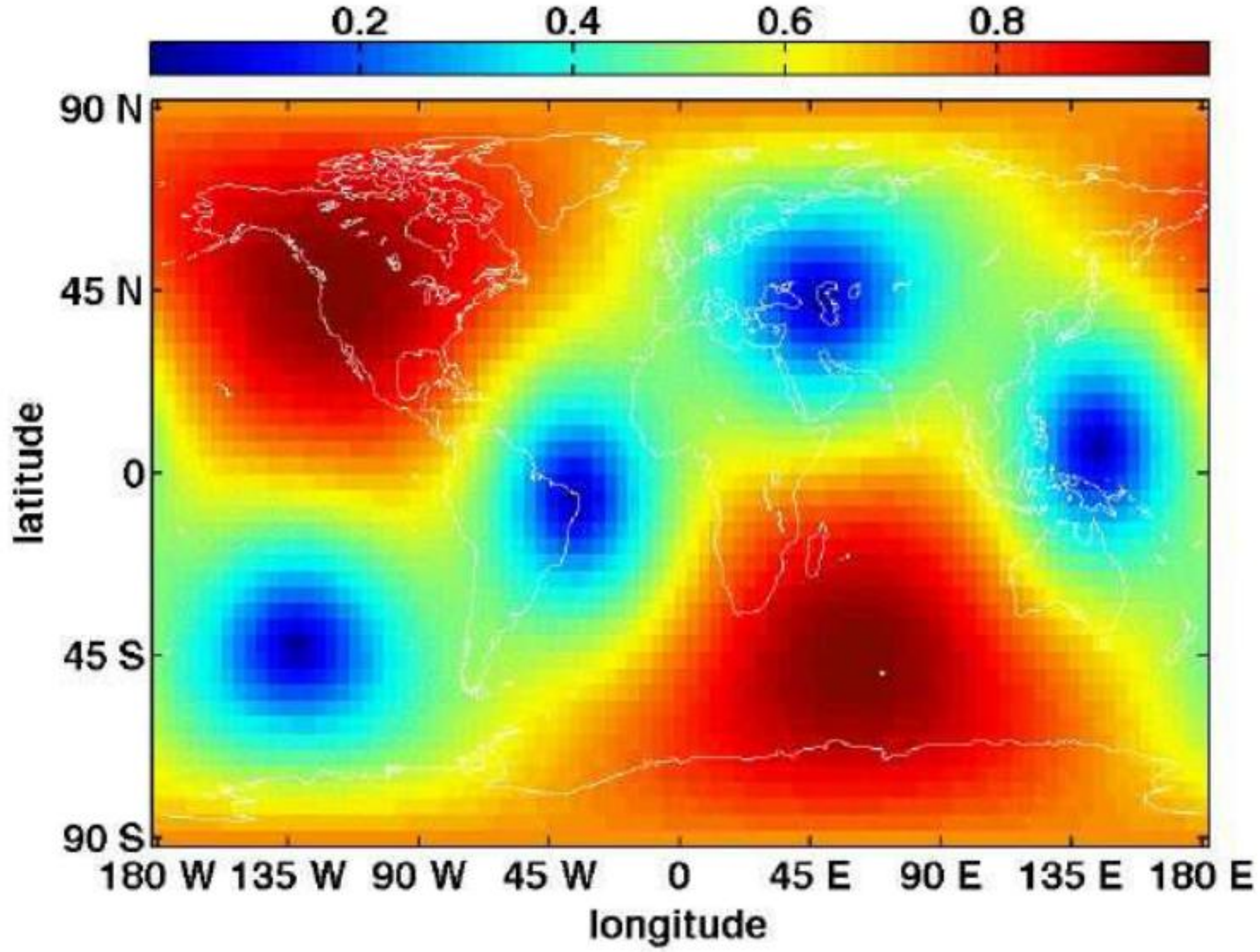
- GW detector is an all-sky monitor with varying sensitivity

- No directional sensitivity

Credits: the LIGO-Virgo-KAGRA collaboration



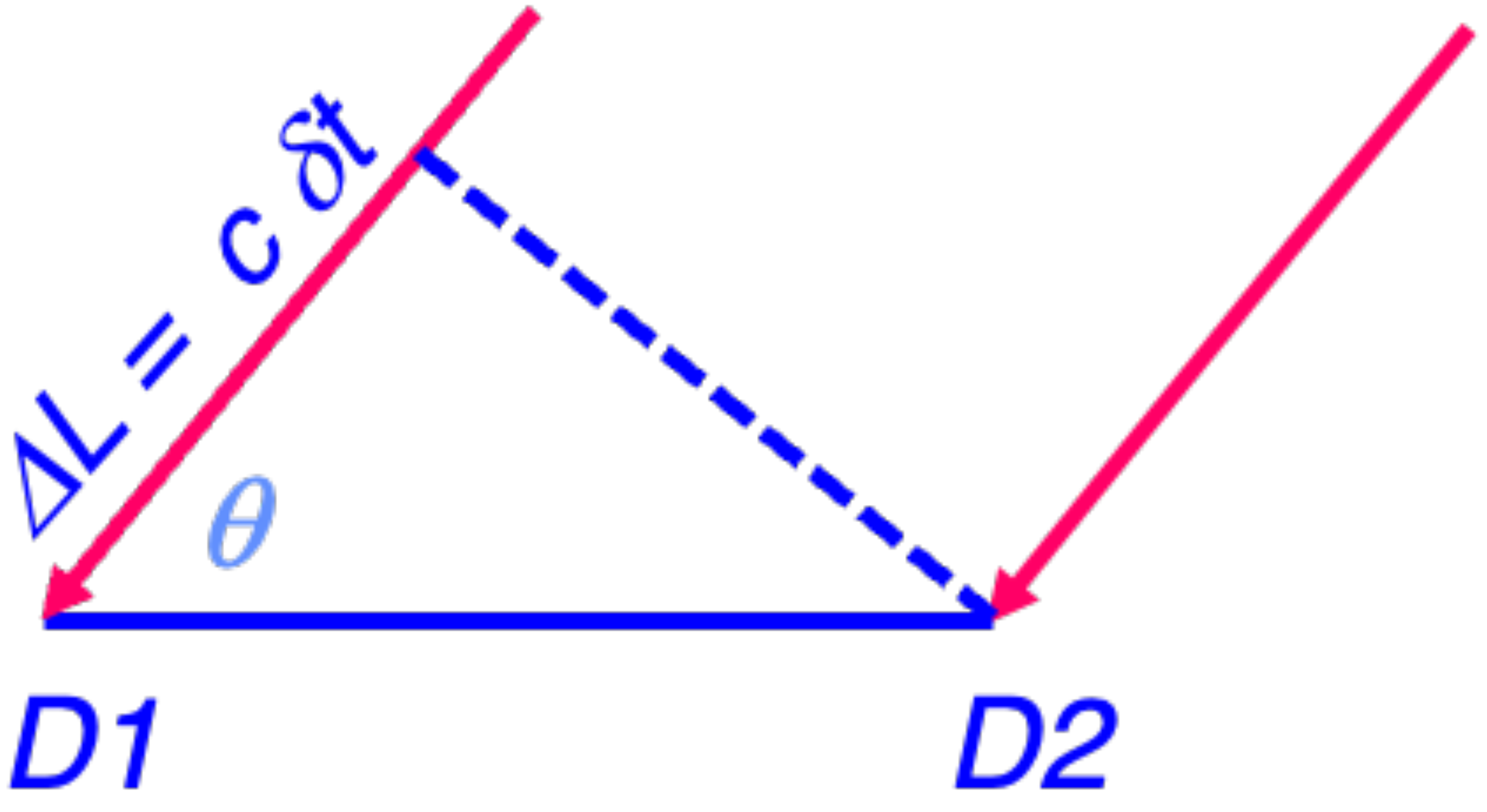
F_+ $\qquad$ $F_\times$ $\qquad$ $\sqrt{F_+^2 + F_\times^2}$

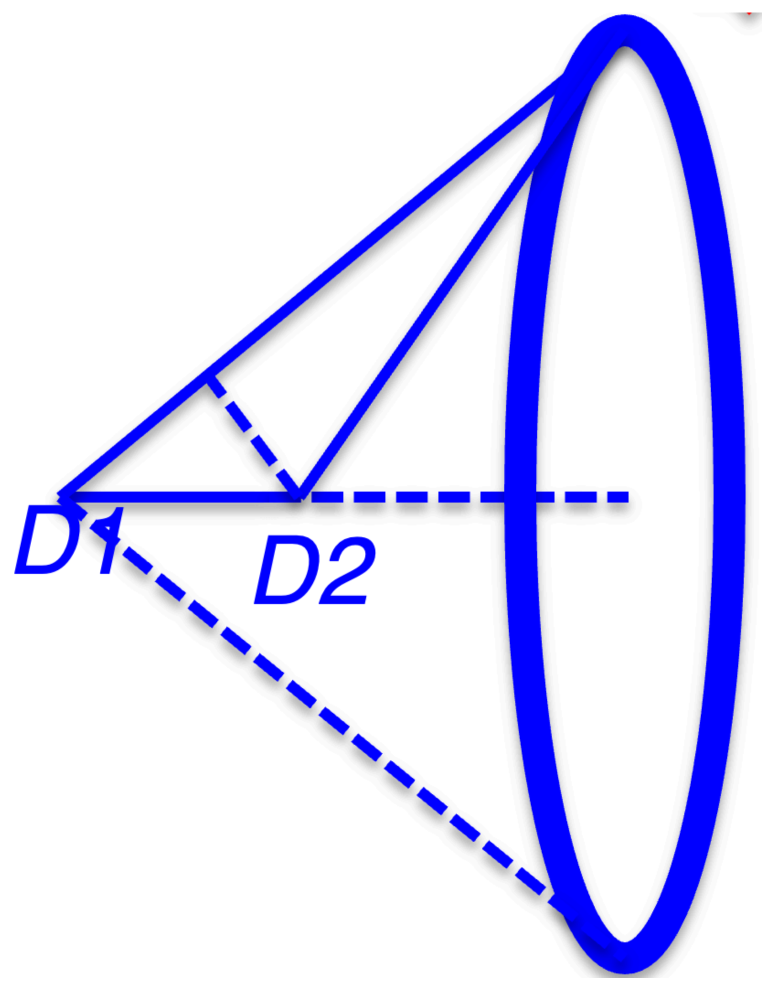


Credits: Hayama et al. 2012

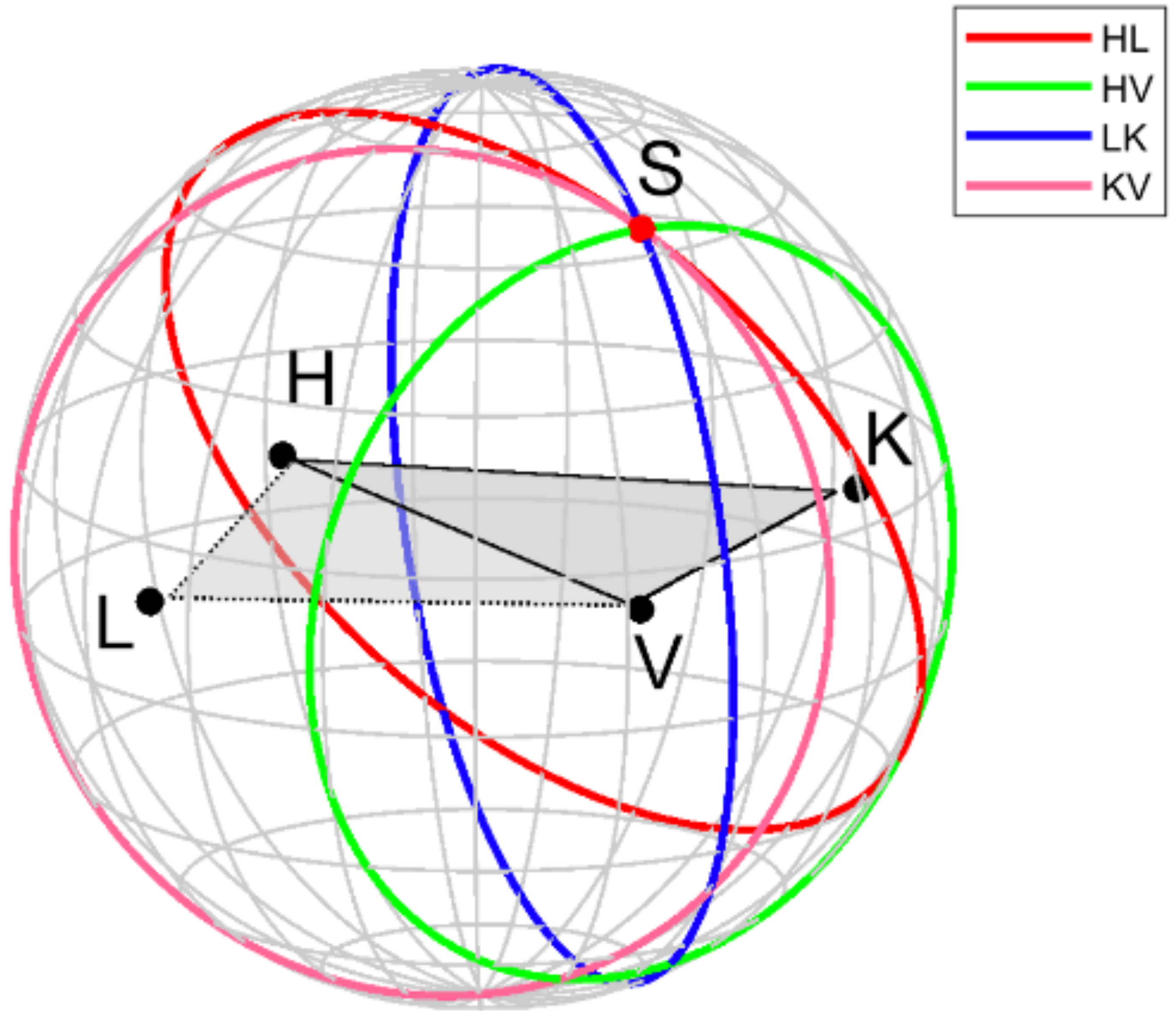
Triangulation

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

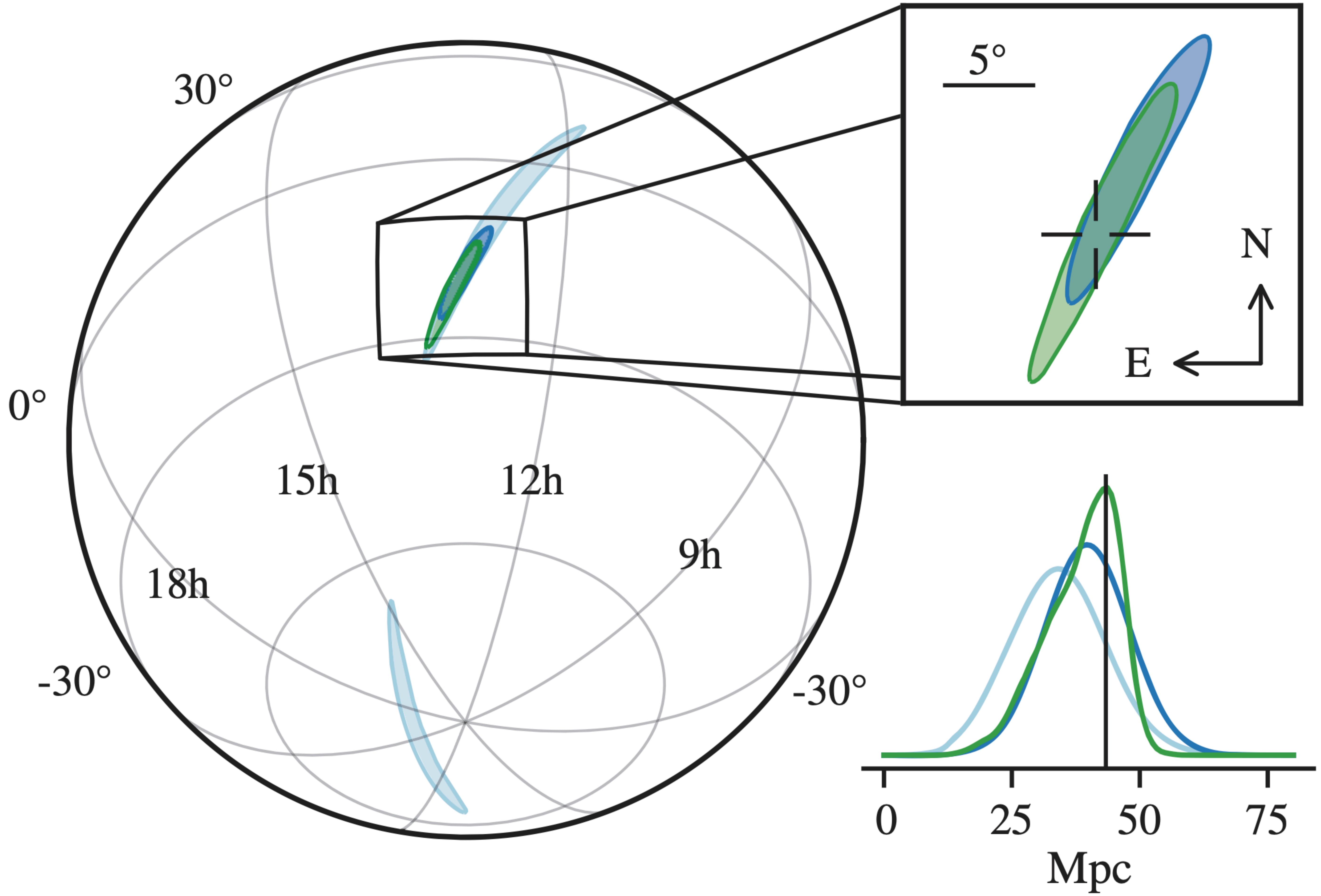




Credits: The LVK collaboration



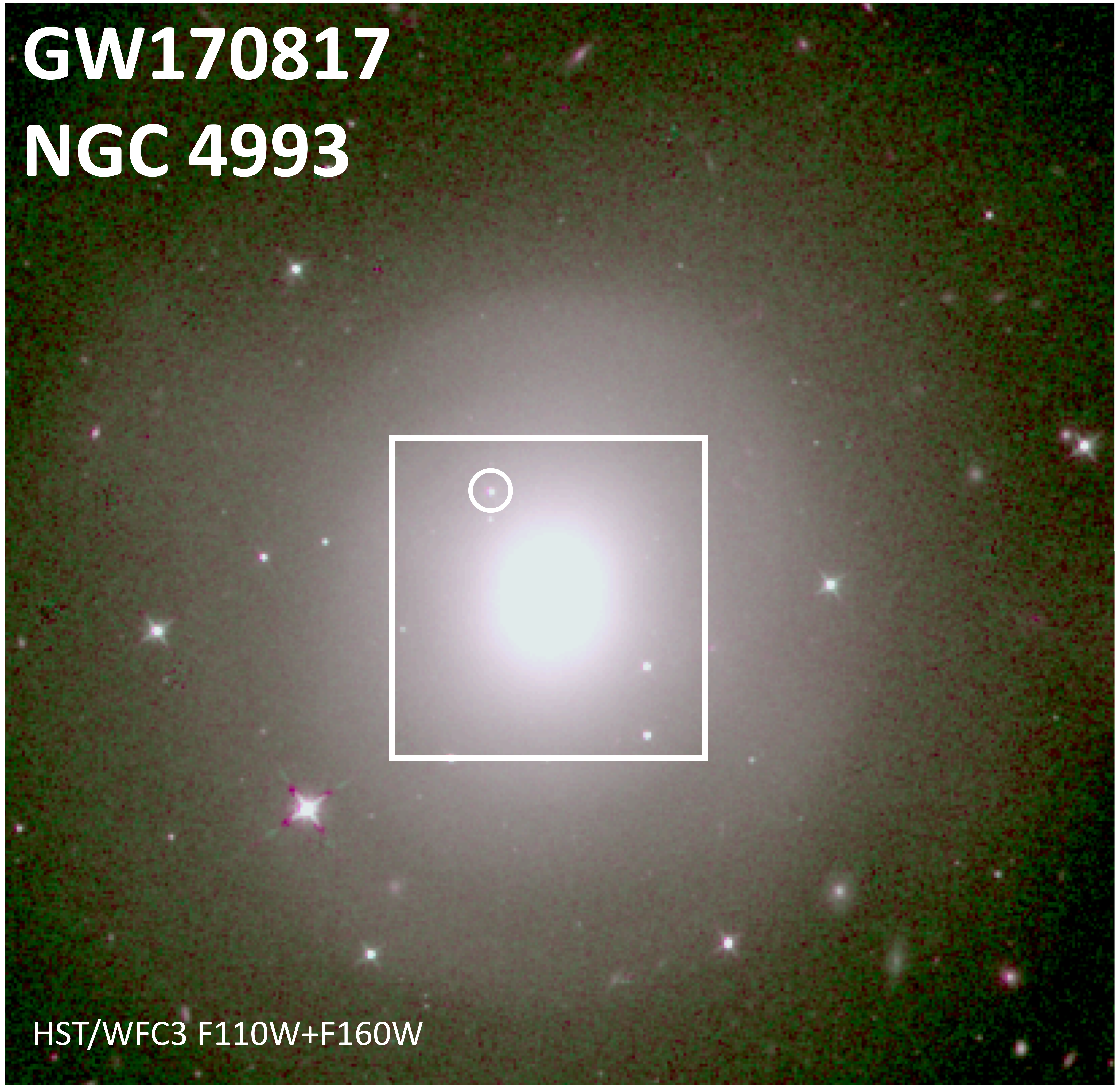
GW170817



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



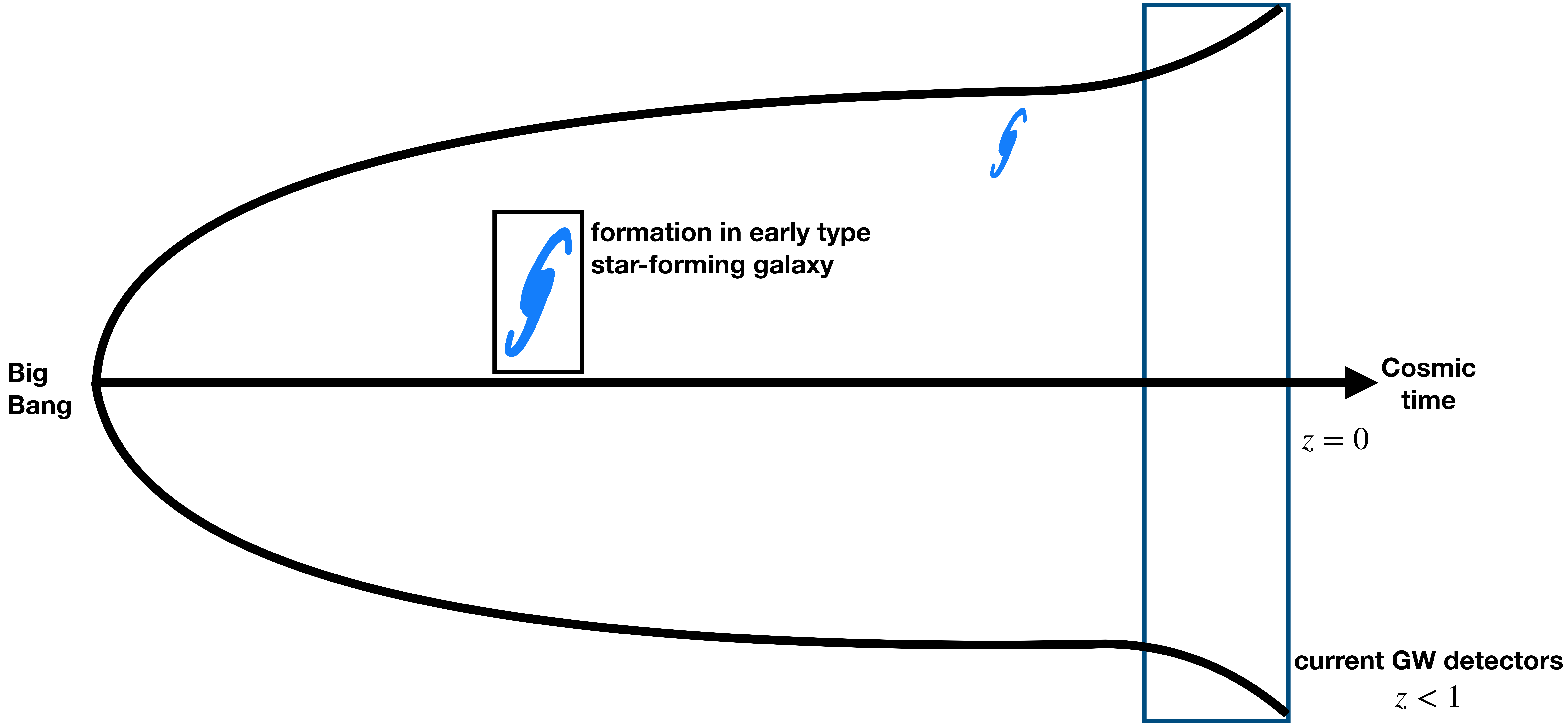
Refs: Levan et al. 2017, Blanchard et al. 2017

How to model host galaxies

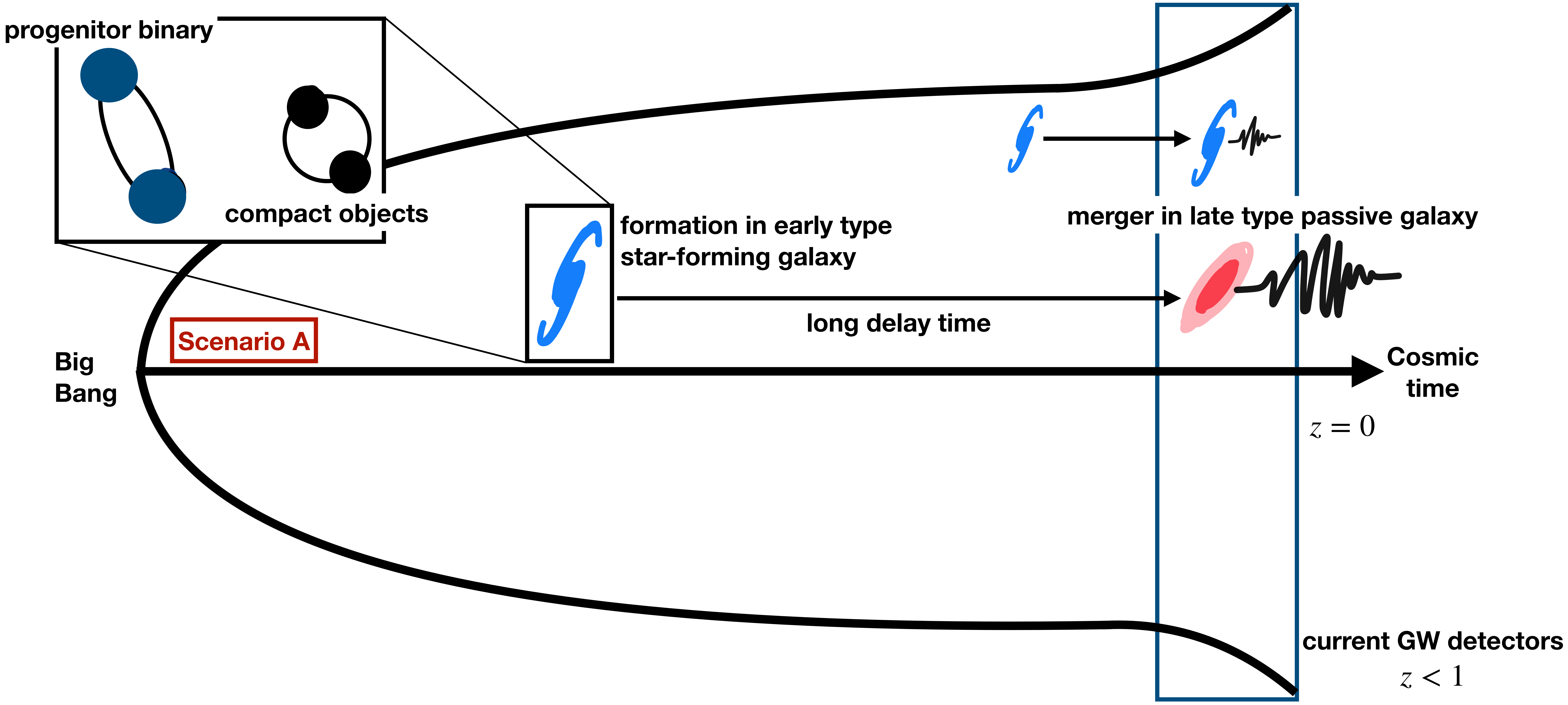
- **Challenge:** interfacing Physics at scales spanning orders of magnitude
  - Evolution of galaxies across history of the Universe and formation of compact object mergers at binary system level
- galaxy catalogs from cosmological simulations

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

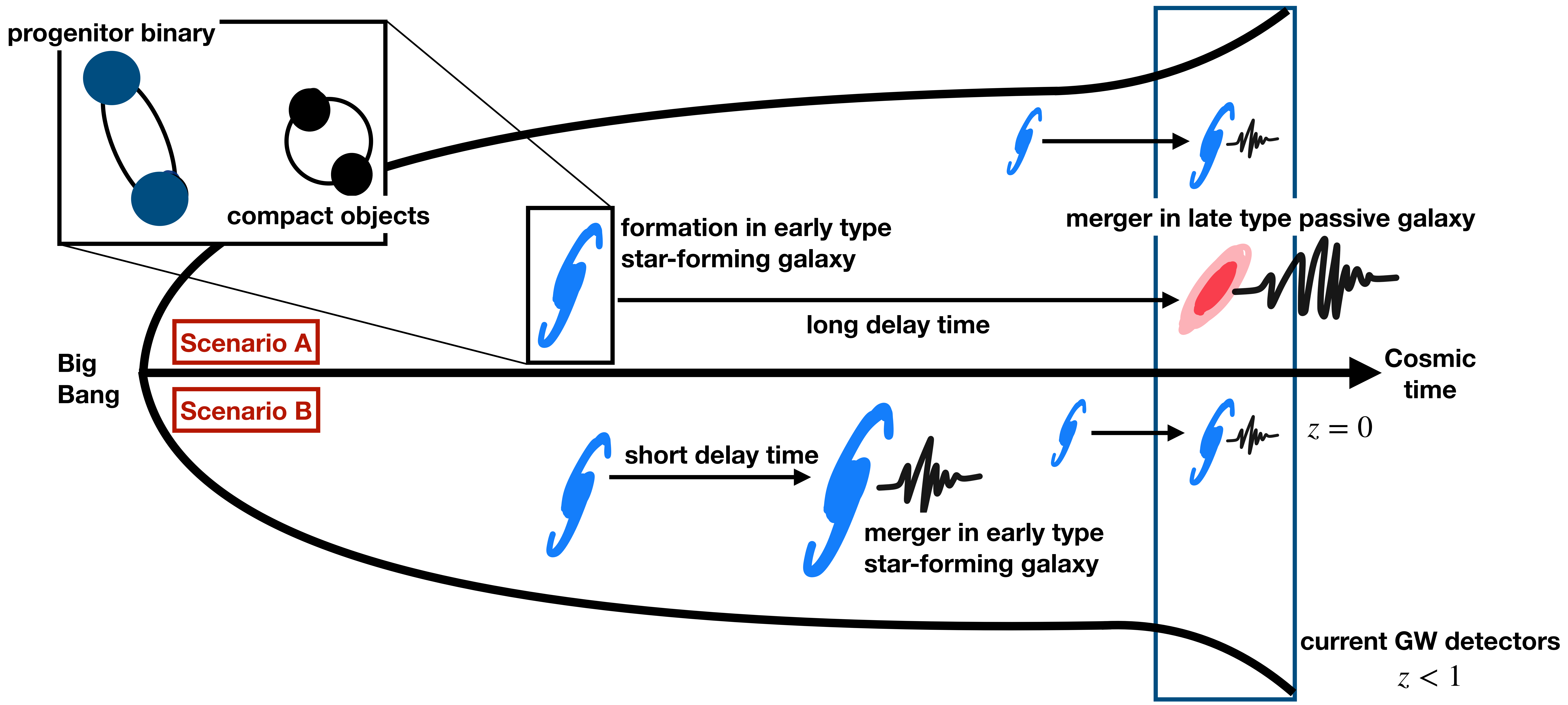
How to model host galaxies



How to model host galaxies



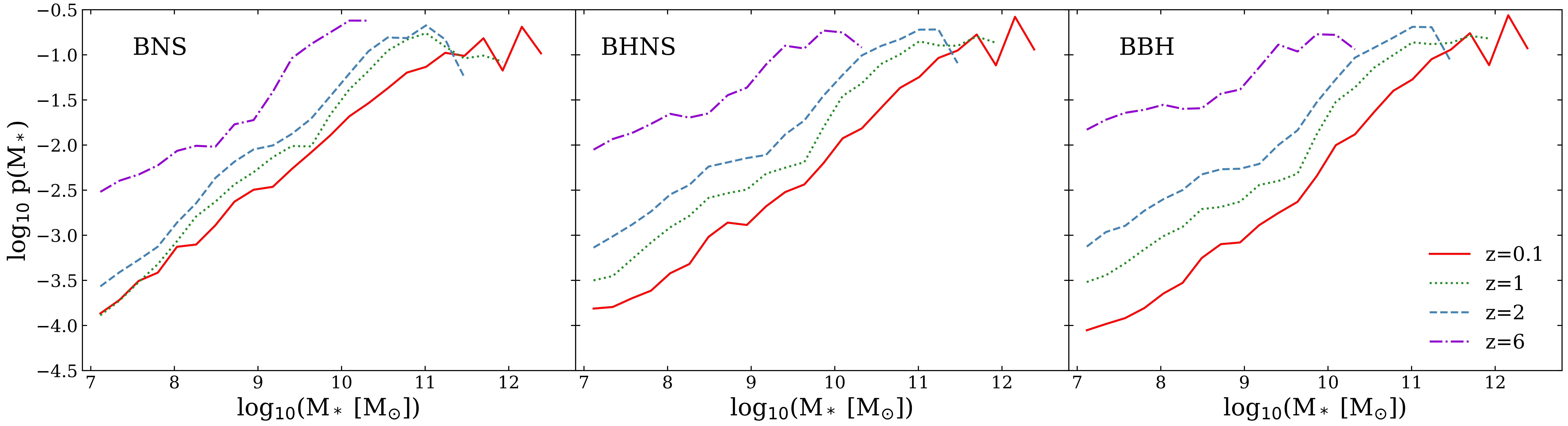
How to model host galaxies



How to rank galaxies

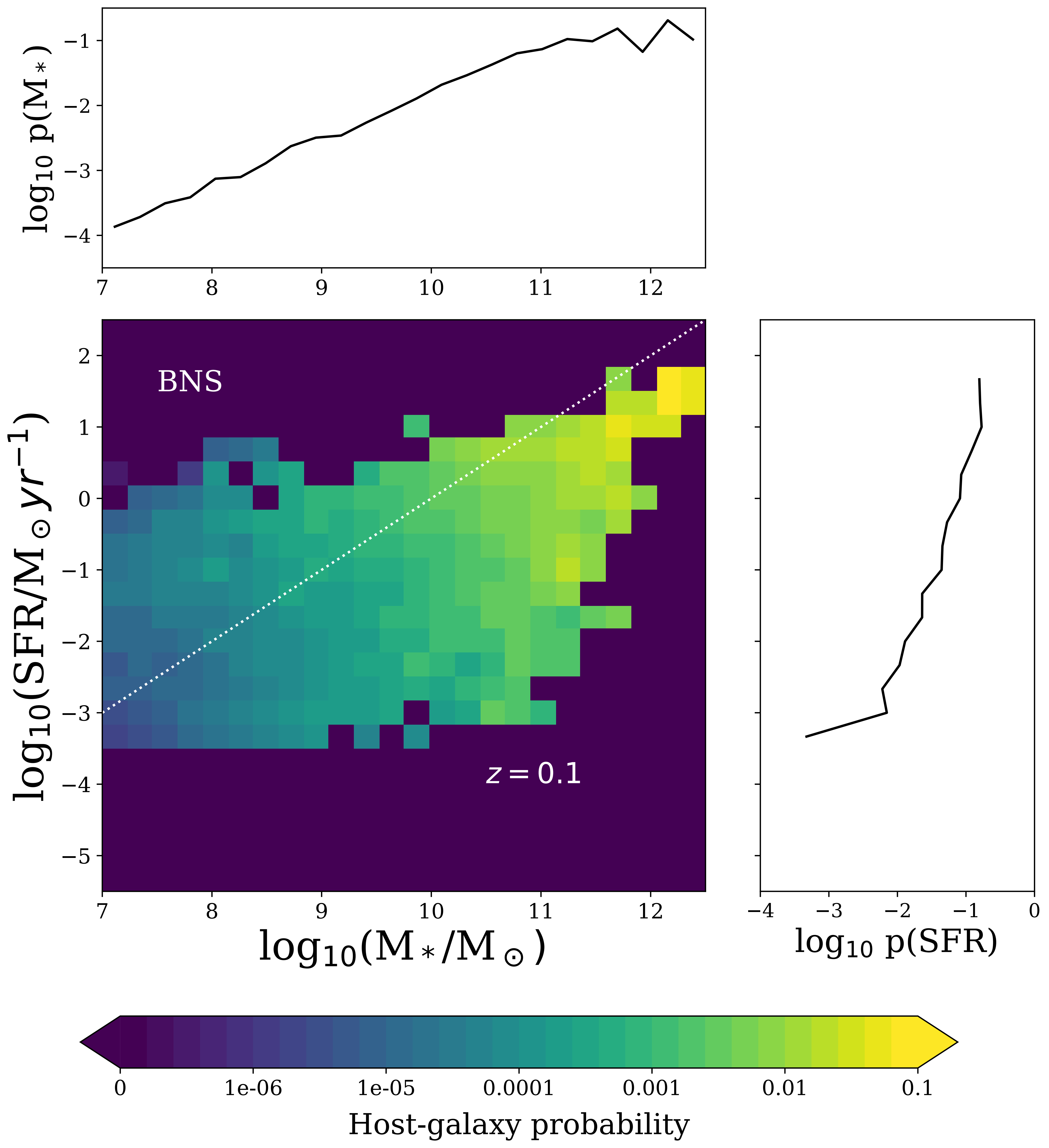
Refs: Artale et al. 2020

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



How to rank galaxies

Strong correlation:
stellar mass VS
merger rate

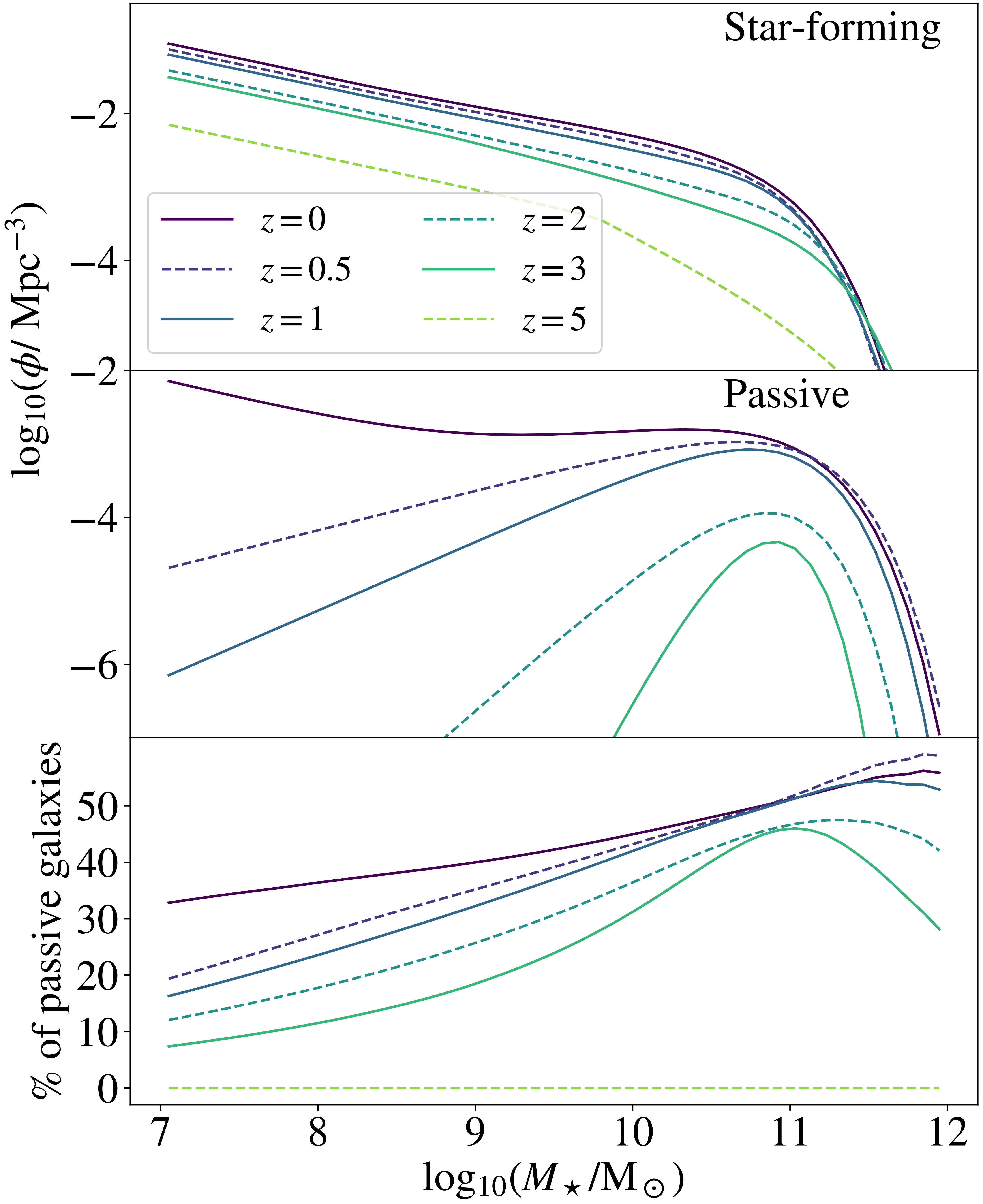


Refs: Artale et al. 2020

How to model host galaxies

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

GSMF



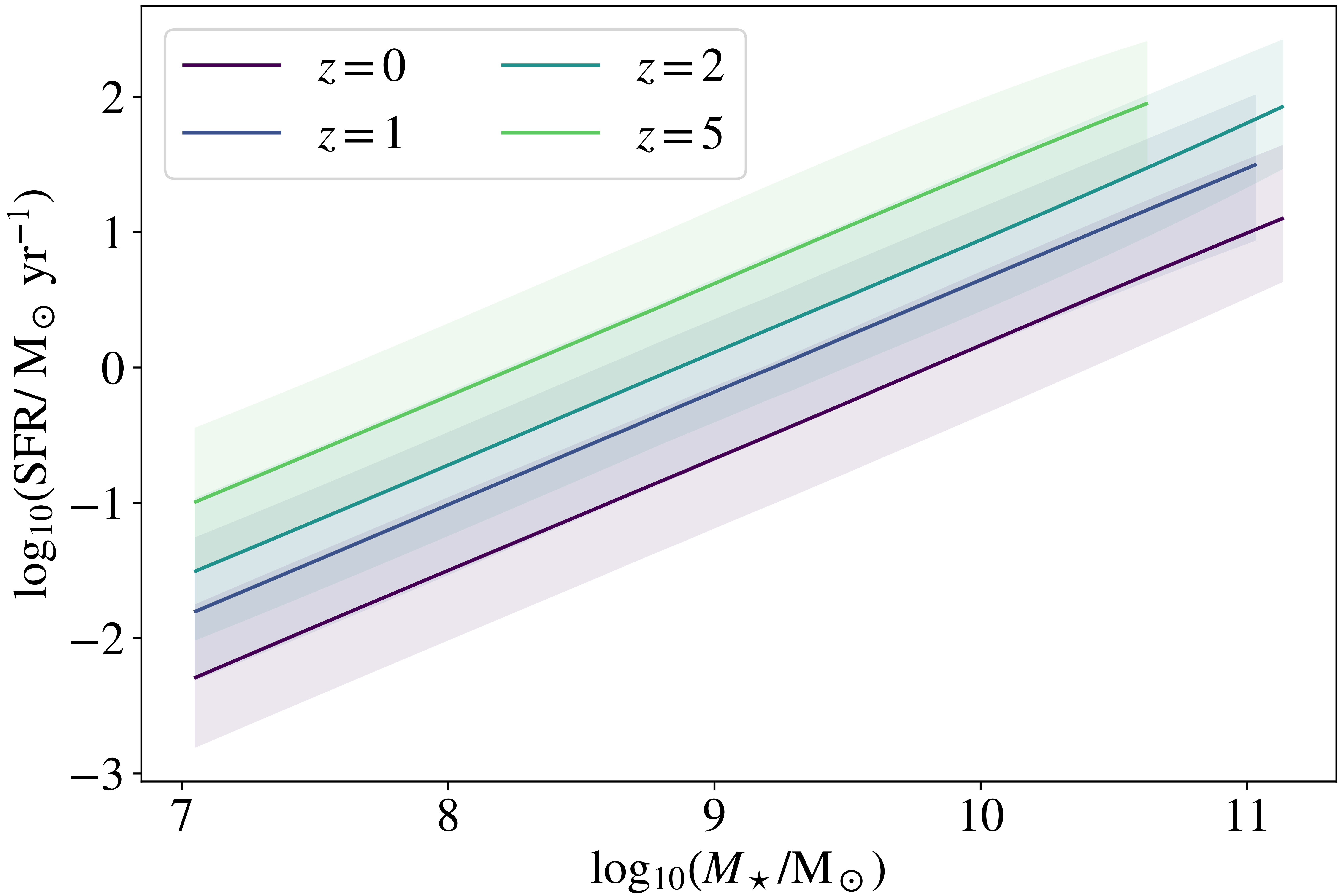
Refs: Chruslinska & Nelemans 2019, Ilbert et al. 2013, Santoliquido et al. 2022

SFR main sequence

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

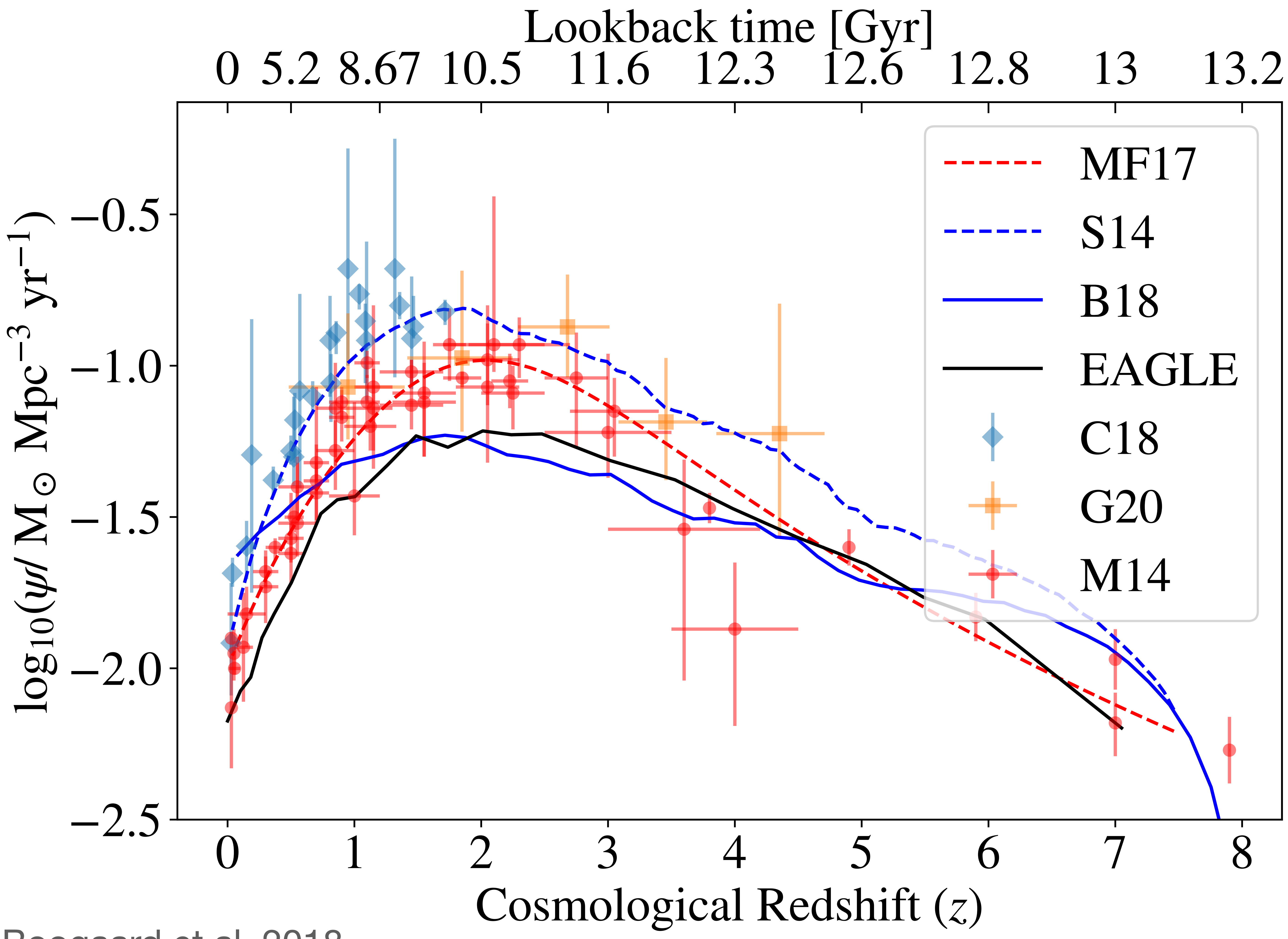
Refs: Boco et al. 2021, Boogaard et al. 2018

SFR main sequence



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

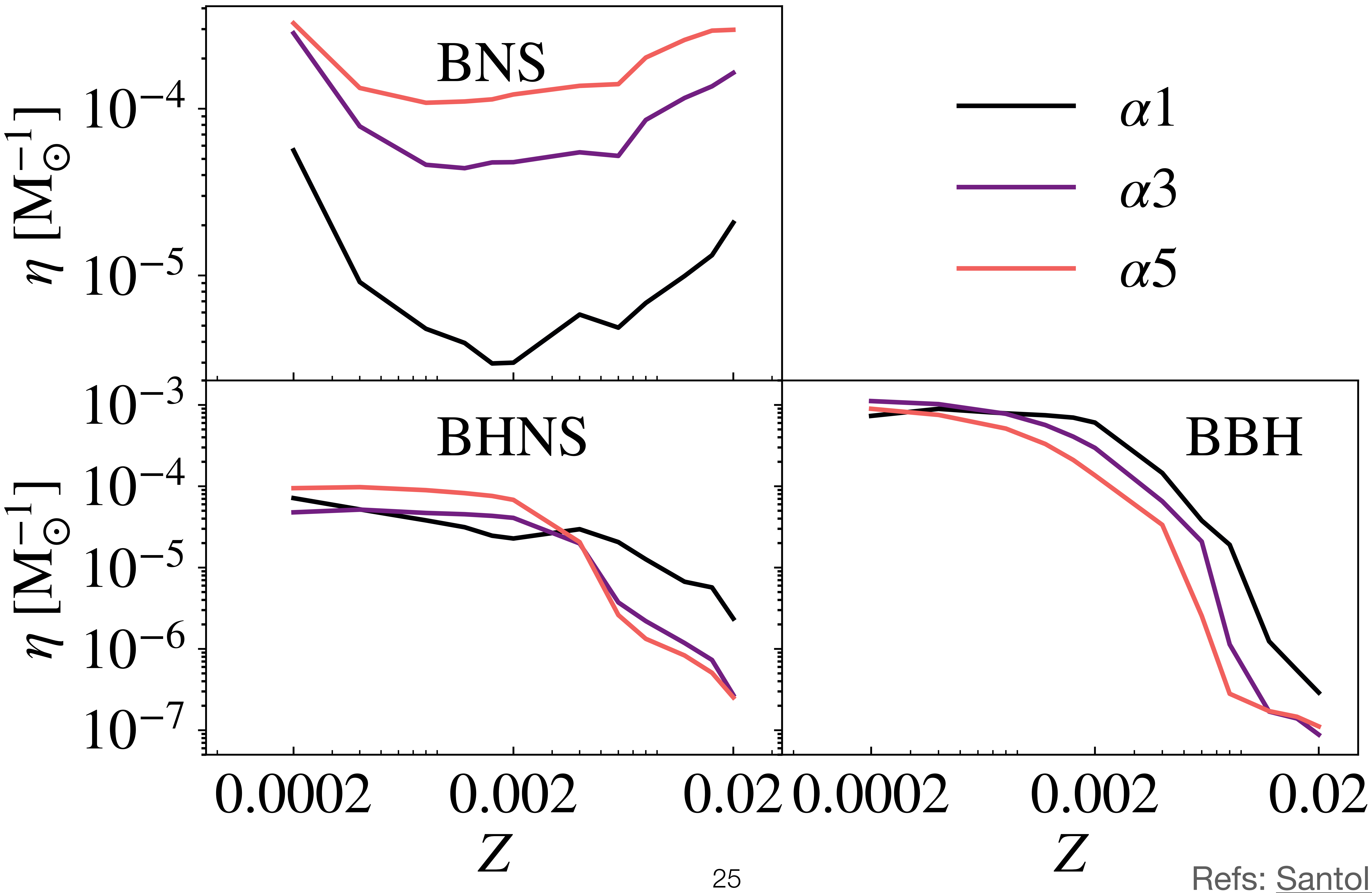
SFR(z)



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

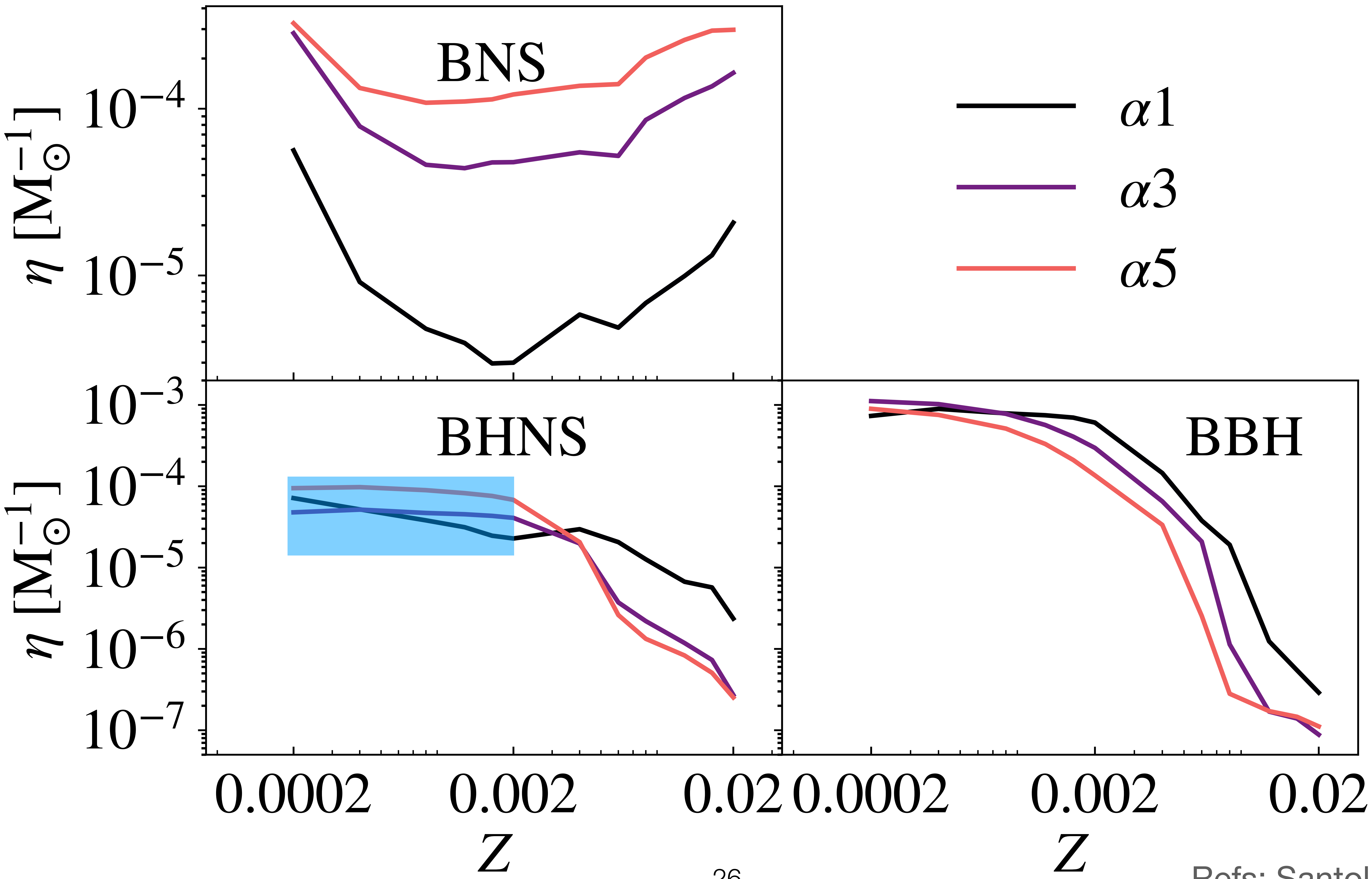
Do you remember metallicity impact on compact object formation?

Merger efficiency



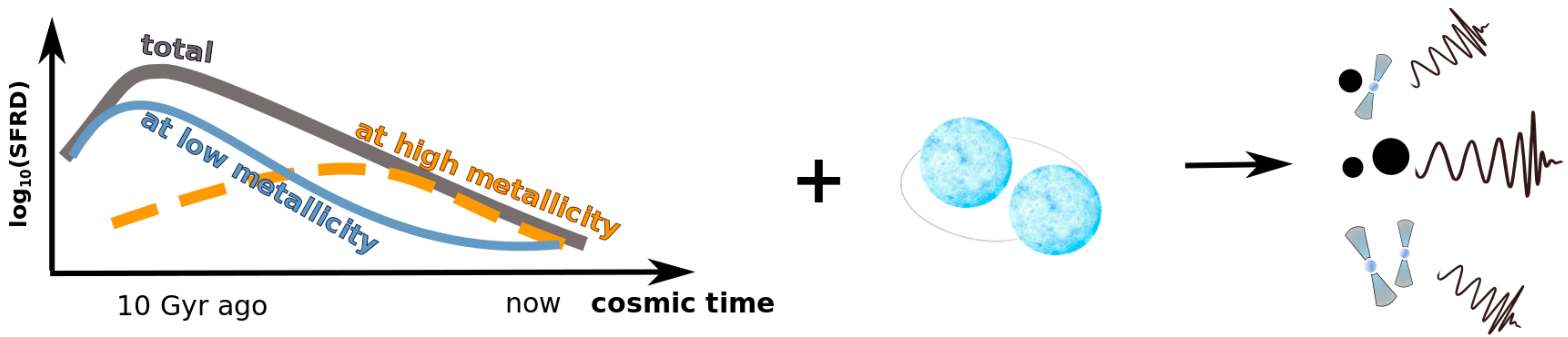
Refs: Santoliquido et al. 2022

Merger efficiency



Refs: Santoliquido et al. 2022

Impact of metallicity



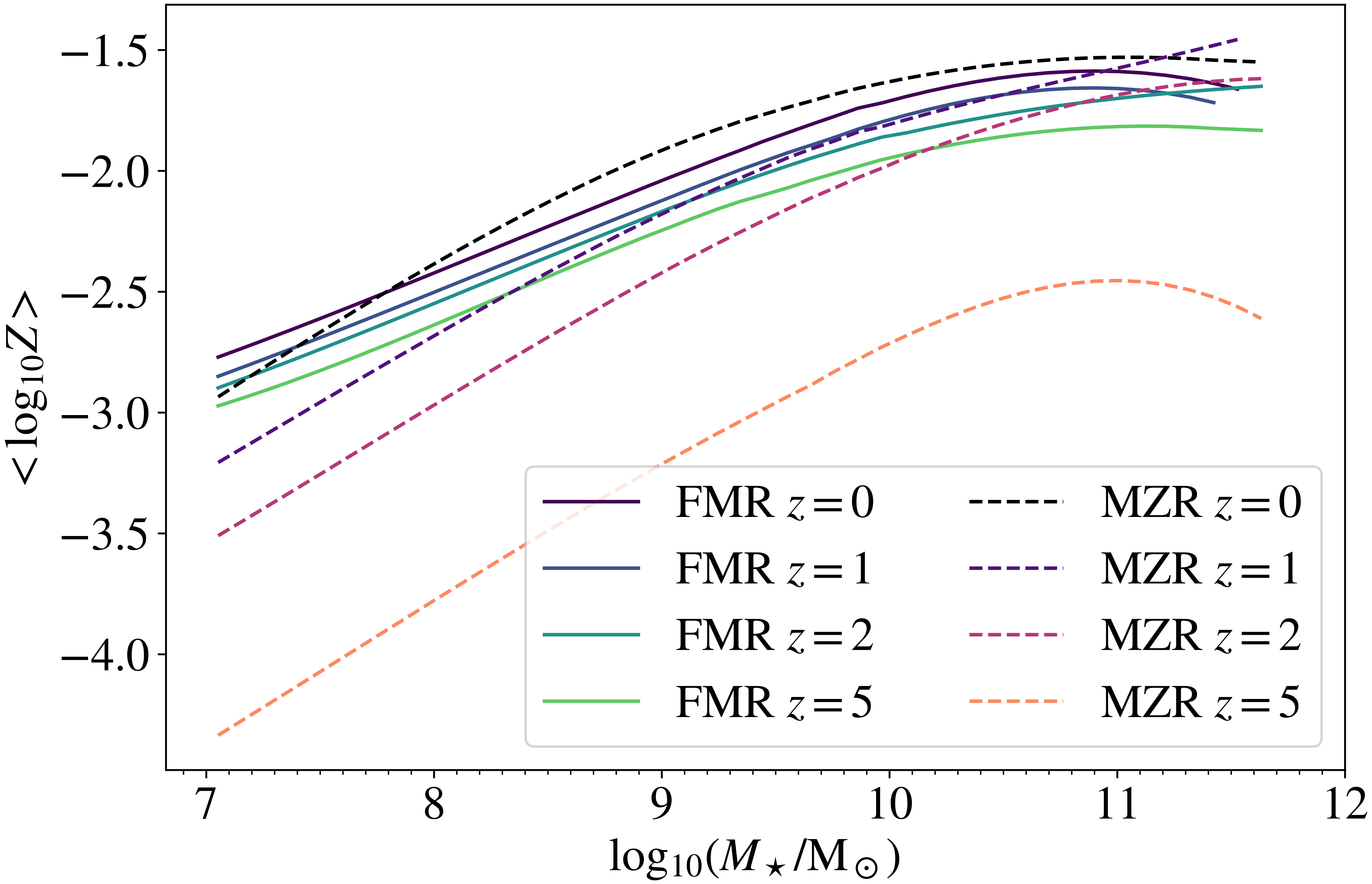
number and metallicity of stars formed at different times

evolution of massive stars
and binaries

population of GW sources

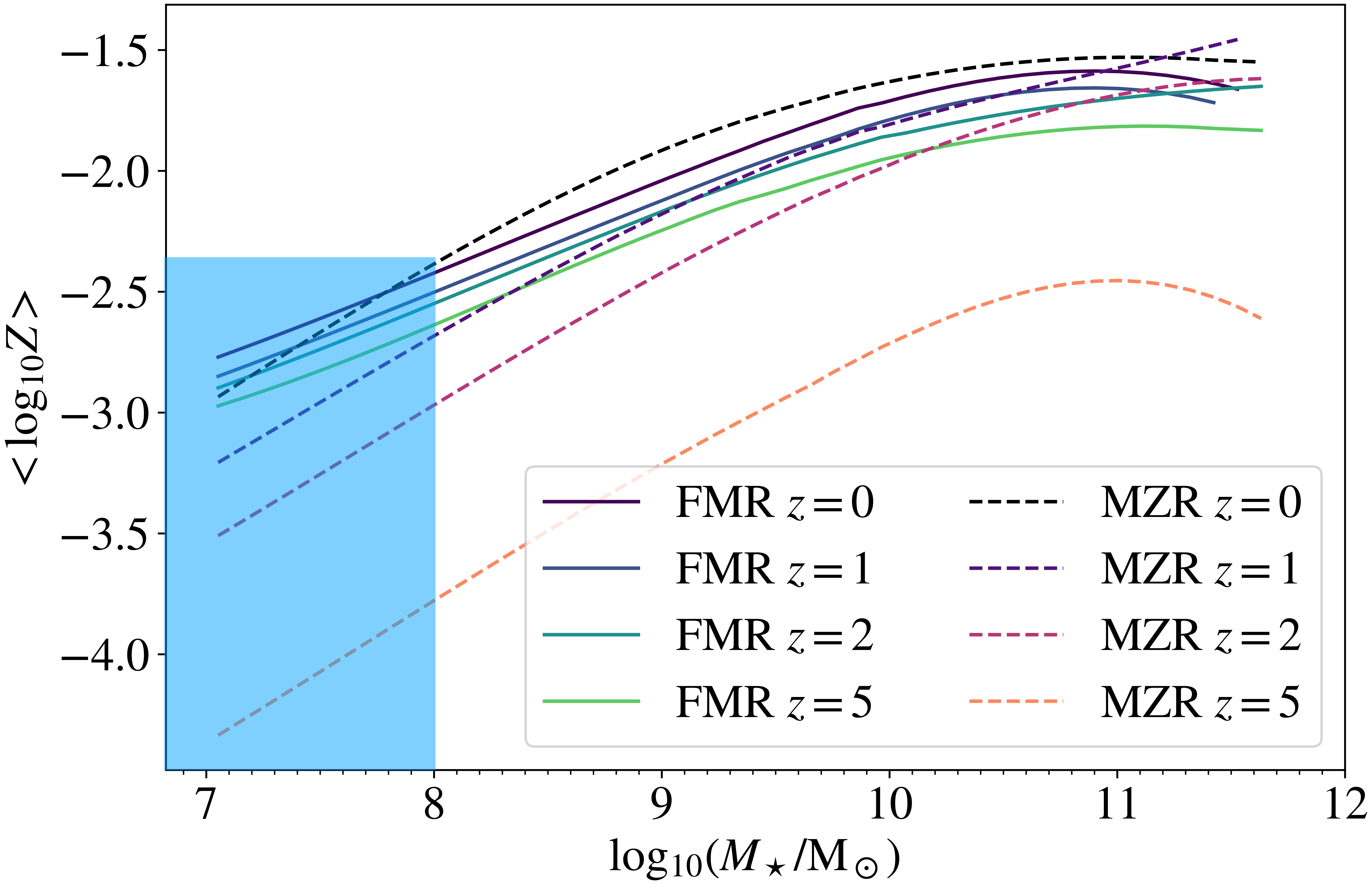
Credits: Chruślinska 2022

Metallicity distribution



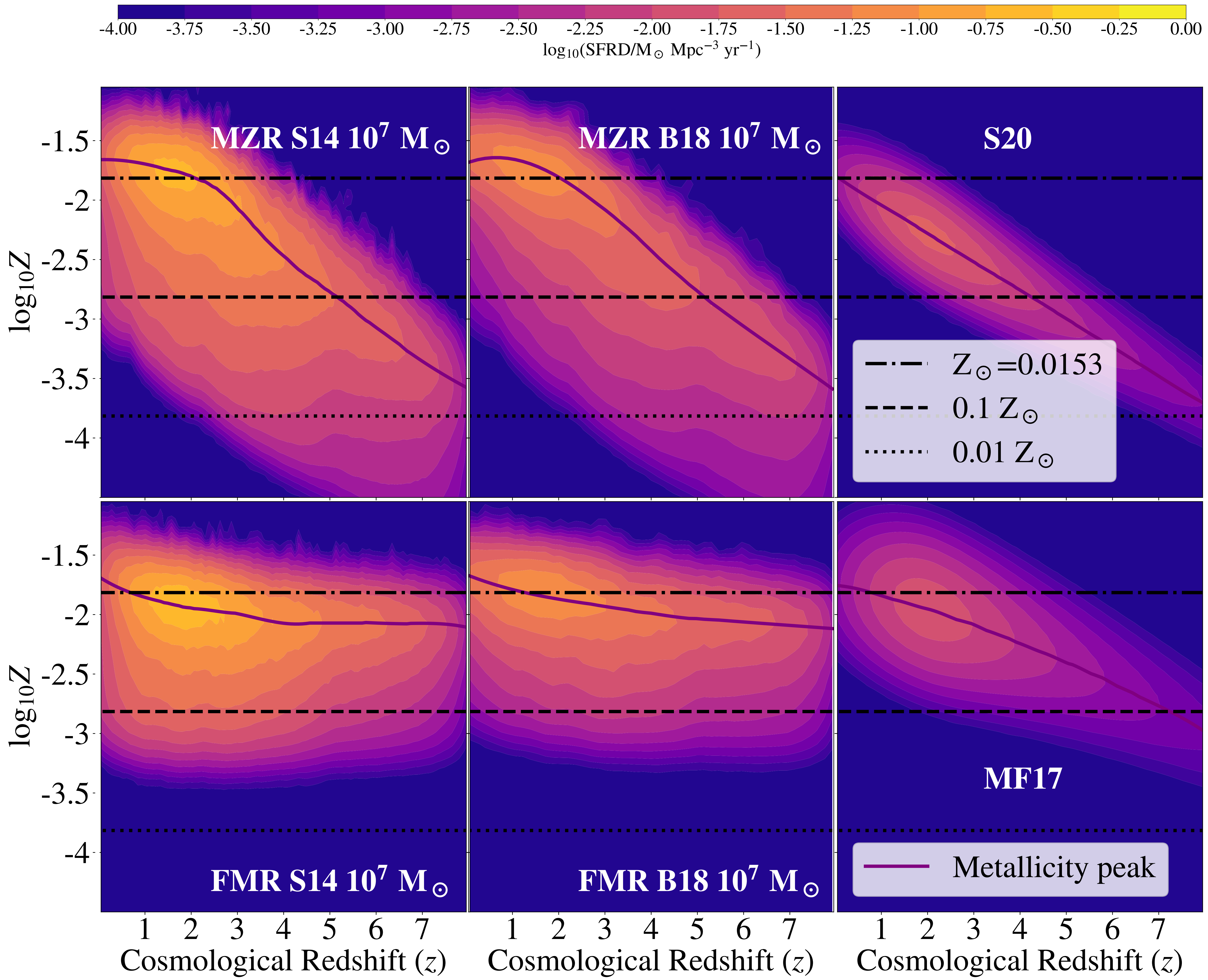
Refs: Mannucci et al. 2011, Chruslinska & Nelemans 2019, Curti et al. 2020,

Metallicity distribution



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

SFRD(z, Z)



Refs: Santoliquido et al. 2022

galaxyRate

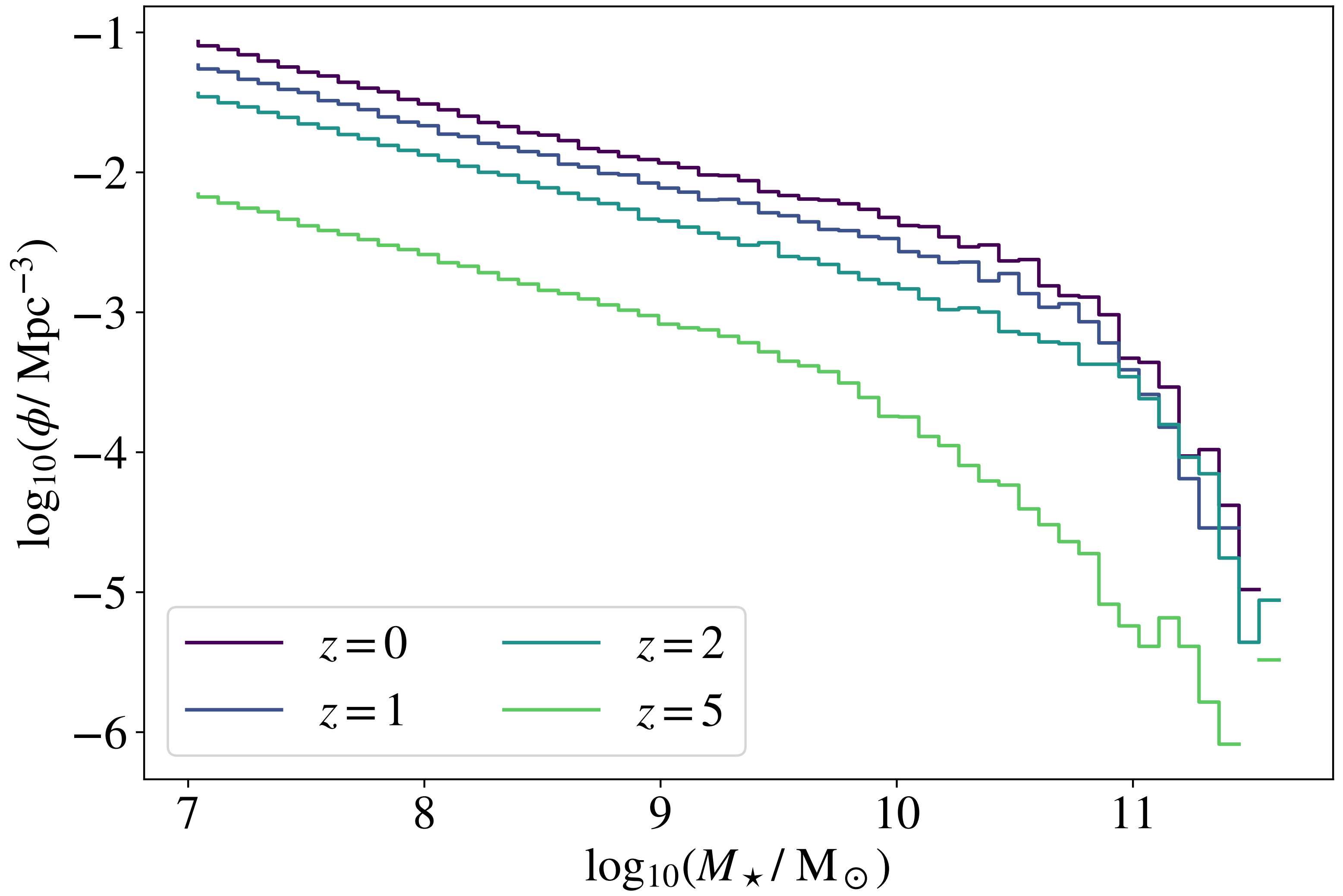

Formation galaxies
Merging compact objects
Host galaxies

Formation galaxies → Merging compact objects → Host galaxies

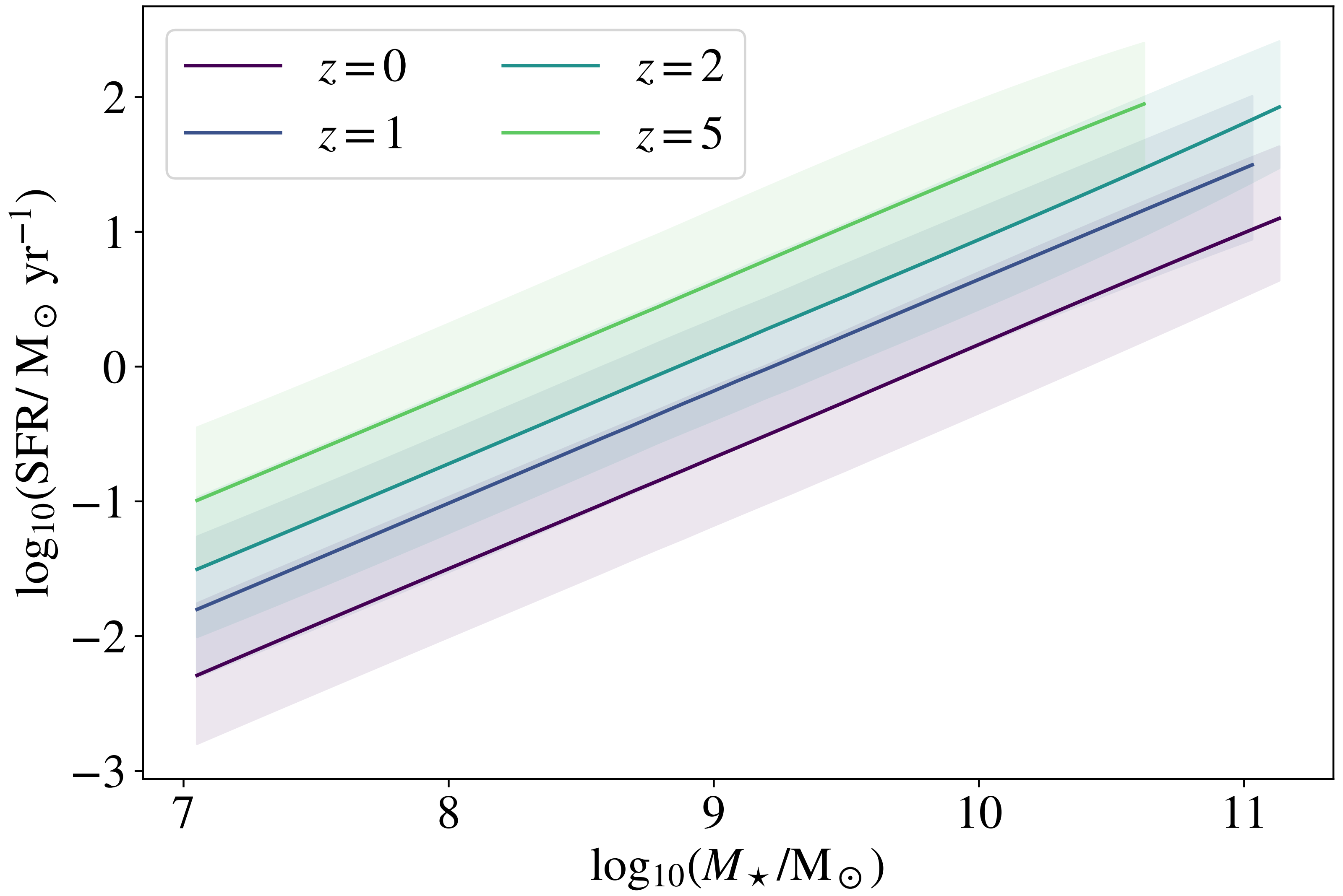
↑

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

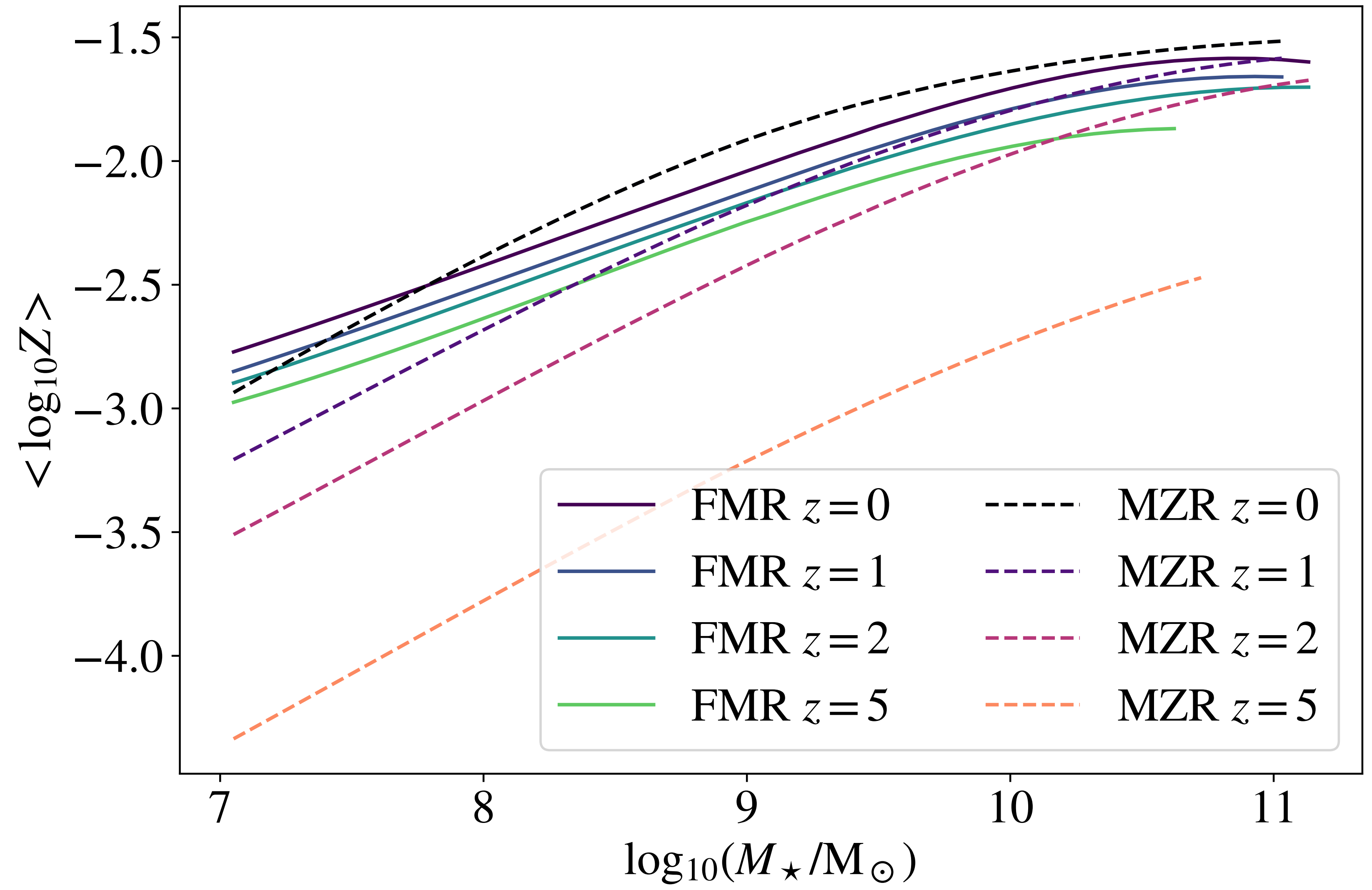
Stellar mass



Star-formation rate



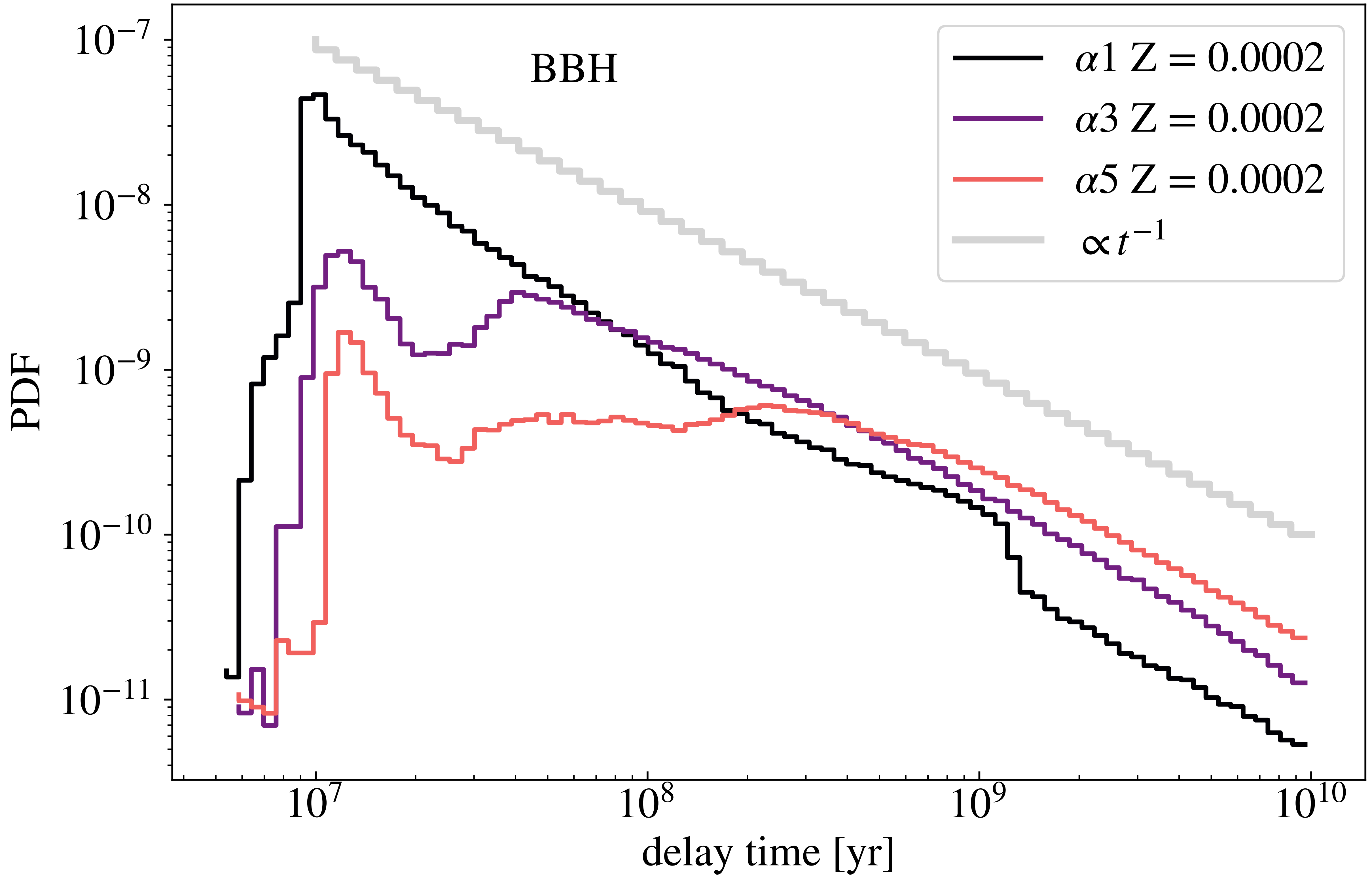
Metallicity



Formation galaxies

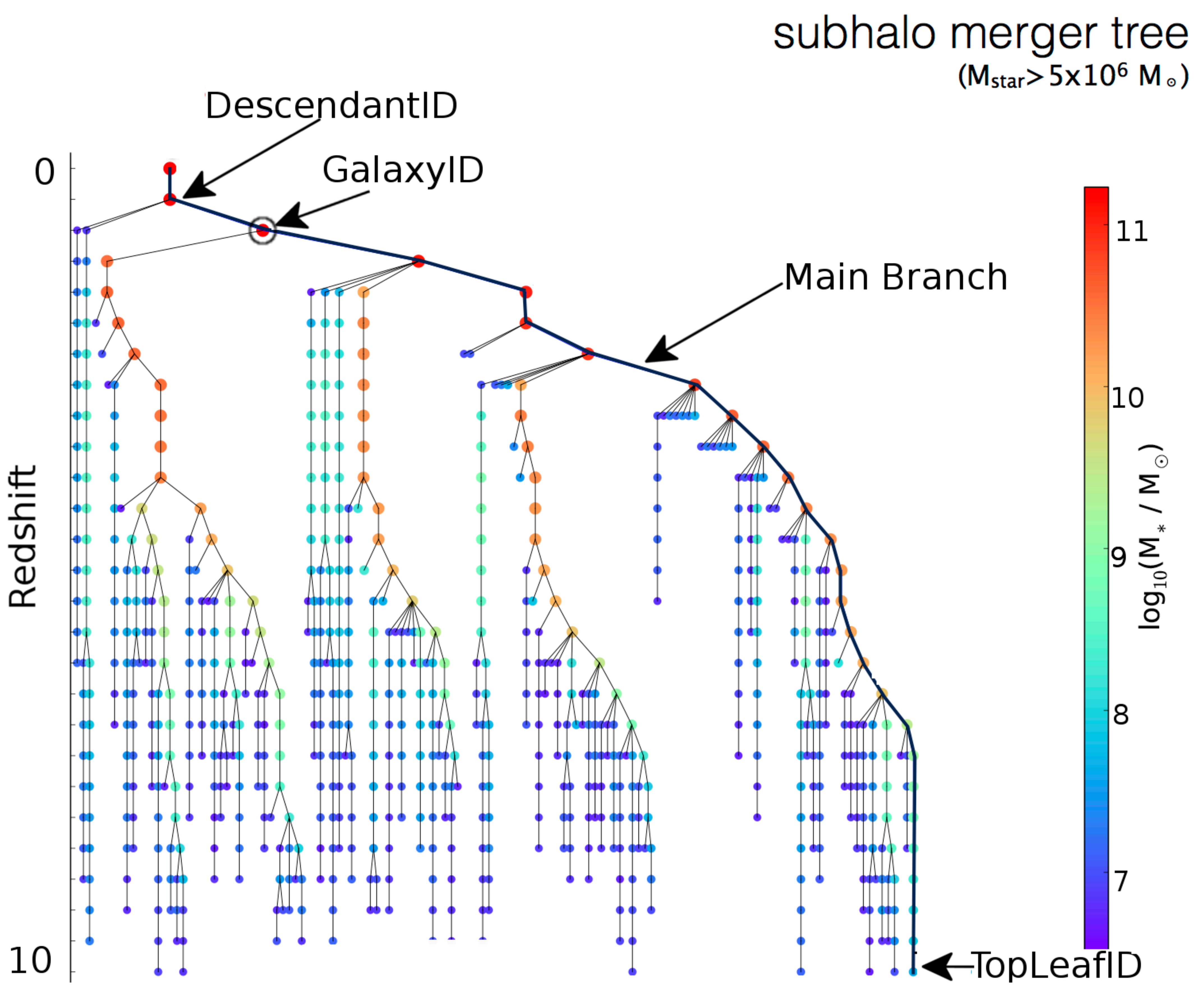
Merging compact objects

Host galaxies



Effect of common envelope on delay time

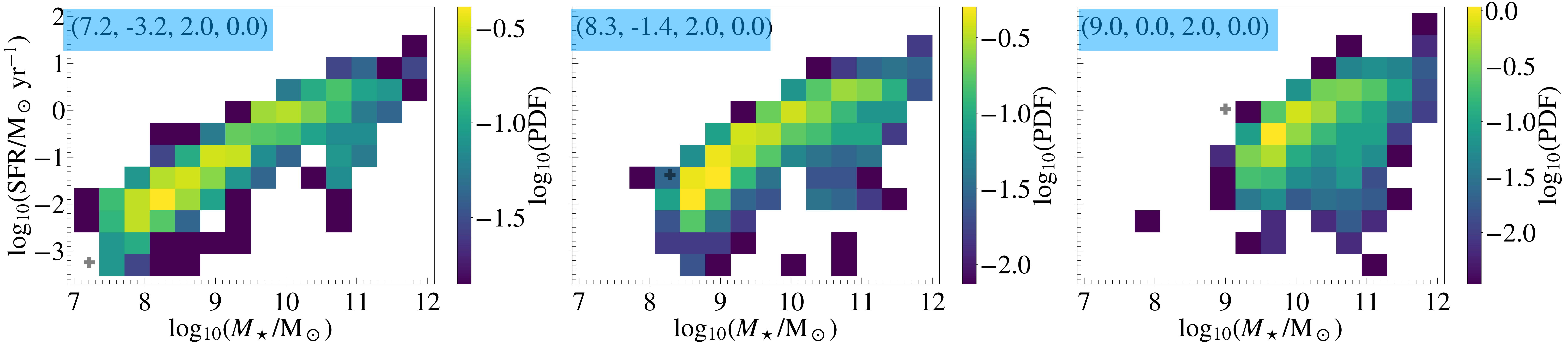
Formation galaxies → Merging compact objects → Host galaxies

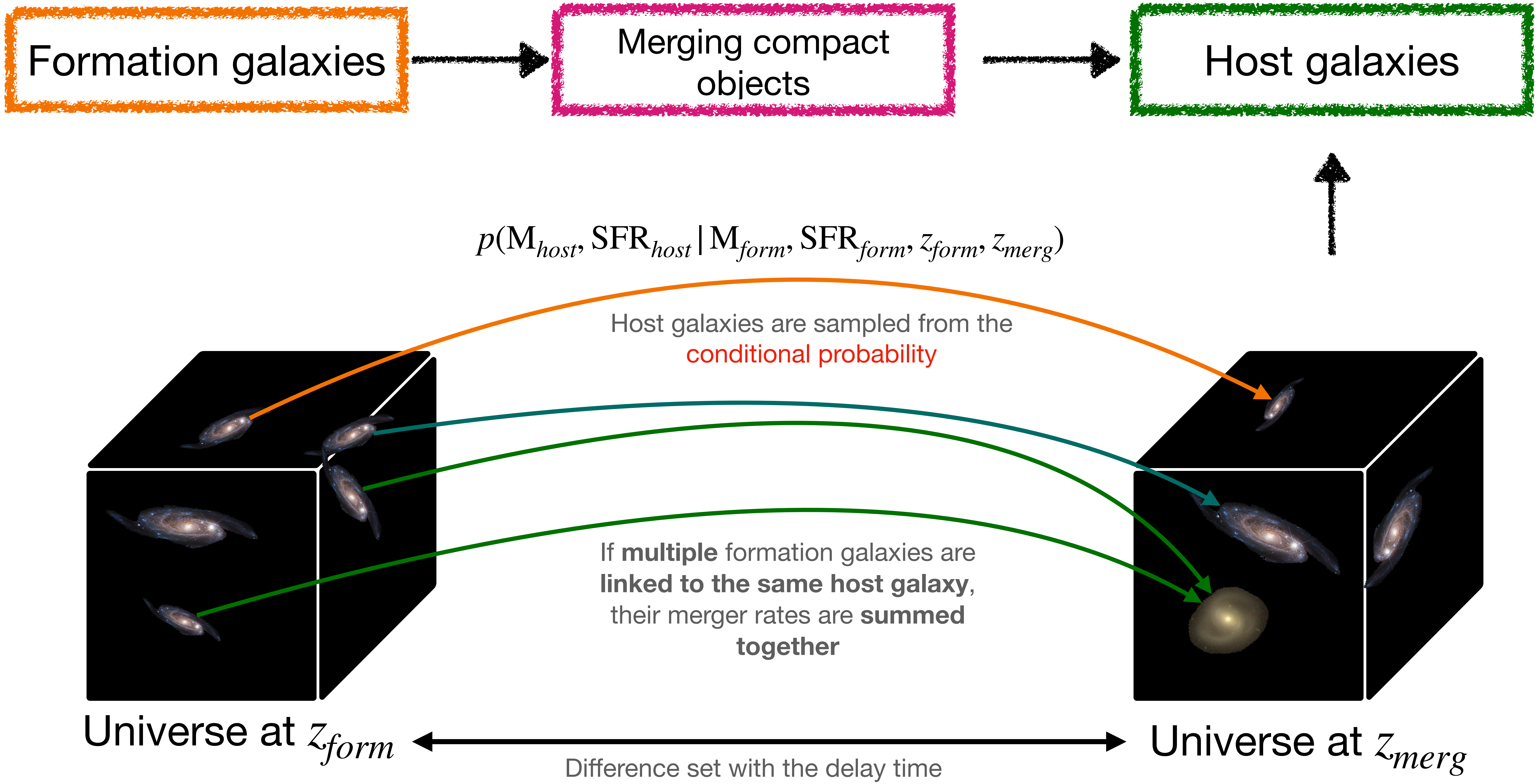


Refs: Schaye et al. 2015, McAlpine et al. 2016

Formation galaxies → Merging compact objects → Host galaxies

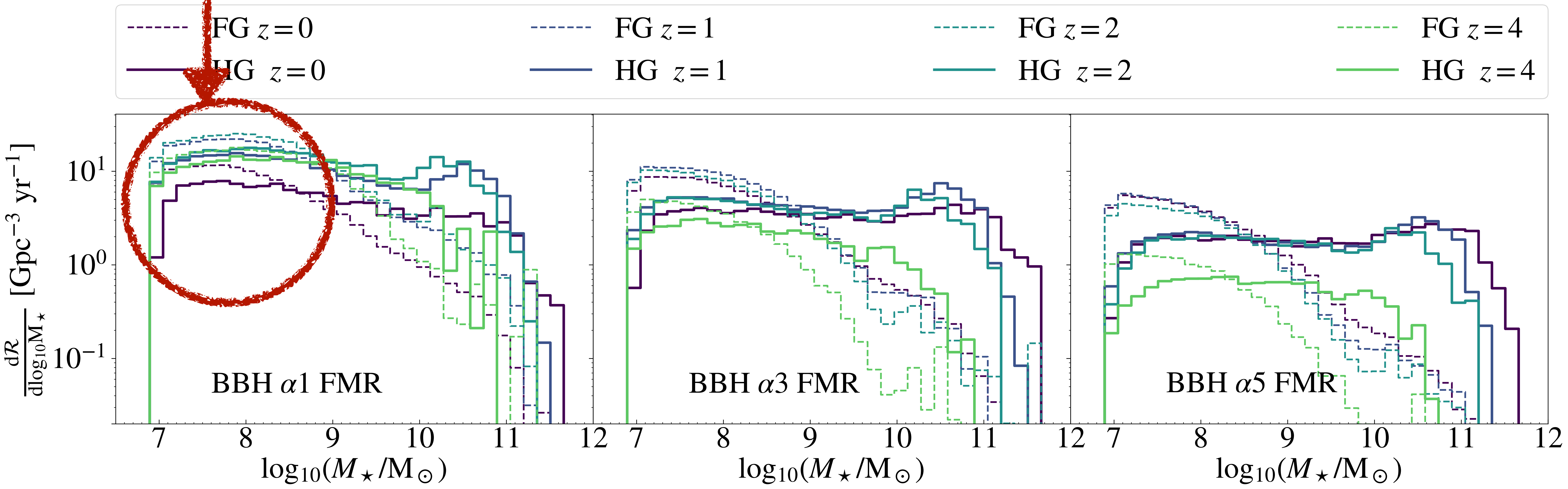
From the **merger trees**, I compute a **conditional probability:** $p(\mathrm{M}_{host}, \mathrm{SFR}_{host} \,|\, \mathrm{M}_{form}, \mathrm{SFR}_{form}, z_{form}, z_{merg})$




Formation galaxies
Merging compact objects
Host galaxies
$p(\mathrm{M}_{host}, \mathrm{SFR}_{host} \,|\, \mathrm{M}_{form}, \mathrm{SFR}_{form}, z_{form}, z_{merg})$
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

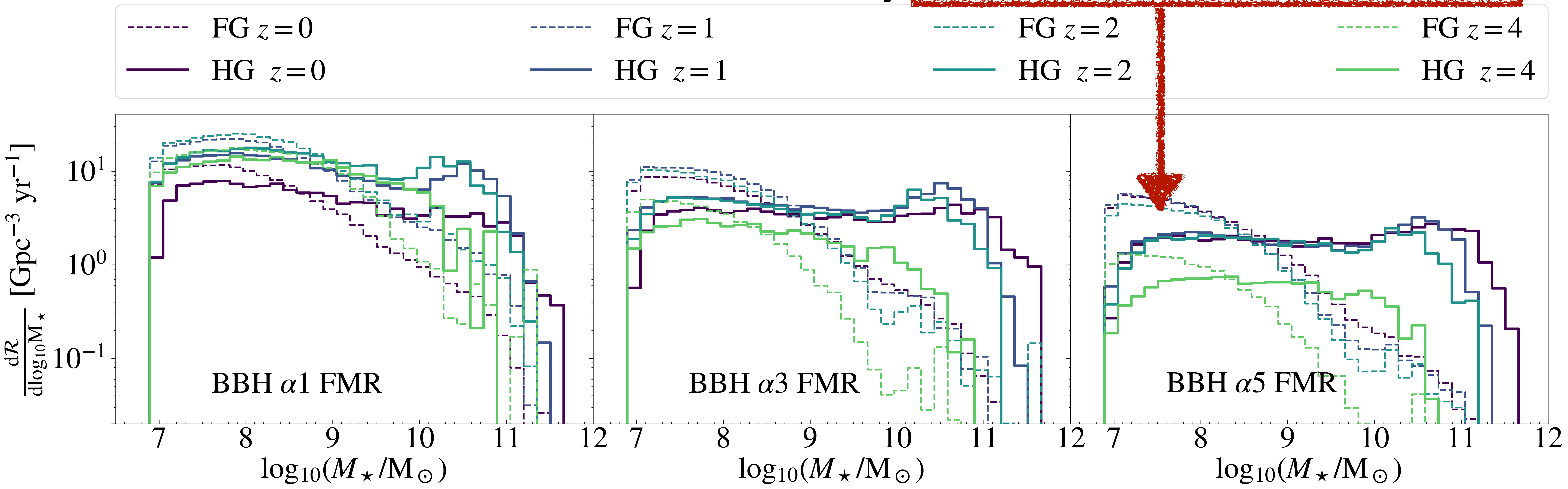
1) BBHs form in low-mass galaxies and merge in low-mass galaxies



`galaxyRate`: host galaxy stellar mass

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

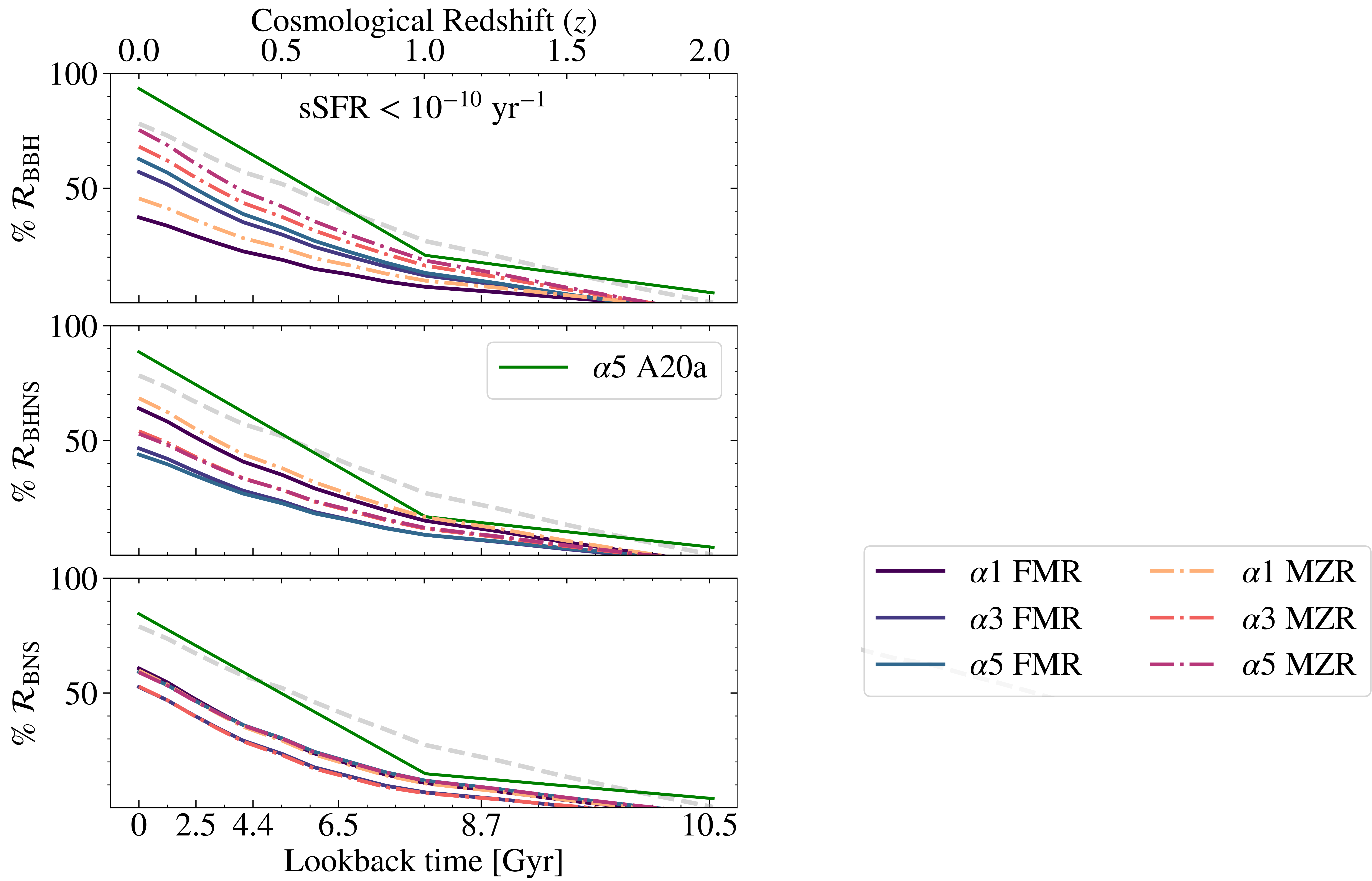
2)



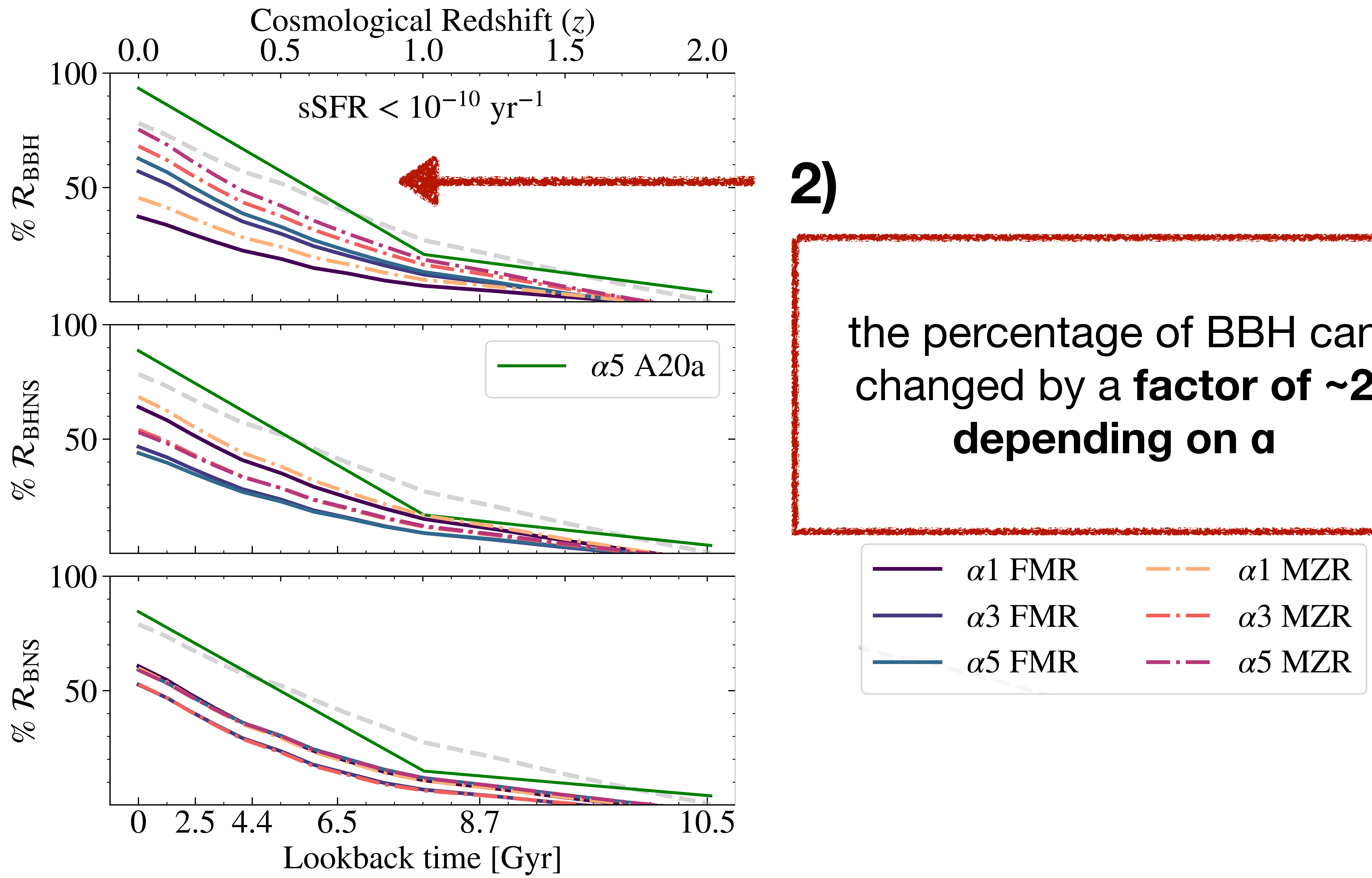
galaxyRate: **passive galaxies**

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?

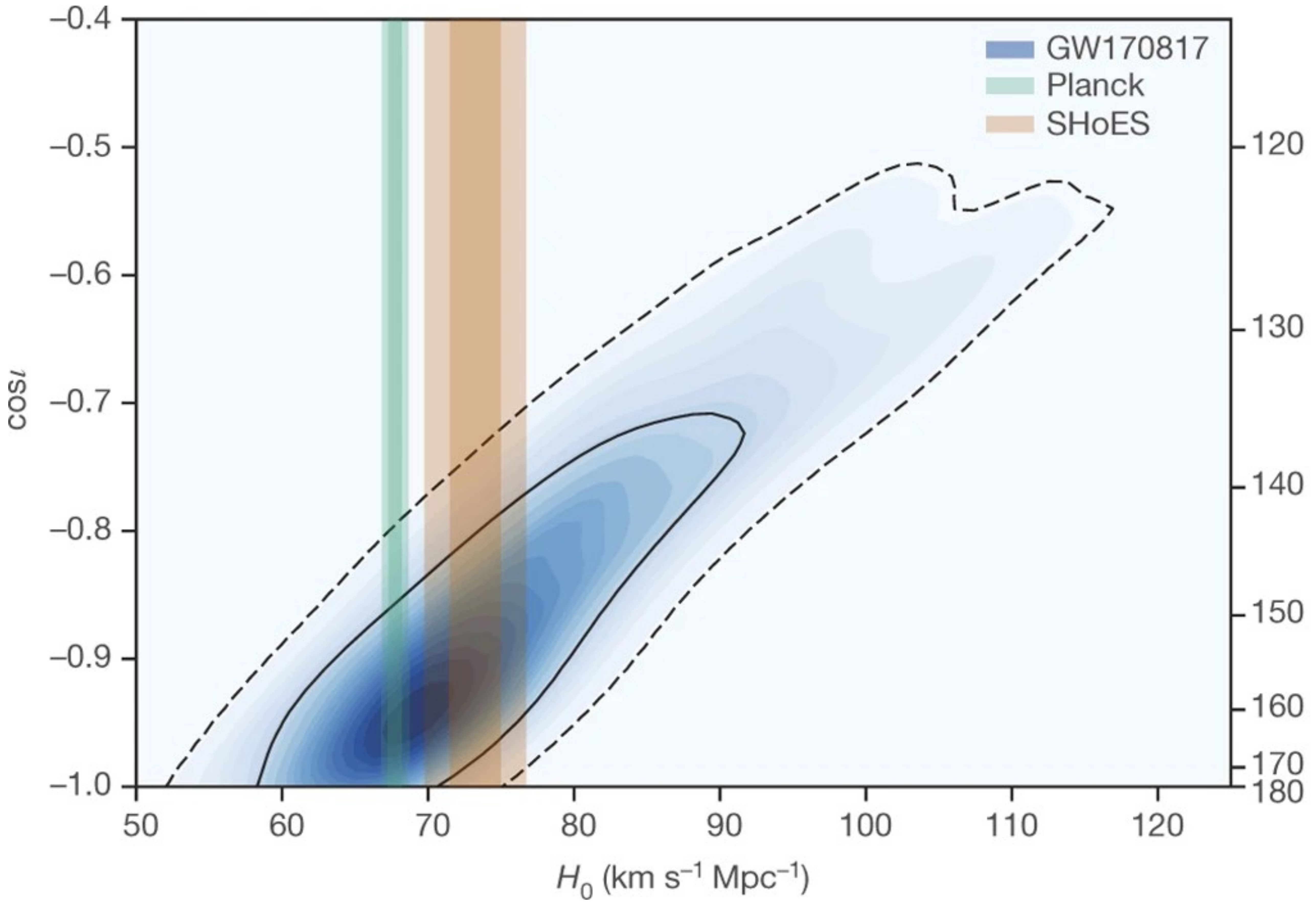
GW and cosmology

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

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

GW and cosmology

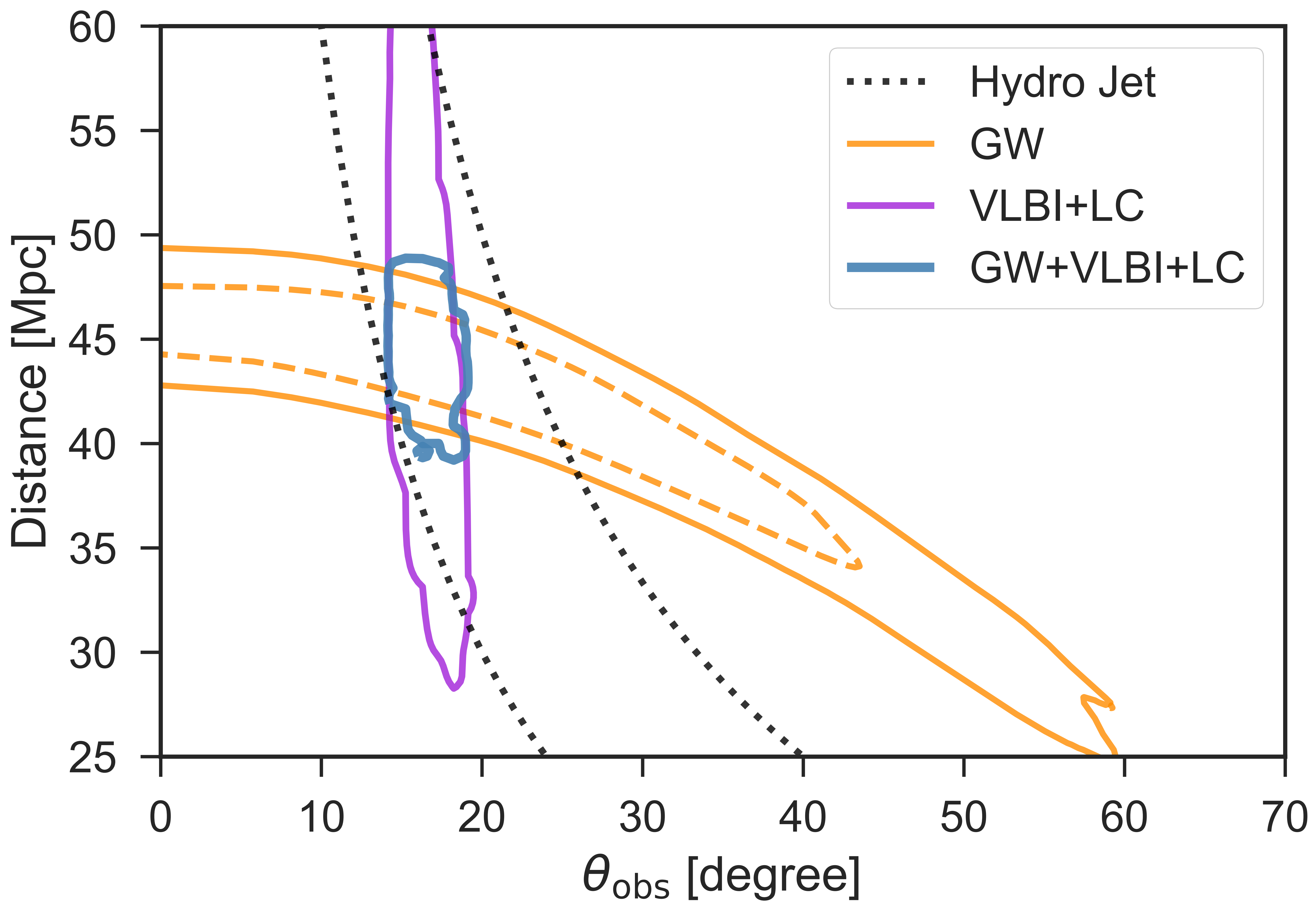
- $v_\mathrm{H} = H_0 d_L$
- Recession velocity from NGC 4993: $v_H = 3017 \pm 166 \text{ km s}^{-1}$
- $d_L = 43.8^{+2.9}_{-6.9}$ Mpc
- $H_0 = 70.0^{+12.0}_{-8.0} \text{ km s}^{-1} \text{ Mpc}^{-1}$ 68% C.I.
- SHoES: Cepheids and type Ia SN



Refs: Abbott et al. 2017

GW and cosmology

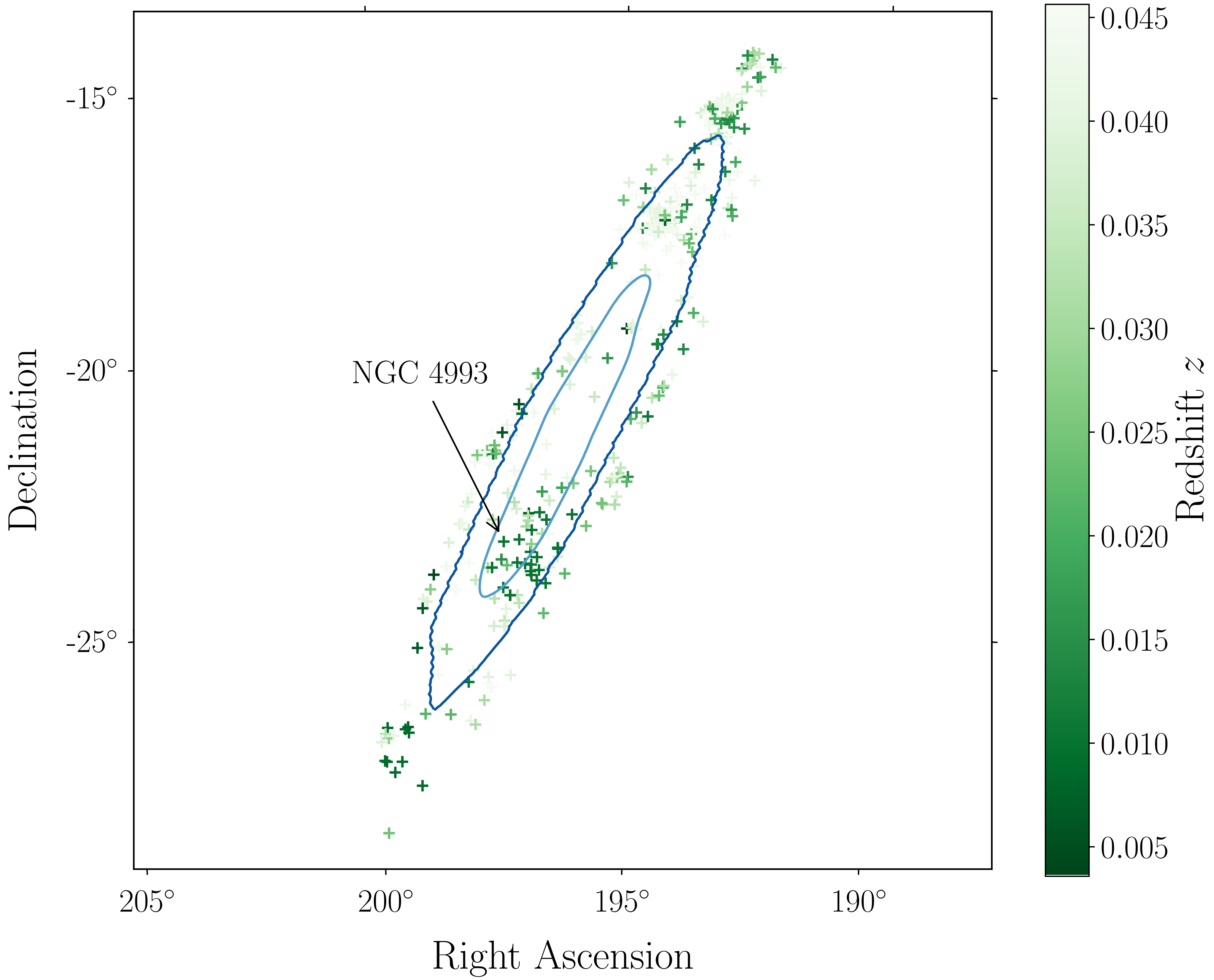
- **Bright sirens:** EM counterpart breaks the inclination angle/ luminosity distance degeneracy ➡️ inclination angle from KN and afterglow models



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
- ET and the future of GW

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!**