The TNG50 Simulation

TNG50 is a new class of cosmological volume simulation – it has been designed to overcome the traditional limitation of compromising volume versus resolution, by simulating a large, fully representative cosmological volume at a resolution which approaches or even exceeds that of modern "zoom" simulations of individual massive galaxies. The simulation realizes a 50 Mpc box sampled by $2160^3$ gas cells, with a corresponding baryon mass of $8 \times 10^4 M_\odot$ (see table above). The median spatial resolution of the star-forming ISM gas is $\sim$100-140 parsecs across cosmic time. It enables us to obtain unparalleled detail, providing a view into the structure, chemo-dynamical evolution, and small-scale properties of galaxies – the image below shows two massive disk galaxies from the simulation to highlight its ability to resolve internal structural details such as spiral arms, bulges, and nuclear bars, together with the extremely thin scale-heights of galactic disks.
First Results from the TNG50 Simulation: 
The evolution of stellar and gaseous disks across cosmic time

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ABSTRACT
We present a new cosmological, magnetohydrodynamical simulation for galaxy formation: TNG50, the third and final installment of the IllustrisTNG project. TNG50 evolves $2 \times 2160^3$ dark-matter particles and gas cells in a volume 50 comoving Mpc across. It hence reaches a numerical resolution typical of zoom-in simulations, with a baryonic element mass of $8.5 \times 10^4 M_{\odot}$ and an average cell size of 70 – 140 parsecs in the star-forming regions of galaxies. Simultaneously, TNG50 samples ~700 (6,500) galaxies with stellar masses above $10^{10} \ (10^8) M_{\odot}$ at $z = 1$. Here we investigate the structural and kinematical evolution of star-forming galaxies across cosmic time ($0.5 < z \lesssim 6$). We quantify their sizes, disk heights, 3D shapes, and degree of rotational vs. dispersion-supported motions as traced by rest-frame V-band light (i.e. roughly stellar mass) and by Hα light (i.e. star-forming and dense gas). The unprecedented resolution of TNG50 enables us to model galaxies with sub-kpc half-light radii and with $\lesssim 300$-pc disk heights. Coupled with the large-volume statistics, we characterize a diverse, redshift- and mass-dependent structural and kinematical morphological mix of galaxies all the way to early epochs. Our model predicts that for star-forming galaxies the fraction of disk-like morphologies, based on 3D stellar shapes, increases with both cosmic time and galaxy stellar mass. Gas kinematics reveal that the vast majority of $10^{9.5-11.5} M_{\odot}$ star-forming galaxies are rotationally-supported disks for most cosmic epochs ($V_{\text{rot}}/\sigma > 2$ – 3, $z \lesssim 5$), being dynamically hotter at earlier epochs ($z \gtrsim 1.5$). Despite large velocity dispersion at high redshift, cold and dense gas in galaxies predominantly arranges in disky or elongated shapes at all times and masses; these gaseous components exhibit rotationally-dominated motions far exceeding the collisionless stellar bodies.

Key words: methods: numerical – galaxies: formation – galaxies: evolution – galaxies: haloes – general cosmology: theory

1 INTRODUCTION
A fundamental goal of galaxy evolution is to understand the prevalence, origin, and evolution of galaxy morphology across mass scales and as a function of cosmic time. The structural morphology of a galaxy – namely, the distribution of mass in three-dimensional space – is dictated by the kinematics of its components. Morphology provides a snapshot of the orbital mix of constituent stars, gas, and dark matter (DM). In turn, both the structural properties and kinematics of a galaxy’s stellar and gaseous bodies are determined by the physical processes governing its formation and subsequent evolution.

Based on observations as well as theoretical studies of galaxies, a basic picture has become broadly accepted: a disk-like morphology (in stellar light) is usually associated with gas-phase kinematics dominated by rotation. This idea is supported by observations of star-forming, disk galaxies in the Local Universe (starting with the Milky Way (Gunn et al. 1979), Andromeda, M51, and other nearby galaxies). However, observations of the higher redshift Universe motivate a more complex scenario. The majority of
**IllustrisTNG Project Overview**

The IllustrisTNG project consists of 18 simulations in total. The individual simulations vary in their physical size, mass resolution, and complexity of physics included. Three physical simulation box sizes are employed: cubic volumes of roughly 50, 100, and 300 Mpc side length, which we refer to as TNG50, TNG100, and TNG300, respectively. The three boxes compliment each other by promoting a focus on various aspects of galaxy formation. The large physical volume associated with the largest simulation box (TNG300) enables the study of galaxy clustering, the analysis of rare objects such as galaxy clusters and provides the largest galaxy sample. In contrast, while the smaller physical volume simulation of TNG50 simulation has a comparatively limited sampling of rare objects, the mass resolution achieved in the smaller volume simulations is a few hundred times higher than the larger volume TNG300 simulation. The TNG50 volume therefore enables a more detailed look at, e.g., the structural properties of galaxies, the detailed structure of gas around galaxies, and the convergence of our physical model. The central volume simulation, TNG100, falls between these two limits. Importantly, the TNG100 volume uses the same initial conditions (adjusted for updated cosmology) as used in the original Illustris simulation, which facilities clean comparisons between the original Illustris results and the updated TNG model.
<table>
<thead>
<tr>
<th></th>
<th>TNG50</th>
<th>TNG100</th>
<th>TNG300</th>
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<tr>
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<td>$\epsilon_{\text{DM,*}}$</td>
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Figure 2. The star formation rate vs. galaxy stellar mass plane in the TNG50 simulation at different redshifts, for all galaxies in the box (centrals and satellites). In this analysis we study exclusively star-forming galaxies, here denoted as blue filled circles. The distinction between star-forming (blue filled circles) and green-valley or quiescent galaxies (black open circles) is made based on a recursive refinement of the star-forming main sequence (SFMS; see Section 4 for details). A SFMS naturally emerges in the simulations and is present down to at least $10^7 \, M_\odot$ in stellar mass, as well as already at high redshift.
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"Quiescent": sSFR < 0.3 ridge line
logical diversity of the observed galaxy populations in recent years; particularly in large-volume hydrodynamical simulations like Illustris (Vogelsberger et al. 2014a,b; Genel et al. 2014; Sijacki et al. 2015) and EAGLE (Schaye et al. 2015; Crain et al. 2015), at roughly kpc and $10^8 M_\odot$ spatial and mass resolution. With Illustris, Snyder et al. (2015); Bottrell et al. (2017a,b) have demonstrated, via realistic mock observations of Illustris galaxies, that the observed connections among mass, star formation, and galaxy structure can arise naturally from models matching global star formation and halo occupation functions, albeit with a deficit of bulge-dominated galaxies. In parallel, Correa et al. (2017) have demonstrated, for example, that the EAGLE model also naturally produces a galaxy population for which stellar morphology is tightly correlated with the location in the color-mass diagram, with the red sequence mostly composed of elliptical galaxies and the blue cloud of disk galaxies.

More recently, the connection between galaxy stellar morphologies and galaxy colors has been recovered also in the successor of Illustris, the IllustrisTNG simulations (Naiman et al. 2018; Nelson et al. 2018b; Marinacci et al. 2018; Pillepich et al. 2018b; Springel et al. 2018), as demonstrated quantitatively by Nelson et al. 2018b. The realism of the galaxies produced by currently-available hydrodynamical simulations is reaching unprecedented quantitative levels indeed with the TNG100 simulation, as explored by Rodriguez-Gomez et al. (2019). Through synthetic images obtained by post-processing the simulated galaxies with SKIRT and including the effects of dust, we have demonstrated that the average $M_{\text{stars}} \geq 10^{10} M_\odot$ TNG100 galaxies exhibit values of optical morphological estimators like Gini-M20, concentration-asymmetry-smoothness statistics, and 2D Sersic indexes and sizes that are in remarkable agreement with Pan-STARRS data at $z \sim 0.05$.

However, in closely comparing structural measurements of galaxies to those available in observations, numerical works have generally neglected to quantify the most intrinsic and less ambiguous characterization of a galaxy’s mass distribution: its three-dimensional shape, as for example approximated by an ellipsoid. Notable studies include Trayford et al. (2018) of EAGLE galaxies, and Zhang et al. (2018) together with Ceverino et al. (2015) and Tomassetti et al. (2016) who qualitatively contrasted the shape fractions inferred from CANDELS data to ~30 high-redshift VELA zoom-in galaxies with stellar masses in the $10^9$–$10^{10} M_\odot$ range, finding broadly similar trends. The bulk of the currently-available structural characterizations of simulated galaxies have focused almost exclusively on the low-redshift Universe.

In general, zoom-in simulations provide trailblazing insights into the formation and evolution of e.g. Milky Way-like galaxies and their morphological components (e.g. Guedes et al. 2013; Grand et al. 2017, with Eris and the Auriga simulations, respectively). However, they have been less useful in broadly testing the outcome of their underlying physical models against population-wide morphological observed estimators, being also more prone to be affected by subtle phenomena, like the butterfly effect (Genel et al. 2019). This is because such projects are designed to sample only a few, or up to a few tens, galaxies at the time. These are often chosen to represent specific classes of galaxies, and typically favor better numerical resolution over statistics in comparison to ~100 Mpc cosmological simulations as mentioned above.

On the other hand, zoom-in simulations from the last five to eight years are the first actually suitable to provide predictions for the internal kinematics of galaxies. In most cases, kinematical analysis has focused on the measurement of the rotation velocities for Milky Way-like local disk galaxies (e.g. Guedes et al. 2011). In a few cases, velocity dispersion has been measured, particularly for disk galaxies at $z = 0$. For example, this has been done for the stellar component with the purposes of understanding radial migration (Roškar et al. 2013); and for the gas component to highlight the direct connection to the star formation-feedback loop (Agertz et al. 2013). Thinking about higher redshifts, Kassin et al. (2014) have analyzed four Milky Way-like galaxies and shown that they follow similar disk-settling trends as the observations suggest, with increasing (decreasing) rotational velocity (gas velocity dispersion) with time. However, those galaxies at high redshifts represent objects chosen, by construction, to be cold disks at $z = 0$. More recently, Hung et al. (2018) have measured the velocity dispersion of star-forming gas in four FIRE galaxies from $z = 0$ to $z = 4$ and found that $\sigma$ increases steeply from $z = 0$ to $z \sim 1.5$, with 100-Myr time variation that is connected to the evolution of the star formation rates and gas-mass inflows. However, also in that work, the simulated galaxies cover a narrow mass range, and with lower masses than those probed by current IFS surveys.

No studies have yet provided an extensive and conclusive analysis of the kinematics of simulated galaxies that can be broadly contrasted to the results from current observations. In fact, so far, no quantitative analysis of the internal kinematics of the galaxies within large uniform-volume simulation projects exists. This is due to the limited numerical resolution of such models, which is generally thought to be insufficient to properly capture even the kiloparsec-scale kinematics that are observationally accessible in the local and high-redshift Universe.

1.3 The current work and TNG50

The new TNG50 simulation that we introduce here provides a transformational step forward in uncovering the structural and kinematical properties of simulated galaxies across cosmic time. Specifically, we model and analyze for the first time the 3D shapes and internal kiloparsec-scale structure and dynamics of thousands of galaxies, including hundreds of $\geq 10^{10} M_\odot$ at $z \geq 1$, all modeled with a physically-motivated, though necessarily simplified, numerical treatment of star formation and feedback that acts below ~100 parsec scales in the ISM.

Our overarching goal is to present theoretical predictions from TNG50 for both H$\alpha$ and stellar-light tracers. We then place them into the context of the findings of currently available long-slit and IFS observations (see above), in anticipation of future, highly detailed high-redshift galaxy observations. Our approach is supported by a numerical model that includes the dominant mechanisms that are expected to influence the evolution of the galaxy properties of interest (see above and Section 2). In particular, we measure the sizes, disk heights, intrinsic 3D shapes, rotational velocities and velocity dispersions of stars and star-forming i.e. H$\alpha$-emitting gas in the inner regions of galaxies, with two objectives. First, to uncover outcomes of TNG50 for which the model has not been in any way calibrated and is thus predictive. Second, to contrast structural versus kinematical features, as well as the properties of the stellar versus gaseous components of galaxies. We hence focus on a redshift regime ($z \geq 0.5$) where such comparisons are currently prohibitive in observations, though soon to emerge, therefore maximizing the predictive return of this work. In this first paper on the topic, we focus on the evolution of galaxy populations on the star-forming main sequence, postponing an analysis of quenched galaxies. We connect galaxy populations across redshift at fixed stellar mass, postponing the study of individual galaxy tracks.

The structure of the paper is as follows. In Section 2, we de-
earlier epochs, and by comparing the extent of stellar bodies to that of the gaseous and star-forming components.

The sizes of TNG50 galaxies, measured independently for different matter components and tracers, are shown in Fig. 3 as a function of galaxy stellar mass, from \( z = 0.5 \) to \( z = 4.0 \). Solid thick curves show medians across the galaxy population in 0.2 dex bins of stellar mass; shaded regions denote \( \pm 1 - 3 \) galaxy-to-galaxy variations. We show, from the largest to the smallest, 3D total gas (gray), 2D projected neutral Hydrogen (green) and 3D stellar (red) half-mass radii, together with 2D, face-on projected, circularized V-band (blue) and H\( \alpha \) (orange) half-light radii, all in physical kpc. As a reminder, here H\( \alpha \) light is a proxy for SFR (see Section 3.2) and traces the location of dense, cool gas.

Noticeably and not surprisingly, the extent of the total gas is much larger than any stellar proxy, at all times, this being the case also for the radii of neutral hydrogen, at least at \( z \geq 0.7 \). Specifically, neutral-hydrogen sizes are about 2-10 times larger than the extent of the stellar and star-forming bodies, and more so at higher redshifts and for more massive galaxies. Stellar- and H\( \alpha \)-light instead trace one another within a factor of \( \sim 1.5 - 2 \) for all redshifts and masses we consider here: in particular, H\( \alpha \) 2D sizes are larger than V-band ones for more massive galaxies at more recent times. This is not a trivial accord: while the spatial distribution of H\( \alpha \) light traces the sites of stars at birth, and can be further affected by radiative processes, a number of physical mechanisms such as galaxy mergers or migration can redistribute stars over their lifetime, affecting the overall stellar sizes differently than those of the cold and dense gas out of which they form. The similarity of optical and H\( \alpha \) sizes of galaxies is, indeed, broadly consistent with observational findings at \( z \sim 1 \) (e.g. *Nelson et al.* 2013, 2016) and provides guidance for future observations at higher redshifts, e.g. with JWST.

![Median galaxy sizes of TNG50 star-forming galaxies as a function of galaxy stellar mass, from low (top) to high (bottom) redshift. Different colors denote 3D or 2D face-on circularized half-mass or half-light radii of different galaxy components. We include both central and satellite galaxies. Shaded areas denote the \( \pm 1 \sigma \) dispersions of the size distributions at fixed stellar mass (omitted for several curves to avoid overcrowding the plot). Gray annotations mark the locus of the typical gravitational softening of the stellar and gaseous resolution elements, for reference.](image)

Importantly, TNG50 galaxies below \( 10^{10}M_\odot \) have half-light radii of 0.5-2 physical kpc on average, with little to no redshift trend. The weak redshift evolution between \( z = 4 \) and \( z = 0.5 \) and below the \( 10^{11}M_\odot \) scale is consistent with observational findings on stellar effective radii, e.g. by *van der Wel et al.* (2014a) and Shibuya et al. (2015) in restframe optical wavelengths. For context, these observations are shown in Fig. 3 (gray symbols, with scatter bars): our 2D face-on circularized radii (blue curves) should be compared to projected long-axis sizes. These are readily available from *van der Wel et al.* (2014a) at \( z \leq 3 \) (gray circles). At higher redshifts, we convert the values from Shibuya et al. (2015) from circularized to long-axis projected sizes by adding 0.15 dex, reflecting the typical projected shape of \( b/a=0.5 \) at this stellar mass and redshift range (square symbols in the lower panel). Observations indicate that low-mass galaxies are at least as small as the TNG50 expectation and the latter are overall in the observational ballpark both in the median and galaxy-to-galaxy variation.

![Median galaxy sizes of TNG50 star-forming galaxies as a function of galaxy stellar mass, from low (top) to high (bottom) redshift. Different colors denote 3D or 2D face-on circularized half-mass or half-light radii of different galaxy components. We include both central and satellite galaxies. Shaded areas denote the \( \pm 1 \sigma \) dispersions of the size distributions at fixed stellar mass (omitted for several curves to avoid overcrowding the plot). Gray annotations mark the locus of the typical gravitational softening of the stellar and gaseous resolution elements, for reference.](image)
Figure 5. Time evolution of the distributions of normalized disk heights, for TNG50 star-forming galaxies. Namely, the distributions represent the relative thickness or flatness of galaxies, in bins of galaxy stellar mass (from top to bottom), derived from either V-band (left) or Hα (right) light. In each panel, thicker and brighter curves depict lower redshifts. Galaxy populations exhibit flatter or “diskier” morphologies at more recent times.

a zeroth-order comparison. Specifically, the dashed and solid thick shaded curves represent the results by Zhang et al. 2018 and van der Wel et al. 2014b based on the same CANDELS data (but at the lowest redshifts, where the latter use SDSS data).

In terms of stellar mass, disk-like galaxies are more numerous towards lower redshift and higher mass: for example, for stellar masses of \(10^{9.5\,\text{--}\,10}\,\text{M}_\odot\), disky galaxies increase rapidly from about 20-30 per cent of the total population at \(z = 4\) to \(\gtrsim 70\) per cent at \(z \lesssim 0.5\); on the other hand, disk-like galaxies dominate the population budget at all redshifts at the high-mass end (\(M_{\text{stars}} \gtrsim 10^{10}\,\text{M}_\odot\)). These findings are qualitatively compatible with those deduced from observations and are thus a confirmation of the TNG model as a whole, even though a more thorough comparison of methodologies and results is needed in the future. At the low-mass end (\(M_{\text{stars}} \lesssim 10^{8}\,\text{M}_\odot\)) disk-like geometries are exceedingly rare, while elongated galaxies becomes progressively more
Figure 6. Stellar light composites of a random sample of $z = 2$ TNG50 star-forming galaxies, selected to have $h_{1/2} \leq 0.1 \times r_{1/2}$ in the V-band and $M_{\text{stars}} \geq 10^9 M_\odot$. Images are for the JWST NIRCam f200W, f115W, and F070W filters (rest-frame), neglecting any dust effects and including all stellar light within the given projection. Every panel is 40 physical kpc on a side. The rich diversity of stellar structure is captured and quantified by the metrics explored herein.
Figure 7. Same as in Fig. 6 but for Hα light, i.e. the light from the star-forming gas within the simulated galaxies. The complex gas-phase structure of $z = 2$ star-forming galaxies and deviations from symmetric disk-like configurations, including the presence of warps and large-scale asymmetries, highlight the challenge of quantifying galactic structure using Hα as a morphological tracer.
Fig. 1.—Selection of eight typical galaxies for each morphological type: four in (a) and four in (b). Top to bottom: Chain, clump-cluster, double, tadpole, spiral, and elliptical galaxies. Images are at $i_{75}$ band, with a line representing 0.5. UDF or our own identification numbers from left to right in (a) are as follows: chains: 6478, 7269, 6922, 3214; clump clusters: CC12, 1375, 2291, 5190; doubles: 637, 4072, 5098, 5251; tadpoles: 3058, 8614, 5538, 6891; spirals: 3372, 3180, 4438, 8275; ellipticals: 2107, 4389, 2522, 4913. In (b), the identifications are: chains: 169 and 170 (two separate galaxies), 1428, 401, 3458-3418; clump clusters: 6486, 4807, 7230, 9159; doubles: 2461, 2558, 4097, 3967; tadpoles: 9543, 5115, 3147, 9348; spirals: 2607, 5805, 7556, 5670; ellipticals: 8, 4527, 4320, 5959. Panel b has an example of an edge-on spiral.

Fig. 2.—Four spiral galaxies showing giant star formation regions, tidal arms, and other asymmetries suggesting interactions. UDF numbers are (left to right) 8585, 2, 2993, 7112. UDF 2 has a bar.
frequent towards higher redshifts. Additionally we note that the CANDELS studies seem to find low fractions of ‘round’ galaxies towards their low-mass end (not shown), whereas those becomes the dominant shape in TNG at $M_{\text{stars}} < 10^{10} M_\odot$. In future analyses we will investigate this possible discrepancy, by focusing on spheroidal and elongated galaxies, by quantifying the consistency between observationally- and theoretically-derived 3D shapes and by checking how galaxy shapes change as a function of stellar ages.

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<th>Shape Distribution</th>
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<td>[10.0 - 11.0]</td>
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6 RESULTS ON KINEMATICAL PROPERTIES

One of the aims of this work is to contrast the information obtained through the structural analysis of galaxies (see previous Section) with properties deduced from their kinematics. In this Section, we explore the degree to which TNG50 star-forming galaxies are rotationally supported or dispersion dominated, performing our analysis on both the stellar and gaseous components, separately and then in comparison to one another.

6.1 Light and kinematical maps

Figures 10 and 11 show maps of the light distribution and velocity fields of a random sample of TNG50 galaxies at $z = 2$. In particular, Fig. 10 focuses on the stellar and stellar light components, while Fig. 11 provides information about the distribution of the Hα-emitting gas in the same galaxies. Each row depicts one galaxy, in edge-on projection (three leftmost panels) and face-on projection (three rightmost panels), where the determination of the projection is given by the mass distribution of the corresponding matter component. Here we do not apply any smoothing or adaptive binning, and the pixelization in the kinematical maps is meant

5 A more comprehensive set of examples is available on the IllustrisTNG website: [www.tng-project.org/explore/gallery/](http://www.tng-project.org/explore/gallery/).
to convey our underlying quantitative analysis procedure. Galaxy rotation velocity is obtained from the edge-on view (to maximize the signal from ordered rotation), while velocity dispersion is obtained from the face-on projection (to minimize any contamination from ordered motion). In both cases, only the line-of-sight component of the velocity field is used, and we directly measure average line-of-sight velocities in projected pixels or radial bins using the velocities of star particles (for stellar mass and V-band based measurements) and star-forming gas cells (for the Hα measurements), as described in Section 3.3.

Our measurements are designed to capture the intrinsic dynamics of our simulated galaxies. These are not a priori easily comparable to observation estimates, where for example the velocities of the gas are obtained via characterization of Hα emission lines. However, in order to connect to the way observational measurements are carried out, we summarize the statistics of the velocity fields in similar fashions, e.g. by averaging velocities over radial bins of finite size or over projected pixels, taken here to be square for convenience, although one could also use equal S/N Voronoi tessellations as often done in integral field spectrograph (IFS) observations. We take 0.5 comoving kpc as our fiducial spatial resolution for the velocity maps and measurements, independent of redshift and galaxy properties. We do not weight the particle-averaged velocities by any observable and we do not impose signal-to-noise cuts to the mapped pixels/spaxels that contribute to the summary statistics, as would be the case in observations. Instead we extract rotation-velocity and velocity-dispersion profiles exclusively from the inner, dense (i.e. most luminous) regions of galaxies. Specifically, we employ a virtual “slit” aligned with the structural major axis of the galaxy that extends from $-2R_{\text{stars}}$, $+2R_{\text{stars}}$ and $-1/5R_{\text{stars}}$, $+1/5R_{\text{stars}}$ along the major and minor (or middle) axes, respectively, as described in Section 3.3.

Figures 10 and 11 visualize the complexity and diversity of the galaxy population kinematics in TNG50. At $z = 2$, the vast majority of star-forming massive galaxies exhibit clear rotation patterns, both in the stellar as well as in the gaseous bodies. Many galaxies present prominent stellar bulges (e.g. galaxies #15226 and #29443) and sometimes stellar bars are already present at early epochs (galaxy #2). Both in the stellar and gaseous components, galaxy disks often exhibit warps at their edges (e.g. galaxy #31833) that seem to correspond to cases where the rotation curves fall at distances slightly larger than the local maximum.

One striking difference from the comparison between the stellar-based and Hα-based maps at these intermediate redshifts is the enhanced complexity of the latter: even through visual inspection of this small sample, it is evident that the line-of-sight velocity-dispersion field traced by the star-forming gas is less coherent, less organized and overall less spatially homogeneous than for the stars. A visual inspection of similar maps at lower redshifts (e.g. $z < 1$) seems to point towards a decrease of such spatial inhomogeneity of the Hα maps.

In the profile panels of Figures 10 and 11 text annotations show the values we derive to characterize the velocity fields of each galaxy: $V_{\text{rot}}$ and $\sigma$. The meaning and derivations of these two numbers are detailed in Table 3. Note that we do not fit the rotation curves and we do not take the asymptotic velocity value of the rotation curves as $V_{\text{rot}}$. First, as noted above, many of the rotation curves exhibit signs of falling at some large distances, requiring fitting functions similar to those adopted e.g. by Wisnioski et al. 2015 rather than arc tangent-like functional shapes. Second, we have verified that our $V_{\text{rot}}$ values typically occur well within the imposed radial distance maxima, and not where the curves still rise. As a result, our values for $V_{\text{rot}}$ correctly represent where and to what degree kinematic disks are “maximal”.

Furthermore, we neglect any possible misalignment between the structural and kinetic major axes. This is an important issue in observations where the structural major axis is determined from the stellar light maps, while kinematics are extracted from the gaseous
Figure 10. V-band light maps, velocity maps and velocity profiles for the stellar component of a random selection of galaxies at $z = 2$ from the TNG50 simulation. In the three leftmost columns, we show edge-on projections of the stellar light and mean line-of-sight velocity, in addition to the radial profiles of the mean line-of-sight velocity along the slit depicted by the black solid lines. In the three rightmost columns, we show the face-on projections of the stellar light and of the line-of-sight velocity dispersion, in addition to the average velocity dispersion profiles along the slit. For all kinematics, we pixelize using square pixels of 0.5 comoving kpc to a side. For each galaxy, two numbers are extracted as indicated in the panels: $V_{\text{rot}}$ and $\sigma$ – see Table 3 for definitions.

cf. Genzel et al. (2017): baryon-dominated rotation curves (falling at large R)
Figure 11. $H\alpha$ light maps, velocity maps and velocity profiles for the star-forming and gaseous component of a random selection of galaxies at $z = 2$ from TNG50. Galaxies and annotations are as in Fig. 10.
both stellar and gaseous $V_{\text{rot}}/\sigma$ measures. The only exception is towards low redshift ($z < 0.7$) where a peculiar non-monotonic mass trend starts to appear around $10^{10.5} - 10^{11} M_\odot$, particularly in the Hα-traced gas. The decline of $V_{\text{rot}}/\sigma$ towards larger masses and lower redshifts could be related to the rapidly increasing importance of minor-merger activity, which would increase $\sigma$.

As a final remark, we note that the stellar values of $V_{\text{rot}}/\sigma$ are lower than those of the gas and interpret this as a larger degree of vertical dispersion-supported motion in the extended stellar bodies of galaxies in comparison to the star-forming gas rotating disks. However, the stellar velocity dispersion fields are remarkably more coherent in space than for the gas, as noticed via inspection of Figures 10 and 11. In practice, the $V_{\text{rot}}/\sigma$ ratio, however measured, does not fully capture the spatial incoherence, complexity and chaotic nature of the gas kinematics across galaxy bodies. The richness of these kinematic fields and the interrelationship between gas-phase and stellar motion motivates more sophisticated observational diagnostics, more robust comparisons, and more the-
with our kinematic finding that the Hα gas is more rotationally supported (larger $V_{\text{rot}}/\sigma$) than the stars. The gaseous component has a smaller (larger) velocity dispersion (rotation velocity) than the stars, at fixed galaxy stellar mass.

From the structural view point, the change in time of the abundance of different morphological classes (Fig. 9) is quite different for stellar versus gaseous bodies, with the Hα-shape demographics being relatively stable across redshift, more so than their stellar counterparts. This contrast is somewhat exaggerated by the artificial classification into three separate classes: while Hα morphologies qualify as disks in almost all cases, their shapes (at fixed galaxy stellar mass) evolve to become flatter (or more elongated) with time (Fig. 5 and 8), consistent with their increase in $V_{\text{rot}}/\sigma$.

In our model, the time evolution towards a larger contribution of rotation vs. dispersion-dominated motions results from a strong decline of the average velocity dispersion from high to low redshifts (Fig. 12, top). For the typical $10^{10.5}$ $M_\odot$ galaxy, the inner (vertical) velocity dispersion of the Hα emitting gas decreases by a factor of a few between $z = 2 \rightarrow 3$ and $z \sim 0.5$, a drop broadly consistent with observational constraints. The decline of $\sigma$ is more pronounced for gas than for stars. In fact, in contrast to previous observational (Kassin et al. 2012, at $z = 0.2 \sim 1.2$) and theoretical work (Kassin et al. 2014, for a handful of $z = 0$ Milky Way-like galaxies), the Hα-probed $V_{\text{rot}}/\sigma$ of TNG50 galaxies at fixed stellar mass is higher at more recent epochs even though the rotational velocities also decrease towards low redshift. More recently, Simons et al. (2017) have found with DEEP2 and SIGMA data a mild increase with time of the average $V_{\text{rot}}$ in galaxies with $10^{9.5-10}$ $M_\odot$ stellar mass, but no time evolution at larger galaxy masses. In fact, it may be difficult to draw an unambiguous redshift trend from the $V_{\text{rot}}$ compilation of data in Fig. 12 of Kassin et al. (2012) – spanning from $z \sim 0.2$ to 3.5 and including IFS results – because of the large scatter and the mix of galaxies of different masses. In a dedicated study, we will address how the TNG50 rotational velocities presented in this paper map into circular velocities and what the simulation predicts in term of shape and time evolution of the Tully-Fisher relation.

The overall physical picture laid out in this paper is assembled in Fig. 15, for a representative bulk of the TNG50 galaxy population across time ($M_{\text{star}} = 10^{9.5-10}$ $M_\odot$). There we show how the level of “diskiness” increases with time, from both a kinematics and structural perspective. In particular, we visualize the time trends of the average $V_{\text{rot}}/\sigma$ (solid dotted curves) and flatness (dashed curves: the inverse of the 3D shape sphericity) normalized to their values at high redshift ($z \sim 3$). As usual, stellar and gaseous kinematical and structural metrics are kept distinct (blue vs. orange). We omit the alternative flatness measure based on normalized disk heights as it gives indiscernible results from those already depicted.

Instead of defining disks based on a fixed threshold on any of our measures (as previously proposed in the literature, e.g. Kassin et al. 2012; Newman et al. 2013; Simons et al. 2017), we instead show the average trends, thereby avoiding possible biases because of choices in definition or measurement methodology. In fact, the
sive black holes. While our effective model of the ISM will under-
estimate small-scale turbulence, all other mechanisms are robustly captured in the TNG simulations. It is fair to speculate that a more ‘explicit’ model of the ISM could produce higher velocity dispersions, although this remains to be demonstrated. In fact, larger dispersion could imply shorter turbulence dissipation times, hence hampering the intuitive enhancement. Further, it is currently unknown if, and to what degree, turbulence originating at scales of tens of parsecs and below contributes to observed gas velocity dispersions, averaged on 0.5-1 kpc scales.

We reiterate that our model for stellar feedback neglects small-scale interactions due to the hydrodynamically-decoupled wind particle scheme. In contrast, the AGN feedback is directly coupled, and energy injection from the central SMBH directly affects the coldest and densest gas in galaxies, producing multi-phase gas ejecta at thousands of km s$^{-1}$ (see Nelson et al. 2019). Furthermore, even for SN-driven winds, our calculations do capture disordered motions indirectly induced by stellar feedback outflows, i.e. complex galactic-scale fountain flows. In future analyses we will aim to further disentangle the physical drivers of the trends presented here. We can anticipate that, for example, the number and prominence of galaxy mergers, the rate of gas inflow, and the feedback-induced motions all decline as the Universe ages, the cosmic star formation rate stalls after the cosmic noon and the galactic gas fractions decrease. The curtailing of the physical processes that are capable of maintaining star-forming and dense gas dynamically hot against cooling is plausibly the reason why gaseous (and stellar) disks settle on rotation-dominated and thinner configurations towards recent epochs.

8 SUMMARY AND CONCLUSIONS

In this work, and together with the companion paper by Nelson et al. 2019, we have introduced a new cosmological magneto-hydrodynamical simulation for galaxy physics: TNG50, the third, final, and most demanding run of the IllustrisTNG project.

Within the current landscape of galaxy simulations, TNG50 provides a unique combination of statistics and resolution. It realizes a uniform volume of 50 comoving Mpc on a side at “zoom”-like resolution. In practice, at $z = 0$, the TNG50 simulation simultaneously samples both a $10^9 M_\odot$ Virgo-like cluster as well as about one hundred Milky Way mass-haloes and thousands of lower-mass dwarf galaxies. This provides generous statistics of massive galaxies, even at high and intermediate redshifts, with $\sim 70$ galaxies more massive than $M_{\text{stars}} = 10^8 M_\odot$ at $z = 1$ and 380 galaxies with $M_{\text{stars}} \geq 10^{10} M_\odot$ at $z = 2$. All these are modeled with a uniform baryonic mass resolution of $8.5 \times 10^4 M_\odot$, a collisionless gravitational softening of 288 parsecs, and a typical cell size of 70 – 140 parsecs within the star-forming regions of galaxies (see Table 1 and Fig. 1 for resolution details).

Leveraging this new numerical laboratory we have investigated the structural and kinematics properties of TNG50 star-forming galaxies across cosmic time. In particular, we have selected galaxies on the star-forming main sequence above $10^7 M_\odot$ at $0.5 \leq z \leq 5$ (Fig. 2) and measured their sizes, disk heights, 3D shapes, maximum rotation velocities, and intrinsic velocity dispersions (see Section 3.3 for methodological details). Our findings are summarized as follows:

- The stellar sizes of our simulated galaxies range from a median of 10 physical kpc for $10^7 M_\odot$ objects at $z \sim 0.5$ to $0.5 - 2$ physical kpc for $10^{8-9} M_\odot$ galaxies at $z \sim 4 - 5$. More massive galaxies are more extended in both V-band and H$\alpha$ light but this relation flattens considerably at high redshifts ($z \gtrsim 2$ and $M_{\text{stars}} \lesssim 10^{10} M_\odot$); see Fig. 3. According to our model, intermediate and low mass galaxies, $M_{\text{stars}} < 10^{10} M_\odot$, exhibit very weak redshift evolution, with their stellar sizes increasing by a factor of two at most between $z = 5$ and 0.5. We find that V-band and H$\alpha$ half-light radii trace each other closely, within a factor of 1.5 for galaxies with $10^{7-11} M_\odot$ at $0.5 < z < 5$.

- The bulk of the $M_{\text{stars}} = 10^{9-11} M_\odot$ main-sequence galaxy population has a typical edge-on “thickness” of $200 - 400$ physical pc, independent of morphological type and redshift. These values are similar for V-band and H$\alpha$ light profiles, and are converged to better than 20-40 percent at the resolution of TNG50. Massive star-forming galaxies exhibit progressively flatter morphologies at lower redshift, based on their edge-on and face-on light profiles (Figures 4 and 5). In particular, galaxy “flatness” decreases by up to a factor of a few between $z = 4 - 5$ and $z = 0.5 - 1$, where the typical star-forming $10^{10-11} M_\odot$ galaxy has $h_{1/2} \lesssim 0.1 h_{1/2}$ at recent epochs ($z \lesssim 1$). The high-mass redshift trend is driven by both height and size evolution, although the latter may dominate.

- We analyze the 3D intrinsic shapes of the stellar as well as H$\alpha$-gas mass distributions (Figures 8 and 9). Based on stellar-mass geometry, the fraction of galaxies with disk-like morphologies increases with time (i.e. more disks at lower redshifts, for all $M_{\text{stars}}$) and is higher for larger stellar mass at fixed redshift. For example, above $M_{\text{stars}} \gtrsim 10^{10.5} M_\odot$, more than 60 per cent of star-forming galaxies exhibit disk-like stellar morphologies at all times. We also find that elongated, ‘cigar-like’ stellar mass distributions are more frequent towards high redshift and low mass. On the other hand, the redshift trends of H$\alpha$-based morphologies are weaker than those derived from stellar mass. This star-forming gas settles into disk-like (or elongated) morphologies for the majority (60-100 per cent) of $> 10^9 M_\odot$ galaxies at all times ($z \lesssim 5$).

- The kinematic fields of TNG50 galaxies (Figures 10 and 11) display a rich phenomenology and wide diversity across the simulated galaxy population. The vertical, intrinsic gas velocity dispersion $\sigma$ is typically more complex and less spatially coherent than the analog traced by star light. Yet, at any given redshift and mass, and without selecting on stellar morphology, the typical velocity $\sigma_{\text{stars}}$ is larger than $\sigma_{\text{gas}}$. For both tracers velocity dispersion decreases with time; the H$\alpha$-probed dispersion declines by a factor of a few between $z \sim 2$ and $z \sim 0.5$ independent of mass (Fig. 12). Nevertheless, clear rotation patterns are identified in both the stellar and gaseous components in all star-forming galaxies also at high redshifts ($z \gtrsim 1$, $M_{\text{stars}} \gtrsim 10^9 M_\odot$, Fig. 13).

- In practice, our model predicts that the vast majority of $M_{\text{stars}} > 10^9 M_\odot$ star-forming galaxies are rotationally-supported gas disks at all times, with values of $V_{\text{rot}}/\sigma$ in excess of 2-3 ($z \lesssim 5$, Fig. 14). These gaseous structures become dynamically colder towards lower redshift. On the other hand, due to their collisionless dynamics, stars in the same galaxies are always dynamically hotter (lower $V_{\text{rot}}/\sigma$ values) than the gas out of which they form, with little variation in redshift or mass. In the TNG model, the increasing gas $V_{\text{rot}}/\sigma$ with time proceeds despite the pronounced decrease of rotational velocities towards low redshift.

In conclusion, the TNG50 simulation produces a main-sequence galaxy population whose stellar and gas structural prop-
erties and kinematics evolve across mass and time, and are qualitatively consistent with observational findings. Namely, the fraction of disk-like galaxies based on 3D stellar shapes rises with both cosmic time and galaxy stellar mass, and the vast majority of $10^{10-11.5} \, M_\odot$ star-forming galaxies are rotationally-supported gaseous disks at all times, although dynamically hotter at earlier epochs. This concordance is a non-trivial confirmation of the outcome of the numerical model and the plausibility of the underlying physical assumptions. It encourages future analyses that we will undertake in order to identify and further disentangle the physical drivers of the trends presented here, and the validity of our general approach, i.e. despite the unavoidable simplifications of the underlying galaxy physics model, particularly in the treatment of the star formation, of the cold dense gas, and of the feedback from stars on small-scales.

Our analysis of TNG50 has uncovered novel predictions for the relation between stellar and Hα-traced galaxy properties and between structural and kinematical measurements. These insights will help guide the interpretation of future observational results. Notably, despite the presence of larger velocity dispersions at high redshift, cold and dense gas principally arranges in disky or elongated shapes at all times and masses. Interestingly, we find that the fraction of “elongated” Hα shapes dominates at low masses at all times ($M_{\text{stars}} \lesssim 10^{9.5} \, M_\odot$ and $z \lesssim 6$) and is negligible also at larger masses. In other words, in the TNG model, star-formation occurs in relatively thin disk-like or slab configurations of dense gas, in accordance with the basic principles of galaxy formation theory. At the same time rotationally-dominant motions in gaseous galactic bodies, as represented by high values of gas $V_{\text{rot}}/\sigma$, increase with time and correlate with an analog, albeit weaker, flattening of gaseous disks towards low redshift. In contrast, gas kinematicst exhibit degrees of rotationally-supported motions that far exceed those of their stellar counterparts, even in galaxies with very flat, disk-like stellar morphologies. This apparent dichotomy reflects the different nature of stars and gas: as the latter can dissipate energy, it cannot remain in high-dispersion equilibrium states with rotating orbits, in contrast to the stars.

In conclusion, with this paper we put forward quantitative predictions for the evolution of galaxy internal kinematics at intermediate and high-redshifts, particularly in as of yet unexplored stellar light tracers, that will be possible to test with ambitious future observatories such as the James Webb Space Telescope (JWST), Giant Magellan Telescope (GMT), and Extremely Large Telescope (ELT).

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