The Kinematics and Dark Matter Fractions of TNG50 Galaxies at $z = 2$ from an Observational Perspective

Hannah Übler$^1$, Shy Genel$^{2,3}$, Amiel Sternberg$^{4,2,1}$, Reinhard Genzel$^{1,5}$, Sedona H. Price$^1$, Natascha M. Förster Schreiber$^1$, Taro T. Shimizu$^1$, Annalisa Pillepich$^6$, Dylan Nelson$^7$, Andreas Burkert$^{1,8}$, Ric Davies$^1$, Lars Hernquist$^9$, Philipp Lang$^6$, Dieter Lutz$^1$, Rüdiger Pakmor$^7$, and Linda J. Tacconi$^1$

$^1$Max-Planck-Institut für extraterrestrische Physik, Giessenbachstraße 1, 85748 Garching bei München, Germany
$^2$Center for Computational Astrophysics, Flatiron Institute, 163 Fifth Avenue, New York, NY 10010, USA
$^3$Columbia Astrophysics Laboratory, Columbia University, 550 West 120th Street, New York, NY 10027, USA
$^4$School of Physics & Astronomy, Tel Aviv University, Ramat Aviv 69978, Israel
$^5$Departments of Physics and Astronomy, University of California, Berkeley, CA 94720, USA
$^6$Max-Planck-Institut für Astrophysik, Karl Schwarzschildstr. 1, 85737 Garching, Germany
$^7$Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany
$^8$Universitäts-Sternwarte, Ludwig-Maximilians-Universität München, Scheinerstr. 1, 81679 München, Germany
$^9$Max-Planck-Institut für extraterrestrische Physik, Gießenbachstraße 1, 85748 Garching bei München, Germany

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ABSTRACT

We contrast the kinematics and dark matter contents of $z = 2$ star-forming galaxies (SFGs) from state-of-the art cosmological simulations within the ΛCDM framework to observations. To this end, we create realistic mock observations of massive SFGs ($M_* > 4 \times 10^{10} M_\odot$, SFR $> 50 M_\odot$ yr$^{-1}$) from the TNG50 simulation of the IllustrisTNG suite, resembling near-infrared, adaptive-optics assisted integral-field observations from the ground. Using observational line fitting and modeling techniques, we analyse in detail the kinematics of seven TNG50 galaxies from five different projections per galaxy, and compare them to observations of twelve massive SFGs by Genzel et al. (2020). The simulated galaxies show clear signs of disc rotation but mostly exhibit more asymmetric rotation curves, partly due to large intrinsic radial and vertical velocity components. At identical inclination angle, their one-dimensional velocity profiles can vary along different lines of sight by up to $\Delta v = 200 \text{ km s}^{-1}$. From dynamical modelling we infer rotation speeds and velocity dispersions that are in the ballpark of observational results. We find low central dark matter fractions compatible with observations ($f_{DM}^c(< R_e) = v_{DM}^2(R_e)/v_{circ}^2(R_e) \sim 0.29 \pm 0.11$), however for disc effective radii $R_e$ that are too small: at fixed $R_e$ the TNG50 dark matter fractions are too high by factors of $1.5 - 5$. We speculate that the differences in kinematics and dark matter content compared to the observations may be due to physical processes which are not resolved in sufficient detail with the numerical resolution available in current cosmological simulations.

1 INTRODUCTION

Recent observations of massive ($M_* \approx 10^{11} M_\odot$) star-forming galaxies (SFGs) at redshift $z \approx 2$, near the peak of cosmic star-formation rate density, have demonstrated that these rapidly evolving galaxies differ from present-day systems in several fundamental ways. First, the $z \sim 2$ SFGs have higher gas-to-stellar mass ratios ($M_{gas}/M_* \sim 1$; e.g. Genzel et al. 2015; Scoville et al. 2017; Tacconi et al. 2018). Second, they are forming stars more rapidly (e.g. Daddi et al. 2007; Rodighiero et al. 2011; Whitaker et al. 2014; Speagle et al. 2014). Third, they have higher intrinsic velocity dispersions relative to ordered rotational motions ($\sigma_0/\sigma_{rot} \sim 0.2$; e.g. Förster Schreiber et al. 2006; Genzel et al. 2008, 2011; Wisnioski et al. 2015; Simons et al. 2017).

In addition to these differences in global properties, several kinematic studies of individual galaxies have also revealed that the central regions of these most massive $z \sim 2$ SFGs are strongly baryon-dominated (e.g. Alcorn et al. 2016; Price et al. 2016, 2020; Wuyts et al. 2016; Genzel et al. 2017, 2020), with galaxy-scale dark matter fractions much lower than for typical SFGs at the current epoch (e.g. Martinsson et al. 2020).
et al. 2013b,a). Because studies of resolved properties are observationally very expensive, stacking approaches have been used to determine typical dynamical properties of high-\(z\) SFGs. Unfortunately, current stacking studies disagree on their main results, largely driven by different methodological concepts and possibly selection effects (Lang et al. 2017; Tiley et al. 2019). However, the differences should not be over-interpreted: the results of dynamical studies of individual galaxies in the local Universe (e.g. Persic & Salucci 1988; Begeman et al. 1991; Sancisi 2004; Noordermeer et al. 2007; de Blok et al. 2008; Lelli et al. 2016) as well as at high redshift (Genzel et al. 2017, 2020; Übler et al. 2018; Lelli et al. 2018; Motta et al. 2018; Drew et al. 2018) show that both rotation curve shapes and dynamical support are contingent on other galaxy properties, such as velocity dispersion, baryonic mass, baryonic surface density, or bulge mass, properties not systematically controlled for in current stacking analyses. Therefore, kinematic studies of individual galaxies still constitute the most robust reference.

Reproducing the detailed properties of high-\(z\) galaxies poses a particular challenge to simulations (see review by Naab & Ostriker 2017). To make progress, recent studies are now focusing on specific tests of simulations against kinematic data by means of mock observations, with varying degrees of observational realism (e.g. Genel et al. 2012; Lovell et al. 2018; Teklu et al. 2018; Pillepich et al. 2019; Simons et al. 2019; Wellons et al. 2020). As one of the most recent models, the IllustrisTNG simulation suite (Nelson et al. 2018; Naiman et al. 2018; Marinacci et al. 2018; Pillepich et al. 2018a; Springel et al. 2018) provides several large realizations of cosmological galaxy populations that can be compared with data.

The goal of this paper is to contrast simulated SFGs from the highest-resolution run of the IllustrisTNG suite, TNG50 (Nelson et al. 2019; Pillepich et al. 2019), to a subsample of recent detailed observations by Genzel et al. (2020). Our main focus is on the kinematics and the associated dark-matter distributions of the most massive, \(z \sim 2\) SFGs. For this purpose we create realistic mock observations of the star-forming gas kinematics of selected massive \(z = 2\) galaxies from TNG50, including specific instrumental effects, and random as well as systematic noise affecting near-infrared observations from the ground. We then apply the same data extraction pipeline and modeling tools to the simulated galaxies that were applied to the galaxies by Genzel et al. (2020).

This approach enables two types of comparisons. First, since the internal structures of the simulated galaxies can be inspected directly, we can assess how accurately the observational pipelines recover (complex) intrinsic structures. Second, given the observational results, particularly the low central dark matter fractions and the role of pressure support as frequently indicated by declining rotation curves, we can ask whether the IllustrisTNG model successfully reproduces the observed properties, or not, assuming that we can identify simulated analogs from the TNG50 volume that are similar enough to the observed galaxies.

This paper is structured as follows: in Section 2, we briefly describe the selection, modeling assumptions, and interpretation of our observational comparison sample by Genzel et al. (2020). In Section 3, we discuss the selection of galaxies from the TNG50 simulation, our mock observations, kinematic analysis, and modeling. In Section 4, we present both mock-observed and intrinsic kinematics, modeling results, and compare to the observational sample with a focus on galaxy-scale dark matter fractions. We summarize and conclude in Section 5.

2 THE OBSERVATIONAL PICTURE

The pioneering work by Genzel et al. (2017) revealed declining rotation curves for a sample of six massive SFGs at \(0.9 < z < 2.4\). Through dynamical modeling of these deep and high-quality data, it was possible to estimate the central dark matter fractions based on a standard Navarro, Frenk, & White halo model (NFW; Navarro et al. 1996). This analysis showed that the \(z \gtrsim 1.5\) targets had very low to negligible central dark matter fractions within the baryonic disc effective radius \(R_e\).

This first study was substantially enlarged through the recent work by Genzel et al. (2020), presenting modeling and analysis of 41 galaxies (including the six objects by Genzel et al. 2017), with a focus on extending towards lower masses and redshifts. This diversified view on the high-\(z\) SFG population reveals a variety of kinematic and dark matter properties. We focus in the present work on a subsample of twelve galaxies at \(z \gtrsim 1.5\) with stellar masses \(M_\star > 4 \times 10^{10} M_\odot\) (including the five \(z \gtrsim 1.5\) galaxies by Genzel et al. 2017). The dynamical analysis by Genzel et al. (2020) shows that these massive, high-\(z\) SFGs are baryon-dominated within \(R_e\), with \(f_{\text{DM}}(\langle R_e \rangle) = v_{\text{circ}}^2(\langle R_e \rangle)/v_{\text{circ}}^2(R_e) \lesssim 0.4\), where \(v_{\text{circ}}\) is the total circular velocity, and \(v_{\text{DM}}\) is the velocity due to dark matter. Throughout this work, we refer to these twelve \(z \gtrsim 1.5\) galaxies as the G20 sample.

2.1 Physical properties

The Genzel et al. (2020) galaxies were selected from the SINS/zC-SINF and KMOS3D integral-field spectroscopic surveys (Förster Schreiber et al. 2009, 2018; Wisnioski et al. 2015, 2019), and from the PHIBSS 1 & 2 interferometric surveys (Tacconi et al. 2010, 2013, 2018; Freundlich et al. 2019). This selection was based on the quality of the available data, extended galaxy sizes \((R_{1/2} \gtrsim 2\text{ kpc})\), and sufficiently high H\(\alpha\) or CO surface brightness (see Genzel et al. 2017, 2020, for more details).

As shown in the left panel of Figure 1, our selected G20 galaxies lie along or somewhat above the main sequence of SFGs at their respective redshifts, with star formation rates SFR=50–400 \(M_\odot\) yr\(^{-1}\). Similarly, their half-light radii \((R_{1/2} \sim 3–9\text{ kpc})\) lie along or somewhat above the mass-size relation (middle panel). Their stellar masses are in the range \(4 \times 10^{10} < M_\star/M_\odot < 3.2 \times 10^{11}\). All galaxies have circular velocities \(v_{\text{circ}}(R_e) \sim 250 – 420 \text{ km s}^{-1}\) and intrinsic velocity dispersions \(\sigma_0 \sim 20 – 80 \text{ km s}^{-1}\).

\(^1\) Throughout the paper, we use \(R_e\) to refer to the baryonic half-mass radius of the thick exponential disc component constrained through our dynamical modeling. We use \(R_{1/2}\) to refer to the total half-light radius (including the bulge).
2.2 Dynamical modeling assumptions

For modeling the baryonic mass distribution, Genzel et al. (2020), following Genzel et al. (2017), considered a combination of a thick exponential and axisymmetric disc and a compact bulge. These choices were motivated by the typical structural properties of high-$z$ SFGs (Wuyts et al. 2011; van der Wel et al. 2014a; Lang et al. 2014), and the available ancillary data. For the results on the dark matter distribution we quote in this paper, Genzel et al. (2020) adopted an NFW halo profile. The NFW profile is a two-power-law density model of the form

$$\rho(r) = \frac{\rho_0}{(r/r_s)^\alpha(1 + r/r_s)^{\beta-\alpha}},$$

where $\alpha = 1$ and $\beta = 3$. In this expression, $r_s$ is the halo scale radius, and $\rho_0$ is the characteristic dark matter density. The halo concentration parameter $c \equiv R_{200,c}/r_s$, where $R_{200,c}$ is the virial radius at which the enclosed density equals 200 times the critical density of the Universe, was fixed to typical values determined through the estimated halo mass based on the stellar mass and redshift of each galaxy (Moster et al. 2013) and assuming standard concentration-mass relations from dark matter-only simulations (Dutton & Macciò 2014). Genzel et al. (2020) performed fits with and without adiabatic contraction being effective (see Blumenthal et al. 1986). Their quoted modeling results which we use in this paper, specifically for the central dark matter fraction, represent averages of fits with and without adiabatic contraction (see their Table D1).

The dynamical analysis further accounted for pressure support expected from turbulent motions following Burkert (2010, 2016). This correction results in a reduction of the rotation velocity $v_{\text{rot}}$ with respect to the circular velocity $v_{\text{circ}}$ as a function of radius:

$$v_{\text{rot}}(r) \equiv \sqrt{v_{\text{circ}}^2(r) - 2\sigma_0^2 \frac{r}{R_d}},$$

where $R_d$ is the disc scale length, and the velocity dispersion $\sigma_0$ is assumed to be constant throughout the disc.

In this paper, we adopt these basic assumptions for our modeling of the simulated galaxies, as detailed in Section 3.5. However, differently than Genzel et al. (2020), we do not average NFW fits with and without adiabatic contraction, but instead consider pure NFW haloes together with contracted dark matter haloes based on their intrinsic mass distributions.

2.3 Observational interpretation

The prominent drop in the observed rotation curves of the majority of the most massive, high-$z$ SFGs (see Figures 1 and 2 by Genzel et al. 2017, and Figure 4 by Genzel et al. 2020) can be explained by a combination of two effects: (i) low central dark matter fractions, and (ii) high turbulent motions that produce outward pressure gradients that counteract inward gravity, leading to reduced rotational speeds at large radii.

The central dark matter fractions inferred by Genzel et al. (2020) for the massive $z \geq 1.5$ SFGs we consider in this work are typically lower than predicted from abundance matching in conjunction with NFW halo profiles (Moster et al. 2013, 2018; Behroozi et al. 2013), and also in comparison to lower resolution cosmological simulations such as TNG100 (Lovell et al. 2018; see also Figure 6 by Genzel et al. 2020). Potential reasons for this are small-scale physical processes that might not be adequately captured in large-scale simulations, particularly at early cosmic times: (i) high-$z$ SFGs are more gas-rich than their equal-mass $z = 0$ counterparts, with dissipation processes efficiently channeling baryonic material to the central regions. (ii) Dark matter could be removed from the central galactic regions due to strong AGN and/or stellar feedback, for which there is clear evidence from observations of gas outflows at high redshift (e.g. Shapley et al. 2003; Weiner et al. 2009; Genzel et al. 2011, 2014; Harrison et al. 2016; Förster Schreiber et al. 2019; Freeman et al. 2019; Swinbank et al. 2019, and reference therein), or due to heating of the halo via dynamical friction caused by in-spiraling baryonic material (e.g. El-Zant et al. 2001; Martizzi et al. 2013; Freundlich et al. 2020; A. Burkert et al., in prep.). A consequence could be an alteration of the dark matter density profiles with less dense cores, such as Burkert (1995) or Einasto (1965) profiles.

Based on a comparison of the mass budget in local galaxies with the high baryonic masses already assembled in the high-$z$ SFGs, Genzel et al. (2017, 2020) concluded that their results are consistent with high-$z$ SFGs likely evolving into early-type systems by the present day, after further consumption and/or ejection of their available cold gas. Since present-day early-type galaxies have similarly low central dark matter fractions (e.g. Thomas et al. 2011; Cappellari et al. 2013; Mendel et al. 2020), this suggests that the central mass budget is set early on in the evolution of the most massive galaxies.

3 SIMULATED GALAXIES AND METHODOLOGY

3.1 The TNG50 simulation

The TNG50 simulation (Nelson et al. 2019; Pillepich et al. 2019) is the highest-resolution volume of the IllustrisTNG project (Nelson et al. 2018; Naiman et al. 2018; Marinacci et al. 2018; Pillepich et al. 2018a; Springel et al. 2018), with a uniform periodic-boundary cube of 51.7 co-moving Mpc on a side, and $2 \times 2160^3$ initial resolution elements, half dark matter particles and half gas cells. The simulations are run with the unstructured moving-mesh code Arepo (Springel 2010) and incorporate dark matter, gas, stars, black holes, and magnetic fields. The dark matter and baryonic mass resolutions in TNG50 are $4.5 \times 10^3 M_\odot$ and $8.5 \times 10^4 M_\odot$, respectively, and the gravitational softening lengths at $z = 2$ are 192 pc for stars and dark matter, and adaptive for gas, with a typical size of 100 – 200 pc for star-forming gas. The simulations account for star formation, stellar population evolution, chemical enrichment through supernovae type Ia and II and through AGB stars, gas radiative processes, the formation, coalescence, and growth of supermassive black holes, and feedback from supernovae and black holes (Weinberger et al. 2017; Pillepich et al. 2018b). TNG50 adopts a Planck Collaboration et al. (2016) cosmology with $h = 0.68$, $\Omega_b = 0.05$, $\Omega_m = 0.31$, $\Omega_\Lambda = 0.69$, and $\sigma_8 = 0.82$. 

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3.2 Sample selection

To select simulated galaxies that resemble the available deep observational data of the most massive, high-$z$ SFGs, we choose central galaxies with stellar mass and SFR matched to the observed sample, with $M_*>4\times10^{10}M_\odot$ and SFR $>50M_\odot$ yr$^{-1}$ at $z=2$. For this initial selection we consider the instantaneous SFR and stellar mass within twice the radius enclosing half of the gravitationally bound stellar mass.

Since, as commented above, the G20 galaxies lie partly above the main sequence, this selection results in a simulated sample that is biased low in SFR, as can be seen in the left panel of Figure 1. It is further known that the TNG model predicts SFRs that are systematically lower by $\sim0.4$ dex at $z\sim2$ compared to the Whitaker et al. (2014) observational reference main sequence (Donnari et al. 2019b,a). Similar offsets relative to observations appear in many cosmological hydrodynamical simulations (e.g. Furlong et al. 2015), and are not yet fully understood (but see the tensions between the observed evolution of galaxy masses or luminosity functions and the observed specific SFRs pointed out by e.g. Leja et al. 2015; Yu & Wang 2016; Wilkins et al. 2019). In principle, we could consider applying a systematic correction in the comparison of our simulated SFRs to the main sequence by elevating them by $\sim0.4$ dex: this would in practice correspond to selecting simulated galaxies based on their distance from the TNG50-calibrated (and not the observed) star forming main sequence. This would result in a good match to the G20 galaxies, as indicated by the arrow in the left panel of Figure 1. From the observational side, recent work indicates that masses (SFRs) based on SED-modeling are systematically underestimated (overestimated), however for high stellar masses and SFRs and at $z\sim2$, as in our sample, these effects are supposedly minor (Leja et al. 2019). Therefore, in this paper, we prefer to proceed by selecting analogs of observed galaxies from the TNG50 galaxy population by imposing cuts on stellar mass and star formation rates based on limits taken at face value and accounting for no observational uncertainties.

In total, 12 central galaxies in the TNG50 volume meet these cuts at $z=2$. Of those, we further exclude five galaxies that are either very compact, therefore hampering the extraction of (resolved) kinematics out to sufficiently large radii, or that are clearly interacting or disturbed. We show projected kinematic maps of the dismissed galaxies in Appendix A.

Figure 1 compares stellar mass, SFR, half-light radius, and gas-to-stellar-mass ratio of our parent sample of simulated galaxies to the observational $z\geq1.5$, $M_*>4\times10^{10}M_\odot$ sample by Genzel et al. (2020). Here, and for the reminder of this paper, we quote SFRs and masses of the TNG50 galaxies within a three-dimensional aperture with radius 20 kpc around the potential minimum, which corresponds to the size of our mock data cubes (see Section 3.3). The half-light sizes quoted for TNG50 refer to the radius containing half of the three-dimensional $K$-band luminosity.\(^2\) The individual

\(^2\) Projected two-dimensional sizes are typically lower by $5-40$ per cent, depending on the projection angle.
In Table 1 we list the physical properties of the selected (top seven rows) and excluded TNG50 galaxies (bottom five rows). Examples of $z = 2$ TNG50 galaxies with different stellar mass and/or SFR properties are shown in Figure 11 by Pillepich et al. (2019).

### 3.3 Mock observations

For each selected simulated galaxy we generate mock observations for five lines of sight, for a total of 35 mocks. We first align the coordinate system of the galaxy using its moment of inertia tensor of the star-forming gas, such that the galactic plane coincides with the $xy$-plane, and the axis of rotation with the $z$-axis. We then define a line of sight by an inclination angle with respect to the $z$-axis and an orientation angle with respect to the $x$-axis. The five lines of sight are equally spaced around the galaxy and correspond to the same inclination and position angle. This choice allows us to examine the rotation symmetry of the simulated galaxies using one-dimensional kinematic extractions.

For each line of sight we bin the star-forming gas cells into a cube in position-position-velocity space which we subsequently convert to angular size and wavelength, such that our final cube sampling is $0.05'' \times 0.05'' \times 2.45 \, \text{Å}$. At $z = 2$, 1$''$ corresponds to 8.0 kpc, and 1 Å corresponds to 15 km s$^{-1}$ in $K$-band. The cube is centered spatially on the potential minimum and in velocity direction on the center-of-mass velocity of the stellar component of the galaxy (which differs insignificantly from that of the gas). Then it is convolved with a three-dimensional Gaussian with a FWHM of 2 kpc and 80 km s$^{-1}$ in the spatial and velocity directions, respectively, to approximate the effects of the instrument point spread function (PSF) and line spread function (LSF) for instruments such as SINFONI at the VLT in adaptive optics mode (Eisenhauer et al. 2003). The PSF and LSF are typically well known from observations of standard stars and sky lines.

We then convert the instantaneous SFR into H$\alpha$ luminosity (Kennicutt 1998). In Appendix B, we briefly discuss the effect of dust on the mock-observations and kinematic extractions. However, accounting for dust does not affect our main conclusions, and we therefore do not include it in the main part of our analysis. To account for realistic noise properties, including from random and systematic sources, and in particular stemming from the strong night sky line emission in the near-IR, we embed the mock data cube into a real noise cube from a deep SINFONI observation at $z \approx 2$ (cf. Genel et al. 2012). To avoid biases due to a specific realization, we also randomize the noise cube for each mock observation. In addition, the mock line emission is scaled to reproduce the typical signal-to-noise ratio (S/N) of deep high-$z$ observations, with an average $S/N$ per spaxel of $S/N \gtrsim 20$ in the central regions.

### 3.4 Kinematic extractions

With our mock data cubes in hand, we derive the kinematic properties of the simulated galaxies following the same

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**Table 1.** Physical properties of the TNG50 galaxies selected for kinematic analysis (top seven rows), and excluded (bottom 5 rows): stellar mass $M_*$, gas mass $M_{\text{gas}}$, and instantaneous star formation rate SFR, all within a three-dimensional aperture with radius 20 kpc around the potential minimum, and the three-dimensional $K$-band half-light size $R_{1/2}$.

| ID, subhalo (symbol) | $M_*$ [$10^{11} M_\odot$] | $M_{\text{gas}}$ [$10^{10} M_\odot$] | SFR [$M_\odot$ yr$^{-1}$] | $R_{1/2}$ [kpc] |
|---------------------|-----------------|-----------------|------------------|-----------------|
| #1, 25822 ($\Delta$) | 1.0             | 0.6             | 71               | 2.0             |
| #2, 39746 ($\circ$) | 1.1             | 0.8             | 119              | 4.0             |
| #3, 55107 ($\bigcirc$) | 1.5             | 1.0             | 110              | 3.7             |
| #4, 60751 ($\gamma$) | 0.5             | 0.5             | 48               | 6.2             |
| #5, 79351 ($\delta$) | 1.2             | 0.6             | 92               | 3.2             |
| #6, 92272 ($\bigcirc$) | 0.5             | 0.3             | 70               | 2.1             |
| #7, 99304 ($\odot$) | 0.6             | 0.4             | 50               | 2.2             |
| #8, 44316             | 0.9             | 0.7             | 309              | 0.7             |
| #9, 50682             | 1.4             | 0.3             | 45               | 1.6             |
| #10, 59076            | 0.9             | 0.3             | 66               | 1.5             |
| #11, 74682            | 0.5             | 0.5             | 114              | 2.1             |
| #12, 101499           | 0.9             | 0.2             | 65               | 0.5             |

Galaxies are shown on top of the underlying galaxy population at $1.5 < z < 2.5$ based on the 3D-HST catalogue (Brammer et al. 2012; Skelton et al. 2014; Momcheva et al. 2016) with selection cuts $\log(M_*/M_\odot) > 9.2$, $K_{AB} < 23$ mag, and for the middle panel also SFR/$M_* > 0.7/H_{\text{Hubble}}$. TNG50 galaxies at $z = 2$ with $M_*>4 \times 10^{10} M_\odot$ and SFR $> 50 M_\odot$ yr$^{-1}$ but excluded from the main kinematic analysis are shown as crosses. In the left and middle panels, the TNG50 galaxies are normalized to the same observationally constrained star-forming main sequence and mass-size relations as are the observations.

Beyond the SFR and stellar mass comparison discussed so far, the half-light sizes of the kinematic sample are comparable but somewhat lower. Similar to systematic differences in SFR when comparing to observations, differences in sizes of SFGs are known for the TNG model: different measures of half-light or half-mass sizes for simulated $M_*>10^{11} M_\odot$ galaxies at $z = 2$ give sizes that are on average lower by factors of 1.5–2 compared to observations (Genel et al. 2018; Pillepich et al. 2019).

For 5/7 included TNG50 galaxies, the gas-to-stellar-mass ratios are lower by up to ~40% compared to what would be predicted by the Tacconi et al. (2018) scaling relations (filled vs. open symbols in the right panel of Figure 1). These relations provide estimates of molecular gas-to-stellar mass ratios and depletion time scales based on redshift, stellar mass, and main sequence offset of a galaxy. Therefore, gas mass estimates based on these scaling relations may correspond to lower limits, while the intrinsic gas masses entering Figure 1 and Table 1 correspond to total gas masses within a 20 kpc radius. Modulo this caveat, the difference between the values calculated directly from the intrinsic $M_{\text{gas}}/M_*$ and the scaling relation predictions for TNG50 galaxies included in the kinematic analysis, is within the typical uncertainty expected for individual galaxies. Furthermore, if we only consider the scaling relation predictions for the TNG50 galaxies (open symbols and small crosses), we find that they are in good agreement with both the values of the G20 sample and the underlying 3D-HST population (both also showing gas ratios based on the Tacconi et al. (2018) scaling relations).

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3 In reality, the PSF can be of more complex functional shape (see Förster Schreiber et al. 2018, for SINFONI observations).
methods used by Genzel et al. (2020). First, we derive the two-dimensional projected Hα velocity and velocity dispersion fields using linefit (Davies et al. 2009, 2011; Förster Schreiber et al. 2009). This code takes into account the instrument LSF and fits a Gaussian profile to the line spectrum of each spaxel of the data cube.

For the extraction of one-dimensional kinematic profiles (the rotation curve and the dispersion profile), we go back to the mock data cube and place a pseudo-slit of width 0.24′′ (2 kpc) on the kinematic major axis of the galaxies to generate a position-velocity diagram. Through cuts in velocity direction of width 4 pixels (∼1.7 kpc) we then extract one-dimensional line profiles for different positions along the kinematic major axis. From those, we extract the velocity and velocity dispersion as a function of distance from the center using linefit.

Through visual inspection, we exclude radial bins where the assumption of a Gaussian profile is not justified by the line shape. This primarily affects extractions close to the galactic centers, where a broad range of velocities is blended through the finite spatial resolution and beam-smearing, and some regions in the galaxy outskirts that are strongly affected by skylines.

We adjust the centers of the one-dimensional profiles based on the steepest velocity gradient along the kinematic major axis, and the peak of the dispersion profile. The so determined kinematic centers deviate from the mock cubes centers (see Section 3.3) by less then the PSF and LSF FWHM.

Following Genzel et al. (2017), we assign minimum uncertainties of ±5 km s$^{-1}$ for the velocity and ±10 km s$^{-1}$ for the velocity dispersion to more realistically account for systematics when the formal fitting uncertainties become very small.

### 3.5 Dynamical modeling

For the modeling of our mock galaxies we use the dynamical fitting code DYSMAL (Cresci et al. 2009; Davies et al. 2011; Wuyts et al. 2016; Übler et al. 2018; S. Price et al. in prep.), a forward-modeling code that allows for the combination of multiple mass components. It accounts for flattened spheroidal potentials (Noordermeer 2008), includes the effects of pressure support on the rotation velocity (Burkert et al. 2010), accounts for beam-smearing effects through convolution with the two-dimensional PSF, and for the instrument LSF. Here, we use again a three-dimensional Gaussian with a FWHM of 2 kpc and 80 km s$^{-1}$ in the spatial and velocity directions, respectively. We assume a velocity dispersion σ$\theta$ that is isotropic and constant throughout the disc.

#### 3.5.1 Baryonic parameters

We assume that the Hα kinematics trace the underlying mass distribution. Systematic studies of representative high-$z$ SFGs have shown that on average sizes based on Hα tracing the young star-forming regions are larger by a factor 1.1-1.2 compared to sizes based on stellar light (Nelson et al. 2016; Wilman et al. 2020). Wuyts et al. (2016) have shown that adopting a larger effective radius would typically increase the total dynamical mass by about 0.06-0.08 dex (see also Übler et al. 2019), but that it would not significantly alter the mass within the effective radius. On the other hand, far-infrared observations have started to reveal important dust aggregations that may obscure the stellar light in the central regions of massive SFGs at $z \sim 2$, suggesting that sizes based on stellar light might be overestimated (e.g. Tadaki et al. 2017; K. Tadaki et al., in prep.). In Appendix B, we show as an example for one galaxy the effect of dust obscuration: the S/N in the central regions is particularly affected, but the extracted kinematics beyond the inner 2 − 3 kpc do not change.

We consider two baryonic components for the dynamical modeling: a thick exponential disc and a central bulge. For the disc, we adopt a ratio of scale height to scale length $h_z/R_d = 0.2$, motivated by the observed fall-off in the distribution of axis ratios of SFGs in this stellar mass and redshift range (van der Wel et al. 2014a), and a Sérsic index $n_{S,\text{disc}} = 1$. For the bulge, we assume an effective radius $R_{e,\text{bulge}} = 1$ kpc and a Sérsic index $n_{S,\text{bulge}} = 4$ (Lang et al. 2014; Tacchella et al. 2015).

For the baryonic disc effective radius $R_e$, we use a Gaussian prior centered on the $K$-band half-light radius $R_{1/2}$, with a standard deviation of 1 kpc and hard bounds of 1.5-10 kpc. Using $R_{1/2}$ as a prior provides an initial (although somewhat uncertain, see discussion above) guess for the disc size that is in principle expected to be larger for bulgy galaxies. From our modeling, we find baryonic disc effective radii that are typically larger by ∼15 per cent compared to the input half-light radii. For the total baryonic mass we use a Gaussian prior centered on the intrinsic value with a standard deviation and hard bounds of 0.2 dex and ±0.5 dex. With this approach, we fold into our modeling the typical uncertainties on those parameters expected from observational data. We assume a flat prior for $B/T$ between 0 and 0.6, motivated by the typical values expected for SFGs in this stellar mass range and redshift (see Lang et al. 2014). For the intrinsic velocity dispersion σ$\theta$, we adopt a flat prior between 10 and 100 km s$^{-1}$, covering the range of values observed in SFGs at $z \sim 2$ (see Übler et al. 2019, and references therein).

We fix the disc inclination and position angle to the intrinsic values of $i = 60^\circ$ and PA$_{\text{kin}} = 90^\circ$, and mock-observe galaxies from different lines of sight keeping inclination and position angle fixed. In doing so, we put our focus on any kinematic asymmetries, and their impact on the dynamical modeling results. For the observations by Genzel et al. (2017, 2020), the inclination is inferred from the minor-to-major axis ratio of the stellar light distribution, known from ancillary data, and fixed for high-inclination systems. Changes/uncertainties in inclination translate directly into changes/uncertainties in the dynamical mass estimate (see e.g. Übler et al. 2018). Therefore, we have tested including the inclination as a model parameter in the range

---

4 We note that the typical ratio of half-light height to half-light size for massive $z = 2$ SFGs in TNG50 is closer to $h_z/R_{1/2} \sim 0.1$ (Pillepich et al. 2019), and from bulge-to-disc decompositions to the azimuthally averaged baryon distribution we find bulge sizes $R_{e,\text{bulge}} < 1$ kpc for our sample. However, because these quantities are typically hard to measure observationally for individual, high-$z$ galaxies, we proceed with these typically adopted values for modeling of observational data.
10

\[ r_{200,c} \approx 174 \text{ kpc} \]

This halo has a virial radius \( R_{200,c} \approx 174 \text{ kpc} \) with a total mass of \( \log(M_{200,c}/M_\odot) = 12.7 \). The substructure visible at a distance of 40 kpc hosts a companion galaxy with a stellar mass ratio to the central galaxy of 1:5 (see Section 4.1). For our modified NFW fit we find a scale radius \( r_s \approx 74 \text{ kpc} \), corresponding to a concentration parameter of \( c = 4.4 \). For the pure NFW fit we find \( r_s \approx 27 \text{ kpc} \), corresponding to \( c = 6.4 \).

\[ i = 30 – 90^\circ \]

The true inclination of \( i = 60^\circ \) is typically recovered within the 1σ MCMC posterior distribution, and the effect on the other model parameters is minor.

\subsection*{3.5.2 Dark matter density profile}

The results by Genzel et al. (2020) that we compare to in this work assume a standard NFW dark matter halo profile for the dynamical modeling, with adiabatic contraction effective, or not (but see their modeling results with free \( \alpha \)). Through modified fits to the intrinsic dark matter density distributions of the TNG50 galaxies with \( \beta = 3 \) but \( \alpha \) as a free parameter, we find that all simulated haloes have a steeper inner slope with respect to a pure NFW halo, with individual values of \( \alpha = 1.4 – 1.7 \). These values indicate contractions of the dark matter haloes (see also Lovell et al. 2018). An example is shown in Figure 2: the intrinsic halo profile (blue dots) is well-fitted by a modified NFW halo with \( \alpha = 1.5 \) (yellow line; except for the companion at \( r \approx 40 \text{ kpc} \)), whereas a pure NFW fit underestimates the dark matter density on galactic scales (red line).

Through these fits to the intrinsic dark matter density distribution, we also constrain the halo concentration parameter \( c = R_{200,c}/r_s \). The scale radius, \( r_s \), is defined to be the radius where the slope of the density profile equals \(- (\beta + \alpha)/2 \). This is by definition –2 for an NFW halo, but varies for our modified NFW haloes with values \( \leq -2 \), leading to larger scale radii (see also Figure 2).

For our fiducial models, we adopt both unmodified and modified NFW profiles for the dark matter distribution, and leave the total halo mass as a free parameter between \( M_{200,c} = 10^{11} - 10^{13.5}M_\odot \).

\subsection*{3.5.3 MCMC setup}

Using Dysmal, we simultaneously fit the extracted one-dimensional velocity and velocity dispersion profiles. We apply Markov chain Monte Carlo (MCMC) sampling to determine the model likelihood based on comparison to the extracted profiles, and assuming Gaussian measurement uncertainties. To ensure convergence of the MCMC chains, we model each galaxy with \( \geq 200 \) walkers per free parameter, and a burn-in phase of 100 steps followed by a running phase of 200 steps (> 10 times the maximum auto-correlation length of the individual parameters). For each free parameter, we adopt the median of all model realizations as our best fit value, with asymmetric uncertainties corresponding to the 68th percentile confidence ranges of the one-dimensional marginalized posterior distributions.

To summarize, in our modeling setup we leave the following five parameters free, using flat or truncated Gaussian priors: the total baryonic mass \( M_{\text{bar}} \), the baryonic disc effective radius \( R_e \), the baryonic bulge-to-total fraction \( B/T \), the intrinsic velocity dispersion \( \sigma_0 \), and the total halo mass \( M_{\text{halo}} \). All other parameters are fixed, including the bulge effective radius, the bulge and disc Sérsic indices, inclination, and position angle. Also the dark matter halo profile shape is fixed, to either NFW, or to the individual, two-power density fits with free \( \alpha \) and \( \beta = 3 \). For the observed galaxies, the best-fit parameters are as published by Genzel et al. (2020).

\section*{4 RESULTS}

\subsection*{4.1 Intrinsic kinematics}

Before we present the results of our mock observations and modeling, we first discuss intrinsic kinematic properties of the TNG50 sample to create a basis for our further discussion. Not all details simulated are accessible for real galaxies, but their study can highlight effects that are potentially relevant to observational work.

In Figure 3 we show different measures of the intrinsic, one-dimensional velocity and velocity dispersion profiles for all selected galaxies. The radial velocity dispersion \( \sigma_r \) (turquoise), the vertical velocity dispersion \( \sigma_z \) (light brown) and \( \sqrt{\sigma^2_{\text{rot}} + \sigma^2_r} \) (blue) are measured ‘locally’, i.e. in \( xy \) bins of 0.5 kpc length, and subsequently averaged, as is the vertical velocity component \( v_z \) (purple lines show \( |v_z| \)). All other properties are azimuthal averages: the rotation velocity \( v_{\text{rot}} \) (salmon), radial velocity \( v_r \) (magenta), and modifications to \( v_{\text{rot}} \) including velocity dispersion (light brown) and vertical and radial motions (dark brown). For the velocity dispersion measures, the final azimuthal averages are luminosity-weighted. In addition, we show as a reference the circular velocity...
\[
\begin{align*}
\nu_{c,\text{sph}} &= \left(\frac{\text{GM}(<r)}{r}\right)^{0.5} \\
\nu_{\text{rot}} &= \left(\frac{\nu_{\text{rot}}^2 + 2\sigma_{3D}^2}{3} \frac{r/R_d}{3}ight)^{0.5} \\
\nu_r &= \left(\frac{\nu_{\text{rot}}^2 + 2\sigma_{3D}^2}{3} \frac{r}{R_d} + \nu_r^2 + \nu_z^2\right)^{0.5} \\
\sigma_r &= |\nu_z| \\
\sigma_z &= \sigma_{3D}/\sqrt{3}
\end{align*}
\]

Figure 3. Different measures of the intrinsic velocity and velocity dispersion of a selection of TNG50 simulated galaxies, as indicated in the legend. The circular velocity \(\nu_{c,\text{sph}}\) (black line) is calculated from the enclosed mass assuming spherical symmetry. The radial velocity dispersion \(\sigma_r\) (turquoise), vertical velocity dispersion \(\sigma_z\) (green), and three-dimensional velocity dispersion \(\sigma_{3D}/\sqrt{3}\) (blue) are measured ‘locally’ in \(xy\) bins of 0.5 kpc length, and subsequently averaged, as is the vertical velocity component \(\nu_z\) (purple lines). All other properties are azimuthal averages. Light and dark brown lines show different corrections to the rotation velocity \(\nu_{\text{rot}}\) (salmon) from turbulent and other non-circular motions. Grey vertical dashed lines indicate the location of the stellar half-light radii (see Table 1). Beyond \(r \sim 2\) kpc, the velocity dispersion is approximately constant with radius. All galaxies show substantial radial (magenta) and vertical motions.

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Figure 4. Projected two-dimensional maps of the star-forming gas and its kinematic properties of the seven TNG50 selected galaxies. The top three rows show PSF-convolved intrinsic parameters (top row: $\Sigma_{SFR}$; second row: velocity; third row: velocity dispersion). The bottom two rows show the velocity and dispersion fields with $S/N \geq 5$ after including realistic noise, discretization into pixels, and Gaussian line fitting (fourth row: velocity; bottom row: velocity dispersion) for the seven selected TNG50 galaxies (columns). The projections correspond to an inclination of $i = 60^\circ$. The panels show $40$ kpc $\times$ $40$ kpc in projection, and the color scale shows $[-2; 1]$ for $\Sigma_{SFR}/(M_{\odot} \cdot \text{yr}^{-1} \cdot \text{kpc}^{-2})$, $[-400; 400]$ km s$^{-1}$ for velocity, and $[0; 150]$ km s$^{-1}$ for velocity dispersion. The mock velocity and dispersion fields retain a large amount of the information content of the intrinsic kinematics in regions of high star-formation rate surface density.

$v_{c,\text{sph}}(r) = \sqrt{G \cdot M(< r)/r}$, calculated from the enclosed mass under the assumption of a spherically symmetric potential (black line). Note that the rotation curve of a thick exponential disc has a peak velocity that is about 10 per cent higher compared to a spherical distribution of the same mass (e.g. Casertano 1983; Binney & Tremaine 2008).

The three different measures of the intrinsic velocity dispersion agree well, suggesting that the velocity dispersion is fairly isotropic. Furthermore, beyond $r \sim 1 – 2$ kpc the velocity dispersion is remarkably constant, suggesting the existence of a galaxy-wide pressure floor, consistent with other galaxy formation models (e.g. Teklu et al. 2018; Wellons et al. 2020). High-quality, adaptive-optics resolution observations of individual galaxies support roughly constant and isotropic velocity dispersions (Genzel et al. 2011; Übler et al. 2019). At the half-light radius (vertical grey dashed line), the velocity dispersion measures are typically below $50$ km s$^{-1}$.

Out to $r \sim 10$ kpc and sometimes beyond, the gas rotation velocity $v_{\text{rot}}$ approximately traces $v_{c,\text{sph}}$. The light brown lines show the rotation velocity corrected for pressure support following Burkert et al. (2010) and using the three-dimensional velocity dispersion $\sigma_{\text{3D}}(r)/\sqrt{3}$. Due to the high rotation velocities ($\sim 250 – 450$ km s$^{-1}$) and the moderate velocity dispersion, the relative effect of this pressure effect of including a ‘thermal term’ (Pillepich et al. 2019) to account for unresolved or sub-grid gas motions.
support correction is small for most simulated galaxies. For galaxies #1, #2, and #5, the pressure correction overshoots \( v_{\text{c,sph}} \) at \( r \sim 5 - 10 \) kpc. Due to the different assumption about the mass distribution for \( v_{\text{c,sph}} \), this is not unexpected.

All simulated galaxies show substantial amounts of vertical \( v_z \) and radial motions \( v_r \). The magnitudes of these motions are often correlated (e.g., galaxy #1, top left panel), suggesting streaming motions diagonal to the galactic plane, possibly related to minor mergers (as opposed to pure radial inflow triggered by bar or disc instabilities). To assess the impact of these additional non-circular motions, we ‘correct’ the rotation velocity in a simplistic attempt not only for pressure support, but also for radial and vertical motions as follows:

\[
v_{\text{circ}}(r) \equiv \sqrt{v_{\text{rot}}^2(r) + 2\frac{\sigma_z^2(r)}{3} + v_z^2(r) + v_r^2(r)}
\]  

(3)

This correction leads to the dark brown line, which in some cases corresponds better to \( v_{\text{c,sph}} \) (see also Wellons et al. 2020), seen especially in the outer regions of galaxies #5-7 at \( r \gtrsim 7 \) kpc (beyond their visible extent). These motions, however, most likely correspond to low-surface brightness, misaligned accreting gas.

In general, the non-circular motions present in the TNG50 galaxies could also explain the sometimes large differences in rotation curve shapes at fixed inclination that we discuss later on in Section 4.3 (see also Oman et al. 2019).

**Comments on environment:** Some of the deviations from circular motions in the simulated galaxies could stem from tidal interactions with other massive galaxies (not in our main sample), a factor that is not captured by our initial selection criteria. Indeed, galaxies #2, #3, and #4 have in their vicinity (\( \Delta r = 30 - 60 \) kpc) another massive galaxy (mass ratio \( \geq 1:2 \) for #2 and #4, and mass ratio 1:5 for #3). Galaxies #2, #3, and #4 also show asymmetries in their extracted rotation curves, and among different lines of sight (see Figures 5 and 6). Galaxy #1 has a companion with mass ratio \( \geq 1:2 \), but at a distance of 140 kpc. In contrast, galaxies #5, #6, and #7 are sufficiently isolated from similarly massive objects to be considered undisturbed, supporting the above interpretation of accreting gas being responsible for the large vertical and radial motions beyond \( r = 7 \) kpc.

Five galaxies in the selected G20 sample have potentially close (\( \Delta r = 6 - 21 \) kpc) but low-mass (mass ratios 1.8–1.50) companions (see Table 1 by Genzel et al. 2020). As discussed in detail by Genzel et al. (2017, 2020), even such smaller satellites can in theory affect the kinematics of the main galaxy, if they are close enough. In Section 4.3 we present an analysis of the symmetry properties of the simulated and observed rotation curves. From this analysis, we do not see any evidence that these five systems are systematically more asymmetric compared to the other galaxies without companions. We refer the reader to Genzel et al. (2020) for a more in-depth presentation of the environmental properties of the full observational sample.

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6 In Appendix C, we briefly describe the effect of vertical and radial motions on the kinematic extraction of rotation velocity and velocity dispersion.
Kinematics and dark matter fractions of $z = 2$ galaxies in TNG50

Figure 5. Extracted kinematics along five different lines of sight (columns) for galaxy #3 from TNG50. The inclination is always $i = 60^\circ$.

Top row: noise-free, convolved velocity map, 40 kpc $\times$ 40 kpc in projection, with colors corresponding to [-400; 400] km s$^{-1}$; second row: extracted velocity along the kinematic major axis; bottom row: extracted velocity dispersion along the kinematic major axis, corrected for the ‘instrument’ LSF. Otherwise, the extracted profiles are shown in ‘observed space’, i.e. not corrected for inclination and ‘beam smearing’. Not shown here are velocity and dispersion extractions for emission regions with highly non-Gaussian line profiles, typically found in the central 0.2 – 0.5″ of the mock data. The horizontal grey lines in the top row panels illustrate the pseudo slit used for the one-dimensional kinematic extractions. The kinematic extractions correspond well to the intrinsic kinematic features: particularly the rotation velocities can differ substantially along different lines of sight. Variations in the velocity dispersion are more modest, and typically within the uncertainties, which can however become large in the outer regions.

and 1 indicates complete overlap, including uncertainties). This is done for each radial bin, if necessary using linear interpolation, and then divided by the sum of radial bins to get a normalized value for each rotation curve. For the TNG50 galaxies, we find values of 0.09 to 0.73 (0.20 to 0.64 when averaged among different lines of sight per galaxy), with a median 0.46 (0.45). In the comparison G20 sample, we find values of 0.38 to 0.81, with a median of 0.58. Because this measure is directly affected by the signal-to-noise ratio, we recalculate the coefficient by fixing the width of the normal distributions (i.e. the velocity uncertainty) to a common value of 10 km s$^{-1}$, to capture the rotation curve asymmetry independent of S/N. While the values for the G20 galaxies change slightly, for a median value of 0.57, for the simulated galaxies we now find a substantially lower median of 0.27.

We use a second method to characterise asymmetry: we fit a quadratic function to one side of the rotation curve, calculate the reduced chi-squared statistics ($\chi^2_{\text{red}}$), and compare it to the other side of the rotation curve through point reflection. The difference between the goodness-of-fit for both sides is $\Delta \chi^2_{\text{red}}$, and we calculate it independently for fits to both sides of the rotation curve. We find average values of $\chi^2_{\text{red}} = 0.9$ when considering only one side of a rotation curve, indicating that small values of $\Delta \chi^2_{\text{red}} \sim 1$ would correspond to both good fits and symmetric rotation curves. We find mean (median) $\Delta \chi^2_{\text{red}} = 46.8$ (5.8) for the simulated galaxies, and mean (median) $\Delta \chi^2_{\text{red}} = 2.1$ (1.6) for the G20 sample. Again, we repeat our calculations for fixed velocity uncertainties of $\delta v_{\text{rot}} = \pm 10$ km s$^{-1}$. For the TNG50 galaxies, we find mean (median) $\Delta \chi^2_{\text{red}} = 41.4$ (18.1), while for the G20 sample we find mean (median) $\Delta \chi^2_{\text{red}} = 3.7$ (3.4). This test shows that the large $\Delta \chi^2_{\text{red}}$ we find for the TNG50 galaxies is not due to S/N, but is because the rotation curves are less symmetric.

Both methods demonstrate that the simulated galaxies show large asymmetries in their rotation curves, and are less regular compared to the galaxies observed by Genzel et al. (2020). For their full sample, Genzel et al. (2020) find that only 3/41 rotation curves show significant devia-

7 Some galaxies in our G20 comparison sample have a larger FWHM ($\sim 5$ kpc) due to seeing-limited observations. To test the effect of a larger PSF size on the (as)symmetry of our simulated sample, we repeated our mock-observation and kinematic extractions for galaxy #3, now mimicking seeing-limited data. Perhaps surprisingly, we find no systematic effect of the PSF size on the symmetry of the extracted kinematics using both measures described above. This is probably because we trace kinematics out...
Figure 6. Extracted velocity profiles along five different lines of sight (colors) for galaxies #1, #2, #4, #5, #6, and #7 (from left to right and top to bottom). The rotation curves are shown in ‘observed space’, i.e. not corrected for inclination and ‘beam smearing’. We find variations in extracted major axis velocities along different lines of sight, particularly for galaxies #4, #5, #7, and #3 (Figure 5).

4.4 Dynamical modeling performance

For all seven galaxies, we model the one-dimensional kinematics along all five lines of sight with DYSMAL. Generally, asymmetric kinematics along the major axis hamper successful modeling because the code assumes axisymmetric mass distributions.

The unique advantage of modeling mock observations is that we can compare the modeling results to intrinsic properties of the simulated galaxies. However, in comparing the output of our dynamical modeling to these intrinsic values, it is important to keep in mind some model assumptions. We discuss those assumptions in Section 4.4.1 for velocity dispersion, baryonic mass, and central dark matter fraction, before we compare model outputs and intrinsic values in Section 4.4.2.

4.4.1 Relation between model output and intrinsic measurements

(i) For baryonic masses, our model assumes a specific mass distribution of a thick exponential disc and a central bulge, while for our intrinsic measurement we simply sum the baryonic mass of the central galaxy within a sphere of radius $r = 20$ kpc. For comparing intrinsic and model baryonic masses, we therefore use the model baryonic mass within $20$ kpc, $M_{\text{bar},20}$, instead of the total mass integrated to infinity. Typically, 99 per cent of $M_{\text{bar}}$ are encompassed in $M_{\text{bar},20}$ (97 per cent for the largest galaxy #4). Intrinsically, there might be some amount of additional, extra-planar, stellar or gaseous material within $r = 20$ kpc that is not reflected in our dynamical model that assumes a specific mass distribution. Therefore, we would expect model baryonic masses $M_{\text{bar},20}$ that tend to be lower compared to the intrinsic measurement.

(ii) For velocity dispersions, our model assumes an isotropic and constant value throughout the galactic disc, while our intrinsic measurement captures the local velocity dispersion and its azimuthally averaged variations (see Section 4.4.1).
For a more meaningful comparison, we therefore use the median of the azimuthally averaged, local, intrinsic velocity dispersion to compare to our model output. Furthermore, our kinematic model neglects any specific motions besides velocity dispersion and in-plane disc rotation, such as inflows, outflows, or warps. Since substantial vertical and radial motions are present in the simulated galaxies (see Section 4.1), we would expect model velocity dispersions that tend to be higher compared to our intrinsic measurements.

(iii) For dark matter fractions, our primary model output is $f_{\text{DM}}^m(< R_e) = \frac{\sigma^2_{\text{DM}}(< R_e)}{\sigma^2_{\text{tot}}(< R_e)}$, following Genzel et al. (2017, 2020), while our intrinsic measurement gives the fraction of dark matter mass to total mass within a sphere of a certain radius, $f_{\text{DM}}^e(< R_e) = \frac{M_{\text{DM}}(< R_e)}{M_{\text{tot}}(< R_e)}$. For a spherical mass distribution, $f_{\text{DM}}^m$ and $f_{\text{DM}}^e$ are identical. However, in our dynamical models most of the baryonic mass is distributed in a flattened $N_s = 1$ disc. Therefore, the velocity-based fraction at the baryonic disc effective radius $R_e$, $f_{\text{DM}}^m(< R_e)$, is typically lower compared to the mass fraction $f_{\text{DM}}^e(< R_e)$ that is agnostic to the inwards distribution of mass – however, $f_{\text{DM}}^m(< R_e)$ can also be larger than $f_{\text{DM}}^e(< R_e)$, for instance in case of large bulge fractions, or low $N_s, \text{disk}$. For comparing intrinsic and model dark matter fractions, we therefore convert our velocity-based, model dark matter fractions, $f_{\text{DM}}^m$, to mass-based dark matter fractions, $f_{\text{DM}}^m$, (see also S. Price, in prep.). On average, $f_{\text{DM}}^m(< R_e)$ is larger by a factor of 1.12 (1.10) compared to $f_{\text{DM}}^e(< R_e)$ for our TNG50 models with modified (unmodified) NFW haloes.

### 4.4.2 Comparison between model output and intrinsic measurements

Considering first the modeling results using a modified NFW halo, we find that those galaxies with the most symmetric rotation curves following the $\Delta \chi^2_{\text{tot}}$ statistics described in Section 4.3 (namely #6 and #1; cf. Figure 6), also have the most accurate modeling results in terms of recovering the central dark matter fraction $f_{\text{DM}}^m(< R_e) = M_{\text{DM}}(< R_e) / M_{\text{tot}}(< R_e)$ (see Table 2). For these galaxies, all lines of sight lead to best-fit values of $f_{\text{DM}}^m$ that agree within their uncertainties with the intrinsic values. Similarly, the best-fit models for the galaxy with the least symmetric rotation curve (#5, cf. Figure 6) do worst in estimating the central dark matter fraction, and only one line of sight has a model $f_{\text{DM}}^m(< R_e)$ that agrees within its uncertainties with the intrinsic value. Overall, we recover $f_{\text{DM}}^m(< R_e)$ in 69 per cent of cases within one standard deviation (68th percentile) of the one-dimensional marginalized MCMC posterior distributions. Note that this success rate is precisely expected from the statistics described in Section 4.3. This is well within typical uncertainties on $f_{\text{DM}}^m(< R_e)$ derived from modeling of observational data at high-$z$, which are 10 – 15 per cent (see also Figure 7).

We recover the baryonic mass within 20 kpc in 74 per cent of cases within one standard deviation of the one-dimensional marginalized MCMC posterior distributions. In
Figure 7. Difference in intrinsic vs. inferred central dark matter fractions \( f^\text{in}_{\text{DM}}(< R_e) = M_{\text{DM}}(< R_e)/M_{\text{tot}}(< R_e) \) based on the dynamical modeling of seven TNG50 simulated galaxies seen from five different projections each. The histograms show the distribution of \( \Delta f^\text{fit}_{\text{DM}}(\sim R_e) = f^\text{fit}_{\text{DM}, \text{fit}}(\sim R_e) - f^\text{fit}_{\text{DM}, \text{true}}(\sim R_e) \) for fits with a modified NFW halo (black) and a pure NFW halo (blue dash-dotted), and the arrows indicate the median \( \Delta f^\text{DM}_{\text{fit}}(\sim R_e) \). The error bar at the top gives the typical uncertainty on the central dark matter fraction for fits to observational data, \( \sigma f^\text{DM}(\sim R_e) \approx \pm 0.11 \). For our TNG50 galaxies, the model setup with a modified (i.e. contracted) NFW halo slightly underestimates the central dark matter fraction by 0.05 per cent on average, and the setup with an NFW halo by 0.13 per cent.

Figure 7 illustrates the deviations from the true dark matter fraction for our model setups with a standard and a modified NFW halo. The histograms show the distribution of \( \Delta f^\text{DM}_{\text{fit}} = f^\text{fit}_{\text{DM}, \text{fit}} - f^\text{fit}_{\text{DM}, \text{true}} \) for fits with a modified NFW halo (black) and a pure NFW halo (blue dash-dotted), and the arrows indicate the median \( \Delta f^\text{DM}_{\text{fit}} \). As in Tables 2 and 3, we consider the dark matter mass fraction within \( r = R_e \), where \( R_e \) is the model output best-fit baryonic disc effective radius. While both model setups (slightly) underestimate \( f^\text{DM}(< R_e) \) on average, the modified NFW setup performs somewhat better. For the TNG50 galaxies, this is not unexpected: recall from Figure 2 that the NFW fit generally underestimates the dark matter density within the inner \( \sim 10 \) kpc for those galaxies. Assumptions on the halo profile can potentially have a systematic effect on galaxy-scale dynamical masses and total dark matter halo masses derived from observed kinematics. Genzel et al. (2020) show that the low central dark matter fractions of their massive, high-\( z \) SFGs (our comparison sample), can be explained if the associated haloes have central cores, instead of a cuspy NFW profile (see also S. Price et al., in prep.).

4.5 Comparison to observations

We now compare intrinsic, as well as mock-observed and subsequently modelled properties of the TNG50 sample to the selected G20 galaxies. For this, we average our modeling results using a modified (i.e., contracted) and a standard NFW halo, similar to the observational comparison values by Genzel et al. (2020) which are averages of adiabatically contracted and standard NFW haloes.

4.5.1 Intrinsic velocity dispersion

We start with the intrinsic velocity dispersion \( \sigma_0 \). As discussed in Section 2.3, this is an important quantity in the observational interpretation of the results by Genzel et al. (2017, 2020) because of its effect on the outer rotation curve shape through potential reduction of rotational speeds via pressure support. In Section 4.1 we showed for the TNG50 sample that different measures of the intrinsic velocity are approximately constant as a function of radius, and that our modeling procedure can recover the intrinsic velocity dispersion within one standard deviation of the marginalized MCMC posterior distribution in most cases (Section 4.4).

In Figure 8 we show \( \sigma_0 \) as a function of stellar mass for the intrinsic and modeled simulated data, together with observations from Genzel et al. (2020) and Uhler et al. (2019). Intrinsically, the TNG50 sample spans azimuthally-averaged values of \( \sigma_0 \sim 10 \) – 55 km s\(^{-1}\) (colored error bars), with galaxy-wide (excluding the inner 1.5 kpc) medians ranging between \( \sigma_0 \sim 20 \) – 40 km s\(^{-1}\) (filled symbols; see also Figure 3). Through modeling of our mock-observations, we recover the galaxy wide median in \( > 50 \) per cent of cases within one standard deviation of the marginalized posterior distribution (open symbols; see Tables 2 and 3). For our TNG50 kinematic sample, there is a tendency to recover high values of \( \sigma_0 \) from an NFW fit to the simulated data.

\( ^9 \) This should be even more pronounced when standard concentration parameters were assumed instead of the typically higher values determined from an NFW fit to the simulated data.
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4.5.2 Central dark matter fraction

As a final step, we now turn to the dynamical contribution of dark matter on galactic scales. In the left panel of Figure 9 we show the velocity-based dark matter fraction within the baryonic disc effective radius $f_{\text{DM}}^v(< R_e) = \delta f_{\text{DM}}^v(< R_e) = \delta v_{\text{sys}}^v(R_e)$ as a function of circular velocity $v_{\text{sys}}(R_e)$. Grey circles indicate the observations by Genzel et al. (2020), whereas open colored symbols correspond to our dynamical modeling results for the mock-observed TNG50 galaxies.

For our simulated sample, we find values of $f_{\text{DM}}^v(< R_e) = 0.09 - 0.57$, and typical uncertainties of $\delta f_{\text{DM}}^v(< R_e) \sim 0.11$. 34 per cent (12/35) of best-fit dynamical models indicate dark matter fractions of $f_{\text{DM}}^v(< R_e) \leq 0.2$, and 86 per cent (30/35) $f_{\text{DM}}^v(< R_e) \leq 0.5$, comparable to the results for the selected G20 sample. The average central dark matter fraction of our modeled TNG50 mock observations is $f_{\text{DM}}^v(< R_e) \sim 0.29$, while for the selected G20 galaxies it is lower by about 30 per cent, with $f_{\text{DM}}^v(< R_e) \sim 0.19$. However, considering the uncertainties from the dynamical modeling of both real and simulated galaxies, we conclude that the majority of mock-observations are, at face value, in broad agreement with the dark matter fractions found by Genzel et al. (2020). In particular, this applies to galaxy #1, for which all lines of sight give $f_{\text{DM}}^v(< R_e) < 0.2$. This galaxy has also intrinsically the lowest dark matter fraction.

There is however another important aspect to this comparison. As pointed out in Section 3.2, the simulated galaxies have on average smaller sizes compared to the G20 sample. This is also reflected in the modelling results, as can be seen in the right panel of Figure 9, where we show $f_{\text{DM}}^v(< R_e)$ as a function of baryonic disc effective radius $R_e$. At fixed galactocentric distance, the difference between the dark matter fractions inferred from observations and simulations is striking. Where the dynamical modeling of the mock-observations indicates $f_{\text{DM}}^v(< R_e) < 0.2$, the corresponding baryonic disc effective radii are always smaller than $\sim 4.5$ kpc. In contrast, the low dark matter fractions of the G20 sample are found over a large range in disc sizes, from $R_e \sim 4$ kpc to $R_e \sim 7$ kpc. Importantly, Genzel et al. (2020) consider including the effects of thermal motions for the gas velocity dispersion measurement. Their Figure 12 shows the typical effect for massive SFGs at $z = 2$ is about $\pm 10$ km s$^{-1}$, which we indicate in our Figure 8 by the black arrow (note the log scale). Including this effect would bring the $\sigma_v$ values (both intrinsic and mock-observed) of the selected TNG50 galaxies in better agreement with the average velocity dispersion of observed SFGs. In fact, if we apply a Kolmogorov-Smirnov statistic to the subsample by ¨Ubler et al. (2019) and the TNG50 dynamical modeling output with the addition of $\pm 10$ km s$^{-1}$ for thermal motions, we find that the samples are consistent with being drawn from a common parent sample, whereas without the thermal term they differ by more than 3$\sigma$.

Figure 8. Gas velocity dispersion $\sigma_v$ as a function of intrinsic stellar mass $M_*$ for the simulated galaxies selected from TNG50 at $z = 2$ (colored symbols), compared to the observational data by Genzel et al. (2020) (large grey circles) and ¨Ubler et al. (2019) (small light grey circles; see main text). Constraints from mock-observed and modelled galaxies are shown as open symbols, where larger sizes indicate higher goodness-of-fit. Filled symbols indicate the median of the intrinsic, azimuthally averaged ‘local’ velocity dispersion, and the corresponding error bar indicates the full range of values at distances $r = 1.5 - 20$ kpc. The black arrow approximately indicates (note the log scale) how far the intrinsic median values would increase if a ‘therm al term’ were included in the measurement of the velocity dispersion (see Pillepich et al. 2019). Overall, both the intrinsic and mock-observed plus modelled velocity dispersions broadly agree with observations, with on average somewhat lower values.

The simulation results are compared to the model output by Genzel et al. (2020) (large grey circles). To give a better sense of typical dispersion values of massive, star-forming discs at this cosmic epoch, we show a subset of $z \geq 1.5$ KMOS$^{3D}$ data by ¨Ubler et al. (2019) (small light grey circles). This subset has been selected with the same stellar mass and SFR cuts as the TNG data, and shows a spread of $\sigma_v \sim 20 - 100$ km s$^{-1}$, with a median of 49 km s$^{-1}$. Compared to this sample representative of main sequence star-forming discs, the selected TNG50 galaxies lie in the lower half of the observed scatter (see also Vincenzo et al. 2019).

For the comparison to the intrinsic values of $\sigma_v$ in the simulations the measurement procedure plays an important role. As described in Section 4.1, our $\sigma_{v, \text{true}}$ ranges give luminosity-weighted azimuthal averages of the ‘local’ velocity dispersion, which is measured in $xy$ bins of 0.5 kpc length. The average of the medians of these measurements at distances $r = 1.5 - 20$ kpc is 29 km s$^{-1}$. For this way of measuring velocity dispersion, this value is typical of massive $\log(M_*/M_\odot) = 10.5 - 11$ SFGs in TNG50 (see Figure A1, black line, by Pillepich et al. 2019). Pillepich et al. (2019) consider including the effects of thermal motions for the gas velocity dispersion measurement. Their Figure 12 shows the typical effect for massive SFGs at $z = 2$ is about $\pm 10$ km s$^{-1}$, which we indicate in our Figure 8 by the black arrow (note the log scale). Including this effect would bring the $\sigma_v$ values (both intrinsic and mock-observed) of the selected TNG50 galaxies in better agreement with the average velocity dispersion of observed SFGs. In fact, if we apply a Kolmogorov-Smirnov statistic to the subsample by ¨Ubler et al. (2019) and the TNG50 dynamical modeling output with the addition of $\pm 10$ km s$^{-1}$ for thermal motions, we find that the samples are consistent with being drawn from a common parent sample, whereas without the thermal term they differ by more than 3$\sigma$. 

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Figure 9. Left: Dark matter fraction within the baryonic disc effective radius $f_{DM}^m(< R_e) = \frac{v_{circ}^2(R_e)}{v_{DM}^2(R_e)}$ as a function of circular velocity at the baryonic disc effective radius $v_{circ}(R_e)$ for the selected simulated TNG50 galaxies at $z = 2$ with $M_* > 4 \times 10^{10} M_\odot$ and SFR $> 50 M_\odot \text{yr}^{-1}$ (colored symbols), in comparison to the selected observational data by Genzel et al. (2020) (grey circles). For the mock-observed and modelled TNG50 galaxies, larger sizes indicate higher goodness-of-fit (averaged over our setups with modified and unmodified NFW haloes). Within the modeling uncertainties, the simulated and observed populations largely overlap, but the simulated galaxies are offset towards higher velocities and dark matter fractions. Right: $f_{DM}^m(< R_e)$ as a function of baryonic disc effective radius $R_e$, with symbols as in the left panel. Here we see a more distinct offset of the simulated and observed galaxies, where at fixed $R_e$ the observed galaxies always have smaller dark matter fractions.

Genzel et al. (2020) also find a strong anti-correlation between $f_{DM}^m(< R_e)$ and baryonic surface density that is qualitatively also found in IllustrisTNG. This suggests that the discrepancy between real and simulated galaxies reported here is likely underestimated, given the smaller sizes of the TNG50 galaxies at comparable masses.

We explore the connection between central dark matter fractions and the distances at which they are measured in Figure 10. Here, we show as colored lines the intrinsic dark matter fraction as a function of radius for the simulated galaxies. As before, the open colored symbols correspond to the model outputs that are now converted to show the enclosed dark matter mass fractions $f_{DM}^m(< R_e) = M_{DM}(< R_e)/M_{tot}(< R_e)$, as described in Section 4.4.1. By the grey shaded area we indicate the approximate location of the twelve $M_* > 4 \times 10^{10} M_\odot$, $z \geq 1.5$ SFGs observed by Genzel et al. (2020) (which have values of $f_{DM}^m(< R_e)$ that are on average higher by only four per cent, compared to $f_{DM}^m(< R_e)$). For our TNG50 mock-observations, we find an average value of $f_{DM}^m(< R_e \sim 3.7kpc) \pm 0.32 \pm 0.11$, consistent the intrinsic dark matter fraction profiles of all galaxies except the largest one (galaxy #4). For the selected G20 galaxies, instead, we find an average value of $f_{DM}^m(< R_e \sim 5.9kpc) \sim 0.20 \pm 0.10$. These observations suggest dark matter fractions that are increasing more slowly with radius out to at least the dynamically inferred effective radii (typically $R_e \sim 6 $ kpc), and all lie below the intrinsic dark matter fraction profiles of the TNG50 sample. Based on our dynamical modeling output for the simulated galaxies, less than half (15/35) of the models would be compatible with a similar profile shape, and, with the exception of one model (for galaxy #4), would constrain these shallower profiles out to smaller radii.

Comments on sizes: For our dynamical modelling we have used the three-dimensional $K$-band half-light radius as an input prior on the baryonic disc effective radius, mimicking the approach by Genzel et al. (2017) (see Section 3.5). Genzel et al. (2020) have either used the same approach as Genzel et al. (2017), or in some cases fixed $R_e \equiv R_{1/2}$. Obviously, the distance from the center at which a dark matter fraction is measured has an impact on its value. We have explored using different setups with respect to $R_e$ in our dynamical modelling, such as a flat prior with hard bounds of $2 - 12$ kpc, fixing $R_e$ to the intrinsic baryonic disc half-mass radius based on a bulge-to-disc decomposition of the azimuthally averaged baryonic surface density (average 7.5 kpc), or fixing $R_e$ to half-light sizes measured from random projections of post-processed mock images (average 6.6 kpc; see Rodriguez-Gomez et al. 2019, for details). Consistent with expectations, dynamical models with larger $R_e$ also give larger $f_{DM}^m(< R_e)$. Considering such model outputs with, for instance, $R_e \sim 6 - 7.5$ kpc, we find typical values of $f_{DM}^m(< R_e) > 0.5$ for the selected TNG50 galaxies. In comparison, the observationally constrained dark matter fractions at these distances are $f_{DM}^m(< R_e) \sim 0.1 - 0.45$ for the selected G20 galaxies. While the lowest $f_{DM}^m(< R_e)$ constrained from the selected TNG50 galaxies are comparable to the highest $f_{DM}^m(< R_e)$ constrained from the selected
G20 galaxies at such $R_e$, the average dark matter fractions from dynamical modeling are a factor of about two higher for the selected TNG50 galaxies. This is also consistent with the intrinsic dark matter fraction profiles shown in Figure 10.

We further illustrate the offset of mass-based dark matter fractions and sizes in the observed and simulated sample in Figure 11. Here we show $f_{\text{DM}}^n(< R_e)$ ($f_{\text{DM}}^n(< R_{1/2, 3D})$) on the $x$–axis and $R_e$ ($R_{1/2, 3D}$) on the $y$–axis. For the modeled TNG50 sample we now plot only one data point per galaxy, which is an average of the fits to the five lines of sight with both a standard and a modified NFW halo (large colored symbols). In addition, we show all $z = 2$ TNG50 galaxies (centrals and satellites) with stellar masses $M_* > 2 \times 10^9 M_\odot$ (small colored points). Since we do not have a dynamical measurement of the baryonic disc effective radius for this larger TNG50 sample, we use the three-dimensional stellar half-mass radius $R_{1/2, 3D}$ and compute the dark matter mass fraction within. Thin grey lines connecting our selected and modeled TNG50 galaxies with the smaller symbols identify the corresponding matches, and the black arrow indicates the average shift for both quantities when going from this simple measurement of dark matter fraction within the $R_{1/2, 3D}$ to the more complex model output of $f_{\text{DM}}^n$ within the dynamically inferred $R_e$. At face value, this figures illustrates that at fixed central dark matter fraction, the observed galaxies are larger by factors of $4-14$ on average. In selecting the most massive and highly star-forming systems from the TNG50 $z = 2$ snapshot, i.e. those simulated galaxies corresponding most closely in mass and SFR to our G20 reference selection, and by measuring at $R_e$ inferred from dynamical modeling, this stark difference reduces to factors of 1.2–3.5 for dynamically modeled and averaged lines of sight. This underlines the importance of sample selection and analysis techniques.

The color-coding of the $z = 2$, $M_* > 2 \times 10^9 M_\odot$ TNG50 population indicates their baryonic surface density within the three-dimensional stellar half-mass radius. Genzel et al. (2020) find a steep correlation between central dark matter fraction and baryonic surface density with typical values in the range $\log(\Sigma_{\text{bar}}/(M_\odot {\text{kpc}}^{-2})) \approx 8 - 9.5$, which is qualitatively also seen in TNG100 (see their Figure 8). Similar to TNG100, we find that also in TNG50, very low dark matter fractions ($f_{\text{DM}}^n(< R_e) < 0.2$) are found only for very compact systems with $\log(\Sigma_{\text{bar}}/(M_\odot {\text{kpc}}^{-2})) > 9.5$.

We remind the reader that the observed galaxies are
selected to mostly have larger than average sizes by requiring spatially well resolved systems (see Figure 1). In Figure 11, we roughly indicate by the grey box the parameter space that is therefore not probed by observations in the G20 sample (see Genzel et al. 2020, for details). Intrinsically, only one the TNG50 galaxies selected by \( M_\text{s} > 4 \times 10^{10} M_\odot \) and SFR \( > 50 M_\odot \text{ yr}^{-1} \) lies substantially above the observed \( M - R \) relation by van der Wel et al. (2014) with a half-light size of \( R_{1/2} = 6.2 \text{ kpc} \) (#4, green triangle). Its intrinsic dark matter fraction \( f_{\text{DM}}(< R_e) \) is short of 60 per cent, 1.5 - 6 times that of the selected G20 galaxies with similar sizes. The model-derived, mass-based dark matter fractions for this galaxy range from 0.27 for one line of sight to 0.41 - 0.57 for the other four lines of sight, all at similar best-fit \( R_e \sim 6 - 6.5 \text{ kpc} \). The large range in derived dark matter fractions is due to the galaxy’s major axis kinematics that are very line-of-sight dependent (see upper right panel in Figure 6). Intrinsically, at a distance from the center of \( \sim 6 \text{ kpc} \) all seven simulated galaxies have dark matter fractions of \( f_{\text{DM}} > 0.4 \). Ideally we would need a larger sample of high-\( z \), high-resolution simulated galaxies that feature extended discs such as the observational sample, to understand if the large but high-\( f_{\text{DM}} \) galaxy #4 is characteristic for the IllustrisTNG model, or not.

## 5 SUMMARY AND DISCUSSION

We have studied the detailed kinematics of seven massive, \( z = 2 \) SFGs from the TNG50 simulation. Our focus was on the observational perspective and the comparison to a selection of twelve massive, high-\( z \) SFGs observed by Genzel et al. (2017, 2020). We created mock observations from five projections for each simulated galaxy including effects of the instrumental PSF and LSF, discretization into pixels, and realistic, random as well as systematic noise. We applied standard observational tools for kinematic analysis and dynamical modeling, specifically the same tools used for the analysis of real galaxies by Genzel et al. (2020).

Such accurate comparisons including all relevant observational effects, and possible systematics due to analysis tools, are crucial to highlight real differences between observations and simulations. This lays the foundation to further constrain physical models entering state-of-the-art cosmological simulations.

We also emphasize that our conclusions are limited by the small sample of TNG50 galaxies that meet our selection criteria of massive \( z = 2 \) SFGs, and physical differences that may remain as a consequence.

**Global intrinsic properties.** The simulated galaxies lie in a similar parameter space of \( M_\star, \text{SFR}, R_{1/2} \) and gas-to-stellar mass ratios compared to the Genzel et al. (2020) sample (Section 3.2; Figure 1), with the former two by selection. Small differences in these global properties of the observed and simulated samples should not be over-interpreted, given the low-number statistics in both the observational and simulated samples, and the known systematic differences in SFRs and sizes between observations and the TNG model (Genel et al. 2018; Donnari et al. 2019b; Pillepich et al. 2019).

The intrinsic dark matter halo profiles of the TNG50 galaxies are steeper than NFW, possibly due to adiabatic contraction, with typical inner slopes of \( \alpha \sim 1.6 \) (Section 3.5.2; Figure 2; see also Lovell et al. 2018).

**Intrinsic kinematics and the role of pressure support.** The intrinsic, azimuthally averaged gas rotation velocities of the TNG50 sample are flat on galactic scales. Falling intrinsic rotation curves are only seen for three of the seven selected galaxies (#5, #6, #7) at distances \( r > 7 - 10 \text{ kpc} \), beyond the visible extent of the galaxies. The azimuthal averages of the luminosity-weighted, local gas velocity dispersions at \( r > 1.5 \text{ kpc} \) are fairly constant with radius, with values \( < 50 \text{ km s}^{-1} \). All galaxies show substantial vertical and radial motions, with values of \( |v_r| \) and \( |v_z| \sim 50 - 200 \text{ km s}^{-1} \) (Section 4.1; Figure 3).

As a consequence of the somewhat low velocity dispersions, the effects of pressure support based on the ansatz by Burkert et al. (2010) are not very important for the TNG50 galaxies. A recent study of pressure gradients in \( 1 < z < 3 \) SFGs from the FIRE-2 simulations (Hopkins et al. 2014, 2018b) indicates that commonly used estimators of pressure support in observational studies, including the Burkert et al. (2010) method, tend to underestimate the true effect of pressure support (Wellons et al. 2020). The Burkert et al. (2010) pressure correction assumes exponential profiles, hydrostatic equilibrium, axisymmetry and an isotropic velocity dispersion which is independent of radius, and consequently further correction factors would have to be applied if any of these assumptions do not hold. While high-S/\( N \), high-resolution observations appear consistent with these assumptions (i.e. only small asymmetries, an isotropic velocity dispersion, and an exponential profile), at least the assumption of axisymmetry is violated for the majority of the TNG50 galaxies. Aside from that, the FIRE-2 galaxies have velocity dispersions that are higher (\( \sigma_0 \approx 100 - 150 \text{ km s}^{-1} \)) than those of our TNG50 sample (\( \sigma_0 \approx 20 - 40 \text{ km s}^{-1} \), neglecting the effects of thermal motions), and also higher than what is observed for real main sequence galaxies at these redshifts (\( \sigma_0 \approx 20 - 100 \text{ km s}^{-1} \); e.g. Übler et al. 2019; and references therein). By keeping in mind that alternative operational definitions of the gas velocity dispersion may imply a factor of 2 - 3 differences in values (see Pillepich et al. 2019), we speculate the difference in gas velocity dispersions (and their kinematic impact) of massive, high-\( z \) main sequence SFGs in the IllustrisTNG and FIRE-2 models to be related to the different implementation of feedback: in IllustrisTNG, stellar feedback-driven winds are hydrodynamically decoupled from the interstellar medium until they escape the galaxy, following Springel & Hernquist (2003), whereas in FIRE-2, mechanical feedback from stars couples directly to the surrounding medium (Hopkins et al. 2018a).

On the other hand, the AGN feedback in IllustrisTNG is directly coupled to the gas, with energy injection from the central super massive black holes directly affecting the coldest and densest gas in galaxies, a feedback channel not included in the FIRE-2 model.

**Mock-observed rotation curve shapes.** We construct rotation curves for all simulated galaxies. Along individual lines of sight, however, most simulated galaxies display substantial asymmetries in their rotation curve shapes, such that outer kinematics may differ by up to \( \Delta v = 200 \text{ km s}^{-1} \) (Figures 5 and 6). These asymmetries are likely caused by minor mergers, as indicated by correlated vertical
and radial gas motions with respect to the disc plane, or by tidal features through interaction with nearby galaxies (Section 4.1; Figure 3).

Quantifying the asymmetries of the TNG50 rotation curves and comparing them to the observations by Genzel et al. (2020), we find that the simulated galaxies have less regular kinematics (Section 4.3). This is likely connected to the large radial and/or vertical motions we intrinsically find for all galaxies.

**Dynamical modeling.** The success of our dynamical models in recovering intrinsic parameters, and in particular the central dark matter fraction \( f_{\text{DM}}^{m}(< R_e) \), depends on two main factors: (i) assumptions on the inner halo profile, and (ii) the regularity of the galaxy kinematics. If we assume a modified (contracted) NFW halo for which we have constrained the inner slope from fits to the intrinsic dark matter density (Section 3.5.2; Figure 2), we recover \( f_{\text{DM}}^{m}(< R_e) = M_{\text{DM}}(< R_e)/M_{\text{tot}}(< R_e) \) in 69 per cent of cases within one standard deviation of the MCMC posterior distribution. Using a standard NFW halo, we are successful only in 34 per cent of cases. For our sample of TNG50 galaxies, the choice of modeling with a standard or a more contracted NFW halo results in an average shift in the inferred DM fraction of about −0.08 (Figure 7). For real galaxies, of course, the dark matter density profile is typically not known, but our results encourage dynamical modeling with variable, or varying, dark matter density profiles. Apart from the halo profile, we see some correlation between the reflection symmetry of rotation curves and the ability of our models to accurately recover the central dark matter fraction: for the two galaxies with the most symmetric rotation curves our modified NFW setup correctly recovers the intrinsic \( f_{\text{DM}}^{m}(< R_e) \) output by the simulation for all lines of sight, while for the galaxy with the most asymmetric rotation curves we find only one best-fit (of five) recovering the intrinsic value (Section 4.4).

**Comparison to observations.** For our comparison to the selected observational results by Genzel et al. (2020), we average the model results using a modified and a standard NFW halo. About 34 (86) per cent of the thus model-derived central dark matter fractions of the TNG50 galaxies have values that are similar, namely \( f_{\text{DM}}^{m}(< R_e) < 0.2 \) (\( f_{\text{DM}}^{m}(< R_e) < 0.5 \)), compared to the results by Genzel et al. (2020). On average, however, the mean central dark matter fraction of the TNG50 galaxies, \( f_{\text{DM}}^{m}(< R_e) \sim 0.29 \pm 0.11 \), is larger than that of the selected observational sample by Genzel et al. (2020) by a factor of 1.5 (Section 4.5; Figure 9). This result becomes more substantiated when comparing the galactocentric distances at which the dark matter fractions are measured (Figures 9 and 11): for the TNG50 galaxies, we typically find dynamically constrained baryonic disc effective radii \( R_e < 5 \) kpc, and all low dark matter fractions \( f_{\text{DM}}^{m}(< R_e) < 0.2 \) are found at \( R_e < 4.5 \) kpc. This is in contrast to the observations by Genzel et al. (2020), where the average value for high-\( z \), massive SFGs, \( f_{\text{DM}}^{m}(< R_e) \sim 0.2 \), is typically measured at \( R_e \sim 6 \) kpc. Taking into account different definitions of input priors on galactic sizes and their effect, we find that the mass- and SFR-matched \( z = 2 \) TNG50 galaxies are generally too compact and/or too dark matter-dominated (Figures 9, 10, and 11).

Similar results have also been found for \( z = 0 \) galaxies. For instance, a recent study by Marasco et al. (2020) shows that massive disc galaxies from the EAGLE and TNG100 simulations live in dark matter haloes that are on average factors of four and two more massive than what has been inferred for corresponding galaxies in the SPARC (Lelli et al. 2016) sample (Pusti et al. 2019). In a comparison of dark matter fractions for different galaxy types and at different redshifts with TNG100 predictions, Lovell et al. (2018) find either broad agreement (e.g. with the results from \( z = 0 \) disc galaxies compiled by Courteau & Dutton 2015 or from \( z = 0 \) early-type galaxies by Alabi et al. 2017 within fixed apertures), or too high dark matter fractions in TNG100 when comparing to observational data (e.g. \( z = 0 \) early-type galaxies by Alabi et al. 2017 within five times the effective radii and by Cappellari et al. 2013 within one effective radius). These authors also note that some of the latter discrepancies would be alleviated if the simulated haloes would not contract due to the presence of baryons.

The massive \( z = 2 \) TNG50 SFGs analysed in this paper differ from real galaxies observed by Genzel et al. (2017, 2020) specifically in their dark matter fractions at the dynamically constrained baryonic disc effective radius. Quantitatively, at fixed \( R_e \) the TNG50 dark matter fractions are too high by factors of 1.5 – 5. Furthermore, different measures of axisymmetry reveal that the simulated galaxies have less regular velocity fields.

We speculate that this may be due to physical processes which are not resolved in sufficient detail with the numerical resolution available in current cosmological simulations. At \( z \sim 2 \), during the peak epoch of cosmic star formation rate density, galaxies are subject to rapid baryon assembly, wide-spread condensation of gas into stars (e.g. Whitaker et al. 2014), and dissipative processes due to large gas fractions (e.g. Tacconi et al. 2018). In addition, galaxies are shaped through stellar feedback-driven outflows, increasing with SFR, and the high duty cycle of active galactic nuclei-driven outflows at high masses (e.g. Förster Schreiber et al. 2019). From the theoretical side, there is no final consensus on the implementation of the relevant physical processes via sub-grid recipes (cf. Naab & Ostriker 2017). This becomes particularly evident when considering the stark variations in kinematics of simulated high-\( z \) SFGs realized through different models of galaxy formation (e.g. this work; Pillepich et al. 2018b, 2019; Teklu et al. 2018; Wells et al. 2020).

The recent observational results by Genzel et al. (2020) highlight for the first time at \( z \gtrsim 1 \) the coupling between central baryonic surface densities and dark matter fractions on galaxy scales. This might point toward efficient heating of the galaxy-scale dark matter halo due to dynamical friction and/or strong feedback – processes that might not be sufficiently resolved or appropriately modelled by current state-of-the-art cosmological simulations.

The observational findings and the differences between observed and simulated kinematics and dark matter contents carved out in this work encourage future model improvements and comparisons. From observational side it would be helpful to have representative measurements of the gas content and distribution for individual galaxies for which Hα kinematic observations exist as well. This would allow to investigate in more detail, for instance, if simulated dark matter fractions are too high and galaxies are too compact due to a lack of galactic gas content at high redshift.
Finally, in this paper we have focused on the high-mass end of the star-forming main sequence at \( z \sim 2 \). It would be interesting to expand upon the present work by e.g. including lower-mass or lower-redshift galaxies.

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**APPENDIX A: DISMISSED GALAXIES**

In Figure A1 we show those 5/12 TNG50 galaxies that met the stellar mass and SFR selection cuts (see Table 1), but were dismissed from further kinematic analysis because they show signatures of strong interaction or disturbance, and/or they are too compact to extract extended rotation curves (such systems would also be excluded from observational studies for the same reasons). The galaxies in columns 1-4 all have a similarly massive galaxy (mass ratio \( \geq 1:2 \)) in their vicinity (\( \Delta r = 30 - 60 \) kpc), and particularly the first object shows a high-surface brightness accretion or tidal stream. The galaxy in column 5 is undisturbed, but also the most compact object meeting our other selection criteria. Similarly, the other four objects are very compact in addition to their disturbed kinematics.

**APPENDIX B: EFFECT OF DUST ON EXTRACTED KINEMATICS**

We explore the effect of accounting for dust in our mock-observations and kinematic extractions by using a model that accounts for spatially-resolved dust attenuation. The implementation follows the fiducial dust model (C) by Nelson et al. (2018)\(^\text{10}\) and makes use of results by Cardelli et al. (1989); Calzetti et al. (1994). We refer the reader to Nelson et al. (2018) for details.

In addition to applying the model to the simulated galaxies, we scale our noise prescription (i.e., integration time) such that we ‘observe’ the galaxy out to similar distances from the center compared to the main analysis. This choice enables a direct comparison of the extracted kinematics. In Figure B1 we show for sightline 3 of galaxy #3 the mock-observed velocity map, corresponding \( S/N \) map, and one-dimensional major axis velocity and dispersion profiles. The bottom row includes dust. In this galaxy as well as in the full sample, particularly the star-forming galaxy centers are affected by dust. Accounting for dust can lead to a more ring-like appearance of the systems, as illustrated in the \( S/N \) maps (such structures are also observed in real galaxies; see e.g. Genzel et al. 2008). With our noise scaling of choice, the overall \( S/N \) is much lower in the mock-observation including dust. This is transferred also to the one-dimensional kinematic extractions: there are fewer reliable data points, and the uncertainties are larger. For a direct comparison, we plot in the bottom right panels of Figure B1 extractions at the same distances from the center as in the top right panels, but we show unreliable extractions in grey. We emphasize that the overall kinematic properties of our TNG50 galaxies do not change when accounting for dust, however the \( S/N \) and therefore the quality of the kinematic extractions are affected. Particularly the line widths translating into velocity dispersion are more sensitive to this decrease in \( S/N \).

**APPENDIX C: NON-CIRCULAR MOTIONS AND KINEMATIC ASYMMETRIES**

In Section 4.1, we discussed the substantial vertical and radial motions in our sample of TNG50 SFGs. Here, we want to briefly demonstrate by reference to one example the effect of artificially removing these components on the extracted kinematics, which we call ‘equilibration’. This procedure exploits the full knowledge about the simulated data and aims at evaluating the effect of non-rotational motions on the regularity of the extracted kinematics. Specifically, the method artificially removes vertical and radial velocity components of the star-forming gas. To achieve this, the galaxy is divided into circular 0.5 kpc-sized regions, inside each of which the mean radial and vertical velocity is subtracted from each resolution element. This results in no impact on the tangential velocity and a minimal impact on the velocity dispersion.

We demonstrate the procedure and its effect by example of galaxy #3, sightline 2, which (before equilibration) underestimates the central dark matter fraction by a factor of \( \sim 3 \). In Figure C1 we show its projected two-dimensional kinematics before (left) and after (right) equilibration. The procedure particularly leads to more mirror-symmetric and smoother velocity maps. In Figure C2 we compare the corresponding one-dimensional kinematic extractions after creating mock data cubes for the processed galaxy with the original extractions. Note that for this exercise we use the identical noise cube in order to ensure a consistent comparison. In good agreement with the intrinsic two-dimensional kinematics shown in Figure C1, the fall-off on the receding side of the rotation curve is less extreme after equilibration, while the velocity dispersion along the kinematic major axis is not much affected. The more regular behaviour of the kinematics facilitates the line fitting and results in higher \( S/N \) on average (\( \Delta S/N \approx 0.07 \) for the full two-dimensional map, with \( \Delta S/N \sim 10 \) in the center) such that the uncertainties on the extracted kinematics are slightly smaller, and extractions out to somewhat larger distances from the center are possible.

To quantify the gain in symmetry through equilibration, we compare the results of our asymmetry analysis (see Sec-

\(^{10}\) Neglecting, however, the spatially-unresolved component used in their model (B), which applies for young stars, not for gas.
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Figure A1. Projected two-dimensional maps of the convolved intrinsic parameters (top row: $\Sigma_{\text{SFR}}$; second row: velocity; third row: velocity dispersion) for the five dismissed TNG50 galaxies (columns). The projections correspond to face-on, i.e., an inclination of $i = 0^\circ$. The panels show 40 kpc $\times$ 40 kpc in projection, and the color scale shows [-400; 400] km s$^{-1}$ for velocity, and [0; 150] km s$^{-1}$ for velocity dispersion. The galaxies were dismissed due to strong interaction/disturbance signatures and/or because they were too compact for a kinematic analysis meeting the purpose of this work.

Figure B1. Illustrating the effect of dust on the $S/N$ and extracted kinematics for galaxy #3, sightline 3. From left to right: velocity map showing pixels with $S/N > 3$ and color scale [-400; 400] km s$^{-1}$; corresponding $S/N$ map; extracted one-dimensional rotation velocity and velocity dispersion for mock-observations without (top) and with (bottom) dust, following the method by Nelson et al. (2018). See text for details.

Using the overlapping coefficient, we find for the example shown in Figure C2 an increase in symmetry from 0.41 to 0.54 (with 1 being completely symmetric, including uncertainties), i.e., by 32 per cent. If we consider our second method of fitting a quadratic function to one side of the rotation curve and calculating the reduced chi-squared statistics for the other side, we find a decrease from $\Delta \chi^2_{\text{red}} = 7.0$ to $\Delta \chi^2_{\text{red}} = 1.7$. Both methods show that the extracted rotation curve after equilibration is more symmetric.

Comparing the dynamical modeling results before and after equilibration for this example, we find that the baryonic parameters ($M_{\text{bar}}, R_e, B/T, \sigma_0$) don’t change beyond their 1$\sigma$ uncertainties of the marginalized posterior distributions. However, the estimates of total dark matter mass and central dark matter fraction do: $f_{\text{DM}}(< R_e)$ doubles
from 0.09 to 0.18, and is therefore in better agreement with the intrinsic value, but still too low by a factor of \( \sim 2 \). The estimate of the total halo mass increases from \( \log(M_{\text{halo}}/M_\odot) = 11.7 \) to 12.2. This estimate is still lower than, but much closer to, the value of \( \log(M_{\text{halo}}/M_\odot) = 12.7 \) determined through the modified NFW fit to the intrinsic dark matter density distribution. This shows that the kinematic asymmetries caused by vertical and radial motions negatively affects the ability of our dynamical modeling to recover intrinsic values, particular with respect to dark matter.

More generally, the differences between the kinematic extractions along different lines of sight are reduced through the equilibration procedure. However, while more similar, there are still differences between different lines of sight that are larger than can be accounted for by uncertainties. Overall, the effect of the equilibration technique on the regularity of the two- and one-dimensional kinematics underlines the impact of non-axisymmetric motions in the simulated galaxies.

**DATA AVAILABILITY**

No new data were generated or analysed in support of this research.

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**Figure C1.** Projected velocity and velocity dispersion maps before (left) and after (right) removing velocity components vertical and radial with respect to the disc plane (‘equilibrized’) for galaxy #3, sightline 2. The projections correspond to an inclination of \( i = 60^\circ \). The panels show 40 kpc × 40 kpc in projection, and the color scale shows \([-400; 400]\) km s\(^{-1}\) for velocity, and \([0; 150]\) km s\(^{-1}\) for velocity dispersion. Both the velocity and velocity dispersion fields become smoother and more regular with the vertical motions removed.

**Figure C2.** One-dimensional kinematic extractions from the mock data cubes before (red) and after (blue) removing vertical and radial velocity components for galaxy #3, sightline 2. The rotation curve becomes more symmetric, and through increased S/N extractions at larger galactocentric distances are possible. Effects on the velocity dispersion are minor.
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