European Organisation for Astronomical Research in the Southern Hemisphere

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APPLICATION FOR OBSERVING TIME

PERIOD: **96Z**

DDT

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: **X–0**

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

2. Abstract / Total Time Requested

Total Amount of Time:

The existence of Ultra-Diffuse Galaxies (UDGs) in local galaxy clusters has come as a stunning surprise. It is completely unclear how and where UDGs have formed, and this may be a serious challenge for our theory of galaxy formation. To be able to survive in a cluster environment, indirect estimates suggest them to be extremely (95-99%) centrally dark-matter dominated. A major step towards understanding would be to *directly* measure their masses. We have performed this important measurement using a weak-lensing study, and the first results are ground-breaking; UDGs are hosted by truly massive haloes, and these have thus failed to form a proper galaxy. Before we can submit it to Nature, we aim to verify the redshift distribution of fore- and background interlopers in our sample. We aim to obtain this missing information using VLT/VIMOS, by obtaining redshifts for 60 UDG candidates in Abell780, 20 of which we expect to be fore- and background objects.

3.

Run	Period	Instrument	Time	Month	Moon	Seeing	Sky	Mode	Type
A	96	VIMOS	7h	mar/apr	d	n	PHO	s	

4. Number of nights/hours

Number of nights/hours	Telescope(s)	Amount of time
a) already awarded to this project:		
b) still required to complete this project:		

5. Special remarks:

Due to our deep photometric imaging data with excellent astrometric calibration, these observations can be taken in pre-image-less MOS (PILMOS) mode. 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 with high expected scientific return, when the seeing is above the seeing limit imposed by large (public) VLT/VIMOS programs.

6. Principal Investigator: RFJvdBurg

6a. Co-investigators:

A.	Muzzin	1370
H.	Hoekstra	1716
C.	Sifón	1716

7. Description of the proposed programme

A – Scientific Rationale: One of the most surprising recent results in the field of galaxy formation has come from the Dragonfly telescope (Abraham & van Dokkum 2014), which discovered a significant population of very large diffuse galaxies in the Coma cluster (van Dokkum et al. 2015a). Although low surface brightness galaxies are not an unknown population, as their discovery dates back several decades (Impey et al. 1988; Turner et al. 1993; Dalcanton et al. 1997), the galaxies identified by van Dokkum are even larger and more diffuse. These galaxies, which were labeled 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), are exceptionally unusual, and very little is known about their origin and evolution. Since their first recognition, several other studies have studied UDGs in different data sets (Mihos et al. 2015; Koda et al. 2015; van Dokkum et al. 2015b; van der Burg et al. 2016, hereafter vdB16), but we have not come any closer to an explanation.

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), even after potential stripping by the violent encounters expected to happen with other galaxies during their time in the clusters. This extreme dark-matter content may hold clues towards their formation process, and help us understand how UDGs differ from the main population of dwarfs. It may even hint towards a possible solution to the too-big-to-fail problem (Boylan-Kolchin et al. 2011), namely that some of the massive haloes in the Universe have in fact been very inefficient at forming galaxies. Although this is an intruiging possibility, and would rule out that UDGs are the result of tidal heating processes acting on more compact dwarfs, it is based on completely circumstantial evidence.

A *direct* measurement of the halo masses of UDGs is paramount for understanding this galaxy population. Because these galaxies 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, without by-eye verification, vdB16). With these data, we have performed the first *direct* mass measurement of UDGs using weak gravitational lensing (Sífon et al., not yet submitted). Remarkably, the lensing measurement appears to confirm the hypothesis from van Dokkum et al. 2015a, namely that UDGs are hosted by massive dark-matter haloes. This is the first *direct* measurement of their masses, and this finding would undermine the straightforward mapping of stellar mass to dark-matter mass that is generally assumed in galaxy evolution studies. Because of its potential high impact, we intent to publish this ground-breaking result in Nature.

Before submission, we have to be aware of the assumptions that go into the lensing analysis. While we have most of these under control, the main remaining uncertainty in our interpretation of the lensing signal is the unknown distances to the back(and fore-)ground sources that enter into the lensing sample. Whereas the study in vdB16 estimates the statistical contamination *fraction* (by number), knowing the redshifts of the contaminants is essential to estimate the signal they contribute to the stacked lensing measurement. In particular for example, interlopers that appear to be at higher redshift than the cluster may add significantly to the lensing signal (because their total mass is higher at a given apparent magnitude). Thanks to its multiplexing capability and its large FoV, we estimate that VLT/VIMOS is the most efficient instrument to obtain a statistical sample of redshifts for these faint UDG candidates, using which we can verify our lensing result.

B – Immediate Objective: We propose a spectroscopic study of two three-hour masks with VLT/VIMOS on cluster Abell 780, which will allow us to obtain redshifts for ∼60 UDG candidates. Covering an area up to R_{200c} (projected), we expect ∼40 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 (to date, only one confirmed using Keck spectroscopy by van Dokkum et al. 2015b, see Fig. 4). Even more critical for the lensing study, it also gives us a sample of ∼ 20 fore- and background objects. Identifying the nature of these contaminants (in particular their redshifts) provides the key unknown in our study, with which we can then confirm their high dark matter content. We expect these galaxies, with a large angular size, to certainly be below a redshift $z < 0.20$, and with the proposed setup we will be able to measure their redshifts.

Besides this primary science driver for the DDT program, these data will also help us to demonstrate which science scopes are feasible with a potential large bad-seeing program. Using the DDT data we can already put first constraints on the average stellar ages and metallicities of the UDGs. We will start a study of their projected phase space, as proposed by Weinmann et al. 2011 to be used to study and separate the dynamical histories of different galaxy populations in clusters. 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.

We expect the clusters in our sample to be 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, and yet 2) distant enough that a significant number falls in the VLT/VIMOS FoV, which allows us to multiplex and maximize the scientific return.

7. Description of the proposed programme and attachments

Description of the proposed programme (continued)

References: Abraham & van Dokkum 2014, PASP, 126, 55 • Dalcanton et al. 1997, AJ, 114, 635 • 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 • Turner et al. 1993, MNRAS, 261, 39 • van der Burg et al. 2016, subm. to A&A (ArXiv:1602.00002, vdB16) • van Dokkum et al. 2015a, ApJ, 798, L45 • van Dokkum et al. 2015b, ApJ, 804, L26 •

Attachments (Figures)

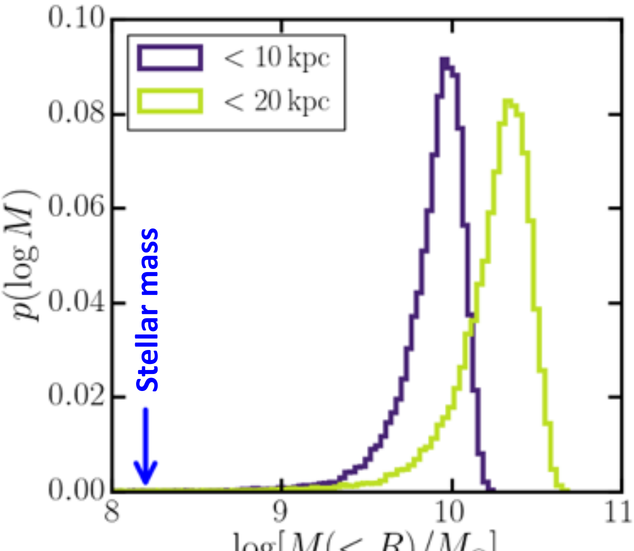

Fig. 1

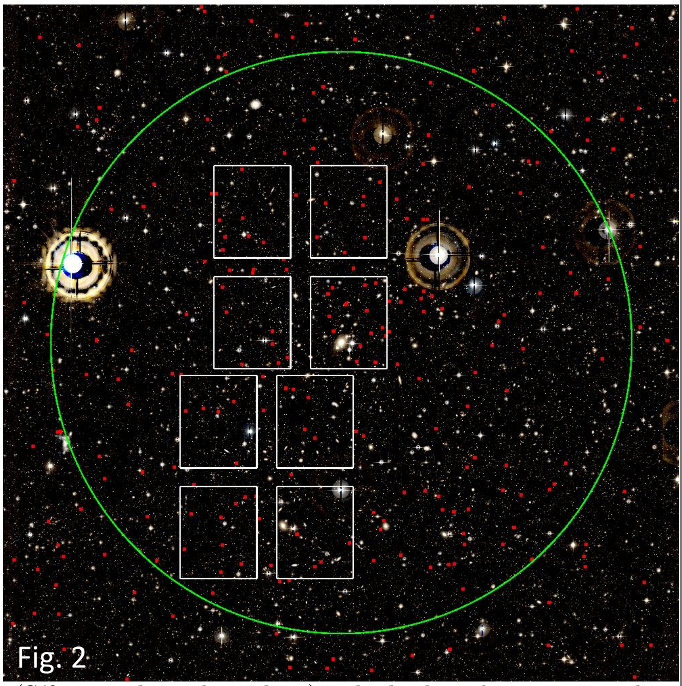

Fig. 2

Fig. 1: Preliminary results from our lensing analysis (Sífon et al. to be subm.), which *directly* measures the mass associated with UDGs. The blue error 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 780, with the estimated virial radius R_{200c}, centered 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 ~ 60 UDG candidates, the same exposures allow us to go for deep spectroscopic identification of more compact dwarf galaxies, with the same total magnitude as the UDGs. This serves as an important comparison sample.

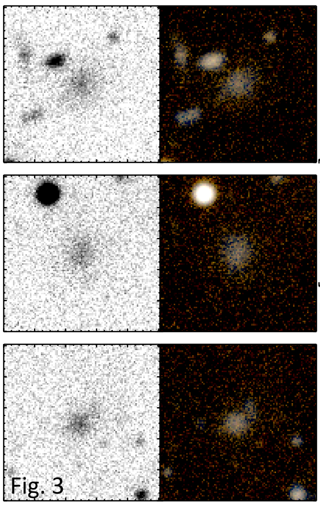

Fig. 3

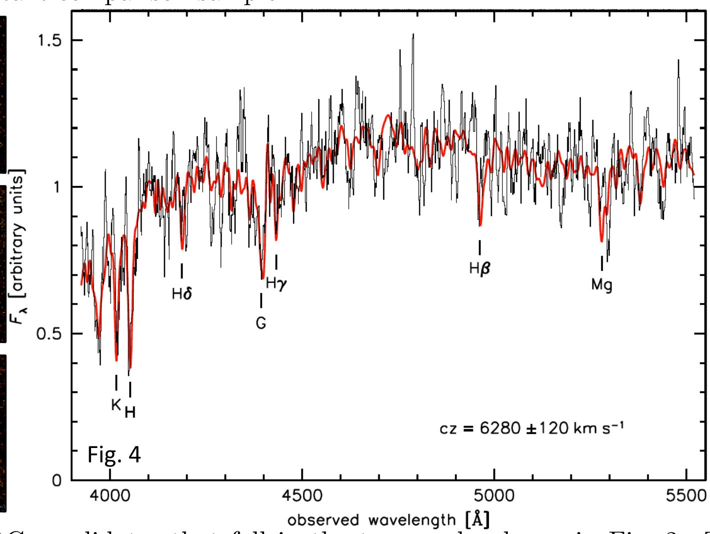

Fig. 4

Fig. 3: Three of the ~60 cluster UDG candidates that fall in the two masks shown in Fig. 2. Their mean effective surface brightnesses within their effective radii are ~ 25.0 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, the observations are only feasible under the darkest possible conditions.

Time Justification: (including seeing overhead) We are aiming at obtaining absorption-line redshifts for galaxies with radii $r_{\rm eff} > 1.5''$ (1 kpc $\simeq 1''$ at z=0.055), and mean surface brightnesses in the R-band of 24.5 mag arcsec^{-2} within this radius. This is challenging, but after binning per 5 pixels in the spectral direction, and summing along the spatial direction, we expect to obtain 3.0<S/N<6.0 per spectral element redward of the 4000Å-break (effective resolution=3.5Å) in three hours of integration. The estimate above is based on a maximally old galaxy template, and the smallest galaxies in our sample, and is therefore a slightly pessimistic estimate. For a slightly bluer spectrum (as indicated by the $g-r$ colours measured in vdB16), we expect a similarly significant measurement for larger galaxies in our sample ($r_{\rm eff} \simeq 4.0''$), with a mean surface brightness of 25.5 mag arcsec^{-2}. These estimates are in line with the spectrum obtained by van Dokkum et al. 2015b in half this exposure time on a similarly bright galaxy (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. Due to the larger aperture and sensitivity, Keck/LRIS is more efficient at measuring redshifts for a single galaxy, but with roughly twice the integration time and the multiplexing capability at VLT/VIMOS, we expect the latter to be the most efficient instrument to obtain a larger spectroscopic sample. Three hour integrations thus allow us to obtain redshifts for the majority of the UDG candidates that fall on the masks.

A main goal of this program is to measure redshifts of fore- and background interlopers among the UDG candidates. We expect them to certaintly have redshifts below $z < 0.20$ due to their large angular sizes and faint magnitudes. Little of these interlopers is known, 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.

Since we expect this to be a possible bad-seeing program, we estimated the slit losses expected under different seeing conditions. As a pessimistic scenario, we consider the smallest 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.

With two 3-hour masks (covering 60 UDG candidates and an even larger number of smaller dwarfs with similar magnitudes, which we use as a comparison), we request a total of 7 hours. This includes overheads of telescope and instrument setup, and MOS acquisition.

8a. Telescope Justification:

The low surface brightness of these UDGs forces us to consider large-aperture telescopes. Although e.g. Keck has a larger aperture, VLT/VIMOS provides a relatively large FoV which allows us to simultaneously target $\sim$ 30 UDGs per exposure. This multiplexing capability makes this the most efficient instrument to identify them by measuring their redshifts, and to help understand their origin.

8b. DDT Justification:

We have a significant and probably ground-breaking weak-lensing measurement of UDGs in clusters, which is the first *direct* measurement of their masses, and this confirms earlier indirect estimates that these galaxies are completely dominated by dark matter. With this DDT program we will be able to address the main remaining uncertainty which is essential for the analysis, namely an understanding of the nature (and particularly redshifts) of the contaminating sources in the UDG sample. Secondly, this relatively small DDT proposal will help us investigate which science goals are feasible for a possible large bad-seeing program at VLT/VIMOS.

8c. Calibration Request:

Standard Calibration

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

The PI has not used any ESO facility.

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:

VIMOS is not available for GTO programmes, and the targets and science scope are completely different from those of other programmes/instruments.

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 submitted (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 780	09 18 05.7	-12 05 44.0	7				

Target Notes: This is a note about targets.

12. Scheduling requirements

13. Instrument configuration

Period	Instrument	Run ID	Parameter	Value or list
96	VIMOS	A	MOS-grisms	HR-Blue