Galactic Collisions Across Cosmic Time: How Mergers Shape Galaxy Evolution

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NEMZETI KÖZSZOLGÁLATI EGYETEM

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Large Scale structure and the cosmological principle

- **The Cosmological Principle Challenge:** Current cosmological models predict an upper theoretical size limit of **~100-200 Mpc** for bound structures.

  - **Hercules–Corona Borealis Great Wall** (~2-3 Gpc) Horváth+ 2013
  - **Giant GRB Ring** (~1.7 Gpc) Balázs+ 2015
  - **Huge Large Quasar Group (Huge-LQG)** (~1.2 Gpc) Clowes+ 2013
  - **The Giant Arc** (~1 Gpc) Lopez+ 2021
  - **The Giant Ring** (~400 Mpc) Lopez+ 2026

- Structures like the *Hercules–Corona Borealis Great Wall* and the *Giant GRB Ring* significantly exceed this limit, challenging our current understanding of the early Universe's homogeneity.

Star formation and galaxy mergers

- Galaxy mergers shape galaxies’ star formation processes by
  - inducing star formation in interacting regions
  - providing material inflow to maintain star formation
  - minor mergers (one of the galaxies is a dwarf) create interacting regions with mixed ISM properties

- Looking at merger events through cosmic time scales
  - IllustrisTNG cosmological simulation
  - JWST high-z recent results

- **How does merger-induced star formation compare to the star formation history of the Universe?**

- **Under what conditions were today's stars formed?**

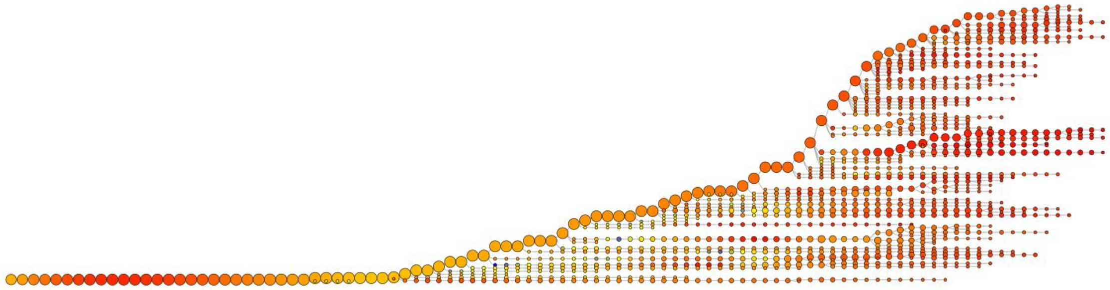
- **How does local galaxy density influence merger events?**

- **Are minor mergers major contributors of mass growth?**
  - Suess+ 2023: 30% of total added mass (z=0.5 - 3)

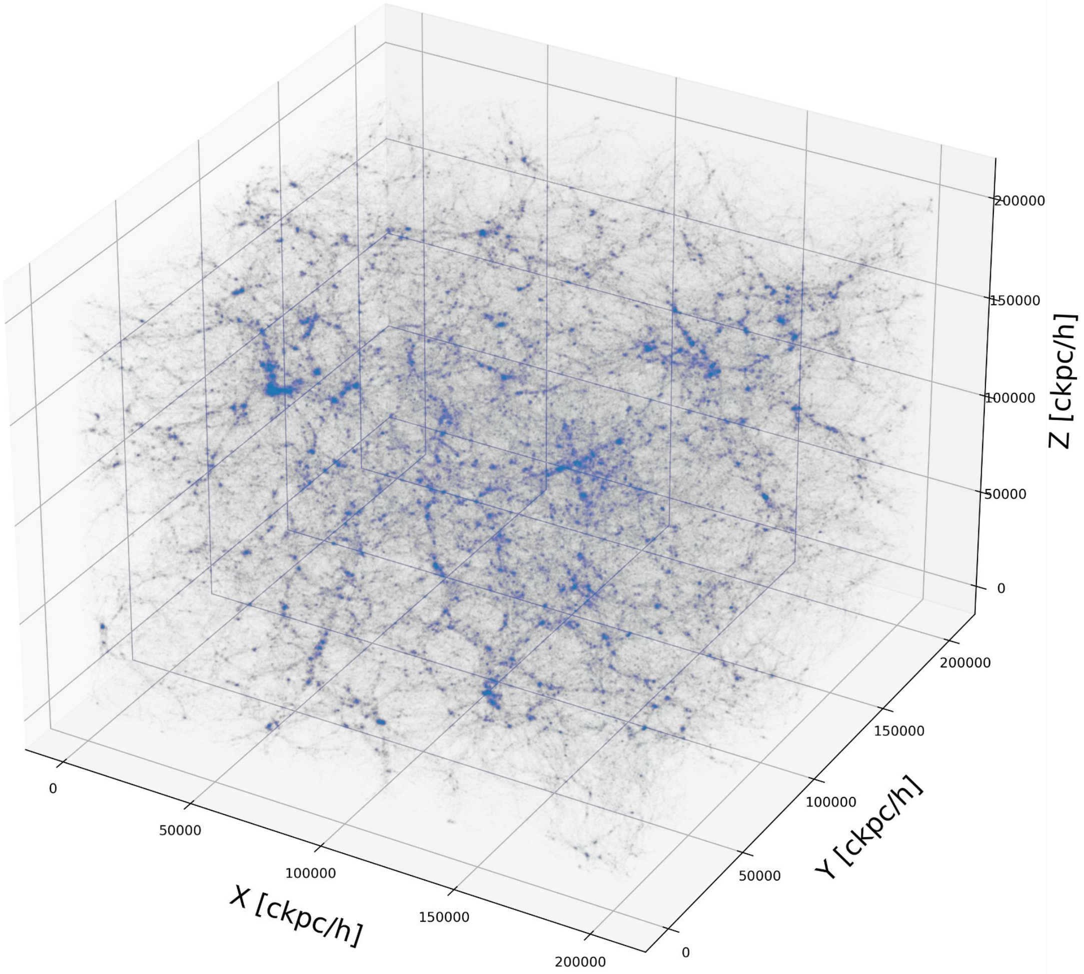
IllustrisTNG

Pillepich+ 2017, Springel+ 2017, Nelson+ 2017 , Naiman+ 2017, Marinacci+ 2017

- Cosmological magneto-hydrodynamical simulation for galaxy formation and evolution
- ΛCDM cosmology with Planck 2015 parameters
- 100 snapshots z = 20 - 0
- Merger trees for identifying merging galaxies
  - first progenitor: most massive galaxy in a merger
  - next progenitor: second most massive galaxy in a merger
  - descendant: merged galaxies



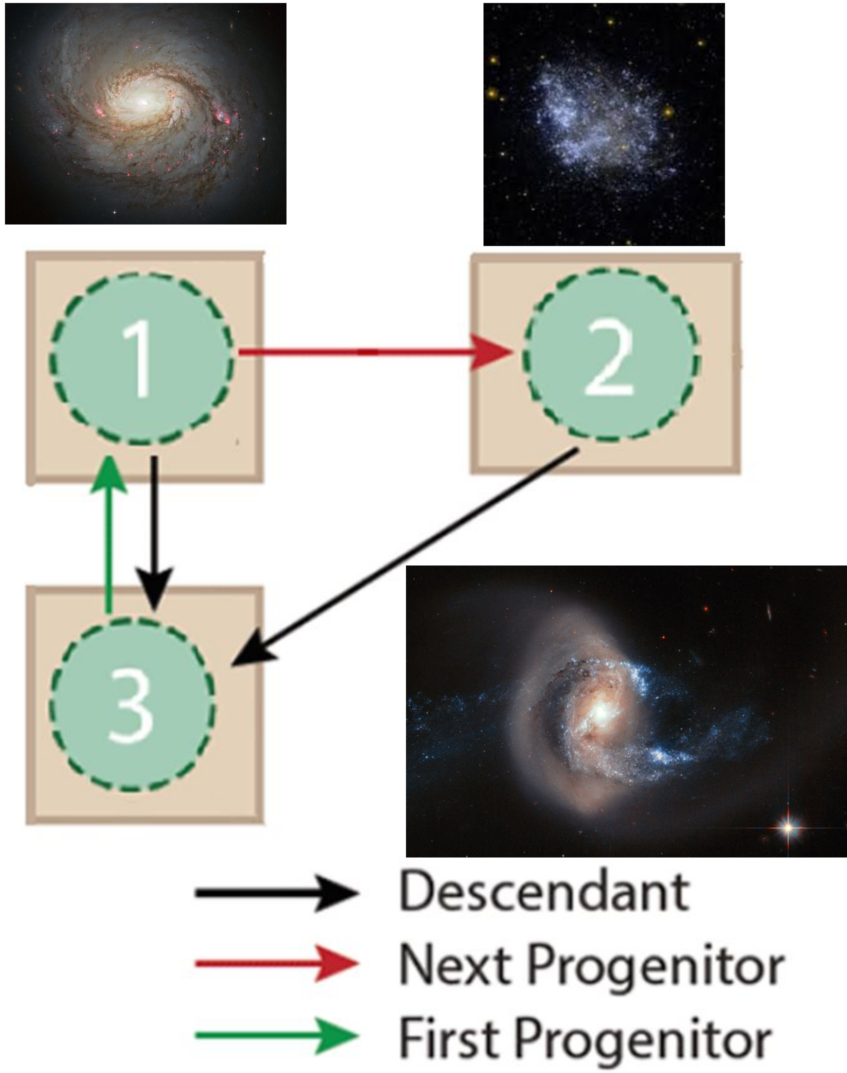
Example of a TNG merger tree



Galaxies in the TNG 300-1 volume at z=0

Merger Tree

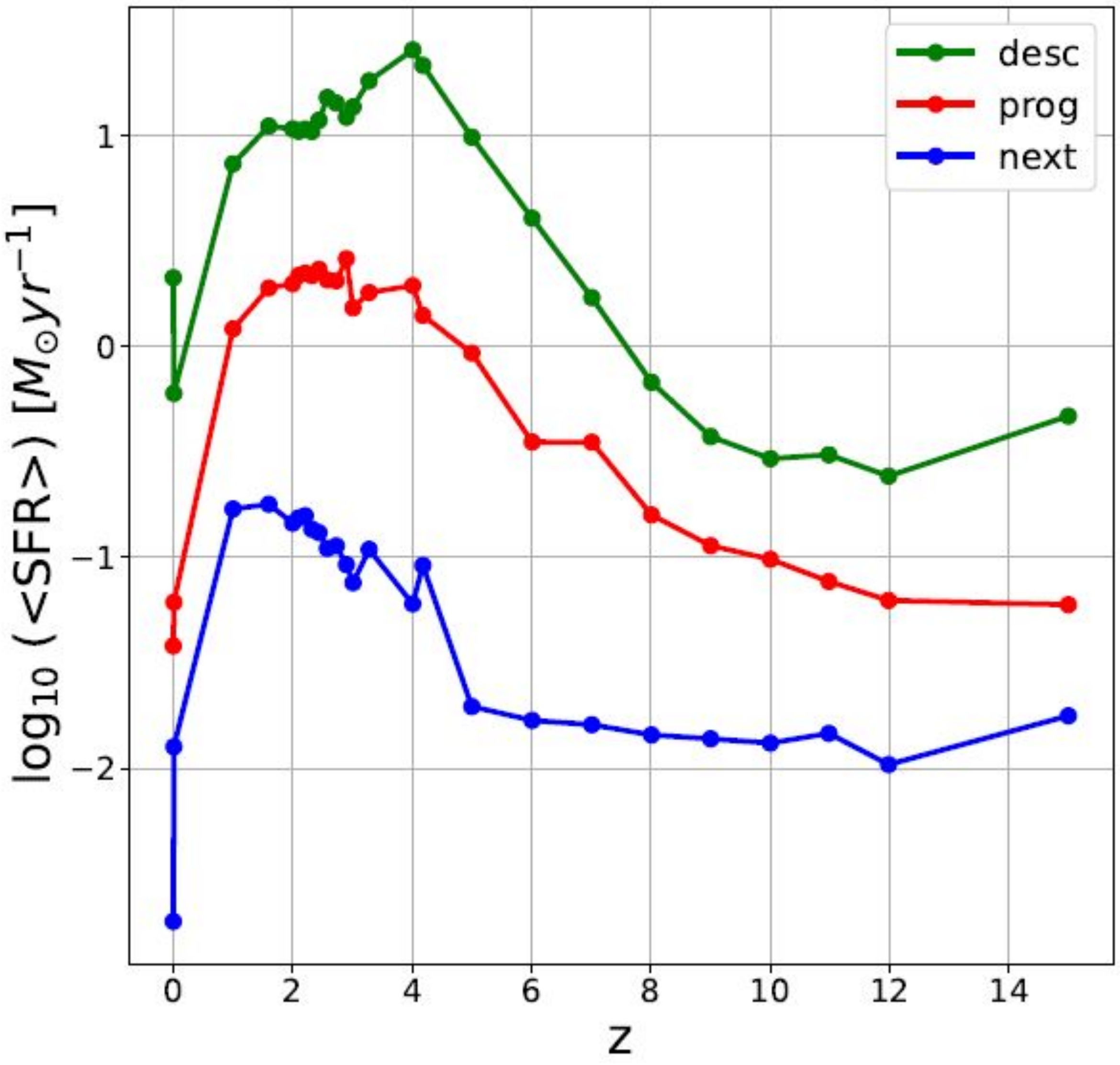
- Data structure with galaxy evolution
- Trees in the simulation: The members of each tree are "related" to each other
- Sublink algorithm Rodriguez-Gomez+ 2015 for descendant search
  - 1. Candidates identification for each subhalo (galaxy): subhalos in the following snapshot with common particles
  - 2. Candidates scored: based on a merit function □ binding energy rank of each particle
  - 3. Unique descendant = descendant with the highest score
- Descendant galaxies appear on the next or following snapshot
- If two progenitor galaxies have identical descendants, they are merger galaxies



Merger star forming rate (SFR) from TNG 300-1

- TNG300-1, 302.6^3 Mpc^3 volume
- Snapshots from z = 15 - 0
- Average SFR in snapshots

- Descendant galaxies' average SFR increases from merger
- Average SFR maximum at z=3



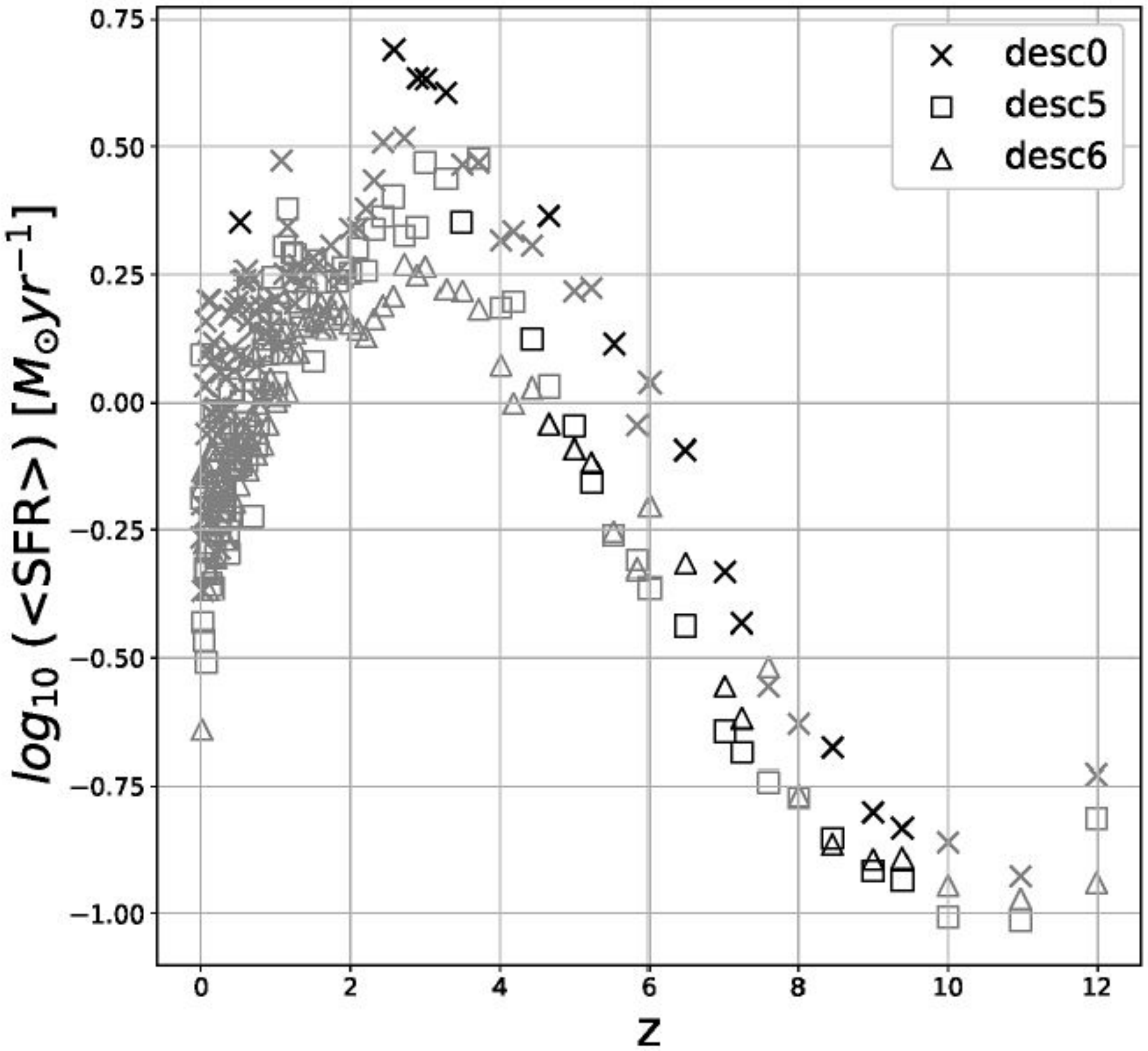
Merger Tree comparing

- Average star formation rate versus redshift in three individual merger tree (Koncz+ 2023)

- Compared to the simulated JWST observational data from z = 5 to z = 10 (D’Silva+ 2022)

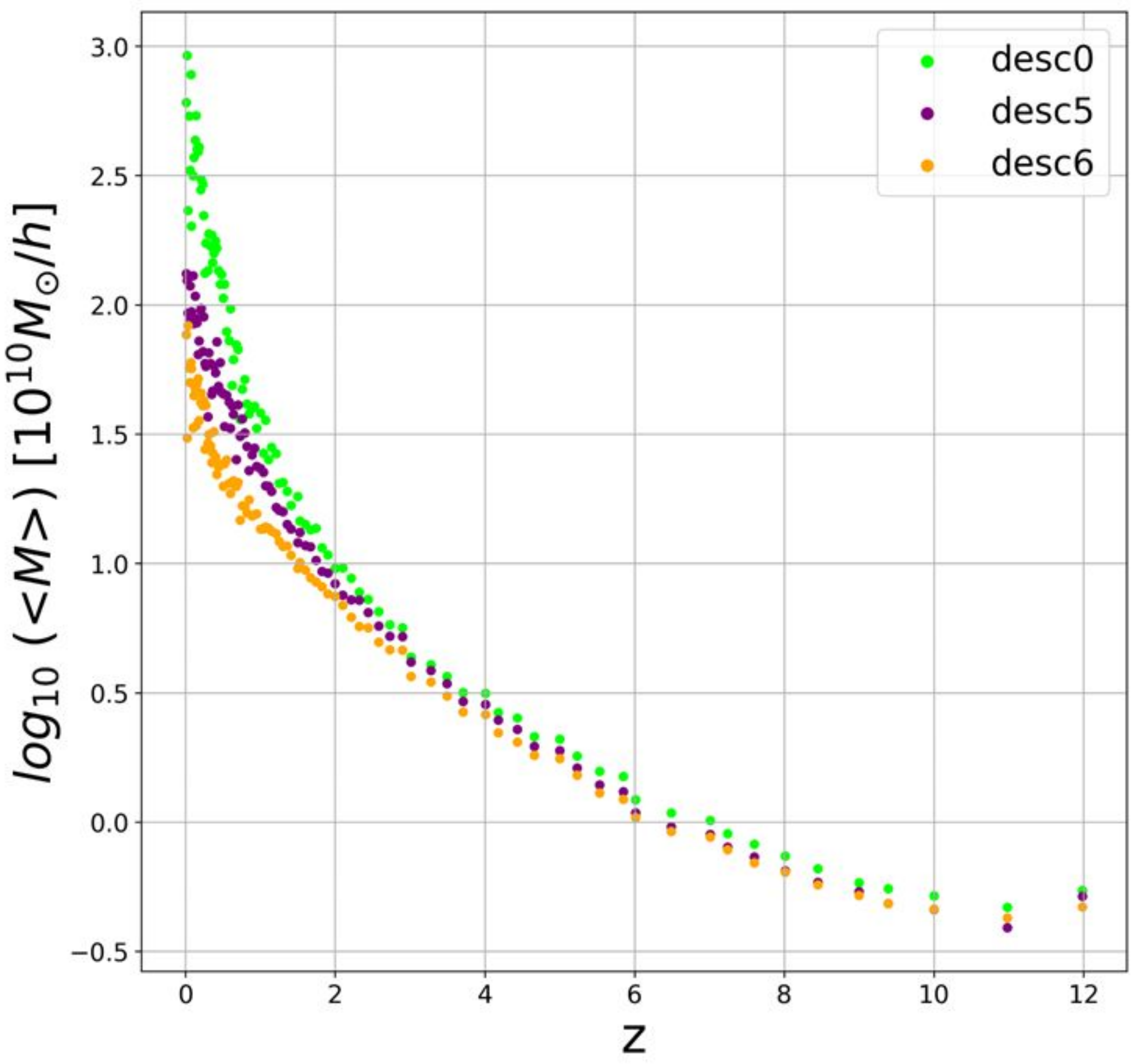
- most of the uncertainties are higher than the differences between the merger trees

- Individual merger trees are precise enough to examine the average properties of the galaxies at high redshifts



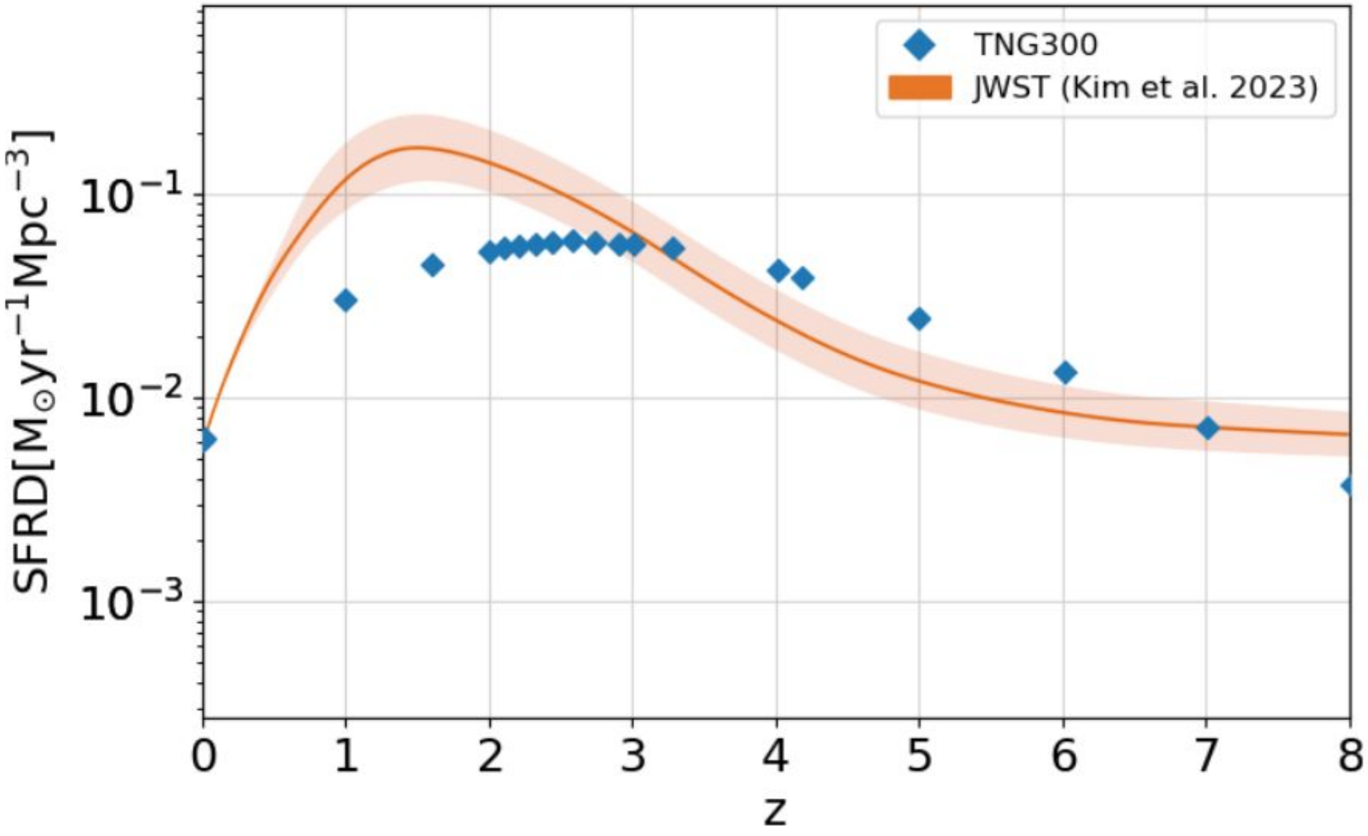
Merger Tree comparing

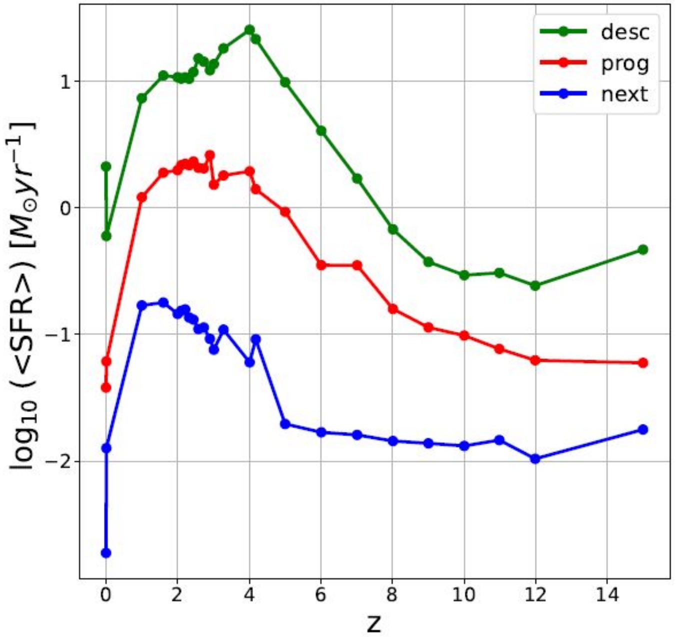
- The average mass of galaxies versus redshift in three individual merger tree (Koncz+ 2023)
- Compared to the simulated JWST observational data from z = 5 to z = 10 (D’Silva+ 2022)
- most of the uncertainties are higher than the differences between the merger trees
- Individual merger trees are precise enough to examine the average properties of the galaxies at high redshifts



SFR comparison with recent JWST study

- Seong Jin Kim et. al. 2023, Cosmic Star Formation History
  - from total IR luminosity density
- Maximum before z = 2





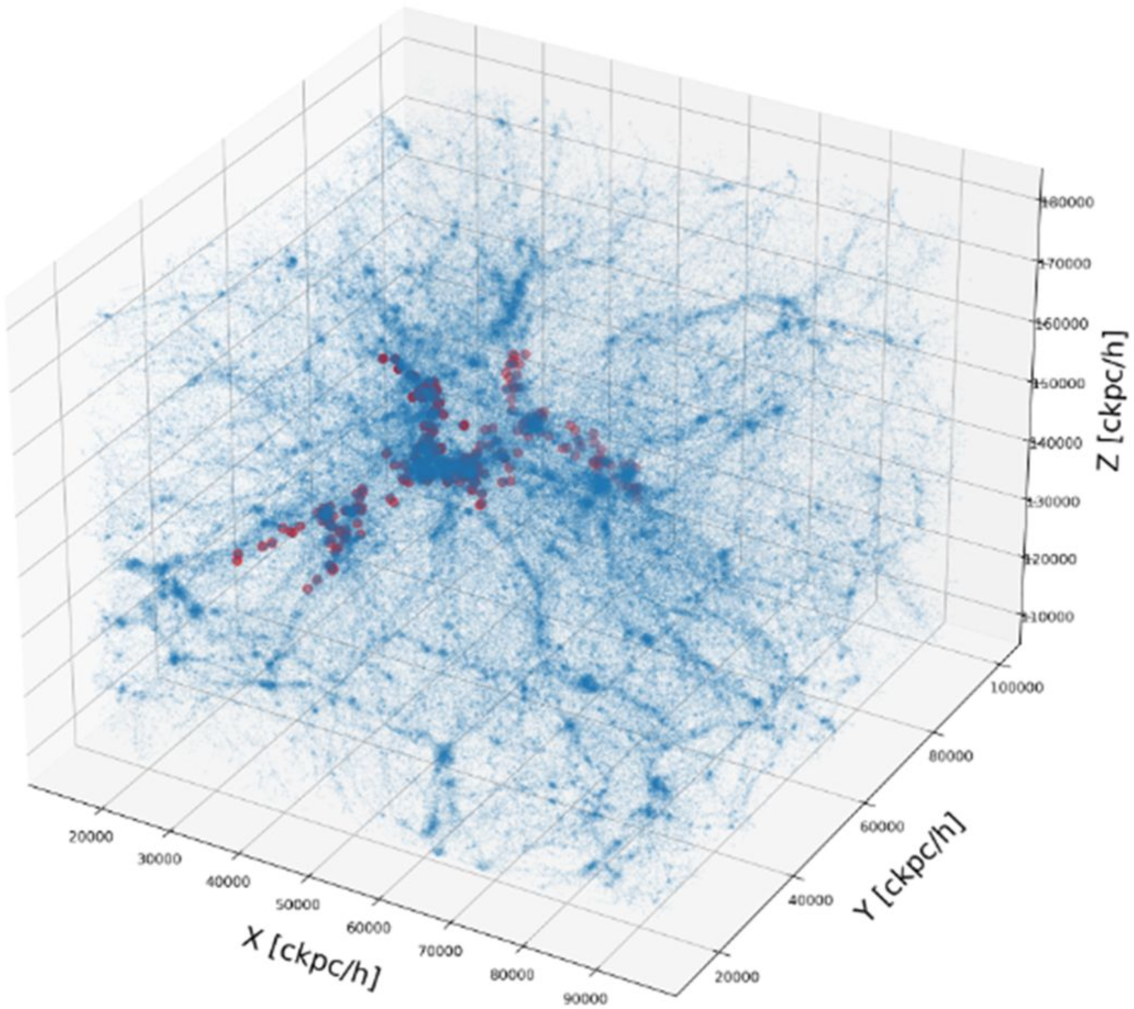
Minor merger distribution from TNG 300-1

- TNG300-1, 302.6^3 Mpc^3 volume
- 11 snapshots z = 10 - 0 (integers)

Criteria for descendants:

- Subhalos with sufficient stellar mass (>10^9 $M_\odot$) are classified as galaxies

- Mergers at z=0 are concentrated around overdensities

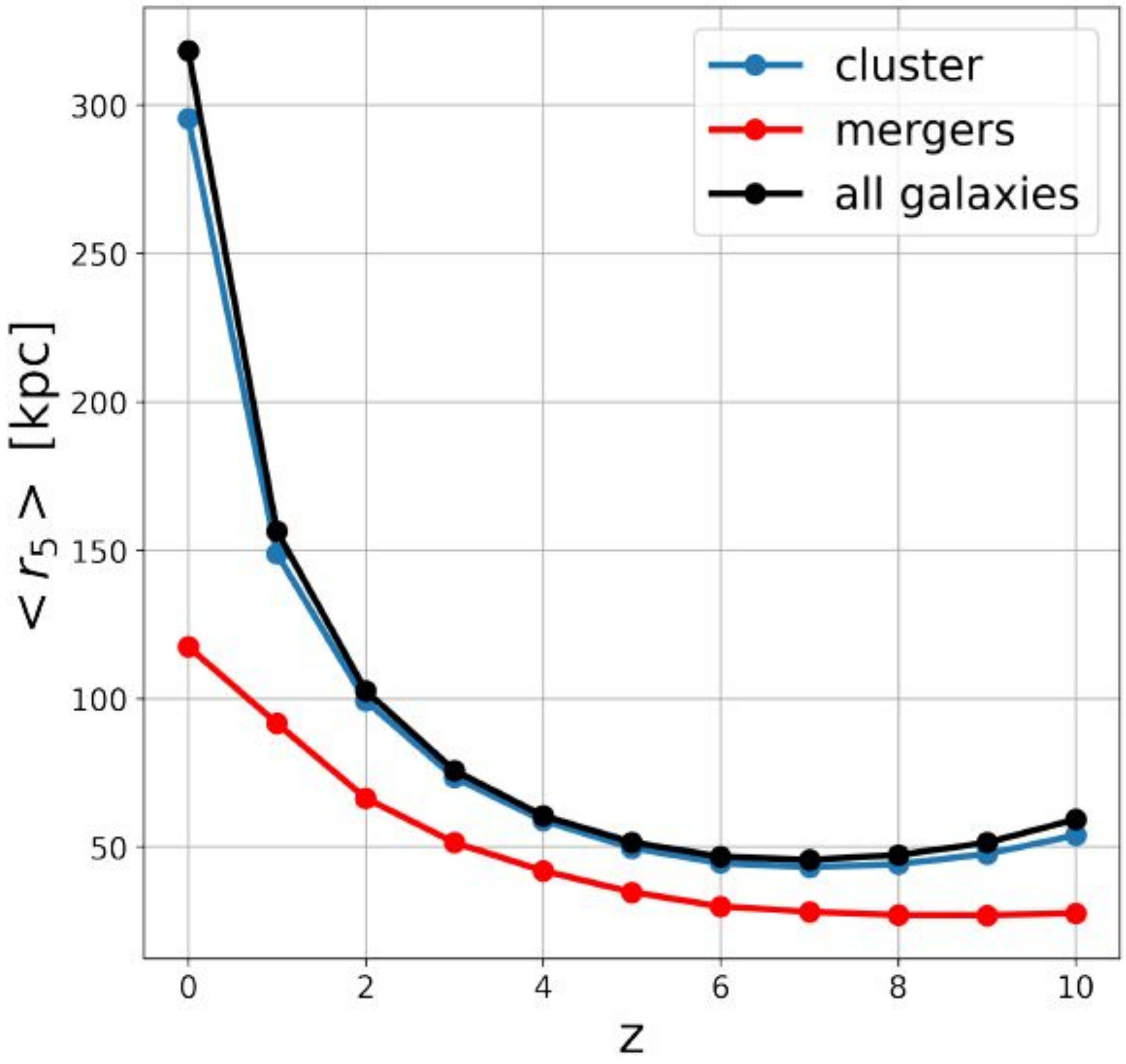


Merging galaxies in the 0. merger tree overlaid on the nearby galaxies in blue at z=0.

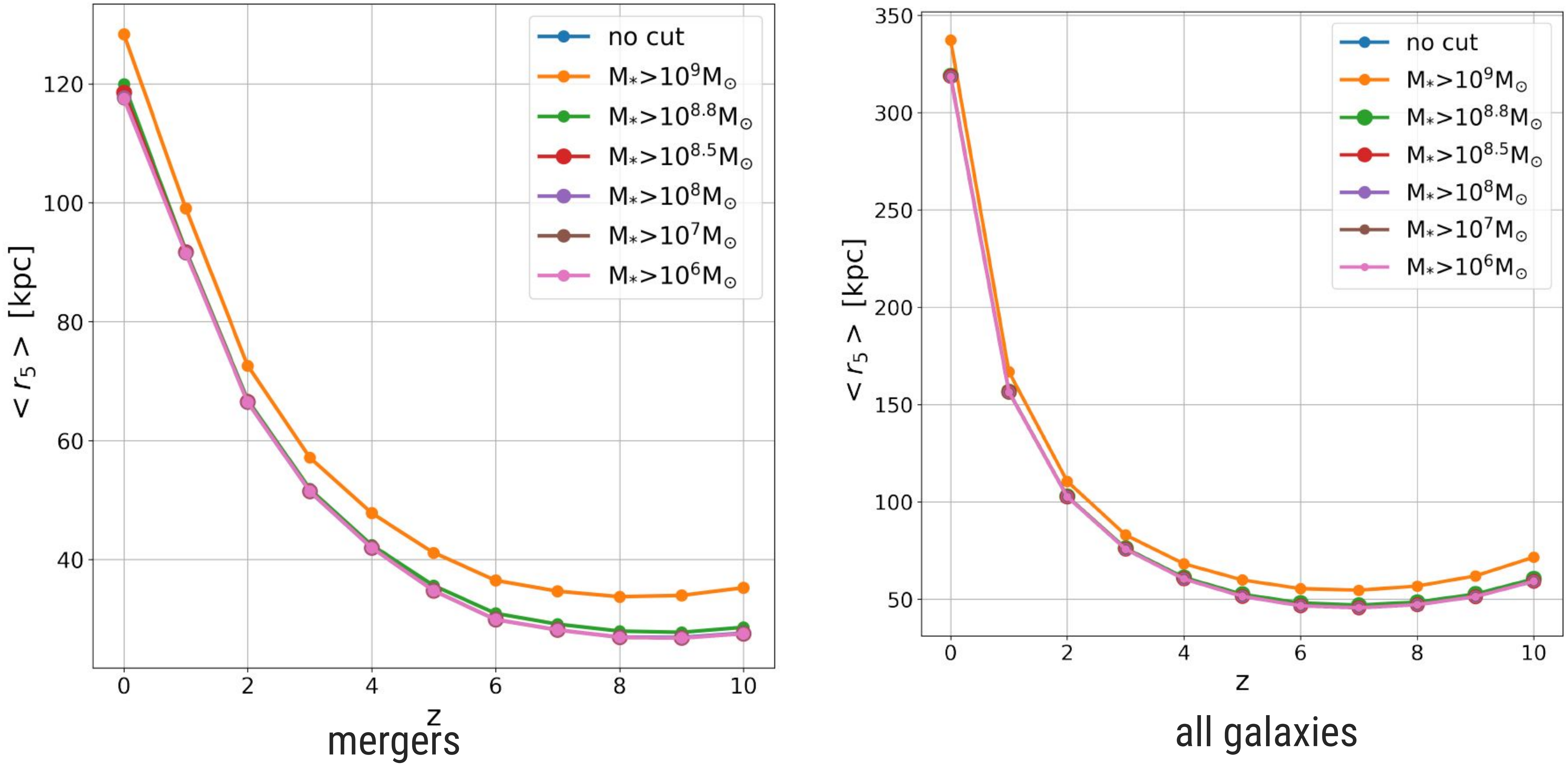
Minor merger distribution from TNG 300-1

- Local density η (as in Apashanka+ 2022) for the 5th closest neighbour, averaged for all galaxies in the snapshots

$$V(r_k) = \frac{4}{3}\pi r_k^3 \qquad \eta_k = \frac{k-1}{V(r_k)}$$



Mass Cuts for r5 Distances



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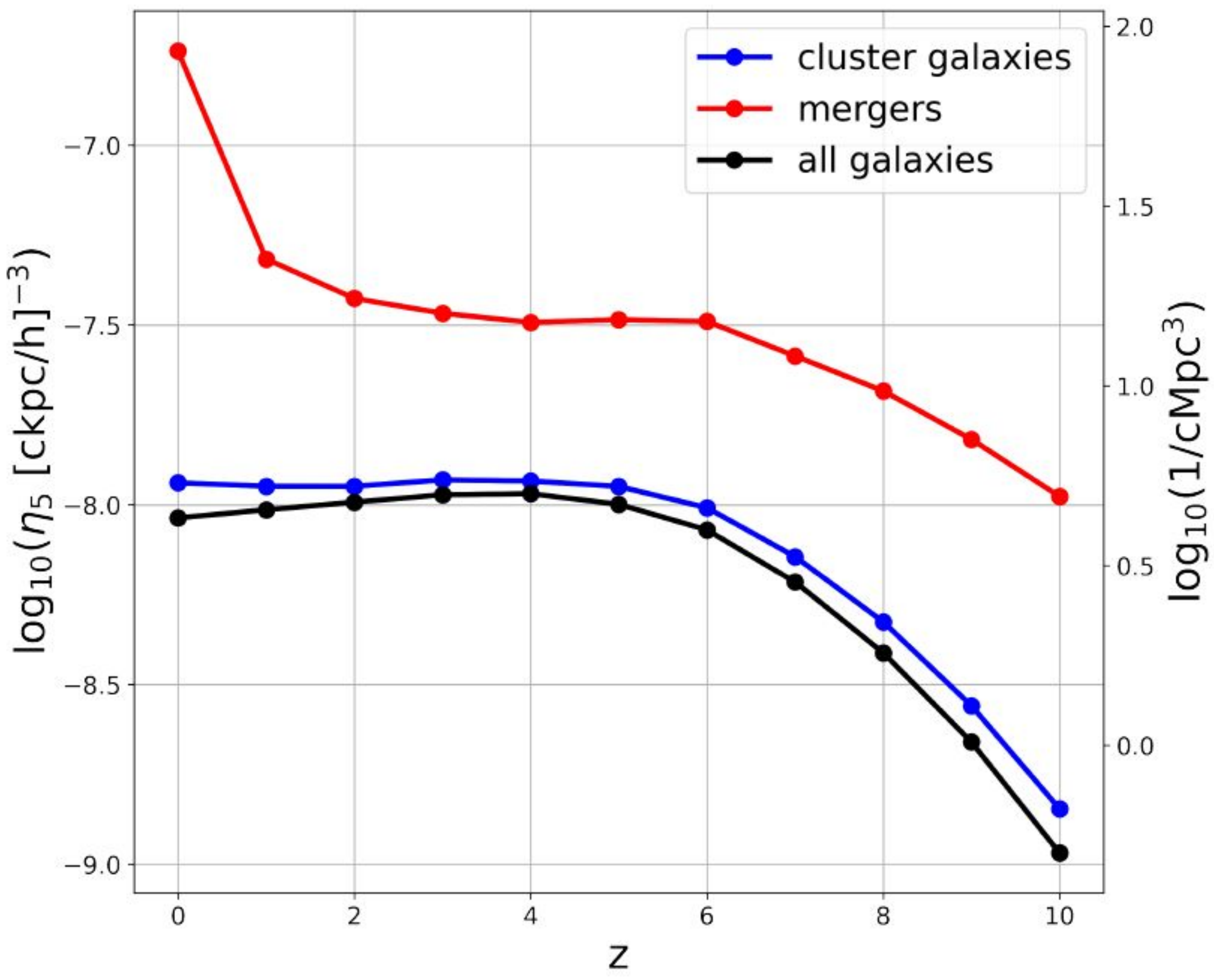
  - mergers @ z=4:~15 galaxies /Mpc^3
    z<1: >30 galaxies/Mpc^3 (e.g. Virgo cluster)
  - other galaxies: ~5 galaxies /Mpc^3

- Density of all galaxies, constant up to z = 6,
  - Density of mergers increases high at low z

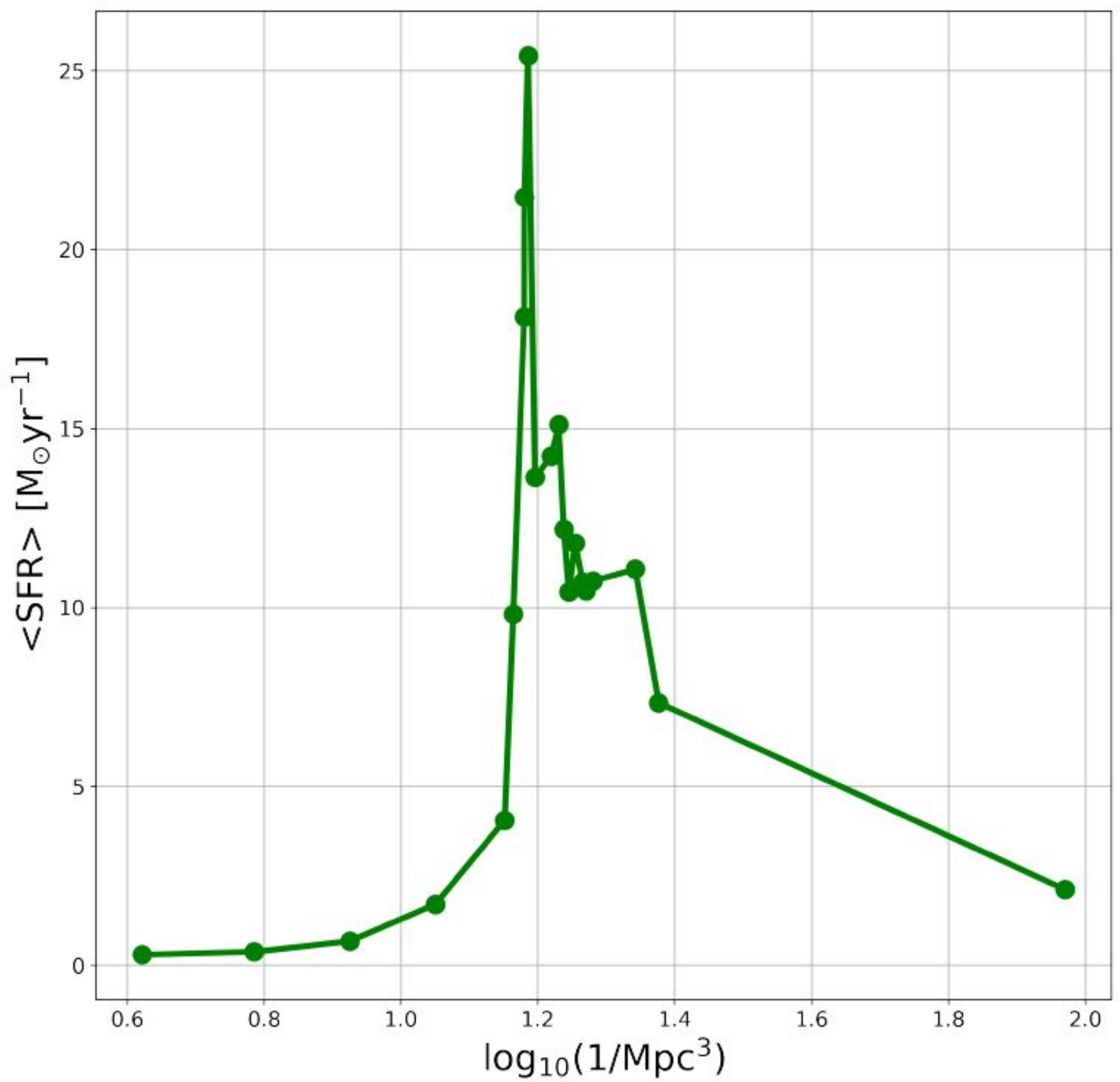


Minor merger distribution from TNG 300-1

- Galaxy mergers average star formation rate versus the galaxy density.

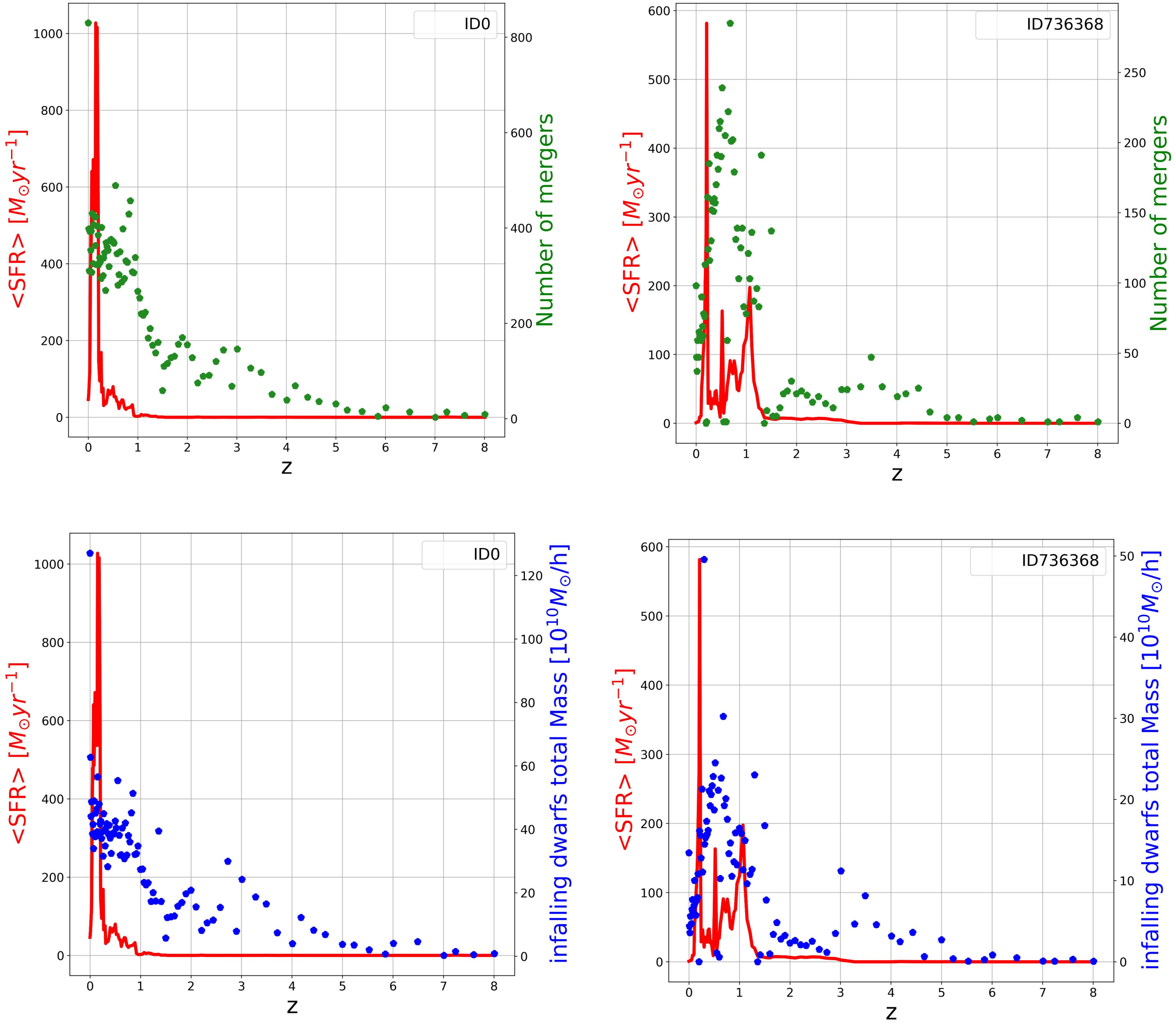
- Galaxies star formation is highly increasing at the density ~16 galaxy/Mpc3, but at more dense environments the SFR is decreasing.

- Extremely dense regions could cause the quenching of galaxies.



Mass buildup by minor mergers in TNG 300-1 compared to JWST study

- Sample of 38 massive, quiescent galaxies
  - $\log(M_*/M_\odot) > 10.6$
  - $\log(sSFR) < -10.5$
- Snapshots z = 0 - 8
  - Infalling mass through mergers
  - Descendant SFR



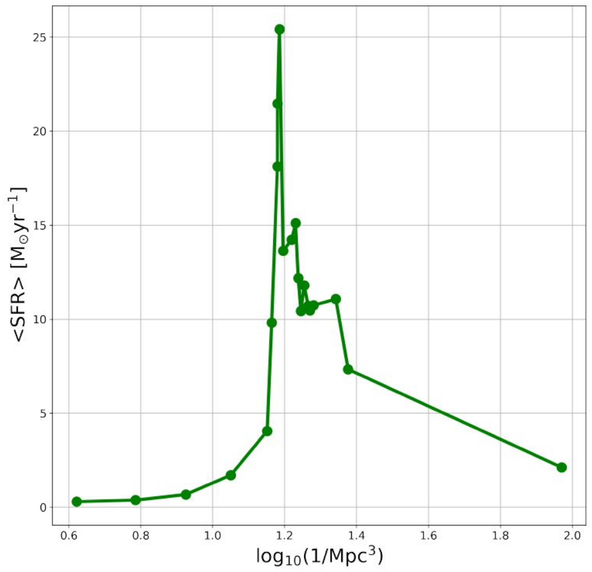
- 5-25% infalling mass comes from mergers
  - Suess+ 2023: 30% (z=0.5 - 3)

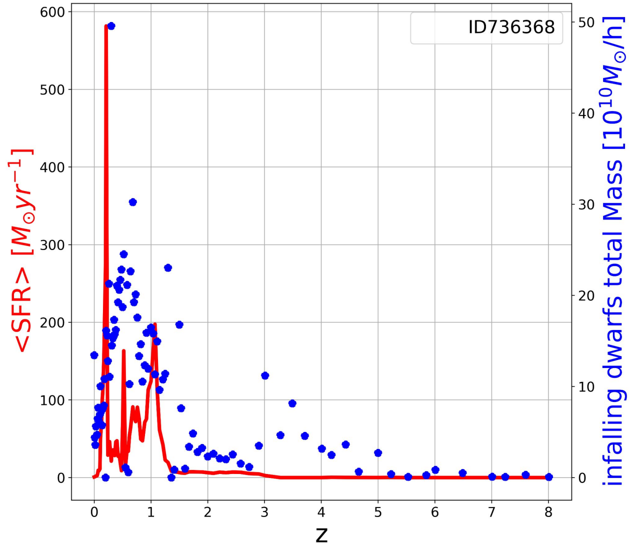
Summary

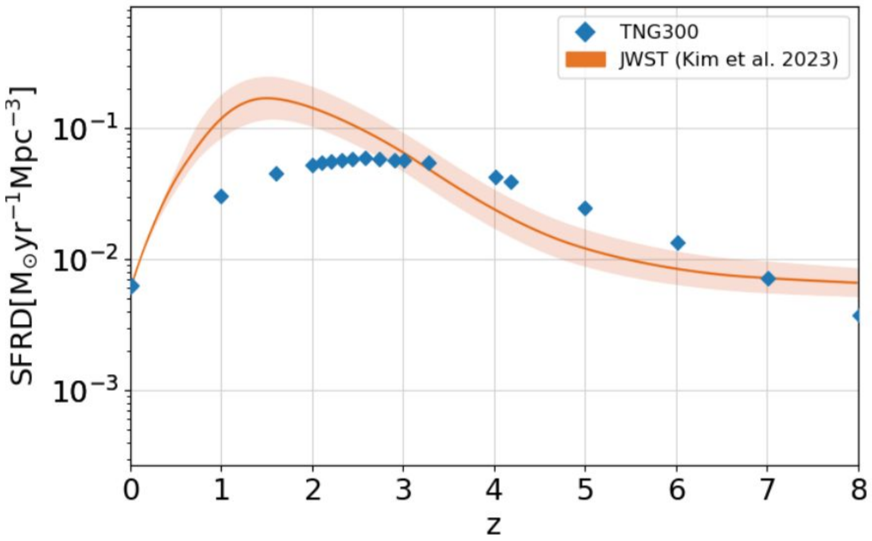
- Investigated star formation in IllustrisTNG galaxy mergers
- Processed merger trees of 100-1 and 300-1 volumes
- Compared results to recent JWST studies

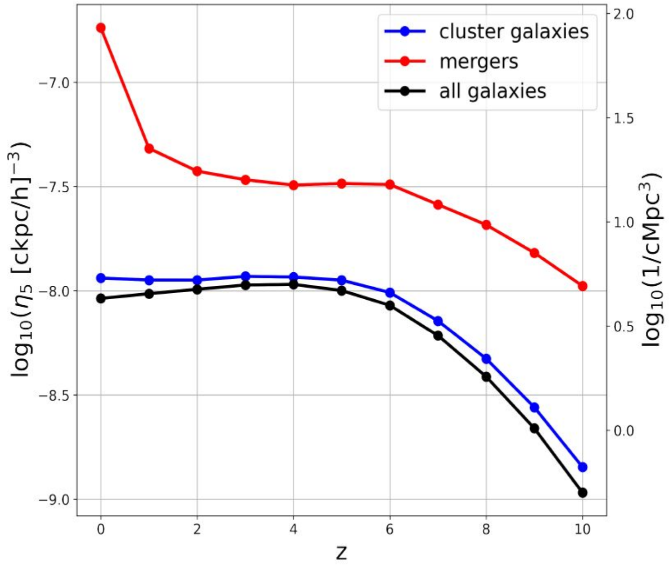
- Minor mergers concentrate around overdensities, especially at z=0
- 5-25% infalling mass comes from mergers (z = 0 - 8)
    - Suess+ 2023: 30% (z=0.5 - 3)

- SFR maximum in mergers around z=3, why?









Supplements

IllusrtisTNG

- side length of simulation box (L): 205000 [ckpc/h] c = comoving, h = 0.6774 [100 km/s/Mpc]
- galaxy formation model is built upon the cosmological simulation code AREPO Springel 2010
- AREPO solves the coupled equations of ideal MHD and self-gravity
- Gravitational forces are calculated with a Tree-Particle-Mesh (Tree-PM) scheme
- the solution of the magneto-hydrodynamical equations are obtained in a quasi-Lagrangian fashion
- For cosmological simulations, gravity is treated in a fully Newtonian framework using periodic boundary conditions
- starting redshift: 127 , ending redshift: 0
- 100 snapshots for every run. These include all particles/cells in the whole volume.
- Starting snapshot: z=20.05 (13.624 Gyr Lookback time)
- number of dark matter particles: 1.5625 × 10^10
- number of gas tracer particles: 1.5625 × 10^10
    - minimum physical gas cell radius: 47 pc
    - median gas cell radius,: 31.2 kpc
    - mean radius of star-forming gas cells: 715 pc

		TNG50	TNG100	TNG300
Volume	$[\mathrm{Mpc}^3]$	51.7^3	110.7^3	302.6^3
L_{box}	$[\mathrm{Mpc}/h]$	35	75	205
N_{GAS}	-	2160^3	1820^3	2500^3
N_{DM}	-	2160^3	1820^3	2500^3
N_{TR}	-	2160^3	2×1820^3	2500^3
m_{baryon}	$[\mathrm{M}_\odot]$	8.5×10^4	1.4×10^6	1.1×10^7
m_{DM}	$[\mathrm{M}_\odot]$	4.5×10^5	7.5×10^6	5.9×10^7
$\epsilon_{\mathrm{gas,min}}$	$[\mathrm{pc}]$	74	185	370
$\epsilon_{\mathrm{DM},\star}$	$[\mathrm{pc}]$	288	740	1480

IllusrtisTNG – Key Physical Processes

- **Gas physics:** radiative cooling and heating (primordial + metal-line) with evolving background radiation
- **Star formation:** in the dense interstellar medium
- **Chemical evolution:** enrichment from SNe Ia, SNe II, and AGB stars → tracking elements (H, He, C, N, O, Ne, Mg, Si, Fe)
- **Stellar feedback:** galactic-scale outflows
- **Supermassive black holes:** formation, mergers, and gas accretion

  Black hole feedback:
  - quasar mode (thermal, high accretion)
  - wind mode (kinetic, low accretion)
- **Magnetic fields:** amplification from weak primordial seed fields

Star Formation Rate (SFR) in IllustrisTNG

In IllustrisTNG, galaxies are represented as **subhalos**.
A subhalo contains different particle and cell types: dark matter, gas, stars, black holes.

The **star formation rate** (SFR[$M_\odot$/yr]) describes how **much stellar mass is formed per unit time in a galaxy**.

The **simulation models star formation in dense, cold gas regions**. Gas cells **above a density threshold are allowed to form stars** according to a subgrid model based on the **Schmidt–Kennicutt relation**:

$$\dot{\rho}_\star \propto \rho_{gas}^{1.5}$$

This means that regions with **higher gas density produce stars more efficiently**.

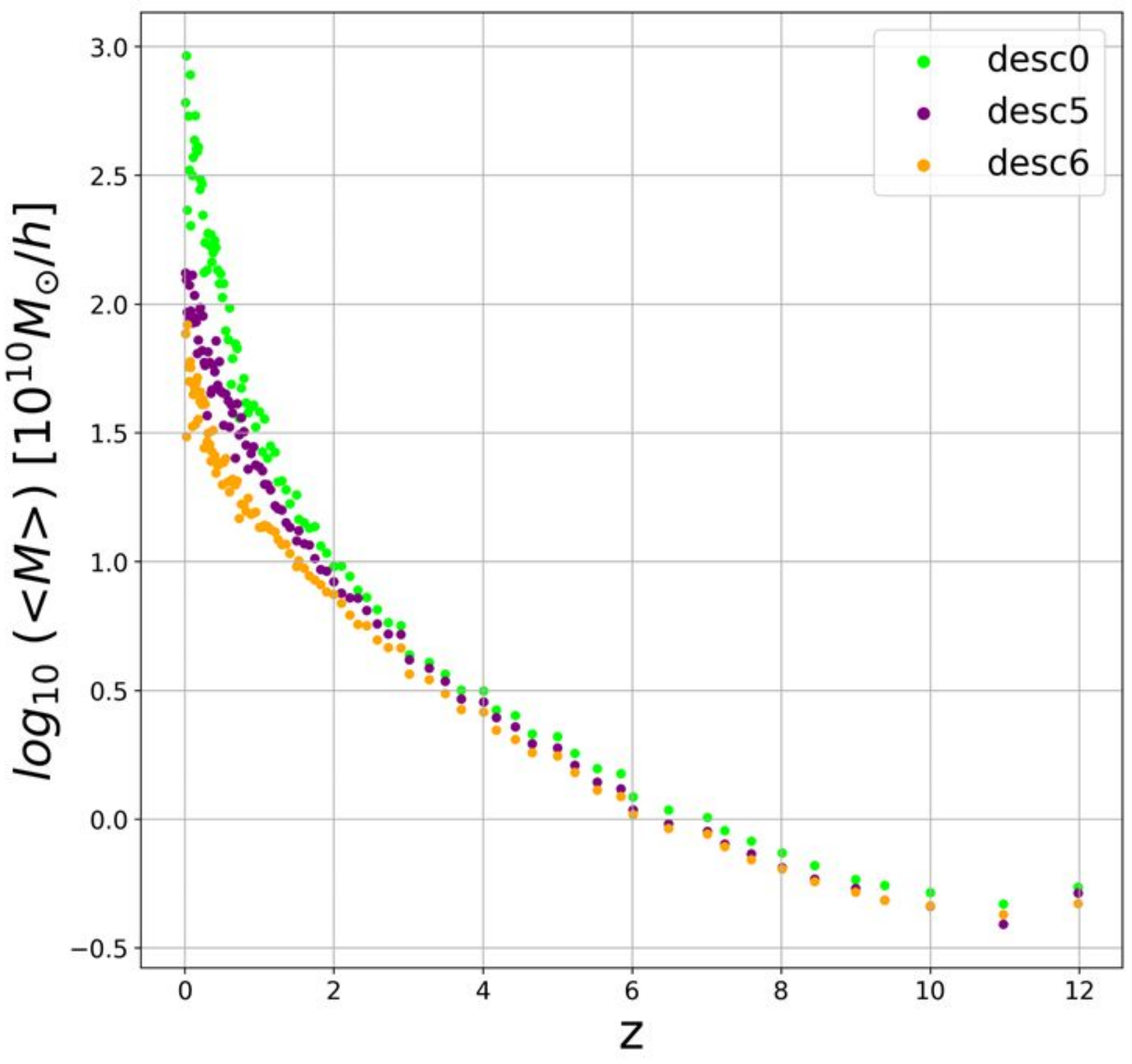
For a given galaxy (subhalo), the total star formation rate is computed as the **sum of the SFR values of all star-forming gas cells** belonging to that subhalo. Important catalog field: **SubhaloSFR**

This parameter is commonly used to distinguish: **star-forming galaxies, quenched/passive galaxies**

The IllustrisTNG model is based on the **multiphase interstellar medium (ISM) framework** introduced by Springel & Hernquist (2003), where gas above a critical **hydrogen density threshold of n_H ~ 0.1 cm^{-3} is considered star-forming.**

Merger tree comparing

- The average masses (and star formation rates) versus redshift in three individual merger tree
- Mean mass on logarithmic scale versus redshift of the descendant galaxies
- Similar results for each merger tree
- Compared to the simulated JWST observational data from z = 5 to z = 10 D'Silva+ 2022, most of the uncertainties are higher than the differences between the merger trees
- Individual merger trees are precise enough to examine the average properties of the galaxies at high redshifts
- Contributions of the Astronomical Observatory Skalnaté Pleso Koncz+ 2023



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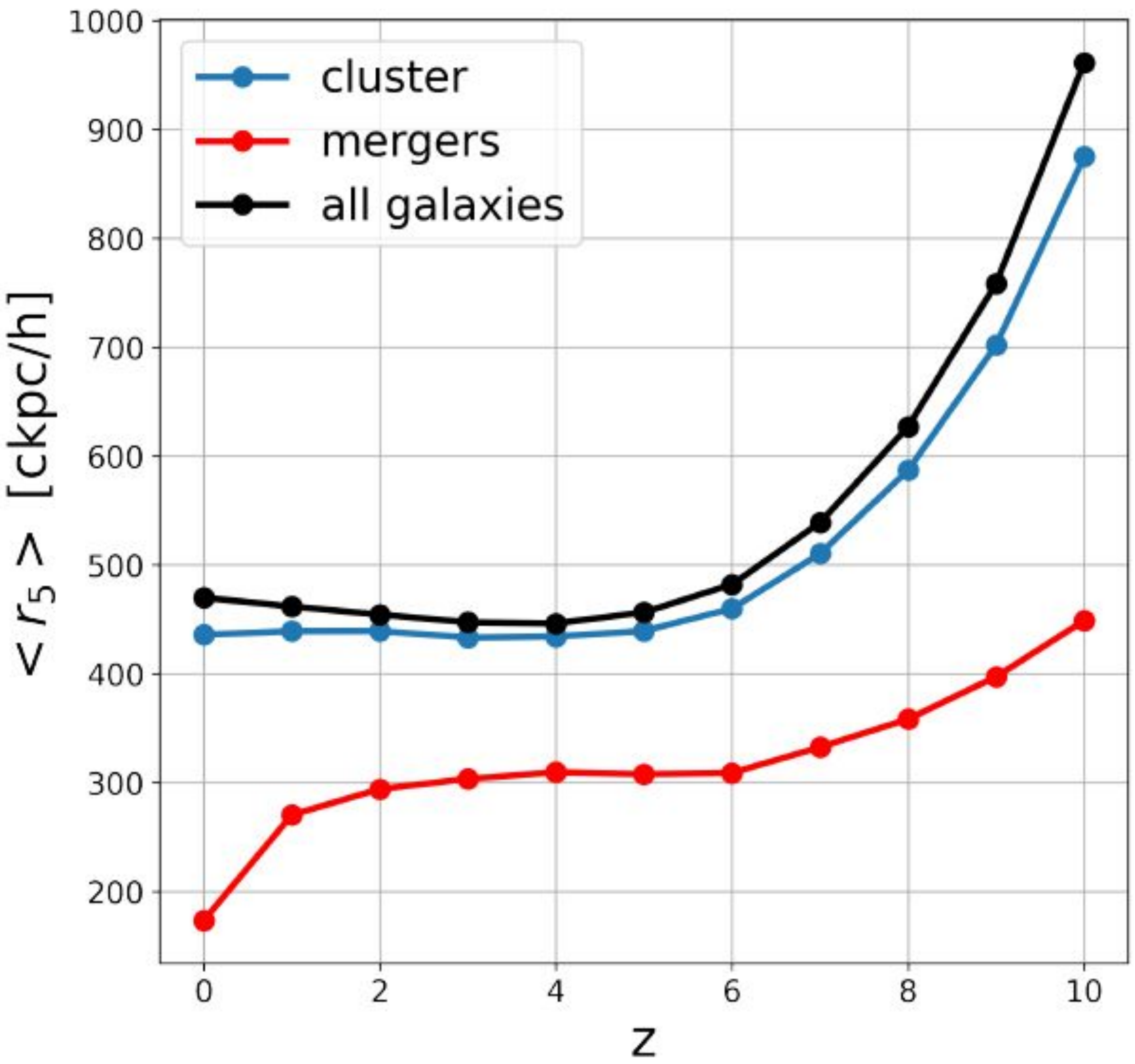

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