European Organisation for Astronomical Research in the Southern Hemisphere

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APPLICATION FOR OBSERVING TIME

PERIOD: **98A**

Important Notice:

By submitting this proposal, the PI takes full responsibility for the content of the proposal, in particular with regard to the names of CoIs and the agreement to act according to the ESO policy and regulations, should observing time be granted.

1. Title

Category: **A–5**

Understanding the Origin of Ultra-Diffuse Galaxies in Clusters using VLT/VIMOS Spectroscopy

2. Abstract / Total Time Requested

Total Amount of Time: 0 nights VM, 27 hours SM

Recent observations have shown that Ultra-Diffuse Galaxies (UDGs) are surprisingly abundant in local clusters of galaxies. Indirect estimates suggest that they must have very massive subhaloes, which may pose a challenge to our theory of galaxy formation. A *direct* measurement of their halos masses is essential to test this hypothesis. We have performed the first measurement using weak lensing, with which we can distinguish between different theories to explain their origin. However, before we can publish this important result, we need to verify a key assumption in the analysis, namely the redshift distribution of the UDG sample. To do so, we propose to determine redshifts for ∼120 UDG candidates in three rich local clusters, ∼40 of which we expect to be background objects. These data will facilitate the first measurement of their halo masses, and allow further constraints on their origin by first measurements of their stellar ages, metallicities, and phase-space distributions.

3.

Run	Period	Instrument	Time	Month	Moon	Seeing	Sky	Mode	Type
A	98	VIMOS	27h	any	d	n	CLR	s	

4. Number of nights/hours

Number of nights/hours	Telescope(s)	Amount of time
a) already awarded to this project:	VIMOS	9h in DDT 296.A-5043
b) still required to complete this project:		

5. Special remarks:

Due to the large sizes of the targeted galaxies, this program can be observed under conditions of relatively bad-seeing (a seeing of FWHM=1.5″ typically only gives ∼10% extra slit losses compared to 0.7″). However, to avoid confusion by brighter galaxies nearby, we impose a seeing constraint of 1.5″. This loose constraint makes this study an excellent alternative/filler with high expected scientific return, when the seeing is above the seeing limit imposed by large (public) VLT/VIMOS programs. Due to our deep photometric imaging data with excellent astrometric calibration, these observations can be taken in pre-image-less MOS (PILMOS) mode.

6. Principal Investigator:

Remco van der Burg, remco.van-der-burg@cea.fr, F, Centre d'Etudes de Saclay

6a. Co-investigators:

A.	Muzzin	Institute of Astronomy, University of Cambridge,UK
H.	Hoekstra	Sterrewacht,University of Leiden,NL
C.	Sifón	Sterrewacht,University of Leiden,NL

7. Description of the proposed programme

A – Scientific Rationale: One of the most surprising recent results in the field of galaxy formation is the discovery of a significant population of very large diffuse galaxies in the Coma cluster (van Dokkum et al. 2015a). Low surface brightness galaxies are not an unknown population, since their discovery dates back several decades (Impey et al. 1988; Turner et al. 1993; Dalcanton et al. 1997); however, the galaxies identified by van Dokkum are even larger and more diffuse than these early samples. Due to their extreme properties, they were labelled ultra-diffuse galaxies (UDGs; faint galaxies with effective sizes $r_{\rm eff} > 1.5\,$kpc and typical surface brightnesses within their effective radii of ∼25 mag arcsec^{-2} in the R-band). Since their first recognition, they have become a hot topic and multiple papers have studied UDGs in different datasets (e.g., Koda et al. 2015; Mihos et al. 2015; van Dokkum et al. 2015b; Beasley et al. 2016; Torrealba et al. 2016; van der Burg et al. 2016, hereafter vdB16), but we have not come any closer to an explanation for their origin and evolution.

Perhaps the biggest mystery is that UDGs appear to be abundant in galaxy clusters, while one would expect such apparently feeble galaxies to be easily disrupted by tidal effects and close encounters with other galaxies in high-density environments (e.g. Moore et al. 1996). Their radial distribution in the clusters, and in particular their existence down to only ∼ 300 kpc from the cluster centres, suggests that their masses are far greater than their observed stellar mass. This leads to estimated central dark-matter fractions of 95-99% (van Dokkum et al. 2015a, vdB16), and the interpretation that these galaxies may be "failed" Milky-Way type galaxies (van Dokkum et al. 2015a). On the contrary, a recently proposed theory for their formation suggests that UDGs could simply be the high-spin tail of the normal dwarf population (Amorisco & Loeb 2016). *These two opposing scenarios predict UDG subhalo masses that differ by up to 2 orders of magnitude.*

A *direct* measurement of the halo masses of UDGs is paramount to test these different proposed theories, and to explain the origin of this population. Because UDGs are extremely diffuse, current instruments are not suited for measuring their dynamical masses through spectroscopy. However, we have a data set of excellent-quality photometric images, with which we have also performed the first systematic search for UDGs (i.e. objective/reproducible, vdB16). With these unique data, which were obtained to study the dark matter halos of regular cluster members (Sífon et al. in prep.), we have now performed the first direct mass measurements of UDGs using weak gravitational lensing, following the methodology described in Sifón et al. 2015: the analysis separates the overall cluster signal (which dominates at large scales), from the UDG signal (which dominates at small scales). Remarkably, our lensing measurement seems to confirm the hypothesis that UDGs are hosted by massive haloes ($M_{\rm tot} \simeq 10^{10}$ for $M_\star \simeq 10^8$, so ∼99% dark matter in their centres, see Fig. 1).

Before we can publish this important result, it is crucial to establish the robustness of the lensing analysis. While we can measure the lensing signal accurately (see e.g. Hoekstra et al. 2015), the correct interpretation relies critically on understanding the level of contamination of the lens sample by interlopers (predominantly background galaxies). In contrast to the study in vdB16, where we could estimate the statistical contamination *fraction* (by number), knowing the redshifts of the contaminants is essential to account for their contribution to the stacked lensing measurement: e.g. interlopers at higher redshift than the cluster have a higher lensing efficiency. As a consequence, we should consider our current results more like upper limits, *until we better understand our sample of lenses.* An improved characterization would also help us to include more clusters (at slightly higher redshift) in the analysis, which enhances the precision of the measurement, and the leverage to distinguish between the different proposed scenarios.

B – Immediate Objective: To meet these scientific goals, we require spectroscopic redshifts of a large enough, representative, subset of the vdB16 sample of UDGs candidates. By placing ∼ 2-3 VIMOS masks on each of the 8 clusters, we will spectroscopically characterize an overall sample of 270 UDGs, ∼20-30% of the vdB16 sample within R_{200c}. Given the competitive nature of this hot topic, we have recently been awarded a DDT pilot program to observe 2 masks on Abell 780 (see Box 9 for a more detailed description of the DDT program and its relation to the current proposed main program). However, given the much larger spectroscopic sample that is required to fully characterize the redshift distribution of UDG candidates, we propose our main program in 2016B, with two 3-hour masks on each of the clusters Abell 85, Abell 119 and Abell 133. This will allow us to obtain redshifts for ∼120 UDG candidates. Covering an area up to R_{200c}, we expect ∼80 of these to be part of the cluster, based on our current estimate of the contamination (vdB16). This will greatly enhance the current sample of spectroscopically-identified UDGs in clusters. Note that to date, *only one UDG has been spectroscopically confirmed* by van Dokkum et al. 2015b. This proposal should complete the observations for half the sample, namely the clusters observable in the B-semester. We will submit a proposal next period for similar observations of the remaining clusters to finalise the sample.

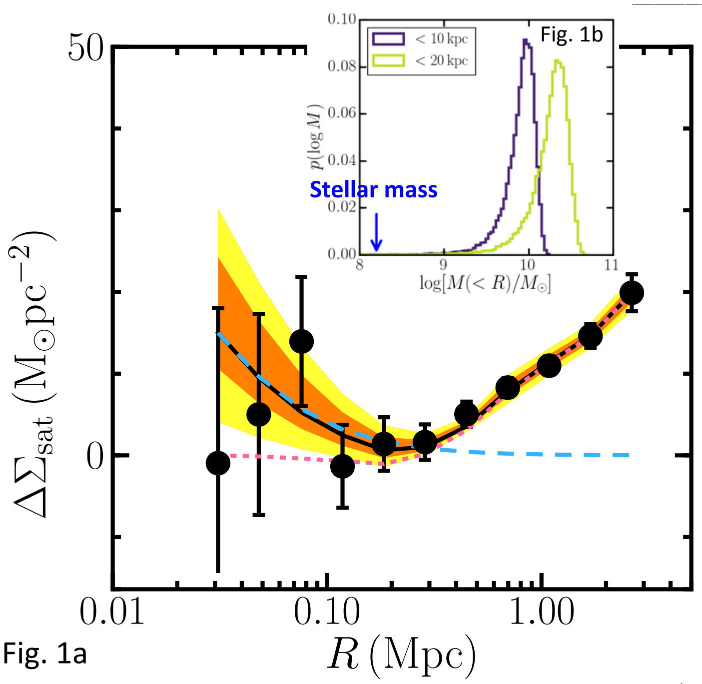
Given the excellent photometric data of these clusters, and the redshift range (see Box 8a) for which VIMOS multiplexing efficiency is maximal, we foresee this data set to be *the* sample for studying the UDG population in multiple ways. First and foremost it will allow for a robust lensing measurement of the halos masses, which is currently the key question regarding their origin. However, it will also allow for a determination of their stellar ages and metallicities (from stacking their spectra), as well as their accretion history into the cluster. The many extra available slits will be placed on more compact cluster dwarf candidates (similar luminosities, but sizes of $0.5 \lesssim r_{\rm eff} \lesssim 1.0$ kpc), which serve as a comparison sample in this analysis. All of these studies, made possible by this relatively modest proposal, will provide essential clues to the origin of these enigmatic galaxies.

7. Description of the proposed programme and attachments

Description of the proposed programme (continued)

References: Amorisco & Loeb 2016, subm. to MNRAS Letters (ArXiv:1603.00463) • Beasley et al. 2016, ApJL in press (ArXiv:1602.04002) • Dalcanton et al. 1997, AJ, 114, 635 • Hoekstra et al. 2015, MNRAS, 449, 685 • Impey et al. 1988, ApJ, 330, 634 • Koda et al. 2015, ApJ, 807, L2 • Mihos et al. 2015, ApJ, 809, L21 • Moore et al. 1996, Nature, 379, 613 • Muzzin et al. 2012, ApJ, 746, 188 • Sifón et al. 2013, ApJ, 772, 25 • Sifón et al. 2015, MNRAS, 454, 3938 • Torrealba et al. 2016, subm. to MNRAS (ArXiv:1601.07178) • Turner et al. 1993, MNRAS, 261, 39 • van der Burg et al. 2016, A&A in press. (ArXiv:1602.00002, vdB16) • van Dokkum et al. 2015a, ApJ, 798, L45 • van Dokkum et al. 2015b, ApJ, 804, L26

Attachments (Figures)



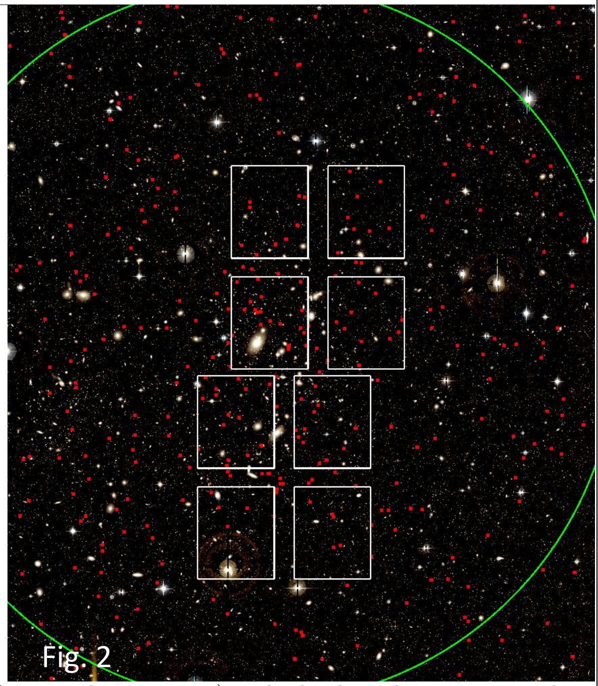
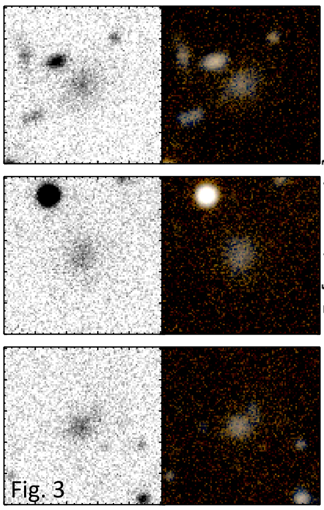


Fig. 1a: Preliminary results from our lensing analysis (Sifón et al. in prep.), which *directly* measures the halo mass associated with UDGs. **b:** The blue arrow marks the average stellar mass of the UDGs, while the histograms show posterior probability distributions of the total masses within 10 kpc and 20 kpc (i.e. roughly where we observe the stellar mass to be). Combined, these suggest a central dark matter fraction of $\sim 95-99\%$, in line with the stunning results which were based on indirect estimates.

Fig. 2: A $g-r$ colour image of Abell 85, with the estimated virial radius R_{200c}, centred on the BCG, shown with the green circle. The red points mark the identified UDG candidates. The white rectangles mark the two proposed VLT/VIMOS masks on the cluster. Besides covering UDG candidates (~ 50 of which we can place slits on in these two masks), the same exposures allow us to go for spectroscopic identification of more compact dwarf galaxies with the same total magnitude as the UDGs. This serves as an important comparison sample.



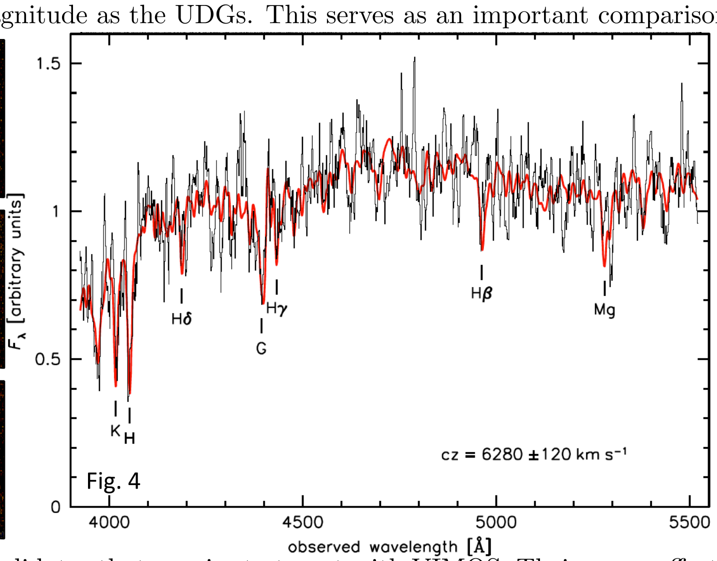


Fig. 3: Three typical cluster UDG candidates that we aim to target with VIMOS. Their mean effective surface brightnesses within their effective radii are ~ 24.5 mag arcsec^{-2}.

Fig. 4: Spectrum obtained on a similarly bright and extended source with 1.5 hour integration time on Keck/LRIS (van Dokkum et al. 2015b), which illustrates the feasibility of this program.

8. Justification of requested observing time and observing conditions

Lunar Phase Justification: Due to the very low surface brightnesses of our targets, and the observations at blue wavelengths, this is only feasible under dark conditions, up to 3 days from new moon.

Time Justification: (including seeing overhead) The aim of this program is to obtain absorption-line redshifts for galaxies with radii $r_{\rm eff} > 1.5''$ (1 kpc $\simeq 1''$ at z=0.05), and mean surface brightnesses in the R-band of 24.5 mag arcsec^{-2} within this radius. We plan to use VIMOS in MOS mode with the HR blue grism and $1''$ slits, which gives a spectral resolution of R=1150 at the central wavelength. We will bin per 5 pixels in the spectral direction, leading to an effective resolution of 3.6Å, and sum along the spatial direction. Using the VIMOS ETC, we find that the $\sqrt{5}$ improvement in S/N yields 3.0<S/N<6.0 per spectral element redward of the 4000Å-break ($\lambda_{\rm obs} > 4200$Å) in three hours of integration. The estimate above is based on the "Elliptical galaxy" template, and the smallest galaxies in our sample, and is therefore a slightly pessimistic estimate. For a somewhat bluer spectrum (as indicated by their $g - r$ colours, cf. vdB16), such as "E Galaxy", we obtain a similar S/N for larger galaxies ($r_{\rm eff} \simeq 4.0''$), with a mean surface brightness of 25.3 mag arcsec^{-2}. We will verify this strategy with the results from our DDT pilot, which we will have prior to PH2 of this main program.

We stress that these estimates are in line with the same quality of spectrum obtained by van Dokkum et al. 2015b (see Fig. 4), in half this exposure time on a similarly bright UDG (note that they report *central* surface brightnesses in the g-band, while we report *mean* surface brightnesses in the r-band), but using Keck/LRIS. We have to use a twice longer integration time to compensate for the larger aperture and sensitivity of Keck/LRIS.

A main goal of this program is to measure redshifts of fore- and background interlopers among the UDG candidates. We expect interlopers to almost certainly have redshifts below $z < 0.20$ due to their large angular sizes. Little is known of these interlopers, but if they have old stellar populations we expect to locate their 4000Å in 75% of the cases (spectral range covered depends on the position of the slit in the field of view). The presence of possible emission lines would further refine a redshift measurement.

We estimate the slit losses expected under different seeing conditions. As a pessimistic scenario, we consider a small round galaxy in our sample (with $r_{\rm eff} \sim 1.5''$), an exponential (Sérsic-n=1) light profile, and a slit width of $1''$. A seeing FWHM of $1.5''$ would give only 10% extra slit losses compared to a seeing FWHM of $0.7''$. This effect is minimal compared to any VIMOS program that targets higher-z galaxies, since these are much smaller. Given our flexible constraints, *this program is thus an excellent filler program under bad-seeing conditions.*

Given our long integration times, yet very loose seeing constraints, we request a waiver to 1.5-hour OBs. Overheads of telescope preset, mask acquisition, 4 reads per OB, arc lamp calibration, result then in 18 OBs to observe the six masks. We thus request a total time of 27 hours (which would be 36 hours without a waiver).

8a. Telescope Justification:

The low surface brightness of these UDGs forces us to consider large-aperture telescopes. Keck has a larger aperture than the VLT; however, the most blue-sensitive instrument (LRIS, e.g. van Dokkum et al. 2015b) has a FoV of only $6' \times 8'$. With $4 \times (8' \times 7')$, the FoV of VLT/VIMOS is notably larger. The clusters in our sample are at the ideal redshifts $0.04 \lesssim z \lesssim 0.06$, which maximizes scientific merit of VLT/VIMOS, because these clusters are 1) nearby enough that UDGs can be easily identified with minimal contamination from fore- and background interlopers (vdB16), and yet 2) distant enough that a significant number falls in the VLT/VIMOS FoV (see Fig. 2), which allows us to multiplex and maximize the scientific return. VLT/VIMOS is capable of placing ~ 5 times more UDG slits per exposure than LRIS. This multiplexing capability makes this the most efficient instrument to identify a statistical sample of UDGs by measuring their redshifts, and to help understand their origin.

8b. Observing Mode Justification (visitor or service):

Given our flexible requirements in terms of observing conditions (in particular image quality), this program would ideally be executed in service mode. Our loose seeing-constraint makes this study an excellent alternative/filler with high expected scientific return, when the seeing is above the seeing limit imposed by the large (public) VLT/VIMOS programs. Due to our deep photometric imaging data with excellent astrometric calibration, these observations can be taken in pre-image-less MOS (PILMOS) mode.

8c. Calibration Request:

Standard Calibration

9. Report on the use of ESO facilities during the last 2 years

We have been awarded 9 hours for a DDT pilot program (296.A-5043, PI=vdBurg) to observe two VIMOS masks on Abell 780, which is a cluster taken from the same sample (vdB16). The DDT allows us to make a first assessment of the redshift distribution of the UDG candidates (we placed slits on 30 UDG candidates, ~ 20 of which we expect to be cluster members, and on a comparison sample of 50 more compact dwarfs with the same luminosities). The DDT will also help us to better understand the technical aspects of how to optimize target selection and exposure times, given the large range in sizes and SBs for these galaxies. The 2 masks are currently in the queue, and should be observed before PH2 submission of this proposed main program to help verify/finetune our settings. Apart from this, the PI has not used any ESO facility. Our team has extensive experience with optical multi-object spectroscopy. Team member Muzzin planned and reduced the observations for the GCLASS survey (e.g., Muzzin et al. 2012) which comprised ~ 220 hr of Gemini/GMOS spectroscopy. Team member Sifón has also performed and reduced multi-object spectroscopy of clusters from VLT/FORS2 and Gemini/GMOS (e.g., Sifón et al. 2013). We have the necessary experience and reduction software in place for a quick turnaround of these data.

9a. ESO Archive - Are the data requested by this proposal in the ESO Archive (http://archive.eso.org)? If so, explain the need for new data.

The proposed data will be completely unique.

9b. GTO/Public Survey Duplications:

This program has no overlap with previous or on-going GTO programmes and public surveys.

10. Applicant's publications related to the subject of this application during the last 2 years

Remco F.J. van der Burg, Adam Muzzin, and Henk Hoekstra, 2016, A&A in press. (ArXiv:1602.00002): "The abundance and spatial distribution of ultra-diffuse galaxies in nearby galaxy clusters"

11. List of targets proposed in this programme

Run	Target/Field	α(J2000)	δ(J2000)	ToT	Mag.	Diam.	Additional info	Reference star
A	Abell 85	00 41 50.3	-09 18 11.2	9			$z = 0.055$	
A	Abell 119	00 56 16.0	-01 15 18.2	9			$z = 0.044$	
A	Abell 133	01 02 41.7	-21 52 55.8	9			$z = 0.056$	

Target Notes: The coordinates correspond to the central galaxies (BCGs) of these clusters. The two masks per cluster will be slightly off-set from these locations (by up to $\sim$15 arcmin).

12. Scheduling requirements

13. Instrument configuration

Period	Instrument	Run ID	Parameter	Value or list
98	VIMOS	A	MOS-grisms	HR-Blue
98	VIMOS	A	MOS-slits-targets	1.0, targets:extended