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Athena: the X-ray observatory to study the hot and energetic Universe

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Abstract. Hot gas pervades the Universe: about half of the baryonic content in the Universe is expected to be at $T > 10^5$ K, and there are as many baryons at $T > 10^7$ trapped in galaxy clusters as there are locked into stars. There is an intimate relation between this hot gas, which delineates the large-scale structure of the Universe, and the most energetic phenomena occurring in the immediate vicinity of super-massive black holes, through a poorly known process called Cosmic Feedback. Studying the hot and energetic universe requires X-ray observatories in space, whose capabilities greatly exceed those of the current workhorse observatories: NASA's *Chandra* and ESA's *XMM-Newton*. *Athena* has been selected by ESA as the L2 mission (due for launch in 2028), to address the “Hot and Energetic Universe” science theme. It will be a large X-ray observatory capable of addressing the above topics, and many other fundamental questions in contemporary astrophysics. Here we present the *Athena* science objectives, the mission concept and its payload, including the X-ray telescope and its two baseline instruments: a Wide Field Imager (WFI) and an X-ray Integral Field Unit (X-IFU).

1. Introduction

ESA's Cosmic Vision 2015-2025 scientific programme will be implemented in terms of a number of missions of different sizes, with L-class missions being the flagships of the programme. Three L-class missions are contemplated. The first one was selected in 2012 and is JUICE, a mission to Jupiter's icy moons due for launch in 2022. For the selection of the L2 and L3 missions, ESA appointed a senior Science Survey Committee (SSC) in 2013 to recommend the scientific themes to be addressed by



those two mission opportunities with nominal launch years of 2028 and 2034, respectively. The SSC reviewed over thirty community White Papers and recommended that L2 should address *The Hot and Energetic Universe* and L3 should address *The Gravitational Universe* [1]. ESA's governing bodies adopted that recommendation in November 2013.

The Hot and Energetic Universe [2] refers to the baryonic component of the Universe at such high temperatures which is largely undetectable by observational facilities at wavelengths longer than X-rays. There is a very substantial fraction of the baryonic Universe in this form: 50% of the baryons are thought to be at $T > 10^5 \text{ K}$ and 30 to 40% at $T > 10^6 \text{ K}$. The amount of hot baryons trapped in groups and clusters of galaxies at temperatures $T > 10^7 \text{ K}$ is of the same order than that locked into stars throughout the Universe. Hot gas is expected to trace the large-scale structures delineated by the dark matter potential wells, and it has an intimate relation with the very energetic phenomena arising in the immediate vicinity of black holes. Accretion onto Super-Massive Black Holes (SMBH) is accompanied by large releases of energy, both in the form of radiation and of mechanical energy. Massive winds and outflows transport this mechanical energy to galaxy scales, effectively terminating star formation and further SMBH growth, but also to larger (cluster) scales, excavating bubbles in the intra-cluster hot gas. This process is generically named Cosmic Feedback, it governs the life of the galaxies but its physical grounds are still poorly understood.

The intimate link between the hot and the energetic Universe calls for an X-ray observatory class mission to study these and other related topics. The *Athena* mission [3], selected by ESA in June 2014, will consist of a single large-aperture X-ray telescope equipped with two state-of-the-art focal plane instruments. *Athena*, being an observatory, will enable enormous science progress in many corners of astronomy, besides addressing the Hot and Energetic Universe theme.

This paper presents the *Athena* science goals in Section 2. Section 3 describes the science requirements and mission concept as submitted to ESA in response to the Call for Missions and selected in June 2014. In Section 4 we place *Athena* in a broad astrophysical context and note the opportunities for synergies with gravitational wave observatories, eLISA in particular.

2. The hot and energetic Universe

2.1. How do baryons assemble and form the large-scale structures in the Universe that we see today?

Hot gas pervades the Universe. On the largest scales, clusters of galaxies signal the locations where dark matter created the deepest potential wells. X-ray baryonic gas at temperatures above a million degrees is trapped in these potential wells and in an approximate local hydrostatic equilibrium. Determining how baryons accrete and dynamically evolve inside these potential wells which formed around $z \sim 2$ is a question of high cosmological significance [4]. Quantifying the number of such first building blocks of the dark matter structure in the form of gas-filled groups of galaxies with mass $> 5 \times 10^{13} M_{\text{Sun}}$ will constrain large-scale structure formation, as their sky density is highly sensitive to the adopted model.

Measuring gas bulk velocities and turbulence can determine the physics on how baryons assemble and dynamically evolve in the cluster potential wells. How much gravitational energy is dissipated in to mechanical energy is not known, but models predict motions and turbulence at the level of 200 km/s. High-resolution X-ray spectroscopic imaging of cluster gas is essential to determine this [5].

It is also clear that astrophysical processes other than gravitational attraction drive the evolution of groups and clusters [4]. Supernovae and/or Active Galactic Nuclei (AGN) inject excess entropy during cluster history, which is reflected in deviations from a purely gravitational entropy profile. Determining when this excess energy was injected and what was the driving process is a must to

understand large-scale structure and, indeed, assess the use of galaxy clusters as cosmological probes. Cluster entropy profiles need to be obtained out to $z \sim 1-2$ to determine this.

Since clusters are the largest hot gas reservoirs in the Universe, they retain direct information about overall chemical evolution. Elements produced by stellar evolution and ejected by Supernovae and winds are trapped inside cluster potential wells. In nearby galaxy clusters elemental abundances and their spatial distribution across the cluster are needed to understand the relative contribution from type Ia and core-collapse Supernovae as well as from AGB stars to the chemical enrichment of the intra-cluster medium. In more distant clusters, determining abundances of trace elements like Fe, O and Si in cluster cores, spanning a broad range of masses and redshifts ($0 < z < 2$) will reveal the chemical evolution of the Universe [5].

AGN at cluster centres are responsible for preventing the gas from massively cooling to very low temperatures and result in massive amounts of star formation. Jets constitute the most powerful incarnations of AGN mechanical energy releases on cluster scales. Bubbles in the hot gas excavated by these jets measure the “instantaneous” mechanical power being released, while ripples in the distribution of hot gas across the whole cluster result from the integrated AGN action during its various evolution phases [6]. Detailed density and temperature diagnostics in cool cluster cores will reveal the delicate balance between heating and cooling.

Finally, the majority of hot baryons are not in clusters and their location and physical state is currently unknown [7]. More than 30% of the baryons in today’s Universe are expected to reside in the Warm/Hot Intergalactic Medium (WHIM), following a filamentary structure tracing dark matter. Galaxy outflows and super-winds from starburst galaxies are further contributors to this tenuous intergalactic gas, whose mere detection is at the limit (if not beyond) the capabilities of current facilities. Determining the local baryon abundance requires detecting resonance absorption lines from various elements (O, Ne, C, etc) towards bright background X-ray sources. In addition, detecting this tenuous gas in emission will also reveal its ionization state and elemental abundances [7]. All this requires very sensitive weak line spectroscopy detection capability. As the number of bright X-ray sources in the sky is limited, Gamma-ray Burst (GRB) afterglows will also be used as X-ray lighthouses illuminating our line of sight towards the distant Universe.

2.2. How do black holes grow and shape the Universe?

SMBH growth and star formation are two fundamental astrophysical processes that drive galaxy evolution. SMBH grow by accretion, mergers, chaotic accretion (of smaller black holes) or a combination of all of them. All of these processes produce copious amounts of radiation and some of them are also expected to produce strong gravitational wave signals. X-rays are a particularly privileged part of the electromagnetic spectrum to use when looking at growing SMBH because they originate very close to the event horizon (closer than radiation at longer wavelengths), there is little contamination in X-rays from the host galaxy and finally X-rays can penetrate through significant amounts of obscuring gas.

Similar to star formation, accreting SMBH (AGN) are expected to be present from the earliest phases of galaxy evolution. During the re-ionisation ($z \sim 6-10$) the number density of AGN depends strongly on the seeds of these SMBH, be those Population III star remnants (seed masses $\sim 10^3 M_{\text{Sun}}$) or the result of direct halo gravitational collapses (seed masses $\sim 10^5-10^6 M_{\text{Sun}}$). Galaxy formation models are not constrained enough by current observations as to being able to predict the SMBH distribution at that epoch. Optical surveys (e.g., with *Euclid*) will be able to find out the tip of the iceberg, i.e., the most massive and actively accreting SMBH at those epochs. But the average AGN population (X-ray luminosity $\sim 10^{43}-10^{44}$ erg/s), which is needed to constrain SMBH seeds, will only be accessible through deep X-ray surveys [8]. Further information on the early universe can be obtained from X-ray

observations of high- z GRB afterglows, using the fast response capability that will be implemented in *Athena*. Absorption features from heavy elements (or lack of them) will reveal whether the progenitors of these high- z GRBs are Population III stars or whether some chemical enrichment has already happened in the parent stellar populations.

SMBH accretion is known to happen very often in obscured environments, where there is very little (or no) radiation leakage. This has prevented so far to have a complete census of growing SMBH, including Compton-thick objects, where no direct X-rays escape from inside, but where a tiny fraction of reflected X-rays can be seen. *Athena* will perform such a complete census out to the epoch where most of the accretion and star formation in the Universe happened ($z \sim 2$) [9]. In addition, the incidence of AGN winds and outflows including the most energetic ultra-fast outflows will be assessed and the mechanical energy released through these outflows will be measured in a number of case studies via high-resolution X-ray spectroscopy. This will deliver a complete picture of the SMBH growth at $z \sim 2$, which together with the optical/IR galaxy surveys mapping star formation, will reveal the details on how galaxy evolution bursted at that particular epoch of cosmic history.

In nearby galaxies, the energy released by growing SMBH will be measured to exquisite detail. Significant amounts of mechanical energy are known to be associated to molecular outflows and to ionized gas. The current picture misses an essential ingredient, which is the massive outflows that are just beginning to be seen in X-rays. These could dominate in some cases the mechanical energy ejected by growing SMBH [10]. In addition, *Athena* will also measure the amounts of gas, metals and energy that AGN outflows and superwinds from starburst galaxies deposit in their surroundings.

Cosmic feedback is a truly remarkable phenomenon, where something happening at the scale of the event horizon of a SMBH impacts and largely drives the life of galaxies and clusters. Understanding the physics of matter under strong gravity conditions is essential to properly model this phenomenon. In the immediate vicinity of black holes, a number of relativistic effects take place and some of them have a direct observational impact [11]. *Athena* will measure, through a number of observational techniques, the spin of black holes in binaries. Specifically through X-ray spectroscopy, it will conduct a survey of AGN spins, whose distribution reflects the dominant SMBH growth mode (e.g., smooth accretion spins up SMBH, while chaotic accretion spins them down). Reverberation mapping, a technique at the edge of current observational capabilities, will in addition reveal the geometry of the material surrounding the SMBH.

2.3. Additional science cases

With the performance required to meet the above science goals, *Athena* will be able to tackle a number of other science goals, spanning virtually all corners of Astrophysical research.

Examples of such cases include the study of solar system body's atmospheres and exospheres as well as of the solar wind through charge exchange with these [12]. It also includes star formation, young stellar objects, ultra-cool dwarfs, outflows and magnetic fields in massive stars and planetary nebulae [13] as well as end points of stellar evolution such as neutron stars, black hole X-ray binaries, white dwarfs and ultra-luminous X-ray sources [14]. Furthermore, *Athena* allows to investigate the explosion mechanisms in Supernovae through their remnants [15] and study the cold and hot phases of the interstellar medium [15].

Last, but not least, the fast response capability of *Athena* will enable the study of all types of transient sources [16], including indeed GRBs. By 2028, astronomy might be driven –at least in part– by transient science, thanks in part to projects like LSST [17]. *Athena* should be able to observe transient sources a few hours after the trigger happens, and do that in a significant fraction of the transients.

3. The Athena mission

3.1. Athena Science Requirements

To address the Hot and Energetic Universe scientific goals, a large aperture X-ray telescope is needed together with two focal plane instruments: a Wide Field Imager (WFI) providing sensitive X-ray imaging over a large field of view [19] and an X-ray Integral Field Unit (X-IFU) delivering spatially resolved high-resolution X-ray spectroscopy [20]. These payload elements, and other mission systems, need to meet a number of rather stringent requirements to be able to address the above science goals. A description on the *Athena* science requirements is given in the mission proposal [3], and here only a qualitative description of these requirements on the most representative performance parameters is presented. Some key *Athena* performance parameters are illustrated in Figure 1.

The *Athena* X-ray telescope [18] will have an effective area of 2 m^2 at 1 keV and 0.25 m^2 at 6 keV. The former is driven by point source sensitivity (needed for surveys), and many spectroscopic measurements utilizing soft X-rays; the latter is driven by the need to use the Fe emission line to trace cluster gas properties as well as strong gravity effects around black holes. The angular resolution is specified to be 5 arcsec (half-energy width), largely driven by the needed point-source sensitivity and capability to match faint source positions to those at other wavelengths; 5 arcsec is also the scale of structures that develop in nearby cool cluster cores due to feedback from AGN.

The WFI [19] needs to have a large field of view ($40' \times 40'$) in order to provide sufficient survey grasp and efficiently find early galaxy groups, high- z AGN and significant numbers of obscured AGN at $z \sim 2$. In addition, this enables observing most galaxy clusters in a single pointing. AGN reverberation mapping requires a moderate spectral resolution at 6 keV of 150 eV. A high count-rate capability for the WFI is also needed to study stellar-mass black holes.

The X-IFU [20] is required to have a spectral resolution of 2.5 eV at energies below 6 keV, along with an rms gain stability of a fraction of an eV. These values define respectively the ultimate weak line sensitivity needed to detect WHIM absorption lines, as well as the ultimate accuracy to which hot gas motions can be measured in clusters. At this resolution, OVII emission line triplets can be safely resolved and used to diagnose hot gas. The required field of view is $5'$ in diameter (the shape of the field of view is still under study), which ensures that distant clusters ($z > 0.2$) can be observed in a single pointing. The X-IFU should be able to observe down to 0.2 keV in order to access important C lines from warm gas in local objects and at moderate redshifts.

The spacecraft itself should be rather agile, so it can react quickly to Target of Opportunity alerts, including GRBs. *Athena* will have a fast re-pointing capability (of the order of a few hours) to a large fraction of the sky, so enough fluence (flux integrated over time) can be obtained when observing GRBs. The absolute astrometric error needs to be below $3''$, which can be reduced in WFI observations to $1''$ using post-fact reconstruction.

3.2. The Athena mission concept

Athena is the result of maturing a concept that began with the X-ray Evolving Universe Spectroscopy (XEUS) mission [21] selected for study by ESA in 2007, then followed by the International X-ray Observatory (IXO) [22] and that later become the *Athena*-L1 mission [23]. The *Athena* mission will consist of a single spacecraft launched into an L2 halo orbit by an Ariane V – class launcher, containing as science payload a single aperture X-ray telescope with a focal length of 12 m, and two focal plane instruments whose position can be changed by a movable instrument platform. The WFI is

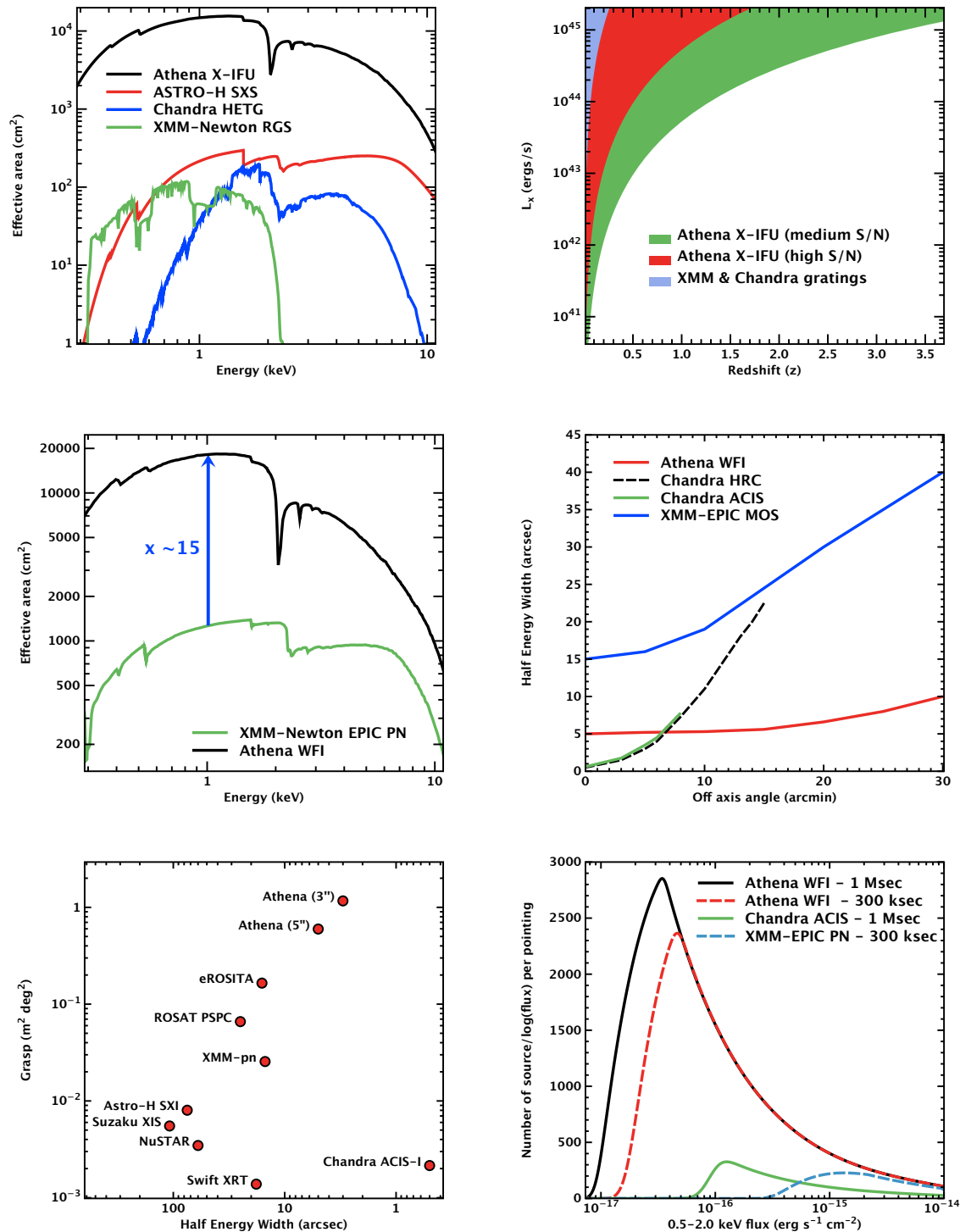


Figure 1. From top left to bottom right, *Athena* performance vs earlier missions: (a) effective area for high-resolution spectroscopy; (b) L_X - z parameter space available for high-resolution spectroscopy; (c) effective area for imaging and medium-resolution spectroscopy; (d) spatial resolution at various off-axis angles; (e) survey grasps and (f) survey speed in sources per pointing

a Si-based detector with DEPFET active pixel sensor readout [19], delivering sensitive imaging

capabilities over a large field of view, modest energy resolution and high count-rate capability. The X-IFU is a calorimeter array, whose front-end sensor is made of absorbers thermally coupled to Transition Edge Sensors operating at 100 mK [20]. It will provide spatially resolved high-resolution X-ray spectroscopy for both point-like and extended sources.

The *Athena* mission proposed to ESA will last for 5 years, which will be sufficient to achieve the full set of Hot and Energetic Universe science goals, and accommodate a significant amount of additional science goals. It is expected, however, that the mission could be extended if there are strong scientific and programmatic reasons. The vast majority of the observations will be allocated following a traditional call for proposals and peer review process, although some time is expected to be guaranteed to consortia providing payload and other mission elements. The possibility of defining key programmes before launch, with the goal of securing some of the most demanding science goals, has been flagged in the mission proposal and will receive further consideration. It is envisaged that international partners, in particular NASA and JAXA, could participate in *Athena*, which will remain in any case a European flagship mission.

4. *Athena* in context

The Astrophysical landscape around 2028 will be significantly different to the one that we have today. A plethora of large astrophysical observatories will be available along the whole electromagnetic spectrum. Among those, ALMA, the ELTs (ESO's E-ELT, TMT and GMT) and JWST will be the dominant deep sky facilities at (sub)millimeter, optical and infrared wavelengths, in addition to LSST. The SKA could complement those facilities at cm-radio wavelengths and CTA will be the first true observatory at TeV energies.

Athena will be the X-ray element of the family. Its sensitivity has been designed to peer into the earliest growing SMBH at a comparable depth to which JWST and the ELTs will find the first star-forming galaxies and ALMA will see their cold Interstellar Medium. In the particular context of transient sources, as a number of gravitational wave sources are expected to be, the fast reaction capability of *Athena* might be instrumental in providing electromagnetic counterparts to the gravitational wave events. Cosmic X-rays arise either in extended gravitational potential wells (the Hot Universe) or in the deepest gravity potential wells (the Energetic Universe). In realistic conditions, it would be extremely surprising that a gravitational wave event, coming from a dramatic change of a strong gravitational field, would not come accompanied by copious X-ray emission. LIGO and VIRGO experiments first, and eLISA later will teach us how to identify gravitational wave events with electromagnetic signals. In the specific case of eLISA, where low-frequency gravitational waves from coalescing SMBH will be detectable, there will be a very important synergy with *Athena* in trying to discern what is the relative contribution from mergers and smooth accretion to SMBH growth. The hope is that both *Athena* and eLISA will be looking at the sky together for a number of years.

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