

LETTER TO THE EDITOR

# Supermassive black hole wake or bulgeless edge-on galaxy?

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## ABSTRACT

A recent paper reported the serendipitous discovery of a thin linear object interpreted as the trail of star-forming regions left behind by a runaway supermassive black hole (SMBH) kicked out from the center of a galaxy. Despite the undeniable interest in the idea, the actual physical interpretation is not devoid of difficulty. The wake of a SMBH produces only small perturbations in the external medium, which has to be in exceptional physical conditions to collapse gravitationally and form a long (40 kpc) massive ( $3 \times 10^9 M_{\odot}$ ) stellar trace in only 39 Myr. Here we offer a more conventional explanation: the stellar trail is a bulgeless galaxy viewed edge-on. This interpretation is supported by the fact that its position–velocity curve resembles a rotation curve, which, together with its stellar mass, puts the object exactly on the Tully–Fisher relation characteristic of disk galaxies. Moreover, the rotation curve ( $V_{\max} \sim 110 \text{ km s}^{-1}$ ), stellar mass, extension, width ( $z_0 \sim 1.2 \text{ kpc}$ ), and surface brightness profile of the object are very much like those of IC 5249, a well-known local bulgeless edge-on galaxy. These observational facts are difficult to interpret within the SMBH wake scenario. We discuss in detail the pros and cons of the two options.

**Key words.** Galaxy: halo – galaxies: individual: IC 5249 – galaxies: kinematics and dynamics – galaxies: fundamental parameters – galaxies: peculiar – galaxies: structure

## 1. Introduction

Recently, [van Dokkum et al. \(2023, hereafter VD23\)](#) discovered a remarkable thin extended object ( $\sim 0''.25 \times 5''$ ; see Fig. 1a) roughly aligned with a nearby galaxy. It was interpreted as the stellar wake induced by the passage of a supermassive black hole (SMBH) kicked out from the galaxy by the slingshot effect of a three-body encounter of SMBHs. This object would be the first example of its class; to date the ejection of SMBHs through this potential mechanism has never been observed. It would also provide a new discovery channel for rogue SMBHs and for the process of SMBH ejection from galaxies. In the scenario put forward by VD23, the SMBH producing the wake was ejected with a (projected) speed of  $\sim 1600 \text{ km s}^{-1}$  and is observed 39 Myr after the three-body encounter, creating a stellar linear structure 40 kpc long and 2 kpc wide, with a stellar mass on the order of  $3 \times 10^9 M_{\odot}$ . As it happens with the SMBH ejection, the formation of such a thin long massive stellar structure may conceptually occur, but would be the first observation of this phenomenon. Despite the undeniable interest in this eye-catching idea, the actual physical interpretation is not devoid of difficulty.

The physical mechanism invoked for the creation of a stellar wake is not specific to SMBHs. It will work for any massive compact object wandering in the halo of a galaxy, including globular clusters, dark matter sub-halos (e.g., [Buschmann et al. 2018](#)), and intermediate-mass black holes (e.g., [Di Matteo et al. 2022](#)). Thus, if the physical conditions of the gas in the circumgalactic medium (CGM) that could potentially trigger the formation of a 40 kpc-long stellar trail were common, then long massive bright stellar trails around galaxies would be ubiqui-

tous. Since this is not the case, the proposed creation of a stellar trail driven by the passage of a SMBH through the CGM of a galaxy is doubly exceptional: it requires the ejection of a SMBH from a galaxy surrounded by a large massive CGM about to self-collapse gravitationally.

Thus, in view of the potential difficulties and to broaden the range of possibilities, here we explore another more traditional explanation of the observation, namely that the object is a bulgeless galaxy viewed edge-on. Indeed, this idea was mentioned in VD23, but not developed further. We use publicly available data (Sect. 2) to show that the stellar mass of the object plus the observed line-of-sight velocities interpreted as a rotation curve places the object precisely on the baryonic Tully–Fisher relation (TFR) that characterizes disk galaxies (Sect. 3). In addition, we carry out a comparative analysis between the object and the local bulgeless edge-on galaxy IC 5249 (Sect. 3; Fig. 1b). IC 5249 has similar properties attributed to the object when interpreted as a bulgeless edge-on galaxy: similar stellar mass, rotation curve, disk orientation, extension, and width. Evidence for and against the two scenarios (SMBH wake and bulgeless edge-on galaxy) is discussed in Sect. 4. Throughout this work we adopt a cosmological model with  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_m = 0.3$ , and  $\Omega_{\Lambda} = 0.7$ . All magnitudes are in the AB magnitude system.

## 2. Data

We analyze two sources in this paper: the object and the bulgeless galaxy IC 5249. All used data are archival or from the literature, as declared below.

## 2.1. The object

The object was observed with the Advanced Camera for Surveys (ACS) WideField Channel (WFC) on board of the *Hubble* Space Telescope as part of the program GO-16912 (PI: van Dokkum) available through the MAST archive<sup>1</sup>. The data consists of one orbit in the F606W band and one in the F814W band, corresponding to an exposure time of 2064 s in F606W and the same in F814W. The charge-transfer efficiency (CTE) corrected data were downloaded from MAST, and flc files were used to build the final drizzled mosaics with Astrodrizzle (Gonzaga et al. 2012). Figure 1a shows a color stamp of  $7''.5 \times 3''.5$  ( $\sim 60 \text{ kpc} \times 30 \text{ kpc}$  at  $z = 0.964$ ) centered on the object and generated from F606W and F814W.

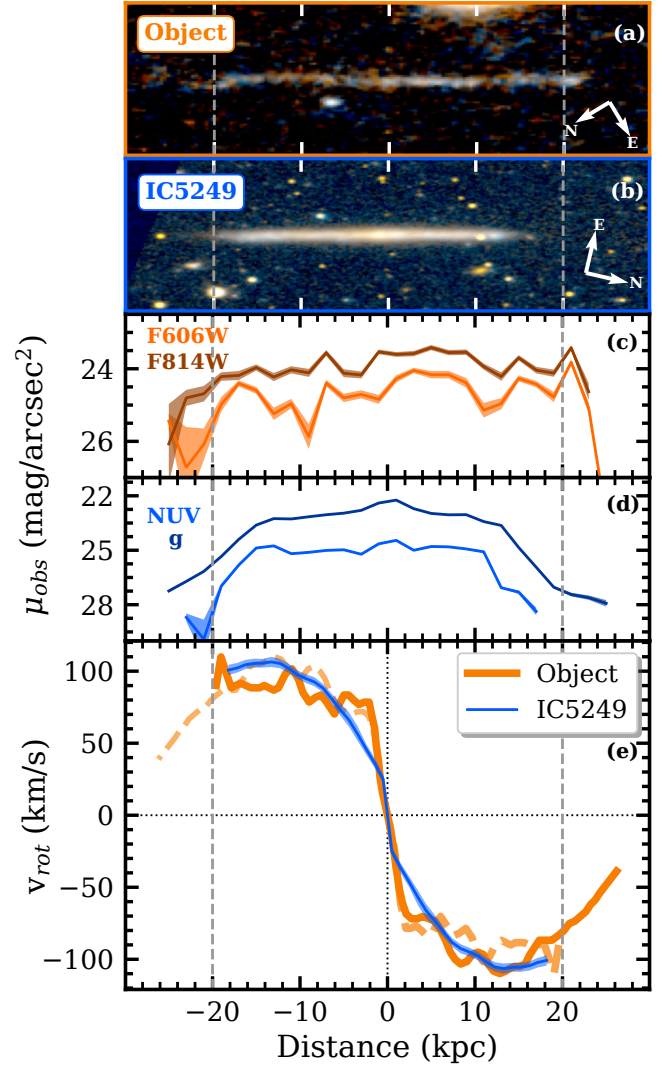
Figure 1c shows the surface brightness profiles of the object in the F606W and F814W bands, extracted averaging  $\pm 1 \text{ kpc}$  along the trace. The shaded areas represent  $1\sigma$  errors in the profiles, propagated from the photometric error of all the spaxel contributing to each surface brightness bin.

The position–velocity curve shown in Fig. 1e (solid orange line) is a replica of the line-of-sight velocity of the object provided by VD23 in the top left panel of their Fig. 10. The velocities in VD23 Fig. 10 between the location of the host galaxy and  $\sim 20 \text{ kpc}$  are not used for our analysis as they do not represent real measurements but a simple interpolation. The velocities were measured in the [OIII] $\lambda 5007$  emission line detected using the LIRIS spectrograph on Keck I (Oke et al. 1995). We interpret the position–velocity curve of the object as a rotation curve. In our rendering,  $V_{\text{rot}} = 0$  was estimated as the average between the minimum and maximum velocities of the curve. Then the center of rotation is the position where the observed  $V_{\text{rot}}$  is zero. The position thus determined sets the origin of distances in Fig. 1e, and also in Figs. 1a and 1c and in the top panel of Fig. 3.

According to VD23, the spatially integrated brightness of the object is  $\approx 40\%$  of the brightness of the closest galaxy (the host from which the SMBH was escaping in their proposed scenario). This closest galaxy and the object have nearly identical colors, implying similar mass-to-light ratios. The stellar mass of the host is estimated in VD23 to be  $M_{\text{host}} \approx 7 \times 10^9 M_{\odot}$ ; therefore, the inferred mass of the object is  $M_{\star} \approx 0.4 \times M_{\text{host}} \approx 2.8 \times 10^9 M_{\odot}$ .

## 2.2. IC 5249

IC 5249 is a well-known nearby (redshift 0.007) bulgeless galaxy (e.g., Karachentsev et al. 1999). In order to compare with the F606W and F814W bands of the object at its redshift, we retrieved the closest available images for this galaxy: in the near-ultraviolet (NUV; GALEX, Martin et al. 2005) and  $g$  (DECaLS; Dark Energy Survey Collaboration 2016). Although the  $u$  band would be a better choice to replicate F814W, it is not available. Figure 1b shows a color image generated from the NUV and  $g$  images. For ease of comparison, it is shown at the same physical scale and orientation as the object. The surface brightness profiles in the two bands are shown in Fig. 1d, extracted averaging  $\pm 1 \text{ kpc}$  along the trace of the galaxy. Although barely visible, errors derived in the same way as for the object are included as well. The rotation curve of this galaxy shown in Fig. 1e (blue solid line; the light blue region denotes the error) is taken from Banerjee & Bapat (2017) from HI observations by O’Brien et al. (2010) with the Australia Telescope Compact Array (ATCA). The distance of this galaxy (33 Mpc) was taken from NED<sup>2</sup> to set

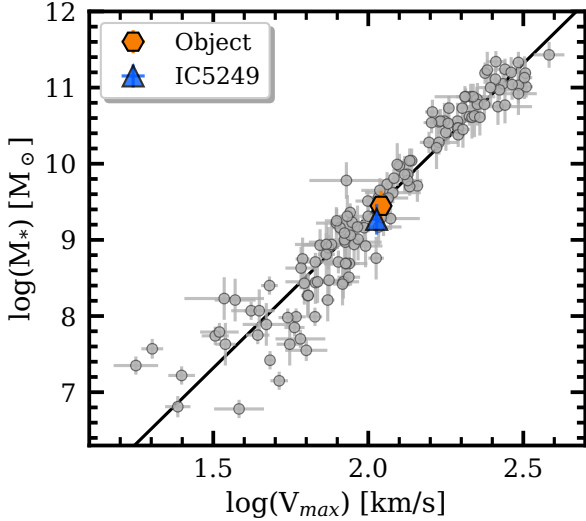


**Fig. 1.** Summary plot giving evidence for the VD23 object being a bulgeless edge-on galaxy. *Panel (a)*: two-color image of the object, i.e., of the conspicuous thin long structure in the image. *Panel (b)*: two-color image of local galaxy IC 5249 presented at the same spatial scale and orientation as the object. The bands (NUV and  $g$ ) were chosen to approximately represent the restframe wavelengths where the object was observed (F606W and F814W). *Panel (c)*: surface brightness profiles of the object in F606W and F814W (see inset). *Panel (d)*: surface brightness profiles of IC 5249 in NUV and  $g$  (see inset). *Panel (e)*: position–velocity curve of the object from Fig. 10 in VD23 (thick orange line). The same curve flipped both around  $x = 0$  (vertical dotted line) and  $y = 0$  (horizontal dotted line) is also represented (orange dashed lines) to emphasize the symmetry of the observed position–velocity curve, as expected from the rotation of a galaxy. The rotation curve of IC 5249 was also included without any scaling or adjustment (blue solid line; the light blue region represents the noise, as provided by Banerjee & Bapat 2017). The five panels share the same  $x$ -axis with the vertical dashed lines, separated by  $40 \text{ kpc}$ , included for comparison. See Sects. 2 and 3 for further details.

all physical scales. The value of  $V_{\text{max}} \approx 106 \text{ km s}^{-1}$  was obtained directly from the rotation curve. To calculate the stellar mass of IC 5249, we used the integrated signals in the DECaLS  $g$  and  $r$  images with the mass-to-light ratio from Roediger & Courteau (2015) and assuming a Chabrier (2003) initial mass function. The mass of the galaxy thus computed is  $\sim 1.9 \times 10^9 M_{\odot}$ .

<sup>1</sup> <https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html>

<sup>2</sup> <https://ned.ipac.caltech.edu/>



**Fig. 2.** Tully–Fisher relation from Lelli et al. (2019, gray points with error bars) with the stellar masses from Lelli et al. (2016). This rendering represents stellar mass vs. maximum rotational velocity. The figure also includes the object (orange hexagon;  $M_\star = 2.8 \times 10^9 M_\odot$ ,  $V_{\max} = 110 \text{ km s}^{-1}$ ) and the galaxy IC 5249 (blue triangle;  $M_\star = 1.9 \times 10^9 M_\odot$ ,  $V_{\max} = 106 \text{ km s}^{-1}$ ). Both objects lie close to each other and precisely on the relation. The solid black line is a linear fit to the gray points of the form  $\log M_\star = A \times \log V_{\max} + B$ , with  $A = 4.0 \pm 0.1$  and  $B = 1.3 \pm 0.2$ .

### 3. Interpretation as a bulgeless edge-on galaxy

The baryonic TFR (Tully & Fisher 1977) links the baryon mass with the maximum rotational velocity of a disk galaxy. In practice, it is a main signpost for being a galaxy, so fundamental as to be routinely employed to determine absolute distances to galaxies from the observed rotational velocities and apparent magnitudes (e.g., the textbooks by Phillipps 2005; Harwit 2006; Sparke & Gallagher 2006). Figure 2 shows a recent rendering of the stellar TFR as worked out by Lelli et al. (2019) for local galaxies (the stellar masses are from Lelli et al. 2016). Using the stellar mass and the maximum rotational velocity derived in Sect. 2, the object happens to appear right on the TFR (see the orange hexagon). Repeating the same exercise for IC 5249 yields very similar results (blue triangle in Fig. 2). Thus, the location of the object on the TFR provides solid support for our conjecture that it is a galaxy.

More evidence can be extracted from Fig. 1. The images of the object and the local galaxy are quite similar both in extension and width (cf. the two top panels of the figure). The image of the object is clumpier or more irregular, but this is to be expected because (1) high redshift galaxies in general form stars more actively and are therefore clumpier (e.g., Elmegreen & Elmegreen 2005; Elmegreen et al. 2005), and (2) the redder band used for the object (F814W, corresponding to restframe wavelengths between 3500 and 4700 Å) is significantly bluer than the  $g$  color filter (from 4000 to 5500 Å) used for IC 5249. It is well known that star-forming galaxies appear more irregular in bluer bandpasses (e.g., Kuchinski et al. 2001; Mager et al. 2018).

The surface brightness profiles of IC 5249 and the object along the semimajor axes are also quite similar (Figs. 1c and 1d). These surface brightness profiles were obtained using an aperture of 2 kpc for both objects. Both profiles are fairly flat with a sharp drop in the outskirts. The radial position of the

edges (where the sharp drops are located; see Trujillo et al. 2020; Chamba et al. 2022) are  $R_{\text{edge}} = 15 \text{ kpc}$  for IC 5249 and 20 kpc for the object. The edges of both objects tend to be bluer (Figs. 1c and 1d). There are some differences in the global colors (IC 5249 is redder) and the presence of a small bulge in IC 5249, which is not visible in the object.

The position–velocity curve of the object provided by VD23 (their Fig. 10, top left panel) is plotted as a solid orange line in Fig. 1e. The same curve flipped both around  $x = 0$  and  $y = 0$  is also represented (orange dashed lines) to highlight the anti-symmetry of the observed position–velocity curve, as expected from the rotation of a galaxy. The blue solid line represents the rotation curve of IC 5249 from Banerjee & Bapat (2017), and is included without any scaling or adjustment. The agreement between the object and IC 5249 is remarkable, supporting that the position–velocity curve of the object is indeed the rotation curve of a galaxy. In addition to the overall agreement in shape and amplitude, we note the tendency of both curves to drop in the outskirts, a property often observed in high redshift galaxies (e.g., Genzel et al. 2017) that tells us about the relative importance of baryons to dark matter.

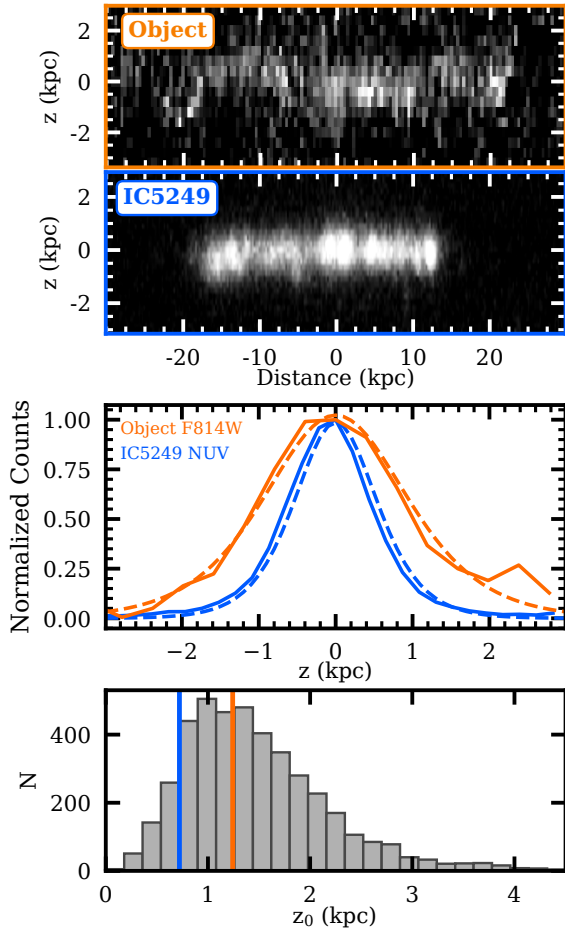
We also investigated whether the width of the object is compatible with being a bulgeless galaxy. Figure 3 shows images of the object (in the F814W band) and IC 5249 (in the NUV band). Visually, they have similar widths. To quantify this statement, the central panel of Fig. 3 shows the distribution of counts across the object and IC 5249. To create these profiles, the distribution of counts of both galaxies was collapsed along the long axes (horizontal in Fig. 3). By fitting the vertical distribution of counts to the commonly used function  $\text{sech}^2(z/z_0)$ , with  $z_0$  the scale height, we obtain  $z_0 = 0.72 \text{ kpc}$  for IC 5249 (in very nice agreement with the value of 0.724 kpc reported by Banerjee & Bapat 2017) and  $z_0 = 1.24 \text{ kpc}$  for the object. The fits are shown as dashed lines in the central panel of Fig. 3. The bottom panel of the same figure compares the derived values of  $z_0$  with the scale heights of the sample of edge-on disks from Bizyaev et al. (2014). The widths of IC 5249 and the object are both perfectly normal in terms of scale height, a result well known for bulgeless galaxies (see, e.g., Bizyaev et al. 2017).

### 4. Discussion

The main arguments for the object to be a bulgeless edge-on galaxy are: (1) its position–velocity curve resembles a rotation curve that, together with its stellar mass, puts the object right on the TFR (Fig. 2), and (2) the rotation curve, stellar mass, extension, width, and surface brightness profile of the object are very much like those of IC 5249 (Fig. 1), which without much forcing could be a local analog.

However, there are three additional observables mentioned by VD23 that require further analysis for the object to be accommodated into the edge-on disk scenario. First, the object is not completely straight (Fig. 1, top panel), with variations of  $< 0.5 \text{ kpc}$ . This could be due to warps in the disk or simply because we are observing in the UV restframe, where galaxies are more irregular since the UV traces individual star-forming regions (see the discussion in Sect. 3). Second, the line ratio  $[\text{OIII}]/\text{H}\beta$  exceeds the canonical limit for HII regions in two positions along the stellar trace, reaching the value of 10 expected for shocks or active galactic nuclei (AGN). However, the observed  $\text{H}\beta$  line is extremely weak and noisy in these points, and a factor of two uncertainty in its flux would bring the ratio back to HII region values. Moreover, some extreme star-forming galaxies (e.g., green peas and the like; Steidel et al. 2014;





**Fig. 3.** Width of the stellar trace. Top panels: F814W image of the object and NUV image of IC5249. Middle panel: normalized profiles in counts along the vertical direction (along  $z$  in the top panels). The dashed lines show  $\text{sech}^2(z/z_0)$  fits to these vertical cuts (see detailed description in Sect. 3). Bottom panel: histogram of scale heights for edge-on galaxies from Bizyaev et al. (2014). The vertical colored lines indicate the values of the scale heights from the fit for the object (orange) and IC 5249 (blue).

Leitherer 2020) provide ratios very close to the highest found in the object. Another possibility is that the emission is tracing shocks created by star formation in HII regions, without the intervention of any SMBH. Those shocks are not uncommon when supernova-driven bubbles meet the interstellar medium (ISM) or can be caused by the random motions associated with the ISM turbulence (e.g., Sánchez et al. 2014; Della Bruna et al. 2022). Third, the change in color along the stellar trace has a pattern that reproduces the evolution of a young single stellar population with time (Fig. 9 in VD23), indicating linearly increasing aging from left to right in Figs. 1a and 1c. Within the stellar disk scenario, the changes in color would have to be produced by the random mixture of younger and older populations that co-exist in the disk. This explanation avoids a serious issue of the systematic age variation explanation of colors, namely, the absence of a systematic surface brightness variation of the stellar trace (Fig. 1c). With some dependence on the details of the single-stellar population modeling and on the bandpass of observation, we should expect a systematic luminosity variation from the oldest stars (leftmost point in Fig. 1a) to the youngest stars (rightmost point) of around 2 magnitudes (e.g., Leitherer et al.

1999; Conroy et al. 2009). This significant variation in magnitude is simply not observed.

The overdensity expected from the passage of a SMBH is not large, which implies very special physical conditions in the IGM for the star formation to be triggered. If such conditions were regularly met, it would imply that the passage of any massive compact object, for example a globular cluster, would trigger star formation, and galaxies would be plagued with conspicuous stellar wakes. Thus, the scenario where the object is produced by the ejection of a SMBH is doubly exceptional: it requires the ejection of a SMBH from a galaxy that then encounters a huge massive gas cloud about to self-collapse gravitationally. In addition, the SMBH scenario does not explain the two main observational features supporting the galaxy hypothesis, namely why the object fits in the TFR (Fig. 2) and why its main observational properties agree so well with those of a local bulgeless galaxy with similar stellar mass (IC 5249; Fig. 1). Other observables where the SMBH wake scenario seems to do a remarkably good job also face problems, however. These observables are the color variation of the trail and its transverse displacement according to time from the SMBH pass. If the change in color were produced by the aging of the stellar population, the surface brightness should change systematically along the stellar trace, being about two magnitudes fainter at the older end (see the discussion above). As for the transverse displacement, the agreement relies on the implicit assumption that the gas cloud transverse velocity is zero at the older end of the stellar trace. Even if this might happen, it represents an ad hoc assumption, without which the agreement between the observed transverse displacement and line-of-sight velocity goes away.

In short, in this Letter we present a number of solid arguments supporting the scenario where the object discovered by VD23 could be a bulgeless edge-on galaxy. If it is, it would not be a common galaxy in the sense of being bulgeless and particularly long for its stellar mass and redshift. However, it is not very uncommon either since thousands of this kind of galaxy (often called thin galaxies or flat galaxies) are already known (e.g., Karachentsev et al. 1999). One of them, IC 5249, has been used here to highlight the close resemblance of the object with these galaxies.

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