

Is Milky Way stable all the way ? A TNG50 view from cosmic noon to the present day

K. ADITYA ¹ AND SANDEEP KATARIA ²

¹*Raman Research Institute, C. V. Raman Avenue, 5th Cross Road, Sadashivanagar, Bengaluru, 560080, India*

²*Space, Planetary & Astronomical Sciences & Engineering (SPASE), IIT Kanpur, 208016, India*

ABSTRACT

We investigate the stability of Milky Way analogs (MWAs) in the TNG50 simulation against the growth of local axisymmetric instabilities, tracing their evolution from cosmic noon ($z = 2.5$) to the present day ($z = 0$). Using a two-component stability criterion that accounts for stars, gas, and the force field of the dark matter halo, we compute the net stability parameter (Q_T), the critical gas surface density (Σ_c), and the instability timescale (τ) for 10 barred and 10 unbarred MWAs. We find that these galaxies remain stable to axisymmetric instabilities at all epochs, with $Q_T^{\min} > 2$. The stability levels increase toward higher redshift, where enhanced gas velocity dispersion counterbalances the destabilizing effect of larger gas fractions. Further, the barred MWAs consistently show lower $Q_T^{\min}$ than unbarred ones. The gas density remains subcritical ($\Sigma_g < \Sigma_c$) across radii and epochs, implying that local axisymmetric instabilities are not the primary channel for star formation. Growth timescales are short (a few Myr) in central regions but increase exponentially to several Gyr in the outer disc, naturally explaining the concentration of star formation toward galactic centers. We study the effect of gas dissipation and turbulence in ISM and find that while MWAs are stable against axisymmetric instabilities ($Q_T > 1$), a combination of gas dissipation and turbulence in ISM can destabilize the disc at small scales even when $Q_T > 1$.

Keywords: Galaxies (573) — Galaxy dynamics (591) — Galaxy kinematics (602) — Gravitational instability (668) — Milky Way Galaxy (1054) — Galaxy bars (2364) — Hydrodynamical simulations (767)

1. INTRODUCTION

Local gravitational instabilities play a central role in various galaxy formation and evolution processes, and have been investigated since the pioneering works of V. Safronov (1960); A. Toomre (1964); P. Goldreich & D. Lynden-Bell (1965). The theoretical models of disc instabilities allow us to quantify the dynamical state of the system through a single number often called *disc instability criterion* first proposed for a self-gravitating disc of stars by A. Toomre (1964). This criterion over the years has been developed and modified to describe self-consistently the dynamical and structural information available from observations, for eg: stability of disc of stars (A. Toomre 1964), stability of gas disc P. Goldreich & D. Lynden-Bell (1965), gas + stellar disc (C. Jog & P. Solomon 1984; C. J. Jog 1996; A. B. Romeo & J. Wiegert 2011), multiple self-gravitating disc components (R. R. Rafikov 2001; A. B. Romeo & N. Falstad 2013), effect of dark matter (C. J. Jog 2014; K. Aditya 2024), effect of disc thickness (S. E. Meidt et al. 2022; C. Nipoti et al. 2024) and effect of turbulence (V. Hoff-

mann & A. B. Romeo 2012; M. Shadmehri & F. Khajenabi 2012). Thus, the current theoretical models of local gravitational instabilities encapsulate the complete mass inventory of the galaxy, multiple stellar and gas components, and their dark matter halo, and kinematic information through each component’s velocity dispersions and rotation velocity.

The theory of local instabilities is closely connected to the observed star formation; since the instabilities drive the fragmentation of the gas disc into gas clumps, which eventually form stars R. C. Kennicutt Jr (1989); B. Wang & J. Silk (1994); F. Bournaud et al. (2007); O. Agertz et al. (2009); A. Dekel et al. (2009); M. R. Krumholz et al. (2018), with more stable discs exhibiting a lower star formation rate K. Aditya (2023). The stability criterion also explains the morphological differences in the nearby galaxies, with irregular galaxies exhibiting higher stability levels than the spirals (K. Aditya 2023). Similarly, low surface brightness galaxies and superthin galaxies (K. Aditya & A. Banerjee 2021; K. Aditya et al. 2022) show an overall higher net stability level than nearby disc galaxies. Recent high-resolution multi-wavelength observations are beginning to probe how instabilities regulate structure on smaller,

sub-galactic scales. For example, studies based on galaxies from the PHANGS (Physics at High Angular Resolution in Nearby Galaxies) survey (E. Schinnerer et al. 2019) show that the multi-scale filamentary structure observed in their gas discs aligns with the critical length scale predicted by turbulent Jeans instabilities (S. E. Meidt et al. 2023).

At higher redshift, observational studies have shown that galaxies are prone to local gravitational instabilities (R. Genzel et al. 2017; F. Walter et al. 2022; F. Rizzo et al. 2020; K. Aditya 2023; C. Bacchini et al. 2024). Recent James Webb Space Telescope observations have revealed that disc galaxies were already assembling in the early universe, within the first few billion years after the Big Bang (R. J. Smethurst et al. 2025; S. Gillman et al. 2024). Although the galaxies observed in the early universe were precursors to the galaxies in the local universe, it is not straightforward to make a one-to-one mapping of the nearby galaxies and their progenitors observed in the early universe. Large cosmological simulations, such as TNG50 (D. Nelson et al. 2019), provide us with an opportunity to make a one-to-one connection between galaxies observed in the local universe and their high-redshift progenitors, enabling us to study their continuous evolution. In the present study, we use a sample of Milky Way Analogs (MWAs) (A. Pillepich et al. 2024) from the TNG50 suite of simulations to answer the following questions describing the dynamical state of the galaxy at different stages of its evolution from cosmic noon to the present day.

1. How do stability levels change across the galaxy, and are stability levels driven by stars or by gas?
2. How does the critical gas surface density vary spatially, and how does it relate to the actual gas surface density?
3. How does the timescale for the growth of instabilities vary across the galaxy?
4. How is star formation distributed across the galaxy disc?

We will present our sample of MW analogs from TNG50 simulations in §2 and the dynamical model of disc instabilities in §3. We will present the results from our work in §4, discuss the implications of our results in §5, and summarize our results in §6.

2. MILKY WAY ANALOGS FROM TNG50 SIMULATIONS

We select our sample from the TNG50 suite of simulations. The TNG50 suite of simulations has the smallest volume but offers the highest resolution. It evolves a $(50 \text{ Mpc})^3$ comoving volume, sampled with 2160^3 dark matter particles and 2160^3 initial gas cells (D. Nelson

et al. 2019; A. Pillepich et al. 2019), achieving a baryonic mass resolution of $\sim 8.5 \times 10^4 M_\odot$ and a dark matter particle mass resolution of $\sim 4.5 \times 10^5 M_\odot$. TNG50 employs the moving-mesh code AREPO (R. Weinberger et al. 2020) and incorporates the IllustrisTNG galaxy formation model, as described in detail by A. Pillepich et al. (2018) and R. Weinberger et al. (2018). The simulation solves the coupled equations of gravity and magnetohydrodynamics in an expanding Universe, while also modeling key baryonic processes such as radiative cooling and heating, star formation, stellar evolution, and chemical enrichment, as well as feedback from stars and supermassive black holes (SMBHs), including their seeding and growth. The gas in the TNG simulations is modeled with subgrid physics of multiphase ISM having cold (dense clouds where stars form) and hot (diffuse gas heated by supernova) gas components (V. Springel & L. Hernquist 2003). The threshold criteria for star formation are reached when the density of gas (n_H) $\geq 0.13 \text{ cm}^{-3}$. The model is tuned to produce the Kennicutt-Schmidt relation (R. C. Kennicutt Jr 1998) and controls the star formation rate accordingly. The initial conditions were set at redshift $z = 127$, assuming a cosmology consistent with the Planck 2015 results (P. Planck 2016). The stellar particles in TNG50 simulations represent simple mono-age stellar populations, characterized by an initial mass function (IMF) following G. Chabrier (2003). TNG50 is particularly well-suited for studying disc instabilities due to its high mass and spatial resolution (D. Nelson et al. 2019; A. Pillepich et al. 2019). At $z = 0$, the smallest gas cells reach sizes as small as 9 pc, while typical gas cells in star-forming regions of massive galaxies range from 50–200 pc. The gravitational potential is softened on resolution-element-dependent scales: stellar and dark matter particles have a softening length of 288 pc, and gas cells down to 72 pc. These resolutions are sufficient to robustly derive key quantities such as stellar and gas surface density profiles, velocity dispersion profiles, and the total gravitational potential. These are crucial ingredients for computing the local stability of disc galaxies against axisymmetric instabilities. We select our sample from the TNG50 Milky Way analog catalog (A. Pillepich et al. 2024). The catalog contains 198 Milky Way/M31 analogs, with disk morphologies, stellar masses in the range $M_* = 10^{10.5} - 10^{11.2} M_\odot$, and residing in Milky Way-like Mpc-scale environments at $z = 0$. We select a small representative subset of 10 barred and 10 unbarred MWAs from the parent catalog with similar dynamical masses for our analysis. The division into barred and unbarred galaxies is based on classification provided by Y. Rosas-Guevara et al. (2020, 2022); T. Zana et al. (2022). We select stars and gas by applying a simple geometric cutoff between $-1.5 \text{ kpc} < z < 1.5 \text{ kpc}$ and $R > 1 \text{ kpc}$ at all epochs. The simple geometric cutoff allows us to probe and compare the same spatial region of the galaxy at all epochs. In order to access the local stability of the

galaxies against the growth of gravitational instabilities, we need to measure the surface densities of the stellar and gas discs, radial velocity dispersion of stars and gas, and the circular velocity of stars, gas, and the dark matter halo. We use the publicly available package `pynbody` (A. Pontzen et al. 2013) to compute the radial profiles of the physical parameters. We derive the radial profiles of the input parameter profiles for $R > 1.0 kpc$, in 25 logarithmic bins. We show the face-on projections of stellar and gas distribution of our sample of barred and unbarred galaxies from TNG50 in Figures 1 and 2, respectively.

We show the input parameters for our sample of unbarred and barred galaxies in Figures 3 and 4, respectively, at various redshifts. We find that the asymptotic rotation velocity of the MW analogs decreases from $z = 0$ to $z = 2.5$, indicating that the progenitors of current MWAs did not yet assemble their present-day mass budget at cosmic noon. Both barred and unbarred galaxies have higher radial velocity dispersions at the cosmic noon than today. Also, the radial velocity dispersion of stars is consistently higher than gas at any epoch. However, between the barred and the unbarred samples, the barred galaxies have an overall higher velocity dispersion and asymptotic rotation velocity than the unbarred ones. The stellar surface density starts becoming greater than or comparable to the gas surface density starting from $z > 1$, in the outer radius. Overall, we find that the progenitors of the current MWAs at the cosmic noon have a smaller total mass, typically a higher gas surface density than stars, and a higher radial velocity dispersion than their values at the present epoch.

3. DYNAMICAL MODEL OF LOCAL DISC INSTABILITIES

We define the dynamical state of a galaxy using four quantities;

1. the net local stability of the galaxy (Q_T),
2. critical surface density Σ_c ,
3. time scale for the growth of local instabilities τ
4. star formation rate (SFR).

In this section, we will describe how we compute the first 3 quantities (Q_T , Σ_c , & τ) and we will derive the radial profiles of star formation rates from the precomputed star formation rates provided in TNG50 MWA catalogs. We model the galaxy as a coaxial and coplanar disc of stars and gas interacting gravitationally. Each component is specified by its radial velocity dispersion, surface density, and angular frequency, the combined system is under the influence of the force field of the dark matter halo. The condition for the stability (Q_T) of a gravitationally coupled two-component system in equilibrium

with the dark matter halo is given by (K. Aditya 2024)

$$\frac{2}{1 + Q_T^2} = \frac{(1-f)}{X_{\star-g}(1 + \frac{(1-f)^2 q_\star^2}{4X_{\star-g}^2} + R)} + \frac{f}{X_{\star-g}(1 + \frac{f^2 q_g^2}{4X_{\star-g}^2} + R)}. \quad (1)$$

In the above equation, the parameter R quantifies the stabilizing contribution of the dark matter halo on the two-component star+gas disc and is defined as $R = \frac{\kappa_{DM}^2}{\kappa_{disc}^2}$, where κ_{DM}^2 is the epicyclic frequency squared derived from the gravitational potential of the dark matter halo, and κ_{disc}^2 corresponds to that of the combined baryonic disc composed of stars and gas. The epicyclic frequency κ at a radius R is defined as

$$\kappa^2(R) = \left(R \frac{d\Omega^2(R)}{dR} + 4\Omega^2(R) \right) \quad (2)$$

where Ω is the angular frequency defined as $\Omega^2(R) = \frac{1}{R} \frac{d\Phi}{dR} = \frac{V^2}{R^2}$, Φ and V are the gravitational potential and the circular velocity of each component respectively. We use the circular velocity of each component to derive its respective epicyclic frequency. Also, $q_\star$ and q_g are the classical one-component stability criterion for stars and gas (A. Toomre 1964), defined as $q_\star = \kappa_{disc} \sigma_{R,\star} / \pi G \Sigma_\star$ and $q_g = \kappa_{disc} \sigma_{R,g} / \pi G \Sigma_g$ respectively. The gas fraction is defined as $f = \Sigma_g / (\Sigma_\star + \Sigma_g)$, and $X_{\star-g} = \kappa_{disc}^2 / [2\pi G(\Sigma_\star + \Sigma_g)k_{min}]$. $X_{\star-g}$ is the dimensionless wavelength at which it is hardest to stabilize the two-component system. The value of k_{min} for the two-component system is given by

$$k^3(4\sigma_{R,\star}^2\sigma_{R,g}^2) - 3k^2(2\pi G \Sigma_\star \sigma_{R,g}^2 + 2\pi G \Sigma_g \sigma_{R,\star}^2) + 2k\kappa_{net}^2(\sigma_{R,g}^2 + \sigma_{R,\star}^2) - (2\pi G \Sigma_\star + 2\pi G \Sigma_g)\kappa_{net}^2 = 0, \quad (3)$$

where, $\kappa_{net}^2 = \kappa_{disc}^2 + \kappa_{DM}^2$ and $\kappa_{disc}^2 = \kappa_\star^2 + \kappa_g^2$. We use the values of $\Sigma_\star$, Σ_g , $\sigma_{R,\star}$ and $\sigma_{R,g}$, in conjunction with circular velocities of stars, gas and dark matter to estimate κ of each component and then k_{min} . We then finally proceed to compute $X_{\star-g}$ and then Q_T . For more details, see C. J. Jog (1996); K. Aditya (2024).

D. Lin et al. (1993); B. Wang & J. Silk (1994); S. Boissier et al. (2003); A. Burkert & L. Hartmann (2013) show that the star formation occurs above a gas surface density called the critical gas surface density. The critical gas density is defined as (B. Wang & J. Silk 1994; S. Boissier et al. 2003)

$$\Sigma_c = \gamma \frac{\kappa_{net} \sigma_{R,g}}{\pi G} \text{ and } \gamma = \left(1 + \frac{\Sigma_\star \sigma_{R,g}}{\Sigma_g \sigma_{R,\star}} \right)^{-1}. \quad (4)$$

The time scale for the growth of gravitational instabilities, which measures how quickly the gas is converted into stars, is given by (J. Talbot & W. D. Arnett 1975; A. K. Leroy et al. 2008; T. Wong 2009)

$$\tau = \frac{2\pi}{\frac{\pi G \Sigma_g}{\sigma_{R,g}} \left(1 + \frac{\Sigma_\star \sigma_{R,g}}{\Sigma_g \sigma_{R,\star}} \right)}. \quad (5)$$

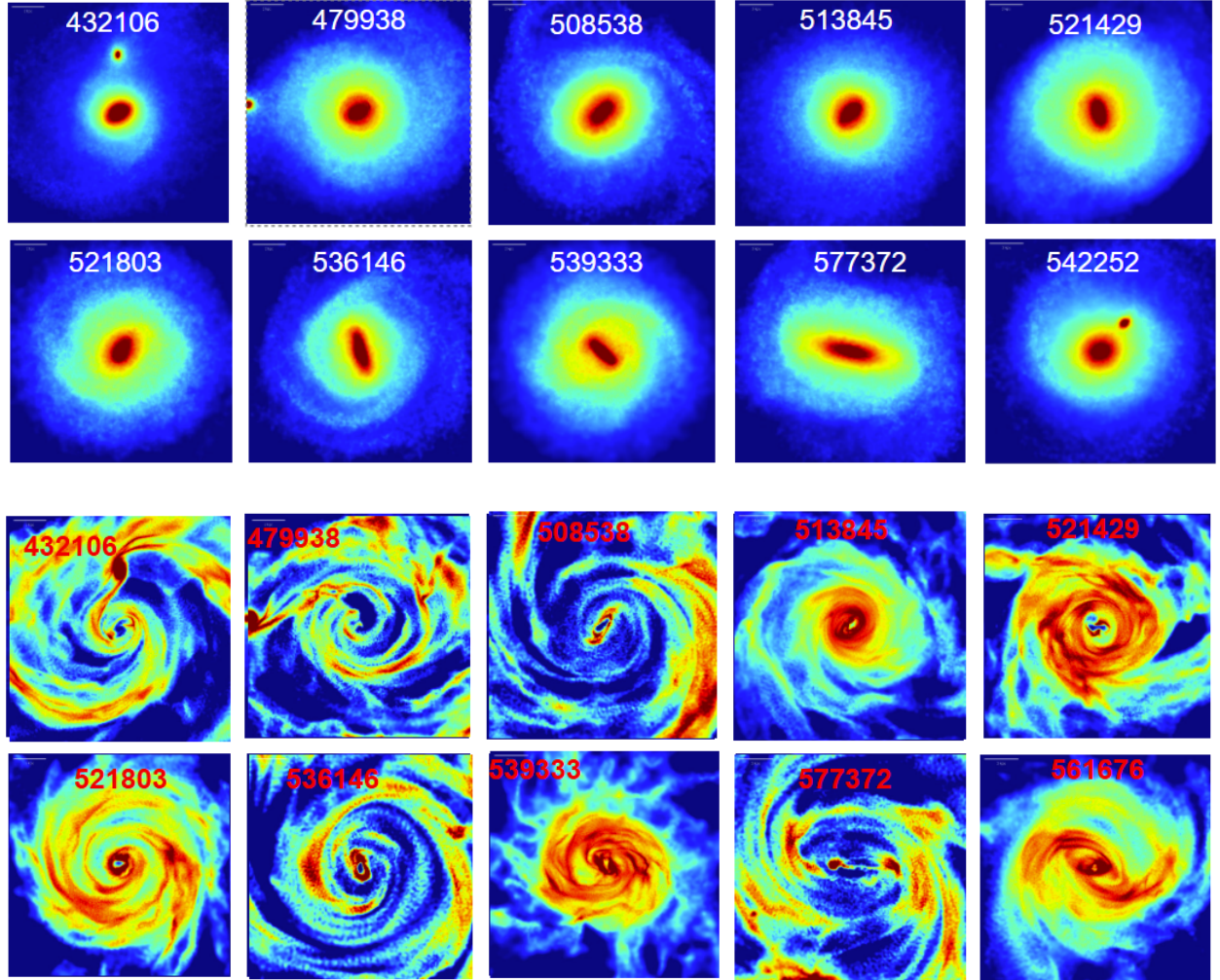


Figure 1. Face-on maps of stellar density [top] and gas density [bottom] for barred galaxies at $z = 0$. The red color corresponds to the highest density, and the blue color corresponds to the lowest density.

4. RESULTS

With all the ingredients and machinery in place for computing the local stability, critical gas density, and time scale for growth of instabilities, we will present how these quantities vary across the MWAs from cosmic noon ($z=2.5$) to the present day ($z=0$).

4.1. How stability varies across the galaxy disc ?

We present the radial profile of the stability parameter (Q_T) against the growth of local axisymmetric instabilities in Figure 5. We divide our sample into two subsets of barred and unbarred galaxies to assess if the presence of a bar has any impact on local stability levels. We observe that the MWAs are dynamically stable against the growth of local axisymmetric instabilities ($Q_T > 2$) from $z = 2.5$ to $z = 0$. The minimum value of Q_T decreases at lower redshifts, approaching $Q_T^{\min} \approx 2$, especially in the case of the barred galaxies. Moreover, between barred and unbarred MW analogs, barred analogs

consistently have a smaller $Q_T^{\min}$ at all epochs. The net stability profiles, represented by Q_T , closely follow those of the gas disc (Q_g) across all redshifts for both barred and unbarred samples, except between $z=0$ and $z=0.5$ in barred galaxies, where the stellar disc dominates the overall stability. The progenitors of Milky Way analogs at $z = 2.5$ have not yet assembled their full mass budget and remain significantly less massive compared to their present-day counterparts. While the gas surface density is higher at this epoch, the resulting destabilizing effect is offset by substantially higher radial velocity dispersions and additional dynamical support from the dark matter halo, which together act to stabilize the MWAs. The stellar disc remains stable throughout the redshift range $z = 0$, as the increase in surface density over time is counteracted by its consistently high velocity dispersion.

4.2. Self-regulation of stability levels

Equation (1) allows us to quantify the effect of the dark matter halo on the net stability of the disc. A value

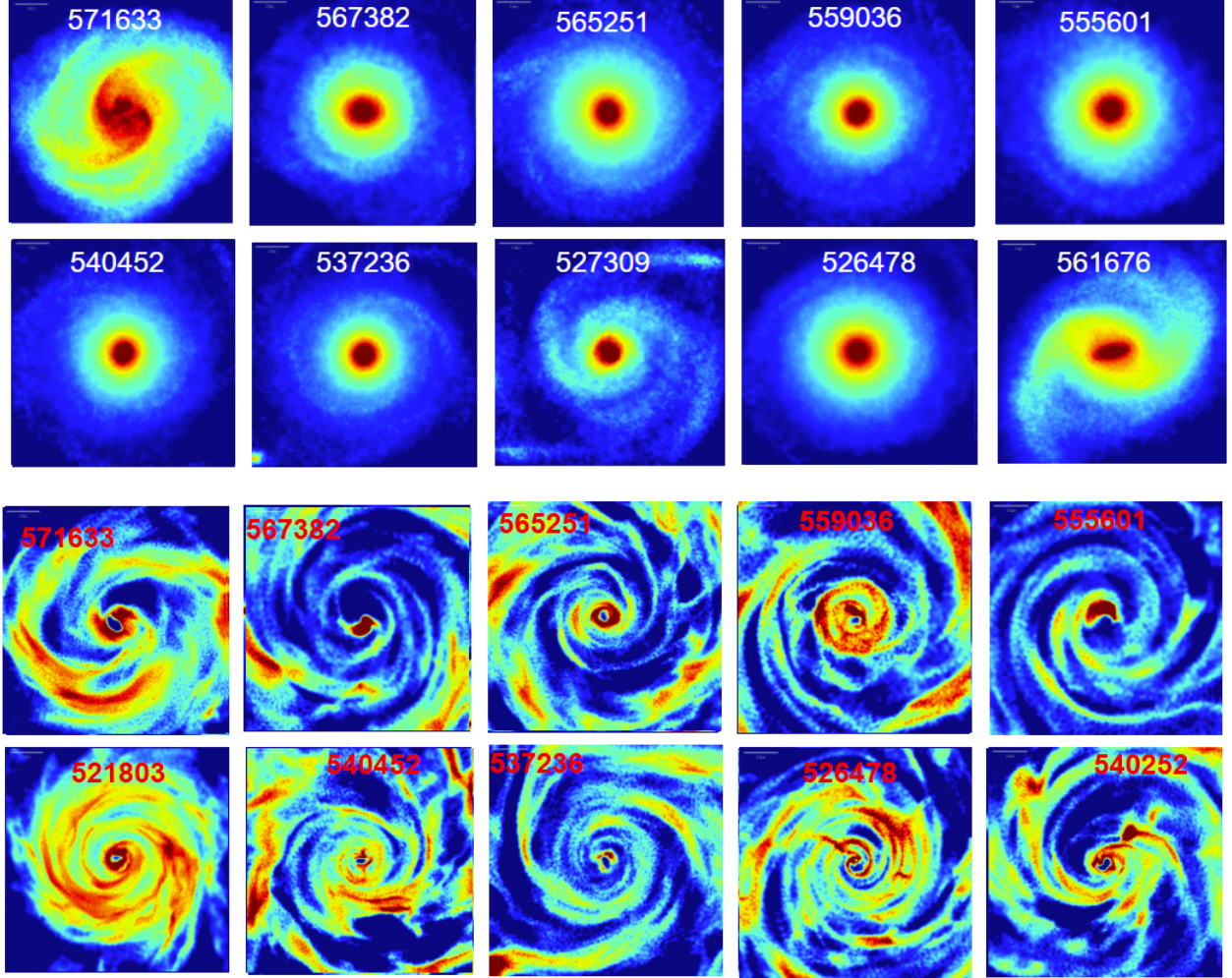


Figure 2. Face-on maps of stellar density [top] and gas density [bottom] for unbarred galaxies at $z=0$. The red color corresponds to the highest density, and the blue corresponds to the lowest density.

of $R=0$ in equation (1) turns off the stabilizing effect of the dark matter halo, and the net stability of the galaxy is simply due to the combined self-gravity of stars and gas only. From Figure 5, we can see that the *stellar+gas* disc remains stable $Q_T > 1$ even after excluding the dark matter’s contribution at all epochs. This indicates that surface densities and the velocity dispersion of stars and gas self-regulate themselves such that the galaxy is stabilized against axisymmetric instabilities even without the contribution of the dark matter halo. These results emphasize that the stellar and gas components can self-regulate the overall stability levels starting from $z=2.5$. The self-regulation is observed in both the barred and unbarred galaxies. Self-regulation of gravitational instabilities has been verified extensively for local galaxies spanning diverse morphologies, e.g., see A. B. Romeo & N. Falstad (2013); A. B. Romeo & K. M. Mogotsi (2017, 2018); A. B. Romeo et al. (2023); K. Aditya (2023) and for self-regulation of instabilities in hydrodynamical sim-

ulations, see F. Renaud et al. (2021) and T. Ejdetjärn et al. (2022).

4.3. How does the critical gas surface density vary across the galaxy ?

The critical gas surface density, $\Sigma_c(R)$, provides an alternative measure of the net gravitational stability of galactic discs. The disc becomes locally unstable whenever the actual gas surface density, $\Sigma_g(R)$, exceeds this critical threshold. In Figure 6, we present the radial profiles of both $\Sigma_c(R)$ and $\Sigma_g(R)$. It is evident that the galaxies remain sub-critical at all redshifts, i.e. $\Sigma_g(R)$ consistently lies below $\Sigma_c(R)$. This difference is especially pronounced in the outer regions, where the measured gas surface density drops more steeply than the critical threshold. While both Σ_c and Σ_g increase with redshift, the enhanced dynamical support due to an increase in the velocity dispersion ensures that the discs remain stable against local gravitational instabilities. Notably, in barred galaxies, the central values of Σ_g approach Σ_c

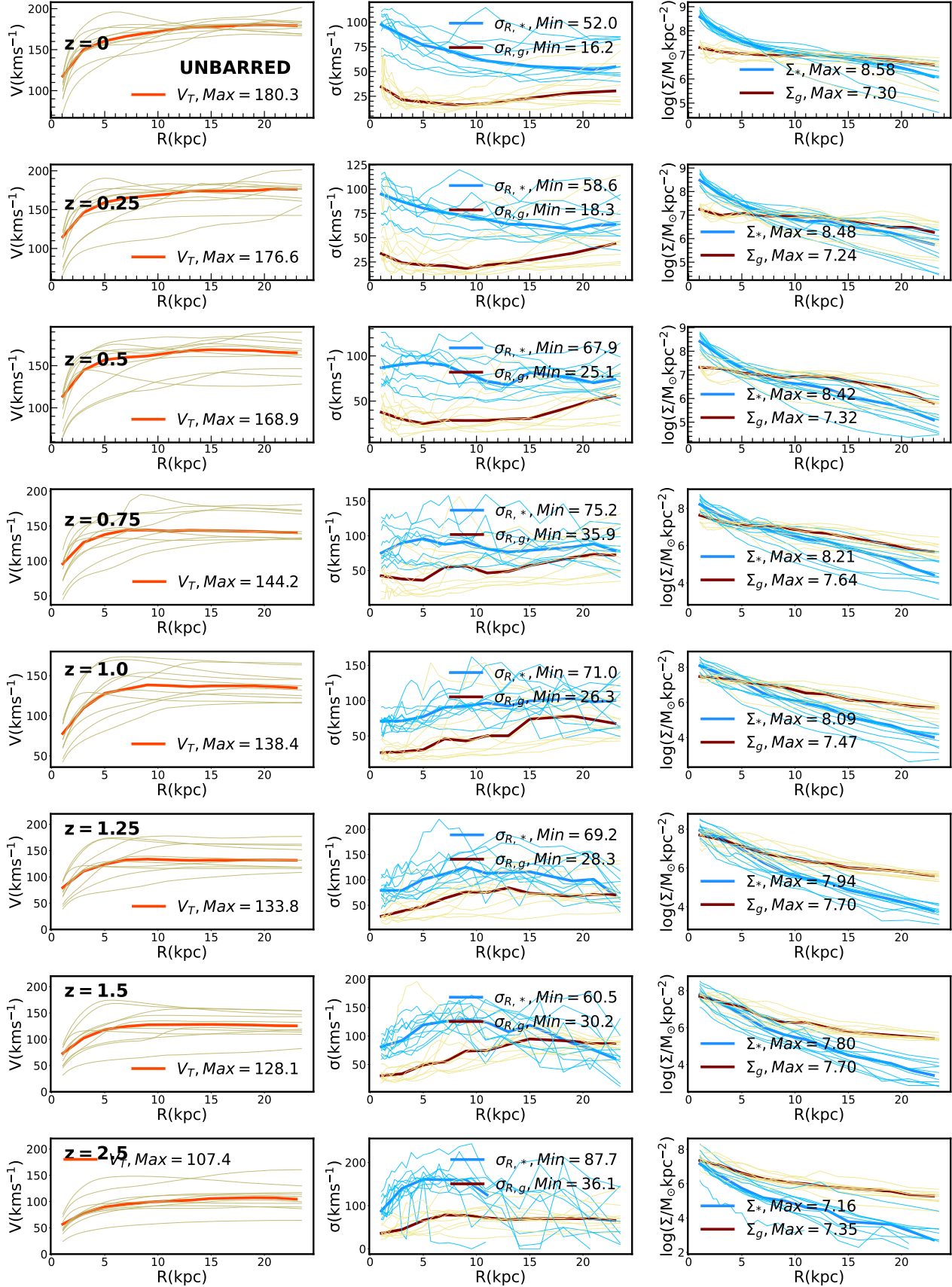


Figure 3. Input parameters used to assess the stability of the unbarred subset of Milky Way analogs against local gravitational instabilities at various redshifts. In the first panel, we show the total circular velocity; in the second and third panels, we show radial velocity dispersion and surface density of stars and gas, respectively. The thick solid line shows the median profile of each parameter, while the thin lines represent individual subhalos.

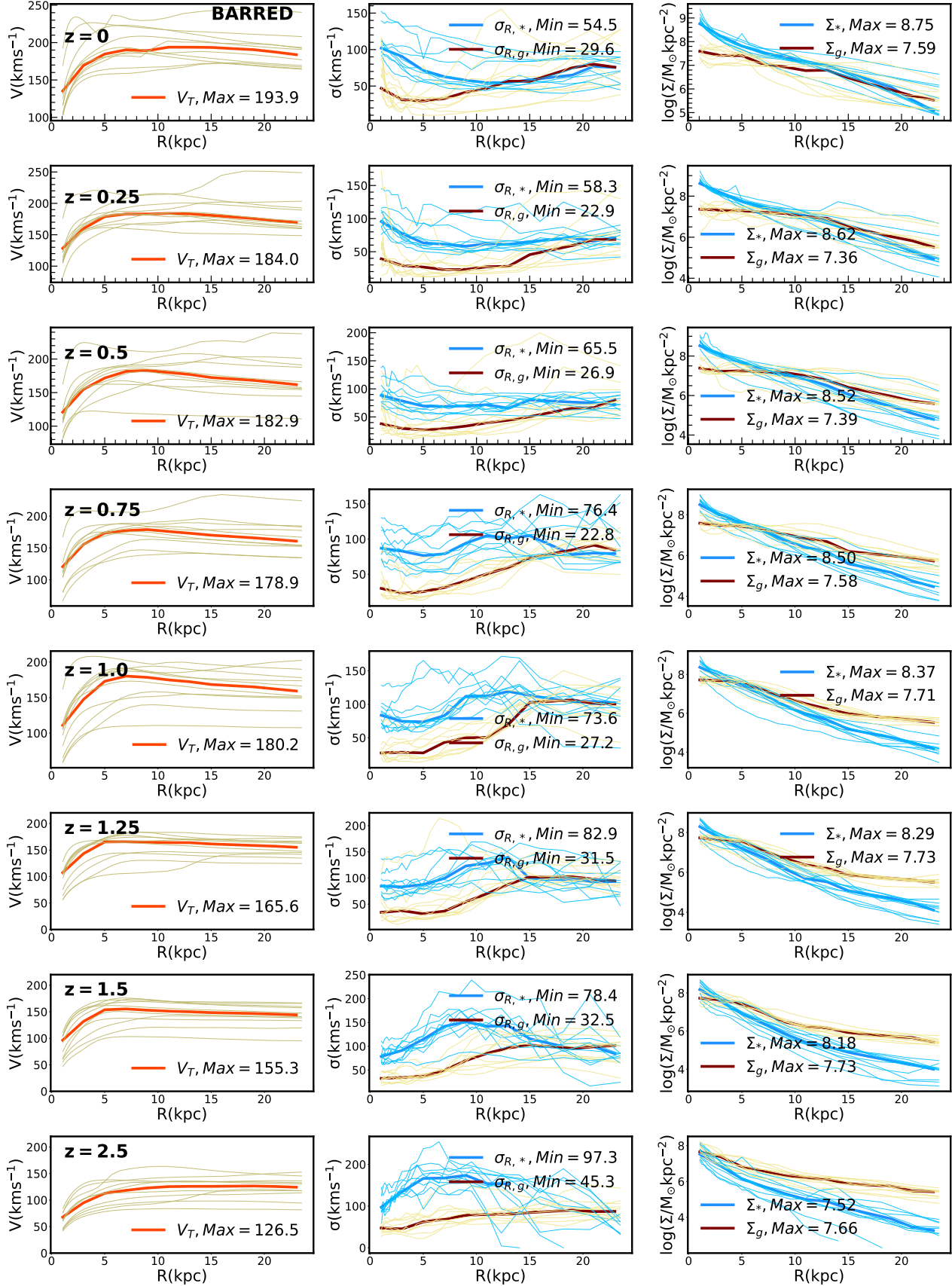


Figure 4. Input parameters used to assess the stability of the barred subset of Milky Way analogs against local gravitational instabilities at various redshifts. In the first panel, we show the total circular velocity; in the second and third panels, we show the radial velocity dispersion and the surface density of stars and gas, respectively. The thick solid line shows the median profile of each parameter, while the thin lines represent individual subhalos.

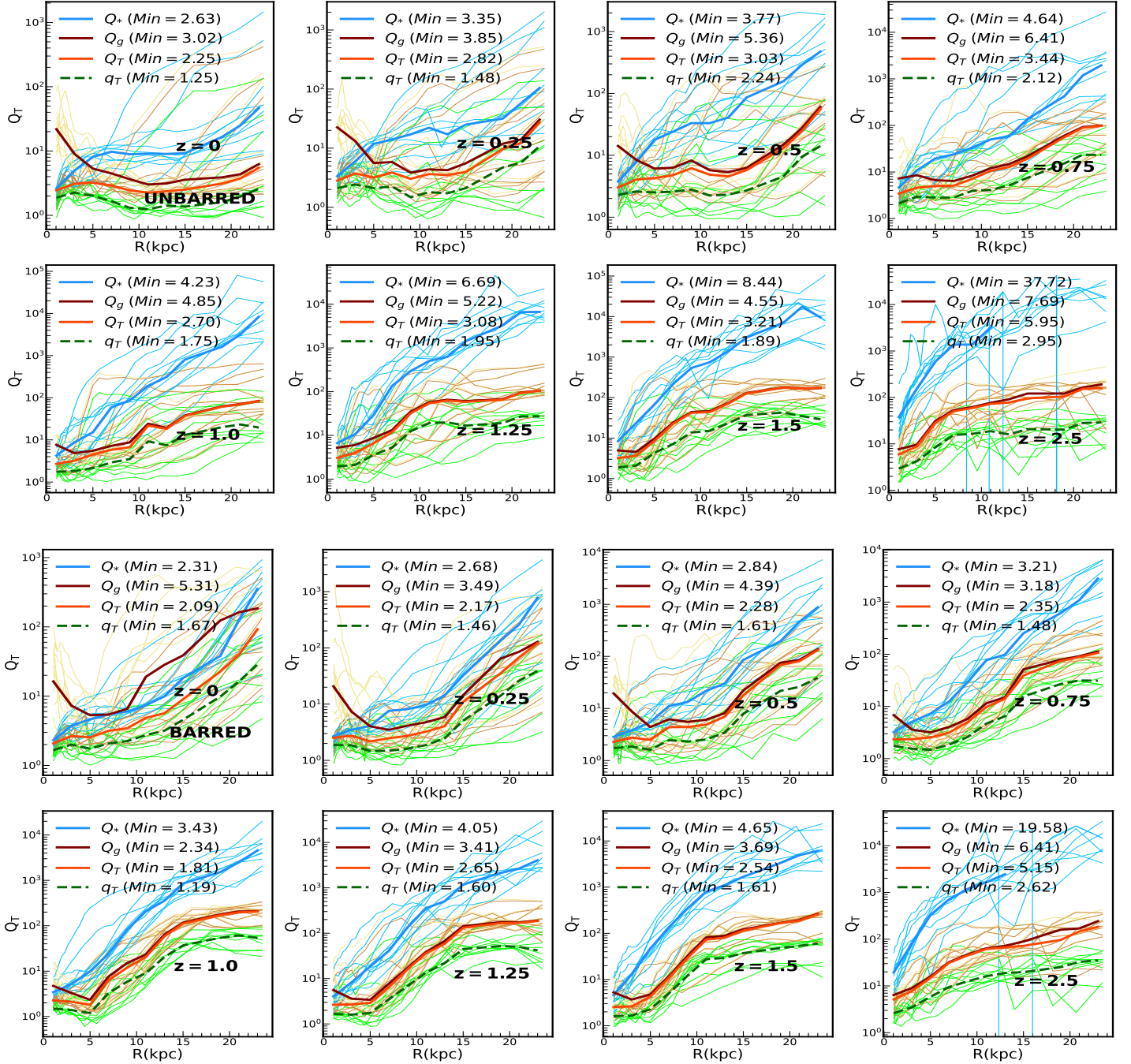


Figure 5. We show the radial variation net stability levels of the galaxy (Q_T), and the stability of just stars (Q_*) and gas (Q_g) across the disc of MWAs. The green curve depicts the stability of galaxies by excluding the stabilizing effect of the DM halo. In the top two rows, we show our results for unbarred MW analogs; in the bottom two panels, we show the results for the barred subsets.

more closely than in unbarred systems, consistent with the relatively lower values of Q_T^{min} in the barred MWAs.

4.4. How does the timescale for the growth of instabilities vary across galaxy?

In Figure 7, we show the radial variation of the timescale for growth of instabilities, $\tau(R)$, for Milky Way analogs across a range of redshifts. We find that τ increases systematically with galactocentric radius, with consistently smaller values in the inner regions and at all epochs, for both barred and unbarred samples. This indicates that local gravitational instabilities can convert gas into stars on timescales of a few Myr in the center. In contrast, star formation via instability-driven collapse can require several Gyr in the outer disc. As redshift increases, the central values of τ also increase, reflecting the higher velocity dispersions at earlier times, which suppress the rapid growth of instabilities. Between barred and unbarred, barred galaxies exhibit systematically lower values of τ at all redshifts relative to unbarred systems. Moreover, barred galaxies show a steeper exponential increase in $\tau(R)$, implying that instabilities are strongly confined to the inner few kpc.

4.5. How is star formation distributed across the galaxy?

We show the radial SFR profiles measured directly from the TNG50 snapshots in Figure 8. The SFR profile peaks in the central region and declines exponentially towards the outskirts. Unbarred galaxies exhibit central SFRs of $\sim 0.15\text{--}0.28 M_\odot \text{yr}^{-1}$ at $z \leq 1.25$, which then fall to $\sim 0.02\text{--}0.05 M_\odot \text{yr}^{-1}$ by $z = 2.5$. On the other hand barred galaxies maintain higher central SFRs, ranging from $\sim 0.43 M_\odot \text{yr}^{-1}$ at $z = 0$ up to ~ 0.59 at $z = 1.0$, then declining to ~ 0.17 by $z = 2.5$. The radial distribution of SFR remains uniform in the unbarred MWAs at $z = 0$ and $z = 0.25$, but becomes steeper as we move to higher z . However, between barred and unbarred MWAs, barred ones consistently have more centrally concentrated star formation and are characterized by steeper slopes. The centrally concentrated SFR in barred MWAs is consistent with the smaller Q_T and steep critical density and instability time scales observed in these galaxies. We also observe that the peak star formation does not consistently trend along the redshift.

4.6. Instabilities hiding in plain sight

In the preceding sections, we observe that the galaxies in TNG50 are stable against the growth of local gravitational axisymmetric instabilities at all radii and epochs. However, studies by A. B. Romeo et al. (2010); V. Hoffmann & A. B. Romeo (2012); B. G. Elmegreen (2011); F. Renaud et al. (2018) show that disc galaxies become susceptible to instabilities even when $Q_T > 1$, through gas dissipation and turbulence in ISM at much smaller scales. B. G. Elmegreen (2011), show that the gas dissipation modifies the pressure term in the gas disc $\sigma_g^2 k^2$ by

a factor of $\omega/(\omega + \delta\sigma_g k)$, where δ^{-1} is the time scale for dissipation as a fraction of crossing time. E.g. $\delta = 0.5$, mean 2 crossing times. The stability function, including the gas dissipation (B. G. Elmegreen 2011), is given by

$$F_\delta(k, \omega) = \frac{2\pi G \Sigma_g k}{\kappa_{net}^2 + \omega^2 + k^2 \sigma_R^2 g^2 \left(\frac{\omega}{\omega + \delta k \sigma_{R,g}} \right)} + \frac{2\pi G \Sigma_\star k}{\kappa_{net}^2 + \omega^2 + k^2 \sigma_{R,\star}^2}. \quad (6)$$

The above equation assumes that the disc is razor thin and uses the two-fluid approximation à la C. Jog & P. Solomon (1984); C. J. Jog (1996). The two-fluid stability function (C. Jog & P. Solomon 1984; C. J. Jog 1996; K. Aditya 2024) is obtained by setting $\delta = 0$ and then $\omega = 0$

$$F_{2f}(k) = \frac{2\pi G \Sigma_g k}{\kappa_{net}^2 + k^2 \sigma_{R,g}^2} + \frac{2\pi G \Sigma_\star k}{\kappa_{net}^2 + k^2 \sigma_{R,s}^2}. \quad (7)$$

The effect of gas dissipation can be readily understood by comparing the $F_\delta(k)$ and $F_{2f}(k)$, at their marginal stability ($\omega = 0$). The stability function $F_\delta(k)$ at $\omega = 0$ is just

$$F_\delta(k) = \frac{2\pi G \Sigma_g k}{\kappa_{net}^2} + \frac{2\pi G \Sigma_\star k}{\kappa_{net}^2 + \omega^2 + k^2 \sigma_{R,\star}^2}. \quad (8)$$

At $\omega = 0$, the two-fluid disc loses its pressure support from the gas because of dissipation, and the stabilization of the gas component is only by rotation. In other words, gas dissipation removes the pressure contribution in the denominator, so the destabilizing self-gravity terms in the numerator acquires a larger weight. Specifically, since

$$\frac{2\pi G \Sigma_g k}{\kappa_{net}^2} > \frac{2\pi G \Sigma_\star k}{\kappa_{net}^2 + k^2 \sigma_{R,\star}^2},$$

$$F_\delta(k) > F_{2f}(k).$$

Thus, when gas pressure support is lost through dissipation, the enhanced self-gravity makes the disc unstable.

In a different scenario, A. B. Romeo et al. (2010); V. Hoffmann & A. B. Romeo (2012) showed that a galaxy can become unstable if the surface density and the velocity dispersion of the gas component are scale dependent even when the galaxy is stable against axisymmetric instabilities. A. B. Romeo et al. (2010); V. Hoffmann & A. B. Romeo (2012) phenomenologically model the turbulence in the ISM using the Larson type scaling relation given by

$$\Sigma'_g = \Sigma_g \left(\frac{k}{k_0} \right)^{-a} \quad \& \quad \sigma'_g = \sigma_{R,g} \left(\frac{k}{k_0} \right)^{-b},$$

and show that the galaxy is unstable for $b > (a + 1)/2$ and $-2 < a < 1$, even when $Q_T > 1$. The stability function incorporating turbulent ISM can be written as

$$F_{turb}(k) = \frac{2\pi G \Sigma_g k^{1-a} k_0^a}{\kappa_{net}^2 + \sigma_{R,g}^2 k^{2-2b} k_0^{2b}} + \frac{2\pi G \Sigma_\star k}{\kappa_{net}^2 + k^2 \sigma_{R,\star}^2}. \quad (9)$$

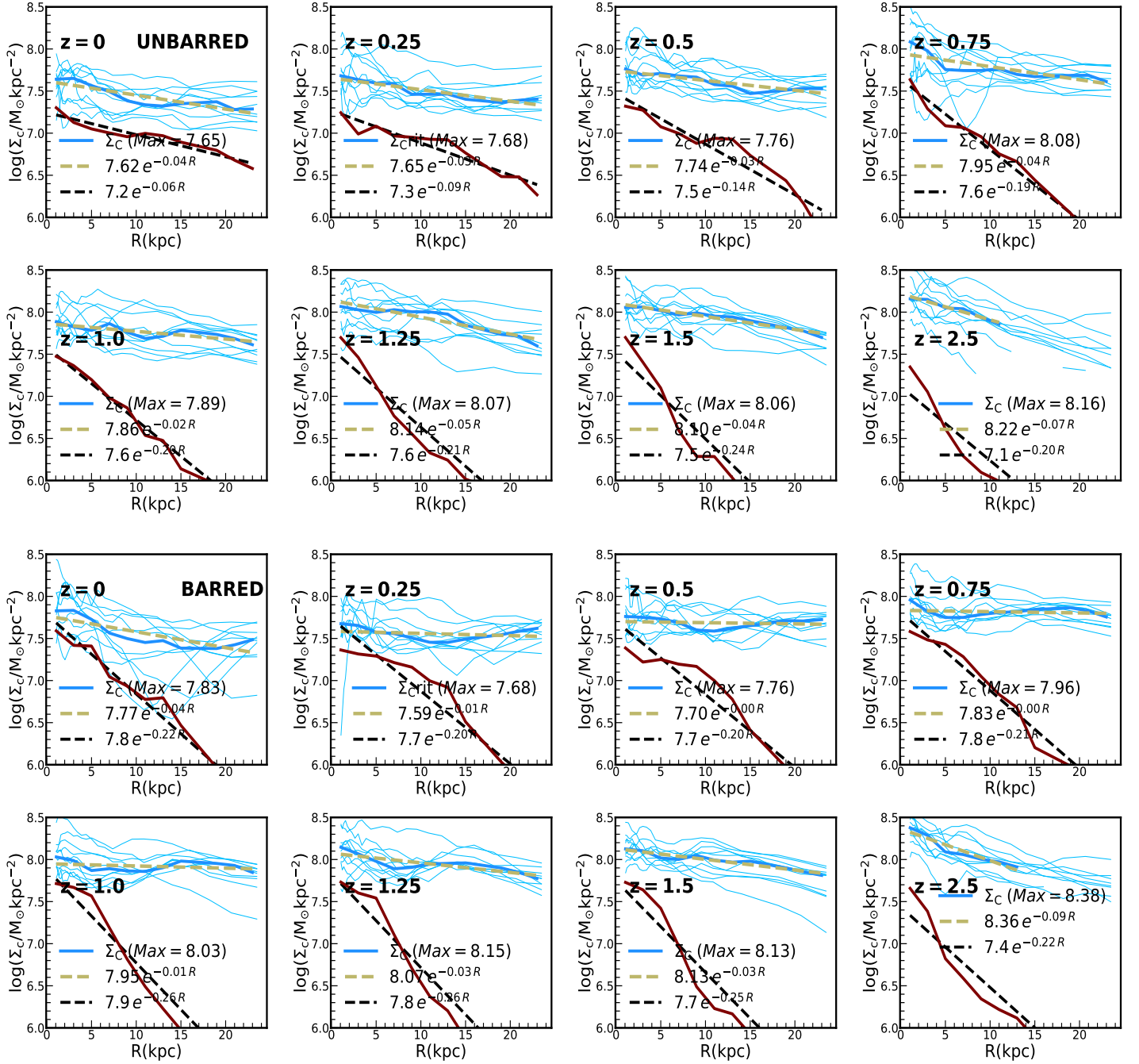


Figure 6. We show the radial variation of critical gas density (Σ_c) of MW analogs (blue), and the measured gas surface density (crimson). The dashed lines indicate exponential fits to the critical and the measured gas density. In the top two rows, we show our results for unbarred MW analogs; in the bottom two panels, we show the results for the barred subsets.

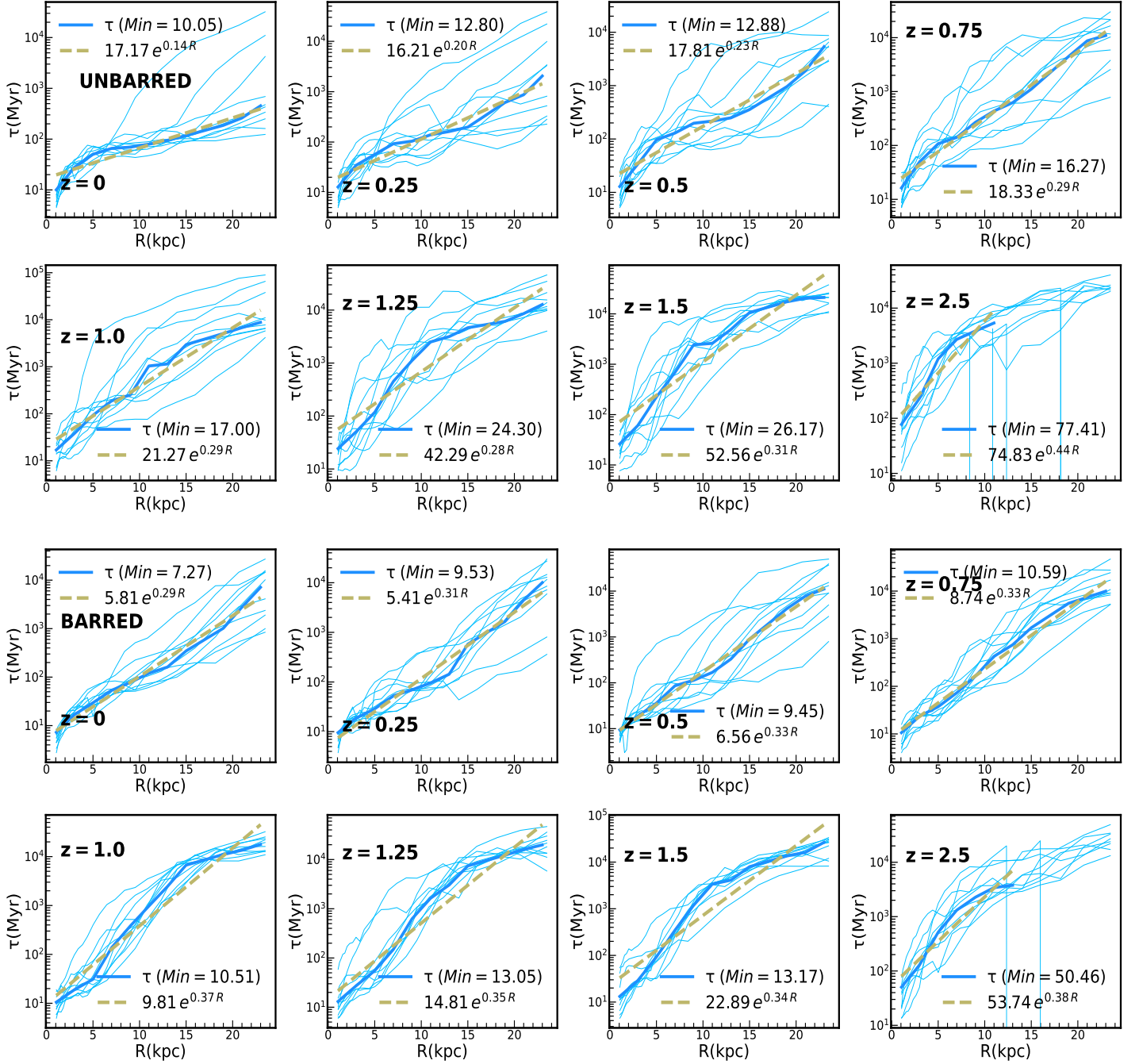


Figure 7. We show the radial variation of time scale for growth of local gravitational instability τ of MW analogs (blue). The dashed lines indicate exponential fits to τ . In the top two rows we show our results for unbarred MW analogs, and in the bottom two panels, we show the results for the barred subsets.

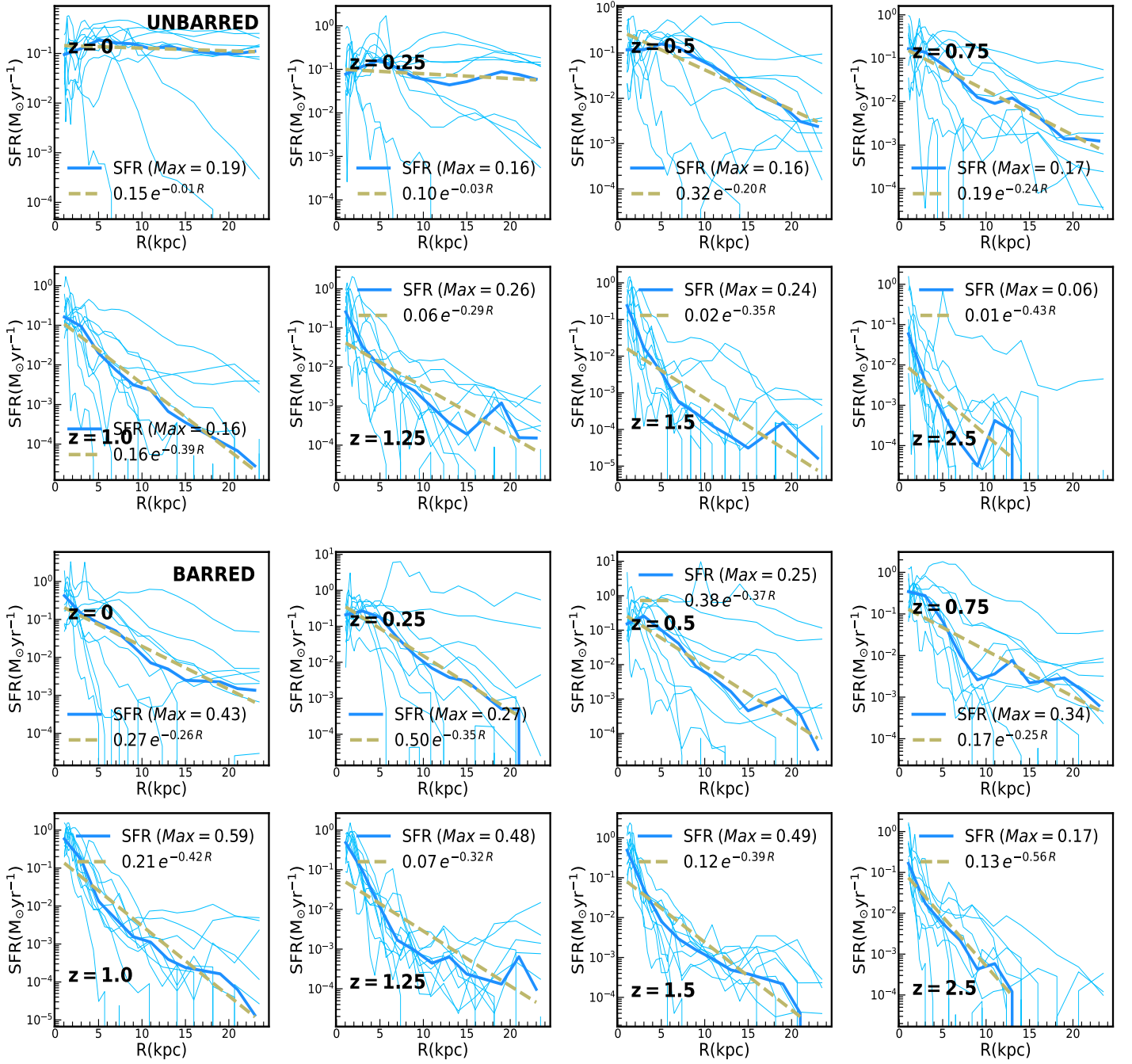


Figure 8. We show the radial variation of star formation rates (SFR) for MWAs (blue). The dashed lines indicate exponential fits to SFR. In the top two rows, we show SFR for unbarred MWAs; in the bottom two panels, we show the SFR for the barred subsets.

As an example, for $a = -1$ and $b = 1$, the self-gravity term in the numerator scales as $\sim k^2$ (instead of $\sim k$ in the standard F_{2f}), indicating that the turbulence in the ISM can drive local disc instabilities even when the $Q_T > 1$. We show the stability functions $F_{2f}(k)$, $F_\delta(k)$, and $F_{turb}(k)$ for our sample of MWAs in Figure 9 to illustrate the impact of gas dissipation and turbulence in the ISM. The functions are plotted at marginal stability, i.e., $\omega = 0$. For the scale-dependent case of $F_{turb}(k)$, we focus on the special choice $a = -1$ and $b = 1$, where the contribution from self-gravity scales as $\sim k^2$, in contrast to the $\sim k^1$ dependence in $F_{2f}(k)$ and $F_\delta(k)$. We derive the stability functions shown in Figure 9 using the input parameters that yield the minimum value of Q_T . Figure 9 shows that the stability functions have similar behavior at small k or large scale but diverge from each other at small scales. Consistent with the discussion in the preceding paragraphs, we can see that $F_\delta(k)$ is higher than $F_{2f}(k)$, since the energy in the gas component has completely dissipated and the gas component is now supported only through rotation, compared to rotation + dispersion support for the gas component in the two-fluid case. So, the self-gravity now has to counteract only the rotation to destabilize the galaxy. So at all epochs, the gas dissipation can effectively destabilize the disc at smaller scales, even when the disc is stable against axisymmetric instabilities. In the second scenario, we plot the stability function corresponding to the turbulent ISM with $a = -1$ and $b = 1$, and use $k_0 = 1 \text{ kpc}^{-1}$. We can clearly see that F_{turb} for $a = -1$ and $b = 1$ can destabilize the disc at small scales, more strongly than gas dissipation, and the standard two-fluid case, since the self-gravity of the gas component now scales as k^2 . Furthermore, we observe that $F_{2f}(k)$ for barred galaxies is at least equal to or greater than the unbarred ones, but we do not see a common trend in $F_\delta(k)$ and $F_{turb}(k)$ for barred and unbarred galaxies. Thus, while the MWAs may appear stable against axisymmetric instabilities, as indicated by their large values of Q_T^{min} , the effects of gas dissipation and turbulence in the ISM can nevertheless continue to drive instabilities at small scales.

5. DISCUSSION

In this section, we will compare the stability levels of MWAs from TNG50 with the previous observational studies that have measured stability levels for galaxies in the local and early universe.

5.1. Q_{RW} versus Q_T

Before comparing the net stability of galaxies in this study with observations from the literature, we first pause to examine the similarities and differences between the various multi-component stability criteria employed in observational works. We use the simple MW model presented in K. Aditya (2024). The stellar surface density is described by an exponential profile, $\Sigma_\star(R) = 640 M_\odot \text{pc}^{-2} e^{-R/3.2 \text{ kpc}}$, where $\Sigma_{\star,0} = 640 M_\odot \text{pc}^{-2}$

is the central stellar surface density and $R_D = 3.2 \text{ kpc}$ is the scalelength of the stellar disc (D. Mera et al. 1998). The gas surface density follows a similar exponential form, $\Sigma_{g,0}(R) = 28.2 M_\odot \text{pc}^{-2} e^{-1.65R/(4R_D)}$, where $\Sigma_{g,0} = 28.2 M_\odot \text{pc}^{-2}$ and $R_{25} = 4R_D$ is the radius at which the B-band surface brightness drops to $25.5 \text{ mag arcsec}^{-2}$ (F. Bigiel & L. Blitz 2012). The stellar velocity dispersion is modeled as $\sigma_\star(R) = \frac{1}{0.6} \sqrt{\frac{2\pi G R_D \Sigma_\star(R)}{7.3}}$ (A. K. Leroy et al. 2008; A. B. Romeo & K. M. Mogotsi 2017). For the gas disc, we assume a constant velocity dispersion of $\sigma_g = 10 \text{ km s}^{-1}$, consistent with HI observations in the Milky Way and other nearby galaxies (D. Tamburro et al. 2009; K. Mogotsi et al. 2016). The dark matter density is modeled using a pseudo-isothermal halo profile, characterized by a central density $\rho_0 = 0.035 M_\odot \text{pc}^{-3}$ and a core radius $R_c = 5 \text{ kpc}$ (D. Mera et al. 1998). These inputs provide a reference model for evaluating disc stability and enable direct comparison between different stability criteria in the literature. A. B. Romeo & J. Wiegert (2011) derive a 2-component criterion for studying local gravitational instabilities, which was extended to a multi-component case by A. B. Romeo & N. Falstad (2013). Both are based on earlier work by C. Jog & P. Solomon (1984); G. Bertin & A. Romeo (1988); A. B. Romeo (1992); C. J. Jog (1996); R. R. Rafikov (2001). The inverse sum approximation of B. Wang & J. Silk (1994) is given by

$$\frac{1}{Q_{WS}} = \frac{1}{Q_g} + \frac{1}{Q_\star}. \quad (10)$$

The above approximation assumes that the net stability of the galaxy reflects the most unstable component, $Q_{WS} = Q_\star$, $Q_g \rightarrow \infty$ and $Q_{WS} = Q_g$, $Q_\star \rightarrow \infty$. Thus, by design the Q_{WS} is smaller than the stability of each of individual components and is smaller than Q_T presented in this work, see Figure 10. The Q_{RW} presented by A. B. Romeo & J. Wiegert (2011) improves the approximate criterion presented by B. Wang & J. Silk (1994), and is given by

$$\frac{1}{Q_{RW}} = \begin{cases} \frac{W_\sigma}{T_\star Q_\star} + \frac{1}{T_g Q_g} & \text{if } T_\star Q_\star > T_g Q_g \\ \frac{1}{T_\star Q_\star} + \frac{W_\sigma}{T_g Q_g} & \text{if } T_\star Q_\star < T_g Q_g \end{cases} \quad (11)$$

where the weight function W_σ is given by

$$W_\sigma = \frac{2\sigma_\star \sigma_g}{\sigma_\star^2 + \sigma_g^2}, \quad (12)$$

and the thickness correction factors are defined as

$$T_\star \approx 0.8 + 0.7 \frac{\sigma_{\star,z}}{\sigma_{\star,R}}, \quad T_g \approx 0.8 + 0.7 \frac{\sigma_{g,z}}{\sigma_{g,R}}. \quad (13)$$

The criterion for stability of galactic disc against axisymmetric instabilities presented by A. B. Romeo &

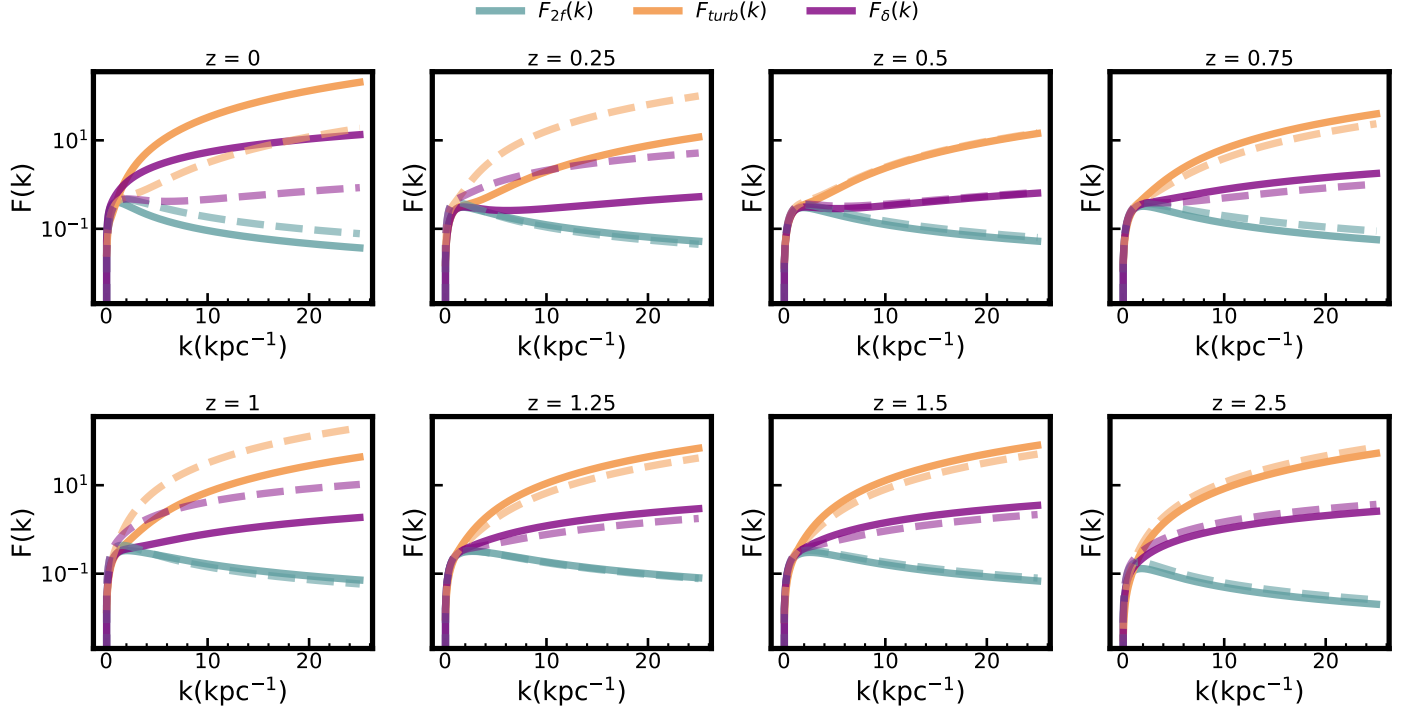


Figure 9. The stability function $F_{2f}(k)$, $F_{\delta}(k)$ and $F_{turb}(k)$ corresponding to the input parameters that give minimum value of Q_T . The *dashed* lines correspond to the barred galaxies and *solid* lines depict the unbarred MWAs.

J. Wiegert (2011), combines the $Q_{\star}$ and Q_g through weighted harmonic means and includes the thickness correction by taking into account the ratios of the velocity dispersion in the radial and the vertical direction. The Q_{RW} curve is higher than the Q_T used in this work and as such would provide conservative upper limits on the stability profiles of galaxies (see Figure 10). Q_T lies in between the inverse sum approximation derived by B. Wang & J. Silk (1994) and thickness-corrected weighted harmonic means approximation derived by A. B. Romeo & J. Wiegert (2011).

5.2. Galaxies at $z = 0$

A. B. Romeo & J. Wiegert (2011); A. B. Romeo & N. Falstad (2013) studied the stability of 12 local star-forming galaxies observed as part of the THINGS survey (A. K. Leroy et al. 2008), and found that nearby spiral galaxies typically have $Q_{RW} > 1$, with a global median value of 2.2, indicating that these galaxies are stable against the growth of axisymmetric perturbations. More recent work by C. Bacchini et al. (2024) investigated the stability of galaxies over a wide redshift range ($0 < z < 5$) using a 3D criterion developed by C. Nipoti et al. (2024). C. Bacchini et al. (2024) found no unstable gas discs in the redshift range $0 < z < 1$. It is important to note that the analysis by C. Bacchini et al. (2024) is a one-component treatment of the gas disc. K. Aditya (2023) examined the stability of 175 nearby galaxies from the SPARC catalog (F. Lelli et al. 2016),

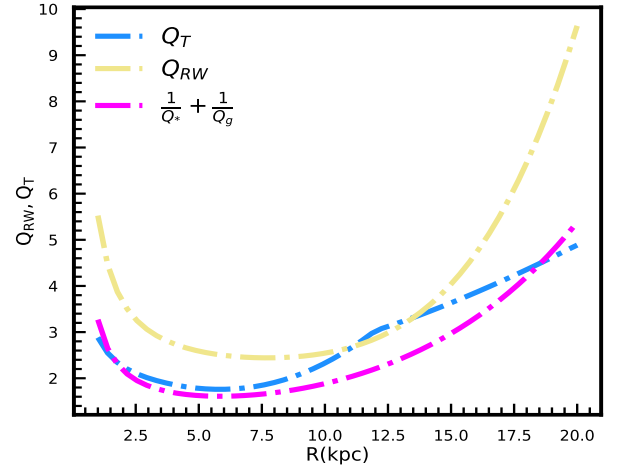


Figure 10. We compare the stability criterion (Q_T) used in this work with Q_{WS} and Q_{RW} used in literature.

which includes galaxies with diverse physical and morphological properties, and found that 91% of SPARC galaxies have a $Q_{RW}^{min} > 1$. K. Aditya (2023) found that only a total of 15 galaxies in the SPARC catalog show $Q_{RW}^{min} < 1$, of which 5 are irregulars and 10 are spirals. We find that, similar to the observations, MWAs also have $Q_T^{min} > 2$, with the barred galaxies having a smaller Q_T^{min} compared to the unbarred ones. Furthermore, A. K.

Leroy et al. (2008, 2013) measure the gas depletion time scale equal to 2.2Gyr for galaxies in the THINGS sample, which is comparable to our measurement of τ beyond the central 2kpc . Similarly, our measurement of $\Sigma_g/\Sigma_c \approx 0.4$ is comparable to $\Sigma_g/\Sigma_c \approx 0.5 - 0.7$ predicted by S. Boissier et al. (2003); K. Aditya (2023).

5.3. Galaxies at cosmic noon ($z = 2.5$)

C. Bacchini et al. (2024) study the stability of gas disc in two galaxies; zC-400569 at $z \approx 2.24$ and zC-488879 $z \approx 1.47$ (R. Genzel et al. 2014; F. Lelli et al. 2023). C. Bacchini et al. (2024) find that the gas disc of zC-400569 is locally unstable, however zC-488879 remains stable at all radius. However, we find that none of the MWAs in our study are prone to instabilities at $z = 2.5$. zC-400569 already has a stellar mass equal to $10^{11}M_\odot$ at $z = 2.5$, comparable to MW's present day stellar mass. However, none of the MWAs in our sample have assembled a stellar mass comparable to $10^{11}M_\odot$ at $z = 2.5$. Furthermore, the both zC-488879 and zC-488879 have an observed star formation rate equal to $10^2 M_\odot \text{yr}^{-1}$ compared to $0.01 - 0.1 M_\odot \text{yr}^{-1}$ for TNG50 MWAs at $z=2.5$.

5.4. Beyond cosmic noon

C. Bacchini et al. (2024) and (K. Aditya et al. 2023) quantify the stability levels in a sample of 6 dusty star-forming galaxies (DSFGs) observed by (F. Rizzo et al. 2020, 2021). To reiterate the difference between the analysis, C. Bacchini et al. (2024) measured the stability of the gas disc using the simple Toomre stability criterion and the 3D criterion presented by C. Nipoti et al. (2024), and K. Aditya (2023) used the two-component criterion (A. B. Romeo & J. Wiegert 2011) to assess the net stability of the galaxy disc consisting of stars and gas. The DSFGs observed by F. Rizzo et al. (2020, 2021) have stellar mass $> 10^{10}M_\odot$ and star formation rates $> 10^2 M_\odot \text{yr}^{-1}$. K. Aditya (2023) finds that the gas component is Toomre unstable in only 2 galaxies out of 6, compared to 5 unstable gas discs in C. Bacchini et al. (2024). However, K. Aditya (2023) shows that all six galaxies are susceptible to the growth of local axisymmetric instabilities $Q_{RW} < 1$ when the self-gravity of both stars and gas is included, highlighting the importance of a multi-component stability analysis.

5.5. Local Instability (Q_T), global Instability (Bars) & star formation

From Figure 5, we find that $Q_T(r < 5\text{kpc})$ of the barred galaxies is close to 2 since $z \approx 1.5$, given most of the bars in the TNG50 form around this epoch (Y. Rosas-Guevara et al. 2022). While for the unbarred galaxies, the $Q_T(r < 5\text{kpc})$ is always larger than that of barred galaxies at all epochs since $z \approx 1.5$ to the present epoch. This agrees with the notion that global non-axisymmetric instabilities become prominent in colder disks having lower velocity dispersion (J. P. Ostriker & P. J. E. Peebles 1973; S. K. Kataria & M. Das 2018, 2019;

S. K. Kataria et al. 2020; K. Aditya & A. Banerjee 2025) and higher surface density (S. K. Kataria & J. Shen 2022; S. Ansar et al. 2023; S. K. Kataria & M. Vivek 2024). However, the prediction of the star formation rates is underestimated in the region where the local stability criterion (Q_T) is close to 1 in the TNG50. This indicates the subgrid resolution for baryonic physics, i.e., star formation and stellar feedback, used in these simulations. The impact of subgrid resolution has been quantified recently for AURIGA galaxies (R. Pakmor et al. 2025) and TNG50 galaxies (Y. Rosas-Guevara et al. 2025), which can severely affect the star formation rates by a factor of more than 2.

5.5.1. What does $Q_T \geq 1$ means ?

The MWA in our sample remains remarkably stable at all radii and all epochs ($z < 2.5$). In the two-fluid stability paradigm, $Q_T \geq 1$ essentially means that the axisymmetric perturbations will continue oscillating. On the other hand, a value of $Q_T < 1$ is associated with growing/decaying axisymmetric perturbations. S. Inoue et al. (2016), study formation of clumps in zoom-in cosmological simulations and show that the $Q_{RW} < 1$ is confined only to collapsed clumps due to high surface density, however the inter-clump region continues to remain stable $Q > 1$. Interestingly, S. Inoue et al. (2016) find that the proto-clumps continue to be stable $Q_{RW} = 1 - 3.3$, with some of their models exceeding even $Q_{RW} > 3.3$. S. Inoue et al. (2016), conclude that the clump formation is inconsistent with the standard linear stability analysis, also see F. Renaud et al. (2021). However, B. G. Elmegreen (2011), showed that gas dissipation can increase the instability threshold from $Q_T = 1$ to $Q_T = 2 - 3$. So, a value of $Q_T = 2 - 3$, is consistent with dissipative instabilities if the turbulence decays on timescale similar to the dynamical timescales. A. B. Romeo et al. (2010); F. Renaud et al. (2021), argue that the growth of instabilities is scale-dependent and that instabilities can grow on smaller scales, even when $Q_T > 1$ on larger scales. A. B. Romeo et al. (2010); V. Hoffmann & A. B. Romeo (2012), show that when the gas density and dispersion are scale dependent $\Sigma_g \propto l^a$ and $\sigma_g \propto l^b$, then the disc remains unstable for $b > (a + 1)/2$ and $-2 < a < 1$, even when $Q_T > 1$. Studies by S. Michikoshi & E. Kokubo (2014); D. Ceverino et al. (2015); S. Inoue et al. (2016) point out that the discs can become unstable through non-linear and violent disc instabilities even when $Q_T > 1$. Thus, although our sample of MWAs from TNG50 are stable against the growth of axisymmetric instabilities, these galaxies may still be susceptible to perturbations driven by gas dissipation, scale-dependent instabilities, and violent non-linear disc processes, which can operate even when $Q_T > 1$.

6. SUMMARY

In this work, we have quantified the net stability levels of Milky Way analogs from the TNG50 against the

growth of local axisymmetric instabilities. We choose a representative sample of 20 MWAs (10 barred + 10 unbarred) from the TNG50 catalog and follow the evolution of their dynamical properties from $z = 2.5$ to $z = 0$. We find that:

1. The MW analogs in TNG50 are stable against local axisymmetric instabilities from cosmic noon $z = 2.5$ to the present day. The minimum value of the median $Q_T^{min} > 2$, with relatively higher values of Q_T^{min} at higher redshift. A higher gas velocity dispersion counteracts the increase in gas density at higher redshifts, which can potentially destabilize the galaxy.
2. The barred galaxies in our sample consistently have a smaller Q_T^{min} at all epochs. This is consistent with the smaller time scale in which instabilities can convert gas into stars and higher star formation rates observed in the barred galaxies. The time scale for the growth of instabilities increases steeply with radius in the barred galaxies compared to the unbarred ones.
3. The gas density is subcritical at all epochs. So, the local axisymmetric instabilities are not the main channel of star formation. The star formation persists despite subcritical densities, with the barred galaxies exhibiting a higher SFR ($0.1 - 0.6 M_\odot \text{yr}^{-1}$), compared to the unbarred galaxies ($< 0.3 M_\odot \text{yr}^{-1}$).
4. The timescale for growth of instabilities rises exponentially in MWAs. The inner regions can convert gas in a few Myrs compared to Gyrs in the outer disc. This naturally explains the centrally peaked star formation profiles.
5. Although the progenitors of the MWAs at $z=2.5$ have a higher gas surface density, they also exhibit higher gas velocity dispersions and a smaller dynamical mass. Thus, the combined support of gas dispersion and dark matter halo ensures that $Q_T \gg 1$, even during the early stages of formation. Thus, the higher gas fraction alone does not guarantee the growth of axisymmetric instabilities.
6. Despite removing the contribution of the dark matter halo, the stellar+gas disc remains stable. This implies that the stellar+ gas disc self-regulates the surface densities and velocity dispersions. The self-regulation mechanism operates in both barred and unbarred galaxies and at all epochs.
7. We study the effect of gas dissipation and turbulence in ISM and find that the gas dissipation and turbulent ISM can destabilize the disc galaxy even when the galaxies are stable against axisymmetric instabilities.

8. We conclude that the MWAs are stable against growth of axisymmetric instabilities at all epochs ($Q_T > 1$); *from cosmic noon to the present day*. However, we note that even when $Q_T > 1$, these galaxies continue to be unstable through gas dissipation, and scale-dependent instabilities driven by turbulence in the ISM. All these processes aid in increasing the threshold instability levels from $Q_T < 1$ to $Q_T = 2 - 3$.

7. ACKNOWLEDGEMENTS

The IllustrisTNG simulations were undertaken with compute time awarded by the Gauss Centre for Supercomputing (GCS) under GCS Large-Scale Projects GCS-ILLU and GCS-DWAR on the GCS share of the supercomputer Hazel Hen at the High Performance Computing Center Stuttgart (HLRS), as well as on the machines of the Max Planck Computing and Data Facility (MPCDF) in Garching, Germany. SKK acknowledges the support from the INSPIRE Faculty award (DST/INSPIRE/04/2023/000401) from Department of Science and Technology, Government of India.

REFERENCES

- Aditya, K. 2023, *Monthly Notices of the Royal Astronomical Society*, 522, 2543
- Aditya, K. 2024, *Monthly Notices of the Royal Astronomical Society*, 532, 3839
- Aditya, K., & Banerjee, A. 2021, *Monthly Notices of the Royal Astronomical Society*, doi: [10.1093/mnras/stab155](https://doi.org/10.1093/mnras/stab155)
- Aditya, K., & Banerjee, A. 2025, *The Astrophysical Journal*, 992, 179, doi: [10.3847/1538-4357/ae0991](https://doi.org/10.3847/1538-4357/ae0991)
- Aditya, K., Banerjee, A., Kamphuis, P., et al. 2023, *Monthly Notices of the Royal Astronomical Society*, 526, 29
- Aditya, K., Kamphuis, P., Banerjee, A., et al. 2022, *Monthly Notices of the Royal Astronomical Society*, 509, 4071
- Agertz, O., Teyssier, R., & Moore, B. 2009, *Monthly Notices of the Royal Astronomical Society: Letters*, 397, L64
- Ansar, S., Kataria, S. K., & Das, M. 2023, arXiv e-prints, arXiv:2304.00724, doi: [10.48550/arXiv.2304.00724](https://doi.org/10.48550/arXiv.2304.00724)
- Bacchini, C., Nipoti, C., Iorio, G., et al. 2024, *Astronomy & Astrophysics*, 687, A115
- Bertin, G., & Romeo, A. 1988, *Astronomy and Astrophysics* (ISSN 0004-6361), vol. 195, no. 1-2, April 1988, p. 105-113. Research supported by the Ministero della Pubblica Istruzione and CNR., 195, 105
- Bigieli, F., & Blitz, L. 2012, *The Astrophysical Journal*, 756, 183
- Boissier, S., Prantzos, N., Boselli, A., & Gavazzi, G. 2003, *MNRAS*, 346, 1215, doi: [10.1111/j.1365-2966.2003.07170.x](https://doi.org/10.1111/j.1365-2966.2003.07170.x)
- Boissier, S., Prantzos, N., Boselli, A., & Gavazzi, G. 2003, *Monthly Notices of the Royal Astronomical Society*, 346, 1215
- Bournaud, F., Elmegreen, B. G., & Elmegreen, D. M. 2007, *The Astrophysical Journal*, 670, 237
- Burkert, A., & Hartmann, L. 2013, *The Astrophysical Journal*, 773, 48
- Ceverino, D., Dekel, A., Tweed, D., & Primack, J. 2015, *Monthly Notices of the Royal Astronomical Society*, 447, 3291
- Chabrier, G. 2003, *Publications of the Astronomical Society of the Pacific*, 115, 763
- Dekel, A., Sari, R., & Ceverino, D. 2009, *The Astrophysical Journal*, 703, 785
- Ejdetjärn, T., Agertz, O., Östlin, G., Renaud, F., & Romeo, A. B. 2022, *Monthly Notices of the Royal Astronomical Society*, 514, 480
- Elmegreen, B. G. 2011, *The Astrophysical Journal*, 737, 10
- Genzel, R., Förster Schreiber, N. M., Lang, P., et al. 2014, *ApJ*, 785, 75, doi: [10.1088/0004-637X/785/1/75](https://doi.org/10.1088/0004-637X/785/1/75)
- Genzel, R., Schreiber, N. F., Übler, H., et al. 2017, *Nature*, 543, 397
- Gillman, S., Smail, I., Gullberg, B., et al. 2024, *Astronomy & Astrophysics*, 691, A299
- Goldreich, P., & Lynden-Bell, D. 1965, *Monthly Notices of the Royal Astronomical Society*, 130, 125
- Hoffmann, V., & Romeo, A. B. 2012, *Monthly Notices of the Royal Astronomical Society*, 425, 1511
- Hoffmann, V., & Romeo, A. B. 2012, *MNRAS*, 425, 1511, doi: [10.1111/j.1365-2966.2012.21675.x](https://doi.org/10.1111/j.1365-2966.2012.21675.x)
- Inoue, S., Dekel, A., Mandelker, N., et al. 2016, *Monthly Notices of the Royal Astronomical Society*, 456, 2052
- Jog, C., & Solomon, P. 1984, *The Astrophysical Journal*, 276, 127
- Jog, C. J. 1996, *Monthly Notices of the Royal Astronomical Society*, 278, 209
- Jog, C. J. 2014, *The Astronomical Journal*, 147, 132
- Kataria, S. K., & Das, M. 2018, *MNRAS*, 475, 1653, doi: [10.1093/mnras/stx3279](https://doi.org/10.1093/mnras/stx3279)
- Kataria, S. K., & Das, M. 2019, *ApJ*, 886, 43, doi: [10.3847/1538-4357/ab48f7](https://doi.org/10.3847/1538-4357/ab48f7)
- Kataria, S. K., Das, M., & Barway, S. 2020, *A&A*, 640, A14, doi: [10.1051/0004-6361/202037527](https://doi.org/10.1051/0004-6361/202037527)
- Kataria, S. K., & Shen, J. 2022, *ApJ*, 940, 175, doi: [10.3847/1538-4357/ac9df1](https://doi.org/10.3847/1538-4357/ac9df1)
- Kataria, S. K., & Vivek, M. 2024, *MNRAS*, 527, 3366, doi: [10.1093/mnras/stad3383](https://doi.org/10.1093/mnras/stad3383)
- Kennicutt Jr, R. C. 1989, *Astrophysical Journal*, Part 1 (ISSN 0004-637X), vol. 344, Sept. 15, 1989, p. 685-703., 344, 685
- Kennicutt Jr, R. C. 1998, *Annual Review of Astronomy and Astrophysics*, 36, 189
- Krumholz, M. R., Burkhardt, B., Forbes, J. C., & Crocker, R. M. 2018, *Monthly Notices of the Royal Astronomical Society*, 477, 2716
- Lelli, F., McGaugh, S. S., & Schombert, J. M. 2016, *AJ*, 152, 157, doi: [10.3847/0004-6256/152/6/157](https://doi.org/10.3847/0004-6256/152/6/157)
- Lelli, F., Zhang, Z.-Y., Bisbas, T. G., et al. 2023, *A&A*, 672, A106, doi: [10.1051/0004-6361/202245105](https://doi.org/10.1051/0004-6361/202245105)
- Leroy, A. K., Walter, F., Brinks, E., et al. 2008, *The astronomical journal*, 136, 2782
- Leroy, A. K., Walter, F., Sandstrom, K., et al. 2013, *The Astronomical Journal*, 146, 19
- Lin, D., Papaloizou, J., Levy, E., & Lunine, J. 1993, *University of Arizona, Tucson*, 749
- Meidt, S. E., Rosolowsky, E., Sun, J., et al. 2022, arXiv preprint arXiv:2212.06434

- Meidt, S. E., Rosolowsky, E., Sun, J., et al. 2023, *The Astrophysical Journal Letters*, 944, L18
- Mera, D., Chabrier, G., & Schaeffer, R. 1998, *Astronomy and Astrophysics*, 330, 953
- Michikoshi, S., & Kokubo, E. 2014, *The Astrophysical Journal*, 787, 174
- Mogotsi, K., de Blok, W., Caldú-Primo, A., et al. 2016, *The Astronomical Journal*, 151, 15
- Nelson, D., Springel, V., Pillepich, A., et al. 2019, *Computational Astrophysics and Cosmology*, 6, 2
- Nipoti, C., Caprioglio, C., & Bacchini, C. 2024, *Astronomy & Astrophysics*, 689, A61
- Ostriker, J. P., & Peebles, P. J. E. 1973, *ApJ*, 186, 467, doi: [10.1086/152513](https://doi.org/10.1086/152513)
- Pakmor, R., Fragkoudi, F., Grand, R. J., et al. 2025, arXiv preprint arXiv:2507.22104
- Pillepich, A., Nelson, D., Hernquist, L., et al. 2018, *Monthly Notices of the Royal Astronomical Society*, 475, 648
- Pillepich, A., Nelson, D., Springel, V., et al. 2019, *Monthly Notices of the Royal Astronomical Society*, 490, 3196
- Pillepich, A., Sotillo-Ramos, D., Ramesh, R., et al. 2024, *Monthly Notices of the Royal Astronomical Society*, 535, 1721
- Planck, P. 2016, *Astron. Astrophys.*, 594, A13
- Pontzen, A., Roškar, R., Stinson, G., & Woods, R. 2013, *Astrophysics Source Code Library*, ascl
- Rafikov, R. R. 2001, *Monthly Notices of the Royal Astronomical Society*, 323, 445
- Renaud, F., Romeo, A. B., & Agertz, O. 2021, *Monthly Notices of the Royal Astronomical Society*, 508, 352
- Renaud, F., Athanassoula, E., Amram, P., et al. 2018, *Monthly Notices of the Royal Astronomical Society*, 473, 585
- Rizzo, F., Vegetti, S., Fraternali, F., Stacey, H. R., & Powell, D. 2021, *Monthly Notices of the Royal Astronomical Society*, 507, 3952
- Rizzo, F., Vegetti, S., Powell, D., et al. 2020, *Nature*, 584, 201
- Romeo, A. B. 1992, *Monthly Notices of the Royal Astronomical Society*, 256, 307
- Romeo, A. B., Agertz, O., & Renaud, F. 2023, *Monthly Notices of the Royal Astronomical Society*, 518, 1002
- Romeo, A. B., Burkert, A., & Agertz, O. 2010, *Monthly Notices of the Royal Astronomical Society*, 407, 1223
- Romeo, A. B., & Falstad, N. 2013, *Monthly Notices of the Royal Astronomical Society*, 433, 1389
- Romeo, A. B., & Mogotsi, K. M. 2017, *Monthly Notices of the Royal Astronomical Society*, 469, 286
- Romeo, A. B., & Mogotsi, K. M. 2018, *Monthly Notices of the Royal Astronomical Society: Letters*, 480, L23
- Romeo, A. B., & Wiegert, J. 2011, *Monthly Notices of the Royal Astronomical Society*, 416, 1191
- Rosas-Guevara, Y., Bonoli, S., Puchwein, E., Dotti, M., & Contreras, S. 2025, *A&A*, 698, A20, doi: [10.1051/0004-6361/202453160](https://doi.org/10.1051/0004-6361/202453160)
- Rosas-Guevara, Y., Bonoli, S., Dotti, M., et al. 2020, *MNRAS*, 491, 2547, doi: [10.1093/mnras/stz3180](https://doi.org/10.1093/mnras/stz3180)
- Rosas-Guevara, Y., Bonoli, S., Dotti, M., et al. 2022, *MNRAS*, 512, 5339, doi: [10.1093/mnras/stac816](https://doi.org/10.1093/mnras/stac816)
- Safronov, V. 1960, *Annales d'Astrophysique*, Vol. 23, p. 979, 23, 979
- Schinnerer, E., Leroy, A., Blanc, G., et al. 2019, *Messenger*, 177, 36
- Shadmehri, M., & Khajenabi, F. 2012, *Monthly Notices of the Royal Astronomical Society*, 421, 841
- Smethurst, R. J., Simmons, B. D., Géron, T., et al. 2025, *Monthly Notices of the Royal Astronomical Society*, 539, 1359
- Springel, V., & Hernquist, L. 2003, *MNRAS*, 339, 289, doi: [10.1046/j.1365-8711.2003.06206.x](https://doi.org/10.1046/j.1365-8711.2003.06206.x)
- Talbot, R. J., J., & Arnett, W. D. 1975, *ApJ*, 197, 551, doi: [10.1086/153543](https://doi.org/10.1086/153543)
- Tamburro, D., Rix, H.-W., Leroy, A., et al. 2009, *The Astronomical Journal*, 137, 4424
- Toomre, A. 1964, *The Astrophysical Journal*, 139, 1217
- Walter, F., Neeleman, M., Decarli, R., et al. 2022, *The Astrophysical Journal*, 927, 21
- Wang, B., & Silk, J. 1994, *The Astrophysical Journal*, 427, 759
- Weinberger, R., Springel, V., & Pakmor, R. 2020, *The Astrophysical Journal Supplement Series*, 248, 32
- Weinberger, R., Springel, V., Pakmor, R., et al. 2018, *Monthly Notices of the Royal Astronomical Society*, 479, 4056
- Wong, T. 2009, *The Astrophysical Journal*, 705, 650
- Zana, T., Lupi, A., Bonetti, M., et al. 2022, *Monthly Notices of the Royal Astronomical Society*, 515, 1524–1543, doi: [10.1093/mnras/stac1708](https://doi.org/10.1093/mnras/stac1708)