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# SDSS J124155.33+114003.7 – a missing link between compact elliptical and ultracompact dwarf galaxies

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## ABSTRACT

We report the discovery of a compact object ( $R_e = 32$  pc,  $M_B = -12.34$  mag) at a projected distance of 9 kpc from Messier 59, a giant elliptical in the Virgo cluster. Using *HST* imaging and SDSS spectroscopy, both available in the Virtual Observatory, we find that this object has a blue core containing one-quarter of the light, and a redder  $n = 1$  Sérsic envelope, as well as luminosity-weighted age of  $9.3 \pm 1.4$  Gyr, a metallicity of  $-0.03 \pm 0.04$  dex and a velocity dispersion of  $48 \pm 5$  km s<sup>-1</sup>. While ultracompact dwarf galaxies (UCDs) in the face-on view of the Fundamental Plane are found to form a sequence connecting the highest-luminosity globular clusters with the lowest-luminosity dwarf ellipticals, the compact object near M59 lies in between this UCD sequence and the positions of compact ellipticals. Its stellar age, metallicity, and effective surface brightness are similar to low-luminosity ellipticals and lenticulars, suggesting that SDSS J124155.33+114003.7 is a result of the tidal stripping of such an object.

**Key words:** galaxies: dwarf – galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: kinematics and dynamics – galaxies: stellar content.

## 1 INTRODUCTION

Compact elliptical galaxies (cEs) are high surface brightness, low-luminosity objects having small effective radii, like M32, the prototypical cE, and are typically an order of magnitude smaller than dwarf elliptical galaxies (dEs) of the same luminosity. However, cEs represent a rare class of objects, including only six definite members identified so far. They are found exclusively in the vicinities of massive galaxies in groups, as M32 and NGC 5846A, or cluster cD galaxies, as NGC 4486B and ACO496 J043337.35–131520.2 (Chilingarian et al. 2007a, hereafter C07a), or in the central regions of massive clusters as two cEs in Abell 1689 (Mieske et al. 2005). The global structural properties of cEs follow those of giant elliptical galaxies (gEs) and of the bulges of lenticulars and early-type spirals, placing them on the extension of the Kormendy (1977) relation towards smaller effective radii and higher surface brightnesses. At the same time, their velocity dispersions are considerably higher than expected for their luminosities by the Faber & Jackson (1976) relation.

Galaxies of this class exhibit rather unusual stellar population properties: their metallicities are much higher than expected for

their luminosities; apart from M32, their stars are usually very old and their  $\alpha/\text{Fe}$  abundance ratios are significantly supersolar (Sánchez-Blázquez et al. 2006; C07a). The combination of their kinematics and stellar populations supports the scenario of tidal stripping of more massive galaxies (Nieto & Prugniel 1987; Choi, Guhathakurta & Johnston 2002).

Ultracompact dwarf galaxies (UCDs, Philipps et al. 2001) initially discovered as extragalactic sources unresolved from the ground-based observations, represent another class of compact stellar systems. At least an order of magnitude smaller than cEs ( $R_e \sim 10$  pc), but still significantly larger than globular clusters (GCs, Drinkwater et al. 2003; Jordán et al. 2005), UCDs are well studied only in the two nearest clusters of galaxies: Fornax (Drinkwater et al. 2000) and Virgo (Haşegan et al. 2005; Jones et al. 2006). Some candidate UCDs have been also found in nearby galaxy groups (Evstigneeva et al. 2007a).

UCDs, initially defined on a morphological basis, probably represent a heterogeneous class of objects (Mieske et al. 2006) of different origins. The concepts of UCD formation include: (i) very massive globular clusters having the same origin as ‘normal’ ones (Mieske, Hilker & Infante 2002); (ii) stellar superclusters formed in gas-rich mergers of galaxies (Fellhauer & Kroupa 2002, 2005); (iii) end-products of small-scale primordial density fluctuations in dense environments (Philipps et al. 2001); (iv) tidally stripped nucleated

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dEs (dENs, Bekki, Couch & Drinkwater 2001; Bekki et al. 2003) or simply dENs with very low surface brightness outer components (cf. Drinkwater et al. 2003).

UCDs occupy a region of the Fundamental Plane (FP, Djorgovski & Davis 1987) between the sequences of globular clusters and dEs (Drinkwater et al. 2003). Up to now, the structural, dynamical and stellar population properties of the brightest and most-massive UCDs are still quite far from those of cEs.

In this Letter, we report the discovery of a compact galaxy in the Virgo cluster with the properties placing it between the brightest UCDs and the cEs. Our results are based on the analysis of archival spectral and imaging data, available in the International Virtual Observatory.

## 2 DISCOVERY OF SDSS J124155.33+114003.7: DATA AND TECHNIQUES USED

SDSS J124155.33+114003.7 (hereafter M59cO for compact object) has been serendipitously discovered in SDSS-DR6 (Adelman-McCarthy et al. 2008) in the course of a study of the luminosity function of the Virgo cluster (Mamon et al., in preparation): M59cO is the only object within  $62 \text{ deg}^2$  ( $1 R_{\text{vir}}$ ) around M87, classified as a galaxy by the SDSS photometric and spectroscopic pipelines but as a point source visually. It lies just 2.1 arcmin to the north-west of the giant elliptical galaxy M59, which itself sits in the nearest known compact group of galaxies (Mamon 1989), which contains the even brighter galaxy M60. We adopt the M59 distance modulus of 30.87 mag (Mei et al. 2007), yielding a spatial scale of  $72 \text{ pc arcsec}^{-1}$ .

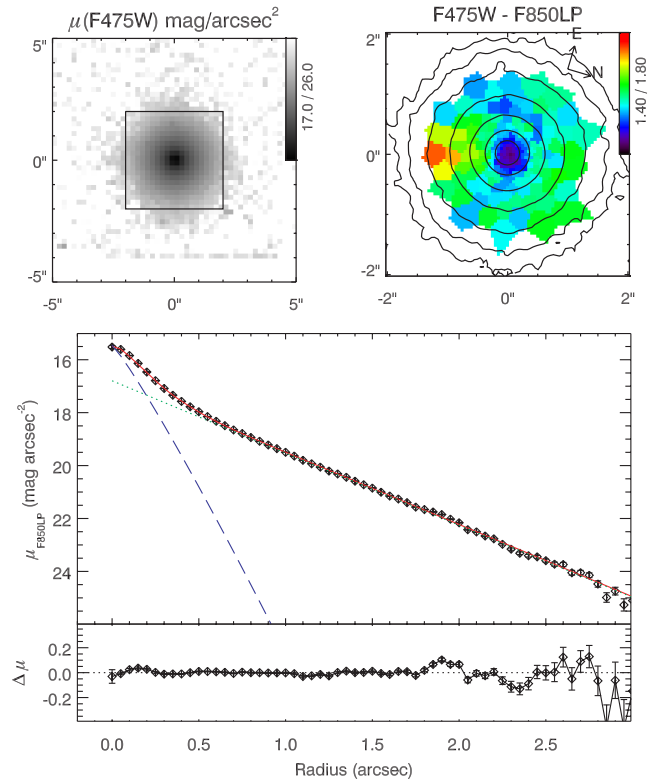
We have searched for the complementary data sets in the Virtual Observatory using CDS Aladin (Bonnarel et al. 2000), and found: (i) a spectrum ( $R = 1800$ ) of this galaxy in a 3-arcsec-wide aperture obtained by the SDSS; (ii) fully calibrated *HST* ACS (WFC) images in the two photometric bands, *F475W* ( $g'$ ) and *F850LP* ( $i'$ ) from the Virgo Cluster ACS Survey (Côté et al. 2004) provided by the ACS Associations service of the Canadian Astronomical Data Centre.

The high-resolution evolutionary synthesis simple stellar populations (SSPs), computed with PEGASE-HR (Le Borgne et al. 2004), have been fitted against the SDSS-DR6 spectrum of M59cO in order to obtain parameters of the stellar population and internal kinematics, using the ‘NBursts’ spectral fitting technique (Chilingarian et al. 2007b) for a single SSP. The variations in the spectral resolution as a function of the wavelength provided by the SDSS were used to broaden the SSP models. We have used the wavelength range between 4050 and 5700 Å. The blue limit is due to the wavelength range of the PEGASE-HR models (4000 Å), while the red limit has been set to work only in the blue arm of SDSS and avoid the ‘jump’ of the line-spread-function width in the combined SDSS spectrum.

## 3 PROPERTIES OF SDSS J124155.33+114003.7

### 3.1 Photometric properties

The total (corrected isophotal) *F475W* AB magnitude ( $m_{F475} = 18.12 \pm 0.03$ ), measured using SExtractor (Bertin & Arnouts 1996), is in good agreement with the SDSS values ( $m_{g'} = 18.08 \pm 0.01$ , Petrosian magnitude). Converting this magnitude into the *B* band according to Fukugita, Shimasaku & Ichikawa (1995), assuming an elliptical galaxy spectral energy distribution ( $B - g' =$



**Figure 1.** Top left-hand panel: *HST* ACS image of M59cO in the  $g'$  band. Top right-hand panel:  $g' - i'$  colour map, derived from the *HST* ACS. Bottom panel: light profile of M59cO in the F850LP photometric band with its best-fitting model, containing an inner Sérsic core with  $n$  close to 1 (blue dashed line), and an exponential outer profile (green dotted line) and their superposition red solid curve.

$0.55 \text{ mag}$ )<sup>1</sup> and correcting it for the Galactic extinction (Schlegel, Finkbeiner & Davis 1998), we end up with a total absolute magnitude  $M_B = -12.34$ . With SExtractor, we find an effective radius of  $R_e = 0.43 \text{ arcsec} \equiv 32 \text{ pc}$ , yielding a mean surface magnitude within  $R_e$  of  $\langle \mu_B \rangle_e = 18.69 \text{ mag arcsec}^{-2}$ , as bright as the brightest known UCDs.<sup>2</sup>

The unsharp masking technique, applied to the images, has not revealed any structures embedded in the object. We have fitted the *HST/ACS* surface photometry of M59cO using both the IRAF STSDAS. ISOPHOTE.ELLIPSE task and the GALFIT software package (Peng et al. 2002) (see Fig. 1, bottom panel). Both techniques give highly consistent results. The model profiles have been convolved with the ACS point spread function (PSF) constructed for both filters at the position of M59cE on the ACS frame using the TINY TIM software<sup>3</sup> with the K4V star spectrum as a template. None of the Sérsic, King, nor ‘Nuker’ models was able to represent well the light distribution

<sup>1</sup> The stellar population parameters and broad-band colours of M59cO are similar to those of intermediate-luminosity ellipticals.

<sup>2</sup> Two objects from Evstigneeva et al. (2007b), VUCD 7 and UCD 3 are slightly more luminous. However, both of them have extended ‘haloes’, containing a significant fraction of the stellar light. Thus, the recovered luminosities of the compact components, derived from their table 10, are considerably lower than that of M59cO. On the other hand, the faintest known cE, M32, is about 15 times more luminous ( $M_B = -15.34$ , Graham 2002, converted into the *B* band).

<sup>3</sup> <http://www.stsci.edu/software/tinytim/>

of the galaxy. The best two-component fitting is obtained with either two Sérsic profiles with  $n \simeq 1$  (i.e. exponential profiles) or else an exponential profile and a compact King core. The galaxy is almost perfectly round – the ellipticity of the isophotes remains under 0.03 at all radii. The  $B$ -band extinction-corrected best-fitting values for the inner and outer components are as follows:  $R_{e,\text{in}} = 13 \pm 1$  pc,  $\langle \mu \rangle_{e,\text{in}} = 18.13 \pm 0.09$  mag arcsec $^{-2}$ ,  $m_{\text{tot},\text{in}} = 19.78$  mag,  $R_{e,\text{out}} = 50 \pm 2$  pc,  $\langle \mu \rangle_{e,\text{out}} = 20.01 \pm 0.04$  mag arcsec $^{-2}$ ,  $m_{\text{tot},\text{out}} = 18.82$  mag.

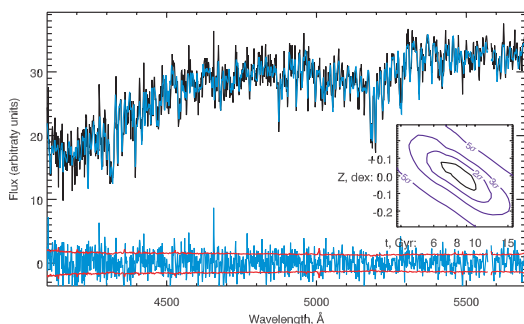
We obtain a  $g' - i'$  colour map by degrading the  $F475W$  image, which has slightly better resolution (full width at half-maximum of 0.090 arcsec), to the resolution of the  $F850LP$  image (0.092 arcsec) using the simple transformation:  $I_{475}^{\text{degraded}} = F^{-1}[F(I_{475})F(\text{PSF}_{850})/F(\text{PSF}_{475})]$ , where  $F$  and  $F^{-1}$  stand for direct and inverse Fourier transforms, respectively. For colour information at the periphery of the object, we have applied Voronoi adaptive binning (Cappellari & Copin 2003) to the  $F850LP$  image with the target signal-to-noise ratio of 100.

The  $g' - i'$  colour map obtained in this fashion is presented in Fig. 1 (upper right-hand panel). Tessellae containing more than 120 pixel (low-signal regions) are masked. The core is  $\sim 0.15$  mag bluer than the surrounding envelope. The size of the blue core matches well the parameters of the inner component (exponential or King core) obtained by GALFIT and 1D light profile analyses. It may be the signature of a younger stellar population in the nucleus of M59cO, as found in three bright dEs in Virgo and a low-luminosity lenticular NGC 130 (Chilingarian et al. 2007c, 2008b).

### 3.2 Kinematics and Stellar Population

Fitting the SDSS spectrum of M59cO, we have derived the following values of kinematical and stellar population parameters:  $v = 708 \pm 3$  km s $^{-1}$ ,  $\sigma_v = 48 \pm 5$  km s $^{-1}$ ,  $t = 9.3 \pm 1.4$  Gyr,  $Z = -0.03 \pm 0.04$  dex. The spectrum and its best-fitting SSP model are shown in Fig. 2. The radial velocity of M59cO differs by  $\sim 270$  km s $^{-1}$  from M59 ( $v_r = 440$  km s $^{-1}$ ). This can be considered as evidence of their gravitational interaction. We scanned the  $\chi^2$  parameter space on a pre-defined age–metallicity grid as described in appendix A of Chilingarian et al. (2007b), to provide realistic uncertainties of the stellar population parameters and locate possible secondary minima. The confidence contours in the age–metallicity space are shown in Fig. 2 (inset).

We have calculated the Lick indices (Worthey et al. 1994) and derived the  $[\text{Mg}/\text{Fe}]$  abundance ratio using models of Thomas, Maraston & Bender (2003) as  $+0.21 \pm 0.10$  dex. However, the fitting residuals do not show the characteristic ‘step’ at 5185 Å usually seen for supersolar  $[\text{Mg}/\text{Fe}]$  abundance ratios due to template mis-



**Figure 2.** SDSS spectrum of M59cO, its best-fitting template and the residuals of the fitting; inner panel: 1 (black), 2, 3 and 5 $\sigma$  confidence levels in age–metallicity space.

match; thus, we suspect some contamination of the Fe $_{5270}$  feature, perhaps by a faint cosmic-ray hit, biasing the measurements of the corresponding Lick index. Thus, we consider the value of +0.2 as an upper limit to the  $[\alpha/\text{Fe}]$  abundance ratio.

## 4 DISCUSSION AND CONCLUSIONS

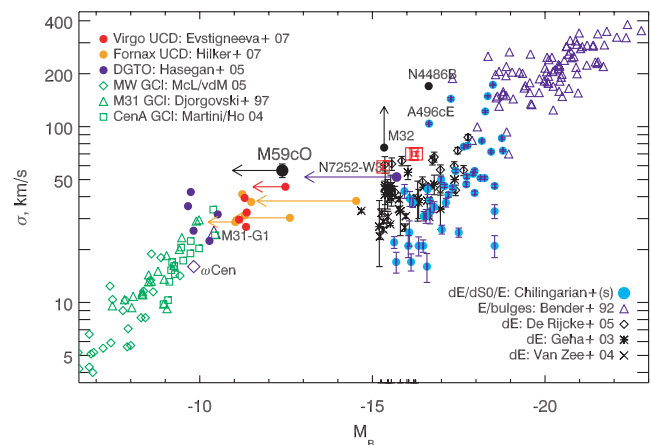
### 4.1 Comparison with known UCDs and cEs

Fig. 3 presents the Faber & Jackson (1976) relation for dynamically hot stellar systems. It is an extended version of fig. 3 from C07a, and includes a full sample of Abell 496 galaxies, UCDs in Virgo and Fornax; dwarf-globular transition objects (DGTOs); GCs in the Milky Way, M31, and NGC 5128; and W3-NGC 7252, the ‘heavy-weight GC’. The velocity dispersions of M59cO and W3 have been corrected by a factor of 1.14 to correct from global to central values (Djorgovski et al. 1997). Other sources of data remain the same as in fig. 3 of C07a. The three UCDs in Fornax and one in Virgo, having extended haloes, are shown as the arrows with ends (as is M59cO), corresponding to the parameters of the compact central structures. For W3, the left-hand end of the arrow corresponds to the predicted luminosity of this object at the age of 10 Gyr (data from Maraston et al. 2004).

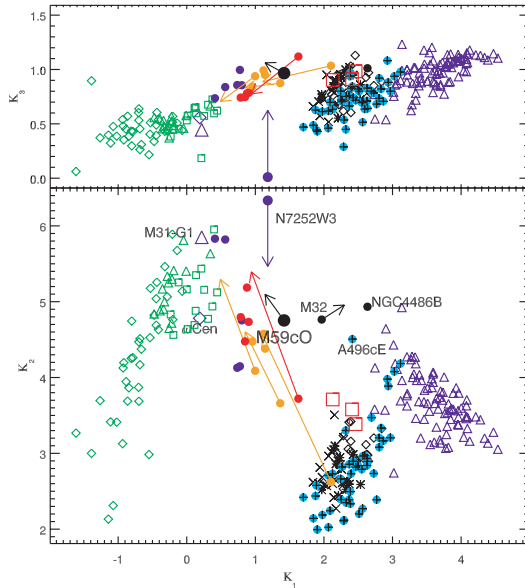
On the Faber–Jackson diagram, the newly discovered object lies on the bright end of the sequence formed by globular clusters, DGTOs and UCDs, being almost 2 mag brighter. A few objects, including all known cEs, reside on the continuation of this sequence at higher luminosities, exhibiting velocity dispersions about three times higher than that of dEs/dS0s of the same brightness.

As already mentioned, the three UCD galaxies with extended stellar haloes (two in Fornax and one in Virgo) brighter than M59cO move towards the left-hand side in Fig. 3 to the ‘usual’ locus of the UCDs, if one only considers their compact components (ends of the arrows in the figure). At the same time, the predicted position of the young heavy-mass cluster NGC 7252-W3, after 10 Gyr of passive evolution, is very close to M59cO.

A more detailed comparison of the physical properties of M59cO with other types of galaxies and GCs is given by the FP. We use the redefinition of the FP in the  $\kappa$ -space proposed by Bender, Burstein &



**Figure 3.** Faber–Jackson relation for giant and dwarf early-type galaxies, bulges of spirals, UCDs, globular clusters and transitional objects. The sources of the data are described in the text. The red squares mark NGC 4467, IC 3653 and VCC 1627 (see Section 4.2 for details). References: McL/vdM = McLaughlin & van der Marel (2005); Chilingarian + (s) = Chilingarian et al. (2008a).



**Figure 4.** FP (in  $\kappa$ -space) for different classes of round stellar systems. The same symbols and colours as in Fig. 3.

Faber (1992), where  $\kappa_1$  is related to the logarithm of the total mass,  $\kappa_2$  proportional to the  $(M/L)_e^3$  is a measure of ‘compactness’, and  $\kappa_3$  is connected to the logarithm of the mass-to-light ratio ( $M/L$ ).

In Fig. 4, we show the two views of the FP:  $\kappa_3$  versus  $\kappa_1$  (‘edge-on’) and  $\kappa_2$  versus  $\kappa_1$  (‘face-on’). The regions, occupied by the different classes of objects, mentioned above, are distinctly visible on the ‘face-on’ view, while the ‘edge-on’ one demonstrates only two sequences: (i) dEs, cEs, gEs and the bulges of spirals on the right-hand side and (ii) GCs, DGTOs and UCDs on the left-hand side. The ‘face-on’ (compactness versus mass) view of the FP shows that UCDs form a sequence connecting the high-luminosity GCs with the low-luminosity dEs. Despite its two-component structure, the outer component of M59cO is still more compact than the extended haloes of UCD 3, UCD 5, FCC 303 and VUCD 7 from Evstigneeva et al. (2007b), whose  $R_e$  range from 107 pc (UCD 3) to 696 pc (FCC 303) and whose quite low surface brightnesses ( $(\mu_B)_e$  from 21.1 to 23.2 mag arcsec $^{-2}$ ) make them rather regular structures, reminiscent of normal dEs.

On the FP, M59cO lies between the loci of UCDs and cEs–gEs, still being closer to UCDs. However, since its stellar population is similar to that of M32 (Rose et al. 2005), we conclude that *SDSS J124155.33+114003.7* is a transitional object between UCDs and cEs.

#### 4.2 Origin of *SDSS J124155.33+114003.7*

The dynamical  $M/L$ s of UCDs vary quite significantly (Drinkwater et al. 2003; Hasegan et al. 2005; Hilker et al. 2007), suggesting the presence of dark matter (DM) in some of them. Hasegan et al. (2005) propose to use  $M/L$  as a criterion to distinguish between UCDs and massive GCs. At the same time, Evstigneeva et al. (2007b) find no evidence for DM in UCDs.

The virial theorem mass estimate is  $M_{\text{vir}} \sim 10.0 R_e \sigma_v^2 / G$ , where  $\sigma_v$  is the global velocity dispersion (Spitzer 1969, with the correction from 3D to 2D half-light radius as in the Hernquist 1990 model). The total mass of M59cO is then  $(1.5 \pm 0.3) \times 10^8 M_\odot$ , in between the most-massive known UCD and the least-massive known cE. The

$B$ -band  $M/L$  of the stellar population, estimated from the PEGASE-HR evolutionary synthesis models for Salpeter initial mass function (IMF) ( $5.9 \pm 0.7$ ), translates into the stellar mass  $M_* = (9.1 \pm 1.7) \times 10^7 M_\odot$ , suggesting that M59cO contains about 40 per cent of DM, making it similar to much more massive dE satellites of M31 (De Rijcke et al. 2006). Had we adopted a Scalo (1986) or Kroupa (2001) IMF, we would have found less stellar mass, hence a higher fraction of DM.

Given the high metallicity of its stellar population, its age of only  $\sim 9$  Gyr suggests that M59cO cannot be a passively evolved primordial object. The presence of DM allows to conclude that it is neither an enormous globular cluster, nor could it have formed as a tidal object in the process of galaxy merger, as the NGC 7252-W3 supercluster was probably created. Thus, the most-tempting possibility is that *M59cO is the tight core of a larger galaxy, severely stripped by the tidal field of M59.*

Comparing the age and metallicity of M59cO to those of dEs and intermediate-luminosity Es (Sánchez-Blázquez et al. 2006; Chilingarian et al. 2007b), we estimate the luminosity of its progenitor to be in the range  $-16.0 < M_B < -18.0$ . Another argument for this scenario is the relatively high surface brightness of the outer component of M59cO: its progenitor could not be a faint dE, otherwise one would expect a much fainter ‘halo’ similar to those of the four UCDs in Evstigneeva et al. (2007b).

Six early-type galaxies from the Virgo ACS Survey host stellar nuclei comparable in luminosity and half-light radii to the inner component of M59cO. We have estimated kinematical and stellar population parameters for four of them, NGC 4387, IC 3653, IC 3328 and VCC 1627, having SDSS-DR6 spectra, while for the remaining two, NGC 4379 and NGC 4467, the literature data have been used (Sil’chenko 2006; Trager et al. 1998). All these galaxies (except IC 3328, which is younger and more metal-poor) exhibit metallicities between  $-0.1$  and  $+0.15$  dex and ages between 5 (IC 3653) and 12 (NGC 4379) Gyr, that is similar to that of M59cO. However, the  $[\text{Mg}/\text{Fe}]$  abundance ratio is strongly supersolar for NGC 4379, and velocity dispersions of NGC 4379 and NGC 4387 are above  $100 \text{ km s}^{-1}$ . The remaining three galaxies with  $-17.0 < M_B < -16.0$  are rather bright and compact and can be considered as ‘transitional’ objects between dE/dS0s and E/S0s. The surface brightness of the inner regions is similar to that of the outer component of M59cO.

Therefore, our best explanation is that *SDSS J124155.33+114003.7* is a result of the tidal stripping of a transitional object between dwarf and normal early-type galaxies, known to have higher surface brightness than fainter dE/dS0s or brighter gEs. In this case, the outer component of M59cO can be considered as a dynamically heated remnant of the progenitor’s thick disc.

The properties of the newly discovered object do not allow to classify it uniquely. It can be considered either as the faintest cE, or as the brightest UCD. However, since it is a product of a violent tidal stripping, as cEs and at least some UCDs are, the exact classification is not that important. The discovery of M59cO contributes a useful piece to the puzzle of galaxy evolution in dense environments.

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