X-RAY OBSERVATORY LYNX

Technology Needs for LYNX: Mirrors, Coatings and Metrology

J. Gaskin, NASA MSFC

18th Annual Mirror Technology SBIR/STTR Workshop 11/05/18

THE PEOPLE BEHIND LYNX

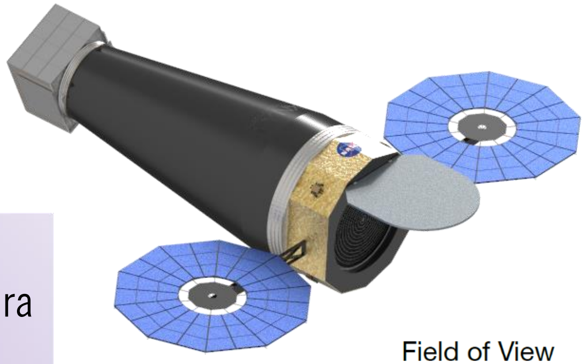
Over 300 total members!

- 22 STDT Members
- 8 Science Working Groups
- Ex-officio International Members
- Instrument Working Group
- Communications Working Group
- Lynx Calibration Working Group
- Optics Working Group

Orgs.	Effort
GSFC	HDXI IDL runs LXM IDL & costing contributed effort MDL (spacecraft)
JPL (ExEP) + X-ray Optics Community	Optics Trade Study facilitation & Evaluation Contributed effort (>35 Volunteers)
X-Ray Grating Spectrometer Team	XGS Trade Study Team (>10 Volunteers)
CAN Study Partners >50% overall contributed	Creare: LXM cryocooler study Hypres: superconducting ADC study Luxel: blocking filter fab. & test Lockheed Martin: LXM cryo-system Northrop Grumman (w/Ball & Harris): Observatory design & analysis
UAH	MBSE modeling of interfaces, requirements & Observatory error budget
Interim Report Red Team	Chair: C. Kouveliotou (GWU) Contributed effort

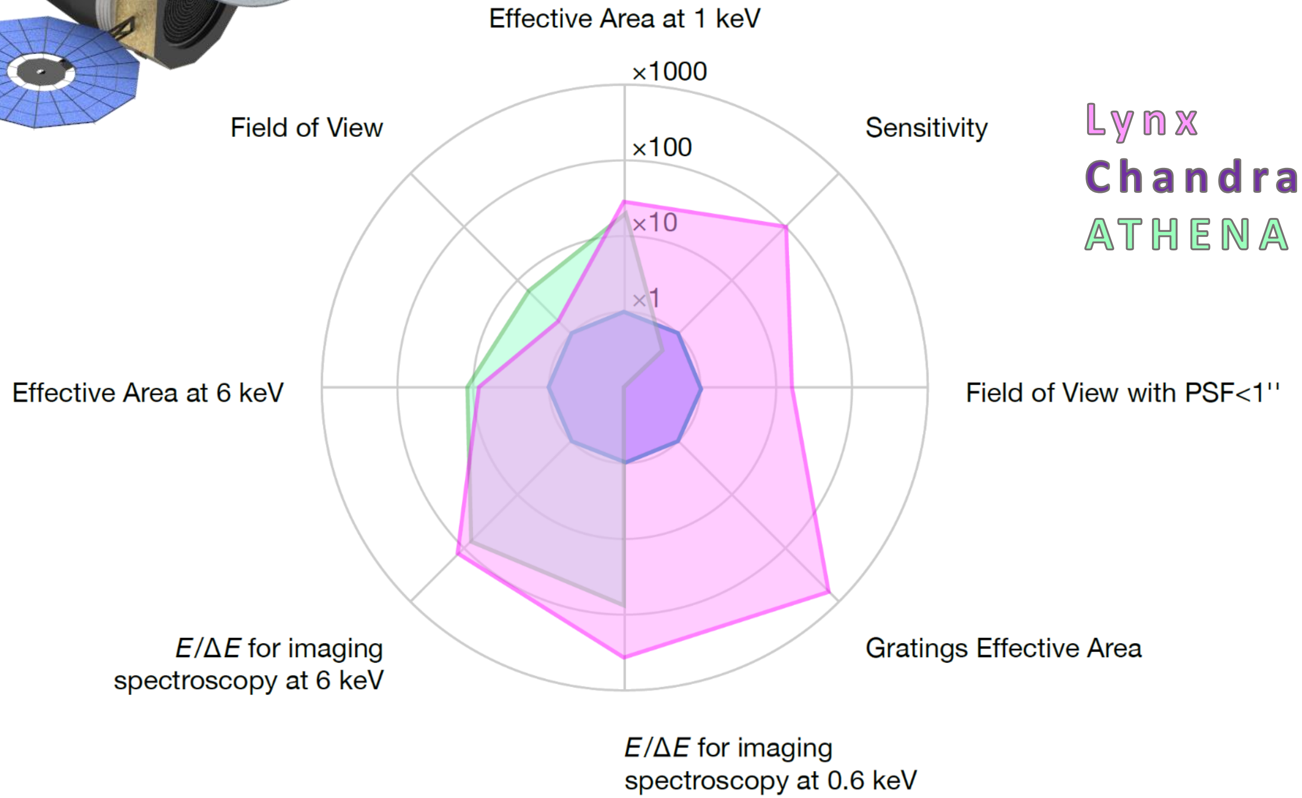
MEET LYNX!

Of the 4 large missions under study for the 2020 Astrophysics Decadal, Lynx is the only observatory that will be capable of directly observing the high-energy events that drive the formation and evolution of our Universe.



Lynx will provide unprecedented X-ray vision into the "Invisible" Universe with leaps in capability over Chandra and ATHENA:

- **Orders of magnitude gain in sensitivity** over Chandra and over Athena, via high throughput with high angular resolution
- **Increased field of view** for arcsecond or better imaging
- **Significantly higher spectral resolution** for point-like and extended sources



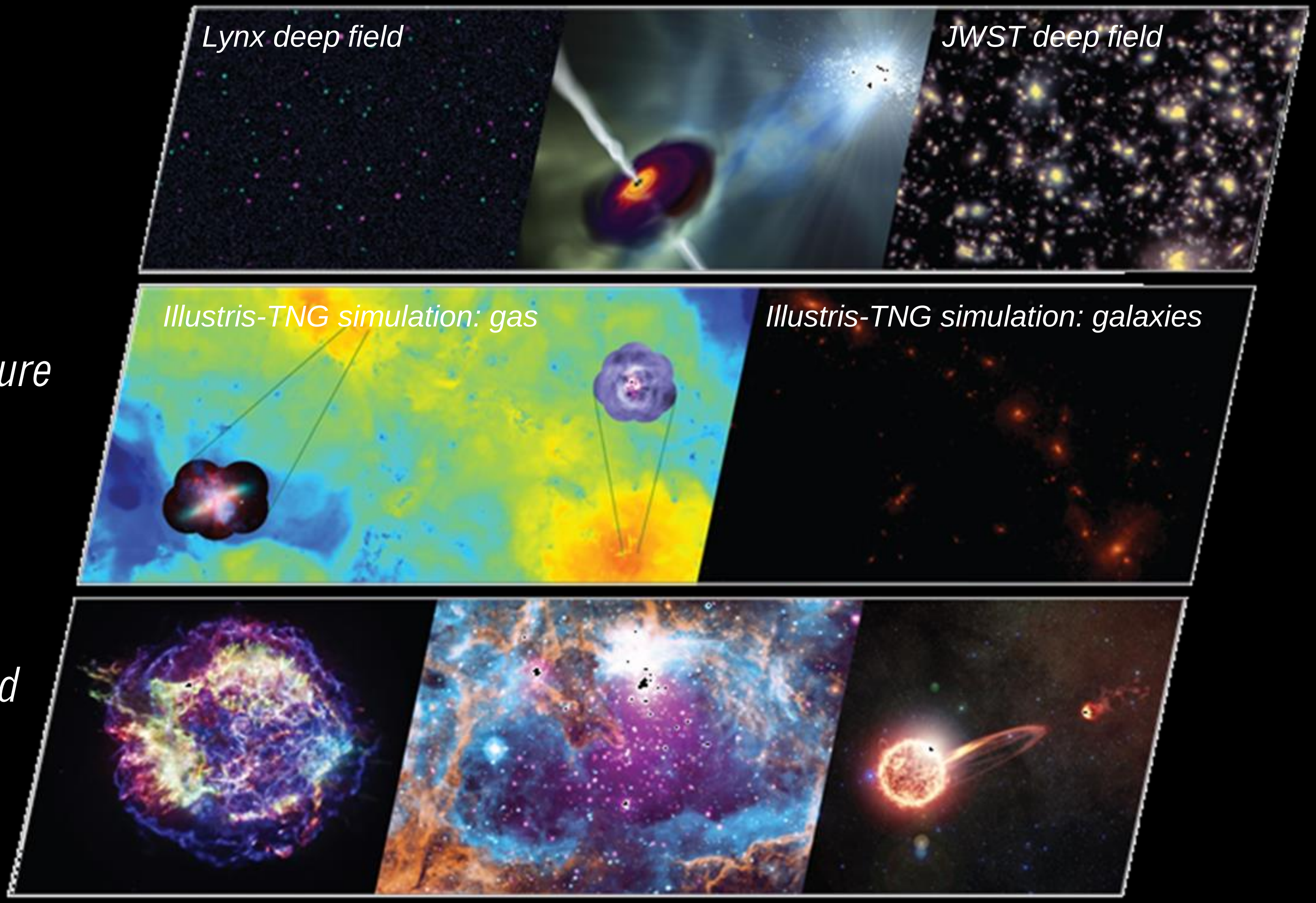
SCIENCE OF LYNX

Through a GO Program, *Lynx* will contribute to nearly every area of astrophysics and provide synergistic observations with future-generation ground-based and space-based observatories, including gravitational wave detectors.

The Dawn of Black Holes

The Invisible Drivers of Galaxy and Structure Formation

The Energetic Side of Stellar Evolution and Stellar Ecosystems



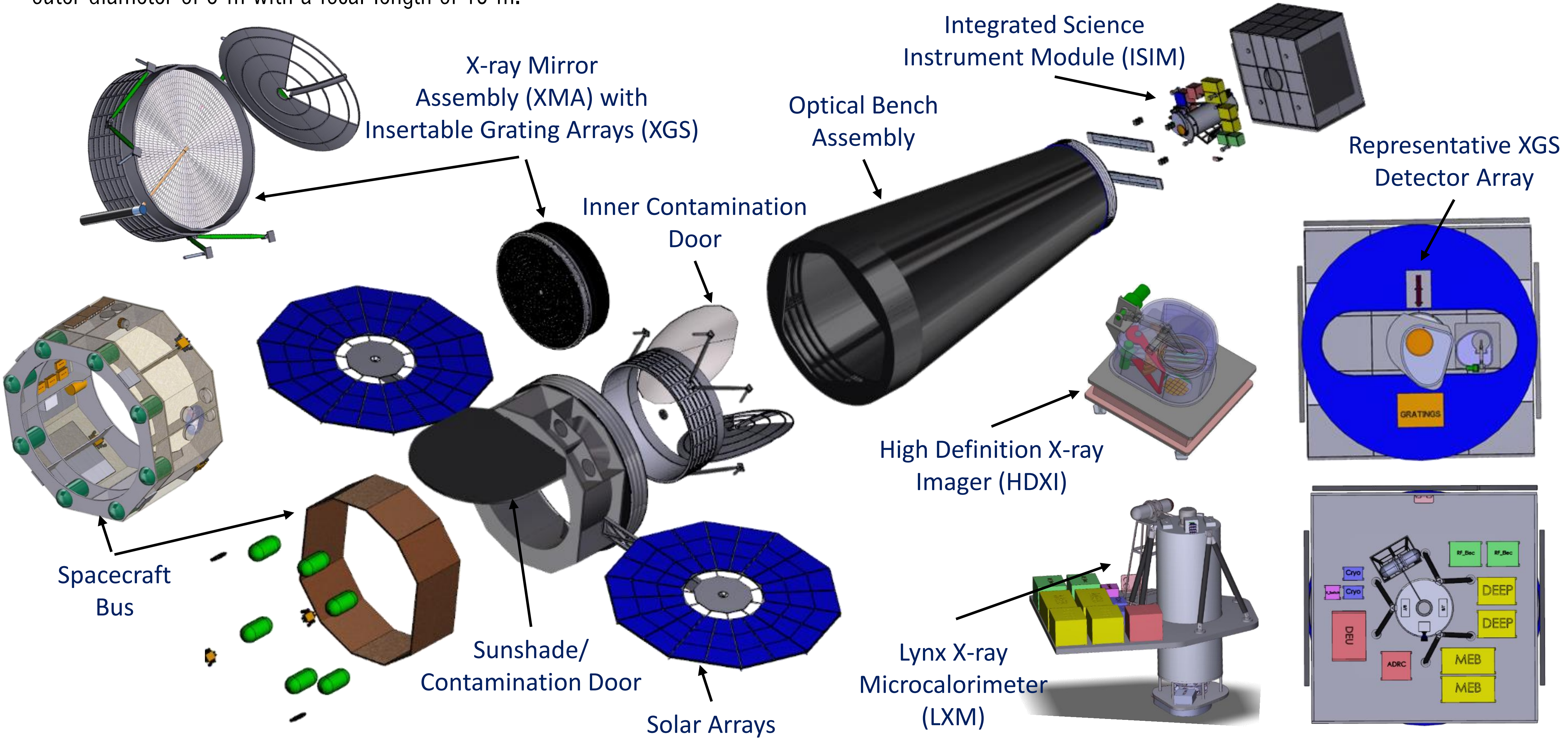
Endpoints of stellar evolution

Stellar birth, coronal physics, feedback

Impact of stellar activity on habitability of planets

LYNX OBSERVATORY CONFIGURATION

2 m^2 of effective area at E = 1 keV is required to execute the three science pillars in under 50% of the 5-yr mission timeline. This is achieved with an outer diameter of 3-m with a focal length of 10-m.



Enabling Technologies TRL Assessment Summary

At Decadal Studies Management Team request, the ExEP, PCOS, and COR Program Offices and the Aerospace Corp assessed the TRL of tech gaps submitted by the teams as of Dec. 2016. Assessment was presented June 2017.

ID	Technology Gap	TRL	
1	High-Resolution 'Lightweight' Optics	~~2~~ 3	Multiple Technologies & Approaches being explored. Expect TRL 3-4 by mid-2020
2	Non-deforming X-ray Reflecting Coatings	3	(same as above)
3	Megapixel X-ray Imaging Detectors (HDXI)	3	Multiple Technologies
4	X-ray Grating Arrays (XGS)	4	Multiple Technologies
5	Large-Format, High Spectral Resolution X-ray Detectors (LXM)	3	Subsystem Heritage

MIRROR CHALLENGES

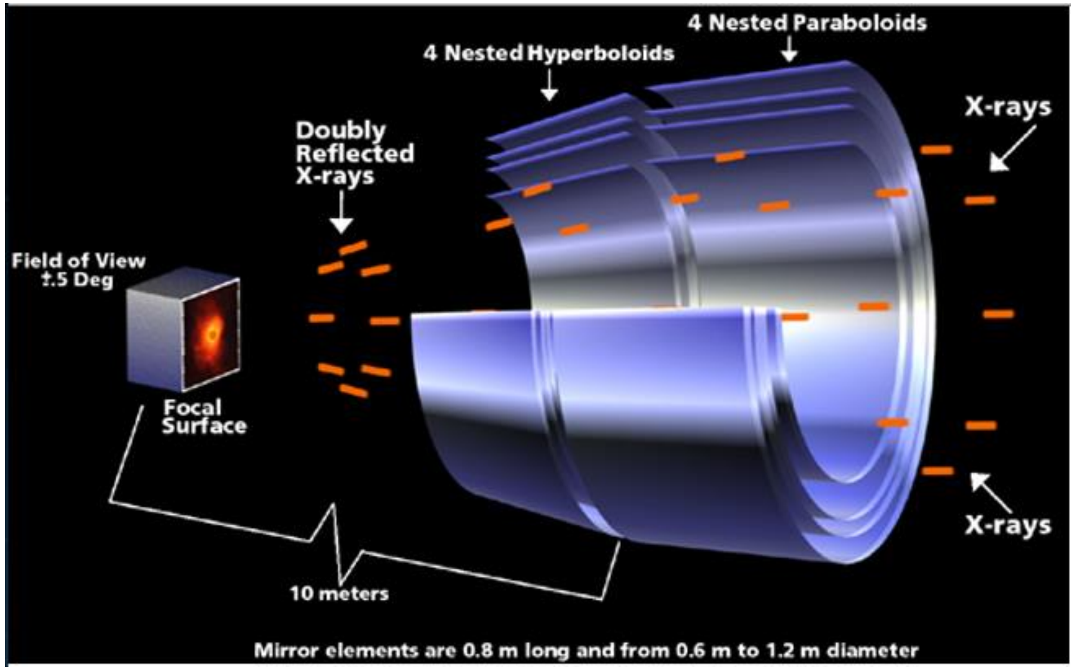
- **Large effective area** is achieved by nesting a few hundred to many thousands of co-aligned, co-axial mirror pairs.
- Must fabricate **thinner mirrors** to allow for greater nesting of mirror pairs and larger effective area while reducing mass
- These thin mirrors must be better that **0.5” HPD** requirement.
- Must **mount and coat** these thin optics **without deforming the optic**, or must be able to correct deformations.

NASA 2018 SBIR S2.04:
X-Ray Mirror Systems Technology, Coating Technology for X-Ray-UV-OIR, and Free-Form Optics

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 $arcmin^2$

Chandra did it! And so can Lynx!



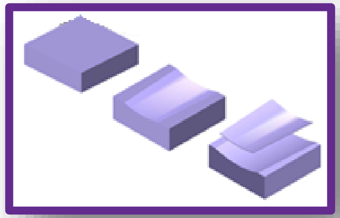
LYNX MIRROR ASSEMBLY

FABRICATION

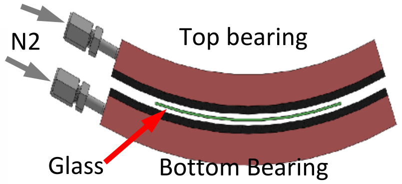
Thermal Forming (GSFC, SAO)

Full Shell (Brera, MSFC, SAO)

Si Optics (GSFC)



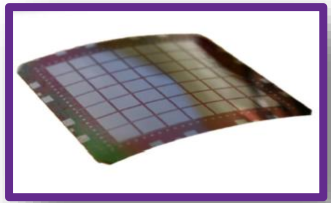
Air Bearing Slumping (MIT)



Testing/Simulation/Modeling

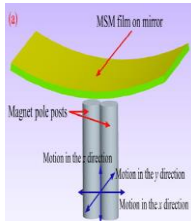
CORRECTION

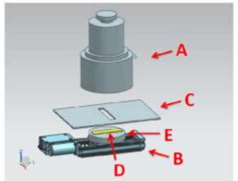
Piezo stress (SAO/PSU)



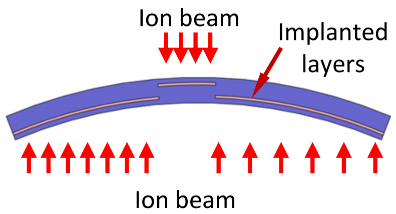
Deposition (MSFC, XRO)

Magnetic & deposition stress (NU)

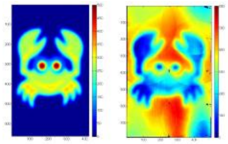




Ion implant stress (MIT)



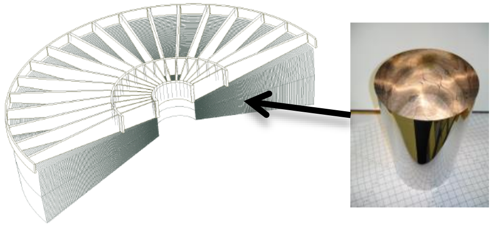
Ion beam figuring (OAB)



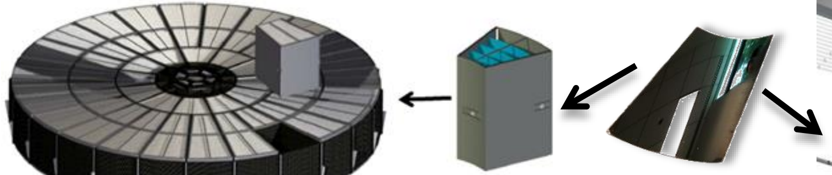
Testing/Simulation/Modeling

INTEGRATION

Full shells Assembly

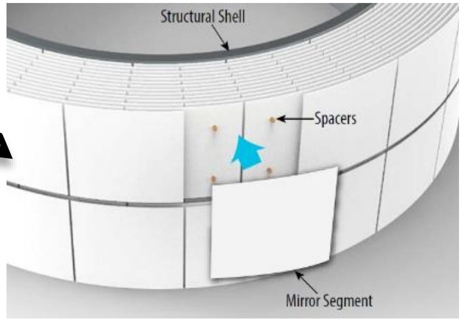


Segmented Wedge Assembly



Segments

Meta-Shell Assembly



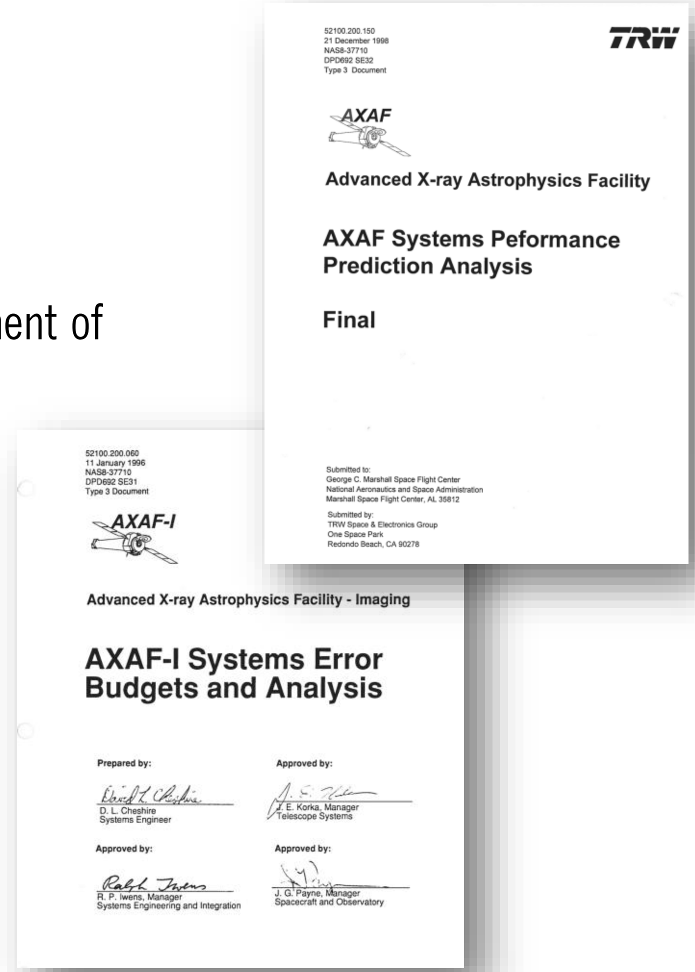
Testing/Simulation/Modeling

Schattenburg talk to NASA PCOS SIG, 04/2016 - Modified

THE LYNX SYSTEM – TECHNICAL PERFORMANCE METRICS

- The quantities listed are key to achieving mission science goals and are considered key technical performance metrics (TPMs).
    - Image quality (system)
    - Effective area
    - Spectral resolution
    - Observing efficiency (related to effective area)

- All key TPMs will have a budget to manage the flow down of requirements and make an assessment of expected performance (prediction) and the path to achieving the expected performance.
    - Gives confidence in the requirements vs. capabilities assessment
    - Gives confidence in the development path for the key payload elements



52100.200.150
21 December 1998
NAS8-37710
DPD692 SE32
Type 3 Document

TRW

AXAF

Advanced X-ray Astrophysics Facility

AXAF Systems Peformance Prediction Analysis

Final

Submitted to:
George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Marshall Space Flight Center, AL 35812

Submitted by:
TRW Space & Electronics Group
One Space Park
Redondo Beach, CA 90278

52100.200.060
11 January 1996
NAS8-37710
DPD692 SE31
Type 3 Document

AXAF-I

Advanced X-ray Astrophysics Facility - Imaging

AXAF-I Systems Error Budgets and Analysis

Prepared by:
D. L. Cheshire
Systems Engineer

Approved by:
J. E. Korka, Manager
Telescope Systems

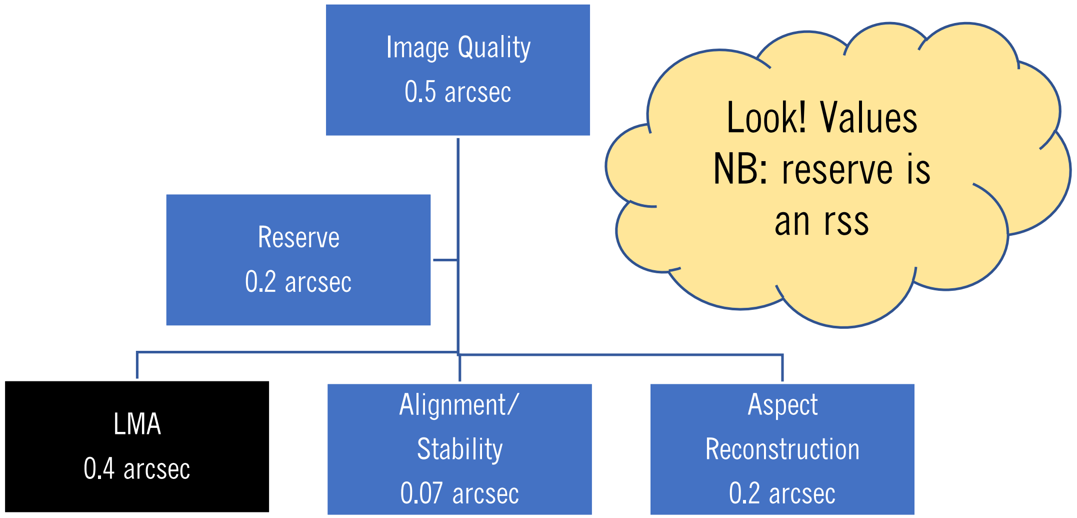
Approved by:
R. P. Iwens, Manager
Systems Engineering and Integration

Approved by:
J. G. Payne, Manager
Spacecraft and Observatory

IMAGE QUALITY– ERROR BUDGET

- Shows how Lynx collects data and makes an image on the celestial sphere
- Lynx looks like Chandra (structurally)
- Lynx Mirror Assembly is 1/3 the f/# so alignment/stability is tighter

Source of Error		Allocation or Requirement (arcsec HPD)	State of the Art (arcsec HPD)	Determination & Verification	Bridging the Gap between State-Of-Art and Requirements
Optical Prescription	Diffraction	0.10	0.10		
	Geometric PSF (on-axis)	0.00	0.00		
Mirror Segment Fabrication	Mirror Substrate	0.20	0.50		
	Coating	0.10	0.20		
Meta-Shell Construction	Alignment	0.10	1.60		
	Bonding	0.20	0.40		
Integration of Meta-shells to XMA	Alignment	0.10	0.10		
	Attachment	0.10	0.22		
Ground to Orbit Effects	Launch shift	0.10	0.10		
	Gravity Release	0.10	0.14		
	On-orbit thermal	0.10	0.16		
On-Orbit Performance (RSS)		**0.40**	**1.77**		



LMA
- Mirror quality
- Element to element alignment
- Meta shell alignment
- Design residual
- 1g-0g effects
- Mount induced distortion

Alignment/Stability
- LMA to ISIM alignment and stability (not corrected by aspect solution)
- ISIM to focal plane alignment and stability not corrected by aspect solution)
- Thermal distortion

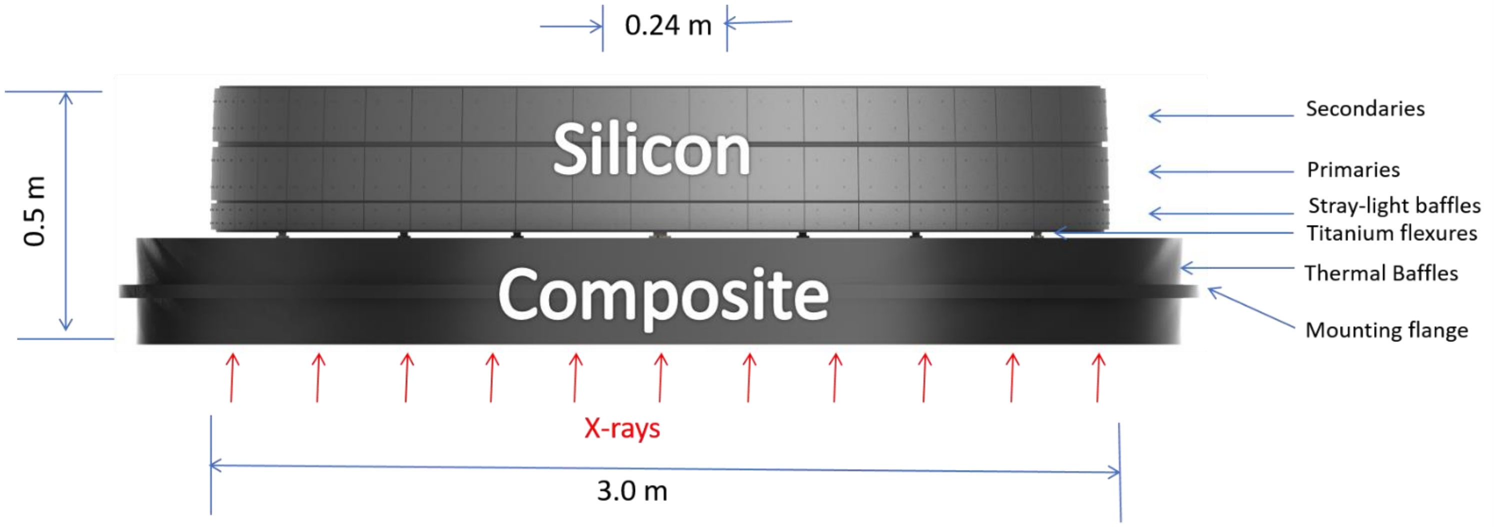
Aspect Reconstruction
- Centroid errors guide stars
- Centroid errors fiducial lights
- Fiducial transfer optics drift

Credit: J. Arenberg (NGAS)

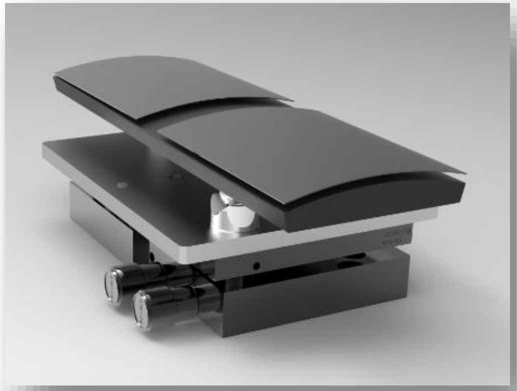
LYNX MIRROR ASSEMBLY – SILICON METASHELL OPTICS

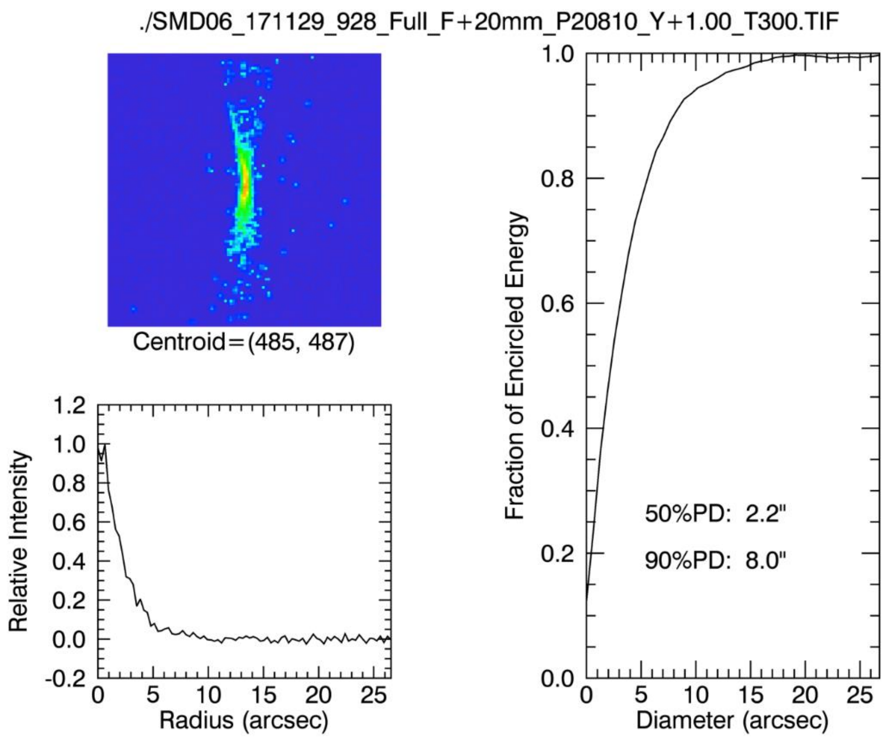
- W. Zhang and Team (NASA GSFC)

XMA Parameter	Requirement
Energy Range	0.3–10 keV
Angular Resolution	0.5 arcsec HPD on-axis; < 1 arcsec HPD across the FOV
Grasp (Effective Area * FOV for <1 arcsecond PSF)	~600 m^2 $arcminutes^2$
Field of View	10 arcmins radius
Effective Area @ 1 keV	2 m^2



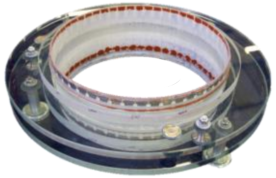
Direct polished mono-crystalline silicon



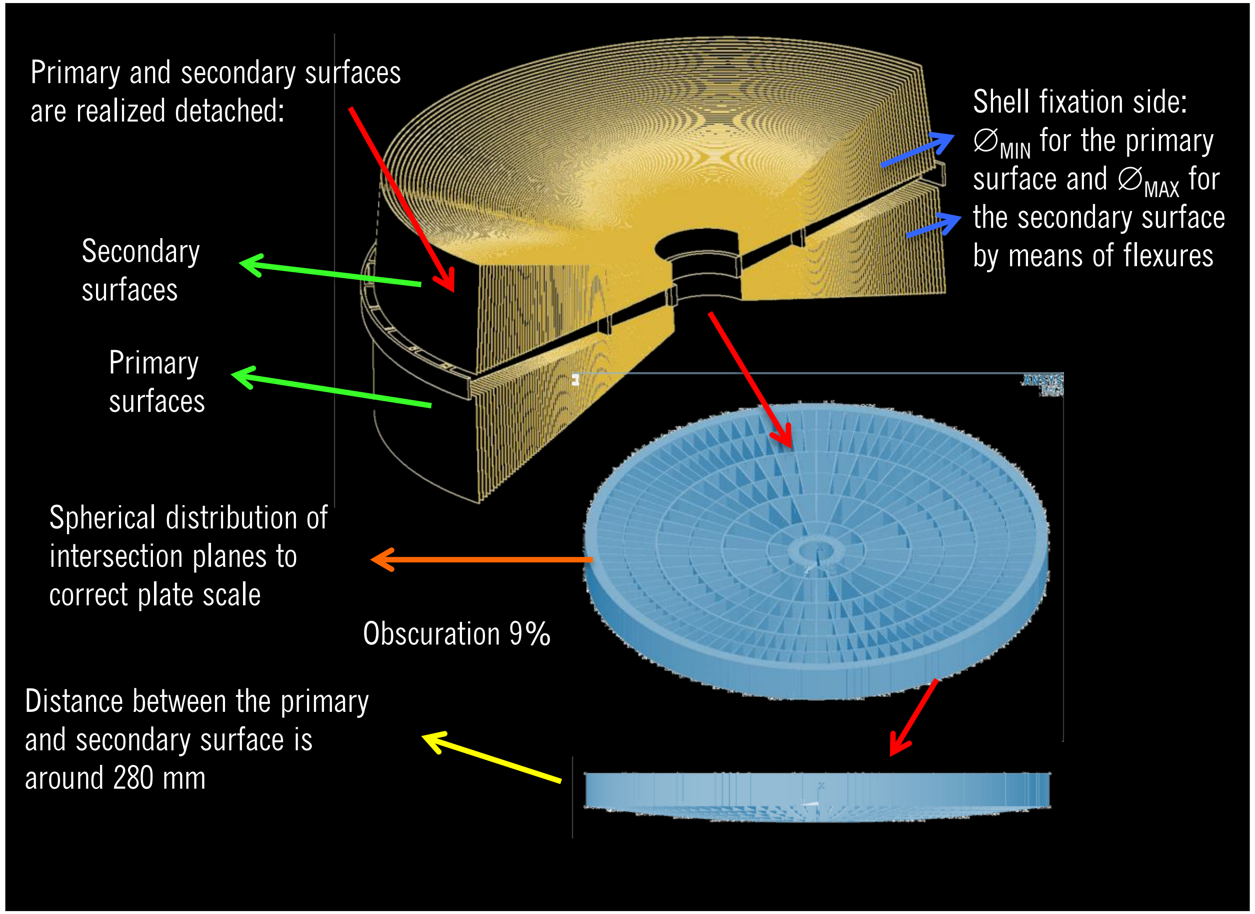


FEASIBLE ALTERNATES - FULL SHELL & ADJUSTABLE OPTICS

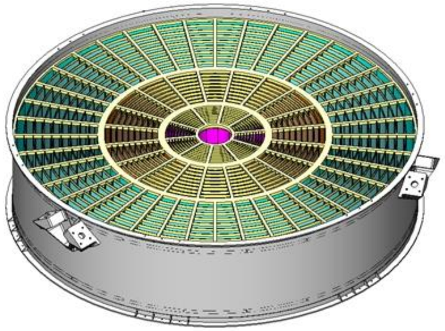
- G.Pareschi, M.Civitani, S.Basso & INAF Team (INAF-OAB)
- K. Kiranmayee , J. Davis, R. Elsner D. Swartz & MSFC Team (MSFC/USRA)

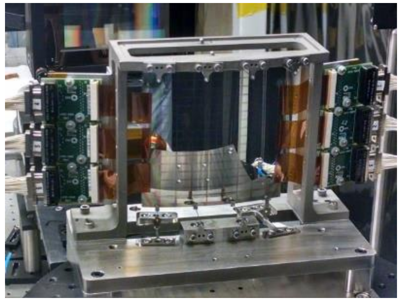


Direct Polished Fused Silica or Similar

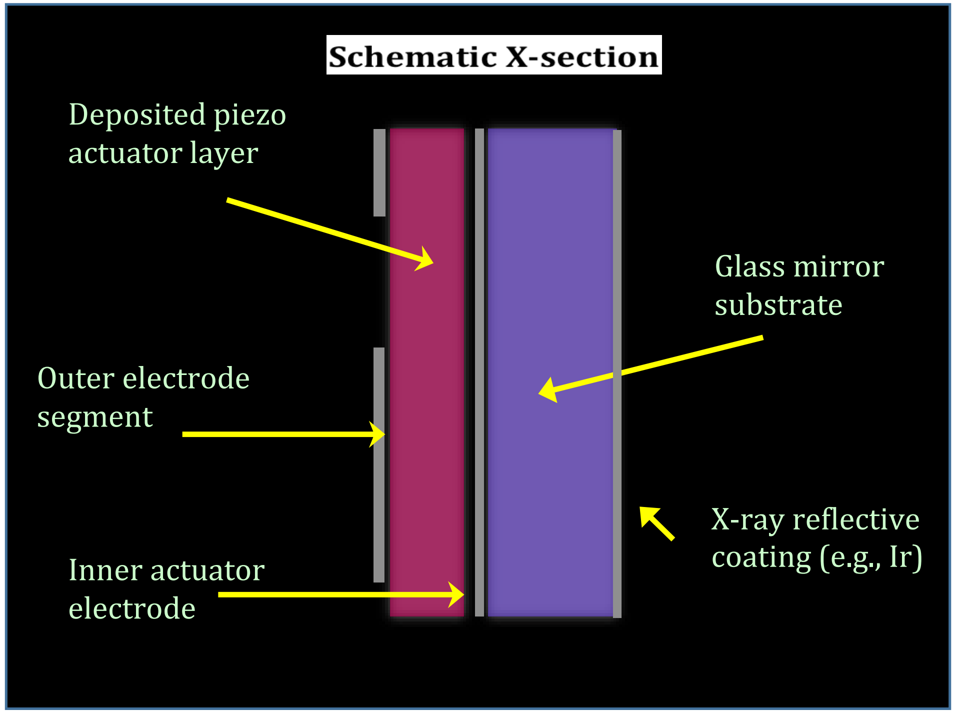


- P. Reid
- SAO Adjustable Optics Team
- PSU Adjustable Optics Team





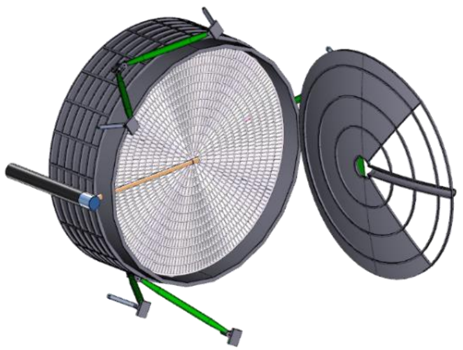
Slumped glass with sputter deposited piezoelectric material



X-RAY MIRROR ASSEMBLY (XMA) METROLOGY

State-of-the-art metrology is required to determine the mirror quality over the entire range of spatial frequencies.

XMA has a 3-m outer diameter, and contains hundreds or thousands of mirror elements!



X-ray Mirror Assembly (XMA)

- Highest spatial frequency (microroughness) *(sub-nm accuracy required)*
  - Assessed with a phase-shifting interferometer with a millimeter-class FOV
  - Or, Atomic Force Microscope
- Lowest spatial frequency (figure error) *(several-nm accuracy required)*
  - Assessed with a phase-shifting interferometer with a much larger FOV
    - For full-shell cylindrical optics, the optic must be extremely precisely rotated about its axis to allow stitching of multiple FOV's
    - For segmented optics, the interferometer may cover the entire segment, but there are then additional, difficult alignment metrology requirements
      - For segmented optics with active figure correction, the correctors' influence functions must also be precisely measured
- Mid-spatial frequency *(few-nm accuracy required)*
  - Usually assessed interferometrically, either by
    - Swapping the objective in the microroughness interferometer to expand the FOV
    - Taking great care to get very high resolution and excellent sensitivity and calibration accuracy in the low spatial frequency interferometer
    - (or both, for greatest spatial frequency overlap!)

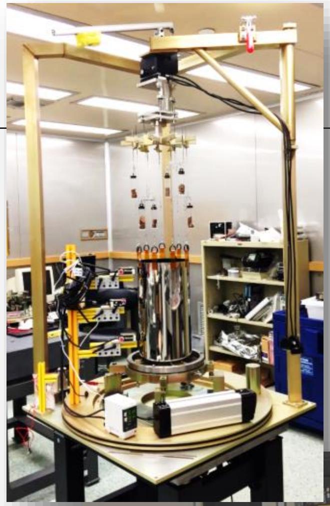
Slide Provided by Paul Glenn (Bauer, Inc.)

ALIGNMENT METROLOGY

- The traditional dividing line between metrology and alignment is blurred for Lynx, because of
  - The large number of mirrors
  - The possibility of a segmented architecture
  - The flexibility of the thin mirrors

- For full-shell cylindrical optics:
  - The flexibility puts strenuous requirements on the transition from holding the optics for metrology, and ultimately attaching them to the structure while monitoring the alignment and aggregate image quality over the full aperture

- For segmented optics:
  - Precision metrology is required as the mirror elements are assembled into modules
  - This metrology may combine direct measurements of the surface figure with indirect measurements of a module's image quality
  - Multiple modules must ultimately be coaligned, either by
    - Monitoring the alignment and aggregate image quality over the full aperture, or
    - Introducing transfer optics to each module that can generate an alignment reference to be compared against those of other modules



Credit: MSFC X-Ray Group

Lester Levitator. Credit: Lester Cohen, SAO

In all these cases, sub-arc-second accuracy is required, which at a focal length of 10 meters implies detection of image shifts or distortions of only a few microns.

Slide Provided by Paul Glenn (Bauer, Inc.)

LYNX THIN FILM COATING REQUIREMENTS

- Low stress thin film coatings (~ 10 MPa) needed to preserve underlying sub-arcsecond figure of thin (~400 μm) substrates.

- High X-ray reflectance for a range of grazing incidence angles (~0.4° (innermost shell)-2.0° (outermost shell)).
  - Although the 2 m^2 effective area requirement is specified @ 1keV, a spectral response up to 10-15keV is desired.
  - Single layer coatings such as Pt, Au, and Ir provide good spectral response up to 10 keV for incidence angles less than the critical angle (i.e. the inner shells).
  - In this regime, (100-150 Å) single layer of Iridium offers best X-ray reflectivity, but coating stress is significant (i.e. ~4GPa (compressive))
  - Interference based coatings (such as multilayers) might be utilized on the outer shells to extend the spectral response at incidence angles beyond the critical angle.

- Low surface roughness to minimize X-ray light scattering (< 5-6Å).
  - Most stress mitigation techniques result in a film microstructure that causes some degree of increase in high frequency surface roughness

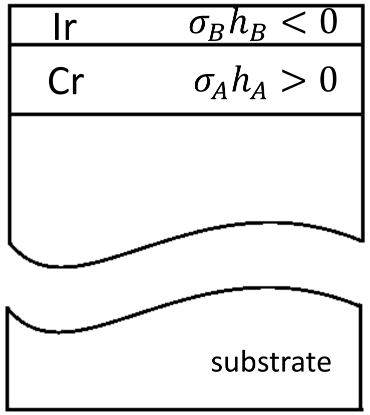
Slide Provided by David Broadway (MSFC)

CURRENT STRESS MITIGATION TECHNIQUES

Stress balancing coatings on same side of substrate:
The technique utilizes a compensating layer(s) whose stress is opposite in sign to the sign of the stress in the layer stack.

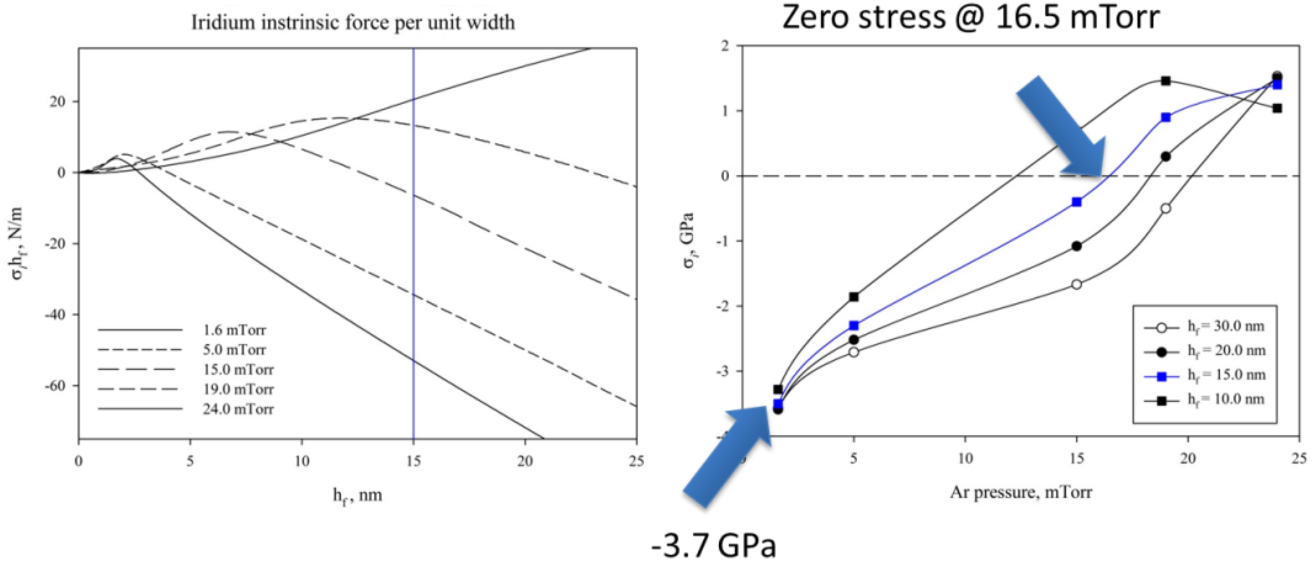
$$\left(\sigma h_f\right)_{Net} = \sigma_A h_A + \sigma_B h_B + \cdots + \sigma_N h_N + \Delta(\sigma h)_{CTE} \approx 0$$

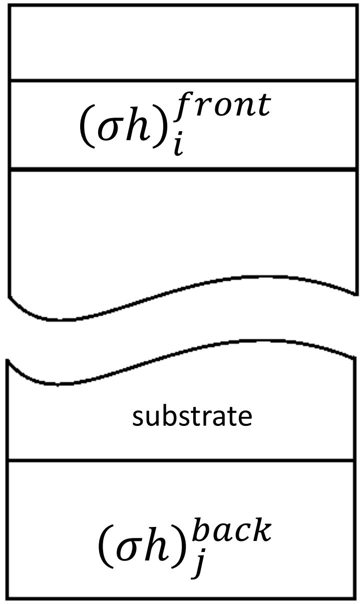
The thickness of the compensating layer is tuned to balance the net stress in the layer stack.



Example: Cr (tensile (+))/Ir (compressive (-))

Argon pressure optimization in magnetron sputtered Ir:





Stress balancing with front/backside coating.

$$\sum_{i}^{N} (\sigma h)_i^{front} = \sum_{j}^{M} (\sigma h)_j^{back}$$

Slide Provided by
David Broadway (MSFC)

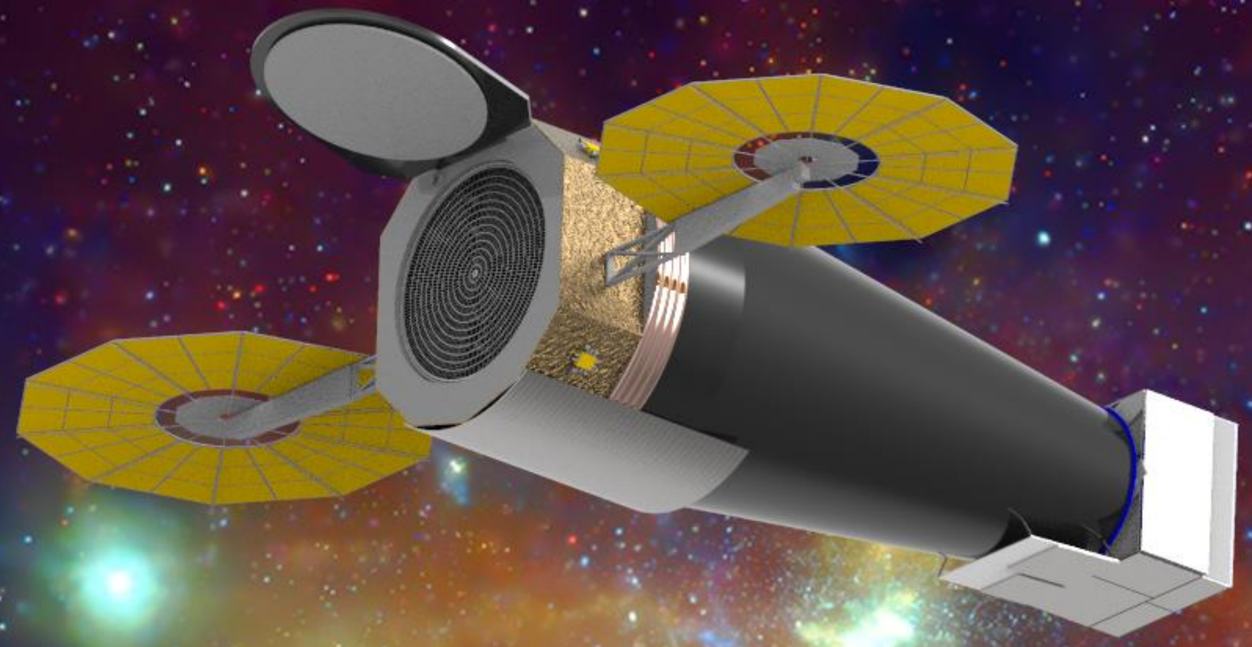
THANK YOU!

Jessica.Gaskin@nasa.gov

Lynx Websites

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

https://www.lynxobservatory.com/



- **Large effective area** is achieved by nesting a few hundred to many thousands of co-aligned, co-axial mirror pairs.
- Must fabricate **thinner mirrors** to allow for greater nesting of mirror pairs and larger effective area while reducing mass
- These thin mirrors must be better that **0.5” HPD** requirement.
- Must **mount and coat** these thin optics **without deforming the optic**, or must be able to correct deformations.