

TRACKING THE ELUSIVE LYNX INTO THE 2020 ASTROPHYSICS DECADAL SURVEY

Dr. Jessica A. Gaskin (Study Scientist, MSFC)



-Presented On behalf of the *Lynx* Team



Tracking the Elusive Lynx

Rare and maddeningly elusive, the “ghost cat” tries to give scientists the slip high in the mountains of Montana



Seldom-seen rulers of their wintry domain, lynx may face new threats. (Ted Wood)

By [Abigail Tucker](#)

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NASA ASTROPHYSICS PLANNING FOR THE 2020 DECADAL SURVEY

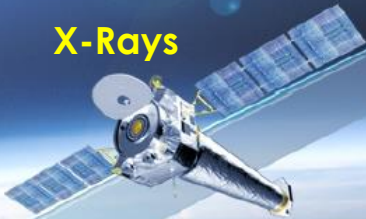
Decadal Survey Missions

UV-Visible-Near IR



1972
Decadal Survey
Hubble

X-Rays



1982
Decadal Survey
Chandra

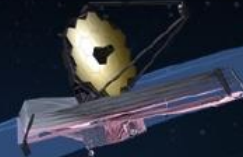
IR



1991
Decadal Survey
Spitzer, SOFIA



Visible-IR



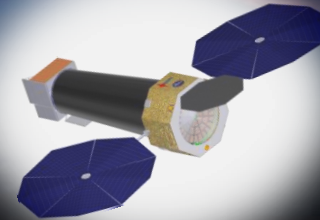
2001
Decadal Survey
Webb

Visible-Near IR



2010
Decadal Survey
WFIRST

X-Rays?



2020
Decadal Survey
Lynx?

Launch in 2030s!



Elusive – in the 2010 Decadal

Chandra/AXAF – 1980 Decadal (Ranked 1st)

Proposal submitted in 1976 (“formal beginning”), Launch 1999

IXO – 2010 Decadal (Ranked 4th)

Lost to WFIRST, New Explorer Missions, and LISA

“The technical risk is medium high. Cost threats and uncertainties due to the immaturity of some of the required technologies have added considerably to the cost appraisal.”

Lynx – 2020 Decadal (launch would be ~2036, or 60 years since the start of Chandra)

Why is this time different?

What can we do differently this time?



2020 Decadal Environment

4 large missions are being studied for the 2020 Decadal

Lynx (Formerly X-Ray Surveyor)

LUVOIR

Origins Space Telescope

HabEx

Probe-class missions (\$400M to \$1B)

Astrophysics Probe is defined as mission with total lifecycle cost (NASA's Phase A through E) in range \$400M to \$1B.

Gravitational wave recent discoveries (L3 contributions)

Relevant X-ray Missions:

ATHENA (ESA) (2028-2038?)

XARM (JAXA) (2021-??)

ASTROSAT (India) (2015-??)

IXPE (SMEX) (2020)

ARCUS (MIDEX) (Phase A)

Continue Explorer class mission cadence or increase cadence?

4 per decade (MIDEX \$250M, SMEX \$165M)

The Process

Astrophysics Decadal Survey Committee

Selected by the National Academies **(NOT NASA!)**

New Worlds, New Horizons in Astronomy and Astrophysics recommends a balanced and executable program that will support research surrounding the most profound questions about the cosmos. The discoveries ahead will facilitate the search for habitable planets, shed light on dark energy and dark matter, and aid our understanding of the history of the universe and how the earliest stars and galaxies formed.

[http://sites.nationalacademies.org/bpa/bpa_049810]



Deliverables

1. science case
2. notional mission concept
3. design reference mission
4. technology assessment
5. cost assessment
6. top level schedule

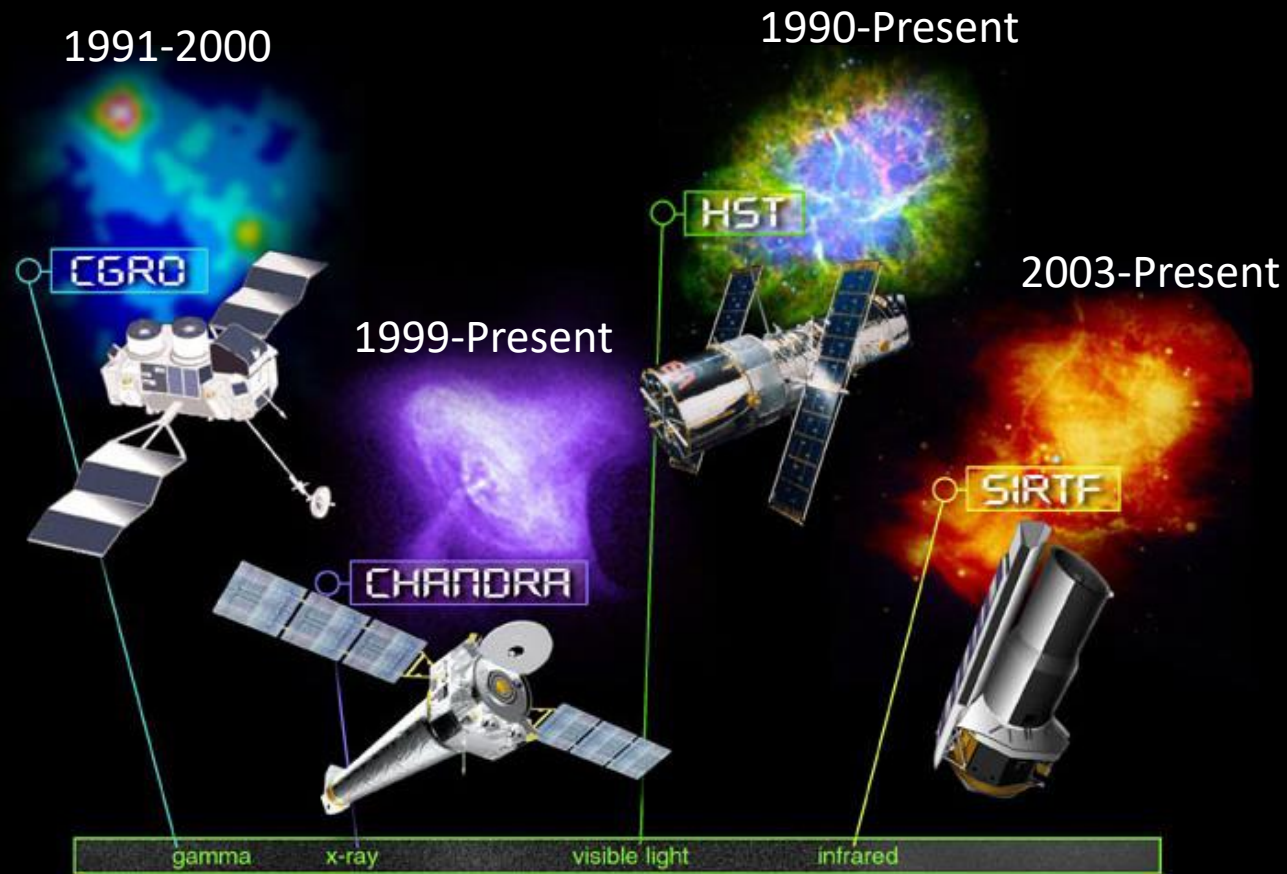
Astronomy Community Chose
4 Missions to Study:

1. Lynx – X-Ray Mission (MSFC + SAO)
2. LUVOIR – Large UV Optical IR (GSFC)
3. OST - Origins Space Telescope Far IR (GSFC)
4. HabEx – Habitable Exoplanets (JPL)

NASA's Great Observatories

NASA's Mission:

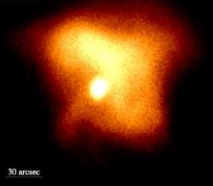
- *Innovate*
- *Explore*
- *Discover*
- *Inspire*



Each observatory was designed to push the state of technology in its intended wavelength region.

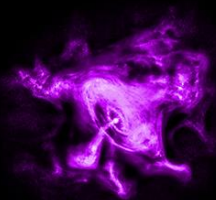
Chandra Vision

Crab Nebula
ROSAT 1991
0.1-2.0 keV



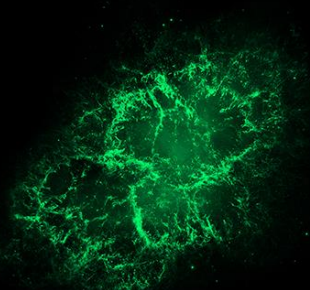
ROSAT
(X-ray)

Resolution: 5 arcsec



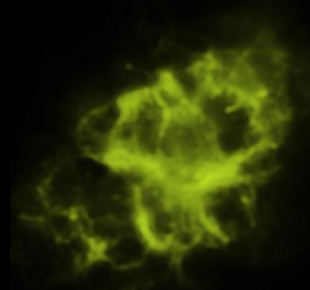
Chandra
(X-ray)

Resolution: 0.5 arcsec



Hubble
(visible)

Resolution: 0.05 arcsec



Spitzer
(IR)



VLA
(radio)

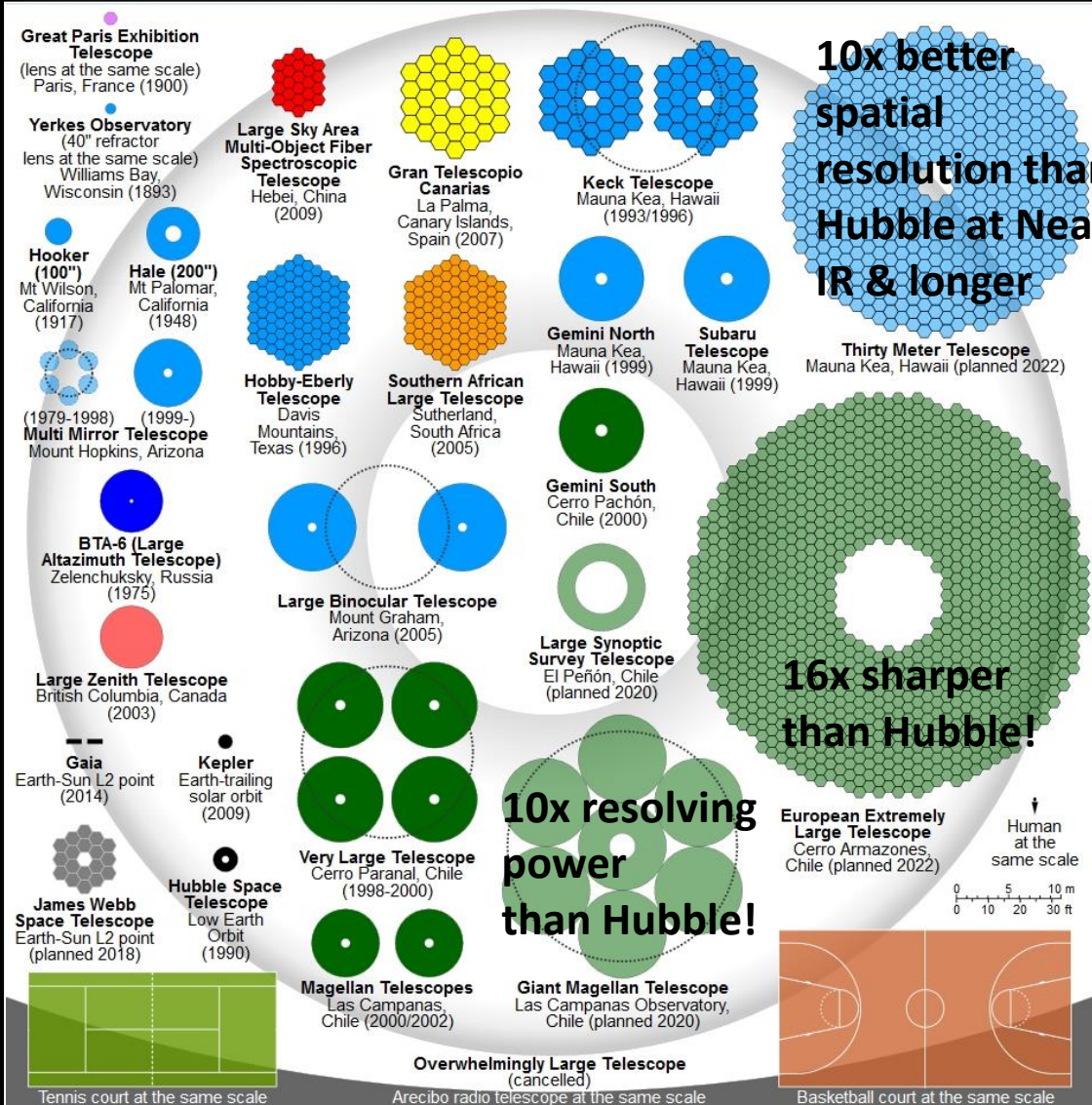


XMM-OM
(UV)

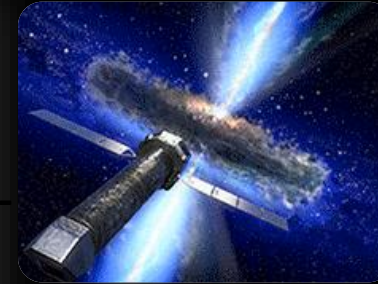
Astrophysics Landscape



Ground & Space



ATHENA



WFIRST



- Mapping hot gas structures & determining their physical properties
- Searching for SMBH
- Dark Energy
- Exoplanets
- Large Area NIR Surveys

What's Next ???

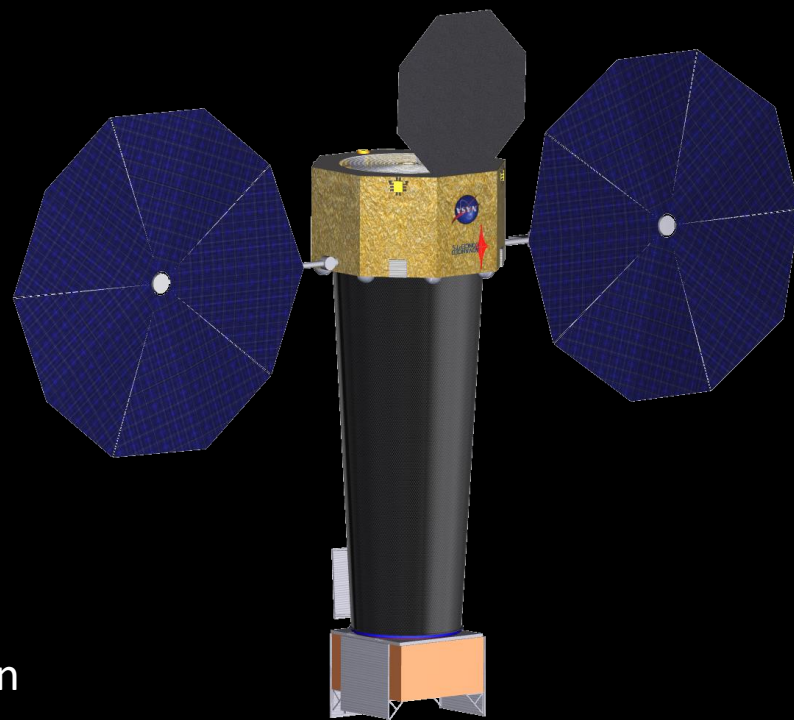
THE VERY LARGE TELESCOPE	<input checked="" type="checkbox"/>
THE EXTREMELY LARGE TELESCOPE	<input checked="" type="checkbox"/>
THE OVERWHELMINGLY LARGE TELESCOPE	<input checked="" type="checkbox"/> (CANCELLED)
THE OPPRESSIVELY COLOSSAL TELESCOPE	<input type="checkbox"/>
THE MIND-NUMBINGLY VAST TELESCOPE	<input type="checkbox"/>
THE DESPAIR TELESCOPE	<input type="checkbox"/>
THE CATAclySMIC TELESCOPE	<input type="checkbox"/>
THE TELESCOPE OF DEVASTATION	<input type="checkbox"/>
THE NIGHTMARE SCOPE	<input type="checkbox"/>
THE INFINITE TELESCOPE	<input type="checkbox"/>
THE FINAL TELESCOPE	<input type="checkbox"/>

<https://xkcd.com/1294/>

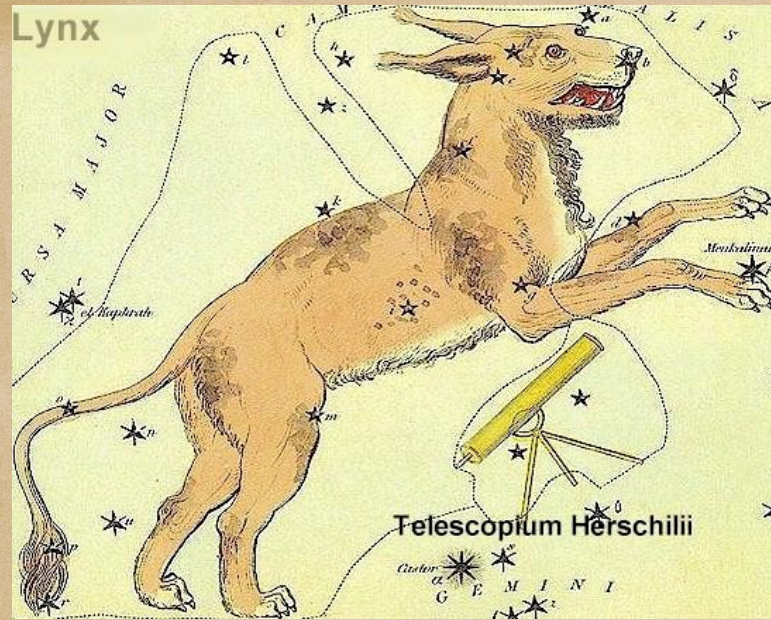
Meet *Lynx*!

***Lynx* is a large X-ray Observatory that will revolutionize our view of the Universe by providing unique insight into the high-energy drivers that govern its formation and evolution.**

- × 50 higher throughput while maintaining *Chandra's* angular resolution.
- × 16 larger solid angle for sub-arcsecond imaging
- × 800 higher survey speed at the *Chandra* Deep Field limit
- High-Resolving Power for grating spectroscopy
- High-resolution, spatially resolved spectroscopy on fine scales



Lynx - Acronym Free!



- ❖ A symbol of great insight
- ❖ Ability to see through rocks and trees to **reveal the true nature of things**.



DIALOGO DI GALILEO GALILEI LINCEO

MATEMATICO SOPRAORDINARIO
DELLO STUDIO DI PISA.

*E Filosofo, e Matematico primario del
SERENISSIMO*

GR.DVCA DI TOSCANA.

Due ne i congressi di quattro giornate si discorre
sopra i due

MASSIMI SISTEMI DEL MONDO
TOLEMAICO, E COPERNICANO;

*Proponendo indeterminatamente le ragioni Filosofiche, e Naturali
tanto per l'una, quanto per l'altra parte.*

CON PRI



VILEGI.

IN FIRENZA, Per Gio:Batista Landini MDCXXXII.

CON LICENZA DE' SUPERIORI.

The historic Accademia dei Lincei (Academy of the 'Lynx-eyed') based their name on this ability to perform incisive and penetrating investigations of the natural world.

Galileo was a proud member, and **the Academy of the Lynx coined the term telescope** for his marvelous device for peering into the cosmos.

- ❖ Much of the baryonic matter and the settings of the most active energy release in the Universe are visible primarily or exclusively in the X-rays

Meet The Team!



Steve Allen, Stanford



Megan Donahue,
MSU



Laura Lopez,
Ohio State



Jessica Gaskin, MSFC
(Study Scientist)



Alexey Vikhlinin, SAO
(Co-Chair)



Feryal Özel, Arizona
(Co-Chair)



Piero Madau, UCSC



Ryan Hickox,
Dartmouth



Mark Bautz,
MIT



Daniel Stern, JPL



Eliot Quataert,
Berkeley



Zoltan Haiman,
Columbia



Niel Brandt, Penn State



Tesla Jeltema,
UCSC



Rachel Osten,
STScI



Dave Pooley, Trinity



Chris Reynolds,
UMD



Andrey Kravtsov,
Chicago



Joel Bregman,
Michigan



Juna Kollmeier,
OCIW



Frits Paerels,
Columbia



Andy Ptak,
GSFC

- **8 Science Working Groups**
 - **Optics Working Group**
 - **Calibration Working Group**
 - **Communications Working Group**
 - **Instrument Working Group**
 - **7 ex-officio International members**
- Over 275 total members!

Science Pillars

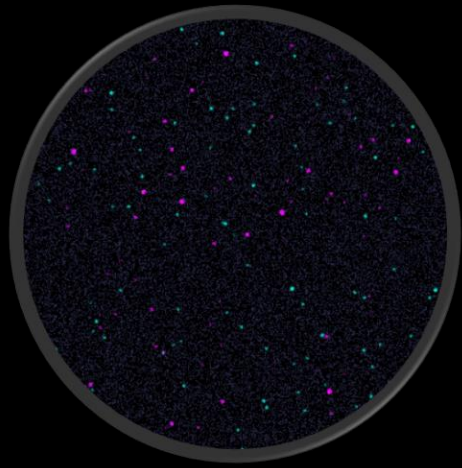
The Dawn of Black Holes

Lynx will observe the birth of the first black holes, when the universe was ~ half a billion years old ($z \approx 10$) and provide a census of the supermassive black hole population in the local and distant universe, follow their growth and assembly across cosmic time, and measure the interplay with their surroundings on all scales.

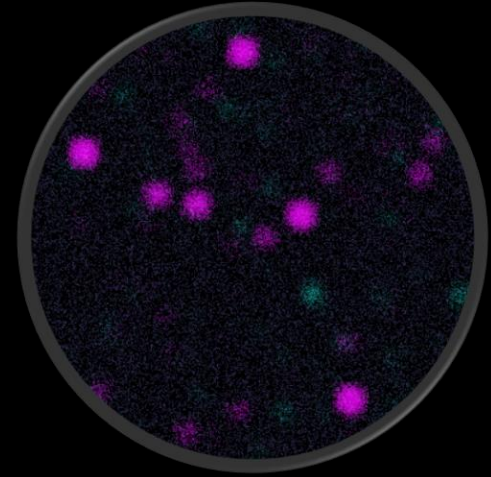
JWST, ~0.06" resolution,
'First Galaxies'



Lynx (4 Msec),
0.5" resolution (minimal
source confusion)
'First Accretion Light'



4 Msec, 5" resolution
Confusion Limited

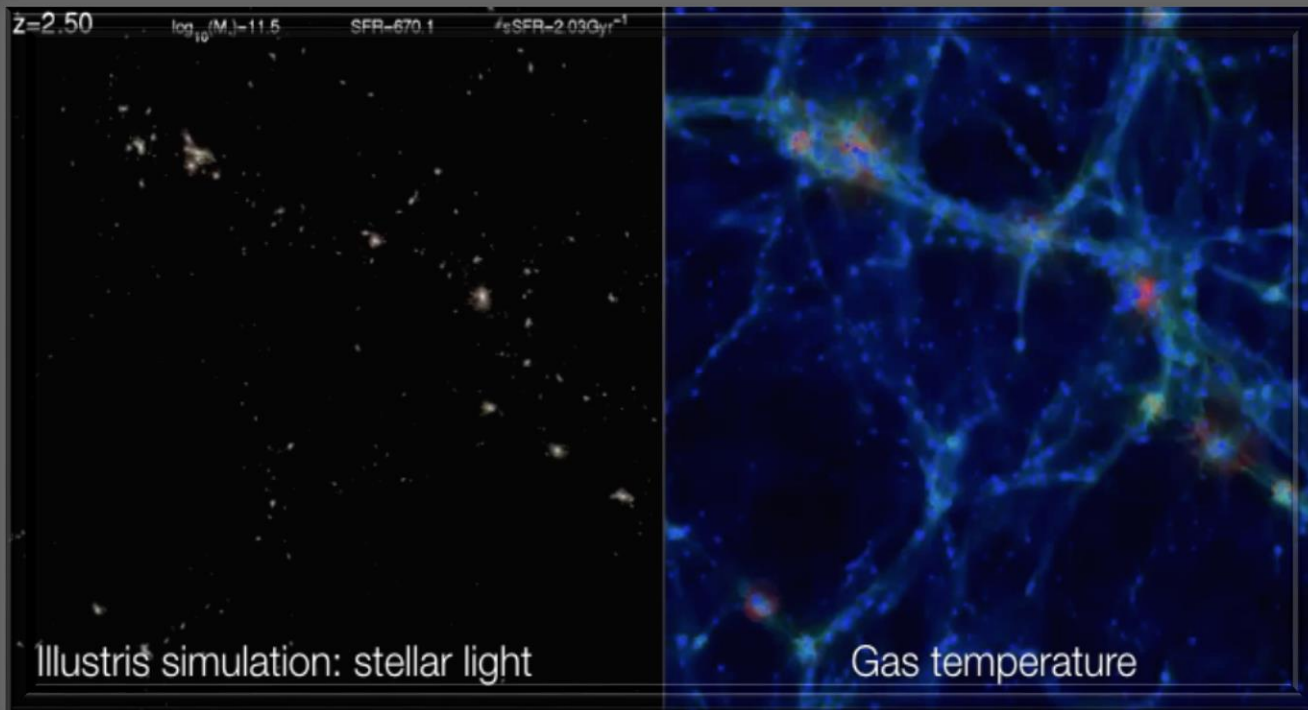


- The detection of quasars at $z > 6$ unveils the presence of supermassive black holes of a few billion solar masses
- The rapid formation process of these early SMBHs is still a mystery. Such discovery implies that seed black holes must have formed early on, and grown via either rapid accretion or BH/galaxy mergers.



The Invisible Drivers Behind Galaxy Formation and Evolution

The assembly, growth, and state of visible matter in cosmic structures is largely driven by violent processes that heats the gas in the CGM and IGM. The exquisite spectral and angular resolution of *Lynx* will make it a unique instrument for mapping the hot gas around galaxies and in the Cosmic Web.





Observatory-Class Science

Lynx will significantly contribute to our understanding of Stellar Lifecycles and will uniquely constrain their local environments and provide insight into our own solar system

How do stars form?

How do circumstellar disks evolve, form planetary systems?

How diverse are planetary systems?

Do habitable worlds exist on other stars?

How do rotation and magnetic fields affect stars?

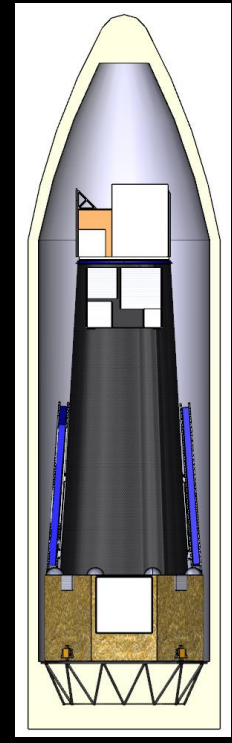
- Uniquely Observe and Characterize feedback from star formation using observations of the Milky Way and Local Group galaxies
- Use X-ray surveys of pre-main sequence stars to map instantaneous star formation in different environments
- Use Lynx data on SNR and stellar remnants to understand the SN explosion mechanism



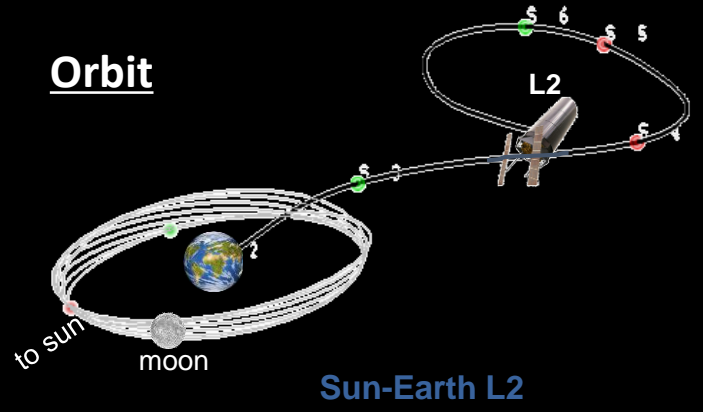
Lynx Mission

Launch Vehicle

Heavy-class launch vehicle is needed



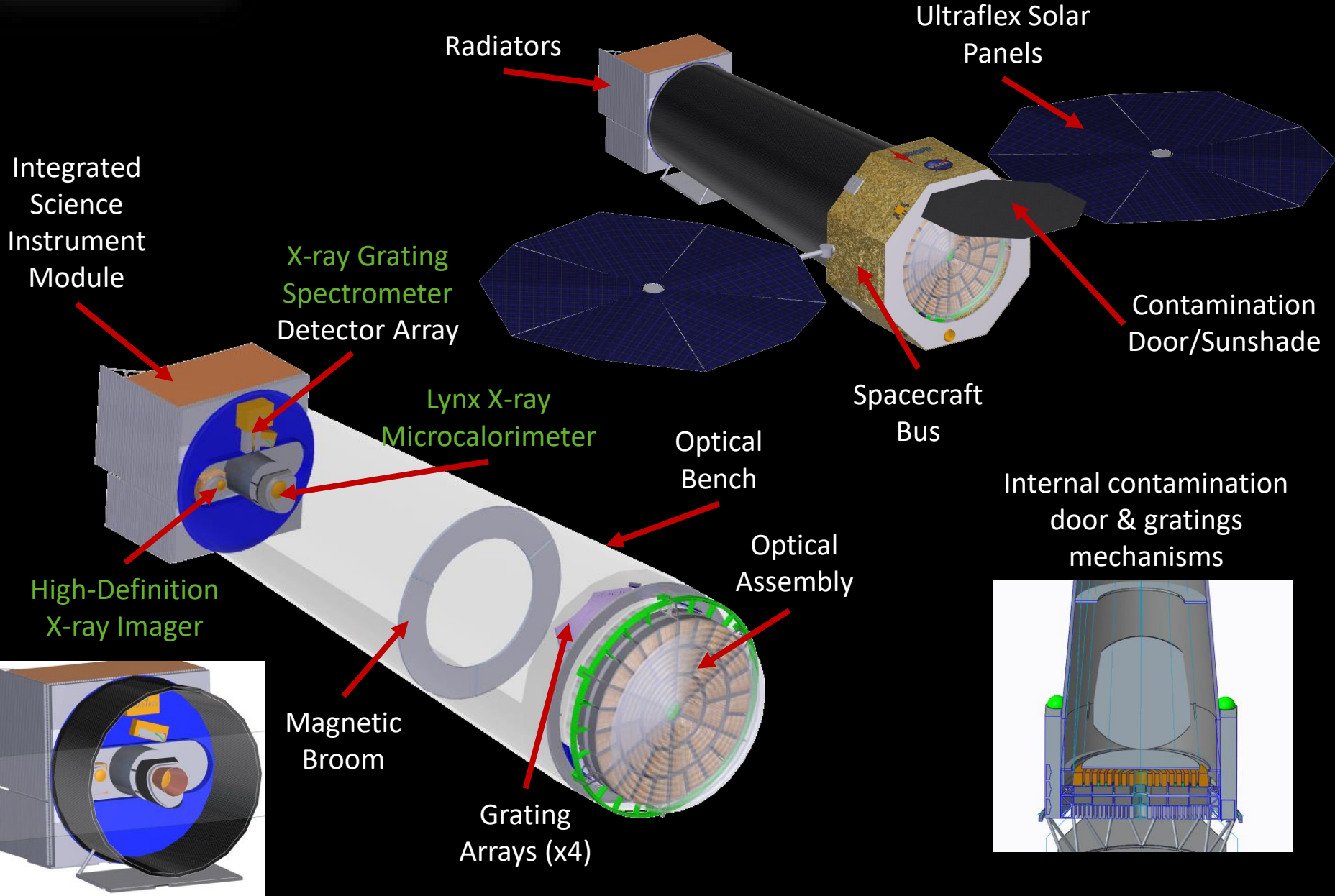
Orbit



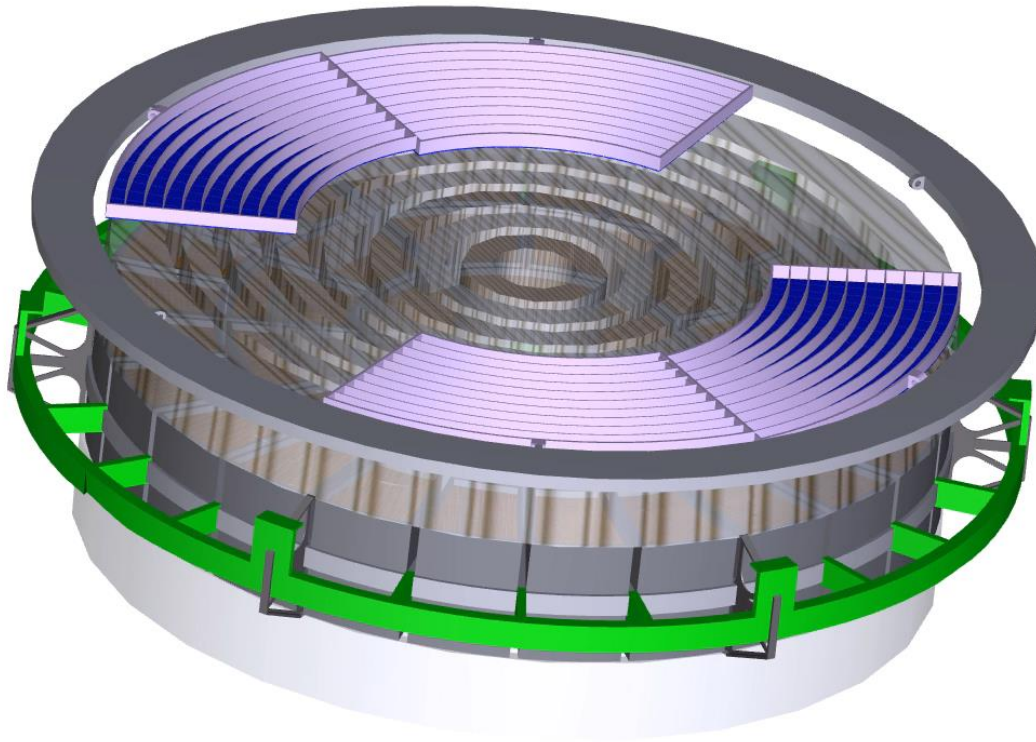
Mission Lifetime : Baseline mission is 10 years, extendable for an additional 10 years

Mission Operations: Chandra-like. Lynx will have a primary science program combined with a general observer program

Lynx Observatory

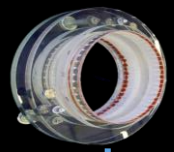


Lynx Animated



Taxonomy of X-ray Telescope Fabrication

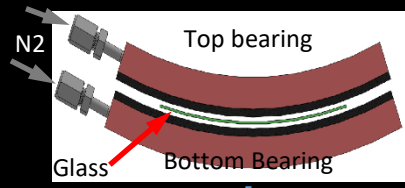
Full Shell
(Brera, MSFC, SAO)



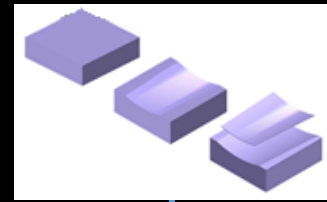
Thermal Forming
(GSFC, SAO)



Air Bearing Slumping (MIT)



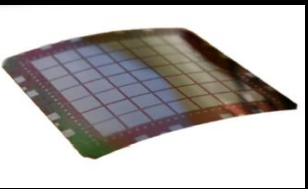
Si Optics (GSFC)



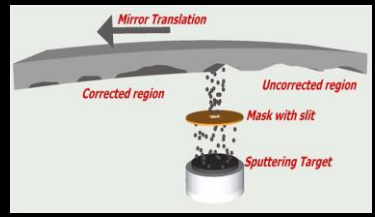
FABRICATION

CORRECTION

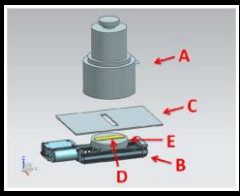
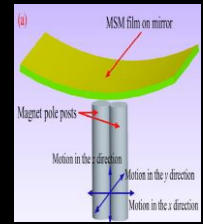
Piezo stress
(SAO/PSU)



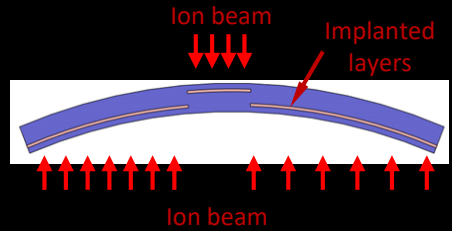
Deposition (MSFC, XRO)



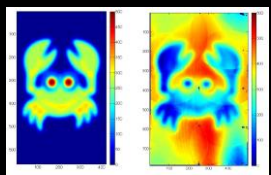
Magnetic & deposition stress (NU)



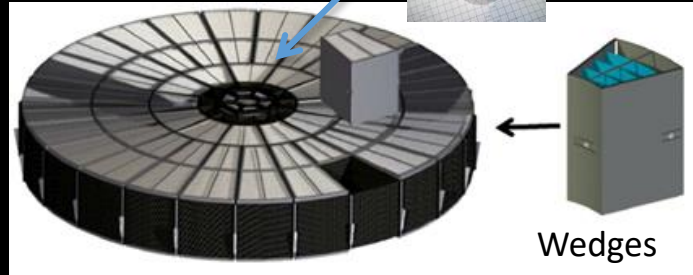
Ion implant stress (MIT)



Ion beam figuring (OAB)



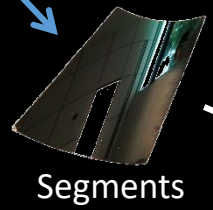
Segmented Assembly



Full shells

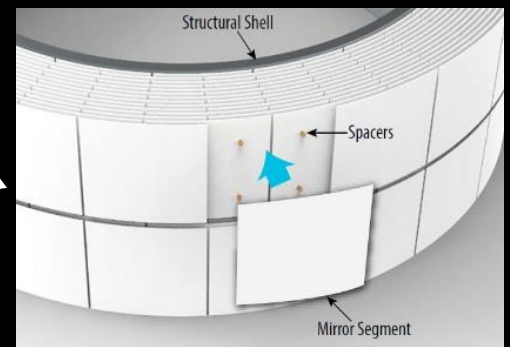


INTEGRATION



Segments

Meta-Shell Assembly



Lynx Optical Assembly

High-resolution X-ray Optical Assembly: 3 Viable Architectures – Trade Study

- Full Shell (Study Leads: K. Kilaru/USRA/MSFC, G. Pareschi/OAB)
- Adjustable Optics (Study Lead: P. Reid/SAO)
- Si Meta-Shell Optics (Study Lead: W. Zhang/GSFC)

Science Driven Requirements

Lynx Optical Assembly

Angular resolution (on-axis)	0.5 arcsec HPD (or better)
Effective area @ 1 keV	~2 m ² (met with 3-m OD)
Off-axis PSF (grasp), A* (FOV for HPD < 1 arcsec)	~600 m ² arcmin ²
Wide FOV sub-arcsec Imaging	10 arcmin radius



Decisional Criteria

Up-select will be based on Science, Technical and Programmatic criteria (TBF)

Examples (not a complete list):

- Does the configuration Satisfy Science Requirements?*
- Is there a feasible path for development?*
- Is there a feasible error budget?*
- Are there existing X-ray measurements and/or analyses?*
- Can it interface with the spacecraft and survive launch?*

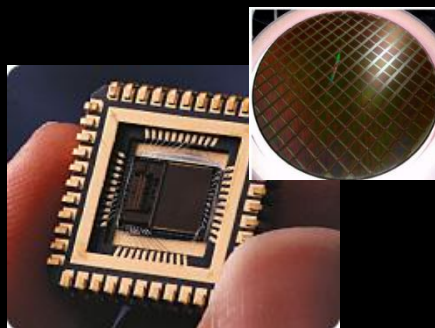
Optics Working Group:

Innovative technologies for mirror elements are pursued at MSFC, SAO, GSFC, MIT, etc. The Lynx Optics Working has been charged with developing a working optical design, identify industry participation, and to assist the STDT with trades and development relevant to the technology roadmap.

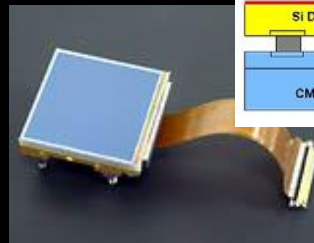
OWG will make a formal recommendation to STDT in Summer 2018

Lynx Instrument Suite

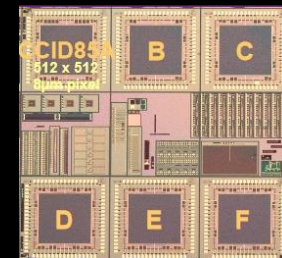
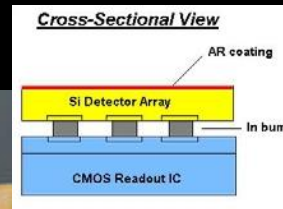
High Definition X-ray Imager (HDXI)



Monolithic CMOS

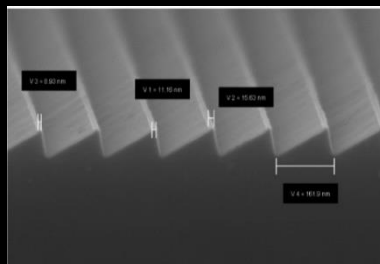


Hybrid CMOS

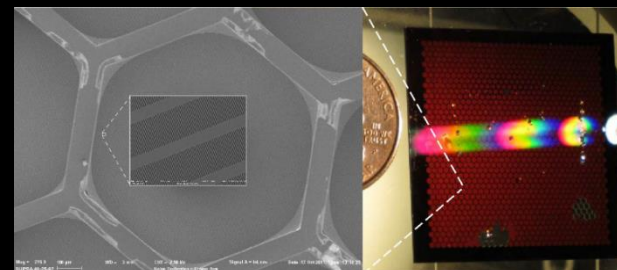


Digital CCD with CMOS readout

X-Ray Grating Spectrometer (XGS)

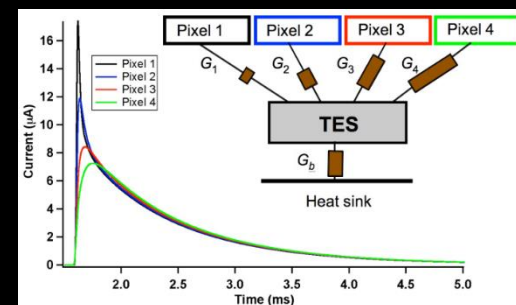
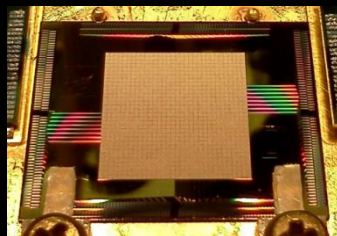


Off-Plane Grating Array



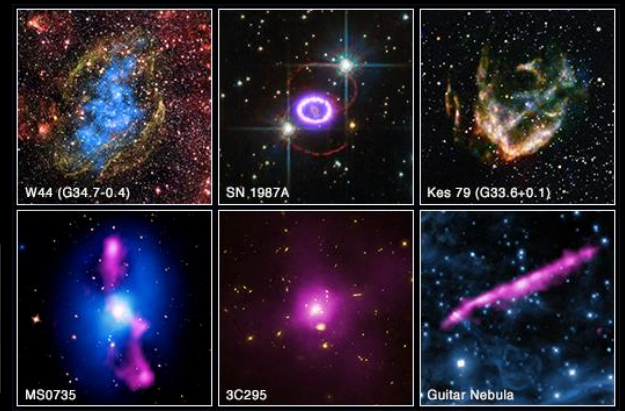
Critical Angle Transmission Grating Array

Lynx X-ray Microcalorimeter (LXM)

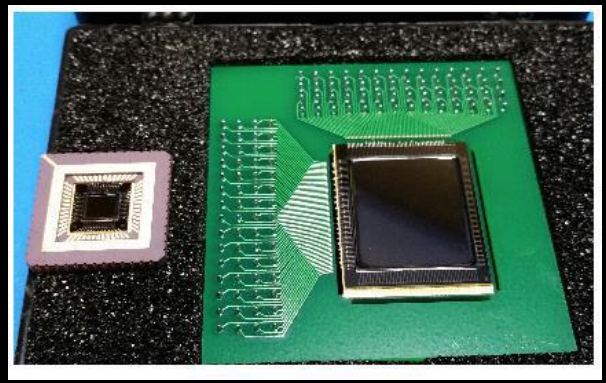




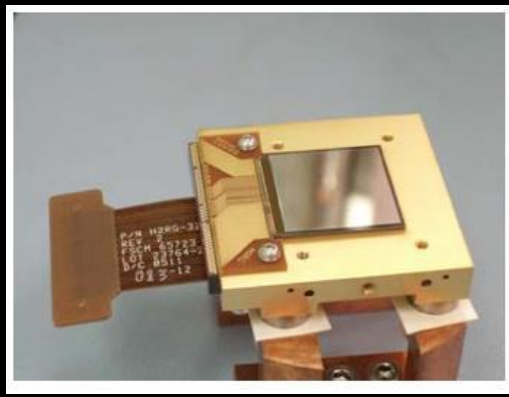
High Definition X-ray Imager (HDXI)



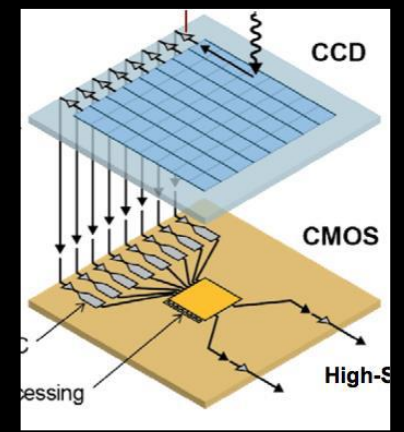
Every X-ray observatory launched in the past 20 years has flown CCDs. Lynx will use Active Pixel Sensors.



Monolithic CMOS (Sarnoff/SAO, and MPE)



Hybrid CMOS (TBE/PSU)



Digital CCDs w/ CMOS readout (LL/MIT)

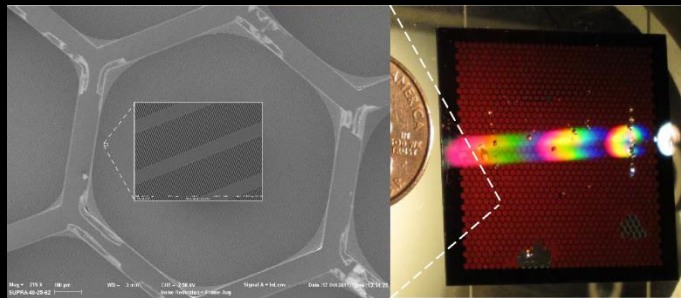
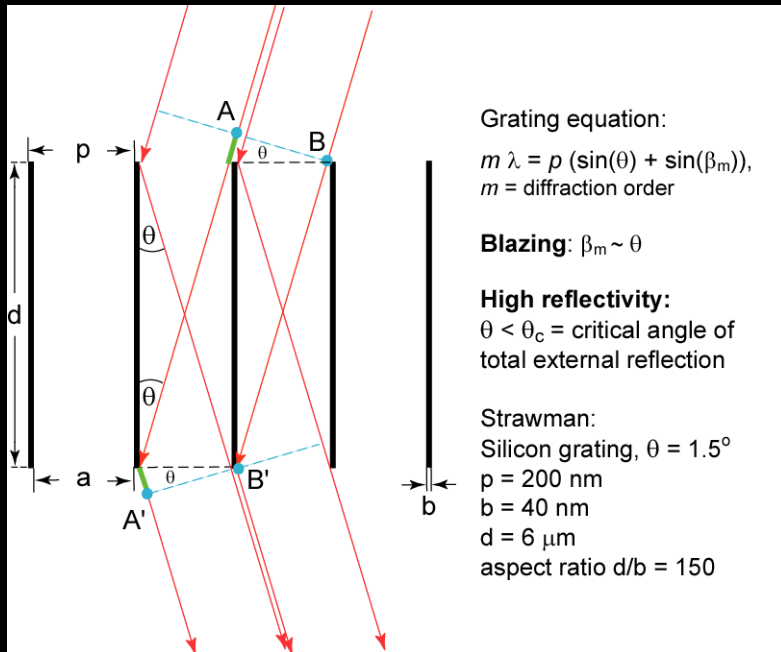
Key improvements over CCDs

- Orders of magnitude higher frame rates
- Significantly improved radiation hardness
- Fully addressable
- Lower power
- Near room temperature operation
- Large format (up to 4Kx4K) abuttable devices
- Near Fano-limited resolution over entire bandpass

X-Ray Grating Spectrometer (XGS)

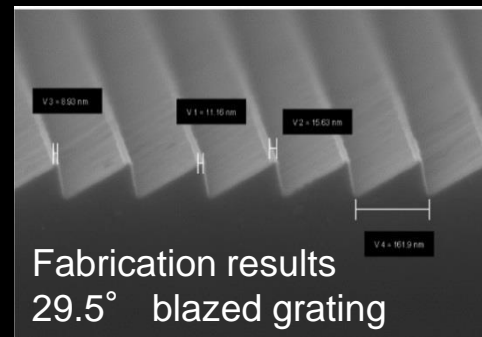
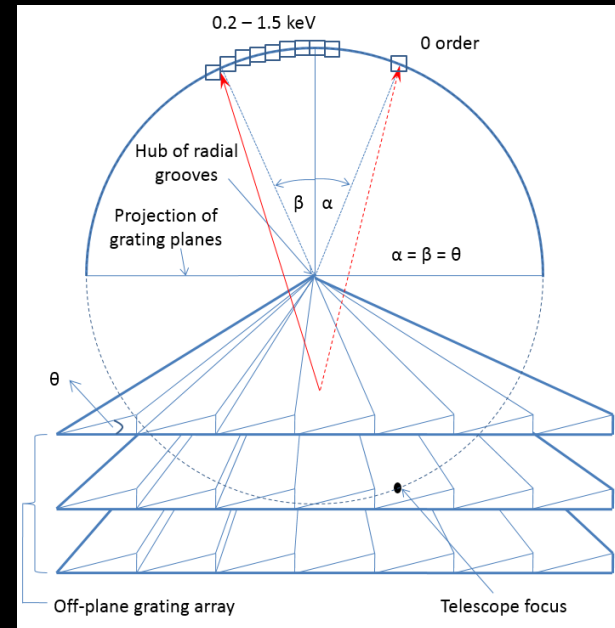
Lynx XGS will provide high spectral resolution ($R > 5000$) and high effective area ($\sim 4000 \text{ cm}^2$) at low energies (0.3-1.0 keV)

CATG (MIT)



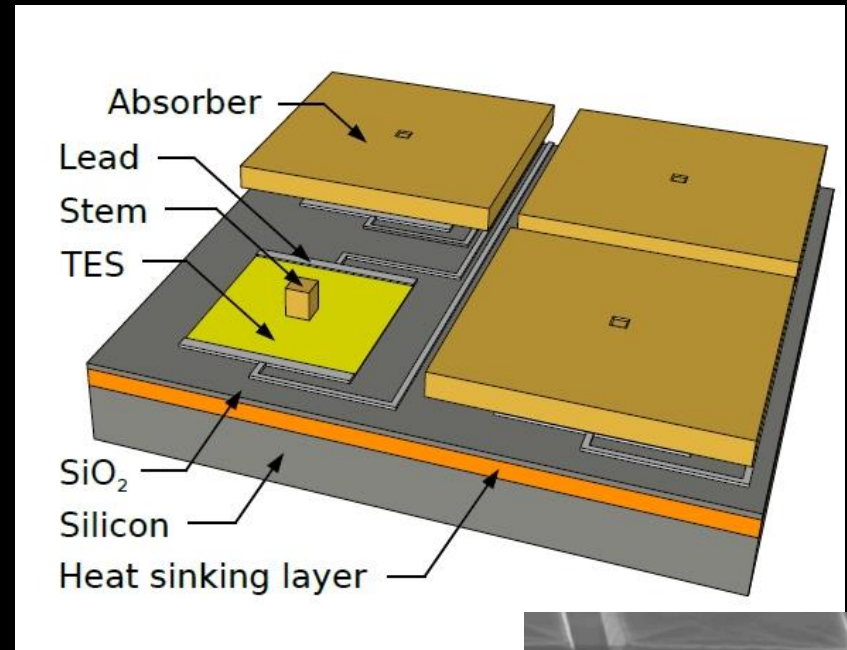
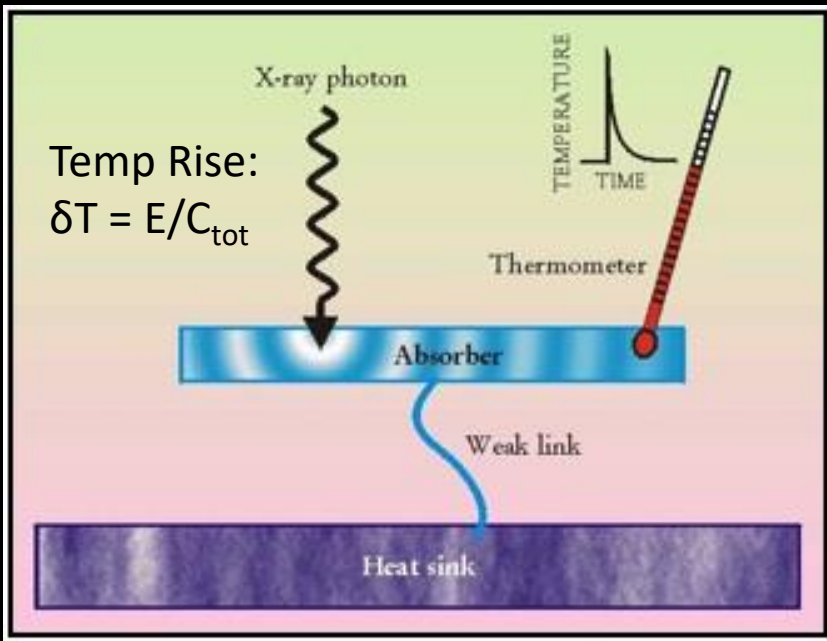
200 nm-period silicon grating membrane with integrated L1 & L2 supports, $> 30 \times 8 \text{ mm}^2$

OPG (Penn State)



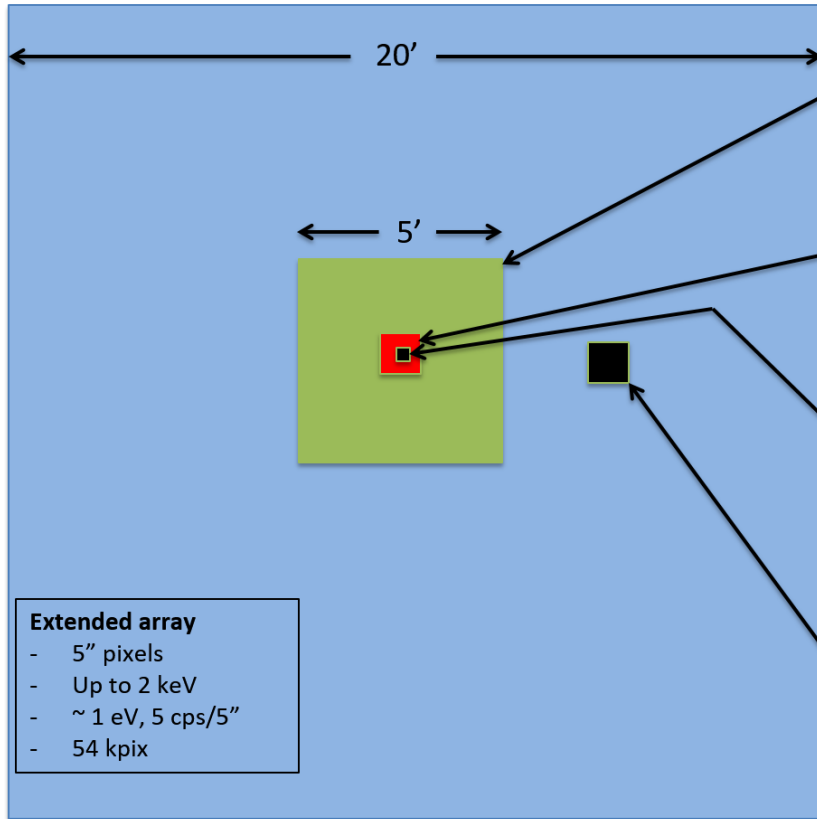
Lynx X-ray Microcalorimeter (LXM)

Converts individual incident X-ray photons (0.2-7 keV) into heat pulses and measure their energy via precise thermometry. Must operate at cold temps of ~50 mK.



- Mapping hot gas in nearby galaxies
- Determining the state of the gas in high-z groups and clusters
- Supernova feedback studies
- Observing spatially-resolved plasma outflow velocities (O VII lines)

Lynx X-Ray Microcalorimeter



Extended array

- 5" pixels
- Up to 2 keV
- ~ 1 eV, 5 cps/5"
- 54 kpix

Main array

- 1" pixels, 5' FOV
- ~ 3 eV, 10 cps/hydra (5")
- up to 7 keV
- 86.4 kpix

Enhancement main array:

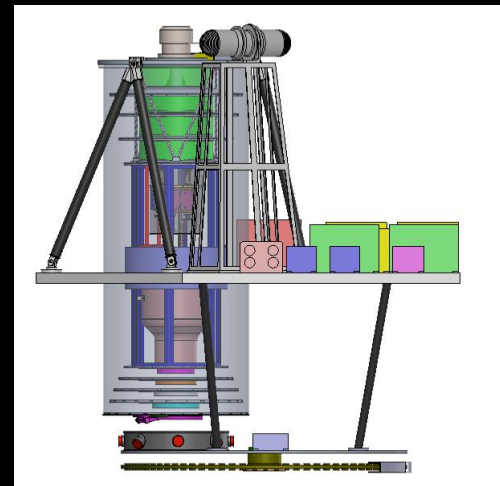
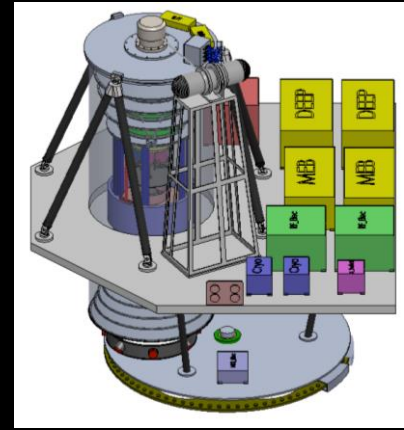
- 0.5" pixels, 1' FOV
- ~ 1.5 eV, 20 cps/hydra-25 (2.5")
- up to 7 keV
- 12.8 kpix

High-res inner array:

- 0.5" pixels, 20" FOV
- ~ 1.5 eV, 20 cps/hydra-4 (1")
- up to 7 keV
- 1.6 kpix

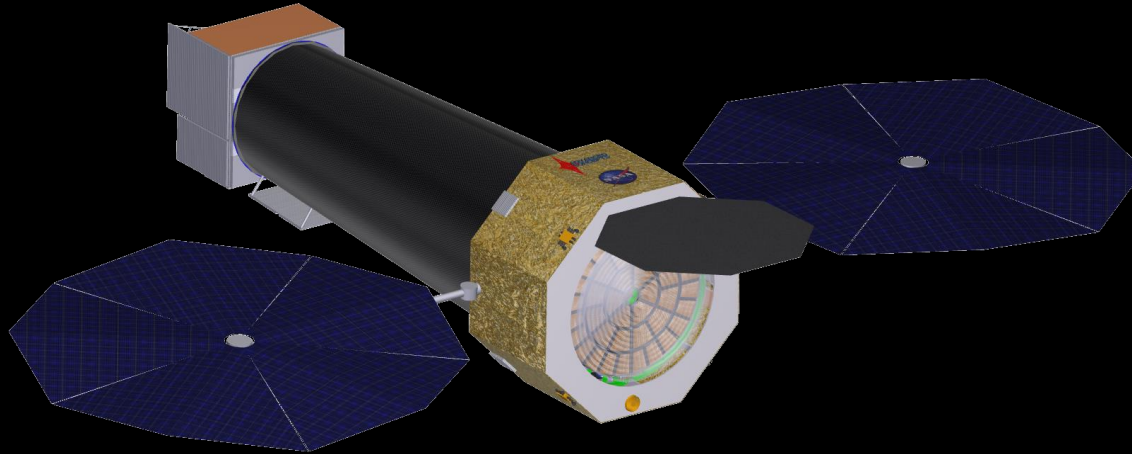
Ultra-hi-res array

- 1" pixels, 1' FOV
- 0.3-0.4 eV (up to ~ 0.75 keV)
- Count rate ~ 80 cps/1"
- 3.6 kpix



Thank you!

<https://wwwastro.msfc.nasa.gov/lynx/>



- ***Leaps in Capability over Chandra and ATHENA:*** 50-100x gain in sensitivity via high throughput with high angular resolution; large field of view for sub-arcsecond imaging; high-resolution spectroscopy for point-like and extended sources
- ***Scientifically compelling:*** frontier science from Dawn of Supermassive Black Holes, to Revealing Invisible Drivers of Galaxy and Structure Formation, to breakthroughs across astrophysics such as: detailed understanding of stellar activity including effects on planet habitability; populations of neutron stars and black holes in Local Group galaxies; highest redshift galaxy clusters; and cosmology
- ***Synergy:*** Great synergy and complementarity with the next-generation facilities —JWST, WFIRST, ATHENA, TMT, EELT, GMT, LISA, ALMA, SKA