LYNX X-RAY OBSERVATORY

CONCEPT STUDY **REPORT**

X-RAY OBSERVATORY

LYNX

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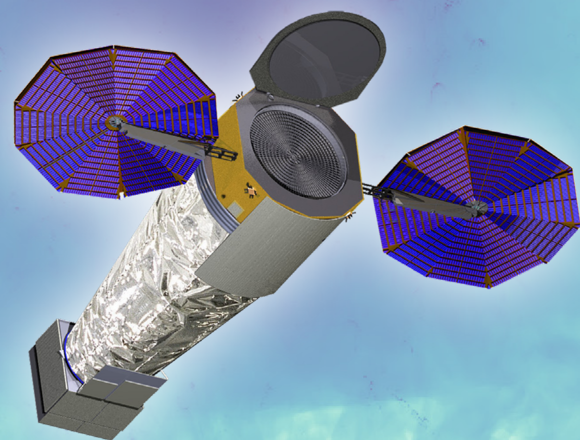

CONCEPT STUDY REPORT

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Additional contributors are listed at the back of this Report.

The Lynx Team is large and growing. We curate an up-to-date list of members at

www.LYNXOBSERVATORY.org / TEAM

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EXECUTIVE SUMMARY

Lynx is a revolutionary X-ray observatory with the power to transform our understanding of the cosmos through unprecedented X-ray vision into the otherwise invisible Universe. It is designed to pursue three fundamental science pillars: 1) seeing the dawn of black holes, 2) revealing what drives galaxy formation and evolution, and 3) unveiling the energetic side of stellar evolution and stellar ecosystems. For its spacecraft design and operational concept, *Lynx* leverages the overarching, proven architecture from *Chandra*. The *Lynx* payload provides extraordinary advances in science capabilities thanks to an extremely powerful combination of sub-arcsecond angular resolution and high throughput of its X-ray mirror, and the transformational spectroscopic capabilities of its science instruments. Strong heritage and substantial maturity in key new technologies lead to a credible cost for this Great Observatory-class mission.

A NEW GREAT OBSERVATORY

X-RAY OBSERVATIONS are indispensable for understanding the cosmos. Their power is immense because much of the baryonic matter and the sites for the most active energy releases in the Universe are primarily observable in X-rays. For the 2030s and beyond, an X-ray observatory with power matching the capabilities in other wavebands is a necessary discovery engine for full exploration of the Universe.

JWST and other upcoming major space- and ground-based facilities are expected to greatly expand science frontiers in the coming decades. This presents both a great opportunity and a challenge for a next-generation X-ray observatory. In many areas, such as tracing black holes during the Cosmic Dawn and understanding the formation and evolution of galaxies, an X-ray observatory is the logical next step. The challenge is that the X-ray science at these new frontiers requires expansion of capabilities by orders of magnitude beyond the current state of the art or anything already planned.

Until recently, such gains were not technologically possible. This has changed thanks to recent breakthroughs and sustained maturation of key technologies for X-ray mirrors and detectors. We are reaping the fruits of U.S. investments in these areas over the past 10–15 years. An X-ray observatory that can extend the science frontiers of the post-*JWST* era is now entirely feasible. *Lynx* is the mission concept that realizes this vision. It will fly revolutionary optics and instrumentation onboard a simple, proven spacecraft. In all aspects, *Lynx* will be a next-generation Great Observatory that is certain to make a profound impact across the astrophysical landscape. It will provide the depth and breadth to answer the fundamental questions that confront us today; just as importantly, it will have capabilities to address questions we have yet to even ask.

Lynx is poised to make a particularly strong impact in the following three areas, which serve as its science pillars and are used to define core performance requirements:

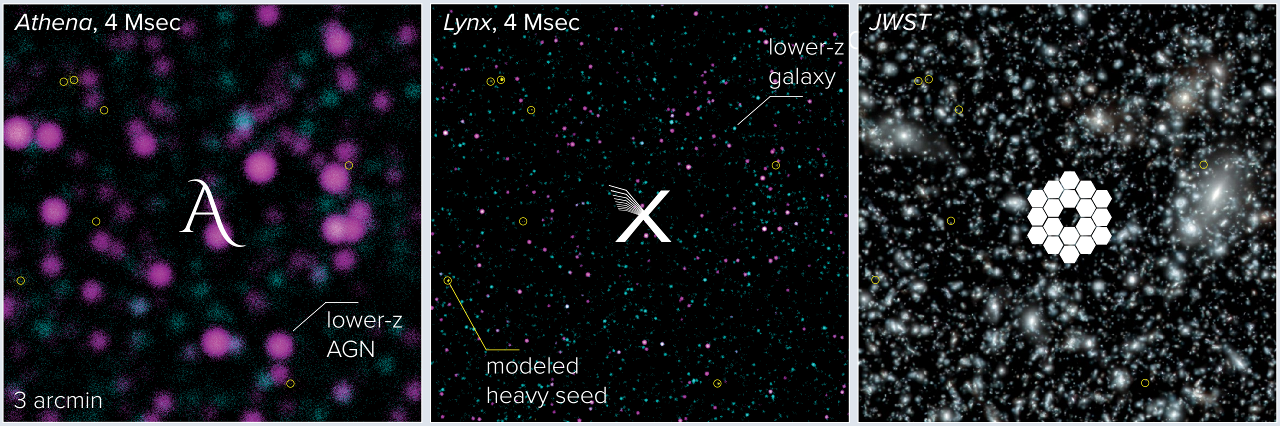
- **The Dawn of Black Holes,**
- **The Invisible Drivers of Galaxy Formation and Evolution,**
- **The Energetic Side of Stellar Evolution and Stellar Ecosystems.**

The capabilities required by these *Lynx* science pillars can be implemented within a proven mission architecture derived from *Chandra*. *Lynx* will have a baseline lifetime of 5 years and be provisioned for 20 years of operation. Operation beyond 20 years is possible with the implementation of in-space servicing and/or the redirection before launch of unused mass margins to accommodate additional station-keeping fuel. *Lynx* easily meets the mass and volume constraints of existing and expected heavy-class launch vehicles. If needed, its 10-m optical bench can be designed with an extension mechanism to reduce length in stowed configuration, further increasing flexibility with respect to future launch options.

Lynx Science Pillars

***The Dawn of Black Holes* —** We now realize that black holes define many aspects of cosmic evolution, and that massive black holes were in place very early in the history of the Universe. Understanding their formation and rapid early growth is one of the most important unsolved problems in astrophysics. *Lynx* will be able to detect the first massive black holes in the first generations of galaxies. The first galaxies will be found and characterized in deep optical and infrared surveys that

the DAWN *of* BLACK HOLES



KEY CAPABILITIES

The key observations are deep surveys over ~ 1 deg^2 with flux limit ~ 10^{-19} erg s^{-1} cm^{-2} to detect black hole seeds with M_{BH} = 10,000 $M_\odot$ at z = 10. This requires:

- On-axis PSF ~ 0.5″ (HPD), and sub-arcsecond imaging within 10′ radius FOV to avoid source confusion.
- A_{eff} = 2 m^2 at E = 1 keV to enable completion of deep surveys within one year.

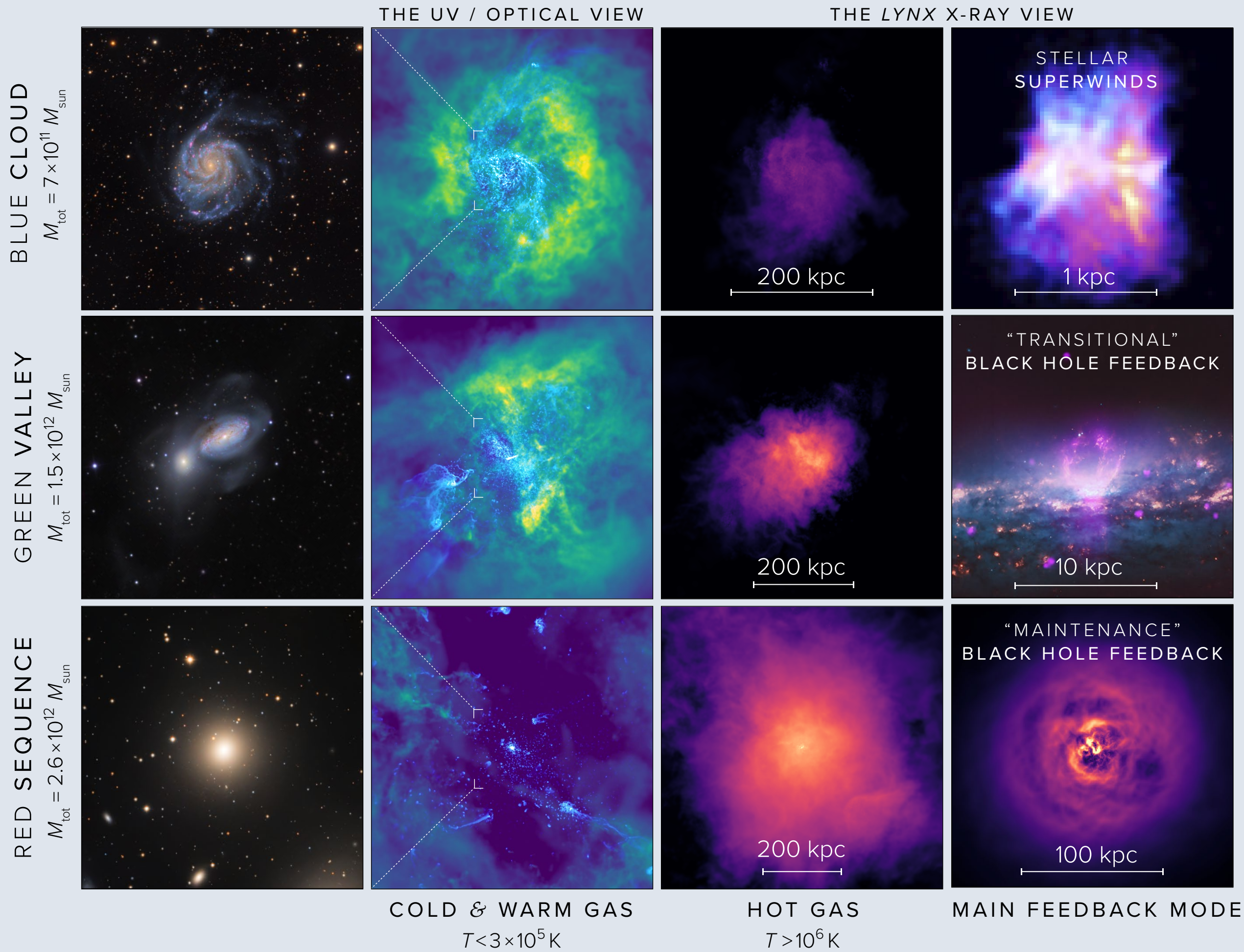
Lynx will provide a sensitivity in X-rays to detect accreting black holes with mass M_{BH} ~ 10^4 $M_\odot$ at z = 10. These observations will open an electromagnetic window into the Dawn of Black Holes. *Lynx*, using X-rays, and *LISA*, using gravitational waves, together will probe the growth of the first black holes by both accretion and mergers, unveiling a complete picture of their early assembly.

Angular resolution is critical for detecting high-z black hole seeds. The panels above show simulated 3′ × 3′ regions in deep surveys by *JWST*, *Lynx*, and *Athena* (a future ESA X-ray observatory with 5″ angular resolution). Unlike *Athena*, *Lynx* will not be affected by "source confusion," and can uniquely associate every X-ray source with a *JWST*-detected galaxy. In the X-ray images, color codes different source populations. In each panel, yellow circles show the locations of high-z black hole seeds (see Fig. 1.3 on p. 21 for more information on how seed models can be tested with *Lynx*). Their fluxes are a factor of ~ 100 below the confusion limit for a 5″ X-ray telescope.

can be obtained with either the almost ready to launch *JWST* or the subsequent *WFIRST* missions. The X-ray flux limits required to detect the first massive black holes are accessible only with *Lynx*.

The Invisible Drivers of Galaxy Formation and Evolution — Unprecedentedly detailed information is now available on the stellar, dust, and cold gas content of galaxies, and yet there is a dearth of understanding of the exact mechanisms of their formation. *Lynx* will expose essential drivers of galaxy evolution which primarily leave imprints in the circumgalactic medium (CGM) extending well beyond the optical size of galaxies and containing most of their baryons. Most of the halo gas in galaxies more massive than the Milky Way is heated above UV ionization states to X-ray temperatures. The energetic processes that define its state are the same ones that regulate growth and create the diversity of galaxy morphologies. While modern UV, optical, and sub-mm observations can map cold and warm gas, these observations are equivalent to seeing only the smoke and sparks in a fire. For a true understanding of the lives of galaxies, we need *Lynx* to see the flame itself.

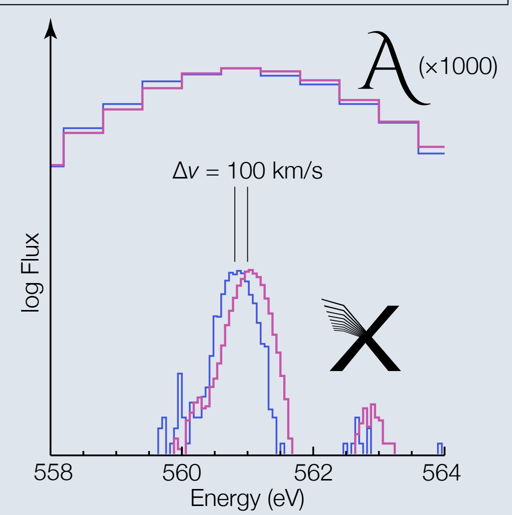
DRIVERS *of* GALAXY EVOLUTION



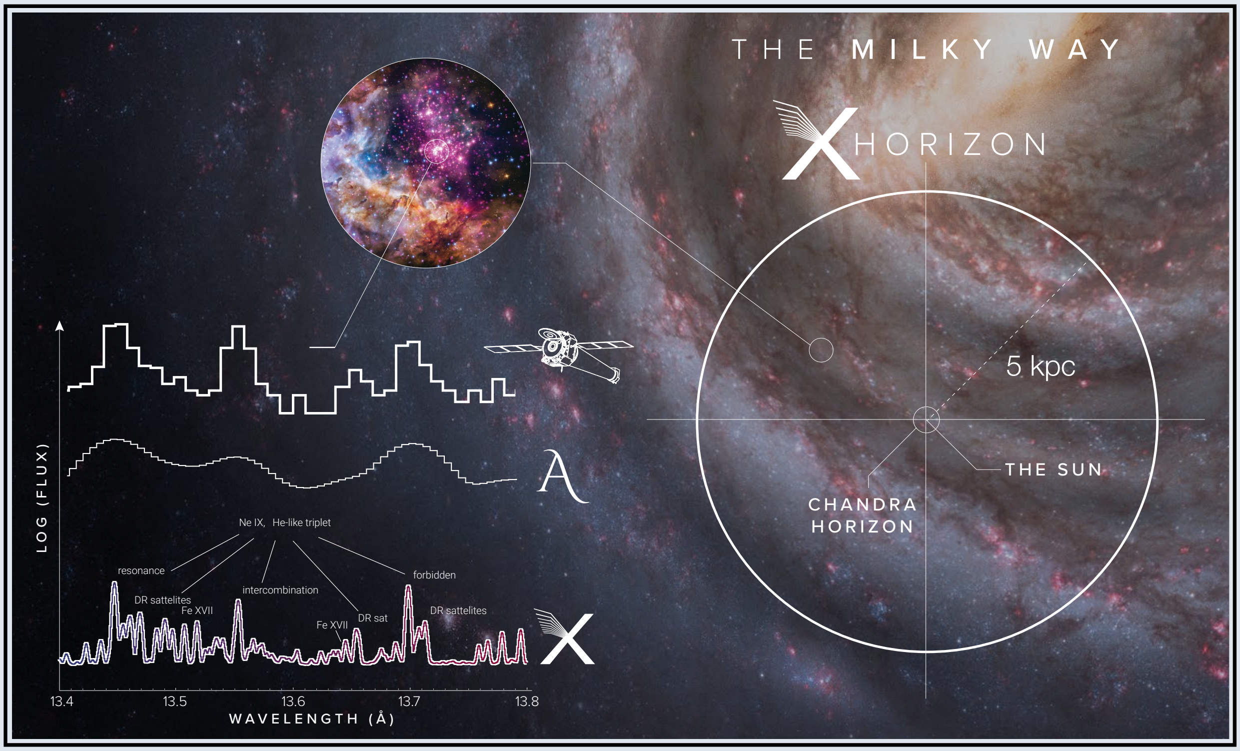
KEY CAPABILITIES

- Map CGM in emission to $0.5r_{200}$: PSF < 1″, $A_{eff} = 2\ m^2$.
- Probe CGM in absorption at ~ r_{200}: gratings with $A_{eff} = 4{,}000\ cm^2$ and $\lambda/\Delta\lambda > 5{,}000$.
- Map velocities in ~ 100 km s^{-1} galactic outflows: microcalorimeter with $E/\Delta E = 2{,}000$ at $E = 0.6$ keV.
- Study AGN feedback in galaxies and clusters: microcalorimeter with 0.5″ pixels.

The sensitivity and spectroscopic capabilities of *Lynx* will enable mapping of the hot galactic halos to ~ 0.5 – 1 virial radii in both emission and absorption. The inner structure of the halos ($\lesssim 0.1 r_{vir}$) is where all primary signatures of ongoing feedback are imprinted. The capabilities of the *Lynx* microcalorimeter will be essential for exposing these signatures. It will simultaneously provide 1″ spatial resolution and $R = 2{,}000$ resolving power at all key energies required, e.g., to map the kinematic and chemical structure of galactic winds *(right)*.



the ENERGETIC SIDE *of* **STELLAR EVOLUTION**

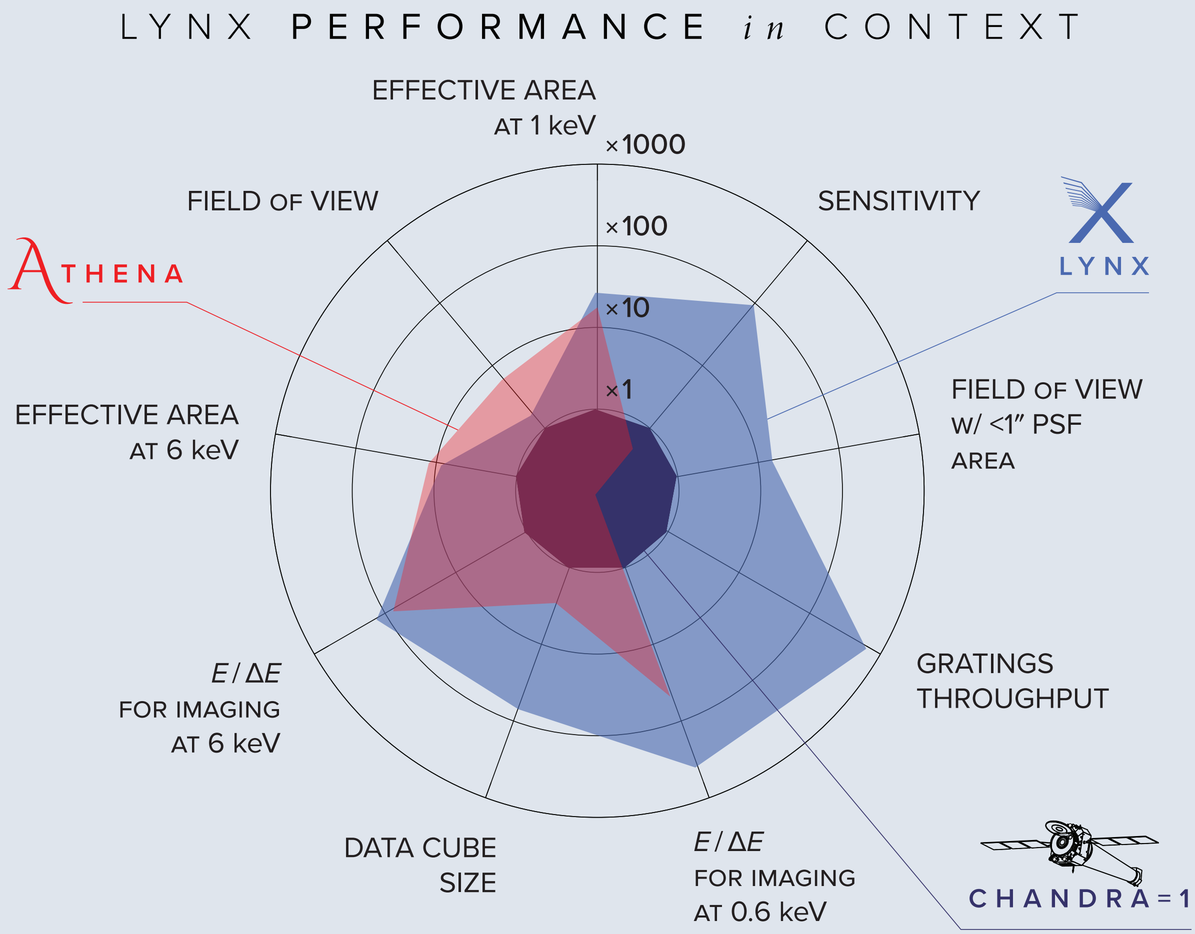


KEY **CAPABILITIES**

- Spatially resolve star cluster cores: PSF ≈ 0.5″.
- Resolve lines in stellar spectra: gratings with $R > 5{,}000$.
- Map 3D structure of supernova remnants: microcalorimeter with $\Delta E = 3$ eV and 1″ pixels.

Lynx will provide unique new capabilities for studying stellar birth, life, and death. Its sensitivity will be sufficient for detecting low-mass young stellar objects to 5 kpc. It will enable vastly more powerful spectral diagnostics for studies of stellar accretion and coronae. Microcalorimeter observations will fully resolve the 3D structure of supernova remnants in the Milky Way and nearby galaxies.

***The Energetic Side of Stellar Evolution and Stellar Ecosystems* —** As we enter the era of multimessenger astronomy following LIGO detections of gravitational waves, and as studies of exoplanets evolve toward holistic assessment of habitable conditions, orders-of-magnitude expansion in capabilities will be needed to observe key high-energy processes associated with stellar birth, life, and death. *Lynx* will meet this challenge and dramatically extend our X-ray grasp throughout the Milky Way and nearby galaxies. The horizon for detecting X-rays as markers of young stars and for detailed stellar spectroscopy will be extended by an order of magnitude. Spatially resolved spectroscopy on arcsecond scales will offer a three-dimensional view of metals synthesized in stellar explosions, and will enable population studies of supernova remnants in the Local Group galaxies. Sensitive observations of X-ray binaries beyond the Local Group galaxies and detailed follow-up of gravitational wave events will transform our knowledge of collapsed stars. *Lynx* will make all these studies possible by combining, for the first time, the required sensitivity, spectral resolution, and sharp vision to see clearly in crowded fields.

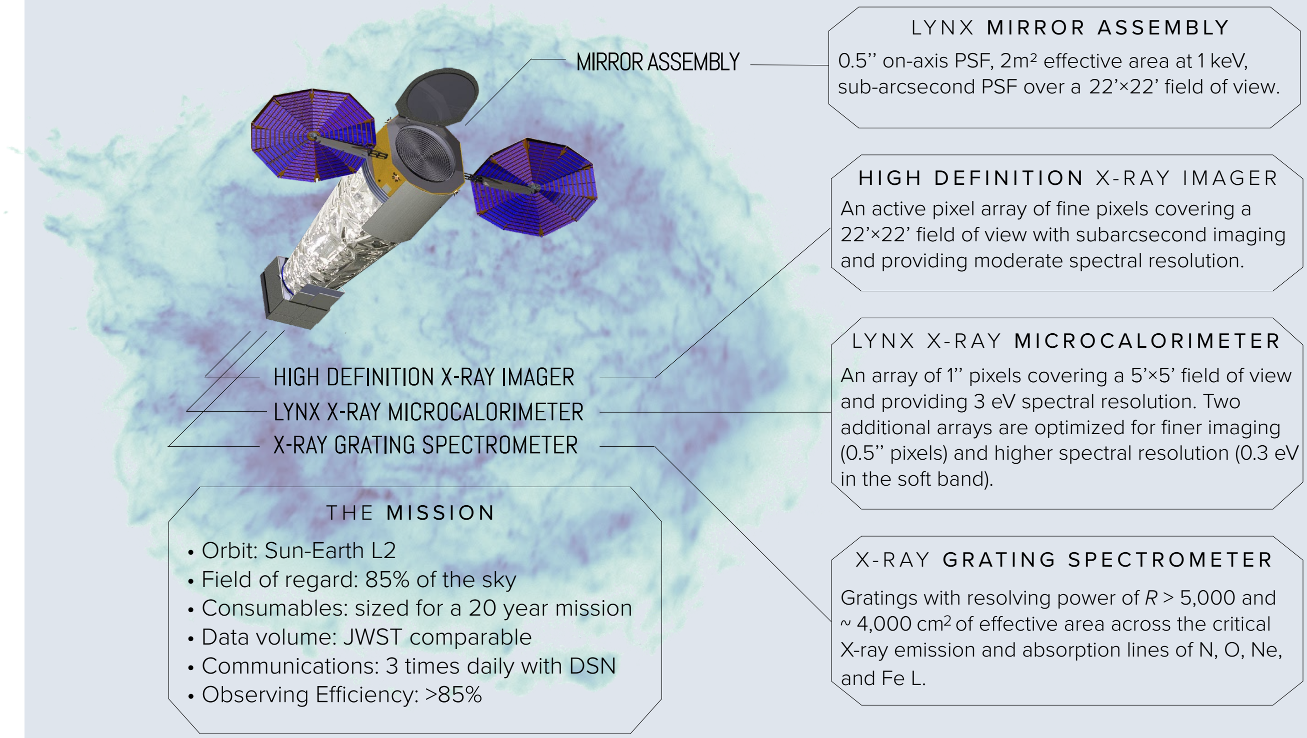


The requirements established by the *Lynx* science pillars translate into the need for orders-of-magnitude performance gains along a number of key axes. The diagram above shows how these gains compare with the performance of *Chandra* (taken to be 1 on all axes) and *Athena* (shown in red). *Athena*, ESA's planned mission, will carry the first large X-ray microcalorimeter and make strides in energy resolution, effective area (especially at high energies), and field of view. It will not, however, make breakthrough gains across the board: not in sensitivity; not in sharp imaging; not in very high spectral resolution. *Lynx* makes primary breakthroughs along these axes, which are precisely the directions required by its science goals. *Lynx* and *Athena* can be viewed as orthogonal missions with different science goals and based on different strengths. *Athena*'s science centers on massive, wide surveys and detailed spectroscopy of relatively bright and isolated objects. With a combination of its high angular resolution, high throughput, and powerful spectroscopic capabilities, *Lynx* opens up the discovery space in the high redshift universe, crowded fields, feedback on galactic scales, and circumgalactic environments.

Mission Design

Lynx will operate as an X-ray observatory with a grazing incidence telescope and detectors that record the position, energy, and arrival time of individual X-ray photons. Post-facto aspect reconstruction leads to modest requirements on pointing precision and stability, while enabling very accurate sky locations for detected photons. The design of the *Lynx* spacecraft is straightforward, with few moving

PAYLOAD & MISSION CHARACTERISTICS



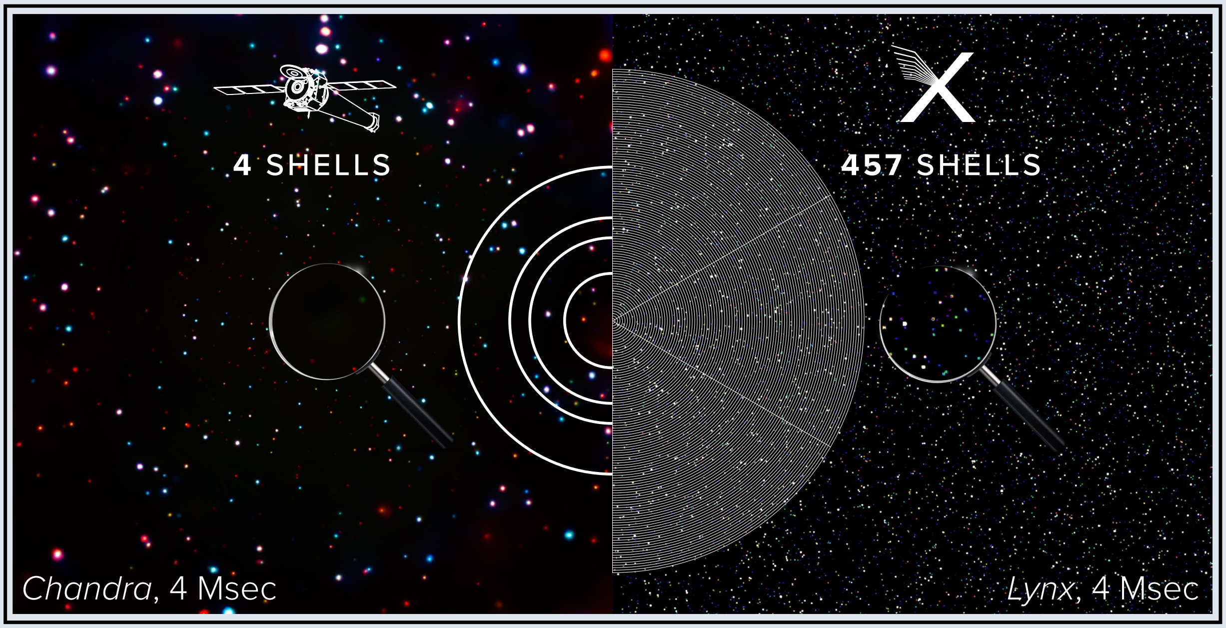
The *Lynx* spacecraft is built around the X-ray mirror assembly that is followed by a large-area insertable grating array. The science instrument module is attached to the spacecraft by an optical bench. It includes the interchangable prime focus detectors, HDXI and LXM, and the off-center XGS readout array at a fixed location. All risk and new development for *Lynx* is isolated to its optics and science instruments. The spacecraft requires no new inventions and, indeed, can use many existing solutions, including those developed for *Chandra* and other past missions.

parts; all of its elements can be procured today. *Lynx* will operate in a halo orbit around Sun-Earth L2, enabling high observing efficiency in a stable environment. Its maneuvers and operational procedures on-orbit are nearly identical to *Chandra*'s, and similar design approaches promote longevity.

The transformational scientific power of *Lynx* is entirely enabled by its payload — the mirror assembly and a suite of three highly capable science instruments. Each of the payload elements features state-of-the-art technologies, but at the same time represents a natural evolution of an existing instrument or technology, with each already having years of funded technology development. Key technologies are currently at Technology Readiness Levels (TRL) 3 or 4. With three years of targeted pre-phase A development in early 2020s, three of four key technologies will be matured to TRL 5 and one will reach TRL 4 by start of Phase A, achieving TRL 5 shortly thereafter.

***The Lynx Mirror Assembly (LMA)* —** The LMA is the central element of the observatory. It is responsible for leaps in sensitivity, spectroscopic throughput, survey speed, and better imaging than *Chandra* because of much-improved off-axis performance. The LMA can be based on three fully feasible mirror technologies: Silicon Metashell Optics (SMO) developed at NASA's Goddard Space

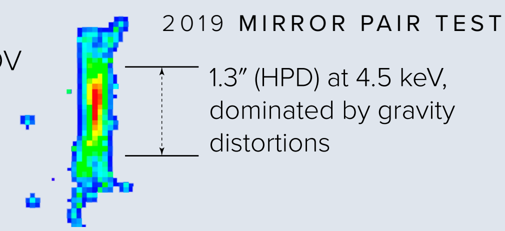
EYES, SHARP *as a* LYNX



0.5″ PSF on-axis, sub-arcsecond across a 22’ × 22’ FOV

50× *Chandra*’s throughput in soft X-rays

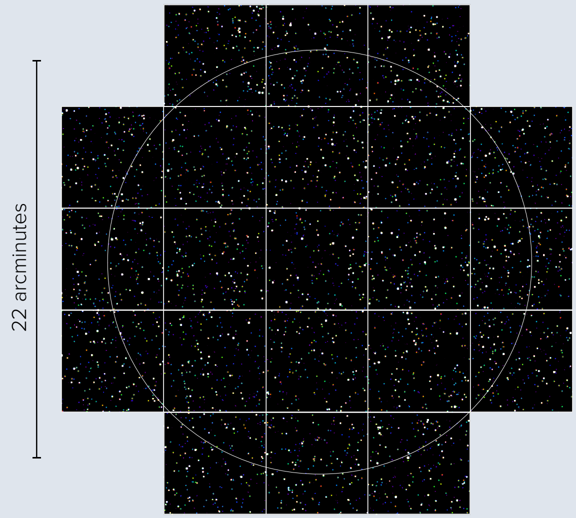
1,000× *Chandra*’s survey speed



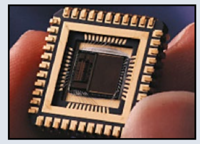
The *Lynx* Mirror Assembly (LMA) keeps *Chandra*’s sub-arcsecond resolution on-axis while providing orders-of-magnitude gains in throughput and FOV size for sub-arcsecond imaging. The LMA is composed of concentric modular metashells, and each module is populated with multiple mirror pair segments. The repeatable production of mirror segments with a surface quality meeting or exceeding required specifications was recently verified (February 2019). A full-illumination X-ray test of an aligned mirror pair on a flight-like mount has produced a 1.3″ image, for which approximately 1″ is attributed to 1-g gravity distortion in the test configuration. Subtraction of well-modeled gravity distortions indicates sub-arcsecond performance for the tested mirror pair in zero-gravity.

Flight Center (GSFC), Full Shell Optics developed jointly by MSFC and the Italian National Institute for Astrophysics, and Adjustable Segmented Optics developed at the Smithsonian Astrophysical Observatory (SAO) and Penn State. The SMO technology was selected for the design reference mission (DRM) following a comprehensive technology assessment trade study, which evaluated the ability of each approach to meet *Lynx* science requirements, the credibility of technology development plans, and the validity of schedule, cost, and risk estimates. The SMO technology is currently the most advanced in terms of demonstrated performance (already approaching what is required for *Lynx*, see figure above). The SMO’s highly modular design lends itself to parallelized manufacturing and assembly, while also providing high fault tolerance: if some individual mirror segments or even modules are damaged, the impact to schedule and cost is minimal.

the HIGH-DEFINITION X-RAY IMAGER (HDXI)



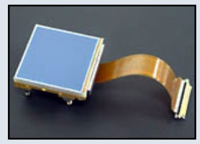
0.3'' Pixel size well-matched to telescope PSF.
Large, curved focal plane (22' × 22').



Monolithic CMOS (Sarnoff / SAO & MPE)

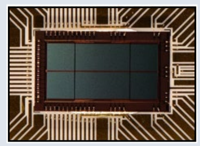
High gain (135 µV / e⁻), low noise (3 e⁻ rms) amplifiers.

PMOS devices ready for X-ray testing with < 1 e⁻ read noise and no RTS noise.



Hybrid CMOS (Teledyne & PSU)

Achieves ~ 80 eV (FWHM) energy resolution at 0.5 keV, in-pixel CDS, no crosstalk. Event-driven readout achieved. Latest scaled-up designs include on-chip digitization.

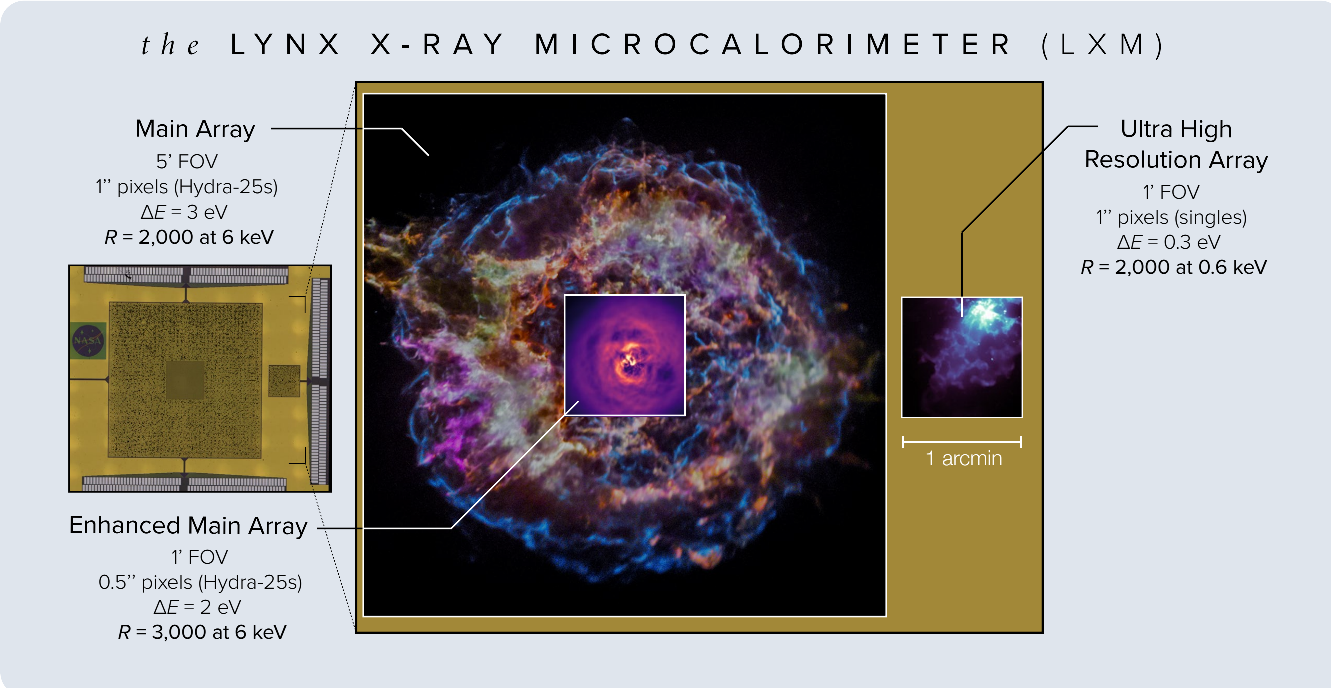


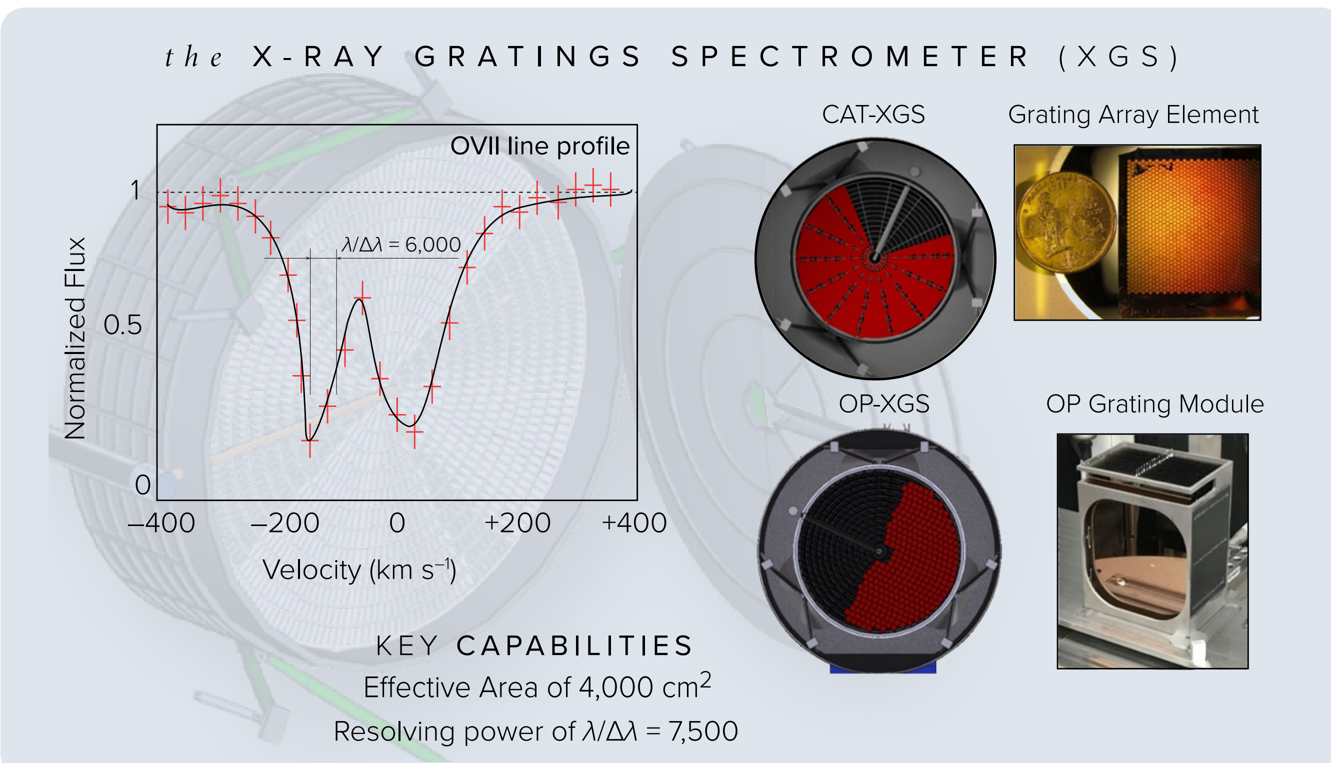
Digital CCD with CMOS Readout (MIT / Lincoln Lab)

Reduced noise (4.6 e⁻). Low-power CMOS clock. Larger (2 Mpix) device in fabrication.

The High-Definition X-ray Imager (HDXI) — The HDXI instrument is the main imager for *Lynx*, providing high spatial resolution over a wide FOV and good sensitivity over the 0.2–10 keV bandpass. Its 0.3″ pixels will adequately sample the *Lynx* mirror PSF over a 22′ × 22′ FOV. The 21 individual sensors are laid out along the optimal focal surface to improve the off-axis PSF. The *Lynx* DRM uses Complementary Metal Oxide Semiconductor (CMOS) Active Pixel Sensor (APS) technology, which is projected to have the required capabilities (i.e., high readout rates, high broad-band quantum efficiency, sufficient energy resolution, minimal pixel crosstalk, and radiation hardness). The *Lynx* team has identified three options with comparable TRL ratings (TRL 3) and sound TRL advancement roadmaps: the Monolithic CMOS, Hybrid CMOS, and Digital CCDs with CMOS readout. All are currently funded for technology development.

The Lynx X-ray Microcalorimeter (LXM) — The LXM is an imaging spectrometer that provides high resolving power (R ~ 2,000) in both the hard and soft X-ray bands, combined with high spatial resolution (down to 0.5″ scales). To meet the diverse range of *Lynx* science requirements, the LXM focal plane includes three arrays that share the same readout technology. Each array is differentiated by its absorber pixel size and thickness, and by how the absorbers are connected to thermal readouts. The total number of pixels exceeds 100,000 — a major leap over past and currently planned X-ray microcalorimeters. This huge improvement does not entail a huge added cost: two of the LXM arrays feature a simple, already proven, "thermal" multiplexing approach where multiple absorbers are connected to a single temperature sensor. This design brings the number of sensors to read out (one of the main power and cost drivers for the X-ray microcalorimeters) to ~ 7,600. This is only a modest increase over what is planned for the X-IFU instrument on *Athena*. As of Spring 2019, prototypes of the focal plane have been made that include all three arrays at 2/3 full size. These prototypes demonstrate that arrays with the pixel form factor, size, and wiring density required by *Lynx* are readily achievable, with high yield. The energy resolution requirements of the different pixel types





is also readily achievable. Although the LXM is technically still at TRL 3, there is a clear path for achieving TRL 4 by 2020 and TRL 5 by 2024.

The X-ray Grating Spectrometer (XGS) — The XGS will provide even higher spectral resolution (R = 5,000 with a goal of 7,500) in the soft X-ray band for point sources. Compared to the current state of the art (*Chandra*), the XGS provides a factor of > 5 higher spectral resolution and a factor of several hundred higher throughput. These gains are enabled by recent advances in X-ray grating technologies. Two strong technology candidates are: critical angle transmission (used for the *Lynx* DRM) and off-plane reflection gratings. Both are fully feasible, currently at TRL 4, and have demonstrated high efficiencies and resolving powers of ~ 10,000 in recent X-ray tests.

***Mission operations* —** The *Chandra* experience provides the blueprint for developing the systems required to operate *Lynx*, leading to a significant cost reduction relative to starting from scratch. This starts with a single prime contractor for the science and operations center, staffed by a seamless, integrated team of scientists, engineers, and programmers. Many of the system designs, procedures, processes, and algorithms developed for *Chandra* will be directly applicable for *Lynx*, although all will be recast in a software/hardware environment appropriate for the 2030s and beyond.

***General Observer approach to Lynx science program* —** The science impact of *Lynx* will be maximized by subjecting *all* of its proposed observations to peer review, including those related to the three science pillars. Time pre-allocation can be considered only for a small number of multi-purpose key programs, such as surveys in pre-selected regions of the sky. Such an open General Observer (GO) program approach has been successfully employed by large missions such as *Hubble*, *Chandra*, and *Spitzer*, and is planned for *JWST* and *WFIRST*. The *Lynx* GO program will have ample exposure time to achieve the objectives of its science pillars, make impacts across the astrophysical landscape, open new directions of inquiry, and produce as yet unimagined discoveries.

Cost and Mission Schedule

The *Lynx* team has conducted extensive parametric cost analyses for all aspects of mission cost, with detailed analyses focused on the spacecraft (broken down to the subsystem level), X-ray optics, each of the science instruments, and mission operations. The analysis utilized the industry-standard PCEC Cost Model, the SEER® hardware model, and the PRICE® TruePlanning® Space Missions and PRICE®-H Hardware models. The resulting costs estimated by these models are consistent and, where comparison is possible, in family with the actuals from past NASA missions. The parametric cost, which serves as the primary estimate, has been validated in multiple ways: an end-to-end grassroots estimate based on a mix of analogies and expert input, an MSFC non-advocate independent cost estimate, and an independent cost and technical evaluation. Finally, the *Lynx* team carried out a thorough mission-level comparison to escalated *Chandra* actuals.

The parametric model and validation methods provide point estimates, which are consistent within ±5%. Confidence levels (CL) are available from the parametric modeling, the MSFC non-advocate independent cost estimate, and the independent cost and technical evaluation. All of these methods give consistent costs at $\lesssim$ 50% CL. For example, at 40% CL, the costs are in the range from \$4.8B to \$4.9B (in FY20\$). This consistency reflects a well-developed mission design with a strong heritage and lessons learned from past and planned missions. There is a larger divergence for higher confidence levels. For example, for a 70% CL, the spread is from \$5.1B to \$6.2B. This naturally reflects uncertainties appropriate for this relatively early stage of the mission design. Overall, consistency is excellent and gives credibility to the estimated *Lynx* mission cost. Note that the quoted costs cover the entire mission lifecycle, from start through 5 years of operations. They include reserves and a conservative passthrough from the NASA Launch Service Providers for a heavy-class launch vehicle. The operations cost is ~ \$400M total, including projected funding of ~ \$100M (FY20\$) for grants.

Even with the huge gains in capability provided by *Lynx*, its costs will only modestly exceed the inflated *Chandra* actuals. This is substantiated by the following considerations: *Lynx* technology development and the mission study have directly benefited from a science community and a contractor base with extensive and applicable experience working on *Chandra* and other recent X-ray missions. Even though personnel and contractors will change, an exceptionally solid mission concept and cost basis for *Lynx* are already in place, given the engagement of this experienced team. Observatory-wide error budgets for mass, power, thermal, and end-to-end performance demonstrate that the requirements are well understood and achievable. The spacecraft and two of the *Lynx* instruments (HDXI and XGS) are modest evolutions of the *Chandra* equivalents and do not require breakthroughs or new inventions. The third instrument, the LXM, is quickly gaining technology maturity from laboratory efforts and from other X-ray missions (*Hitomi*, *XRISM*, *Athena*). Mission operations are particularly well understood, with plans, requirements, algorithms, and cost estimates derived from the *Chandra* experience. The ability to produce a *Lynx* mirror at a cost similar to *Chandra* can be tracked to tangible technological breakthroughs, along with an LMA design amenable to mass production. The status already achieved in key technology areas adds credibility to the development plans to reach TRL 6 for the LMA and the science instruments over the next several years. Taken together, these factors explain the relatively small differences between the *Lynx* costs and inflated *Chandra* actuals.

Mission lifecycle schedule — The *Lynx* team has developed a notional mission schedule that includes all required milestones and key decision points. Given their architecture similarities, the *Lynx* schedule for the system-level assembly, integration, and test closely matches that of *Chandra*, after accounting for its larger size and additional complexities. It is also consistent with the *WFIRST* in-guide schedule to a 2025 launch. The *Lynx* schedule includes ≈ 3 years of pre-Phase A studies, during which time key technologies will be maturated to the levels required to enter Phase A. The funding needed is comparable to that provided for *WFIRST* at the same stage. Durations for Phases A&B and C&D are 42 and 103 months, respectively. Assuming this sequence starts soon after the Astro2020 Decadal Survey makes its recommendation, *Lynx* will launch in 2036.

Contents of this Report

- **The Science of *Lynx*** is discussed in §1–§5. This includes a discussion of the three *Lynx* science pillars and the impact of *Lynx* in many other areas of astrophysics, the Science Traceability Matrix, and a notional plan of observations required to execute the pillar science.
- **Design Reference Mission** is presented in §6 and provides a discussion of the overall rationale for the observatory design, detailed account of the spacecraft and payload elements, system-level error budget, system-level analyses and predicted on-orbit performance, discussion of the launch options, and a concept for mission operations.
- **Technologies.** Review of the current state of the art and near-terms plans is presented in §7. Further information is provided in the special section on *Lynx* of the *Journal of Astronomical Telescopes, Instruments, and Systems* [1]. Detailed roadmaps for further maturation of key technologies are available in the supplemental materials and online.
- **Programmatics.** The discussion of programmatics, including the mission lifecycle schedule, cost, risks and mitigations, is provided in §8. The costing methodology and high-level cost range is presented in §8.5. A detailed cost book is available in the supplemental materials.

- **Observatory Configuration Trade Space.** Sections 9 and 10 provide a comparison of science capability and costs for a representative range of possible mission configurations. The analysis demonstrates that the *Lynx* DRM concept optimizes the "science per dollar" metric.

The Impact of *Lynx* Across the Future Astrophysical Landscape

Lynx will profoundly impact many areas of astrophysics. Obviously, it will play a critical role in the topics directly related to its science pillars, such as studies of the Cosmic Dawn, Black Holes, Galaxy Formation, and Origin of Elements. *Lynx* will also make a major impact in other areas, such as Cosmology, Resolved Stellar Populations, Solar System Observations, and Multi-Messenger Astronomy. Its influence will be seen even in less obvious areas, such as studies of the cold interstellar medium, planets, and protoplanetary disks. This wide impact is a result of gains in sensitivity and spectroscopic capabilities of historical magnitude, equivalent to opening a new wavelength band or introducing a new observational technique.

The *Lynx* imaging component provides a factor of 50× higher throughput, 20× the FOV with sub-arcsecond imaging, and a factor of 1,000× greater speed for surveys compared to the current state of the art (*Chandra*). To put this in context, these improvements are bigger than the tremendous gain in survey power from *Hubble* to the future NASA flagship observatory, *WFIRST*. In terms of sensitivity, *Lynx* will detect sources 100× fainter than those seen in the deepest *Chandra* surveys.

Astronomy is undergoing revolutionary changes, driven in large part by movement toward hyper-dimensional datasets. Fully spatially resolved spectroscopic data cubes provided by instruments such as MUSE on ESO's Very Large Telescope (VLT) enable advancements which rival the leap from the first astro-photograph to state-of-the-art imaging from *Hubble*. There is an equivalent development in the X-rays, from *Einstein* to *Chandra* and onwards to *Lynx*. The X-ray microcalorimeter on *Lynx* will provide an X-ray capability comparable to what MUSE provides in the optical, and what the MIRI and NIRspec instruments on *JWST* will provide in the infrared. To put the relative gains in context, the leap from *Chandra* to *Lynx* is the same as going from a 1-m telescope with a CCD imager to an 8-m VLT equipped with a MUSE spectrograph.

Current cutting-edge and major future astronomical facilities — the Extremely Large Telescopes on the ground, *JWST*, *WFIRST*, Advanced LIGO, *LISA*, ALMA, SKA — all make great leaps in sensitivity, and aim at taking exquisite data in their respective wavebands. To be synergistic with these facilities, a future X-ray observatory must aim in the same direction, and this requires the combined firepower of high angular resolution, high throughput, and spectroscopy. This is precisely what *Lynx* will deliver.