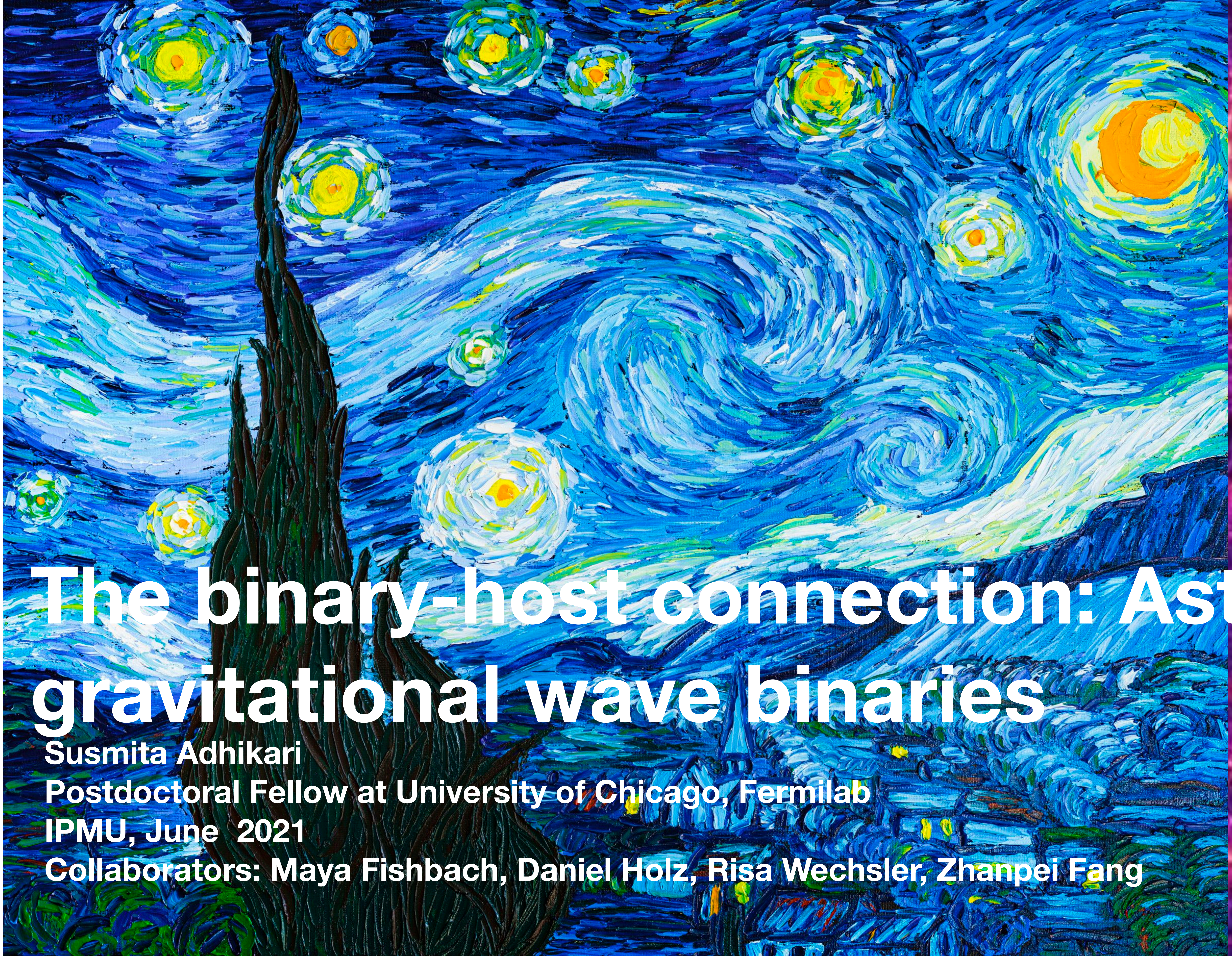
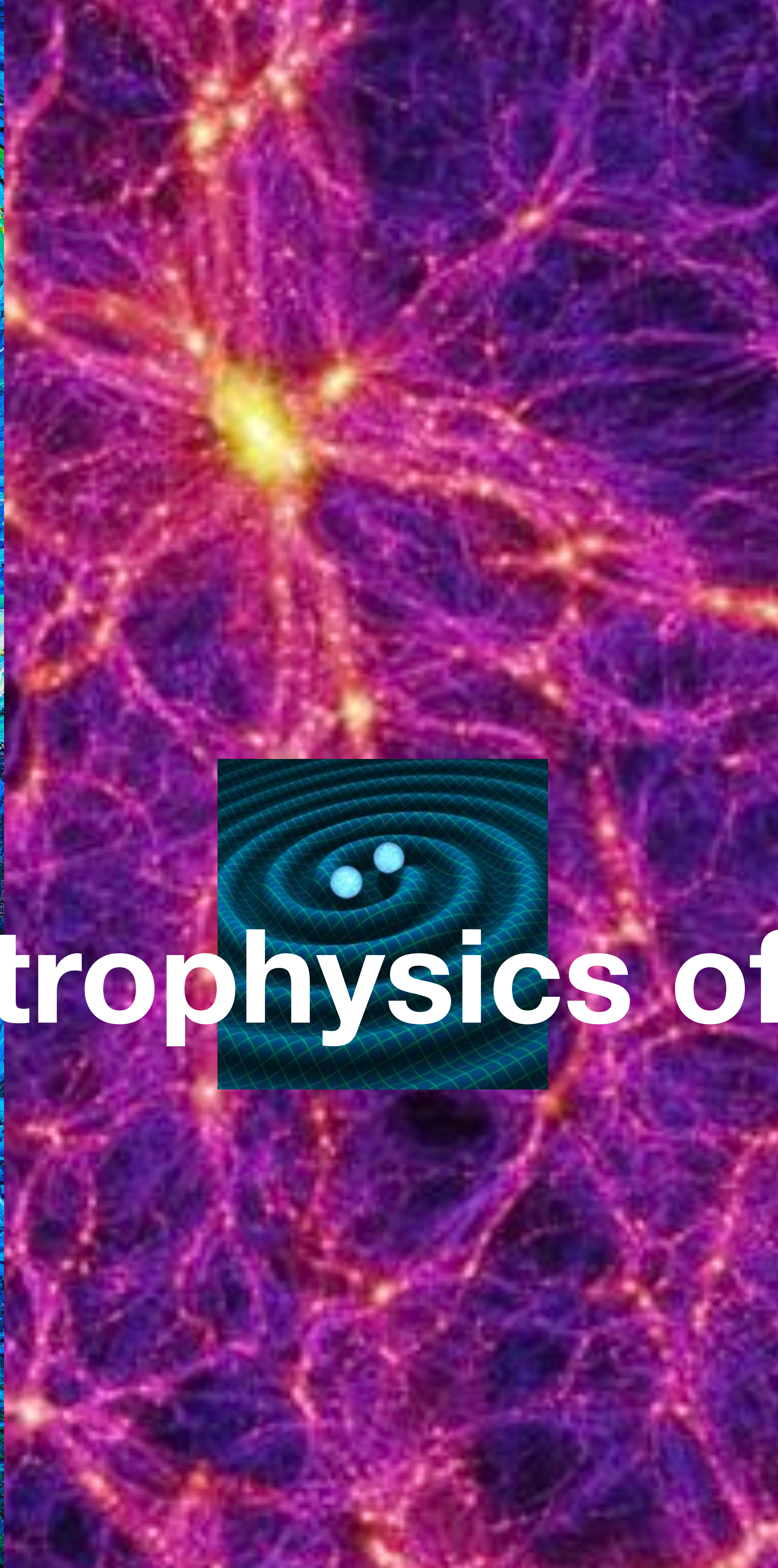



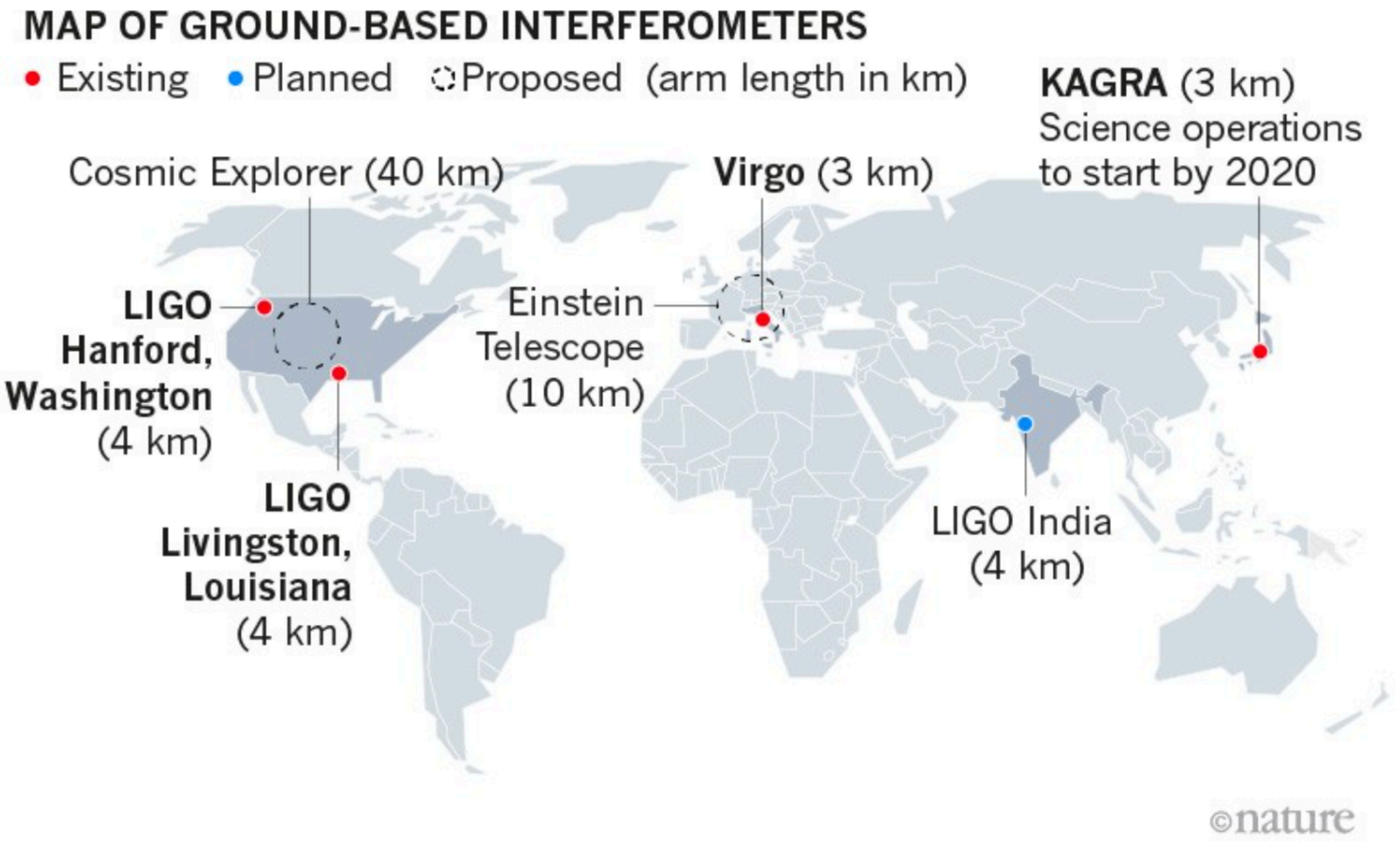
The binary-host connection: Astrophysics of gravitational wave binaries

Susmita Adhikari
Postdoctoral Fellow at University of Chicago, Fermilab

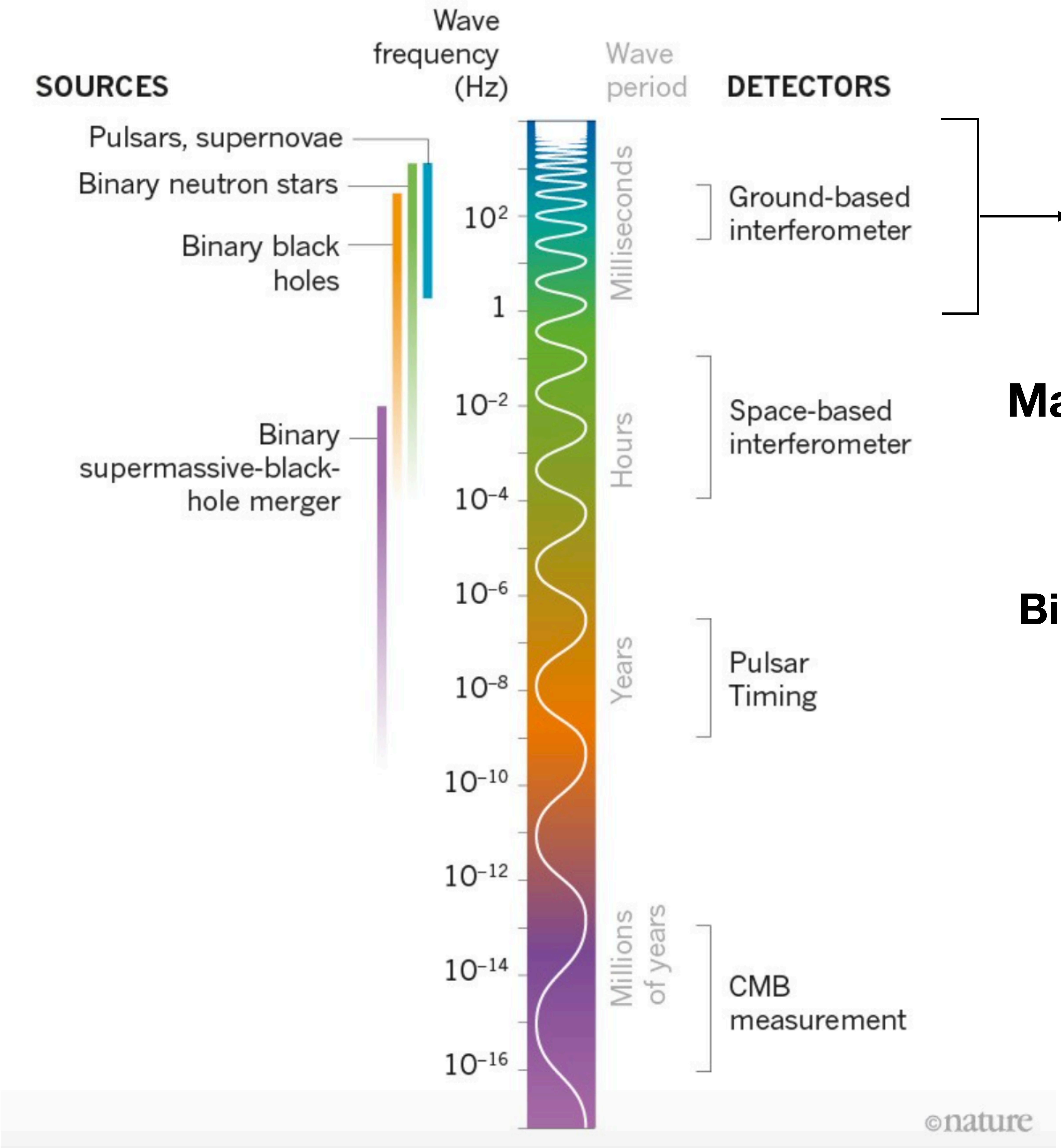
IPMU, June 2021

Collaborators: Maya Fishbach, Daniel Holz, Risa Wechsler, Zhanpei Fang

Gravitational Wave detectors have opened a new window to the universe



Gravitational Wave detectors

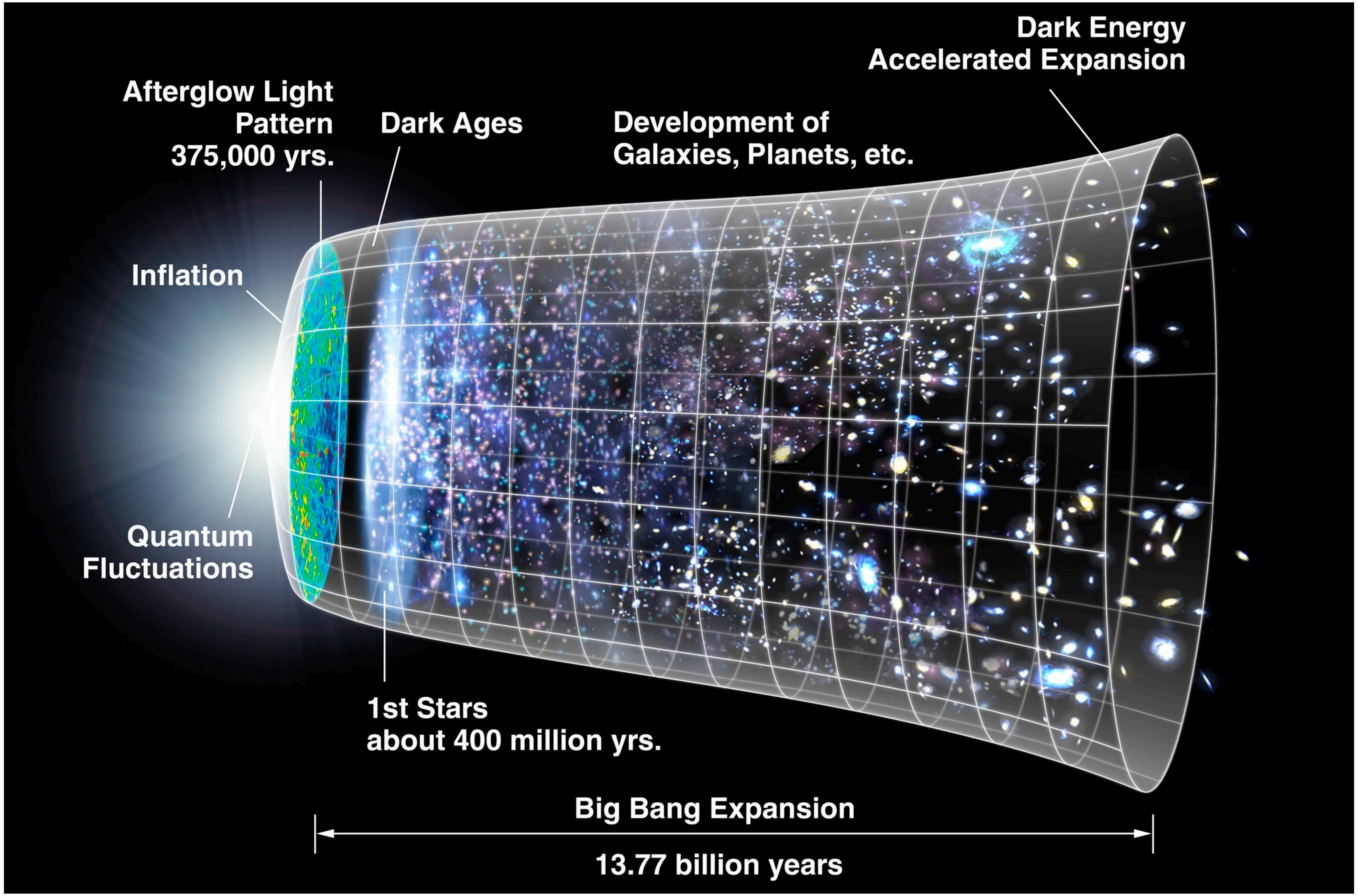


LIGO- VIRGO detectors

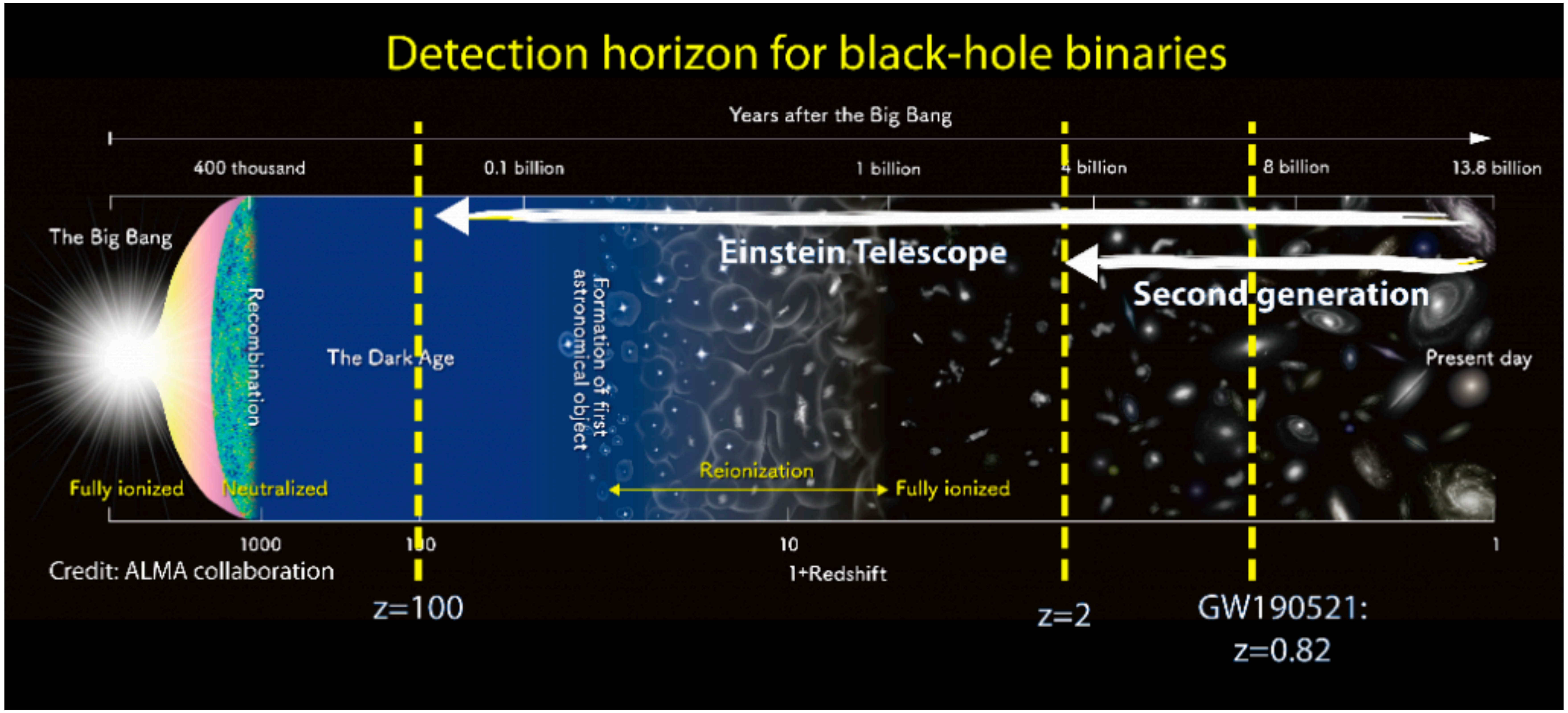
Mainly detecting stellar mass binaries that have high wave frequencies

Binary neutron stars, black hole binaries and Neutron star-black holes binaries.

Evolution of stars through the history of the universe



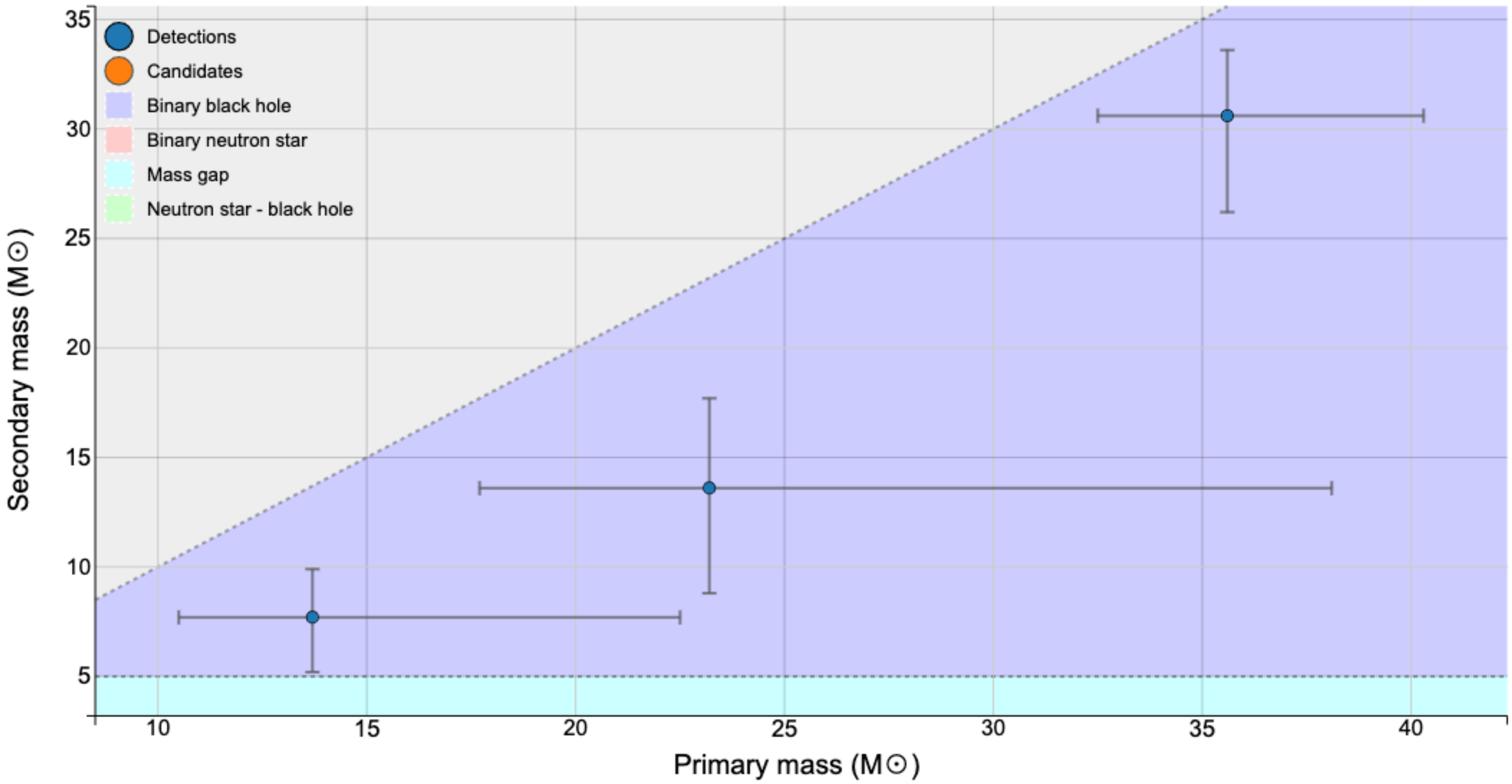
Evolution of stars through the history of the universe



https://optics.org/news/11/9/30

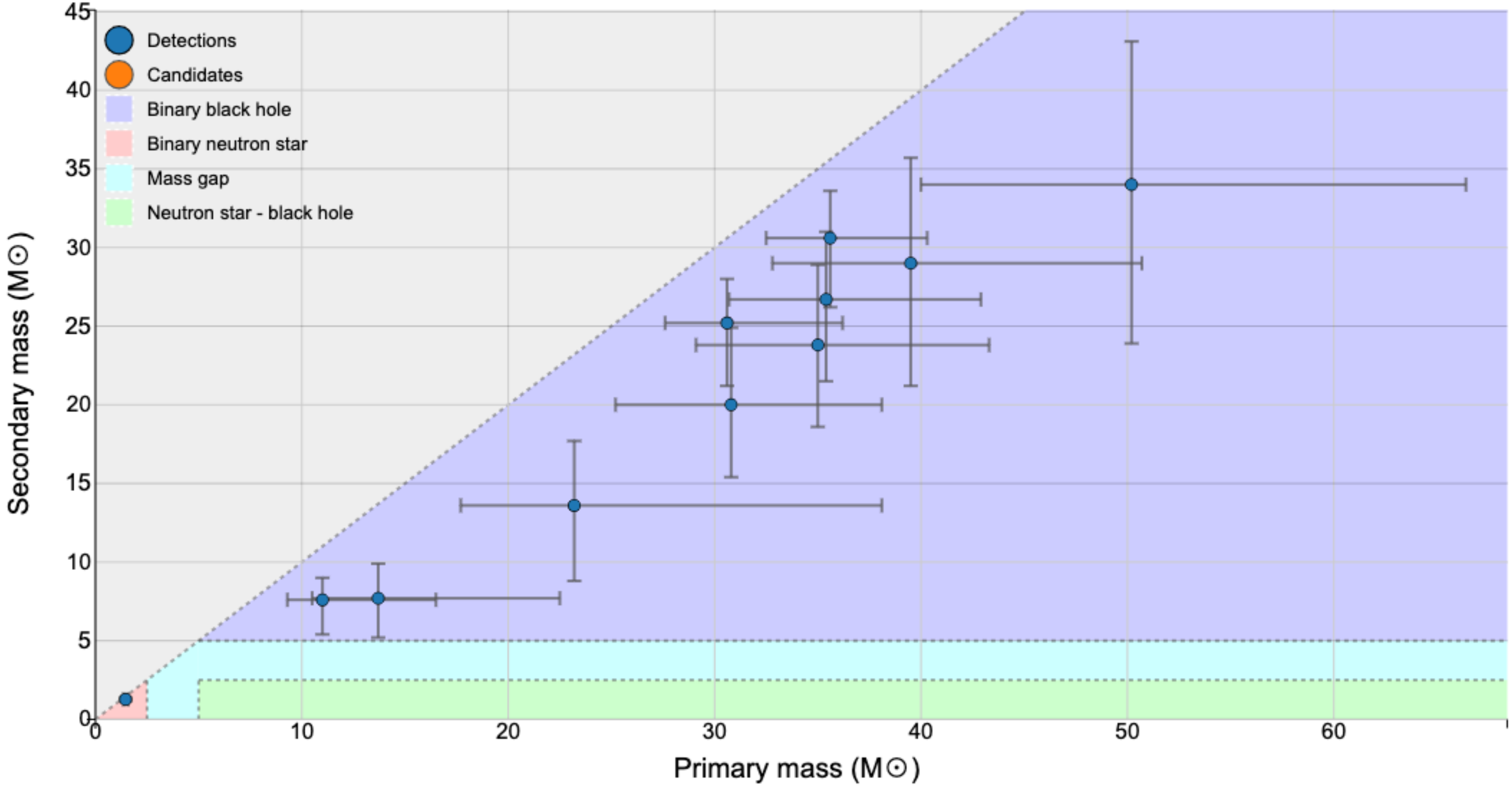
Second generation and future proposed detectors will be probing the first stars in the universe out to distant redshifts

LIGO-VIRGO O1



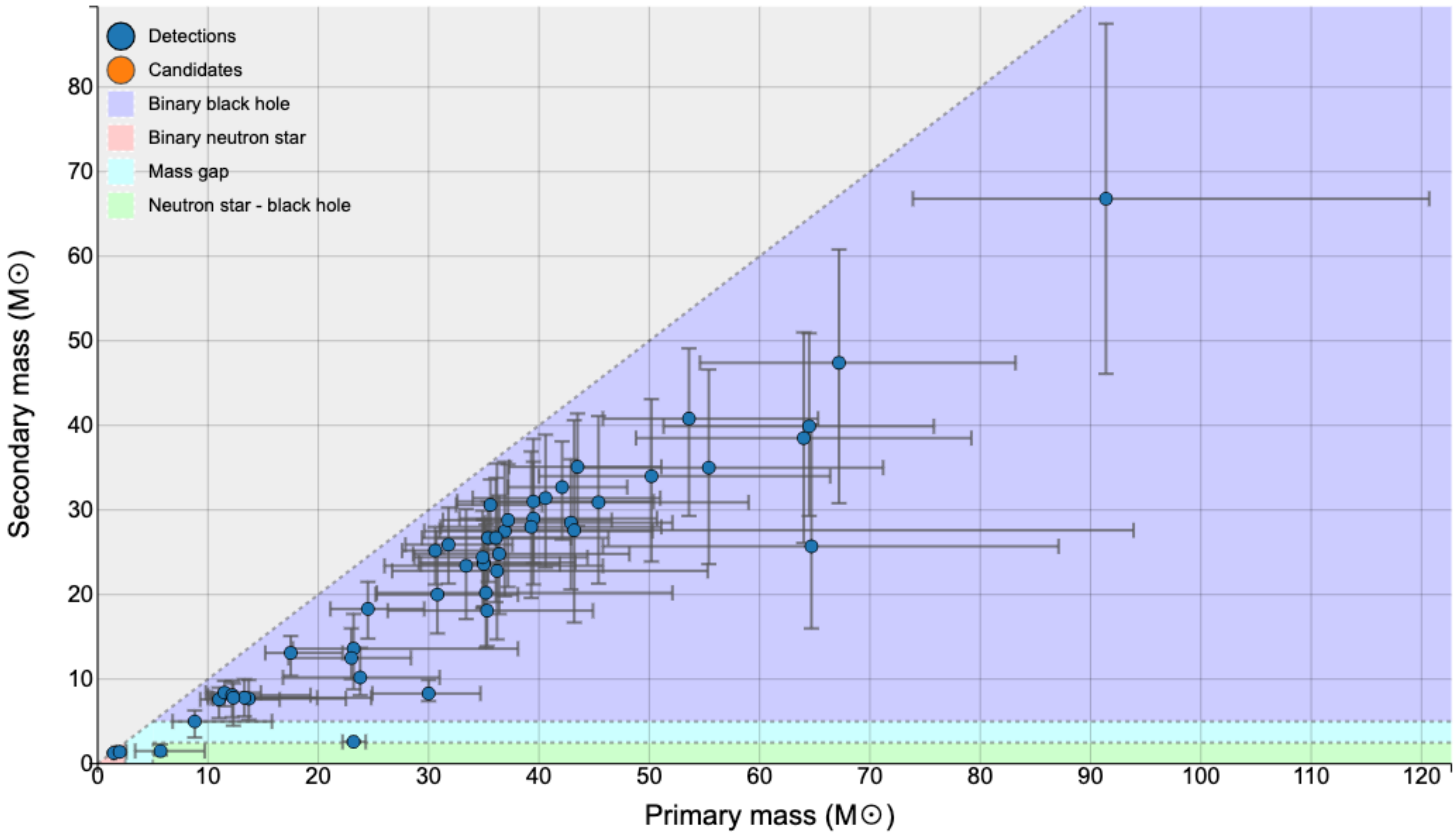
credit: https://www.ligo.org/detections/

LIGO-VIRGO O1+O2



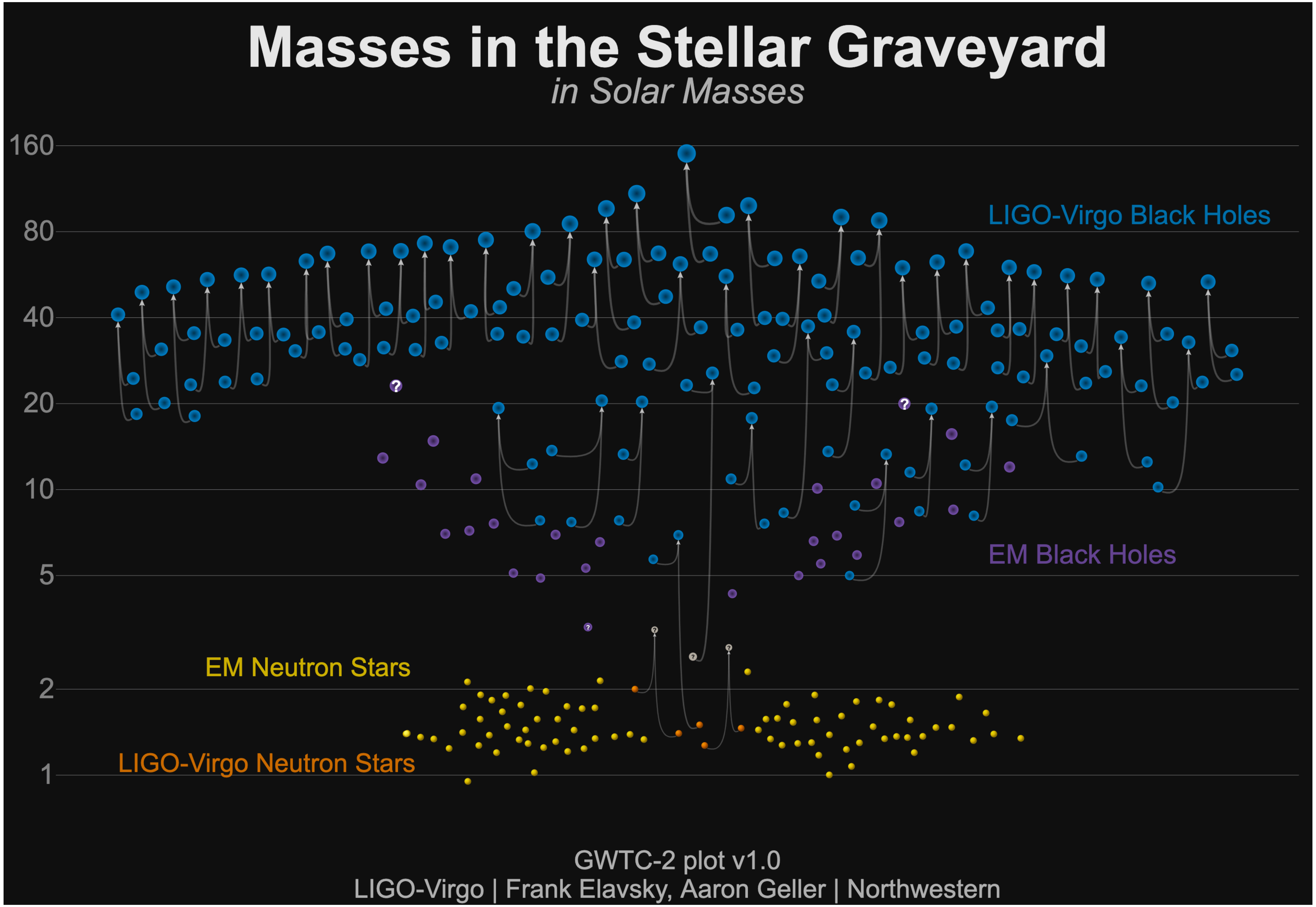
credit: https://www.ligo.org/detections/

LIGO-VIRGO O1+O2+O3

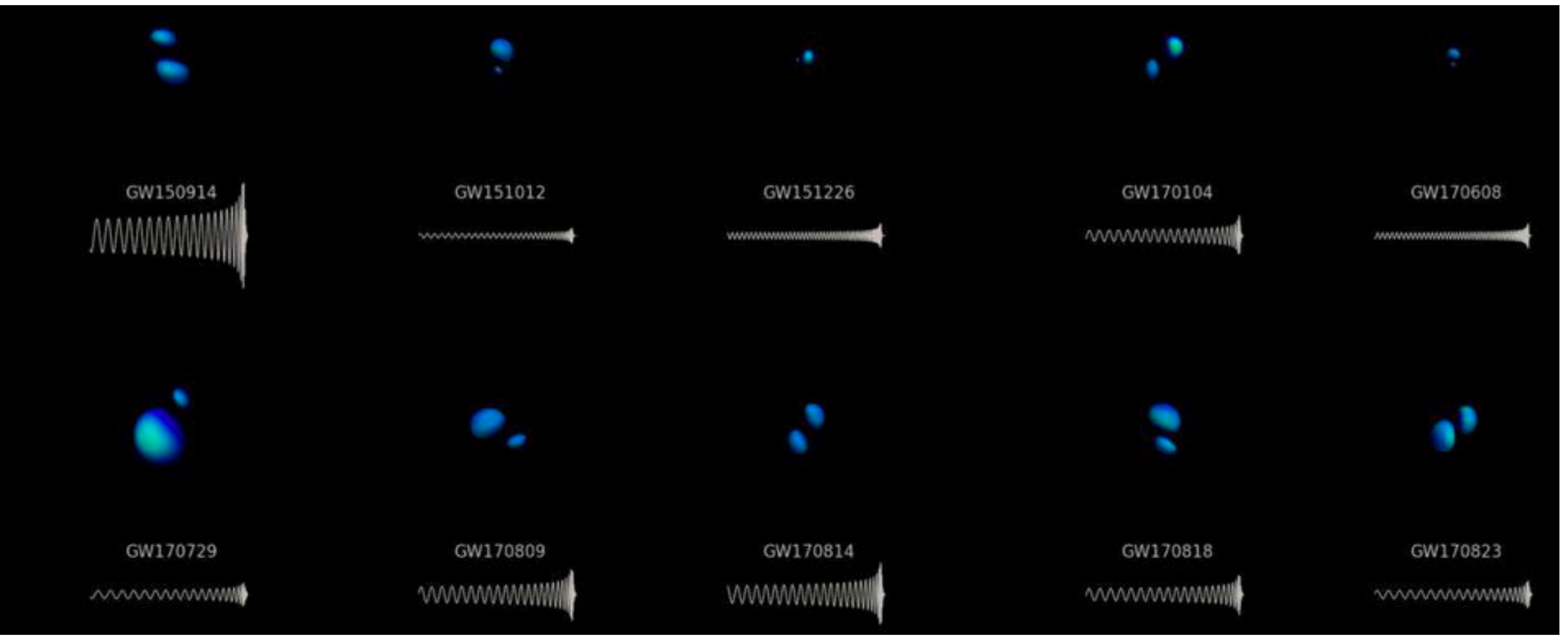


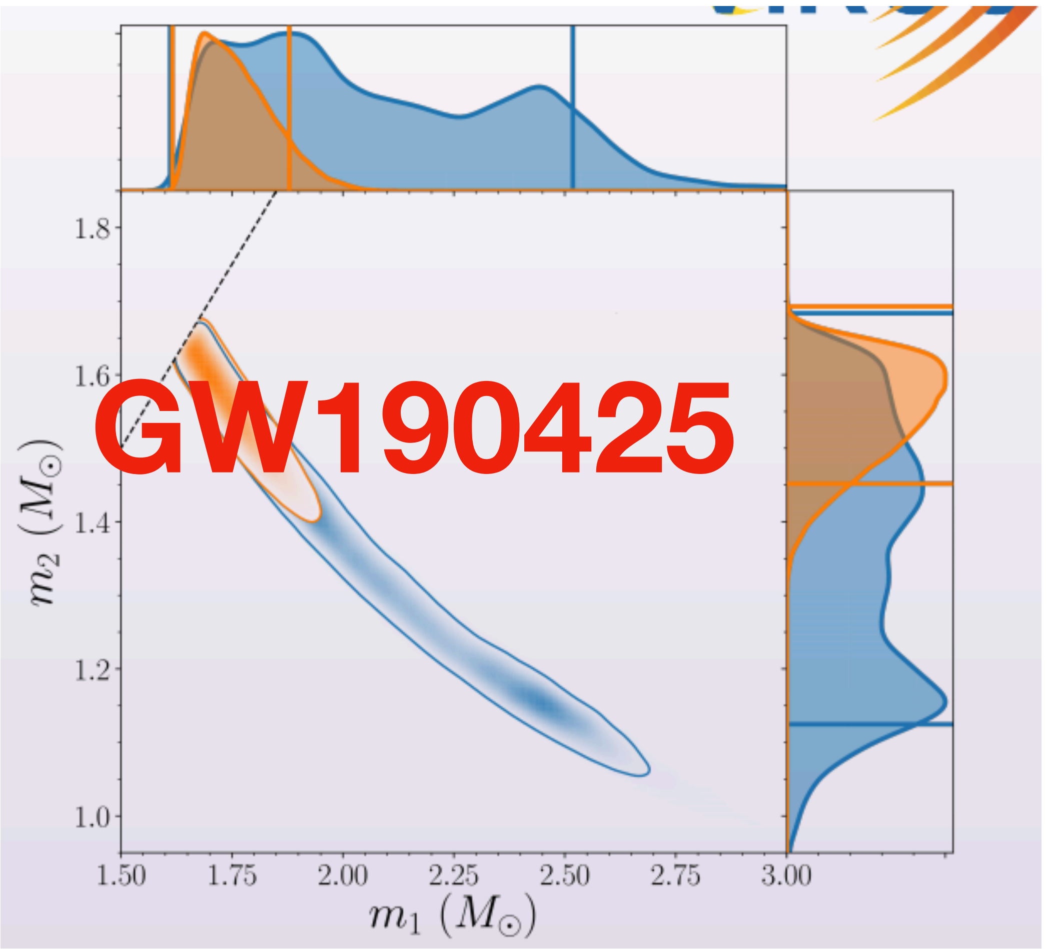
credit: https://www.ligo.org/detections/

The binary zoo from LIGO-VIRGO collaboration



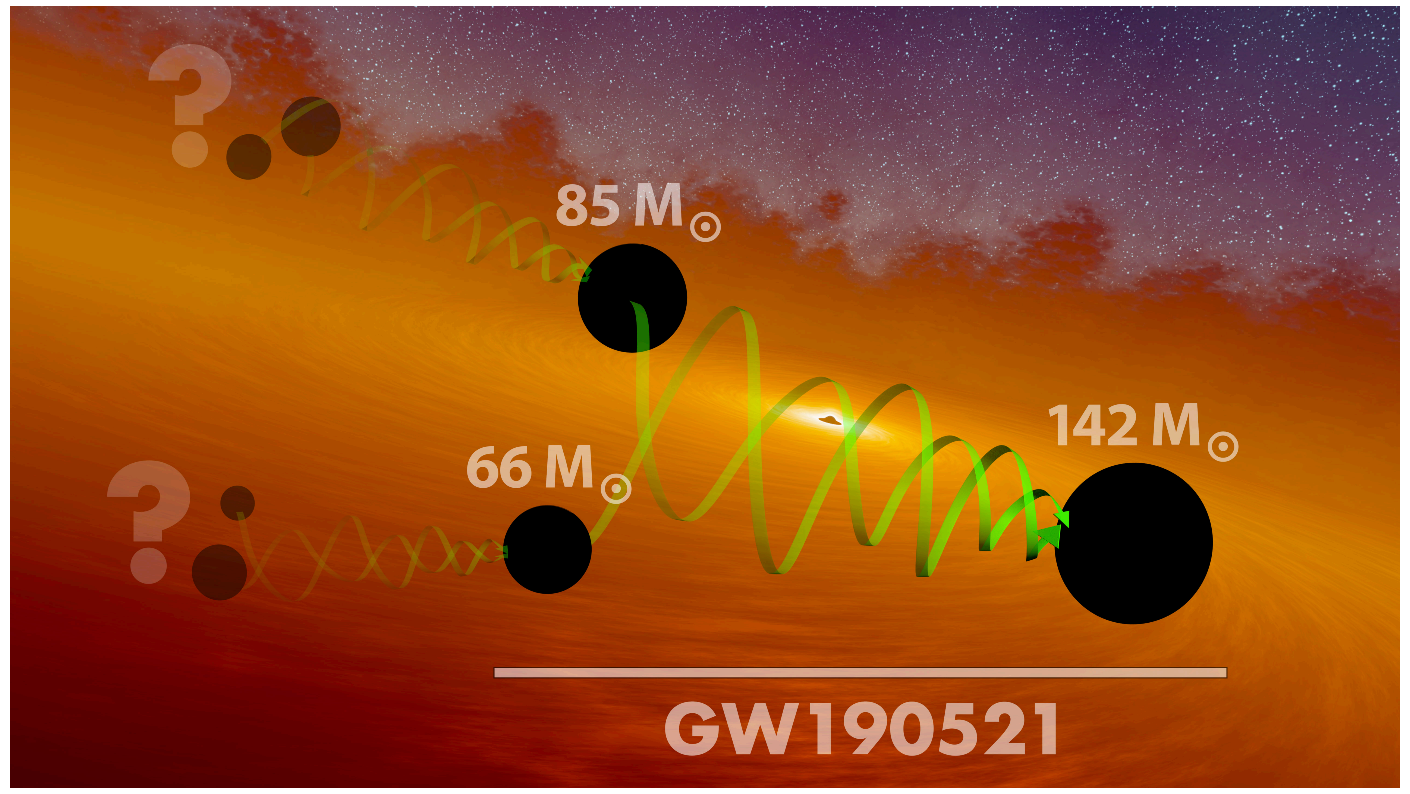
All kinds of diverse, interesting inhabitants in our universe!





No such pair of light NS known in the local galaxy

First electromagnetic wave counterpart!



GW190821

(intermediate mass black hole, individual components in the mass gap)

credit: https://www.ligo.org/detections/

GW190814: heaviest neutron star or lightest black hole? In August 2019, the LIGO-Virgo gravitational-wave network witnessed the merger of a black hole with 23 times the mass of our sun and a binary companion 2.6 times the mass of the sun. Scientists do not know if the companion was a neutron star or a black hole, but either way it set a record as being either the heaviest known neutron star or the lightest known black hole. [Image credit: LIGO/Caltech/MIT/R. Hurt (IPAC).]

Largest known NS or lightest BH?

Different formation scenarios of compact object binaries

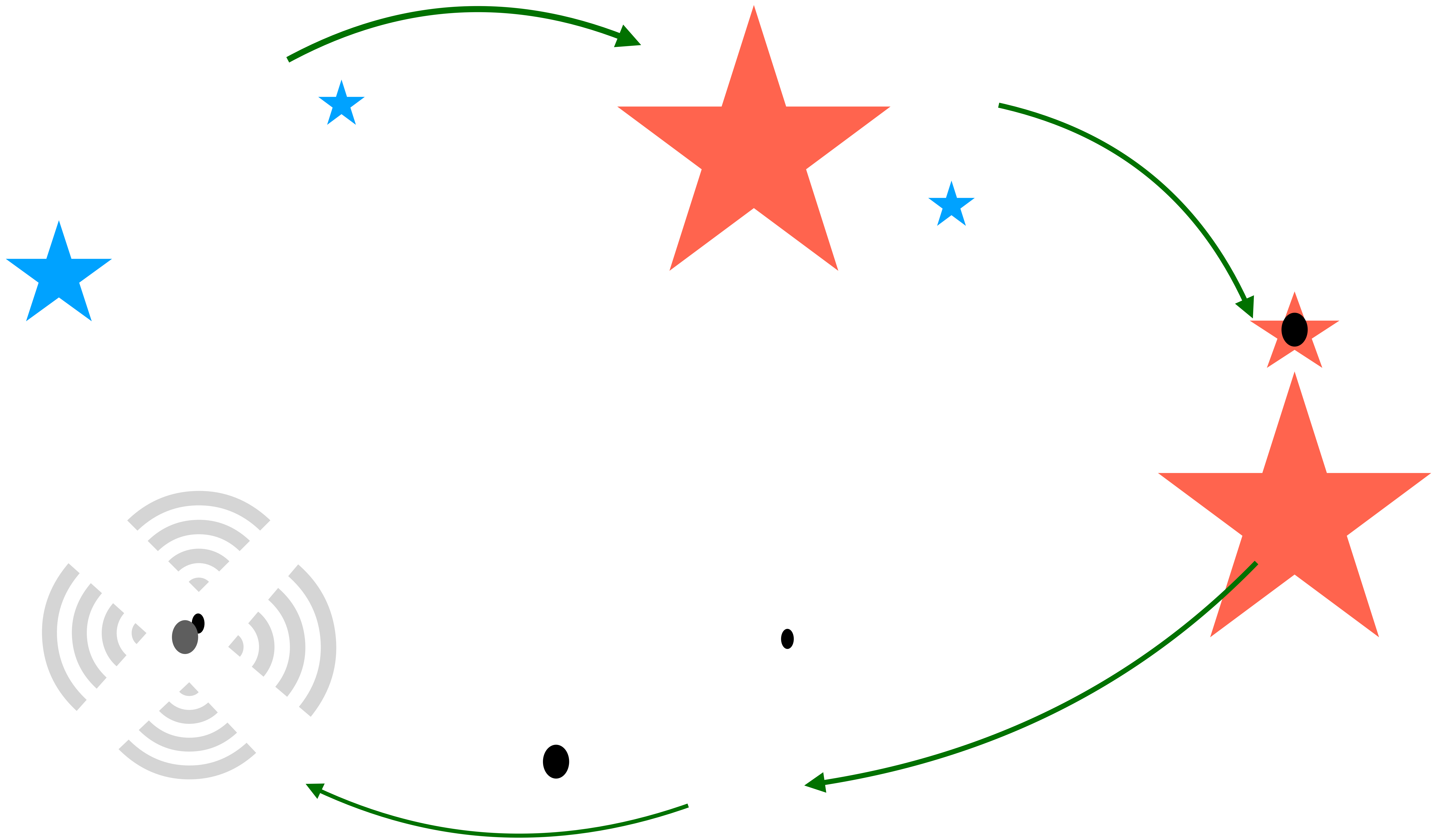
Isolated scenarios -

Common envelope
Homogenous evolution

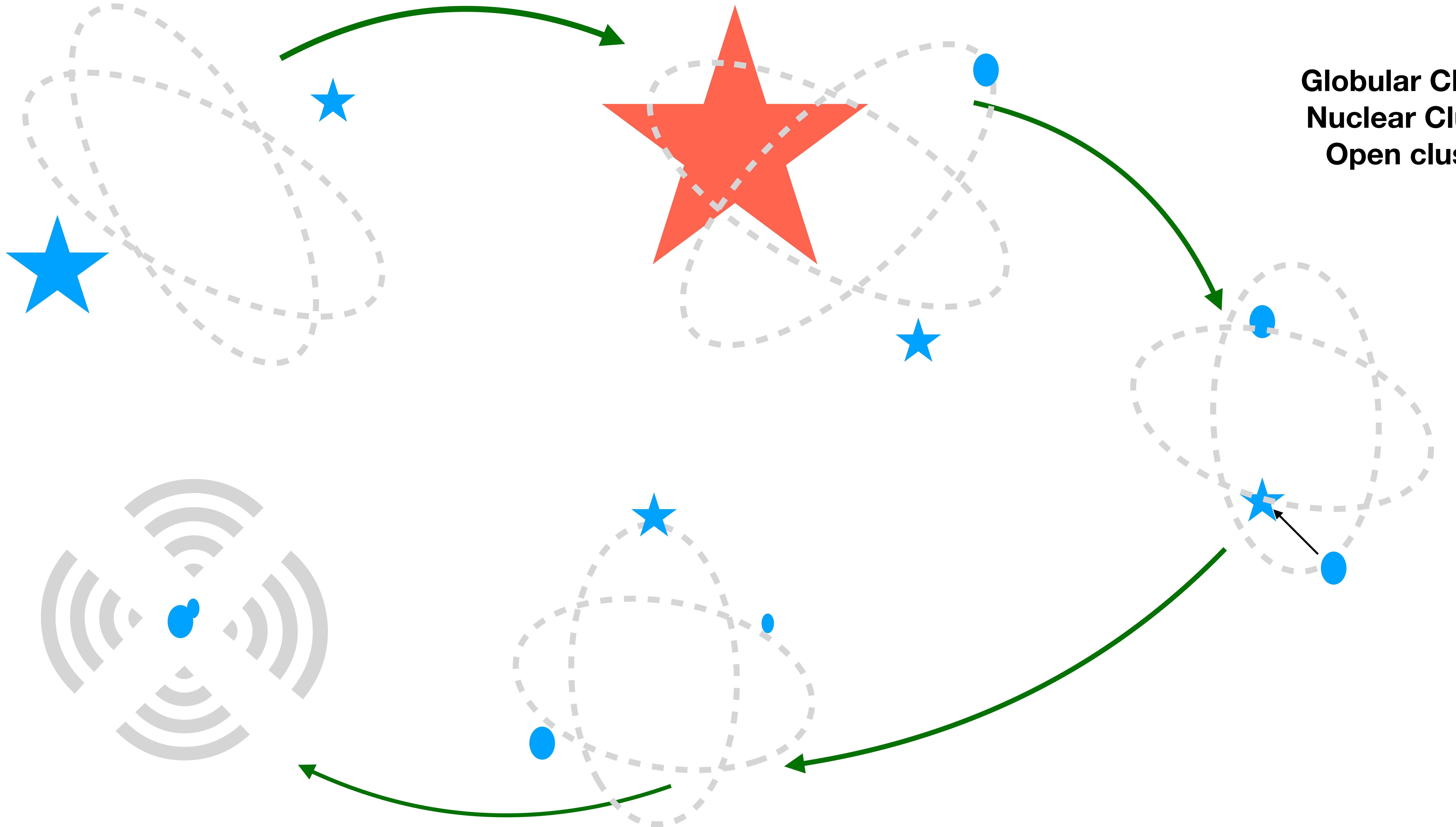
Dynamic formation in dense clusters -

Orbital captures in globular clusters, stellar clusters, nuclear star clusters

Isolated scenario - Common scenario for neutron star mergers

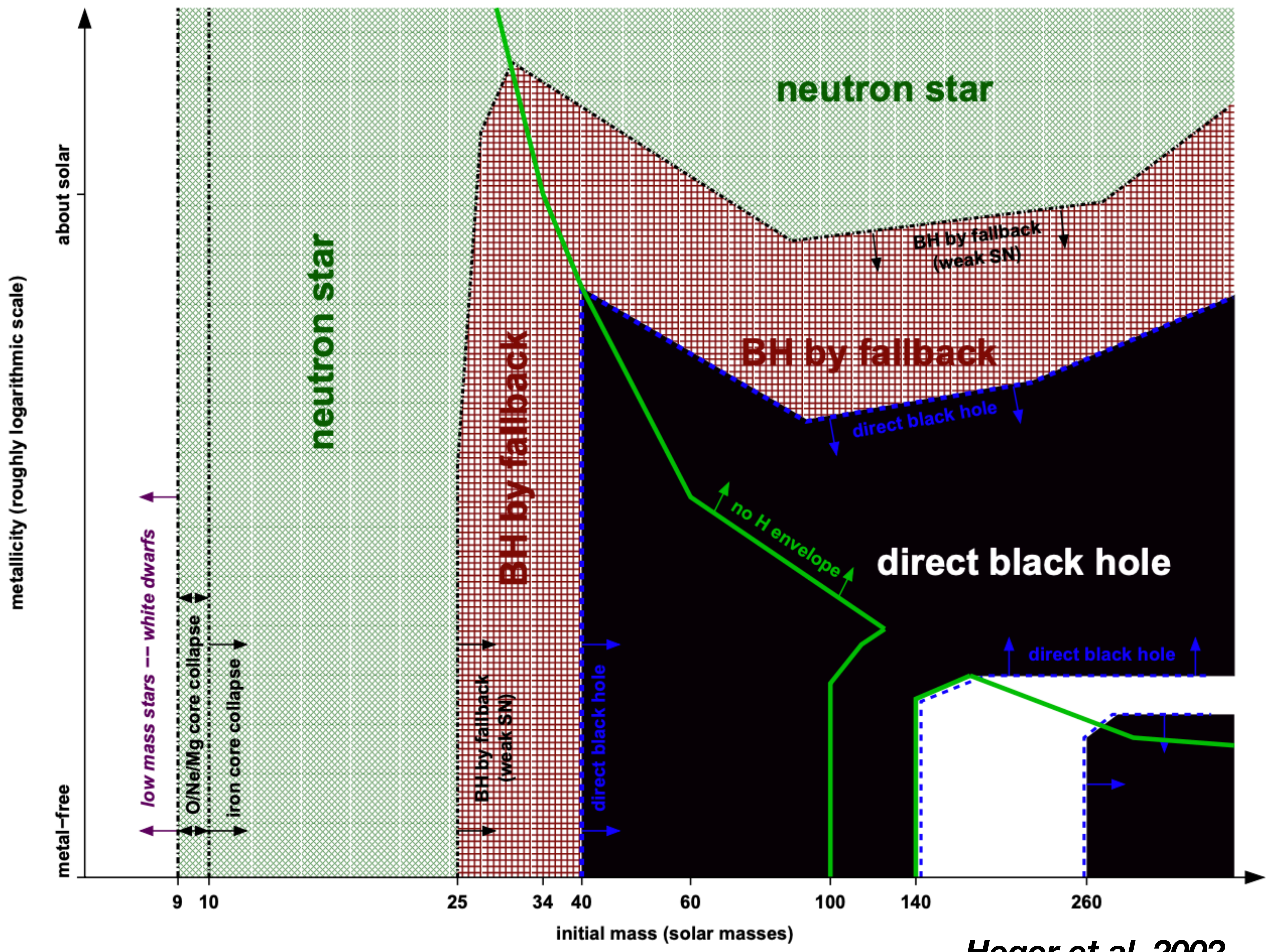


Dynamical interactions - Common scenario for BBHs



Globular Clusters
Nuclear Clusters
Open clusters

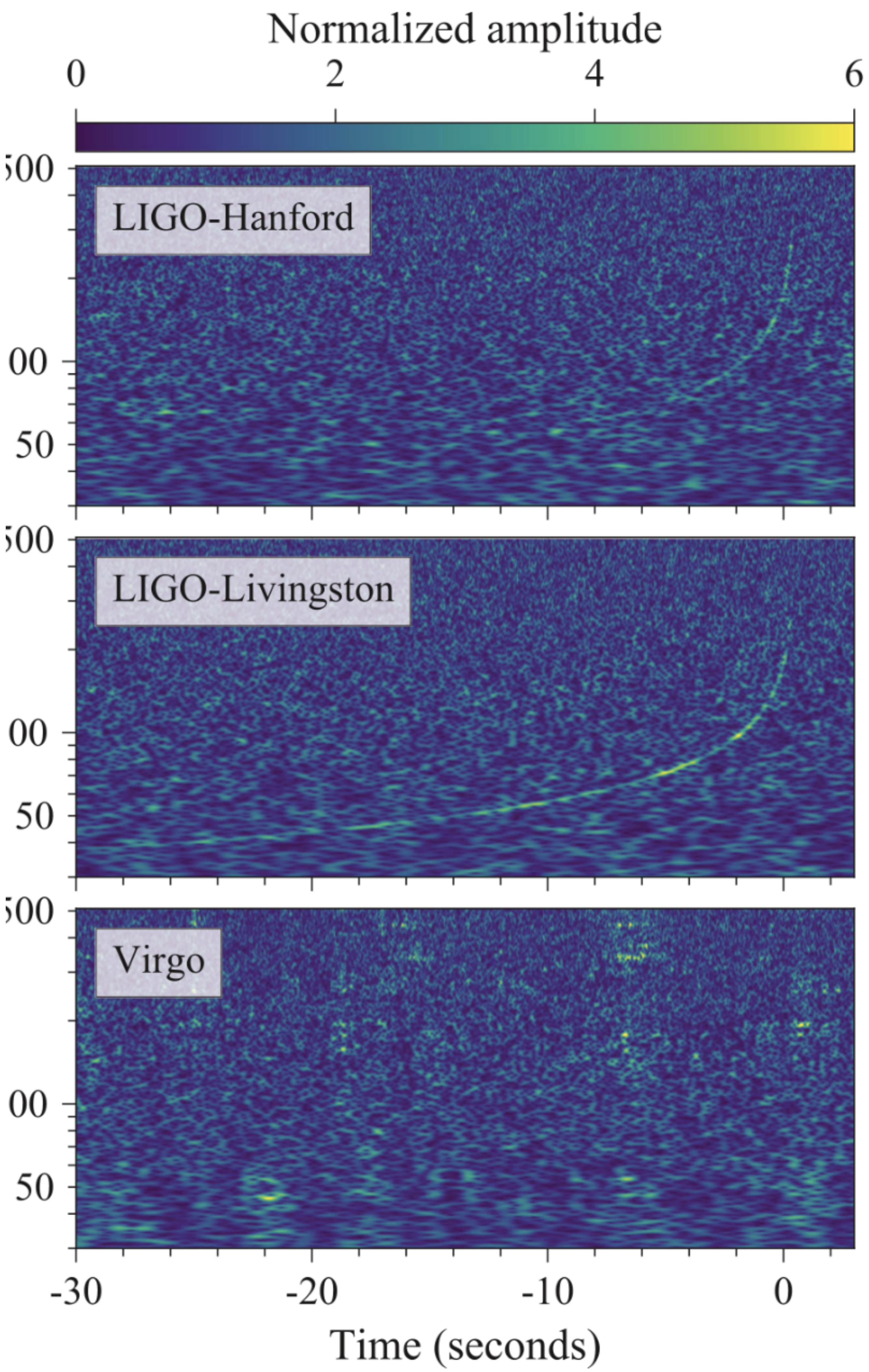
How stars end their lives depend intimately on their environment



Heger et al. 2002

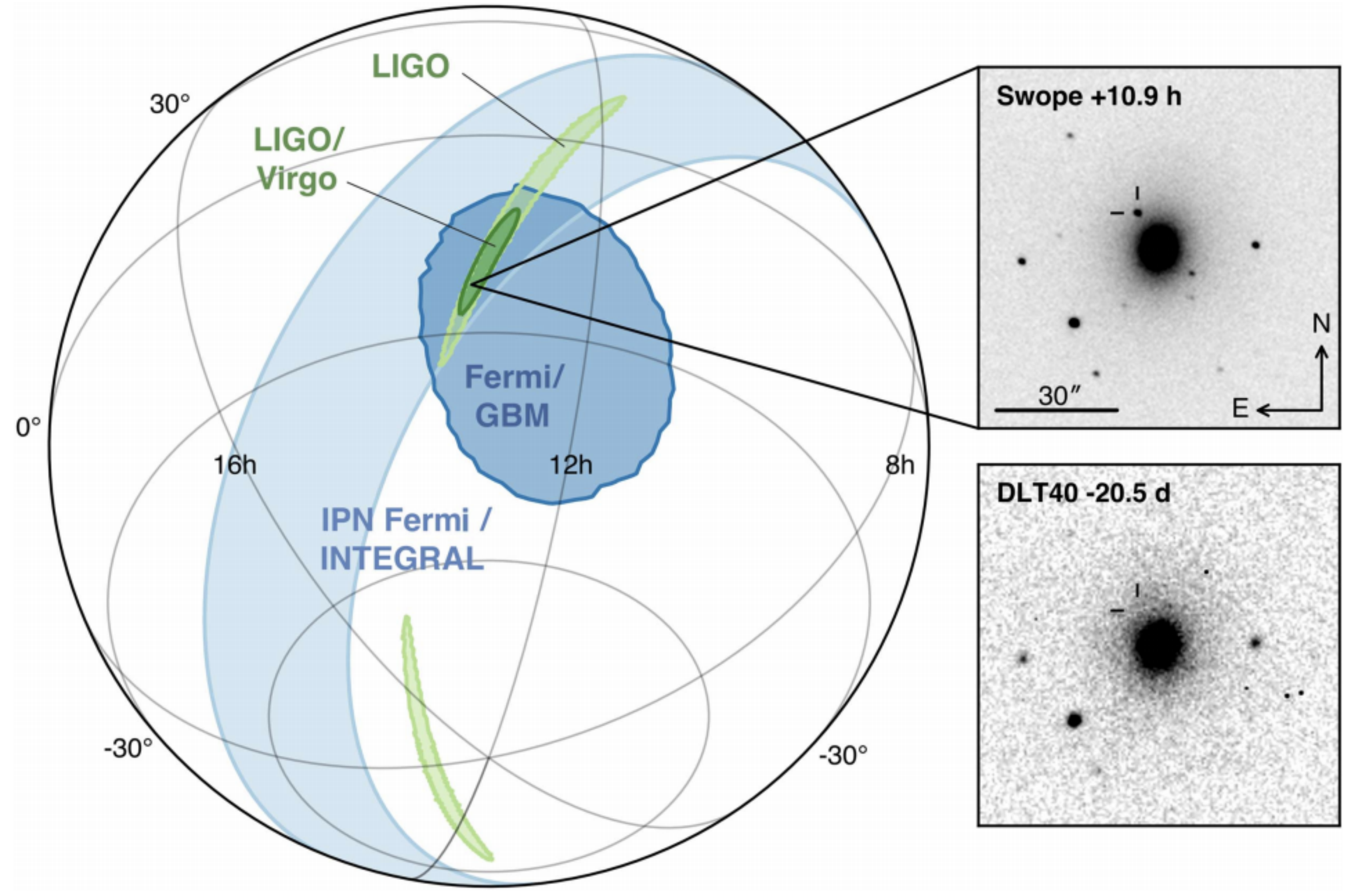
Stellar evolution depends on many factors where they form

A Gravitational Wave event with an electromagnetic counterpart



Abott et al. 2017

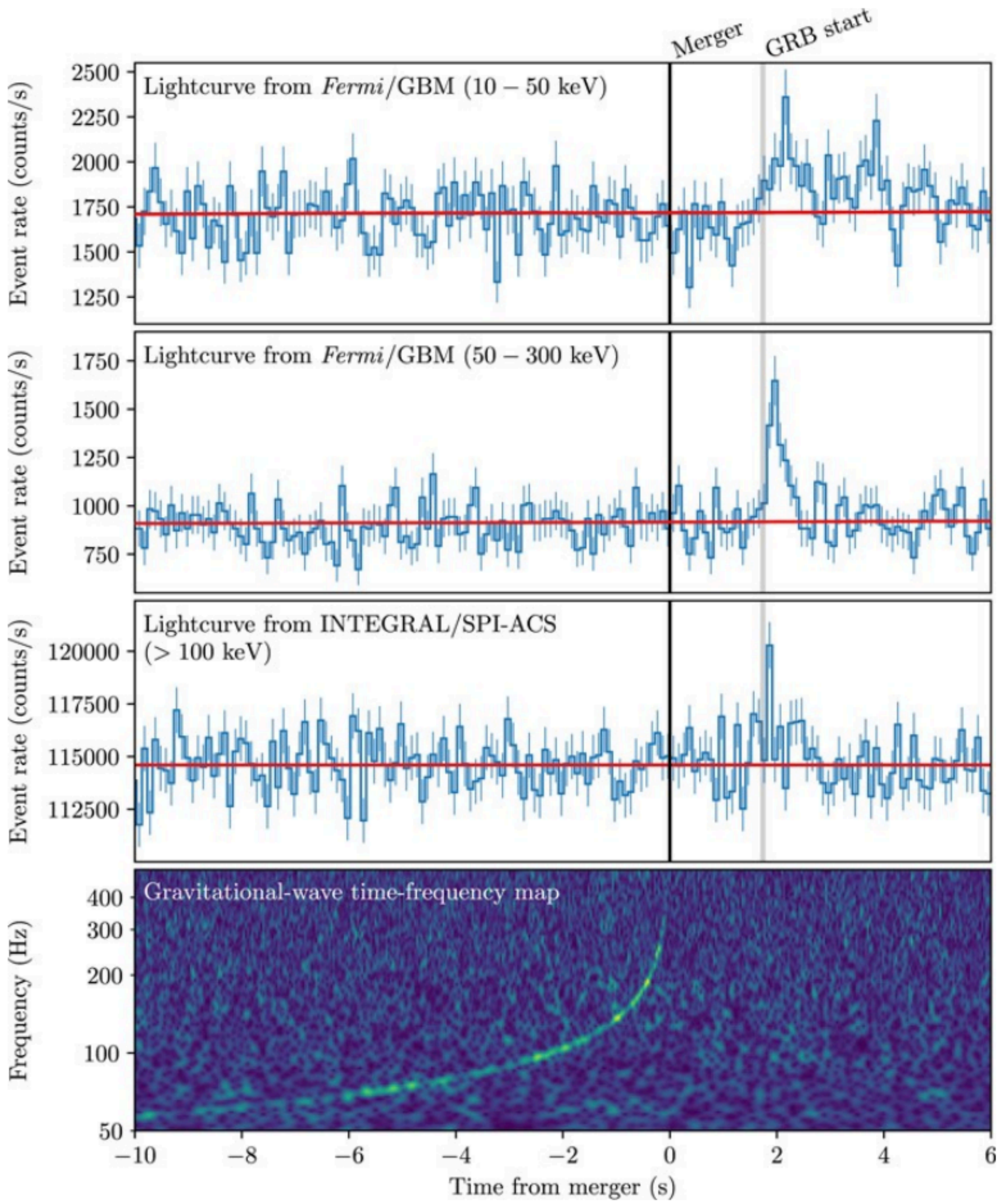
GW170817



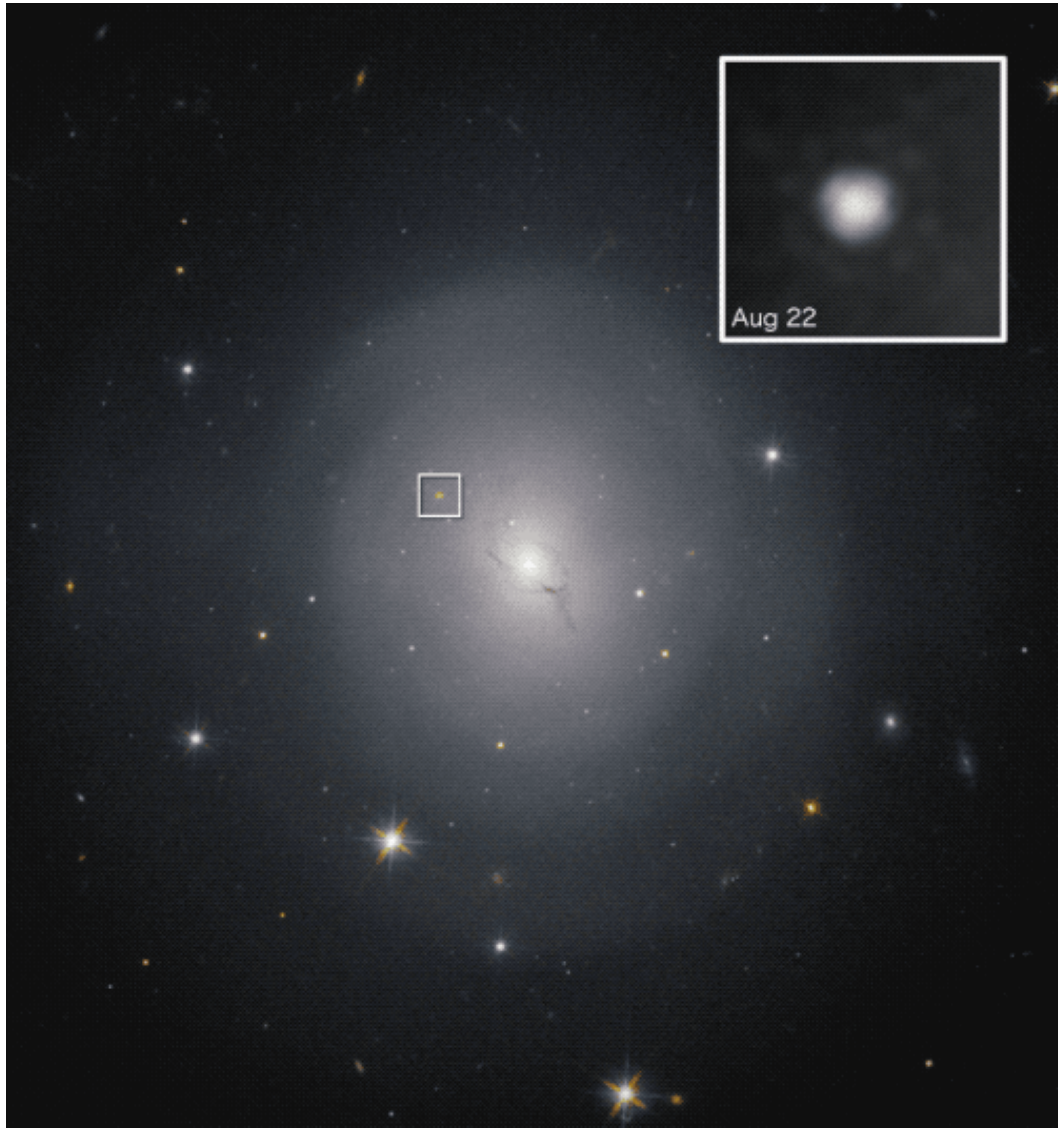
- **First binary neutron star merger that was detected with a counterpart**
- **Total mass of 2.74 Msun**
- **40 Mpc h^-1**

This event was observed nearly throughout the electromagnetic spectrum

For the first time we glimpsed into the host galaxy of the merger



Abott et al. 2017, Goldstein et al. 2017



NGC4993

The event was observed across the electromagnetic spectrum!

Followed by a short GRB after ~ 1.7 seconds

Binary systems evolve within cosmic structure and co-evolve with galaxies through cosmic time

Credit: ALMA (ESO/NAOJ/NRAO), Alves et al.

Credit: ALMA (ESO/NAOJ/NRAO), Alves et al.

Hubble: NGC3147

Credit: ALMA (ESO/NAOJ/NRAO), Alves et al.

Hubble: NGC3147

Abell cluster

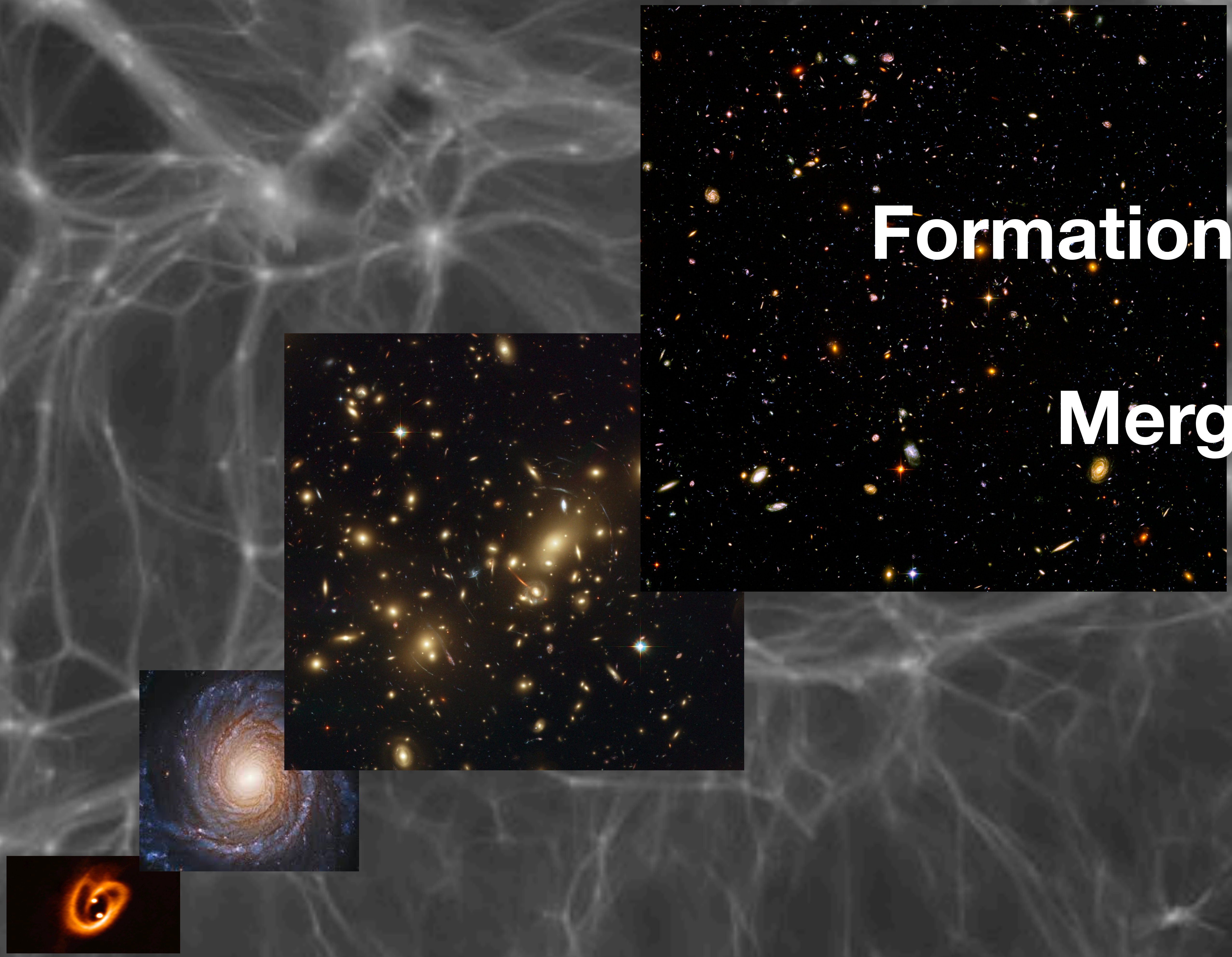
Credit: ALMA (ESO/NAOJ/NRAO), Alves et al.

Hubble: NGC3147

Abell cluster

credit: Hubble/ESA

Binary systems co-evolve with the structure in the universe



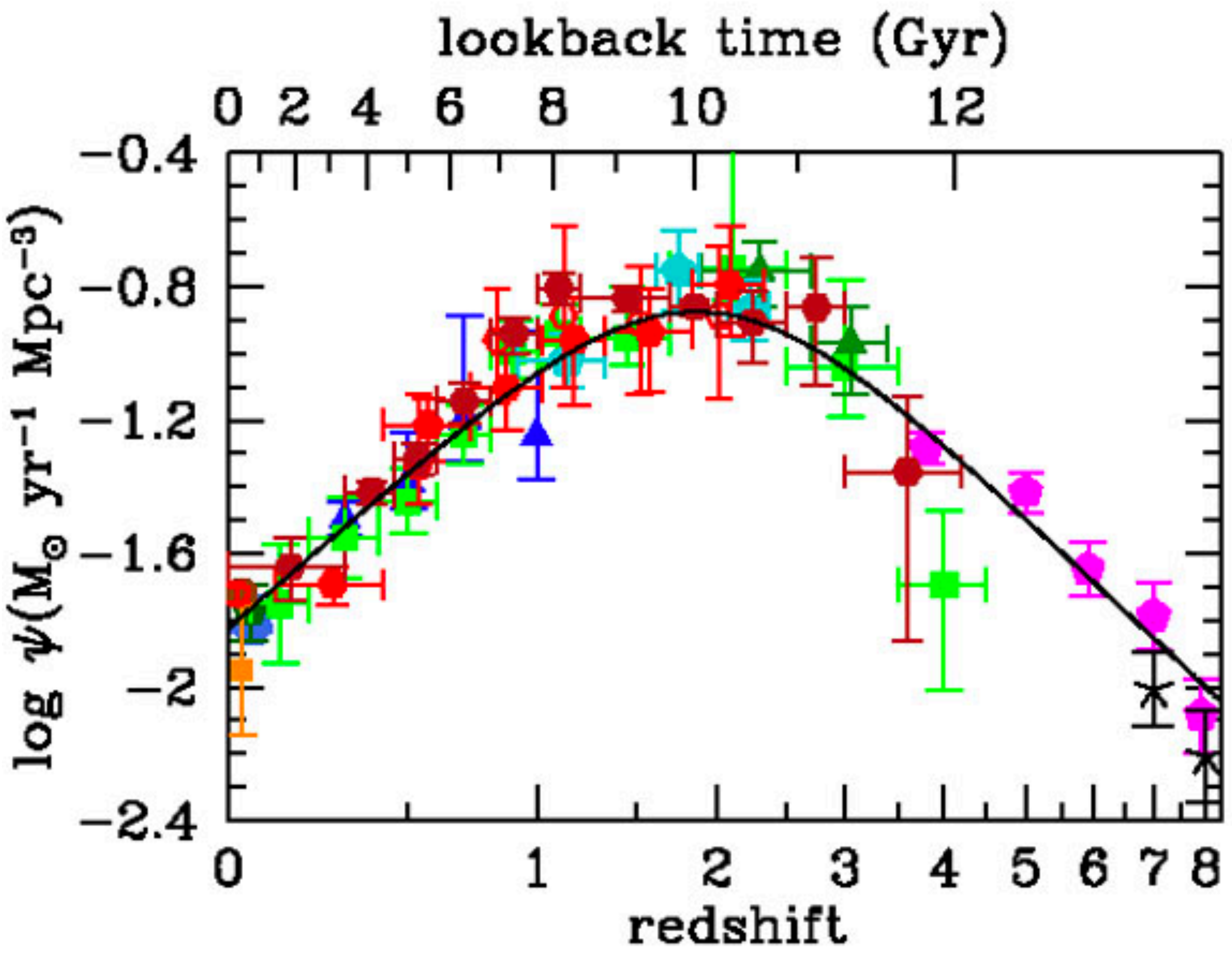
Relevant timescales :

Formation time: When do these systems for

Merger times: When do they merge?

Host galaxies can evolve significantly

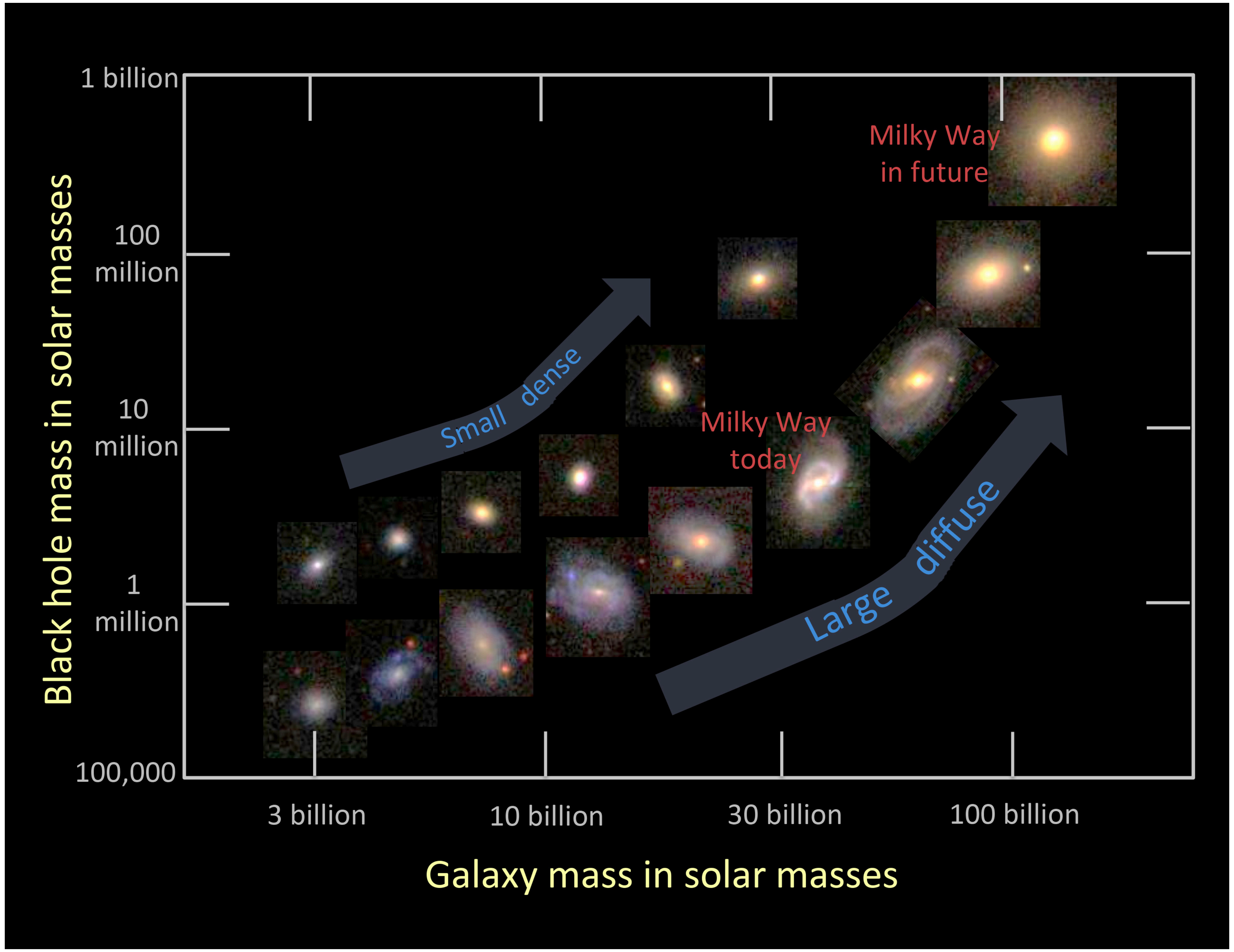
If timescales are of ~Hubble time



Madau et al. 2014

Staff formation history of the universe

Galaxies evolve from being blue, star-forming and spiral to red, quiescent and elliptical



Credit: Sandra Faber/Sofia Quiros/SDSS

The galaxies where the binaries form can be very different from where they merge

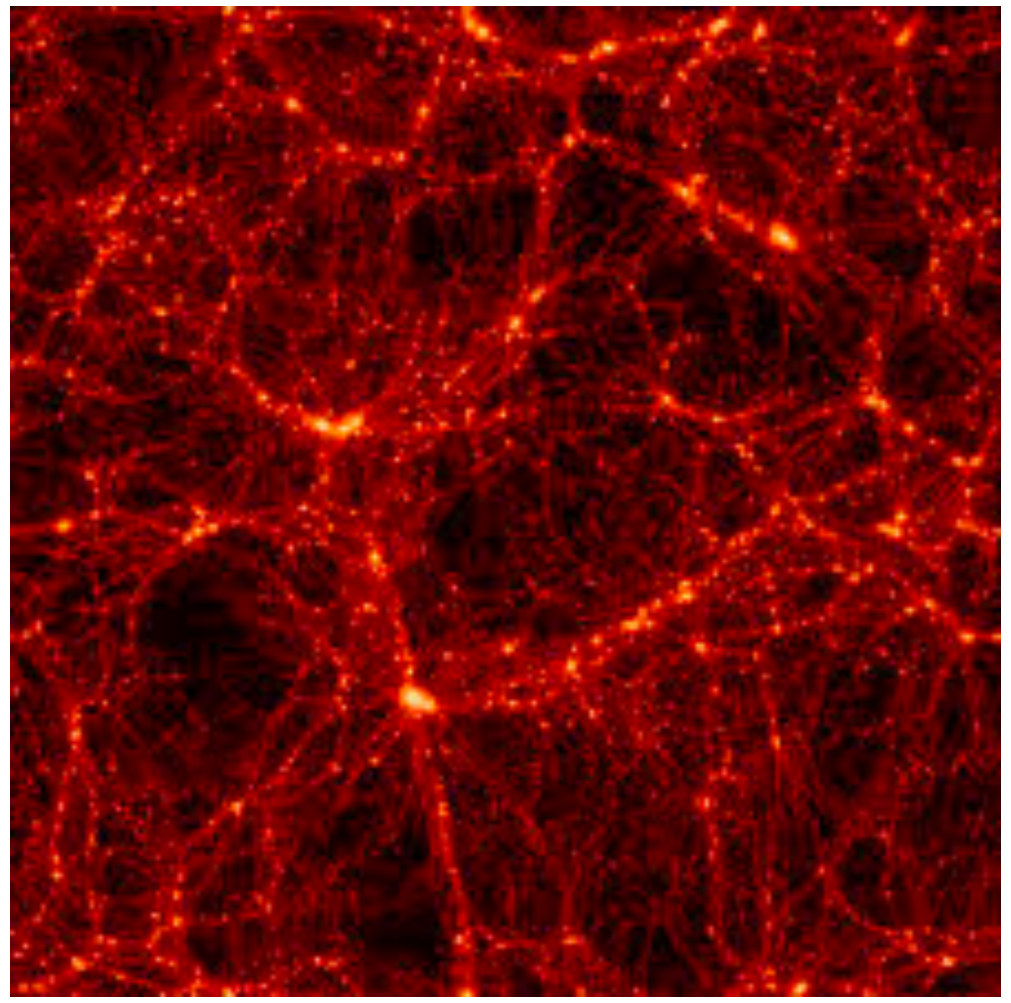
Properties of the hosts, therefore encode information about the binary evolution

What do the properties of the host galaxies tell us about the underlying binaries?

Galaxy properties like its age, color, star-formation rate, stellar mass and their evolution through time depend often depend on the underlying cosmic web and its evolution

They are often time driven by mergers, environments, AGNs deeply connected to cosmi evolution of structure

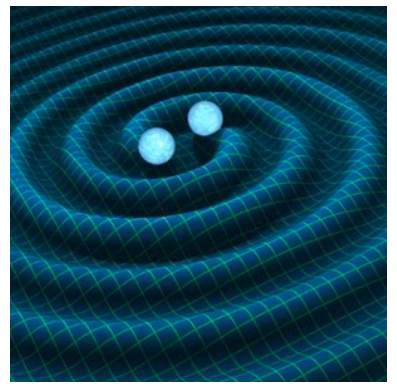
Modeling Binary evolution in a Cosmological Volume



DM-only simulation

Semi-analytic Modelling

Simple modelling



The binary–host connection: astrophysics of gravitational wave binaries from their host galaxy properties

Susmita Adhikari,[1] Maya Fishbach,[2,3] Daniel E. Holz,[2,3,4,5] Risa H. Wechsler,[1,6] and Zhanpei Fang[1]

[1]Kavli Institute for Particle Astrophysics and Cosmology and Department of Physics, Stanford University, Stanford, CA 94305, USA
[2]Department of Astronomy and Astrophysics, The University of Chicago, Chicago, IL 60637, USA
[3]Kavli Institute for Cosmological Physics, The University of Chicago, Chicago, IL 60637, USA
[4]Department of Physics, The University of Chicago, Chicago, IL 60637, USA
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[6]SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA

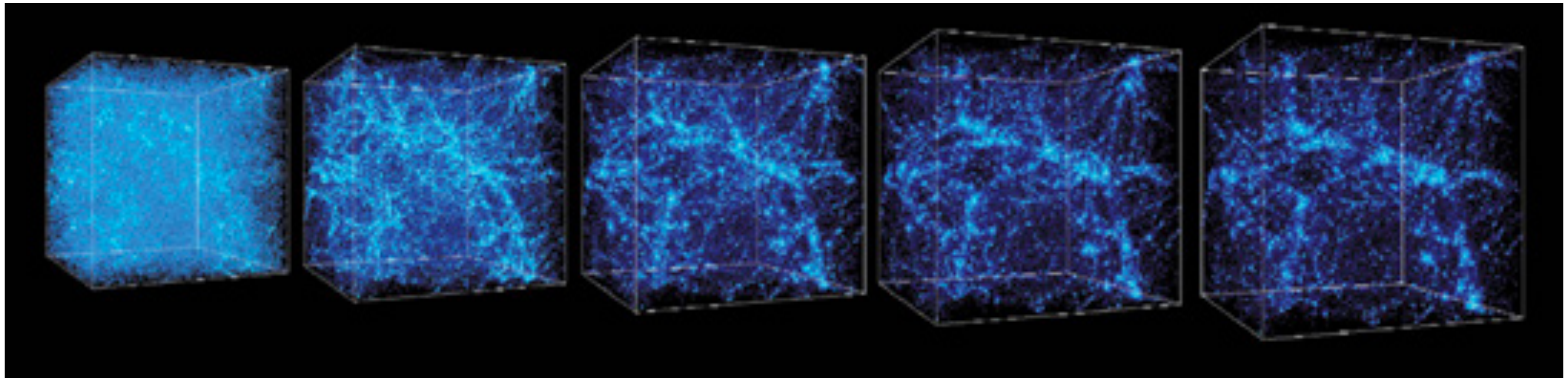
UNIVERSE MACHINE SIMULATIONS

Behroozi et al. 2018

- **Populates a dark-matter only simulation with galaxies.**
- **Based on semi-empirical model that parametrizes the correlation between the star-formation rate of a galaxy and the properties of its parent halo,**

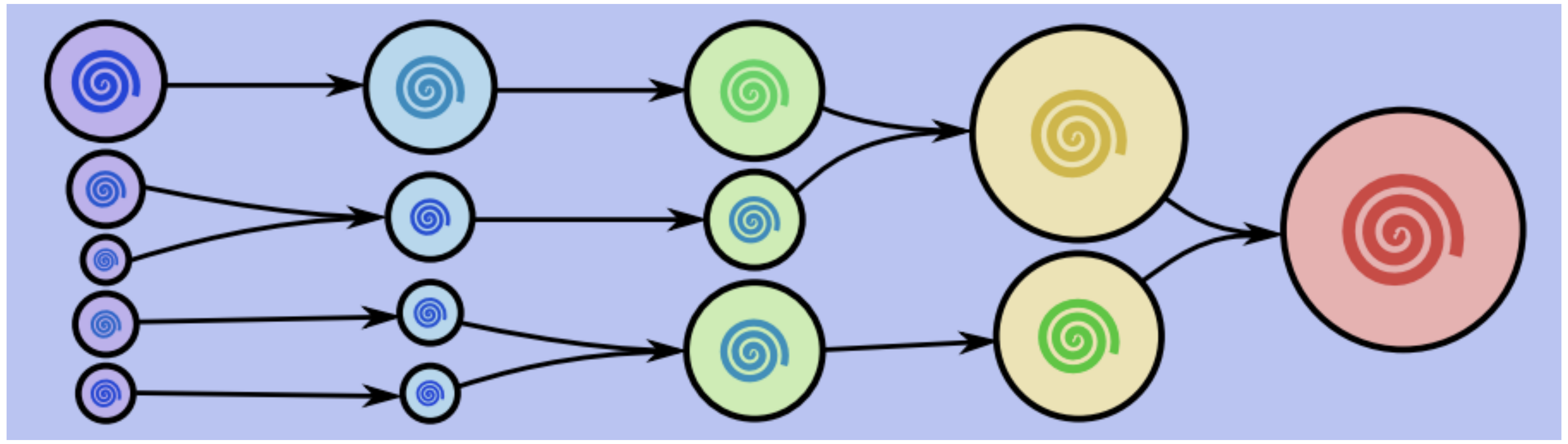
$$SFR = f(M_h, dM_h/dt, z)$$

- **43 parameter model**
- **Bolshoi simulations**
- **2048^3 particles**
- **250 Mpc/h volume**



Bolshoi simulation 2010

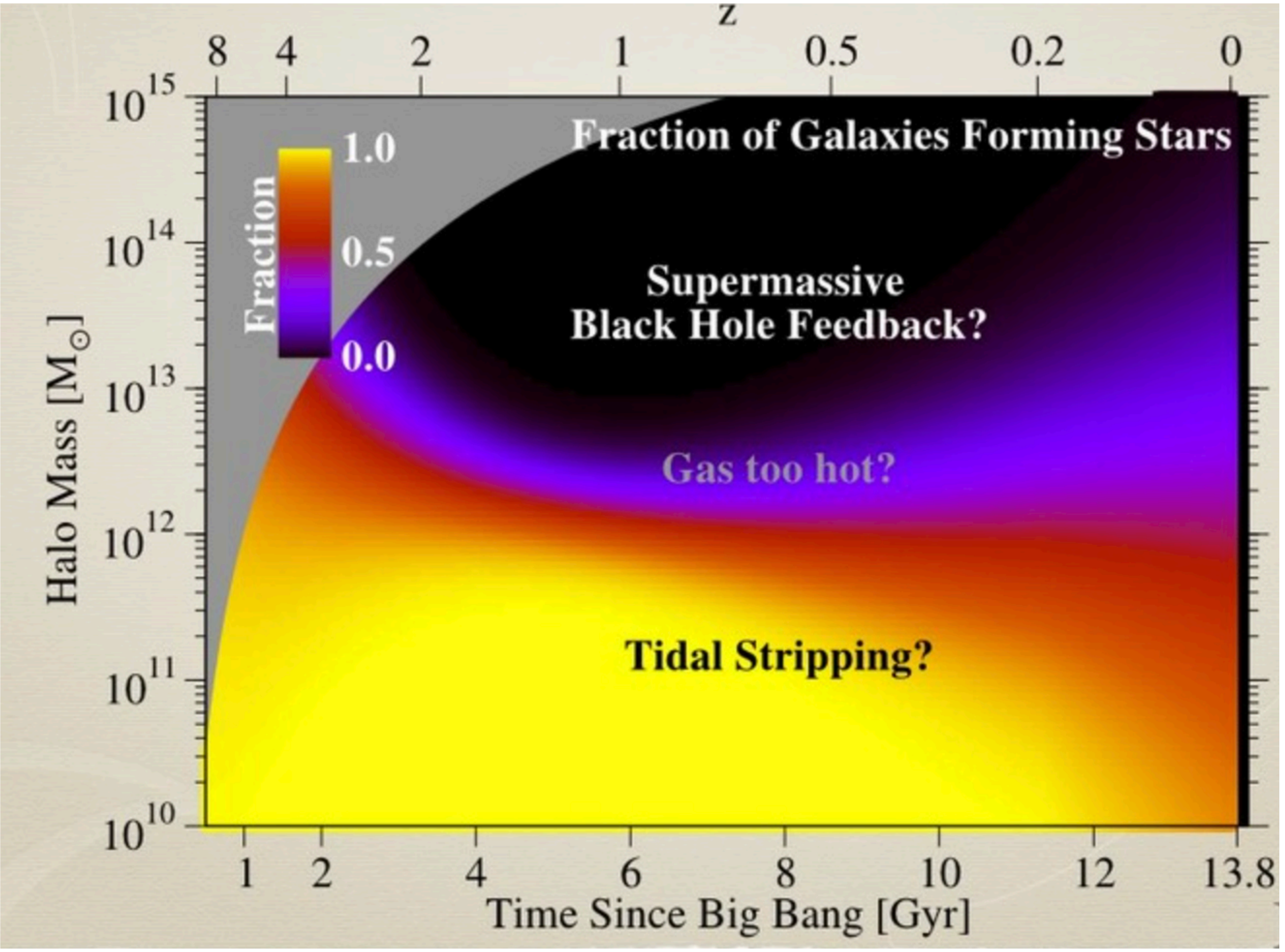
Maps the merger history of cosmic structure (dark matter halos) to galaxy star-formation evolution



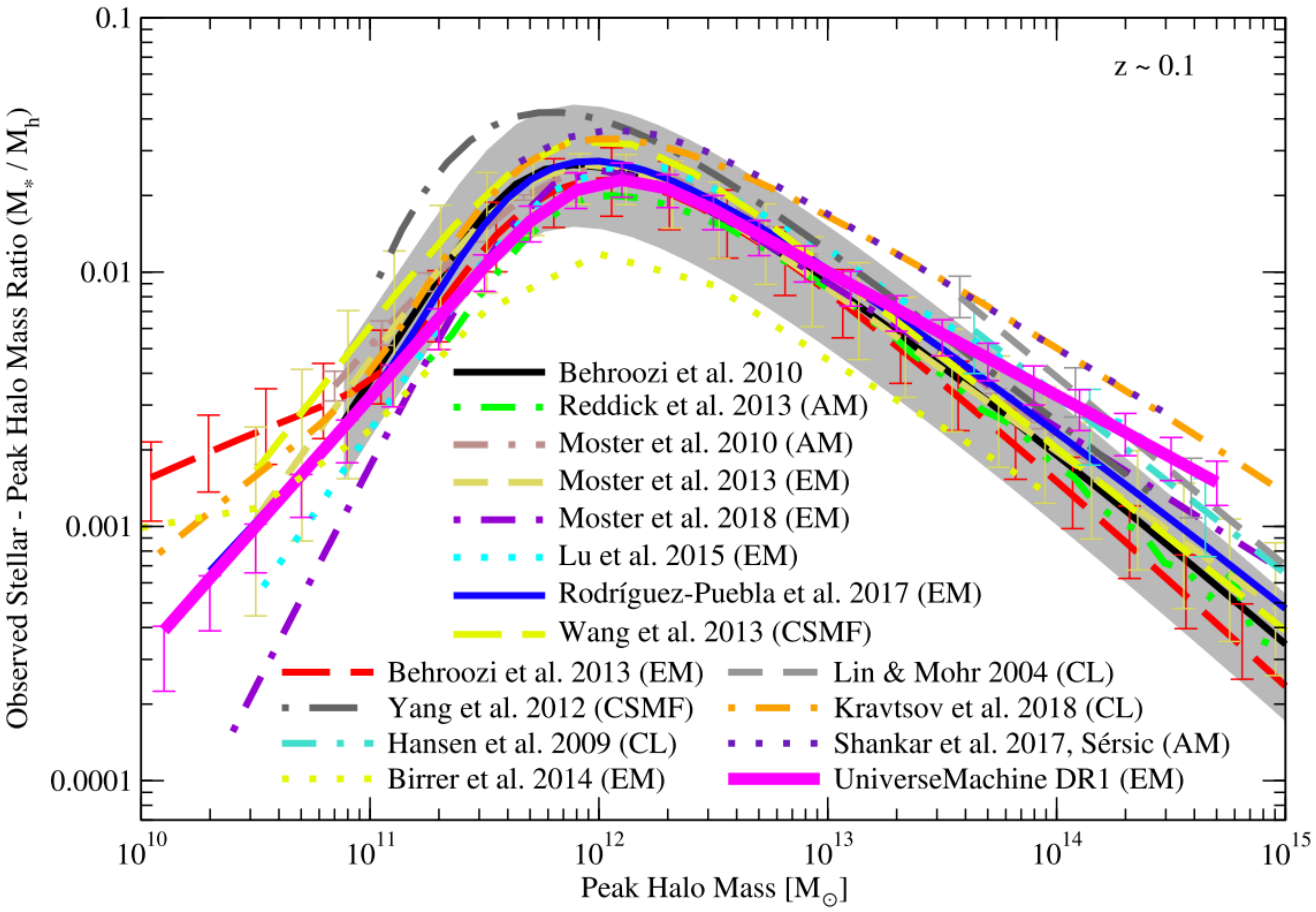
Type	Redshifts	Primarily Constrains
Stellar mass functions[a]	0 – 4	SFR–$v_{\rm Mpeak}$ relation
Cosmic star formation rates[a]	0 – 10	SFR–$v_{\rm Mpeak}$ relation
Specific star formation rates[a]	0 – 8	SFR–$v_{\rm Mpeak}$ relation
UV luminosity functions	4 – 10	SFR–$v_{\rm Mpeak}$ relation
Quenched fractions[a]	0 – 4	Quenching–$v_{\rm Mpeak}$ relation
Autocorrelation functions for quenched/SF/all galaxies from SDSS[b]	∼0	Quenching/assembly history correlation
Cross-correlation functions for galaxies from SDSS[b]	∼0	Satellite disruption
Autocorrelation functions for quenched/SF galaxies from PRIMUS[a]	∼0.5	Quenching/assembly history correlation
Quenched fraction of primary galaxies as a function of neighbour density[b]	∼0	Quenching/assembly history correlation
Median UV–stellar mass relations[b]	4 – 8	Systematic stellar mass biases
IRX–UV relations	4 – 7	Dust

Set of observations that is used to constrain the model

UNIVERSEMACHINE Simulations



Behroozi et al. 2018

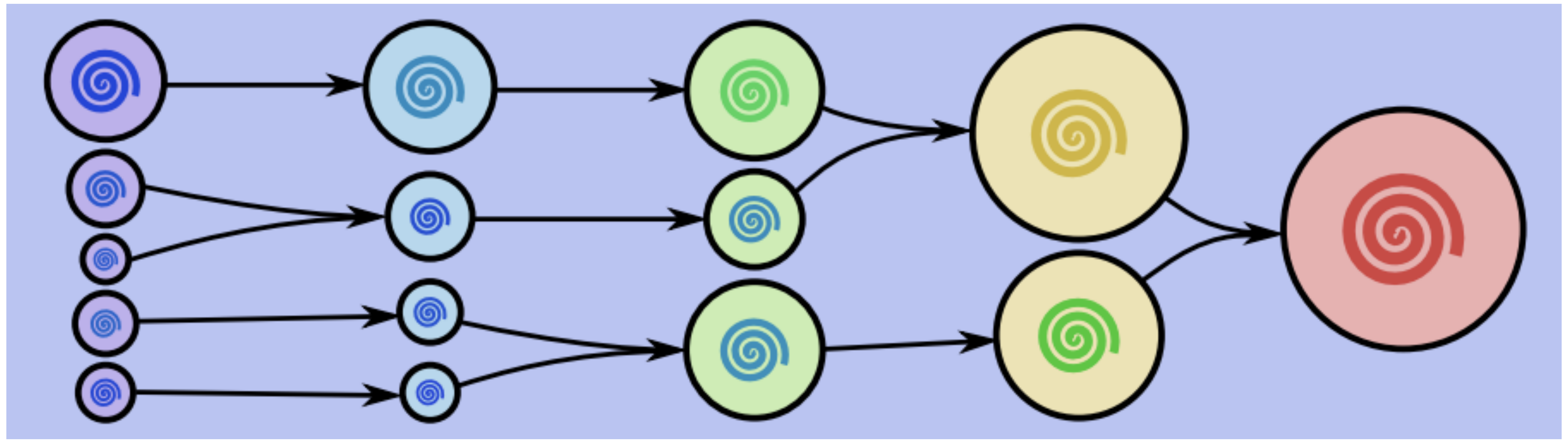


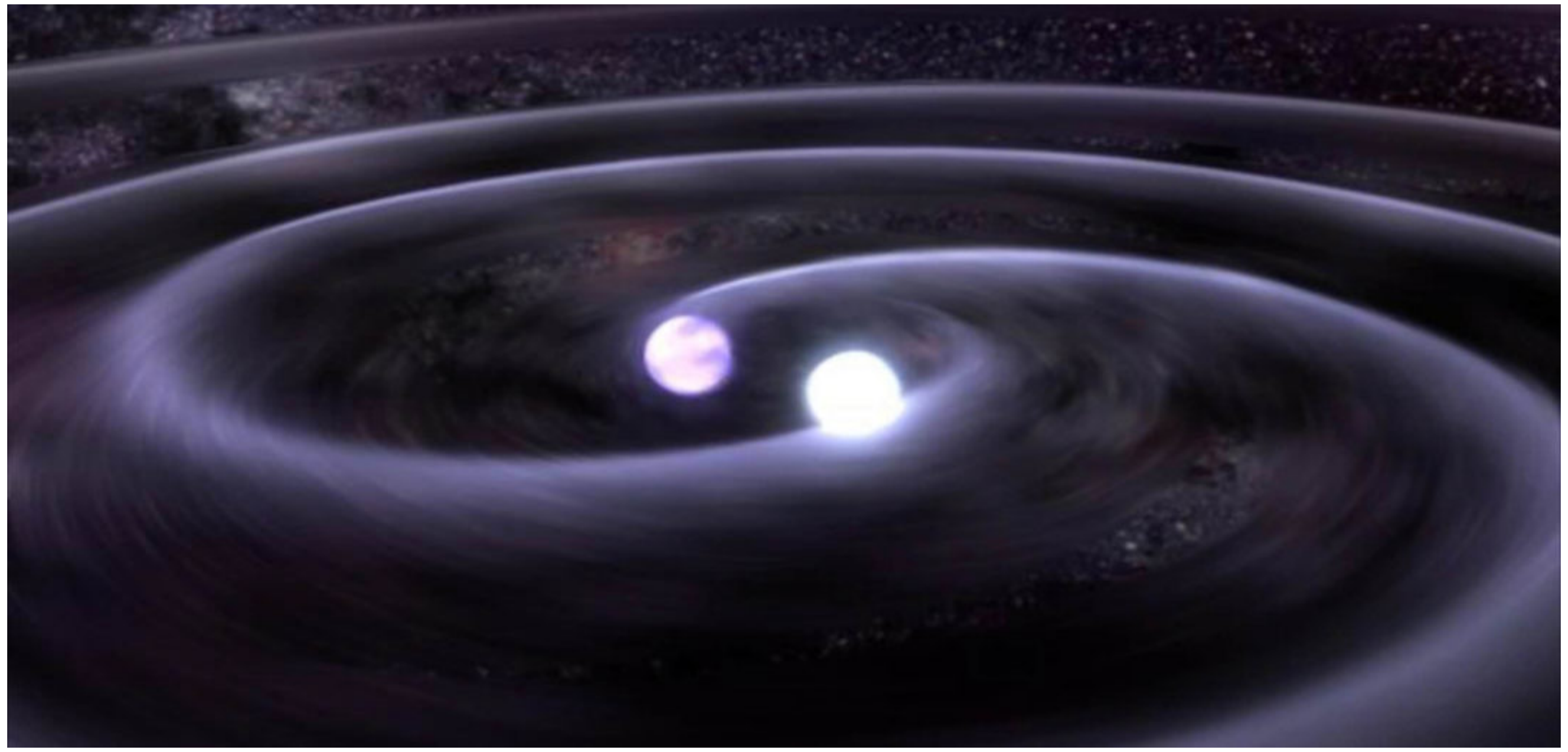
Behroozi et al. 2018

Fraction of galaxies forming stars at a given halo mass

Stellar mass halo mass relation at z=0

Populate the Universe Machine simulations with binaries

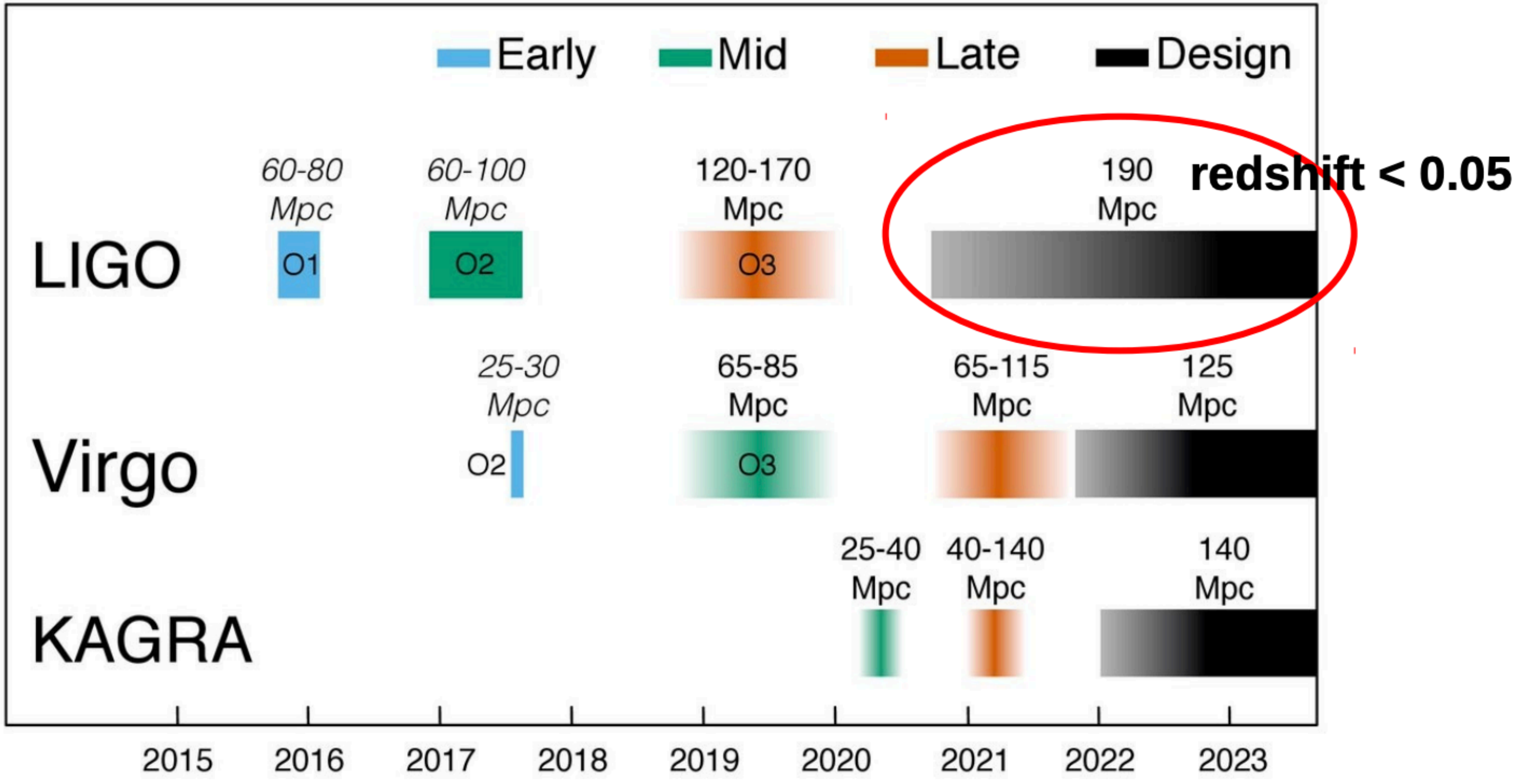




(i) Populate simulations with a merger time model for isolated binary evolution (NS-NS)

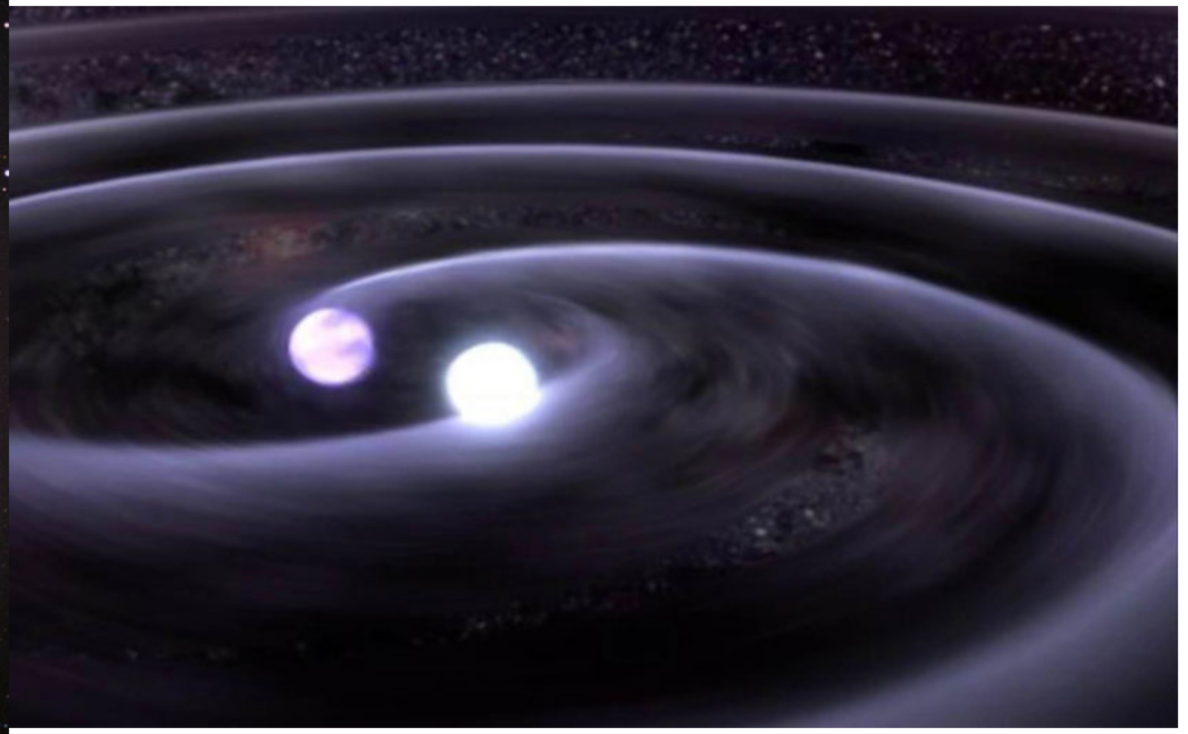
(ii) Simple questions about how the distribution of host galaxies change if binaries trace different galaxy properties

Focussing on low redshift NS-NS mergers where we are most likely to see a counterpart



Credits: LVC

Binary formation is tied to the star-formation rate of the galaxy



Characterized by a merger time distribution

$$dP/dt \propto (t - t_d)^{-\alpha}$$

Merger time corresponds to the time elapsed between formation of the binary system and eventual merger.

Power-law distribution is expected from the distribution of initial orbital separations of binary systems.

How does the delay-time distribution effect the observed properties of the host galaxies?

$$\mathcal{R}(z_f) = \lambda \int_0^{t(z_f)} \frac{dP}{dt}(t_f - t)\Psi_g(t)dt$$

$\Psi_g(t)$ Star-formation history - Number of stars formed per year

$\frac{dP}{dt}$ Delay time distribution

Merger rate of binaries for a given galaxy in the simulation

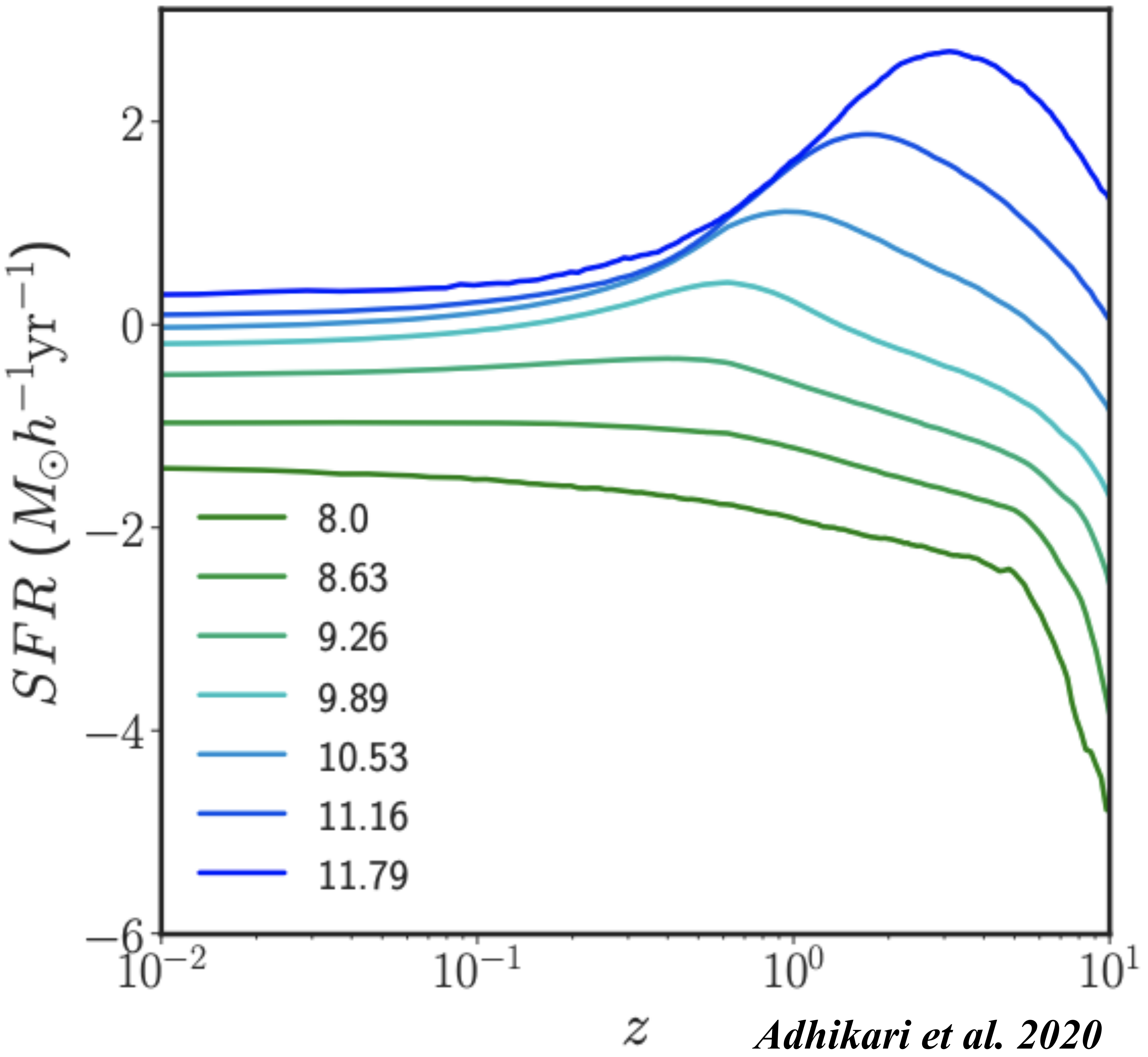
Star formation history depends on the evolution of the galaxy in the cosmic web

The total merger rate density in the universe is given by the convolution of $R(z_f)$ with the halo mass function $\Phi(M)(\Phi(L))$

Populate the Universe Machine simulations with binaries

- **Universe Machine provides galaxy properties - Star formation history of each galaxy in the volume and its evolution.**
- **Assign a merger rate to every galaxy based on delay time distribution.**
- **Vary the parameters to see the different galaxy distributions.**

delay time - t_d
Slope of distribution - α



Adhikari et al. 2020

Star formation history in different stellar mass bins

Galaxy properties at redshift $z = 0$

Massive galaxies reach the peak of their SFRs earlier in time -> more likely to form most binary systems then.

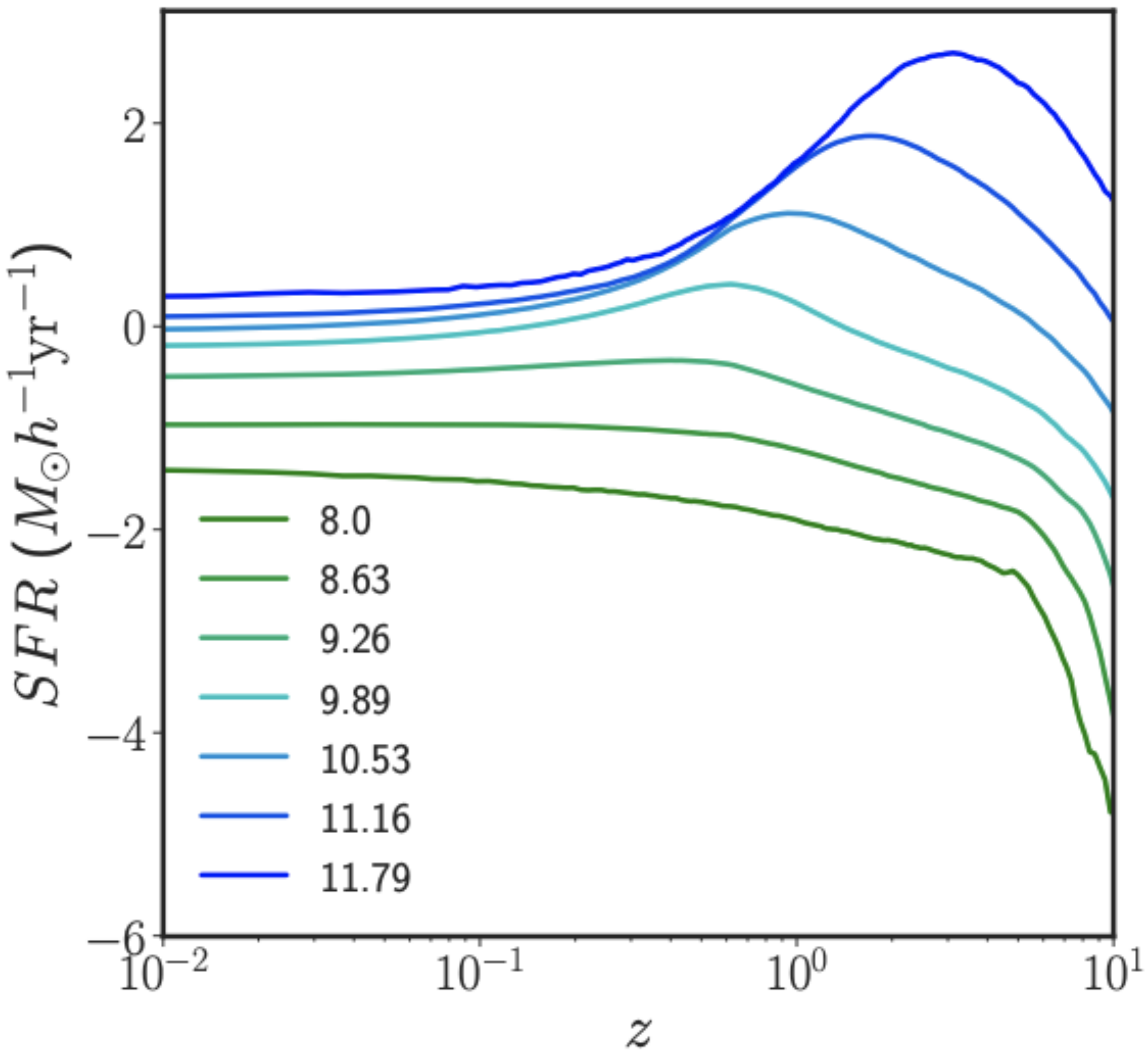
Blue, star-forming galaxies are still forming new massive stars

Stellar mass

specific Star-formation rate/ color

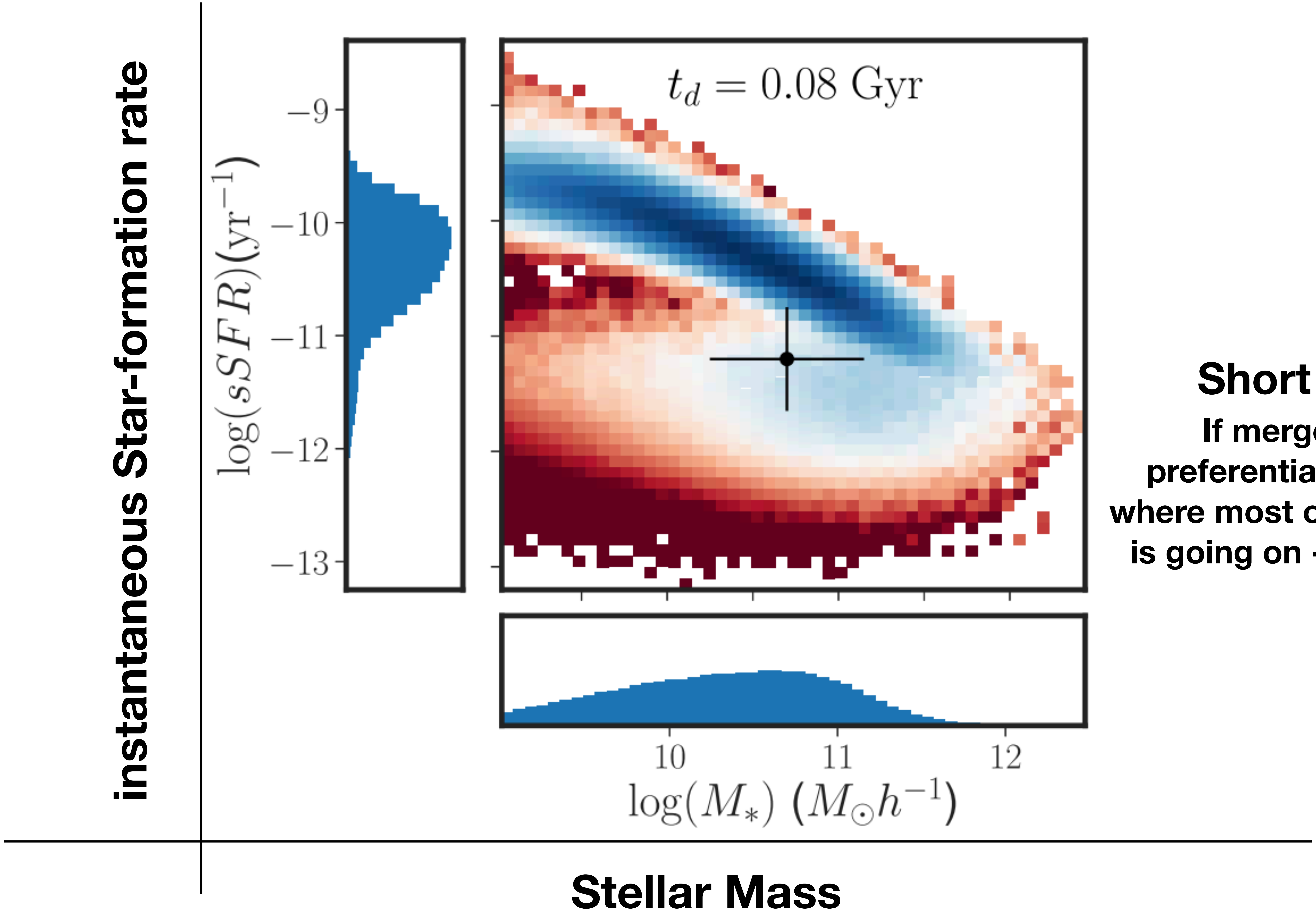
Local Density

Halo Mass



Adhikari et al. 2020

How does the star-formation rate and stellar mass of observed galaxies change?

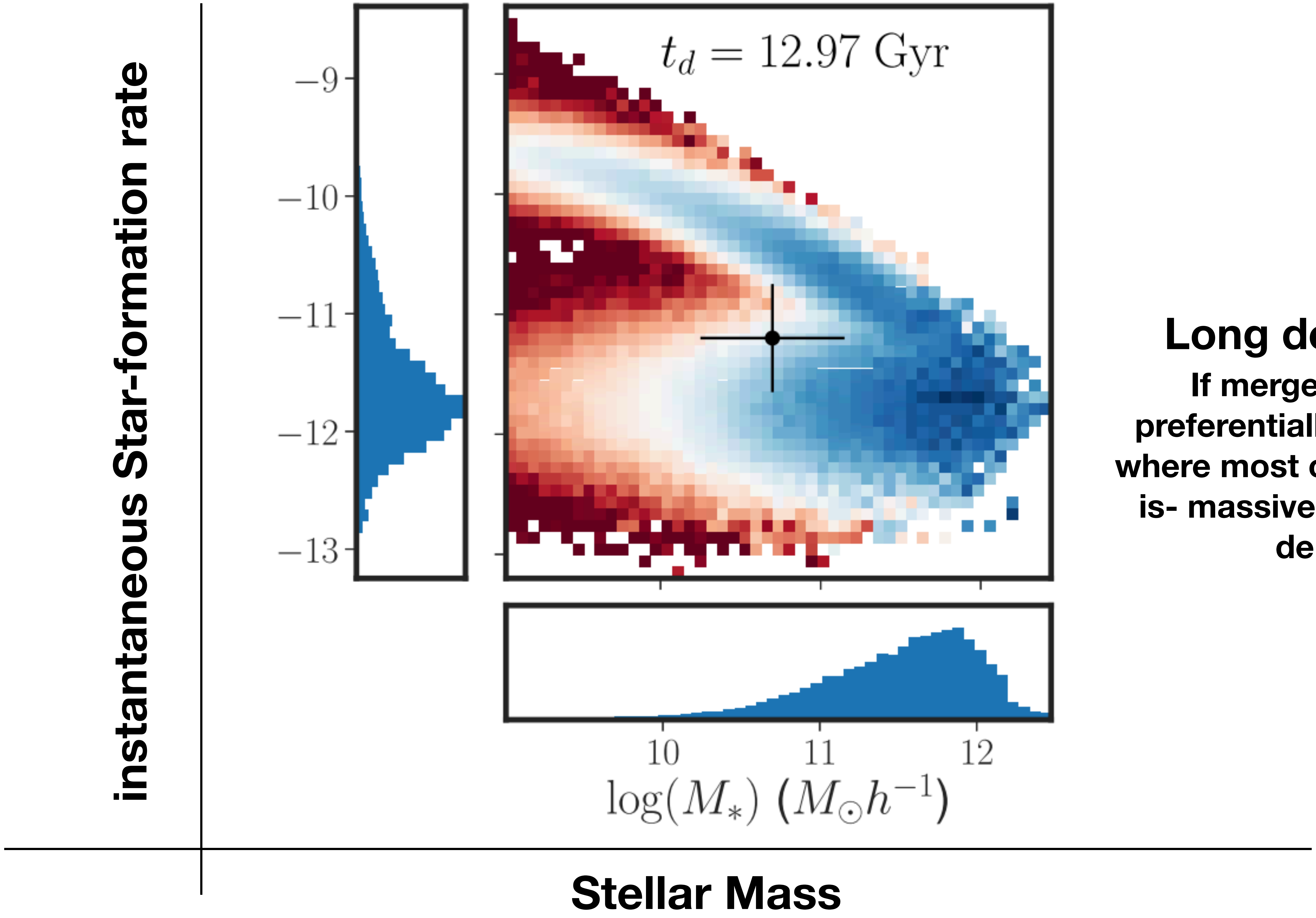


Short delay time

If mergers take place preferentially in the universe where most of the star-formation is going on -> short delay time

Adhikari et al. 2020

How does the star-formation rate and stellar mass of observed galaxies change?

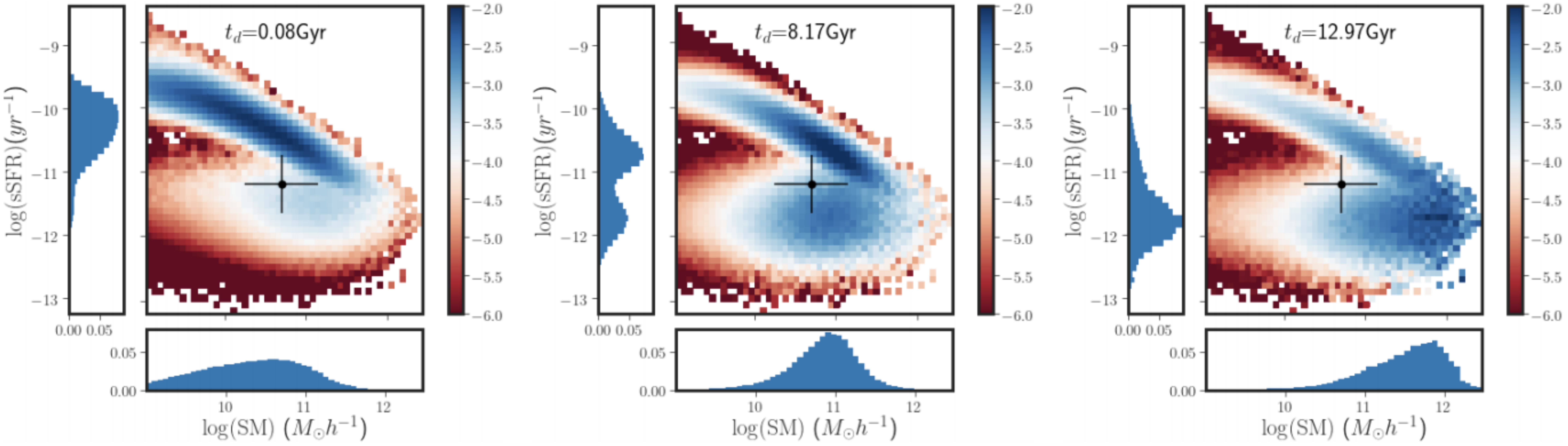


Long delay time

If mergers take place preferentially in the universe where most of the stellar mass is- massive galaxies -> long delay time

Adhikari et al. 2020

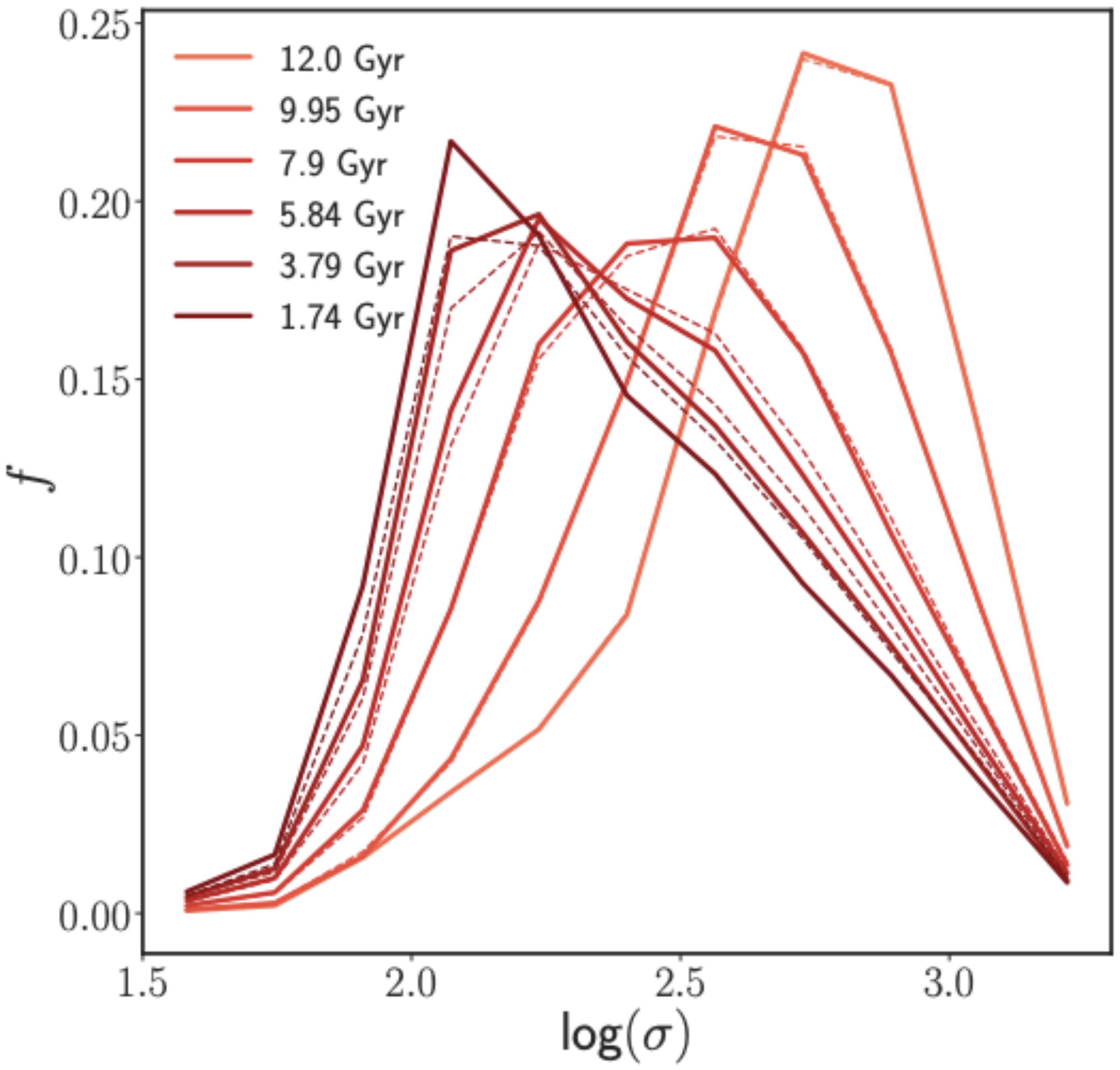
Populate Universe machine galaxies with Merger rates by integrating their star-formation histories



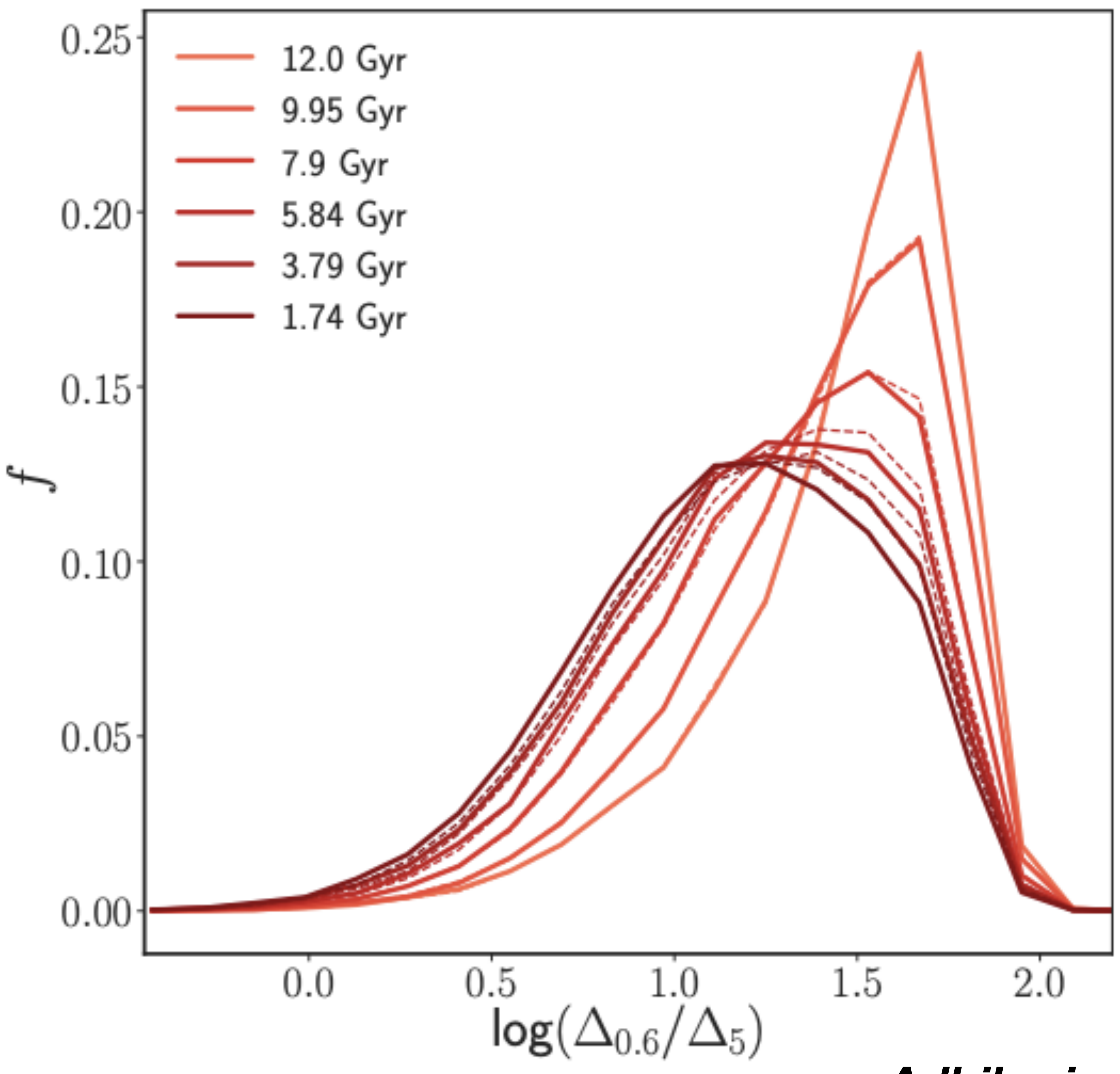
Adhikari et al. 2020

Different delay time predict different distribution of galaxy properties

Properties of their host dark matter halos and local environments



halo velocity dispersion

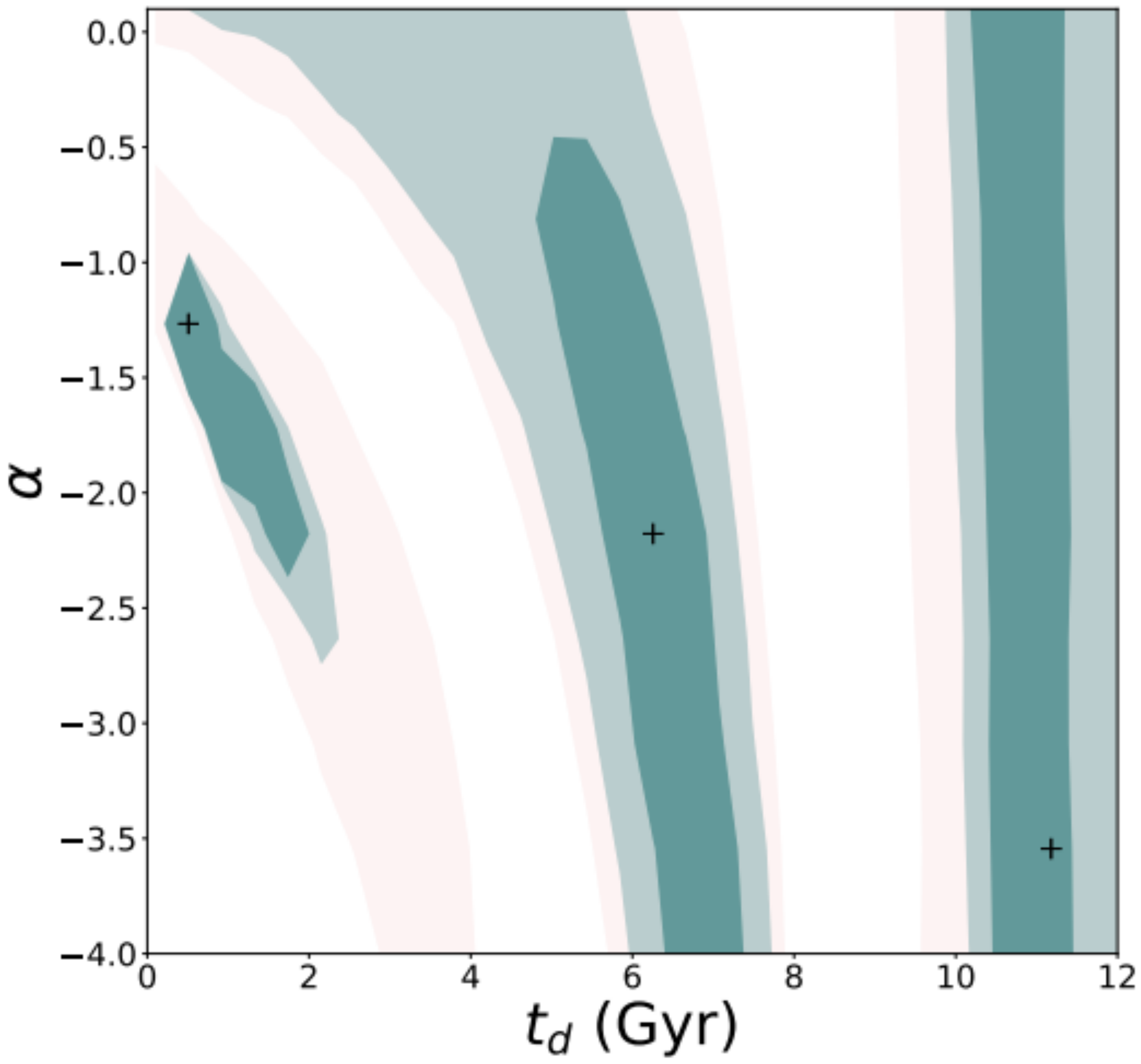


local density ratio

Adhikari et al. 2020

Long delay times trace higher halo masses and events which are in dense environments locally.

Constraining delay time models with galaxy properties



Constraints on the delay time model using four host properties $[M_*, sSFR, \sigma_h, \Delta_r]$

30 events

100 events

Constraints using stellar mass only 30 events

Adhikari et al. 2020

Light blue shade shows constraints from 30 events using SM, SFR, HM and density

(i) simple questions about how the distribution of observed host galaxies change

What happens if binary mergers trace galaxy properties like…

If black hole mergers happen in globular clusters

Galaxy Stellar Mass

Galaxy Halo Mass

Star-formation rate

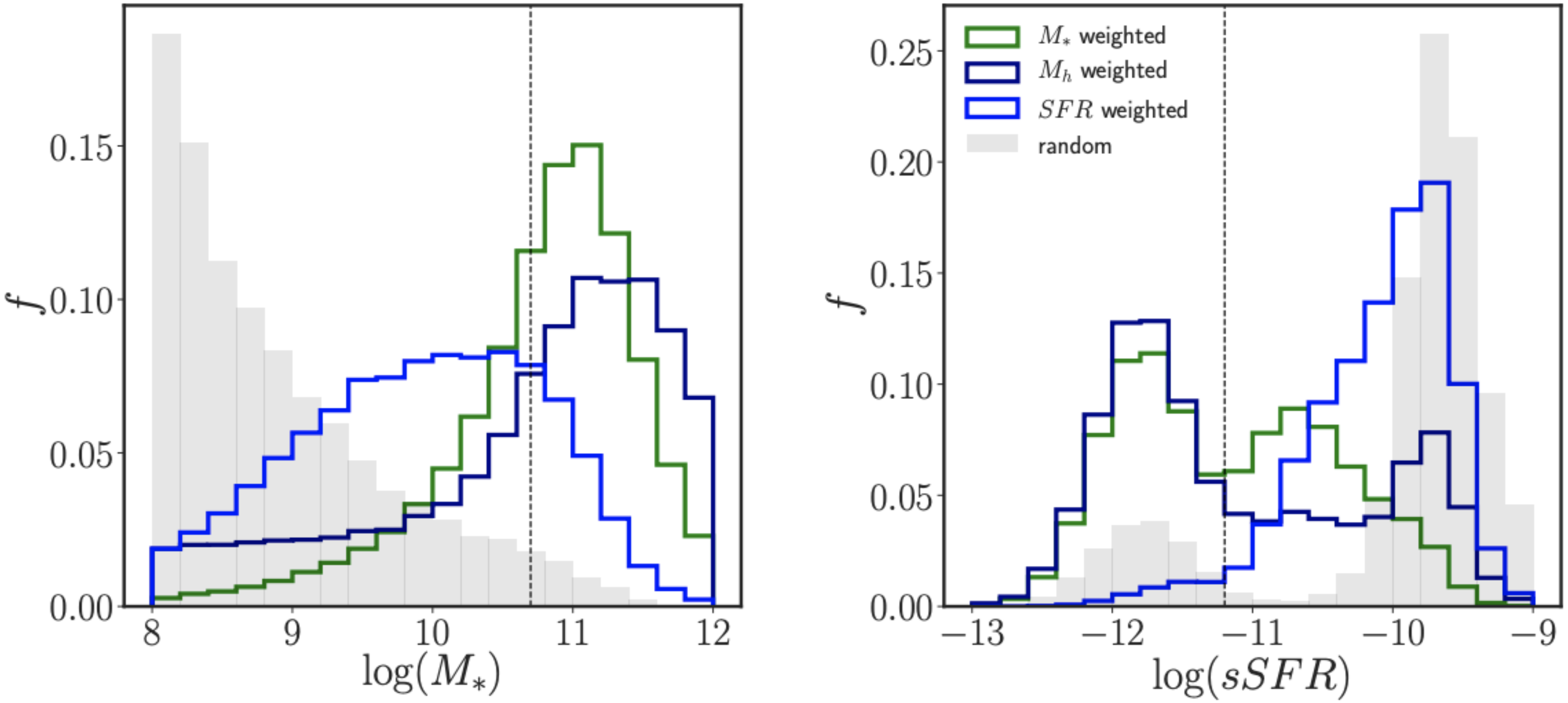
Random Sample

SM - traces long delay times, massive galaxies

SFR - traces short delay times

Halo mass- Traces formation in globular clusters (the number of GCs trace total halo mass as opposed to galaxy stellar mass)

(i) simple questions about how the distribution of observed host galaxies change



What happens if binary mergers trace galaxy properties like…

Galaxy Stellar Mass

Galaxy Halo Mass

Star-formation rate

Random Sample

Adhikari et al. 2020

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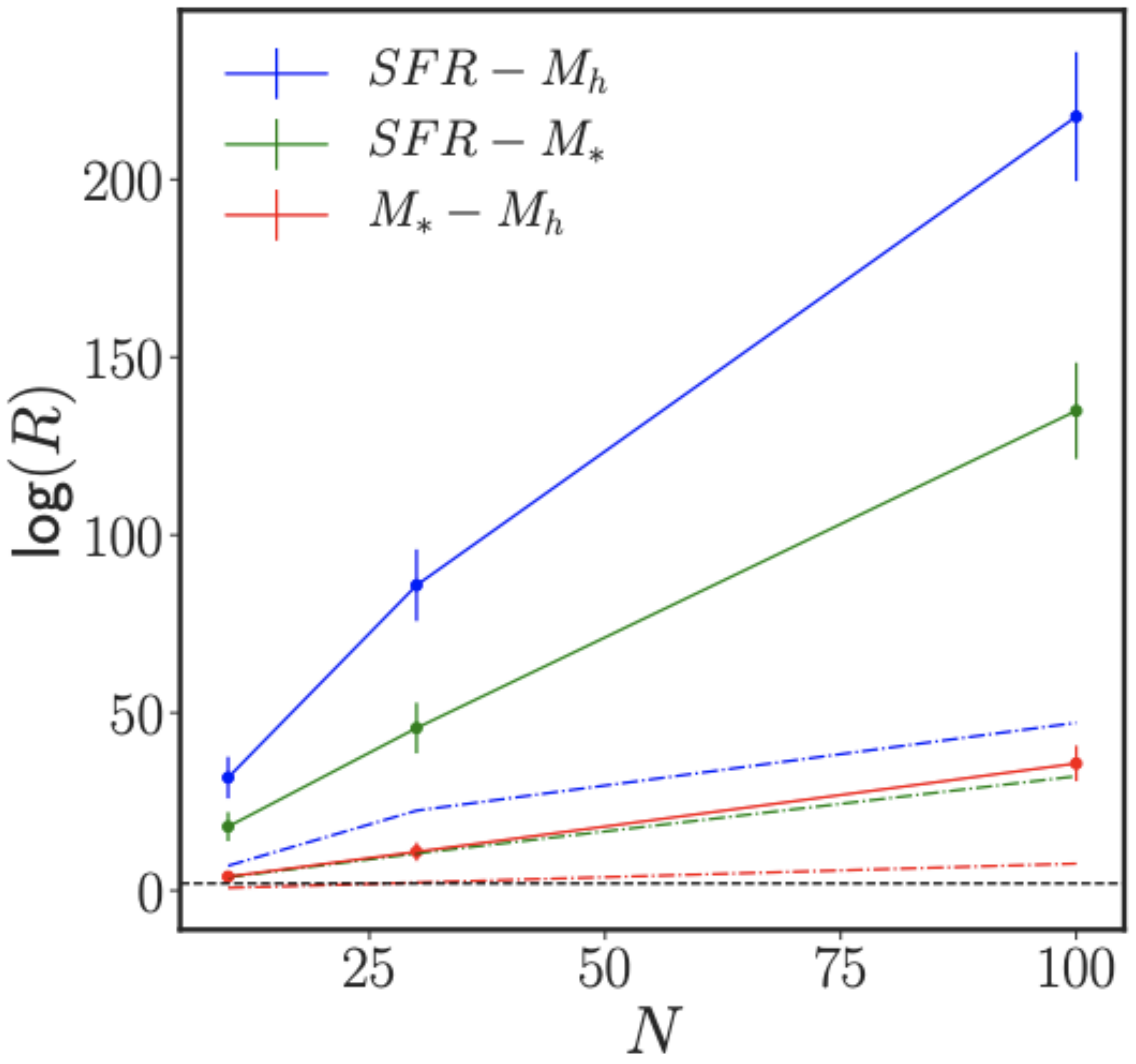
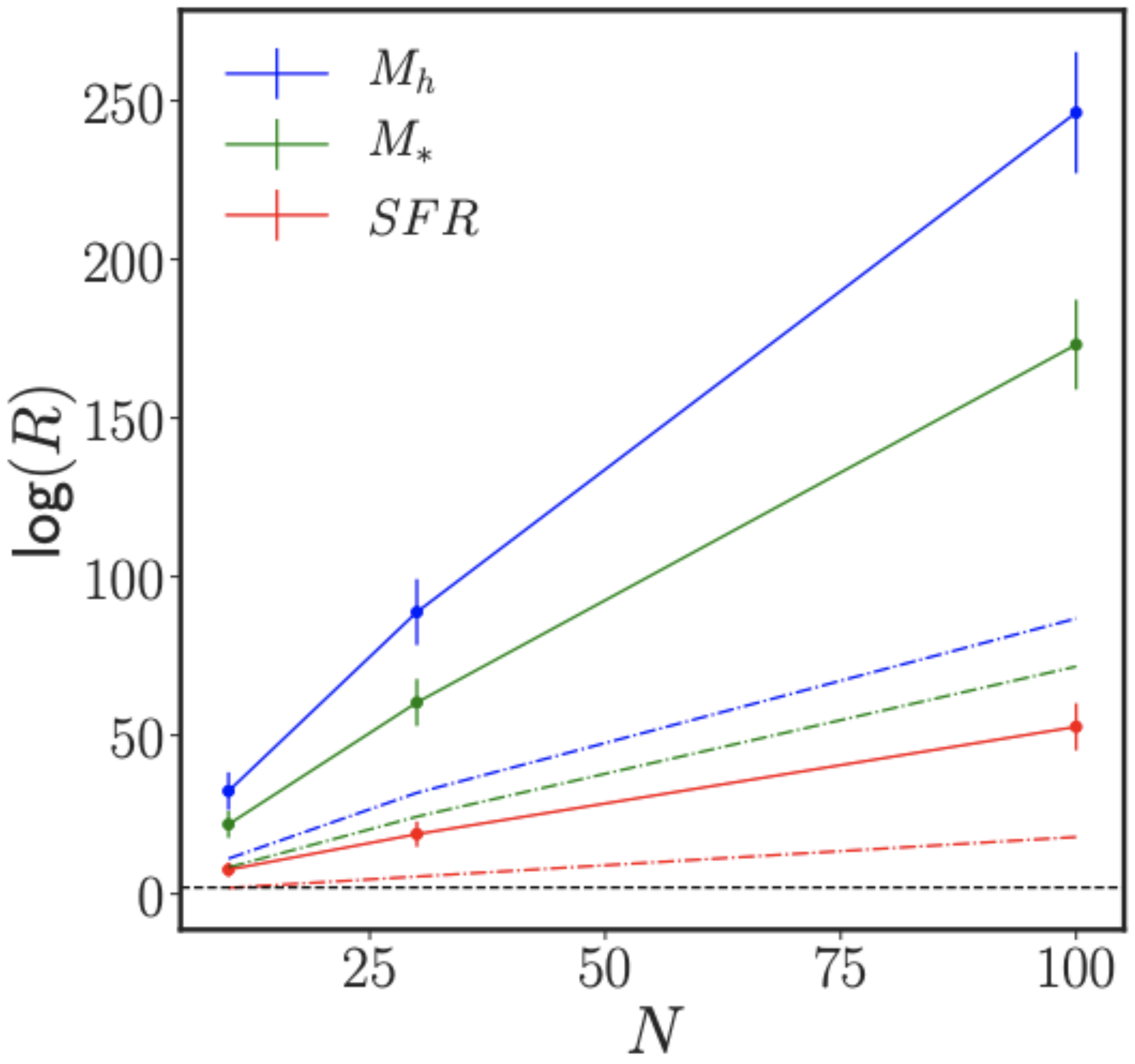


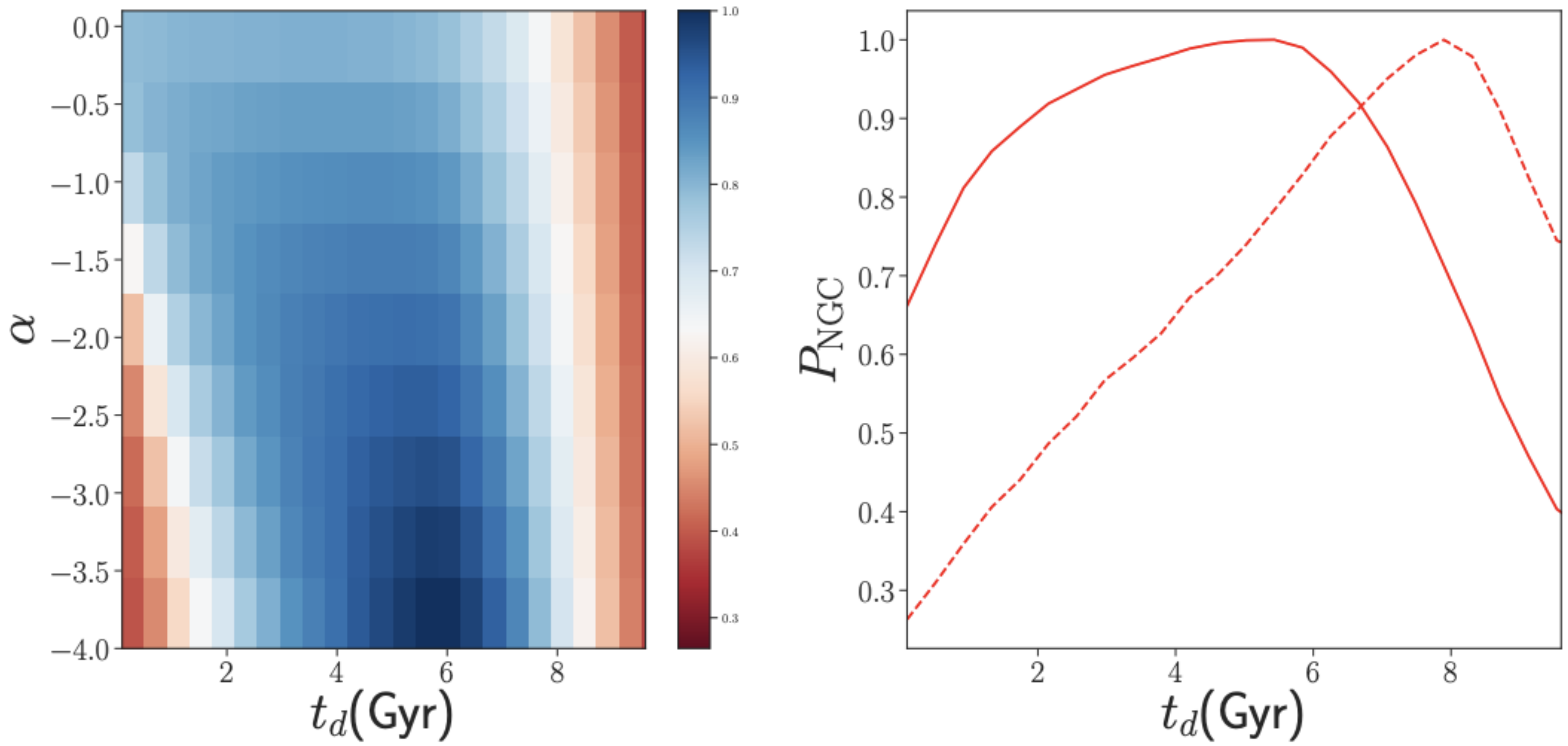


Adhikari et al. 2020

Distributions are significantly different that a few 10s of events can distinguish between the inherent formation channels.

~order of 100 events are required to distingusing between mixture models.

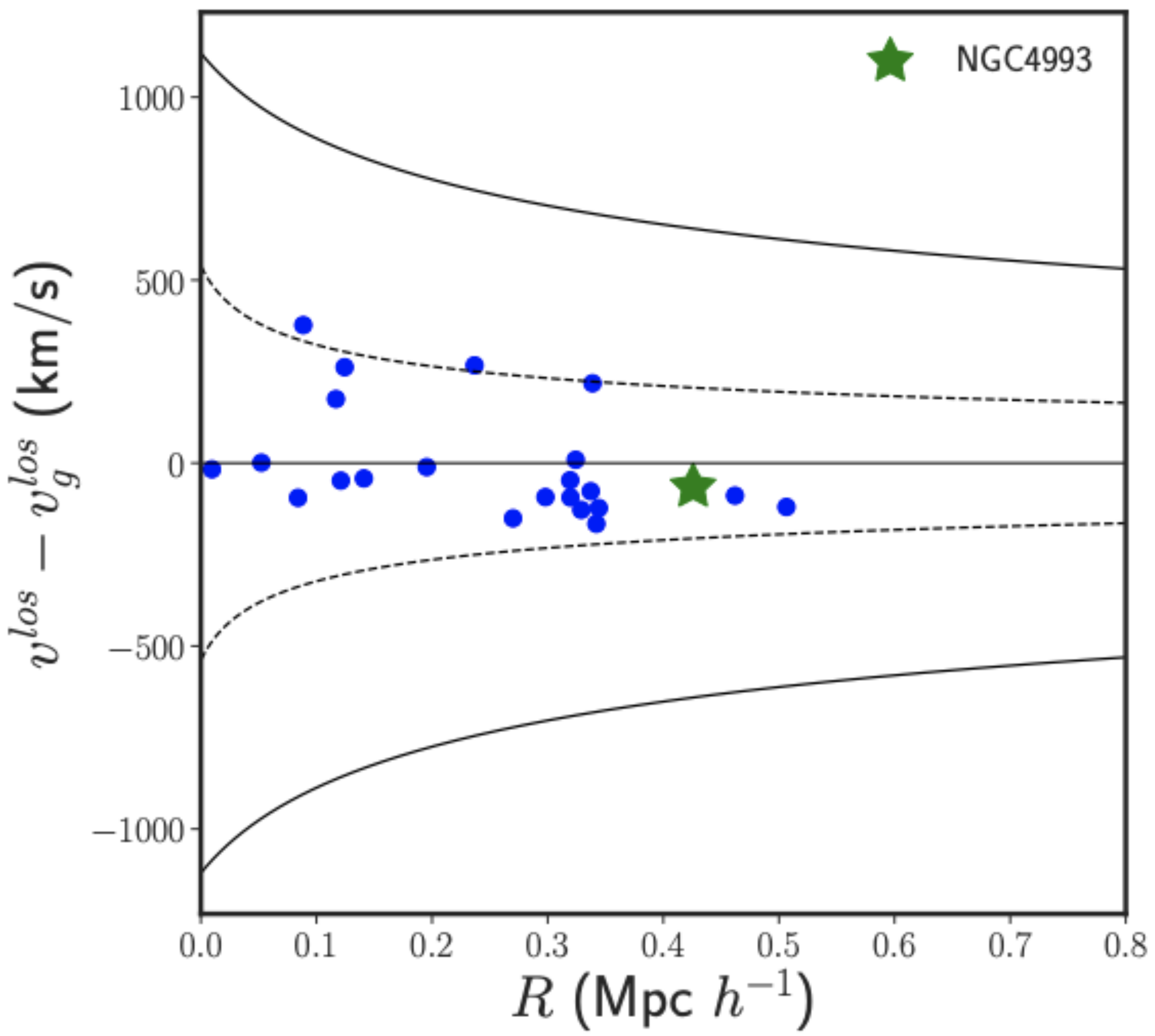
Some things we learnt about NGC 4993



Adhikari et al. 2020

It prefers a long delay time given its stellar mass and star-formation rate

Some things we learnt about NGC 4993

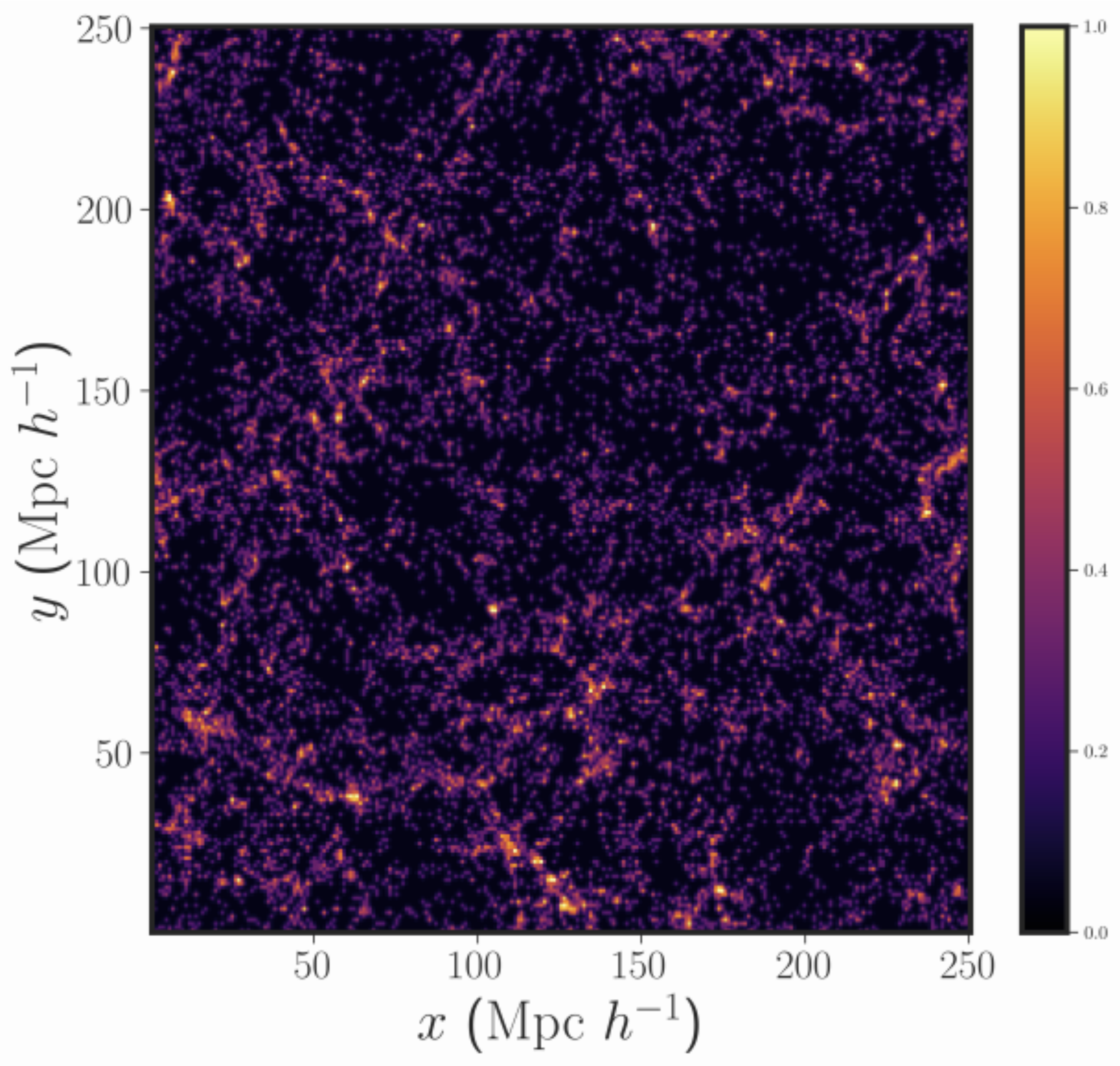


Not clear if NGC 4993 is a satellite galaxy or a central. The velocity dispersion of the purpoted group is more consistent with being a 10^12 object

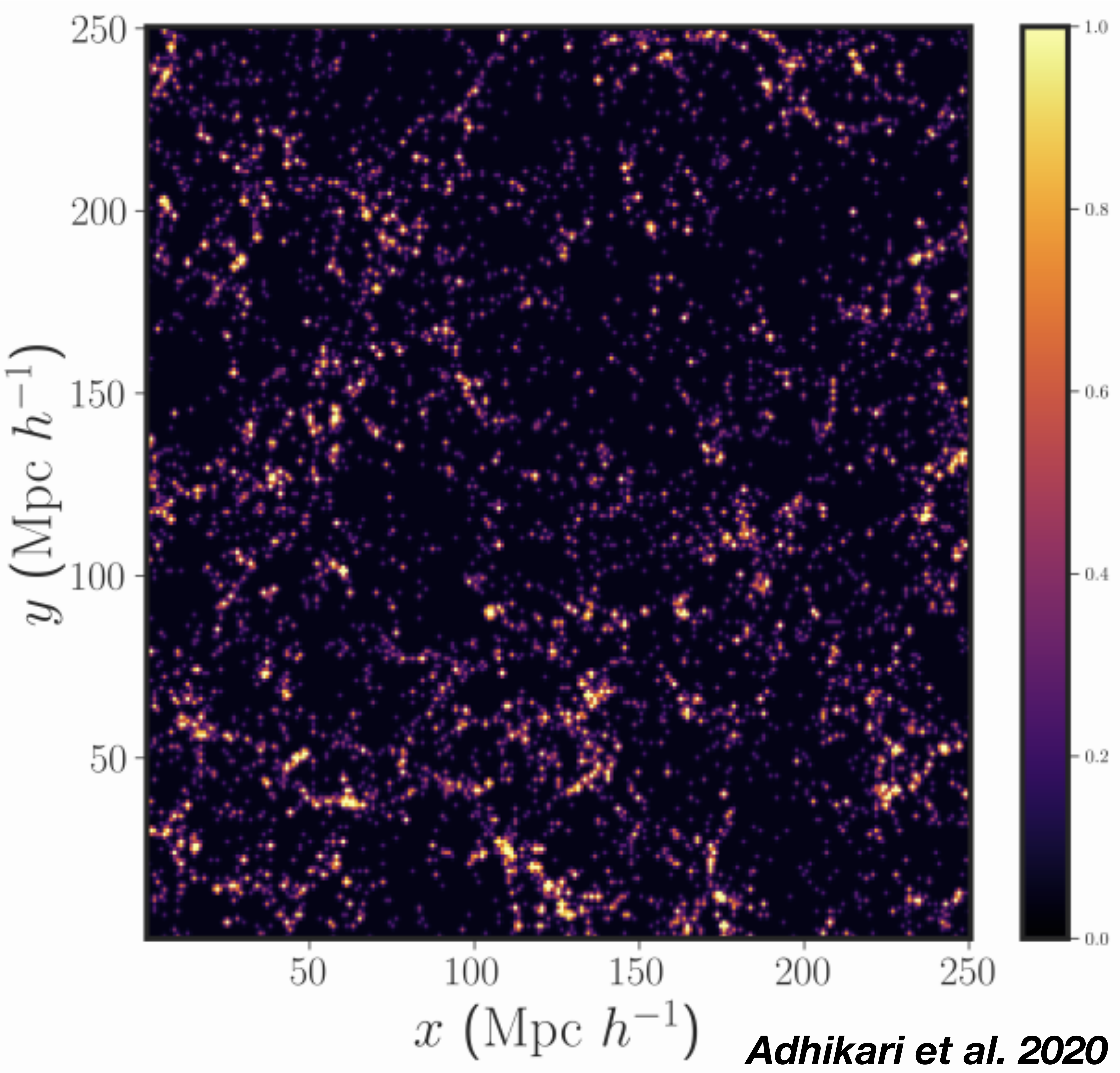
Delay time distributions strongly affect clustering properties

Clustering of events in the sky

Short delay time



Long delay time



Adhikari et al. 2020

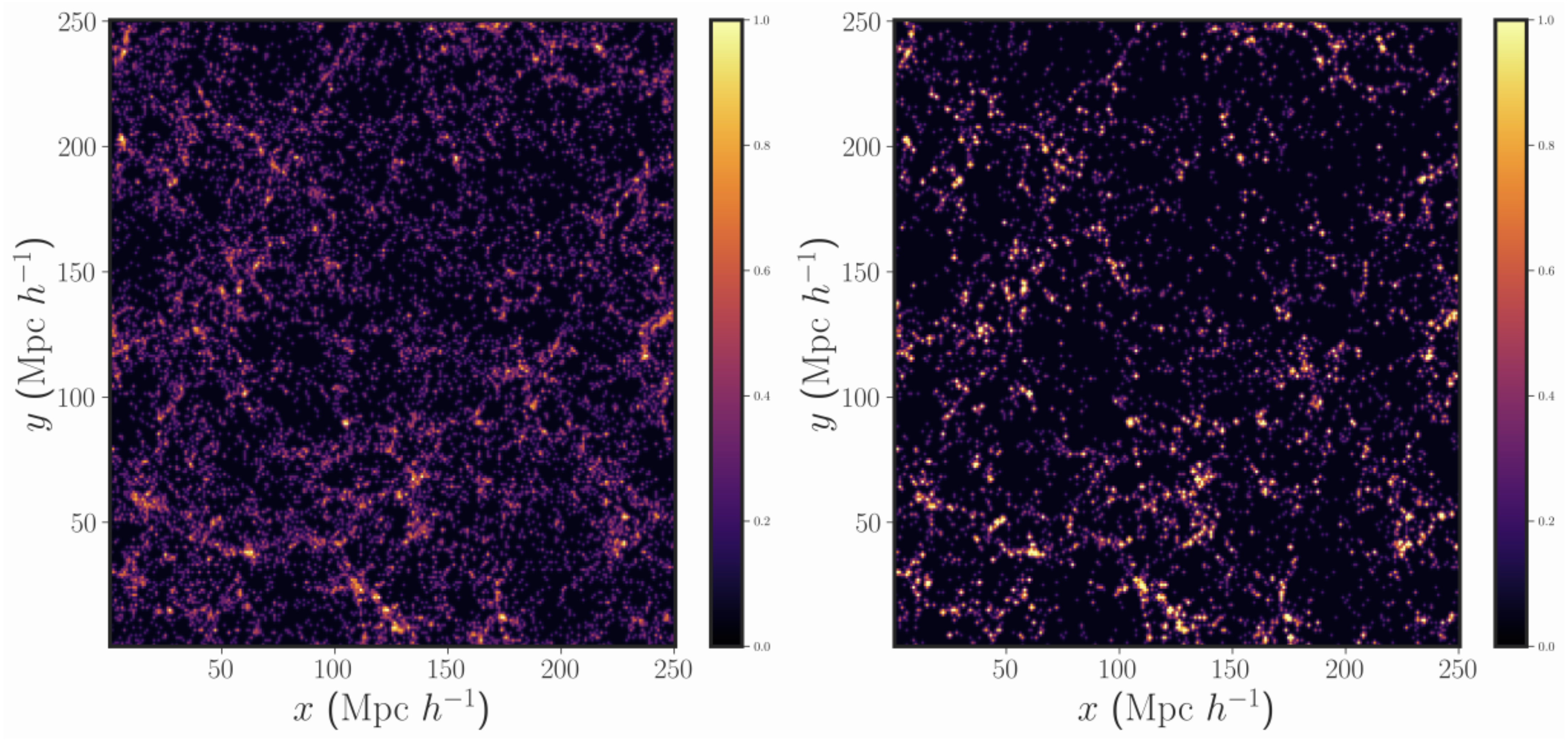
If binaries merge soon after birth, they are more clustered than random, mostly live in Milkyway like galaxies

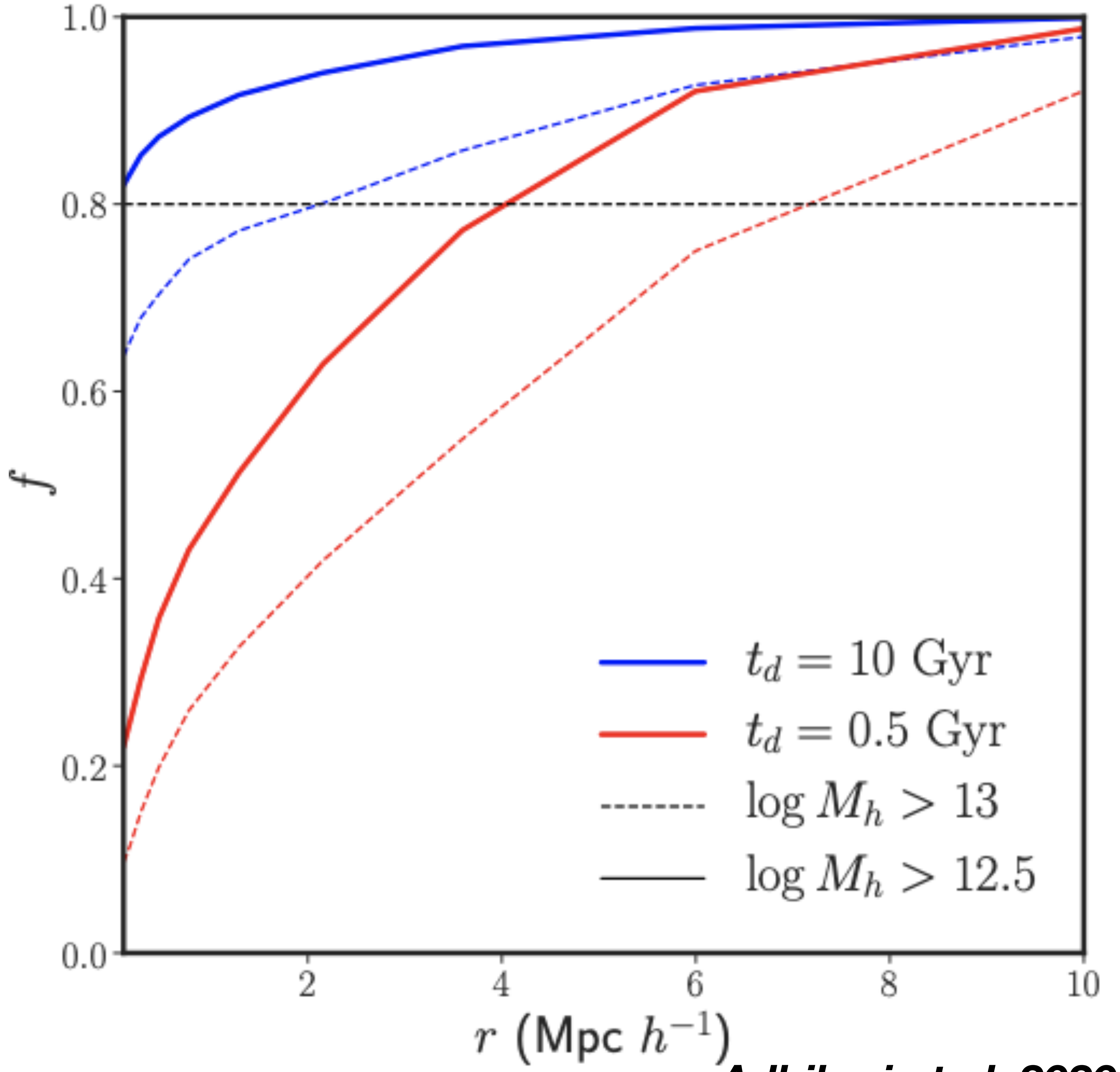
If binaries merge after long delay, they are more likely to be in clumps, near groups and massive clusters

Can we optimize search strategies?

Currently we only use stellar mass to assign likelihood to a host galaxy
Can we do better?

If the underlying population has long delay times, we expect the events to be clustered in the local universe. We can look for counterparts near massive groups.





Adhikari et al. 2020

The future is exciting!

We are only begun scraping the surface

- In the future - Develop light cones for gravitational wave events
- Include priors on merger time distributions
- Develop models to assign host probabilities based on galaxy properties
- Metallicity evolution to incorporate BBHs
- Cross-correlation studies

PBH clumps - source: quanta magazine

In Summary - The future is exciting

- The interplay of galaxy evolution and binaries will teach us about the underlying astrophysics!
- Understanding these connections help us better predict hosts of mergers. Helping localize events.
- Host galaxy properties, including stellar mass, sfr, the parent halo mass, local clustering of galaxies contain important information about the evolution of binaries.
- Can distinuguish simple models and formation channels with an order of a 10 events.
- Understanding the host properties can also help survey strategies to look for EM counterparts or to probabilistically determine cosmology from GW events.