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European Organisation for Astronomical Research in the Southern Hemisphere

Organisation Européenne pour des Recherches Astronomiques dans l'Hémisphère Austral
Europäische Organisation für astronomische Forschung in der südlichen Hemisphäre

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APPLICATION FOR OBSERVING TIME PERIOD: **80A**

Important Notice:

1. Title Category: **A–5**

A *Very Large Telescope* Search for Decaying Axions in the $z = 1.237$ Lensing Cluster RDCS 1252.9-2927

2. Abstract

Determining the nature of the Dark Matter is the most important and long-lasting problem in cosmology. One of the few well-motivated hypotheses is the *axion*, which will decay to produce optical line-emission in galaxy clusters. We propose to search for this emission in the massive, $z = 1.237$, lensing cluster RDCS 1252.9-2927. By doing so, we will explore the axion mass-window 8 eV − 14 eV, which has not yet been targeted by cluster observations. Our expected signal is ~ 6 times higher than in past work, affording a greater chance of detection, and covering a significantly larger region of axion parameter space. We have demonstrated the reliability of our data-analysis technique by analyzing archived VIMOS/IFU observations of lower-redshift clusters. **The proposed observations may yield evidence for a specific dark-matter candidate and will provide important constraints to the nature of the Dark Matter.**

3.

Run	Period	Instrument	Time	Month	Moon	Seeing	Sky Trans.	Obs.Mode
A	79	VIMOS	25h	mar	d	$\leq 1.0''$	CLR	s

4. 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:

Take advantage of this box to provide any special remark using up to three lines

6. Principal Investigator: J.P. Kneib (OAMP–Marseilles, F, jean-paul.kneib@oamp.fr)

CoI(s): D. Grin (Caltech, USA), G. Covone (INAF–Capodimonte Observatory, I), E. Jullo (Santiago, ESO), M. Limousin (DARK Cosmology Centre, Copenhagen, DK), M. Kamionkowski (Caltech, USA)

7. Is this proposal linked to a PhD thesis preparation? State role of PhD student in this project

Yes / Daniel Grin. Student is analyzing the reduced data. / starting

8. Description of the proposed programme

A) Scientific Rationale: Dark Matter and Axions: A very significant fraction of VLT time is devoted to determining the amount and distribution of the dark matter, but remarkably enough, virtually no time has been allocated to determine the *nature* of the dark matter. Constraints from big-bang nucleosynthesis (BBN) and CMB anisotropies tell us that the bulk of the dark matter is cold and non-baryonic. Strong/weak lensing observations, X-ray emission studies, and other dynamical probes all confirm that the bulk of the mass in galaxy clusters is also dark, cold, and non-baryonic (Clowe et al. 2006). **For several decades, the two-dark matter candidates preferred (*by far!*) by theorists have been weakly interacting massive particles (WIMPs) and the axion**.

The axion was postulated by Peccei and Quinn (1977) to solve the strong CP (charge-parity) problem. The axion would decay to two photons with lifetime $\tau(a \rightarrow \gamma\gamma) = 6.8 \times 10^{24} \xi^{-2} m_{\mathrm{a,eV}}^{-5}$ s (Ressell 1991), where ξ parameterizes the two-photon coupling of the axion. Measuring or constraining ξ is crucial for understanding the properties of axionic dark matter. The simplest axion models predict $\xi \approx 1$ (Raffelt 1996), but there are axion models with much lower values of ξ (Kaplan 1985, Moroi 1998). Models with $\xi < 0.01$, however, become increasingly far-fetched. **Our proposed observation will be the first to explore such low values of the coupling ξ (Fig. 1) and may be a definitive test of the axion hypothesis between 8 eV and 14 eV.** The mass of the axion can theoretically take on a wide range of values. However, astrophysical observations and laboratory experiments constrain the axion mass to lie in one of two windows, $10^{-6} < m_{\mathrm{a,eV}} < 10^{-3}$ or $1 < m_{\mathrm{a,eV}} < 20$, where $m_{\mathrm{a,eV}}$ is the axion mass in units of eV. Axions in either of these mass windows will have cosmologically important abundances today. Axions in the more massive window will be produced thermally in the early universe, and freeze out with abundance in the range $0.08 \times (m_{\mathrm{a,eV}}/11) < \Omega_{\mathrm{a}} h^2 < 0.15 \times (m_{\mathrm{a,eV}}/11)$ (Kolb and Turner 1990), thus bracketing the best-fit ΛCDM value. Their velocity today would be in the range $2.7 \times 10^{-4} < m_{\mathrm{a,eV}} \left\langle v_a^2/c^2 \right\rangle < 4.9 \times 10^{-4}$ (Turner 1987), so sufficiently massive ($m_{\mathrm{a,eV}} > 1$) axions will be *cold* dark matter *today*, bound in gravitational clusters, and contribute a fraction Ω_a/Ω_m of a cluster's mass density. However, axions in the eV mass-range will be relativistic at the onset of structure formation, and are thus candidates for the hot component of mixed dark-matter models *in the early universe* (Moroi 1998). If we see no signal in the eV range, and if axions exist with mass 5×10^{-5}eV (inside the remaining mass window), they will have a non-thermal relic abundance of $\Omega_{\mathrm{a}} h^2 \approx 0.13$, and could be most or all of the dark matter. Consequently, **a detection and even a null search will be cosmologically significant**.

Axion Decay in Galaxy Clusters: Axion decay will produce a sharp emission line with intensity (Ressell 1991)

$$I_\lambda = \frac{6.8 \times 10^{-21} m_{\mathrm{a,eV}}^7 \xi^2 \Sigma/(\mathrm{g\ cm^{-2}}) \mathrm{e}^{\frac{-(\lambda_{\mathrm{r}}-\lambda_{\mathrm{a}})^2}{\lambda_{\mathrm{a}}^2} \frac{c^2}{2\sigma^2}}}{\sigma_{1000}(1+z_{\mathrm{cl}})^4} \tag{1}$$

in units of ergs $\mathrm{cm^{-2}\ s^{-1}\ arcsec^{-2}\ \AA^{-1}}$, where λ_r is wavelength in the cluster rest-frame, σ_{1000} is its velocity dispersion in units of $1000\,\mathrm{km\,s^{-1}}$, and Σ is the projected surface mass-density of the cluster. For typical cluster densities, the predicted specific intensity of the line is detectable, in spite of the long lifetime of the axion. Energy/momentum conservation requires each photon to carry away half the axion rest-mass energy, so the (de Broglie) wavelength of the axion line would be $\lambda_a = 24,800\text{Å}\, m_{\mathrm{a,eV}}^{-1}$ in the cluster rest-frame. **Thus, at redshifts $z < 0.2$, decaying axions in the mass window $3.0 < m_{\mathrm{a,eV}} < 8.0$ could be detected in optical spectra by the presence of a prominent narrow, heretofore unidentified emission-line with intensity proportional to the cluster's surface mass-density and velocity dispersion equal to that of the cluster.**

Past Telescope Searches for Axions: This idea was first implemented by Bershady, Ressell, and Turner (1991) using long-slit spectra of galaxy clusters. Using the spatial dependence of the axion line and assuming a flat sky-background, sky was subtracted and the density-dependent component of these spectra was extracted. Bershady et al. (1991) subtracted spectra taken at the edge of the field from spectra taken near the cluster core to obtain 'on-off' spectra. If axions exist, they should be part of the diffuse dark-matter halo of galaxy clusters and cleanly detectable via spectroscopy of high density regions, even away from individual cluster galaxies. Slits were thus placed away from known cluster galaxies and further masks applied to avoid confusion of any galactic emission with axion decay. Spectra were first visually inspected, and then cross-correlated to search for line emission due to axion decay. No axion line was observed, and limits were put on ξ (Bershady et al. 1991). These limits can now be considerably improved by using the significantly higher detector and collecting area of the VLT. **An IFU is optimal for such work, as highly spatially-resolved spectra may be used, along with lensing-derived density-maps of clusters, to optimally weight spatial regions where maximum signal is expected. Use of an IFU will also facilitate robust separation of the sky background from the expected signal, which is density dependent.** Although the signal traces the cluster density, it will be diffuse compared to emission from galaxies in the field-of-view. IFUs are ideal for detecting such diffuse intracluster emission.

Ongoing Work in this Area: We have used archival VIMOS IFU spectra of A2667 ($z = 0.233$, Covone et al. 2006) and A2390 ($z = 0.228$, Jullo et al. 2007) to search for optical line-emission from decaying axions (Grin et al. 2006). Mass maps of these clusters derived using strong-lensing (Covone et al. 2006, Jullo et al. 2007)

8. Description of the proposed programme (continued)

are used to obtain a clean subtraction of sky from density-dependent signal. *Our sky-subtraction technique is a statistical generalization of the 'on-off' technique tested by Bershady et al. (1991), and is thus well motivated and reliable.* The lensing mass-maps were used to obtain optimally weighted one-dimensional spectra which emphasize regions of the cluster where the highest signal is expected. When searching for evidence of axion decay, we masked out IFU fibers coinciding with galaxies and other bright individual sources. We put an upper limit on emission from axion-decay and thus improved the upper limits on ξ by a factor of ~ 4, in the mass window $4.5 < m_{\rm a,eV} < 7.7$ (Grin et al. 2006). We directly apply lensing mass-maps of the clusters, and so unlike the work of Bershady et al. (1991), our analysis makes no assumptions about the dynamical state of the clusters. By moving to higher redshift ($z \approx 1.2$), we will explore the mass range $8.3 < m_{\rm a,eV} < 13.9$. Although the specific intensity of the axion line falls off as $(1+z)^{-4}$, it also increases as $m^7_{\rm a,eV} \propto (1+z)^7$. The overall scaling with redshift is $I_\lambda \propto (1+z)^3$, and so if axions exist in this mass range, we expect a substantially (factor of 6) higher flux than we would if they existed in the lower mass range. We propose deep IFU observations of RDCS 1252, in order to detect axion decays with high S/N. If the quality of the data is comparable to that obtained for A2667 and A2390, the range of ξ values explored will be a factor of ~ 100 lower than the best existing upper limits in this mass range, thanks to the higher redshift of the cluster (e.g. Fig. 1). **To address concerns that the peculiarities of IFU data-reduction or sky subtraction are thwarting our search, or alternatively, leading to an artificial signal, we have conducted an extensive simulation**. For 10 candidate axion-masses and $3-4$ values of ξ at each mass, we simulated axion-decay emission in our data cube for A2667, applying Eq. (1) and lensing maps. Visual inspection and statistical analysis of the data cubes yielded clear evidence for the inserted line when ξ exceeded its upper limit, e.g. Fig. 3. We recovered the correct value of ξ to a precision of 10% for all cases in which ξ exceeded its upper limit. **Thus, both our sky-subtraction technique and our limits are robust**. **References:** Bershady, M. A. et al., Phys. Rev. Lett. **66**, 1398 (1991)– Clowe, D. et al. (2006), accepted by ApJL, astro-ph/0608407– Covone, G. et al. (2006), A&A **456**, 409, astro-ph/0511332– Jullo, E. et al. (2006), in prep.– Grin, D. et al. (2006), "A Telescope Search for Decaying Relic Axions," in prep. for submission to Phys. Rev. D– Lombardi, M. et al., ApJ **623**, 42 (2005)–Moroi, T., and Murayama, H., Phys. Lett. B **553**, 126 (2003)–Peccei, R. D. & Quinn, H.R, Phys. Rev. Lett. **38**, 1440 (1977)– Ressell, M. T., Phys. Rev. D **44**, 3001 (1991)– Raffelt, G. G., Stars as Laboratories for Fundamental Physics: The Astrophysics of Neutrinos, Axions, and Other Weakly Interacting Particles. The University of Chicago Press, Chicago (1996)– Lombardi, M. et al., ApJ **623**, 42(2005)– Turner, M. S., Phys. Rev. Lett. **59**, 2489 (1987).

B) Immediate Objective: We propose 16.5 hrs of deep VIMOS/IFU observations of RDCS 1252, the most distant known lensing-cluster ($z = 1.237$), in order to search for emission from decaying axions in the mass window 8.3 eV − 13.9 eV. The requested time is a factor of 5.5 longer than our archival observations of A2667 and A2390, increasing the likelihood of observing a faint line. The high redshift of this cluster alone will extend the range of observable two-photon couplings of the axion by a factor of 100, thus significantly improving upon the work of Bershady et al. (1991). VIMOS observations will allow us to measure the redshifts of strongly-lensed multiple images, thus improving both the cluster mass-model and the reliability of limits on ξ. The axion-decay line has FWHM of 35 − 60 Å, sufficiently wide to be resolved with the LR-B grism, whose wavelength range is appropriate for this axion mass range.

C) Telescope Justification: Our challenging scientific goals can only be met by wide, deep, integral-field spectroscopy of a high-z cluster of galaxies. VIMOS has the only IFU on an 8 − 10m telescope with a field-of-view wide enough to cover the central regions of a high-z galaxy cluster. Moreover, the very faint features we are aiming to detect will necessarily require the light collecting power of a 8m telescope. The highly spatially-resolved spectra obtained with VIMOS will allow us to apply lensing-maps of RDCS 1252 (Lombardi et al. 2005), and thus obtain optimally weighted one-dimensional spectra with a clean axion-sky separation. Therefore, **VLT/VIMOS is the only choice for using an IFU to observe the decays of axions within our target mass range in massive galaxy clusters.**

D) Observing Mode Justification (visitor or service): The present program will only require standard observational procedures, and so we only ask for service mode observations.

E) Strategy for Data Reduction and Analysis: We now have considerable experience reducing and analyzing VIMOS/IFU data. We will use a modified VIPGI pipeline that generates data cubes with no sky-subtraction applied (VIPGI sky-subtraction would wipe out any diffuse signal). Our reduction procedure corrects for variable fiber efficiency via continuum arc-lamp exposures instead of the usual VIPGI procedure, which uses sky-line fluxes. We will then use our own routines to mask IFU fibers falling on known sources and subtract sky. We will generate a one-dimensional spectrum by averaging over the IFU using optimal weights, obtained from the lensing mass-map and an estimate of the flux noise. We will begin our analysis using publicly available weak-lensing maps of RDCS 1252, but will then improve the mass-maps using strong lensing constraints obtained using the requested VIMOS/IFU data. The resulting improvement in lensing models of RDCS 1252 will be an important windfall of the requested time.

8. Attachments (Figures)

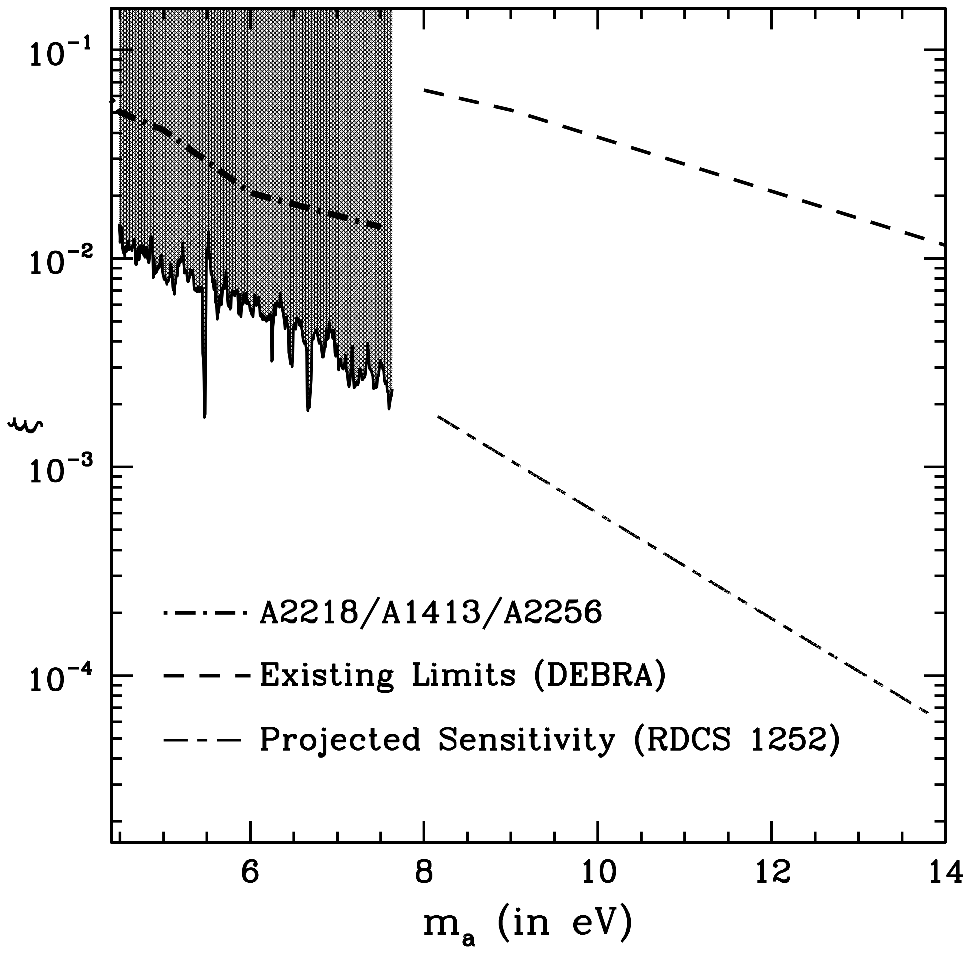

Fig. 1: Comparison of existing limits on the two-photon coupling of a 4.5 eV − 14 eV axion with the projected sensitivity of our proposed observations, adapted from Grin et al. (2006). Grey shaded area indicates the region of parameter space excluded by Grin et al. (2006). The region above the dotted-dashed line in the shaded area was excluded by Bershady et al. (1991). We rescale their limits using a ΛCDM cosmology and modern mass-models of the clusters A2218, A2256, and A1413. This re-scaling *improves* the constraints of Bershady et al. (1991) and thus yields a fair comparison between our limits and theirs. We also show the projected region of parameter space (everything above the long-short dashed line) covered by our requested IFU spectroscopy of the lensing cluster RDCS 1252 ($z = 1.237$). We compare with the best existing limits in that axion mass window (everything above the long dashed line), which come from limits on the intensity of the Diffuse Extragalactic Backround Radiation (DEBRA), also appropriately rescaled (Ressell 1991).

8. Attachments (Figures)

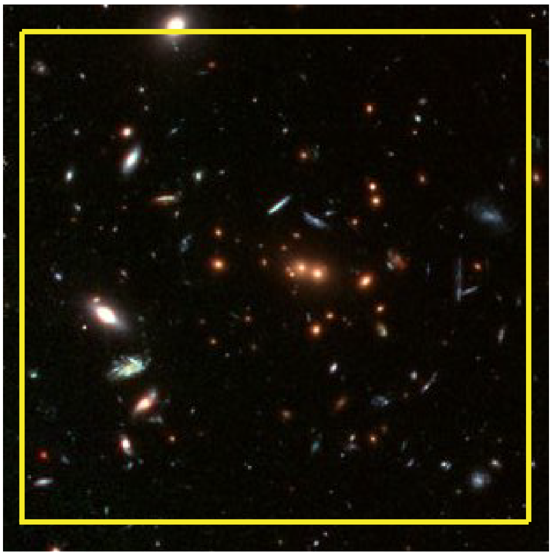

Fig. 2: HST/ACS combined I+Z band image of the massive galaxy cluster RDCS 1252.9-2927 (z = 1.237) with an overlaid outline of the VIMOS/IFU f.o.v. (i.e. about 54 ×54 arcsec^2). Strongly distorted blue galaxies are clearly detected in the cluster core. Some of them are likely to be $z > 2$ strongly lensed galaxies. East is up and North is to the right. Credit: NASA, J. Blakeslee et al., ESA, P. Rosati et al.

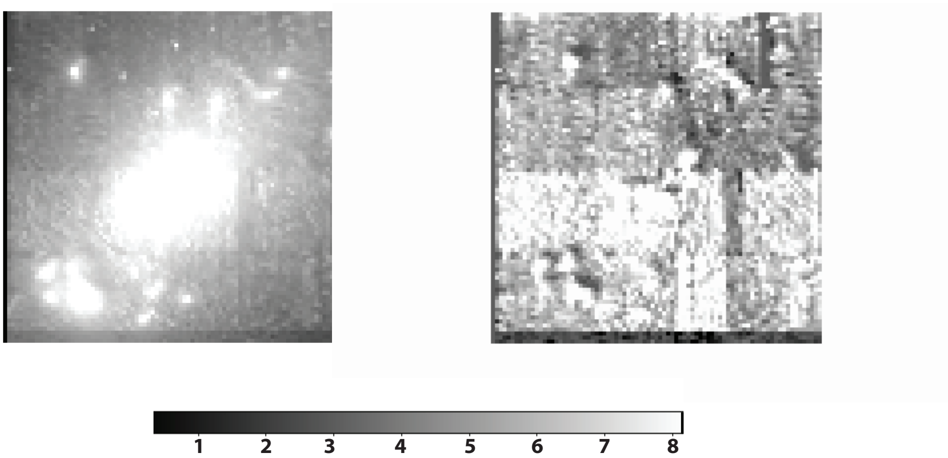

Fig. 3: The left panel of this figure shows a simulated slice of the A2667 IFU data cube at 4255.2Å, with an axion-decay emission-line inserted ($m_{\rm a,eV} = 7.2$, $\xi = 0.011$). The flux scale is in units of 10^{-18} erg s^{-1} cm^{-2} Å^{-1}. This slice, which lies at the expected line centroid, shows evidence of the inserted axion line. The resulting 'emission' clearly traces the cluster mass-density profile. The right panel of this figure shows a simulated slice of the same data cube, but at 5267.2Å, well away from the line center. As expected, no signature of axion emission is present this far away in wavelength from the line center. The high intensity of the predicted signal results from the relatively high Ω_a and short axion lifetime at $m_{\rm a,eV} = 7.2$. Failure to observe such a signal rules out the stated values of the axion mass and two-photon coupling.

9. Justification of requested observing time and lunar phase

Lunar Phase Justification: Dark time is mandatory since we aim to measure low flux-levels between 4000Å and 6800Å using the LR-B grism.

Time Justification: (including seeing overhead) In order to estimate the necessary on-target time to detect a diffuse, narrow ($35-60$Å) emission-line from axions using the LR-B grism, we considered our recent work on the VIMOS/IFU survey of massive clusters. The archival data used for A2667 and A2390 were obtained with 3 hours of exposure time using the LR-B grism, and allowed us to reach a flux limit of $\sim 2.5 \times 10^{-19}$ ergs s^{-1}Å^{-1}cm^{-2} from two-photon decays of axions. In order to improve the S/N ratio of a potential signal from axion in the cluster halo by a factor of ~ 2.3, we need 5.5 times longer exposure time, i.e. a total of ~ 16.5 hours. Taking into account the higher redshift of RDCS 1252, our *expected* signal will be a factor of $\left(\frac{1+1.237}{1+0.23}\right)^3$ larger, yielding a factor of ~ 100 (Fig. 1) improvement in the accessible range of ξ over the best existing upper limits, *in the mass window* $8.3 < m_{\rm a,eV} < 13.9$. This improvement follows from the higher redshift of the cluster alone. Even in the case of a null search, the new upper limits on ξ will extend to values a factor of ~ 100 lower than previously explored, as shown in Fig. 1. Using the VIMOS/IFU ETC, we estimate that with a ~ 16.5 hr observation, the spectrum of a $z = 2.5$, V=24 star-burst galaxy will have S/N ~ 10. This will also allow us to obtain essential redshift information for strong-lensing arcs, facilitating the construction of a better mass model of the cluster. We will apply our previous experience and use large dithering (i.e., about 5-10 arcsec), so as to compensate for the large spatial variations in the efficiency of the IFU fibers. As indicated in the VIMOS Users Manual, each 40 minutes of observing time requires 20 minutes of overhead, and so we ask for a total of 25 hours of telescope time.

Calibration Request: Standard Calibration

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

The PI has had no proposal accepted as PI during the last 2 years (4 observing periods).

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

Covone, G. et al. 2006, A&A **456**, 409, astro-ph/0511332.

Covone, G., Kneib, J.-P., Soucail., G., Jullo, E., Richard, J., astro-ph/060186, to appear in "Sciences Perspectives for 3D Spectroscopy. ESO Astrophysics Symposia." Ed by M.Kissler-Patig, M.M. Roth and J.R. Walsh.

Jullo, E. et al. (2006), in prep.

Grin, D. et al. (2006), "A Telescope Search for Decaying Relic Axions," in prep. for submission to Phys. Rev. D.

Cypriano, E. S., Lima Neta, G. B., Sodré L., Kneib, J.-P., Campusano, L. .E., ApJ **630**, 38 (2005).

Smith, G. P., Kneib, J.-P., Smail, I., Mazotta, P., Ebeling, H., & Czoske, O., MNRAS **359**, 417 (2005).

Bardeau, S., Kneib, J.-P., Czoske, O., Soucail, G., Smail, I., Ebeling, H., Smith, G. P., A&A **434**, 433 (2005).

Kneib, J.-P., Ellis, R. S., Santos, M. R., Richard, J., ApJ **607**, 697-703 (2004).

Santos, M. R., Ellis, R. S., Kneib, J.-P., Richard, J., Kuijken, K., ApJ **606**, 683-701(2004).

Cypriano, E. .S. , Sodré, L. Jr., Kneib, J.-P., Campusano, L. E., ApJ **613**, 95 (2004).

12. List of targets proposed in this programme

Run	Target/Field	α(J2000)	δ(J2000)	ToT	Mag.	Diam.	Additional info	Reference star
A	RDCS 1252.9-2927	12 52 54.4	-29 27 17	25			Galaxy Cluster	

Target Notes: Deep HST/ACS archival imaging is available for this cluster, and weak-lensing generated mass maps have been published.

12b. ESO Archive - Are the data requested by this proposal in the ESO Archive (http://archive.eso.org)? If yes, explain why the need for new data.

No. There are 5 hours of VIMOS/IFU observations in LR-Red on this cluster. However, the observations obtained were plagued by wind, poor seeing, thin clouds, and a sub-optimal dithering procedure, and thus, no useful data on RDCS 1252 were obtained.

13. Scheduling requirements

14. Instrument configuration

Period	Instrument	Run ID	Parameter	Value or list
79	VIMOS	A	IFU 0.67"/fibre	LR-Blue