The NewAthena mission concept in the context of the next decade of X-ray astronomy

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Large X-ray observatories such as *Chandra* and XMM-Newton have been delivering scientific breakthroughs in research fields as diverse as our Solar System, the astrophysics of stars, stellar explosions and compact objects, accreting super-massive black holes, and large-scale structures traced by the hot plasma permeating and surrounding galaxy groups and clusters. The recently launched observatory XRISM is opening in earnest the new observational window of non-dispersive high-resolution spectroscopy. However, several quests are left open, such as the effect of the stellar radiation field on the habitability of nearby planets, the Equation-of-State regulating matter in neutron stars, the origin and distribution of metals in the Universe, the processes driving the cosmological evolution of the baryons locked in the gravitational potential of Dark Matter and the impact of supermassive black hole growth on galaxy evolution, just to mention a few. Furthermore, X-ray astronomy is a key player in multi-messenger astrophysics. Addressing these quests experimentally requires an order-of-magnitude leap in sensitivity, spectroscopy and survey capabilities with respect to existing X-ray observatories. This paper succinctly summarizes the main areas where high-energy astrophysics is expected to contribute to our understanding of the Universe in the next decade and describes a new mission concept under study by the European Space Agency, the scientific community worldwide and two International Partners (JAXA and NASA), designed to enable transformational discoveries: NewAthena. This concept inherits its basic payload design from a previous study carried out until 2022, *Athena*.

Cosmological simulations suggest that most of the baryons in the universe are "hot" [1], *i.e.* in a temperature and density regime where copious X-rays are emitted by thermal particles. Consequently, several fundamental questions in modern astrophysics require sensitive X-ray observations to be ultimately answered. These observations involve the study of systems as diverse as individual stars and their planetary environment; the result of stellar explosions such as neutron stars, stellar-mass black holes and supernova remnants; and hot gas halos surrounding individual galaxies or permeating the space among galaxies in groups and clusters, eventually connecting to the Cosmic Web. Furthermore, super-massive black holes most likely play a key role in shaping the cosmological evolution of their host galaxies, ultimately driving their rate of star formation. The quest for the root cause of this elusive "feedback mechanism" requires measuring both the populations and the energetics of accreting super-massive black holes at the centre of galaxies, Active Galactic Nuclei (AGN). To this scope, X-ray measurements are indispensable.

In the 2030s, a suite of large multi-wavelength astronomical facilities will be operational or will have surveyed the sky at unprecedented sensitivity from the radio to the very high-energy γ-rays. Furthermore, multi-messenger astrophysics is expected to reach full maturity in the second half of the next decade, with the deployment of the 3rd generation of ground-based gravitational wave arrays, new neutrino facilities [2,3], and the first space-borne gravitational wave observatory, LISA [4]. Explosive and transient phenomena in the Universe are often associated with the emission of high-energy radiation. Sensitive X-ray observations of neutrino- and gravitational wave-emitting sources are a key tool of multi-messenger astrophysics.

An X-ray observatory matching and complementing this suite of facilities will therefore allow us to uniquely address a set of fundamental questions in modern astrophysics such as:

- How does the stellar radiation field affect the habitability of planetary systems, and is in turn influenced by the presence of nearby planets?
- What is the Equation-of-State regulating matter in neutron stars?
- What is the origin of the high-energy processes in the close environment of black holes?
- What distribution of supernovae and supernova explosions leads to the mixture of metals we measure in the local Universe? How are metals distributed through the Cosmos?
- What drives the cosmological co-evolution of galaxies and super-massive black holes?
- How does supermassive black hole feedback shape the large-scale baryon distribution?
- How do large-scale structures in the Universe form and evolve? What physics defines their hot gas content?
- What is the astrophysical nature of the most common celestial sources of neutrinos and gravitational waves?

These questions remain open despite the enormous advances brought by past and operational flagship X-ray observatories such as *Chandra* and *XMM-Newton* [5]. In this paper, we explore the enhancement in science performance which will allow these open questions to be addressed. In the last section, we advocate a new mission concept under study by the European Space Agency (ESA) and in the science community worldwide, capable of achieving this science performance: *NewAthena*.

How do black holes grow and influence galaxy evolution?

It is now well established [6] that most massive galaxies host at their centres a Super-Massive Black Hole (SMBH, with mass $\geq 10^6$ $M_\odot$). The SMBH masses are well correlated with the masses of their host galaxies (with a better correlation with their central parts) [7]. This leads to the question of how a system with the size of the inner solar system (the typical scale of the event horizon of the central SMBH) could affect (or perhaps even control) phenomena on scales millions to billions of times larger. This mystery is compounded by the parallel evolution across cosmic time of the growth of galaxies via star formation and the growth of SMBH via accretion of material from their surroundings, a process enabling them to shine as AGN [8]. Both processes were much stronger in the past, with a broad peak around redshift z~1-3 (the so-called Cosmic Noon), and a fast decrease towards the present date. The exact behaviour at higher z is strongly debated: galaxy growth seems to have had a slower increase sustained in time from high z~10, while AGN power may have grown faster starting at lower z, although the recent detection by JWST of luminous AGN with SMBH of masses $\sim 10^7$-10^9 $M_\odot$ at z>5 challenges current models [9]. Whatever the explanations to the facts above, the growth of galaxies and of the SMBH in their centres must be inextricably connected, in what is called the co-evolution of AGN and galaxies [10], but the physical processes that drive such co-evolution remain poorly understood. The stupendous amount of radiation from the AGN can generate energetic outflows of material [11], perhaps pushing or heating the interstellar and intergalactic medium to the point where star formation is no longer possible or sparking star formation [12]. Alternatively (or perhaps complementarily), galactic star formation and SMBH growth could be controlled by the flow of intergalactic gas into galaxies [13], maybe enhanced by mergers and/or by external fuelling [14]. Understanding the physical and astrophysical drivers of the AGN-galaxy co-evolution is one of the main topics of current extragalactic astronomy.

In accreting black hole systems over the whole mass range, an X-ray telescope with a collecting area significantly larger than currently operational observatories will enable for the first time studies of the highly variable inner accretion flow close to its dynamical time scale in AGN (~hours). These studies will, for example, allow us to establish the location and nature of the primary source of hard X-rays, and its connection to the typically observed fast outflows, expected to be launched from the inner accretion disk. Such observations will also measure the black hole spin to a high precision. The distribution of spin in local Universe AGN is a sensitive probe of their growth processes [15].

Strong energetic relativistic outflows from the inner region around the SMBH have been measured in X-rays [11]. It is crucial to understand how such outflows around SMBHs are launched, and how they are connected to the larger scale feedback in the surrounding galaxies. Sensitive, time-resolved X-ray spectroscopic observations are indispensable to determine the outflow energy and mass rates from the local Universe to the Cosmic Noon, fundamental quantities that remain impossible to constrain over a significant fraction of the AGN population, even in the deepest AGN observations with the *Chandra* and XMM-Newton spectrometers. Furthermore, the impact of such AGN-driven outflows up to Cosmic Noon can be gauged by identifying spectral signatures in the overall AGN population through a sufficiently deep extragalactic survey. This is beyond the capabilities of even the most powerful X-ray survey mission flown to date, *eROSITA* [16] (cf. the right panel of Figure 1).

The space density of X-ray detected AGN exceeds that of radio-, UV- or optically selected AGN by a large factor [17, 18, 19]. Furthermore, X-rays can pierce through the obscuration known to exist around the centres of many of these objects [20]. A large area-sensitive X-ray extragalactic survey would constrain the overall SMBH accretion rate density, reaching AGN around the knee of the luminosity function (whence most of the black hole mass growth occurs), out to the epoch of reionization for unobscured objects, and characterising moderate to intermediate obscuration up to z~6-7 (which may dominate accretion growth [21]; cf. the left and central panel of Figure 1). This critical part of the parameter space is difficult to reach for facilities at other wavelength with sufficient statistics. Other spectral ranges and facilities would be able to detect high-z heavily obscured AGN in great numbers (e.g. SKA, [22,23]), but their characterisation and recognition as such would require extensive additional multi-wavelength data (see, *e.g.*, synergies with future ESO mission as described in [24]). This leads back to the key role that an X-ray observatory capable of providing a wide census of the AGN population through Cosmic ages would have in this quest.

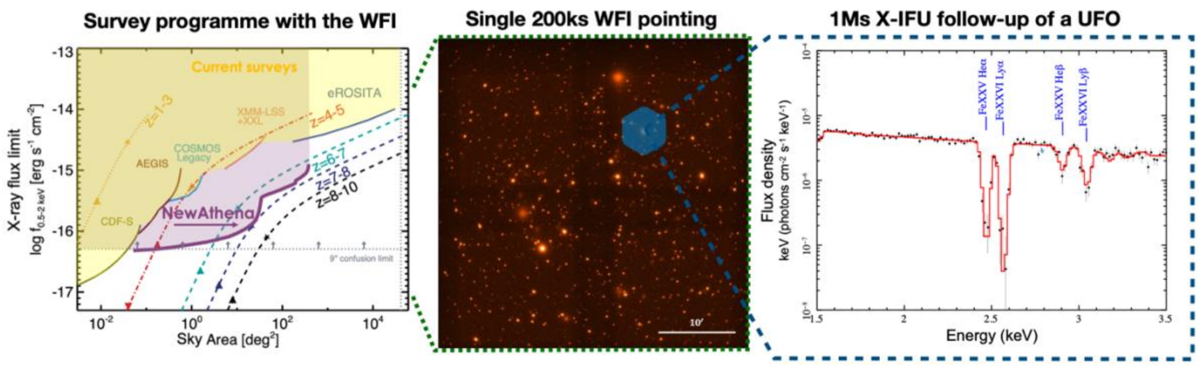

Figure 1 - Illustration of the survey capability of the NewAthena Wide Field Imager (WFI). Left panel: X-ray limiting flux versus sky coverage for a representative sample of current X-ray survey (yellow shaded area) compared to the improvement enabled by the NewAthena/WFI (purple shaded area). The dashed lines indicate the area coverage to different flux limits required to reveal statistical samples of AGN in various redshift ranges, with stars indicating the characteristic luminosity, L, where most growth occurs. The grey dotted horizontal line indicates the flux corresponding to the confusion limit for the NewAthena telescope on-axis Point Spread Function (9" Half Energy Width). Central panel: simulation of a 200 ks WFI observation of an extragalactic field with SIXTE [56]. It is based on the Chandra Deep Field South simulation from the aforementioned publication with an updated AGN population to cover the full field of view. The blue hexagon represents the field-of-view of the X-Ray Integral Field Unit (X-IFU) instrument, targeting a candidate AGN with an ultra-fast outflow identified from the WFI survey Right panel: zoom of a 1 Ms X-IFU simulation of an Ultra-Fast Outflow in an AGN at z~2 around the transitions of He- and H-like iron. The outflow parameters are: column density, $N_H=10^{24}$ cm^{-2}; ionization parameter log(ξ)=4; velocity v/c=0.1. The error bars in the spectrum are at the 1σ level.*

X-ray emission from neutron stars: probe of dense matter physics and multi-messenger astrophysics

The detection of gravitational waves emanating from the binary neutron star merger GW170817, followed by multi-band observations of its electromagnetic counterparts where X-rays played a crucial role [25], marked the advent of multi-messenger astronomy. In the forthcoming decades, we anticipate similar events occurring at a frequency of almost one per day, when the next generation of gravitational wave interferometers becomes operational [26]. X-ray measurements of jets, their angular structure, and orientation can disentangle the distance and inclination of a gravitational wave source, thereby enhancing the precision of cosmological inferences. Furthermore, X-ray observations can track the activity of the merger remnant and the emergence of kilonova afterglows [27], providing novel constraints on the behaviour of dense matter before and after the merger. This requires a large area X-ray facility matching the technological development of ground-based GW arrays [28].

Likewise, with a large X-ray observatory, we may finally approach the longstanding goal of constraining the equation of state for dense matter. This is a fundamental challenge in both physics and astrophysics. One promising approach has long been recognized: measuring the mass and radius of a neutron star. While most neutron stars are identified as radio pulsars, a selected few exhibit periodic X-ray modulations of emitted radiation from their surfaces, a direct consequence of their rotation and their hot surface temperature. If this periodic emission stems from one (or multiple) hot spot(s) on the star's rotating surface, we can predict the emission observed by a distant observer using a technique known as raytracing. This method traces the path of light from the neutron star's surface to the observer through the curved spacetime around the star, with the effects of general relativity encoded in the resulting periodic emission observed from the neutron star's surface [29]. The light curve model derived from this approach can then be compared to observations to constrain various parameters, including the neutron star's mass and radius. The Neutron star Interior Composition ExploreR (NICER) mission has pioneered this kind of measurements [30,31]. However, the accuracy in the determination of the neutron star radius (10-15%) is still insufficient to significantly constraint the Equation-of-state. Only a large X-ray observatory with a low and well characterized internal background will be able to measure the mass and radius of a large sample of neutron stars at the percent level required to provide a strong constraint on the dense matter equation of state.

Mapping the dynamical assembly of intergalactic plasma in the large-scale structure

The structure we observe today on the largest scales of the cosmos originates from tiny density perturbations left after the Big Bang. Under the influence of gravity, small over-dense clumps of matter have merged over time, leading to a web-like structure of galaxies, galaxy groups, galaxy clusters, and large-scale filaments, spanning the observable Universe [32]. This succession of mergers injects kinetic energy into the newly formed structures, which is eventually dissipated into heat. This is why most of the normal, baryonic matter is today in the form of a diffuse plasma with temperatures reaching millions to hundreds of millions of degrees, filling the space around and between galaxies in the cosmic web. X-ray astronomy offers one of the most detailed physical diagnostics of this hot Intergalactic/Intra-cluster medium (IGM/ICM) through its emission and absorption signatures.

Whether in the form of shock fronts or turbulence driven during the ongoing mergers, it is expected that the signatures of the structure formation process are most directly traced by the gas velocity field. This can be directly probed, in principle, by imaging the Doppler shifts and broadening of X-ray emission lines from the ICM. However, such measurements have remained largely out of reach for previous X-ray observatories. Therefore, little is known about how the kinetic energy is injected and eventually thermalized during large-scale structure growth. Recently, XRISM has inaugurated the era of eV-level, non-dispersive X-ray spectral imaging over the 1.7-12 keV energy band [33] with its micro-calorimeter instrument *Resolve* [34]. While this will give us valuable insight into the gas dynamics in local, bright, hot clusters of galaxies, an additional leap in effective area and spatial resolution are needed to effectively map bulk motions and turbulence over a substantial fraction of these objects' volume, and to trace the evolution of the ICM dynamics up to higher redshift. An improved sensitivity to low surface brightness emission would further allow us to probe the gas entropy at the outer edges of galaxy clusters, reaching much higher redshifts than current facilities, obtaining a complementary test of how the heating processes evolve over cosmic time.

Shocks and turbulence generated during galaxy cluster mergers are also believed to lead to the acceleration of a small fraction of particles to relativistic energies [35]. Mapping the corresponding gas motions with a powerful X-ray spectro-imaging instrument thus offers a key to understanding the creation of cosmic-ray electrons and the amplification of magnetic fields, detected in the radio band in the form of radio halos and radio relics.

Once heated by the gravitational assembly process, most of the gas would take longer than the Hubble time to radiatively cool and condense into stars. A notable exception is in the dense, bright centers of cool-core galaxy clusters. However, despite the short cooling times, it was observed that the star formation here remains inefficient: It is widely believed that

AGN-ICM interaction provides the energy needed to prevent the gas from cooling. Understanding this *dynamical* process requires us to probe the associated gas kinematics. None of the existing operational X-ray missions can achieve this measurement at the required level of spatial and spectral resolution, even in very nearby objects like M87. This field requires non-dispersive spectroscopy as well as an order-of-magnitude advancement in effective area and spatial resolution with respect to *Resolve* [34], whose optics exhibit only a moderate spatial resolution (~1' Half Energy Width, HEW), cf. Figure 2 for an illustration of the required performance enhancement.

Far from being limited to the Brightest Cluster Galaxies (BCGs), feedback from AGN and supernovae is now recognised as a lynchpin in the evolution of *all* galaxies. At the L* mass regime corresponding to more "typical" galaxies, much less is known about the feedback substructures, because these gaseous haloes are significantly fainter in X-rays compared to the ICM. The "eROSITA bubbles" above and below the Galactic plane have been interpreted as evidence of past episodes of energetic feedback [36], and some of our state-of-the-art models of galaxy formation predict that these features are common in Milky Way/M31 analogues at z=0 [37]. An observatory carrying X-ray optics with a HEW of ~10" and an effective area about one order of magnitude larger than *Chandra* and *XMM-Newton* would enable us to search for such feedback bubbles in other nearby galaxies, therefore testing this model prediction and informing the future development of galaxy evolution codes.

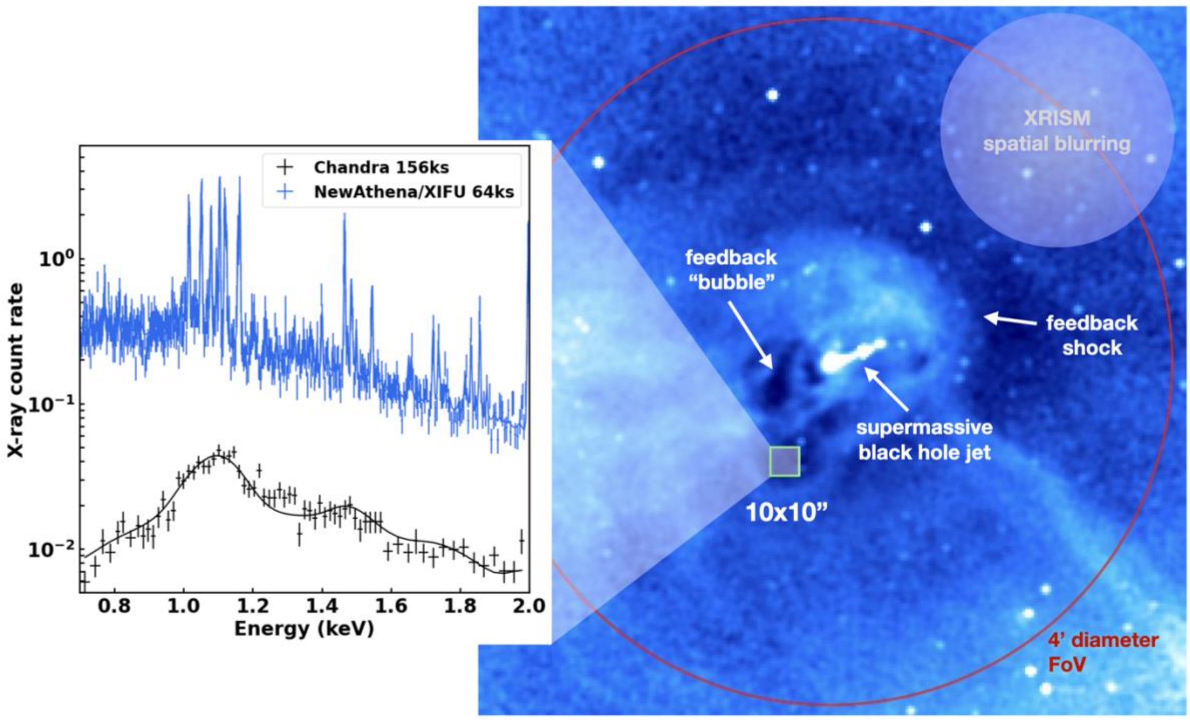

Figure 2 - Left Panel: comparison between the NewAthena X-ray Integral Field Unit (X-IFU) spectrum of a "feedback bubble" in M87 (64 ks) compared with an archival Chandra/ACIS observation of the same region (156 ks). The spectra are extracted from the grey square in the ACIS image. The red circle represents the X-IFU field-of-view. The light blue circle represents the Point Spread Function of the XRISM/Resolve, whose size is comparable to the region mostly affected by the interaction between the relativistic jet and the ICM. The error bars in the spectrum are at the 1σ level.

Feedback processes result in heating the gas and, especially in lower mass systems, also expelling it out to large distances from the host galaxy, sometimes unbinding it completely. This leaves an imprint in how the gas mass fraction varies with halo mass; for large samples of low mass systems out to large redshifts, this effect is most easily probed indirectly by, e.g., looking at the luminosity-temperature relation. A survey conducted by a sensitive, wide field X-ray imager would enable the detection of several thousand galaxy groups ($M_{500}<5\times10^{13}\,M_{\odot}$) at z≥1 with accurate measurements of temperature and luminosity. Constraints in this mass and redshift regime, which is beyond the capability of future surveys based on the Sunyaev-Zeldovich effect (e.g., CMB-S4) due to their modest angular resolution, would provide critical information for understanding and modelling galaxy, galaxy group and cluster evolution, and for accurately applying cosmological tests that require understanding of the non-linear regime, for instance those based on gravitational lensing.

How is the gas ejected by feedback eventually distributed? Where does it end up and how does it circulate through the veins and tendrils of the cosmic web? To answer this question, we ultimately need to detect the most diffuse hot plasma located in the outskirts of L* galaxy haloes and extending beyond the bounds of virialized structures into the large-scale structure filaments that connect them. These are the most common baryonic reservoirs in the Universe, wherein most of the normal matter resides. A sensitive, wide field of view soft X-ray imaging telescope will enable detecting several instances of the brightest and hottest Large-Scale Structure (LSS) filaments connecting to massive local galaxy clusters. Recent *eROSITA* results [38] demonstrate that such systems exist. Going to even lower gas densities, such as those expected in the outskirts of the circumgalactic medium (CGM) of typical L* galaxies, the surface brightness is predicted to drop much below that of the Milky Way foreground. This emission is predominantly in the form of spectral lines [39], in particular the He-like Kα Oxygen transitions at a rest-frame energy of 0.57 keV. A detector with a spectral resolution of a few eV would enable all lines from the OVII triplet for a target at redshift ≥0.035 to be cleanly separated from the corresponding Milky Way line transitions, enabling the detection of much lower density gas than is possible in broad-band imaging. Combined with a field of view of a few arcminutes, such capabilities would open a new window on the properties of the CGM on scales ~100 kpc from the galaxy centres. This provides arguably the cleanest test of existing galaxy formation models, because the modelling uncertainties related to treating the (even more complex) central interstellar medium are minimised.

Finally, the *most* diffuse gas in the LSS can be efficiently studied through the absorption features against bright background sources. The search for this gas component requires a combination of effective area and energy resolution far exceeding the capability of existing X-ray spectrometers, despite some claim of marginal WHIM detection in extremely deep observation with the *XMM-Newton* RGS [40]. Such measurements would allow to determine where most of the normal matter resides in the local Universe, providing a solution to the decade-long quest for the “missing baryons”.

Probing the evolution of metal factories in the Universe

The chemical enrichment history of the Universe is a broad topic with multidisciplinary appeal. The ICM represents the integrated enrichment averaged over billions of supernova explosions, making it a particularly clean probe to test cosmic nucleosynthesis. We need a significant improvement in instrument capability and control of the background (at a level of a few percent) to map the Fe abundance measurements for local clusters *routinely over their entire volume* out to R_{500}, and down to the mass scale of groups of galaxies [41].

Detecting other chemical elements, in addition to Fe, is even more challenging. A full study of the evolution of metals in the ICM, constraining the relative yield of different classes of supernovae as well as details of their explosive mechanisms, requires high-resolution X-ray spectroscopic measurements coupled with a large effective area, enabling measurements of the chemical composition in galaxy clusters up to an epoch commensurate to the Cosmic Noon. Abundances of rare elements such as Potassium and Titanium are of particular interest because current supernova nucleosynthesis models *heavily* underpredict the abundances of these two elements, compared to Galactic archaeology constraints [42].

A complementary approach to study the origin of heavy elements in the Galaxy, as well as among the most powerful cosmic ray accelerators, is to observe the explosion of stars via supernovae, and their remnants in the Galaxy. The non-thermal X-ray component of such remnants, power-law like, gives important clues on the synchrotron emission due to the magnetic field and consequently the role of SNR in generating galactic cosmic rays. Only a large X-ray observatory will be able to study several of such acceleration engines and to disentangle their geometry, element abundances, and possible anisotropies related to the past explosion.

Back to our backyard: probing star-planet interaction with accurate X-ray spectroscopy

Almost 80% of stars may have hosted proto-planetary disks leading to the formation of planets. For the proximity of their habitable zones, the M-type stars are prime candidates for the characterization of potentially habitable exoplanets, and often show strong X-ray flares that may have an impact on the planet formation and their atmosphere. Giant planets appear to be scarce around M dwarfs, but terrestrial planets and super-Earths have an estimated occurrence rate approximately 3.5 times higher than around solar-mass stars [43]. This might be due to the star-planet interaction preferentially disrupting gas giant planets, something that X-ray emission can uniquely probe [44]. A future large X-ray observatory might be able to diagnose flows in stellar coronae on minute timescales, spanning a factor of 20 in temperature, and can connect near-stellar activity with transient mass loss that would also impact planetary environments.

NewAthena: a large-scale open observatory for the 2030s

ESA is studying a mission concept able to address the scientific quests described in this paper. This concept, **NewAthena**, is a direct evolution of *Athena*, a mission selected in 2014 to address the scientific theme of the “Hot and Energetic Universe” [45]. During the *Athena* Phase A, a cohort of scientists and engineers at ESA, in the Instrument Consortia, the International Partners (JAXA and NASA), and the broad science community have contributed to developing the science case of the *Athena* observatory. This paper heavily relies on the scientific case developed for *Athena*. We refer readers interested in the original *Athena* science cases to the White Papers published together with [45], as well as to [46] and [47]. NewAthena may join a fleet of new X-ray observatories possibly operational in the next decade such as the X-ray probe AXIS [48], or dedicated high-resolution spectroscopic facilities such as HUBS [49].

In 2022, ESA started a "reformulation" of the mission profile and science case, because the estimated costs exceeded the level of resources available in the ESA Science Program. The new concept carries the same scientific payload as on *Athena*: a Wide Field Imager [50] based on an active silicon detector, with a 40'x40' field-of-view and moderate (CCD-like) energy resolution; and a pixelated X-ray Integral Field Unit (X-IFU) [51], with unprecedented energy resolution (ΔE≤4 eV) over more than 1500 pixels, of about 5" side each. The two instruments can be moved to the focal plane of a single tube, 12-m focal length, telescope with a large effective area and an average ~10" HEW angular resolution over the whole WFI field-of-view (~9" on-axis). The main scientific requirements of NewAthena are listed in Tab. 1.

*Table 1 - **NewAthena key scientific requirements.***

Parameter	Requirement value
X-IFU total effective area at 7 keV	0.087 m^2
X-IFU total effective area at 1 keV	0.60 m^2
X-IFU Energy resolution at 7 keV	4 eV
X-IFU Field of View (effective diameter)	4 arcmins
X-IFU Pixel Size on the sky	5 arcsecs
X-IFU Background (2-7 keV)	5×10^{-3} photons cm^{-2} s^{-1} keV^{-1}
WFI Effective area at 1 keV	0.86 m^2
WFI Field of view (side)	40x40 arc mins
WFI Background (2-10 keV)	8×10^{-3} photons cm^{-2} s^{-1} keV^{-1}
Background knowledge accuracy	5%
Optics angular resolution on-axis @ 1 keV	9 arc secs
Field-of-view averaged optics angular resolution @1 keV	on-axis + 1 arc sec
Point source (45 off-axis) X-ray stray light area ratio against on-axis area	1×10^{-3}
Field of regard	34%
ToO Response time	12 hours

These scientific requirements of NewAthena were endorsed by the Science Program Committee of the European Space Agency in November 2023. For comparison, the scientific requirements of the Athena mission are described in [45].

The *NewAthena* telescope is based on Silicon Pore Optics technology [52], characterized by the largest ratio between area and mass for space-qualified X-ray optics to date [53]. They enable an effective area of the two focal plane instruments exceeding that of operational X-ray observatories by one order of magnitude or more at 1 keV. Coupled with the large field-of-view, the large effective area ensures that the WFI grasp – the products between these two quantities – exceeds by a large factor even that of X-ray missions specifically designed to perform X-ray surveys such as *eROSITA* [16] (Fig. 3). Micro-calorimeter detectors largely exceed the resolving power of gratings detectors above 2 keV (and, obviously, the resolving power of CCD detectors at all energies).

It is useful to compare the spectroscopic performance of different instruments by using suitable combinations of basic instrument science performance parameters. These spectroscopic Figures-of-Merit (FoM) are proportional to the signal-to-noise ratio to detect an absorption or emission line. In this paper, we compare in Figure 4 the FoM for the detection of a weak line, and the measurements of velocity centroid (shift) and width (broadening) of a strong line. For all these FoM, the *NewAthena* X-IFU exceeds the performance of existing imaging, dispersive and non-dispersive spectrometers by more than one order-of-magnitude over most of the sensitive bandpass.

NewAthena is planned to be launched in 2037. It is therefore *the* X-ray observatory matching the suite of large-scale observational facilities operational in the 2030s, and providing the required combination of sensitivity, energy resolution and field-of-view that will enable transformational progress in all the scientific fields discussed in this paper, and undoubtedly many more.

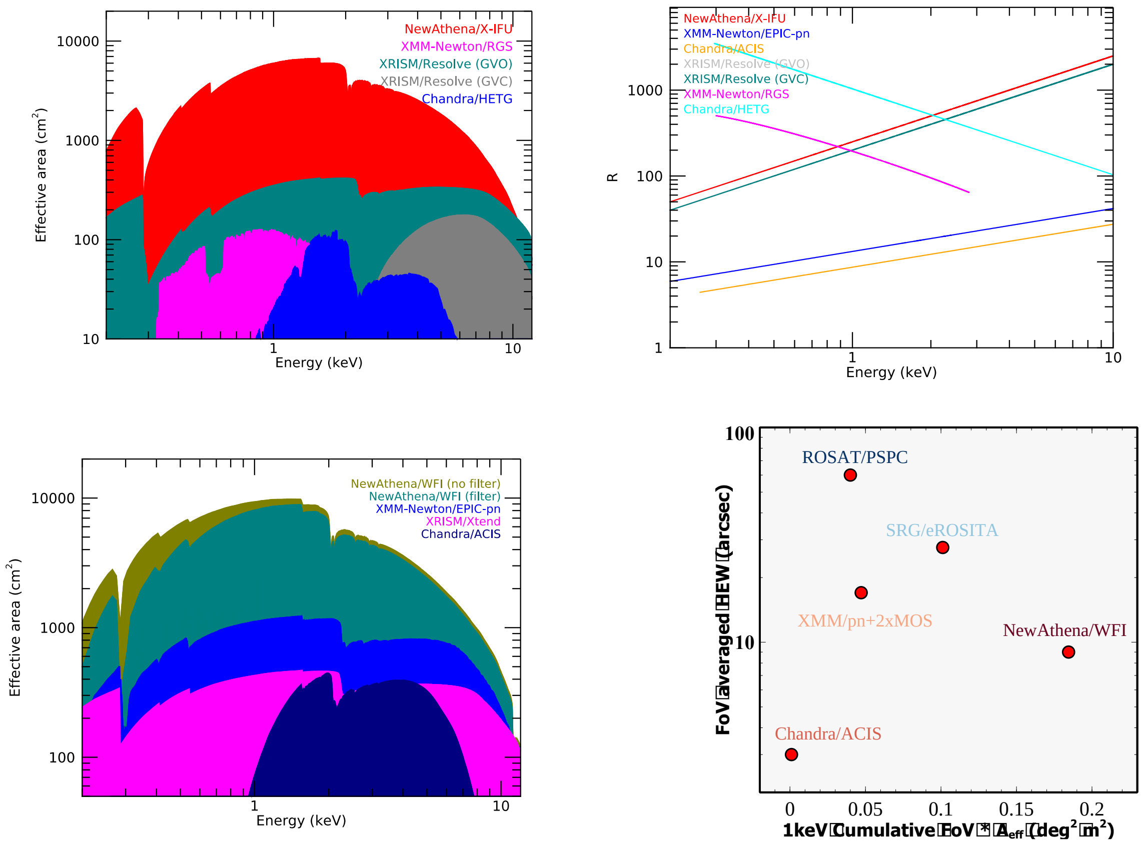

Figure 3 – Effective area of the NewAthena instruments and X-IFU resolving power R (=E/ΔE, where ΔE is the energy resolution) as a function of energy are compared with operational high-resolution spectroscopic instruments. For the XRISM/Resolve we show the configuration with the Gate Valve Open (GVO; nominal requirement) and Closed (GVC; current operational set-up). For RGS we show the area after the failure of two CCDs in 2000. The resolving power of two operational instruments based on Charged Couple Device (Chandra/ACIS and XMM-Newton/EPIC) is also shown for comparison. Note that the resolving power of the XRISM/Resolve is the same for the GVO and GCV configurations. The WFI grasp at 1 keV as a function of the field-of-view-averaged HEW is compared against past and operational survey X-ray instruments.

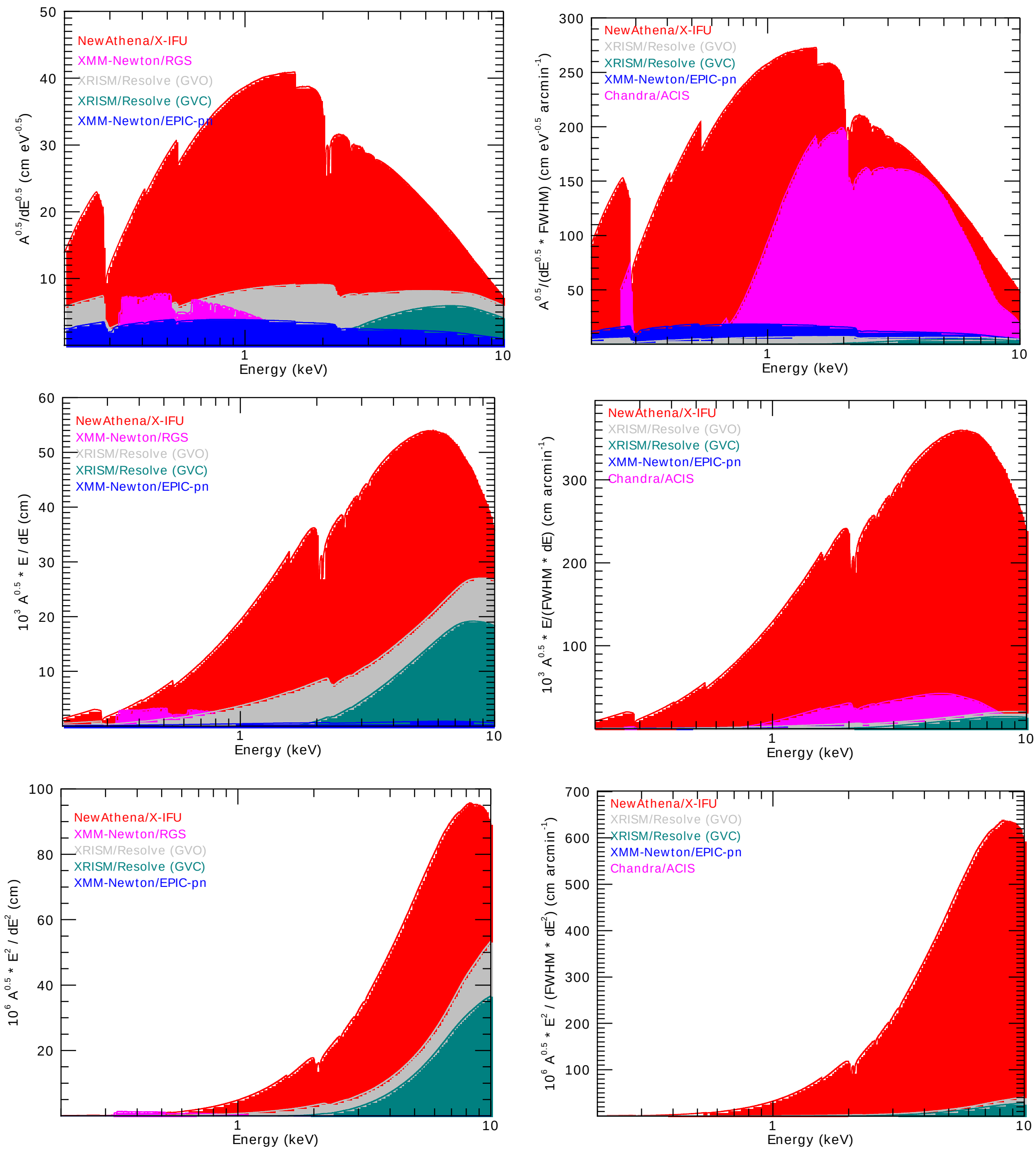

Figure 4 - Spectroscopic FoM comparing the NewAthena X-IFU with operational X-ray spectrometers. From top to bottom: detection of weak lines, shift (velocity) and width (broadening) of strong lines. Left column: point-like sources. Right column: extended sources. The definitions are in the y-axis label. The extended source FoM are calculated from the point-like source ones by dividing the by a further factor equal to the telescope Full Width Half Maximum, to account for the sum in quadrature of the signal-to-noise ratio in a number of independent spatially-resolved extraction regions.

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Data availability
The Chandra/HETG spectrum shown in Figure 2 has been extracted from data available in public archives. All the NewAthena simulations shown in this paper were generated using public telescope and instrument responses made available by ESA and by the NewAthena Instrument Consortia. The instrument responses used to produce Figures 3 and Figure 4 are publicly available on the web sites of the corresponding missions.

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package [54], a generic, mission-independent Monte Carlo simulation toolkit for X-ray astronomical instrumentation, has been extensively used to create the figures in this manuscript. Part of the performance simulations for NewAthena have been provided by SIMPOSIuM, an ESA financed project aimed to develop an open source SPOs simulation tool [55]. The bottom right panel of Figure 3 was kindly provided by Arne Rau (MPE, Garching). Comments by Didier Barret and Erik Kuulkers on an earlier version of the manuscript are gratefully acknowledged.

Author contributions

This manuscript was prepared in a collaborative fashion by all authors. Each of them contributed to a specific section or sub-section and provided inputs for the generation of the figures. More specifically:

- Francisco J. Carrera, Matteo Guainazzi and Nanda Rea coordinated the preparation of the manuscript. They defined the structure of the paper, and wrote the manuscript introduction
- Francisco Carrera coordinated the elaboration the section: "How do black holes grow and influence galaxy evolution?"
- James Aird, Francisco Carrera, Thomas Dauser, Delphine Porquet, and Pierre-Olivier Petrucci contributed to the Section: "How do black holes grow and influence galaxy evolution"
- Matteo Guainazzi coordinated the elaboration of the sections: "Mapping the dynamical assembly of intergalactic plasma in the large-scale structure" and "Probing the evolution of metal factories in the Universe"
- Dominique Eckert, Fabio Gastaldello, Gabriel W. Pratt, Thomas H. Reiprich, and Aurora Simionescu contributed to the sections: "Mapping the dynamical assembly of intergalactic plasma in the large-scale structure" and "Probing the evolution of metal factories in the Universe"
- Nanda Rea coordinated the elaboration of the sections: "Back to our backyard: probing star-planet interaction with accurate X-ray spectroscopy" and "X-ray emission from neutron stars: probe of dense matter physics and multi-messenger astrophysics"
- Nandra Rea, Lia Corrales, Elisa Costantini, Hironori Matsumoto, Rachel Osten, and Eleonora Troja contributed to the sections: "Back to our backyard: probing star-planet interaction with accurate X-ray spectroscopy" and "X-ray emission from neutron stars: probe of dense matter physics and multi-messenger astrophysics"
- Matteo Guainazzi and Daniele Spiga contributed to the elaboration of the section "NewAthena: a large-scale open observatory for the 2030s"
- James Aird and Francisco Carrera prepared Figure 1
- Aurora Simionescu prepared Figure 2
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