LYNX X-RAY OBSERVATORY

a project whitepaper submitted to the

2020 DECADAL SURVEY *on* ASTRONOMY & ASTROPHYSICS

by

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LYNX

A NEW GREAT OBSERVATORY

X-RAY OBSERVATIONS are essential for understanding the complexities of the cosmos. Their great power stems from the fact that much of the baryonic matter, as well as the sites for some of the most active energy releases in the Universe, are primarily observable in the X-ray band. 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 future 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 totally 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 will make a profound impact across the astrophysical landscape. It will provide the depth and breadth to answer those questions that confront us today; just as importantly, it will have capabilities to address those questions we have yet to even ask.

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

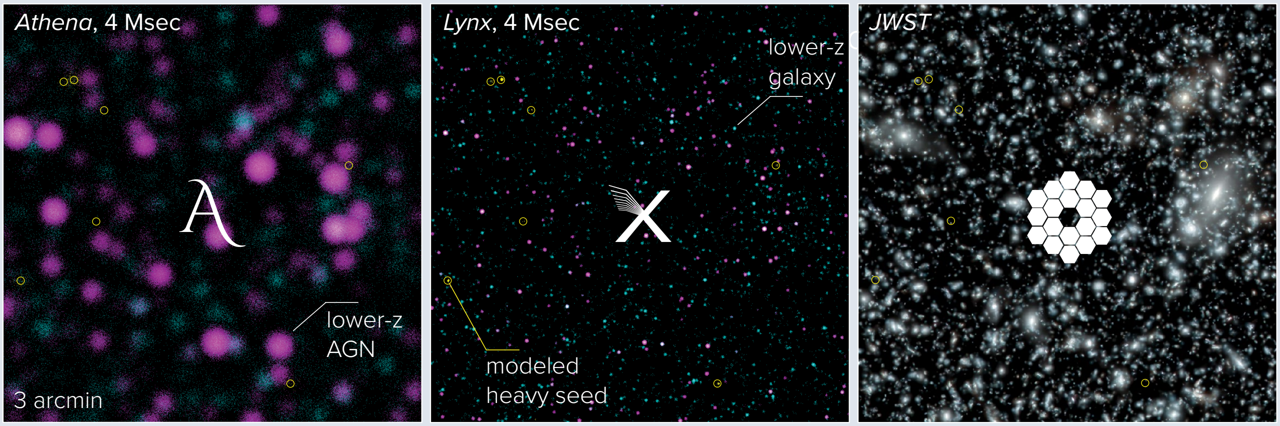
- **The Dawn of Black Holes,**
- **The Invisible Drivers of Galaxy Formation and Evolution,**
- **The Energetic Side of Stellar Evolution and Stellar Ecosystems.**

The set of capabilities required by these *Lynx* science pillars can be implemented within a proven mission architecture derived from *Chandra*. The design reference mission (DRM) is described in the *Lynx* mission study report and is briefly summarized below. *Lynx* will have a baseline lifetime of 5 years and will 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 the flexibility with respect to future launch options.

Lynx Science Pillars

The Dawn of Black Holes — We now realize that black holes play a huge role in 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 &

THE DAWN OF **BLACK HOLES**



KEY **CAPABILITIES**

The key observation is 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-arcsec 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.

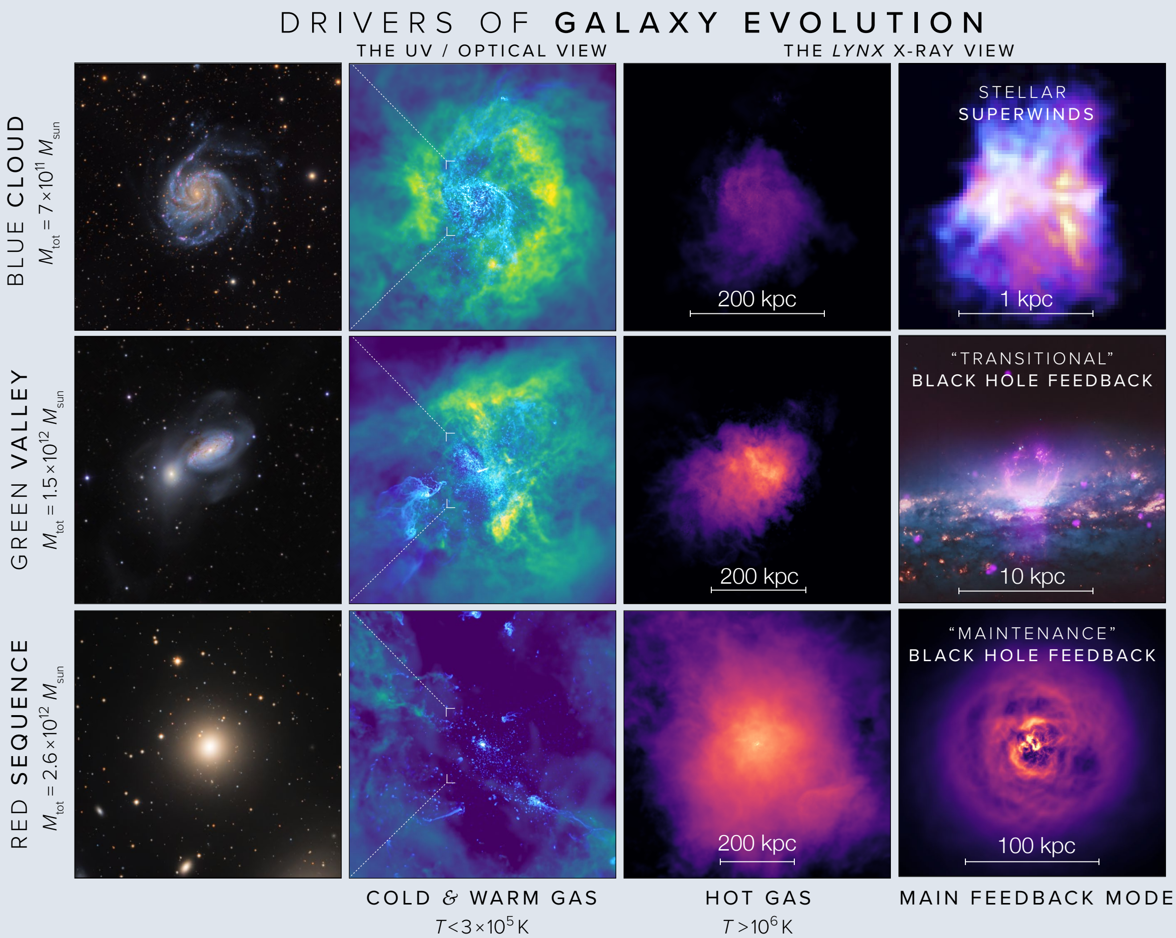
infrared surveys that can be obtained with either the almost ready to launch *JWST* or the subsequent *WFIRST* mission. The X-ray flux limits required to detect the first massive black holes are accessible only with *Lynx*.

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 first black holes by both accretion and mergers, unveiling a complete picture of their early assembly.

Angular resolution is critical for the ability to detect 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, colors code different source populations. In each panel, yellow circles show the locations of high-z black hole seeds (note that ~ 1″ – 2″ offsets from the JWST counterparts are expected in the model shown here). Their fluxes are a factor of ~ 100 below the confusion limit for a 5″ X-ray telescope.

Relevant Astro2020 science white papers: [1–11].

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 the exact mechanisms of their formation. *Lynx* will expose essential drivers of galaxy evolution, such as energy feedback, which primarily leave imprints in the circumgalactic medium (CGM) extending well beyond the optical size of galaxies and contain most of their baryons. Most of halo gas in galaxies more massive than the Milky Way is heated above the UV ionization states to X-ray temperatures. The energetic processes that define its state, are the same ones that regulate the 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 true understanding of the lives of galaxies, we need to see the flame itself.

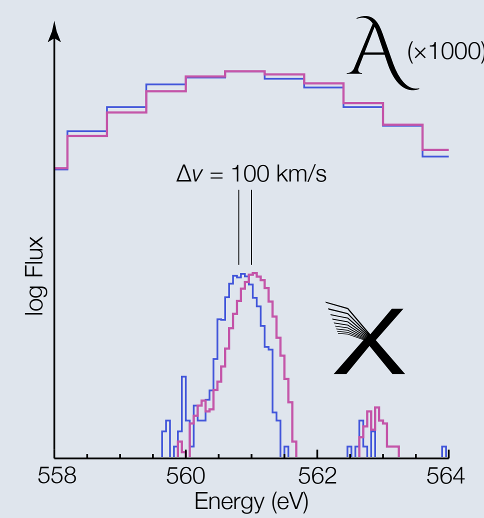


KEY CAPABILITIES

- 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} = 4000 cm^2 and $\lambda/\Delta\lambda > 5000$.
- Map velocities in ~ 100 km/s galactic outflows: microcalorimeter with $E/\Delta E$ = 2000 at E = 0.6 keV.
- Study AGN feedback in galaxies and clusters: microcalorimeter with 0.5″ pixels.

Lynx sensitivity and spectroscopic capabilities will enable mapping of the CGM to ~ 0.5 – 1 virial radii in both emission and absorption. Its microcalorimeter will simultaneously provide 1-arcsec spatial resolution and R = 2000 resolving power at all key energies required to map the kinematic and chemical structure of galactic winds *(right)*. These capabilities will allow *Lynx* to expose all primary signatures of ongoing feedback imprinted in the inner structure of the galactic halos.

Relevant Astro2020 science white papers: [12–22].



THE ENERGETIC SIDE OF **STELLAR EVOLUTION**

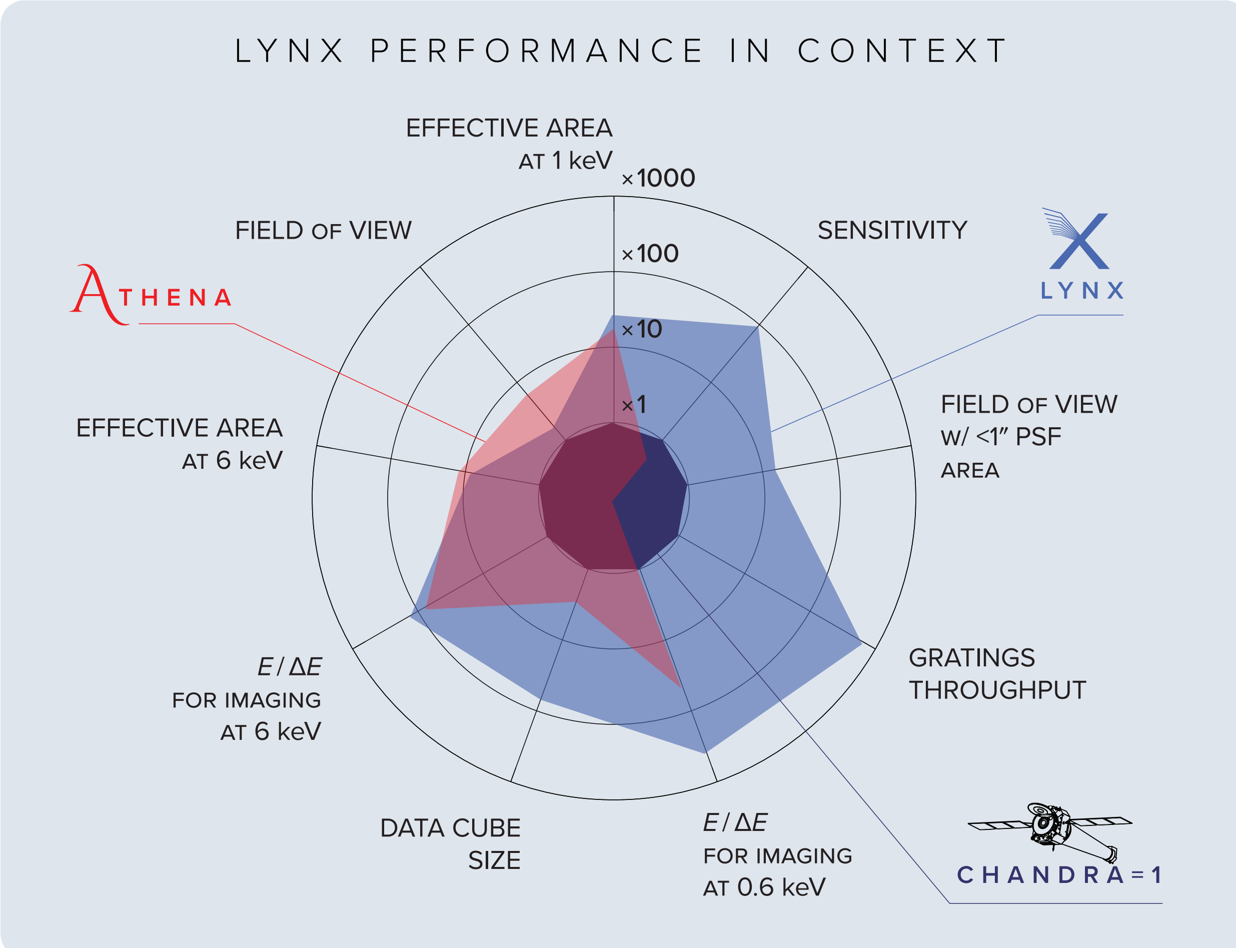
KEY **CAPABILITIES**

- Spatially resolve star cluster cores: PSF ≈ 0.5″.
- Resolve lines in stellar star spectra: gratings with $R > 5000$
- Map 3D structure of supernova remnants: microcalorimeter with ΔE = 3 eV and 1″ pixels

The Energetic Side of Stellar Evolution and Stellar Ecosystems. — As we enter the era of multimessenger astronomy following LISA detections of gravitational waves and studies of exoplanets evolve toward holistic assessment of habitable conditions, orders-of-magnitude expansion in capabilities will be needed to observe key relevant high-energy processes associated with stellar birth, life, and death. *Lynx* will meet this challenge and drastically extend our X-ray grasp throughout the Milky Way and nearby galaxies. The effective horizon for detecting X-rays as markers of young stars and for detailed stellar spectroscopy will be pushed out by an order of magnitude. Spatially resolved spectroscopy on arcsec 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-ups 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 in crowded fields.

Relevant Astro2020 science white papers: [18, 19, 23–26, 26–30].

The requirements set by the *Lynx* science pillars translate into the needs for orders-of-magnitude performance gains along a number of key axes. The diagram on the next page shows how these gains compare with the performance of *Chandra* (taken to be 1 on all axes) and of *Athena* (shown in red). *Athena* is ESA's planned mission, which will carry the first large X-ray microcalorimeter



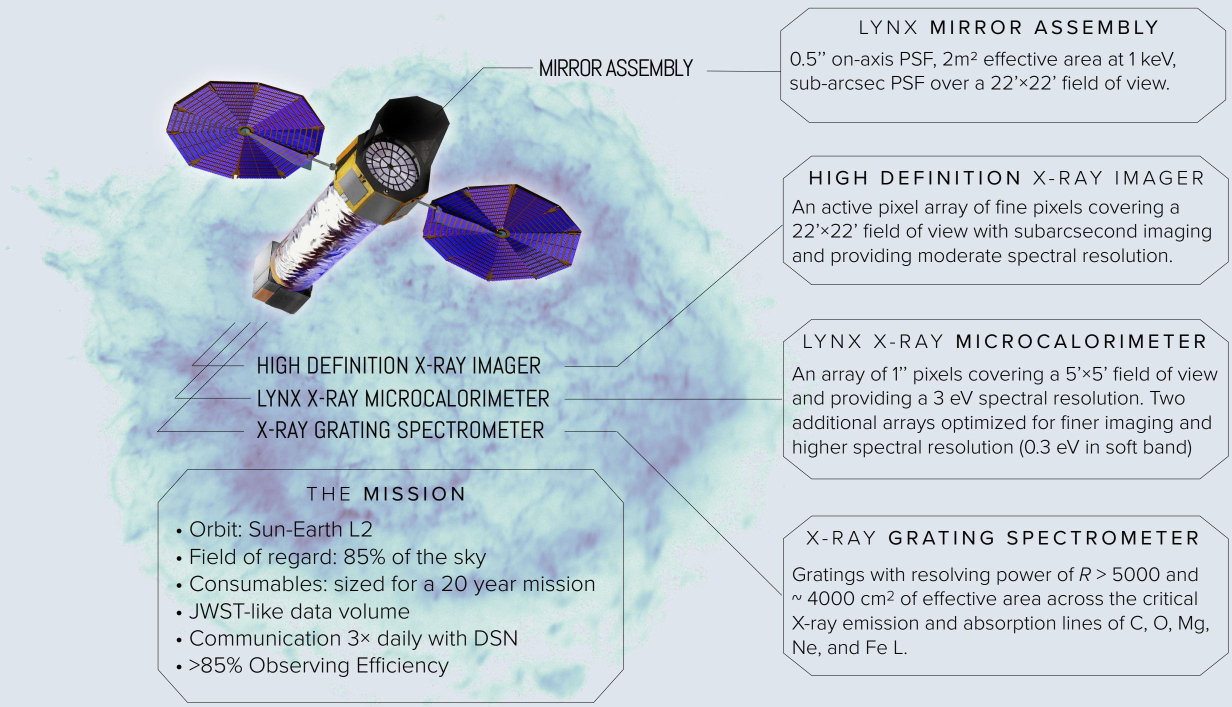
and make leaps forward in energy resolution, effective area (especially at high energies), and field of view. It will not, however, make breakthrough gains across the board: not in sensitivity; not in sharp imaging; not in very high spectral resolution. *Lynx* makes primary breakthroughs along these axes, and they are precisely the directions required by its science goals. *Lynx* and *Athena* can be viewed as orthogonal missions, with different science goals, emphases, and strengths. *Athena*'s science is based on massive, wide surveys and detailed spectroscopy of relatively bright and isolated objects. *Lynx*'s package of high angular resolution, high throughput, and powerful spectroscopic capabilities opens up 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 recording individual X-ray photons. Post-facto aspect reconstruction leads to modest requirements on pointing precision and stability, while enabling very accurate sky locations for X-ray events, telemetered to the ground along with their energy and timing information. The design of the *Lynx* spacecraft is straightforward with minimal mechanisms (see callout box on the next page); 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. *Lynx* maneuvers and operational procedures on-orbit are close to identical to *Chandra*'s, and similar design approaches promote longevity.

Lynx' transformational scientific power 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-

PAYLOAD & MISSION CHARACTERISTICS



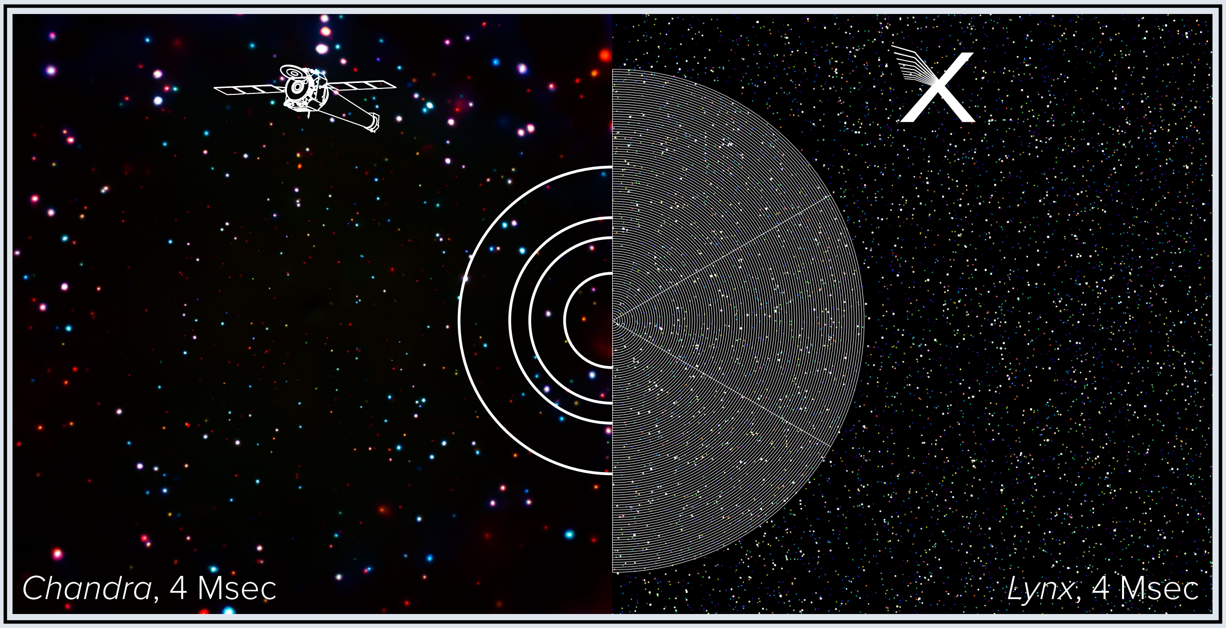
The *Lynx* spacecraft is built around the X-ray mirror assembly that is followed by a large-area insertable grating array. The science instrument module is attached to the spacecraft by an optical bench. It includes the interchangable prime focus detectors, HDXI and LXM, and the off-center XGS readout 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 developed for *Chandra* and other past missions.

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 the Technology Readiness Levels (TRL) of 3 to 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 and achieve 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 for better imaging than *Chandra* because of much-improved off-axis performance. The LMA can be based on three fully feasible mirror technologies. The technology selected for the design reference mission — Silicon Metashell Optics (SMO) developed at GSFC — is currently the most advanced one in terms of demonstrated performance (approaching that required for *Lynx*, see figure on next page). The SMO mirror system has highly modular design which lends itself well to parallelized manufacturing and assembly. A modular design also provides 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) — The HDXI instrument is the main imager for *Lynx* that will provide high spatial resolution over a wide FOV and good sensitivity over the 0.2–10 keV

EYES, SHARP AS A LYNX

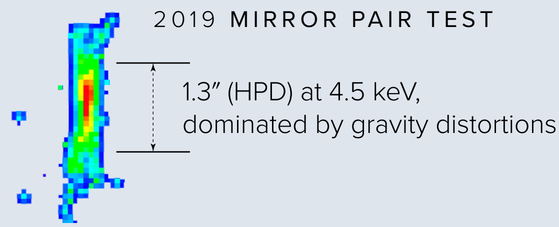


0.5″ PSF on-axis, stable across a 22’ × 22’ FOV

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

1000× *Chandra*’s survey speed

2019 **MIRROR PAIR TEST**



The *Lynx* Mirror Assembly (LMA) keeps *Chandra*’s subarcsec resolution on-axis while providing orders-of-magnitude gains in throughput and FOV size for sub-arcsec imaging. The LMA is composed of concentric modular metashells. Each module is populated with multiple mirror pair segments. The repeatable production of mirror segments with surface quality meeting or exceeding required specifications was recently verified (February 2019). A full-illumination X-ray test of 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 the well-modeled gravity distortions indicates sub-arcsec performance for the tested mirror pair in zero-gravity.

bandpass. Its 0.3 arcsec 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 (high readout rates, high broad-band quantum efficiency, sufficient energy resolution, minimal pixel cross talk, 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 of these are currently funded for technology development.

The Lynx X-ray Microcalorimeter (LXM) — The LXM is an imaging spectrometer that provides high resolving power (R ~ 2000) in both the hard and soft X-ray bands, combined with high spatial resolution (down to 0.5 arcsec scales). To meet the diverse set of *Lynx* science requirements, the LXM focal plane includes three arrays that share the same readout technology. Each array is differentiated by the absorber pixel size and thickness, and by how absorbers are connected to thermal readouts. The total number of pixels is just over 100,000 — a major leap over other past and currently planned X-ray microcalorimeters. However, two of the LXM arrays feature a simple, already proven, "thermal" multiplexing approach where multiple absorbers are connected to a single temperature sensor. This 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 of 2019, prototypes of the focal plane have been made that include all three arrays at 2/3 of the full size. These prototypes demonstrate that arrays with the pixel form factor, size, and wiring density needed for *Lynx* are readily achievable, with high yield. The energy resolution requirements of the different pixel types is also readily achievable. Although LXM is technically still at TRL3, there is a clear path for achieving TRL4 by 2020, and TRL5 by 2024.

The X-ray Grating Spectrometer (XGS) — The XGS will provide yet higher spectral resolution (*RE* = 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 the X-ray grating technologies. Two strong candidates are critical angle transmission (used for the *Lynx* DRM) and off-plane reflecting grating technologies. They are both fully feasible, are 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 blueprints for operating *Lynx* and for developing the systems to do so, resulting in significant cost reductions 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 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. This open General Observer (GO) program approach has been successfully executed by past 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 & Mission Schedule

The *Lynx* team has conducted extensive parametric cost analyses for the spacecraft (breaking it down to 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, the PRICE® TruePlanning® Space Missions, and PRICE®-H Hardware models. The resulting costs estimated by these models are consistent and also are in family with the actuals from past NASA missions. The parametric cost, which serves as the primary estimate for the *Lynx* concept study, has been validated in multiple ways: via a direct comparison with inflated *Chandra* actuals, via an end-to-end grassroots estimate based on analogy and expert input, via an independent cost assessment with confidence levels, and via an independent cost and technical evaluation. This consistency reflects a well-developed mission design, with strong heritage and lessons learned from past and planned missions. It gives credibility to the estimated *Lynx* mission cost. **The estimated cost of the *Lynx* mission falls into the Large category, >$1.5B.***

Even with the huge gains in capability provided by *Lynx*, its costs will only modestly exceed the inflated *Chandra* actuals, which is substantiated by the following considerations. *Lynx* technology development and the mission study have directly benefitted from having a science community and a contractor base with extensive and applicable experience from 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. 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, LXM, is quickly gaining heritage (*Hitomi*, *XRISM*, *Athena*). Mission operations are particularly well understood, with plans, requirements, algorithms, and cost estimates derived from *Chandra* experience. The ability to produce a *Lynx* mirror at a cost similar to *Chandra*'s 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 achieve TRL6 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, which includes all required milestones and key decision points. Given the architecture similarities, the *Lynx* schedule for the system-level assembly, integration, and test closely matches that of *Chandra*, after accounting for larger size and additional complexities. It is also consistent with the *WFIRST* in-guide schedule to a 2025 LRD. The *Lynx* schedule includes ≈ 3 years of pre-Phase A studies, during which key technologies will be maturated to the levels required to enter Phase A. The funding needed is comparable to that provided for the *WFIRST* program at the same stage. Durations for Phases A&B and C&D are 42 and 103 months, respectively. Assuming this sequence can start soon after the Astro2020 Decadal Survey makes its recommendation, *Lynx* will launch in 2036.

Lynx mission study report and further information

The primary source of information about *Lynx* is the mission study report which will submitted shortly to NASA and, following their review and assesments, will be made available to the Astro 2020 Survey Committee. The report describes the following:

- **The Science of Lynx**. This includes the discussion of *Lynx* science pillars and of its impact 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.** The report presents 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.

* At the time of this writing, external reviews of the cost estimate are underway with feedback expected shortly. While the *Lynx* team is confident in the validity of its cost analysis, it is prudent to provide the cost only after this feedback is received and acted upon. All of the cost data, with all available supplemental information, will be provided in ~ 6 weeks via the *Lynx* mission study report.

- **Technologies.** The report includes reviews of the current state-of-the art, near-terms plans, and detailed roadmaps for further maturation of key technologies. Further information is provided in the JATIS Special Section on *Lynx* [31].
- **Programmatics.** The discussion of programmatics includes the mission lifecycle schedule, risks and mitigations. A discussion of the costing methodology and high-level cost range will be provided, along with a detailed cost book in the supplemental materials.
- **Mission Configuration Trade Space.** This section provides a comparison of science capability and costs for a representative range of possible mission configurations. The analysis demonstrates that the concept presented in the report optimizes the "science per dollar" metric.

The *Lynx* team will provide any further information requested by the Astro 2020 Survey Committee and topical panels. We also note that *Lynx* technologies are progressing quickly. Major new tests for X-ray mirrors and the microcalorimeter instrument are planned for ~ late Fall of 2019. Since technical readiness of the missions will likely be a major factor in their evaluations, the *Lynx* team would like to provide the Survey Committee with relevant updates, e.g., via an invitation to Large NASA Missions Study Teams to provide a report on recent technical progress at an appropriate time, possibly the first half of 2020.

Lynx impact across the future astrophysical landscape

Lynx will impact many areas of astrophysics in a profound way. Obviously, it will play a critical role in the topics directly related to its science pillars, such as studies of Cosmic Dawn [32–35], Black Holes [9, 10, 15, 36, 37], Galaxy Formation [38–45], and Origin of Elements [16, 25, 46]. *Lynx* will make a major impact in other areas such as Cosmology [47], Resolved Stellar Populations [24, 48], Solar System observations [49], and Multi-Messenger Astronomy[50]. Its influence will be seen even in less obvious areas such as studies of ISM [51–53], planets [54], and protoplanetary disks [23]. 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-arcsec imaging, and a factor of 1000× greater speed for surveys compared to the current state-of-the-art (*Chandra*). To put this in context, this is 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 that 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 should aim in the same direction, and this requires a combined firepower of high angular resolution, high throughput, and spectroscopy. This is precisely what *Lynx* will deliver.

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