

The Dawn of Black holes Drivers of Galaxy Formation and Evolution

Microphysics of cosmic plasmas

Exploring the Time Variable Universe

The innermost regions of black holes

White Paper Submitted to Astro2020 Decadal Survey

PI Richard Mushotzky and the AXIS Team

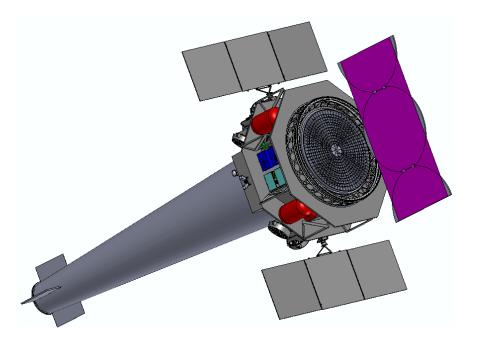
The Energetic Side of Stellar

Evolution

THE ADVANCED X-RAY IMAGING SATELLITE

Authors: Richard F. Mushotzky¹, James Aird², Amy J. Barger³, Nico Cappelluti⁴, George Chartas⁵, Lía Corrales⁶, Rafael Eufrasio^{7,8}, Andrew C. Fabian⁹, Abraham D. Falcone¹⁰, Elena Gallo⁶,
Roberto Gilli¹¹, Catherine E. Grant¹², Martin Hardcastle¹³, Edmund Hodges-Kluck^{1,8}, Erin Kara^{1,8,12}, Michael Koss¹⁴, Hui Li¹⁵, Carey M. Lisse¹⁶, Michael Loewenstein^{1,8}, Maxim Markevitch⁸, Eileen T. Meyer¹⁷, Eric D. Miller¹², John Mulchaey¹⁸, Robert Petre⁸, Andrew J. Ptak⁸, Christopher S. Reynolds⁹, Helen R. Russell⁹, Samar Safi-Harb¹⁹, Randall K. Smith²⁰, Bradford Snios²⁰, Francesco Tombesi^{1,9,21,22}, Lynne Valencic^{8,23}, Stephen A. Walker⁸, Brian J. Williams⁸, Lisa M. Winter^{15,24}, Hiroya Yamaguchi²⁵, William W. Zhang⁸

Contributors: Jon Arenberg²⁶, Niel Brandt¹⁰, David N. Burrows¹⁰, Markos Georganopoulos¹⁷, Jon M. Miller⁶, Colin A. Norman¹⁷, Piero Rosati²⁷



A Probe-class mission study commissioned by NASA for the NAS Astro2020 Decadal Survey

March 1, 2019

AUTHOR AFFILIATIONS

¹ Department of Astronomy, University of Maryland, College Park, MD 20742

² Department of Physics and Astronomy, The University of Leicester, Leicester LE1 7RH, UK

³ Department of Astronomy, University of Wisconsin-Madison, Madison, WI 53706

⁴ Physics Department, University of Miami, Coral Gables, FL 33124

⁵ Department of Physics and Astronomy, College of Charleston, Charleston, SC 29424

⁶ Department of Astronomy, University of Michigan, Ann Arbor, MI 48109

⁷ The Catholic University of America, Washington, DC 2006

⁸ NASA Goddard Space Flight Center, Greenbelt, MD 20771

⁹ Institute of Astronomy, Cambridge CB3 0HA, UK

¹⁰ Department of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA 16802

¹¹ INAF-Osservatorio Astronomico di Bologna, 40129, Bologna, Italy

¹² Kavli Institute for Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139

¹³ Centre for Astrophysics Research, University of Hertfordshire, Hatfield, Hertfordshire, QQ62+JJ, UK

¹⁴ Eureka Scientific, Oakland, CA 94602

¹⁵ Center for Theoretical Astrophysics, Los Alamos National Laboratory, Los Alamos, NM 87545

¹⁶ Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723

¹⁷ Department of Physics, University of Maryland Baltimore County, Baltimore, MD 21250

¹⁸ Carnegie Observatories, Pasadena, CA 91101

¹⁹ Department of Physics and Astronomy, University of Manitoba, Winnipeg, MB R3T 2N2, Canada

²⁰ Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138

²¹ Department of Physics, University of Rome Tor Vergata, 00133, Rome, Italy

²² INAF Astronomical Observatory of Rome, 00078, Monteporzio Catone, Italy

²³ Department of Physics & Astronomy, Johns Hopkins University, Baltimore, MD 21218

²⁴ National Science Foundation, Alexandria, VA 22314

²⁵ Institute of Space and Astronautical Science, Sagamihara, Kanagawa 252-5210, Japan

²⁶ Northrop Grumman Aerospace Systems, Redondo Beach, CA 90278

²⁷ Department of Physics and Earth Science, University of Ferrara, 44122, Ferrara, Italy

1	SUMMARY	1
2	AXIS IN THE FRAMEWORK OF 2020s ASTRONOMY	2
3	MISSION CAPABILITIES AND DESIGN DRIVERS	3
4	TECHNICAL IMPLEMENTATION 4.1 Optics	3 4 8 9
5	 5.1 The Puzzle of Early Massive Black Holes 5.2 Surveying the Distant Black Holes 5.3 Peering at the Vicinity of the Black Hole 5.3.1 Sizes of quasar X-ray emitting regions. 5.3.2 Evolution of SMBH spins in quasars at 0.5 < z < 5. 5.3.3 Imaging BH accretion disks using caustic crossing method. 5.3.4 Ultrafast outflows in quasars. 5.4 Growing a Supermassive Black Hole 5.4.1 SMBH mergers. 	10 10 11 12 12 12 13 13 13 14
6	6.1.1 AXIS discovery space for AGN jets.	16 16 17 18 20 20 21 22 22 24
7	 7.1 Plasma Equilibration Times 7.2 Heat Conductivity 7.3 Viscosity 7.4 Cosmic Ray Acceleration at Shocks 7.5 Magnetic Field Amplification and Damping at Shocks 7.6 Diffusion of Cosmic Rays 	26 26 26 27
8	THE TRANSIENT AND VARIABLE UNIVERSE 8.1 Tidal Disruption Events	 28 28 29 29 30 30
9	THE MILKY WAY AND NEARBY UNIVERSE 9.1 The Galactic Center 9.2 Supernova Remnants 9.3 Dust Halos in the Interstellar Medium	

9.4 Local Volume X-ray Binaries 9.5 Pulsar Wind Nebulae	
10 SOLAR SYSTEM AND EXOPLANETS 10.1 Comet Chemistry 10.2 Variability of the Jovian Magnetosphere and Exosphere 10.3 Evolution of Planetary Atmospheres in the Solar System 10.4 High-Resolution Mapping of Elements on the Lunar Surface 10.5 Exoplanet Atmospheres	33 33 34
11 AXIS MIRROR ASSEMBLY 11.1 The Silicon Metashell Approach 11.2 Mirror Technology Development 11.3 Mirror Segment Fabrication 11.4 Mirror Segment Coating 11.5 Mirror Segment Alignment 11.6 Testing and Qualification of the Mirror Module 11.7 Technology Development Schedule	34 35 36 37 37 39 41 41
12 AXIS DETECTOR ASSEMBLY 12.1 Focal Plane Detectors 12.1.1 CCD Technology Development. 12.1.2 CMOS Technology Development. 12.2 Sensor Housing 12.3 Optical and Contamination Blocking Filters 12.4 Focus Mechanism 12.5 Front-End Electronics Design and Technology Development	41 42 43 43 44 44 44
13 SPACECRAFT AND MISSION OPERATIONS 13.1 Pointing accuracy and in-orbit angular resolution 13.2 Rapid response to transient sources	45 46
14 COST ESTIMATE 14.1 Descopes 14.2 Enhancements	48 49 50
15 ACRONYMS AND ABBREVIATIONS	51
16 REFERENCES	54

1 SUMMARY

Over the last 40 years, X-ray observations have proven crucial for advancing major areas of astrophysics. Indeed, much of the baryonic matter in the Universe, including the most active and luminous sources, are best studied in the X-ray band. Key advances in X-ray optics and detector technology have paved the way for the Advanced X-ray Imaging Satellite (*AXIS*), a Probe-class mission that is a major improvement over *Chandra* — with higher-resolution imaging over a larger field of view at much higher sensitivity, and flexible mission operations allowing *Swift*-like transient science. The design and operations allow an extensive guest observer program open to all areas of science. *AXIS* can be launched in the 2020s and will transform our understanding in several areas of astrophysics. Among them are:

• The growth and fueling of supermassive black holes (SMBHs): Deep surveys will reveal the formation and evolution of early black holes (BHs). Resolving dual active galactic nuclei (AGN) will quantify the frequency of BH mergers. Observations, at an unprecedented angular resolution, of gravitationallylensed quasars and hot gas within the Bondi radius of nearby galaxies will allow us to study the matter in the immediate vicinity of the SMBHs.

• Galaxy formation and evolution: *AXIS* will detect and resolve powerful outflows from AGN and supernovae driven winds during the peak era of star formation, and separate X-ray binary (XRB) emission from AGNs at even higher redshifts. *AXIS* will study the warm and hot gas in and around nearby galaxies and the intergalactic medium near galaxy clusters — the ultimate reservoir of energy and metals expelled from the galaxies over their lifetime.

• The microphysics of cosmic plasmas: AXIS will find and resolve shocks, instabilities and perturbations in the intracluster medium and supernova remnants (SNRs). These are sensitive probes of basic plasma properties and processes, such as viscosity, heat conductivity, equilibration timescales, and acceleration and diffusion of cosmic rays — crucial building blocks for understanding and modeling a wide range of astrophysical phenomena.

• The time variable universe: Rapid repointing will enable observations of violent cosmic events out to high redshift, including the early stages of supernovae, the electromagnetic counterparts of gravitational waves from SMBH mergers, tidal disruption events, neutron star mergers, AGN flares, and stellar flares.

• A wide variety of cutting-edge science: A high angular resolution X-ray observatory such as *AXIS* can provide critical data for a wide variety of areas such as the origin of the elements, the habitability of exoplanets around active stars, proper motions in AGN jets and SNRs, the nature of dust in the interstellar medium (ISM), and allow for a detailed mapping of the elements on the surface of the Moon and aurorae on Jupiter.

AXIS is designed to make these and other scientific advances within the constraints of a Probe class mission. Its groundbreaking capability is due to improved imaging over NASA's existing flagship X-ray observatory, *Chandra*, and the European Space Agency's planned *Athena* mission. Relative to *Chandra*, the *AXIS* on-axis Point Spread Function (PSF) is nearly twice as sharp; its field of view for subarcsecond imaging 70 times larger by area; its effective area at 1 keV is 10 times larger (Table 1). The *AXIS* low-inclination, low-Earth orbit (LEO) ensures a low and stable detector background, resulting in 50 times greater sensitivity than *Chandra* for extended sources.

AXIS has a rapid repointing response with operations similar to Swift, but is 100 times more sensitive for time domain science (as measured by the product of source sensitivity and response time). These capabilities open up a vast discovery space, and complement the next generation of astronomical observatories, such as *JWST*, *WFIRST*, *LSST*, *SKA*, *TMT*, *ELT*, *GMT*, or *CTA*. As seen by the strong synergy between *Chandra* and *XMM-Newton*, a high-throughput, high-spectral-resolution mission (*Athena*) operating at the same time as a high-angular-resolution mission (*AXIS*) greatly increases the range of scientific discovery.

The simplicity of the AXIS design — a single mirror and detector, and few moving parts — results in a robust, low-cost design. AXIS builds on developments in X-ray mirror technology over the past decade that

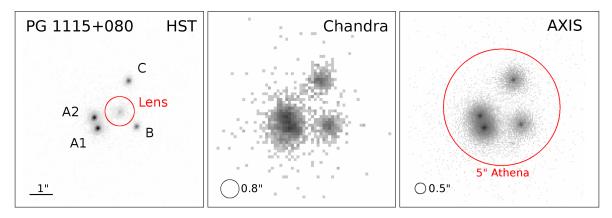


Fig. 1— *AXIS* will be able to measure the innermost stable circular orbit and spin of the SMBH in the quadruply-lensed quasar PG1115+080 (HST image at left) through monitoring spectral variability of the quasar's multiple lensed images (A1, A2, B, C). An archival 30 ks *Chandra* image (0.8'' HPD) has limited photon statistics and does not separate the A1 and A2 images, whereas a 30 ks *AXIS* exposure (0.5'' HPD) will yield high-quality spectra from each quasar image and the variability on timescales much shorter than those accessible for *Chandra*.

produce high-angular-resolution, lightweight X-ray optics at reasonable cost, utilizing precision polishing and thin single-crystal silicon mirrors developed at Goddard. An angular resolution better than 2.2" for a mirror segment pair module was demonstrated in 2018¹ and **as of early 2019, mirror segments with figure quality of 0.5**" **HPD have been regularly fabricated at GSFC.** The baseline *AXIS* small-pixel detector array builds on a long legacy of X-ray CCD and benefits from 25 years of technology development, providing improved photon localization and thus better effective angular resolution, much faster readout time, and broader energy band. Both CCD and CMOS type detectors with the required properties are already under development^{2,3}.

AXIS successfully completed NASA/GSFC Instrument (IDL) and Mission (MDL) Design Lab studies, during which the telescope, detector and spacecraft designs were developed using proven components and modern technical approaches compatible with the AXIS science requirements. The estimated mission costs are consistent with the \$1B Probe mission cost guideline in 2018 dollars. The single technology area requiring significant development is the construction of the X-ray mirror. Successful development of the AXIS optics will serve as the technological and scientific pathfinder for a major US-led high energy astrophysics mission in the 2030s.

2 AXIS IN THE FRAMEWORK OF 2020s ASTRONOMY

A new era of astronomical discovery in the imaging, spectral, and time domains is underway with the next generation of observatories being planned and now in operation that span the electromagnetic spectrum. *AXIS* is highly complementary to these observatories, with its ability to respond rapidly to transients, observe the highest redshift BHs, identify the electromagnetic counterparts of gravitational wave sources, and probe feedback over a wide range of redshift and galaxy mass.

While *Chandra* and *XMM-Newton* were well-matched to the available sensitivity at other wavelengths in 1999, current X-ray facilities are insufficient to address the cutting-edge, high-profile science goals attainable with the latest space-borne (*Herschel* and, soon, *Euclid* and *JWST*) and ground-based (e.g, *LSST* and *ALMA*) observatories, as well as the planned *WFIRST* and 30-m ground based telescopes. *AXIS* will expand the frontiers of X-ray astronomy in a manner that complements and enhances these goals and guides those observatories. *AXIS* will make major breakthroughs in the study of the universe by virtue of its high angular resolution over a wide field of view, high sensitivity to point-like and diffuse X-ray emission, and its rapid response to transient sources (see figures of merit in Figs. A.4–6).

AXIS capabilities are critical for identifying unique counterparts and making morphological comparisons with sources seen at other wavelengths. For example, at the 1.6 μ m wavelength where WFIRST is near peak-sensitivity,^{*} there are 0.16 sources per arcsec² at an AB mag of 28⁴, and AXIS' resolution is required for unambiguous X-ray counterpart identification and characterization.

AXIS has the field of view, resolution, and sensitivity to provide complementary data to the WFIRST, ELT, TMT, and GMT cameras. In turn these observatories will provide the data to obtain precise redshifts, bolometric luminosities and other physical properties for the sources AXIS will discover using optical data through to the submillimeter and millimeter (which will include obscured sources). The use of wide spectral energy coverage with matching sensitivity and resolution is key to mapping the redshift evolution, galaxy masses, and star formation rates of the host galaxies of the AGN population and partitioning the spectral energy distribution into AGN and non-AGN components (Section 6.3). This is critical, since most massive high-redshift galaxies host AGNs.

Three major X-ray missions are under development: *eROSITA* will launch in 2019, *XRISM* in 2021, and *Athena* in the early 2030s. These missions form a rich complementary environment for *AXIS*. Prior to *AXIS*, the all-sky *eROSITA* will discover a large sample of relatively bright X-ray sources that *AXIS* or *Athena* can follow up. Meanwhile, *XRISM* will take the first high spectral resolution observations of moderate samples of bright sources. *Athena* is a planned major ESA X-ray mission with moderate angular resolution (5") and powerful spectroscopic and timing capabilities. *AXIS* could be launched close to the *Athena* launch date; its high angular resolution imaging would complement *Athena*'s high spectral resolution. For deep imaging, *Athena* is fundamentally limited by confusion (Fig. 3), becoming confusion-limited⁵ at a 0.5–2 keV flux of $\sim 2 \times 10^{-17}$ erg s⁻¹ cm⁻² for a beam size of 5". In contrast, the *AXIS* confusion limit is $\sim 10^{-19}$ erg s⁻¹ cm⁻². This faint confusion limit, combined with high effective area, will allow *AXIS* to detect sources that are more than an order of magnitude fainter than the deepest *Chandra* detections over a field of view that is 7 times larger than the higher-resolution (HPD<3") portion of the Chandra field used for deep surveys.

3 MISSION CAPABILITIES AND DESIGN DRIVERS

The prime scientific drivers of the mission design are: 1) The growth of SMBHs and the astrophysical drivers of galaxy evolution for the 0.5'' angular resolution; 2) the evolution of structure over cosmic time and the physics of plasmas in clusters for the $24' \times 24'$ field of view; 3) the physics in the immediate vicinity of BHs for the energy resolution; 4) the detection and characterization of the hot baryons in and around galaxies, the early stages of supernovae, and tidal disruptions of stars by SMBHs for the collecting area and low energy range; 5) the physics of plasma, shocks, and cosmic ray acceleration for the high energy range and low background, requiring in turn LEO; 6) time-domain astronomy for the rapid slewing and quick response to target-of-opportunity (ToO) requests, 7) the high observing efficiency and the ability to observe bright sources free of photon pile-up and to study rapidly variable sources for the maximum detector readout rate; 8) the budget and mass limit for the simple, robust design.

The flowdown of science requirements into technical implementation is summarized in Science Traceability Matrix (page 6–7); a summary of the *AXIS* capabilities and science drivers is given in Table 1; and a comparison with *Chandra* with regard to the PSF and effective area is shown in Fig. 2. Figures of Merit for imaging, low surface brightness, and timing science are shown in Figs. A.4–6 (page 5) in comparison with other current and future missions. The imaging capabilities of *AXIS*, *Chandra* and *Athena* are compared in Fig. 1 using an example of the quadruple gravitational lens PG1115+080.

4 TECHNICAL IMPLEMENTATION

AXIS achieves major scientific breakthroughs as a Probe class mission through the combination of a major advance in X-ray optics, substantial improvement in detector performance and X-ray filters, a straightfor-

^{*}https://wfirst.gsfc.nasa.gov/science/WFIRSTScienceSheetFINAL.pdf

TECHNICAL IMPLEMENTATION

Feature	Value	AXIS vs. Chandra	Science Driver		
Angular resolution (HPD, at 1 keV)	0.5" on-axis 1" at 15' off-axis	1.6 imes sharper 28 imes sharper	Point source detection, separation, excision		
Energy band	0.2-12 keV	Similar	Soft and hard X-ray sensitivity		
Effective area (mirror + detector)	5800 cm ² @ 0.5 keV 7000 cm ² @ 1.0 keV 1500 cm ² @ 6.0 keV	$15 \times (\text{launch}), 10^3 \times (2018)$ $10 \times (\text{launch}), 40 \times (2018)$ $6 \times$	Faint source detection and analysis		
Energy Resolution	60 eV @ 1.0 keV 150 eV @ 6.0 keV	Similar	Resolving emission lines		
Timing Resolution	< 50 ms	$64 \times$ faster readout; pile-up limit $6 \times$ brighter	Variable sources; observing bright sources		
Field of View	$24' \times 24'$	$70 \times$ for $< 1''$ imaging	Extended sources, surveys		
Detector Background	$2 \times 10^{-4} \text{ ct s}^{-1} \text{ keV}^{-1}$ arcmin ⁻² @ 1 keV	$4 \times$ lower; $50 \times$ better sky/background ratio	Sensitivity to low surface brightness objects		
Slew Rate	120°/5 min	Comparable to Swift	Observing efficiency, ToO response		

Table 1 — AXIS mission parameters, compared with Chandra ACIS best-in-class values.

ward and cost-efficient operations philosophy in a LEO that minimizes background and detector degradation while optimizing response time and observing efficiency, and low-cost launch capability.

4.1 Optics

The *AXIS* mirror assembly provides a major leap forward from the state of the art represented by *Chandra*. This dramatic improvement is enabled by the silicon metashell optics (SMO) concept, and recent progress that is the culmination of a \sim 20-year technology development effort.

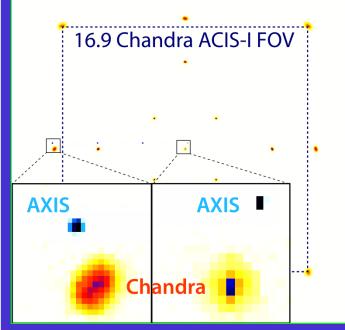
The SMO technology is the same as baselined for the *Lynx* Flagship study. Mirrors of 0.5 mm thickness with extremely accurate surface figure are fabricated from stress-free, mono-crystalline silicon substrate using rapid, deterministic, precision polishing. Taking advantage of the availability of abundant, inexpensive large blocks of mono-crystalline silicon and the equipment and knowledge accumulated by the semiconductor industry to process it, this technology provides a three-fold set of improvements over *Chandra*: (1) better angular resolution, on and off axis; (2) an order of magnitude reduction of mass per unit effective area; and (3) an order of magnitude cost reduction per unit effective area. *AXIS* introduces aspects of Type-I Wolter-Schwarzschild design to improve off-axis PSF performance over that of the *Chandra* Type-I Wolter design. Additional improvement of the off-axis performance is obtained by introducing mirror elements with a smaller axial-length-to-focal-length ratio than *Chandra*'s.

The *AXIS* mirror is entirely made of silicon, resulting in much larger tolerances on mirror on-orbit operating temperature and thermal control and significant reduction in thermal environmental control during construction, testing, and transportation on the ground. The highly modular approach to mirror construction is amenable to parallel production and straightforward de-scoping if needed. The mirror segment dimensions are similar to semiconductor industry silicon wafer dimensions, allowing the use of commercially available equipment and knowledge to minimize cost and production time. The major technology developments needed are the coating of mirror segments to enhance reflectivity without figure distortion and their integration into mirror modules (aligning and bonding).

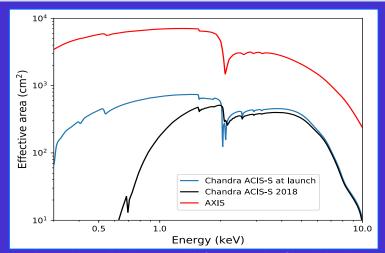
An angular resolution of 2.2'' for a segment pair (1.3'' at 1 keV if effects of gravity distortion and energy dependence are subtracted) was achieved during the most recent X-ray performance measurement



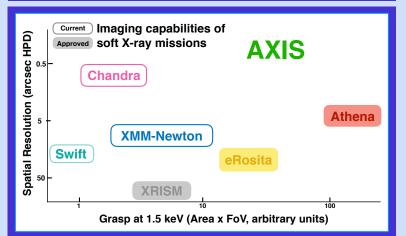
24 arcmin AXIS FOV



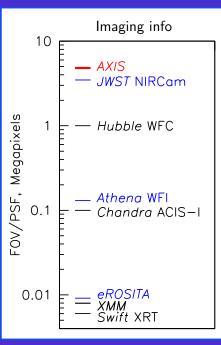
A.1 The AXIS field of view and PSF, shown in comparison to Chandra ACIS-I. Optics breakthroughs allow AXIS to have unprecedentedly sharp angular resolution across its entire field of view. This is especially important for survey science.



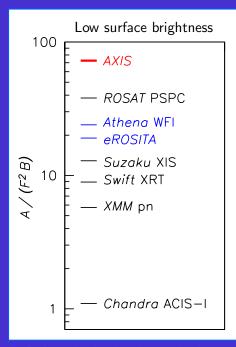
A.2 The effective collecting area of AXIS, compared to Chandra's value at launch and as of 2018. Contamination on the Chandra filters has led to a significant low-energy degradation over the years, making AXIS particularly important for soft X-ray studies.



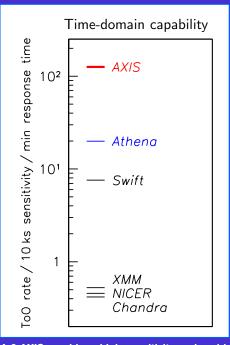
A.3 Imaging capabilities of soft X-ray missions: AXIS and its place among current and planned X-ray missions covering a comparable energy band. AXIS has the best resolution and second best grasp.



A.4 The field of view divided by the point spread function, giving the total number of resolution elements ("pixels") in an observation. Planned missions are in blue and existing missions in black.



A.5 Ratio of sky signal to detector background (A is effective area, F is focal length and B is background) that determines sensitivity to low surface brightness, such as that in galaxy clusters and filaments of the Cosmic Web.



A.6 AXIS combines high sensitivity and rapid response time (< 4 hr) and will devote 10% of observing time to ToOs. AXIS excels in its ability to respond to transients from LSST, LISA, LIGO, and other time domain surveys.

A×IS Science Traceability Matrix								
Science Goal	Science Objectives	Physical Parameters	Observables	Intrument Requirements Parameter	Baseline Requirement Value	Threshold Requirement Value	Goal Value	Mission Parameters
	Study SMBH	ling by olving hot within the BH sphere of uence (R _{Bondi}) Density and temperature structure of the accreting gas within R _{Bondi} in >10 nearby AGN	Obtain soft X-ray spectra from >5 regions within R_{Bondi} to map temperature and density of the accreting gas to < 10%	PSF, on-axis	0.5″	1″	0.3″	
	fueling by resolving hot gas within the SMBH sphere of influence (R _{Bondi}) in nearby galaxies			Effective area at 0.5 keV	5500 cm ²	4000 cm ²	6000 cm ²	
				Minimum energy Energy resolution (FWHM) at 1 keV	0.2 keV 60 eV	0.3 keV 100 eV	0.2 keV 50 eV	
	Map coronal	Size of the X-ray	Measure the light curves	PSF, on-axis	0.5″	1″	0.3″	
	and accretion			Effective area at 6 keV	1500 cm ²	1000 cm ²	1600 cm ²	
Determine the Origin and Evolution of SMBHs	disk emission corona, the and ultrafast region producing outflows the soft excess, in distant and the gravitationally molecular torus lensed AGN	in the energy bands in which these emission components dominate for ~100 lensed AGNs	Energy resolution (FWHM) at 6 keV	150 eV	170 eV	130 eV		
	Determine	Redshifts of inner regions of accretion disk	Measure the shifts in spectral features in ~30 gravitationally lensed AGNs	PSF, on-axis	0.5″	1"	0.3″	
	ISCO and spin			Effective area at 6 keV	1500 cm ²	1000 cm ²	1600 cm ²	
	parameters of distant AGN			Energy resolution (FWHM) at 6 keV	150 eV	170 eV	130 eV	
	offset/recoiling AGN in distant galaxies black hole	Constrations of	Perform blind	PSF, on-axis	0.5″	1"	0.3″	
		dual AGN down to 3 kpc at the peak of cosmic	search of the ~750,000 serendipitous AGN that AXIS will detect over a 5 year mission	PSF, FoV average	1″	2″	0.75″	
			Observe a sample	PSF, on-axis	0.5″	0.7″	0.3″	
	Study relativistic AGN jets	Nature of jet X-ray emission; linear sizes of time-variable knots	of z>2 jets and examine their spectra; measure light curves of X-ray knots in nearby jets	Effective area at 1.0 keV	6500 cm ²	5000 cm ²	7500 cm ²	
	Study hot gas in and around galaxies	Density, temperature, and abundance profiles of hot gas in and around hundreds of galaxies (targeted + survey), including at large distances	Map the intensity of faint thermal X-ray emission dominated by soft spectral lines and examine their spectra	PSF, on-axis	0.5″	1"	0.3″	
				Effective area at 0.5 keV	5500 cm ²	4000 cm ²	6000 cm ²	
Determine the Astrophysical Drivers of Galaxy Evolution				Particle background at 1 keV	2x10 ⁻⁴ c/s/ arcmin²/keV	4x10 ⁻⁴ c/s/ arcmin²/keV	10 ⁻⁴ c/s/ arcmin ² /keV	LEO
		Density, temperature, and metallicity of gas between 1–2 virial radii around clusters	Map the intensity of faint X-ray emission from Cosmic Web filaments near clusters and examine their spectra	PSF, FoV average	1″	2″	0.75″	
				FoV	24'x24'	15'x15'	36'x36'	
				Particle background	$2 \times 10^{-4} \text{ c/s/}$	4x10 ⁻⁴ c/s/	10^{-4} c/s/	LE0
				at 1 keV Bandpass	arcmin ² /keV 0.2–5 keV	arcmin ² /keV 0.5–2 keV	arcmin ² /keV 0.2–12 keV	

AXIS Science Traceability Matrix

C. States					A State State		the second de	Sec. 3
Science Goal	Science Objectives	Physical Parameters	Observables	Intrument Requirements Parameter	Baseline Requirement Value	Threshold Requirement Value	Goal Value	Mission Parameters
	Resolve		Search for	PSF, on-axis	0.5″	1″	0.3″	
	shocks in the		shocks in cluster	FoV	24'x24'	15'x15'	36'x36'	
	intracluster medium of low-z clusters to study heat conduction and electron-ion equilibration	Temperature profiles across shock fronts in cluster outskirts	outskirts; obtain X-ray spectra in few-arcsec	Particle background	6x10 ⁻⁴ c/s/	1.2x10 ⁻³ c/s/	3x10 ⁻⁴ c/s/	LEO
				(1–5 keV)	arcmin ²	arcmin ²	arcmin ²	
			wide bins across shock fronts to measure electron temperatures	Bandpass	0.5–8 keV	0.5–5 keV	0.2–12 keV	
Understand the Microphysics of Cosmic Plasmas	Map gas stripping from galaxies to determine plasma viscosity	Temperature and morphology of gaseous tails behind infalling galaxies and groups	Search for stripping tails; map the X-ray brightness and morphology of stripping tails; obtain X-ray spectra to determine temperature	Particle background (1—5 keV)	6x10 ⁻⁴ c/s/ arcmin ²	1.2x10 ⁻³ c/s/ arcmin ²	3x10 ⁻⁴ c/s/ arcmin ²	LEO
	Resolve shock precursors in SNR to measure diffusion of relativistic paricles in plasma	Emission from energetic particles streaming ahead of fast shock waves	Search for very faint extended precursor emission in front of synchrotron- dominated shock waves; map its brightness and extent	PSF, on-axis	0.5″	1"	0.3″	
	Observe early stages of SNe	Emission from core-collapse SNe as soon as possible after shock breakout	Measure rapidly (minutes to hours) brightening soft continuum emission	Effective area at 0.3 keV	3000 cm ²	2500 cm ²	4500 cm ²	
				Rapid response				Fast slew, LEO
	Resolve ULX pulsation	Periodicity in large, broad sample of ULX out to 250 Mpc	Measure light curve periodicity	Readout time	50 ms	50 ms	10 ms	
Examine the Time Variable Universe	Detect tidal disruptions of stars in massive black holes	Spectral evolution potentially from super-Eddington to sub-Eddington states. Follow-up monitoring of TDE candidates identifided from multi- wavelength surveys.	Examine soft X-ray spectra to characterize thermal emission, outflows, and column density changes.	Effective area at 0.3 keV	3000 cm ²	2500 cm ²	4500 cm ²	

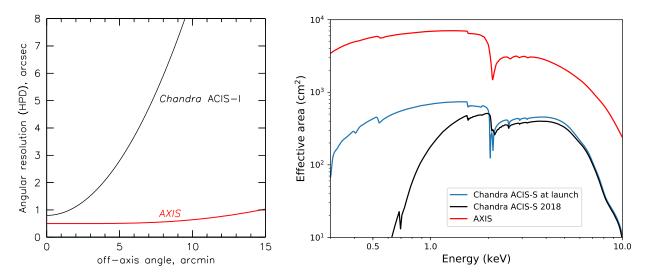


Fig. 2—*AXIS* has larger effective area and better imaging performance than *Chandra*. Its on-axis PSF will have a 0.5" half-power diameter (HPD) at E = 1 keV, of which 0.4" is the mirror contribution (§13). The optical design of the *AXIS* mirror is optimized for a sub-1" PSF over the entire *AXIS* field of view. *Chandra*'s on-axis HPD is 0.8" (0.6" mirror-only) and increases more steeply with off-axis angle.

in summer 2018. Mirror development is funded at \$2.4M a year by NASA for the foreseeable future, and the schedule anticipates TRL 5 by the end of 2022, making mirror modules meeting the *AXIS* requirement of 0.3" HPD (each module). Assembling 188 modules into a mirror will yield HPD of 0.4" on-axis (§11), and detector and aspect errors will result in an in-orbit PSF of 0.5" HPD (§13.1) — an improvement over *Chandra*'s 0.8".[†] The *AXIS* PSF will stay sharper than 1" over a r = 15' field of view, a great improvement over r < 2' for *Chandra* (Fig. 2).

4.2 Detectors

The *AXIS* focal plane exploits the high angular resolution, broad spectral coverage, wide field of view, and high throughput provided by the optics, and capitalizes on the extensive heritage from previous X-ray observatories that utilized solid-state silicon CCD detectors of similar size, quantum efficiency (QE), and spectral resolution to that required by *AXIS*. The key technical challenges are pixel size, readout rate, and fast, low-noise electronics to process and filter the onboard data stream. The *AXIS* LEO minimizes cosmic ray damage to the detectors. Our baseline conceptual design demonstrates the feasibility of using fast parallel-readout CCDs, the workhorse soft X-ray imaging detector of the last 25 years, and CMOS active pixel sensors, which are fast, low-power, radiation-hard devices with less heritage, and our current design incorporates both. Considering both technologies at this stage minimizes technical risk; we plan to closely follow their advances and select one type of the detector for the flight design.

The baseline AXIS camera design uses four $1.5k \times 2.5k$ CCDs to tile the majority of the focal plane outside of the center, and a single, smaller $1k \times 1k$ CMOS in the center to minimize photon pile-up (when more than one photon hits the same pixel between read-outs, which results in undercounting of photons and skews detected photons to higher energy) for observations of bright targets. The CCDs are tilted to approximate the curved focal plane. Both detectors have $16 \mu m (0.37'')$ pixels and take advantage of subpixel positioning of the electron cloud that results from a photon hit, thus adequately sampling the exquisite mirror PSF. Both types of detectors are baselined to read out at 20 frames/s ($64 \times$ faster than *Chandra* ACIS full-frame) to prevent pile-up and to allow timing of XRBs and transients at the 50 ms level. Both detector types have excellent QE and provide moderate, near-theoretical spectral resolution across the 0.2–12 keV

[†]Chandra Observatory Guide, http://cxc.harvard.edu/proposer/POG

energy band. With an $i \le 8^\circ$ LEO, AXIS will have ~100 times less non-ionizing radiation damage than Suzaku. Radiation damage is further ameliorated through the use of charge injection on the CCDs.

4.3 Spacecraft and Operations

A self-consistent point design for the AXIS instrument system (X-ray telescope and detector) was produced by the GSFC IDL study in February 2018, and incorporated into the GSFC MDL mission point de-The design meets the sign. AXIS science requirements in a class B mission with a five-year nominal lifetime (with consumables sized for >10 years). The spacecraft uses entirely highheritage components and (preoptimization) meets the mass (2300 kg including 20% margin), length, and diameter specifications for launch on a Falcon 9 into a low-inclination $(\leq 8^{\circ})$, LEO. The orbit minimizes the particle background and allows for rapid communication and response times for transient events and a high ob-

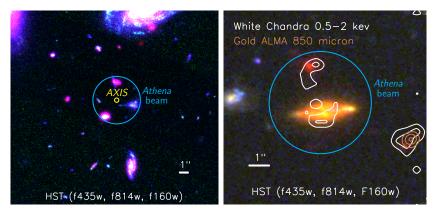


Fig. 3— *AXIS* will pinpoint the ultra-faint X-ray sources to their highredshift galaxy hosts, and to the exact location within the host galaxy. The two panels show *HST* deep survey images. *Left: AXIS* and *Athena* beam sizes. Unambiguous identification of a detected X-ray source with a distant galaxy requires high angular resolution. *Right: Chandra* and *ALMA* contours^{6,7} overlaid onto an image of several closely projected galaxies. The central X-ray sources (white contours) require *Chandra*'s (and *AXIS*') arcsecond resolution to separate them and match to their very different galaxy counterparts. The *AXIS* resolution is also wellmatched to that of *ALMA*, a workhorse for studying high-*z* galaxies in the submillimeter.

serving efficiency of at least 70% in a low inclination orbit.

The design requires six reaction wheels to accommodate the rapid slew rate $(120^{\circ} \text{ in } < 6 \text{ minutes})$ that optimizes efficiency. Three magnetic torquers dissipate angular momentum using the Earth's magnetic field. The only instrument mechanism is a focus adjuster that will be used only once, during commissioning.

AXIS has a straightforward, high-heritage concept of operations based on over 30 years experience from *Chandra, Swift, NuSTAR* and *RXTE*. The relatively low bit rate permits an onboard storage and telemetry system requiring only 4 Gbit/day downlinks using two 10-minute S-band ground station passes. The requirement for ToO response time is 4 hours, similar to that performed by Swift; however, a response time as short as one hour is possible by taking advantage of TDRSS links. The mission schedule assumed for costing estimates a launch \sim 7 years after the start of Phase-A, assuming that TRL 5 is reached before 2023.

SCIENCE WITH AXIS

AXIS will open a large uncharted parameter space in many fields of astrophysics. While it is impossible to predict what discoveries *AXIS* will make, below we describe how it will address some of the most important problems in astrophysics. A broader discussion can be found in the proceedings of the 2018 *AXIS* workshop.[‡] Most of the *AXIS* observing time will be allocated to the Guest Observer program.

[‡]http://axis.umd.edu/workshop2018.html

5 SUPERMASSIVE BLACK HOLES — ORIGIN, EVOLUTION AND PHYSICS

5.1 The Puzzle of Early Massive Black Holes

The origin of SMBHs in the centers of most big galaxies is a major unsolved problem. The existence of $\sim 10^9 M_{\odot}$ black holes only 700-800 million years after the Big Bang requires extremely rapid growth in the early universe. This is in contrast with what is observed in the local universe, where most SMBHs grow at a sub-Eddington rate. The nature of the seeds of these SMBHs is still unknown, since X-ray and optical/near-IR surveys have only sampled the bright end of the AGN luminosity function at z > 5.

Currently the two main hypotheses for the origin of high-redshift massive BHs are: (1) massive direct collapse from primordial gas $(10^{4-6}M_{\odot})$ or (2) from Pop III stellar remnants $(10^{2-3}M_{\odot})$. These seeds would imply very different AGN luminosity functions at high z^8 . *AXIS* can measure those luminosity functions by rapidly performing surveys to very low flux levels. *AXIS* observations will measure every stage of SMBH growth from $10^5 M_{\odot}$ at $z \sim 20$ up to $10^{9-10} M_{\odot}$ at $z \sim 7.5$ (Fig. 4)⁹.

The main observational challenge is the detection and identification of these objects. While X-rays are the most efficient band for detecting AGNs, star formation can significantly contribute to the X-ray luminosity of a galaxy, requiring high angular resolution to locate the accreting BHs in the objects selected by AXIS and at other wavelengths. AXIS provides a unique matching with ultra-distant (and likely irregular and merging) objects that will be discovered by WFIRST, JWST, Euclid, LSST, and 30m class optical telescopes. AXIS will be fundamental in (a) disentangling high-z AGN progenitors from star forming galaxies^{12,13}, (b) sampling the high-z AGN luminosity function down to $L_X \sim 10^{42}$ erg s⁻¹ at $z \sim 10$ (the luminosity of a $10^5 M_{\odot}$ BH accreting at 0.1 Eddington) to fully characterize the BH mass assembly, and (c) detecting low-mass SMBH at z > 10.

Since most very high *z* AGN are expected to be obscured, it will be difficult for *WFIRST* or *LSST* to disentangle the AGN signal from star formation and to locate the BH within a clumpy, gas-

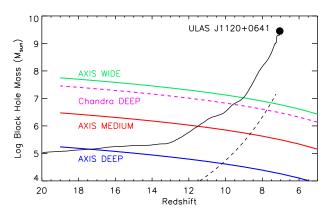


Fig. 4—*AXIS* will resolve the puzzle of high-redshift SMBH. The dot shows the highest-redshift quasar ever discovered¹⁰. Black solid and dashed lines show the mass buildup of a $z = 20 \ 10^5 M_{\odot}$ and $10^3 M_{\odot}$ seed, respectively¹¹. The minimum detectable mass curves for the three proposed *AXIS* surveys (wide, medium, and deep) show that *AXIS* can detect SMBH progenitors to very high z for a broad range of masses.

rich, dusty distant galaxy. Based on recent *ALMA* data⁷, subarcsecond resolution is needed to obtain unambiguous X-ray confirmations for optically/NIR selected SMBH seed candidates.

5.2 Surveying the Distant Black Holes

To hunt for high-redshift sources, AXIS will allocate ~10% of its 5-year mission (15 Ms) to surveys, overlapping with regions surveyed at other wavelengths. We envision deep, medium and wide surveys of 5 Ms each. The wide-field survey will select the rarest objects, while the medium and deep surveys will detect the faintest remote objects with the advantages of pre-selection of candidates from either JWST or WFIRST. AXIS will serendipitously find ~ 100 of z > 6 SMBHs, which will strongly constrain models of the origin of SMBH, and in particular, the progenitors of the recently discovered $10^9 M_{\odot}$ quasar at $z \sim 7$ (Fig. 4).

Figure 5 illustrates how AXIS will exceed current and future surveys in its ability to find the most distant BHs. AXIS will go lower than *Chandra* in flux by 1-2 orders of magnitude and cover a larger solid angle, providing secure source identifications. While future large-area X-ray telescopes, such as *Athena*, will detect a similar number of brighter high-*z* AGN, their precise identification will require AXIS' angular resolution.

Figure 3 illustrates how much easier it will be for *AXIS* to pinpoint those X-ray sources within their host galaxies, allowing the location of the BH for studies at other wavelengths.

AXIS surveys and serendipitous observations will detect $> 10^5$ AGN across all redshifts. For a significant fraction of them, moderate signal to noise X-ray spectra will be obtained and basic spectral quantities such as absorption and continuum shape will be measured. These data will determine the AGN nuclear properties as a function of host and environmental (e.g., halo mass) properties, since in the 2030s deep and wide multiband surveys will provide multiwavelength counterparts and environmental information for most AXIS sources. At the highest z, AXIS will probe how BHs grow within the first large-scale structures by detecting faint companions of luminous AGN in the overdense regions. Simulations suggest that large amounts of gas and galaxy mergers in those regions may trigger accretion. AXIS will allow unprecedented studies of how the AGN output affects the physics of their hosts from the local to the distant Universe.

AGNs are a tracer of the large-scale mass distribution in the early Universe¹⁶. The large number of detected AGNs in *AXIS* surveys will map the large-scale structure for direct comparison with other tracers of structure, over a wide range of redshift.

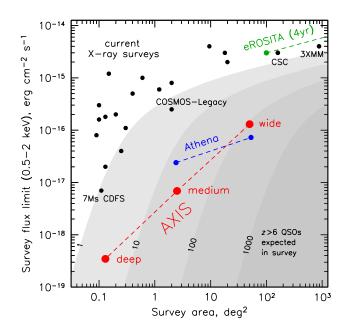


Fig. 5—*AXIS* will be able to probe more and fainter high-*z* sources than any other X-ray instrument, including *Athena*. The plot shows survey area vs. flux limit for planned *AXIS* surveys compared with *Chandra*, *XMM-Newton* and future *Athena* (1-year) and *eROSITA* surveys. Grayscale shows the number of expected z > 6 AGN detectable in the survey ^{14,15}. *AXIS*' subarcsecond angular resolution will provide unequivocal identifications for its detections (Fig. 3).

5.3 Peering at the Vicinity of the Black Hole

AXIS will probe material very close to SMBH — especially when aided by the Universe's own lenses. In the immediate vicinity of BHs, one of the fundamental energy sources in the Universe is at work — accretion of matter onto the BH. For all but the MW Galactic Center, the accretion disk is unresolvable by current instruments, but some quasars fortuitously have a massive galaxy or cluster on its line of sight, which results in gravitational lensing of the quasar. *Macrolensing* is the gravitational bending of light produced by the mass distribution of the foreground lensing galaxy. This lensing often produces multiple quasar images with different image flux ratios, lensing magnification, and time delays. *Microlensing* is the gravitational bending of light produced by stars in the lensing galaxy^{17,18} producing an additional magnification of the affected

- AXIS will provide a complete history of SMBHs up to z = 6 with the deepest survey ever performed
- AXIS will observe the largest sample of "infant" X-ray emitting SMBHs right after seeding at z>6, and potentially up to z = 15–20
- AXIS will pinpoint the exact locations of SMBHs in distant irregular, merging host galaxies, and characterize the large-scale environment of early SMBHs

images. AXIS will revolutionize X-ray observations of lensed systems and let us peer into the immediate environs of massive BHs.

5.3.1 Sizes of quasar X-ray emitting regions. Gravitational microlensing can reveal structure within quasars on small scales that cannot be directly imaged at any wavelength. It produces caustics that magnify as they sweep over the quasar. The strength of the magnification depends on the relative size of the emitting region and caustic, with more compact sources having higher microlensing variability amplitudes. Comparing the variability amplitudes in the X-ray and optical bands places tight constraints on the structure of the accretion disk and the X-ray emitting regions¹⁹. Chandra observations of several bright lensed quasars revealed that the X-ray emitting corona is very compact^{20,21}, $r \sim 6-50r_g$ (where $r_g \equiv GM_{\rm BH}/c^2$).

These spectacular results beg for extension and enhancement. However, the imaging and sensitivity limitations of *Chandra* permits high quality data for only a few lensed quasars. *AXIS* will enable studies of a much larger sample. *AXIS* will constrain the sizes of X-ray emitting regions of quasars ranging from the hot corona and inner accretion flow to the molecular and dusty torus that surrounds the accretion disk. Isolating these emission regions is possible because *AXIS* has the effective area and angular resolution to obtain the microlensing light curve as a function of energy as well as the flexible mission operations that allows the observation of these objects during the critical caustic crossings.

These AXIS observations will be made vastly more productive by the discovery in the LSST survey of >4,000 additional gravitationally lensed systems with ~300 quadruply lensed and ~1000 double quasars that are sufficiently X-ray bright to precisely measure with AXIS. AXIS will likely overlap LSST or other optical surveys, allowing the simultaneous monitoring of caustic crossings of quasars in multiple optical and X-ray bands. AXIS will resolve the vast majority of LSST lensed quasars over a wide range of quasar redshifts, BH masses, radio loudness values, spin and Eddington ratios, allowing the determination of the dependence of the sizes of X-ray emitting regions on these parameters. *eROSITA* measurements of the X-ray fluxes of LSST-lensed quasars will provide the sample of that are bright enough to be *monitored* by AXIS.

5.3.2 Evolution of SMBH spins in quasars at 0.5 < z < 5. The mechanisms leading to the growth of SMBHs will be studied by constraining the evolution of the SMBH spins of quasars with 0.5 < z < 5 with lensing observations. X-ray reflection from the inner regions of a quasar accretion disc produces an iron line that is broadened by gravitational redshift and Doppler shifts²² and is commonly seen in nearby AGN. Quasar microlensing produces energy shifts of the Fe K line as microlensing caustics sweep over the disk^{23,24}. Measurement of these shifts, in particular the maximum observed redshift, enables the determination of the innermost stable circular orbit (ISCO), spin, and inclination angle. The factor of ~10 increase in the collecting area of AXIS and the availability of ~300 X-ray bright, quadruply lensed quasars from LSST, will allow AXIS to obtain spin measurements for a large sample of quasars with 0.5 < z < 5.

5.3.3 Imaging BH accretion disks using caustic crossing method. The detection of individual caustic crossing events would be spectacular, revealing the gradual change in the profile and energy of the Fe line as the caustic sweeps over the accretion disk and corona (see simulation in Fig. 6). *LSST* or other surveys will be continuously monitoring many lensed quasars and thus can provide reliable triggers for caustic crossing events. Monitoring caustic crossings events in individual images with *AXIS* will provide tomographic scans of the accretion disks of SMBHs.

- AXIS will constrain the sizes of X-ray emitting regions of quasars ranging from the hot corona and inner accretion flow to the molecular and dusty torus
- AXIS will constrain the evolution of the SMBH spins of quasars, and provide magnified views of quasar outflows at the epoch of peak AGN activity

5.3.4 Ultrafast outflows in quasars. The detections of ultrafast outflows in distant quasars are rare due to their X-ray faintness. AXIS observations of a considerable number of the highly magnified and thus X-ray bright lensed quasars at z 1-2 with magnifications greater than 10 will provide detections of high signalto-noise absorption signatures of relativistic outflows at redshifts during the crucial phase of BH growth at the peak of cosmic AGN activity.

AXIS will provide spatially resolved and time-resolved spectra of lensed images, thus

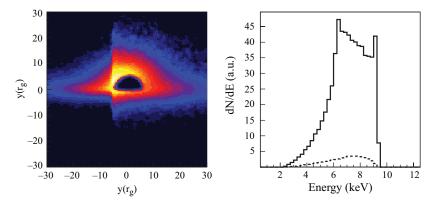


Fig. 6— Gravitational microlensing caustic sweeping over a quasar accretion disk. *Left*: Simulated image of the Fe-K α line emission as seen by a distant observer. Axes are in units of gravitational radius $(r_g \equiv GM_{\rm BH}/c^2)$. *Right*: The resulting energy spectrum of the Fe-K α emission in the rest frame of the source (arbitrary units). Dashed line is the non-microlensed Fe line.

constraining the properties of the outflow in individual images. Lensed images provide spectra of the quasar at different epochs separated by image time delays. Detecting the acceleration phase of the outflowing absorber and constraining its short timescale variability cannot be accomplished with longer exposure times using current X-ray missions; this requires a mission with significantly larger collecting area combined with high angular resolution. The spectral-timing analysis of a sample of high-magnification lensed high-z quasars will thus constrain the energetics of ultrafast outflows near the peak of AGN activity. A comparison between the energetics of these small-scale ultrafast outflows and the large-scale molecular outflows in the host galaxies will be used to infer their contribution to regulating the evolution of their host galaxies^{25,26,27}.

5.4 Growing a Supermassive Black Hole

BHs grow by accreting matter around them and, rarely, by merging with other BHs. Our understanding of these phenomena will benefit enormously from *AXIS*' high angular resolution and sensitivity.

5.4.1 SMBH mergers. The general theory of large-scale structure formation predicts that galaxy mergers are a major component of galaxy growth. Since almost all massive galaxies at low redshift contain central SMBHs, it has long been predicted that when the galaxies merge, their BHs should, too. However, SMBH merger timescales are highly uncertain, and one of the few observational tests of this idea — other than gravitational waves at *LISA* frequencies — is to search for "dual SMBHs" in nearby galaxies³¹. Theoretical calculations indicate that a significant fraction of these sources are actively accreting, which has stimulated an intensive search for dual AGN³². However, despite these efforts, there is currently little information about the occurrence rate of dual AGN. Dual AGN are extremely rare in the radio³³, and optical selection techniques for them are rather inefficient³⁴, as a large fraction of candidates are "false positives."

In contrast, X-ray observations by *Chandra* have discovered all three of the unambiguous, kpc-scale, dual AGN systems known. This result implies a dual AGN fraction of >10% in the nearby hard X-ray selected sample³⁰, 100x larger than studies of double peaked optical sources ($\sim 0.1\%$)³⁵. While *Chandra*

- *AXIS* will study BH growth in galaxy mergers and perform a blind search for dual AGN in over 750,000 AGN
- *AXIS* will study AGN fueling and resolve the accretion flow in the strong gravity region around at least 25 SMBHs in the local universe

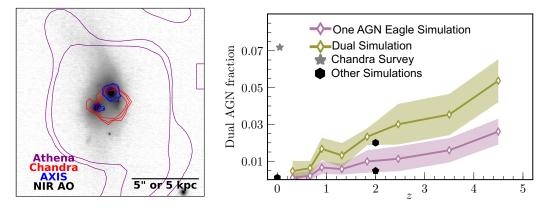


Fig. 8— *Left*: The improved PSF and sensitivity of *AXIS* allows it to easily resolve the two nuclei in the high-resolution NIR image of the merging AGN (CGCG 341-006). The blue contours represent the *AXIS* image, the purple *Athena*, and the red *Chandra*. *Right*: *AXIS* will be able to probe the fraction of dual AGN at various redshifts and provide a direct test of the merger history of BHs. Cosmological simulations predict that the fraction of dual AGN increases dramatically with redshift²⁹. A *Chandra* study of nearby dual AGN³⁰ finds a much higher fraction than models predict.

is limited by its resolution, sensitivity, and field of view in finding more examples, *AXIS* will perform large surveys of deep fields roughly 300 times faster, permitting population studies out to high redshift. (Fig. 8).

Recent high resolution NIR observations of host galaxies of obscured AGN have found that very close mergers may exist in a large fraction of obscured luminous AGN²⁸ (Fig. 7). All but one known confirmed dual AGN are separated by greater than 3 kpc and have luminosities $L_X >$ $10^{42.5}$ erg s⁻¹. At these luminosities and separations, AXIS can detect dual AGN out to z = 2 in 50 ks observations, allowing a blind search of the \sim 750,000 serendipitous AGN that AXIS will detect over a 5-year mission. Such data, along with targeted observations of dual AGN candidates, will permit AXIS to answer critical issues such as the frequency, environment, and luminosity dependence of dual AGN, and whether the obscuration level of AGN is correlated with merger stage. The kpc-scale dual AGN population sampled by AXIS provides key constraints for the SMBH mass merger function for the expected LISA and pulsar timing array SMBH merger rates³⁶.

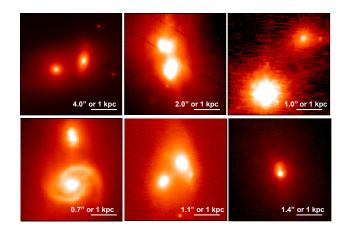


Fig. 7—*AXIS* will resolve potential dual AGN in all of these merger galaxies revealed in adaptive-optics images,²⁸ while most are beyond *Chandra*'s capabilities. Future 30m telescopes and *JWST* will find many more close merging nuclei.

5.4.2 AGN fueling. According to the simplest model of accretion, the Bondi model, the interstellar hot gas in massive galaxies will be accreted by and fuel a SMBH if it falls within the Bondi radius, R_B , where the BH's gravitational potential dominates over thermal motions of the gas. Regardless of whether these assumptions are correct, the hot gas structure within the SMBH's gravitational sphere of influence is key to understanding how it is fueled, how it responds to the large scale gas cooling rate, and how SMBHs evolved from the quasar-era peak to local quiescence.

The virial temperature of gas at R_B for SMBHs is on the order of 10^7 K and emits in the X-ray band. This gas can only be studied with *Chandra* in a few of the nearest systems. The best sources, NGC 3115 and M87,

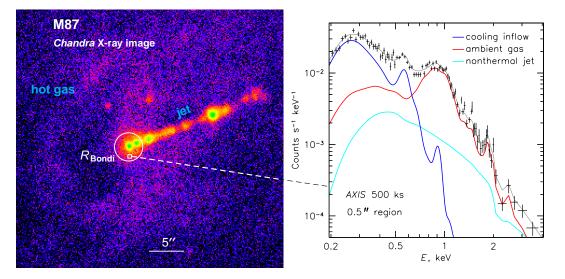


Fig. 9—*Left: AXIS* will map the accreting gas that fuels SMBH in great detail. The black hole's sphere of influence ($R_{Bondi} = 2''$) is shown by the white circle on this *Chandra* image of M87. *Chandra*'s resolution and soft X-ray response limit studies of the gas properties within this region. *Right:* A simulated *AXIS* spectrum for a 0.5"×0.5" region (left) from a 500 ks observation. *AXIS* will map the rapidly cooling, inflowing gas with kT < 0.5 keV (blue curve) that likely feeds the circumnuclear gas disk and fuels the jet activity.

were targeted by a series of Large and Visionary *Chandra* projects^{37,38,39}. Surprisingly, the observations showed a shallow gas profile and declining temperature profile in M87. This implies the presence of strong outflows that expel the vast majority of the gas initially captured by the BH, dramatically reducing the accretion rate. Instead of 10^7 K gas, the X-ray atmosphere is dominated by lower temperature gas at $< 5 \times 10^6$ K (Fig. 9), which appears spatially coincident with cool circumnuclear gas disks observed with HST. Unexpectedly, the gas structure on these scales is a complex mixture of a rapidly cooling inflow fueling the BH and powerful jet-driven outflows. These can be disentangled with *AXIS* imaging and spectroscopy.

AXIS will reveal the emergence of the accretion flow in the strong gravity region around at least 25 SMBHs, and with a high accuracy and level of spatial detail similar to or better than *Chandra*'s ultra-deep M87 study, for the galaxies in the shaded region in Fig. $10^{40,41}$. A potential few-Megasecond AXIS observing program would target several key nearby SMBHs such as M87 with very deep exposures and a larger sample with shallower exposures. The ability to observe a reasonable sample of such objects in 100 ks is a driver on AXIS' low energy collecting area and

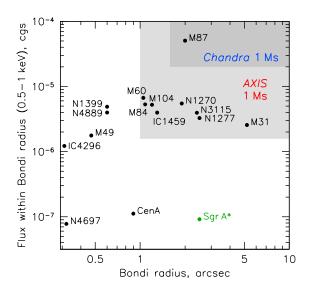


Fig. 10—*AXIS* will dramatically expand the pool of targets for which mapping of gas accretion onto the SMBH is possible. Soft-band fluxes from cool accreting gas within the gravitational sphere of influence of some nearby SMBHs are shown. Shaded regions show targets for which R_{Bondi} is resolved with *Chandra* and *AXIS* and a 1 Ms observation produces > 10⁴ counts within R_{Bondi} , sufficient for detailed mapping of the gas inflow. (Sgr A* is heavily absorbed and needs to be observed at higher energies.)

spectral resolution. These observations will map the detailed density and multi-temperature structure within the BH's sphere of influence (Fig. 9) to reveal transitions in the inflow that ultimately fuel the BH activity, and outflows along the jet-axis that limit the accretion rate, thereby building up the first detailed picture of these accretion flows.

6 ASTROPHYSICAL DRIVERS OF GALAXY FORMATION

Galaxy formation is governed by competing forces and processes. Gas accretes into a dark matter halo under the force of gravity; most of it stays diffuse, but some cools down and forms stars, while some collapses into a central massive black hole. Stars explode as supernovae, while the SMBH turns into an Active Galactic Nucleus (AGN) and produces powerful relativistic jets and X-ray radiation. Both processes inject energy into the newly arriving gas — heating it and expelling some from the galaxy, thus preventing it from forming stars and depriving the SMBH of fuel. The result of this feedback loop is the multitude of galaxies and galaxy clusters that we observe. *AXIS* will greatly advance our understanding of these fundamental processes.

6.1 AGN Jets

Relativistic jets are a crucial link in the feedback loop between SMBH and the gas that feeds it. Their physics is extremely complex. After nearly four decades of study of extragalactic jets, there are still shockingly basic questions about many of their fundamental properties, including how the jet properties connect to properties of the BH (whether spin or mass or some property of the disk), the particle content of the jets, the exact emission mechanism producing high energy photons at kpc scales, and how the radiating particles were accelerated⁴³. This lack of insight produces a large uncertainty in estimates of the total power output of jets, thereby limiting robust measurement of the impact of jets on their surroundings.

Chandra observations have produced major discoveries, which while based on relatively few objects, have significantly changed our understanding of jets such as the detection of an "anomalously" high and hard X-ray flux from a second spectral component in almost all jets; the

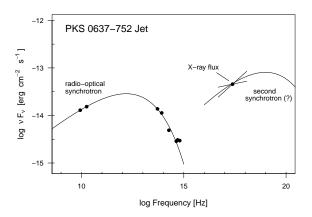


Fig. 11— X-ray observations of AGN jets often reveal an unexpected emission component, possibly synchrotron emission from a second, higher-energy population of electrons than produces the radio-optical component, as shown in this SED for the bright jet in PKS 0637-75⁴². *AXIS* will obtain X-ray data of such quality for objects out to high redshift and over a wide range in AGN and jet parameters.

discovery in two cases of time variability in some of the "knots" in the jet^{44,45}; and from a detailed analysis of Cygnus-A data, the implication that jets are light, implying that the kinetic power and momentum flux are carried primarily by the internal energy of the jet plasma rather than by its rest mass⁴⁶. Extension of these unexpected discoveries to much larger samples covering a wide range in jet and BH properties, over a wide range in redshift, requires a significant improvement in both sensitivity and high-resolution (<1")

The bulk of the X-ray emission comes from synchrotron emission, as alternative models such as inverse Compton scattering of the CMB have been ruled out^{47,48,49,50}. However, the synchrotron emission is pro-

- AXIS will provide the first sensitive observations of high-redshift jets
- *AXIS* will collect the photons necessary to resolve the X-ray spectrum along the jet and conduct variability studies, probing the currently unknown particle acceleration mechanism

duced by a separate population than the electrons which produce the radio through optical emission⁵¹ and makes a significant contribution to the total jet energetics. The existence of this component requires *in situ* particle acceleration (via unknown mechanism) on kpc scales. The recent observations of short timescale X-ray variability in resolved jets^{44,52} implies extremely short radiative loss lifetimes, on the order of years, and thus very small source sizes and efficient particle acceleration. *AXIS* can perform a detailed statistical study of the variability in the jet population which cannot be done by *Chandra* because of the very long exposures needed to obtain sufficient statistics on individual knots in the jets. Only high-resolution, high-sensitivity X-ray imaging can help us understand the underlying physical conditions and processes, and probe the currently unknown particle acceleration mechanisms at play in AGN jets.

6.1.1 AXIS discovery space for AGN jets.

• *High redshift:* At high redshift (z > 2-3), X-rays from inverse Compton upscattering of the CMB start to dominate over the synchrotron, and the environment around those jets is vastly different than in the low-*z* Universe. This provides a unique environment in which to study the jet physics. However, all of the high-*z* jet detections by *Chandra* have only a handful of counts in the resolved jet. *AXIS*, with its angular resolution and large area at low X-ray energies, is an ideal tool for these studies.

• Spectral evolution along the jet: So far this has only been done for a few objects, with contradictory results. The X-ray spectrum is one of our best clues as to the particle acceleration mechanism, but at present we have insufficient data to draw strong conclusions.

• *Jet population: AXIS* will sample a large fraction of the jet population. The statistics of jet X-ray luminosity and its relation to the radio emission will constrain the emission mechanism and the bulk speeds of the X-ray-emitting material.

• *Variability: Chandra* required exposures of more than 50 ks to find the few X-ray variable jets known. With the 10x better sensitivity of *AXIS*, variability studies using 'snapshot' (5 ks) observations will allow for studies of populations and measurements of timescales.

• Jet-ISM interaction: AXIS observations can examine interactions between the jet and the ISM or IGM that it is traveling through, allowing measurements of jet-induced star formation as seen in *Chandra* observations of Cen-A and NGC4258. They can also examine possible heating mechanisms required in the so-called radio mode feedback models (§6).

AXIS' resolution is well-matched to that of existing and upcoming radio facilities (JVLA,

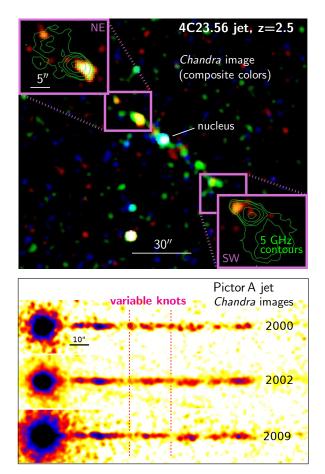
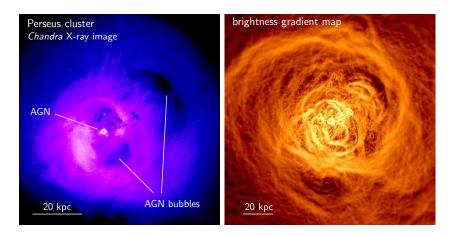


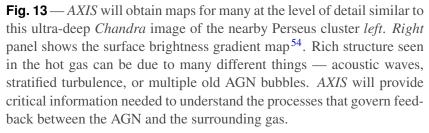
Fig. 12—*Top: AXIS* will have the sensitivity and resolution to study high-redshift jets in great detail. Because of the $(1+z)^4$ brightening of the CMB, inverse Compton emission from cosmic-ray electrons in high-*z* jets starts to dominate, which makes these faint objects invaluable for understanding the complex physics of jets. This *Chandra* image of a z = 2.5 jet⁵³ has only a handful of photons. *Bottom: AXIS* will be able to study jet variability on much shorter timescales than *Chandra*. Variable X-ray knots in a well-resolved nearby jet are shown;⁴⁴ dashed lines indicate knots seen in 2000, which have disappeared in later epochs.

SKA), and complements ground-based optical facilities. It also supports the high-resolution observations of optical synchrotron counterparts from *HST* and, in the future, *JWST*.

6.2 How Black Holes Heat Galaxies and Clusters

Even though SMBH's have a mass of only $\sim 0.1\%$ of their host galaxy, the enormous energy released as it grows (and shines as an AGN) can heat up and/or expel star forming gas from the galaxy, thereby slowing or completely truncating the galaxy's growth⁵⁵. However, the physical processes by which the energy and momentum are transferred to cooling and star-forming gas remain unclear. Revealing how this transfer operates, how it scales with galaxy mass, and how these mechanisms evolve with redshift is essential to understanding galaxy and cluster evolution. It requires resolving complex structures in the hot gas, which contains most of the





feedback energy, on the relevant physical scales (arcseconds for all redshifts).

The most massive systems in the Universe, clusters of galaxies, allow the observation of AGN feedback in action. In the vast majority of relaxed, cool-core clusters, the brightest central galaxy (BCG) hosts a radio-loud AGN⁵⁶. *Chandra* and *XMM-Newton* imaging finds evidence for strong interactions between the jets from the central AGN and the hot intracluster medium (ICM) of the cluster—jet blown cavities/bubbles are ubiquitous, and signs of weak shocks, acoustic waves, and AGN-induced turbulence are also common. These interactions probably cause the AGN to heat the ICM core, thereby offsetting radiative cooling and preventing a cooling catastrophe. The fact that most galaxy clusters possess self-similar ICM temperature and entropy profiles suggests that a self-regulated feedback loop is established whereby some residual cooling fuels the AGN which then heats the ICM core sufficiently to offset 90-99% of the radiative cooling.

While the energetics of AGN-ICM feedback make sense, current X-ray data have failed to reveal the actual physical mechanisms by which the jets heat the ICM or cooling fuels the AGN. High-resolution *Chandra* images of nearby clusters such as Perseus and Virgo reveal rich structure (Fig. 13)⁵⁴, but, because of the small sample size and limited statistics, it remains unclear how to interpret this structure⁵⁷ — are we seeing a cluster core full of acoustic waves, stratified turbulence, or numerous pancake-layers of old bubbles? Each of these have very different implications for the physics of ICM heating and how it will depend upon the density, temperature, and plasma physics of the ICM. High-resolution spectroscopy with

- AXIS will resolve the length scales over which AGN feedback operates in the hot cluster medium
- AXIS will measure the evolving importance of AGN feedback in clusters to z~3
- AXIS will map the impact zones where hot AGN winds meet the ISM

XRISM is expected to provide important constraints on core-integrated cluster dynamics in several bright systems. *AXIS* maps of densities, temperatures, and non-thermal emission on 0.5-10'' scales, in combination with high spectral resolution data from *Athena* for a large sample spanning a wide range of redshifts, masses and cooling rates, will revolutionize our understanding of these structures.

While observations of a few local clusters have enabled the study of the physics of this "kinetic mode" feedback in great detail, we need to understand the cosmic evolution of AGN feedback in clusters over a wide range of cosmic time and mass scale. The best studied case beyond the local Universe, the Phoenix cluster⁵⁹ (z = 0.6), possesses significant quantities of cold gas and AGN-blown X-ray cavities, suggesting that vigorous AGN-feedback has already been established. However, observations at these or higher redshifts require extremely long *Chandra* exposures, producing a limited very small sample⁶⁰.

There is a strong trend for AGN in BCGs to increase in luminosity with increasing look-back time, suggesting a possible switch from radiative-mode to kinetic-mode feedback at some redshift. If this switch does occur, is it a function of cluster mass, cosmic time, or some other parameter? To answer these questions requires large samples of clusters at high redshift with excellent angular resolution and signal-to-noise ratio. *AXIS* observations will build an extensive sample of clusters with sufficiently deep imaging spectroscopy to see ICM cavities and shocks.

These kinetic-mode feedback processes should also operate in galaxy groups and individual massive elliptical galaxies. New evidence⁶¹ suggests that they also operate

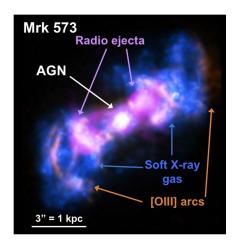


Fig. 14— *AXIS*' angular resolution and sensitivity will allow the precise investigation of the multi-phase and multi-scale interstellar medium in the innermost regions of Seyfert galaxies and probe SMBH feeding/feedback for a large sample of AGN. Three-color composite image of the central $10'' \times 10''$ region of the Seyfert galaxy Mrk 573 is shown⁵⁸; soft X-rays from *Chandra* (blue), radio from *VLA* (purple), optical from *HST* (gold).

in spiral galaxies, thus implicating them in the formation of all massive structures. There is a universal scaling of the entropy profiles of the ICM in clusters, the hot ISM in massive elliptical galaxies, and the CGM in spiral galaxies at low redshift⁶¹. In the ICM case, the profile is shaped by self-regulated AGN-feedback, suggesting that similar processes are at work in the CGM of all galaxies. A direct study of these processes is not possible with *Chandra* — the CGM has very low surface brightness and emits primarily below 1 keV where *Chandras* sensitivity has been severely reduced. *AXIS* will enable the study of feedback in the CGM of individual, L_* spiral galaxies within 100-200 Mpc, measuring the distribution of temperature, metals, entropy, and mass to R < 50 kpc and relic bubbles within R < 20 kpc. The combination of *Athena*'s high spectral resolution and *AXIS*' high angular resolution will reveal how feedback operates over the 10⁴ mass range from massive galaxies to rich clusters.

AGN can also influence their galaxies in an impulsive, violent manner. During a luminous outburst, an AGN can drive a powerful wind that destroys or expels molecular gas from the galaxy. This "radiative-mode" feedback is thought to rapidly suppress star formation in a galaxy. Direct evidence for this phenomenon, however, is elusive. X-ray spectral evidence for high velocity AGN winds in the form of highly blueshifted ionized iron lines is commonly seen. At present there are only a very small number of cases in which the momentum flux of the AGN wind can be related to that of a large-scale molecular outflow from the galaxy²⁵, providing strong circumstantial evidence that the AGN is indeed responsible for driving molecular gas out of the galaxy. The combination of *AXIS*, *Athena*, and *ALMA* data can increase the sample substantially, allowing tests of theoretical models of this process⁵⁵: *AXIS* can spatially resolve the shock

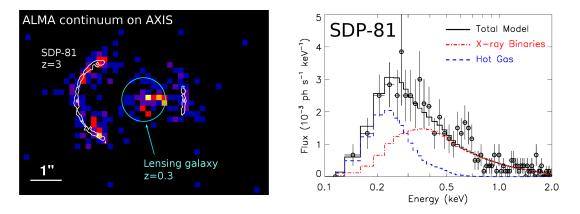


Fig. 15— *AXIS* can resolve star-forming regions in strongly lensed galaxies at z > 2, such as SDP-81⁶² (z = 3.042). This 200 ks exposure shows emission from the lensed galaxy and the lensing galaxy (at z = 0.3). The right panel shows the total spectrum, and *AXIS* is able to detect both XRBs and hot gas.

interaction between the ISM and AGN wind in > 20 nearby systems, while *ALMA* can provide velocityresolved molecular gas maps, and *Athena* high spectral resolution X-ray spectroscopy at 5" scales, thereby constraining models of radiative-mode feedback. The intrinsic multi-phase and multi-scale structure of AGN feeding and feedback is demonstrated by the composite X-ray, optical, and radio image of Mrk 573⁵⁸ (Fig. 14), one of the few such data sets with *Chandra*, showing the hot gas phase interacting and mixing with colder phases.

6.3 Galaxies Across Cosmic Time

The growth of galaxies is regulated by feedback from supernovae and AGN. The balance between the two changes over cosmic time (0 < z < 6) in a way that remains poorly understood because of the diverse set of processes involved. X-rays probe both the impact of energetic outflows on galaxies and the star-formation rate (SFR). *AXIS* will be able to measure these processes to z > 1 and will help to identify the drivers of galaxy evolution over most of cosmic time. An angular resolution of < 1'' is needed to resolve galaxies at z > 0.25, and a large collecting area at E < 1 keV is needed to detect redshifted soft X-ray emission from the ISM and SNRs.

6.3.1 Star formation across cosmic time. Star formation is regulated both by local ISM processes and by galaxy-scale gravitational processes. There is a tight correlation (the "main sequence") between SFR and the galaxy stellar mass, M_* , for star-forming galaxies that is independent of redshift⁶³. Galaxy evolution is also affected by mergers, the density of nearby galaxies, and the properties of dark-matter halos. Understanding the diversity of galaxies requires reliable SFR measurements up to and past the peak epoch of star formation as a function of these parameters.

A major challenge in measuring star formation with far-IR measurements is the contribution of obscured AGN which are ubiquitous in massive galaxies at z > 1. AXIS will unambiguously detect these AGN out past the peak of star formation, and provide an independent measure of SFR using XRBs allowing the accurate assessment of the star formation history of most galaxies.

- AXIS will measure star formation rates in early galaxies through HMXB scaling relations
- AXIS will identify and measure the impact of galactic winds to z>1
- AXIS will discover how X-ray binaries contribute to cosmic reionization

ASTROPHYSICAL DRIVERS OF GALAXY FORMATION

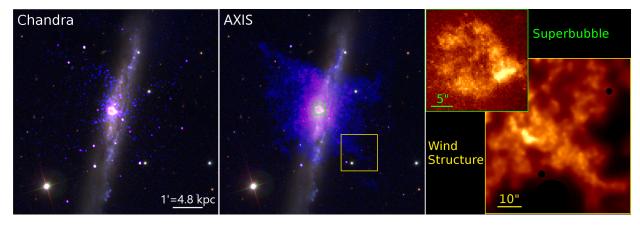


Fig. 16—*AXIS* will measure the temperatures, densities, and abundances of filaments in at least 25 galactic superwinds, whereas *Chandra* can do this for 2-3. For example, we show the soft X-ray wind (0.3–2 keV) around NGC 3079 as seen with *Chandra* (*left*) and *AXIS* (*center*) for 100 ks each, overlaid on the optical image. *AXIS* will resolve and accumulate many counts in structures 1-3'' wide (*right*).

AXIS measurements of the high-mass X-ray binary (HMXB) population measures the SFR since it correlates strongly with the total luminosity of HMXBs⁶⁴. At z > 1, many galaxies have SFR $\ge 100 M_{\odot} \text{ yr}^{-1}$, giving a HMXB contribution that can be detected by AXIS in 100 ks at z = 1 (or ~ 1 Ms for z = 2), with higher SFR galaxies detected to even greater distances⁶⁵. Stacking analyses can extend these studies beyond z = 5. While Athena will also detect these systems, the superior resolution of AXIS (< 2.5 kpc at z > 1) is needed to separate the HMXB and the (often dominant) AGN contribution.

AXIS can also measure the conditions of the hot ISM around intense star-forming regions and the resolved SFR (from HMXBs) at z > 3 by observing strongly lensed galaxies⁶⁶. Fig. 15 shows a simulated 200 ks observation of a z = 3.04 lensed galaxy⁶² with SFR= 500 M_{\odot} yr⁻¹. Herschel observations show that there are numerous high-z systems bright enough for AXIS observations.

6.3.2 Stellar feedback. Star formation regulates itself as stellar winds and supernovae (SNe) disperse and heat the gas and prevent cooling of the hot, ambient circumgalactic medium. AXIS will determine the origin of X-rays in local galactic winds, measure the power and frequency of hot winds up to $z \sim 1$, understand how HMXBs contribute to the Epoch of Reionization, and characterize the faint, hot ISM in elliptical galaxies.

During periods of intense star formation, multiple SNe combine to form overpressured hot bubbles that can break out of the disk and drive winds^{67,68}. These winds also contain a large mass in cool gas, which can escape the galaxy, thereby removing fuel for star formation; they may be the primary reason that star formation has declined since $z \sim 2-3$, when such winds were common. Determining their impact on host galaxies and the CGM, as well as the primary driving mechanism (thermal pressure, radiation pressure, or cosmic-ray momentum) requires precise measurements of the wind mass, metal, and energy outflow rates which can be constrained from spatially resolved X-ray spectroscopy. *AXIS* will obtain spectra from individual filaments for at least 25 nearby galactic winds in 20-150 ks exposures (e.g., Fig. 16). In deeper exposures (survey fields or targets selected from optical catalogs), *AXIS* can detect and resolve strong winds ($L_X > 10^{41}$ erg s⁻¹, as seen in nearby examples such as Arp 220 or NGC 6240) to $z \sim 1$, where stellar feedback was much more active. The temperatures, masses, and abundances of these winds will clarify the role of stellar vs. AGN feedback in quenching galaxies.

AXIS will also probe how HMXBs contribute to reionizing the Universe at z > 6. HMXBs can either directly ionize gas with X-rays or remove gas enshrouding nearby, very young star clusters that have yet to produce SNe and which emit ionizing photons. AXIS will provide detailed maps of several local analogs of Lyman-break galaxies^{69,70,71}, which show multiple knots of HMXB emission, along with extended hot gas^{72,73}. These features indicate the locations of "channels" that allow ionizing radiation to escape⁷⁴. AXIS

can survey a sample of about 50 low-*z* Lyman-break analogs in a total of only 1 Ms.

6.4 Intergalactic Medium — Where Everything Ends Up

The hot intergalactic medium, IGM (a.k.a. WHIM, warm-hot intergalactic medium) is believed to be the main reservoir of the "missing baryons" in the local Universe, and the ultimate depository of metals and entropy produced in galaxies over cosmological time. UV and X-ray measurements of the IGM have long been attempted, but so far, only a fraction of it — the relatively dense, colder phase visible through the OVI absorption in FUV — has been unambiguously detected.

AXIS will open a large discovery space by probing the emission from the theoretically predicted 10^{6-7} K IGM that should dominate the baryonic budget at low redshifts. In combination with X-ray absorption line studies from future X-ray missions and the UV absorption line studies of the colder IGM phase, the AXIS data will allow a complete census of the cosmic baryons and metals at low redshift. Owing to a combination of low background and high collecting area (Fig. A.5), AXIS will be able to measure the flux and spectrum from very low surface brightness regions, allowing access to emission from the dynamic regions at the interface between clusters, galaxies and the Cosmic Web.

6.4.1 Cluster outskirts and the Cosmic Web. Galaxy clusters act as "IGM traps," attracting and compressing the IGM and making it more readily observable in X-ray emission. Most of this material lies beyond the virial radius⁷⁶. The surface brightness in these outskirts is extremely low, requiring the low detector background of AXIS (Fig. A.5) to characterize. Arcsecond or better angular resolution is critically important for the removal of the CXB point sources. As shown in Fig. 17, AXIS can trace the IGM out to twice the virial radius $(2r_{200})$ of most clusters, where the IGM exists along the giant filaments of the Cosmic Web. In these regions we expect to find infalling galaxy-sized and group-sized objects (with the accompanying shock fronts and gas stripping), as well as the IGM filaments (see Fig. 18c). These observations will test cosmic structure formation theory as it probes the transition from the weakly- to stronglynonlinear regimes⁷⁷.

AXIS will measure the plasma temperature and iron abundance of bright regions of the IGM filaments (Fig. 18d). Cosmological simulations indicate that metals in the cluster outskirts should originate from galaxy formation feedback far in the past⁷⁸, making the IGM metallicity a particularly powerful probe of the physics of galaxy formation. *AXIS* map-

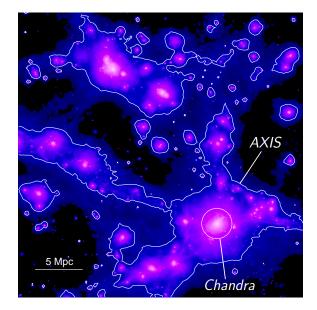


Fig. 17—*AXIS* will see how galaxy clusters connect to the Cosmic Web. In this cosmological simulation of Large Scale Structure, ⁷⁵ color shows X-ray brightness of the intergalactic plasma, revealing a web of giant filaments with galaxy clusters as bright nodes. *AXIS* will reach much farther into those dynamic, but very dim regions (out to the white contour) than any other X-ray instrument.

ping of the iron abundance in the filaments will provide a guide to the Athena calorimeter observations.

- AXIS will allow the first complete census of cosmic baryons and metals at low redshift, including the majority of the "missing baryons" in the local Universe
- AXIS will map the unexplored, dynamic regions of the Cosmic Web around galaxy clusters

ASTROPHYSICAL DRIVERS OF GALAXY FORMATION

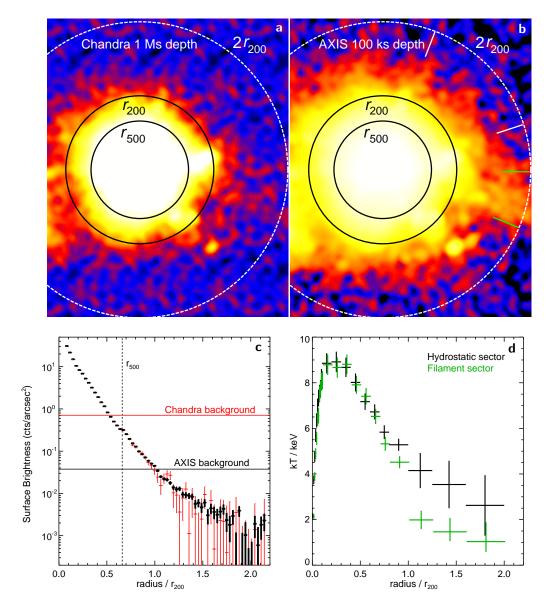


Fig. 18—*AXIS* will provide unsurpassed capability for exploring the dynamic outermost regions of galaxy clusters. Panels *a* and *b* show X-ray images of the same cluster from cosmological simulations as observed by *Chandra* (1 Ms) and *AXIS* (100 ks), respectively. They have the same number of cluster counts, but *AXIS* is able to probe the cluster emission to much larger radii, where clusters interface with the Cosmic Web. It can determine densities, metallicities and temperatures out to $2 \times r_{200}$ in a routine exposure. *XMM-Newton* and *Chandra* can only reach r_{200} in rare ultra-deep exposures. *AXIS* will be able to study the cluster hydrostatic regions (white dashes) and giant filaments connecting the cluster to the Cosmic Web (green dashes). (c) X-ray surface brightness profile in the 0.8-5 keV band extracted from a sector shown by white dashes in (b). The background levels (detector + unresolved CXB) are shown by horizontal lines. (d) *AXIS* temperature profiles for the sectors shown in (b) with white and green dashes.

For the "hydrostatic" cluster regions (Fig. 18d), temperatures provide an estimate of the total cluster mass. Comparison with estimates from gravitational lensing from *Euclid* and *WFIRST* will allow estimates of the non-thermal pressure components in the ICM as a function of radius and constrain the dominant physical processes in the low-density plasma.

6.4.2 The hot Circumgalactic Medium. Regions of the IGM surrounding individual galaxies—the circumgalactic medium (CGM)—represent another phase of the "missing baryons." ACDM predicts that galaxies with virial temperatures exceeding 10^6 K ($\geq L_*$) are surrounded by massive, extended hot halos, as infalling gas is shock-heated to $T_{\rm vir}$ and relaxes to quasi-hydrostatic equilibrium⁷⁹. The hot CGM is a reservoir of fuel for star formation and the dominant repository of mass, energy, and metals from galactic winds. Measuring these quantities and discovering how they are linked to cooler CGM components⁸⁰ provides powerful constraints on galaxy formation models.

Direct detections beyond R > 20 kpc are presently limited to a very small sample of massive galaxies with unusually bright and hot CGM⁸¹. The total extent and mass of the halos of L_* galaxies remain controversial, since measurements are only possible with present capabilities with stacking analyses. *AXIS* will detect the extended CGM around individual L_* galaxies within d < 200 Mpc, and around more massive galaxies to $z \sim 0.1-0.2$. The expected surface brightness falls below that of the soft X-ray background within $R \sim 20-50$ kpc of the disk (several arcminutes for a typical target). With its wide field of view, *AXIS* will model the local Galactic foreground and the time-variable solar wind charge exchange from the same observation allowing robust background subtraction.

AXIS' high resolution enables precise measurements of the mass, temperature, metal content, and entropy of the hot gas by removing contaminating point sources and distinguishing SNe-powered hot fountains (which have much higher surface brightness) from the extended CGM. This separation is essential to measuring the enrichment and entropy of the hot CGM. *AXIS* can obtain secure measurements of the entropy and metal content around a representative sample of galaxies with an investment of several Ms.

7 MICROPHYSICS OF COSMIC PLASMAS

Modern astrophysics relies on computer simulations to understand complex phenomena in the Universe, from solar flares to supernova explosions, black hole accretion, galaxy formation, and the emergence of Large Scale Structure (LSS) in the entire cosmological volume. However, we cannot model all the relevant scales of an astrophysical problem from first principles. For example, turbulence in the cosmological volume is driven by structure formation on the galaxy cluster scales (10^{24} cm), but can cascade down to scales as small as the ion gyroradius (10^{8-9} cm). Such a dynamic range is impossible to implement in codes. The only way to perform realistic simulations of macroscopic phenomena is to measure the relevant microscopic plasma properties experimentally and encode them at the "subgrid" (below-resolution) level. However, many key cosmic plasma properties, such as viscosity, heat conductivity, and the energy exchange between thermal and relativistic particle populations and the magnetic field remain largely unmeasured. Theoretical estimates span orders of magnitude, resulting in qualitatively different numerical predictions for galaxy stripping, evolution of galaxy clusters and many other processes.

Many of these properties can be probed through X-ray studies of galaxy clusters and SNRs. These objects are filled with a 10^{6-8} K optically-thin, X-ray emitting plasma permeated by magnetic fields and ultra-relativistic particles. The plasma is collisionless and "hot" in the plasma-physics sense — the ratio of thermal to magnetic pressure is typically > 100 in clusters and > 10 in SNR. This regime is directly relevant to a wide range of astrophysical systems.

A phenomenon particularly sensitive to plasma physics is shock fronts in clusters and SNR. These special locations permit study of such basic plasma properties as heat conductivity, the electron-ion temperature

- AXIS will measure fundamental properties of cosmic plasmas such as effective viscosity, heat conductivity, equilibration timescales
- AXIS will advance our understanding of cosmic ray acceleration by finding and resolving shocks in clusters and supernova remnants

MICROPHYSICS OF COSMIC PLASMAS

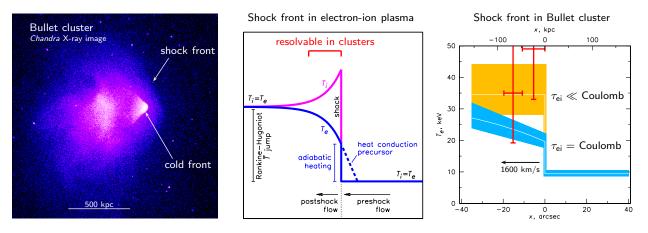


Fig. 19—*AXIS* will advance plasma physics by resolving shock fronts in galaxy clusters. *Left*: X-ray image of the Bullet cluster, the textbook example of a bow shock. The shock is driven by a moving subcluster (the bullet), whose front boundary is a "cold front." *Middle*: Expected electron and ion temperature profiles across a shock front in plasma. Temperatures are unequal immediately after the shock and then equalize. If electron heat conduction is not suppressed, a temperature precursor is also expected. *Right: Chandra* deprojected electron temperature profile immediately behind the Bullet shock (crosses; errors are 1σ) with models for Coulomb collisional and instant equipartition⁸². This measurement favors fast electron-proton equilibration, but uncertainties are large. *AXIS* will perform a definitive test by using many more shocks.

equilibration timescale, and the physics of cosmic ray acceleration and amplification of magnetic fields⁸³. As cosmic shock waves occur at all scales, these studies can have truly universal applications.

Another powerful plasma probe is provided by the ubiquitous, sharp contact discontinuities, or "cold fronts," found in the intracluster medium⁸³. While *Chandra* has provided tantalizing new results for shocks and cold fronts, it has only scratched the surface of what can be learned. Using these natural laboratories for plasma physics requires much greater collecting area and lower background, while maintaining high angular resolution to resolve the sharp spatial features and remove contamination from faint point sources.

7.1 Plasma Equilibration Times

The common assumption that all particles in a plasma have the same local temperature may not be true if the electron-ion equilibration timescale is long compared to heating timescales. This timescale is fundamental for such processes as accretion onto black holes and X-ray emission from the intergalactic medium. It can be directly measured using cluster shocks.

At a low-Mach shock, ions are dissipatively heated to a high temperature, T_i (which cannot be directly measured), while electrons are adiabatically compressed to a lower temperature, T_e . The two species then equilibrate to the mean post-shock temperature⁸⁴ (Fig. 19). From the X-ray brightness and spectra, we can measure the plasma density and T_e across the shock. Because sonic Mach numbers of cluster shocks are low (M = 2-3), the density jump at the shock far from its asymptotic value and thus provides an accurate value of M, giving the post-shock temperature. If the equilibration is via Coulomb collisions, the region over which the electron temperature T_e increases is tens of kpc wide — resolvable with AXIS at distances of z < 2. This direct test is unique to cluster shocks because of the fortuitous combination of the linear scales and relatively low Mach numbers; it cannot be done for the solar wind or SNR shocks.

A Chandra T_e profile across the prominent shock in the Bullet cluster (Fig. 19) suggests that $T_e - T_i$ equilibration is much quicker than Coulomb⁸⁵, although with low statistical confidence and a considerable systematic uncertainty that requires a sample of shocks. This measurement at present is limited to only three shocks and the results are contradictory^{85,86,87}. With *Chandra*, suitable shock fronts are rare. *AXIS* will be able to find hundreds more shocks, select a sample of suitable ones, and robustly determine this basic plasma property.

7.2 Heat Conductivity

Heat conduction erases temperature gradients and competes with radiative cooling, and is of utmost importance for galaxy and cluster formation. The effective heat conductivity in a plasma with tangled magnetic fields can be anywhere from zero to one-third of the Spitzer value, with a large range of predictions for the conductivity parallel to the field lines^{89,90}. The existence of temperature gradients in clusters confirms that conduction across magnetic field lines is very low^{91,92,93}, but estimates for the average conductivity⁹⁴ or the parallel component⁹³ are poor. Shock fronts are unique locations where the parallel component can be constrained. Electron-dominated conduction should result in an observable T_e precursor to the shock temperature jump (Fig. 19). AXIS will have the requisite sensitivity and resolution to measure this effect in the temperature profiles of cluster shocks.

7.3 Viscosity

Plasma viscosity governs the damping of turbulence and sound waves, suppression of hydrodynamic instabilities, and mixing of different gas Simulation of galaxy infall and stripping

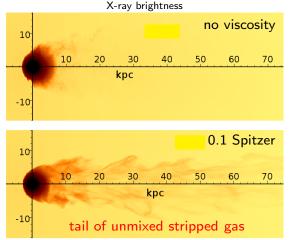


Fig. 20—*AXIS* will be able to probe plasma viscosity by searching for very low-contrast extended X-ray features that should accompany galaxies and groups as they fall into clusters. Viscosity determines how the gas is stripped from the infalling galaxies and how easily it mixes with the ambient gas. If viscosity is not completely suppressed, the galaxies should exhibit tails of stripped gas⁸⁸.

phases, but its value is largely unconstrained. X-ray observations of galaxy clusters can measure it in two ways. One is via detailed observations of cold fronts — sharp X-ray brightness edges ubiquitous in merging subclusters (e.g., Fig. 19) and cluster cores⁸³, where they are produced by "sloshing" of the gas in the cluster potential well⁹⁵. Sloshing produces velocity shear across the cold front, which should generate Kelvin-Helmholtz instabilities. However, if the ICM is even mildly viscous, these instabilities will be suppressed^{96,97}. These subtle features can only be seen with high resolution and lots of photons. *Chandra* has discovered Kelvin-Helmholtz instabilities in a few cold fronts and put an upper limit on the effective isotropic viscosity of 1/10 the classical value^{98,99,100,101}. To constrain the viscosity from below requires finding instabilities at different growth stages and for a range of density contrasts. *AXIS* will resolve the structure for many more cold fronts and thus measure the effective viscosity.

Plasma viscosity can also be probed by observing stripping of galaxies and groups as they fly through the ICM. Figure 20 shows a striking difference in the simulated X-ray appearance of the tail of the cool stripped gas behind an infalling galaxy. In an inviscid plasma, the gas promptly mixes with the ambient ICM, but a modest viscosity suppresses the mixing and makes the long tail visible. A deep *Chandra* image of a Virgo elliptical M89 favors efficient mixing and a reduced viscosity¹⁰². Other infalling groups in the cluster periphery do exhibit unmixed tails¹⁰³. *AXIS* will have the requisite sensitivity to study these subtle, low-contrast extended features, most of which will be found in the low-brightness cluster outskirts, to constrain effective viscosity — and directly observe its effect on gas mixing.

7.4 Cosmic Ray Acceleration at Shocks

Across the universe, shocks accelerate particles to very high energies via the first-order Fermi mechanism. Microscopic details of this fundamental process remain poorly known for astrophysical plasmas, and particle-in-cell simulations are still very far from covering realistic plasma parameters.

Many galaxy clusters exhibit striking "radio relics" in their outskirts¹⁰⁴. These Mpc-long, arc-like structures are synchrotron signatures of ultrarelativistic ($\gamma \sim 10^4$) electrons. In some clusters, radio relics

coincide with X-ray shock fronts, strongly suggesting that ICM shocks are responsible for those high energy electrons 105,106 . However, the shock Mach numbers are low (M = 1.5 - 2.5), and it is puzzling how they can have the acceleration efficiency needed to produce the relics. To gain insight, we need a systematic comparison of shocks in the X-ray and radio. A large number of relics have been found recently by *LOFAR*, *GMRT* and *MWA*, but most are located far in the cluster outskirts, where the X-ray emission is too dim for *Chandra* but accessible to *AXIS* with its superb sensitivity to low surface brightness objects.

7.5 Magnetic Field Amplification and Damping at Shocks

Shocks should produce large variations of the magnetic field on small linear scales, but the exact mechanism for field amplification is unclear. SNRs offer the chance to study shocks on the relevant scales - much smaller than those in clusters but much greater than those accessible to in situ measurements in the solar wind. Several SNRs show thin filaments of X-ray synchrotron emission in areas where shock velocities exceed several thousand km s^{-1} . In SN 1006, the width of these rims varies with energy, implying that the relativistic electrons rapidly age in a field as strong as $100 \,\mu\text{G}^{109}$ — inconsistent with the field damping quickly behind the shock. However, in another well-studied SNR, Tycho, the thin

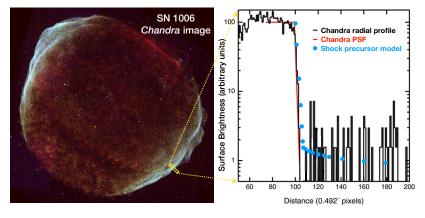


Fig. 21 — *AXIS* will measure the X-ray precursors of fast shocks as particles diffuse upstream. *Left*: the *Chandra* image of SN 1006¹⁰⁷, with a radial profile extracted from the yellow box shown in right panel. The red curve shows the *Chandra* PSF, while the blue dots show a potential shock precursor model¹⁰⁸. Even with *Chandra*'s resolution, the background level is too high to detect whether this precursor is present. *AXIS*' much lower background and increased sensitivity will reveal if the predicted precursor exists.

synchrotron rims suggest strong amplification at the shock followed by quick damping¹¹⁰. Could there be two different mechanisms by which magnetic fields are amplified and subsequently damped in shock waves? Observing more synchrotron-dominated shocks will answer this question. SN 1006 and Tycho observations required very long integration times with *Chandra*; all other similar remnants are simply too faint. *AXIS* properties are perfectly suited to drastically increase the sample size and accuracy for solving this problem.

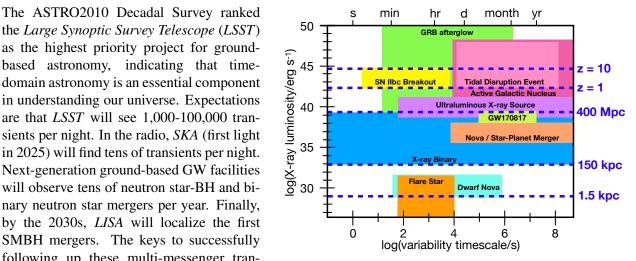
7.6 Diffusion of Cosmic Rays

Some accelerated particles must diffuse from behind the shock into the upstream medium. In SNR shocks dominated by non-thermal synchrotron emission from accelerated particles, faint X-ray emission should be present ahead of the shock, yet this emission has never been detected ¹⁰⁷ (Fig. 21). Finding and characterizing this precursor will put tight constraints on the universal properties of fast shock waves, such as the degree of magnetic field amplification and the diffusion and scattering length of energetic particles. Angular resolution is critical here; searching for this in Galactic SNRs will be possible with *AXIS*.

7.7 Feedback in Shocks from Particle Acceleration

When the energy in the accelerated particles becomes comparable to the energy in thermal gas, the shock dynamics change. In Tycho's SNR, the locations of the forward and reverse shocks and the contact discontinuity are inconsistent with theoretical predictions¹¹¹. This implies that the forward shock was efficiently accelerating cosmic rays, robbing the post-shock gas of energy and lowering the gas temperature. Such direct observations are invaluable for modeling the acceleration process^{112,113}. However, only a very few

SNRs have a high enough surface brightness at the shock for *Chandra* observations to test the theories. By greatly expanding the number of accessible objects and covering a broad range of shock Mach numbers, AXIS will revolutionize this field .



THE TRANSIENT AND VARIABLE UNIVERSE 8

Fig. 22 — The X-ray luminosity and variability timescale of various astrophysical phenomena. On the right axis (in blue), we denote the distance out to which AXIS can detect these transients in a 20 ks exposure.

their evolution. Guided by the appropriate decision trees, AXIS will make critical detailed follow-up observations of a wide range of these new discoveries (Fig. 22).

8.1 Tidal Disruption Events

the Large Synoptic Survey Telescope (LSST) as the highest priority project for ground-

based astronomy, indicating that time-

are that LSST will see 1,000-100,000 tran-

in 2025) will find tens of transients per night.

will observe tens of neutron star-BH and bi-

nary neutron star mergers per year. Finally,

following up these multi-messenger tran-

sients are (1) high sensitivity (i.e., low con-

fusion limit and high effective area) to probe

high redshifts and faint targets with short ex-

posures, and (2) rapid and flexible response time to track transients quickly and monitor

Roughly one star per galaxy every 10 thousand years gets disrupted by the strong tidal forces of the central SMBH¹¹⁴. The accretion of the bound stellar material causes a short-lived flare of emission, known as a Tidal Disruption Event (TDE). Recently, TDEs have garnered excitement from a range of astronomical communities because, as opposed to continuously accreting BHs in AGN, they are an impulse of accretion onto a normally hidden BH. Some of the AXIS TDE science includes:

8.1.1 Super-Eddington accretion in TDEs. The fallback rate from the tidally disrupted stars is initially highly super-Eddington for $M_{\rm BH} < 10^7 M_{\odot}$ and drops with time. Thus, TDEs are laboratories for studying the transition from super-Eddington to sub-Eddington on timescales of months or less and for testing MHD simulations of super-Eddington flows¹¹⁵. Understanding the X-ray component of super-Eddington TDEs is key, as this is the emission coming from the innermost regions, where ultrafast outflows and jets may be launched. AXIS' unprecedented sensitivity, angular resolution, and fast slew capabilities provide fast identification of the X-ray counterpart of TDEs, allowing the monitoring of their intensity and spectral

- AXIS will have a response time under 4 hours, 100x the effective area of Swift, and will dedicate 10% of observing time for follow-up of transients
- AXIS will observe $10^6 M_{\odot}$ SMBH mergers at z=2, which are too faint for current or proposed wide-field X-ray monitors
- AXIS will detect and resolve events like the NS-NS merger GW170817 out to ~400 Mpc

evolution over time. Currently, *Swift* is the key X-ray instrument for monitoring TDEs. With *AXIS*, we have 70x more counts per unit time than Swift, giving a complete spectrum over a broad energy range. *AXIS*'s exquisite sensitivity in the softest energy bands, where X-ray TDEs emit most of their energy, will determine the physical origin of the X-ray emission and its connection to the optical and UV emission.

8.1.2 Finding the missing intermediate-mass black holes. Recently, an off-nuclear X-ray TDE candidate was discovered ¹¹⁶ with spectral characteristics indicating it was the disruption of a white dwarf by a BH of mass $10^{4.5-5}M_{\odot}$. This result shows that TDEs are a promising way to find populations of BHs that cannot be detected dynamically. *AXIS* has the high angular resolution required to disentangle these off-nuclear intermediate-mass BHs from the central SMBH. This is especially important for TDEs found from wide-field X-ray monitors like the Einstein Probe (to launch in 2023) that have much poorer angular resolution.

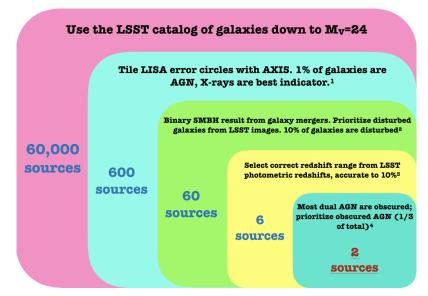
TDEs in the next decades will be detected to much larger redshift, requiring increased X-ray sensitivity to obtain a precise localization and measure the spectra and timing behavior. At present, due to a small sample size and low signal to noise, there are very few constraints on when the X-ray emission is produced, which is crucial to determine the physics of the TDE emission.

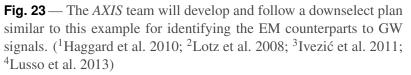
8.2 X-ray Counterparts to *LIGO* Binary Neutron Star Merger Events

The recent discovery of gravitational waves (GWs) and EM detections¹¹⁷ from a binary neutron star merger¹¹⁸ has opened a new field of observational astronomy. X-ray afterglows of neutron star mergers can constrain the external density, magnetic fields, and jet structure¹¹⁹. Further, X-rays can constrain the binary inclination, which, in the GW signature, is highly degenerate with the distance of the object. This is essential for using GWs as a cosmological probe.

By the early 2020s, most GW events will be found at $d \sim 200$ Mpc. If these events are like GW170817, their X-ray afterglow will have $F_X \sim 8 \times 10^{-16}$ erg s⁻¹ cm⁻², below the sensitivity of *Chandra* for a 100 ks exposure. *AXIS* could detect such an afterglow in only ~5 ks, allowing monitoring of the light curve, crucial for modeling the nature of the jet. Longer exposures will determine the source spectrum.

Arcsecond angular resolution was important for the GW170817 X-ray afterglow, since it was offset from an AGN nucleus by 10". At 200 Mpc, a similar event would be 2" away from the nucleus; *Athena*, with its \sim 5" resolution, would not be able to distinguish the event from an AGN. Good angular res-





olution is key, as AGN, ultraluminous X-ray sources (ULXs), and magnetars are highly variable and of similar luminosity, and could be confused with the neutron star merger.

In the late 2020s, the next generation ground-based GW detectors will expand the detection range to \sim 400 Mpc. The rate of detections of GW events will increase by an order of magnitude to \sim 100 per year. *AXIS*' large area and fast slew capabilities allow for short exposures and good flexibility, so it can monitor the evolution of several merger events per year and perform rapid searches for the counterparts.

8.3 Electromagnetic Counterparts to LISA SMBH Mergers

ESA's *LISA* GW mission is scheduled to launch in the early 2030s, during the lifetime of *AXIS*. While the exact SED of these events is not known, it is likely that the candidates will be AGN-like. Some simulations predict that most of the luminosity originates in hot mini-discs around the two SMBHs¹²⁰, so X-rays may be the best wavelength to find the EM counterparts of *LISA* GW events.

LISA can detect BH inspiral and mergers from $10^{3-7}M_{\odot}$ BHs up to a redshift of $z = 20^{121}$. *AXIS* is wellsuited to observe the 'average' 10^6M_{\odot} merger, which will occur at the peak of star formation at z = 2. We make the conservative assumption that the source is at 10% of the Eddington luminosity, where the X-rays are 10% of the bolometric luminosity. We therefore expect $F_X = 3 \times 10^{-16}$ erg s⁻¹ cm⁻², several orders of magnitude below the limiting flux of current or proposed wide-field X-ray monitors. *AXIS* can detect this flux with ~15 photons in 15 ks. However the details of SED are highly uncertain. Even if the source is moderately obscured ($N_{\rm H} = 5 \times 10^{22}$ cm⁻², as is seen for many dual AGN²⁸), the estimated flux at z = 2 is $F_X = 10^{-16}$ erg s⁻¹ cm⁻², and *AXIS* can detect ~15 photons in 50 ks.

We show in Figure 23 a scenario in which *AXIS* can identify the EM counterpart. *LISA* will localize 1 GW event per year with an error circle of $< 1 \text{ deg}^2$, with a distance measure within 10%, and ~ 5 events per year with error circles of 10 deg² or more¹²². The "warning" time, when a position can be reasonably estimated, is $\sim 16-35 \text{ days}^{123}$. *AXIS* will tile the 1 deg² error circle in six 15 ks pointings ($\sim 1 \text{ day}$) and alert the community, providing roughly 10 high probability candidate GW events (Fig. 23). *AXIS* will monitor those few candidates for the 16-35 days before merger, searching for periodicities^{124,125} or atypical AGN SEDs, which may indicate which candidate is the GW source, depending on the actual fluxes.

8.4 Serendipitous Time Domain Science

AXIS will serendipitously detect transients, like ULXs, novae, and core-collapse SN, out to ~ 250 Mpc (Fig. 22). AXIS will detect an average of ~1.5 MW-mass galaxies per field of view; in a 50 ks exposure, it will detect all of the ULXs in those galaxies, which occur at the rate of ~1 per 3 galaxies. With AXIS' <50 ms time resolution, it can be used to search for ULX pulsation¹²⁶, since the fastest known ULX has a period of 0.419 s. AXIS can detect classical novae ($L_X \sim 10^{35}$ erg s⁻¹) out to a distance of ~1 Mpc, allowing X-ray flux measurements for all classical novae in the Local Group. Core-collapse SNe have $L_X \sim 10^{38-41}$ erg s⁻¹, depending on the type of explosion and how long after the explosion it is observed. AXIS can detect a SN with $L_X \sim 10^{40}$ erg s⁻¹ at a distance of 400 Mpc, which allows access to a huge number of targets: assuming a SN rate of 10^{-2} galaxy⁻¹ yr⁻¹ and a space density of 0.01 massive galaxies Mpc⁻³, there will be 2×10^4 SN yr⁻¹, which AXIS can discover serendipitously.

9 THE MILKY WAY AND NEARBY UNIVERSE

9.1 The Galactic Center

Arcsecond X-ray imaging resolution is indispensable for studying the Galactic Center (GC). *Chandra* imaging discovered extended X-ray emission from the accretion flow of Sgr A*^{127,37,128} and revealed the population of compact objects in the GC, placing constraints on the stellar history and dynamical evolution of the Galactic bulge and GC region and strong constraints on stellar mass BHs near the GC^{129,130,131}. X-ray observations have elucidated the structure of the GC ISM and the accretion history of Sgr A* through iron

- AXIS will measure the luminosity of Sgr A* for several hundred years in the past
- AXIS will map Fe-group elements in supernova remnants to determine how they exploded
- AXIS will measure interstellar dust grain size and composition from scattering halos
- AXIS will measure the luminosity functions for XRBs in different environments

fluorescence of GC molecular clouds^{132,133,134}. *AXIS* will enable a deeper view of the GC population of BHs, Sgr A* flares and accretion flow and dust echoes. The higher signal-to-noise for iron fluorescence combined with high spatial resolution will extend by several hundred years the measurement of Sgr A* X-ray luminosity in the past, a unique observation for any SMBH.

9.2 Supernova Remnants

Many unsolved problems about SNRs, such as the progenitors of the various SN types and how they relate to the remnants produced, and how SNR populations of nearby galaxies correlate with the local star-formation history, require AXIS' capabilities to solve. Mapping the distribution of elements in the SNR is crucial, as the wide range of explosion models for both Type Ia and core-collapse SNe predict vastly different ejecta distributions. It is particularly important to map Cr, Mn, and Ni for SN Ia remnants, as their locations allow the mass determination of the Type Ia-progenitor. These lines are faint and diffi-

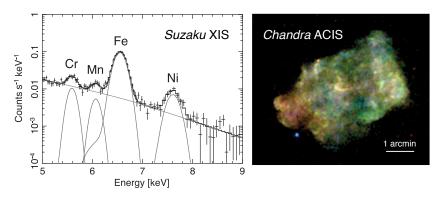


Fig. 24— *AXIS* will map the spatial distribution of Fe-peak elements (Cr, Mn, Fe and Ni) with unprecedented accuracy in many supernova remnants, determining the mechanism of the Type Ia supernova progenitor explosions. *Left: Suzaku* spectrum of the Galactic SNR $3C397^{135}$, integrated over the entire remnant. *Right: Chandra* high-resolution falsecolor image of the remnant¹³⁶ in broad energy bands (red 0.8–1.5 keV, green 1.5–3 keV, blue 3–7 keV bands). The CCD energy resolution is sufficient to separate the lines; *AXIS* will be the first instrument to combine the necessary angular resolution and sensitivity to map the emission in individual spectral lines.

cult to observe with current observatories (see Fig. 24), with the low S/N making element distribution mapping impossible. Only *AXIS* will have sufficiently high angular resolution and sensitivity to make such observations for SNR in the Milky Way and, for the first time, other nearby galaxies. This capability will allow the comparison of the SNR population with the local star-formation history in other galaxies, in addition to constraining SN progenitor models¹³⁷. Detailed studies of the spectral lines in SNR with the high spectral resolution of the forthcoming X-ray calorimeter missions (*XRISM*, *Athena*) will provide complementary dynamical and ionization constraints, which combined with *AXIS* data provide a major step forward in our understanding.

9.3 Dust Halos in the Interstellar Medium

Understanding the structure and composition of Milky Way dust is vital for studies of the CMB, as dust can greatly impact CMB polarization measurements^{138,139}. X-rays also provide otherwise unobtainable constraints on interstellar dust models, which currently rely on degenerate results from other wave-lengths^{140,141,142}. *AXIS* will probe interstellar dust through observations of scattering halos around bright flaring sources, produced from small-angle scattering by intervening dust, which has a scattering cross-section that increases rapidly with grain size and is sensitive to grain composition¹⁴³. *AXIS*' rapid response time and low background allow for X-ray tomography studies of the ISM for ~50 sightlines over *AXIS*' minimum 5-yr lifetime, to greater precision than current stellar population extinction maps¹⁴⁴ (Fig. 25).

9.4 Local Volume X-ray Binaries

XRBs provide insights into star formation histories and stellar dynamics. The XRB luminosity function (XLF) steepens with age¹⁴⁵ and depends on metallicity, so measuring the XLF independently constrains the IMF and metallicity^{146,147,148} for direct comparison with results derived from

optical, UV, IR and mm observations. AXIS will detect XRBs down to a $L_X = 10^{36.5}$ erg s⁻¹ in galaxies within d < 20 Mpc for exposures of ~ 100 ks, determining the parameters of the HMXB XLF and providing an independent SFR indicator for normal galaxies which is insensitive to dust and has totally different systematics¹⁴⁹, with hundreds of XRBs detected per galaxy. These data will be used in the high-z regime to determine the fraction of low mass XRBs that originate in dense stellar clusters, identify runaway HMXBs, and measure the dependence of the HMXB population on metallicity. Finally, monitoring galaxies within 10 Mpc (10-30 ks visits) over the mission lifetime will quantify the variability among XRBs down to $10^{37.5}$ erg s⁻¹ and provide spectra

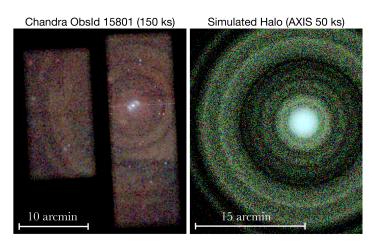


Fig. 25—*AXIS* will produce images of dust scattering halos of unprecedented quality, allowing detailed study of the composition and structure of the scattering medium, as well as a historic record of the source's flares. *Left: Chandra* binned composite-color image of Cir X-1. Red: 1-2 keV, green: 2-3 keV, blue: 3-5 keV. *Right*: Simulated 50 ks halo observation with *AXIS* (no point sources.)

and timing for the brightest sources that will connect the classification of XRBs in the Local Group to the wider population of galaxies and clarify the origin, nature and lifetime of ULXs. *AXIS*' 50 ms time resolution will allow studies of the periodicity of \sim 99% of all known accreting X-ray pulsars in the Milky Way, LMC, SMC and other nearby galaxies.

9.5 Pulsar Wind Nebulae

Pulsar Wind Nebulae (PWNe) are synchrotron bubbles of relativistic plasma inflated by the rotational energy loss of a fast spinning neutron star. Confinement of the wind by the SN ejecta leads to the formation of a 'termination shock,' at which particles are accelerated and beyond which the nebula forms. The termination shock is often at < 0.1 pc from the pulsar, thus requiring subarcsecond resolution to resolve it (Fig. 26). Chandra has provided insight into some of their fundamental properties, such as the origin of the characteristic torus-jet structures and the strength of the nebular magnetic field^{151,152}, but studies have been limited to a few nearby, bright, young PWNe. AXIS will study a much larger sample of PWNe in our Galaxy and the Magellanic Clouds, and will shed light on the physics of pulsar wind magnetization, wind propagation, and particle acceleration.

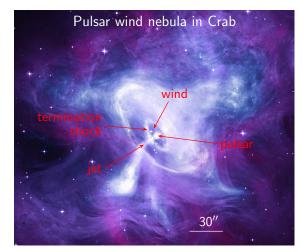


Fig. 26—*AXIS* will produce high-resolution images for many PWN, allowing multiband study of these potentially most powerful particle accelerators in the local Universe. Figure shows a multiband image of the Crab nebula¹⁵⁰ (white/blue: *Chandra*, purple: HST, pink: *Spitzer*). With *AXIS*, such level of detail will become possible for many PWN.

10 SOLAR SYSTEM AND EXOPLANETS

With its superior sensitivity and angular resolution, *AXIS* can use variable X-ray emission to probe the composition of local comets and the evolution of solar system planetary atmospheres. *AXIS* will also characterize exoplanet habitability and the role of X-rays in planet formation and evolution through observing exoplanet host stars and X-ray transits due to exoplanets.

10.1 Comet Chemistry

There are two sources of X-rays from comets. First, charge exchange (CX) between solar wind ions and neutral atoms in cometary atmospheres produces low energy 0.1–1.0 keV X-rays¹⁵³ (first detected in Comet Hyakutake 1996/B2¹⁵⁴). Second, nano-sized dust/ice particles scatter solar X-rays^{155,156} at E > 1 keV. These mechanisms can probe the comet surface and subsurface chemistry for comets crossing the snow line, where the surface layers are sublimated. *AXIS* will resolve CX-driven X-ray emission from comets as far out as 2.5 au from the Sun, raising the number of comets visible in the X-rays from 0.5 yr⁻¹ to ~4 yr⁻¹, while also permitting a comprehensive study of scattered light at E > 1 keV.

10.2 Variability of the Jovian Magnetosphere and Exosphere

Jovian X-rays come from Jupiter's disk, poles, and flux torus¹⁵⁷. The disk X-rays are scattered solar photons^{158,159}, while the polar and flux tube components are coupled to the particles, fields, and "weather" of the Jovian magnetosphere and exosphere^{160,161,162}. Each source is strongly variable, and AXIS' sensitivity will allow, for the first time, monitoring and mapping of each component with a cadence that can be correlated with the JUNO optical and UV maps (Fig. 27). This will be instrumental in studying Jovian magnetic field properties

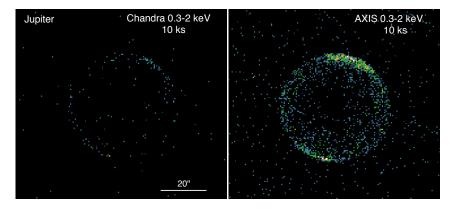


Fig. 27— As shown by these simulated *Chandra* (*left*) and *AXIS* (*right*) observations of Jupiter aurora, *AXIS*' much larger soft X-ray effective area will resolve daily fluctuations in Jovian X-ray emissions and magnetic field reconnections on 1000-km scales, allowing comparison of these changes to daily auroral and atmospheric weather events. The aurora is only in view for 10-20 ks per 10-hour Jovian day.

known to fluctuate on 1-3 day timescales, due to the loading/unloading rates of Io plasma in the Jovian magnetosphere.

10.3 Evolution of Planetary Atmospheres in the Solar System

The role that X-rays play in the development and destruction of planetary atmospheres is still not well understood. Solar UV light is known to cleave Earth's atmospheric ozone, and land-based life was not viable until terrestrial ozone was abundant enough to block >90% of UV photons at the surface. Whereas extreme UV and X-ray flares may damage atmospheres by removing bulk gas, depleting ozone (by up to 90% after X-ray flares¹⁶³), and dissociating water, X-ray flares are also linked to higher abundances of various chemicals in protoplanetary systems^{164,165,166}. *AXIS* will provide robust spatial characterization of localized impacts of solar X-rays/solar wind ions on planetary atmospheres, as well as probe the dissipation of X-ray photons and excited secondary particles throughout the atmosphere. Over larger time-scales, *AXIS* will investigate the impact of solar flares on the release of energetic particles from the upper atmosphere, as well as on atmospheric size and density. Through studying the different atmospheres of our neighboring planets

- AXIS will investigate variations in comet emissions during perihelion approach, including rapid outflow events and bow shock generation upon crossing the snow line
- *AXIS* will observe high-energy particle transfer in Jupiter's upper atmosphere and test results from *JUNO* observations
- AXIS will study the impact of stellar X-ray activity on planetary atmosphere evolution in Solar System and exoplanet environments

under extreme UV insulation, AXIS will study the dependence between atmospheric chemical abundance and high-energy solar activity at high spatial and temporal resolution.

10.4 High-Resolution Mapping of Elements on the Lunar Surface

Lunar X-rays¹⁶⁷ are dominated by fluorescence line emission from O, Mg, Al, and Si^{168,169}. *AXIS* can use these lines to map abundances of the Moon with a resolution of 2 km in only 100 ks, comparable to the 1-10 km resolution maps of only a small fraction of the lunar surface obtained by lunar orbiters/landers (e.g., *Clementine, LRO*), and an order-of-magnitude improvement on the 20 km resolution of *SELENE*¹⁷⁰.

10.5 Exoplanet Atmospheres

Rocky planets have been discovered in the "habitable zone" around several M-dwarfs, and *TESS* will discover many more. However, such planets may lose all their water due to stellar flares, which can dissociate water and then evaporate the hydrogen. The extent to which this occurs is unknown, especially among late M-dwarfs. *Chandra* enabled a breakthrough study of magnetic activity in young and evolved stellar populations^{171,172}, but *AXIS* will perform deeper stellar surveys and measure activity in smaller "bins" of spectral type for many more stars, crucial to determining the typical activity of planet-bearing stars.

AXIS will directly study "hot Jupiter" planetary atmospheres through transits. To date, the only X-ray transit observed was in HD 189733b, the first detected, canonical hot Jupiter. The depth and length of the transit constrain the atmospheric evaporation rate¹⁷³, and *AXIS* will enable observations of at least an order of magnitude more transits than is currently possible. There is also evidence that hot Jupiters affect the magnetic fields of their host stars, as gauged by X-ray flux^{173,174}. *AXIS* will be able to confirm or refute this picture with a much larger sample.

MISSION IMPLEMENTATION

New technology allowing a large, sharp, lightweight X-ray mirror is the major advance that makes the above scientific developments possible and sets *AXIS* apart from all the existing and planned X-ray missions. The basis of the *AXIS* mission design is simplicity — one mirror, one detector with long heritage, no moving parts (beyond the post-launch focus adjustment), low-Earth orbit for low background, and a low-radiation environment and fast response.

11 AXIS MIRROR ASSEMBLY

The AXIS mirror assembly represents a quantum leap from the state of art represented by Chandra. It is made possible by the recent conception and development of the silicon meta-shell optics technology pursued by the Next Generation X-ray Optics (NGXO) team at NASA Goddard Space Flight Center. The design and implementation of the AXIS mirror assembly drives the AXIS science performance and programmatic requirements on mass, volume, production cost, and schedule. It also incorporates knowledge and lessons learned from designing and building mirror assemblies for past and current observatories, including Chan-

AXIS MIRROR ASSEMBLY

Parameter (unit)	Value	Comment
Focal length (mm)	9000	Fits within a Falcon 9 fairing
Outer diameter (mm)	1700	Fits within a Falcon 9 fairing; provides A_{eff} at 1 keV
Inner diameter (mm)	300	Provides $A_{\rm eff}$ at 6 keV
Dimensions of tunical mimor	100 (axial)	Balances diffraction limits and off-axis response
Dimensions of typical mirror segments (mm)	100 (azim)	Balances manufacturability and number of segments
segments (mm)	0.5 (thick)	Meets mass requirements
Number of mirror segments	16,568	Not including stray light baffle segments
Number of mirror modules	188	The mirror segments are assembled into 188 separate modules, each are separately and fully tested
Number of meta-shells	6	The modules are assembled into 6 separate meta-shells.
Mass of mirror assembly (kg)	454	Includes mass of mirror segments, stray light baffles and spider platform to which meta-shells are attached
Mirror-only effective area (cm ²)	1 keV: 7700 6 keV: 1600 12 keV: 180	Large effective areas are made possible by the small thickness of the mirror segments
Mirror on-axis PSF (HPD, arcsec)	0.4	$1.5 \times$ better than <i>Chandra</i> 's mirror; a combination of precision polishing technology and mono-crystalline silicon
Mirror 15' off-axis PSF (HPD, arcsec)	1.0	$28 \times$ better than <i>Chandra</i> ; Wolter-Schwarzschild design and short axial length of mirror segments

Table 2 — Characteristics and key parameters of the AXIS Mirror Assembly

dra, *XMM-Newton*, *Suzaku*, and *NuSTAR*. Table 2 lists the characteristics of the *AXIS* mirror assembly for our baseline design.

11.1 The Silicon Metashell Approach

The silicon meta-shell optics (SMO) technology has been in development since 2012. It combines the precision optical polishing technology that made *Chandra*'s exquisite PSF possible with the use of mono-crystalline silicon material, fabricated into 0.5mm thick mirrors. Taking advantage of the ready availability of mono-crystalline silicon, and the equipment and processing knowledge accumulated by the semiconductor industry, this technology meets the following three-fold requirement on the *AXIS* X-ray mirror

Metashell	Mass	Effective Area (cm ²) at:			
	(kg)	1 keV	4 keV	6 keV	12 keV
1 (inner)	37	480	390	410	180
2	49	840	610	620	3
3	58	1180	720	530	0
4	67	1500	670	60	0
5	73	1740	420	5	0
6	80	1960	120	1	0
Total	363	7700	2900	1600	180

Table 3 — Contributions of each metashell to mass and area.

assembly: (1) better PSF than the *Chandra* mirror's 0.6'' HPD, (2) more than 10 times lighter per unit effective area, and (3) more than 10 times less expensive per unit effective area.

AXIS uses a variant of the Type-I Wolter-Schwarzschild design, which meets the Abbe sine condition

for imaging, giving better off-axis PSF than the Type-I Wolter design used by *Chandra*¹⁷⁵. The off-axis PSF is further improved by a slight defocusing of the on-axis PSF from the geometrically perfect PSF to one that is somewhat larger (negligible compared to diffraction limits). Most importantly, since the off-axis PSF degradation is dominated by focal surface curvature, inversely proportional to the length of the mirror element in the optical axis direction and different for shells of different radius, *AXIS*' use of shorter mirror segments (100 mm compared to *Chandra*'s 840 mm) improves the theoretical off-axis PSF by a large factor.

There are four major steps in building the AXIS mirror assembly, as illustrated in Fig. 28: (1) mirror segment fabrication, (2) integration of mirror segments into mirror modules, (3) integration of mirror modules into mirror metashells, and finally (4) integration of mirror metashells into the final mirror assembly. The AXIS mirror assembly has several salient features that make it easy to accommodate on the observatory. First, the entire mirror assembly is made of silicon, except for trace amounts of iridium for enhancing X-ray reflectance, chromium for binding the iridium to the silicon surface, silicon oxide for canceling the thin film stress of the iridium, and epoxy for bonding mirror segments to structures, all of which have no significant thermal or structural impact. This effectively uniform material composition enables the mirror assembly to operate at a temperature different from room temperature ($\sim 20^{\circ}$ C) at which it is built and tested. The lack of a stringent operating temperature constraint significantly re-

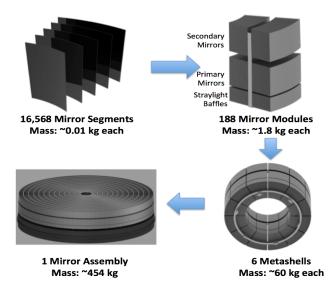


Fig. 28— A hierarchical approach to build the *AXIS* mirror assembly that enables mass parallel production. It uses commercially available materials and equipment to minimize both production cost and schedule.

duces the need for precise thermal environmental control, reducing costs of building, testing, and operating the mirror assembly. Second, the modular approach makes it highly amenable to parallel production. The mirror segment's similarity in dimension to the semiconductor industry silicon wafer makes its production highly similar to the wafer production process, allowing use of commercially available equipment and knowledge to minimize cost and schedule. Third, the large numbers of mirror modules and mirror metashells make it easy to manage spares. The modest size of the mirror modules requires no special equipment to handle, test, or qualify.

Only the fabrication of mirror segments, and integrating (aligning and bonding) them into mirror modules, require technology development. The other two, integrating modules into meta-shells and integrating meta-shells in turn into the mirror assembly at the required level of precision, are routine engineering and I&T work implemented in many past missions.

11.2 Mirror Technology Development

The NGXO team at NASA Goddard Space Flight Center was established to develop X-ray mirror technology to meet the needs of future X-ray missions such as *AXIS* and *Lynx*. Their work started in 2001 with development of a precision glass slumping process to meet the requirements of the *Constellation-X* mission. Concurrent with that development, the NGXO team successfully fabricated over 10,000 glass mirror segments for the highly successful *NuSTAR* mission. In 2012, the technique of combining precision polishing technology with mono-crystalline silicon was adopted. This allows us to achieve high angular resolution with a very light mass. Further, it has the added benefit that it uses readily-available semiconductor industry mono-crystalline silicon material, with corresponding processing equipment and technology.

11.3 Mirror Segment Fabrication

The fabrication of a mirror segment (Fig. 29) starts with a block of mono-crystalline silicon, measuring $150 \times 150 \times 75$ mm (Fig. 29.1). After an approximate conical contour is cut into the block, it is ground on a computer numerical control machine to improve the approximation to within 20 μ m of the mathematical prescription. The conical form is then lapped on a stainless steel cone that is precisely machined with prescribed cone angle and radius. After this step, the conical surface is an excellent first order approximation to the prescribed mirror segment figure (Fig. 29.2). The block is next

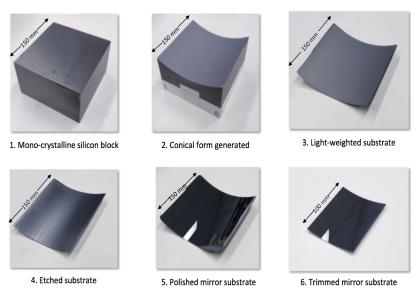


Fig. 29— Fabricating a mirror segment takes about four days of calendar time and 10 hours of labor per segment.

placed under a slicing saw to cut off the conical thin shell (Fig. 29.3). Damage to the crystal structure from the lapping and slicing operations results in unpredictable deformation. This damage is removed, and therefore its conical shape restored, by etching the thin shell in a standard HNA (hydrofluoric acid, nitric acid, and acetic acid) solution that removes the atoms that were displaced from their lattice locations (Fig. 29.4). The conical shell is then temporarily bent into a cylindrical shape, and polished on a cylindrical surface padded with synthetic silk that has been developed by the semiconductor industry for polishing silicon wafers (Fig. 29.5). This is equivalent to the stress-polishing invented by and successfully applied to mirror segments for the Keck Telescopes.

At the end of the 20-hour polishing process, the mirror segment attains the required micro-roughness. The mirror segment at this stage, however, has severe figure errors near its four edges as a result of the polishing process. In the next step, about 25mm from each of the four sides of the mirror segment is trimmed with a standard abrasive saw, resulting in a mirror segment that is approximately $100mm \times 100mm \times 0.5mm$ (Fig. 29.6). As an integral part of each of these steps, any damage to the crystal structure is carefully removed by either HNA etching or careful polishing, ensuring that no surface or subsurface damage that stores energy and causes stress and figure distortion remains. The last step in mirror fabrication uses a state-of-the art ion-beam figuring machine to improve the figure of the mirror segment to 0.2'' HPD (two reflection equivalent), which meets the *AXIS* requirements. Typically the ion-beam figuring step removes about 300 nm of material from the mirror surface, improving the figure from about 3'' to 0.3'' while leaving the excellent micro-roughness intact, at about 0.3 nm RMS as measured on $0.4mm \times 0.4mm$ square. As of February 2019, mirror segments with figure quality of 0.5'' HPD have been regularly fabricated. Further improvement in the mirror fabrication process in 2019 is expected to result in mirror segments of 0.2'' HPD or better.

11.4 Mirror Segment Coating

After it is qualified by extensive measurements, the mirror segment is coated with 30 nm of reflectanceenhancing iridium. The compressive stress of the iridium coating, which can severely distort the figure, is compensated for by approximately 300 nm of silicon oxide on the backside. The coating is accomplished in steps illustrated in Fig. 30. After the mirror segment is fabricated, it is heated to 1,050° C to grow a

	TRL-4	TRL-5	TRL-6
Illustration			
Description	Fabrication, alignment, and bonding of single pairs of mirror segments to achieve progressively better PSF, culminating in 0.3" HPD.	Alignment and bonding of 2-3 pairs of mirror segments to achieve 0.3" HPD. Demonstrate the structural and other environmental integrity of the mirror bonds.	Alignment and bonding of many (>3) pairs of mirror segments to achieve 0.3" HPD for a mirror module, passing all environmental tests.
Objectives	1. Develop and verify mirror fabrication and mirror coating processes. 2. Develop and verify the basic elements of alignment and bonding procedures for precision and accuracy.	1. Develop and verify mechanics and speed of co-alignment and bonding processes. 2. Conduct environmental tests: vibration, thermal vacuum, and acoustic to verify structural and performance robustness.	1. Develop and verify meta-shell production process: mirror fabrication, coating, alignment, and bonding. 2. Validate production schedule and cost estimates. 3. Develop plan for mass production.
2018 Status	Repeated building/testing, achieving $\sim 2''$ HPD.	Build and test one module, achieving $\sim 5''$ HPD.	In progress.
Completion	December 2020	December 2022	December 2024

Table 4 — The status and maturation plan for the mirror technology.

 \sim 300-nm layer of silicon oxide on its backside, a standard, proven industrial process. As with the iridium thin film, the silicon oxide film has compressive stress. Next, \sim 30 nm of iridium is sputtered on the mirror segment. The stresses of the oxide film and the iridium film largely cancel each other out. However, the cancellation is not always complete, leaving behind a residual figure distortion.

In the final step, the residual figure distortion is measured on an interferometer, from which a residual stress map is calculated. It is then converted into a thickness map of the silicon oxide film. This thickness map is finally fed into an ion-beam figuring machine for residual stress removal, achieving precise cancellation of figure distortion. The validity of this process was fully demonstrated in a collaborative

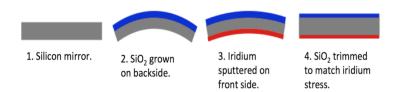


Fig. 30— Coating a mirror segment with reflectance-enhancing iridium layer without degrading its figure has been demonstrated in the laboratory.

effort between the NGXO group and scientists at MIT's Kavli Institute using a wet chemical process to trim the silicon oxide thickness¹⁷⁶. Several mirror segments have been coated and treated in this manner and display a net PSF degradation of less than 0.2" HPD (two reflections equivalent).

As of February 2019, the NGXO group had installed a state-of-the-art ion beam figuring machine. The machine is fully operational and the NGXO group is making 0.5'' mirror segments on a routine basis. It is anticipated that in 2019 the entire process of coating a mirror segment shown in Fig. 30 will be fully demonstrated to meet *AXIS* and *Lynx* requirements.

11.5 Mirror Segment Alignment

Fig. 31 shows schematically the integration of mirror segments into a mirror module. One important point to note is that, while three points uniquely determine the location and orientation of a flat mirror, it takes four points to uniquely determine the location and orientation of a curved mirror. Therefore, each mirror segment is aligned and bonded using 4 spacers (Fig. 31). The process starts by attaching four spacers on a silicon plate for each mirror segment. The four spacers are then ground to precise heights under the guidance of a radius gauge. The mirror segment is next placed on the spacers, and its alignment is checked by a set of precise Hartmann measurements using a laser beam. The alignment errors determined by the Hartmann measurements are then used for further grinding of the heights of the spacers. This iteration of measure-and-grind continues until the mirror segment achieves its prescribed alignment. Once alignment is

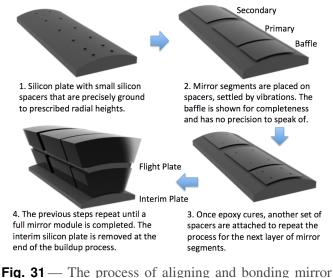


Fig. 31— The process of aligning and bonding mirror segments to make a mirror module is straightforward. Note that, except for the epoxy and trace amounts of iridium and silicon oxide on each mirror segment, all components are made of silicon, including mirror segment, spacers, the interim plate, and the flight plate.

achieved, a small amount of epoxy is applied on top of each of the four spacers and the mirror segment is placed on them. When the epoxy cures, the mirror segment is permanently bonded. This process is done in parallel with the segment fabrication and takes 4 hours of clock time and 10 hours of labor per segment.

The validity of the alignment and bonding process has been demonstrated by testing of several mirror modules containing one or two pairs of mirror segments, achieving 2.2" HPD under full illumination with 4.5 keV photons in an X-ray beam line. A test image shown in Fig. 32 was obtained with the mirror module in horizontal position (due to limitations of the beam line) and includes the effect of gravity, which is analyzed and determined to be about 1.5'', leaving about 1.6'' for the intrinsic image error for the module. The intrinsic error further includes the effect of energy-dependent scattering. After correcting the image from 4.5 keV to 1 keV X-rays, the image quality becomes 1.3" HPD (bottom of Table 5).

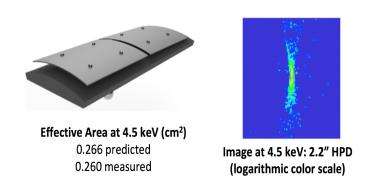


Fig. 32— Laboratory measurements have validated the mirror development approach. A pair of mirror segments have been fabricated, aligned, bonded, and tested in an X-ray beam, achieving a PSF of 2.2'' HPD (uncorrected for gravity distortion) with expected effective areas. Further optimization and improvement in alignment and bonding are needed to realize the full potential of the mirror segments of 0.3'' HPD.

Further refinement of the alignment and bonding process will be done in 2019 to fully realize the 0.3'' potential of the mirror segments, including better control of the absolute radial placement of each mirror segment, and fine adjustment of the mirror segment in the axial direction. We expect that, by sometime in 2019, X-ray images of 0.4'' HPD will be obtained with a fully aligned and bonded mirror pair with full illumination.

Source of error		Req. (″ HPD)	2018 status (″ HPD)	Notes
Optical prescription	Diffraction Geometric PSF (on-axis)	0.1 0.05	0.1 0.05	Weighted mean of all shells at 1 keV. The on-axis design PSF is degraded to achieve best possible off-axis PSF
Mirror segment fabrication	Mirror substrate	0.2	0.5	With one iteration on an ion-beam machine. With two iterations substrates should meet requirements.
	Coating	0.1	0.2	20nm iridium and 5nm of chrome as a bonding layer on the frontside. 300 nm of silicon oxide on the backside. Better stress cancellation achievable by finer trimming of the oxide.
Mirror module	Alignment	0.1	1.1	Dominated by Hartmann measurement precision (to be improved by using shorter λ and less coherent light).
	Bonding	0.2	0.4	0.4" is an upper limit. Additional measurements/testing are needed.
Meta-shell construction	Alignment	0.1	0.1	Each module's image to be within $0.1''$ of the total image (de-center error = 3 μ m, de-space error = 10 μ m, and roll angle error <0.1''). Pitch and yaw requirements $\approx 10''$.
	Bonding	0.1	0.1	
Integration of meta-shells	Alignment	0.1	0.1	
	Attachment	0.1	0.1	These numbers are based on
Ground-to-orbit effects	Launch shift	0.1	0.1	preliminary analyses, but show that requirements can be met.
	Gravity Release	0.1	0.15	
	Thermal	0.1	0.15	
In-orbit mirror performance		0.4	1.3	On-axis mirror assembly (not including jitter/detector pixellation).

Table 5 — The mirror error budget.

11.6 Testing and Qualification of the Mirror Module

Successful technology development requires constructing mirror modules demonstrated to meet all requirements, including those involving science performance, environment, production budget and schedule. The mirror module, typically composed of dozens of mirror segments, once completed, undergoes a battery of science performance and spaceflight environmental tests. For science performance, it is subject to measurement in an X-ray beam for both PSF and effective area at several energies, both before and after environmental tests that include vibration, thermal vacuum, acoustic, and shock components.

11.7 Technology Development Schedule

X-ray mirror technology was recognized by the astronomical community and NASA to be of strategic importance. The NGXO team is funded at \$2.4M a year to advance the silicon meta-shell optics technology. We expect that this level of funding is adequate to achieve TRL-5 for *AXIS* by 2022 (Table 4). Additional project-specific funding is needed to achieve TRL-6. Table 5 shows a comparison of major error terms to requirements. Most of the error terms are at present within a factor of ~ 2 of meeting *AXIS* requirements. We are in the process of procuring necessary tooling to build and test a mirror module with 12 pairs of mirror segments, but designed to have a angular resolution of 5". This mirror module will be subject a set of X-ray performance tests before and after a battery of environmental tests, including vibrations, acoustics, and thermal vacuum, a necessary step towards better understanding of the mirror construction process.

12 AXIS DETECTOR ASSEMBLY

The design of the *AXIS* focal plane is driven by the need to take advantage of the *AXIS* mirror assembly. The key technical challenges for *AXIS* are: small pixel size; high readout rate with low noise to ensure good low energy response; and fast, low-noise onboard processing electronics. The *AXIS* design exploits ongoing technical advances toward "fast, low-noise, megapixel X-ray imaging arrays with moderate spectral resolution," identified by the 2017 Physics of the Cosmos Program Annual Technology Report as a top-priority technology development[§]. Our plan utilizes both fast parallel-readout CCDs, capitalizing on decades of heritage provided by X-ray CCD detectors used to great success aboard *Chandra*, *Suzaku*, *Swift*, and *XMM-Newton*, and a fast, low-power CMOS active pixel sensor with less heritage. At present, considering the use of both technologies minimizes technical risk in the design phase and allows us to take advantage of detector technology developments of the last 25 years and those anticipated over the next few years based on ongoing development work. The final design will likely incorporate a single detector technology and greatly simplify many aspects of the focal plane reducing risk and cost in the construction phase. A summary of the *AXIS* detector assembly design and drivers is given in Table 6.

12.1 Focal Plane Detectors

The baseline *AXIS* Focal Plane Array (FPA) incorporates a hybrid approach that exploits two technologies currently in advanced development: CCDs with low clock power and fast, massively parallel readout; and, CMOS active pixel sensors, which are fast, low-power, radiation-hard devices. The *AXIS* FPA uses four $1.5k \times 2.5k$ CCDs to tile the majority of the focal plane outside of the center, and a single, smaller $1k \times 1k$ CMOS in the center (see Fig. 33) to minimize pile-up of bright targets. The CCDs are tilted to match the curved focal plane, minimizing image distortion. Both detector types are back-illuminated and fully depleted to 100 μ m to ensure high QE across the *AXIS* band of 0.2–12 keV. The 16 μ m (0.37") pixel size is sufficient to sample the 0.4" mirror PSF, because charge from a single photon is spread across multiple pixels and can be centroided through sub-pixel positioning^{177,178} (and thus each photon's position can be determined) to 0.15" (HPD). This accuracy will be significantly better than that for *Chandra* ACIS, even though it has a comparable pixel size. Even with the necessary multi-pixel event reconstruction, readout noise of less than 4 e^- ensures good soft response¹⁷⁹.

[§]https://ntrs.nasa.gov/search.jsp?R=20170009472

AXIS DETECTOR ASSEMBLY

Parameter	Value	Comment
Focal plane layout	4 CCD, 1 CMOS	See Fig. 33
Field of view	$24' \times 24', 6.4 \times 6.4$ cm, 4000×4000 pixels	Set by chip size and science
Pixel size	16 μm, 0.37"	Same pixel size for both detector types; sub-pixel positioning localizes photons to 0.15" HPD (samples mirror PSF)
CCD format (pixels)	2500×1500 pixels, 4×2.4cm 32 output nodes per CCD	Backside-illuminated frame-transfer devices
CCD serial / parallel transfer rates	2.5 MHz / 0.6 MHz	
CCD frame rate	20 fps	
CCD radiation damage mitigation	Charge injection, trough	
CMOS format	1000×1000 pixels, 1.6×1.6 cm	
CMOS frame rate	>20 fps (goal >100 fps)	Optional 100×100 pixel sub-array (bright sources)
Depletion depth	$100 \ \mu m$	
Energy band	0.2–12 keV	Telescope and depletion depth
Readout noise	<4e ⁻	Energy resolution requirement
Spectral resolution (FWHM)	60 eV@1 keV, 150 eV@6 keV	
Optical and contamination blocking filters	40 nm Al 30 nm Al + 45 nm polyimide	On-chip Warm offset filter at +20 °C
Focal plane temperature	−90 °C	Reduces radiation-induced CTI in CCDs. CMOS can be warmer.
Data rate: FPA \rightarrow FEE Data rate: FEE \rightarrow MEB	3840 Mbps 1 Mbps	All 5 sensors Assume 200 bit/evt, 1000 evt/s

Table 6 — Characteristics and key parameters of the baseline AXIS Focal Plane Array

Both types of detectors are baselined to read out at 20 frames/s (fps) — $64 \times$ that of *Chandra* ACIS — with the CMOS projected to read out faster than 100 fps for pointed observations of bright sources. With this design (and taking into account the *AXIS* greater collecting area), sources up to $6 \times$ brighter than the the *Chandra* pile-up limit will be observed free of pile-up. Faster readout improves time resolution and allows timing studies to take better advantage of the large collecting area. It also results in fewer optical photons contaminating each frame, thus allowing for thinner filters and much higher soft X-ray sensitivity.

12.1.1 CCD Technology Development. Si-based CCD detectors offer excellent QE, and near-theoretical spectral resolution across the *AXIS* energy band. The primary challenges for *AXIS* are (1) fast, low-noise readout at low power; and (2) mitigating the charge-transfer effects of on-orbit radiation damage. Both of these obstacles have been overcome in recent years.

The MIT Lincoln Laboratory Digital CCD (DCCD) development effort combines fast, low-noise readout amplifiers with low-voltage charge transfer². Devices with high-speed p-channel JFET outputs incorporating clock swings of 3V were tested at speeds of 2.5 MHz, producing responsivity over 20 μ V/ e^{-} and only 5.5 e^{-} of amplifier readout noise, close to the AXIS requirement of $< 4 e^{-}$ total readout noise. Achievement of 4 e^- in the next few years is likely. The effects of radiation damage on *AXIS* are greatly ameliorated by the benign radiation environment of low inclination LEO and use of charge injection whereby sacrificial charge is periodically introduced during frame transfer to fill traps; this successfully mitigated radiation damage to the *Suzaku*/XIS, with a loss of only 5% of the field of view¹⁸⁰. SPENVIS simulations show that *AXIS* is subject to ~100x less non-ionizing radiation damage than *Suzaku*, since in its $\leq 8^{\circ}$ inclination LEO, *AXIS* does not traverse as deeply into the South Atlantic Anomaly as *Suzaku* in its 31° inclination orbit.

12.1.2 CMOS Technology Development. Hybrid CMOS X-ray detectors have been developed and successfully flight-proven over the past decade. These devices are active pixel sensors, made by hybridizing a Silicon detection layer to a Silicon readout-integrated-circuit (ROIC) layer through an indium bump bond. Each individual pixel has its own readout circuitry, and there is no transfer of charge from pixel to pixel. As a result, the device is inherently radiation hard since any radiation damage is limited to a narrow site in the silicon lattice with no effect on other pixels, and the device is inherently low power since there is no need to drive large capacitive loads to transfer charge throughout the device. These active pixel sensors have the ability to readout the signal through multiple output lines and to readout designated windows at higher clock rates. The Teledyne H1RGTM HyVisI and H2RGTM HyVisI devices[¶] are high TRL, as is the SIDECARTM ASIC^{||} that typically runs them, with flight missions such as OCO-2. A more recent device, the X-ray version of a 1024×1024 pixel HyVisI array bonded to an H2RGTM ROIC with 32 output lines, was recently flown successfully on the *WRX-R* rocket flight¹⁸¹. A standard H1RGTM has 1024×1024 pixels and can readout through 16 parallel output lines at pixel rates ranging from 100 kHz to 5 MHz for each of the individual lines. These devices can also read out an individual window through a dedicated line in order to achieve very rapid frame rates in a small window for bright source observations.

Read noise of these devices has improved, reaching 5.5 e^- (RMS) for the most recent test devices and 6.5 e^{-1} (RMS) for the technologically mature devices¹⁸¹. The energy resolution of the best devices is presently 148 eV (FWHM) at 5.9 keV and 78 eV (FWHM) at 0.53 keV¹⁸², and we expect to reach a read noise of less than $4 e^{-}$. The detector power is $\sim 200 \text{ mW}$ for a typical $1k \times 1k$ device. Currently, the best read noise is achieved when operating the devices with many parallel readout lines at individual line rates of \sim 200 kHz. Future developments are expected to improve the read noise at higher rates and/or to multiplex more parallel output lines. There are also less mature devices that can achieve sev-

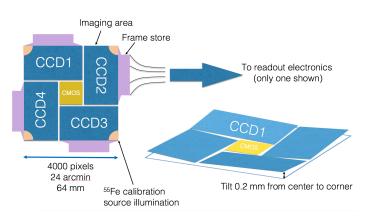


Fig. 33— The baseline *AXIS* Focal Plane Array utilizes a CCD/CMOS hybrid design. Both detector technologies are included to capitalize on parallel technological development; the final design will likely use a single detector technology.

eral orders of magnitude faster effective frame rates through readout of only the pixels with a valid X-ray event above a set threshold; small versions of these devices have been tested, and larger versions are currently being fabricated.

12.2 Sensor Housing

The FPA is housed in a vacuum chamber mounted to a baseplate, and features a commandable vacuum door and ⁵⁵Fe calibration sources that illuminate the corners of the focal plane for monitoring and calibrating

[¶]http://www.teledyne-si.com/products/Documents/H2RG%20Brochure%20-%20September%202017.pdf

^{||} http://www.teledyne-si.com/products-and-services/imaging-sensors/sidecar-asic

sensor performance as in *Suzaku*. The FPA itself is mounted on a plate that is thermally isolated from the housing and that regulates the temperature of the FPA through a heat pipe to an external radiator (Fig. 34). The FPA is maintained at -90.0 ± 0.5 °C during normal operation with this radiator and a trim heater thermally coupled to the mounting plate. A louvered radiator fin on the dark side of the telescope barrel shielded from the sun can support passive cooling of the FPA to -65 °C, assuming 9W of power dissipation from the FPA. We expect the power dissipation to be significantly less for the flight focal plane given the lower power use of the CCDs under technology development as described above, and in CMOS detectors. Higher operating temperature (up to -60 °C) is also possible given the fast readout that reduces the effects of dark current, and charge injection that mitigates CCD radiation damage.

12.3 Optical and Contamination Blocking Filters

AXIS incorporates a hybrid approach to block optical and UV photons from reaching the light-sensitive detectors, and prevent build-up of molecular contamination on the cold surfaces in the light path. The detectors have 40 nm of Al directly deposited on the sensor surface to eliminate light-leak, a smaller amount than previous instruments due to the faster readout and resulting looser light-blocking requirements of the baseline *AXIS* FPA. A contamination blocking filter composed of an additional 30 nm Al and 45 nm polyimide is located 4 cm above the focal plane beneath the door of the sensor housing, where it is held at +20 °C to provide additional light blocking and prevent the kind of molecular contamination that has built up on the cold filters of previous instruments (e.g. *Chandra* ACIS, *Suzaku* XIS). The FPA may be heated to +20 °C in a decontamination mode.

12.4 Focus Mechanism

The sensor housing is directly mounted on a focus mechanism (Fig. 34). The design suspends the Detector Assembly on three tangential flexures and controls tip, tilt, and piston with three linear actu-The focus mechanism ators. moves the estimated 20 kg of suspended mass with a resolution of ± 1 arcmin in tip and tilt and $\pm 12 \ \mu m$ in piston, over a range of $\pm 1^{\circ}$ in tip and tilt and ± 2 mm in piston—sufficient to sample the expected on-orbit focal length uncertainty. Once focus is achieved during com-

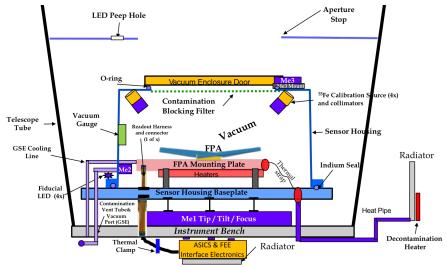


Fig. 34—*AXIS* baseline Focal Plane Assembly block diagram strongly resembles those of successful X-ray CCD instruments.

missioning, the actuators will be locked in place, though later adjustments may be made if needed.

12.5 Front-End Electronics Design and Technology Development

The Front-End Electronics (FEE) digitize the output signal from the detectors. This may be accomplished using a dedicated SIDECARTM ASIC for each CCD and CMOS detector, located in the FEE box on the opposite side of the instrument bench from the sensor housing. In this configuration, the FEE ASICs can run warm.

The SIDECARTM ASICs provide bias voltages and clock control to the detectors and amplify and convert the analog output to digital signal. This signal, totaling 900 (240) Mbps for each CCD (CMOS) running at 20 fps and 12 bits pixel⁻¹ is transferred to a set of FPGAs, one per detector, which perform event processing to reduce the large data stream to ~ 1 Mbps total X-ray plus background events. These are

transferred by digital line to the Master Electronics Box (MEB) on the spacecraft end of the observatory for packaging, filtering, and telemetry.

The FEE design requires placing it on the warm side of the instrument bench with a dedicated radiator to maintain the -10 to +40 °C operating temperature range. To eliminate parasitic heat loads between this stage and the -90 °C FPA, the cable harness between the FPA and FEE box is run through a thermal clamp maintained at -40 °C.

While current technology is sufficient to achieve the necessary frame time, *AXIS* is expected to capitalize on ongoing technology development. For example, the VERITAS family of ASIC chips¹⁸³ currently under development provides fast, multichannel, low-noise readout for CCDs and DEPFET active pixel sensors, with the latter planned as the detector technology for the *Athena* Wide-Field Imager¹⁸⁴. This technology can be adopted with some modifications for the *AXIS* detector FEE.

13 SPACECRAFT AND MISSION OPERATIONS

The GSFC Mission Design Lab (MDL) studied the AXIS mission concept using the instrument (X-ray telescope and detector) point design output from the IDL described above. The estimated instrument mass and power are 750 kg and 300 W, respectively. The total wet mass, including the de-orbit systems, is 2300 kg (including 20% margin). The estimated average AXIS power consumption is 720 W for the entire spacecraft and instrument, and peak power is 1200 W, provided by 8.2 m^2 of solar panels producing 2600 W at launch and 1200 W after 10 years. A 145 A hr battery provides power during eclipses. The low-inclination LEO minimizes

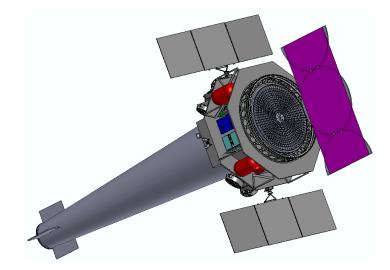


Fig. 35 — Mission Design Lab model of the AXIS observatory.

the particle background and allows for rapid communication and response times.

The resulting spacecraft design, shown in Fig. 35, meets all of the *AXIS* science requirements in a class B mission with a nominal five year lifetime (with consumables sized for at least ten years). The spacecraft meets the mass, length, and diameter specifications for launch into this orbit on a *SpaceX* Falcon 9.

13.1 Pointing accuracy and in-orbit angular resolution

Achieving a final on-axis angular resolution of 0.5'' HPD requires keeping all non-mirror contributions to $\leq 0.1''$. The in-orbit PSF budget is given in Table 7. The startrackers mounted at the mirror track the motion of the mirror axis with a 0.1'' accuracy. These offsets are applied in ground processing to the positions of the X-ray photons as registered by the detector (§12.1). Because the photon arrival time is quantized by 50 ms (the detector readout period), any motions within that interval cannot be corrected and will result in broadening of the PSF. In addition to the rigid-body motions of the telescope, it will flex due to thermal distortions, etc., which will mostly result in translation of the detector with respect to the mirror axis. These motions will be tracked using a metrology system employing fiducial lights mounted at the detector assembly and observed by a startracker mounted at the mirror (using either the *Chandra* scheme¹⁸⁵ or a separate startracker pointed toward the detector). These offsets are applied to the X-ray photon positions to map them to the mirror reference frame. Again, motions within 50 ms cannot be corrected (but will be very small). Preliminary metrology system engineers consulted by the AXIS team expect the requirements in

SPACECRAFT AND MISSION OPERATIONS

Error	Req. (″ HPD)	Note
Poin	ting errors	s not affecting angular resolution:
Pointing maneuver accuracy	15	Target should fall near detector center
Absolute celestial location from startrackers	1	Can be significantly reduced in post-processing using IDs of hundreds of X-ray sources in every observation
Co	ontribution	is to on-axis angular resolution:
Mirror PSF	0.4	from Table 5
Detector photon positioning	0.15	from Table 6, prediction based on CCD simulations
Startracker accuracy for relative pitch, yaw	0.1	Knowledge of relative tilt of telescope w.r.t. sky during observation. Roll error has negligible effect on on-axis PSF.
Telescope rigid-body pitch, yaw in 50 ms	0.1	Uncorrectable telescope motion over the 50 ms detector integration time. Motions on longer timescales are corrected in ground processing using startracker data.
Telescope flex in 50 ms	0.1	Uncorrectable motion of detector in mirror ref. frame over detector integration time. Motions on longer timescales are corrected in ground processing using metrology system data.
Detector metrology system accuracy	0.1	Corresponds to 5μ m detector translation in plane perpendicular to optical axis; roll, pitch, yaw are negligible.
Telescope length stability	0.1	Corresponds to detector defocusing by $10\mu m$
Total angular resolution	0.5	All contributions added in quadrature

Table 7— Angular resolution and pointing error budget. (For a 2D Gaussian, HPD= 2.35σ)

Table 7 to be achievable using current motion damping technology and reaction wheels and three startracker camera heads with a 4 Hz readout rate and standard interpolation algorithms.

We note that, while ambitious, the above requirements are certainly technically feasible. *Hubble*, a telescope of similar size and shape, working in a similar LEO, launched 3 decades ago, achieved a 20 times better in-orbit angular resolution than our goal for *AXIS* — without the luxury of fast detector readout and photon-by-photon image reconstruction used in the X-ray. *HST* is held *stable* to 0.01" over the span of >1000 s exposures. This compares to our requirement of 0.1" telescope stability over the 50 ms detector integration time and 0.1" attitude *knowledge* for longer timescales, which is applied to each X-ray photon to map it onto the sky.

All the above requirements are for the *relative* attitude motions within an observation. The startrackers will also provide $\sim 1''$ knowledge of the absolute celestial position. In each observation, *AXIS* will have hundreds of serendipitous X-ray point sources. If needed, their identification with optical/IR/radio counterparts from available surveys will allow a much more accurate determination of the position in post-processing.

13.2 Rapid response to transient sources

Optimizing observing efficiency and allowing for rapid response to transients requires a slew rate of 120° in < 6 minutes. With this slew rate and our nominal observing program, the efficiency was estimated by the MDL to be at least 70%, giving a net observing time of $\sim 2.2 \times 10^7$ s per year. Six Honeywell HR-16 reaction wheels, each with 100 N m s capacity, were baselined by the MDL. Three magnetic torquers dissipate accumulated angular momentum using the Earth's magnetic field. The field of regard is set primarily by requiring a 45° Sun exclusion angle to avoid stray light and maintain thermal control and avoidance of the bright Earth and Moon.

AXIS has a straightforward operational concept. After launch and commissioning, the instrument will undergo a \sim 1-month standard checkout and calibration phase to determine the optical axis, confirm the effective area and angular/spectral resolution, and optimize the focus. The only instrument mechanism is the focus adjuster which is expected to be used only during commissioning, although it will be available during the mission if necessary.

During normal operations, target sequences will be generated on a weekly basis by the Science Operations Center (SOC) and transmitted to the Mission Operations Center (MOC) for uploading. Most fields will be observed for total integration times of 50-100 ks and will not require continuous observation to build up the required exposure. This flexibility enables a smooth and automatic restart after interruptions caused by ToOs, described below. The detectors primarily operate in fullreadout mode, with a secondary partial readout mode used to reduce pile-up for bright sources. Despite the

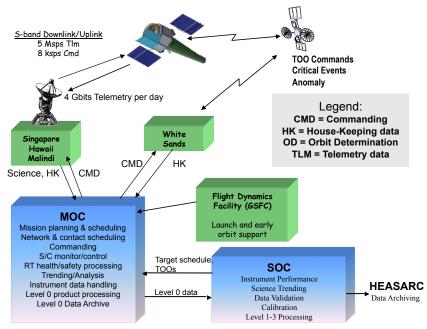


Fig. 36— The Ground Operations plan for *AXIS* is simple and utilizes proven elements.

large format detectors, the total data rate is modest as only X-ray photon events identified by on-board processing are telemetered to the ground, except for daily bias frames for calibrating read noise, and full frame dumps during low telemetry (typically, three every few months) for dark current calibration. The onboard storage (128 Gbit) and telemetry system were designed to support 4 Gbit/day downlink using two 10-minute S-band ground station passes, and allows for the handling of ground system outages. Data volumes as high as 40 Gbit/day may be accommodated with additional downloads. There are no requirements for rapid downlink.

AXIS will support approximately five ToOs per week. Most of these are expected to be responses to the community. After approval by the SOC, a ToO will be sent to the MOC for upload to AXIS. The spacecraft will be designed to accept a ToO interrupt to observe a new target and then automatically return to the preset target sequence when complete, similar to *Swift* operations. The AXIS requirement for ToO response, based on the extensive *Swift* legacy, is four hours. Normal operations are designed assuming two downlink passes per day using the Near-Earth Network (NEN), although there are many more opportunities for ToO uplinks. In rare cases, response times as short as one hour are possible by taking advantage of TDRSS. TDRSS would be used during launch and for critical command and control communication.

The ground system architecture is shown in Fig. 36. Science and housekeeping (HK) data will be downloaded on a daily basis. HK will be checked for anomalies and trended at the MOC. After Level 0 processing, both datastreams will be transferred to the SOC for pipeline processing. The pipeline software will be based on heritage from existing missions including *Chandra*, *Swift*, and *Suzaku*. In normal operations, data will undergo validation and verification at the SOC within one week of observation and then be submitted to the HEASARC for distribution and archiving.

The mission schedule assumed for costing is shown in Fig. 37. AXIS launch commences \sim 7 years after

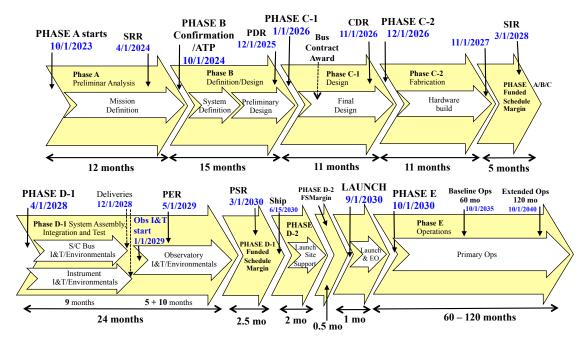


Fig. 37— The *AXIS* mission schedule used for estimating cost assumes an experience-based seven-year development period (phases A-D).

the start of Phase-A assuming that TRL 5 is achieved before early 2023.

14 COST ESTIMATE

The *AXIS* mission point design cost (phases A-E) was estimated using standard GSFC Integrated Design Center (IDC) MDL and IDL methods, applied to a standard work breakdown structure (WBS). The *AXIS* instrument was defined as a self-contained unit that included the mirror, detector system and electronics, and the connecting structure (tube). The instrument cost was generated in the IDL using a combination of PRICE-H for the hardware based on a detailed Master Equipment List (MEL). Software costs not estimated through PRICE-H were estimated with other standard tools (SEER)**.

The IDL estimate was \$150M. This estimate underestimated the mirror cost at \$60M (with no reserves). The *AXIS* team used a self-developed grassroots tool to refine the mirror cost estimate (see appendix in the engineering package). The more realistic mirror cost estimate is \$200M. We also added \$20M to the instrument cost for a metrology system, which was not included in their study. These adjustments lead to a total instrument cost of \$330M.

The mission cost estimate (Phases A-E) was generated within the MDL (Table 8). The instrument cost (adjusted IDL cost) appears as WBS 5.0. Standard "wraps" were applied to the instrument and spacecraft cost estimates for several WBS elements: 1.0 Management (8%), 2.0 Systems Engineering (8%), 3.0 Safety and Mission Assurance (5%), 4.0 Science/Technology (10%), and 9.0 Ground Systems (7.3%). The MDL used experience-based percentage estimates for WBS 7.0 Mission Operation System (15.4%) and 10.0 Systems Integration and Test (7.3%). WBS 8.0 Launch Vehicle Services was fixed at \$150M. Reserves of 30% were applied to all WBS elements, except Launch Services. The total *AXIS* point design cost estimate including reserves is \$1,012M.

The "public" cost table, which conveys the cost by mission phase and groups some WBS elements, is shown in Table 9. The Phase A cost was estimated at 3% of the total mission cost, consistent with NASA experience on similarly sized missions. The Phase E cost is composed of the Mission Operation System

^{**} https://galorath.com/

WBS	Top-level WBS	Source	Point Estimate	30% reserve	Total
			(\$M)	(\$M)	(\$M)
1.0	Project Management	Wrap	35	11	46
2.0	Systems Engineering	Wrap	35	11	46
3.0	Safety and Mission Assurance	Wrap	22	7	29
4.0	Mission Science ^a	Wrap	44	13	57
5.0	Payloads (incl. I&T prior to S/C I&T)	IDL	330	99	429
	<i>Optics^b</i>	Team	200		
	Detector	IDL	31		
Structure, electronics,		IDL	99		
	harness, metrology				
6.0	Spacecraft ^c	MDL	110	33	143
7.0	Missions Operations System	MDL	42	12	54
	Downlink costs ^d	MDL	4		
	MOS (Phases E&F)	MDL	38		
8.0	Launch Vehicle/Services	MDL	150	0	150
9.0	Ground Systems	Wrap	31	9	40
10.0	10.0 Systems Integration and Test		13	4	17
Total N	ASA Phase A-E				\$1,012

^a No technology development costs included (TRL-6 assumed).

^b Optics cost not from the IDL underestimate, but from the Goddard mirror group (W. Zhang) grassroots estimate.

^c Any items of interest from PRICE-H analysis, otherwise note that "PRICE-H is a low-confidence estimate based on the MEL with no cost risk considerations."

^d "Downlink costs will not actually be charged to NASA missions but must be reported in the proposal."

Table 8 — IDC Mission Design Lab Cost Summary. Estimates are in \$M.

(WBS 7.0) and 80% of the science line (WBS 4.0) from the MDL estimate. To maintain consistency with the MDL cost, 30% reserve was used for Phases A-E. Supporting materials, including the mission MEL and the IDL and MDL technical summaries, can be found in the accompanying Engineering Package.

The limitations of this cost estimate should be noted. In particular, the IDC design represents a point design. While the spacecraft concept is high-heritage and thus presents a low-cost growth risk, it contains several known inefficiencies that would be removed through a more thorough design study (e.g., in-house vs. out-of-house, avionics choice, propellant system). It is also likely that some subsystems have been underspecified (e.g., attitude control). Additionally, as was documented in the previous X-ray Probes study^{††}, we believe the extensive mission operations heritage for *AXIS*-like missions will reduce the operations costs (WBS 7.0 and 9.0) below the wrap value. Cost growth beyond a putative Probe cost cap can be offset through descopes such that the primary mission science objectives can still be achieved.

14.1 Descopes

Almost no primary *AXIS* science objective requires a given *instantaneous* collecting area. Hence, the mirror size could be reduced to fit *AXIS* within a particular cost envelope. The scientific trade is prioritizing the science objectives against the longer exposures that would be needed to achieve them. Since the *AXIS* sensitivity is photon limited for all the observations described in this report, the scaling of exposure time

^{††}https://pcos.gsfc.nasa.gov/studies/completed/x-ray-probe-2013-2014.php

with mirror area is essentially linear, and performing these science trade studies is straightforward. The obvious approach to reducing mirror size, which has the least cross coupling to other systems and could be applied nearly any time during the mission development, is removal of one or more metashells. Table 3 shows the relative reduction of mass and effective area at several energies provided by the removal of each metashell.

If a mirror descope is required, taking it early in the program offers substantial benefits. The mirror size drives the entire observatory configuration. This means that a mirror size reduction prior to Preliminary Design Review (PDR) could lead to substantial savings throughout the system (e.g., less massive optical bench, smaller wheels, less massive propellant system). A scaling estimate performed during the X-ray Probe studies earlier in the decade suggests that an integrated design without the outer metashell could reduce the overall mission cost by as much as 10 percent.

Our baseline cost for the detector is conservative, because we plan on selecting a single type of chips from the two included in the current hybrid design. This simplifying "descope" will occur very early in the program. The cost saving here is nominal, but the technical risk reduction could be substantial.

Project Phase Cost (FY18 \$M) Α Total Cost Phase A 21 Total Cost Phases B-D 894 89 Mgmt, SE, MA Science 9 Telescope 194 Detector 30 B-D 96 Payload structure, etc. Spacecraft, including ATLO 119 MOS/GDS 30 Launch vehicle and services 150 Reserves 177 Total Cost Phases E-F 97 E-F **Operations** 75 22 Reserves **Total Lifecycle Cost** \$1,012

14.2 Enhancements

AXIS was designed expressly to provide the most sensitive, and thus the largest, possible X-ray observatory within the \$1B cost

Table 9— This parametric total lifecycle cost estimate is based on the Probe's Master Equipment List derived from the Final Engineering Concept Definition Package that accurately reflects the mission described in this report.

guideline. The availability of such a powerful capability might induce NASA to explore broadening the scientific reach. One incremental enhancement to our current concept would be to enlarge the detector array to cover the off-axis angles where the mirror PSF broadens above 1" but is still under 5" HPD (*Athena*'s resolution). This can be achieved by adding an outer ring of four more chips (Fig. 33) to extend the field of view to $36' \times 36'$ (double our nominal FOV by solid angle) and take full advantage of the mirror's superb imaging capability.

Another possible enhancement would be to add a second focal plane instrument. While the team did not study adding instruments to *AXIS*, some plausible enhancements were studied for similar-sized missions during the X-ray Probes Concepts study earlier in the decade^{‡‡}. The incremental costs for enhancements identified there are likely valid estimates for *AXIS*. As an example,one of the Probe concepts studied (the Notional Calorimeter mission) could have been augmented with a grating spectrometer at an estimated increase in cost of \$150M. (The cost of the Notional X-ray Grating Spectrometer probe, a mission with similar capability to that of adding a grating to *AXIS*, was estimated to cost \$750M.) Other modest augmentations might include a side-mounted hard X-ray telescope (for which arcsecond angular resolution would not be required), a polarimeter, or a redundant imaging detector.

^{‡‡}https://pcos.gsfc.nasa.gov/studies/completed/x-ray-probe-2013-2014.php

Missions and Facilities	S
ALMA	Atacama Large Millimeter Array
Athena	Advanced Telescope for High ENergy Astrophysics (future)
Chandra	Chandra X-ray Observatory
ACIS	Advanced CCD Imaging Spectrometer (Chandra detector)
СТА	Cherenkov Telescope Array (future)
ELT	European Extremely Large Telescope (future)
eROSITA	Extended Roentgen Survey with an Imaging Telescope Array (future)
ESA	European Space Agency
Euclid	European space cosmology mission (future)
GMT	Giant Magellan Telescope (future)
GMRT	Giant Meter-wave Radio Telescope
GSFC	NASA's Goddard Space Flight Center
HEASARC	High Energy Astrophysics Science Archive Research Center
Herschel	Herschel Space Observatory
HST	Hubble Space Telescope
JVLA	Karl G. Jansky Very Large Array
JWST	James Webb Space Telescope (future)
LIGO	Laser Interferometer Gravitational-wave Observatory
LISA	Laser Interferometer Space Antenna (future)
LOFAR	Low-Frequency Array
LSST	Large Synoptic Survey Telescope
Lynx	Lynx X-ray Surveyor (NASA Flagship study)
MWA	Murchison Wide-Field Array
NASA	National Aeronautics and Space Administration
NGXO	Next-generation X-ray Optics lab at GSFC
NuSTAR	Nuclear Spectroscopic Telescope Array
SKA	Square Kilometer Array (future)
Spitzer	Spitzer Space Telescope
Suzaku	Japan-US X-ray imaging spectroscopy mission (past)
Swift	Neil Gehrels Swift Observatory
TESS	Transiting Exoplanet Survey Satellite
ТМТ	Thirty Meter Telescope (future)
WFIRST	Wide Field Infrared Survey Telescope (future)
WRX-R	Water Recovery X-ray Rocket
XIS	X-ray Imaging Spectrometer (Suzaku detector)
XMM-Newton	X-ray Multi-Mirror Mission (Newton)
XRISM	X-ray Imaging and Spectroscopy Mission (future)

15 ACRONYMS AND ABBREVIATIONS

Astronomical Terms	
AGN	Active galactic nucleus (powered by an accreting massive black hole)
BCG	Brightest cluster galaxy (in a galaxy cluster)
BH	Black hole
CMB	Cosmic microwave background
CGM	Circumgalactic medium (gas around, but bound to, galaxies)
CX	Charge exchange (between an ion and neutral atom)
CXB	Cosmic X-ray background (can be resolved into AGNs)
FUV	Far ultraviolet (typically $\lambda < 2000 \text{\AA}$)
GC	Galactic Center
GW	Gravitational wave
HMXB	High-mass X-ray binary (compact object with a massive star)
ICM	Intracluster medium (hot gas in a galaxy cluster)
IGM	Intergalactic medium (diffuse gas between galaxies)
IMF	Initial mass function (of stars)
ISCO	Innermost stable circular orbit $(3GM/c^2)$ in the Schwarzschild metric)
ISM	Interstellar medium
LMC	Large Magellanic Cloud
LMXB	Low-mass X-ray binary (compact object with a dwarf star)
LSS	Large-scale structure (of the Universe)
MHD	Magnetohydrodynamic
NIR	Near-infrared
NS	Neutron star
Pop III	Population III stars (first generation of stars)
PWN(e)	Pulsar wind nebula(e)
RMS	Root-mean square
SED	Spectral energy distribution
SFR	Star-formation rate
SMBH	Supermassive black hole
SMC	Small Magellanic Cloud
SN(e)	Supernova(e)
SNR	Supernova remnant
TDE	Tidal disruption event (a star shredded by a black hole)
ULX	Ultraluminous X-ray source ($L_X > L_{Edd}$ for $10M_{\odot}$)
WHIM	Warm-hot intergalactic medium
XLF	X-ray luminosity function
XRB	X-ray binary (neutron star or black hole with a companion star)

Technical Terms	
ASIC	Application-specific integrated circuit
CCD	Charge-coupled device (detector)
CMOS	Complementary metal-oxide-semiconductor (active pixel detector)
CTI	Charge-transfer inefficiency (in a detector)
DEPFET	DEpleted P-channel Field Effect Transistor (active pixel detector)
E/PO	Education and public outreach
ETU	Engineering test unit
FEE	Front-end electronics
FOV	Field of view
FPA	Focal plane array (AXIS detector array)
FPGA	Field-programmable gate array
fps	Frames per second
FWHM	Full width at half-maximum
GSE	Ground systems engineering
$H(1,2)RG^{TM}$	Teledyne focal plane array detector
НК	Housekeeping (data)
HPD	Half-power diameter (image region containing 50% of flux)
IDC	Integrated Design Center
IDL	Instrument design lab
I&T	Integration and Testing
JFET	Junction gate field-effect transistor
LEO	Low-earth orbit (like ROSAT, Swift, Suzaku; unlike Chandra, Athena, Lynx)
MDL	Mission design lab
MEB	Master electronics box
MEL	Master equipment list
MOC	Mission operations center
NEN	Near-Earth Network
PDR	Preliminary design review
PSF	Point-spread function (image of a point source)
QE	Quantum efficiency (probability for a detector to register an X-ray photon)
ROIC	Readout integrated circuit
SIDECAR TM	Teledyne System Image, Digitizing, Enhancing, Controlling, and Retrieving
SMO	Silicon metashell optics
SOC	Science operations center
STM	Science traceability matrix
TDRSS	Tracking and Data Relay Satellite System
ToO	Target of opportunity
TRL	Technology readiness level
WBS	Work breakdown structure (for costing)

16 REFERENCES

- 1. Zhang, W. W. et al. Astronomical x-ray optics using mono-crystalline silicon: high resolution, light weight, and low cost. In Space Telescopes and Instrumentation 2018: Ultraviolet to Gamma Ray, vol. 10699 of Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, 1069900 (2018).
- Bautz, M. et al. Toward fast low-noise low-power digital CCDs for Lynx and other high-energy astrophysics missions. In Space Telescopes and Instrumentation 2018: Ultraviolet to Gamma Ray, vol. 10699 of Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, 1069917 (2018).
- 3. Falcone, A. D. *et al.* The high definition x-ray imager (HDXI) instrument on the Lynx X-ray Surveyor. In Space Telescopes and Instrumentation 2018: Ultraviolet to Gamma Ray, vol. 10699 of Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, 1069912 (2018). 1807.05282.
- 4. Guo, Y. *et al.* CANDELS Multi-wavelength Catalogs: Source Detection and Photometry in the GOODS-South Field. *ApJS* **207**, 24 (2013).
- 5. Aird, J. *et al.* The Hot and Energetic Universe: The formation and growth of the earliest supermassive black holes. *arXiv e-prints* (2013).
- 6. Luo, B. et al. The Chandra Deep Field-South Survey: 7 Ms Source Catalogs. ApJS 228, 2 (2017).
- 7. Cowie, L. L. *et al.* A Submillimeter Perspective on the GOODS Fields (SUPER GOODS). III. A Large Sample of ALMA Sources in the GOODS-S. *ApJ* 865, 106 (2018).
- Ricarte, A. & Natarajan, P. The observational signatures of supermassive black hole seeds. *MNRAS* 481, 3278–3292 (2018).
- 9. Bañados, E. *et al.* An 800-million-solar-mass black hole in a significantly neutral Universe at a redshift of 7.5. *Nature* **553**, 473–476 (2018).
- 10. Mortlock, D. J. et al. A luminous quasar at a redshift of z = 7.085. Nature 474, 616–619 (2011).
- 11. Pacucci, F., Volonteri, M. & Ferrara, A. The growth efficiency of high-redshift black holes. *MNRAS* **452**, 1922–1933 (2015).
- 12. Natarajan, P. *et al.* Unveiling the First Black Holes With JWST:Multi-wavelength Spectral Predictions. *ApJ* **838**, 117 (2017).
- 13. Pezzulli, E. *et al.* Faint progenitors of luminous $z \sim 6$ quasars: Why do not we see them? *MNRAS* **466**, 2131–2142 (2017).
- 14. Vito, F. *et al.* The hard X-ray luminosity function of high-redshift $(3 < z \le 5)$ active galactic nuclei. *MNRAS* **445**, 3557–3574 (2014).
- 15. Vito, F. *et al.* High-redshift AGN in the Chandra Deep Fields: the obscured fraction and space density of the sub-L_{*} population. *MNRAS* **473**, 2378–2406 (2018).
- 16. Cappelluti, N. *et al.* The nature of the unresolved extragalactic cosmic soft X-ray background. *MNRAS* **427**, 651–663 (2012).
- 17. Paczynski, B. Gravitational microlensing at large optical depth. ApJ 301, 503-516 (1986).
- Wambsganss, J., Paczynski, B. & Schneider, P. Interpretation of the microlensing event in QSO 2237 + 0305. *ApJ* 358, L33–L36 (1990).
- 19. Kochanek, C. S. Quantitative Interpretation of Quasar Microlensing Light Curves. ApJ 605, 58–77 (2004).

- 20. Pooley, D. *et al.* The Dark-matter Fraction in the Elliptical Galaxy Lensing the Quasar PG 1115+080. *ApJ* 697, 1892–1900 (2009).
- 21. Chartas, G. et al. Gravitational lensing size scales for quasars. Astronomische Nachrichten 337, 356 (2016).
- 22. Reynolds, C. S. An X-ray spectral study of 24 type 1 active galactic nuclei. MNRAS 286, 513-537 (1997).
- 23. Chartas, G. *et al.* Measuring the Innermost Stable Circular Orbits of Supermassive Black Holes. *ApJ* **837**, 26 (2017).
- 24. Krawczynski, H. & Chartas, G. Simulations of the Fe K α Energy Spectra from Gravitationally Microlensed Quasars. *ApJ* **843**, 118 (2017).
- 25. Tombesi, F. *et al.* Wind from the black-hole accretion disk driving a molecular outflow in an active galaxy. *Nature* **519**, 436–438 (2015).
- 26. Feruglio, C. *et al.* The multi-phase winds of Markarian 231: from the hot, nuclear, ultra-fast wind to the galaxy-scale, molecular outflow. *A&A* **583**, A99 (2015).
- 27. Feruglio, C. *et al.* On the discovery of fast molecular gas in the UFO/BAL quasar APM 08279+5255 at z = 3.912. *A&A* **608**, A30 (2017).
- 28. Koss, M. J. *et al.* A population of luminous accreting black holes with hidden mergers. *Nature* **563**, 214–216 (2018).
- 29. Rosas-Guevara, Y. M., Bower, R. G., McAlpine, S., Bonoli, S. & Tissera, P. B. The abundances and properties of Dual AGN and their host galaxies in the EAGLE simulations. *MNRAS* **483**, 2712–2720 (2019).
- 30. Koss, M. *et al.* Understanding Dual Active Galactic Nucleus Activation in the nearby Universe. *ApJ* **746**, L22 (2012).
- 31. Steinborn, L. K. *et al.* Origin and properties of dual and offset active galactic nuclei in a cosmological simulation at z=2. *MNRAS* **458**, 1013–1028 (2016).
- 32. Satyapal, S. *et al.* Galaxy pairs in the Sloan Digital Sky Survey IX. Merger-induced AGN activity as traced by the Wide-field Infrared Survey Explorer. *MNRAS* **441**, 1297–1304 (2014).
- 33. Burke-Spolaor, S. A radio Census of binary supermassive black holes. MNRAS 410, 2113–2122 (2011).
- 34. Nevin, R., Comerford, J., Müller-Sánchez, F., Barrows, R. & Cooper, M. The Origin of Double-peaked Narrow Lines in Active Galactic Nuclei. II. Kinematic Classifications for the Population at z < 0.1. *ApJ* **832**, 67 (2016).
- 35. Rosario, D. J. *et al.* Adaptive Optics Imaging of Quasi-stellar Objects with Double-peaked Narrow Lines: Are They Dual Active Galactic Nuclei? *ApJ* **739**, 44 (2011).
- 36. Kelley, R. L. *et al.* The Astro-H high resolution soft x-ray spectrometer. In *Space Telescopes and Instrumentation* 2016: Ultraviolet to Gamma Ray, vol. 9905 of Proc. SPIE, 99050V (2016).
- 37. Wang, Q. D. *et al.* Dissecting X-ray-Emitting Gas Around the Center of Our Galaxy. *Science* **341**, 981–983 (2013).
- 38. Wong, K.-W. *et al.* The Megasecond Chandra X-Ray Visionary Project Observation of NGC 3115: Witnessing the Flow of Hot Gas within the Bondi Radius. *ApJ* **780**, 9 (2014).
- 39. Russell, H. R. *et al.* The imprints of AGN feedback within a supermassive black hole's sphere of influence. *MNRAS* **477**, 3583–3599 (2018).
- 40. Garcia, M. R. *et al.* X-ray and Radio Variability of M31*, The Andromeda Galaxy Nuclear Supermassive Black Hole. *ApJ* **710**, 755–763 (2010).

- 41. van den Bosch, R. C. E., Greene, J. E., Braatz, J. A., Constantin, A. & Kuo, C.-Y. Toward Precision Supermassive Black Hole Masses Using Megamaser Disks. *ApJ* **819**, 11 (2016).
- 42. Meyer, E. T. *et al.* Ruling out IC/CMB X-rays in PKS 0637-752 and the Implications for TeV Emission from Large-scale Quasar Jets. *ApJ* **805**, 154 (2015).
- 43. Blandford, R., Meier, D. & Readhead, A. Relativistic Jets in Active Galactic Nuclei. arXiv e-prints (2018).
- 44. Marshall, H. L. et al. A Flare in the Jet of Pictor A. ApJ 714, L213–L216 (2010).
- 45. Snios, B. et al. Variability and Proper Motion of X-Ray Knots in the Jet of Centaurus A. ApJ 871, 248 (2019).
- 46. Snios, B. *et al.* The Cocoon Shocks of Cygnus A: Pressures and Their Implications for the Jets and Lobes. *ApJ* **855**, 71 (2018).
- Stawarz, Ł., Sikora, M., Ostrowski, M. & Begelman, M. C. On Multiwavelength Emission of Large-Scale Quasar Jets. *ApJ* 608, 95–107 (2004).
- 48. Hardcastle, M. J. Testing the beamed inverse-Compton model for jet X-ray emission: velocity structure and deceleration. *MNRAS* **366**, 1465–1474 (2006).
- 49. Meyer, E. T. *et al.* New ALMA and Fermi/LAT Observations of the Large-scale Jet of PKS 0637-752 Strengthen the Case Against the IC/CMB Model. *ApJ* **835**, L35 (2017).
- 50. Breiding, P. *et al.* Fermi Non-detections of Four X-Ray Jet Sources and Implications for the IC/CMB Mechanism. *ApJ* **849**, 95 (2017).
- 51. Georganopoulos, M., Meyer, E. & Perlman, E. Recent Progress in Understanding the Large Scale Jets of Powerful Quasars. *Galaxies* **4**, 65 (2016).
- 52. Hardcastle, M. J. et al. Deep Chandra observations of Pictor A. MNRAS 455, 3526–3545 (2016).
- 53. Blundell, K. M. & Fabian, A. C. The X-ray and radio-emitting plasma lobes of 4C23.56: further evidence of recurrent jet activity and high acceleration energies. *MNRAS* **412**, 705–710 (2011).
- Sanders, J. S., Fabian, A. C., Russell, H. R., Walker, S. A. & Blundell, K. M. Detecting edges in the X-ray surface brightness of galaxy clusters. *MNRAS* 460, 1898–1911 (2016).
- 55. Faucher-Giguère, C.-A. & Quataert, E. The physics of galactic winds driven by active galactic nuclei. *MNRAS* **425**, 605–622 (2012).
- 56. Burns, J. O. The radio properties of cD galaxies in Abell clusters. I an X-ray selected sample. *AJ* **99**, 14–30 (1990).
- 57. Zhuravleva, I., Allen, S. W., Mantz, A. & Werner, N. Gas Perturbations in the Cool Cores of Galaxy Clusters: Effective Equation of State, Velocity Power Spectra, and Turbulent Heating. *ApJ* **865**, 53 (2018).
- 58. Paggi, A., Wang, J., Fabbiano, G., Elvis, M. & Karovska, M. CHEERS Results on Mrk 573: A Study of Deep Chandra Observations. *ApJ* **756**, 39 (2012).
- 59. Russell, H. R. *et al.* Alma Observations of Massive Molecular Gas Filaments Encasing Radio Bubbles in the Phoenix Cluster. *ApJ* **836**, 130 (2017).
- 60. Hlavacek-Larrondo, J. *et al.* The rapid evolution of AGN feedback in brightest cluster galaxies: switching from quasar-mode to radio-mode feedback. *MNRAS* **431**, 1638–1658 (2013).
- 61. Babyk, I. V. *et al.* A Universal Entropy Profile for the Hot Atmospheres of Galaxies and Clusters within R ₂₅₀₀. *ApJ* **862**, 39 (2018).

- 62. Dye, S. *et al.* Revealing the complex nature of the strong gravitationally lensed system H-ATLAS J090311.6+003906 using ALMA. *MNRAS* **452**, 2258–2268 (2015).
- 63. Brinchmann, J. *et al.* The physical properties of star-forming galaxies in the low-redshift Universe. *MNRAS* **351**, 1151–1179 (2004).
- 64. Lehmer, B. D. *et al.* A Chandra Perspective on Galaxy-wide X-ray Binary Emission and its Correlation with Star Formation Rate and Stellar Mass: New Results from Luminous Infrared Galaxies. *ApJ* **724**, 559–571 (2010).
- 65. Lehmer, B. D. *et al.* The Evolution of Normal Galaxy X-Ray Emission through Cosmic History: Constraints from the 6 MS Chandra Deep Field-South. *ApJ* **825**, 7 (2016).
- Negrello, M. *et al.* The Herschel-ATLAS: a sample of 500 μm-selected lensed galaxies over 600 deg². *MNRAS* 465, 3558–3580 (2017).
- 67. Veilleux, S., Cecil, G. & Bland-Hawthorn, J. Galactic Winds. ARA&A 43, 769-826 (2005).
- 68. Heckman, T. M. & Thompson, T. A. A Brief Review of Galactic Winds. arXiv e-prints (2017).
- 69. Heckman, T. M. *et al.* The Properties of Ultraviolet-luminous Galaxies at the Current Epoch. *ApJ* **619**, L35–L38 (2005).
- 70. Cardamone, C. *et al.* Galaxy Zoo Green Peas: discovery of a class of compact extremely star-forming galaxies. *MNRAS* **399**, 1191–1205 (2009).
- 71. Izotov, Y. I. *et al.* Eight per cent leakage of Lyman continuum photons from a compact, star-forming dwarf galaxy. *Nature* **529**, 178–180 (2016).
- 72. Prestwich, A. H. *et al.* Ultra-luminous X-Ray Sources in HARO II and the Role of X-Ray Binaries in Feedback in Lyα Emitting Galaxies. *ApJ* **812**, 166 (2015).
- 73. Basu-Zych, A. R. *et al.* Exploring the Overabundance of ULXs in Metal- and Dust-poor Local Lyman Break Analogs. *ApJ* **818**, 140 (2016).
- 74. Micheva, G., Oey, M. S., Jaskot, A. E. & James, B. L. Mrk 71/NGC 2366: The Nearest Green Pea Analog. *ApJ* 845, 165 (2017).
- 75. Dolag, K., Meneghetti, M., Moscardini, L., Rasia, E. & Bonaldi, A. Simulating the physical properties of dark matter and gas inside the cosmic web. *MNRAS* **370**, 656–672 (2006).
- 76. Walker, S. et al. The Physics of Galaxy Cluster Outskirts. Space Sci. Rev. 215, 7 (2019).
- 77. Power, C. *et al.* nIFTy Galaxy Cluster simulations VI: The gaseous outskirts of galaxy cluster. *arXiv e-prints* (2018).
- 78. Biffi, V. *et al.* The origin of ICM enrichment in the outskirts of present-day galaxy clusters from cosmological hydrodynamical simulations. *MNRAS* **476**, 2689–2703 (2018).
- 79. White, S. D. M. & Frenk, C. S. Galaxy formation through hierarchical clustering. ApJ 379, 52–79 (1991).
- 80. Tumlinson, J., Peeples, M. S. & Werk, J. K. The Circumgalactic Medium. ARA &A 55, 389-432 (2017).
- 81. Bregman, J. N. et al. The Extended Distribution of Baryons around Galaxies. ApJ 862, 3 (2018).
- 82. Markevitch, M., Govoni, F., Brunetti, G. & Jerius, D. Bow Shock and Radio Halo in the Merging Cluster A520. *ApJ* **627**, 733–738 (2005).
- 83. Markevitch, M. & Vikhlinin, A. Shocks and cold fronts in galaxy clusters. Phys. Rep. 443, 1-53 (2007).

- 84. Zeldovich, Y. B. & Raizer, Y. P. *Elements of gasdynamics and the classical theory of shock waves* (Academic Press, New York, NY, ed. W.D. Hayes & R.F. Probstein, 1966).
- 85. Markevitch, M. Chandra Observation of the Most Interesting Cluster in the Universe. In Wilson, A. (ed.) *The X-ray Universe 2005*, vol. 604 of *ESA Special Publication*, 723 (2006). astro-ph/0511345.
- Russell, H. R. *et al.* Shock fronts, electron-ion equilibration and intracluster medium transport processes in the merging cluster Abell 2146. *MNRAS* 423, 236–255 (2012).
- 87. Wang, Q. H. S., Giacintucci, S. & Markevitch, M. Bow Shock in Merging Cluster A520: The Edge of the Radio Halo and the Electron-Proton Equilibration Timescale. *ApJ* **856**, 162 (2018).
- 88. Roediger, E. *et al.* Stripped Elliptical Galaxies as Probes of ICM Physics: II. Stirred, but Mixed? Viscous and Inviscid Gas Stripping of the Virgo Elliptical M89. *ApJ* **806**, 104 (2015).
- 89. Schekochihin, A. A., Cowley, S. C., Kulsrud, R. M., Rosin, M. S. & Heinemann, T. Nonlinear Growth of Firehose and Mirror Fluctuations in Astrophysical Plasmas. *Physical Review Letters* **100**, 081301 (2008).
- 90. Kunz, M. W., Schekochihin, A. A. & Stone, J. M. Firehose and Mirror Instabilities in a Collisionless Shearing Plasma. *Physical Review Letters* **112**, 205003 (2014).
- 91. Ettori, S. & Fabian, A. C. Chandra constraints on the thermal conduction in the intracluster plasma of A2142. *MNRAS* **317**, L57–L59 (2000).
- 92. Vikhlinin, A., Markevitch, M. & Murray, S. S. A Moving Cold Front in the Intergalactic Medium of A3667. *ApJ* **551**, 160–171 (2001).
- 93. Wang, Q. H. S., Markevitch, M. & Giacintucci, S. The Merging Galaxy Cluster A520—A Broken-up Cool Core, A Dark Subcluster, and an X-Ray Channel. *ApJ* 833, 99 (2016).
- 94. Markevitch, M. *et al.* Chandra Temperature Map of A754 and Constraints on Thermal Conduction. *ApJ* **586**, L19–L23 (2003).
- 95. Ascasibar, Y. & Markevitch, M. The Origin of Cold Fronts in the Cores of Relaxed Galaxy Clusters. *ApJ* 650, 102–127 (2006).
- 96. Roediger, E. *et al.* Viscous Kelvin-Helmholtz instabilities in highly ionized plasmas. *MNRAS* **436**, 1721–1740 (2013).
- 97. ZuHone, J. A., Kunz, M. W., Markevitch, M., Stone, J. M. & Biffi, V. The Effect of Anisotropic Viscosity on Cold Fronts in Galaxy Clusters. *ApJ* **798**, 90 (2015).
- Roediger, E., Kraft, R. P., Forman, W. R., Nulsen, P. E. J. & Churazov, E. Kelvin-Helmholtz Instabilities at the Sloshing Cold Fronts in the Virgo Cluster as a Measure for the Effective Intracluster Medium Viscosity. *ApJ* 764, 60 (2013).
- 99. Su, Y. *et al.* Deep Chandra Observations of NGC 1404: Cluster Plasma Physics Revealed by an Infalling Early-type Galaxy. *ApJ* **834**, 74 (2017).
- Ichinohe, Y., Simionescu, A., Werner, N. & Takahashi, T. An azimuthally resolved study of the cold front in Abell 3667. MNRAS 467, 3662–3676 (2017).
- 101. Wang, Q. H. S. & Markevitch, M. A Deep X-Ray Look at Abell 2142 Viscosity Constraints From Kelvin-Helmholtz Eddies, a Displaced Cool Peak That Makes a Warm Core, and A Possible Plasma Depletion Layer. *ApJ* 868, 45 (2018).
- Kraft, R. P. *et al.* Stripped Elliptical Galaxies as Probes of ICM Physics. III. Deep Chandra Observations of NGC 4552: Measuring the Viscosity of the Intracluster Medium. *ApJ* 848, 27 (2017).

- 103. Eckert, D. et al. The stripping of a galaxy group diving into the massive cluster A2142. A&A 570, A119 (2014).
- van Weeren, R. J., Röttgering, H. J. A., Brüggen, M. & Hoeft, M. Particle Acceleration on Megaparsec Scales in a Merging Galaxy Cluster. *Science* 330, 347 (2010).
- 105. Giacintucci, S. et al. Shock acceleration as origin of the radio relic in A 521? A&A 486, 347–358 (2008).
- 106. Shimwell, T. W. *et al.* Another shock for the Bullet cluster, and the source of seed electrons for radio relics. *MNRAS* **449**, 1486–1494 (2015).
- 107. Winkler, P. F. *et al.* A High-resolution X-Ray and Optical Study of SN 1006: Asymmetric Expansion and Small-scale Structure in a Type Ia Supernova Remnant. *ApJ* **781**, 65 (2014).
- Morlino, G., Amato, E., Blasi, P. & Caprioli, D. Spatial structure of X-ray filaments in SN 1006. MNRAS 405, L21–L25 (2010).
- 109. Ressler, S. M. et al. Magnetic Field Amplification in the Thin X-Ray Rims of SN 1006. ApJ 790, 85 (2014).
- Tran, A., Williams, B. J., Petre, R., Ressler, S. M. & Reynolds, S. P. Energy Dependence of Synchrotron X-Ray Rims in Tycho's Supernova Remnant. *ApJ* 812, 101 (2015).
- 111. Warren, J. S. *et al.* Cosmic-Ray Acceleration at the Forward Shock in Tycho's Supernova Remnant: Evidence from Chandra X-Ray Observations. *ApJ* **634**, 376–389 (2005).
- 112. Kosenko, D., Blinnikov, S. I. & Vink, J. Modeling supernova remnants: effects of diffusive cosmic-ray acceleration on the evolution and application to observations. *A&A* **532**, A114 (2011).
- Warren, D. C. & Blondin, J. M. Three-dimensional numerical investigations of the morphology of Type Ia SNRs. MNRAS 429, 3099–3113 (2013).
- 114. Rees, M. J. Tidal disruption of stars by black holes of 10 to the 6th-10 to the 8th solar masses in nearby galaxies. *Nature* **333**, 523–528 (1988).
- 115. Coughlin, E. R. & Begelman, M. C. Hyperaccretion during Tidal Disruption Events: Weakly Bound Debris Envelopes and Jets. *ApJ* **781**, 82 (2014).
- 116. Lin, D. *et al.* A luminous X-ray outburst from an intermediate-mass black hole in an off-centre star cluster. *Nature Astronomy* **2**, 656–661 (2018).
- 117. Abbott, B. P. et al. Multi-messenger Observations of a Binary Neutron Star Merger. ApJ 848, L12 (2017).
- 118. Abbott, B. P. *et al.* GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral. *Physical Review Letters* **119**, 161101 (2017).
- 119. Troja, E. *et al.* The outflow structure of GW170817 from late-time broad-band observations. *MNRAS* **478**, L18–L23 (2018).
- 120. Tang, Y., Haiman, Z. & MacFadyen, A. The late inspiral of supermassive black hole binaries with circumbinary gas discs in the LISA band. *MNRAS* **476**, 2249–2257 (2018).
- 121. Amaro-Seoane, P. et al. Laser Interferometer Space Antenna. arXiv e-prints (2017).
- Lang, R. N. & Hughes, S. A. Localizing Coalescing Massive Black Hole Binaries with Gravitational Waves. *ApJ* 677, 1184–1200 (2008).
- 123. Haiman, Z. Electromagnetic chirp of a compact binary black hole: A phase template for the gravitational wave inspiral. *Phys. Rev. D* **96**, 023004 (2017).
- Graham, M. J. *et al.* A possible close supermassive black-hole binary in a quasar with optical periodicity. *Nature* 518, 74–76 (2015).

- 125. D'Orazio, D. J., Haiman, Z. & Schiminovich, D. Relativistic boost as the cause of periodicity in a massive black-hole binary candidate. *Nature* **525**, 351–353 (2015).
- 126. Bachetti, M. *et al.* An ultraluminous X-ray source powered by an accreting neutron star. *Nature* **514**, 202–204 (2014).
- 127. Baganoff, F. K. *et al.* Chandra X-Ray Spectroscopic Imaging of Sagittarius A* and the Central Parsec of the Galaxy. *ApJ* **591**, 891–915 (2003).
- 128. Roberts, S. R., Jiang, Y.-F., Wang, Q. D. & Ostriker, J. P. Towards self-consistent modelling of the Sgr A* accretion flow: linking theory and observation. *MNRAS* **466**, 1477–1490 (2017).
- 129. Muno, M. P. *et al.* A Catalog of X-Ray Point Sources from Two Megaseconds of Chandra Observations of the Galactic Center. *ApJS* **181**, 110–128 (2009).
- 130. Dexter, J. & O'Leary, R. M. The Peculiar Pulsar Population of the Central Parsec. ApJ 783, L7 (2014).
- 131. Hailey, C. J. *et al.* A density cusp of quiescent X-ray binaries in the central parsec of the Galaxy. *Nature* **556**, 70–73 (2018).
- 132. Ponti, G., Terrier, R., Goldwurm, A., Belanger, G. & Trap, G. Discovery of a Superluminal Fe K Echo at the Galactic Center: The Glorious Past of Sgr A* Preserved by Molecular Clouds. *ApJ* **714**, 732–747 (2010).
- 133. Capelli, R., Warwick, R. S., Porquet, D., Gillessen, S. & Predehl, P. The X-ray lightcurve of Sagittarius A* over the past 150 years inferred from Fe-K α line reverberation in Galactic centre molecular clouds. A&A 545, A35 (2012).
- 134. Ryu, S. G. *et al.* X-Ray Echo from the Sagittarius C Complex and 500-year Activity History of Sagittarius A*. *PASJ* **65**, 33 (2013).
- 135. Yamaguchi, H. *et al.* A Chandrasekhar Mass Progenitor for the Type Ia Supernova Remnant 3C 397 from the Enhanced Abundances of Nickel and Manganese. *ApJ* **801**, L31 (2015).
- 136. Safi-Harb, S., Dubner, G., Petre, R., Holt, S. S. & Durouchoux, P. Chandra Spatially Resolved Spectroscopic Study and Multiwavelength Imaging of the Supernova Remnant 3C 397 (G41.1-0.3). *ApJ* **618**, 321–338 (2005).
- 137. Margutti, R. *et al.* Results from a Systematic Survey of X-Ray Emission from Hydrogen-poor Superluminous SNe. *ApJ* **864**, 45 (2018).
- 138. Draine, B. T. & Fraisse, A. A. Polarized Far-Infrared and Submillimeter Emission from Interstellar Dust. *ApJ* **696**, 1–11 (2009).
- 139. Draine, B. T. & Hensley, B. Magnetic Nanoparticles in the Interstellar Medium: Emission Spectrum and Polarization. *ApJ* **765**, 159 (2013).
- 140. Zubko, V., Dwek, E. & Arendt, R. G. Interstellar Dust Models Consistent with Extinction, Emission, and Abundance Constraints. *ApJS* **152**, 211–249 (2004).
- 141. Jenkins, E. B. A Unified Representation of Gas-Phase Element Depletions in the Interstellar Medium. *ApJ* **700**, 1299–1348 (2009).
- 142. Valencic, L. A. & Smith, R. K. Interstellar Dust Properties from a Survey of X-Ray Halos. ApJ 809, 66 (2015).
- 143. Mathis, J. S. & Lee, C.-W. X-ray halos as diagnostics of interstellar grains. ApJ 376, 490–499 (1991).
- 144. Heinz, S. *et al.* Lord of the Rings: A Kinematic Distance to Circinus X-1 from a Giant X-Ray Light Echo. *ApJ* **806**, 265 (2015).
- 145. Lehmer, B. D. *et al.* On the Spatially Resolved Star Formation History in M51. II. X-Ray Binary Population Evolution. *ApJ* **851**, 11 (2017).

- 146. Coulter, D. A. et al. Testing the Universality of the Stellar IMF with Chandra and HST. ApJ 835, 183 (2017).
- 147. Peacock, M. B. *et al.* Evidence for a Constant Initial Mass Function in Early-type Galaxies Based on Their X-Ray Binary Populations. *ApJ* **784**, 162 (2014).
- 148. Peacock, M. B. *et al.* Further Constraints on Variations in the Initial Mass Function from Low-mass X-ray Binary Populations. *ApJ* **841**, 28 (2017).
- 149. Gilfanov, M., Grimm, H.-J. & Sunyaev, R. L_X-SFR relation in star-forming galaxies. *MNRAS* **347**, L57–L60 (2004).
- 150. Weisskopf, M. C. *et al.* Discovery of Spatial and Spectral Structure in the X-Ray Emission from the Crab Nebula. *ApJ* **536**, L81–L84 (2000).
- 151. Kargaltsev, O., Misanovic, Z., Pavlov, G. G., Wong, J. A. & Garmire, G. P. X-Ray Observations of Parsec-scale Tails behind Two Middle-Aged Pulsars. *ApJ* **684**, 542–557 (2008).
- 152. Bucciantini, N., Arons, J. & Amato, E. Modelling spectral evolution of pulsar wind nebulae inside supernova remnants. *MNRAS* **410**, 381–398 (2011).
- 153. Wegmann, R., Dennerl, K. & Lisse, C. M. The morphology of cometary X-ray emission. A&A 428, 647–661 (2004).
- 154. Lisse, C. M. *et al.* Discovery of X-ray and Extreme Ultraviolet Emission from Comet C/Hyakutake 1996 B2. *Science* **274**, 205–209 (1996).
- Snios, B., Lewkow, N. & Kharchenko, V. Cometary emissions induced by scattering and fluorescence of solar X-rays. A&A 568, A80 (2014).
- 156. Snios, B., Lichtman, J. & Kharchenko, V. The Presence of Dust and Ice Scattering in X-Ray Emissions from Comets. *ApJ* **852**, 138 (2018).
- 157. Waite, J. H., Jr. *et al.* ROSAT Observations of X-Ray Emissions from Jupiter During the Impact of Comet Shoemaker-Levy 9. *Science* **268**, 1598–1601 (1995).
- 158. Branduardi-Raymont, G. *et al.* Latest results on Jovian disk X-rays from XMM-Newton. *Planet. Space Sci.* 55, 1126–1134 (2007).
- 159. Branduardi-Raymont, G. *et al.* Spectral morphology of the X-ray emission from Jupiter's aurorae. *Journal of Geophysical Research (Space Physics)* **113**, A02202 (2008).
- 160. Crary, F. J. & Bagenal, F. Coupling the plasma interaction at Io to Jupiter. Geophys. Res. Lett. 24, 2135 (1997).
- Connerney, J. E. P., Acuña, M. H., Ness, N. F. & Satoh, T. New models of Jupiter's magnetic field constrained by the Io flux tube footprint. J. Geophys. Res. 103, 11929–11940 (1998).
- 162. Clarke, J. T. *et al.* Ultraviolet emissions from the magnetic footprints of Io, Ganymede and Europa on Jupiter. *Nature* **415**, 997–1000 (2002).
- 163. Segura, A., Walkowicz, L. M., Meadows, V., Kasting, J. & Hawley, S. The Effect of a Strong Stellar Flare on the Atmospheric Chemistry of an Earth-like Planet Orbiting an M Dwarf. *Astrobiology* **10**, 751–771 (2010).
- 164. Glassgold, A. E., Galli, D. & Padovani, M. Cosmic-Ray and X-Ray Heating of Interstellar Clouds and Protoplanetary Disks. *ApJ* **756**, 157 (2012).
- 165. Cleeves, L. I., Bergin, E. A. & Adams, F. C. Exclusion of Cosmic Rays in Protoplanetary Disks. II. Chemical Gradients and Observational Signatures. *ApJ* **794**, 123 (2014).
- Cleeves, L. I. *et al.* Variable H¹³CO⁺ Emission in the IM Lup Disk: X-Ray Driven Time-dependent Chemistry? *ApJ* 843, L3 (2017).

- 167. Adler, I. *et al.* Apollo 15 Geochemical X-ray Fluorescence Experiment: Preliminary Report. *Science* **175**, 436–440 (1972).
- 168. Schmitt, J. H. M. M. et al. A soft X-ray image of the moon. Nature 349, 583-587 (1991).
- 169. Wargelin, B. J. *et al.* Chandra Observations of the "Dark" Moon and Geocoronal Solar Wind Charge Transfer. *ApJ* **607**, 596–610 (2004).
- 170. Yokota, S. *et al.* First direct detection of ions originating from the Moon by MAP-PACE IMA onboard SELENE (KAGUYA). *Geophys. Res. Lett.* **36**, L11201 (2009).
- 171. Feigelson, E. D. et al. X-Ray-emitting Young Stars in the Orion Nebula. ApJ 574, 258–292 (2002).
- 172. Núñez, A. *et al.* Linking Stellar Coronal Activity and Rotation at 500 Myr: A Deep Chandra Observation of M37. *ApJ* **809**, 161 (2015).
- 173. Poppenhaeger, K., Schmitt, J. H. M. M. & Wolk, S. J. Transit Observations of the Hot Jupiter HD 189733b at X-Ray Wavelengths. *ApJ* **773**, 62 (2013).
- Poppenhaeger, K. & Wolk, S. J. Indications for an influence of hot Jupiters on the rotation and activity of their host stars. A&A 565, L1 (2014).
- 175. Saha, T. T. & Zhang, W. W. submitted to Proc. SPIE (2019).
- 176. Yao, Y. et al. submitted to JATIS (2019).
- 177. Li, J. *et al.* Chandra ACIS Subpixel Event Repositioning: Further Refinements and Comparison between Backside- and Frontside-illuminated X-Ray CCDs. *ApJ* **610**, 1204–1212 (2004).
- 178. Bray, E., Burrows, D. N., Falcone, A. D., Wages, M. & Chattopadhyay, T. Exploring fine subpixel spatial resolution of hybrid CMOS detectors. In *Space Telescopes and Instrumentation 2018: Ultraviolet to Gamma Ray*, no. 10699204 in Proc. SPIE (2018).
- 179. Miller, E. D. *et al.* The effects of charge diffusion on soft x-ray response for future high-resolution imagers. In Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, vol. 10699 of Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, 106995R (2018).
- 180. Koyama, K. et al. X-Ray Imaging Spectrometer (XIS) on Board Suzaku. PASJ 59, 23-33 (2007).
- 181. Chattopadhyay, T. et al. X-ray hybrid CMOS detectors: recent development and characterization progress. In Space Telescopes and Instrumentation 2018: Ultraviolet to Gamma Ray, vol. 10699 of Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, 106992E (2018). 1807.03351.
- 182. Hull, S. V., Falcone, A. D., Burrows, D. N., Wages, M. & McQuaide, M. Small pixel hybrid CMOS x-ray detectors. In *High Energy, Optical, and Infrared Detectors for Astronomy VIII*, vol. 10709 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, 107090E (2018).
- 183. Herrmann, S. et al. VERITAS 2.2: a low noise source follower and drain current readout integrated circuit for the wide field imager on the Athena x-ray satellite. In *High Energy, Optical, and Infrared Detectors for Astronomy VIII*, vol. 10709 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, 1070935 (2018).
- Meidinger, N. et al. The Wide Field Imager instrument for Athena. In Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, vol. 10397 of Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, 103970V (2017).
- 185. Aldcroft, T. L., Karovska, M., Cresitello-Dittmar, M. L., Cameron, R. A. & Markevitch, M. L. Initial performance of the aspect system on the Chandra Observatory: postfacto aspect reconstruction. In Truemper, J. E. & Aschenbach, B. (eds.) X-Ray Optics, Instruments, and Missions III, vol. 4012 of Proc. SPIE, 650–657 (2000).