

Gravitational Wave Astrophysics

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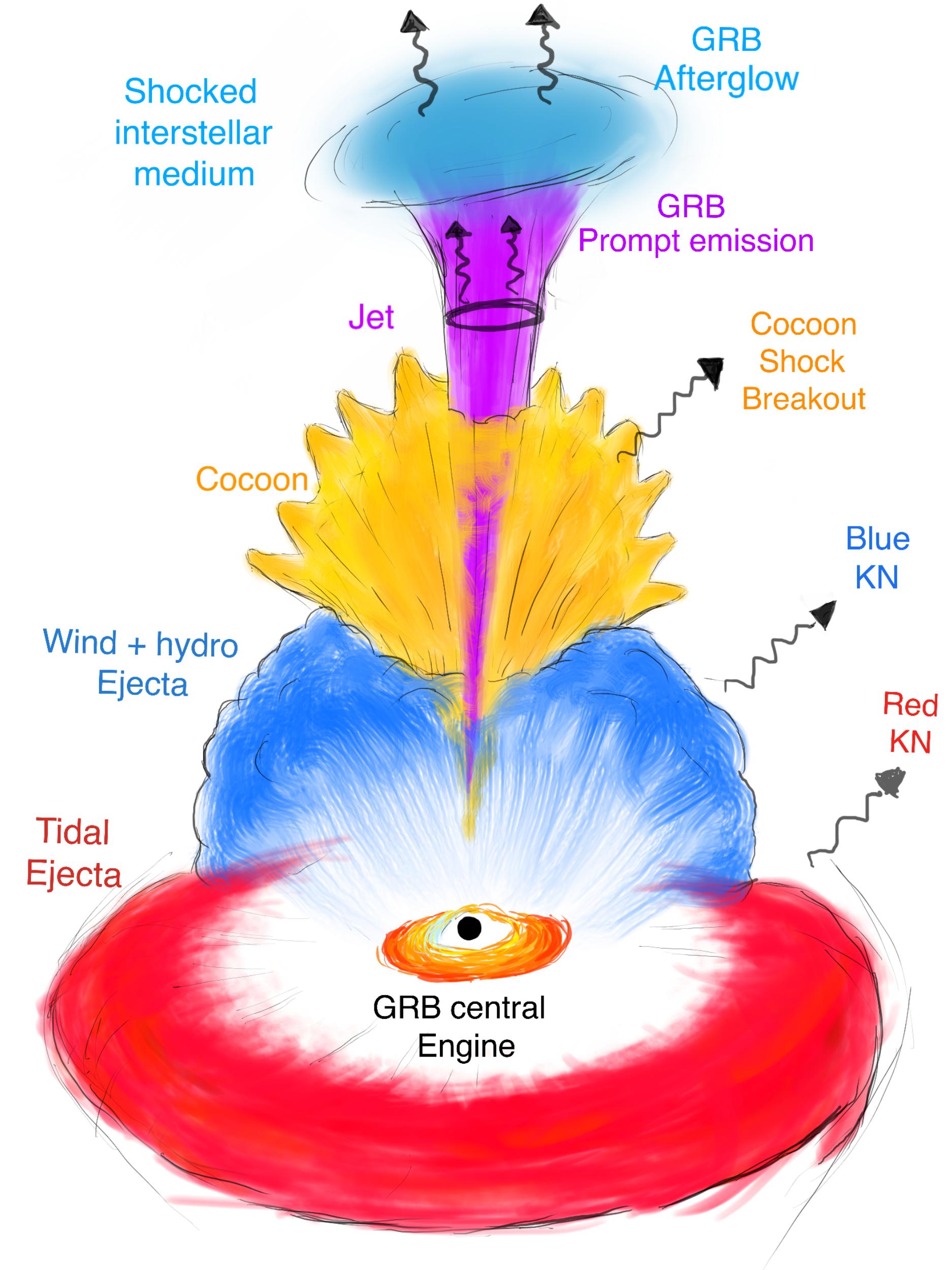
In this lecture, you will learn

- Multimessenger astrophysics
- Host galaxies and how to model them
- GW events 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

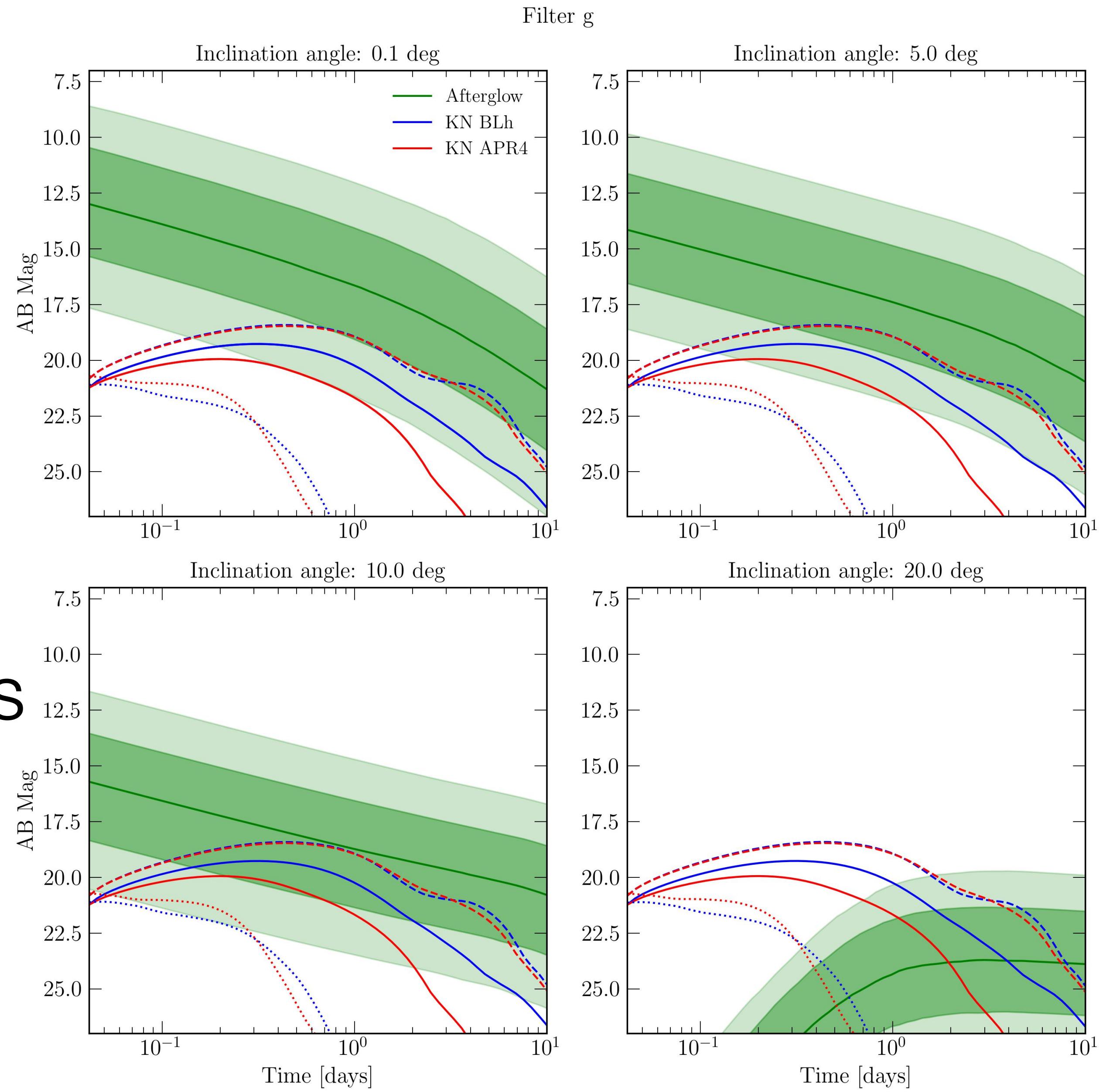


The Kilonova

- $$L_{\text{peak}} = 2.5 \times 10^{40} \frac{\text{erg}}{\text{s}} \left(\frac{v_{\text{ej}}}{0.1 c} \frac{10 \text{ cm}^2/\text{g}}{k} \right)^{0.65} \left(\frac{m_{\text{ej}}}{0.01 M_{\odot}} \right)^{0.35} \left(\frac{\dot{e}_0}{5 \times 10^{16} \text{ erg s}^{-1} \text{ g}^{-1}} \right)$$
- m_{ej} and v_{ej}  **Astrophysics**
- k (opacity)  **Atomic Physics**
- \dot{e}_0 (radioactive heating rate)  **Nuclear Physics**

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

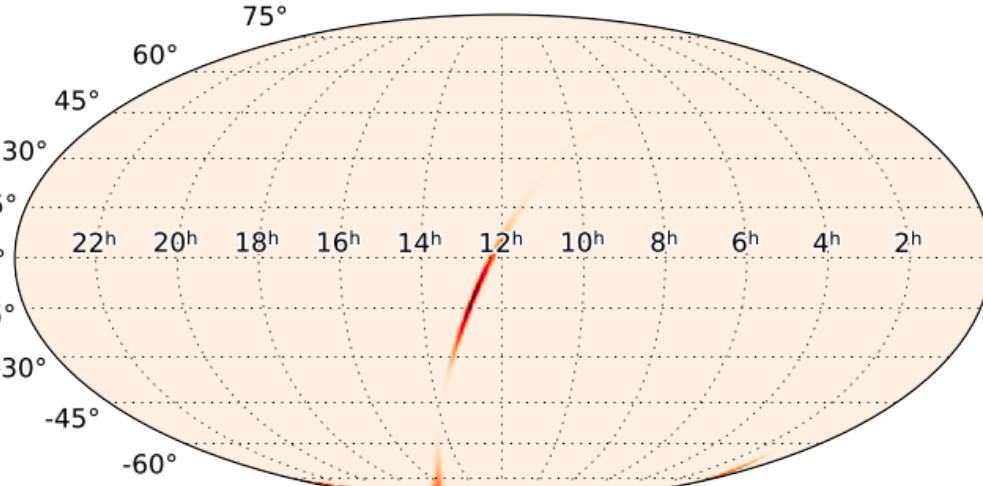
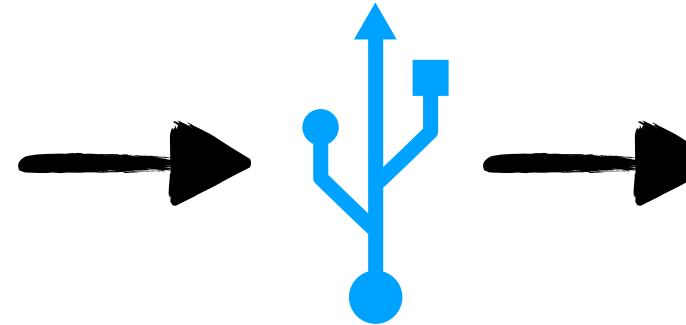


Low latency

Detectors



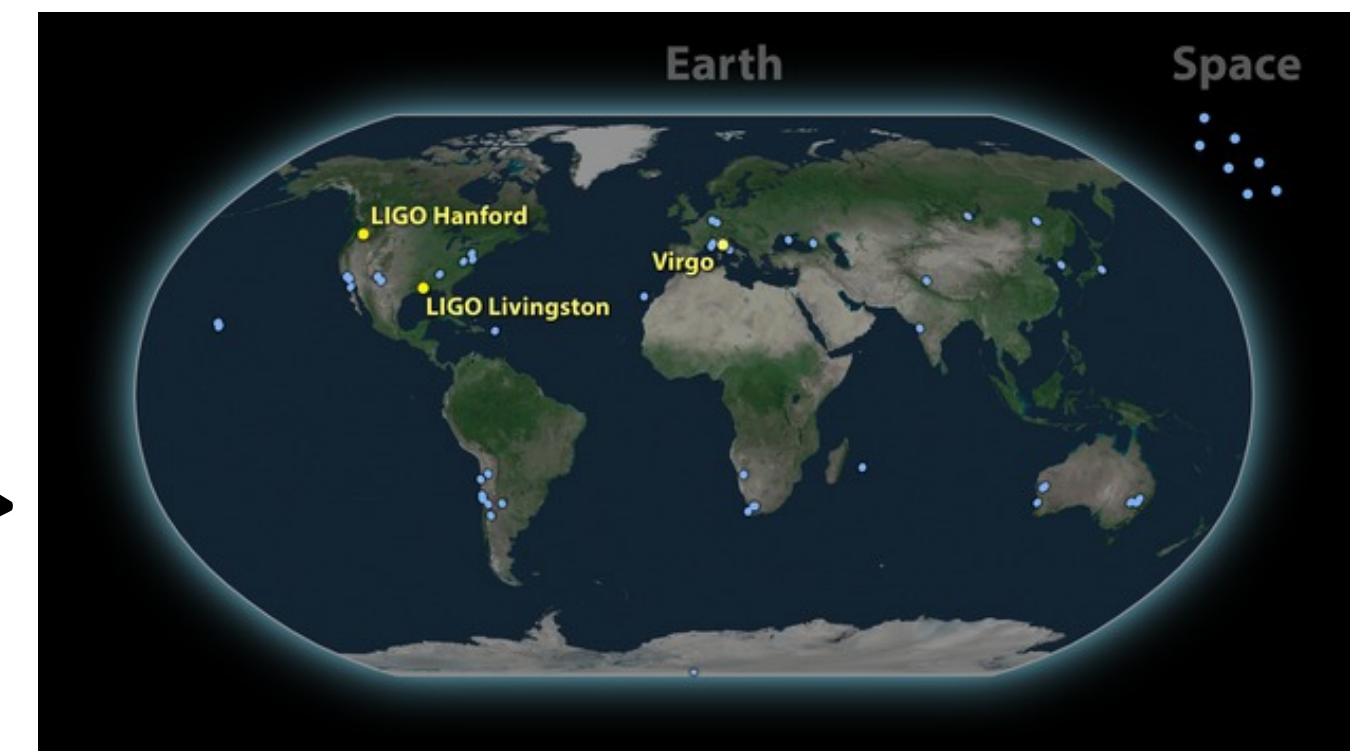
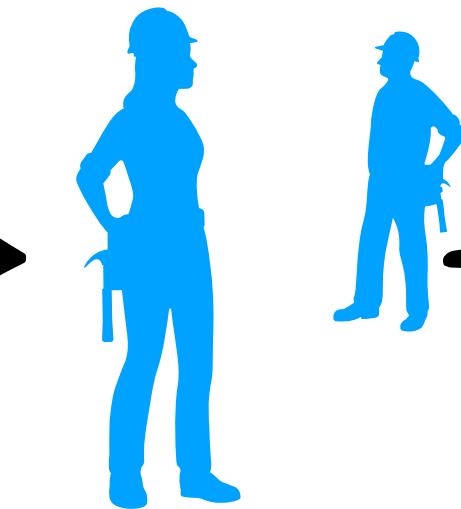
Automatic searches



Credits: [The LIGO-Virgo-KAGRA collaboration](#)

Sky localisation

Human validation



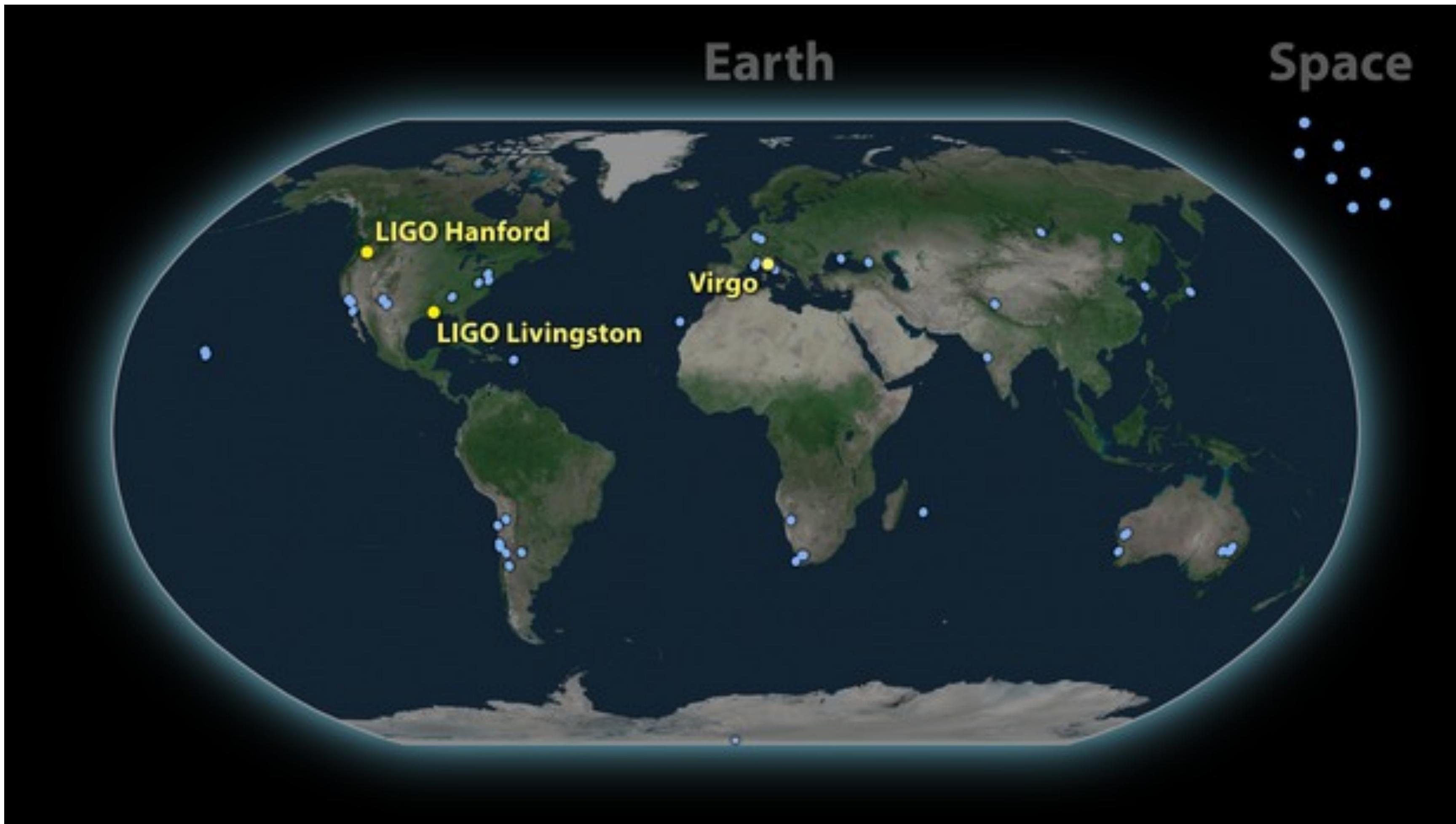
Credits: [The LIGO-Virgo-KAGRA collaboration](#)

~ few minutes

~ 30 minutes

Low latency

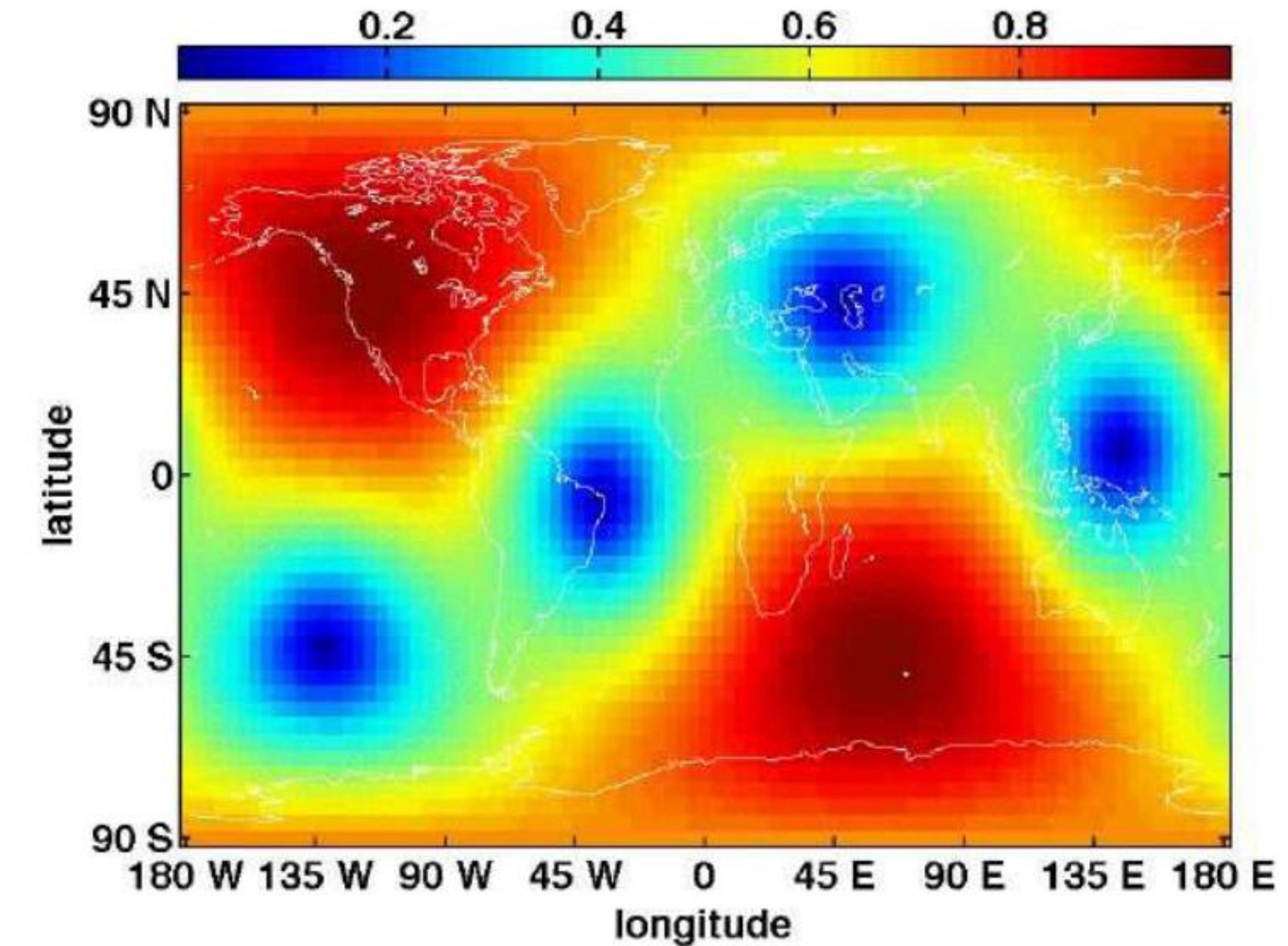
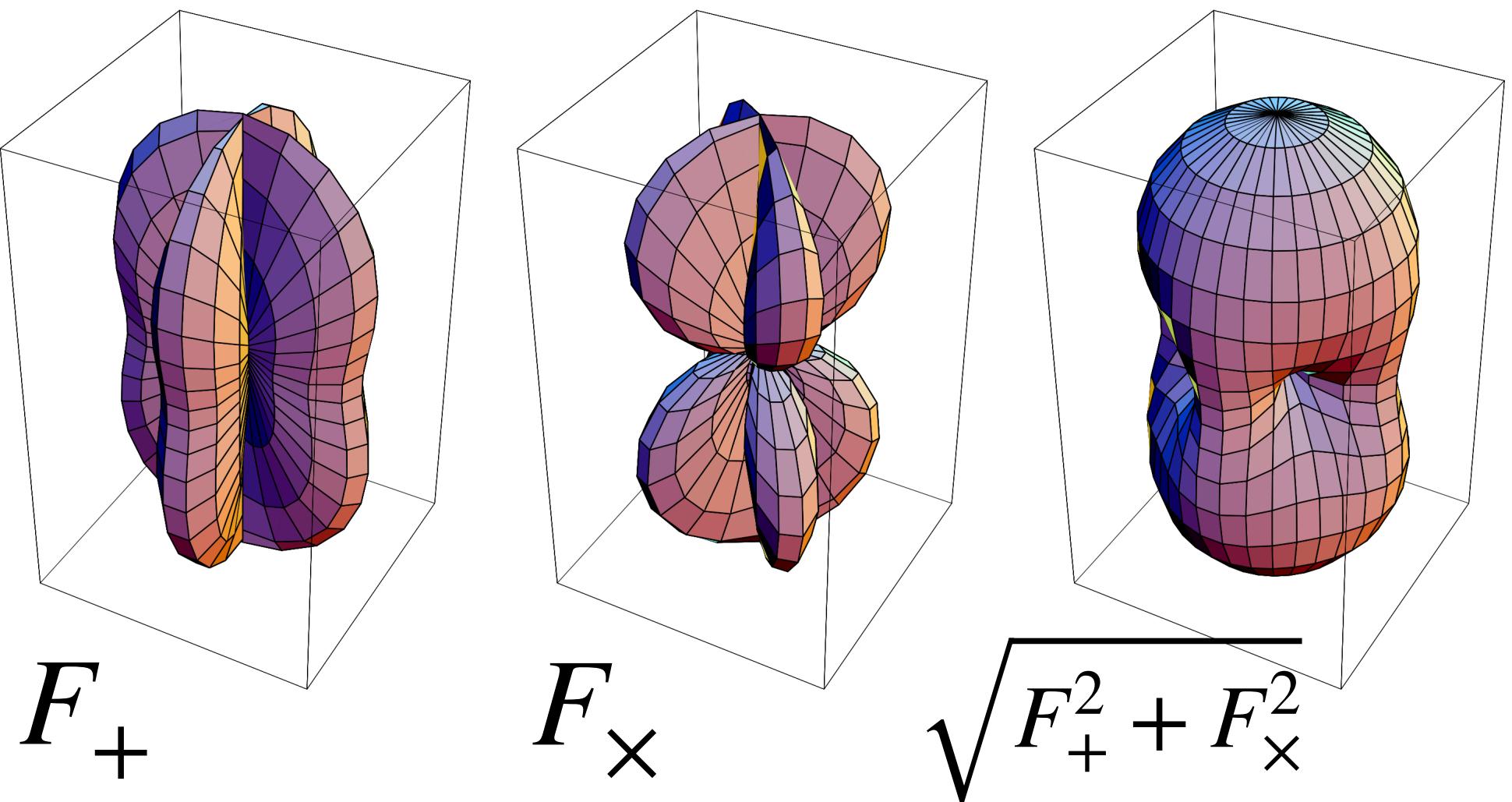
EM facilities



Sky localisation

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

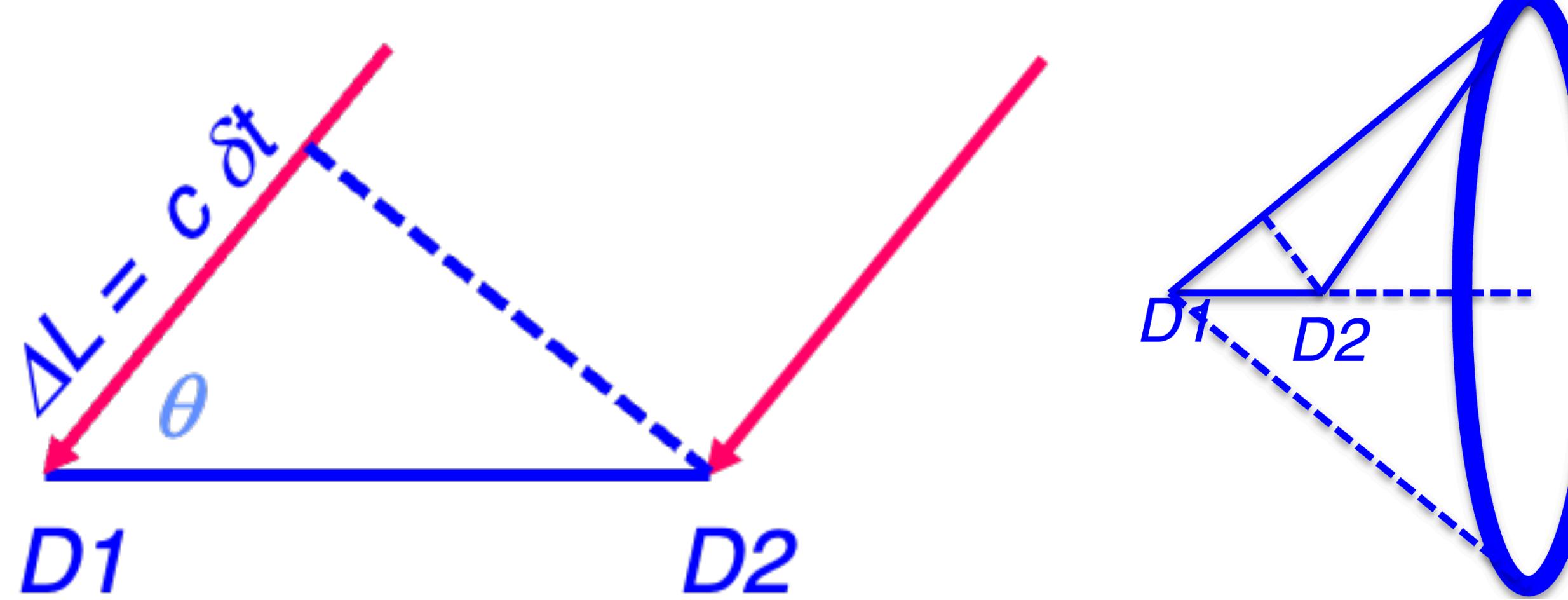
Credits: [the LIGO-Virgo-KAGRA collaboration](#)



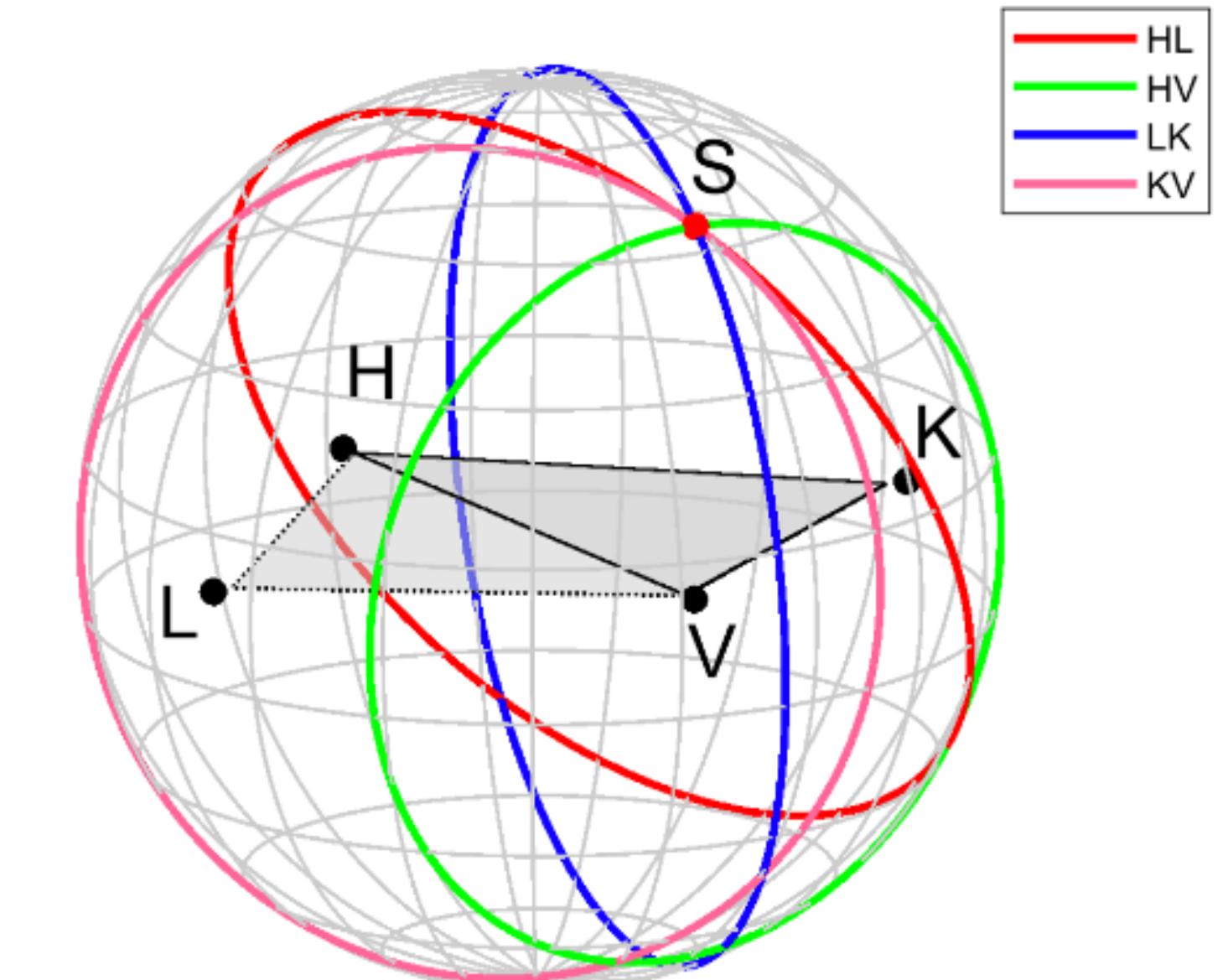
Credits: [Hayama et al. 2012](#)

Triangulation

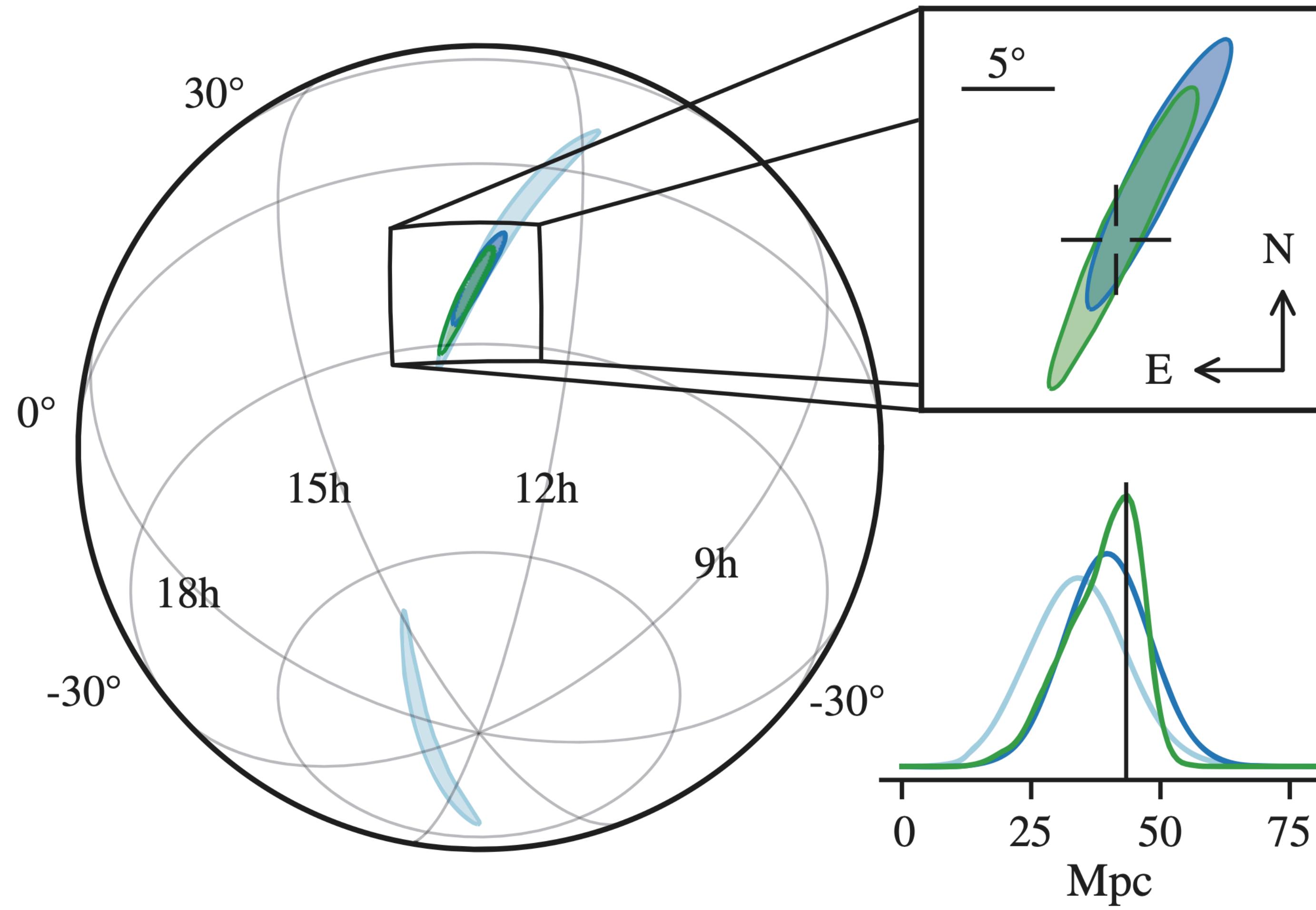
- Sky position of GW sources is evaluated with triangulation
- Difference in the arrival time at the detectors
- $\Delta\Omega \propto SNR^{-2}$



Credits: [The LVK collaboration](#)



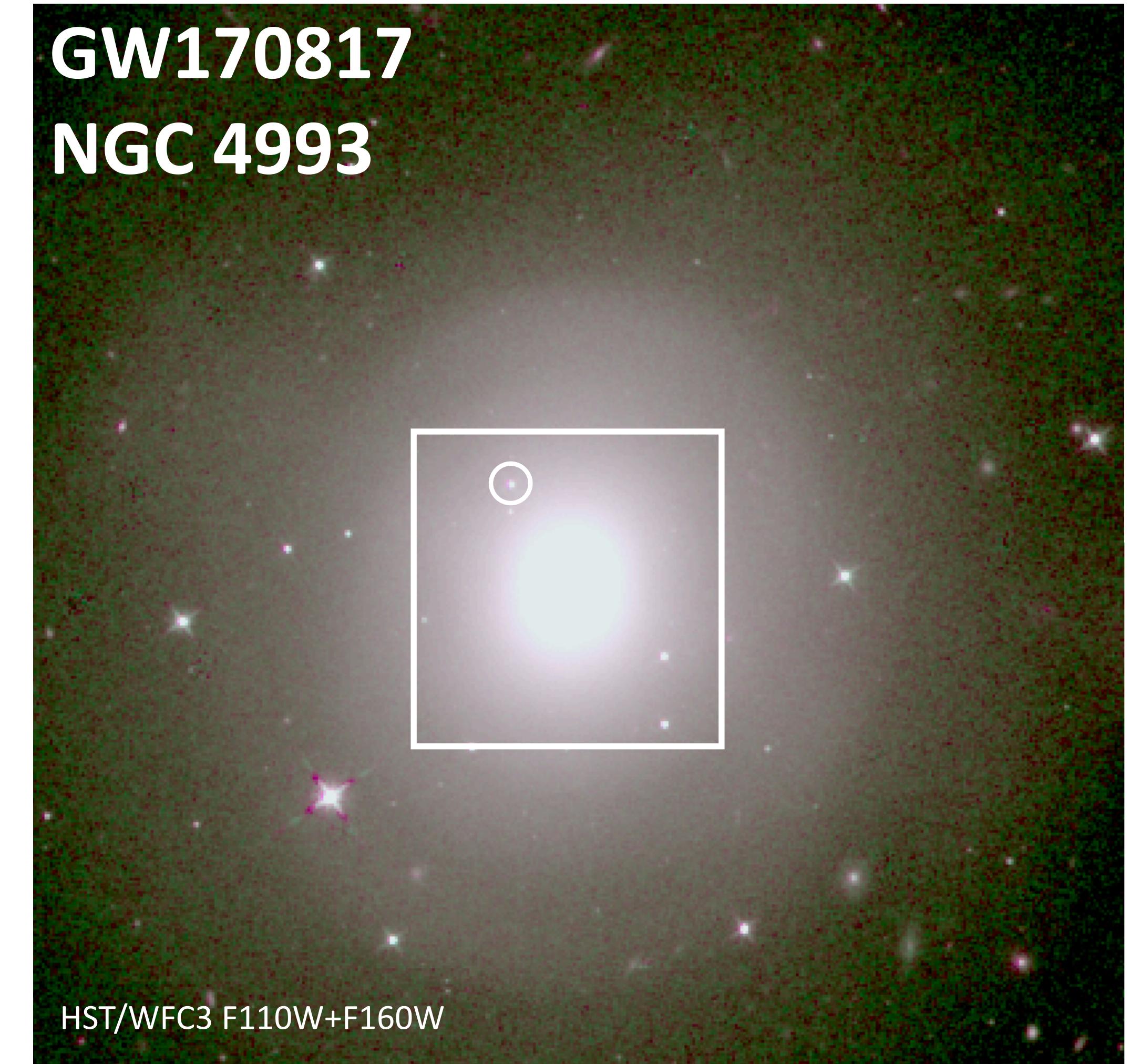
GW170817



Credits: [The LVK collaboration](#)

GW170817 host galaxy

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



Refs: [Levan et al. 2017](#), [Blanchard et al. 2017](#)

How to model host galaxies

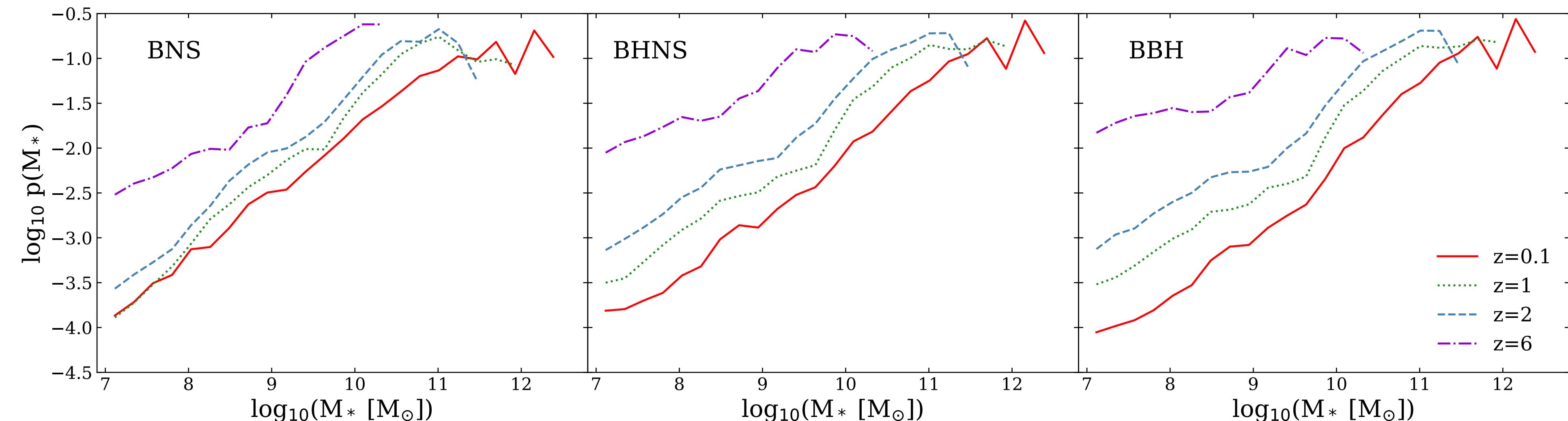
- **Challenge:** interfacing Physics at scales spanning orders of magnitude
 - Evolution of galaxies across history of the Universe and formation of compact object mergers at binary system level
 - We can do that with galaxy catalogs from cosmological simulations

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 rank galaxies

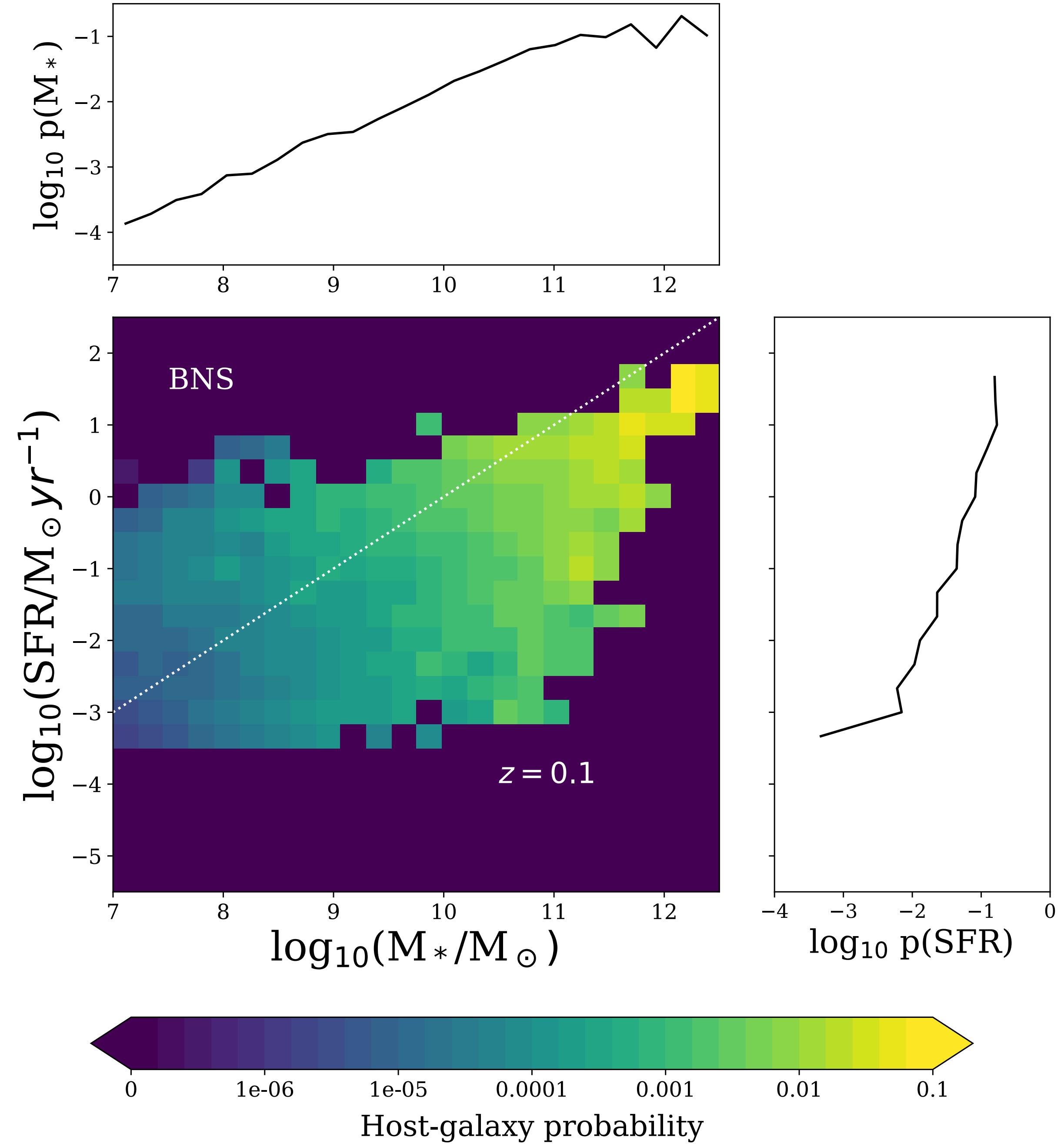
- $p(\text{galaxy } k) \propto p(M, \text{SFR}) p_{\text{loc}}(\text{galaxy } k)$
- $p(M, \text{SFR}) \propto N_{GW}/N_{\text{galaxies}}$
- N_{GW} total number of mergers and N_{galaxies} total number of galaxies at (M, SFR)

Refs: [Artale et al. 2020](#)



How to rank galaxies

Strong correlation:
stellar mass VS
merger rate



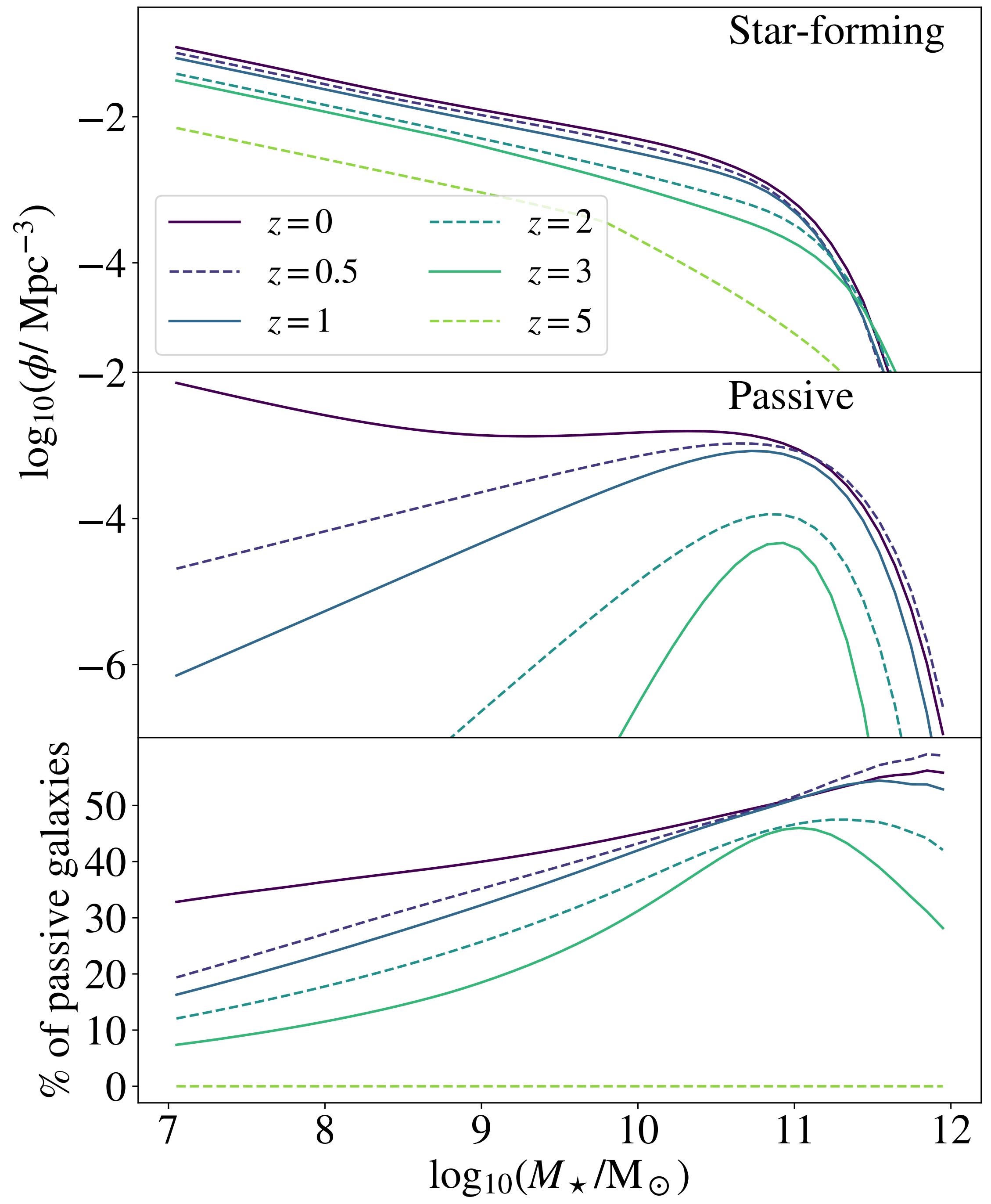
Refs: [Artale et al. 2020](#)

How to model host galaxies

- Need to explore the parameter space?
- alternative approach: **galaxyRate**
- **key physical processes** shaping host galaxy properties

GSMF

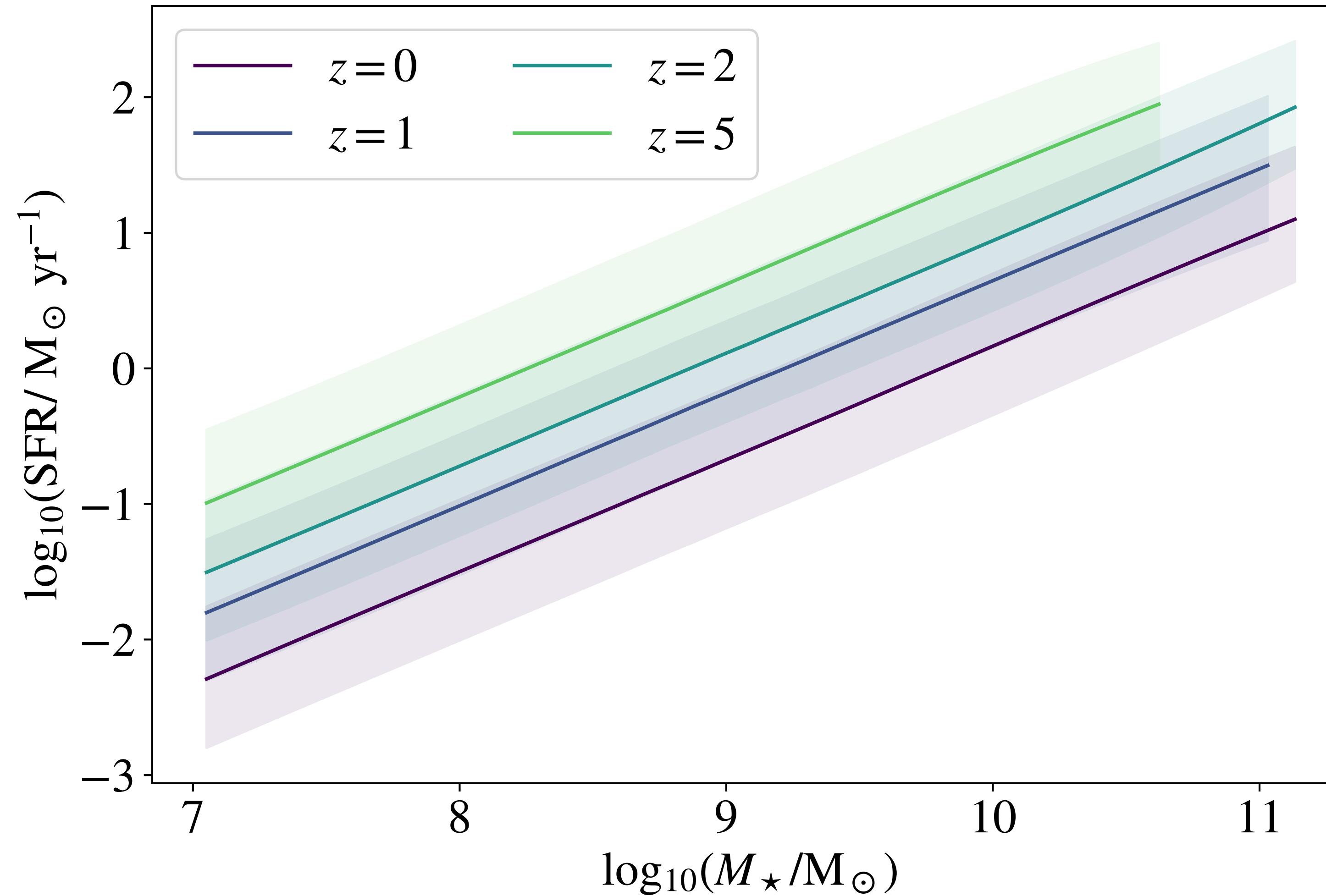
Refs: [Chruslinska & Nelemans 2019](#), [Ilbert et al. 2013](#),
[Santoliquido et al. 2022](#)



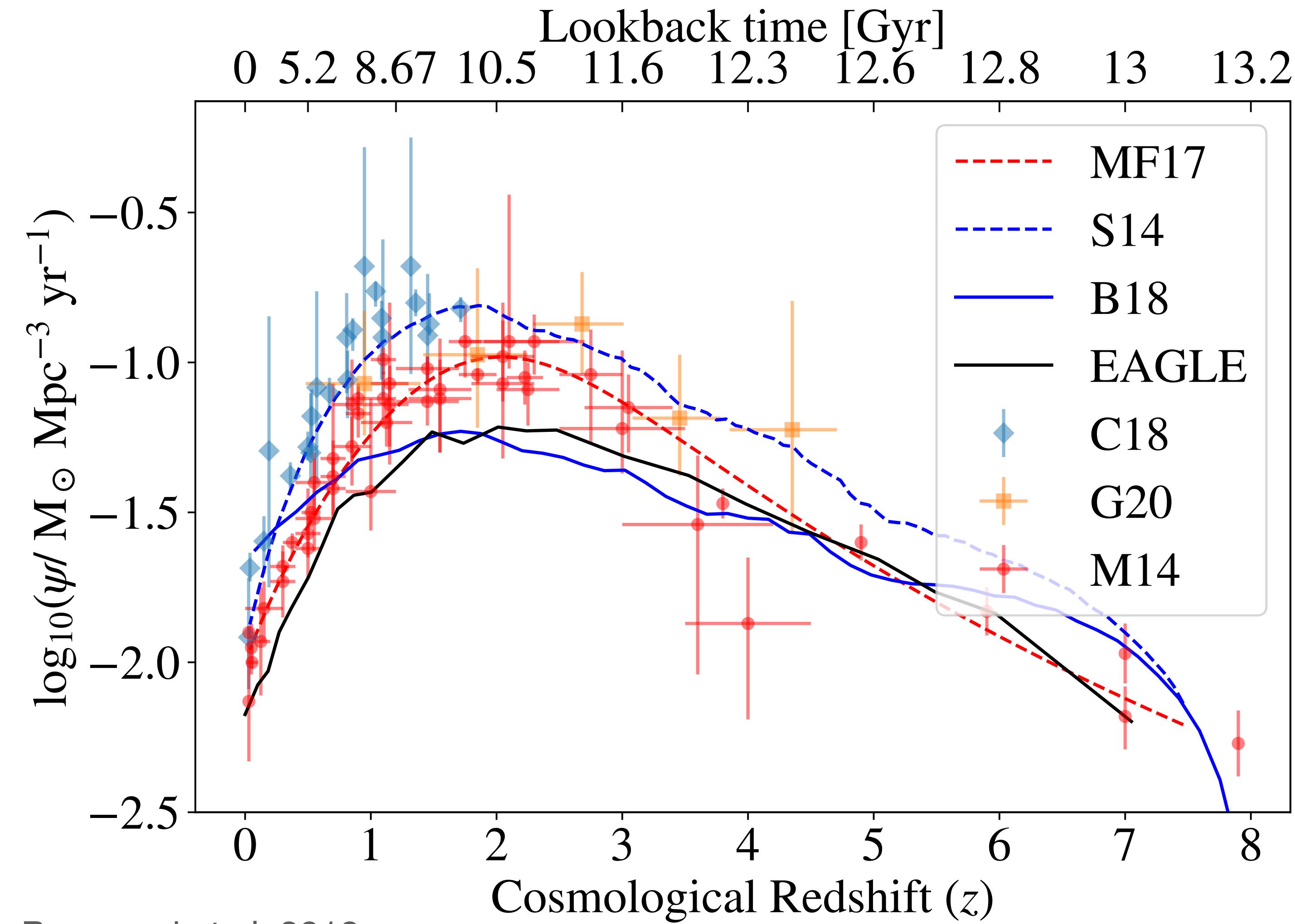
SFR main sequence

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

SFR main sequence



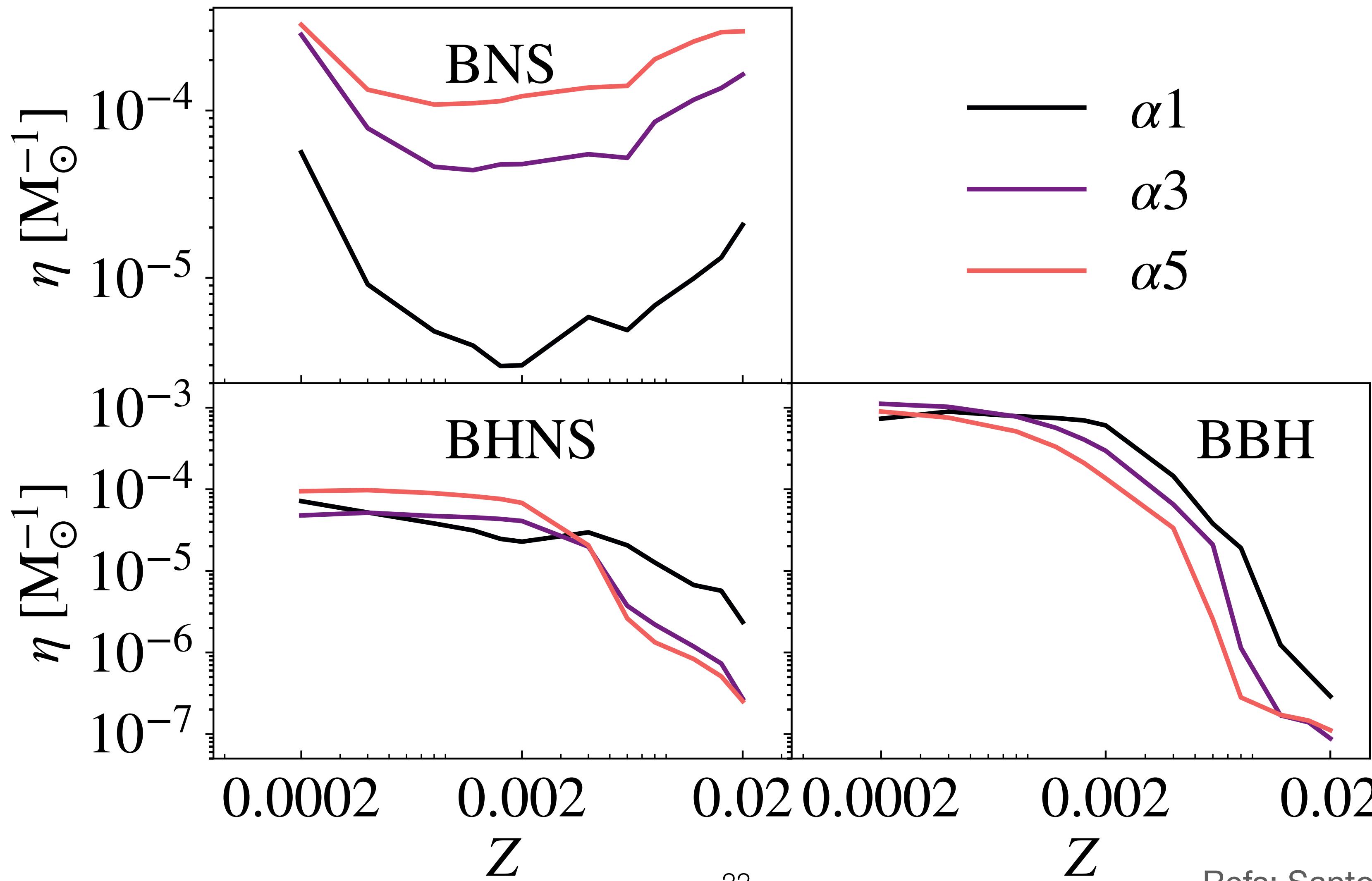
SFR(z)



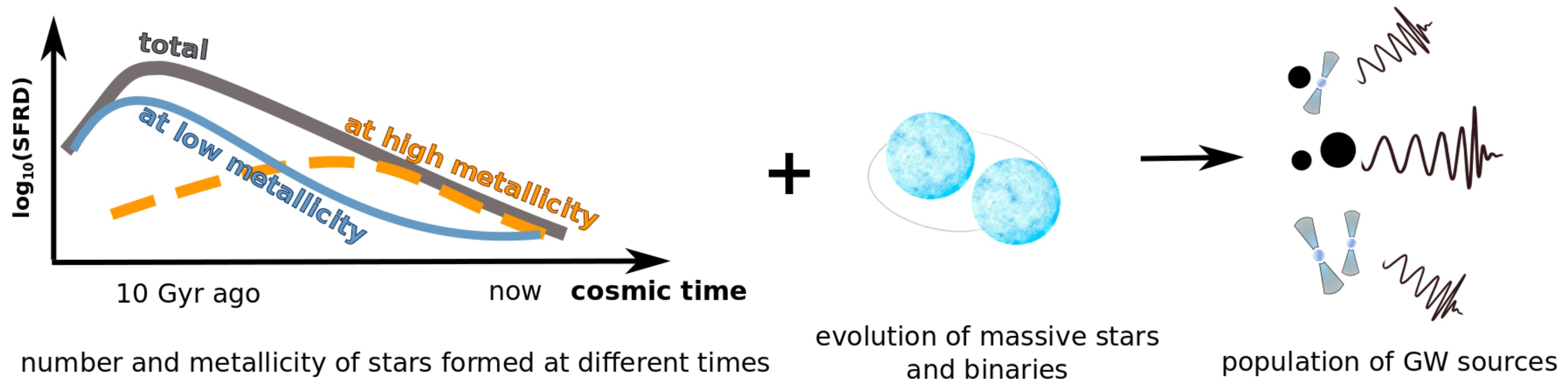
Refs: [Speagle et al. 2014](#), [Boogaard et al. 2018](#),
[Madau and Fragos 2017](#), [Schaye et al 2015](#)

Do you remember metallicity impact on compact object formation?

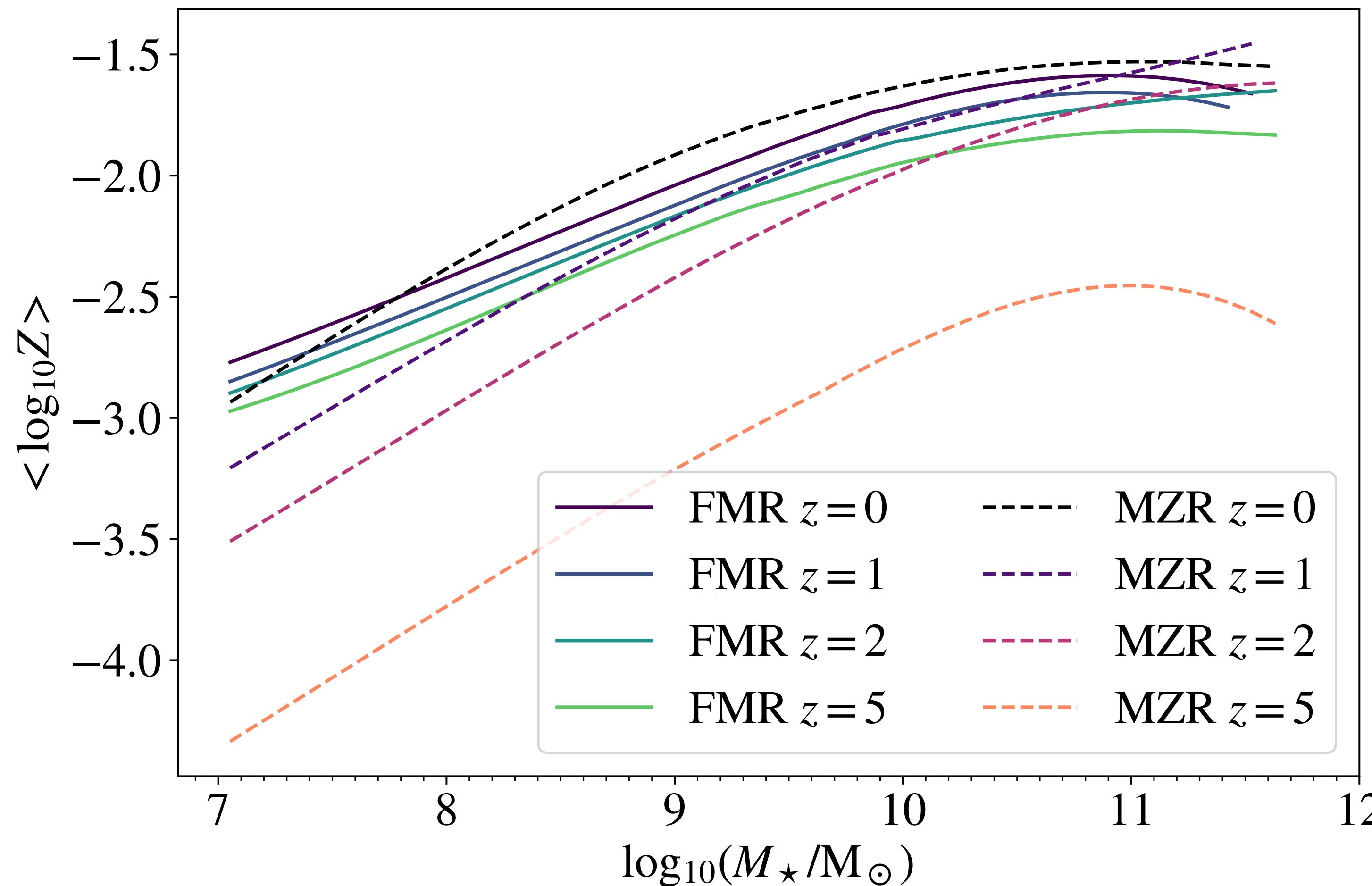
Merger efficiency



Impact of metallicity

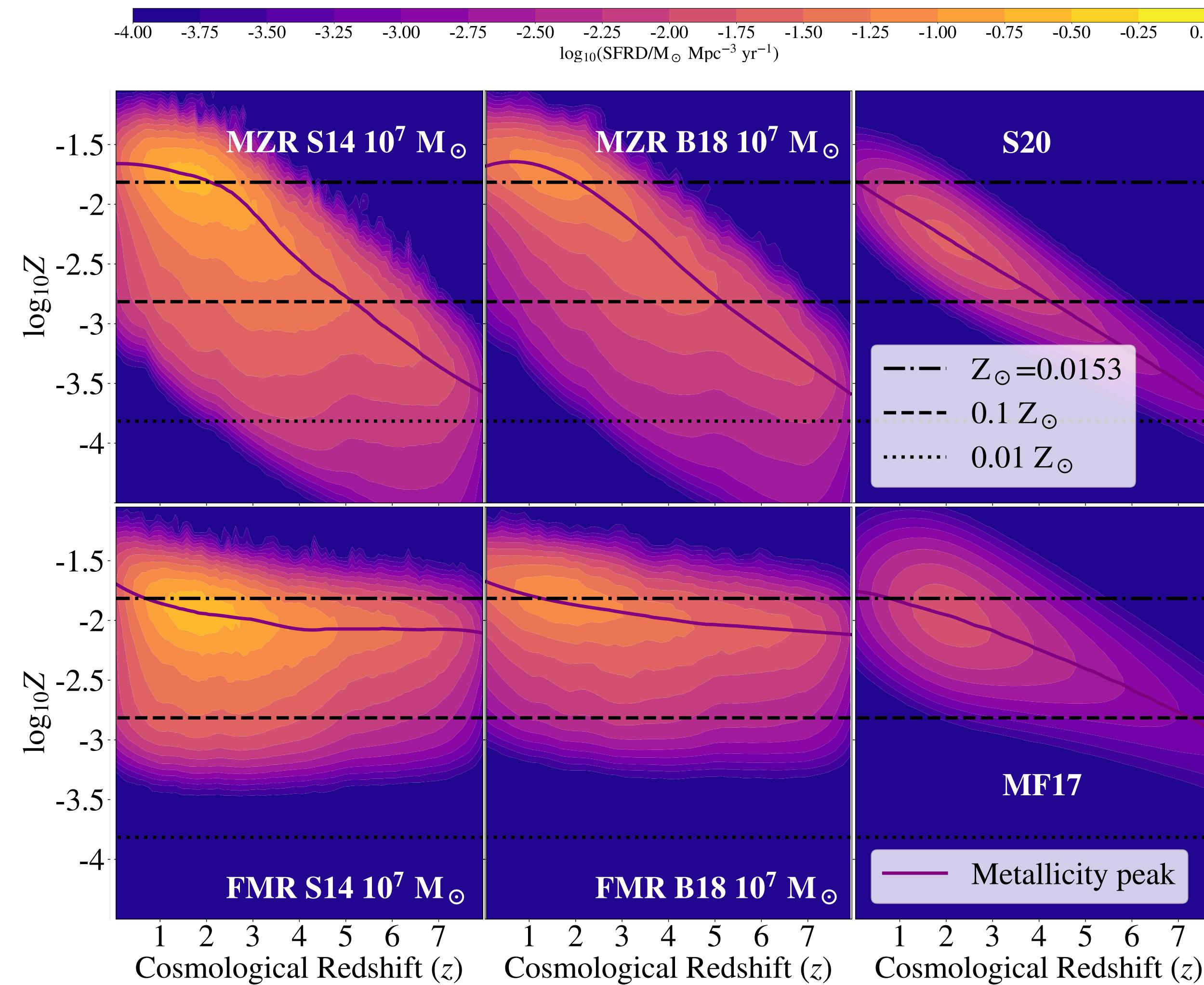


Metallicity distribution



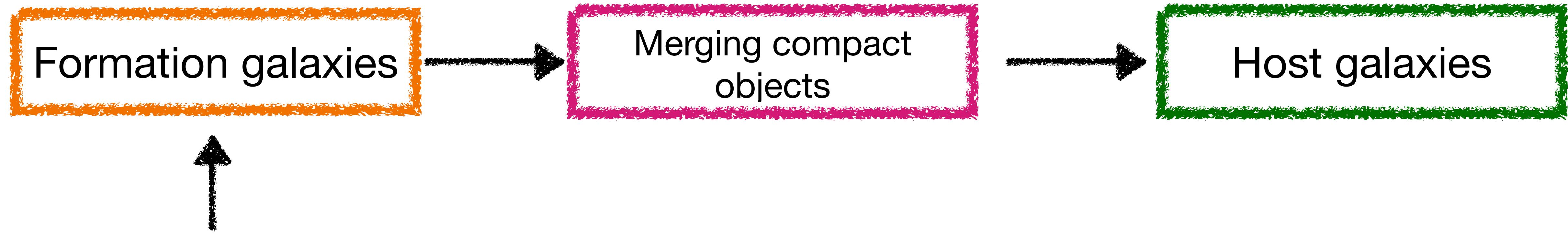
Refs: [Mannucci et al. 2011](#), [Chruslinska & Nelemans 2019](#), [Curti et al. 2020](#),

SFRD(z , Z)

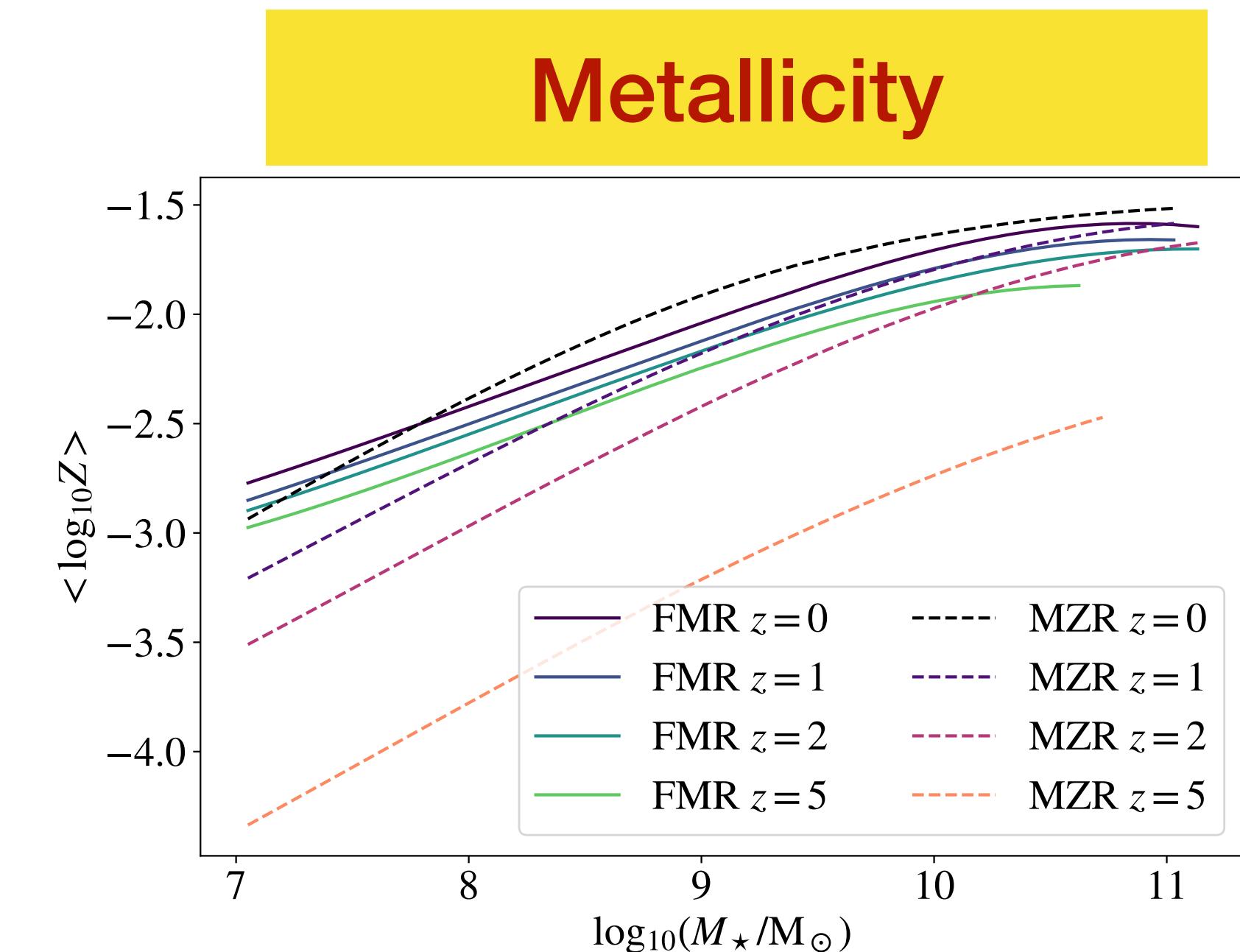
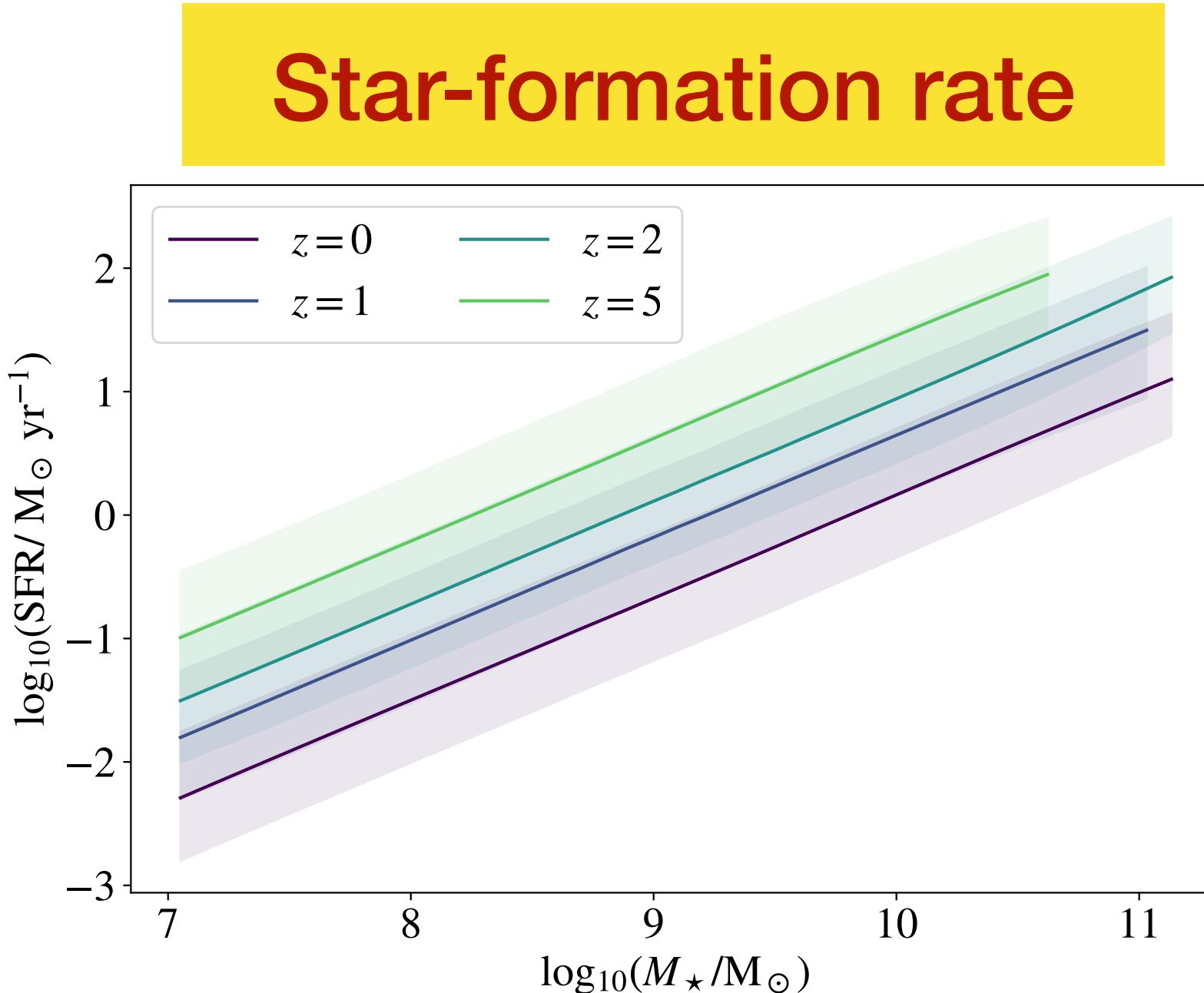
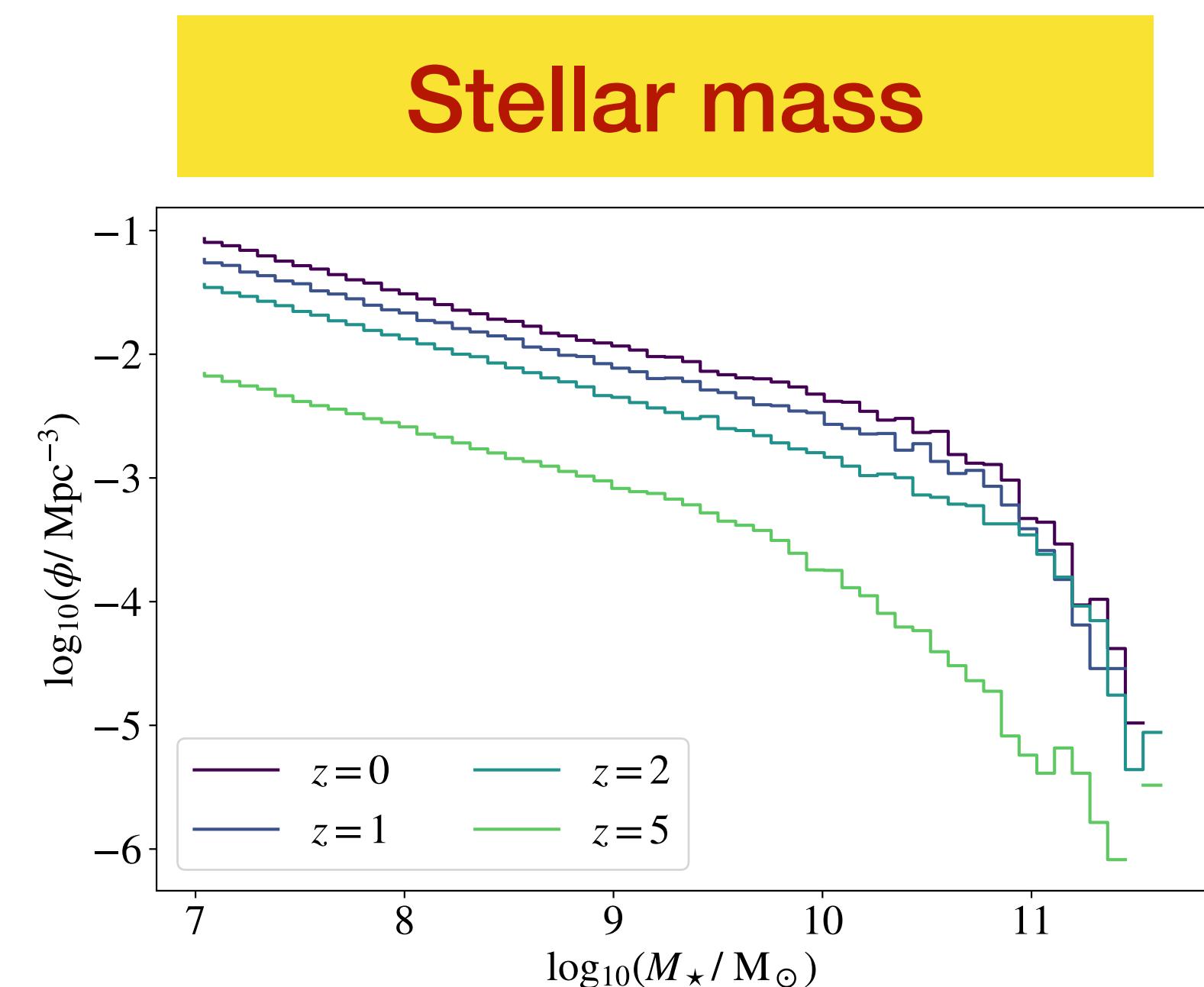


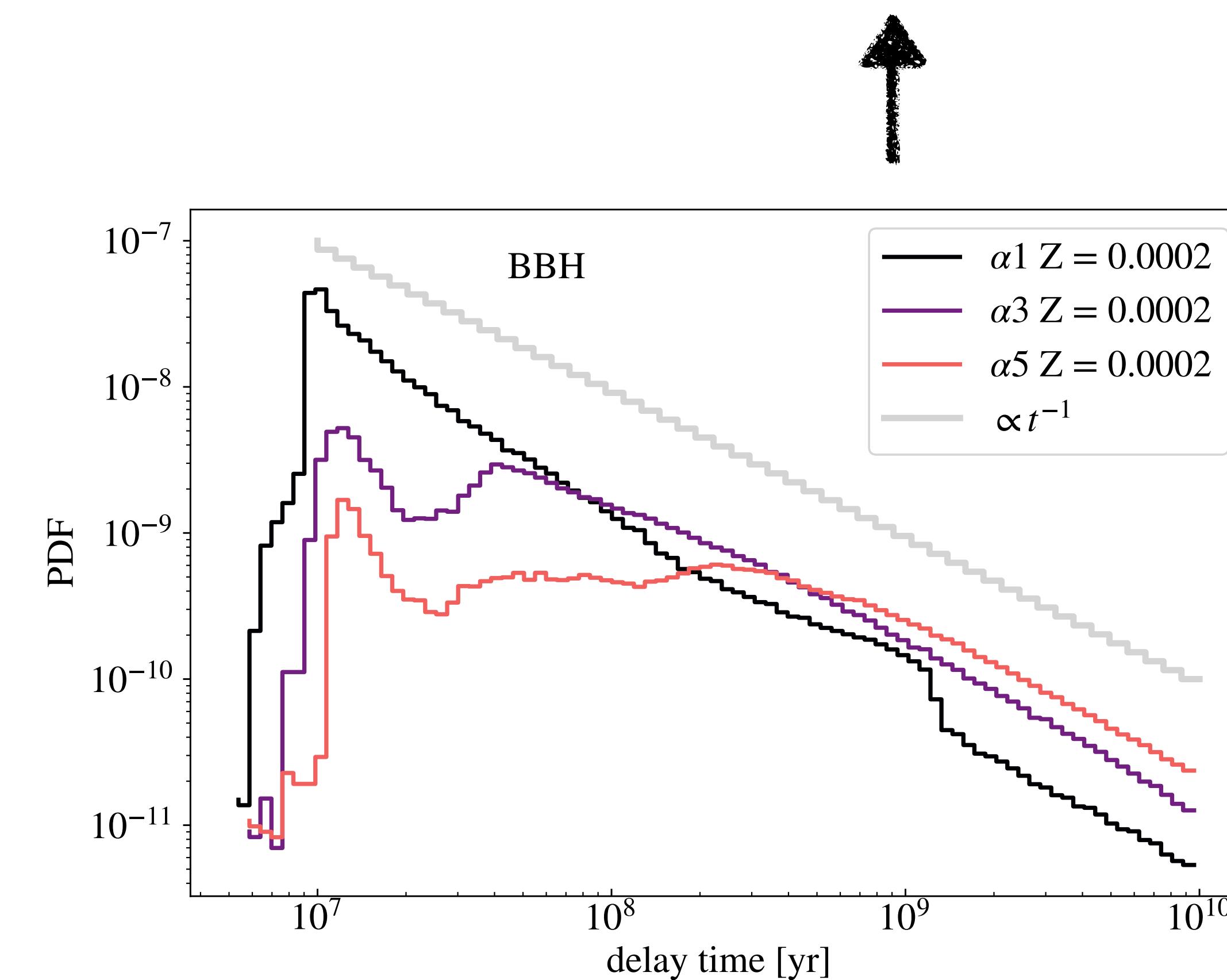
galaxyRate



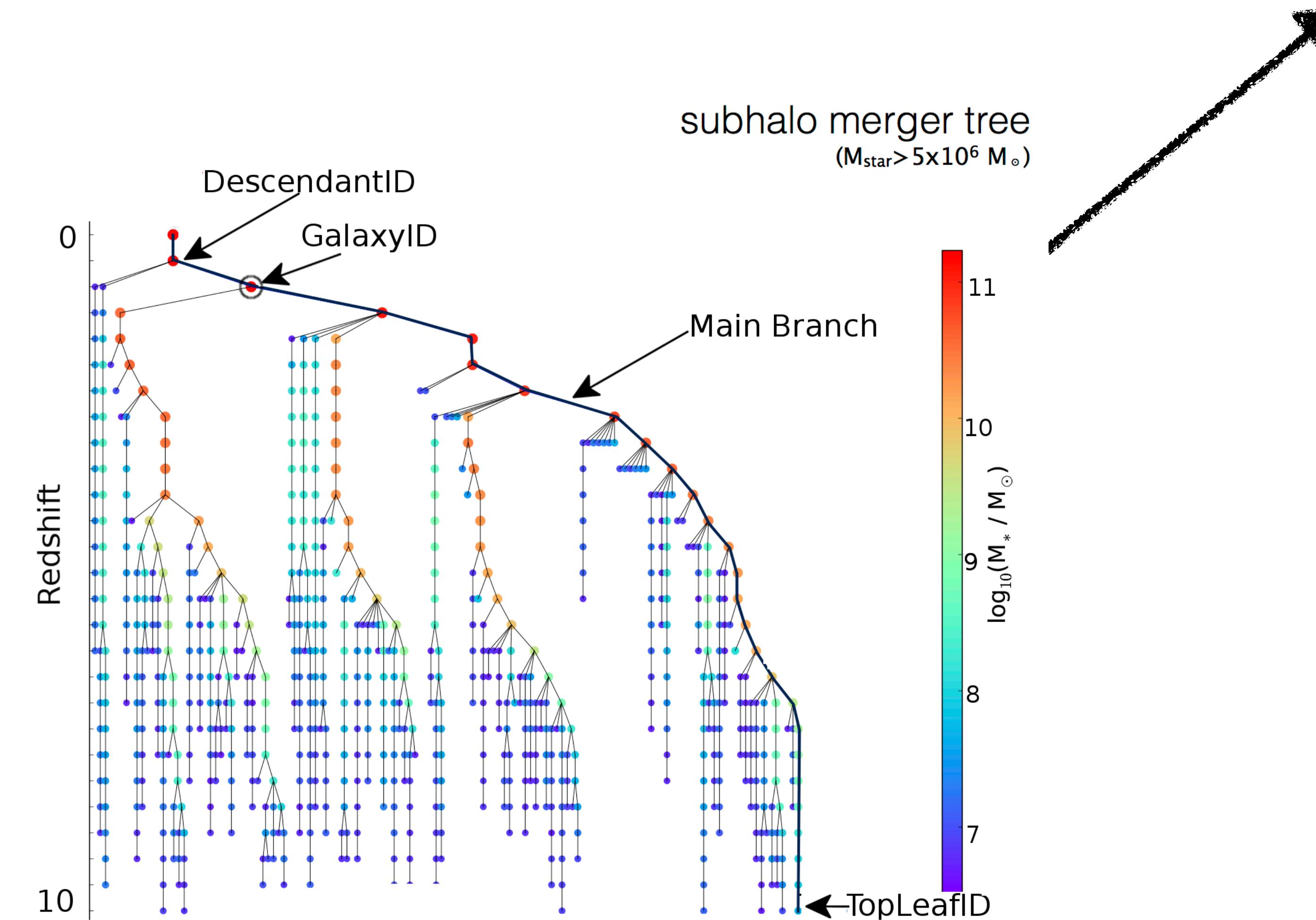


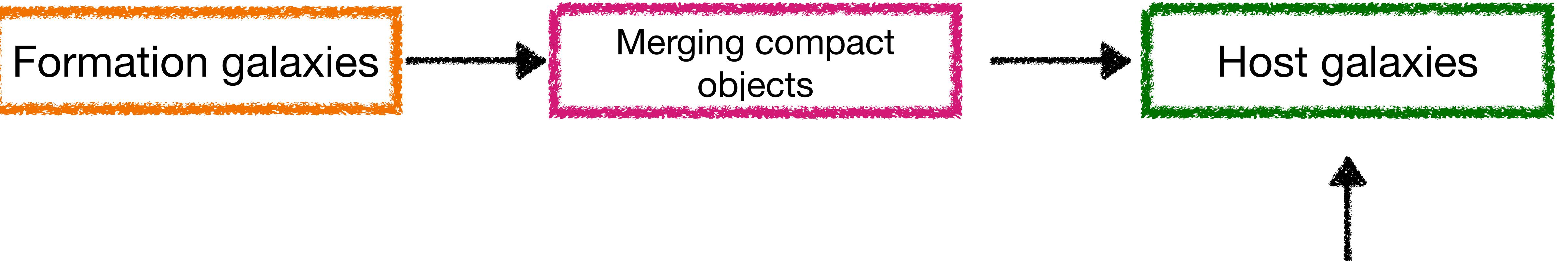
Population of star-forming galaxies from **observational scaling relations**





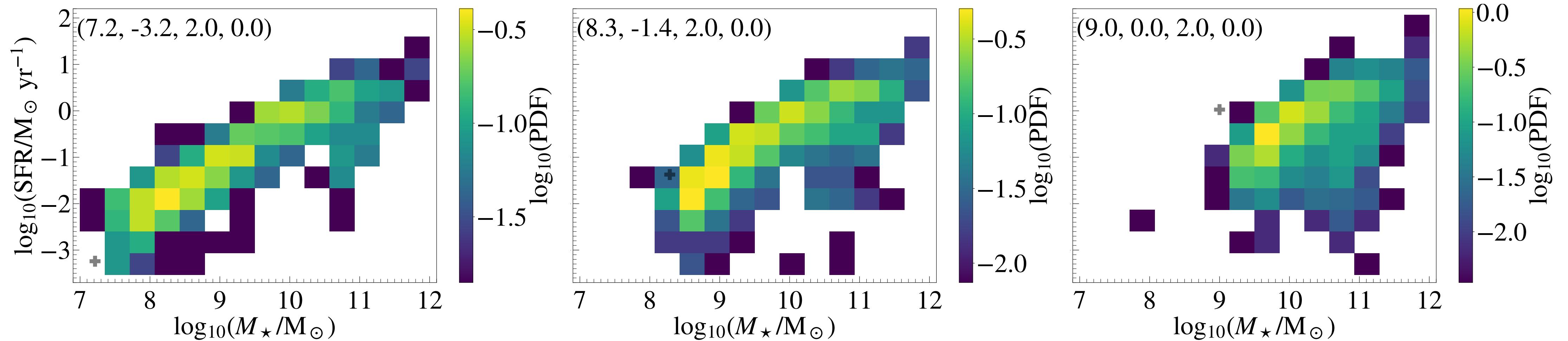
Effect of common envelope





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

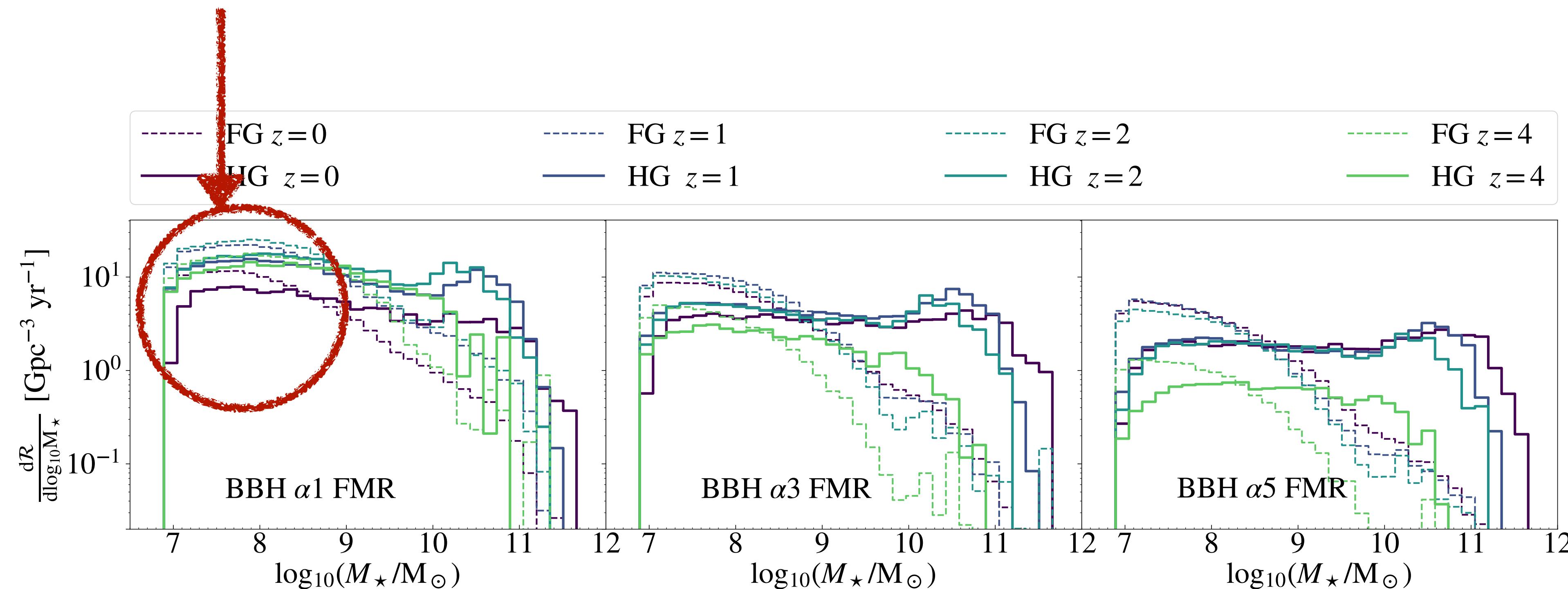
I sample the properties of the host galaxy



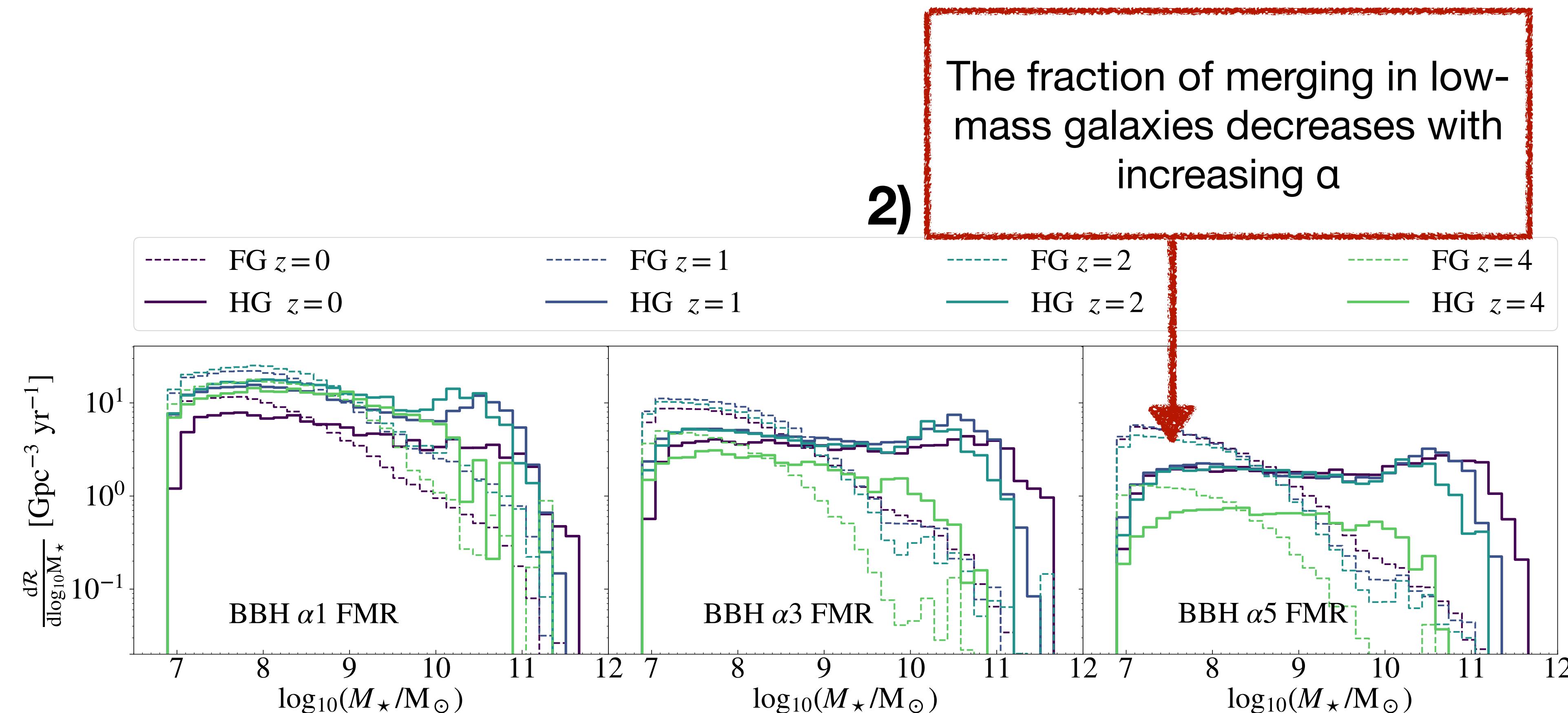
galaxyRate: host galaxy stellar mass

1)

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



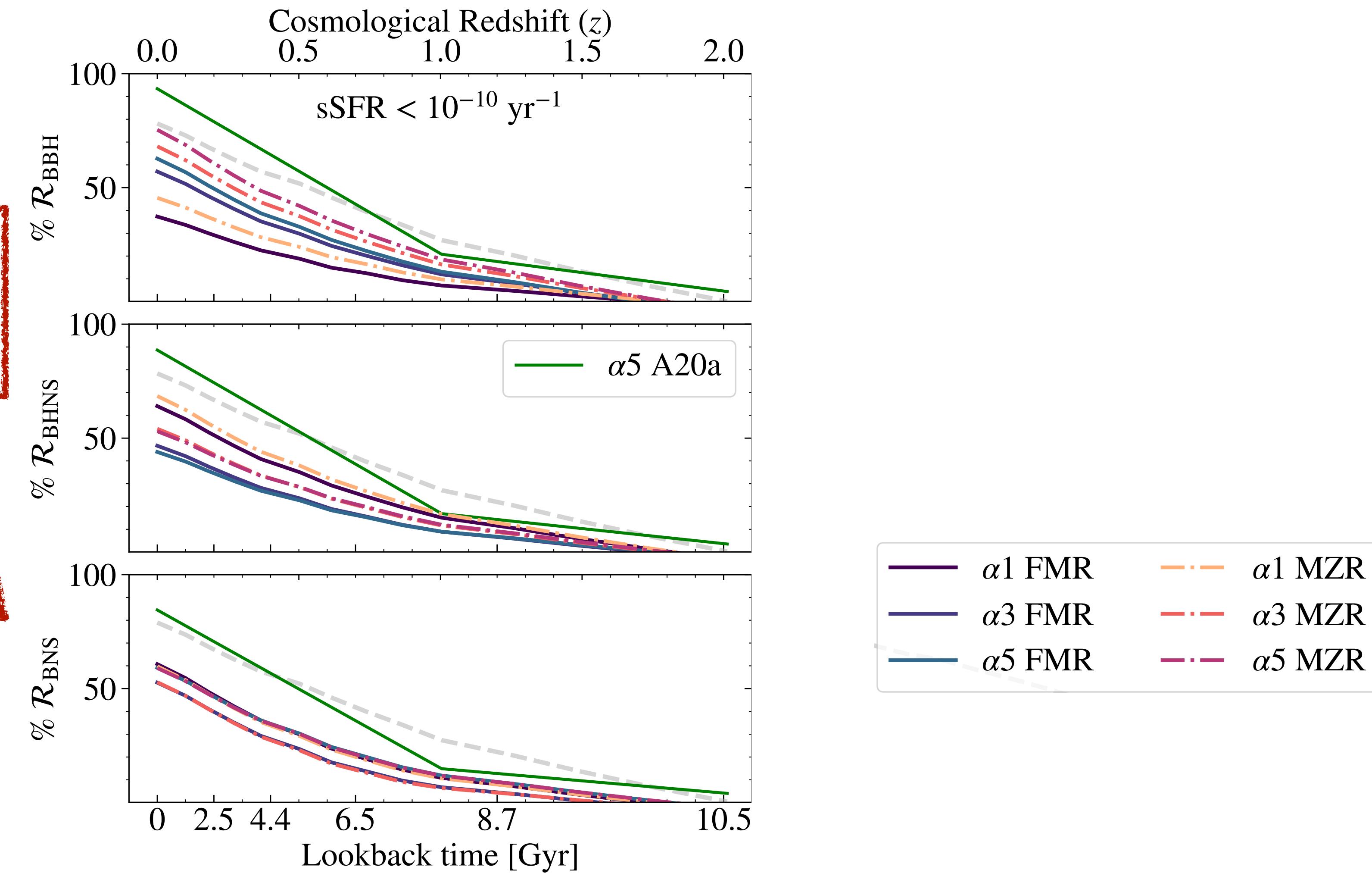
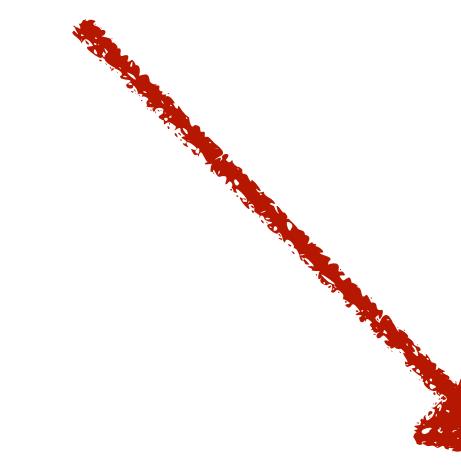
galaxyRate: host galaxy stellar mass



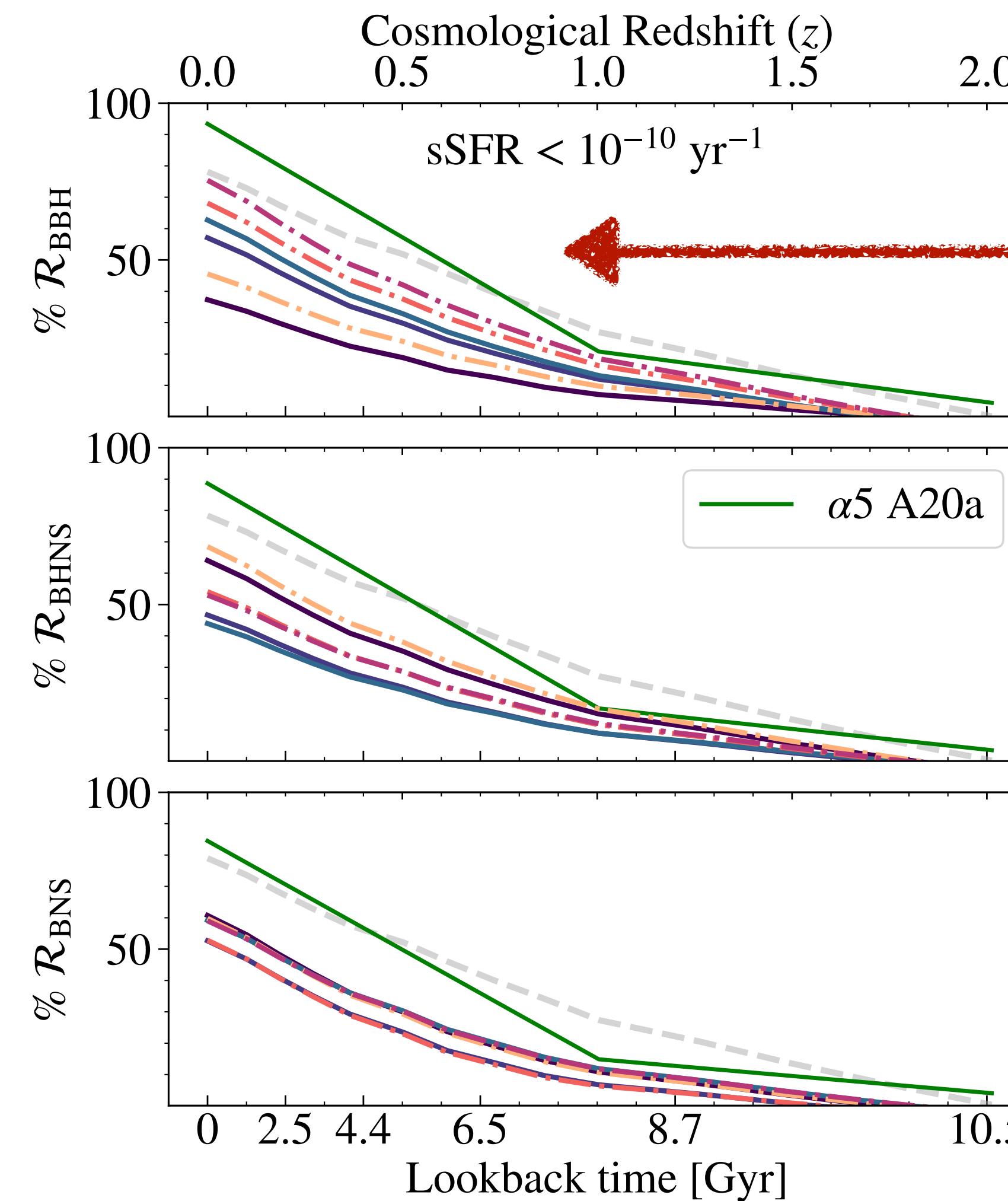
galaxyRate: passive galaxies

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

| | |
|------------------------|------------------------|
| $\alpha 1 \text{ FMR}$ | $\alpha 1 \text{ MZR}$ |
| $\alpha 3 \text{ FMR}$ | $\alpha 3 \text{ MZR}$ |
| $\alpha 5 \text{ FMR}$ | $\alpha 5 \text{ MZR}$ |

Can host galaxies be useful in other ways?

GW and cosmology

- GW are standard sirens

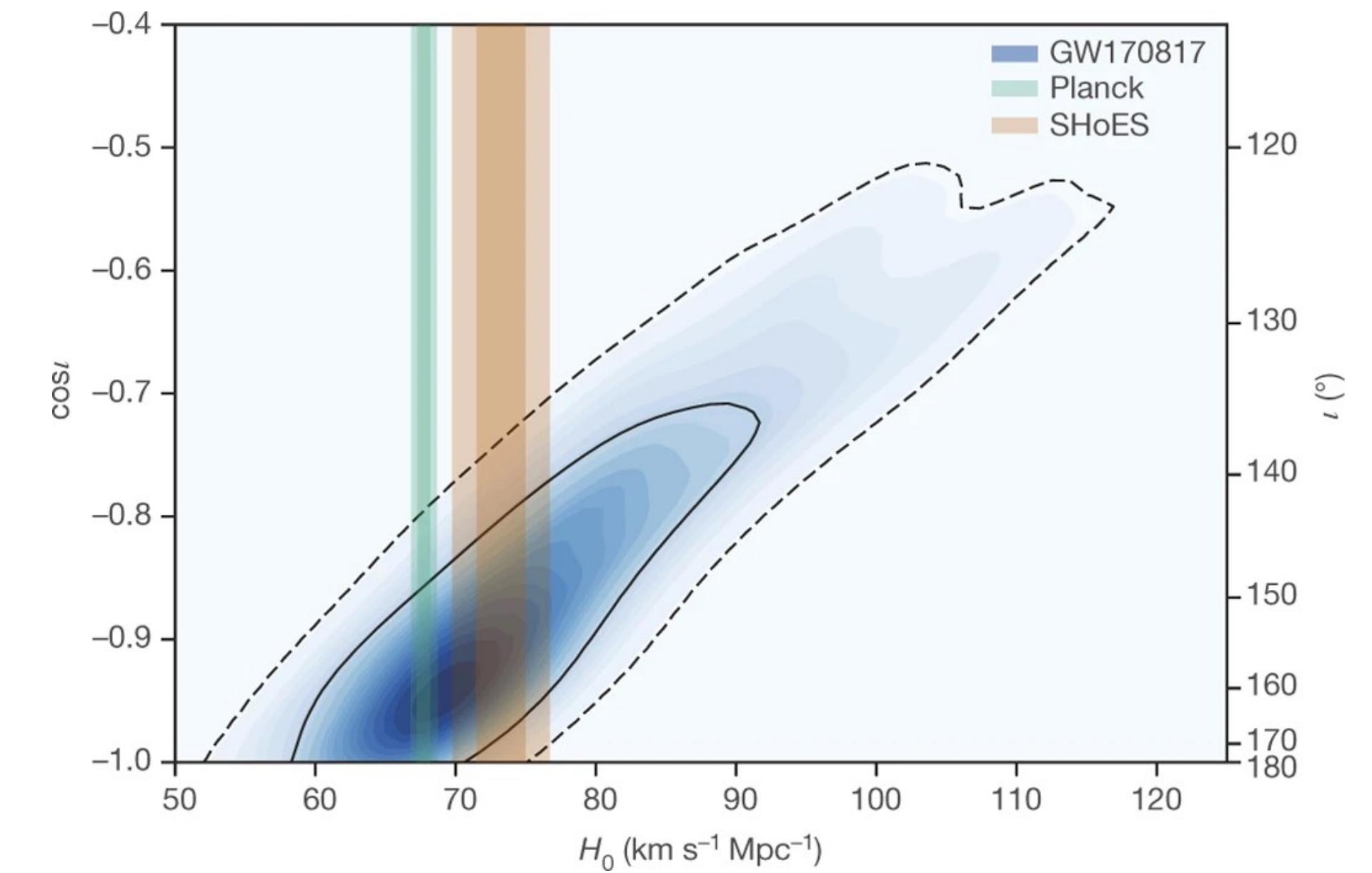
- $$h_+ = \frac{2(1+z)\mathcal{M}}{d_L} (\pi(1+z)\mathcal{M}f)^{2/3} (1 + \cos^2 i) \cos 2\phi_N(t)$$

- $$h_\times = -\frac{4(1+z)\mathcal{M}}{d_L} (\pi(1+z)\mathcal{M}f)^{2/3} \cos i \sin 2\phi_N(t)$$

- Chirp mass
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

GW and cosmology

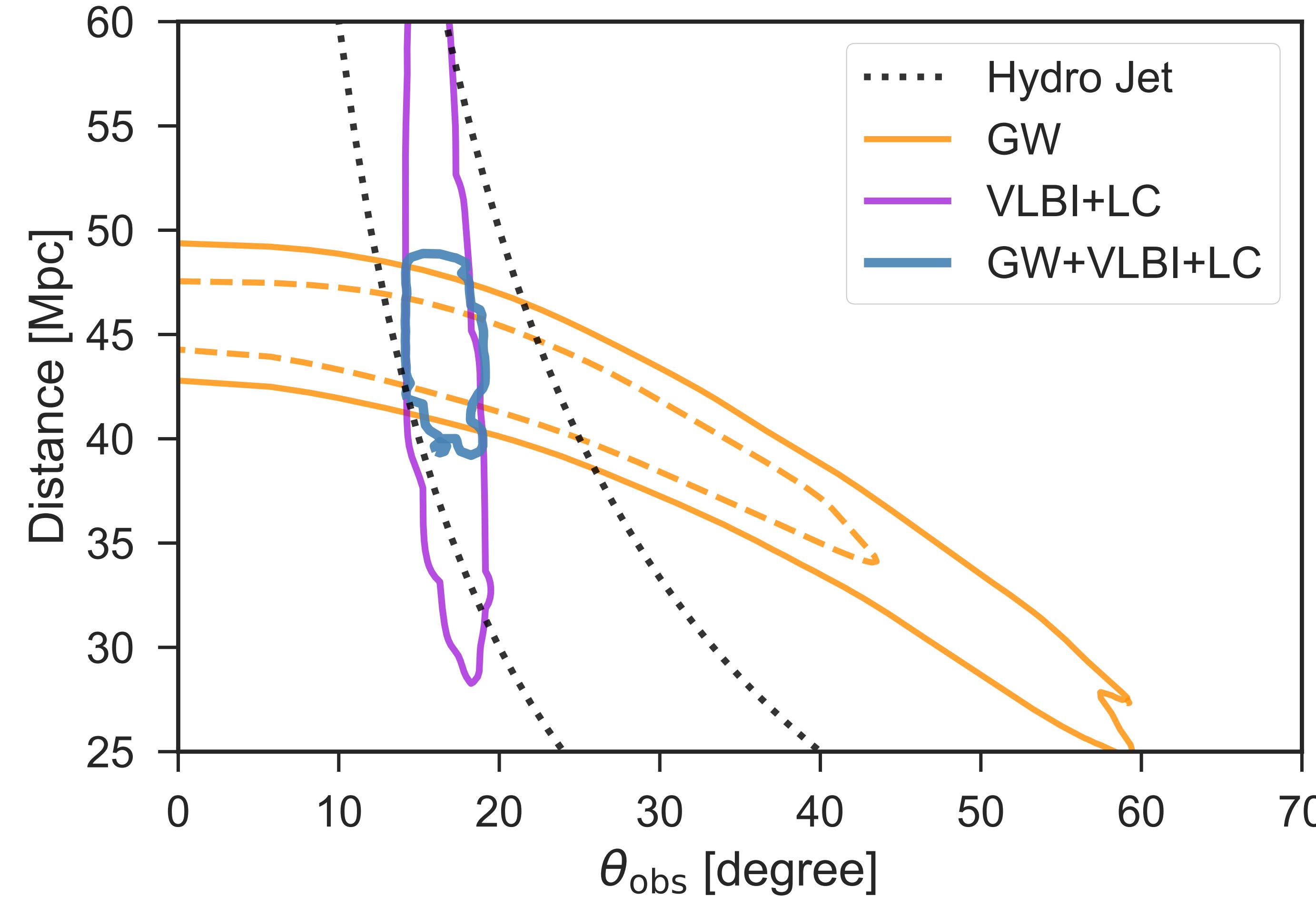
- $v_H = H_0 d_L$
- Recession velocity from NGC 4993:
 $v_H = 3017 \pm 166 \text{ km s}^{-1}$
- $d_L = 43.8^{+2.9}_{-6.9} \text{ Mpc}$
- $H_0 = 70.0^{+12.0}_{-8.0} \text{ km s}^{-1} \text{ Mpc}^{-1}$ 68% C.I.
- SHoES: Cepheids and type Ia SN



Refs: [Abbott et al. 2017](#)

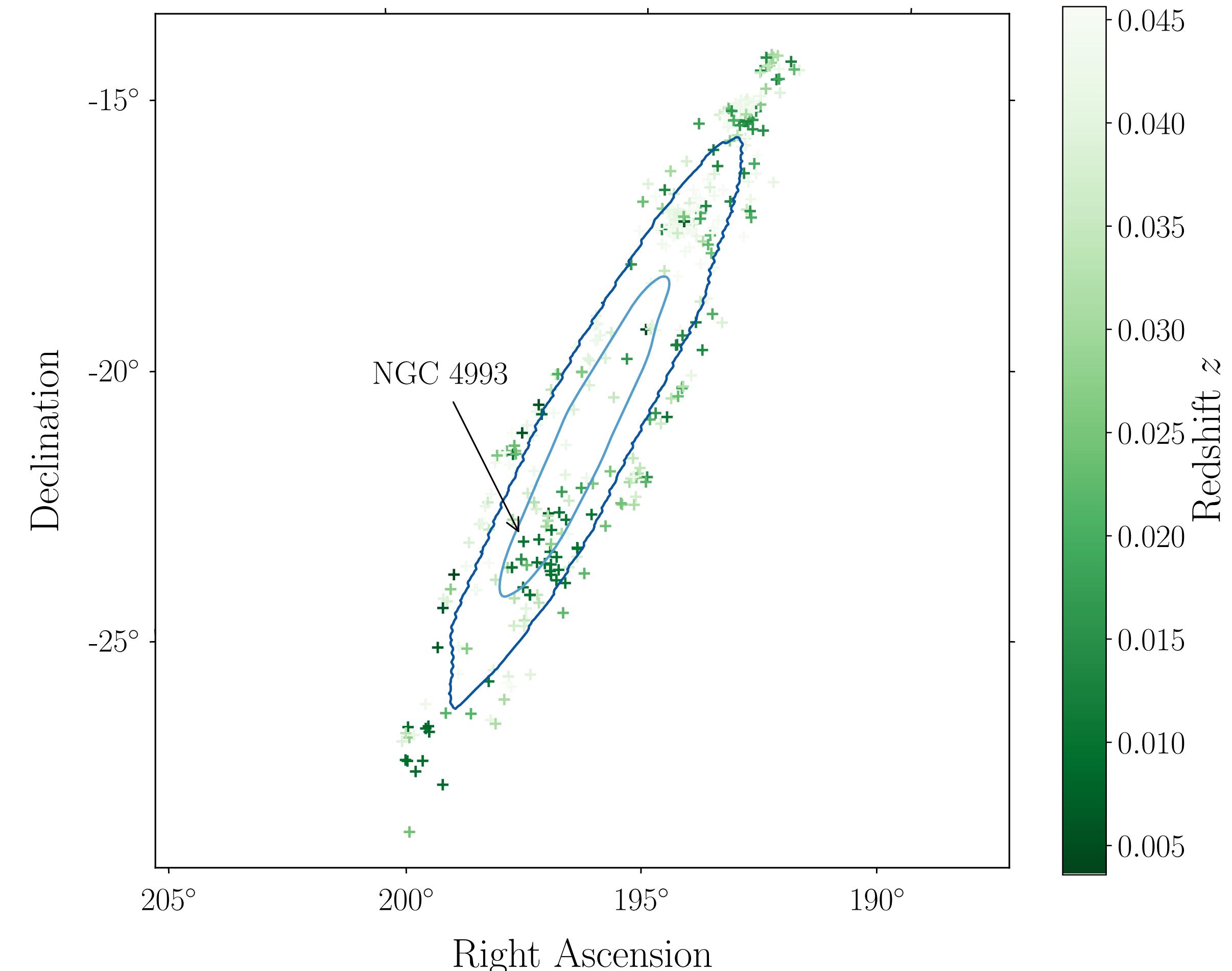
GW and cosmology

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



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)



What you did (not) learn today

Tomorrow

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