

TNG 50 Galaxies with High Gas Fraction at $z=0$

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Abstract. This work investigates the physical mechanisms responsible for the present-day dichotomy between gas-rich and gas-poor galaxies. Using the TNG50 cosmological simulation, we construct a controlled sample of galaxies at $z = 0$, matched in stellar mass, to isolate the roles of internal evolution and environment in shaping their gas content. Galaxies are classified according to their gas fraction, allowing a direct comparison between high-gas-fraction (HGFG) and low-gas-fraction (LGFG) systems. We find that LGFGs are typically more massive, reside in denser and dynamically hotter environments, and exhibit higher velocity dispersions, indicating that environmental processes such as ram-pressure stripping and tidal interactions play a major role in gas depletion. Tracing their evolutionary histories reveals two distinct pathways: LGFGs experience an early, intense phase of star formation followed by rapid gas consumption and quenching, while HGFGs evolve more gradually, sustained by continuous gas accretion. These results suggest that the present-day gas content of galaxies is determined by a combination of early evolutionary processes and environmental effects, and that gas-rich galaxies may represent a distinct evolutionary channel rather than the tail of a continuous distribution.

Resumo. Este trabalho investiga os mecanismos físicos responsáveis pela dicotomia atual entre galáxias ricas em gás e galáxias pobres em gás. Utilizando a simulação cosmológica TNG50, construímos uma amostra controlada de galáxias em $z = 0$, com massas estelares semelhantes, para isolar os papéis da evolução interna e do ambiente na formação de seu conteúdo gasoso. As galáxias são classificadas de acordo com sua fração de gás, permitindo uma comparação direta entre sistemas com alta fração de gás (HGFG) e baixa fração de gás (LGFG). Descobrimos que as LGFGs são tipicamente mais massivas, residem em ambientes mais densos e dinamicamente mais quentes e exibem maiores dispersões de velocidade, indicando que processos ambientais como a remoção por pressão dinâmica e interações de maré desempenham um papel importante na depleção de gás. O rastreamento de suas histórias evolutivas revela dois caminhos distintos: as LGFGs experimentam uma fase inicial intensa de formação estelar, seguida por rápido consumo de gás e extinção, enquanto as HGFGs evoluem mais gradualmente, sustentadas pela acreção contínua de gás. Esses resultados sugerem que o conteúdo atual de gás das galáxias é determinado por uma combinação de processos evolutivos iniciais e efeitos ambientais, e que galáxias ricas em gás podem representar um canal evolutivo distinto, em vez da cauda de uma distribuição contínua.

Keywords. galaxies

1. Introduction

The gas content of a galaxy is the fundamental fuel for star formation, governing its ability to grow and evolve. Over cosmic time, this primordial gas reservoir is gradually consumed by star formation and expelled by feedback mechanisms, leading to a population of galaxies in the local Universe ($z \approx 0$) that is predominantly gas-poor. However, a minority of galaxies manage to retain significant gas fractions ($GF = M_{\text{gas}}/M_{\star}$), sometimes in surprisingly isolated environments. A classic example is the dwarf galaxy DDO 154, which boasts a $GF > 30$ despite having no major neighbors within 300 kpc, challenging simple models of gas depletion.

A galaxy's evolution is shaped by both intrinsic processes, such as its stellar mass growth and feedback from supernovae and active galactic nuclei, and by its surrounding environment, where mechanisms like ram-pressure stripping and tidal interactions can remove gas. The central question in galaxy evolution is determining the relative importance of these factors in producing the observed dichotomy between gas-rich, star-forming galaxies and gas-poor, quiescent ones.

In this work, we investigate the physical mechanisms primarily responsible for this division at the present day. We utilize the TNG50 cosmological simulation (Pillepich et al. 2019; Nelson et al. 2019) to overcome the limitations of observational studies. By constructing a controlled sample of gas-rich and gas-poor galaxies matched in key properties, we can effectively isolate the environmental and evolutionary factors that differentiate these two populations and trace their distinct formation histories.

2. Sample Selection and Analysis at $z=0$

The galaxy sample was selected from the TNG50-1 simulation at snapshot 99 ($z = 0$). We began with two parent catalogs of galaxies pre-classified as having either a high gas fraction (HGFG) or a low gas fraction (LGFG). To ensure a robust and physically meaningful comparison, we applied a series of stringent selection criteria to these initial catalogs.

The selection was restricted to galaxies that had $\log_{10}(M_{\star}/M_{\odot}) > 8.0$, were Dark Tide-dominated ($DM > M_{\star} + M_{\text{gas}}$), and were of cosmological origin, i.e., with `SubhaloFlag = 1`.

From this filtered set, a final sample of 368 pairs was constructed using a matching algorithm. For each galaxy in the smaller group (e.g., HGFG), the algorithm finds the best match in the larger group (LGFG) by minimizing the Euclidean distance in a normalized parameter space defined by M_{\star} . This method ensures that for each HGFG, there is a LGFG counterpart with a similar mass.

To understand the fundamental differences between the resulting HGFG and LGFG populations at $z = 0$, we performed a Spearman rank correlation analysis on their key physical properties. The correlation matrix (Figure 1) reveals the monotonic relationships between variables, highlighting underlying physical connections.

To quantify the typical differences, we divided the sample into gas-rich (HGFG, defined as $GF \geq 1$) and gas-poor (LGFG, $GF < 1$) groups and calculated the median value for several key

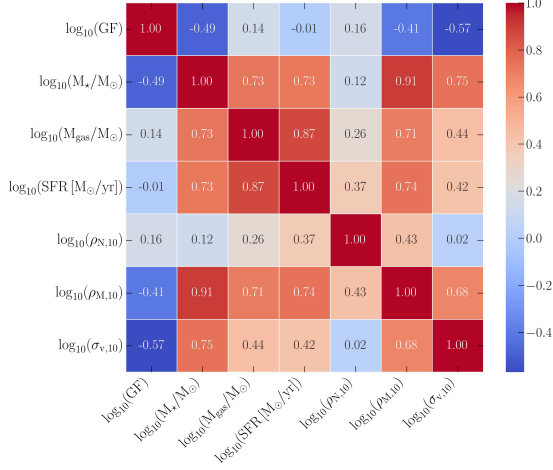


FIGURE 1. Spearman correlation matrix for the full matched sample at $z = 0$. Red colors indicate a positive correlation (as one variable increases, the other tends to increase), while blue indicates a negative correlation. The analysis includes galaxies with $\text{SFR} > 0$.

TABLE 1. Comparison of Median Values for HGFG and LGFG populations.

Property	HGFG ($\text{GF} \geq 1$)	LGFG ($\text{GF} < 1$)
Stellar Mass [M_\odot]	3.3×10^9	1.2×10^{10}
Gas Mass [M_\odot]	2.3×10^9	1.8×10^9
SFR [M_\odot/yr]	0.53	0.79
Mass Density [$\frac{M_\odot}{\text{kpc}^3}$]	4247	14964
Vel. Dispersion [km/s]	140.4	226.5

properties. The results, shown in Table 1, highlight the systematic distinctions between the two populations.

The analysis reveals that the most significant separators between the two groups are environmental and intrinsic mass properties. The LGFG population resides in environments with a 60% higher velocity dispersion and that are 3.5 times denser in mass than their HGFG counterparts. This strongly suggests that environmental processes, such as ram-pressure stripping and tidal interactions prevalent in dynamically "hot" and dense regions, are highly effective at depleting gas reservoirs.

Furthermore, the typical LGFG is 3.6 times more massive in stars than the typical HGFG. This indicates that internal evolutionary processes are also critical; more massive galaxies have converted a larger fraction of their initial gas budget into stars over cosmic time. In contrast, the current Star Formation Rate (SFR) is not a reliable separator, as the larger LGFGs still form stars at a comparable, or even slightly higher, rate.

The distributions of the two populations are distinct in both mass and environment, as can be seen in the Figure 2. The distribution of LGFGs is shifted toward higher values of environmental mass density ($\rho_{M,10}$), stellar mass (M_\star), and stellar mass environmental velocity dispersion (σ_v) when compared to the HGFG population, reinforcing the idea that both internal evolution and external environmental factors are the main drivers in the formation of the gaseous content of galaxies.

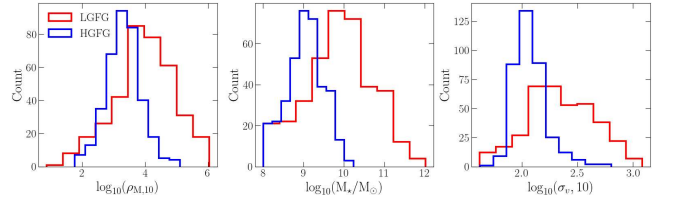


FIGURE 2. Comparison of the Low Gas Fraction (LGFG, red lines) and High Gas Fraction (HGFG, blue lines) galaxy populations. The panels show the distributions of environmental mass density (left), stellar mass (center), and velocity dispersion (right).

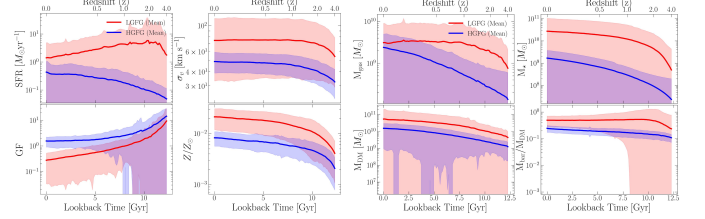


FIGURE 3. Left: Evolution of key physical properties (SFR, σ_v , Gas Fraction, and Metallicity). LGFGs (red) show early peaks in SFR and rapid chemical enrichment, while HGFGs (blue) exhibit a more gradual and sustained evolution. Right: Evolution of mass components. LGFGs accumulate stellar mass more rapidly at early times. While the dark matter halos were matched at $z = 0$, their evolutionary paths remain statistically indistinguishable over cosmic time.

3. Comparative Evolutionary History

We performed an analysis of the evolutionary tracks for the sample of 368 HGFG and 368 LGFG. Although they are equivalent in total mass and environment at $z = 0$, their histories are fundamentally different, supporting a "two-path" framework for galaxy evolution.

Low-Gas-Fraction Galaxies (LGFG): A "Violent and Inefficient" Path. LGFGs follow a history marked by early and intense activity. They experience a strong peak in star formation at high redshift ($z > 1$), leading to rapid gas consumption and early chemical enrichment. This "bursty" phase dynamically heats the system, resulting in consistently higher velocity dispersions (σ_v). Their evolution is dominated by powerful feedback cycles that, despite efficiently converting gas into stars, ultimately expel the gas reservoir, leading to quenching and the low gas fractions observed today.

High-Gas-Fraction Galaxies (HGFG): A "Steady and Efficient" Path. In contrast, HGFGs exhibit a smoother and more prolonged evolutionary history. Their star formation rate is more sustained, growing steadily over cosmic time without a prominent early peak. This gentle buildup is supported by continuous cosmological gas accretion that effectively replenishes the fuel for star formation. As a result, they enrich chemically more gradually and remain dynamically colder (lower σ_v), preserving their large gas reservoirs and positioning them for continued growth.

4. Conclusions

- The primary distinction between HGFG and LGFG galaxies at $z = 0$ is driven by a combination of intrinsic mass and local environment. LGFGs are typically 3.6 times more massive in stars and reside in environments that are 3.5 times denser and dynamically hotter (σ_v , 60% higher).

- The two populations follow fundamentally different evolutionary histories. LGFGs undergo an early, intense phase of star formation (a "violent path"), leading to rapid gas depletion and quenching. In contrast, HGFGs evolve more gradually (a "steady path"), sustained by continuous gas accretion that preserves their fuel reservoir over cosmic time.
- At present day, LGFGs are characterized by high Star Formation Efficiency (SFE) but low specific Star Formation Rate (sSFR), typical of quenching systems efficiently consuming their last fuel. HGFGs show the opposite trend (low SFE, high sSFR), indicating a state of sustained, ongoing growth.
- While the TNG simulations provide a powerful framework for this analysis, it is noteworthy that they tend to overestimate the gas fractions of local universe galaxies by a factor of 2–3 compared to observations Diemer et al. (2019). This suggests that the physical mechanisms responsible for gas depletion may be even more pronounced in reality than modeled in the simulation.

That galaxies with high GF values exist and that their evolutionary paths are different is undeniable. What is questionable is whether they represent a different group from others or if they are simply parts of a general distribution. For this assertion to be true, we need an independent parameter that isolates HGFGs.

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