The XMM Large Scale Structure Survey and its Multi-λ Follow-up[1]

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Abstract

We present a unique European project which aims at mapping the matter distribution in the distant universe from hundreds of megaparsecs to galaxy scales. This comprehensive scientific approach constitutes a new step in the synergy between space- and ground-based observatory resources and therefore a building block of the forthcoming Virtual Observatory.

1. The New Generation of Surveys

Over the last two decades there has been tremendous growth in effort to systematically map the matter distribution in the universe. This has been motivated by questions which are fundamental to cosmology. Firstly, how much matter is there; secondly, what form does it take; and thirdly, how is it distributed? The first two questions directly relate to the mean cosmic density, a parameter that governs the eventual fate of the universe. It has been convincingly argued that up to 90% of the existing matter may be invisible, possibly non baryonic, and only detectable through its gravitational effects. At the same time, there is increasing evidence that a significant fraction of the "normal" matter may be hidden in obscured objects as well as in warm diffuse intergalactic clouds.

The third question relates directly to the origin and evolution of the large-scale distribution of matter, and this issue is still open to considerable debate. Although the universe appears homogeneous and isotropic on the largest scales, local surveys of galaxies have revealed the existence of foam-like structure. Galaxies are confined within sheets and filaments surrounding large "voids" with scales of 100 h^{-1} Mpc. Galaxy clusters are usually located at the intersections of these sheets and filaments. In the current standard theoretical paradigm, structure originated in the very early universe and is observed directly at an early time in the cosmic microwave background radiation (CMB). It was subsequently amplified, first by gravity and then by the effects of galaxy formation to produce the presently observed structure. The present-day "cosmic web" is therefore shaped by the details of several key cosmological processes. It depends upon the process which first originated structure, on the nature and amount of dark matter, on the nature of galaxy formation and on the specific values of cosmological parameters. Because of this, observational studies of large-scale structure (LSS) constrain these processes and parameters, complementing observations of the CMB and of constraints from supernovae (SN) on the cosmic expansion rate. Observations of large-scale structure are therefore a key element in our global understanding of the universe.

The most direct way to study LSS is to map the galaxy distribution over a large area of sky and to considerable depth, the strategy adopted by the Sloan, 2dF and VIRMOS surveys. This gives the best possible mapping of structures traced by galaxies, together with strong constraints on models for structure evolution. Unfortunately, it is extremely data-intensive. Moreover, the results depend on both the global cosmological parameters and the details of galaxy formation. Breaking the degeneracy between these two factors is nontrivial. The study of structure using only clusters of galaxies can offer significant advantages both because it is easier to define a complete sample of objects over a very large volume of space and because the objects themselves are in some respects "simpler" to understand (at least in terms of their formation and evolution). Consequently, with currently available observational resources, larger volumes of the universe can be studied to substantially greater depth, and the interpretation of the results is less dependent on models of how galaxies form. *Such studies can independently check cosmological parameter values determined from the CMB and SN studies, can break the degeneracy between the shape of the power spectrum and the matter density, and can check other fundamental assumptions of the standard paradigm (e.g. that the initial fluctuations were gaussian).* Unfortunately, clusters of galaxies become increasingly difficult to identify optically with increasing distance because their contrast against foreground and background galaxies is strongly reduced. This has greatly hampered investigations of high-redshift optically selected clusters.

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[1] http://vela.astro.ulg.ac.be/themes/spatial/xmm/LSS/index_e.html

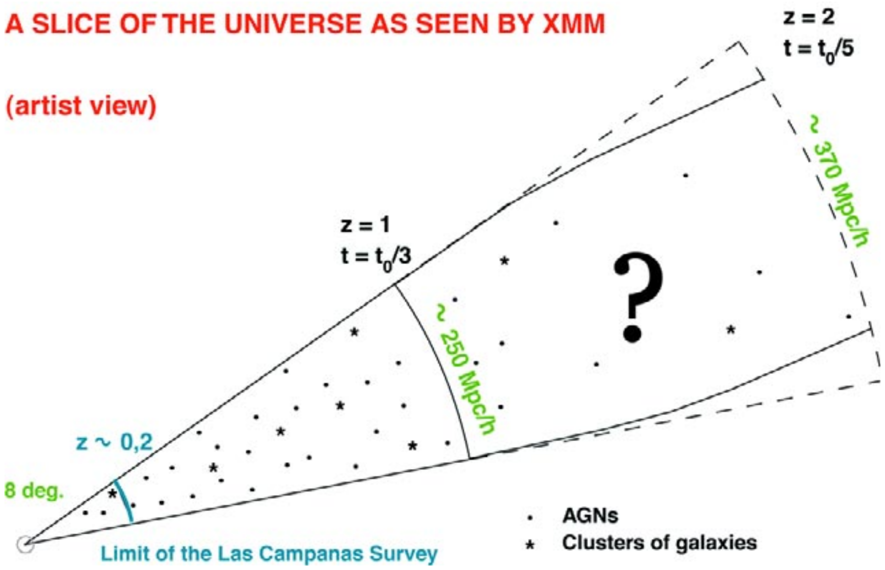

Figure 1: An artist view of the XMM-LSS. Transversaeal distances are in comoving units. QSOs should be discovered out to a redshift of ~ 4. Some 300 sources per square degree are expected, with a density of about 15 clusters per square degree. For the first time, a huge coherent volume of the distant universe will be uniformly sampled.

On the other hand, X-ray observations are well suited for detecting distant clusters: cluster emission is extended and so easily distinguishable from (point-like) QSOs, and confusion and projection effects are negligible. Following on from the REFLEX cluster survey, based on the ROSAT All-Sky-Survey (Guzzo et al. 1999, Böhringer et al. 2001), and taking advantage of the unrivalled sensitivity of the XMM-*Newton* X-ray observatory, we have designed an XMM wide area survey with the aim of tracing the large-scale structure of the universe out to a redshift of z ~ 1–2 as traced by clusters and QSOs: the XMM-LSS Survey (Fig. 1).

The X-ray survey is coupled with an extensive follow-up programme of radio, optical and IR observations. Our approach makes full use of the current range of European and other observational facilities to observe the survey region over the widest possible range of wavelengths. Especially, *extensive and high-quality optical information – imaging and spectroscopy – is crucial for the success of the programme.* As a result, we will be able to identify clusters with unprecedented efficiency and reliability. In addition, our multi-wavelength observations of the XMM-LSS sources (clusters and AGNs) will form the basis of a uniquely comprehensive study of the evolution of the structure of the universe from hundreds of Mpc down to galaxy scales. For the first time, it will be possible to map and study the distributions of hot gas, luminous galaxies, and obscured or dark material in a coherent way. We will compare the results of our observations with the predictions of various cosmological scenarios using extensive numerical simulations generated as part of our programme.

The wide scope of the project has motivated the set-up of a large consortium in order to carry out both the data reduction/management and the scientific analysis of the survey. The XMM-LSS Consortium comprises the following institutes: Saclay (Principal Investigator), Birmingham, Bristol, Copenhagen, Dublin, ESO/Santiago, Leiden, Liège, Marseille (LAM), Milan (AOB), Milan (IFCTR), Munich (MPA), Munich (MPE), Paris (IAP), Santiago (PUC) as well as two US Scientists, S. Snowden (NASA/GSFC) and G. Bryan (MIT). The XMM-LSS team has also a well-defined collaboration with the SWIRE SIRTF Legacy Programme team (PI, C. Lonsdale).

2. The XMM Large-Scale Structure Survey

2.1 The survey design

The survey consists of adjacent 10 ks XMM pointings, separated by 20′. It will ultimately cover a region of 8 × 8 sq. deg. to a mean sensitivity of about 3 10^{-15} erg/s/cm^2 for point sources in the [0.5–2] keV band (with a deeper central 2 sq. deg. area). This makes the XMM-LSS some 1000 times more sensitive than the REFLEX survey and the only wide area X-ray deep survey for the coming decade. There are no prospects for a comparable survey with the forthcoming X-ray missions currently under study such as XEUS or Constellation-X. The XMM-LSS field is located around RA = 2 h 20 m, Dec = –5 deg. Out of the 300 expected sources per square degree, about 15 will be clusters of galaxies, 200 active nuclei, and the rest, nearby galaxies and stars. A histogram of the predicted cluster redshift distribution is shown on Figure 2.

2.2 Basic follow-up

In order to ensure the necessary identification and redshift measurement of the X-ray sources, we have started an extensive multi-wavelength follow-up programme. Optical and NIR imaging has been initiated at CFHT and CTIO and will be continued with the 2nd generation of wide-field imagers such as MegaCam[2] and WFIR (CFHT) and the NIR camera to be installed at UKIRT. The survey field would be an ideal initial target for VISTA (ESO/UK). Subsequent spectroscopic identifications and redshift measurements will mainly be performed by the VLT/VIRMOS instrument at ESO and other 4–8-m-class telescopes to which the consortium has access. The goal is to obtain redshifts for all detected clusters and for a representative selection of the QSO population. The complete survey region is being mapped using the VLA at 74 MHz and 325 MHz.

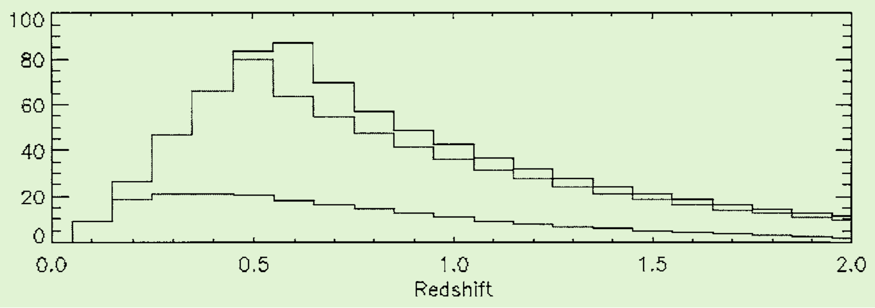

Figure 2: The predicted XMM-LSS cluster redshift distribution, computed using the local cluster luminosity function and properties; redshifted thermal spectra convolved with the XMM response were simulated, source number counts were computed and, finally, these were compared to the survey sensitivity limit. Three detection bands are shown ([2–10], [0.6–8] and [0.4–4] keV, from bottom to top respectively). The [0.4–4] keV band is the most sensitive for clusters, whereas the hardest one is quite inefficient since the majority of the cluster/group population has a temperature of the order of 2–3 keV (rest frame). Up to 800 clusters are expected out to z = 1 and of the order of 100 between 1 < z < 2 (if there is no evolution).

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[2] http://www.cfht.hawaii.edu/Instruments/Imaging/Megacam

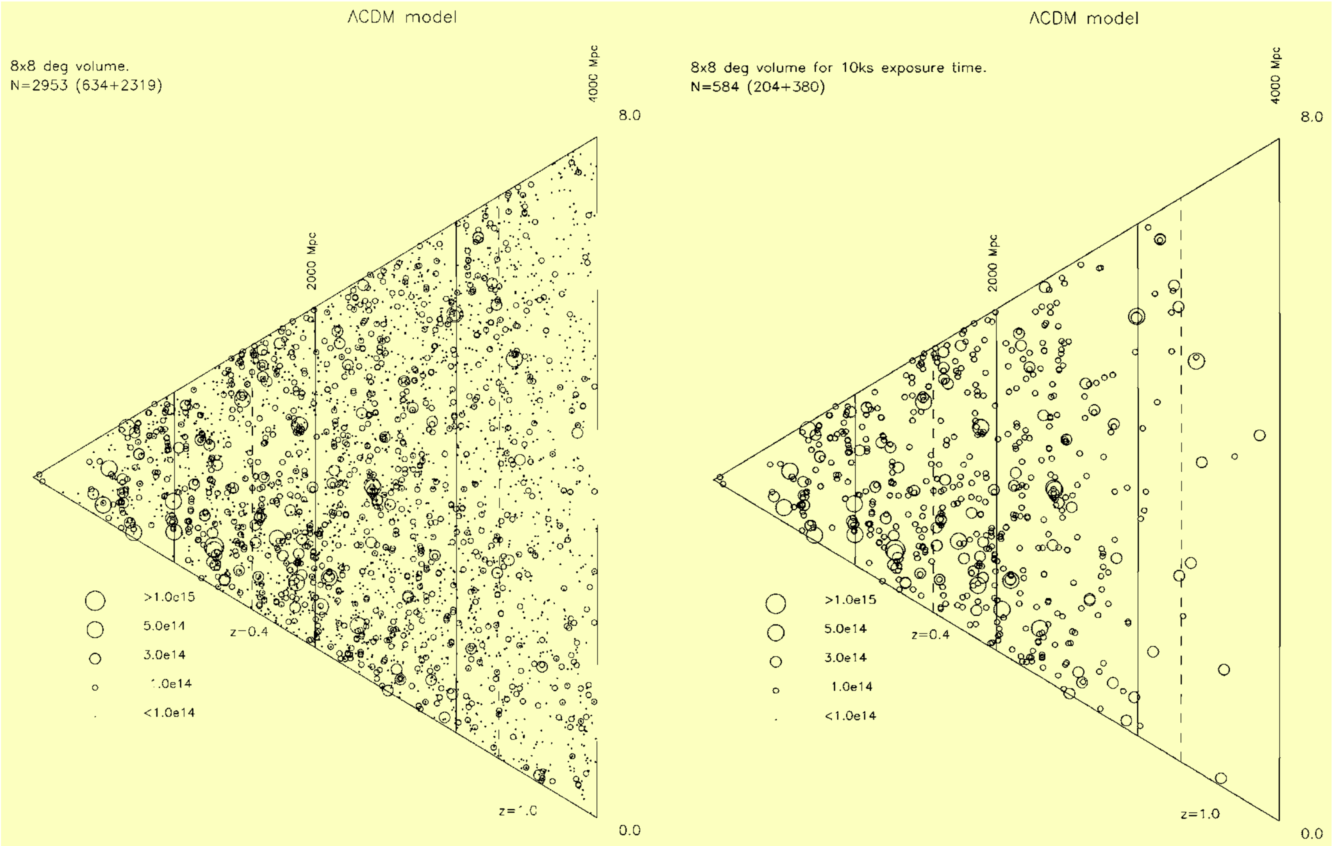

Figure 3: Simulation of the XMM-LSS cone, using the Hubble Volume[3] Lightcone cluster catalogue for a ΛCDM model. Symbol sizes indicate cluster masses. Together with Figure 2, this wedge diagram shows, in a striking manner, how the XMM-LSS will provide the next hierarchical step as compared to traditional galaxy surveys. Points are now galaxy clusters, the size of point indicating the cluster mass which are the carriers of a cosmologically significant parameter: their mass. Predicted numbers of clusters in the 0 < z < 0.5, 0.5 < z < 1 bins are given in brackets. Left: the cluster distribution; cosmic evolution can be appreciated from the decrease of the number density of massive clusters at high redshift. Right convolution by the XMM-LSS selection function: only massive clusters are detectable at high redshift. (Valtchanov et al. 2001, Virgo)

2.3 Data release

A first version – quality certified – of *the multi-λ XMM-LSS catalogue will be released to the international community* no later than one year after the completion of the XMM AO1 observations (2003) and will be subsequently updated on a yearly basis as the X-ray coverage and associated follow-up proceed. The public version of the catalogue will be hosted at Centre de Données de Strasbourg.

3. Expected Science

The survey has been designed to have sufficient depth and angular coverage to enable the determination of the cluster 2-point correlation function in two redshift bins (0 < z < 0.5, 0.5 < z < 1) to an accuracy of better than 15% for the correlation length. In more qualitative terms, we shall obtain a 3D map of the deep potential wells of the universe within an unprecedented volume. Beside these main goals, we can also address several other *key cosmological issues* as well as any question related to *serendipitous science* using our multi-wavelength data set.

– The survey is deep enough to allow a search for massive ($L_{2\text{–}10\ \mathrm{keV}} \sim 3\ 10^{44}$ erg/s) clusters out to a redshift of ~ 2 (Fig. 2). The number density of such systems is of key importance since the cosmological constraints provided by the cluster number density evolution are complementary to those of LSS.

– We shall compute, to a high degree of accuracy, the 2-point correlation function of X-ray QSOs out to z ~ 4.

– The study of the combined X-ray/optical/radio evolution of clusters and QSOs, of their galaxy content and of their environment is another obvious by-product of the XMM-LSS. This is particularly important at redshifts above 1, where galaxy and cluster mergers are expected to be more common and star formation is more pronounced than in the local universe. Indeed, preheating and shocks are thought to influence the ICM properties of forming clusters. Moreover, these effects are redshift dependent since cluster sizes, densities and temperatures are expected to vary as a function of redshift, on a purely gravitational basis. Although there is both theoretical and observational evidence for traces of feedback in the low-redshift cluster population (e.g. David et al. 1993, Metzler et al. 1994), its influence needs to be assessed and quantified at earlier times (Menci & Cavaliere 2000). The radio data provide an important source of complementary information for our understanding of merger processes, as well as probing the magnetic fields and high-energy particles in the clusters which affect the state of the ICM.

– Finally, it will be possible to see how the QSO population fits into the LSS network defined by the cluster/group population. This will directly complement the understanding of AGN in terms of unification schemes. Indeed, these schemes alone do not explain the observed strong QSO clustering, or the fact that BL Lac objects (for example), are preferentially found in clusters or groups (Wurtz et al. 1997). The environmental properties of AGNs, as supplied by our survey are key to understanding their formation. In addition, the XMM-LSS data set will also provide decisive statistical information regarding the effect of gravitational lensing on QSO properties.

3.1 Advanced follow-up

Subsequently to the core programme science, a detailed follow-up will be undertaken for objects that appear espe-

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[3] http://www.physics.lsa.umich.edu/hubble-volume

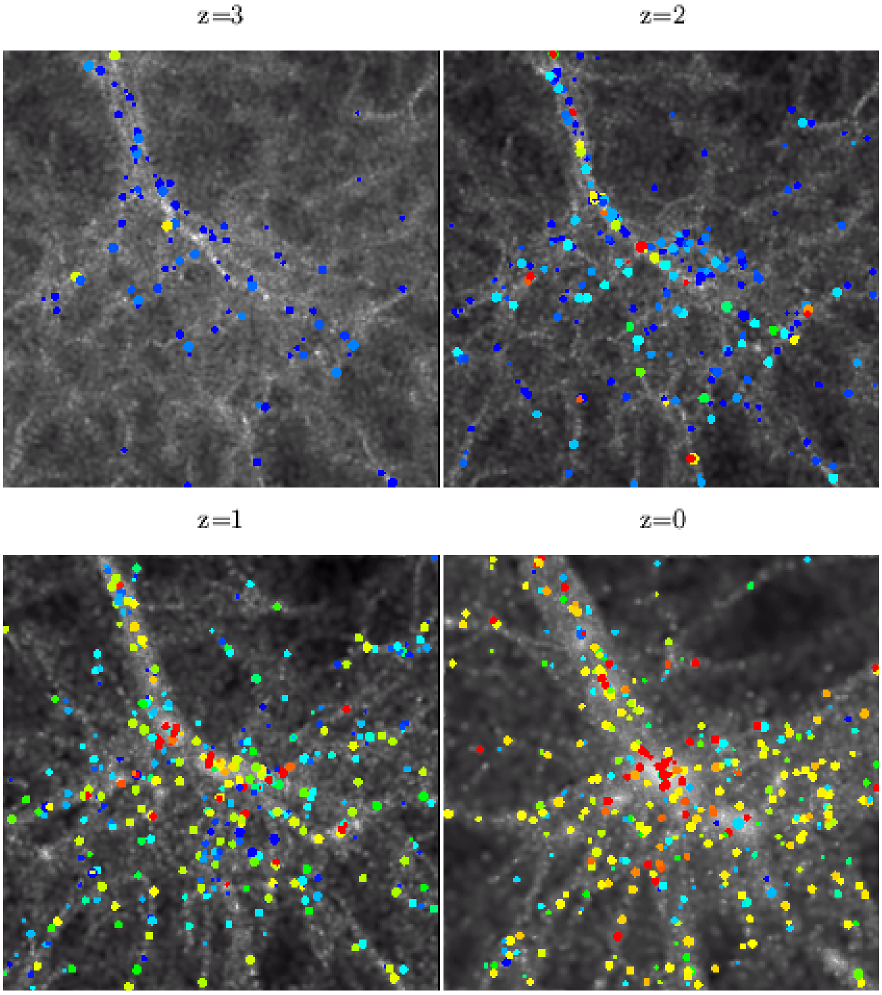

Figure 4: This simulation, performed by the MPA group, nicely illustrates one major goal of the XMM-LSS/SWIRE collaboration: the study of the evolution of structure from large scales (the images here are 40 Mpc across ; the XMM-LSS will encompass scales more than 10 times larger at z = 1) down to individual galaxies. The combined data set will provide the an ideal playground resource to study all kinds of environmental aspects. In these images the dark matter distribution is represented in grey-scale while galaxies are represented by the coloured symbols with symbol size corresponding to stellar mass and symbol colour to specific star-formation rate. The hot gas was not followed explicitly in this simulation but other simulations from MPA and elsewhere show it to follow the dark matter closely, being especially bright (in X-rays) at the filament intersections where galaxy clusters form. The evolution of structure and of the galaxy population from redshift 3 to 0 are clearly visible. This particular simulation assumed a critical density universe (τCDM, $\Omega = 1$, $\Gamma = 0.21$, $\sigma_8 = 0.6$). Evolution is much slower in simulations of low-density universes (Kauffman, Colberg, Diaferio, White 1999).

cially relevant to other cosmological studies.

– For example, deep XMM pointings will be used to study complexes of high-z forming clusters (Pierre et al. 2000).

– Also, the expected high density of QSOs in the survey will allow us to derive a detailed 3D picture of the baryon distribution from high-resolution optical spectroscopy of the Lα forest (e.g. Cen & Ostriker 1999).

– The deep and high-quality optical coverage of the entire 64 square degree area by MegaCam will enable an unprecedented weak-lensing analysis[4]. The cosmological implications of the results will be directly compared to the constraints derived from the XMM-LSS cluster sample.

– Sunyaev-Zel'dovich observations (S-Z) are also planned. Clusters in the XMM-LSS field will be targets of the prototype OCRA (One-Centimetre Radiometer Array) instrument from 2002. The full XMM-LSS field will be mapped by the complete OCRA, and will be an early target of the Array for Microwave Background Anisotropy (AMiBA) after 2004. This will enable a statistical analysis of the physics of the ICM as a function of redshift. In the long term, these observations will also provide invaluable information on the low-density structures such as cluster outskirts and

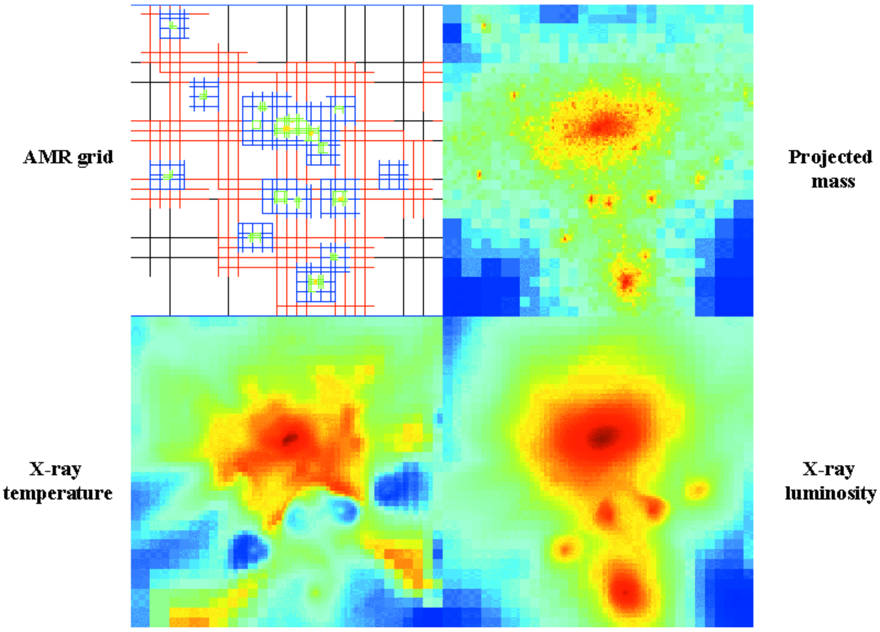

Figure 5: This simulation (12.5 h^{-1} Mpc a side) represents a cluster of galaxies of 7 10^{14} solar masses. It has been performed by RAMSES, an adaptive mesh refinement code recently developed at CEA Saclay and designed to study the formation of large-scale structures in the universe with high spatial resolution. The upper left panel shows the resolution of the simulation grid which automatically follows density contrasts. The upper right panel is the resulting projected mass, which is especially relevant for comparison with weak lensing analyses. The lower panel shows the predicted X-ray properties of the cluster; merging sub-groups have clearly lower temperatures than the central main body. Such simulations are essential to understand the observed global properties of clusters; in particular how physical processes such as cooling or feedback from early star formation, modify the properties of the intracluster medium with respect to what is expected from a pure gravitational evolution. The understanding of these phenomena is necessary to relate the evolution of the observed properties of clusters to cosmology (Teyssier 2001).

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[4] http://terapix.iap.fr/Descart/

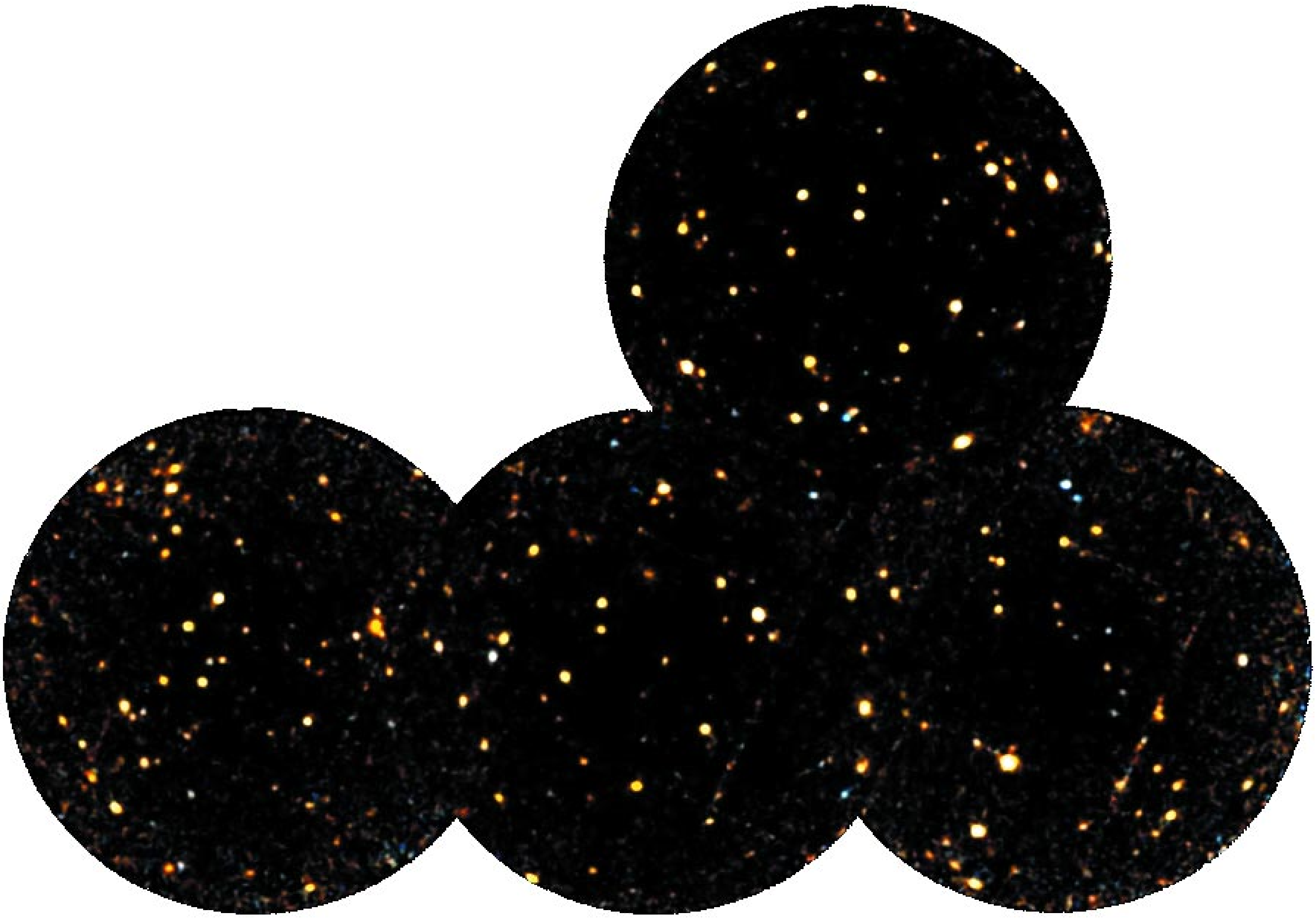

Figure 6: First XMM pointings of the survey obtained during the Guaranteed Time part of the programme owned by the Liège/Milano/Saclay groups. This preliminary mosaic in true X-ray colours is a fraction of the central deeper 2 sq.deg. area; red: soft sources (< 2 keV), blue: hard sources (> 2 keV). The individual images have a diameter of 25 arcmin and the exposure time is 20 ks on each field. The source density is found to be ~ 600 / sq.deg. in the [0.5–2] keV band (Valtchanov et al. 2002, in preparation). [Based on observations obtained with the XMM-Newton observatory, an ESA science mission with instruments and contributions directly funded by ESA Member States and the USA (NASA).]

their connections to the cosmic filaments. These measurements are complementary to the X-ray and weak lensing data regarding the masses of clusters and the structure of the hot gas they contain. The three data sets together should provide an independent and direct check of the extragalactic distance scale.

3.2 Associated SIRTF Legacy Programme

The SIRTF Wide-area InfraRed Extragalactic Survey (SWIRE[5]) will cover 10 sq.deg. of the XMM-LSS in 7 wavebands from 4 to 160 μm. The estimated IR source numbers in this area are around 20000/900/250 and 700/50/500 for starbursts/spiral-irregular/AGN in the $0 < z < 1$ and $1 < z < 2$ redshift intervals, respectively.

The coordinated SWIRE observations will clarify an important aspect of environmental studies: how star formation in cluster galaxies depends on the distance to the cluster centre, on the strength of the gravitational potential, and on the density of the ICM (as inferred from the X-ray data). Galaxy environment and optical spectroscopic properties will be the main parameters in modelling IR activity. Here also, the location of IR AGNs within the cosmic web will help establish their nature. The combined X-ray/FIR observations will also provide invaluable information regarding the existence and properties of highly obscured AGNs. Finally, a comparison of the LSS distribution of matter given by the X-ray (hot matter), IR (obscured matter) and weak lensing (dark matter) analyses will help understand bias mechanisms as a function of environment, scale and cosmic time.

4. Simulations

Our consortium has carried out extensive simulations in order to optimise the scientific outcome of the survey. We illustrate this by three examples focussing on some of the main goals of the XMM-LSS: Figures 3, 4, 5.

5. A Glimpse to of the First Observations

The first XMM observations were performed in July 2001 in excellent conditions. A pre-view is presented on Figure 6.

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[5] http://www.ipac.caltech.edu/SWIRE