Observational insights on the origin of giant low surface brightness galaxies

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4 November 2020

ABSTRACT

Giant low surface brightness galaxies (gLSBGs) with dynamically cold stellar discs reaching the radius of 130 kpc challenge currently considered galaxy formation mechanisms. We analyse new deep long-slit optical spectroscopic observations, archival optical images and published H/\textit{i} and optical spectroscopic data for a sample of seven gLSBGs, for which we performed mass modeling and estimated the parameters of dark matter haloes assuming the Burkert dark matter density profile. Our sample is not homogeneous by morphology, parameters of stellar populations and total mass, however, six of seven galaxies sit on the high-mass extension of the baryonic Tully–Fisher relation. In UGC 1382 we detected a global counter-rotation of the stellar high surface brightness (HSB) disc with respect to the extended LSB disc. In UGC 1922 with signatures of a possible merger, the gas counter-rotation is seen in the inner disc. Six galaxies host active galactic nuclei, three of which have the estimated black hole masses substantially below those expected for their (pseudo-)bulge properties suggesting poor merger histories. Overall, the morphology, internal dynamics, and low star formation efficiency in the outer discs indicate that the three formation scenarios shape gLSBGs: (i) a two-stage formation when an HSB galaxy is formed first and then grows an LSB disc by accreting gas from an external supply; (ii) an unusual shallow and extended dark matter halo; (iii) a major merger with fine-tuned orbital parameters and morphologies of the merging galaxies.

Key words: galaxies: kinematics and dynamics, galaxies: evolution, galaxies: formation, galaxies: individual, galaxies: haloes, galaxies: disc

1 INTRODUCTION

Freeman (1970) discovered that the majority of galactic discs have exponential light profiles with nearly the same $B$-band central surface brightnesses of 21.65 mag arcsec$^{-2}$. However, over a decade later, deep photometric observations revealed the existence of fainter systems which were named low surface brightness (LSB) galaxies. Bothun et al. (1987) discovered a separate subclass of a stellar system, giant LSB galaxies (gLSBGs) with a disc radius up-to 130 kpc (Boissier et al. 2016) that is nearly ten times the radius of the Milky Way. These galaxies pose a problem in the currently accepted hierarchical galaxy formation paradigm. Despite they are among the most massive known galaxies reaching dynamical masses of $10^{12}$ $M_{\odot}$ and ~ $10^{11}$ $M_{\odot}$ in stars, they have large-scale dynamically cold discs. It is very difficult to grow such high stellar mass in the hierarchical clustering paradigm without numerous major mergers (Rodriguez-Gomez et al. 2015) that would likely overheat and destroy the discs (Wilman et al. 2013). Most gLSBGs live in a sparse environment or total isolation (Saburova et al. 2018), and perhaps this can help to preserve gLSB discs through the cosmic time (Galaz et al. 2011; Pérez-Montaño & Cervantes Sodi 2019). However, at a certain stage of the gLSBGs evolution there should exist a large reservoir of gas sufficient to foster the formation of a massive gaseous disc.

The question ‘how do gLSBGs form?’ remains a matter of debate (see, e.g. Kasparova et al. 2014; Galaz et al. 2015; Hagen et al. 2016; Boissier et al. 2016; Saburova et al. 2018, and references therein). The recent studies discuss the two groups of gLSBGs formation scenarios, (i) non-catastrophic scenarios involving either
slow gas accretion from filaments or secular evolution and (ii) catastrophic models based on major and/or minor merger events.

The major advantage of catastrophic scenarios from the point of view of simulations is that they could work within the current galaxy formation framework. For example, Zhu et al. (2018) found an analogue of Malin 1 in the IllustrisTNG simulation, which satisfactorily reproduced most observed properties of Malin 1 and was formed by a merger of three quite massive galaxies. Saburova et al. (2018) considered a major merger scenario among others in the case of UGC 1922, a gLSB with a counter-rotating inner gaseous disc. Using dedicated N-body/hydrodynamical simulations they argued that its gLSB disc can be the result of an in-plane merger of a giant early-type spiral (Sa) galaxy and a gas-rich late-type (Sd) giant companion on a prograde orbit. However, the counter-rotation observed in the central gaseous component with respect to the outer disc of UGC 1922 should be the result of another (minor) merger event. Despite relatively high environment of UGC 1922 compared to other gLSBs, Saburova et al. (2018) proposed that the major merger scenario could also be a viable option for other galaxies of this class, which have fewer known companions.

Earlier, Mapelli et al. (2008) proposed another configuration of the catastrophic scenario that could lead to the formation of a gLSB, a bygone head-on collision of a galaxy with a massive intruder, which could form a system similar to Malin 1 as a result of the expansion of a collisional ring. The weak point of this scenario is that the progenitor galaxy that experienced a collision should be already an LSB system. Also, Kasparova et al. (2014), Boissier et al. (2016) and Hagen et al. (2016) did not find evidences in favour of this scenario for Malin 2, Malin 1 and UGC 1382. Instead, to explain the origin of UGC 1382, Hagen et al. (2016) lean towards another widely discussed formation channel proposed by Peña-Rubio et al. (2006), the accretion of several gas-rich low-mass satellites. Similar scenario is also proposed as one of the channels of the formation of massive discs by Jackson et al. (2020).

Despite the fact that most gLSBs have diffuse clumps in their discs (Kasparova et al. 2014; Boissier et al. 2016; Hagen et al. 2016; Saburova et al. 2018) which can be traces of recent mergers, the minor merger scenario by Peña-Rubio et al. (2006) contradicts to most published Hi gLSB observations (see, e.g. Pickering et al. 1997; Mishra et al. 2017) because it predicts the fall-off of the rotational velocity at the periphery of the disc, which is not observed.

Along with the catastrophic formation scenarios for gLSBs, several studies proposed non-catastrophic solutions, the scenarios which do not include a major merger or disruption of the satellites. Noguchi (2003) discussed the transformation of normal HSB spirals to gLSBs through dynamical evolution due to a bar, which induces non-circular motions and radial mixing of disc matter that flattens the disc density profile. Kasparova et al. (2014) proposed that the large radius of the disc could be related to a ‘spare’ and shallow dark matter halo. They found that the dark matter halo of Malin 2 has the peculiarly high radial scale and low central density, and concluded that it could have caused the formation of a giant disc.

Saburova (2018) studied high surface brightness disc galaxies with slightly smaller (compared to gLSBs) but still very large radii and highlighted a similar trend of larger radial scales of dark matter haloes for these systems in comparison to “normal-sized” disc galaxies. Central densities of dark matter haloes of HSB giant discs lie within the scatter for ordinary galaxies. Perhaps, to form a gLSB, both a large scale and a lower central density of the dark halo are required.

The evidences in favour of this idea were found e.g. in Pérez-Montaño & Cervantes Sodi (2019) who concluded that the spin parameters of LSB galaxies are systematically higher than those of HSB systems. If the baryons share the specific angular momentum with a dark halo (Fall & Efstathiou 1980) than it could lead to larger radial scales of stellar discs and their lower baryonic surface densities in LSB galaxies, which was proved by self-consistent hydrodynamic simulations (see, e.g. Kim & Lee 2013). The properties of dark halos could in turn be related to the environment both at the stage of the galaxy formation and during its latter lifespan.

Most published works on gLSBs are devoted to individual objects primarily because such objects are very difficult to observe and study in detail. In this paper we discuss a larger sample that includes seven gLSBs. We present new observations for the four gLSBs: Malin 2, NGC 7589, UGC 1382 and UGC 6614 and compare them to the data already available in the literature for Malin 1, UGC 1378 and UGC 1922. We present the results of long-slit spectral observations with the Russian 6-m telescope and the 8-m Gemini-North telescope. These data fill the central gap in low-resolution profiles of internal kinematics derived from radio observations in Ht (Mishra et al. 2017; Pickering et al. 1997) and give important clues about the central structure of gLSBs. It allows us to build the most complete picture of the formation and evolution of these unusual systems up-to-date.

The paper is organised as follows. We describe our sample and properties of individual galaxies in Section 2. The details of observations and data reduction performed in this study are given in Section 3. We discuss the results of mass modelling of the rotation curves in Section 4 and give the details on it in Appendix A. In Section 5 we discuss the star formation rates of gLSBs, properties of their central regions, their position on the baryonic Tully–Fisher relation, and propose the formation scenarios for each galaxy and compare gLSBs with other extended LSB and giant HSB galaxies. Section 6 summarizes our findings.

2 OUR SAMPLE OF GIANT LOW SURFACE BRIGHTNESS GALAXIES

Our sample includes 7 objects. To compare them against known high- and low-surface brightness galaxies, we display them in the size–luminosity diagram (see Fig. 1, coloured symbols) presenting a circularized effective radius \( r_{\text{eff}} \) versus \( V \)-band absolute magnitude. In some cases we converted the available \( g \)-band fluxes and \( g - r \) colours into the \( V \) band using the transformations from Jester et al. (2005). We display bulges and gLSB disc separately. The former are shown with black outlines and darker colours. The black lines correspond to constant mean surface brightnesses. We also plot slightly smaller extended LSB galaxies (black squares, Greco et al. 2018); ultra-diffuse galaxies (small crosses, van Dokkum et al. 2015; Chilingarian et al. 2019), several families of early-type galaxies (Brodie et al. 2011, small triangles); galaxies with morphological types later than 2 (i.e. discs) from the Hyperleda database (small circles). From the sample of Greco et al. (2018) we took only the objects with available spectroscopic redshifts.

From Fig. 1 it is evident that LSB discs of gLSBs have similar mean surface brightnesses to LSBs extending their locus to higher luminosities and also for a given luminosity they are much more extended compared to ‘normal’ late-type galaxies from Hyperleda.

\footnote{We calculate a circularized effective radius following Greco et al. (2018) as \( r_{\text{circ}} = (1 - \epsilon)^{1/2} r_{\text{eff}} \), where \( \epsilon \) is an ellipticity and \( r_{\text{eff}} \) is a measured half-light radius.}
At the same time, bulges of gLSBGs are similar to those in HSB early- and late-type galaxies.

We present the general properties of the gLSBGs from our sample in Tables 1, 2. Below we briefly describe every individual system.

Malin 1 is the prototype of the gLSBG class discovered by Bothun et al. (1987). Similar to most gLSBGs, it has a prominent bulge and faint extended spiral arms. It shows signs of an active galactic nucleus (AGN) lying in the borderline of the LINER–Seyfert classification by emission line ratios (Junais et al. 2020). Deep images of the galaxy revealed the well pronounced low surface brightness spiral arms (Galaz et al. 2015; Boissier et al. 2016) while the central part resembles a ‘normal’ barred early-type spiral galaxy (SB0/a) with a bulge and an HSB disc. Like Malin 1, Malin 2 is of low density. Based on multi-band images of Malin 1, Boissier et al. (2016) conclude that its extended disc has been forming stars with a low star-formation efficiency for several Gyr.

Malin 2 is relatively well studied since its discovery by Bothun et al. (1990). It has a prominent bulge and a gLSB disc with a spiral structure. According to Ramirez et al. (2011) Malin 2 shows AGN activity. The estimated mass of the central black hole, $9 \times 10^5 M_\odot$ (Ramirez et al. 2011) appears to be lower than expected for the observed stellar velocity dispersion. However, the Hα line profile decomposition done using the technique presented in Chilingarian et al. (2018) does not reveal a broad-line component hence questioning the black hole mass estimate from Ramirez et al. (2011). Das et al. (2010) revealed the presence of extended molecular gas in the disc of Malin 2 with the mass in the range from $4.9 \times 10^8 M_\odot$ to $8.3 \times 10^8 M_\odot$. The observed ratio of molecular to atomic hydrogen surface density is significantly higher than that expected in normal galaxies for the observed low value of the turbulent gas pressure and the total gas density. According to Kasparova et al. (2014), one possible explanation for this imbalance is the high content of undetected cold gas (dark gas) in Malin 2. The fact that Malin 2 is bright in the NUV indicates the ongoing star formation in the system. The SFR estimate based on the NUV flux is $4.3 M_\odot$ yr$^{-1}$ (Boissier et al. 2008). Kasparova et al. (2014) also give the measurement of the SFR surface density in the disc of Malin 2 of $2.5 \times 10^{-4} M_\odot$ yr$^{-1}$ kpc$^{-2}$ based on the archival GALEX data.

NGC 7589 was mentioned for the first time by Sprayberry et al. (1995). This galaxy has spiral arms, two bars and a ring. According to Lelli et al. (2010) NGC 7589 consists of a HSB central part and a gLSB disc. The available H$\alpha$ rotation curve exhibits a plateau at about 200 km s$^{-1}$ from the radius of 5.9 kpc, there is no H$\alpha$ data in the the inner part (Lelli et al. 2010).

NGC 7589 is a Seyfert 1 galaxy with the mass of the central black hole estimated at $9.44 \times 10^6 M_\odot$ (Subramanian et al. 2016). The upper limit of the molecular hydrogen mass is $8.25 \times 10^8 M_\odot$ which corresponds to the low ratio of the molecular-to-atom hydrogen of 0.081 (Cao et al. 2017). However, the global star formation rate is not very low: $1.00 M_\odot$ yr$^{-1}$ (deduced from the NUV flux, Cao et al. 2017) or 0.73 and 1.14 M$\odot$ yr$^{-1}$ (determined from FUV and NUV luminosities by Boissier et al. 2008).

UGC 1378 was classed as a gLSB galaxy by Schombert (1998). Saburova et al. (2019) studied it in details using long-slit spectral observations and deep multi-band optical photometry. Similarly to Malin 1 it has a complex morphology that includes a Milky-way sized central part with a bulge, bar and an HSB disc that is immersed in a large low surface brightness disc. The global star formation rate based on the infrared data is between 1.2 and 2.3 M$\odot$ yr$^{-1}$ (Saburova et al. 2019). At the same time, the star formation rate surface density of the LSB disc appears to be lower than expected for the given gas surface density, which can indicate the presence of accretion. No CO(1-0) emission was detected from the disc of this galaxy.

UGC 1382 had been mis-classified as an elliptical galaxy before Hagen et al. (2016) noticed that it had an extended spiral structure visible in UV images obtained by Galaxy Evolution Explorer (GALEX, Martin et al. 2005). Further analysis of the multi-wavelength data revealed that it appears to be a gLSB with HSB bulge+disc surrounded by a gLSB disc. The global SFR of UGC 1382 is 0.42 M$\odot$ yr$^{-1}$ and the SFR surface density of UGC 1382 is similar to that of the outer regions of spiral galaxies which is typical for low efficiency of star formation (Hagen et al. 2016). UGC 1382 lives in the low-density environment, at the same time Hagen et al. (2016) also discovered a possible remnant of a satellite embedded in its LSB disc.

UGC 1922 was erroneously classified as an elliptical galaxy too (see, e.g. Huchra et al. 2012). Schombert (1998) revealed the extended gLSB disc in it. Saburova et al. (2018) performed deep long-slit and photometric observations of this galaxy and discovered the presence of a kinematically decoupled central component, which counter-rotates with respect to the main disc of the galaxy. The deep photometry of UGC 1922 revealed the asymmetric spiral structure with “rows” and irregular star formation on the NW-side. The disc appeared to be strongly dynamical overheated. Unlike many other gLSB galaxies UGC 1922 is not isolated but a member of a group that includes 7 members (Saulder et al. 2016).

UGC 6614 was initially studied by Schommer & Bothun (1983). It has a prominent bulge, spiral arms and a ring. Like NGC 7589 it has an AGN and can be classified as LINER (Subramanian et al. 2016). The nucleus of UGC 6614 is bright in X-ray, optical and radio frequencies. The large amplitude, short time scale

Figure 1. Position of gLSB discs and bulges on the size-luminosity relation are shown by coloured and darker outlined symbols respectively. Bulge and disc positions of the same galaxy are connected by a line. Black squares show LSB galaxies from Greco et al. (2018) with spectroscopic redshifts. Small triangles display early-type galaxies from Brodie et al. (2011). Small circles correspond to late-type galaxies (with morphological type t > 2) from the Hyperleda database. Small crosses show ultra diffuse galaxies from van Dokkum et al. (2015) and Chilingarian et al. (2019). The solid diagonal lines show three values of a constant mean surface brightness.
of X-ray variability of UGC 6614 can be indication of active intense accretion on-to the central black hole (Naik et al. 2010). The estimate of the central black hole mass is $4.44 \times 10^6 M_\odot$, which appears to be lower than expected for observed stellar velocity dispersion similarly to that of Malin 2, that can indicate that it is not in co-evolution with the host galaxy bulge (Subramanian et al. 2016). The CO(1-0) emission was detected from the disc of UGC 6614 and the molecular gas traces its spiral arms (Das et al. 2006). The corresponding estimate of the mass of molecular gas in the disc is $2.8 \times 10^8 M_\odot$ (Rahman et al. 2007). We obtained the higher value of the global SFR based on GALEX FUV data and SFR vs UV-luminosity relation from Kennicutt (1998): $2.24 M_\odot$ yr$^{-1}$ and 1.44 for peripheral LSB regions. Our global SFR estimate is also higher than that derived by Wyder et al. (2009) from NUV data (1.95 $M_\odot$ yr$^{-1}$). The colour $FUV - NUV = 1.01$ mag of UGC 6614 is higher than what is usually observed in LSB galaxies according to Wyder et al. (2009). Together with a relatively low value of the SFR surface density of $2.14 \times 10^{-4} M_\odot$ yr$^{-1}$kpc$^{-2}$ (Wyder et al. 2009), $3.17 \times 10^{-4} M_\odot$ yr$^{-1}$kpc$^{-2}$ (current work), the red $FUV - NUV$ colour can indicate the absence of large amounts of stars younger than $10^8$ yr. UGC 6614 contains a noticeable amount of dust: $2.6 \times 10^8 M_\odot$, the dust-to-gas mass ratio is 0.01 (Rahman et al. 2007) which is more than ten times higher than the typical value in spiral galaxies (Bettoni et al. 2003). Another interesting detail observed in UGC 6614 is the blue shifted ionised gas emission in H$\alpha$ that could indicate a jet or an accretion disc hot spot along the line-of-sight (Ramya et al. 2011).

### Table 1. Equatorial coordinates (J2000.0) from NASA/IPAC Extragalactic Database (NED)\footnote{https://ned.ipac.caltech.edu/} for the gLSBGs from our sample.

| Galaxy | RA       | Dec      |
|--------|----------|----------|
| Malin 1| 12h36m59.350s | +14d19m49.32s   |
| Malin 2| 10h39m52.483s | +20d50m49.36s   |
| NGC 7589| 23h18m15.668s | +00d15m40.19s   |
| UGC 1378| 01h56m19.24s | +73d16m58.0s    |
| UGC 1382| 01h54m41.042s | -00d08m36.03s   |
| UGC 1922| 02h27m45.930s | +28d12m31.83s   |
| UGC 6614| 11h39m14.872s | +17d08m37.21s   |

### Figure 2. Direct images of the seven gLSBGs from this study. The slit positions are overplotted on the images of Malin 2, NGC 7589, UGC 1382 and UGC 6614. We used g, r, z images from DECaLS (Dey et al. 2019) for Malin 2 and UGC 6614 and from Subaru Hyper Suprime-Cam (Aihara et al. 2019) for NGC 7589 and UGC 1382. For Malin 1 we show a u, g, r-band image from the CFHT-Megacam Next Generation Virgo cluster Survey reproduced from Junais & Boissier (2019). For UGC 1378 we use a g, r, z-band image from the MMT Binospec from Saburova et al. (2019). For UGC 1922 we present a g-band image taken with 2.5-m telescope of the Caucasian Mountain Observatory, Sternberg Astronomical Institute from Saburova (2018).
presented here (Malin 2, UGC 6614, NGC 7589 and UGC 1382) we also over-plot the slit positions.

The spectrosopic data reduction for SCORPIO using our in-house based pipeline is described in detail in Saburova et al. (2018). It includes a bias subtraction and overscan clipping, flat-field correction, the wavelength calibration using arc lines\(^3\), cosmic ray hit removal, linearization, co-adding; the night sky subtraction using the algorithm described in Katkov & Chilingarian (2011) and flux calibration using the spectrophotometric standard stars Feige 34, BD 55+2642, Feige 110.

We took into account the instrumental line-spread function of the spectograph along the slit and across the wavelength range, which we determined by fitting the twilight sky spectrum observed during the same night with a R = 10000 Solar spectrum using the ppxf full spectrum fitting technique (Cappellari & Emsellem 2004). We then fitted the galaxy spectra using intermediate-resolution (R = 10000) PEGASE.HR (Le Borgne et al. 2004) simple stellar population models (SSP) computed for the Salpeter IMF (Salpeter 1955) convolved with the instrumental line-spread function of SCORPIO using the sBursts full spectral fitting technique (Chilingarian et al. 2007ab). As the result of the procedure, we obtained the best-fitting parameters of an SSP model, that is age (T) and metallicity [Fe/H] (dex) of stellar population. The line-of-sight velocity distribution (LOSVD) of stars was parametrized by the Gauss-Hermite function until the 4th order (see van der Marel & Franx 1993). The resulting LOSVDS are characterized by the line-of-sight velocity, velocity dispersion and Gauss-Hermite moments \(h_3\) and \(h_4\) which reflect the deviation of a LOSVD from the pure Gaussian profile.

We also analyzed the emission spectra which we obtained by subtracting the best-fitting stellar population templates from observed spectra. We fitted emission lines by a single Gaussian profile and derived the velocity and velocity dispersion of ionised gas also taking into account the instrumental line-spread-function.

\(^3\) To improve the wavelength solution accuracy we took arc spectra every 2 h and used them to reduce the corresponding science frames.

### Table 2. Basic properties of the sample of gLSBGs: name; radius of LSB disc (4 disc radial scale lengths for all galaxies except Malin 1 for which we used the distance to the furthestmost measured points from the centre above the noise level and with an approximate exponential radial distribution of surface brightness; morphological type; mass of H\(_2\) pc.

![Table 2. Basic properties of the sample of gLSBGs: name; radius of LSB disc (4 disc radial scale lengths for all galaxies except Malin 1 for which we used the distance to the furthestmost measured points from the centre above the noise level and with an approximate exponential radial distribution of surface brightness; morphological type; mass of H\(_2\) pc.](http://leda.univ-lyon1.fr/)

### Table 3. Observing log for SCORPIO.

![Table 3. Observing log for SCORPIO.](http://archive.gemini.edu/)

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\(^4\) HyperLeda database (Makarov et al. 2014): [http://leda.univ-lyon1.fr/](http://leda.univ-lyon1.fr/)

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\(^{15}\) To improve the wavelength solution accuracy we took arc spectra every 2 h and used them to reduce the corresponding science frames.

\(^{16}\) http://archive.gemini.edu/
3.2 Results of the analysis of spectroscopic data.

In Fig. 3 we demonstrate the main results of the analysis of spectral data for Malin 2. The left-hand column corresponds to the profiles of velocity and velocity dispersion for ionised gas (shaded lines) and stars (circles). The central column shows age and metallicity of stellar population. The right-hand column gives the profiles of $h_3$ and $h_4$ for the stellar LOSVD. The stars do not show clear rotation in the inner region.

The trend of stellar metallicity is very close to that found by Kasparova et al. (2014) – the decreasing radial gradient from almost solar metallicity in the centre. The age of stellar population is very old in the bulge region. The values of $h_3$ and $h_4$ are close to zero.

In Fig. 4 we demonstrate the results of our data analysis for NGC 7589. The designations are the same as in Fig. 3. As one can see in Fig. 4, the kinematics of the ionised gas of NGC 7589 is very complex: the velocity dispersion measured from the [O III] line rises with the distance from the centre, which is not seen in Hβ. It leads to a lower velocity and a shallower velocity gradient for [O III] in comparison to those derived from Hβ. This likely happens due to the presence of an AGN in NGC 7589 (see Sect. 2). The stellar age appears to be younger for the innermost part in comparison to that at larger radii. It and the non-zero values of $h_3$ and $h_4$ could be an indirect indication for the nuclear disc in the galaxy.

In Fig. 5 we present the results for UGC 1382. The gaseous component counter rotates with respect to the stars at all radii. The ionised gas is co-rotating with the extended Hα disc if we compare our profile with the Hα velocity map presented in Hagen et al. (2016). The stars in the centre are very old and show the considerable increase of metallicity. The age of stellar population of HSB part of the galaxy that we obtained in the current paper is significantly higher than that derived by Hagen et al. (2016) from SED fitting that is likely caused by the presence of a small fraction of young stars that strongly affect the blue part of the SED. The $h_3$ value is close to zero, at the same time $h_4$ is roughly 0.1 which could indicate the presence of a kinematically decoupled stellar component.

In Fig. 6 shows the kinematics and stellar population profiles for GMOS-N and SCORPIO observations of UGC 6614. The kinematics in the inner region of UGC 6614 is also very complex. The motion of the ionised gas is different from that of the stellar population. In the innermost region ($R \leq 5$ arcsec) the ionised gas does not rotate or even shows signs of counter-rotation. In contrast to UGC 1922, the inverted velocities are visible here only for one position angle $PA = 296^\circ$ and are concentrated in the innermost region unlike in UGC 1382 where the counter-rotation of the gas is global. Hence, probably this feature traces the AGN-driven gas outflow noticed by Ramya et al. (2011) rather than a kinematically decoupled nuclear component. However, a high-resolution 2-dimensional velocity field is needed to draw firm conclusion. The velocity dispersion measured from the [O III] line differs from that of Hβ, similarly to NGC 7589, where the AGN also can affect the kinematics.

Another peculiarity of the ionised gas LOS velocity profile is a drop of the velocity on both sides from the centre at the radius of ~30 arcsec, in the vicinity of the inner bright ring of the galaxy. This drop manifests itself also in the velocity profile of stars. The change of the gradient of the velocity is similar to that often observed in galaxies with bars (see, e.g. Saburova et al. 2017, and references therein). It is possible that the ring we see in UGC 6614 is a resonant ring. It could be oval, elliptical ring in which elliptical streamlines occur and non-circular motions show themselves in the decrease of the LOS velocity. Possibly, there was a weak bar in UGC 6614 before, which aided in accumulation of the material in the ring.

McGaugh et al. (2001) also obtained ionised gas LOS velocity profile of UGC 6614 in the Hα line from the long-slit observations at $PA = 108^\circ$. In the inner region of their profiles one can see the hint of the change of the velocity gradient. The rotation curve obtained in current paper is in a good agreement with their data – showing rotation velocity amplitude of ~ 200 km s$^{-1}$ and the minimum at 10 kpc (see Fig. A5).

The stellar population of the bulge of UGC 6614 is old and metal-rich. The age of stars decreases with the distance from the centre and appears to be about 2–3 Gyr outside the region where the bulge dominates the luminosity. The metallicity of stars in this radius is roughly ~0.5 dex. The values of $h_3$ and $h_4$ are non-zero, in particular $h_3$ anti-correlates with the velocity and $h_4$ has a minimum in centre, which is usually observed in barred galaxies (see, e.g. Saburova et al. 2017, and references therein).

3.3 Surface photometry of NGC 7589 and UGC 6614

To estimate the structural parameters of NGC 7589 and UGC 6614 we performed their surface photometry. We took publicly available data from the Subaru HyperSuprimeCam Strategic Survey DR2 for NGC 7589 and Zwicky Transient Facility (ZTF) (Bell et al. 2018) survey for UGC 6614, both in the r band. We performed the isophote analysis using the \texttt{PHOTUTILS} python library. Then we found a multi-component best-fitting model by minimizing $\chi^2$ statistics for several light profiles. During this procedure we convolve our model with a PSF, which we derived by fitting unsaturated stars in the same image.

NGC 7589 has a complex morphology in the centre which includes two bars and a ring. We excluded the central 17 arcsec from our analysis and fitted only the outer part of the light profile by a Sersic component and an exponential disc.

UGC 6614 spans two adjacent fields in ZTF, hence we co-added them into one mosaic using the SWARP software (Bertin 2010). Unlike ZTF-images, images in other surveys like SDSS or Legacy Survey, where spatial resolution is significantly better, have artifacts near bright objects which are usually caused by the local sky background subtraction algorithm. In case of UGC 6614 these artifacts prevent a precise light profile decomposition that includes an LSB disc, that is why we decided to use much shallower ZTF data unaffected by sky over-subtraction. We fitted the profile of UGC 6614 by two Sersic components. A one-dimensional multi-component light profile decomposition is known to be unstable.
with respect to the additive background in the original image and also requires a rather fine-tuned initial guess (see e.g. Chilingarian et al. 2009b), therefore it is crucial to use data with a precisely subtracted sky background.

We demonstrate the results of the decomposition of the profiles into inner and LSB disc components for NGC 7589 and UGC 6614 in Figs. 7, 8. The parameters of LSB discs and inner components are provided in Table 5 for both galaxies.

4 DYNAMICAL MODELING USING THE ROTATION CURVE DECOMPOSITION

The dark matter halo is known to play an important role in galaxy evolution. Here we derive the parameters of dark matter haloes in gLSBGs to compare them to HSB galaxies. In the previous studies of gLSBGs, Pickering et al. (1997); de Blok et al. (2001); Hagen et al. (2016); Lelli et al. (2010); Junais et al. (2020) also performed mass modelling but they used different profiles of dark matter halo (Einasto, NFW and pseudo-isothermal) for different galaxies, hence no direct comparison of the objects is possible. Therefore, here we perform the rotation curve decomposition using the same dark matter halo profile for all galaxies in our sample. We combine the optical data presented in this paper with the published Hβ data, and then decompose the rotation curves for Malin 2, NGC 7589, UGC 1382 and UGC 6614. We derived the optical rotation curves from the Hβ and [O III] emission lines corrected for the systemic velocity, symmetrically reflected about the galaxy centre and de-projected using the inclination angle provided in Table 2.

In the decomposition procedure, we included the following components: a stellar disc, a bulge, an Hβ disc, and a Burkert (1995)
dark matter halo. We used the gas surface densities from published H\textsc{i} observations. The details of the procedure of mass modelling are described in Saburova et al. (2016).

We fixed the contributions of stellar components according to the colour and spectral information. We also performed a decomposition of the combined rotation curve of Malin 1 using the published data. The results of mass modelling for UGC 1378 and UGC 1922 are taken from Saburova et al. (2019, 2018).

In Fig. 9 we plot the parameters of dark matter haloes against the 25 mag B-band isophote of gLSBGs and the sizes of gLSB discs from Table 2. We also plot the parameters of intermediate-size and giant HSB galaxies from Saburova (2018) (black dots and triangles). The solid lines show the running median for HSB galaxies. From Fig. 9 it is evident that gLSBGs behave differently from HSB galaxies, some of them lie on the continuation of the best-fitting relation for HSB galaxies, but some deviate from it. This could suggest different nature and formation scenarios for different gLSBGs in our sample.

For NGC 7589, Malin 2, UGC 6614 and UGC 1922\footnote{We chose Burkert profile to compare with the sample of giant HSB galaxies where it was used by Saburova (2018).}, the parameters of the dark haloes agree better with the radius of the gLSB disc than with \( R_{25} \). The three remaining gLSBGs lie close to HSB galaxies in the diagrams for optical radius. This could indicate that the parameters of dark haloes of some of gLSBGs are connected to the sizes of their HSB parts, which can favour the two-stage formation of these systems. At first, the HSB part is formed, then a build-up of an extended LSB part occurs. Interestingly, the HSB-part of Malin 2 is also very extended.

5 DISCUSSION

5.1 Baryonic Tully–Fisher relation for gLSBGs

The baryonic Tully–Fisher (1977) relation (Sprayberry et al. 1995; McGaugh & Schombert 2015) (TF) connects the total baryonic mass (gas+stars) to the maximal circular velocity in a galaxy. In Fig. 10 we display seven gLSBGs from our sample compared to the best-fitting linear correlations for the baryonic TF relation from the literature. Continuous and dashed thick lines show the relations obtained by Lelli et al. (2019) (the one with the lowest scatter) and Ponomareva et al. (2018) (the final one). Thin continuous and dashed lines give the uncertainties of the correlations given in the corresponding papers. Our gLSBGs are shown with the same symbols as in Fig. 9. We computed the baryonic mass as a sum of stellar disc and bulge masses from Table 9, Saburova (2018); Saburova et al. (2019), and the H\textsc{i} masses from Table 2. For UGC 1922 the disc mass is estimated from the photometric mass-to-light ratio. The velocities are also taken from Table 2.

As one can see in Fig. 10, gLSBGs occupy the top right corner of the TF relation with high rotational velocities and large baryonic masses. Most of them lie within the uncertainty of the correlation found by Lelli et al. (2019).
On the origin of gLSBGs

Figure 6. Analysis of spectral observations of UGC 6614 for three different position angles obtained at BTA and Gemini. Top two rows, left: stellar kinematics, $v$ (top) and $\sigma$ (bottom); centre: stellar populations, age (top) and metallicity (bottom); right: LOSVD deviation from the Gaussian shape, $h_3$ (top) and $h_4$ (bottom). Two bottom rows: $v$ (top) and $\sigma$ (bottom) of ionised gas for different PA and emission lines (see the legend). Left- and right-hand panels demonstrate full radial profiles and their zoomed central regions correspondingly.

Table 6. The parameters of the main structural components of the galaxies with 1$\sigma$ uncertainties. The columns contain the following data: (1) galaxy name; (2) and (3) – radial scale and central density of the DM halo; (4) mass of the DM halo inside the LSB disc radius given in Table 2; (5) central surface density of the bulge, (6) disc mass;

| Galaxy  | $R_s$  | $\rho_0$ | $M_{\text{halo}}$ | $(I_0)_b$ | $M_{\text{disc}}$ |
|---------|-------|---------|--------------------|------------|------------------|
|         | kpc   | $10^{-3}$ M$_\odot$/pc$^3$ | $10^{10}$ M$_\odot$ |           | $10^3$ M$_\odot$/pc$^3$ | $10^{10}$ M$_\odot$ |
According to Ogle et al. (2019), the baryonic TF relation breaks for rotational velocities higher than 340 km s$^{-1}$, however, in our sample only UGC 1922 rotates that fast. This galaxy has the largest deviation from the relation found by Lelli et al. (2019) at the same time not being an outlier from the regression found by Ponomareva et al. (2018).

### 5.3 Formation scenarios of gLSBGs

The main goal of our study is to choose realistic formation scenarios of gLSBGs based on the observational data of all stellar systems of this type studied in detail up-to-date. We are trying to understand whether the processes leading to the formation of such unusual galaxies are extremely uncommon making gLSBGs ‘unique’.

Our observational data suggest that no single formation mechanism can explain all seven gLSBGs presented here. At the same time, we consider only three of the considered scenarios because each of them is consistent with all observations of at least one gLSBG: (i) a scenario involving a major merger, similar to that proposed in Saburova et al. (2018) and Zhu et al. (2018); (ii) an explanation of unusual properties of giant LSB discs through the peculiar properties of the dark matter halo, namely the low central density and the high radial scale of the halo (Kasparova et al. 2014); (iii) a two-stage formation scenario in which the giant disc is formed by accretion of gas on a pre-existing ‘normal’ HSB galaxy (Saburova et al. 2019).

In Table 7 we give a short summary of the signatures that we expect in each for the three considered scenarios. Table 8 assess all possibilities for each galaxy in our sample.

We give the detailed discussion for the considered formation
On the origin of gLSBGs

Figure 9. Left: the optical radius ($R_{25}$) compared to the parameters of dark matter halo, central density (top) and radial scale (bottom). Right: the same but for the disc radii from Table 2 for gLSB and $R_{25}$ for HSB-galaxies. The gLSBGs are shown by coloured symbols. Black triangles correspond to the giant HSB galaxies from Saburova (2018), black dots are for galaxies of moderate size, the solid lines are the running medians for non-LSB galaxies.

Table 7. Expected signatures of the proposed formation scenarios of gLSBGs.

| Signatures                        | Scenario                  | Major merger | Sparse dark halo | Gas accretion on a pre-formed galaxy |
|----------------------------------|---------------------------|--------------|------------------|--------------------------------------|
| DM parameters agree with the giant disc radius | No                        | Yes          | No                |
| Two discs with different scalelengths | No                        | No           | Yes               |
| Dynamical overheating of the disc | Expected                  | Not expected | Not expected      |
| Disturbed morphology             | Expected                  | Not expected | Not expected      |
| Presence of satellites           | Expected                  | Not expected | Not expected      |

Table 8. Assessment on the proposed formation scenarios for each galaxy in our sample.

| Major merger | Sparse Dark halo | Gas accretion on a pre-formed galaxy |
|--------------|------------------|-------------------------------------|
| Malin 1      | Possibly Uncertain | Possibly                           |
| Malin 2      | No                | Yes                                |
| NGC7589      | No                | Yes                                |
| UGC1378      | No                | No                                 |
| UGC1382      | Possibly          | No                                 |
| UGC1922      | Yes               | Possibly                           |
| UGC6614      | No                | Yes                                |

scenarios in the next subsections. But first, we explain why we do not find enough of the supporting evidence for some other mechanisms discussed in the literature.

We believe that the scenario of the outer disc formation as the result of a dwarf satellite merger (proposed by Peñarrubia et al. (2006) for Messier 31) has difficulties explaining the gLSB disc formation for several reasons. (i) An extended LSB disc often contains a substantial fraction of the baryonic matter in a gLSBG: their masses in UGC 1378 and UGC 1922 are $8 \times 10^{10}$ and $1.8 \times 10^{10} M_\odot$ (Saburova et al. 2019; Saburova 2018) (see also Table 6 for the masses of the extended discs obtained in this paper). In all our cases, the masses of atomic hydrogen exceed $10^{10} M_\odot$ (Table 2), and it is $10$–$100$ times more than we can expect for a dwarf galaxy satellite (see e.g. Bettoni et al. 2003). (ii) Another reason is that we do not observe a rapid decline in rotation curve in the peripheries of giant LSB discs (see, e.g., Kasparova et al. 2014) expected in the dwarf satellite merger scenario. Random orientation and high eccentricity of the orbits of infalling satellites predicted by some numerical simulations in the $\Lambda$CDM cosmology will likely lead to the loss of angular momentum by both gas and stars and form a dynamically hot stellar halo with the gas sinking to the centre rather than forming a disc. A potential solution exists if numerous satellites infall onto the gLSBG progenitor from a thin vast rotating plane like the ones discovered around the Andromeda galaxy (Ibata et al. 2013) and Centaurus A (Müller et al. 2018) suspected to be aligned with the large scale structure of the Universe (Libeskind et al. 2015). Such planes despite being recognized as one of the ‘small scale problems’ of $\Lambda$CDM (Bullock & Boylan-Kolchin 2017), are successfully reproduced in numerical simulations (see e.g. Ibata et al. 2014; Santos-Santos et al. 2020). However, the feasibility of this gLSBG formation scenario still remains in question because most known gLSBGs do not have many satellites observed...
which makes it even less realistic and does not really explain the formation of a giant LSB disc.

5.3.1 The origin of the central regions of gLSBGs

One possible way to understand the evolution of a galaxy is to explore its inner regions and a nucleus. The structure of the bulge and the mass of the central black hole can help us to better understand the merger history of the galaxy because they are expected to co-evolve (see e.g. Kormendy & Ho 2013, and references therein).

One can notice from Table 2 that gLSBGs host AGN in six out of seven considered cases – such an occurrence rate of AGN is extremely high in comparison to HSB galaxies (Ho et al. 1997). The high frequency of low-luminosity AGN signatures in gLSBGs compared to other late-type galaxies was also noticed by Schombert (1998).

Another detail that becomes evident when looking at Fig. 12 and Table 2 is that gLSBGs tend to have low masses of central black holes ($M_{BH}$) which sometimes even get close to the intermediate-mass black hole regime. Subramanian et al. (2016) noted a systematic offset of LSB galaxies from the $M_{BH} - \sigma_*$ relation where stellar velocity dispersion $\sigma_*$ is averaged within one effective radius. According to Subramanian et al. (2016), LSB galaxies tend to have lower masses of black holes than what is expected for the values of velocity dispersions in their bulges.

In Fig. 12, we show the $M_{BH} - \sigma_*$ for gLSBGs from our sample and compare them to a large sample of ‘normal’ galaxies and the regression found by Sahu et al. (2019). The stellar velocity dispersion measurements of gLSBGs come from this study and from Reshetnikov et al. (2010); Saburova (2018); Saburova et al. (2019). The adopted black hole masses and corresponding data sources are given in Table 2. Open and filled circles demonstrate early- and late-type galaxies from Sahu et al. (2019). We use the regression obtained by Sahu et al. (2019) for both early- and late-type galaxies (the situation does not change significantly if we consider the regression found only for galaxies with discs). From Fig. 12, it is clear that three of the five gLSBGs with measured black hole masses deviate from the relation found by Sahu et al. (2019), and UGC 6614 lies on the margin of the $1\sigma$ range having a slightly lower $M_{BH}$ than expected for its $\sigma_*$. This can indicate that the bulges of the considered gLSBGs did not co-evolve with the central black holes and either were formed in-situ via secular evolution or grew via minor mergers, which are not expected to increase the $M_{BH}$ mass because dwarf galaxies do not often host central massive black holes. Kormendy et al. (2011) who reported the pseudobulge classification for galaxies with dynamically detected black holes. Kormendy et al. (2011) who reported the pseudobulge classification for galaxies with dynamically detected black holes, found out that the black hole masses correlate very little at best with pseudobulge properties.

Graham (2014) showed that pseudobulges are difficult to identify and their classification is quite subjective. However, it should be noted that Malin 1, Malin 2 (for a model with two discs), UGC 6614, UGC 1378, and UGC 1922 have Sérsic indices $n < 2$ and their bulges do not look rounder than the discs which could be the main argument for their classification as pseudobulges. It makes the high frequency of AGN activity among gLSBGs even more interesting, since the AGN signatures in the emission line ratios decreases significantly for the galaxies with pseudobulges (Yesuf et al. 2020). It could indicate the presence of the current gas supply to the centres.

7 The seventh galaxy – UGC 1378 may also contain AGN according to Schombert (1998).
of gLSBGs leading to the AGN activity and related to the accretion of material either from a filament or from a gas-rich satellite. The counter-rotation of gas that we observe in UGC 1382 and UGC 1922 could also be related to the external gas accretion. Khoperskov et al. (2020) showed that the AGN is efficiently triggered by the retrograde gas infall into a galaxy.

At the same time, according to Kormendy et al. (2011), the growth of central black holes in pseudobulges is driven rather not by global processes like major merger but more by local and stochastic processes. In this regime, black holes are not expected to co-evolve with the bulges and hence their masses might not correlate with the properties of bulges – exactly what we see in Fig. 12 for gLSBGs except NGC 7589 (and possibly UGC 6614). This could imply that there were not a lot of major merger events in the history of most gLSBGs and their baryonic masses were accumulated by some other processes. The study of globular clusters in UGC 6614 using deep HST images also provides evidences that the galaxy accumulated its stellar mass through sporadic star formation activity and its star formation history lacks dominant starburst events which could be induced by major mergers Kim (2011).

Taking into account all these facts, we conclude the observed properties of central parts and central black holes of gLSBGs support the scenario of the gLSB disc formation by external cold gas accretion either from cosmic filaments or from gas-rich satellites and disfavour their formation by major mergers.

5.3.2 Gas accretion on a pre-existing galaxy (HSB+LSB)

About a decade ago (Lelli et al. 2010) it became clear that some gLSBGs have a complex structure consisting of an inner ‘normal’ HSB early-type spiral galaxy immersed in an extended LSB disc. Discs of such HSB+LSB galaxies cannot be described by a single exponential profile. We expect that the extent of the dark halo in such galaxies is in good agreement with the $R_{25}$ size of the HSB part. The relatively low radial scale of the dark matter halo can indicate that the accreted gas could have the angular momentum differing from that of the HSB disc. In this case, there is a two-stage build-up of the galactic disc and the main question is: where did the additional material (gas and stars?) for the LSB disc formation come from? The environment of such galaxies has to, firstly, have a source for cold gas accretion, and secondly, a possible close interaction should not tear off the LSB periphery of the disc by tidal effects. If the additional material originates from a cosmic filament, then the environment of such a galaxy should be sparse. Observational data for four of seven gLSBGs do not contradict this scenario.

In the case of Malin 1 several facts speak in favour of this formation mechanism. Malin 1 shows a complex double disc structure including HSB and LSB parts (Lelli et al. 2010). The outer part is much bluer than the inner one (Galarza et al. 2015). The age of the extended disc is young (Boissier et al. 2016). The current burst of star formation in the extended disc could have been induced by a recent minor merger about 1 Gyr ago (Reshetnikov et al. 2010).

NGC 7589 also demonstrates the HSB+LSB structure (Lelli et al. 2010). The positional angle of the major axis of NGC 7589 changes with radius evident from both, photometric analysis and the twist of isovelocity lines in the H$\alpha$ velocity field published by Pickering et al. (1997). This can indicate the external origin of the outer LSB structure. This galaxy also possesses a massive companion with the velocity difference of roughly 100 km s$^{-1}$ (NGC 7603 which has disturbed spiral arms and is twice the size of NGC 7589). Both, the extended blue disc of NGC 7589 and the disturbed appearance of NGC 7603 could be the traces of past interactions of these two galaxies. The elongated thin spiral arms could be possibly short-living and related to the density wave in the disc induced by a recent tidal interaction between these two systems. In this case, the interaction ‘lit up’ the giant disc of NGC 7589 which became more visible with the spiral arms and the blue colour of the extended disc because an interaction induced burst of star formation.

UGC 1378 was studied in details in Saburova et al. (2019) who proposed a two-step formation scenario in which the gas accretion onto a ‘typical’ HSB spiral galaxy similar to the Milky Way led to the formation of the extended LSB disc.

UGC 1382 is a lenticular galaxy with an extended LSB disc. Our data reveal that the ionised gas in the centre rotates in the opposite sense to the old stellar disc, but it co-rotates with the giant H$\alpha$ disc described by Hagen et al. (2016). That is, there is a counter-rotation of the large-scale discs along all distances from the galaxy center. Assuming a natural evolutionary link between the extended H$\alpha$ disc and the LSB disc we expect that the stellar LSB disc also counter-rotates with respect to the HSB part. Our absorption-line spectra unfortunately do not reach the LSB part and cannot be used to support or refute this hypothesis. However, a counter-rotating LSB disc might contribute to the stellar LOSVD even in the HSB part of the galaxy. This hypothesis is supported by non-zero values of $h_3$ and $h_4$ profiles (see right panel Fig. 5) suggestive of a non-Gaussian shape of the stellar LOSVD. To check this idea we recovered stellar LOSVD in a non-parametric shape applying methodology from Kavkov et al. (2011, 2016). Unfortunately, we did not find clear signs of the stellar counter-rotation like two distinct peaks or long tails in the LOSVD. We detected a slightly non-Gaussian shape and a peaked structure of the LOSVD slightly varying from one bin to another likely caused by the noise in the data. This means that the LSB stellar disc is too faint to be detected in the region dominated by the HSB disc. Therefore, only dedicated ultra-deep spectroscopy of the external LSB disc might confirm our expectation about counter-rotation of the stellar LSB part in this galaxy.
The HI disc of UGC1382 with a rotational velocity of 280 km s\(^{-1}\) (Hagen et al. 2016) has signs of ongoing star formation (as we can see by the presence of UV-bright spirals in GALEX images). Our spectrum fitting gives very old age of the central part with the trend of the age decreasing with the radius, i.e. a negative age gradient (see Fig. 5). According to Hagen et al. (2016) the age of the LSB spirals is 4 Gyr older than the HSB part. Such a difference with our data can be associated with the age estimation methodology (spectral vs. photometric) and the adopted star formation histories (SSP vs. exponentially declining). We believe that the counter-rotation of the large-scale HI disc could indicate the gas accretion from a filament (Algorry et al. 2014) on a pre-existing early-type disc galaxy (probably, S0).

5.3.3 Sparse dark halo

The second scenario is a non-catastrophic formation of a single disc with a large radial scale in a sparse dark matter halo (large radial scale and low central density). In four cases, Malin 2, NGC 7589, UGC 6614 and UGC 1922, the radial scale of the dark halo is in agreement with the size of an extended disc. However, one should keep in mind that the estimate of the dark halo scale is very uncertain due to the low resolution of the gas kinematics derived from HI data. So, in the case of UGC 1922, the uncertainty is too high to make firm statements on the shallowness of its halo. Normal-sized LSB galaxies are probably formed in haloes with low concentrations of a rapidly rotating host as a result of the centrifugal equilibrium (Mo et al. 1998; Bullock et al. 2001; Kim & Lee 2013), and the extreme cases of such haloes can host gLSBGs. The reasons for the formation of a dark halo with such properties can be found in numerical models of proto-halo mergers and they can probably be related to the low density environment (Macciò et al. 2007).

5.3.4 Major merger

In the modern galaxy formation framework, massive galaxies with stellar mass \(\sim 10^{11} M_\odot\) should have experienced at least one major merger in their lifetime (Rodríguez-Gomez et al. 2015). However, such events are more likely to occur in a dense environment. It is expected that a galaxy formed in this way will have a hot stellar disc (if the disc survives at all) and, probably, perturbed morphology (Saburova et al. 2018). However, all existing data for gLSBGs except UGC 1922, show the contrary. The prominent well-organized spiral structure can indirectly evidence that the discs of most known gLSBGs are thin and, consequently, are not significantly overheated (Saburova et al. in prep.). To confirm the catastrophic scenario we need to estimate the stellar velocity dispersion in the region of the LSB disc of a gLSBG. This is a very challenging observational task. The modern spectrographs allow astronomers to probe velocity dispersions down to 10–15 km s\(^{-1}\) at surface brightnesses as low as \(\mu_g = 25.5\) mag arcsec\(^{-2}\) in UDGs (Chilingarian et al. 2019), which should, in principle, be sufficient for some gLSB discs. However, because of young and potentially metal-poor stellar populations anticipated in gLSBGs, their spectra are expected to have much shallower absorption lines leading to the drastic increase of uncertainties of internal kinematics for the spectra of the same depth (Chilingarian & Grishin 2020). A viable solution is to find edge-on gLSBGs where the surface brightness is boosted because of the line-of-sight integration through the disc.

Zhu et al. (2018) proposed a major merging scenario for Malin 1 which does not contradict to its observed properties including the absence of the gradient of the stellar age in the disc. We also observe two red satellites projected on-to the LSB disc of Malin 1 (Reshetnikov et al. 2010; Galaz et al. 2015) which could be the survived remnants of larger galaxies that interacted with it. Their structural properties put them into the rare class of compact elliptical galaxies (Chilingarian et al. 2009a) proven to be formed via tidal stripping of massive progenitors (Chilingarian & Zolotukhin 2015). A low-luminosity compact galaxy is also orbiting UGC 1382. One should keep in mind, however, that the study by Zhu et al. (2018) does not mention whether they succeeded to reproduce the light profile described by a sum of two exponential components, as it was demonstrated for Malin 1 by Lelli et al. (2010).

In the case of Malin 2 we can exclude the major merger scenario once its disc is only mildly dynamically overheated and Kasparova et al. (2014) observed a steep metallicity gradient for the gas in the disc which is likely to be flattened during mergers (see, e.g. Zasov et al. 2015, and references therein).

UGC 1922 described in detail in Saburova et al. (2018) seems to differ from all other other known gLSBGs. It has a strongly overheated stellar disc with clumpy irregular spiral arms. The ionised gas in the inner region counter-rotates with respect to the outer part of the galaxy. Saburova et al. (2018) reproduced most of the observed features of the galaxy in the model of an in-plane merger of giant Sa and Sb galaxies. Therefore UGC 1922 is likely a result of a major merger. This assumption is also supported by the fact that this is the only galaxy in our sample significantly deviating from the Tully–Fisher relation.

5.4 Comparison with other galaxies with extended LSB and XUV discs

The demarcation between gLSBGs and ‘normal’ extended LSB galaxies in the parameter space is rather arbitrary. We limit this study to the objects disc radii larger than 50 kpc, which we consider as an informal boundary for gLSBGs. At the same time, LSB galaxies with moderate sizes have similar properties to gLSBGs and might have similar formation scenarios. Therefore, it might be useful to compare our sample against extended LSBGs with disc scale lengths somewhat smaller than 50 kpc. One prominent case is NGC 5533 with the LSB disc with the scale length of approximately 9 kpc (Noordermeer & van der Hulst 2007). Despite being substantially smaller than UGC 1378, this galaxy has a similar complex structure that contains an ‘HSB’ galaxy embedded in extended LSB disc (Sil’chenko et al. 1998). Since the two galaxies have similar structural properties even though at different spatial scales, it will be helpful to compare their general characteristics. Stellar populations in the HSB part of NGC 5533 are also similar to those of UGC 1378. The HSB stellar disc of NGC 5533 is metal-poor and has an intermediate age (2 – 4 Gyr). The bulge has solar stellar metallicity and a slightly older age of 6 – 7 Gyr (I. Katkov, private communication). The HI rotation curve of NGC 5533 is declining (Noordermeer et al. 2007) which results in a small radial scale of the dark halo (Noordermeer 2006). The complex HSB+LSB structure and a low radial scale of the dark halo suggests that the extended LSB disc of NGC 5533 similarly to that UGC 1378 could have been formed by the accretion of gas on-to a pre-existing early-type spiral galaxy.

Another extended LSB system is NGC 5383 with the disc scale length of 9.7 kpc (van der Kruit & Bosma 1978). This galaxy has a strong bar and extended LSB spiral structure similar to that of NGC 7589. The system also has a companion UGC 8877 at the distance of roughly 30 kpc with the velocity difference of 100 km s\(^{-1}\).
We see the bifurcation of the spiral arms of NGC 5383. Tidal forces could impose a new mode of the density wave in the disc, which gave the rise to the faint spiral arms like e.g. in the interacting system Arp 82 (Zasov et al. 2019).

Systems similar to, e.g. UGC 1382, but with smaller disc sizes can be found in the deep images from the MATLAS project (Mass Assembly of early-Type GaLAxies with their fine Structures Duc et al. 2015). One good example is UGC 9519, a dwarf S0 galaxy surrounded by an extended LSB disc with a radius of ~30 kpc, showing spiral structure. Sil'chenko et al. (2019) found out that gas in the inner part of UGC 9519 rotates in the nearly polar plane with respect to the stellar disc and the outer disc is decoupled from the main body of the galaxy. The decoupled kinematics of gas could indicate that it was accreted from the external sources (Sil'chenko et al. 2019).

The starforming gLSBGs can be considered as an extension of the class of galaxies extended ultraviolet discs (XUV discs Gil de Paz et al. 2005; Thilker et al. 2005, 2007) to larger disc sizes and thus could have possibly evolved in a similar way. Hagen et al. (2016) classified UGC 1382 as a Type I XUV disc similar to the prototypical XUV disc galaxies M 83 and NGC 4625 (Gil de Paz et al. 2005; Thilker et al. 2005). Boissier et al. (2016) also notes that Malin 1 could be an extreme case of an anti-truncated XUV disc. According to Thilker et al. (2007), Type I XUV discs are found in up to 20 per cent of galaxies and span the entire range of Hubble types. The global characteristics of galaxies with XUV discs are similar to those of ‘normal’ galaxies, which can indicate that the formation of an XUV disc could be a stage of ‘normal’ galaxy formation process.

Thilker et al. (2007) pointed out that an interaction could trigger the formation of an XUV disc, or, in other words, trigger a burst of star formation in the extended gaseous disc which would have remained passive and ‘dark’ otherwise. Another possible trigger may be a high specific rate of gas accretion (i.e. accretion rate per unit stellar mass).

It is interesting to compare gLSBGs with the famous Hoag’s Object, an unusual giant ring galaxy in a low-density environment discovered by Hoag (1950). The blue and young ring surrounds an elliptical galaxy hosting old metal-rich stellar population (Finkelman et al. 2011). The radius of the ring is about 25 kpc and it has a clearly visible spiral-like pattern. Finkelman et al. (2011) proposed that the peculiar structure and observed properties of the Hoag’s Object are the result of the gas accretion onto a pre-existing elliptical galaxy. The Hoag’s Object could thus be a special case of a “failed” gLSBG in which instead of a giant LSB disc, the star-forming ring was formed due to some specific properties of the system, e.g. a triaxial potential of the elliptical galaxy, which could lead to the prominent gap between the core and the ring.

5.5 Comparison of gLSBGs with oversized HSB galaxies
Ogle et al. (2016) found out that about 6 per cent of the most optically luminous galaxies have giant HSB discs with isophotal diameters of 55 – 140 kpc. This sample was extended by Ogle et al. (2019) which also included non-starforming ‘super-lenticulars’ in addition to super-spirals and giant elliptical galaxies. A small fraction of the super-luminous galaxies had disturbed morphology indicating recent mergers. Similarly to gLSBGs, super LSB discs are red inside and blue outside which could be consistent with the on-going growth of the disc by accretion and minor mergers (Ogle et al. 2019). Kasparova et al. (2020) studied in detail the edge-on ‘super-lenticular’ NGC 7572 with an exceptionally massive thick disc and concluded that the thin disc growth was likely stopped prematurely by the dense cluster environment. Otherwise, this object would have become an enormous ‘super-spiral’ if it could continue to grow its disc from an external gas supply.

Saburova (2018) also studied giant HSB discy galaxies at lower redshifts compared to those from the sample of Ogle et al. (2016) and using different selection criterion, the isophotal radius rather than luminosity used in Ogle et al. (2016). Saburova (2018) derived the parameters of dark haloes of giant HSB galaxies and concluded that they tend to have high halo masses and radial scales in agreement with their large disc radii. Thus, Saburova (2018) proposed that the size of HSB giants is due to the sparse dark halo being similar to the formation scenario by Kasparova et al. (2014) proposed for the gLSBG Malin 2.

An interesting case is the giant spiral galaxy LEDA 1970716 discovered by visual inspection of DECaLS optical images. It has an asymmetric spiral arm with blue clumps of star formation. One possible trigger could have been induced by the interaction with neighbouring galaxies. Another similarly perturbed galaxy is NGC 4017 surrounded by the tidal debris resulting from the recent interaction, where one of the tidal tails lies on the continuation of the spiral arm (Sengupta et al. 2017; Zasov et al. 2018). These examples demonstrate the possibility of the giant LSB disc formation by gravitational interactions (flybys).

6 SUMMARY
We collected long-slit spectral observations for four gLSBGs galaxies in addition to the three systems with the data available in the literature. We also performed surface photometric analysis for NGC 7589 and UGC 6614 on deep archival images. We analysed all available information for the sample of seven gLSBGs and compared them to galaxies of moderate sizes and to giant HSB galaxies (‘super-spirals’).

Observational data favor the external origin of the giant LSB discs for most gLSBGs. For NGC 7589, UGC 1378 and UGC 1382 we argue for the two-stage formation scenario in which the extended LSB disc is a result of gas accretion on a pre-existing early-type galaxy. There also exist gLSBGs like UGC 1922 which were likely formed by a major merger. For Malin 1 and UGC 1382 we also can not exclude the major merger hypothesis. Some alternative formation scenarios are also feasible. For Malin 2, UGC 6614 and possibly NGC 7589 we found high radial scale and low central density of their dark haloes, so the unusual properties of their discs could be dictated by the sparse dark matter haloes.

The proposed formation scenarios are supported by the following observed properties of gLSBGs:

- We detected a counter-rotation of ionised gas in the inner parts of two out of seven considered gLSBGs. Similar high statistical frequency of the kinematically decoupled kinematics is observed in isolated lenticular galaxies (Katkov et al. 2014), where the external origin of gas via accretion is a preferred scenario.
- The star formation rate surface densities of gLSBGs are too low for their gas content, which can be a result of the inefficient star formation, e.g. because of the low gas volume density or very recent accretion of gas.
- At least six out of seven presented gLSBGs host active galactic nuclei. Such high AGN rate requires the presence of gas supply reaching the central regions of the galaxies. At the same time, the central black hole masses appear to be significantly lower than...
expected for the obtained central stellar velocity dispersions, in agreement with previous findings by Ramya et al. (2011); Subramaniam et al. (2016). This can indicate that there were not many major merger events in the history of gLSBGs similar to galaxies with smaller bulges hosting active intermediate-mass black holes (Chilingarian et al. 2018).

- We performed the mass modelling of optical+$\text{H}^i$ rotation curves of the seven gLSBGs using the Burkert dark matter density profile. The derived parameters of dark haloes show different behavior compared to the LSB disc radius and $R_{\text{app}}$ which can indicate different formation scenarios of the considered galaxies.
- Stellar populations in the central parts of most of the presented gLSBGs are old and metal-rich arguing for a two-stage gLSBG formation.

We conclude that the 7 presented gLGBGs do not form a homogeneous class of objects and one should consider several alternatives for their formation scenarios, most of which require an external origin of material to form gLSB discs.

APPENDIX A: DETAILS ON THE FITTING OF ROTATION CURVES FOR INDIVIDUAL GALAXIES

For Malin 1 we utilized the combined optical and $\text{H}^i$ rotation curve and surface density profile plus the R-band surface brightness profile from Lelli et al. (2010). We took optical the major axis rotation curve from Junais et al. (2020).\footnote{We decided to use only the major axis since it was taken with the narrowest slit to avoid possible biases due to a non-homogeneous illumination of the slit and also to minimize the uncertainty because of poorly known orientation of the disc.} We used a non-parametric definition of the contribution of the disc to the rotation curve. For this, we obtained the bulge parameters from the fitting of the light brightness using a Levenberg-Marquardt non-linear least-squares minimization routine in mxi. (Chilingarian et al. 2009b). We fix R-band mass-to-light ratios to 3.0 for the disc and limited it to the range 2...6 for the bulge, which correspond to the densities in agreement with those found by Boissier et al. (2016). We present the results of the rotation curve fitting in Fig. A1.

Our estimate of the dark halo radial scale appear to be higher than that obtained by Lelli et al. (2010) but within the range given by Junais et al. (2020) even keeping in mind that they used pseudoisothermal dark matter profiles rather than the Burkert profile.

For Malin 2 we constructed a combined ionised gas (current paper) and $\text{H}^i$ rotation curve (Pickering et al. 1997). We use the parameters of the bulge obtained in g band from the light profile published in Kasparova et al. (2014) (Sersic index $n = 0.89 \pm 0.00$, central surface brightness $\mu_0 = 18.47 \pm 0.06$ mag arcsec$^{-2}$, effective radius $R_e = 1.10 \pm 0.05$ arcsec), and a non-parametric definition of the surface density profile of the disc. The disc g-band mass-to-light ratio was limited in the range 1.98...3.89 according to the SED fitting (lower value) and the criterion of the marginal gravitational stability of the disc applied to the stellar velocity dispersion data at $r = 20$ arcsec from Kasparova et al. (2014) in a similar way as it was done for UGC 1378 (see Saburova et al. 2019).

The value following from the marginal gravitational stability is about twice as high as that resulting from the spectral and SED fitting obtained in Kasparova et al. (2014), which can indicate the mild overheating of the disc, especially if one takes into account the uncertainty because of the stellar IMF. The bulge mass-to-light ratio was limited to 3.33...5.0 according to Kasparova et al. (2014). The results of the decomposition are shown in Fig. A2. One can see that for Malin 2, the model of its rotation curve rises too steep compared to observations. The probable reason of this discrepancy is the resolution of the spectral data that could smooth the steep rise of the rotation curve in the inner 2 kpc where the inconsistency is observed (the seeing quality corresponded to the resolution 1.3 kpc).

The radial scale of dark matter halo appears to be in good agreement with that found by Kasparova et al. (2014) if one applies the transformation coefficient from a pseudoisothermal to Burkert dark halo profiles from Boyarsky et al. (2009).

For NGC 7589 we performed the decomposition of the $r$-band light profile obtained from the SUBARU HSC data (Aihara et al. 2019). The surface brightness profile shows complex behaviour in the inner part due to the presence of two bars, a nuclear mini-bar with the radius of 2.5 arcsec and the ‘normal’ large-scale bar with the radius of 15 arcsec. Because of this, we calculated the contribution of the inner component to the rotation curve only approximately by considering it as the point mass $V^2 = GM/R$ and masked out the inner part of the rotation curve during the fitting. The mass $M$ was estimated from the $r$-band luminosity in the aperture with the radius of 17 arcsec without the contribution of the LSB disc ($1.7 \times 10^{10} L_{\odot}$). The $\text{H}^i$ data are taken from Lelli et al. (2010). The inner rotation curve was derived in this paper from the ionised gas kinematics. The mass-to-light ratio of the inner component was limited in the range 1.4...2.8 during the fitting. The lower value corresponds to the stellar population with the age of 4 Gyr and solar metallicity (see Fig. 4) for the Kroupa IMF. The upper value comes from the bulge colour $g - r = 0.76$ obtained from the SDSS images and the Roediger & Courteau (2015) model $M/L$-colour relations. For the disc we considered the $M/L_r$ in the range 1.3...2 according to its
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Figure A2. The results of the rotation curve decomposition for Malin2. The $\chi^2$ map for the parameters of Burkert dark matter halo (top) and the fitting of the rotation curve (bottom). Black and red symbols on the rotation curve correspond to optical and H\textsc{i} data respectively.

Figure A3. The results of the rotation curve decomposition for NGC7589. The designations are the same as in Fig. A2. Central part of the rotation curve was masked-out during the fitting.

Figure A4. The results of the rotation curve decomposition for UGC1382. The designations are the same as in Fig. A2.

colour $g - r = 0.56$ estimated from the SDSS images and model relations from Roediger & Courteau (2015) and Bell et al. (2003). The result of the rotation curve modeling for NGC7589 is shown in Fig. A3.

The dark halo radial scale is in good agreement with that obtained by Lelli et al. (2010) for a pseudoisothermal dark halo, however they maximized the contribution of the stellar component, which we did not do here.

For UGC 1382 the ionised gas is co-rotating with the H\textsc{i} disc, which allowed us to build the combined rotation curve. We took the H\textsc{i} data from Hagen et al. (2016), the structural parameters of the bulge from Hagen et al. (2016), and a non-parametric definition of the disc surface density profile – we obtained it as a difference between the total and a bulge $r$-band surface brightness profiles. The $r$-band mass-to-light ratio of the bulge was limited in the range $3 \ldots 5$ according to the stellar metallicity $-0.1$ and old age 13 Gyr for Kroupa (Kroupa 2001) and Salpeter (Salpeter 1955) stellar initial mass functions(see Fig. 5). For the disc the limits $1.2 \ldots 2.66$ come from the relation by Roediger & Courteau (2015) and the $g - r$ colour of the disc and from Hagen et al. (2016). We present the results of modeling in Fig. A4. Hagen et al. (2016) also performed the mass modeling of the rotation curve of UGC 1382, however they used the Einasto and NFW dark halo density profiles. Their model shows a similar behaviour to ours, the baryonic contribution to the rotation curve dominates only in the inner 10 kpc, while the dark halo dominates at larger radii.

For UGC 6614 due to the complex gas kinematics in the inner region we excluded the innermost points (R $\leq$ 1.6 kpc) from our analysis. We calculated the ionised gas rotation curve from the two spectral cuts ($PA = 240, 270^\circ$) based on the measurements in H\alpha and [O\textsc{iii}] emission lines. We estimated the circular velocity

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from the observed line-of-sight velocity and the radial coordinate \( R \) taking into account inclination of the disc and the angle between the radius-vector of a given point and the major axis of a galaxy. We adopted the inclination according to Pickering et al. (1997). The situation with the position angle is more complex since the value \( PA = 296^\circ \) did not agree with our kinematics in the inner region of UGC 6614, thus we adopted \( PA = 265^\circ \) for the inner 35 arcsec, and \( PA = 296^\circ \) for the outer data points.

We added the ionised gas rotation curve to \( H_\alpha \) velocities from Pickering et al. (1997) and obtained the combined rotation curve for the fitting procedure. We used the structural parameters of the bulge from our analysis of the ZTF survey \( r \)-band image discussed above. We used a non-parametric definition of the disc profile as a difference between total and bulge surface brightness profiles. The \( r \)-band mass-to-light ratio of the bulge was limited in the range: 2.57...4.54. The upper value corresponds to the stellar population with the age of 12 Gyr and metallicity \(-0.2\) for the Salpeter IMF, the lower value is for the age 12 Gyr for the Kroupa IMF. The range of disc mass-to-light ratio was estimated from the \((g-r) = 0.4\) mag colour of the disc and the \(M/L_r\)-colour relation from (Roediger & Courteau 2015) taking into account the age 1 Gyr and the metallicity \(-0.7 \) dex in the region outside the dominance of bulge: 0.4...2.3. We present the fitting results for UGC 6614 in Fig. A5. As one can see from the figure, the model includes the HSB part associated with the pseudo-bulge component and the LSB part in a form of a non-parametrical disc. This model looks similar to that of Malin 1 and NGC 7589 constructed by Lelli et al. (2010).

de Blok et al. (2001) also performed the mass modelling for UGC 6614 using pseudoisothermal and NFW dark halo density profiles. For the pseudoisothermal halo they derived the dark halo radial scale 12.18 kpc using a constant stellar \( R \)-band mass-to-light ratio 1.4. It appears to be in good agreement with the scale obtained here for the Burkert profile if one applies the transformation coefficients from Boyarsky et al. (2009). Pickering et al. (1997) obtained somewhat higher dark halo radial scale of 24.48 kpc, but they considered only \( H_\alpha \) data as the only available at the moment.

APPENDIX B: NEW CANDIDATE LSB GALAXIES

To learn more on the formation and evolution of LSBGs it is important to increase the sample. We visually searched for the LSB galaxies candidates in DECaLS deep images. In Table B1 we present a list of new giant LSB galaxies with the radii of the discs of 50 kpc or more. We also give the coordinates, the outermost radii to which we see the discs in DECaLS images, the adopted redshift-based distances for each system. For WISEA J151622.90+561317.6 we used the Hubble Space Telescope (HST) images and give the disc radius as a distance to the clumpy stricture on the far outskirts of the disc, in this case we probably observe the formation of a giant disc. The sample listed in Table B1 will be used in the future studies.

APPENDIX C: DATA AVAILABILITY

The data underlying this article will be shared upon request to the corresponding author.

ACKNOWLEDGEMENTS

We are grateful to Anatoly Zasov, Françoise Combes, and Frédéric Bournaud for fruitful discussion. The spectral data reduction and interpretation of the results were supported by the Russian Science Foundation (RScF) grant No. 19-12-00281. The mass modeling of the rotation curves was done with the support of the Russian Science Foundation (RScF) grant No. 19-72-20089. IC’s research is supported by the Telescope Data Center of the Smithsonian Astrophysical Observatory. We acknowledge the usage of the HyperLedas database (http://leda.univ-lyon1.fr). KG acknowledges the support from the Foundation of development of theoretical physics and mathematics ‘Basis’ (category: students). Observations conducted with the 6-m telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences carried out with the financial support of the Ministry of Science and Higher Education of the Russian Federation (including agreement No. 05.6!9.21.0016, project ID RFMEF61919X0016). Based on observations obtained with MegaPrime/MegaCam, a joint project of CFHT and CEA/DAPNIA, at the Canada-France-Hawaii Telescope (CFHT) which is operated by the National Research Council (NRC) of Canada, the Institut National des Science de l’Univers of the Centre National de la Recherche Scientifique (CNRS) of France, and the University of Hawaii. This study is based in part on data collected at Subaru Telescope and retrieved from the HyperSuprimeCam data archive system, which is operated by Subaru Telescope and Astronomy Data Center at National Astronomical Observatory of Japan and on observations obtained at the international Gemini Observatory (proposals GN-2005B-Q-61 and GN-2006B-Q-41, data retrieved from the Gemini Science Archive, http://archive.gemini.edu/), a program of NSF’s NOIRLab, which is managed by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation on behalf of the Gemini Observatory partnership: the National Science Foundation (United States), National Research Council (Canada), Agencia Nacional de Investigación y Desarrollo (Chile), Ministério de Ciência, Tecnologia e Inovação (Argentina), Ministério da Ciência, Tecnologia, Inovações e Comunicações (Brazil), and Korea Astronomy and Space Science Institute (Republic of Korea). The Pan-STARRS1 Surveys (PS1) and the PS1 public science archive have been made possible
through contributions by the Institute for Astronomy, the University of Hawaii, the Pan-STARRS Project Office, the Max-Planck Society and its participating institutes, the Max Planck Institute for Astronomy, Heidelberg and the Max Planck Institute for Extraterrestrial Physics, Garching. The Johns Hopkins University, Durham University, the University of Edinburgh, the Queen’s University Belfast, the Harvard-Smithsonian Center for Astrophysics, the Las Cumbres Observatory Global Telescope Network Incorporated, the National Central University of Taiwan, the Space Telescope Science Institute, the National Aeronautics and Space Administration under Grant No. NNX08AR22G issued through the Planetary Science Division of the NASA Science Mission Directorate, the National Science Foundation Grant No. AST-1238877, the University of Maryland, Eotvos Lorand University (ELTE), the Los Alamos National Laboratory, and the Gordon and Betty Moore Foundation. The Legacy Surveys consist of three individual and complementary projects: the Dark Energy Camera Legacy Survey (DECaLS; NOAO Proposal ID 2014B-0404; PIs: David Schlegel and Arjun Dey), the Beijing-Arizona Sky Survey (BASS; NOAO Proposal ID 2015A-0801; PIs: Zhou Xu and Xiaohui Fan), and the Mayall z-band Legacy Survey (MzLS; NOAO Proposal ID 2016A-0453; PI: Arjun Dey). DECaLS, BASS and MzLS together include data obtained, respectively, at the Blanco telescope, Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatory (NOAO); the Bok telescope, Steward Observatory, University of Arizona; and the Mayall telescope, Kitt Peak National Observatory, NOAO. The Legacy Surveys project is honored to be permitted to conduct astronomical research on Iolkam Du’ag (Kitt Peak), a mountain with particular significance to the Tohono O’odham Nation.

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**Table B1. A new sample of giant LSB galaxies. The full version of the table is available in electronic form.**

| Galaxy | Ra, Dec | Radius (kpc) | D (Mpc) | note |
|--------|---------|--------------|--------|------|
| 2MASX J23211236+0505273 | 333.0474, 5.0908 | 80 | 473 | interacting |
| PGC 1197350 | 30.4738, 15.5190 | 50 | 165 | |
| WISEA J131144.79+075635.3 | 197.9365, 7.9480 | 51 | 293 | |
| SDSS J155042.62+263624.4 | 237.6931, 26.5918 | ~70 | 744 | uncertain distance |
| 2MASX J14542890+2319365 | 223.6205, 23.3263 | 661 | 57 | |
| LEDA 1682814 | 224.1188, 23.1768 | 677 | 50 | |
| 2MASX J09164603+2835271 | 219.0954, 28.5215 | 65 | 220 | asymmetrical, probably interacting |
| SDSS J12350.95+042550.1 | 170.96228, 4.430583 | 70 | 880 | |
| UGC 4219 | 121.678271, 39.090217 | 80 | 166 | asymmetrical, probably interacting |

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