Galaxy Cluster Archaeology[1]

With the discovery of an X-ray luminous cluster of galaxies at $z = 1.4$ we have extended the horizon for studies of well-evolved galaxy clusters to a look-back time of 9 Gyrs. This record-breaking cluster was detected as an extended X-ray source in an archival XMM-Newton observation during the pilot study phase of a search for distant clusters. This result, combined with additional newly-identified candidates from our programme, demonstrates the potential of the XMM-Newton archive to provide a substantial sample of very distant clusters for detailed cosmic evolution studies.

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It is a unique feature of astronomy among all natural sciences that it provides us with a look into the past, thanks to the long light travel times involved in covering cosmic distances. Thus our fundamental curiosity for the origin of things that make up our world today can be satisfied in the "archaeology of astronomy" by direct observations of distant objects. Galaxy clusters as the largest, well-characterized objects play a special role in this study of cosmic origins. Firstly, they form an integral part of the large-scale matter distribution in the Universe, which on cluster scales ($\geq 10\ h_{70}^{-1}$ Mpc) is determined by the dynamics and geometry of the Universe, the growth of structures by gravitational instabilities, and the seeds of density fluctuations set during an early, probably inflationary epoch. The statistics of the galaxy cluster population is therefore a sensitive measure of the cosmological parameters, the nature of the Dark Matter, and the imprint of first structures from inflation (e.g. Borgani & Guzzo 2001). That is, galaxy clusters are important probes to test cosmological models.

Secondly, they form ideal cosmological laboratories for the study of a representative part of the Universe including coeval galaxy populations and an intergalactic medium, easily studied in X-rays. Much progress has already been made with the study of the present-day and intermediate-redshift galaxy cluster population. Just to mention three of the important lessons learned: The abundance and the spatial distribution of galaxy clusters clearly show that we live in a low-density Universe with a density parameter, $\Omega_m \sim 0.3$–0.4 (e.g. Schuecker et al. 2003). Most of the early-type galaxy population of the clusters we observe today has been in place already at redshift 1 and mostly experienced passive galaxy evolution since then (e.g. Holden et al. 2005). Galaxies make up only a minor fraction of the baryonic matter in the clusters and by implication in the Universe as a whole (e.g. White et al. 1993).

Galaxy clusters are late comers to the Universe, as expected in the well-established hierarchical structure formation scenario, in which smaller objects form first and larger mass aggregates are assembled subsequently. Within our well-supported cosmological framework we expect that massive clusters already exist out at redshifts above $z \sim 2$, and poor clusters and groups of galaxies should still be around at redshifts of 3. So far we have only explored the redshift range up to $z \sim 1$ and only few clusters are known at larger distances. Thus a largely uncharted and very promising territory still lies ahead of us.

What we now need is a method to efficiently detect and clearly characterize distant galaxy clusters including information on their mass and dynamical state. X-ray observations are found to provide by far the best tool for such studies: (i) since X-ray luminosity is tightly correlated to the gravitational mass (Reiprich & Böhringer 2002), (ii) because bright X-ray emission is only observed when the cluster is well evolved showing a very deep gravitational potential well, (iii) because the X-ray emission is highly peaked and thus projection effects are minimized, and (iv) since massive clusters are still well observed at high redshifts (while the individual galaxies disappear more and more into the dense galaxy background with increasing distance, the collective X-ray light of the whole cluster still stands out). The power of X-ray observations is revealed by comparison to pure optical searches. With X-ray observations one selects preferentially well-collapsed and nearly-relaxed structures resembling the dark matter halos modeled by theoreticians, while optical searches also pick looser structures. When for example the distant $z \sim 1$ clusters found in the Red Sequence Survey conducted by Mike Gladders, Howard Yee and colleagues (Gladders & Yee 2000, 2004) are followed-up with *Chandra* X-ray observations, they find less X-ray luminous clusters than they expected for the observed optical richness (Hicks et al. 2004).

The largest success in finding distant evolved galaxy clusters has so far been achieved with the *ROSAT* Deep Cluster Survey (RDCS) led by Piero Rosati which provided four well-evolved galaxy clusters with redshifts above $z > 1$ (Rosati et al. 2002). This survey was based on the search for galaxy clusters as extended X-ray sources in archival *ROSAT* pointed observations. Now a much more powerful archive of X-ray observations collected with ESA's *XMM-Newton* observatory is at our disposal. *XMM-Newton* provides more than an order of magnitude more photon-collecting power, has a wider X-ray energy window and images the objects with three times better angular resolution than the *ROSAT* PSPC detector used for the RDCS.

With the above goals in mind we have started a pilot study to explore the prospects of an *XMM*-based survey. We now have the very first results which already provide a breakthrough discovery of the most distant, yet well-evolved X-ray-luminous cluster at $z = 1.393$ (ESO press release 04/2005; Mullis et al. 2005). Encouraged by this success and the proof of our concept, we are embarking on a comprehensive search project. Here we

[1] Based on observations with *XMM-Newton*, an ESA science mission with instruments and contributions directly funded by ESA member states and NASA, together with extensive follow-up observations with the ESO VLT.

report on our survey strategy and on the discovery of the most distant evolved galaxy cluster.

Survey Strategy

Our search for distant galaxy clusters starts with X-ray observations from the *XMM-Newton* data archive, from where we select the best fields with clean exposure times above 10 ksec, outside the band of the Milky Way and the Magellanic Clouds, and without large-scale X-ray sources which blind the field of view. Essentially all extended X-ray sources at high galactic latitudes ($|b_{II}| \geq 20$ deg) are galaxy clusters. Therefore we apply a source detection algorithm that screens the data for extended sources. With *XMM-Newton's* angular resolution (~ 8 arcsec half-power radius, ~ 64–68 h_{70}^{-1} kpc at $z = 1.0$–1.5) we are still able to well separate distant clusters from X-ray point sources given enough X-ray signal. Figure 1 shows for example the X-ray source detection for the discovered distant cluster in the field of the *XMM-Newton* observation of the Seyfert galaxy NGC 7314. Extensive tests have shown that typically 80 source photons are enough to establish a source extent which brings us to a median survey flux limit of ~ 10^{-14} erg s^{-1} cm^{-2}, about a factor of three deeper than the typical flux limit of the deepest *ROSAT*-based searches. For these flux limits we expect about 1 cluster with $z \geq 1$ and about 2.5 clusters with $z \geq 0.8$ per deg^2 (Figure 9).

The next step is a careful screening of the extended sources to look for nearby cluster counterparts in the public Digitized Sky Survey (DSS) images, data from the ESO and other public archives, and information in the literature and public data bases for previous identifications. We want to clearly focus this project on distant clusters. Figure 2 illustrates that clusters up to redshifts of 0.5 can be recognized as counterparts of X-ray sources in the second-epoch DSS images. This allows us a very efficient removal of the nearby clusters from our candidate list. More distant clusters will show blank fields in observations at these depths and they enter our candidate list for the first optical follow-up observations.

As the most efficient way to proceed, we decided to make use of the very high red-sensitivity of FORS-2 at the ESO-VLT to take snapshot images of these candidates in the R (16–19 min) and in the z (8 min) bands which not only allows us to detect distant cluster galaxies out to redshifts of at least $z = 1.4$ but also to get a photometric redshift estimate (Gladders & Yee 2000). The R&z filter combination traces the cluster distances very effectively because its brackets the 4 000 Å break in the relevant redshift regime. With the given flux limit of our survey we hardly expect to find clusters above redshifts of $z \sim 1.5$ (Figure 9). Therefore the sensitivity limit of FORS2 R and z band imaging in detecting high z cluster galaxies is well matched to our survey. Results of the red-sequence cluster detection and redshift estimate are shown in Figures 3 and 4 and will be illustrated further in the next section. With an overhead of an estimated 4–6 red sequence snapshot observations to find one $z \sim 1$ cluster candidate and a total "snap shot observing time" (including overheads) of 30 min, we arrive at an economic way of establishing good candidates of redshift $z > 0.8$ clusters, so as to be as complete as possible for our $z \geq 1$ survey.

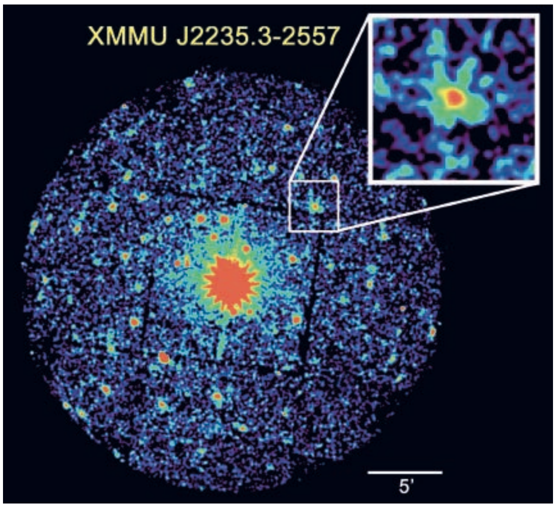


Figure 1: *XMM-Newton* image targeting NGC 7314 in which the distant cluster XMMU J2235.3-2557 (2.8′ × 2.8′ inset) was newly discovered as an extended X-ray source.

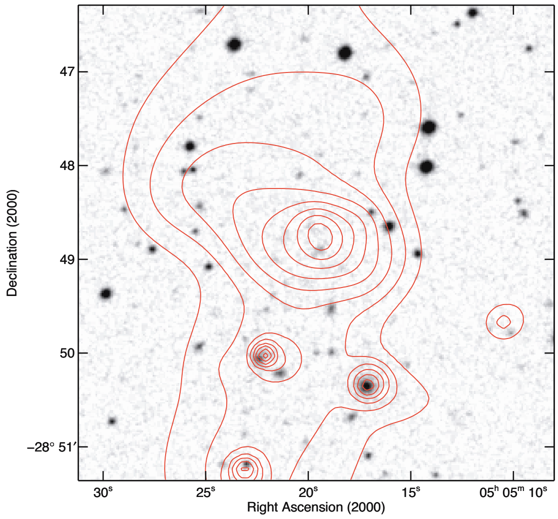


Figure 2: Example of a cluster candidate flagged by our analysis of archival *XMM-Newton* observations. X-ray contours (0.5–2 keV) are overlaid on a DSS optical image. The previously known cluster ($z = 0.509$) is clearly detected on this image.

The distant cluster XMMU J2235.3-2557

The detection technique with which XMMU J2235.3-2557 was selected as a distant cluster candidate is illustrated in Figure 3. The red-sequence colour, $R - z = 2.1$, gives a redshift estimate of $z \sim 1.4$. Thus far only this best distant cluster candidate from the 9 deg^2 pilot study was observed spectroscopically. It has proven to be well selected and turns out to be by far the most distant X-ray cluster observed so far with a redshift of $z = 1.393$ established by 12 concordant galaxy redshifts (Figures 5 and 6; Mullis et al. 2005)[2]. In the *XMM-Newton* observation ~ 280 source photons were recorded which allows for a good flux measurement, a rough X-ray image of the cluster (Figure 5) and a rough X-ray spectrum. The fairly compact, centrally peaked X-ray morphology, the high X-ray luminosity of $L_X = (3.0 \pm 0.2)\ 10^{44}\ h_{70}^{-2}$ erg s^{-1} in the 0.5 to 2 keV band, and the temperature estimate of $T_X \sim 6_{-1.8}^{+2.5}$ keV mark XMMU J2235.3-2557 as a well-collapsed, massive cluster of galaxies whose mass is probably around $3\ 10^{14}\ h_{70}^{-1}\ M_\odot$ (Mullis et al. 2005). With these properties the cluster falls close to the L_X-T_X relation established for other high redshift clusters (Rosati et al. 2002). The velocity dispersion of the cluster indicated by the 12 redshifts, $\sigma_g = 762 \pm 265$ km s^{-1}, is also consistent with other global parameters. Another sign that the cluster is a well-settled object,

2 The discovery of even more distant clusters has repeatedly been reported (e.g. Ouchi et al. 2005). These structures are not expected and have not been shown to be collapsed, nearly virialized objects as the galaxy clusters observed in X-rays to which we refer. Therefore they are most likely protoclusters, loose structures that are bound to collapse at intermediate redshifts and form the clusters that we observe today.

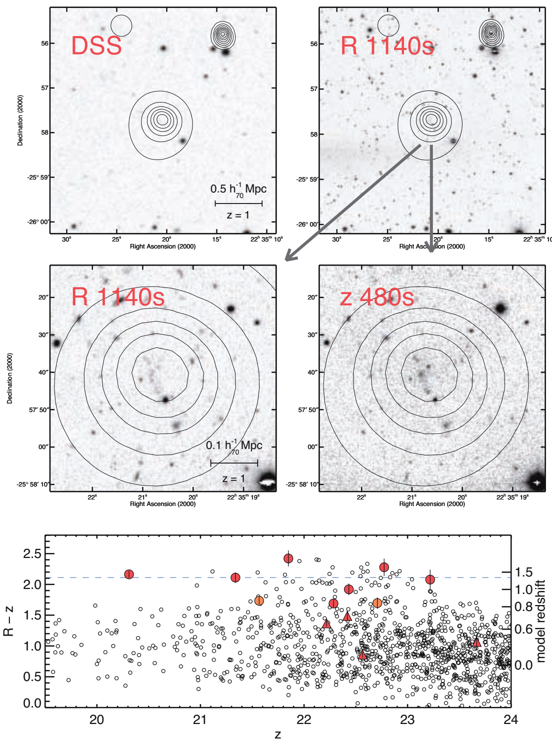
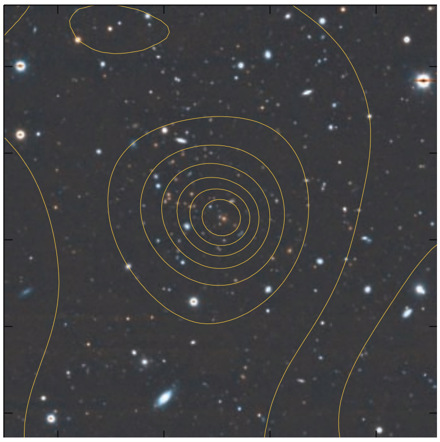


Figure 3 (left): Red-sequence detection technique applied to the cluster XMMU J2235.3-2557 at $z = 1.39$. **Top:** X-ray flux contours overlaid on the DSS and FORS2 R (1140s) and z (480s) band images. The distant cluster is clearly extended in X-rays and lacks an optical counterpart in the DSS image. **Bottom:** Colour-magnitude diagram of the 7′ × 7′ cluster centered field (AB magnitudes). Spectroscopically confirmed cluster galaxies at $1.38 < z < 1.40$ are marked in red and $1.37 < z < 1.38$ in orange. The location of the cluster red sequence calibrated by reasonable galaxy evolution models indicates a cluster redshift significantly beyond $z = 1$.

is a central dominant galaxy very close to the X-ray maximum (offset 3.7″, 31h_{70}^{-1} kpc) which marks presumably the gravitational centre of the cluster.

We also secured observations of this cluster with VLT-ISAAC in the K_s-band (3600 sec) through director's discretionary observing time in December 2004. A composite colour image of the cluster is shown in Figure 7 (see next page). Overall the galaxies identified as spectroscopic cluster members show very red colours, implying that these galaxies are observed to be already old even at these large look-back times. Assuming that the cluster galaxies form at a redshift of 3 and then evolve passively to the observed redshift (e.g. Daddi et al. 2000) approximately explains the observed colour distribution (Rosati et al., in preparation).

With its high redshift, this cluster provides a look-back time of 9 Gyrs, 0.5 Gyrs more than with the previously most distant cluster RDCS 1252-29 ($z = 1.24$). Figure 8 (see next page) illustrates the increasing horizon in our X-ray galaxy cluster studies. It is remarkable that at these redshifts we still observe a cluster galaxy population that is well aged and shows a pronounced red sequence in the colour-magnitude diagram. It allows us to characterize galaxy populations for the first time in high-density environments at the largest look-back times accessible to date. There are more, urgent questions we want to address with a laboratory at this large look-back time, such as: do we still find a lot of Fe in the intracluster medium as observed in X-rays in more nearby clusters? Are clusters more compact with increasing redshifts as predicted by structure-formation models? We are confident, that deep observations with *VLT ISAAC*, *SPITZER*, *HST*, *Chandra*, and *XMM-Newton*, that we have proposed, will bring us much closer to answering these questions.



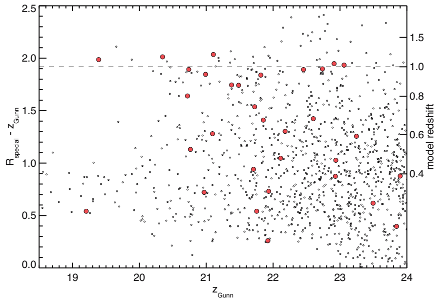


Figure 4: **Left:** X-ray flux contours overlaid on a FORS2 R+z band colour image of one of the distant cluster candiates (5′ × 5′ FOV). **Right:** Colour-magnitude diagram for the same cluster. Objects within 30″ of the X-ray centroid are highlighted in red. The red sequence indicates a redshift of $z \sim 1$ (horizontal line).

Prospects for a Comprehensive Survey

Any general conclusions on cosmic evolution from observations of distant clusters cannot be based on a single cluster, but have to be drawn from a statistical analysis of the evolution of the whole galaxy cluster population. Therefore it is important to obtain a sizable, statistically defined sample of objects in the high-redshift range. Because clusters are rare objects in the Universe, large search volumes are required. To conduct a large enough dedicated survey with expensive, medium-field-of-view X-ray space observatories like *XMM-Newton* (FoV = 26′ × 27′) becomes almost prohibitive. Therefore the search for distant clusters becomes a typical application of the data accumulating in the *XMM-Newton* archive, which provides a total survey area unrivaled by any dedicated project.[3]

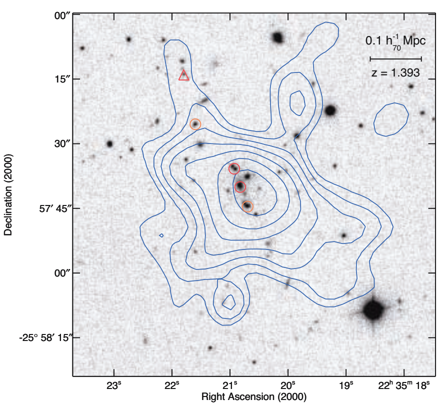


Figure 5: VLT ISAAC *K*-band image of XMMU J2235.3-2557 overlaid with X-ray contours (0.5 to 2 keV). Spectroscopically confirmed cluster members at $1.38 < z < 1.40$ are marked in red and $1.37 < z < 1.38$ in orange. Additional spectroscopically confirmed galaxy members lie outside this FOV. (Mullis et al. 2005).

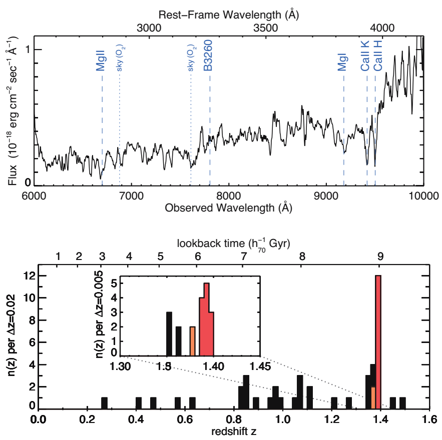


Figure 6: **Top:** FORS2 spectrum of the brightest cluster galaxy with $z = 1.3943 \pm 0.0003$ obtained with 4hr integration. **Bottom:** Histogram of galaxy redshifts measured in the FORS2 MXU observation in a region of 7′ × 7′ around the cluster centre of XMMU J2235.3-2557 (Mullis et al. 2005).

3 The XMM-LSS collaboration led by M. Pierre is conducting a medium-sized XMM-Newton survey for galaxy clusters (e.g. Pierre et al. 2004).

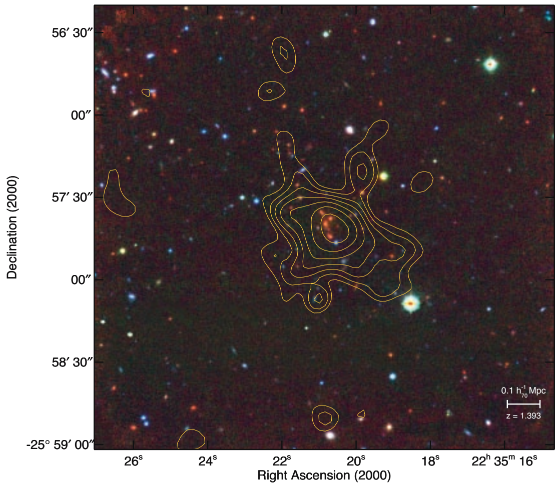


Figure 7 (above): Composite colour image of XMMU J2335.3-2557 overlaid with X-ray contours. The red channel is an ISAAC K_s-band image (3 600s), the green channel a FORS2 z-band image (480s) and the blue channel a FORS2 R-band image (1 140s) (Mullis et al. 2005).

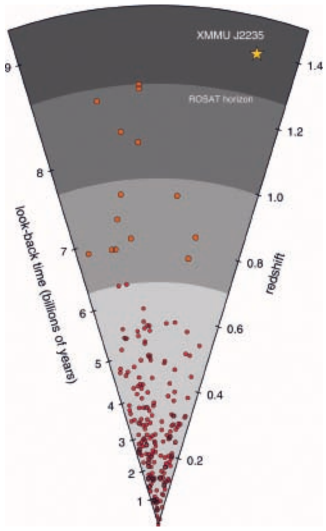
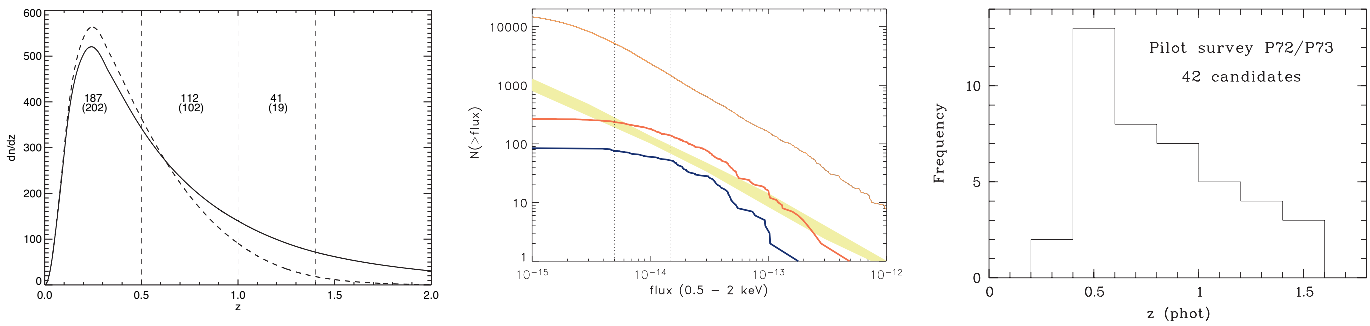


Figure 8 (left): Cone diagram illustrating the reach of ROSAT in the search for distant clusters in comparison to the new window opened by *XMM-Newton*. Redshift is marked on the right and the corresponding cosmic look-back time on the left axis. The ROSAT clusters shown are those from the RDCS and the 160 deg^2 surveys (Rosati et al. 2002, Vikhlinin et al. 1998). The newly discovered cluster at z = 1.4 illuminates a remote regime well beyond the ROSAT horizon.

Figure 9 (below): **Left:** Expectations for the cluster detections as a function of redshift for a 14 deg^2 survey as calculated on the basis of the RDCS and 160 deg^2 surveys (Rosati et al. 2002, Mullis et al. 2004). The solid line gives the expectations for no evolution and the dashed line the more realistic predictions including the estimated evolutionary effects. **Middle:** Number counts as a function of detected flux in the best screened 12 deg^2 survey region: all detected X-ray sources (upper, orange line), all clearly extended sources (middle, red line), distant cluster candidates (lower, blue line). The yellow band indicates the logNlogS curve derived by Rosati et al. (2002) from the RDCS. **Right:** Distribution of the estimated photometric redshifts of the candidates from our pilot study.



Our goal in the present approach is to find at least 50 galaxy clusters at $z \geq 1$. A sample of at least this size is necessary to construct well-defined distribution functions, like the X-ray luminosity function, for comparison with lower redshift samples, to cover a range of X-ray luminosities and morphologies to look for trends in the relation of the galaxy population with cluster mass and dynamical state, and to have a good enough statistical basis to constrain cosmological models (e.g. Haiman et al. 2001). With the statistics shown in Figure 9 this requires a search in a sky area of at least 50 deg^2 and comprises the search in about 500–600 deep *XMM-Newton* exposures (see also Romer et al. 2001). This amount of data already exists in the archive and has been screened by us (Schwope et al. 2004).[4] Figure 9 shows the results from a very careful screening of ~ 25 % of this survey area in the form of a logNlogS number counts diagram. The results show that we have slightly more candidates in the flux regime above 10^{-14} erg s^{-1} cm^{-2} than predicted promising a high completeness of the sample with some room for an unavoidable contamination fraction.

In summary the prospects for this survey look very promising. Even though the project is very ambitious, the expenses are still moderate. We have demonstrated that the VLT-FORS2 instrument can very efficiently be used to detect galaxy clusters out to redshifts of z ~ 1.4 and to obtain a first redshift estimate with short imaging exposures. With this rapid way to select the high z candidates we can clearly focus our project on the most distant clusters. We only include candidates with photometric redshifts of $z \geq 0.8$ to be complete at $z \geq 1$ and thus limit the more expensive spectroscopic observations to a minimum. To achieve the final goal of this project of finding at least 50 $z \geq 1$ clusters we will also make use of observations in the northern sky at other observatories. However, the very efficient detection method described here which builds on the special properties of the VLT-FORS2 instrument, will be unrivaled and the project conducted at the ESO VLT will remain the important core of this project.

4 In the coming three years there should even be enough observations for a survey covering more than 100 deg^2. A similar survey is also possible with *Chandra* but the larger field of view and larger photon collecting power of *XMM-Newton* makes this observatory the prime choice.

References

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