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The Wide Field X–ray Telescope

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The Wide Field X-ray Telescope mission (WFXT) is a high resolution, high collecting area and wide field of view X-ray telescope with low background. Its goal is to image at least half of the X-ray sky down to low fluxes and detect several millions of Active Galactic Nuclei and hundred thousands of groups and clusters of galaxies, characterizing the X-ray spectra for a large fraction of them. This result is achieved not only thanks to the large effective area and the large solid angle covered by the planned WFXT surveys, but mostly thanks to the sharp point spread function (~ 5 arcsec Half Energy Width), constant as a function of the off-axis angle. Such a high resolution over a field of view of one square degree, can be obtained with a polynomial X-ray mirror design. The angular resolution is crucial in avoiding source confusion down to fluxes as low as few $\times 10^{-17}$ erg s^{-1} cm^{-2} in the 0.5-2 keV band, and in discriminating point from extended sources. These features open up science cases which are out of reach of any other X-ray mission equipped with mirrors built in the classical Wolter I configuration. Among the many science goals which can be addressed: the thermodynamics of the Intra Cluster Medium and its interactions with star formation and nuclear activity in the cluster galaxies traced up to $z > 1$; the most constraining cosmological tests with clusters of galaxies; the evolution of the large scale structure of the Universe, including AGN clustering evolution and possible detection of protoclusters up to redshift $z \sim 2$; the physics of accretion onto supermassive black holes up to very high redshift ($z \geq 6$); the cosmic star formation history seen in X-ray up to redshift $z \sim 1.5$; the physics of compact sources in the Galaxy. The sensitivity and the spectral quality of the WFXT surveys will bring the X-ray sky to the same level of future wide–area surveys at longer wavelengths, a product which is not delivered by any other existing or planned X–ray mission.

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1. WFXT overview

The Wide Field X-ray Telescope mission is constituted by three co-aligned wide-field X-ray telescopes with a 1 square degree field of view (FOV) and a ~ 5 arcsec angular resolution (HEW, Half Energy Width) constant over the full field of view, and equipped with CCD or CMOS detectors. With more than ten times the collecting area of Chandra and more than ten times Chandra's (ACIS-I) field of view, WFXT will perform sensitive deep surveys in the 0.5-7 keV energy band, that will discover extremely large populations of high redshift AGN, clusters of galaxies, starburst and normal galaxies, and Galactic objects, characterizing the spectra for more than hundred thousands sources. The key ingredient of WFXT is the polynomial perturbation optics design with SiC or glass mirror shells [1].

X-ray mirrors are usually built in the Wolter I (paraboloid-hyperboloid) configuration which provides, in principle, perfect on-axis images. This design exhibits no spherical aberration on-axis but suffers from field curvature, coma and astigmatism, which make the angular resolution to degrade rapidly with increasing off-axis angles. More general mirror designs than Wolter's exist in which the primary and secondary mirror profiles are expanded as a power series. These polynomial solutions are well suited for optimization purposes, which may be used to increase the angular resolution at large off-axis positions, degrading the on-axis performances [4] [3]. This is the mirror design adopted for the WFXT mission.

The constant, high angular resolution over the large FOV, makes WFXT the only X–ray mission in the 0.5-7 keV energy band, able to reach low flux limits (few $\times 10^{-17}$ erg s^{-1} cm^{-2}) without hitting source confusion, apart from Chandra. It is a matter of fact that the classical Wolter I optics would never perform efficiently in survey mode, given the strong degradation of the angular resolution as a function of the off-axis angle. Angular resolution is not only crucial to reach low flux limits, but also to discriminate between pointlike and extended sources.

One of the best way to express the survey efficiency is the *grasp*, which is simply the product of the effective area of the telescope multiplied by the solid angle of the FOV. A comparison of the grasp of different X-ray telescopes is shown in Table 1. Grasp measures the speed with which a survey can cover an area of the sky down to a given flux limit. In these terms, WFXT is already about an order of magnitude more efficient than the X-ray survey mission eRosita [8], as shown in Table 1. In the left panel of Figure 1, we show the flux limit versus the solid angle for past, present and future X-ray surveys. We stress the fact that the WFXT surveys, whose flux limit is plotted separately for point and extended sources, provide a qualitative breakthrough. However, it's not only a matter of size, which means collecting the largest number of photons from the largest solid angle on the sky. Most of the science, indeed, is possible only thanks to the image quality. We have to bear in mind that angular resolution is not only important for source identification, but also for source characterization. The power of WFXT is better shown in the right panel of Figure 1. This plot shows that, irrespective of the grasp, there is a parameter space (namely the covered solid angle - angular resolution plane) where WFXT is standing alone (with the exception of Chandra, which, on the other hand, has a grasp lower by more than two orders of magnitude).

To summarize, the use of polynomial mirrors is crucial in making a quantum leap towards the next generation X-ray survey, otherwise, the X-ray sky will not reach the same quality level of the sky as imaged in other wavebands. Note that even more powerful X-ray telescopes will not

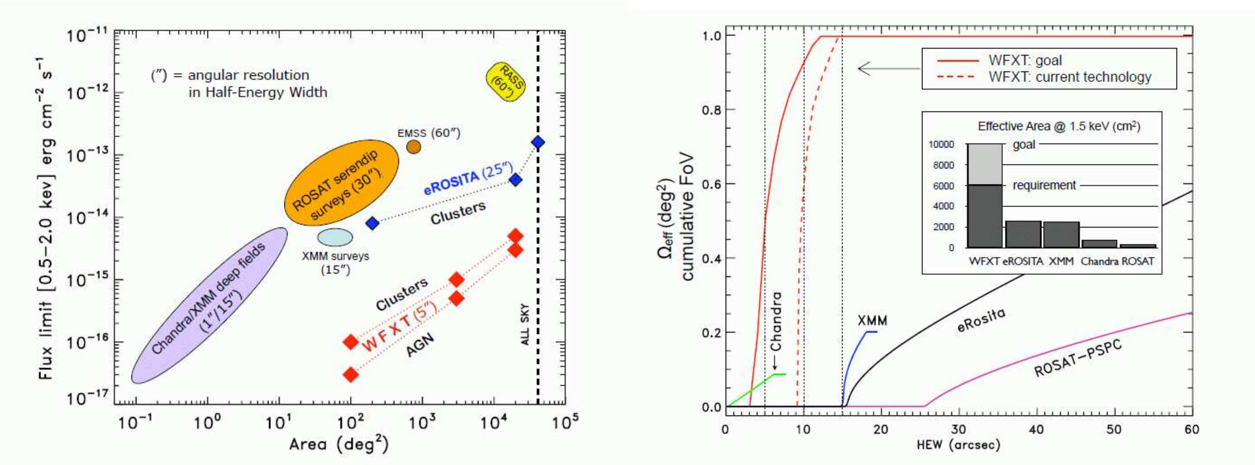


Figure 1: Left panel: flux limit versus solid angle for past, present and future X-ray surveys. Note the quantum leap provided by WFXT thanks to the low flux limits, both for point and extended sources, achieved thanks to the sharp angular resolution. Right panel: cumulative field of view versus angular resolution (HEW) for pointed observations with present, past and future X-ray missions. This plot shows that the superior performances of WFXT are mostly due to the angular resolution.

	WFXT	eROSITA	XMM	ROSAT	IXO	Chandra (ACIS-I)
Grasp	9000	1250	900	630	1500	50
HEW	5	25-30	15-25	25-60	5	1-5

Table 1: Grasp (cm^2 deg^2) and angular resolution (Half Energy Width in arcsec) for WFXT compared to planned and existing X-ray telescopes.

achieve this goal, since they are not designed as survey machines. In the next Sections we will briefly describe the WFXT survey strategy and present some of the science goals which are unique to WFXT.

2. WFXT as a survey machine

In five years of operation, WFXT will carry out three surveys: the first will cover most of the extragalactic sky ($\sim$ 20000 deg^2) at $\sim$ 500 times the sensitivity, and twenty times better angular resolution than the ROSAT All Sky Survey; the second survey will map $\geq$ 3000 deg^2 to deep Chandra or XMM sensitivity; and the third will probe $\geq$ 100 deg^2, or 1000 times the area of the Chandra Deep Fields, to the deepest Chandra sensitivity. The flux limits and the expected number of detected sources are shown in Table 2. From these surveys, WFXT will generate a legacy dataset of $\geq 5\times10^5$ groups and clusters of galaxies, and $> 1.5\times10^7$ AGN, plus ten of thousands of normal Galaxies up to $z > 1$, and many Galactic objects. The main point here is not only the large numbers of sources, but also their spectral characterization. An effective example is given in Figure 2, left panel, where we show the expected number of detected groups and clusters of galaxies (with $kT > 1$ keV) as a function of the recovered number of photons. This plot is obtained

Quantity	Deep	Medium	Wide
Ω (deg^2)	100	3000	20,000
Exposure	400 ksec	13 ksec	2 ksec
Total Time	1.37 yr	1.37 yr	1.72 yr
S_{min}(0.5-2 keV) point-like erg s^{-1} cm^{-2} at 5σ	3×10^{-17}	5×10^{-16}	3×10^{-15}
Total AGN detected	5×10^5	4×10^6	1×10^7
S_{min}(0.5-2 keV) extended erg s^{-1} cm^{-2} at 5σ	1×10^{-16}	1×10^{-15}	$5\times10-15$
Total Clusters/Groups	3×10^4	2×10^5	3×10^5

Table 2: Description of WFXT surveys. Values refer to the present WFXT design parameters, those in parentheses to a conservative requirement of $A_{eff} = 0.6$ m^2 and $HEW = 10$ arcsec. Total observing time assumes 76% efficiency for the Wide survey, and 90-95% efficiency for the Deep and Medium surveys since target areas will be in the continuous viewing zone for these surveys. We maintain a ~ 0.5 year contingency within 5 year science mission.

from the analysis of a simulation of 100 square degree observed with WFXT, and therefore it accounts for all the instrumental effects (including vignetting). We set three conservative limits, shown as vertical dashed lines: the limit for spatially resolved analysis (temperature and metallicity profiles for ~ 10 rings) corresponding to 15000 net detected photons; the limit for measuring temperature, metallicity and redshift, corresponding to 1500 net detected photons; and finally the limit for detection, at 100 photons. Therefore we can appreciate the fact that we will be able to obtain a sample of about 3×10^4 groups and clusters with temperature, redshift (thanks to the ubiquitous K–shell Fe line) and surface brightness profile, for which we can derive reliable mass proxy, and therefore use them for cosmological tests without the need of a massive optical follow up. The expected improvement in the number of known high-z clusters, compared to present X-ray surveys, is shown in the cone diagram in the right panel of Figure 2.

The best way to render the capacity of WFXT to perform surveys, is to show the simulated images of the COSMOS field, as seen by XMM, Chandra, and WFXT. In Figure 3 we show clearly that with one tile of the WFXT medium survey (worth 13.2 ks of exposure time), we reach the same depth of Chandra-Cosmos [5] and XMM-Cosmos [2], obtained with 1.8 Ms and 1.5 Ms respectively. Not only the angular resolution of WFXT is significantly better than that of XMM, allowing a lot of additional science, but it is also comparable to that of the Chandra mosaic. Indeed, the Chandra PSF averaged over the entire COSMOS field, it's slightly less than 4 arcsec, which is very close to the WFXT resolution. In other words, WFXT is almost equivalent to Chandra, if Chandra would be used for surveys, with the difference that, in order to complete the 5 years program of WFXT, Chandra would take about 700 years.

3. Science with WFXT

As we said, thanks to its constant angular resolution, WFXT is not just a source counting

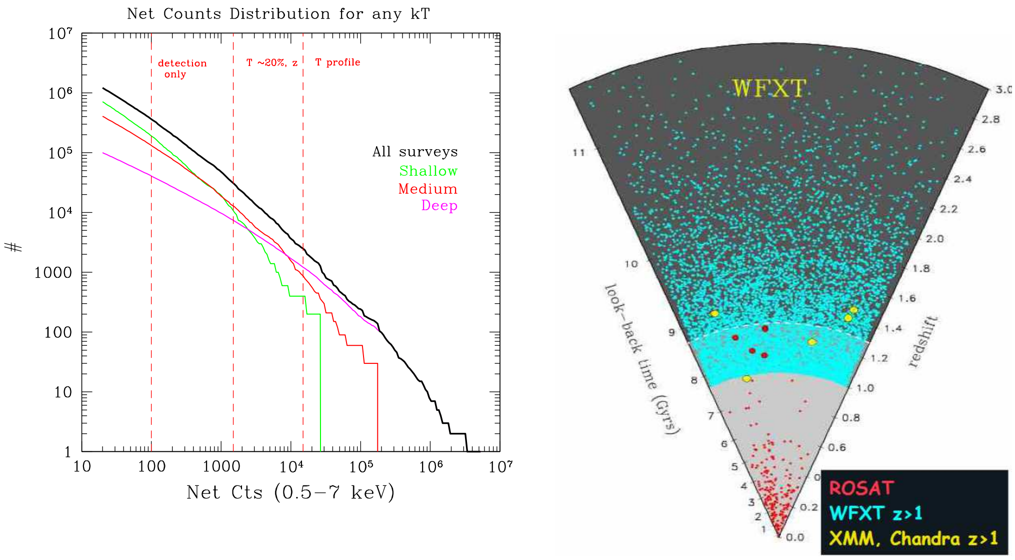


Figure 2: Left panel: the distribution of detected groups and clusters of galaxies ($kT > 1$ keV) as a function of the recovered number of photons (including the effect of vignetting) in each of the three surveys. Vertical dashed lines are conservative limits corresponding to different level of spectral analysis, as explained in the text. Right panel: the redshift distribution of expected WFXT clusters (blue dots) with respect to ROSAT (red dots) and high-z clusters from Chandra and XMM (yellow dots).

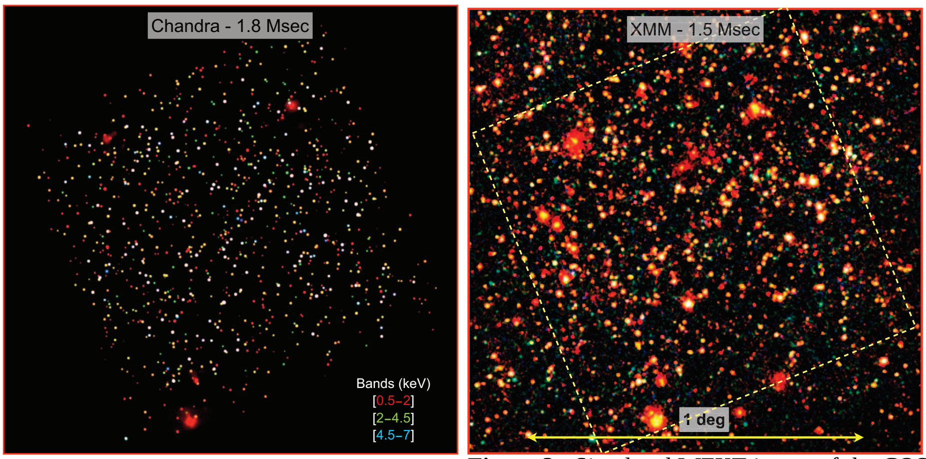
machine, since it is able to characterize a large number of sources, allowing one to address several science cases on the basis of the X-ray data alone.

WFXT science related to the physics of the Intra Cluster Medium (ICM) and the cycle of cosmic baryons is described in [6]. Galaxy clusters mark the only regions where thermo and chemo-dynamical properties of the ICM can be studied in detail up to $z \geq 1$ from X-ray emission. The ICM evolution is directly affected by star formation processes and accretion onto supermassive black holes in the cluster galaxies, as demonstrated by the analysis of nearby X–ray clusters observed by Chandra and XMM in the last ten years. The WFXT contribution to this topic can be synthesized into four main questions:

- When and how entropy is injected into the Inter Galactic medium? Reconstruction the timing and pattern of entropy injection in the ICM has a far reaching implications in tracing the past history of star formation and black hole accretion, and therefore in constraining the “feeback” processes. WFXT will provide a large number of clusters at $z > 0.5$ (more than one thousands clusters observed with 15000 net counts) for which a detailed temperature and metallicity profile can be obtained out to $z \sim 1$.

- What is the history of metal enrichment of the IGM? WFXT will measure the global Fe abundance for ten of thousands of clusters (observed with 1500 net counts) up to $z \sim 1.5$.

- What physical mechanisms determine the presence of cool cores in galaxy clusters? Thanks to the angular resolution, the measure of the concentration parameter (see [10]) for ten of



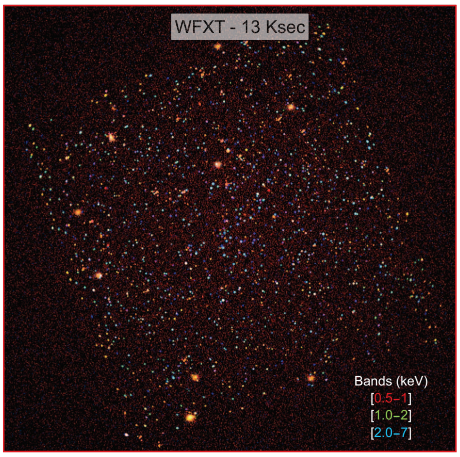


Figure 3: Simulated WFXT image of the COSMOS field observed with Chandra (1 deg^2 [5]) and XMM (~ 2 deg^2 [2]). The flux limit of the three images is similar ($\sim 5 \times 10^{-16}$ erg s^{-1} cm^{-2} in 0.5-2 keV for WFXT and Chandra, somewhat higher for XMM which is confusion limited). However the WFXT image (1 deg^2) is obtained with a single 13 ksec exposure (as part of the Medium survey), with an angular resolution (5 arcsec HEW) closer to Chandra's average (~ 4 arcsec) than XMM ($\gtrsim 15$ arcsec). The WFXT simulation was constructed from the Chandra COSMOS catalog [5]. Bluer sources emit harder X-rays in the 0.5–7 keV band.

thousands of clusters (observed with 1500 net counts) over a broad redshift range will allow one to constrain the cool core evolution and hence the core heating mechanism.

- How is the appearance of proto-clusters related to the peak of star formation activity and black holes accretion? It is only thanks to the angular resolution of WFXT that extended sources at $z \sim 2$, associated to the virialization of the first massive halos, can be detected (with more than 100 net counts), and characterized in the case of deep exposures (400 ks).

In addition to cluster physics, WFXT will explore hundred thousands of groups and small clusters (below 2 keV, a mass range which is largely unexplored). Thanks to the low particle background, due to the low Earth orbit, several important ICM related physics can be explored in the low surface brightness regions in the outskirts of clusters at $z \leq 0.2$. However, one of the most exciting applications will be the robust measurements of Dark Energy parameters, thanks to the quality and the size of the WFXT cluster sample, which allows full control of the systematics. WFXT will also expand the cosmological discovery space, in particular searching for departure from the "concordant" ΛCDM cosmological model, or testing for non GR theories of cosmic acceleretion (see [11]).

WFXT will also play a central role in reconstructing the past history of formation and evolution of supermassive black holes and their effects on the properties of the host galaxies. With an

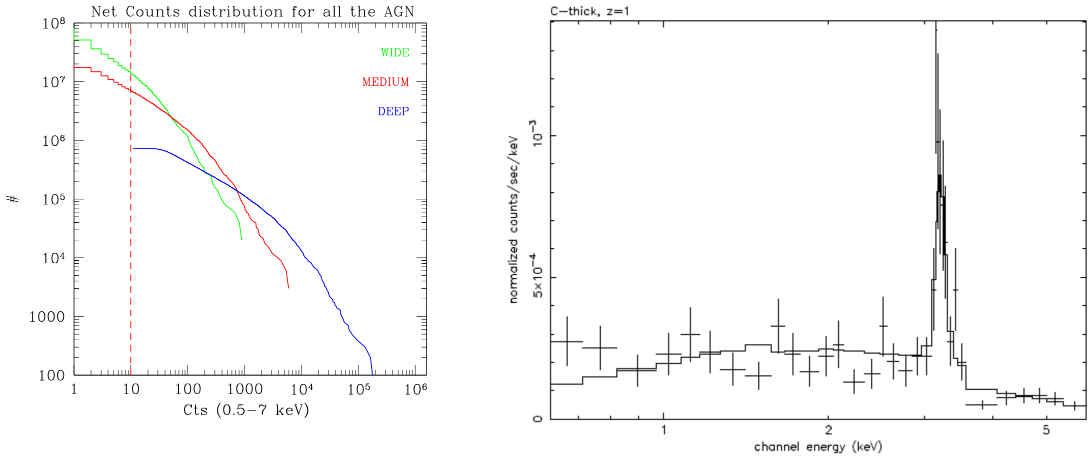


Figure 3: Left panel: number of AGN as a function of the expected net detected photons in the 0.5-7 keV band from the three WFXT surveys. The vertical dashed line mark the reference detection threshold of 10 photons. Right panel: simulated X-ray spectrum of a moderately bright Compton-thick AGN at z = 1 observed with WFXT. About 500 such objects are expected to be observed with WFXT in 5 years. Note the prominent iron K_α line which is both the hallmark of a Compton-thick nucleus and provides the source redshift independently of optical follow-up.

expected sample of more than ten millions of detected AGN (see Figure 3, left panel), we will be able to address the following questions:

- When and how did the first supermassive black holes form? The understanding of the relation between the BH growth and formation of star in galaxies will be highly improved, also thanks to the large number (about 2000) of obscured and unobscured AGN that will be detected at $z > 6$ (see [7]).

- How does the cosmic environment regulate nuclear activity and star formation? Thanks to the large statistics, the WFXT AGN sample will provide measure of the evolution of intrinsic absorption in AGN, of their luminosity function and their clustering, also thanks to the characterization of their spectral properties (we expect at least 3×10^5 AGN whose X-ray spectrum has more than 1500 photons, see an example in Figure 3, right panel). In particular the measure of the prominent Fe line in highly obscured and Compton thick AGN will provide the source redshift independently of optical follow-up.

- What is the history of nuclear activity in a galaxy lifetime? Thanks to repeated passes over the surveyed area, the WFXT mission will provide variability measures for at least 10^5 AGN in a 100 deg^2 survey, down to flux variations of about 20%, and reconstruct the mass accretion rates for thousands of sources.

WFXT will also change our X–ray view of the local Universe. Among the many open questions, WFXT can address the existence of the local bubble, the reconstruction of the recent star formation rate in the solar neighboroud and in molecular clouds, the study of the properties of accreting sources and the ISM in Galactic star forming regions, the Magellanic Clouds and the Local Group galaxies, and the measure of the luminosity function for normal/starburst galaxies (see [9]). In particular WFXT will assemble a sample of about 10^5 normal and starburst galaxies, equally provided by the three surveys. For about 2000 of them, a detailed morphological and spectral analysis will allow one to distinguish the contribution of the ISM, point sources, and AGN. As for Galactic science, WFXT will explore halo stars, the population of Low Mass and High mass X–ray binaries, and SN remnants.

4. Conclusions

The combination of large statistical samples (thanks to the wide solid angle covered), high signal to noise (thanks to the large effective area) and angular resolution (thanks to the polynomial optics design) makes WFXT the most efficient X–ray survey machine. With the data based on the planned WFXT surveys, we will be able to address fundamental questions of how supermassive black holes grow and influence the evolution of the host galaxy and how clusters form and evolve, as well as to perform constraining cosmological tests based on the evolution of the cosmic large scale structure, investigate the properties of star forming and normal galaxies up to high redshift, and study star forming regions in the local Universe with unprecedented sensitivity. All WFXT data will become public through a series of annual Data Releases that will constitute a vast scientific legacy for decades, providing targets for follow-up studies for future X-ray missions, like IXO, large optical telescope like ELT, and longer wavelength facilities like ALMA.

Acknowledgments

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