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Understanding the Formation and Evolution of Dark galaxies in a Simulated Universe

Gain Lee (이가인)[1], Ho Seong Hwang (황호성)[1,2], Jaehyun Lee (이재현)[3], Jihye Shin (신지혜)[3], Hyunmi Song (송현미)[4]

[1] Seoul National University, Seoul
[2] SNU Astronomy Research Center, Seoul
[3] Korea Astronomy and Space Science Institute, Daejeon
[4] Chungnam National University, Daejeon

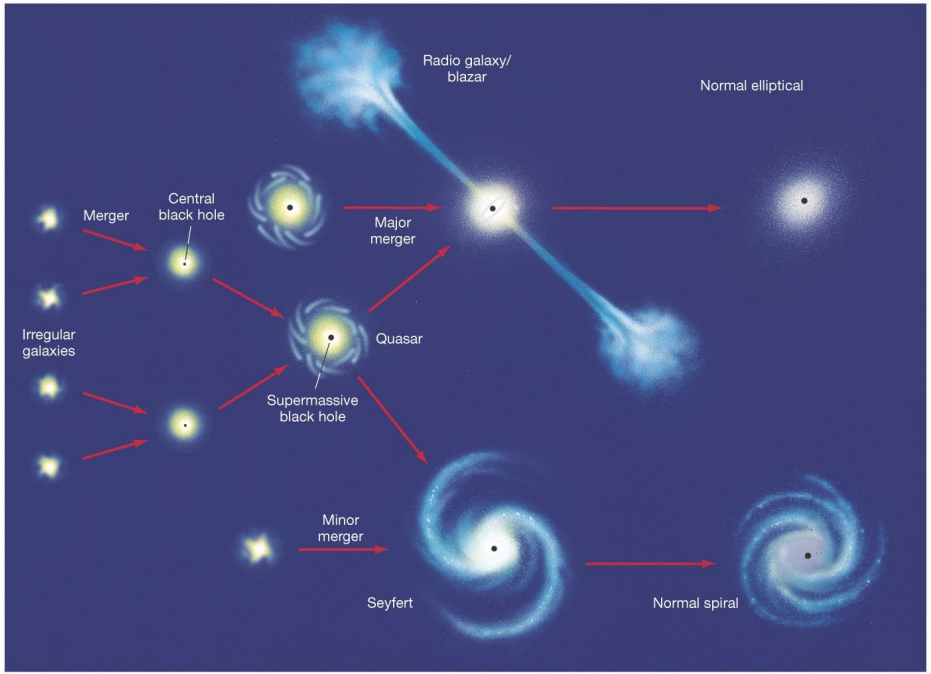
What are dark galaxies?

consist almost of DM, with little or no star

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LCDM cosmology: Hierarchical galaxy formation model

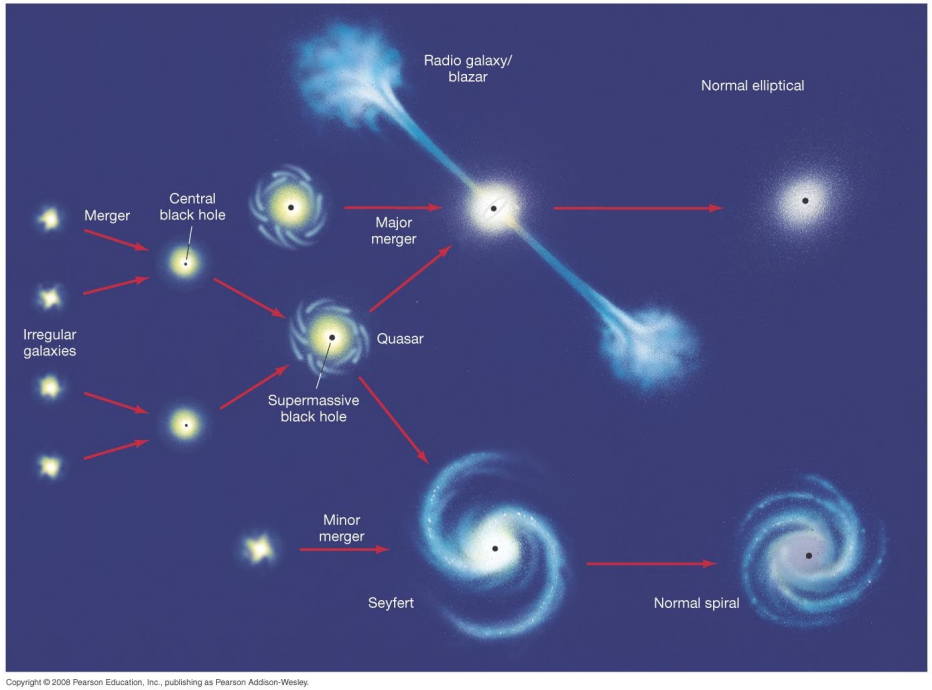


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What are dark galaxies?

consist almost of DM, with little or no star

LCDM cosmology: Hierarchical galaxy formation model



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test the LCDM model

missing satellite problem

mini DM halo



fail to form star



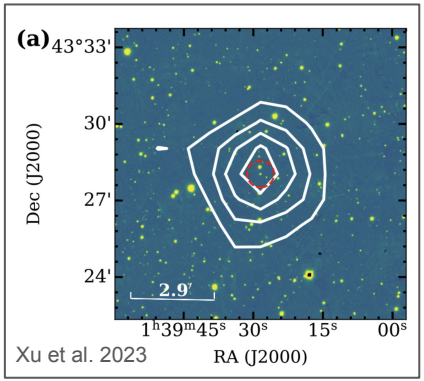
dark galaxy

What are dark galaxies?

consist almost of DM, with little or no star

Observational aspect

- Several **candidates** for dark galaxies: VIRGOHI21 (Minchin et al. 2005), Dragonfly 44 (van Dokkum et al. 2015), AGESVC1 282 (Bilek et al. 2020), AGC 229101 (Leisman et al. 2021) and FAST J0139+4328 (Xu et al. 2023)
- **However**, their existence is **still under debate**:
  intergalactic gas clouds? tidal debris? ram-pressure remnants?



Xu et al. 2023

Theoretical aspect

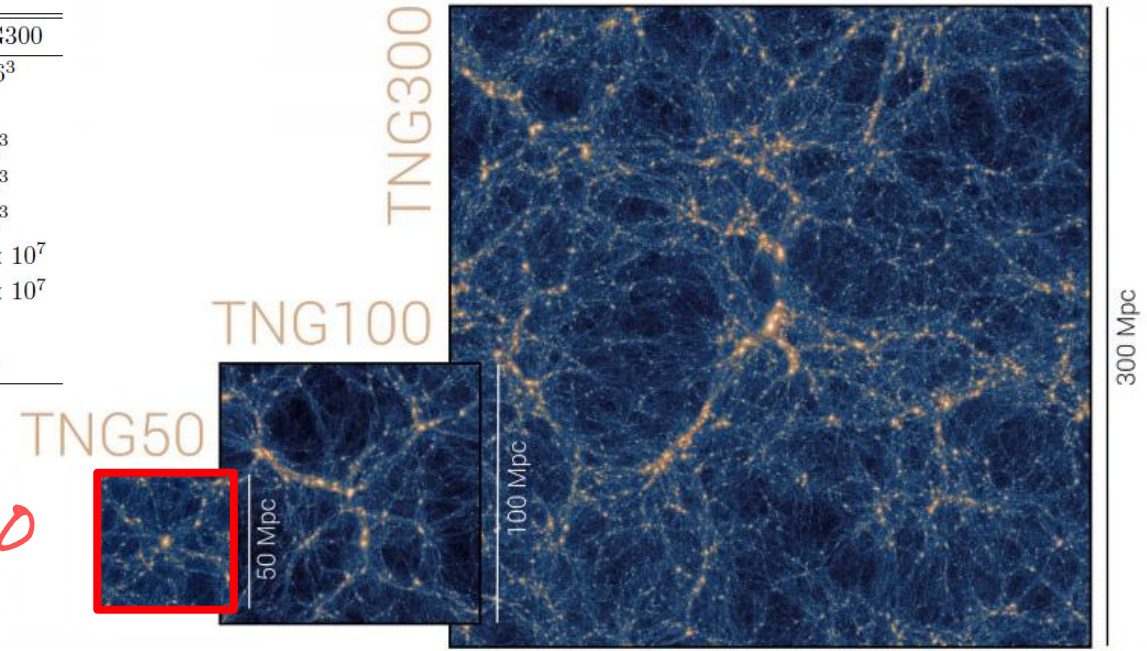
- Some researches have already predicted the existence of dark galaxies:
  Jimenez et al. 1997, Tretham et al. 2001 and Verde et al. 2002
- **Despite these predictions**, there has been **a lack of studies** focusing on characterizing the properties of dark galaxies.
  Benitez-Llambay et al. 2017

Why Illustris-TNG?

- Large, cosmological magneto-hydrodynamical simulations of galaxy formation
- **Pros**: Easily identify true dark galaxies & Ability to trace the cosmic history
- **Cons**: Limited resolution & Dependence on subgrid models

		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
$\epsilon_{\mathrm{gas,min}}$	[pc]	74	185	370
$\epsilon_{\mathrm{DM},\star}$	[pc]	288	740	1480

WE USED TNG50 IN THIS WORK



Sample Selection

Definitions for luminous / dark galaxies

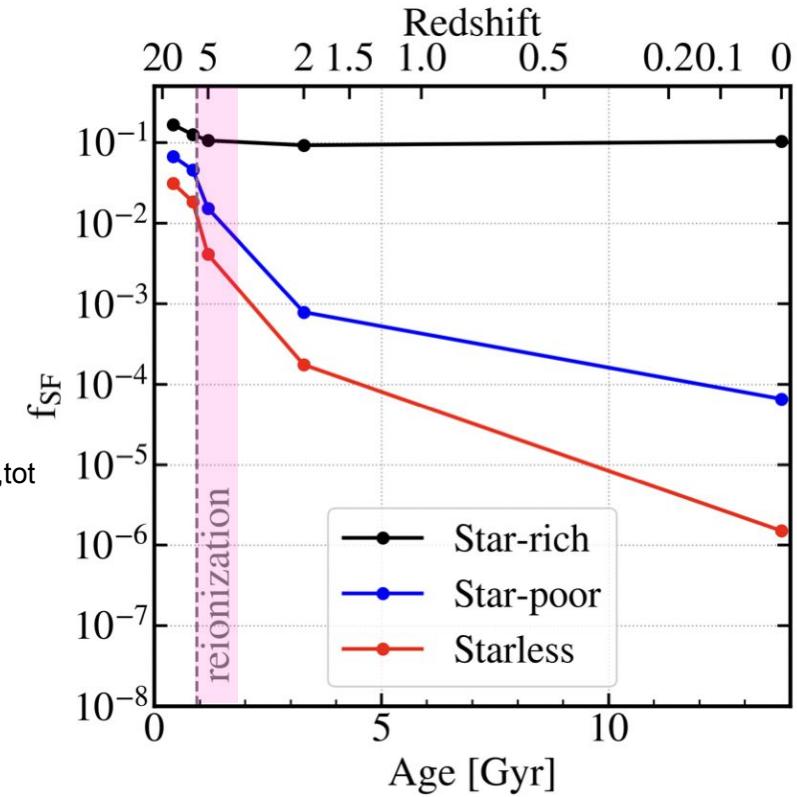
Luminous galaxy | Dark galaxy

	Star-rich galaxy	Star-poor galaxy	Starless galaxy
$M_\star$	$10^{-4}\ M_{tot} \le M_\star$	$0 < M_\star < 10^{-4}\ M_{tot}$	$M_\star = 0$
M_{DM}	All galaxies have similar DM halo masses ~ $10^9\ h^{-1}\ M_\odot$		
$\#_{sample}$	**14,206**	**19,245**	**1,318**

1. Gas properties

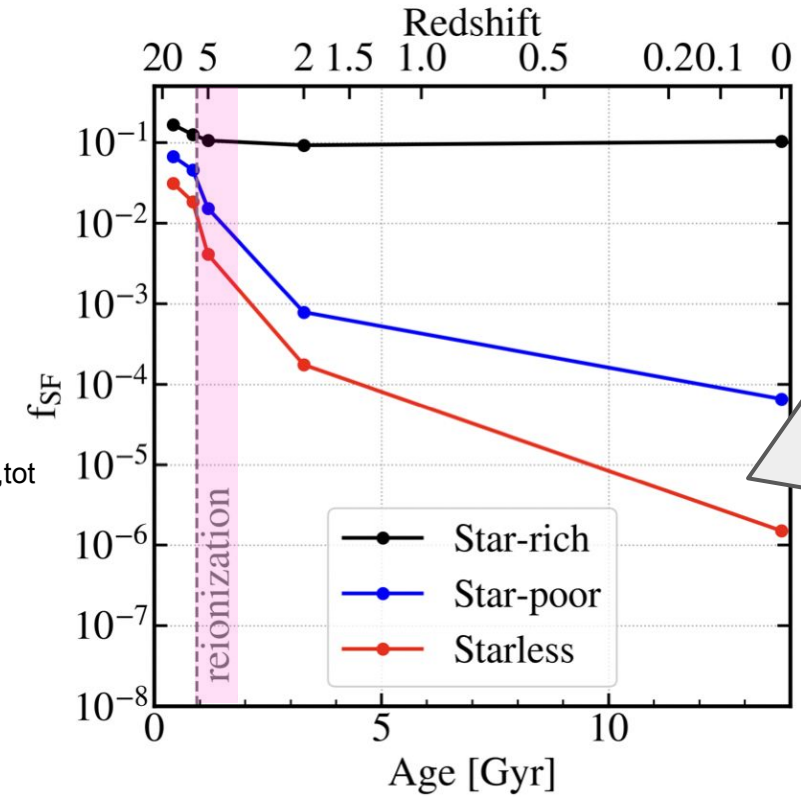
Star-forming gas fraction:

$f_{SF} = M_{gas,SF} / M_{gas,tot}$



1. Gas properties

Star-forming gas fraction:
$f_{SF} = M_{gas,SF} / M_{gas,tot}$



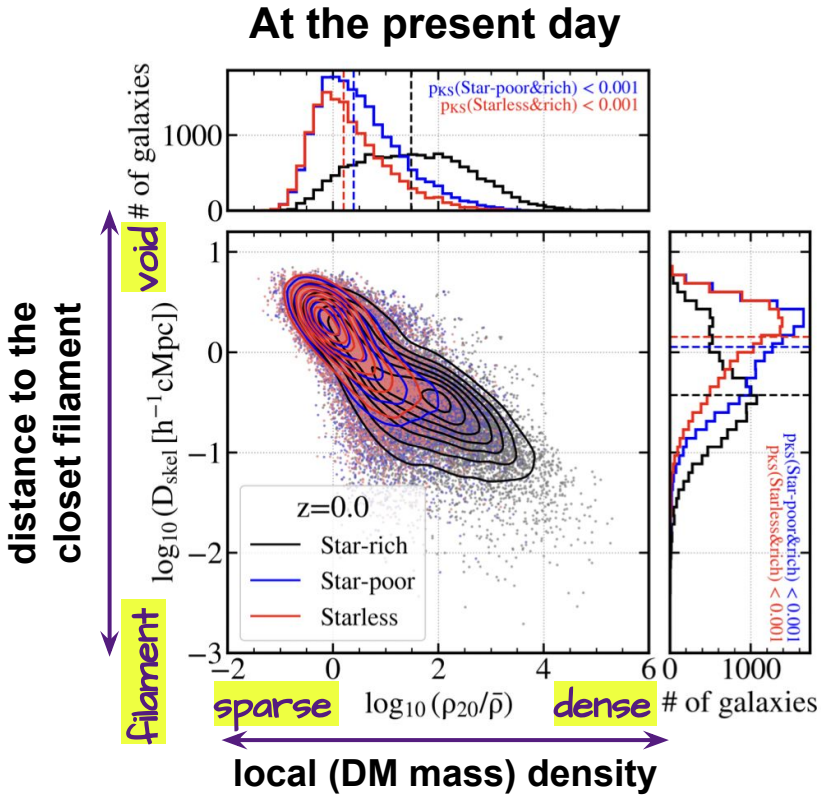
- Dark galaxies contain **less SF gas** throughout cosmic history.
- The SF gas fractions in dark galaxies are **decreasing** after **cosmic reionization**.

heating of gas reservoir

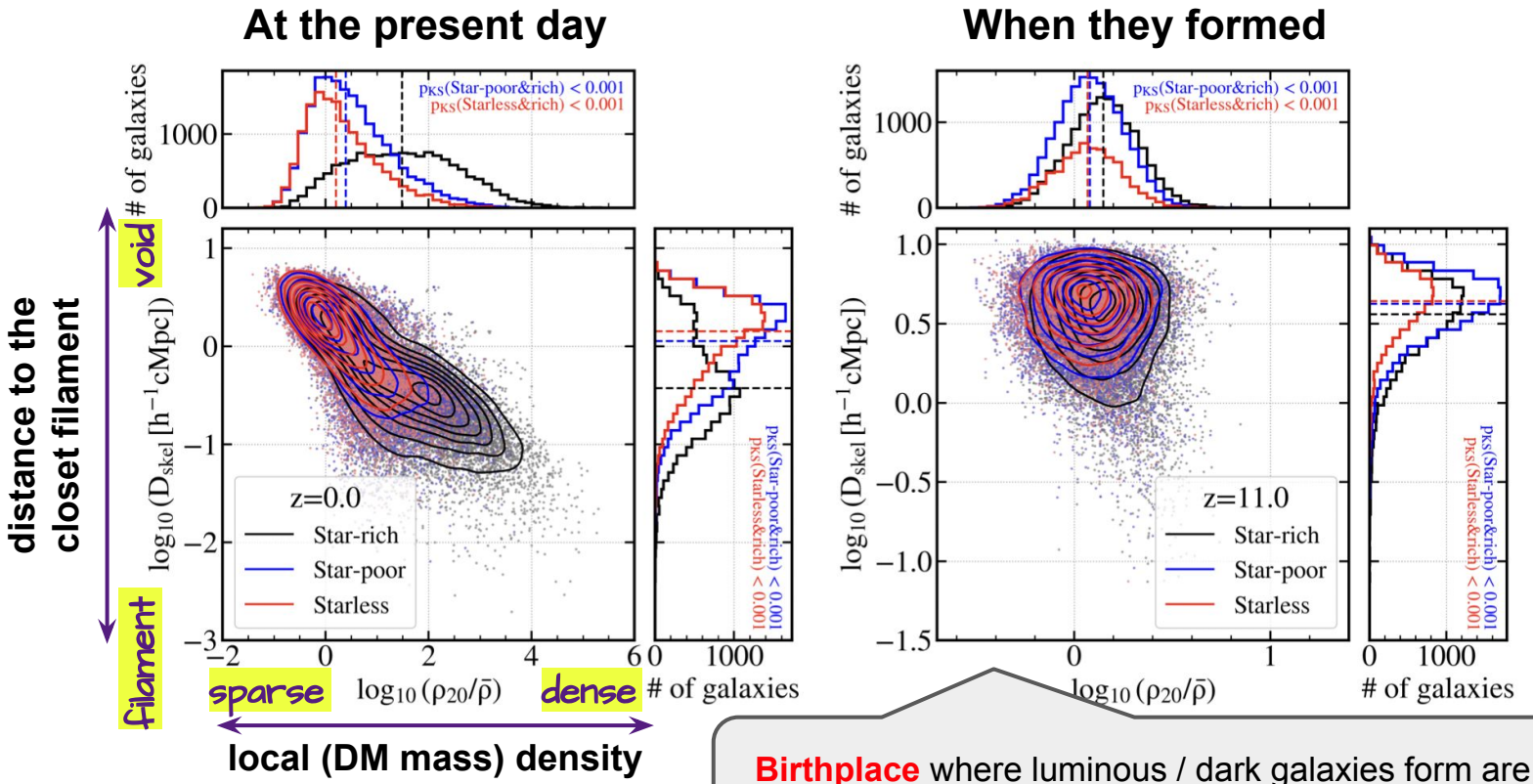
expulsion of gas

suppression further gas accretion

2. Environment (spatial distribution)



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Birthplace where luminous / dark galaxies form are **different**.
This could play important role in subsequence evolution.

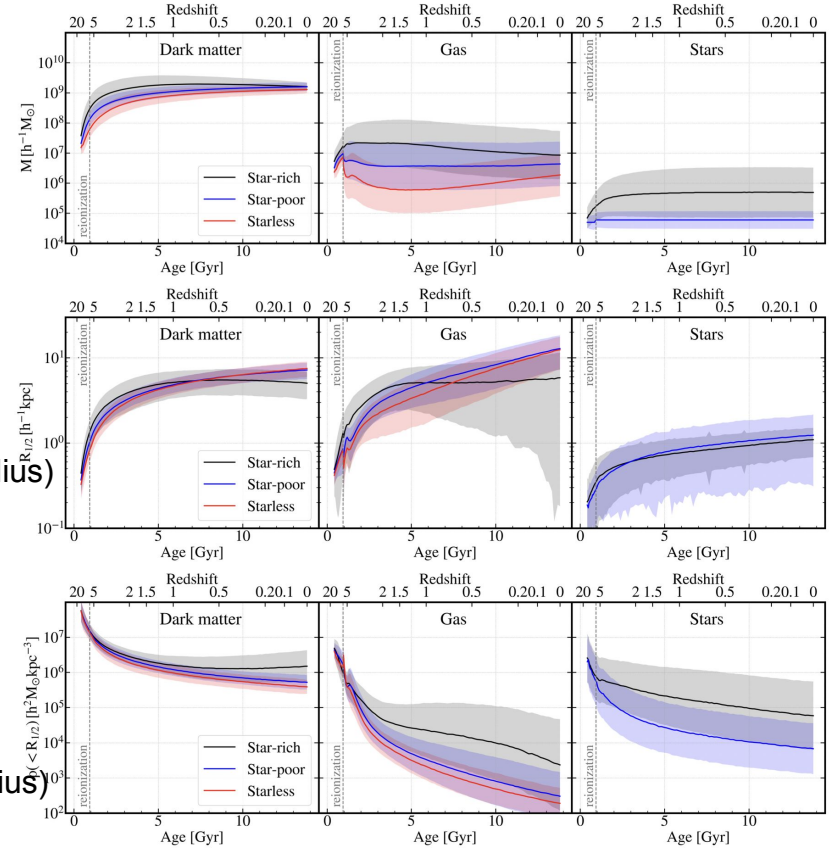
3. Internal properties

dark matter gas star

mass

size
(half-mass radius)

density
(within the
half-mass radius)



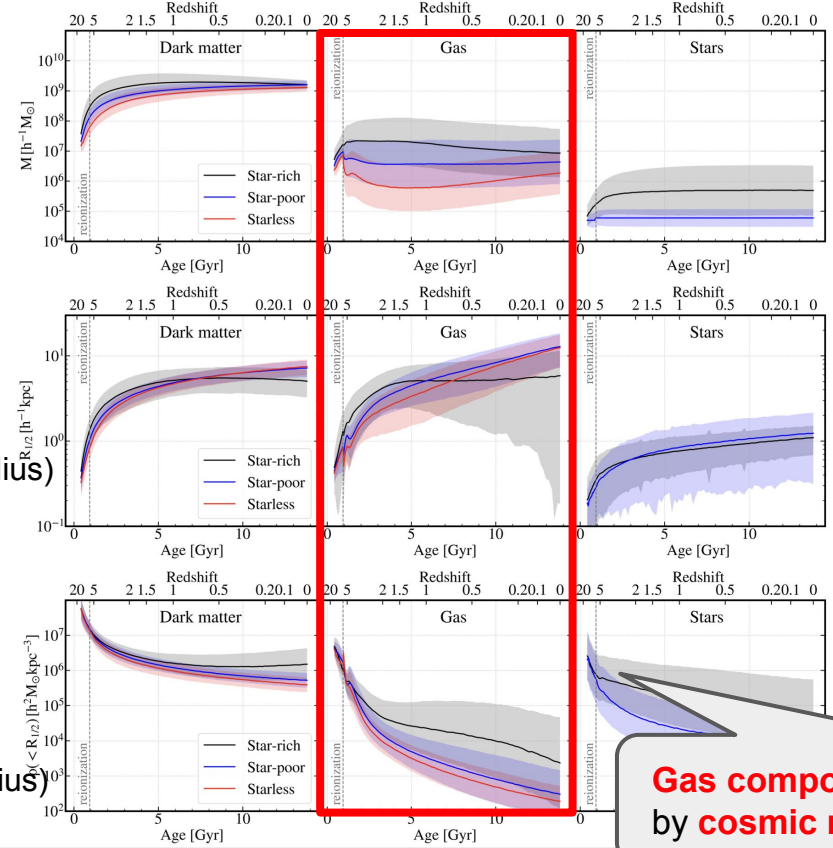
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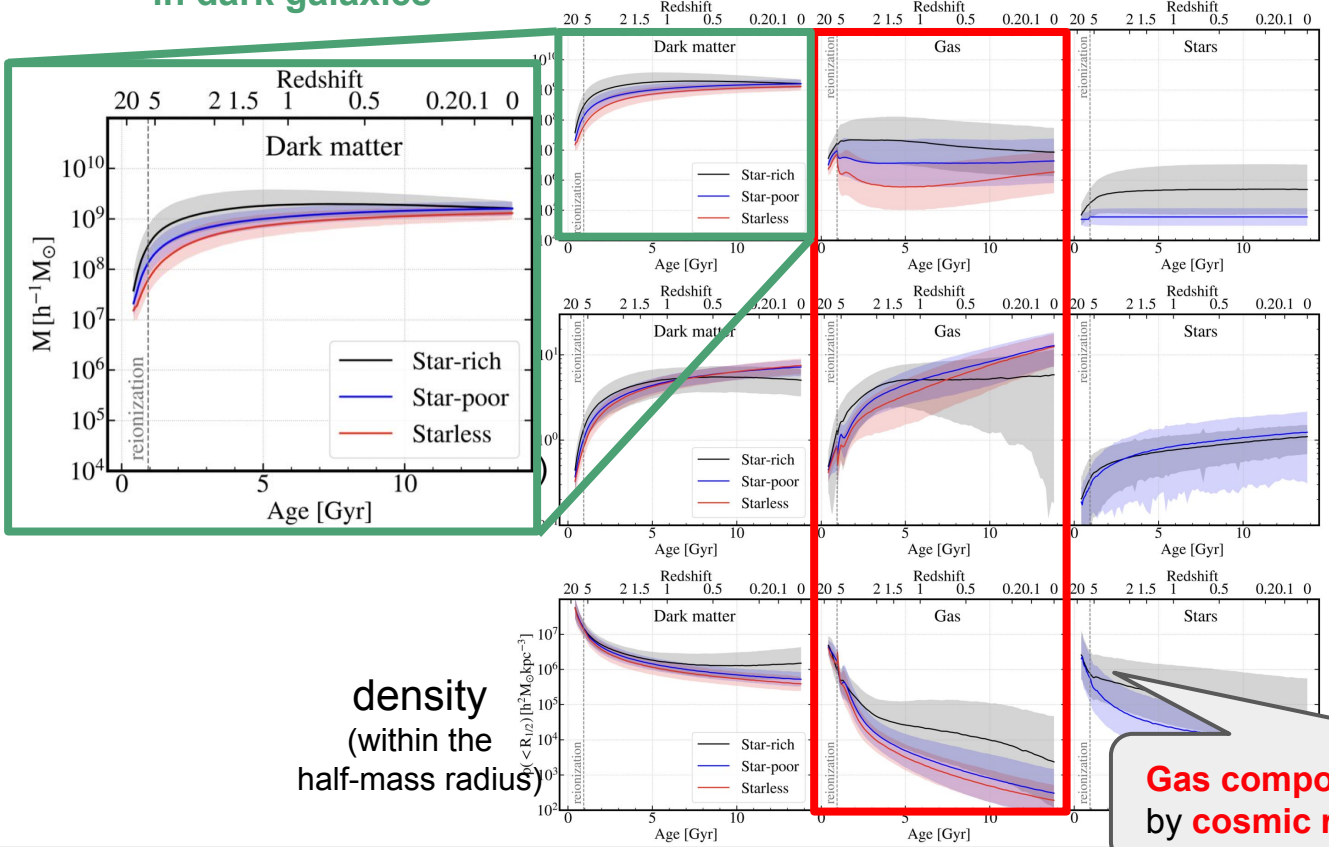


Gas components are strongly affected by **cosmic reionization**.

3. Internal properties

slower mass growth in dark galaxies

dark matter gas star

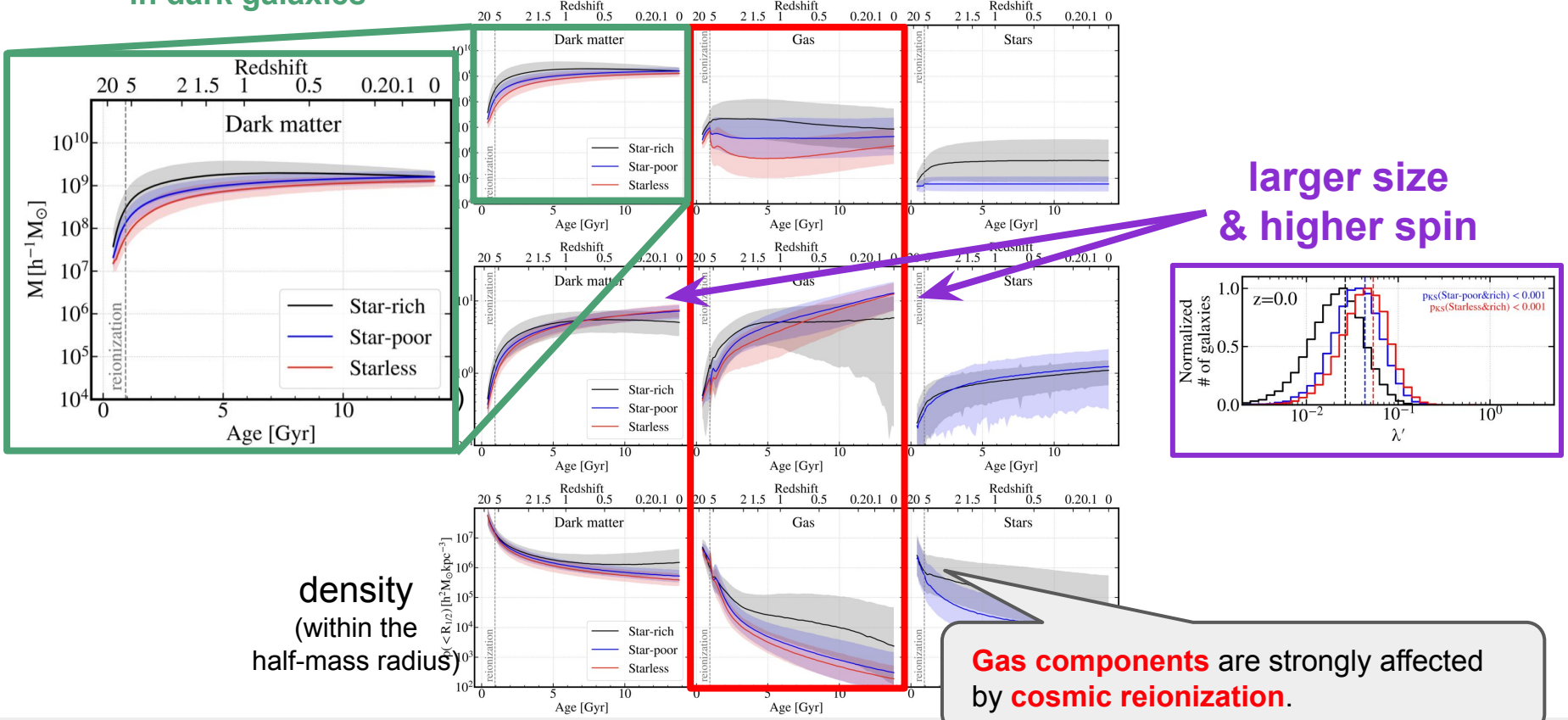


Gas components are strongly affected by **cosmic reionization**.

3. Internal properties

slower mass growth in dark galaxies

dark matter gas star



larger size & higher spin

Gas components are strongly affected by **cosmic reionization**.

Summary & Conclusion

Using **TNG50**, we investigated **dark galaxies** and compared their various properties to those of luminous galaxies.

Our key findings include:

1) **Distinct properties at Present Day (z=0)**
   Dark galaxies are predominantly located in void region, and usually larger in sizes with higher spin parameters, compared to luminous galaxies. They have a lack of star-forming gas.
2) **Inherent Differences from Early Universe (z~11)**
   Even in the early universe, the differences between them still existed, suggesting inherent differences from their formation.
3) **Impact of Environment on Evolution**
   The differences between them become more significant as they evolve in the different environments. Dark galaxies remain isolated, while luminous galaxies experience much frequently mergers.
4) **Role of Cosmic Reionization**
   Heating from CR can suppress star formation, significantly influencing the formation and evolution of dark galaxies. However, we note that the limitations of simulations can oversimplify the effects of CR, impacting accuracy.

These results can contribute to our **understanding** of galaxy formation and evolution, and provide **some hints for finding dark galaxies** in the observable world.

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Backup Slides

Resolution of the TNG simulation

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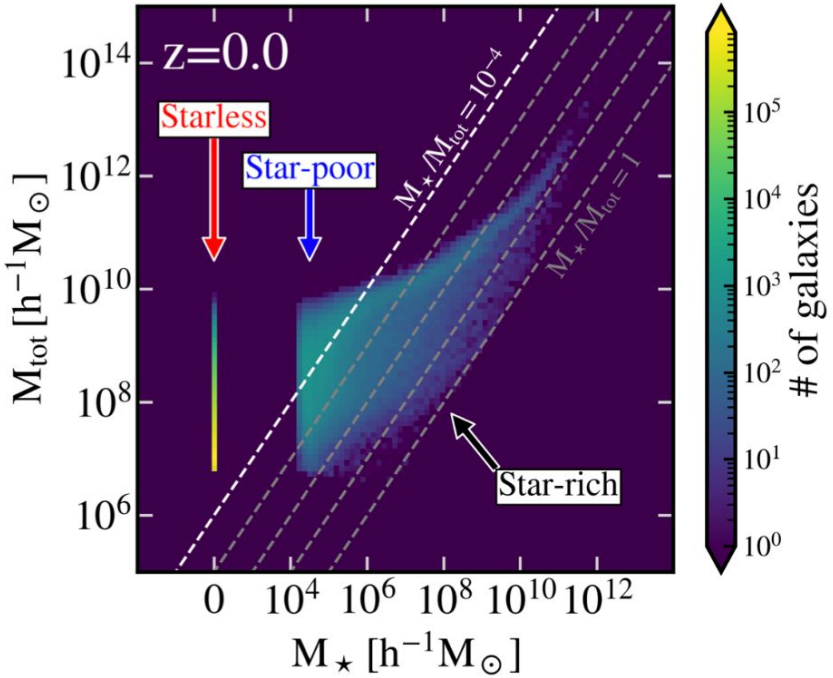


Figure 1. 2D histogram of galaxies at $z = 0$ in terms of their stellar masses and total masses, showing the classification of galaxies. The color indicates the number of galaxies within each bin. A white dashed line is a criterion for distinguishing luminous and dark galaxies. The gap between star-poor and starless galaxies is a result of the resolution. The minimum mass of star particle is around $10^4\,h^{-1}M_\odot$ at $z = 0$.

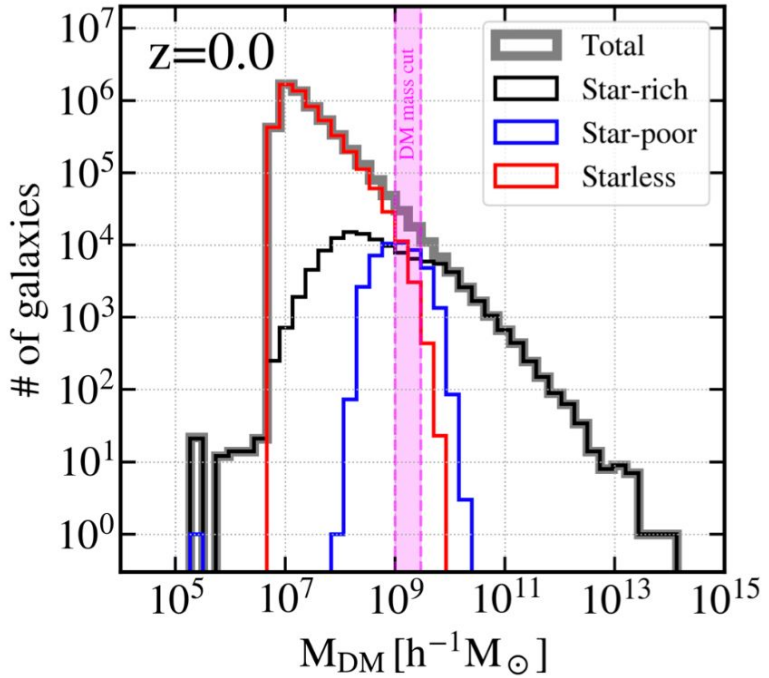


Figure 2. Dark matter mass histogram at $z = 0$. The grey, black, blue, and red colors correspond to the total, star-rich, star-poor, and starless galaxies, respectively. The magenta region highlights the selection area for mass completeness. Our final galaxy sample contains 14,206 star-rich galaxies, 19,245 star-poor galaxies, and 14,318 starless galaxies.

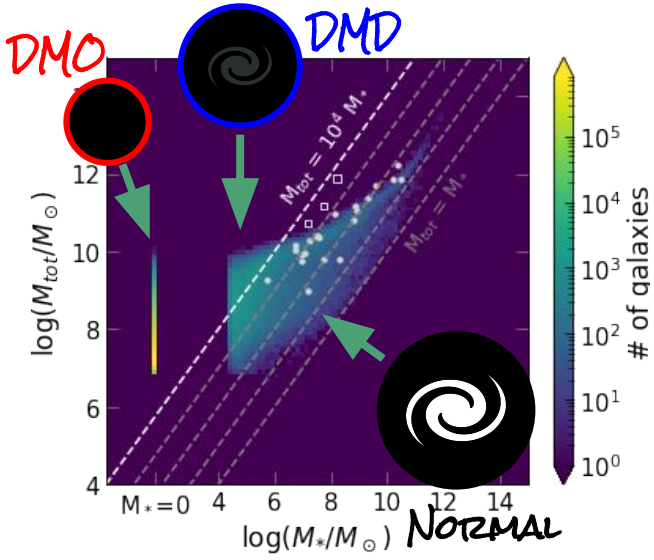
Sample Selection

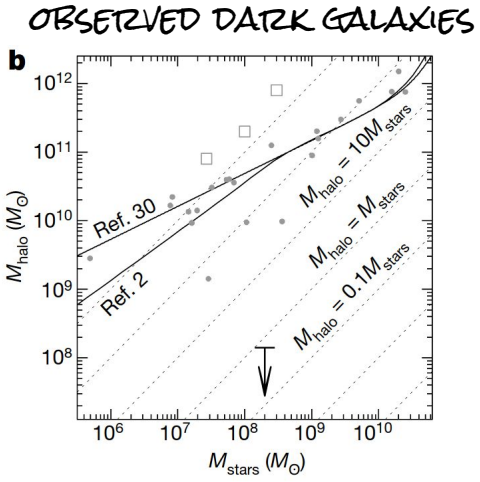
Definitions for normal / dark galaxies

Normal galaxy : Mstar > 0.0001 Mtot

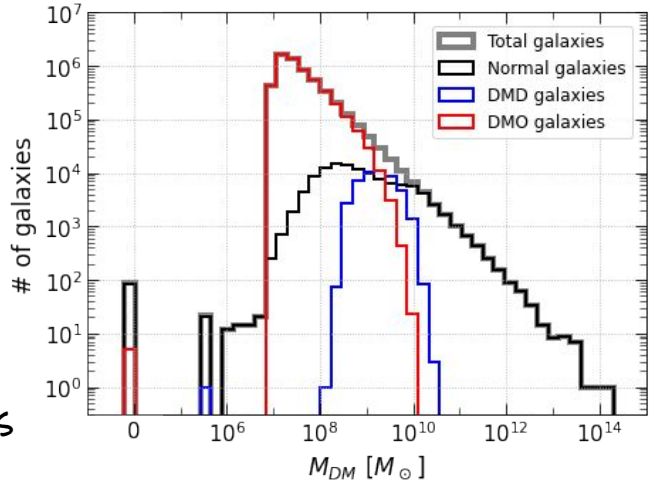
Dark galaxy : Mstar ≤ 0.0001 Mtot

- Dark matter only (**DMO**) galaxies : *Mstar = 0*
- Dark matter dominant (**DMD**) galaxies : *Mstar > 0*





van Dokkum et al. 2018



For mass completeness,

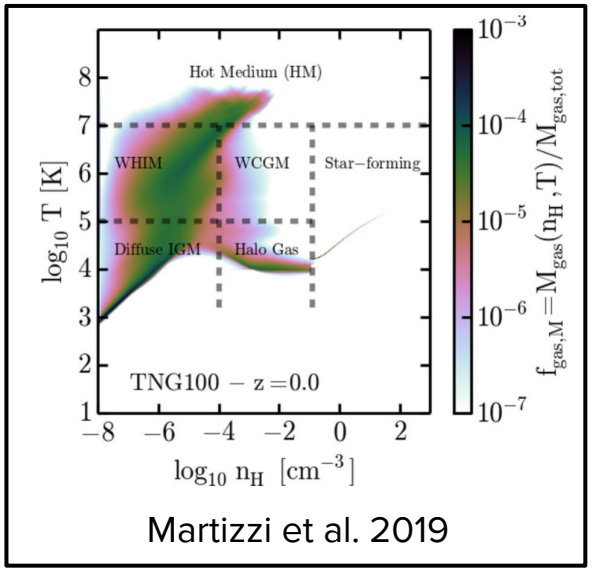
1.5×10^9 Msun ≦ $M_{DM} < 4.3 \times 10^9$ Msun

All selected galaxies have similar dark matter halo masses.

Total	47,687	
Normal	14,219	(29.82%)
DMD	19,161	(40.18%)
DMO	14,307	(30.00%)

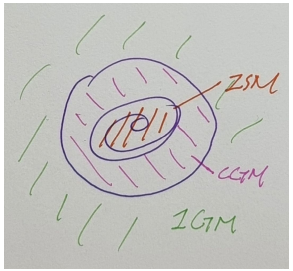
Gas Phase Diagram (Temperature–Density Diagram)

To get some hint for origin of dark galaxies, I plot the gas phase diagrams **at z=0**.



Martizzi et al. 2019

- **Star-forming**: cold and dense gas, adiabatic contraction?
  n_H > 0.13 cm^{-3} ➔ stars are stochastically formed



- **Halo Gas** = cool gas in ISM (galaxy) + CGM (halo)
- **WCGM** = warm CGM
  shock heated and feedback processes near galaxies
- **Diffuse IGM**
  The gas in this phase is located in regions whose over/under-density evolves in the linear regime.
  Hydrogen can be either neutral or ionized,
  but helium and heavier elements are not completely ionized.
- **WHIM** = warm & hot IGM
  contains ionized helium and heavier elements
- **Hot medium**
  temperature larger than the virial temperature of massive galaxy cluster
  shock heated in the most massive DM halos

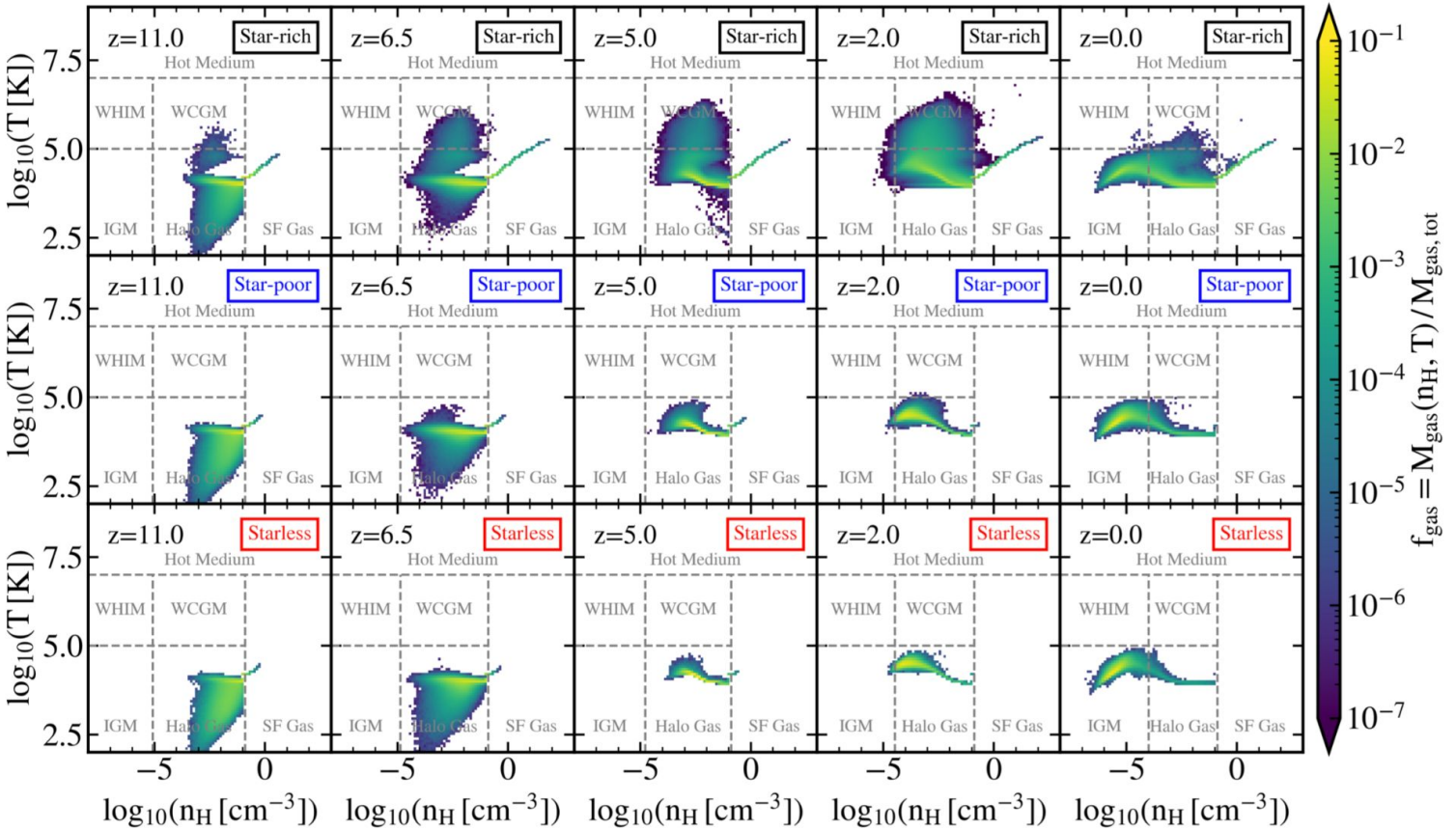
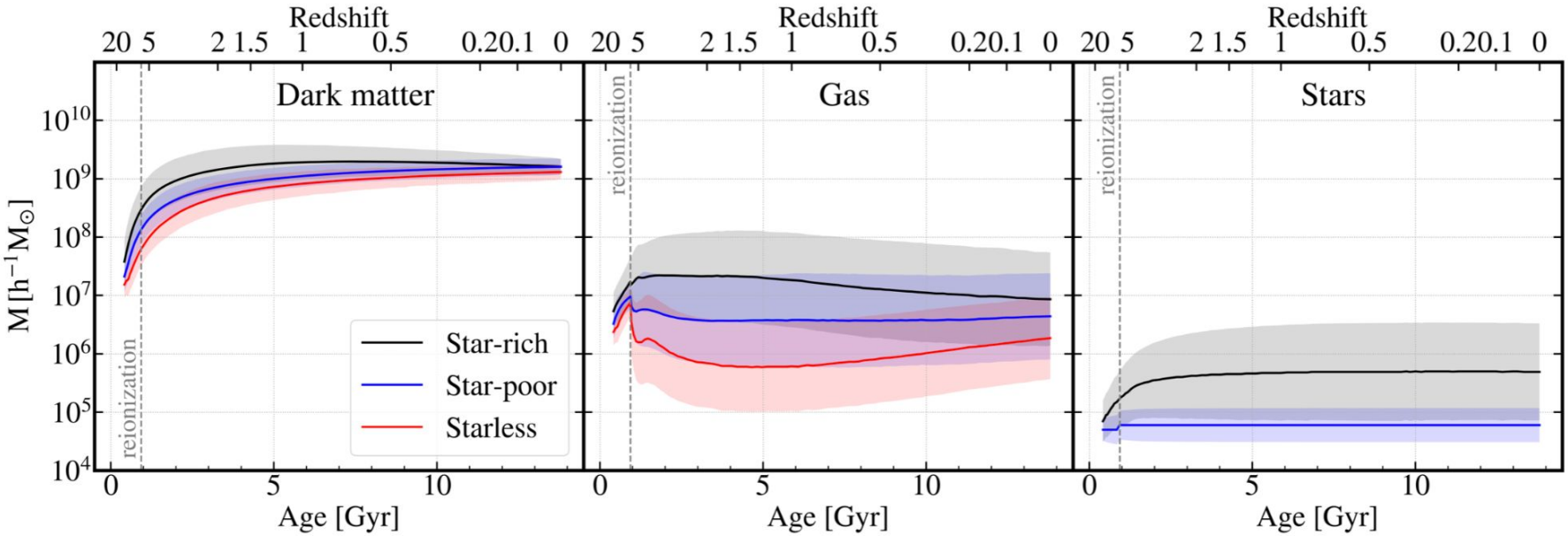
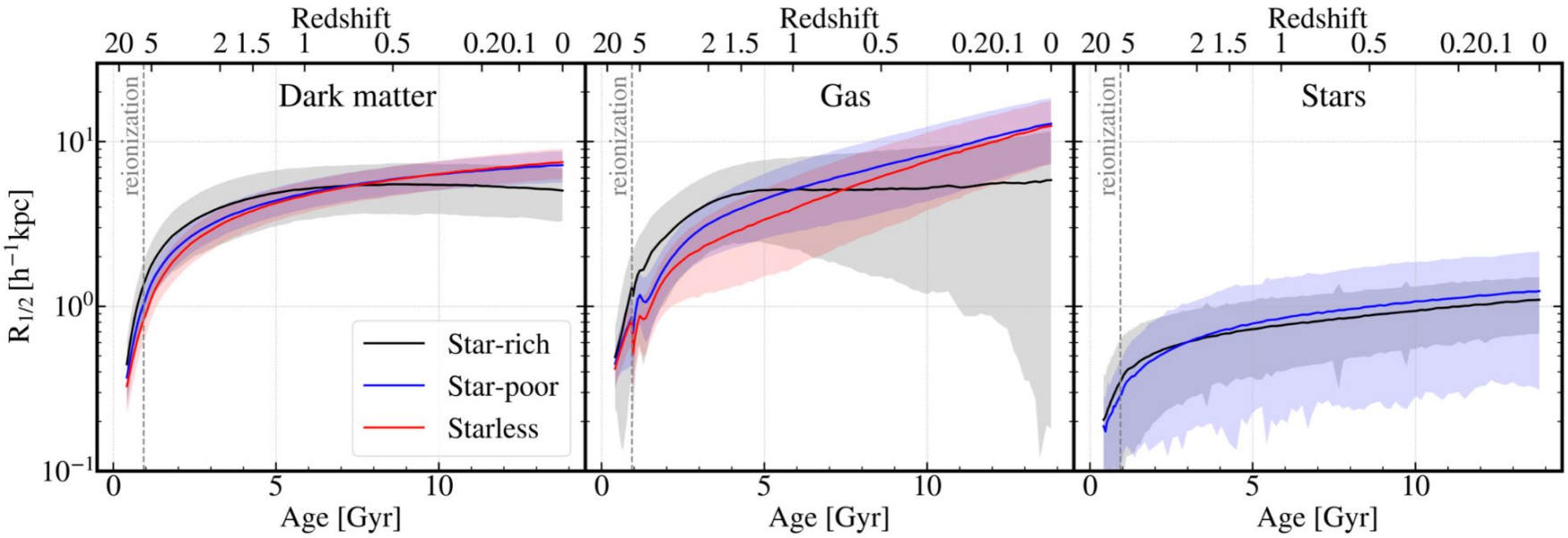


Figure 3. Gas phase diagrams in a density-temperature plane, showing the gas distributions within different types of galaxies (star-rich, star-poor, and starless) across various epochs ($z = 11, 6.5, 5, 2$, and 0). The color represents the mass fraction of gas cells in each bin. The cosmic reionization occurs at $z = 6$.


Redshift
20 5 2 1.5 1 0.5 0.2 0.1 0
Dark matter
Gas
Stars
reionization
$M\,[h^{-1}M_\odot]$
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
Star-rich
Star-poor
Starless
0
5
10
Age [Gyr]


Redshift
20 5 2 1.5 1 0.5 0.2 0.1 0
Dark matter
Gas
Stars
reionization
$R_{1/2}$ [h^{-1}kpc]
10^1
10^0
10^{-1}
Star-rich
Star-poor
Starless
0 5 10
Age [Gyr]

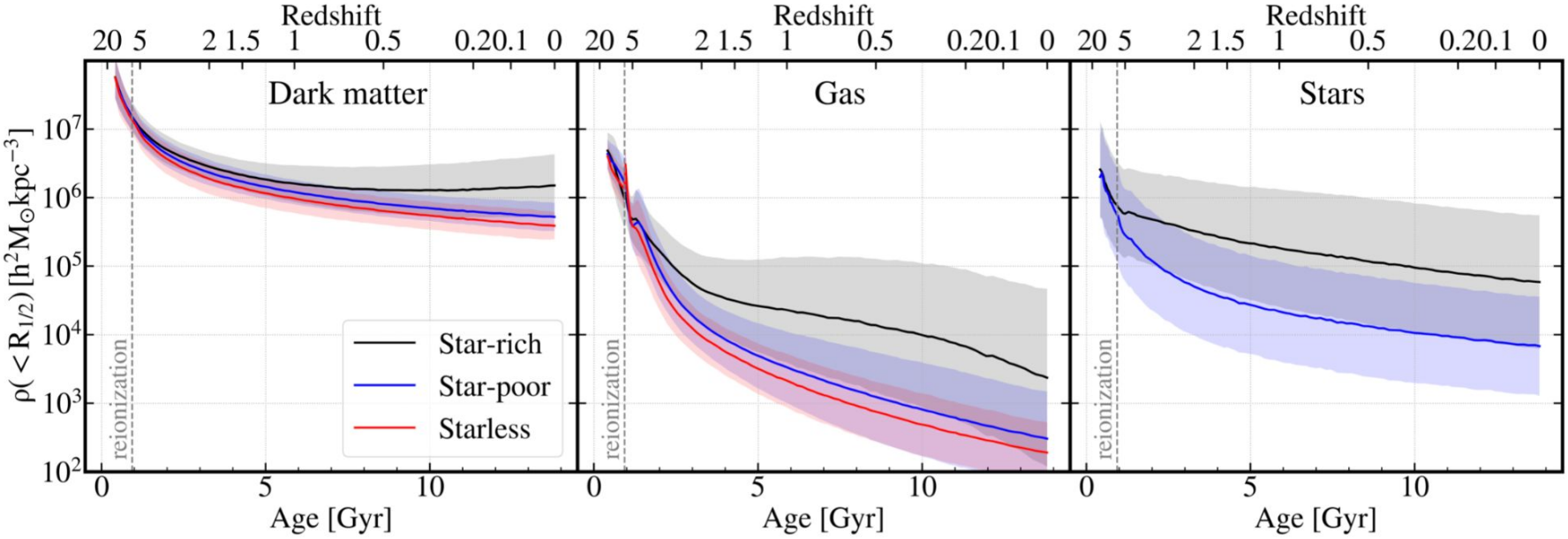
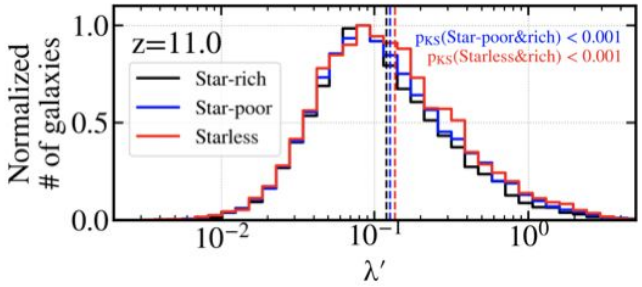
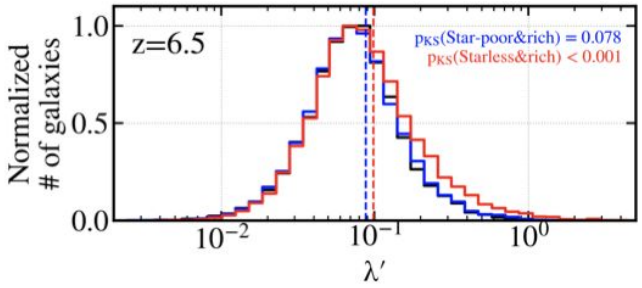


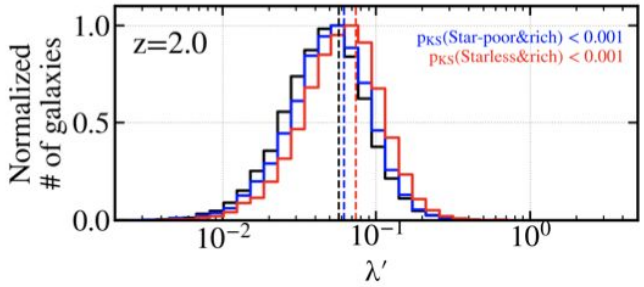
Figure 5. Evolutionary history of star-rich, star-poor, and starless galaxies, in terms of mass (top row), size (half-mass radius; middle row), and density (bottom row). Each row consists of three panels, addressing dark matter on the left, gas in the middle, and stellar components on the right. The curves represent the median values with the shaded regions indicating the 1-σ scatter. Note that the curves and 1-σ scatters are measured from the galaxies with positive stellar or gas mass.

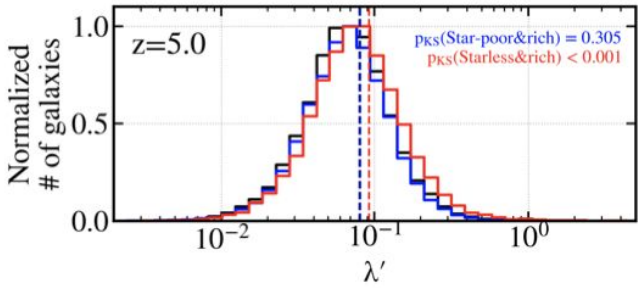
Spin of DM halo

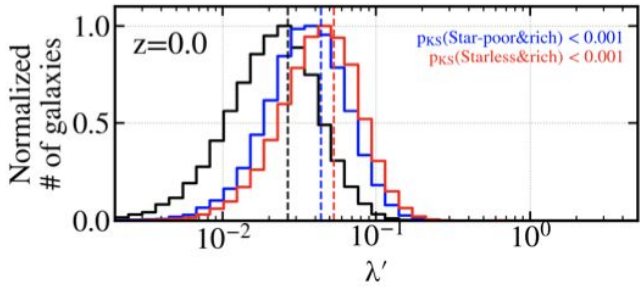


Bullock's spin parameter $\lambda' = \frac{|\mathbf{J}|}{\sqrt{2}MRV}$









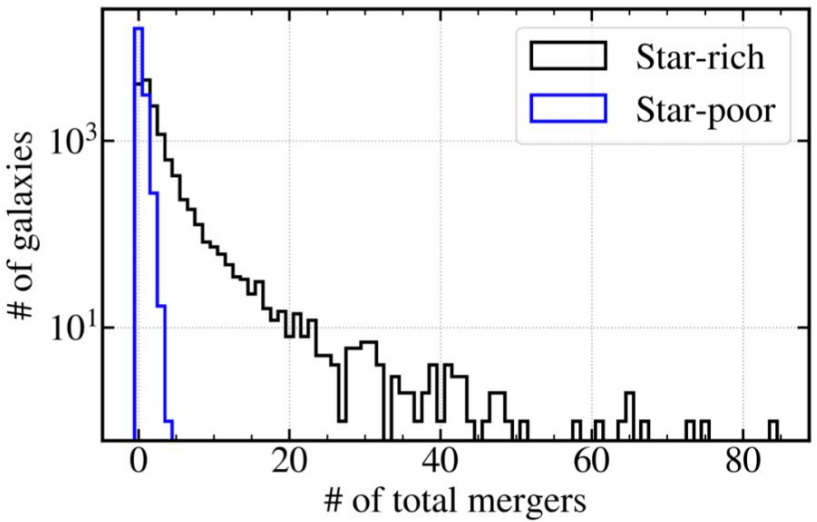


Figure 8. Merger history of star-rich and star-poor galaxies. The histogram shows the total number of mergers experienced by galaxies until $z = 0$. Note that only mergers involving stellar systems are considered here.

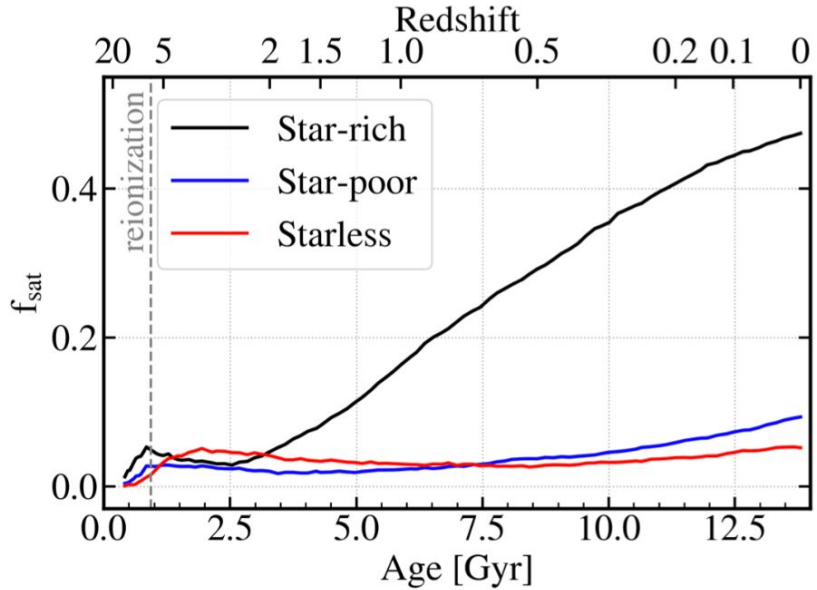


Figure 9. Fraction of satellite galaxies as a function of time for star-rich, star-poor, and starless galaxies. The gray dashed line represents $z = 0$, corresponding to the epoch of cosmic reionization.

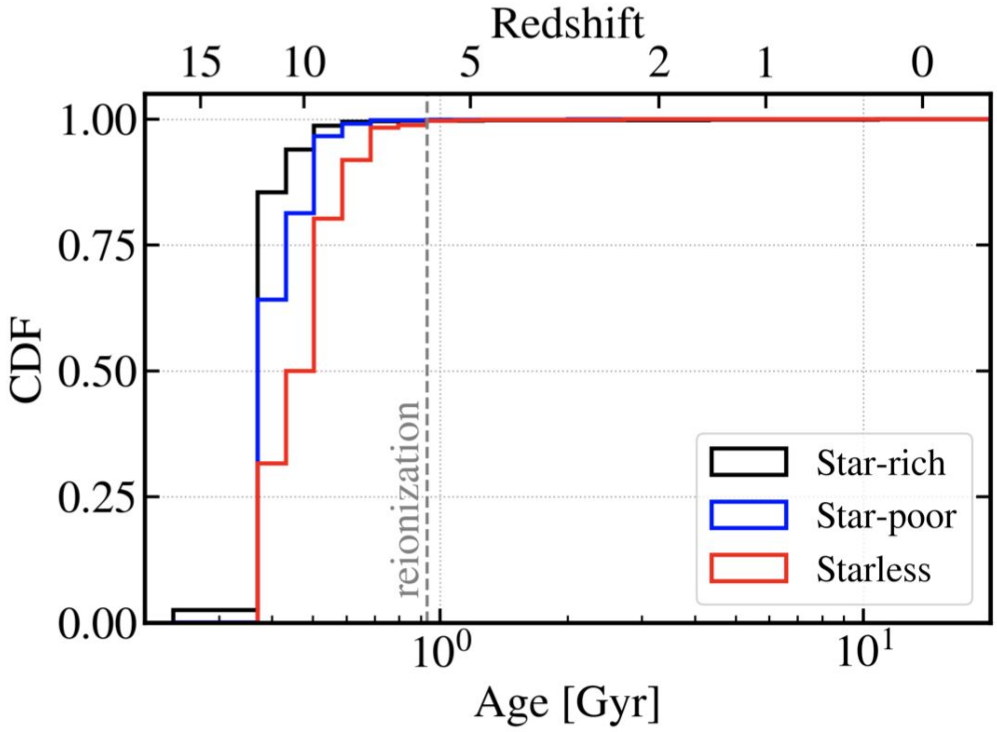


Figure 10. Cumulative distribution function for the time when the galaxies are first identified as SUBFIND groups. The x-axis represents the age of the Universe on a logarithmic scale.