Dynamically cold disks in the early Universe: Myth or reality?

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ABSTRACT

Context. Theoretical models struggle to reproduce dynamically cold disks with significant rotation-to-dispersion support ($V_{\text{rot}}/\sigma$) observed in star-forming galaxies in the early Universe at redshift $z > 4$.

Aims. We aim to explore the possible emergence of dynamically cold disks in cosmological simulations and to understand whether different kinematic tracers can help reconcile the tension between theory and observations.

Methods. We used 3218 galaxies from the SERRA suite of zoom-in simulations, with $8 \leq \log(M_*/M_\odot) \leq 10.3$ and star formation rates SFR $\leq 128 M_\odot/\text{yr}$, within the $4 \leq z \leq 9$ range. We generated hyperspectral data cubes for $2 \times 3218$ synthetic observations of $\text{Hz}$ and [CII].

Results. We find that the choice of kinematic tracer strongly influences gas velocity dispersion ($\sigma$) estimates. In Hz ([C II]) synthetic observations, we observe a strong (mild) correlation between $\sigma$ and $M_\star$. This difference mostly arises for $M_*/10^9 M_\odot$ galaxies, for which $\sigma_{\text{Hz}} > 2\sigma_{\text{CII}}$ for a significant fraction of the sample. Regardless of the tracer, our predictions suggest the existence of massive ($M_*>10^{10} M_\odot$) galaxies with $V_{\text{rot}}/\sigma > 10$ at $z > 4$, maintaining cold disks for $\sim 10$ orbital periods ($\sim 200$ Myr). Furthermore, we find no significant redshift dependence for the $V_{\text{rot}}/\sigma$ ratio in our sample.

Conclusions. Our simulations predict the existence of dynamically cold disks in the early Universe. However, different tracers are sensitive to different kinematic properties. While [C II] effectively traces the thin gaseous disk of galaxies, Hz includes the contribution from ionized gas beyond the disk region, characterized by prevalent vertical or radial motions that may be associated with outflows. We show that Hz halos could be a signature of these galactic outflows. This result emphasizes the importance of combining ALMA and JWST/NIRSpec studies of high-$z$ galaxies.

Key words. galaxies: evolution – galaxies: high-redshift – galaxies: kinematics and dynamics – galaxies: structure

1. Introduction

Disks are almost ubiquitous in the star-forming galaxy (SFG) population of the local Universe. Somewhat surprisingly, recent observations (Ferreira et al. 2022; Kartaltepe et al. 2023; Robertson et al. 2023; Tohill et al. 2024; Pandya et al. 2024) using the James Webb Space Telescope (JWST) have unveiled their presence, in particular, in high stellar mass galaxies, even in the earliest epochs of the Universe, reaching back to $z > 9$. However, these early disks might exhibit distinct dynamical characteristics when compared to their local counterparts.

Extensive observations with the kiloparsec-scale near-infrared Integral-Field-Unit (IFU) of SFGs around cosmic noon ($1 \leq z \leq 3$, e.g., Law et al. 2009; Stott et al. 2016; Förster Schreiber et al. 2018; Mieda et al. 2016; Mason et al. 2017; Turner et al. 2017; Wisnioski et al. 2019; Birkin et al. 2023) have found a significant increase in the gas velocity dispersion ($\sim 50–100 \text{ km s}^{-1}$) compared to local SFG values ($\sim 20–25 \text{ km s}^{-1}$, Andersen et al. 2006; Epinat et al. 2010). Notably, the rotation-to-dispersion ratio ($V_{\text{rot}}/\sigma$) for cosmic-mass disk typically falls in the range $1–10$ (Law et al. 2009; Gnerucci et al. 2011; Genzel et al. 2011; Johnson et al. 2018; Birkin et al. 2023), in contrast to the value of $10–20$ observed in Milky Way and other local spiral disks (Epinat et al. 2010). As a result, a significant conclusion drawn by these studies was that SFGs become dynamically hotter, featuring substantial pressure support, toward high-$z$.

In recent years, significant progress has been made in characterizing the dynamics of normal SFGs during cosmic high noon ($3 \leq z \leq 6$) and even into the epoch of reionization (EoR: $z > 6$) through far-infrared (FIR) emission line observations, in particular, [C II]-158 $\mu$m with the Atacama Large Millimeter/Submillimetre Array (ALMA; Jones et al. 2017; Smit et al. 2018; Bakx et al. 2020; Hashimoto et al. 2019; Harikane et al. 2020; Herrera-Camus et al. 2022; Le Fèvre et al. 2020; Romano et al. 2021; Fujimoto et al. 2021; Tokuoka et al. 2022; Pallanti et al. 2023; Posses et al. 2023). The estimated value of $V_{\text{rot}}/\sigma$ for these galaxies falls in the $\sim 1–7.5$ range. However, these observations are only marginally resolved, leading to a potential underestimate of $V_{\text{rot}}/\sigma$ caused by beam-smearing effects (Kohandel et al. 2020; Rizzo et al. 2022).

Recent breakthrough observations (Rizzo et al. 2020; Lelli et al. 2021; Rizzo et al. 2021; Tsukui & Iguchi 2021; Roman-Oliveira et al. 2023) achieved a higher spatial resolution and sensitivity, robustly characterizing the dynamics of early galaxies. Massive, dusty starburst galaxies ($M_*/10^{10} M_\odot$) at $z > 4$ exhibit disk structures with $V_{\text{rot}}/\sigma \sim 10$. Moreover, Pope et al. 2023 have recently revealed stable rotation-dominated disks ($V_{\text{rot}}/\sigma = 5.3 \pm 3.6$) in relatively low-mass galaxies ($M_*/10^{9} M_\odot$) during cosmic high noon. Adding to
this remarkable progress, Rowland et al. (in prep.) have recently discovered the most distant ($z \approx 7$) massive ($M_* > 10^{10} M_\odot$) dynamically cold disk ($V_{\text{rot}}/\sigma \sim 10$) in REBELS-25 as part of an ALMA large program (Bouwens et al. 2022).

Finally, JWST/NIRspec multi-object spectroscopy of Hα and [O III] emission lines has started to shed light on the kinematics of ionized gas in EoR galaxies (de Graaff et al. 2024; Parlanti et al. 2024), indicating that early galaxies can settle into dynamically cold disks. This is somewhat surprising in contrast to previous findings from Hα surveys at cosmic noon (e.g. Wisnioski et al. 2019). Despite this progress, the statistical relevance of DCDs in early SFGs is uncertain because only a few deeply spatially resolved observations are available.

From a theoretical standpoint, most studies (Dekel & Burkert 2014; Zolotov et al. 2015; Hayward & Hopkins 2017; Pillepich et al. 2019) struggle to explain the existence of DCDs with a fixed dust-to-metal ratio, denoted as $D_{10}$. An initial metallicity floor of $Z_{\text{floor}} = 10^{-3} Z_\odot$ is adopted for the Milky Way (Hirashita & Ferrara 2010), which is similar to Galactic molecular clouds (Federrath & Klessen 2013).

2. SERRA simulations

2.1. Galaxy formation and evolution

The SERRA suite of simulations focuses on studying the formation and evolution of galaxies during the EoR (Pallottini et al. 2022). Gas and dark matter are evolved using a customized version of the adaptive mesh refinement code RAMSES (Teyssier 2002). KROME (Grassi et al. 2014) is employed to model the nonequilibrium chemical network that includes H, H$^+$, H$_2$, He, He$^+$, He$^{++}$, H2, H2$^+$, electrons, and metals, encompassing $\sim$40 reactions (Bovino et al. 2016; Pallottini et al. 2017a).

The tracking of metallicity ($Z$) involves summing heavy elements, assuming solar abundance ratios for different metal species (Asplund et al. 2009). Dust is approximated to scale with a fixed dust-to-metal ratio, denoted as $D = 0.12 (Z/Z_\odot)$, where the gas metallicity $Z_{\text{gas}} = 0.3$ for Milky Way (Hirashita & Ferrara 2002). A Milky Way-like grain size distribution is adopted (Weingartner & Draine 2001). An initial metallicity floor of $Z_{\text{floor}} = 10^{-3} Z_\odot$ is adopted, as expected from pre-enrichment of the intergalactic medium around density peaks (Madau et al. 2001; Pallottini et al. 2014a,b).

The conversion of molecular hydrogen into stars follows a Schmidt (1959)-Kennicutt (1998)-like relation (Pallottini et al. 2017a). These stars in turn act as sources of metals, mechanical energy, and radiation (Pallottini et al. 2017b). Feedback processes inject energy in thermal and turbulent (kinetic) forms. The former can cool via the thermo-chemical evolution modeled by KROME, while the latter dissipates (Teyssier et al. 2013) over an eddy turnover timescale (Mac Low 1999). The specific fractions depend on the process and the environment, as discussed in Appendix A of Pallottini et al. (2017b).

In SERRA, gas kinematics analyses involve two crucial post-processing steps: 1) line emission modeling (Vallini et al. 2017; Pallottini et al. 2019), and 2) the generation of hyperspectral data cubes (HDCs, Pallottini et al. 2019, 2020).

Due to the coarse nature of the chemical network used in hydrodynamical simulations, precise emission computation requires postprocessing of the data to extract kinetic information. The line luminosity ($L_{\text{em-line}}$) for each gas cell was obtained using the spectral synthesis code CLOUDY (Ferland et al. 2017). This process took the interstellar radiation field into account, which is the turbulent and clumpy structure of the interstellar medium (ISM), which was parameterized as a function of the local gas Mach number (Vallini et al. 2018; Pallottini et al. 2022).

With information on $L_{\text{em-line}}$ position ($x$), velocity ($v$), and thermal+turbulent line broadening $(\sigma_{\text{th}}^2 + \sigma_{\text{turb}}^2)^{1/2}$ for each gas cell within a specified field of view (FOV) and along a line of sight direction, we constructed 3D HDCs. These cubes comprise two spatial dimensions and one spectral dimension, effectively mapping the 6D data to coordinates $(x, y, v)$. In HDCs, the surface brightness of the emission line is recorded for each voxel, providing valuable insights into the spatial and spectral distribution of the emission. The contribution of all gas cells within the FOV can be directly summed for optically thin emission lines. However, for optically thick lines, radiative transfer through dust needs to be considered when comparing with pre-dereddened observations (Behrens et al. 2018).

1 The FOV for the HDCs had a side of 2.5 kpc.
We modeled the [C II] 158 μm emission line as a tracer of cold neutral or molecular gas and the nebular Hα emission line as a tracer of warm ionized gas. Different gas-phase tracers can yield different values of \( V_{\text{rot}} \) and \( \sigma \) (Kohandel et al. 2020; Ejdetjärn et al. 2022). We estimated the velocity dispersion of a galaxy separately using two tracers: [C II] observations (\( \sigma_{\text{[CII]}}, \)), and Hα (\( \sigma_{\text{Hα}} \)). Following a similar approach to that of Kohandel et al. (2020), \( \sigma_{\text{em-line}} \) represents the luminosity-weighted, average velocity dispersion, calculated using the moment-2 and moment-0 maps of the corresponding emission line. For the rotational velocity, we estimated \( V_{\text{rot}} \) with the circular velocities of the galaxy, denoted as \( v_c = (GM_{\text{dyn}}/r_d)^{1/2} \), where \( M_{\text{dyn}} = M_\ast + M_{\text{bh}} \) is the dynamical mass within the desired FOV\(^2\), and \( r_d \) is the disk effective radius, that is, where 50% of the gas mass is contained. In other words, we kept \( V_{\text{rot}} \) constant regardless of the tracer we used. Consequently, any differences observed in \( V_{\text{rot}}/\sigma \) for [C II] and Hα synthetic observations arose due to disparities in \( \sigma_{\text{[CII]}}, \) and \( \sigma_{\text{Hα}} \).

We focused on SERRA galaxies that exhibited a stellar mass of \( 10^8 \) \( M_\odot \) at least and covered the redshift range \( 4 \leq z \leq 9 \). Our sample includes 3218 galaxies with SFRs ranging from 0.04 to 128 \( M_\odot \) yr\(^{-1}\) and stellar masses in \( 8 \leq \log M_\ast/M_\odot \leq 10.3 \). We refer to Table 1 for an overview of our sample.

### 3. Rotation support in early galaxies

In Figs. 1 and 2, we present the kinematic characteristics of our sample within the \( M_\ast - \sigma \) and \( V_{\text{rot}}/\sigma - z \) planes, respectively. In both cases, \( \sigma \) values were derived from [C II] 158 μm and Hα synthetic observations. In Fig. 2, along with SERRA galaxies, we plot the predictions from TNG50 simulations (Pillepich et al. 2019)\(^3\), as well as observed data of \( z > 4 \) galaxies through FIR [C II] emission line by ALMA and nebular Hα and \([\text{O III}]\) lines by JWST/NIRspec.

Regarding the \( M_\ast - \sigma \) relation, we find two distinct behaviors for the two tracers. Specifically, we find that \( \sigma_{\text{Hα}} \) exhibits a steeper increase with \( M_\ast \) than \( \sigma_{\text{CII}} \). Interestingly, this trend is particularly pronounced in ~40% of our high-mass bin galaxies and 30% of those in the intermediate-mass bin, where \( \sigma_{\text{Hα}} > 2\sigma_{\text{CII}} \). This behavior is expected because even sur-

\(^2\) While Hα emission is optically thick, we produced the nonattenuated HDCs and left radiative transfer effects for future work.

\(^3\) It is worth noting that this approximation is valid for a thin rotating disk with a low velocity dispersion.

\(^4\) At the center of the galaxies, the dynamical mass is dominated by the baryonic component; see Kohandel et al. (2019) for the rotation curves and (Gelli et al. 2020) for the density profiles.

\(^5\) The redshift evolution for each mass category was obtained by dividing the category into six redshift bins between 4–9, and the markers indicate the mean of the sample in that redshift bin.

\(^6\) We combined the original four mass bins of Fig. 14 in Pillepich et al. 2019 into two composite bins: \( \log(M_\ast/M_\odot) > 10 \) and \( \log(M_\ast/M_\odot) = 9–10 \).

![Fig. 1. Relation of the velocity dispersion and stellar mass in the SERRA galaxy sample: Blue (red) contours show the 1, 2, and 3-sigma probability density function levels for the \( M_\ast - \sigma \) relation derived from synthetic [C II] (Hα) observations. Individual data points are represented by crosses.](image)

Table 1. Relevant properties of the simulated sample.

<table>
<thead>
<tr>
<th>( \log(M_\ast/M_\odot) )</th>
<th># of galaxies</th>
<th>( V_{\text{rot}}/\sigma_{\text{CII}} )</th>
<th>( V_{\text{rot}}/\sigma_{\text{Hα}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \geq 10 )</td>
<td>142</td>
<td>8.5 ± 2.2</td>
<td>5.5 ± 3.2</td>
</tr>
<tr>
<td>9–10</td>
<td>1149</td>
<td>5.0 ± 1.5</td>
<td>3.1 ± 1.3</td>
</tr>
<tr>
<td>8–9</td>
<td>1927</td>
<td>4.1 ± 1.2</td>
<td>3.2 ± 1.1</td>
</tr>
</tbody>
</table>

Notes. We list the number of galaxies in each mass bin and their average \( V_{\text{rot}}/\sigma_{\text{[CII]}} \) and \( V_{\text{rot}}/\sigma_{\text{Hα}} \) ratios.
To better clarify the above findings, we now focus on two representative galaxies in our massive subsample: “Hibiscus” with $M_\star = 1.5 \times 10^{10} M_\odot$ and SFR = 16 $M_\odot$ yr$^{-1}$ at $z = 4.5$ and “Narcissus” with $M_\star = 1.2 \times 10^{10} M_\odot$ and an SFR = 52 $M_\odot$ yr$^{-1}$ at $z = 6.8$. These galaxies have similar [C II] kinematics (i.e., $V_{\text{rot}}/\sigma_{\text{[CII]}} > 10$), but their H$\alpha$ kinematics is very different.

### 4. Discussion

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### 4.1. Why [CII] and H$\alpha$ kinematics are different?

In Fig. 3 we show the synthetic [C II] and H$\alpha$ maps and kinematics observables for a face-on and edge-on views of Hibiscus. The [C II] spectrum is characterized by a narrow and prominently Gaussian-shaped profile ($FWHM \sim 185$ km s$^{-1}$), while the H$\alpha$ spectrum appears to be more complex and broader ($FWHM \sim 437$ km s$^{-1}$) and exhibits high-velocity wings. These broad wings in the spectrum might be indicative of outflowing gas. By comparing the moment maps, we see that the [C II] emission line effectively traces the Hibiscus thin gaseous disk, while H$\alpha$ traces ionized gas that lies beyond the disk plane, including gas that might be in an in- or outflowing state. This difference between various phases of the ISM could conceivably arise because distinct effects of stellar feedback influence them, as suggested by simulations of isolated disk galaxies (Ejdetjärn et al. 2022). This illustrates that the observed velocity dispersion in a given galaxy using H$\alpha$ data may not solely arise from turbulence within the galactic disks. Instead, a substantial contribution from outflows may be in effect, introducing an additional layer of complexity to the data interpretation.

We note that the spatial extent of the [C II] and H$\alpha$ emission in Hibiscus differs significantly. The [C II] is four times more extended than the stellar effective radius, similar to observed high-$z$ galaxies (Fujimoto et al. 2019; Carniani et al. 2020; Fudamoto et al. 2022). The H$\alpha$ distribution is even more far-flung because H$\alpha$ originates from the $T \sim 10^4$ K photoionized regions outside the disk that are part of an expanding,
cooling outflow through which LyC photons percolate. As carbon in these regions is ionized to higher states (e.g., CIII), [C II] emission is limited to denser, more confined regions in which the recombination rates are higher. Interestingly, this shows that Hα halos are intimately linked to the presence and morphology of these outflows, offering intriguing prospects for their detection with JWST.

Finally, it is important to highlight that [C II] kinematics can also be challenging and merits deeper exploration. In particular, observations of the so-called [C II] halos (Gallerani et al. 2018; Fujimoto et al. 2019, 2021; Ginolfi et al. 2020) have been interpreted in the framework of outflow models (Pizzati et al. 2020, 2023), but they have not yet been reproduced by cosmological simulations (Fujimoto et al. 2019; Arata et al. 2020).

4.2. Are high-z dynamically cold disks a transient feature?

To explore the stability of cold disks, we studied the evolutionary path undertaken by individual galaxies in more detail. In Fig. 4 we show the evolution of $V_{\text{tot}}/\sigma$ as a function of lookback time for Hibiscus and Narcissus. When only [C II] emitting gas is considered, both galaxies exhibit a consistent $V_{\text{tot}}/\sigma$ around 2–4 up until roughly 200 Myr. During this interval, the rotation support rises through the effective accretion of gas and the efficient transfer of angular momentum into the disk. When we estimate the disk orbital time $t_{\text{orb}} = 2\pi r_d/V_{\text{rot}}$, it is $\sim$16 Myr for Hibiscus and $\sim$21 Myr for Narcissus. Therefore, these high-z DCDs survive for more than ten orbital times. This characteristic generally holds for massive galaxies in SERRA (see Fig. 3).

Regarding the $V_{\text{tot}}/\sigma_{\text{H}}$, there is an interesting difference between the two systems. As shown in Fig. 3, the Hα emitting gas is found to be dynamically warm in the last $\sim$200 Myr for Hibiscus, which might be attributable to outflows. However, in the case of Narcissus, the gas traced by the two emission lines follows a similar evolutionary path. Despite a slightly lower $\sigma_{\text{CII}}$ than $\sigma_{\text{H}}$, this galaxy remains dynamically cold according to both tracers. Considering the comparable stellar masses of these galaxies, differences in their star formation histories, feedback effects, or other global properties may be cause the different behavior of the tracers.

5. Conclusions

In this paper, we investigated the possible existence of dynamically cold disks (with significant rotation support) in the early Universe using a sample of 3218 normal star-forming galaxies from the SERRA zoom-in cosmological simulations. We analyzed the kinematic of [C II] and Hα in the redshift range of
Fig. 4. Example of the dynamical evolution of two SERRA galaxies traced by [CII] and Hα. At z = 4.5, Hibiscus (top) has a [CII] dynamically cold disk and a turbulent Hα emitting gas that might feature galactic outflows (see also Fig. 3). At z ≈ 6.8, Narcissus (bottom) appears as a supercold galaxy in both [C II] and Hα.

4 ≤ z ≤ 9 for LBGs with 8 ≤ log(M⋆/M⊙) ≤ 10.3 and 0 < SFR/ ≤ 128. Our main conclusions are listed below.

- Stellar mass and gas velocity dispersion are strongly (weakly) correlated in Hα ([C II]) synthetic outflows. The difference mostly arises for M⋆ > 10^9 M⊙ galaxies where σ_{Hα} > 2σ_{[CII]}.
- Regardless of galaxy mass and the chosen kinematic tracer, our analysis reveals no significant redshift dependence in the ratio V_{rot}/σ.
- Massive (M⋆ ≥ 10^{10} M⊙) galaxies in SERRA settle into dynamically supercold disks with V_{rot}/σ > 10 at z > 4. These cold disks are not transient features and last for more than ten galaxy orbital times (∼200 Myr).

We have shown that in SERRA galaxies, [C II] effectively traces the thin gaseous disks within the galaxies, while Hα emission can also trace the ionized gas outside the disk. The differences in the kinematics of [C II] and Hα may be attributed to galactic outflows, although further exploration is necessary to substantiate and statistically quantify this point. We showed that the identification of Hα halos could be a signature of these galactic outflows. We predict that more high-z dynamically cold disks will be found with the increasing availability of deep ALMA observations targeting [C II] 158 μm in galaxies with stellar masses exceeding 10^{10} M⊙.

In view of the essential role of multiple tracers in gaining a comprehensive understanding of early galaxy kinematics, we emphasize that the ALMA-JWST/NIRSpec synergy will be essential.

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References