A giant central red disk galaxy at redshift $z = 0.76$

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Galaxies are usually classified into ellipticals and spirals according to their morphology. Elliptical galaxies, by the definition, have regular elliptical shapes of stellar distribution. They have very little ongoing star formation, and thus they are red in color and old in stellar age. In contrast, spiral galaxies have disk shapes of stellar distribution, though a significant fraction of them possess bulges at the centers. There is usually ongoing star formation in spiral galaxies, so they look blue in color and have young stellar populations [1].

These properties of galaxies can be well understood in the standard paradigm of hierarchical structure formation [2-4]. In the theory, cosmic structures grow by the gravitational instability from the initial tiny quantum fluctuations generated during the inflationary epoch. Dark Matter (DM) halos, which are defined as the dark matter objects with the density about 200 times of the mean density of the Universe, are formed through accreting surrounding smaller DM halos and diffuse matter including DM and gas. The gas, when accreted into a halo, is heated by shocks. The hot gas will cool by radiating its energy, and the cold gas will spiral into the halo center to form a disk (spiral) galaxy. With the growth of a halo, surrounding galaxies can also be accreted into the halo and become its satellites. Because of the dynamical friction, some satellite galaxies, especially those relatively massive ones, will spiral into the center and coalesce with the central galaxy [5, 6]. A merger of a central disk galaxy with a satellite of comparable mass (say, a mass ratio $\geq 0.2$) may significantly change its internal structure, either producing an elliptical galaxy or a disk galaxy with a significant bulge [7-9]. Based on the observed relation between black hole mass and bulge mass [10], we expect there are supermassive black holes (SMBHs) within elliptical galaxies or bulges. The strong energy output and/or material outflow produced by an SMBH can heat and/or blow the surrounding cold gas, thus suppresses the reservoir to form stars and makes the host galaxy look red. Current hydrodynamical simulations of galaxies that have incorporated these (and other) physical processes have successfully reproduced a wide range observed properties of galaxies including the stellar mass, morphology, color, and stellar age [11, 12].

For massive galaxies with stellar mass larger than $10^{11.0} M_\odot$. They are expected to form in DM halos of group and cluster mass [13]. Because of frequent mergers happening in such rich environments, one expects most of massive galaxies are red ellipticals with significant amounts of bulge. Only in a rare case with little merger happened in the past, since no bulge, no SMBH has formed. The central galaxy may keep forming stars, thus becoming a blue disk galaxy. In any case, one would not expect to form a central red disk galaxy in a massive DM halo, as there is no mechanism to stop gas cooling and star formation if no bulge (thus no SMBH) has formed.

In this Letter, we report a massive red central disk galaxy with stellar mass reaching $10^{11.6} M_\odot$. The details of the galaxy are shown in Table 1. The galaxy was discovered when we study the physical properties of massive galaxies in the

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CMASS sample of the Baryon Oscillation Spectroscopic Survey (BOSS) survey [14] in the XMM-LSS region. Performing Spectral Energy Distribution (SED) fitting on multi-band data of the galaxy from FUV to $K_s$ collected by Moutard et al. [15], we get the stellar mass $M_*=10^{11.64}M_\odot$ and the specific star formation rate (sSFR) $10^{-11.38}$ yr$^{-1}$. And the rest-frame $NUV-r$ color is 5.30 based on the SED fitting. As the BOSS survey has taken spectrum for the galaxy, we show it in Figure 1. From the lower panel, we can easily see the best fitting spectrum is typical for an old stellar population: there is no visible emission line and the D4000 break is about 1.9. The stellar mass released by the Wisconsin group [16] using Principal Component Analysis method based on the spectrum is $10^{11.67\pm0.17}M_\odot$, which is well consistent with the stellar mass obtained by our SED fitting. From both the photometry and the spectrum, we can conclude that the galaxy is very massive and its star formation has been quenched. These are the typical features of a massive elliptical galaxy.

However, our analysis of the morphology for the galaxy surprisingly shows that it is a disk galaxy. The radial luminosity distribution of a galaxy can be described by the Sérsic form [17]:

$$I(R) = I_e \exp[-b_n((R/R_e)^{1/n} - 1)],$$

$$\gamma(2n; b_n) = \frac{1}{2}\Gamma(2n).$$

Figure 2  HSC z-band image (left panel), best-fit Sersic model (middle panel) and the residual of the galaxy (right panel).

Figure 3  Radial profiles of z band image and models of the galaxy. Red dots with error bars are the data from HSC z band. Blue solid line shows the profile of the best fitting Sérsic model. Parameters from the best fitting are: Integrated magnitude: $z = 19.64 \pm 0.01$ mag; effective radius: $R_e = 1.035 \pm 0.020$ arcsec; Axis ratio: $b/a = 0.850 \pm 0.010$; Position Angle: $PA = -78.46 \pm 3.87$ deg; Sérsic index: $n = 1.22 \pm 0.06$. Green dot line shows the best fitting of the exponential function.

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which does not show any significant bulge component. To direct measure the bulge/disk ratio, we also performed two component fitting on the galaxy, using an exponential plus de Vaucouleurs profile. The fitting results do not indicate any bulge component, and we can set an upper limit that the bulge contains less than 1/15 stellar light of the galaxy. In fact, the luminosity profile is indeed well described by the exponential profile with $n = 1$ (Green dot line in Figure 3).

As we will discuss below, the environment effects, such as the ram pressure and/or the tidal stripping may help disk galaxies to quench their star formation. It is therefore vital to check whether the galaxy is a central or satellite galaxy. We use the photometric catalog of the second public data release (PDR-2) of the VIMOS Public Extragalactic Redshift Survey (VIPERS) [15]. This catalog contains all sources brighter than 22.5 $\text{mag}$ in the $i$ band in the W1 field which covers the galaxy we study. The $K_s$ band magnitudes from the VIDEO observation [20] are also available in the region around the galaxy. We consider a field of view of a comoving radius 1 Mpc around the galaxy, which corresponds to $\theta = 0.02081$ deg in the sky using the cosmological parameters from the Planck satellite [21]. We use the photometric redshifts $z_{\text{ph}}$ to search for the neighbors. Since the error of $z_{\text{ph}}$ is typically about 0.05 for galaxies with $i < 22.5$ $\text{mag}$ and $K_s < 22.0$ $\text{mag}$ [15], we plot all the galaxies of $K_s \leq 21.0$ $\text{mag}$ within a cylinder of the radius $\theta$ and the length $\Delta z_{\text{ph}} = 0.2$ centered on redshift $z_r = 0.76$ of the red disk galaxy. As shown in Figure 4, there are 7 neighbor galaxies, all of which are at least 1.2 mag fainter than our red disk ($K_s = 18.4$ $\text{mag}$), which confirms that the red disk galaxy is a central galaxy. Since the $K_s$ luminosity is approximately proportional to the stellar mass, we also find that the existence of 7 satellites with the stellar mass larger than 1/10 of the central red disk’s stellar mass is fully consistent with the observed conditional stellar mass function [22].

Thus, The galaxy we find is very likely a massive central red disk. But it is very challenging to explain its formation in current theories of galaxy formation. According to the halo mass and stellar mass relation [13], we expect the galaxy is at the center of the host halo of mass about $5 \times 10^{14} \odot$. As described in the beginning, such a galaxy is hard to maintain its disk structure since frequent merging is inevitable with other spiraling-in galaxies in the rich environment (cluster of galaxies). Even in very rare cases that there is very little merging happened in the recently long enough period, one would expect ongoing star formation activities unless there is enough feedback from the central SMBH. However, as we have not detected the bulge component at the center of the red disk, we would expect that the feedback from SMBH is not an efficient way to quench the whole galaxy. This qualitative reason-

![Figure 4](image)

**Figure 4** Galaxies of $K_s < 21$ $\text{mag}$ within $|\Delta z_{\text{ph}}|$ = 0.1 in the sky area of a comoving radius 1 Mpc centered on the red disk galaxy. Colors of the dots reflect the $K_s$ band magnitude of the neighbor galaxies.

It is interesting to point out that a few studies of red spiral galaxies has appeared recently in literature. Red disks with smaller mass ($\sim 10^{10.0} \odot$) are found at intermediate local densities such as the infall regions of clusters [26, 27]. The tidal force and/or gas ram pressure in such intermediate density environments could be strong enough to destroy the cold gas reservoir, but still too weak to affect the disk structures. Statistical studies of nearby massive red disks ($10^{10.5}$ $\sim 10^{11.0} \odot$) show larger bulge/total mass ratios than their blue counterparts [28, 29]. In other studies, relations beyond the standard scaling rules are proposed to explain the existence of massive red disks. For example, some studies show that massive red disks may exist in smaller halos comparing to other galaxies with the same stellar mass [30]. Gas is exhausted by star formation in these galaxies and no quench mechanism is needed to explain their red color. Moreover, Deviations from the BH-bulge mass and the DM-baryon mass relations have also been proposed [31, 32].

In conclusion, we find a giant red central disk. The existence of this galaxy seriously challenges the current theories of galaxy formation, as there is no known physical mechanism to stop its star formation. Since there are some rare cases that the mergers, which may cause very low Sérsic indices, can not be distinguished from the photomet-

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1) Because the color of galaxies is redder and the merging is less frequent in a fixed time period at $z_r = 0$ than $z_r = 0.7$, we would expect to form more red disk galaxies at $z_r = 0$ than at an earlier epoch.
ric data [33], we plan to confirm its disk morphology with the kinematic data from Integral Field Unit (IFU) observations. Meanwhile, we will search the whole HSC wide field for massive red disks and employ statistical analysis to check whether their properties are deviated from the standard scalings. Meanwhile, we will search the whole HSC wide field

Conflict of interest The authors declare that they have no conflict of interest.

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