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THE *Athena* X-RAY OBSERVATORY

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1. THE HOT AND ENERGETIC UNIVERSE

The 2010 Long Range Plan (LRP[1]) recognized high-energy astrophysics (HEA), not only as an area of high impact fundamental research, but also fraught with potential for Canadian technology development. Two missions of particular interest were identified in the LRP: The JAXA-led *Astro-H* mission (Takahashi et al. 2014) and the International X-ray Observatory (*IXO*). The foresight of the Canadian Space Agency (CSA) led to participation in the *Astro-H* mission and the development of the Canadian Astro-H Metrology System (CAMS; Gallo et al. 2014), which will be delivered to JAXA in January 2015 for installation on the *Astro-H* observatory.

In return for its technical contribution a Canadian science team forms part of the international Astro-H Science Working Group (SWG). The Canadian members have taken principal roles on the team leading efforts toward establishing the science programme for supernovae, black holes, and clusters of galaxies. Several Canadian HQPs (postdocs and students) have been involved at various levels of the project. Our HQPs have worked on science planning and have partaken in calibration and testing of science instruments. Canadian HQPs have engaged with the industry partner and the CSA to work on the internal calibration of the CAMS; and with NASA and JAXA as part of the international Software Calibration Team.

The Canadian SWG members will have access to all proprietary team data obtained in the first year of the mission. All Canadian scientists will be able to propose for telescope access during regular Announcement of Opportunities, but more importantly Canadians will have access to experts on *Astro-H* calibration and data handling from colleagues in Canada.

Building on the success of *Astro-H* we now set our sights on the *Athena* mission (Nandra et al. 2014; hereafter N14). The Advanced Telescope for High ENergy Astrophysics (*Athena*) will be led by the European Space Agency (ESA) and has a planned launch date of 2028. The *Athena* concept evolved from the multinational *IXO* mission, which was considered overly ambitious and risky. *Athena* will chase after many of the same science goals as *IXO*, similarly focusing its attention on the hot and energetic universe, but will do so with a more enhanced and robust design. *Athena* will be delivered within the ESA Large Class Mission (L2) programme.

The *Athena* mission was conceived to address *The hot and energetic Universe* science theme in ESA's *Cosmic Vision* programme[2]. The mission will concentrate on two fundamental questions: (1) How does ordinary matter assemble into the large scale structures that we see today? and (2) How do black holes grow and shape the Universe?

To understand the first question astronomers must map out the hot gas structures that make up clusters of galaxies and the intergalactic medium. One must determine the physical properties of the dominant baryonic matter in the Universe and understand how it evolves over time. The second question extends over vastly different scales. The accretion physics that drives matter into the black hole supplies the energy that generates large scale outflows that impact the formation of stars in galaxies and the environments in clusters of galaxies.

The *Athena* science team decomposed the two fundamental questions into 8 "Level 1" science goals each subdivided into more specific ("Level 2") objectives (Nandra et al. 2014). The eight Level 1 science objectives are to understand: (i) The formation and evolution of groups and clusters of galaxies, (ii) Chemical evolution of hot baryons, (iii) AGN feedback in clusters, (iv) Missing baryons, (v) Formation and early growth of black holes, (vi) Accretion through cosmic time, (vii) Galaxy-scale feedback, and (viii) Accretion physics. The main science requirements are summarized in Fig. 1 and a demonstration of the data quality that will be achieved in these endeavors is shown in Fig. 2.

The *Athena* instruments (Sect. 2) will provide exceptional capabilities that will enable science to be performed on a wide variety of astronomical targets. The observatory will be of great value to the entire astronomical community. Presented in Fig. 3 is a non-exhaustive list of potential science issues that can be confronted with *Athena*.

2. THE *Athena* MISSION

To achieve the science goals outlined above the mission requires a large collecting area, a large field of view, and high spectral resolution. The *Athena* mission concept is designed to meet all science requirements. A summary of the key mission parameters and enabling technology is listed in Fig. 4. In Fig. 5 specific Level 2 science goals are list next to the specific performance parameter that will facilitate the observation.

The single X-ray telescope will incorporate silicon-pore optics that will yield a large collecting area with relatively small mass. The on-axis point spread function (PSF) of 5" (half energy width) at $E < 8\,\mathrm{keV}$ will provide sufficient resolution to reach a confusion-limited sensitivity of $10^{-17}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ in the deepest planned surveys (Fig. 6). The effective area at 1 keV will be an unprecedented $2\,\mathrm{m}^2$, which will yield a large sample of AGN at high redshift (> 400 at $z > 6$ and > 20 at $z = 8 - 10$) and galaxy groups at $z > 2$.

The telescope will have a 12 m focal length and direct X-rays to one of two instruments on a movable instrument platform. One instrument is the X-ray Inte-

[1] http://www.casca.ca/lrp2010/11093_AstronomyLRP_V16web.pdf
[2] http://sci.esa.int/cosmic-vision/

How does ordinary matter assemble into the large scale structures that we see today?	
Key issue	***Athena*+ key observation**
The formation and evolution of groups and clusters of galaxies	
Understand how baryons accrete and evolve in the largest dark matter potential wells of groups and clusters. Determine how and when the energy contained in the hot intra-cluster medium was generated.	Map the structure of the hot gas trapped in galaxy clusters at various redshifts out to the virial radius, resolving gas density and temperature with the WFI. Measure the gas motions and turbulence through X-IFU spatially resolved spectroscopy.
The chemical history of the hot baryons	
Determine when the largest baryon reservoirs in galaxy clusters were chemically enriched. Infer the relative contributions of supernova types, and the initial stellar mass function in protoclusters. Identify the locations in clusters where most of the metals are generated, and determine how they are dispersed.	Measure elemental abundances of heavy elements like O, Ne, Mg, Si, S and Fe, through X-IFU X-ray spectroscopy of groups and clusters at different redshifts. Synthesize the abundances using yields of various SN types and AGB stars. Determine where metals are produced in clusters via spatially resolved spectroscopy of nearby objects.
Cluster feedback	
Understand how jets from AGN dissipate their mechanical energy in the intracluster medium, and how this affects the hot gas distribution.	Measure hot gas bulk motions and energy stored in turbulence directly associated with the expanding radio lobes in the innermost parts of nearby clusters with X-IFU. Use sensitive WFI imaging to detect and characterize large scale ripples and weak shocks in nearby groups and clusters.
Determine whether jets from powerful radio-loud AGN are the dominant non-gravitational process affecting the evolution of hot gas in galaxy groups and clusters.	Use WFI to obtain temperature maps of clusters around radio-loud AGN out to intermediate redshifts and map shock structures. Test jet evolution models and infer their impact at the epoch of group and cluster formation.
Establish how AGN feedback regulates gas cooling in groups and clusters and AGN fuelling	Compare jet power estimates by determining total energy budget and dynamical timescales from X-IFU velocity measurements, with accretion rates for competing fuelling models tuned to precisely measured thermodynamical conditions. Determine importance of AGN-induced turbulence in driving thermal instabilities, via mapping of turbulent velocities in a range of systems.
The Warm-Hot Intergalactic Medium	
Find the missing 50% of baryons at z<2 and reveal the underlying mechanisms driving the distribution of this gas on various scales, from galaxies to galaxy clusters, as well as metal circulation and feedback processes.	Determine the distribution of filaments via X-ray absorption spectroscopy against bright distant objects with X-IFU. For the fraction that can be seen in emission, measure their chemical composition, density, size, temperature, ionization and turbulence.

The Energetic Universe: how do black holes grow and influence the Universe?	
Key issue	*Athena*+ key observation
Formation and early growth of supermassive black holes	
Determine the nature of the seeds of high redshift (z>6) SMBH, which processes dominated their early growth, and the influence of accreting SMBH on the formation of galaxies in the early Universe.	Accreting SMBH, even in obscured environments, will be detected out to the highest redshifts through their X-ray emission in multi-tiered WFI X-ray surveys. The most obscured objects will be unveiled by targeted X-IFU spectroscopy revealing strong reflected iron lines.
Trace the first generation of stars to understand cosmic re-ionization, the formation of the first seed black holes, and the dissemination of the first metals.	X-IFU measurements of metal abundance patterns for a variety of ions (e.g., S, Si, Fe) for at least 10 medium-bright gamma-ray burst X-ray afterglows per year with H equivalent column densities as small as 10^{21} cm^{-2} and gas metallicities as low as 1% of solar.
Obscured accretion and galaxy formation	
Find the physical conditions under which SMBH grew at the epoch when most of the accretion and star formation in the Universe occurred (z~1-4).	Perform a complete census of AGN out to z~3, including those that reside inside a Compton-thick environment. This will be achieved via WFI surveys, where strong iron lines will be the signposts of heavily obscured AGN.
Galaxy-scale feedback	
Understand how accretion disks around black holes launch winds and outflows and determine how much energy these carry.	Use X-IFU to fully characterize ejecta, by measuring ionization state, density, temperature, abundances, velocities and geometry of absorption and emission features produced by the winds and outflows in tens of nearby AGN.
Understand the significance of AGN outflows in determining the build-up of galaxies at the epoch when most stars in present day galaxies formed.	X-IFU observations of nearby AGN/ULIRGs/starbursts will probe the interactions of AGN- and starburst-driven outflows with the ISM, and will provide a local template for understanding AGN feedback at higher redshift.
Understand how the energy and metals are accelerated in galactic winds and outflows and are deposited in the circum-galactic medium. Determine whether the baryons and metals missing in galaxies since z~3 reside in such extended hot envelopes.	Use X-IFU to directly map galactic haloes in nearby galaxies to characterize warm and hot gas outflows around starburst, ULIRG and AGN galaxies. Measure gas mass deposited, mechanical energy and chemical abundances to model baryon and metal loss in galaxies across cosmic time.
The physics of accretion	
Determine the relationship between the accretion disk around black holes and its hot electron plasma. Understand the interplay of the disk/corona system with matter ejected in the form of winds and outflows.	Perform time-resolved X-ray spectroscopy of X-ray binaries and AGN out to significant redshifts (z~1), so that time lags between different spectral components can be found and the transfer function measured. These measurements will then determine the geometry of the disk/corona system, key to understanding how jets and winds are launched.
Infer whether accretion or mergers drive the growth of SMBH across cosmic time.	Measure black hole spins through reverberation, timing, time-resolved spectroscopy and average spectral methods. Use spectroscopy to perform a survey of SMBH spins out to z~1-2 and compare with predictions from merger and accretion models.

FIG. 1.— The key issues and observations that will be addressed with *Athena* are summarized. Taken from Nandra et al. (2013).

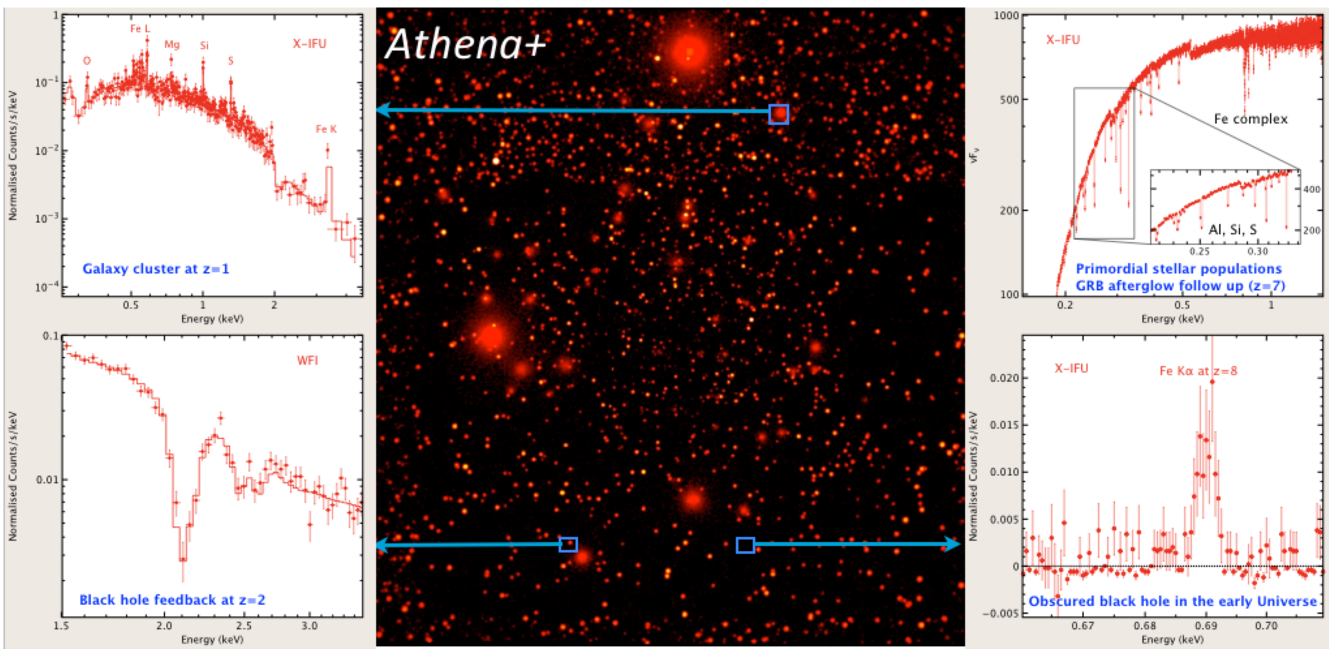

FIG. 2.— The center panel is a simulated deep WFI observation. The surrounding spectra demonstrate the potential of the various instruments in achieving different science goals. Taken from Nandra et al. (2013).

Key issue	*Athena*+ key observation
Planets	
Establish how planetary magnetospheres and exospheres, and comets, respond to the interaction with the solar wind, in a global way that in situ observations cannot offer.	First detailed spectral mapping of Jupiter's X-ray emission, of the Io Plasma Torus, of Mars' exosphere and of X-rays from comets. Fluorescence spectra of Galilean Satellites for surface composition analysis.
Exoplanets	
Extend exoplanet research to incorporate X-ray studies to explore the magnetic interplay between stars and planets.	Measurements of X-ray spectral variability over the activity cycle of the host star and over the planet's orbital period.
Stellar physics	
Assess the mass loss rates of high velocity chemically-enriched material from massive stars to understand the role they play in the feedback processes on Galactic scales.	Time-resolved X-IFU spectroscopy of single and binary massive stars to characterize the large scale structures in their winds and assess their mass-loss rates.
Understand how high-energy irradiation of disks during the formation and early evolution of low and intermediate-mass stars affects disk evolution and eventually planetary system formation	Time resolved X-IFU spectroscopy of the brightest objects to explore the accretion process variability and the modulation due to accretion stream shadowing, and constrain the bulk velocity of accreting material with Doppler line shifts.
Supernovae	
Understanding the physics of core collapse and type Ia supernova remnants, quantifying the level of asymmetry in the explosion mechanism, the production of heavy elements, and their impact on the galactic environment.	First detailed 3D mapping of the hot ejected material in the line of sight (velocity, temperature, ionization state and composition) to determine to the full geometry and properties of the different layers of shocked ejecta.
Stellar endpoints	
Discover how mass loss from disk winds influences the binary evolution and impact the interstellar medium?	Perform multiple X-IFU observations on time-scales shorter than the wind time variability, measuring velocities and ionisation states in the outflow.
Extending the measurements of mass and radius of neutron stars to isolated millisecond pulsars and faint quiescent neutron star binaries	Waveform fitting of X-ray pulses from isolated millisecond pulsars and modeling of atmospheric emission from globular cluster sources.
Sgr A*	
Understand flare production in Sgr A*, the origin of the quiescent emission, and set constraints on the past AGN activity of Sgr A*.	X-IFU observations along with multi-wavelength coverage to measure the ionization process and physical properties of the plasma during the flaring and quiescent states.
Interstellar dust	
Understand the chemical composition of interstellar dust.	X-IFU observation of extended X-ray absorption features.
Interstellar medium	
Determine the chemical composition of the hot gas of the interstellar medium, as a tracer of stellar activity in our and other galaxies.	X-IFU spectrum of the hottest emission and absorption components of the ionized gas characterized by e.g. OVII, OVIII, NeIX

Fig. 3.— Additional science that is enabled by the capabilities of the *Athena* capabilities. Taken from Nandra et al. (2013)

gral Field Unit (X-IFU; Barret et al. 2014), which is a cryogenic X-ray spectrometer based on a large array of Transition Edge Sensors (TES). The TES microcaolimeter, which must be cooled to temperatures less than 100 mK, senses the heat pulses generated by X-ray photons when they are absorbed and thermalized. The temperature increases sharply with the incident photon energy and induces a change in the electrical resistance of the TES, which is registered. The technology will achieve a spectral resolution of 2.5 eV (for $E < 7\,\mathrm{keV}$) over a $5'$ (diameter) field-of-view (FOV). The high spectral resolution imaging will provide information on the chemical composition and dynamics of hot gas in diffuse sources. The X-IFU requirements are shown in Fig. 7.

The second focal plane instrument is the Wide Field Imager (WFI; Rau et al. 2014) – Active Pixel Sensors (APS) based on DEpleted P-channel Field Effect Transistors (DEPFETs). The spectro-imaging technology provides a large field-of-view ($40' \times 40'$) with good angular ($5''$ on-axis) and spectral resolution (150 eV at 6 keV). The architecture allow window-mode readout of the pixel matrices making it possible to address selectively arbi-

Parameter	Requirements	Enabling technology/comments
Effective Area	2 m² @ 1 keV (goal 2.5 m²) 0.25 m² @ 6 keV (goal 0.3 m²)	Silicon Pore Optics developed by ESA. Single telescope: 3 m outer diameter, 12 m fixed focal length.
Angular Resolution	5" (goal 3") on-axis 10" at 25' radius	*Detailed analysis of error budget confirms that a performance of 5" HEW is feasible.*
Energy Range	0.3-12 keV	Grazing incidence optics & detectors.
Instrument Field of View	*Wide-Field Imager:* (WFI): 40' (goal 50')	Large area DEPFET Active Pixel Sensors.
	X-ray Integral Field Unit: (X-IFU): 5' (goal 7')	Large array of multiplexed Transition Edge Sensors (TES) with 250 micron pixels.
Spectral Resolution	WFI: <150 eV @ 6 keV	Large area DEPFET Active Pixel Sensors.
	X-IFU: 2.5 eV @ 6 keV (goal 1.5 eV @ 1 keV)	*Inner array (10"x10") optimized for goal resolution at low energy (50 micron pixels).*
Count Rate Capability	> 1 Crab[3] (WFI)	*Central chip for high count rates without pile-up and with micro-second time resolution.*
	10 mCrab, point source (X-IFU) 1 Crab (30% throughput)	*Filters and beam diffuser enable higher count rate capability with reduced spectral resolution.*
TOO Response	4 hours (goal 2 hours) for 50% of time	*Slew times <2 hours feasible; total response time dependent on ground system issues.*

FIG. 4.— Science driven requirements and the enabling technology are listed. Taken from Nandra et al. (2014).

trary sub-areas of the DEPFET matrix or even to read out different sub-areas at different speeds (Fig. 7).

The *Athena* mission will be operated as an observatory providing access to the entire astronomical community. The nominal mission lifetime will be 5-years and will be launched with an Ariane V-class launch vehicle into a halo orbit around the Sun-Earth second Lagrangian point (L2). The overall performance of the instrument suite is shown in Fig. 8.

3. POTENTIAL CANADIAN INVOLVEMENT

The Canadian community has strong scientific interest in *Athena* that is well document in the 2010 LRP and the HEA Discipline Working Group report to the CSA (Kaspi et al. 2009). A number of Canadian researchers have contributed during the *Athena* proposal phase and have expressed their interest in participating on the science teams in the coming years. As science and instrument work ramps up, the Canadian community will participate in such activities.

There are numerous hardware components that Canadian industry could contribute, particularly to the spacecraft. For example, star trackers and attitude hardware are systems we already have experience building. One intriguing possibility is the potential to develop some of the electronics required for the integral field unit (X-IFU). The CSA has already invested in setting the foundation for this by funding the development of flight qualified readout electronics for transition edge sensors (TES) through their STDP programme. The recently completed contract produced a flight representative version of readout electronics that could be used for *Athena*.

Though *Athena* will possess a rigid optical bench the long focal length and desired angular resolution will require a sophisticated metrology system. The CSA investment into the development of the CAMS metrology system for *Astro-H* created expertise and heritage in optical alignment systems for space telescopes. Such systems are now in high demand for future mission and resulting in contracts for Canadian companies. Similar technology was sought for by ESA to validate a formation flying mission and by independent contractors for a NASA-SMEX proposal.

As we have seen from our modest investment in *Astro-H*, there is true value in participating at an early stage of mission concept and technology development. The technology development for *Athena* will promote and build on current Canadian expertise in industry and academia. Most importantly these activities provide a venue to train the next generation of space researchers and engineers.

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Performance parameter	Requirement	Level 2 Science Goal
Effective area at 1 keV	2 m^2	SG1.1 Finding early groups; SG4.1 Census of warm-hot baryons; SG4.2 Physical properties of the WHIM; SG5.1 High z AGN population; SG5.2 Probing the first generation of stars; SG6.1 Complete census of AGN at the peak of activity of the Universe; SG6.2 Incidence of outflows in z=1-4 AGN; SG6.3 Mechanical energy of AGN outflows at z=1-4; SG6.4 Incidence of ultrafast outflows at z>1; SG8.1 AGN reverberation mapping
Effective area at 6 keV	0.25 m^2	SG1.2 Matter assembly in clusters; SG5.2 Probing the first generation of stars; SG6.1 Complete census of AGN at the peak of activity of the Universe; SG7.1 AGN winds and outflows; SG8.2 Measuring SMBH spins; SG8.3 Measuring spins in GBH
PSF HEW (at E<8 keV)	5" on axis 10" at 25' radius	SG1.1 Finding early groups; SG1.3 Non-gravitational heating processes; SG3.1 Jet energy dissipation in clusters; SG3.2 AGN ripples in clusters; SG3.4 Cumulative energy deposited by radio galaxies; SG5.1 High z AGN population; SG6.1 Complete census of AGN at the peak of activity of the Universe.
X-IFU spectral resolution	2.5 eV	SG1.2 Matter assembly in clusters; SG3.1 Jet energy dissipation on cluster scales; SG4.1 Census of warm-hot baryons; [SG3.3 X-ray cooling cores; SG4.2 Physical properties of the WHIM; SG5.2 Probing the first generation of stars, 3 eV]
X-IFU energy calibration accuracy (rms)	0.4 eV	SG1.2 Matter assembly in clusters; SG3.1 Jet energy dissipation on cluster scales
X-IFU field of view	5' diameter	SG1.2 Matter assembly in clusters; SG3.3 X-ray cooling cores; SG2.1 Metal production and dispersal; SG3.1 Jet energy dissipation in clusters; SG5.2 Probing the first generation of stars.
X-IFU low energy threshold	0.2 keV	SG4.1 Census of warm-hot baryons; SG4.2 Physical properties of the WHIM; SG7.2 Interaction of winds with their environment
X-IFU total optical blocking filter attenuation	Factor 10^{12} at 1200 Å	SG4.1 Census of Warm-Hot baryons; SG7.1 AGN winds and outflows; SG7.2 Interaction of Winds with their environment
WFI field of view	40' x 40'	SG1.1 Finding early groups; SG1.3 Non-gravitational heating processes; SG2.1 Metal production and dispersal; SG3.2 AGN ripples in clusters; SG3.4 Cumulative energy deposited by radio galaxies; SG5.1 High z AGN population; SG6.1 Complete census of AGN at the peak of activity of the Universe.
WFI spectral resolution at 6 keV	150 eV	SG8.3 Measuring spins in GBH; SG8.4 reverberation mapping of X-ray binaries
WFI count rate capability at 80% throughput	1 Crab=2.4 x 10^{-9} ergs s^{-1} cm^{-2} (2-10 keV).	SG8.3 Measuring spins in GBH; SG8.4 reverberation mapping of X-ray binaries
Charged particle background, determined to within a few %	<5 x 10^{-3} cts/cm^2/s/keV	SG1.2 Matter assembly in clusters; SG1.3 Non-gravitational heating processes; SG2.1 Metal production and dispersal; SG6.1 Complete census of AGN at the peak of activity of the Universe
Reconstructed astrometric error	1" (3σ)	SG5.1 High z AGN population; SG6.1 Complete census of AGN at the peak of activity of the Universe
Absolute astrometric error	3" (3σ)	SG3.1 Jet energy dissipation in clusters; SG3.4 Cumulative energy deposited by radio galaxies
GRB trigger efficiency[1]	40%	SG4.1 Census of warm-hot baryons; SG5.2 Probing the first generation of stars
TOO reaction time	< 4 hours	SG4.1 Census of warm-hot baryons; SG5.2 Probing the first generation of stars

FIG. 5.— Specific Level 2 science goals and the specific performance parameter that will facilitate the observation. Taken from Nandra et al. (2014).

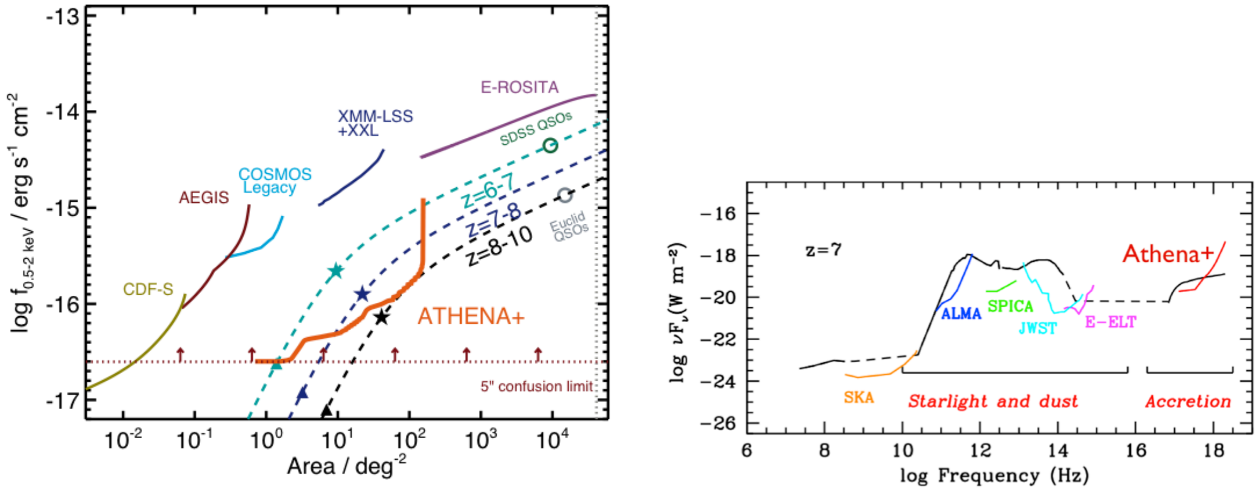

FIG. 6.— Left: The area-flux coverage for a multi-tiered survey with *Athena* WFI compared with existing and planned X-ray surveys. Right: Synergy with contemporary observatories at other wavelengths. The SED of a high redshift ($z = 7$) obscured AGN is shown. Taken from Nandra et al. (2013).

Parameter	Requirements
Energy range	0.3-12 keV
Energy resolution: E < 7 keV	2.5 eV (250 x 250 μm TES pixel)
Energy resolution: E > 7 keV	E/ΔE = 2800
Field of View	5' (diameter) (3840 TES)
Detector quantum efficiency @ 1 keV	>60%
Detector quantum efficiency @ 7 keV	>70%
Gain error (RMS)	0.4 eV
Count rate capability – faint source	1 mCrab (>80% high-resolution events)
Count rate capability – bright source	1 Crab (>30% low-resolution events)
Time resolution	10 μs
Non X-ray background	< 5 10^{-3} counts/s/cm^2/keV

Energy range	0.1 - 15 keV
Field of View	ca. 40x40 arcmin^2 (14.1x14.1 cm^2)
Array format	central array: 256x256 pixel outer arrays: 4x 448x640 pixel
Pixel size	central array: 100x100 μm^2 (1.8 arcsec) outer arrays: 130x130 μm^2 (2.3 arcsec)
Angular resolution (onaxis)	≤ 5 arcsec (oversampling by 2.8)
Quantum efficiency (incl. optical blocking filter)	282eV: 34% 1keV: 98% 10keV: 97%
Energy resolution	ΔE < 150 eV (FWHM) @ 6keV
Readout rate	central array: 7800 fps outer arrays: 2200 fps
Fast timing, count rate capability	8 μs in window mode 0.5 Crab > 88% throughput, < 3% pile-up 1 Crab > 80% throughput, < 5% pile-up
Instrument background at L2	6 x 10^{-4} counts/cm^2/keV/s

FIG. 7.— Performance requirements for the X-IFU (left; Taken from Barret et al. 2014) and the WFI (right; Taken from Rau et al. 2014).

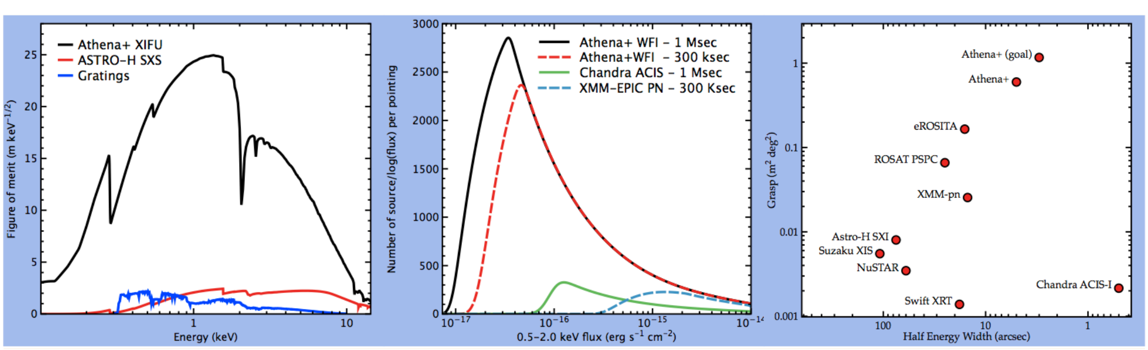

FIG. 8.— Left: Figure of merit for weak spectral line detection of high resolution spectrometers, derived from the number of counts per independent spectral bin. Centre: Number of sources per flux interval expected in single *Athena* WFI pointings at high Galactic latitudes. Right: Grasp (product of effective area and instrument FOV) of various missions as a function of angular resolution. Taken from Nandra et al. (2013).