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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

VISITING ASTRONOMERS DEPARTMENT • Karl-Schwarzschild-Straße 2 • D-85748 Garching bei München • e-mail: visas@eso.org • Tel. : +49-89-32 00 64 73

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

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**

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 Dark Matter is the most important and long-lasting problem in cosmology. One of the few well-motivated DM candidates is the *axion*, which will decay to produce optical line-emission in galaxy clusters. We propose to search for this emission in the $z = 1.237$, lensing cluster RDCS 1252.9-2927, using **3 deep VIMOS/IFU pointings**, in order to explore the axion mass-window $8 - 14$ eV, still unexplored by cluster observations. Our expected signal is ~ 6 times higher than past work, yielding higher sensitivity in a significantly larger region of parameter space. We have demonstrated the reliability of our technique by analyzing archived observations of lower-redshift clusters, thus placing the best direct constraint to axions in the $4 - 8$ eV window. **The proposed observations may yield evidence for a specific DM candidate and will provide important constraints to the nature of Dark Matter.**

3. Run	Period	Instrument	Time	Month	Moon	Seeing	Sky Trans.	Obs.Mode
A	80	VIMOS	25h	any	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:

We have addressed concerns regarding our last proposal: We discuss the unsuitable nature of existing archival observations of clusters and the persisting theoretical motivation for axions in this mass window. We also refer to a complete, submitted preprint (Nov 2006), which describes our completed work in this area.

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. / mid-course

8. Description of the proposed programme

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

The axion solves the strong CP (charge-parity) problem (Peccei and Quinn 1977). The axion would decay to two photons with lifetime $\tau(a \to \gamma\gamma) = 6.8 \times 10^{24}\xi^{-2}m_{\rm a,eV}^{-5}$ s (Ressell 1991), where ξ parameterizes the two-photon coupling of the axion. Measuring or constraining ξ is crucial to understanding the properties of axionic dark matter. The simplest axion models predict $\xi \approx 1$ or $\xi \approx 0.1$ (Raffelt 1996), but conventional axion models can also yield nearly-vanishing values of ξ (Kaplan 1985, Moroi 1998), due to well-known uncertainties in hadronic physics. **The constraint from globular clusters, $\mathbf{m_a\xi \leq 0.7}$, can be completely relaxed in this case. 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.** Astrophysical observations and laboratory experiments constrain the axion mass to lie in one of two windows, $10^{-6} < m_{\rm a,eV} < 10^{-3}$ or $1 < m_{\rm a,eV} < 20$, where $m_{\rm a,eV}$ is the axion mass in units of eV. Axions in these mass windows will have significant abundances today. Axions in the more massive window will be produced thermally in the early universe, and freeze out with abundance in the range $0.08 \times (m_{\rm a,eV}/11) < \Omega_{\rm a}h^2 < 0.15 \times (m_{\rm a,eV}/11)$ (Kolb and Turner 1990), thus bracketing the best-fit ΛCDM value. Their velocity today would be in the range $2.7 \times 10^{-4} < m_{\rm a,eV}\left\langle v_a^2/c^2 \right\rangle < 4.9 \times 10^{-4}$ (Turner 1987), so massive ($m_{\rm a,eV} > 1$) 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. CMB and large-scale-structure (LSS) measurements have imposed new constraints to axion parameters in this mass range. In particular, axions in the few-eV mass range are hot at early times and suppress small-scale structure just as neutrinos of comparable masses do. Such arguments imply an axion-mass bound $m_{\rm a} \leq 1.05$ eV (Hannestad et al. 2005). However, **given model dependences, it is very important in cosmology to use independent techniques.** LSS/CMB bounds depend on the integrated history of density perturbations. **Direct searches depend only on the axion model and the cluster's gravitational potential; they also test the cold dark matter paradigm**. Furthermore, **in cold reheating models**, neutrinos and **axions have lower abundances, evading CMB/LSS bounds, but will show up in telescope searches for axion decay lines (Fig. 4, also Grin et al. 2007)**. Such models succeed in baryogenesis, while diluting unwanted relics (Giudice et al. 2001); they make cosmological axions non-thermally. In this case, our completed null search in a lower mass window implies a bound to the combination $\xi(\Omega_{\rm a}h^2)^{1/2}$. If $\xi \sim 10^{-1}$, our results imply an upper limit $\Omega_{\rm a}h^2 \leq 10^{-4}$ in our mass range, roughly two orders of magnitude stronger than CMB/LSS limits, which probe densities down to $\Omega_{\rm a}h^2 \sim 10^{-2}$. A similar improvement in sensitivity will follow from our requested observations. 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 $\Omega_{\rm a}h^2 \approx 0.13$, and could be most or all of dark matter. Consequently, **a detection or a null search will be cosmologically significant**.

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

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

in units of ergs cm^{-2} s^{-1} arcsec^{-2} Å^{-1}, where λ_r is wavelength in the cluster rest-frame, σ_{1000} is its velocity dispersion in units of $1000\,{\rm km\,s^{-1}}$, 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 wavelength of the axion line would be $\lambda_a = 24,800{\rm Å}\, m_{\rm a,eV}^{-1}$ in the cluster rest-frame. **Thus, at redshifts $\mathbf{z < 0.2}$, decaying axions in the mass window 3.0 – 8.0 eV 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; at redshifts $\mathbf{z \sim 1.2}$, we probe axion masses of 8 – 14 eV.**

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 are part of the diffuse dark-matter halo of galaxy clusters and cleanly detectable via spectroscopy of high density regions, away from individual cluster galaxies. Slits were 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

8. Description of the proposed programme (continued)

be considerably improved by using the significantly higher exposure 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 regions where maximum signal is expected. Use of an IFU will facilitate robust separation of sky background from expected signal, which is density dependent.** IFUs are ideal for detecting the diffuse intracluster emission that we seek.

Completed 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). Strong-lensing mass maps of these clusters (Covone et al. 2006, Jullo et al. 2007) are used to cleanly subtract sky from density-dependent signal. *Our sky-subtraction technique is a robust statistical generalization of the 'on-off' technique of Bershady et al. (1991).* The lensing mass-maps were used to obtain optimally weighted one-dimensional spectra emphasizing IFU fibers with the highest expected signal. We masked out IFU fibers coinciding with 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 apply lensing mass-maps of the clusters, and so unlike past work, our analysis makes no dynamical assumptions. At 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 $m_{\rm a,eV}^{7} \propto (1+z)^{7}$. The overall scaling with redshift is $I_{\lambda} \propto (1+z)^{3}$, so if axions exist in this mass range, we expect a substantially (factor of 6) higher flux than in the lower mass range. We propose deep IFU observations of RDCS 1252, in order to detect axion decays with high S/N and to explore a range of ξ values a factor of ~ 100 lower than the best existing upper limits, thanks to the high redshift of the cluster (Fig. 1). **To check for systematics, we conducted a simulation**. For 10 candidate axion-masses and $3-4$ values of ξ, we simulated axion-decay emission in from 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 (Fig. 3). We recovered the correct value of ξ to a precision of 10% whenever ξ exceeded its upper limit. **Thus, our sky-subtraction technique and our limits are robust**. **References:** Grin, D. et al. (2006), "A Telescope Search for Decaying Relic Axions," submitted to Phys. Rev. D, astro-ph/0611502– 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. (2007), in prep– 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)–Guidice, G.F. et al. (2001), Phys. Rev. D, hep-ph/0005123.

B) Immediate Objective: We propose 16.5 hrs of deep observations of RDCS 1252, the most distant known lensing-cluster ($z = 1.237$), to search for emission from decaying axions in the mass window 8.3 eV $-$ 13.9 eV. **The proposed time, spread over 3 pointings, will allow us to detect a faint emission line and to properly subtract sky, a critical step for our search.** The high redshift of this cluster extends the range of observable two-photon couplings of the axion by a factor of 100, a significant improvement (e.g. Fig.1). 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 to ξ. The axion-decay line has FWHM of $35-60$ Å, resolvable 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 $8-10$m 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 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, **VIMOS(IFU) is the only instrument choice to observe the decays of axions within our target mass range in galaxy clusters**, and obtain a clean separation between sky background and any signal.

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 have considerable experience analyzing VIMOS data. We will use VIPGI with no sky-subtraction (VIPGI subtraction would wipe out a diffuse signal). Our code then corrects for variable fiber efficiency, masks out fibers falling on known sources, and subtracts sky, generating a 1D-spectrum by optimally averaging over the IFU (Grin et al. 2006). We will begin using public weak lensing maps. The observation proposed will yield redshifts for the central blue lensed galaxies, and combining these measurements with deep archival Hubble images, we will make strong-lensing measurements to construct a reliable mass map as we did recently for Abell 1689 (Limousin et al. 2007), Richard et al. (2007), Swinbank et al. (2007). **The resulting improvement in lensing models of RDCS 1252 will be an important science windfall.**

8. Attachments (Figures)

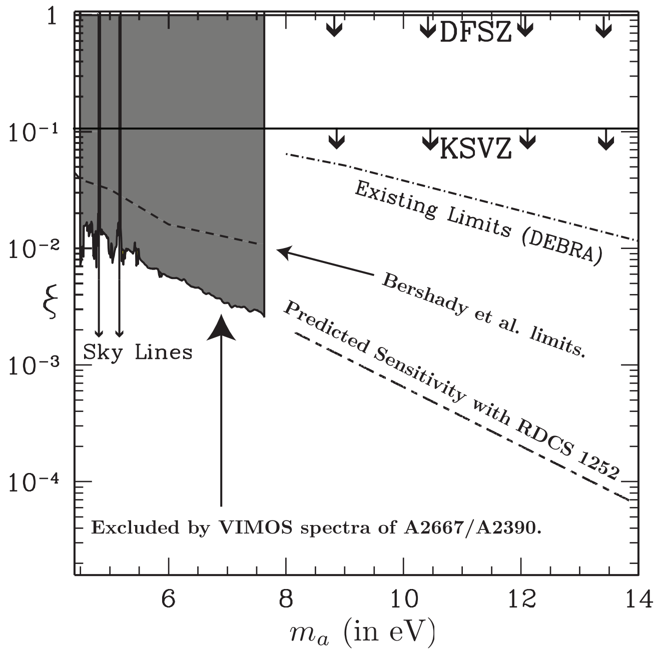

Fig. 1: Comparison of existing limits on the two-photon coupling of a 4.5 eV − 14 eV axion with the projected sensitivity of our proposed observations, adapted from Grin et al. (2006). Grey shaded area indicates the region of parameter space excluded by Grin et al. (2006). The region above the short-dashed 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 short-long 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 dot-dashed line), which come from limits on the intensity of the Diffuse Extragalactic Backround Radiation (DEBRA), also appropriately rescaled (Ressell 1991).

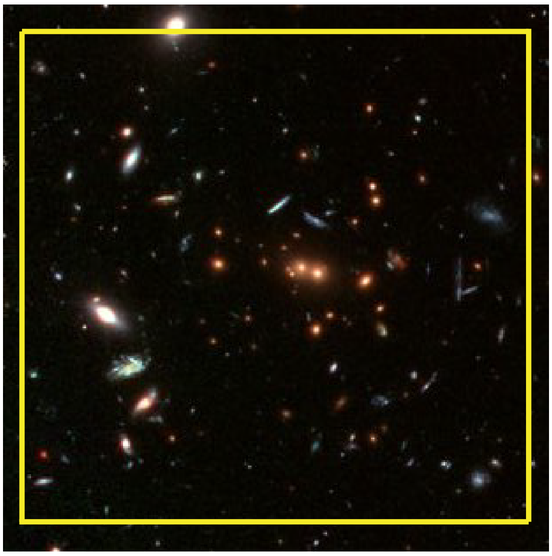

Fig. 2: HST/ACS combined I+Z band image of the massive galaxy cluster RDCS 1252.9-2927 (z = 1.237) with an overlaid outline of the VIMOS/IFU f.o.v. (i.e. about 54 ×54 arcsec^2). Strongly distorted blue galaxies are clearly detected in the cluster core. Some of them are likely to be $z > 2$ strongly lensed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

8. Attachments (Figures)

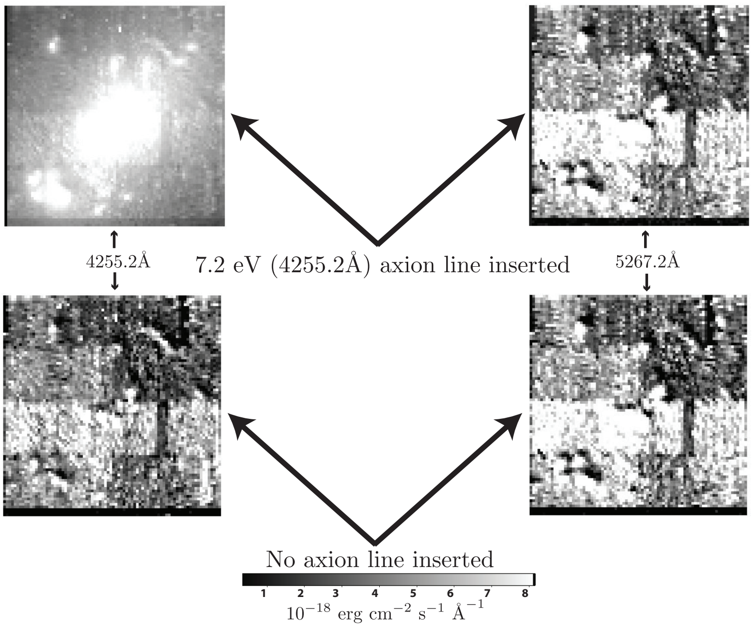

Fig. 3: The left panel of this figure shows a simulated slice of the A2667 IFU data cube at 4255.2Å, with an axion-decay emission-line inserted ($m_{\mathrm{a,eV}} = 7.2$, $\xi = 0.011$). This slice, which lies at the expected line centroid, shows evidence of the inserted axion line. The resulting 'emission' 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. 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 $m_{\mathrm{a,eV}} = 7.2$. Failure to observe such a signal rules out the stated values of the axion mass and two-photon coupling.

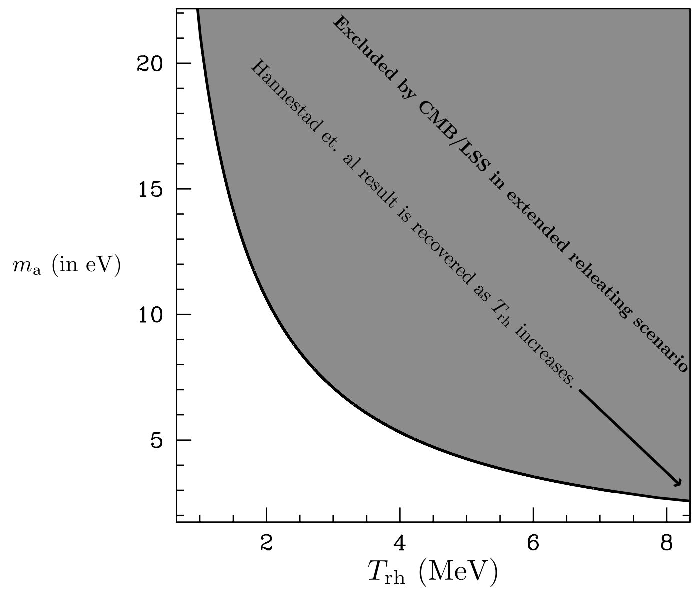

Fig. 4: We show the upper limit to the axion mass from CMB/LSS observations as a function of the reheating temperature in cold reheating models (Giudice et al. 2001). As can be seen, low reheating temperatures relax the upper limit to the axion mass from these considerations; our calculations reproduce publish limits as T_{rh} is increased. This figure shows that cosmological limits to the axion mass may be considerably relaxed. This figure relies on an approximate solution to the Boltzmann equation; a full numerical analysis (Grin et al. 2007) may yield a broader open window.

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 − 60Å) 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 $\mathrm{s}^{-1}\mathrm{\AA}^{-1}\mathrm{cm}^{-2}$ from two-photon decays of axions. In past work, we attained the best sensitivity to axion decay with data from A2390, which consisted of 3 offset pointings, allowing us to cover both low and high-density regions of the cluster. We aim for three nearly non-overlapping pointings on RDCS 1252, aiming for a similar sky-subtraction and sensitivity to a faint signal. With 16.5 hours of total observation (5.5 hours per pointing), we will improve the signal-to-noise ratio of a potential axion decay line detection by a factor of 1.4 over past work. 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* $8.3 < m_{\mathrm{a,eV}} < 13.9$. **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 ~ 5.5 hr pointing, the spectrum of a $z = 2.5$, V=24 star-burst galaxy will have S/N ~ 8 (this is conservative, estimated using the continuum, over 1 wavelength pixel). 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. Each 40 minutes of observing time requires 20 minutes of overhead, and so we ask for a total of 25 hours of time.

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

Grin, D. et al. (2006), "A Telescope Search for Decaying Relic Axions," submitted to Phys. Rev. D, astro-ph/0611502.

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., in prep.

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).

Swinbank, A. M., Bower, R. G., Smith, G. P., Smail, I., Kneib, J.-P., Ellis, R. S., Stark, D. P., Bunker, A. J., MNRAS **368**, 1631 (2006).

Bardeau, S., Soucail, G., Kneib, J.-P., Czoske, O., Ebeling, H., Hudelot, P., Smail, I., Smith, G. P., submited to A&A, astro-ph/0703395.

Schaerer, D., Hempel, A., Egami, E., Pello, R., Richard, J., Le Borgne, J. F., Kneib, J.-P., Wise, M., Boone, F., accepted by A&A, astro-ph/0703387.

Richard, J., Kneib, J.-P., Jullo, E., Covone, G., Limousin, M., Ellis, R. S., Stark, D., Bundy, K., Czoske, O., Ebeling, H., Soucail, G, accepted by ApJ, astro-ph/0702705.

Massey, R., et al., Nature 445 (2007), astro-ph/0701594.

Swinbank, A. M., Bower, R. G., Smith, G. P., WIlman, R. J, Smail, I., Ellis, R. S., Morris, S. L., Kneib, J.-P., accepted by MNRAS , astro-ph/0701221.

Limousin, M., et al., astro-ph/0612165. Smail, I., Swinbank, A. M., Richard, J., Ebeling, H., Kneib, J.-P., Edge, A. C., Stark, D., Ellis, R. S., Dye, S., Smith, G. P., Mullis, C., ApJ **654** L33-L36, astro-ph/0611486.

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 hrs of useless VIMOS/IFU observations in LR-Red (LR-R) on this cluster, plagued by wind, poor seeing, thin clouds; we require LR-B. There are two high-z clusters in the VIMOS/IFU archive. RCS0224 (z=0.77) has been observed with the LR-R and MR-Orange grisms. LR-R yields an axion mass window of 4.80-7.44eV, almost entirely overlapping with our own and thus useless for new axion science. MR-O yields an axion mass range of 4.3-9.0 eV, and thus almost no new information. MR-O reduces the area covered to $\sim$ 30"X30", making it impossible to apply a robust sky-subtraction and expose a faint line. ClG J1216 (z=0.80) has been observed in LR-R/LR-B. LR-R is useless for new axion science; the LR-B data consist of a single pointing on cluster core, making a good sky-subtraction impossible. The axion mass window heavily overlaps with a range we've already probed. Higher-z yields leverage on a much larger mass window.

13. Scheduling requirements

14. Instrument configuration

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