estec

European Space Research
and Technology Centre
Keplerlaan 1
2201 AZ Noordwijk
The Netherlands
T +31 (0)71 565 6565
F +31 (0)71 565 6040
www.esa.int

NewAthena Science Objectives (SCIOBJs)

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DISTRIBUTION

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1 SCOPE OF THIS DOCUMENT

This document lists the whole set of Scientific Objectives (SCIOBJs) of the NewAthena mission. They constitute the goals that the mission shall achieve during its nominal operational life. The duration of the operational life is a programmatic input for this document, and is assumed to be 5 years as per deliberation of the Science Program Committee (SPC) of the ESA Science Program in the November 2023 meeting.

The selection process for NewAthena (originally known as *Athena*) began in March 2013, when ESA issued a call to the European science community to suggest the scientific themes to be pursued by the Cosmic Vision programme's second and third Large missions of the ESA Science Program. In November 2013, the theme of "the Hot and energetic Universe" was selected for L2, with "the gravitational Universe" (now LISA) selected for L3. However, after 8 years of Phase A and Phase B1, the meeting of the SPC June 2022 deliberated that Athena will not be adopted, because the estimated Cost-at-Completion to ESA exceeds the budget allocated for an L-class mission. The mission underwent a **design-to-cost exercise**, aiming at defining a profile consistent with a strict cost cap while preserving its flagship nature. At the November 2023 meeting, the SPC endorsed a rescoped version of the *Athena* X-ray observatory, re-christened as NewAthena. While NewAthena bears a direct relation with the non-longer-existing mission *Athena*, the current document is intended to be self-standing unless otherwise specified.

2 THE NEWATHENA MISSION

NewAthena is a powerful, general-purpose **open observatory**, able to address a **wide range of current astrophysical topics.** Its scientific payload will allow unprecedented studies of a wide range of astronomical phenomena. These include distant gamma-ray bursts, the hot gas found in the space around clusters of galaxies, accreting compact objects such as black holes over their whole mass range and neutron stars, supernova explosion and remnants, stars, white dwarfs, exoplanets and their parent stars, Jupiter's auroras and comets in our own Solar System, and the interstellar medium (gas and dust). By combining a large X-ray telescope with state-of-the-art scientific instruments, NewAthena shall address key questions in astrophysics, among them:

- ascertain the nature of the primary source of high-energy radiation in stellar-mass and super-massive accreting black holes (Active Galactic Nuclei, AGN), and its connection with accretion and ejection mechanisms close to the event horizon;
- determine the mechanism(s) regulating the cosmological co-evolution of accreting black holes and their host galaxies;
- measure the space density of the AGN that dominate the black hole growth;
- constrain the kinematics of hos gas and metals in massive halos (galaxy clusters and groups);
- map the properties of the most common baryonic reservoirs in the Universe, and probe their evolution and connection to the cosmic web;
- constrain supernova explosion mechanisms through the determination of the 3-dimensional kinematics, ionization state and abundances in young remnants;

- provide novel and unprecedented constraints on the dense matter Equation of state observing Galactic neutron stars;
- study Solar-Planet Interactions through the stellar magnetic activity in exoplanet-hosting systems.

NewAthena will also provide a key contribution to **multi-messenger astrophysics**, in synergy with gravitational wave arrays and neutrino telescopes.

The scientific payload of Athena comprises:

- the **X-ray Integral Field Unit** (X-IFU) a cryogenic imaging spectrometer covering the 0.2 to 12 keV energy range with unprecedented energy resolution of ≤4 eV at 7 keV over a field of view with an effective diameter of 4'. Thanks to the telescope de-focusing capabilities, it will be able to perform spectroscopy of sources up to the sub-Crab regime (2-10 keV flux ~10^{-8} erg cm^{-2} s^{-1}) with only moderately degraded energy resolution;
- the **Wide Field Imager** (WFI) covering the 0.2 to 12 keV energy range, based on a silicon active pixel sensor. It features a large field of view, excellent spatial and energy resolution and count rate capabilities up to the Crab regime and beyond.

During each sky observation one of the two instruments will be placed in the focal plane of a single X-ray telescope with a focal length of 12 meter (limited by the launcher fairing). The NewAthena optics ensure a large collecting area exceeding 1 m^2 at 1 keV, an angular resolution of 9" (Half-Energy Width, requirement at 1 keV on-axis) over a field-of-view >40' side. Degradation of angular performance off-axis and vignetting are moderate by design. This combination of large area, high angular resolution and large field of view are made possible using the Silicon Pore Optics (SPO) technology developed by ESA and Cosine Measurement Systems over the last decade. SPO utilises commercially available Si wafers, which have surface figure and roughness quality ideally suited to X-ray optics applications, while ensuring an area-to-mass ratio largely exceeding any other X-ray optics technology flown in space so far.

NewAthena is currently baselined to be launched into a halo orbit at the Sun-Earth L1 (1^{st} Lagrangian) point, which provides for high observing efficiency, uninterrupted observations, and a benign thermal environment.

3 NEWATHENA LEVEL 1 SCIENCE REQUIREMENTS (SCIOBJ)

NewAthena SCIOBJs are extracted from the Science Requirement Document (Issue 1.0 – 17 January 2025).

For each of the reformulated SCIOBJ, this document reports a full justification of the rationale for their choice, as well as of the metric to be used in any future trade-off evaluation. Each SCIOBJ is briefly described by a table with the following general structure:

SCIOBJ number	SCIOBJ title
Motivation	
Presentation of the broader context of the science objective and of the main reasons it is compelling. As a guideline, each MDSOs description should be contained into one page of this document. It may include (self-contained) references. Figures are discouraged.	
Experiment:	
Description of the experiment that the SCIOBJ shall accomplish. It shall number up to three experiments required to achieve the SCIOBJ. Please, identify each experiment with [1], [2], and [3] (for tracking purposes, please number the experiment as "[1]" even if it is the only one in the SCIOBJ.	
Quantification:	
Description of the set of measurements that the experiment needs to perform, and/or of the sample over which the measurement must be carried. Ideally, each experiment shall be linked to one or a small set of observable quantities that are needed to achieve the SCIOBJ. Label each quantification as a, b, c … indicating the experiment number at the end. Multiple requirements can link to multiple experiments.	

This document assumes a statistical significance of 5σ for each measurement, unless otherwise specified.

NAT-SCIOBJ-0001	**Determine the location and nature of the primary source of X-rays and its connection to the inner accretion/ejection mechanisms in AGN and stellar compact objects.**
Motivation	
By combining spectral and timing studies of local AGN, stellar-mass black holes, and neutron star X-ray binaries, *NewAthena* will be able to distinguish between the different spectral components from the primary continuum, the reflection at the inner accretion disk and the ones imprinted by an outflowing wind. A key of these measurements will be that ***NewAthena*** will be able to probe the inner accretion flow close to its dynamical time scale (~ hours for AGN) with the highest possible resolution spectroscopy (depending on the source count rate). The obtained time lags and high-resolution spectroscopic measurements on these short time scales will be able to disentangle reflection at the inner accretion disk from the signature of an outflowing wind. This allows one to measure black hole spins, constrain the time-dependent properties of the winds and outflows, and study the accretion disk and coronal physics. Those detailed measurements will then determine the accretion geometry of the disk/corona system, key to understanding the origin of the hot corona, and how winds are launched.	
Experiment:	
[1] *NewAthena* shall perform time-resolved X-ray spectroscopy [1], spectral-timing analysis [2], and reverberation mapping of local Seyfert galaxies, Galactic black hole and neutron star X-ray binaries [3].	
Quantification:	
a. X-IFU observations of 5 bright local AGN with detected relativistic reflection and established time lags. *NewAthena* must obtain high quality spectral products for short 20-30ks segments of the longer several 100ks observations, that are close to the dynamical time scales (~hours) of these systems. b. High-resolution spectroscopy observations of 5 Galactic BHs and 5 NS, including a determination of the wind properties in those systems through time-resolved spectroscopy. Due to the shorter dynamical time scales of the accretion flow in these systems, *NewAthena* must obtain high quality spectral products at 1 ks time scales and perform several observations at different spectral states per object.	

Additional Notes:

For the brighter Galactic sources (>10 mCrab) the X-IFU may need to be defocused and for the brightest objects the lower energy photons (< 1-2 keV) will need to be reduced in the X-IFU, through the inclusion of a filter along the optical path. For the very brightest sources (above a few 100 mCrab) the defocused WFI fast chip will be required, producing spectra that will yield several 10,000 counts/sec for a Crab source, and therefore allowing to probe even shorter time scales of the wind and inner accretion disk.

The targeted Seyfert galaxies show wind and potentially reflection features. The former are known to have spectral variability in the order of a few hours in AGN (see, e.g., Walton et al., 2014, ApJ, 788, 76; Boller et al., 2021, A&A 647, A6). The analysis of Galactic sources is similar, with the main difference being that they show variation in the wind features on much shorter time scales (at the order of ksec), which can also be probed by *NewAthena* as the flux of the Galactic targets is significantly higher. The time-resolved spectroscopy requires that a longer observation can be subdivided into several parts, where each individual segments is close to the dynamical time scales of the inner accretion flow in these systems.

The same observations of Seyfert galaxies and GBHB and NS can also be studied in the time domain, as the reflection at the inner disk shows a time lag due to reverberation. Models such as reltrans (Ingram et al., 2019, MNRAS, 488, 324) are able to perform spectro-timing analyses that fit the time-averaged spectrum simultaneously with the lag-energy spectrum (see, *e.g.*, Mastroserio, 2020, MNRAS, 498, 4971 for Mrk 335). These analyses will be able to break inherent degeneracies in the method when only fitting time-averaged spectra, such as the mass and spin of the black hole are obtained alongside the primary source height above the black hole.

The SRDT final report shows the feasibility in simulations for each of these studies.

NAT-SCIOBJ-0002	**Determine how outflows are launched from around supermassive black holes and how they impact the evolution of galaxies since Cosmic Noon**

Motivation

NewAthena shall determine how outflows are launched and how they impact galaxy evolution. *NewAthena* shall precisely measure their energetics over AGN lifetime to determine whether they can significantly impact their host galaxies and explain partly or totally AGN/galaxy co-evolution at the epoch when SMBH and galaxy growth peaked.

Experiment:

NewAthena shall measure the global/statistical (incidence, duty cycle) and physical properties (column density, ionisation, outflow velocities) of AGN outflows (warm absorbers - WAs - and ultra-fast outflows - UFOs) near Cosmic Noon (z>1) through the study of time-average spectra of systems identified in the WFI survey, and/or time-resolved spectral analysis also on high-spectral resolution pointings of individual, selected source.

Quantification:

a. Wind energetics in 24 nearby AGN shall be measured via high-resolution spectroscopy with the X-IFU. Wind launching physics from time-resolved spectroscopy of 10 AGN - Observe with WFI at least 30 bright AGN with $44.25<\log(L_X)<44.75$ erg/s at z=1-3 (*i.e.*, at least 10 per 1 luminosity bin and per 3 redshift bins) to determine the WA incidence and to constrain the physical properties (N_H, ξ).
b. Observe with WFI at least 40 bright AGN with $44.25<\log(L_X)<44.75$ erg/s at z=1-4 (*i.e.*, at least 10 per 1 luminosity bin and per 4 redshift bins) to determine the UFO incidence/duty-cycle and to constrain the physical properties (N_H, ξ, v_{out}).
c. Measure outflows (WA and UFO) energetics on AGN lifetime with X-IFU for 30 AGN with $44.25<\log(L_X)<44.75$ erg/s at z=1-3.

NAT-SCIOBJ-0003	**Measure the space density of the AGN that dominate black hole growth out to the epoch of re-ionization**

Motivation:

It is now well established that massive black holes (~10^8 -10^9 $M_{\odot}$) are already in place in the early Universe, during the epoch of re-ionization (z≳6), and that supermassive black holes across the mass range (~10^6-10^9 $M_{\odot}$) play a vital role in shaping the Universe throughout cosmic time. However, observational constraints on the formation and initial growth of such black holes through AGN activity remain limited. Recent studies with JWST, probing small areas of sky, have started to reveal surprisingly large populations of early AGN at z~4-10, primarily via unprecedentedly sensitive infrared (i.e. rest-frame UV/optical) spectroscopy. Nonetheless, sensitive X-ray imaging over large sky areas (>10 deg^2) is required to trace the bulk of the early black hole mass growth, including in obscured AGN that would not be identifiable at other wavelengths.

Experiment:

[1] NewAthena shall carry out a survey over sufficient sky area to identify moderate-luminosity AGN to z=8, measure their luminosities and absorption properties, and thus place a constraint on the black hole accretion density since z=8.

Quantification:

a. Achieve a point source sensitivity of $f_{0.5\text{-}2keV}=1.1\times10^{-16}$ erg/s/cm^2 to enable detection of a moderately obscured (N_H~10^{22} -10^{23} cm^{-2}) AGN with $L_X=10^{44}$ erg/s out to z=8 in a reasonable exposure time (≤200ks) over a significant fraction (>80%) of the WFI FoV. [1]
b. Measure a source position to <1" accuracy and thus reliably identify multiwavelength counterparts to enable redshift measurements. [1]
c. Measure their intrinsic luminosity and constrain both the photon index (Γ) and the level of obscuration (i.e. N_H) via X-ray spectral analysis. [1]
d. Carry out a survey to achieve this sensitivity over sufficient sky area to place a constraint on the black hole accretion density to z=8 (current, conservative model extrapolations indicate that a sky area of ~50 deg^2 will be needed to detect 10 sources at z=7-8 with $L_{2\text{-}10keV}=10^{44}$-$10^{45}$ erg/s and provide the necessary constraints). [1]

NAT-SCIOBJ-0004	**Constrain the kinematics of hot gas and metals in massive haloes**

Motivation

Galaxy clusters are known to form through mergers of smaller structures. Here collisions heat the intracluster gas to temperatures of up to 10^8 K. This complex process injects kinetic energy into them, much of which is eventually thermalised. Gas motions consist of shocks, turbulence and sloshing which can be as high as a few hundred km/s according to theory. Powerful jets from the active galactic nucleus located in the dominant central galaxy also contribute to this process by inflating large cavities in a large fraction of clusters characterised by a cool core. A combination of high effective area, high spectral resolution and sufficient PSF is therefore needed to measure gas kinematics in different key zones of a sample of galaxy clusters to track down the halos building process and to quantify the AGN feedback.
Experiment:
[1] *NewAthena* shall quantify how gravitational energy is dissipated into bulk motions and turbulence by achieving a measurement of these quantities over a significant fraction of the halo volume. [2] *NewAthena* shall quantify how AGN feedback is dissipated into bulk motions and turbulence by mapping these quantities on spatial scales sufficiently small to resolve feedback-related substructures.
Quantification:
a. Map a sample of 10 nearby haloes (clusters and groups) out to a radius of $0.5\times r_{500}$ with X-IFU and detect turbulent line broadening with a significance of 5σ (per spatial bin <100 kpc). [1] b. Map the central region for a sample of 8 nearby haloes (clusters and groups) with X-IFU and detect turbulent line broadening with a significance of 5σ on scales no larger than the feedback-related cavities. [2]

NAT-SCIOBJ-0005	**Map via deep X-ray imaging the properties of the most common baryonic reservoirs in the Universe, and probe their evolution and connection to the cosmic web**
Motivation	
The majority of the baryonic content of the local Universe is expected to be in the form of a hot (T>10^6 K), diffuse plasma that fills the large-scale structure set by the distribution of dark matter. However, because of the low densities involved, most of the diffuse plasma has evaded our census thus far. The large soft-band effective area and wide FoV of the WFI are ideal for mapping extended emission from low-density diffuse plasma in the temperature range $10^6 < T < 10^7$ K. This science objective focuses on determining the physical properties and mass distribution of the circumgalactic medium (CGM) of local Milky-Way analogues and detecting emission from the warm-hot intergalactic medium (WHIM) in filaments connecting to the most massive nodes of the cosmic web. Experiment [1] aims at making a census of the CGM of massive galaxies and of the hot atmospheres of low-mass galaxy groups from the local Universe out to redshift z~1.5, i.e. over more than half of the age of the Universe. This will be achieved using a shallow (10 ks) WFI survey covering an area of 384 deg^2. The survey will be optimised for the detection and characterisation of ~400 groups with $M_{500} < 5\times10^{13}$ $M_\odot$ at z>1 (Zhang et al. 2020, A&A, 642, 17), which will allow to constrain the evolution of the luminosity-temperature and discriminate between the predictions of various AGN feedback models. The survey will also be wide enough to stack emission from about 7,000 local L* galaxies to measure the mass of the CGM in the most common baryonic reservoirs and characterise its radial distribution. The efficiency of the survey critically depends on the WFI effective area at low energy, the WFI field of view, and the PSF. Experiment [2] focuses on the study of the CGM in individual, nearby Milky Way analogues. Following the discovery of the eROSITA bubbles (Predehl et al. 2020, Nature, 588, 227), we now know that previous episodes of SMBH activity in our Galaxy lead to large-scale outflows perpendicular to the Milky Way disk. Such bubbles are found to be common in state-of-the-art galaxy formations simulations (Pillepich et al. 2021, MNRAS, 508, 4667) but have thus far not been detected in external galaxies. Deep observations of nearby galaxies with the WFI will be sufficiently detailed to detect bubbles of expanding gas in external galaxies, if present. The experiment will perform such measurements in a volume-limited sample of 10 local L* galaxies to determine the occurrence of Galactic-scale outflows. The most stringent associated scientific requirements are the effective area of the WFI around 1 keV and the telescope's angular resolution. Experiment [3] targets the hot gas that should be present within the filaments that connect to the most massive nodes of the cosmic web – galaxy clusters. These filaments should contain the hottest and densest phase of the WHIM,	

which makes them suitable for direct detection with X-ray telescopes. Observations with *XMM-Newton* (Eckert et al. 2015, Nature, 528, 105) and *eROSITA* (Reiprich et al. 2021, A&A, 647, A2) show that these filaments can be detected using deep mapping of the surroundings of massive clusters. Pointed WFI observations of optically selected filaments around 5 nearby massive clusters will be used to detect and characterize the WHIM emission in the nodes of the cosmic web. The science case sets strong constraints on the WFI effective area at 1 keV and below, the WFI field of view, and the X-ray stray light level.
Experiment:
[1] *NewAthena* shall measure the mass contained in volume filling diffuse gas in local L* galaxies and low mass galaxy groups from low to high redshift (z~1.5). [2] *NewAthena* shall determine the morphology of the hot haloes surrounding spiral star forming L* galaxies in order to probe the physics of AGN feedback in these systems. [3] *NewAthena* shall image the gas found in the large-scale structure filaments around the most massive local haloes.
Quantification:
a. WFI Survey of 10 ks pointings over 384 deg^2: detect >1000 low mass groups at z >1.0 and/or stack of 7000 L* galaxies. [1] b. Pointed WFI exposures around a volume limited sample of 10 local L* galaxies. [2] c. WFI scans around 5 massive local galaxy clusters to detect 10 LSS filaments. [3]

NAT-SCIOBJ-0006	**Map via deep X-ray spectroscopy the properties of the most common baryonic reservoirs in the Universe, and probe their evolution and connection to the cosmic web**
Motivation:	
Galaxies are known to form through accumulation of matter from the circum- (CGM) / intergalactic (IGM), a warm-hot plasma which contains the vast majority baryons in the Universe. Our poor understanding of such plasma results in a major ignorance of galactic evolution and how it feeds into the formation of structure in the Universe. Intergalactic filaments connect the cosmic web which permeates and feeds galaxies through the CGM, the measurement of whose thermodynamical state is beyond the reach the reach of current facilities. A combination of high effective area, spectral resolution, and sufficient PSF is therefore needed to detect plasma filaments both in the CGM through *emission* lines, and in the IGM via *absorption* lines, to unveil the structure of the cosmic web.	
Experiment:	
[1] *NewAthena* will detect line emission from the outer CGM, to probe its thermodynamical and chemical properties and their connection to galaxy evolution. [2] *NewAthena* will probe the typical properties of the intergalactic medium using absorption studies of bright background sources.	
Quantification:	
a. Follow up a sample of 5-10 CGM haloes, to look for line *emission* with X-IFU. [1] b. Detection of 25 LSS filaments in *absorption* against bright background sources. [2]	

NAT-SCIOBJ-0007	**Chemical enrichment over cosmic time**
Motivation	
The chemical enrichment history of the Universe is a broad topic with multidisciplinary appeal. X-rays offer a unique observation window to perform measurement on a wide range of spatial scales and system cosmological redshifts, due to the brightness of the ICM and the comparatively simple physics of optically-thin plasma. This SCIOBJ has two goals, exploiting the complementarity of the scientific payload onboard NewAthena. Experiment [1] focuses on the use of the WFI to perform Fe abundance measurements for local clusters *mapping the entire volume* out to R_{500} once the details of the spectral model to be used will be constrained by X-IFU measurements (cf. Molendi et al. 2016, A&A, 586, A32). It critically depends on the level of the background intensity and its reproducibility together with the effective area in the hard energy band. The enhanced sensitivity and wide FoV of the NewAthena WFI are needed to robustly confirm the initial conclusions – based on deep and expensive	

XMM-Newton and *Suzaku* monitoring campaigns on a few systems – that the level of chemical enrichment of the ICM is remarkably uniform, both from cluster to cluster, and as a function of radius and azimuth within a single target. This was interpreted as evidence that the intergalactic gas was enriched early in the history of the cosmos, *i.e.* before falling into virialized haloes where the stratified entropy profile prevents convection and efficient mixing. Experiment [2] exploits the unprecedented emission line sensitivity of the NewAthena X-IFU to determine the elemental abundances in the high-redshift ($z \leq 2$) ICM. The ICM represents the integrated enrichment averaged over billions of supernova explosions, making it a particularly clean probe to test cosmic nucleosynthesis. For a representative cluster at z~2, determining the abundance of Mg (using transitions at an observed energy ~0.4 keV) is the most challenging measurement, driving the effective area in the softest X-IFU energy bandpass. The determination of the full abundance pattern up to Ni requires good effective area up to ~2.5 keV. In lower redshift targets, NewAthena X-IFU will enable measurements of the abundances of rare, odd-atomic number elements to test supernova nucleosynthesis patterns and yields. Potassium (K) and Titanium (Ti) are of particular interest, because current supernova nucleosynthesis models *heavily* underpredict the abundances of these two elements, compared to Galactic archaeology constraints (Kobayashi et al. 2020, ApJ, 900, 179). Although XRISM/Resolve could *in principle* enable some of the first detections of these rare elements, the required exposure times would be prohibitively long (Kitayama et al. 2014, arXiv1412.1176. Note that part of the goals of this experiment will be serendipitously achieved with systems observed in the framework of NAT-SCIOBJ-0006.
Experiment:
[1] NewAthena shall determine the elemental abundances, and particularly the Fe abundance through the Fe-K line complex, in a sample of local clusters out to R_{500} providing a robust local anchor to evolution studies. [2] NewAthena shall determine the metal abundance pattern in the intra-cluster medium, and quantify its redshift evolution, using high-resolution spectroscopy with X-IFU.
Quantification:
a. NewAthena shall observe a sample of 10 clusters at $z < 0.1$ mapped with 3 WFI pointings to have a full azimuthal coverage out to R_{500}. [1] b. NewAthena shall observe a sample of 10 moderate-mass clusters at redshift z~2, detecting emission lines from Mg, Si, and Fe, with a significance of at least 3σ (for each element). Further, the same set of observations used in NAT-SCIOBJ-0006 will be analysed to determine the chemical composition in local galaxy clusters and compare these to the higher redshift sample. In local galaxy clusters, NewAthena shall also detect rare chemical elements such as Cl, K, Ti with at least a 5σ significance – either in individual objects, or by stacking. [2]

NAT-SCIOBJ-0008	**Multi-messenger astrophysics**
Motivation:	
-	
Experiment:	
NewAthena shall carry out the first census of X-ray counterparts to gravitational wave sources across cosmic times. Positions, light curves and spectra will be used to enable redshift measurements, to determine the geometry of the emitting outflow, and to discern the nature of the central compact object (either a NS or a BH). In combination with gravitational wave and optical data, *NewAthena* will provide multi-messenger constraints to cosmological parameters.	
Quantification:	
A sample of 16 X-ray afterglows with high-quality jet angle determinations would constrain H_0 to an accuracy of ~2%, versus the 50-100 sources that would be needed without afterglow measurements.	

NAT-SCIOBJ-0009	**Equation of State of Neutron Stars**
Motivation:	
The motivation to measure the equation of state (EoS) of dense matter in neutron stars lies in uncovering the fundamental properties of matter under extreme conditions. Neutron stars are the densest observable objects in the universe, containing matter compressed beyond nuclear densities, where quantum chromodynamics (QCD) governs interactions. Studying their EoS provides crucial insights into the behaviour of nuclear matter and the possible	

existence of exotic states like quark matter or hyperons. The EoS determines the mass-radius relationship of neutron stars, revealing their internal structure and setting the maximum mass limit, which distinguishes neutron stars from black holes. The EoS also connects to the early universe, where similar extreme conditions may have existed, and could shed light on dark matter or physics beyond the Standard Model. Furthermore, it influences neutron star cooling, rotational dynamics, and thermal evolution, linking observations across multiple wavelengths, from X-rays to radio. By constraining the EoS, we not only deepen our understanding of dense matter but also test theories of strong interactions, astrophysics, and gravity in one of nature's most extreme laboratories.

Experiment:

NewAthena shall constrain the radius of several rotational powered pulsars in binary systems emitting thermal X-rays from their hot surface. Using the Pulse Profile Modelling technique, and the available neutron star mass measurements derived by radio timing, *NewAthena* will constrain for the first time the dense matter equation of state with unprecedented accuracy.

Quantification:

Pulse Profile Modelling analysis might be performed with *NewAthena* using both WFI (a.) or X-IFU (b.) data. The current source sample reaches ~15 well known pulsars with already available mass measurements via radio timing observations, and detected X-ray emission, but the number will certainly increase after the new SKA Surveys. A single measurement will be sufficient to improve the error on the radius determination of a pulsar from the 20% currently available via *NICER+XMM-Newton* observations, to ~3% with a 200 ks WFI observation, for the faintest pulsars currently known. Measuring the radii of 4-5 of these objects will allow to measure radii covering a large mass range.

NAT-SCIOBJ-0010	**Probe the accretion physics and accretion flow models at high and low accretion rates, and its change at different time scales**

Experiment:

[1] Observe 25 Ultra Luminous X-ray (ULX) sources (high accretion rates) to understand the geometries that enable super-Eddington accretion, and sub-population within the ULX class.

[2] Study the nature of stellar disruption and the subsequent surge in accretion onto SMBHs during Tidal Disruption Events (TDEs) to probe the dynamics of tidal shearing in the proximity of the event horizon, characterize the orbital and physical evolution of the debris, probe the likelihood of disruption for a given stellar population, and gain insight into the effects of rapid accretion rate changes in SMBH systems.

Quantification:

[1] 25 ULX spanning the $39<\log(L_x[erg/s])<41$ luminosity range.

[2] 5 TDEs by ToO observations.

NAT-SCIOBJ-0011	**Determine the SMBH spin distribution in the local Universe as a probe of the growth process (mergers versus accretion, chaotic versus standard accretion)**

Experiment:

Measure black hole spins through reverberation, timing, time-resolved spectroscopy, and time-average spectral methods. Perform a survey of SMBH spins in the local Universe and compare it with predictions from merger and accretion models. The resulting spin distribution can be compared to the complementary measurements of supermassive black hole binary systems by future gravitational wave observatories.

Quantification:

NewAthena shall determine the spin with a statistical accuracy of ≤10% on a sample of 25 AGN in the local Universe.

NAT-SCIOBJ-0012	**Probe of the first generation of stars and the formation of the first black holes**

Experiment:

NewAthena should determine the elemental abundances of the medium around high-z Gamma-Ray busts by deriving relative elemental abundances distinctive of primeval (Pop III) explosions versus evolved stellar populations in the spectrum of GRB afterglows.
Quantification:
NewAthena shall determine the column density of a $N_H=10^{22}$ cm^{-2} ionized system (assuming solar abundance) at 15% statistical accuracy against the backlight of a 2×10^{-7} erg cm^{-2} GRB at z=7 in a 50 ks observation.

NAT-SCIOBJ-0013	**Probe feedback mapping (stellar or AGN)**
Experiment:	
NewAthena should map the AGN and stellar feedback models (particularly starburst super winds) and their dependence on galactic parameters, such as star-formation rate, galaxy type and morphology, and star formation history, as well as the presence of a low-luminosity AGN. This is done by determining the gas, metal and energy output from AGN and Starbursts (U)LIRGs.	
Quantification:	
TBW	

NAT-SCIOBJ-0014	**Redshift evolution of entropy profiles in cluster outskirts**
Experiment:	
NewAthena shall determine the evolution of the gas thermodynamics during hierarchical gravitational collapse as a function of cosmic epoch by measuring the entropy profiles of a limited sample of massive galaxy clusters. The measurement shall be achieved out to z~2 out to R_{500} and resolve the accretion regions (R_{500} out to R_{200}) in local galaxy clusters.	
Quantification:	
NewAthena shall map a sample of 10 galaxy clusters at z~0.1 to detect the faint emission from the intracluster medium out to R200 and characterize its spectral shape, possibly in combination with SZ measurements in the faint outer regions, to determine the gas temperature with a statistical significance greater than 5σ. Further, the same set of observations as in NAT-SCIOBJ-0009 will be used to determine the entropy profiles of a sample of 10 galaxy clusters at z~2.	

NAT-SCIOBJ-0015	**Residual cooling and thermal instabilities in cool core clusters**
Experiment:	
Measure the gas cooling rate and fuelling of the AGN in hot atmospheres by estimating how much gas is at each temperature in the cores, using temperature sensitive line ratios with X-IFU. The experiment depends on detection of faint low energy lines.	
Quantification:	
Observation of a sample of ~10 nearby cool core clusters with X-IFU.	

NAT-SCIOBJ-0016	**Star-planet interactions**
Experiment:	
Determine mass motions of coronal plasma during flares in order to examine the impact on planetary environments.	
Quantification:	
The peak of a large flare on a planet-hosting star as described in Pillitteri et al., 2022, A&A, 666, 198 was simulated, using tabulated spectroscopic results and *NewAthena*'s X-IFU capabilities. Three scenarios of flaring plasma were considered: a stationary flaring component, along with a 300 and 600 km/s blueshift, on timescales of 800 seconds. *NewAthena* would easily be able to diagnose flows in stellar coronae on these timescales, spanning a factor of 20 in temperature (OVIII to FeXXV), and can connect near-stellar activity with transient mass loss that would also impact planetary environments.	

NAT-SCIOBJ-0017	**Metallicity of rare elements in SNR**
Experiment:	
NewAthena shall measure the abundance of rare elements in supernova remnants ejecta. In particular, Cr, Mn, Ni and Ti resonant transitions fall in the 2-10 keV band. The quantification of the relative strength of these elements will have far-reaching consequences on explosion mechanism and neutrino models.	
Quantification:	
X-IFU will be used to identify the different ejecta. Spatially resolved high-resolutions spectroscopy will be performed for line identification and characterization. For 100 ks exposure, *NewAthena* will detect Mn at more than 4σ and Cr at more than 7σ significance.	

NAT-SCIOBJ-0018	**Non-thermal particle acceleration in SNR**
Experiment:	
NewAthena shall detect the underlying non-thermal emission in SNR spectra. The non-thermal, power-law like, emission quantification will give important clues on the synchrotron emission due to the magnetic field and consequently the role of SNR in generating galactic cosmic rays.	
Quantification:	
Thanks to the effective area in the 2-10 keV region, X-IFU and WFI will be able to establish the non-thermal contribution and its slope and distinguish it from the dominant thermal emission.	

NAT-SCIOBJ-0019	**SN population**
Experiment:	
NewAthena shall efficiently detect off-center SNe in other galaxies. SN detections will help in constraining neutrino models and the role of SN in star formation processes.	
Quantification:	
Using WFI, *NewAthena* will be able to detect off-center SNe, taking SN2011dh in M51 ($L_X = 10^{39}$ erg/s) as reference, up to 200 Mpc, for a total of about 30,000 potential host galaxies.	

NAT-SCIOBJ-0021	**Colliding winds in binaries**
Experiment:	
To be written by the *NewAthena* Science Study Team	
Quantification:	
To be written by the *NewAthena* Science Study Team	

NAT-SCIOBJ-0022	**Magnetospheric accretion in low mass stars**
Experiment:	
To be written by the *NewAthena* Science Study Team	
Quantification:	
To be written by the *NewAthena* Science Study Team	

NAT-SCIOBJ-0023	**Magnetospheric activity in low mass stars**
Experiment:	
To be written by the *NewAthena* Science Study Team	
Quantification:	
To be written by the *NewAthena* Science Study Team	

NAT-SCIOBJ-0024	**Mass loss in massive stars**
Experiment:	
To be written by the *NewAthena* Science Study Team	
Quantification:	
To be written by the *NewAthena* Science Study Team	

NAT-SCIOBJ-0025	**Masses of accreting white dwarfs**
Experiment:	
To be written by the *NewAthena* Science Study Team	
Quantification:	
To be written by the *NewAthena* Science Study Team	

NAT-SCIOBJ-0026	**Magnetars**
Experiment:	
To be written by the *NewAthena* Science Study Team	
Quantification:	
To be written by the *NewAthena* Science Study Team	

NAT-SCIOBJ-0027	**Pulsar-wind nebulae**
Experiment:	
To be written by the *NewAthena* Science Study Team	
Quantification:	
To be written by the *NewAthena* Science Study Team	

NAT-SCIOBJ-0028	**Novae and PNe**
Experiment:	
To be written by the *NewAthena* Science Study Team	
Quantification:	
To be written by the NewAthena Science Study Team	

NAT-SCIOBJ-0030	**Chemistry of the cold ISM**
Experiment:	
To be written by the *NewAthena* Science Study Team	
Quantification:	
To be written by the *NewAthena* Science Study Team	

NAT-SCIOBJ-0031	**Dust-scattering halos**
Experiment:	
To be written by the *NewAthena* Science Study Team	
Quantification:	
To be written by the *NewAthena* Science Study Team	

NAT-SCIOBJ-0032	**Physics of the warm and hot ISM**
Experiment:	
To be written by the *NewAthena* Science Study Team	
Quantification:	
To be written by the *NewAthena* Science Study Team	

NAT-SCIOBJ-0033	**Physics beyond the standard model**
Experiment:	
To be written by the *NewAthena* Science Study Team	
Quantification:	
To be written by the *NewAthena* Science Study Team	

NAT-SCIOBJ-0034	**Extragalactic transients and TDEs**
Experiment:	
To be written by the *NewAthena* Science Study Team	
Quantification:	
To be written by the *NewAthena* Science Study Team	

4 NEWATHENA COMMUNITY WORKING GROUPS

A community of over 1100 scientists has joined the NewAthena science community. They are divided into seven Working Groups (WGs). Six of them deal with broad scientific topics belonging to the mission science case:

Large-scale structure of the Universe (WG1): This WG will coordinate investigations on how NewAthena can enable advancement in our understanding of the hot gas that permeates structures in the Universe at intergalactic and larger scales. This includes groups and clusters of galaxies, as well as feedback of accreting supermassive black holes in Active Galactic Nuclei (AGN) onto the intra-cluster medium. At the core of the scientific purview of this WG is the study of the hot gas origin, chemical composition and physical properties as a probe of large-scale structure formation and evolution.

Galaxies and supermassive black holes (WG2): This WG will encompass NewAthena studies of galaxies and their AGN, and their coevolution at all scales, including the geometry and origin of the X-ray emitting regions, the energetics, incidence and effects of AGN outflows, the effects of kinetic and radiative AGN feedback and of stellar feedback on their host galaxies, and AGN population studies up to high redshift to put constraints on the seeds and growth mechanisms of supermassive black holes.

Stars and their environment (WG3): This WG will coordinate the study of prospective NewAthena observations of stars (stellar activity, colliding winds, magnetospheric accretion, mass loss, to mention just a few examples), their planetary systems and star-planet interactions, supernova remnants, and the physics and chemistry of the Interstellar Medium.

Compact objects (WG4): This WG will coordinate scientific activities related to NewAthena studies of compact objects — white dwarfs (WDs), neutron stars (NSs), and black holes (BHs) — in the Milky Way and nearby galaxies. The main focus will be on extreme systems both in isolation and within binary systems. This includes, e.g. pulsars, magnetars, central compact objects, the potential detection of isolated black holes, cataclysmic variables, low-mass and high-mass X-ray binaries hosting neutron stars and black holes, transitional and classical millisecond pulsars, and ultra-luminous X-ray sources.

Transients and multi-messenger astrophysics (WG5): This WG will coordinate the study of the "transient universe" with NewAthena. This will include the determination of the astrophysical nature of the most common celestial sources of neutrinos and gravitational waves, as well as non-persistent electromagnetic sources, such as e.g. supernovae explosions, tidal disruption events, and gamma-ray bursts.

Cosmology and fundamental physics (WG6): This WG will coordinate studies employing X-ray observations with NewAthena to constrain cosmological parameters (e.g. using clusters or quasars); probe particle physics beyond the standard model; perform tests of general relativity (e.g. through accretion processes in the strong gravity regime or via X-ray counterparts to gravitational wave sources); alongside any other studies that address our fundamental models of physics. It is anticipated that many science projects will use the astrophysical objects that are the focus of other WGs, and thus overlap with those efforts.

The SCIOBJ are mapped to the WGs as per the following table:

SCIOBJ	Formulation	WG#
NAT-SCIOBJ-0001	Determine the location and nature of the primary source of X-rays and its connection to the inner accretion/ejection mechanisms in AGN and stellar compact objects (AGN)	2
NAT-SCIOBJ-0001	Determine the location and nature of the primary source of X-rays and its connection to the inner accretion/ejection mechanisms in AGN and stellar compact objects (XRB)	4
NAT-SCIOBJ-0002	Determine how outflows are launched from around supermassive black holes and how they impact the evolution of galaxies since Cosmic Noon	2
NAT-SCIOBJ-0003	Measure the space density of the AGN that dominate black hole growth out to the epoch of re-ionization	2
NAT-SCIOBJ-0004	Constrain the kinematics of hot gas and metals in massive haloes	1
NAT-SCIOBJ-0005	Map via deep X-ray imaging the properties of the most common baryonic reservoirs in the Universe, and probe their evolution and connection to the cosmic web	1
NAT-SCIOBJ-0006	Map via deep X-ray spectroscopy the properties of the most common baryonic reservoirs in the Universe, and probe their evolution and connection to the cosmic web	1
NAT-SCIOBJ-0007	Chemical enrichment over cosmic time	1
NAT-SCIOBJ-0008	Multi-messenger astrophysics	5
NAT-SCIOBJ-0009	Equation of State of Neutron Stars	4
NAT-SCIOBJ-0010	Probe the accretion physics and accretion flow models at high and low accretion rates, and its change at different time scales (ULX)	4
NAT-SCIOBJ-0010	Probe the accretion physics and accretion flow models at high and low accretion rates, and its change at different time scales (TDE)	2
NAT-SCIOBJ-0011	Determine the SMBH spin distribution in the local Universe as a probe of the growth process (mergers versus accretion, chaotic versus standard accretion)	6
NAT-SCIOBJ-0012	Probe of the first generation of stars and the formation of the first black holes	5
NAT-SCIOBJ-0013	Probe feedback mapping (stellar or AGN)	2
NAT-SCIOBJ-0014	Redshift evolution of entropy profiles in cluster outskirts	1
NAT-SCIOBJ-0015	Residual cooling and thermal instabilities in cool core clusters	1
NAT-SCIOBJ-0016	Star-planet interactions	3
NAT-SCIOBJ-0017	Metallicity of rare elements in SNR	3
NAT-SCIOBJ-0018	Non-thermal particle acceleration in SNR	3
NAT-SCIOBJ-0019	SN population	3
NAT-SCIOBJ-0021	Colliding winds in binaries	3
NAT-SCIOBJ-0022	Magnetospheric accretion in low mass stars	3
NAT-SCIOBJ-0023	Magnetospheric activity in low mass stars	3
NAT-SCIOBJ-0024	Mass loss in massive stars	3
NAT-SCIOBJ-0025	Masses of accreting white dwarfs	4
NAT-SCIOBJ-0026	Magnetars	4
NAT-SCIOBJ-0027	Pulsar-wind nebulae	4
NAT-SCIOBJ-0028	Novae and PNe	4
NAT-SCIOBJ-0029	Double-degenerate binaries	4
NAT-SCIOBJ-0030	Chemistry of the cold ISM	3
NAT-SCIOBJ-0031	Dust-scattering halos	3

NAT-SCIOBJ-0032	Physics of the warm and hot ISM	3
NAT-SCIOBJ-0033	Physics beyond the standard model	6
NAT-SCIOBJ-0034	Extragalactic transients and TDEs	5

It is understood that a given SCIOBJ may be in principle mapped to multiple WGs, for instance because the sources needed to perform the corresponding experiment are the same used for a SCIOBJ belonging to another WG. An example is NAT-SCIOBJ-0011: the technique required to determine the spin of accreting super-massive black holes (X-ray spectroscopy of spectral components produced in the innermost region of a relativistic X-ray illuminated accretion disk) are the same required to test alternative General Relativity prescriptions. In the table, a – to a certain extent arbitrary – choice has been done to define a "reference WG" per SCIOBJ, which will take the responsibility of advising the NASST on the SCIOBJ experiment definition, quantification and associated MOL content.

5 ACRONYMS

AGN	Active Galactic Nuclei
AKE	Absolute Knowledge Error
CCD	Charged-Coupled Device
CE	Cosmic Explorer
CGM	Circum-Galactic Medium
FoV	Field-of-View
ET	Einstein Telescope
GCR	Galactic Cosmic Ray
GRB	Gamma-Ray Burst
HEW	Half-Energy Width
ICM	Intra-Cluster Medium
IGM	Inter-Galactic Medium
LSS	Large-Scale Structure
MHD	Magnetic-Hydrodynamic
NASST	NewAthena Science Study Team
RKE	Relative Knowledge Error
SCIOBJ	Science Objective
SCIREQ	Science Requirement
S/N	Signal-to-Noise
SPO	Silicon Pore Optics
SRDT	Science Redefinition Team
ToO	Target of Opportunity
WHIM	Warm-Hot Intergalactic Medium