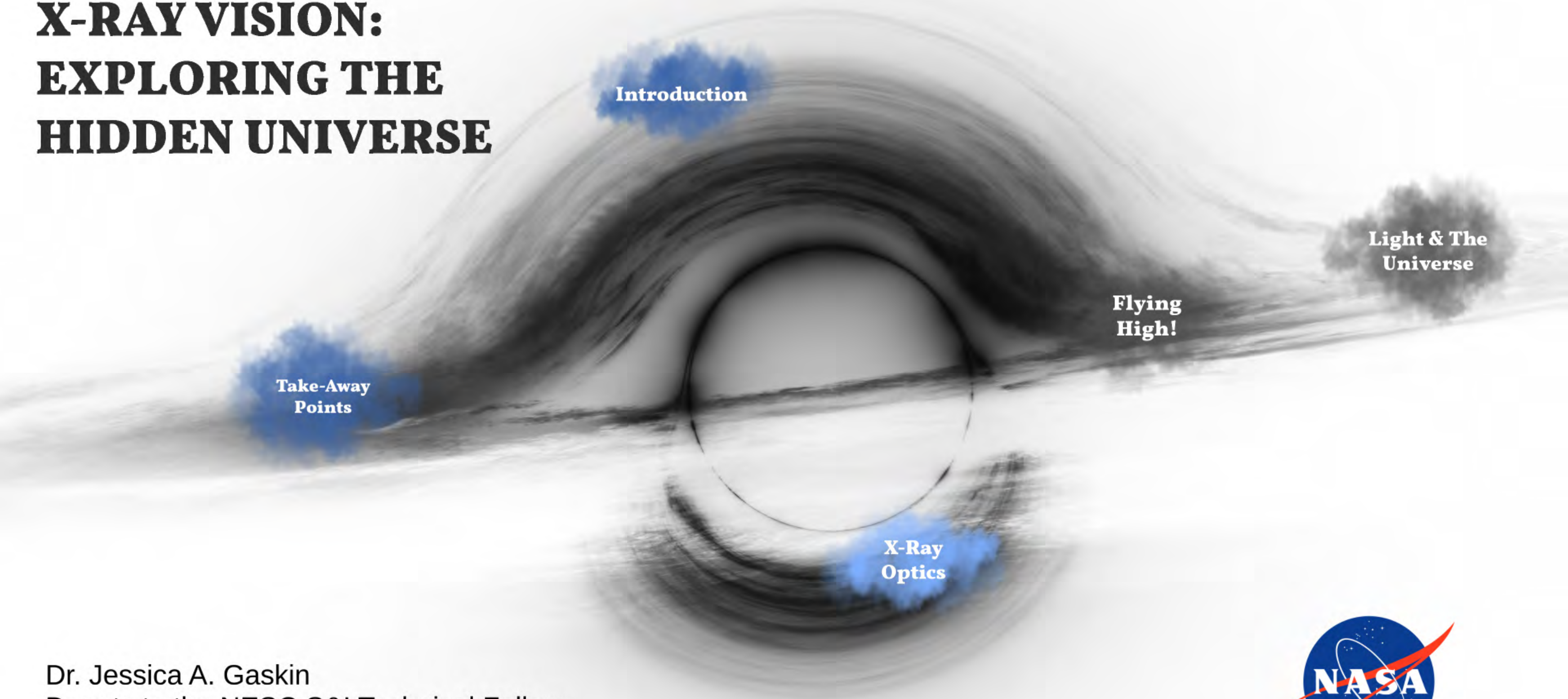
X-RAY VISION: EXPLORING THE HIDDEN UNIVERSE



Dr. Jessica A. Gaskin
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NASA Marshall Spaceflight Center
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Talk Outline

- Light in the Universe
- X-Ray Astronomy Platforms
- NASA MSFC X-Ray Optics & Test Capability
- Take-Away Points

“Light, Light, The visible reminder of invisible light” – T.S. Eliot


Public Domaine

The Visible

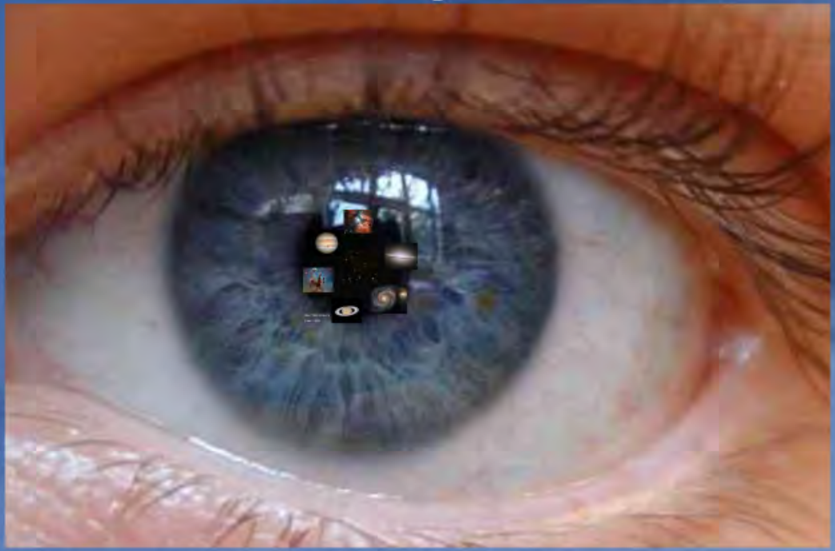
The Invisible

Staying Alive!

The Application of Fundamental Physics to See the Visible Universe

Percival Lowell

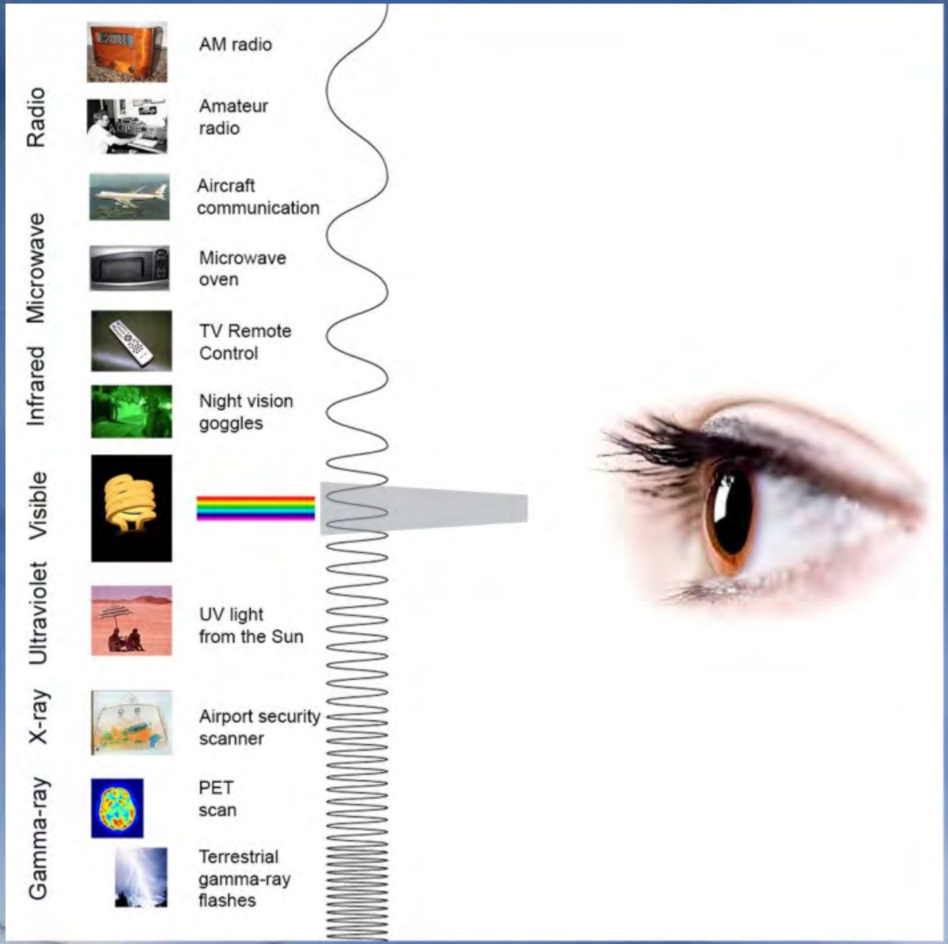
The Eye



The "canals" of Mars, drawn by Percival Lowell in 1905, from visual observations through a 0.61 meter aperture telescope at the Lowell Observatory, Flagstaff, Arizona.

Jezero Crater image taken by the High Resolution Stereo Camera aboard the ESA (European Space Agency) Mars Express orbiter

The Application of Fundamental Physics to See Invisible Light



Credit: NASA's Imagine the Universe

Terrestrial X-Rays

X-Rays From Space

We are surrounded by naturally-occurring radioactive elements in the soil and stones.

Uranium

Radium

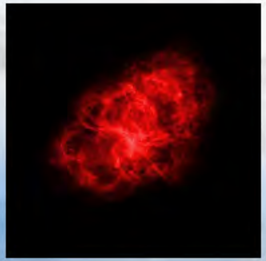
We have radioactive elements (Potassium 40, Carbon 14, Radium 226) in our blood or bones.

The Complete? Universe

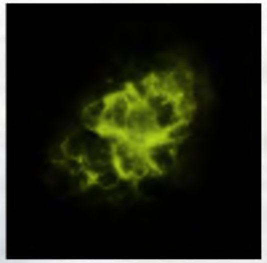
Crab Nebula (Composite Image)

Credit: X-Ray: NASA/CXC/J.Hester (ASU); Optical: NASA/ESA/J.Hester & A.Loll (ASU); Infrared: NASA/JPL-Caltech/R.Gehrz (Univ. Minn.)

XMM (UV)

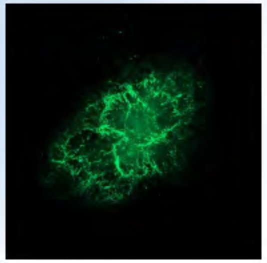


VLA (Radio)



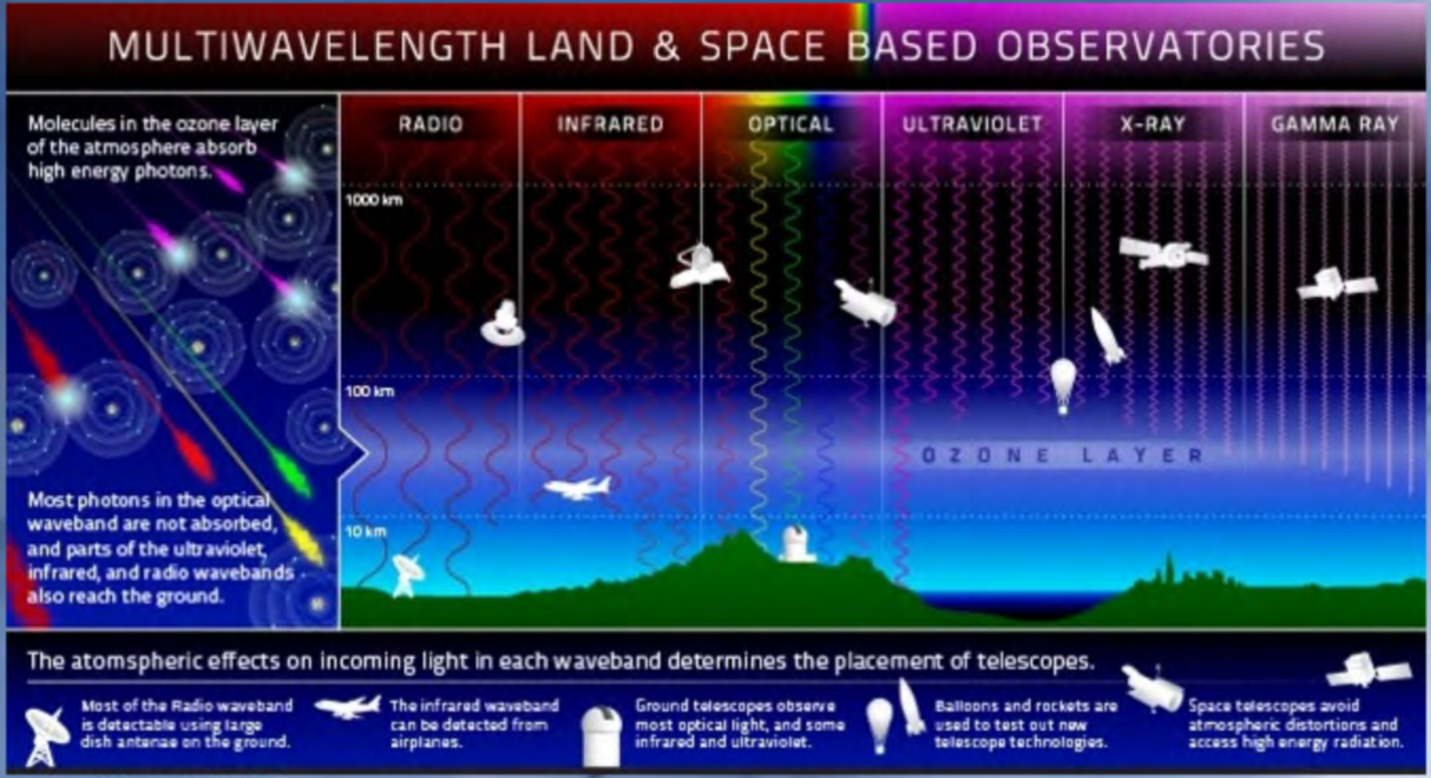
Spitzer (IR)

Chandra (X-ray)



Hubble (Visible)

Our Universe is Bright!



ecuip UChicago/NASA

Staying Alive!

If our atmosphere blocks out X-rays, how can we observe these X-ray emitting astronomical sources?

Flying High!

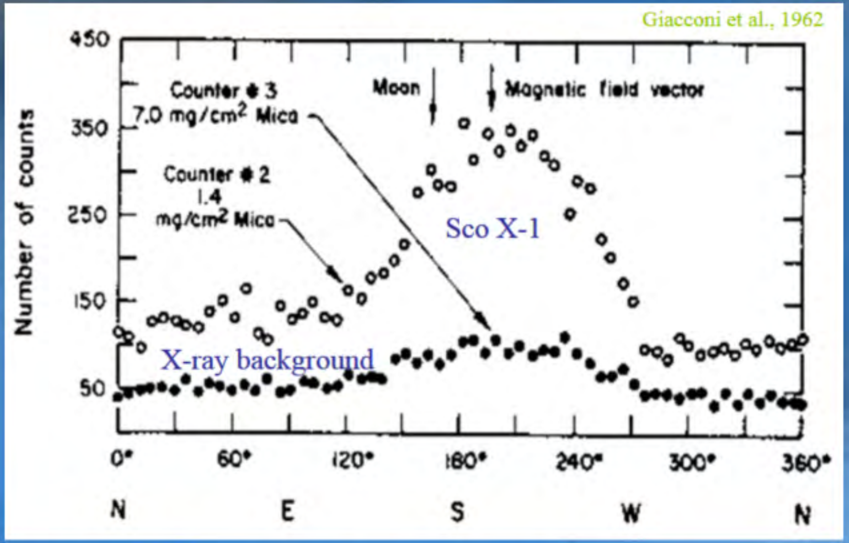
Balloons

Rockets

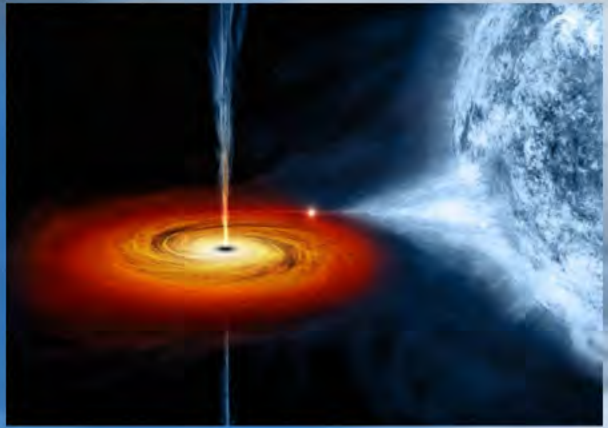
Spacecraft

Rocketry & The Dawn of X-Ray Astronomy

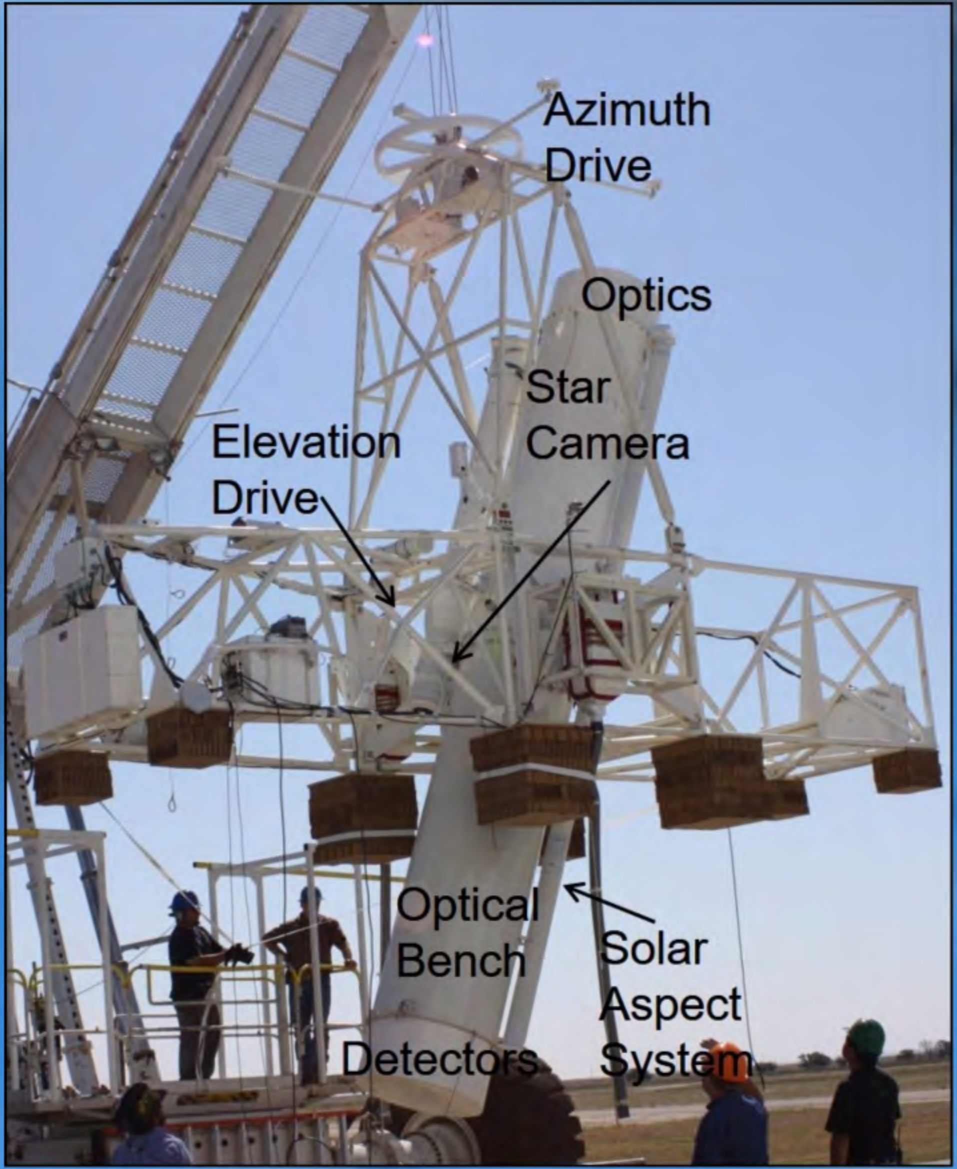
Riccardo Giacconi



First rocket experiment in 1962 - a sort of flying Geiger counter was to look for X-rays created by solar X-rays bouncing off of the Moon.



An artist's drawing of the black hole binary Cygnus X-1. The black hole, at the center of the accretion disk, pulls matter from its large, blue companion star into the disk.
Credit: NASA / CXC / M.Weiss



High Energy Replicated Optics to Explore the Sun (HEROES) Mission

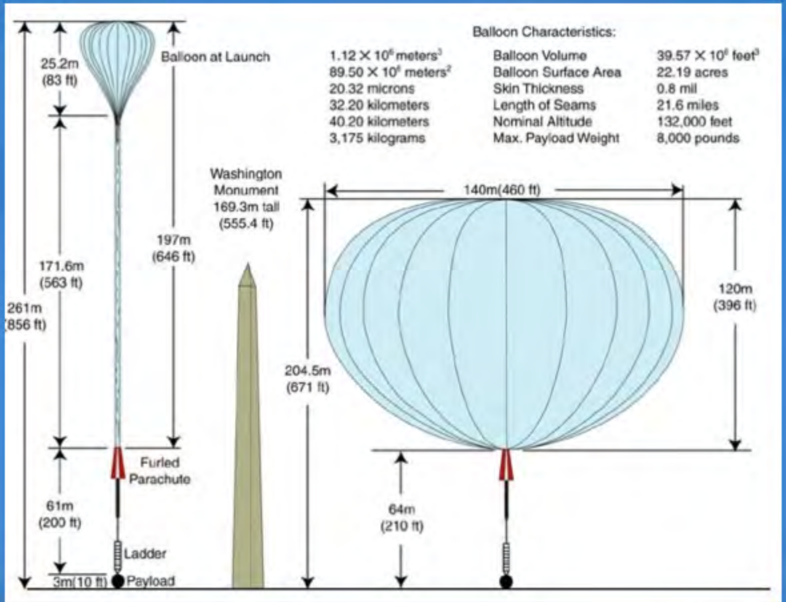
Balloon - Borne Payloads

Scientific Balloons

Launch, Flight, Landing

Conventional and Long Duration Balloon Missions

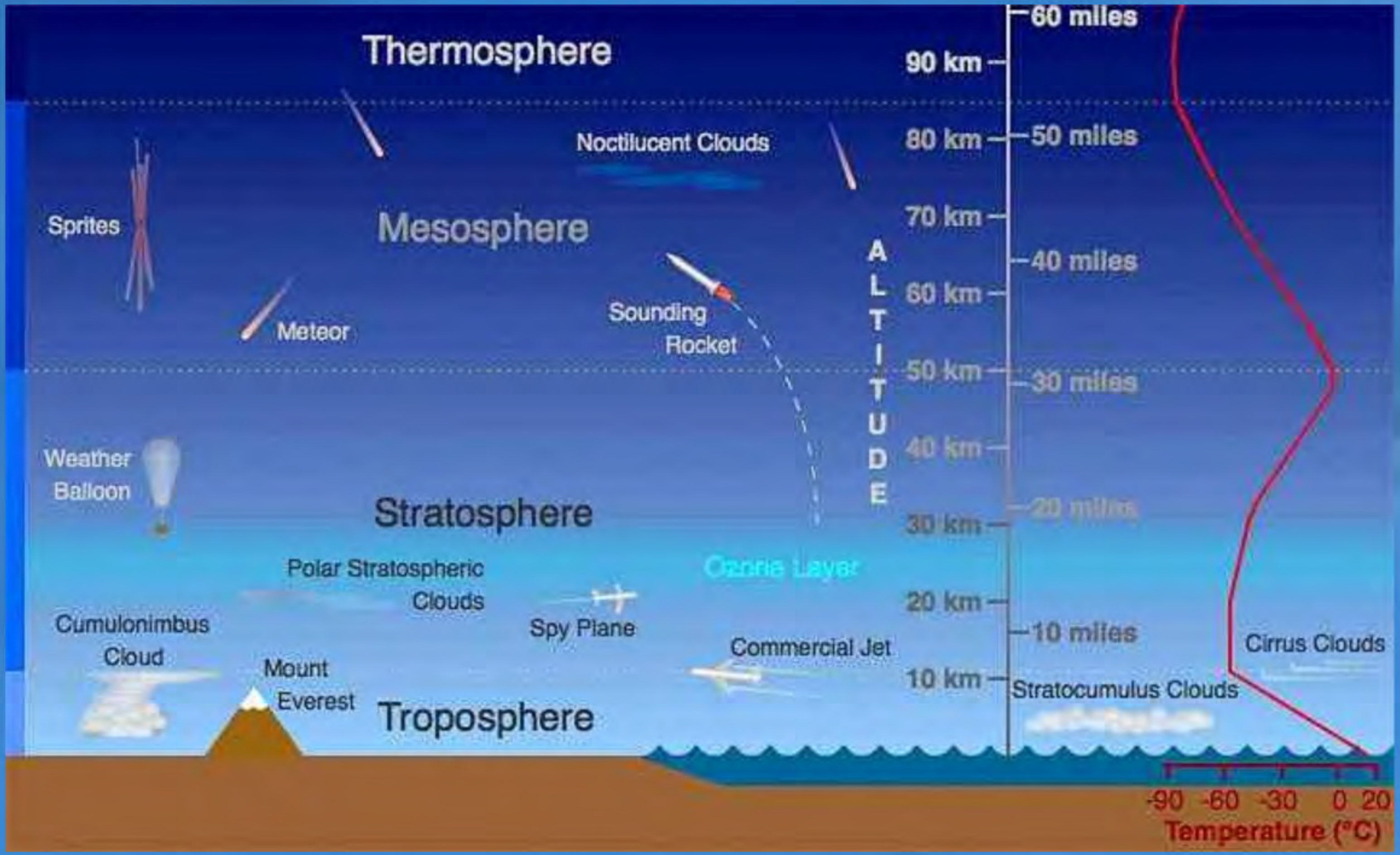
- Vented zero-pressure balloons with ballast.
- Conventional duration balloon missions last ~<48 hours
- Long Duration Flights from Antarctica last up to ~55 days with multiple circumnavigations.
- Ultra-Long Duration Flights can last up to ~100 days.



Credit: NASA/APL

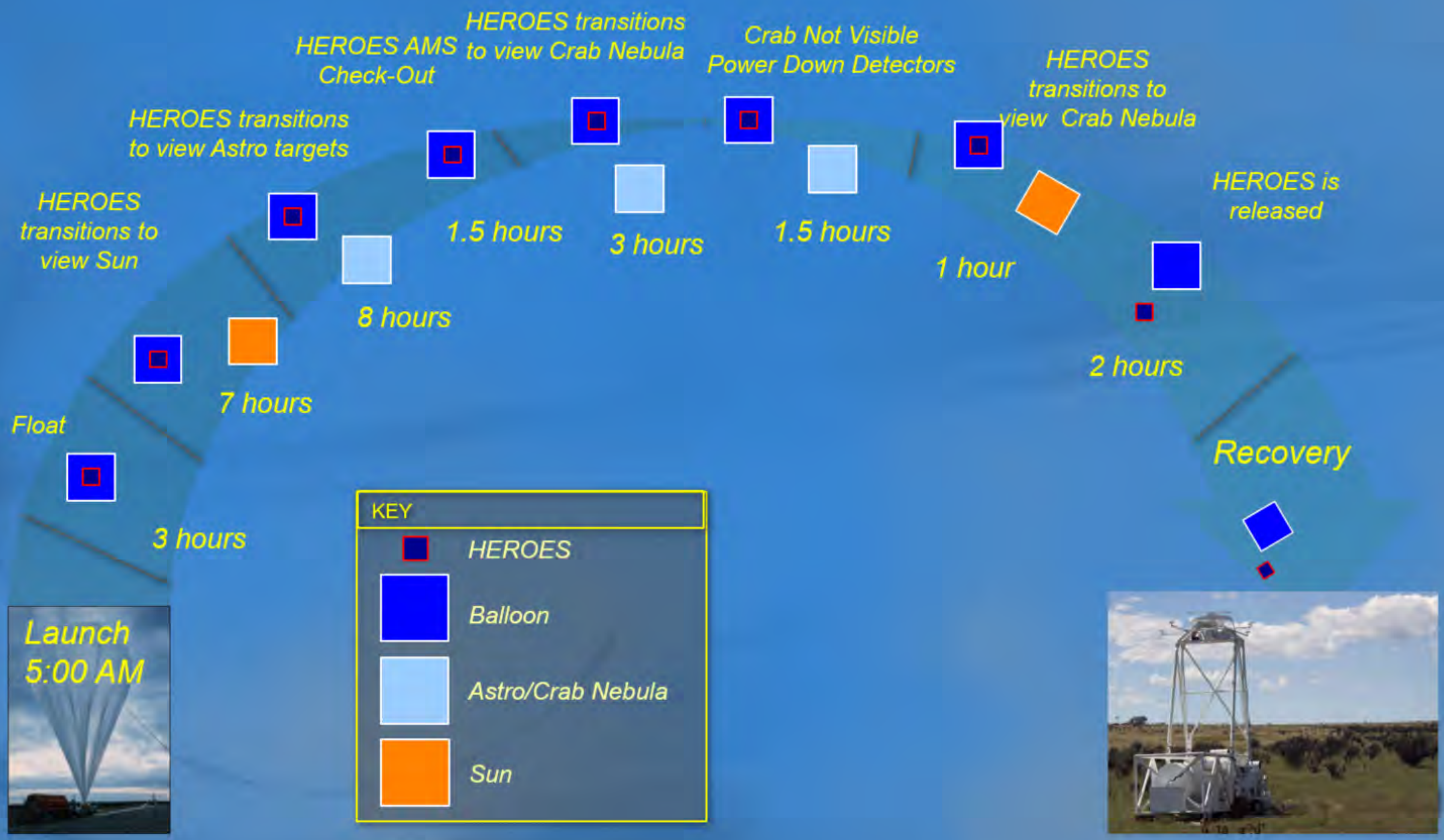
Artist rendition courtesy of NASA

High-Altitude Ballooning Challenges

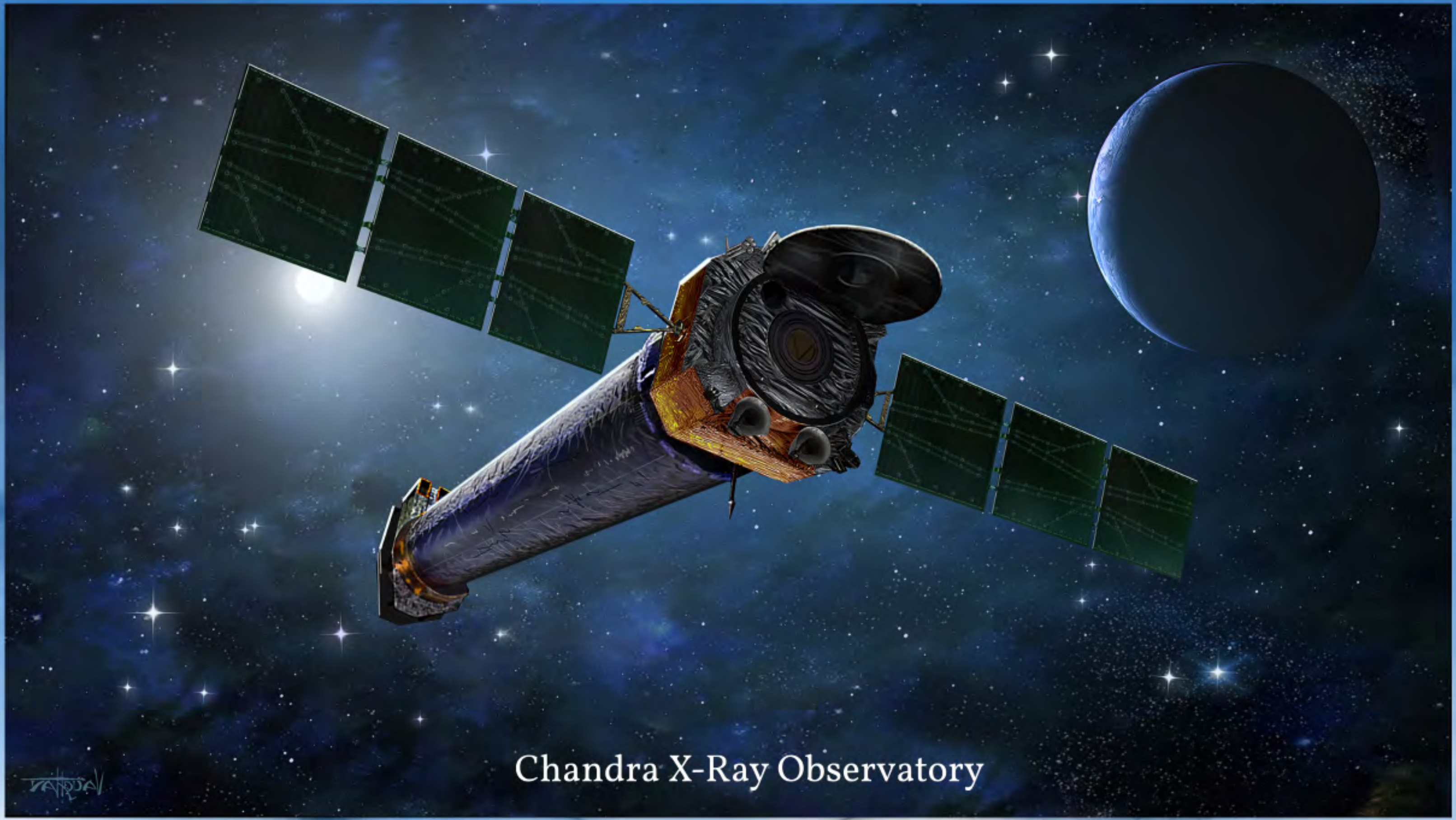


UCAR/Randy Russell

HEROES Observations



Space-Based Missions


Chandra X-Ray Observatory

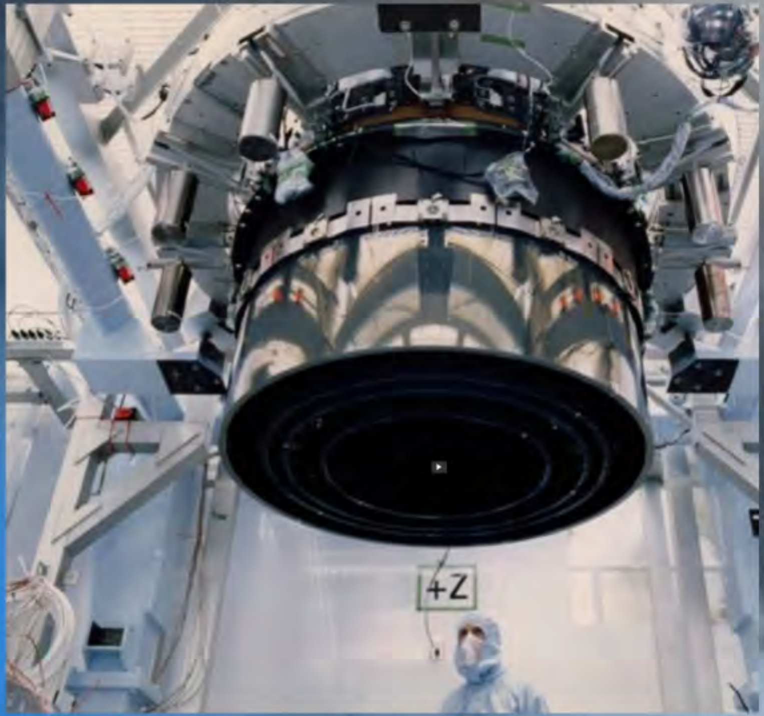
Credit: NASA/CXC & J.Vaughan

X-Ray Optics

Chandra X-Ray Observatory

Lynx Observatory

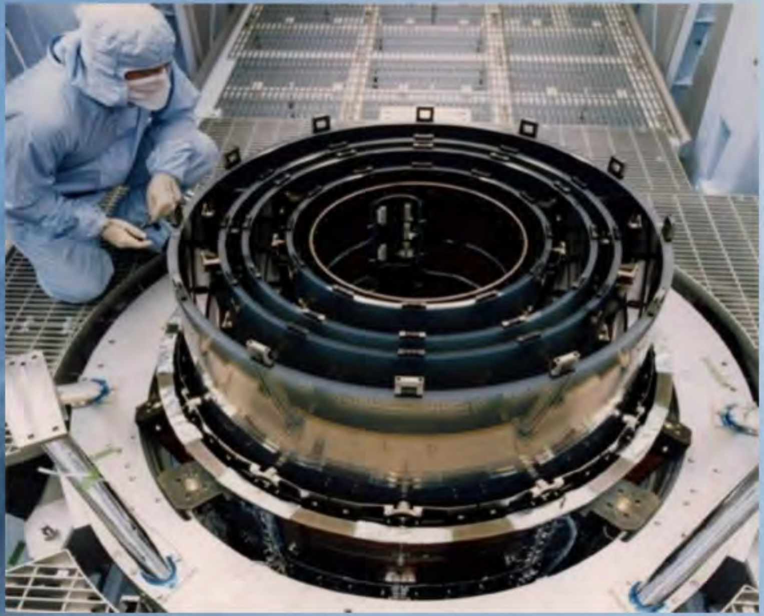
Let's Focus!



"The alignment of the mirrors from one end of the mirror assembly to the other (2.7 meters or 9 feet) is accurate to 1.3 micrometers (50 millionths of an inch) or about one fiftieth the width of a human hair! "

"If the State of Colorado were as smooth as the surface of the Chandra X-ray Observatory mirrors, Pikes Peak would be less than an inch tall."

The mirrors were polished to better than 7 angstroms RMS micro-roughness and have a 600 angstrom iridium coating.



Credit: NASA

Chandra can detect and image X-ray sources that are billions of light years away.

The focusing power is equivalent to the ability to read a newspaper at a distance of half a mile!

Jupiter

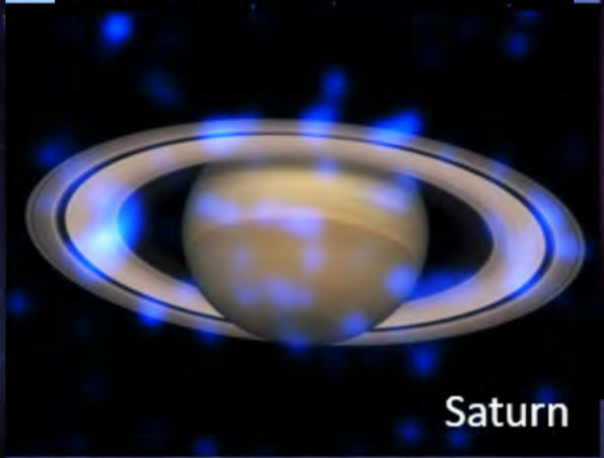
Milky Way Central Region

Crab Nebula

Cass A

NGC 4258 (M106)

Whirlpool Galaxy (M51)



Saturn

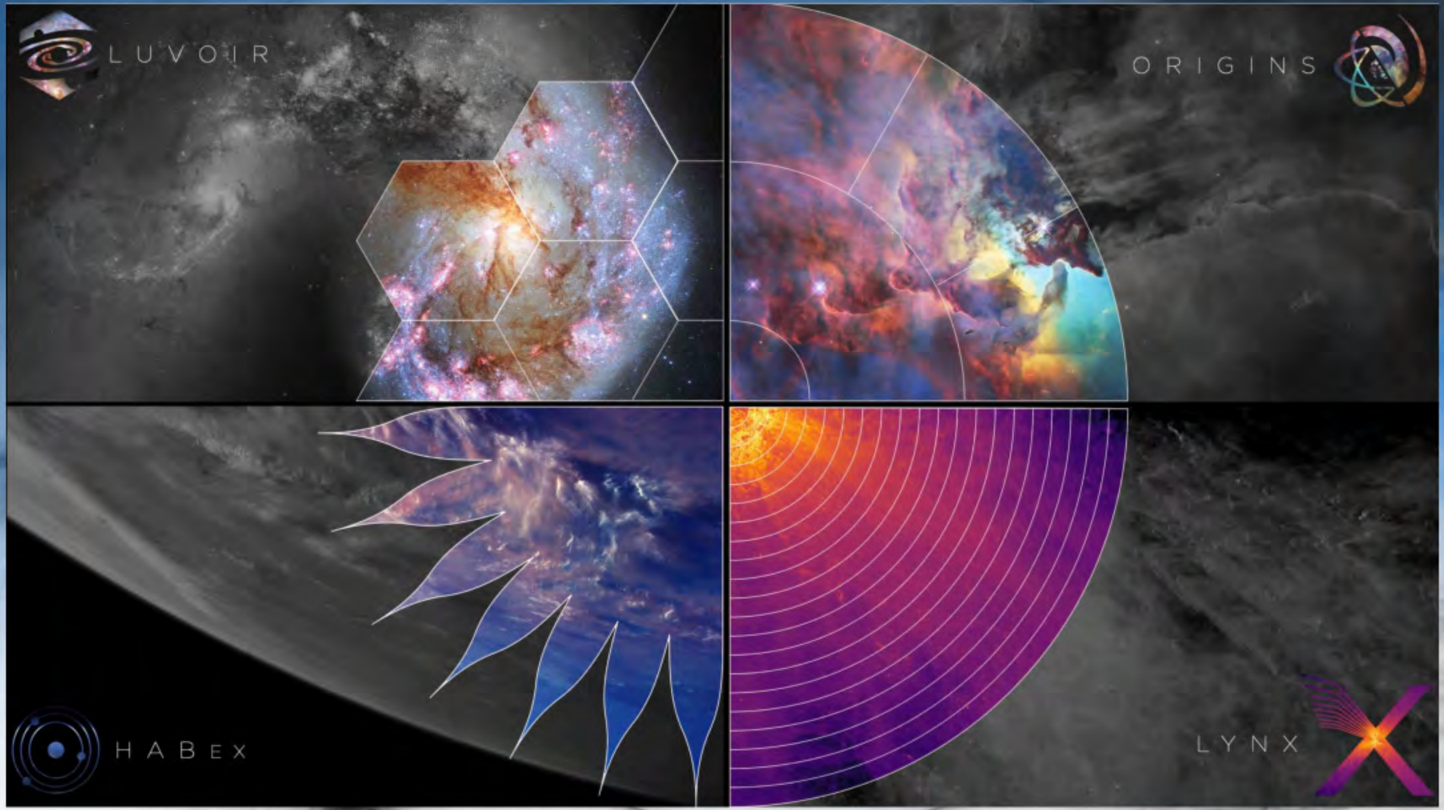
Perseus Cluster

NGC 6357

Cyg X-1

Credit: NASA

The New Great Observatories!



https://www.greatobservatories.org/

X-RAY OBSERVATORY LYNX

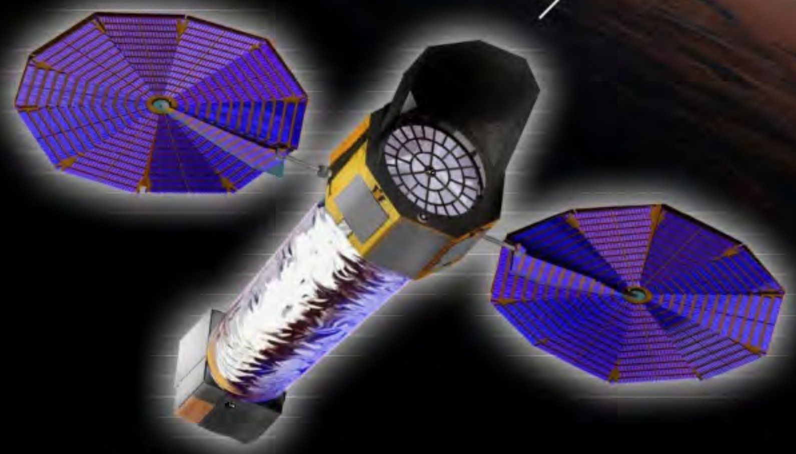
The Next Great X-Ray Observatory!

https://www.lynxobservatory.com/

A NEW GREAT OBSERVATORY

X-RAY MIRROR ASSEMBLY

0.5'' Point-Spread Function, stable over a 20 arcminute FoV



HIGH DEFINITION X-RAY IMAGER

LYNX X-RAY MICROCALORIMETER

X-RAY GRATINGS SPECTROMETER

HIGH DEFINITION X-RAY IMAGER

Designed for exquisite imaging and wide surveys, the HDXI is an active pixel array covering a 20′ x 20′ field of view with subarcsecond imaging.

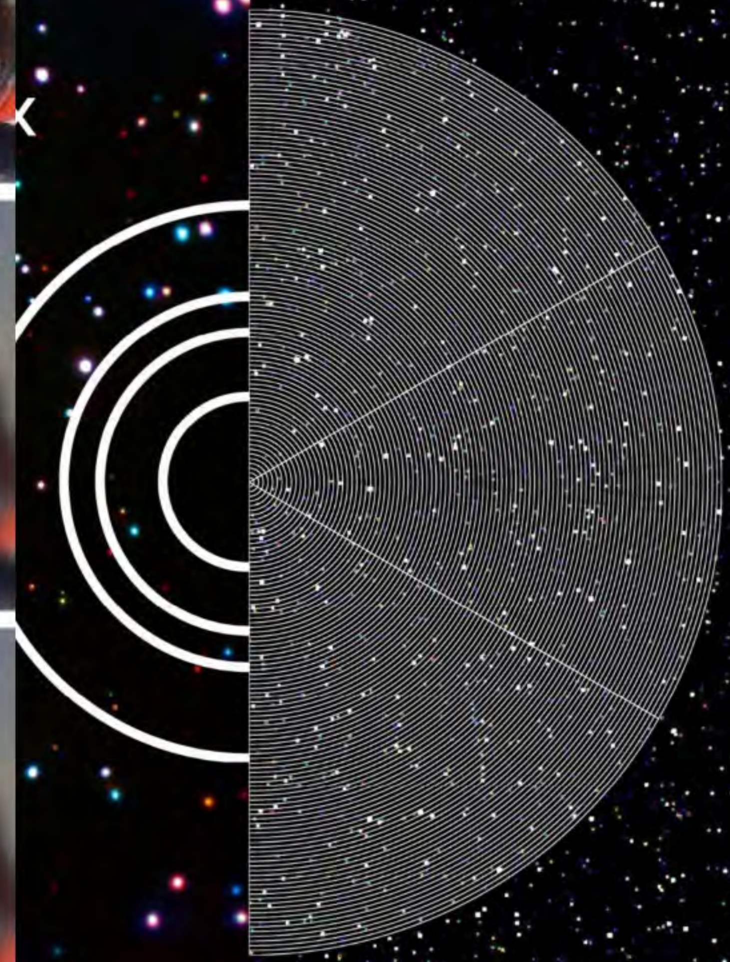
LYNX X-RAY MICROCALORIMETER

Spatially resolved 3 eV spectroscopy across a 5′×5′ field of view, sampled with 1″ pixels. Two subarrays optimized for finer imaging and higher spectral resolution.

X-RAY GRATINGS SPECTROMETER

Spectral resolving power of $R > 5000$ with ~4000 cm^2 of effective area across the critical X-ray emission and absorption lines of C, O, Mg, Ne, and Fe-L.

Created by David J. Marmor, MFA and Michael F. Marmor, MD © 2010 *Archives of Ophthalmology*



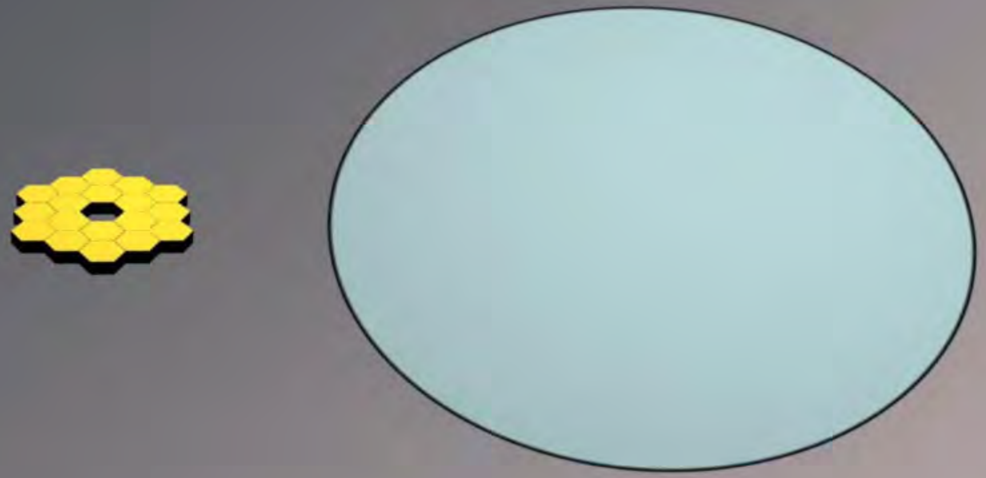
50x higher throughput while maintaining *Chandra's* angular resolution.

Like going from your 8” backyard telescope to a 10-m Keck.

What takes Chandra 8 weeks, Lynx can do in ~1 day for deep surveys.

LYNX X-RAY OBSERVATORY

Lynx Mirror Assembly has a 3m diameter



JWST Primary Mirror: 6.5 m

Lynx Mirror: 25 m
to 3 m diameter assembly

THE SCIENCE

Lynx is designed to pursue three science pillars.

There are ample resources for many other programs, including those unexpected today.

It will be a discovery platform for all.

WWW.HIDDENCOSMOS.ORG

X-Ray Optics Capability at NASA MSFC

Optics Design & Fabrication

Test & Calibration Facilities

MSFC X-Ray Astronomy Group

X-Ray Optics

Science & Technology Office

***Mission**: Provide profound insight into our view of the Universe through our ability to lead the World in the development, flight, and test of advanced X-ray optics; to enable future, impactful science missions; and inspire the next generation of astronomers.*

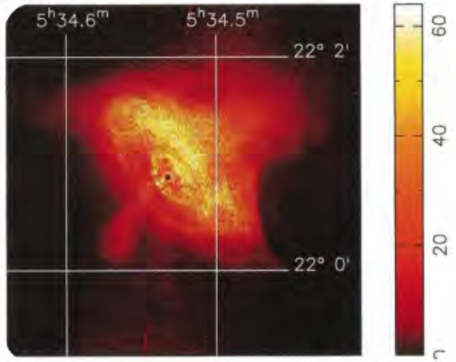
MSFC X-Ray Astronomy Group

- Wayne Baumgartner
- Stephen Bongiorno
- Chien-Ting Chen (USRA)
- Grant Davis (Student UAH)
- Jacqueline Davis
- Steven Ehlert
- Jessica Gaskin
- Danielle Gurgew (USRA)
- Phil Kaaret
- Jeff Kolodziejczak
- Steve O'Dell
- Brian Ramsey (Emeritus)
- Oliver Roberts (USRA)
- Srikanth Panini Singam (NPP ORAU)
- Douglas Swartz (USRA)
- Allyn Tennant
- Nick Thomas
- Martin Weisskopf (Emeritus)

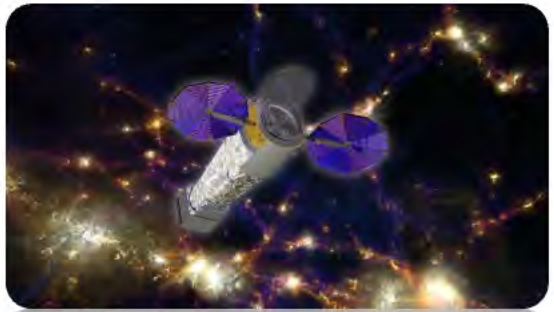
Mission Support & Science Operations

X-Ray Optics

Astrophysics



Mission Concept Development



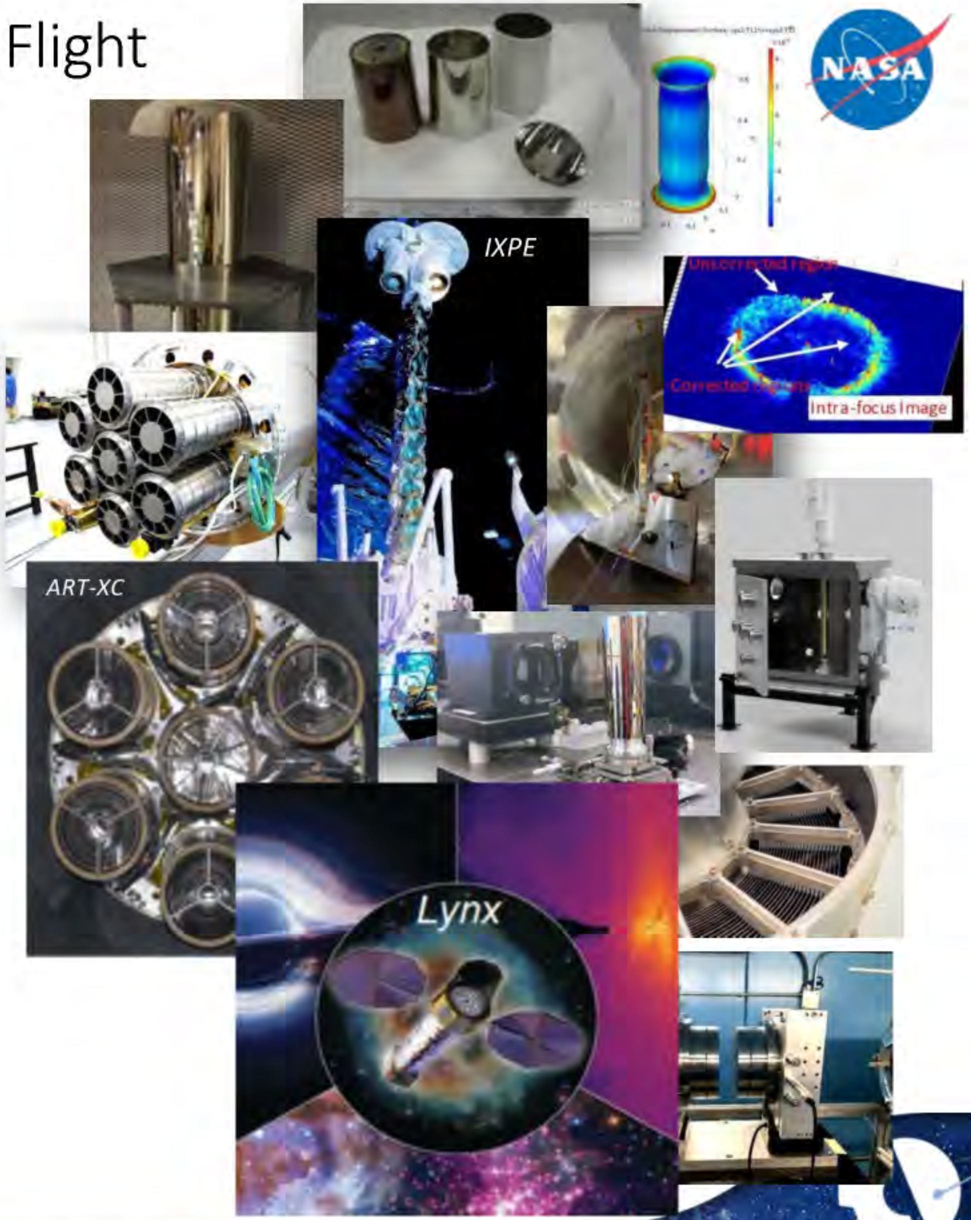
MSFC ADVANCED X-RAY OPTICS: Formulation to Flight

MSFC's goal is to serve the Astronomy Community by:

- Developing the next generation of sub-arcsecond *full-shell* mirrors and assemblies
- Continuing to supply low-cost, moderate-resolution flight mirrors and assemblies
- Enhancing the performance of segmented optics

Essential and *unique* elements that build on decades of NASA and external investments Includes:

- Optical design and analysis
- Mandrel Fabrication/polishing
- Mirror shell replication
- Mirror direct polishing
- Mounting and alignment
- Post figure-correction
- Metrology
- Thin-Film Research
- X-ray test and calibration



MSFC ADVANCED X-RAY OPTICS: Formulation to Flight

- MSFC develops complete mirror assemblies with predictable flight performance for the Astronomy community

- Technology developments are relevant to future strategic X-ray missions that use either full-shell or segmented mirrors (e.g. *Lynx*)

- Provides world-class X-ray test and calibration with the MSFC 100-m X-ray Beamline and X-ray & Cryogenic Facility for community testing of technologies and flight hardware

- Provides X-ray mirror and test capabilities to other SMD divisions (Heliophysics - FOXSI & Planetary-MiXO) and other government entities (NIF, NIST, Sandia National Lab, etc.)

We regularly fly full-shell mirror assemblies!

Chandra

HERO/HEROES Balloon

SRG-ART-XC

IXPE

FOXSI Sounding Rocket

RedSOX

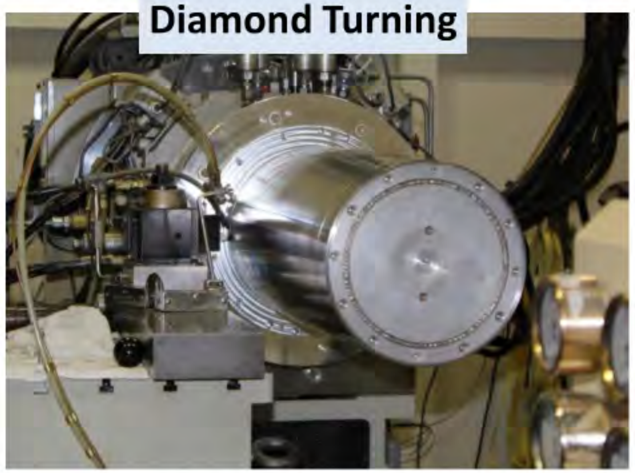
Full-Shell Mirror Shell Production Process: Electroformed Nickel Replication

Mandrels have an aluminum core, with a high-phosphor nickel coating and the prescription is cut into the nickel layer.

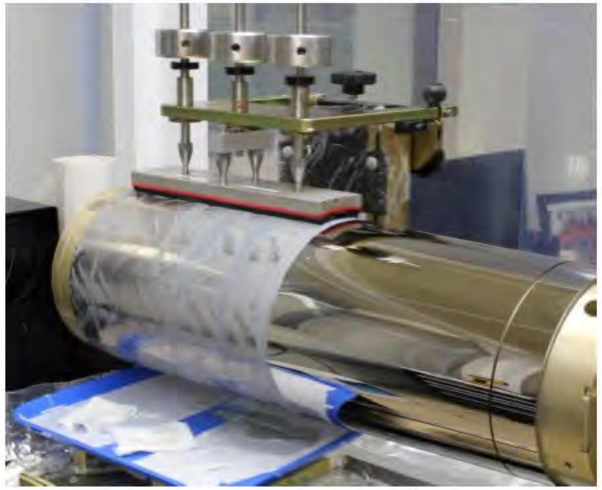
Aluminum Mandrel Blank

EN Plating

Diamond Turning

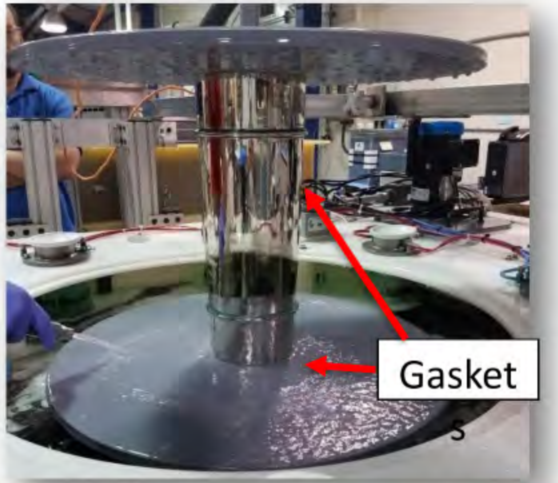


Mandrel Lap Polishing



Zeeko Polishing

Mirror Shell Electroforming



Mirror Shell After Separation

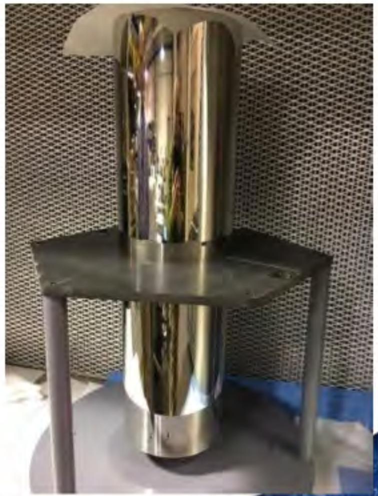


Figure correction via deterministic CNC polishing: X-ray mandrels

Jeff Kolodziejczak, Patrick Champey

Developed techniques to ensure robust convergence.

- Remove out-of-band errors with lap polishing before CNC.
- Lap super-polish for final surface finish before final fine-slurry CNC pass.
- Verify alignment and registration before every pass.

CNC deterministic polishing improved figure error by 25x.

1.9-2.0 nm RMS final mandrel convergence errors after CNC polishing.

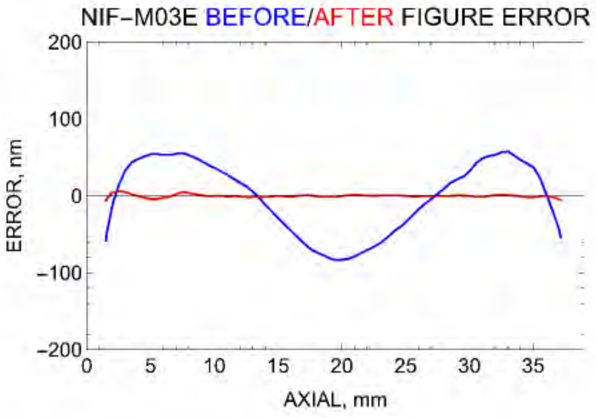
- 54mmDx70mmL mandrel
- predicted HPD:

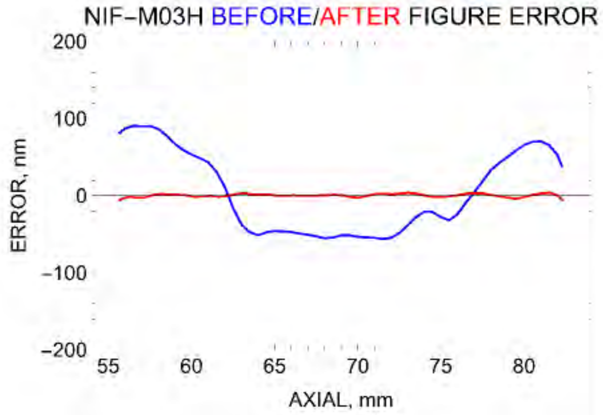
E + Ideal H: 1.0 arcsec

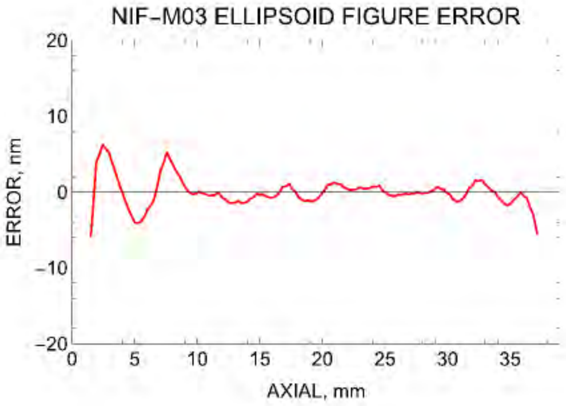
H + Ideal E: 1.8 arcsec

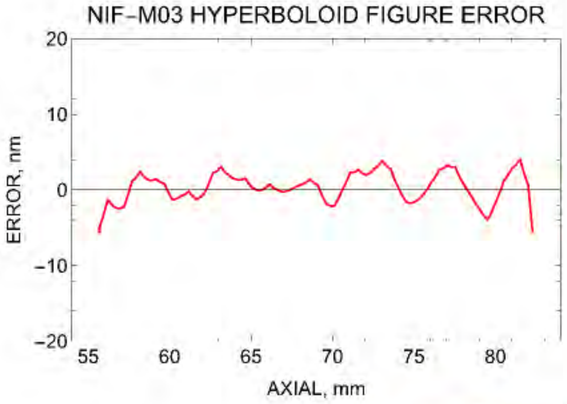
E + H: 2.3 arcsec

8.1 microns at object

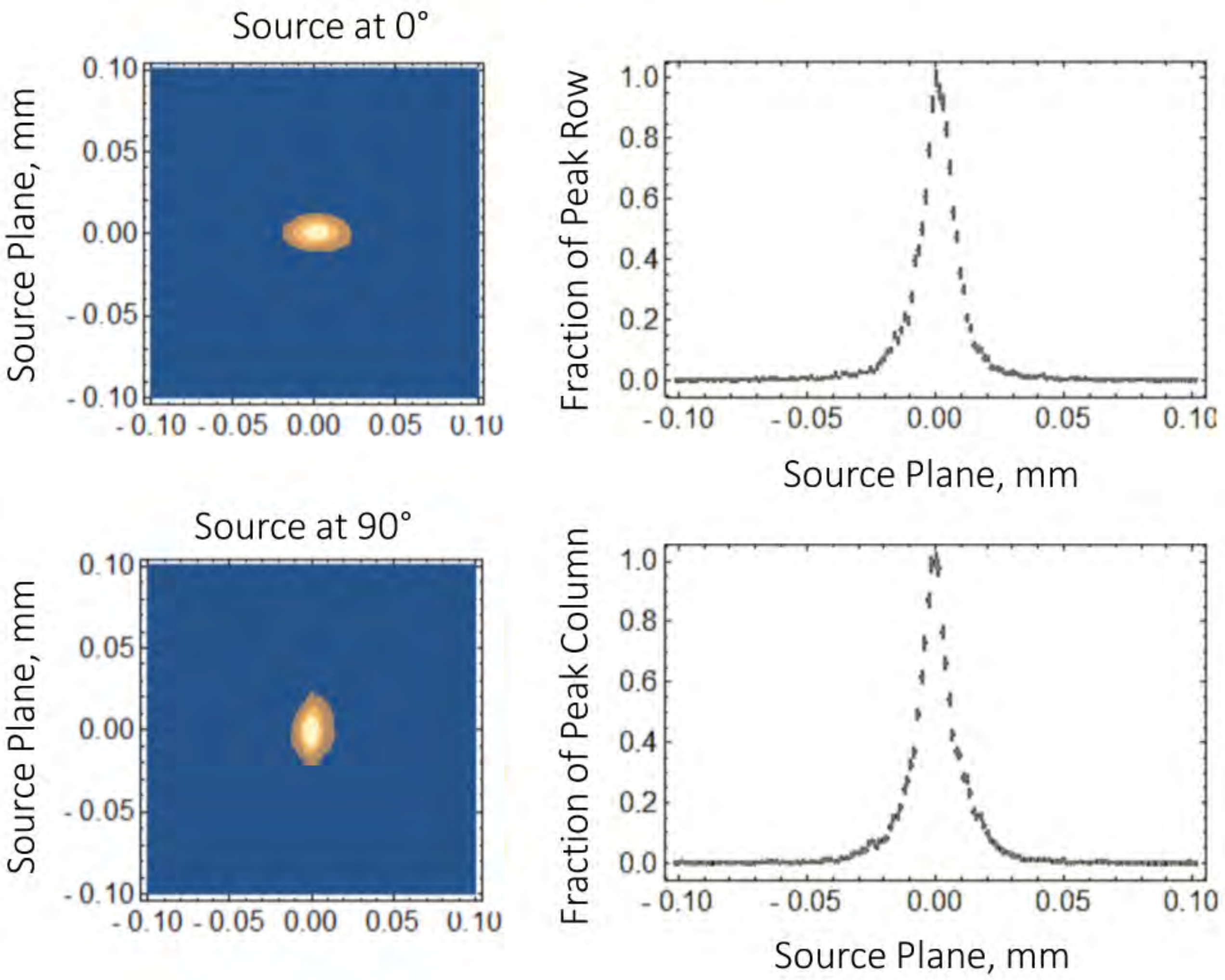








Measured FWHM X-Ray Performance



13.0 microns FWHM in source plane

Assuming 9.4 micron source implies
2.58 arcsec optic contribution.

X-ray Performance:
2.3±0.3(1σ) arcsec FWHM
8.1±1.0 microns in source plane

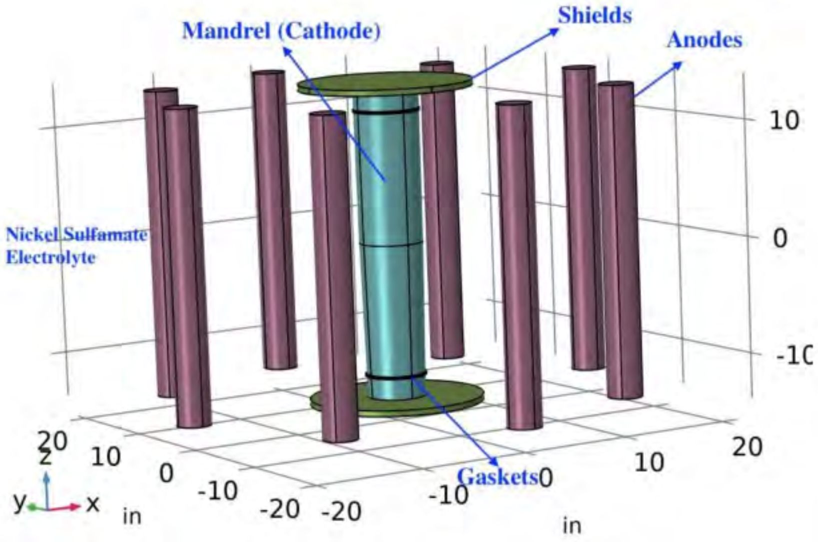
11.6 microns FWHM in source plane

9.4 micron source implies
2.0 arcsec optic contribution

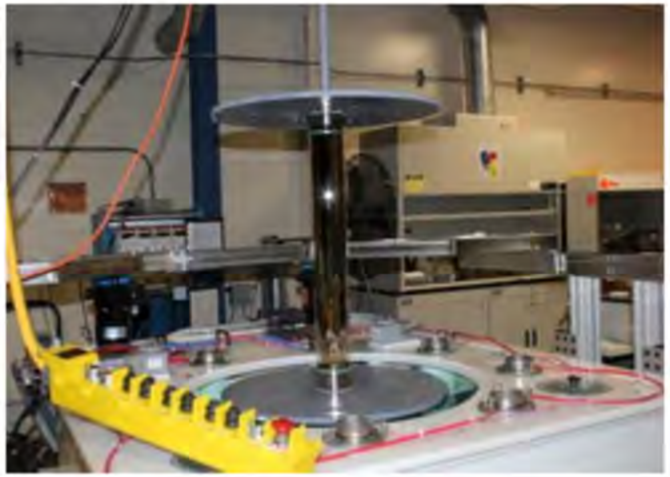
Electroformed Replication Technology

Srikanth Panini Singam

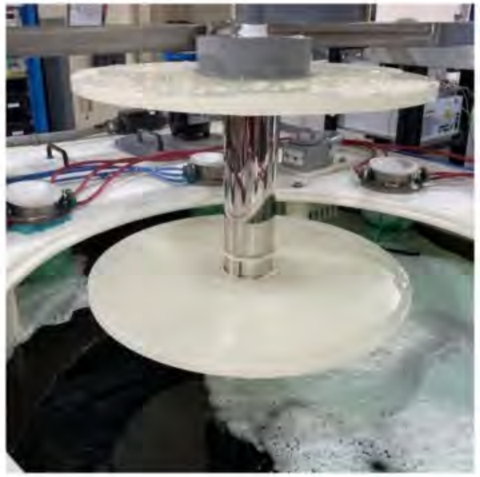
- Material from anodes deposits on mandrel taking its shape.
- Alloys like Ni-Co, Ni-P, Ni-Co-P are used by using different anodes simultaneously.
- Optics is separated from mandrel using ice water bath.
- Excellent reproducibility with predictable performance.



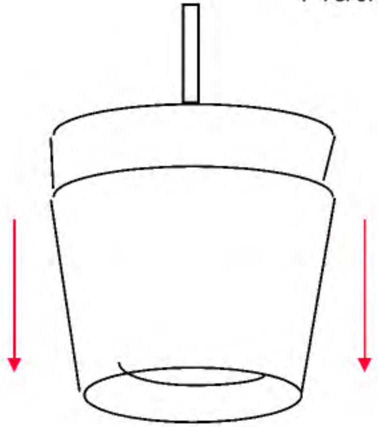
Plating tank configuration



1. Loading mandrel



2. Mandrel with NiCo Plating



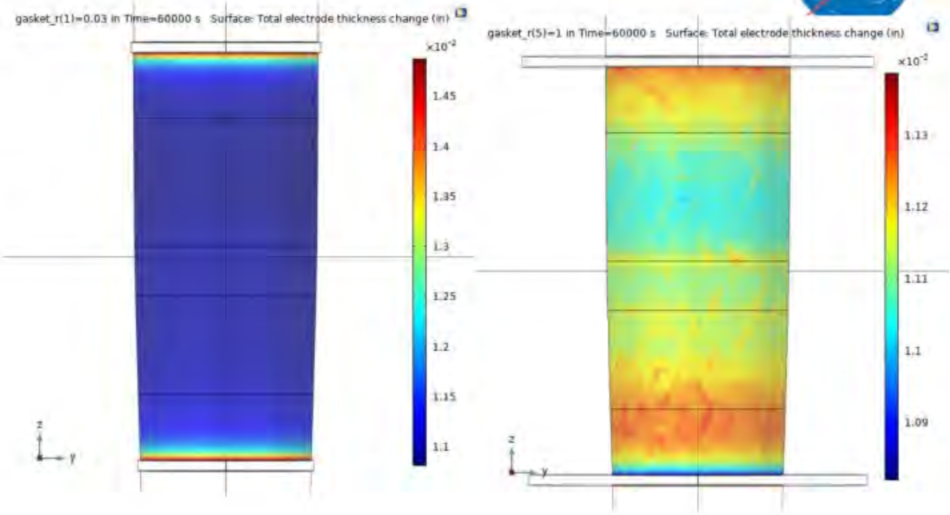
3. Shell separation

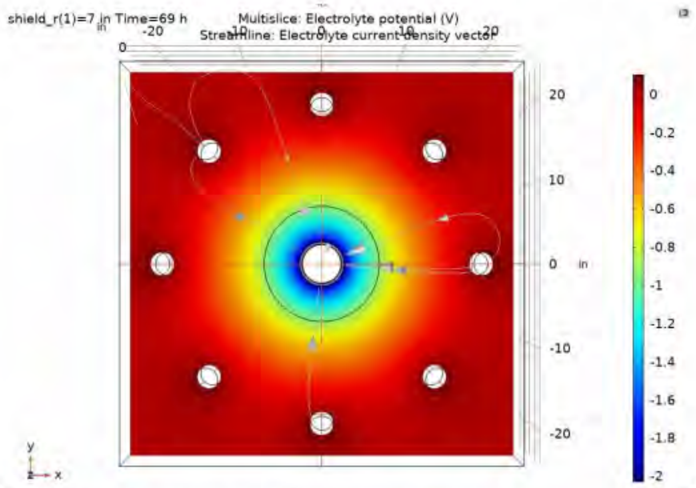
4. NiCo electroformed optics

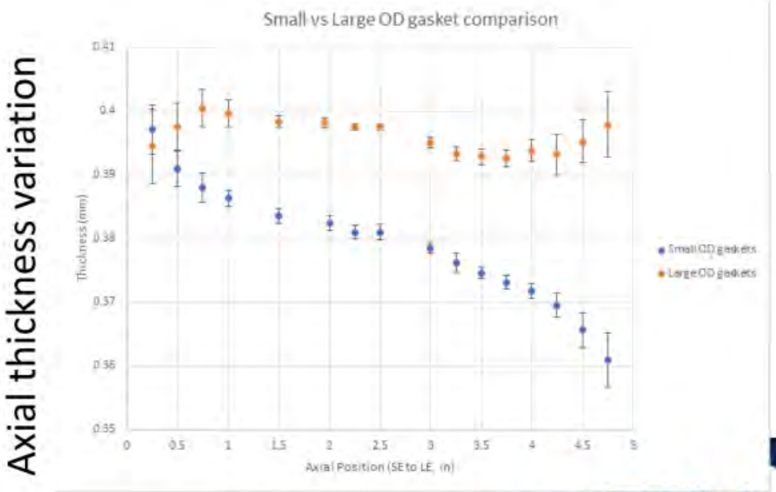
Towards sub-arcseconds optics…

COMSOL simulations

- Axial thickness variations contribute about a few arc seconds PSF.
- Modelling helps to understand the process with greater precision.
- Optimizing the plating geometry to control the local E-fields to have uniform thickness and stress.
- Significantly lowered the replication errors.
- Optics matches the mandrel at a few arc-second level.
- Ex: Sandia Optics (with same mandrel):
  - **102" (HPD) with out optimization.**
  - **4.6" (HPD) with optimized gaskets.**
- Further optimization of process is being carried out for FOXSI optics.



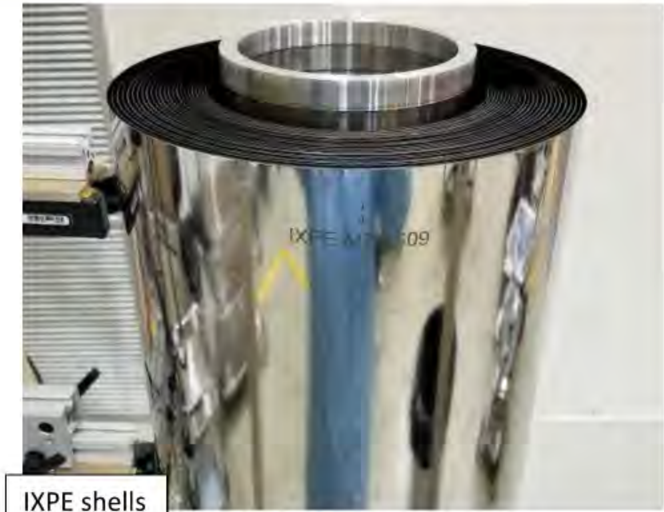




Champey et.al, 2022

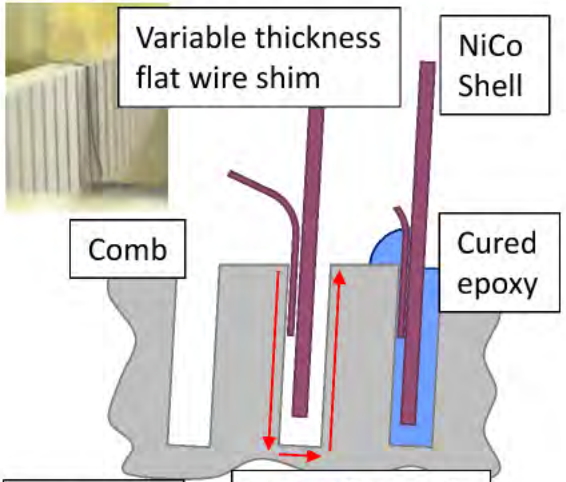
Shell Alignment and Mounting Background

Stephen Bongiorno



IXPE shells

Shell alignment



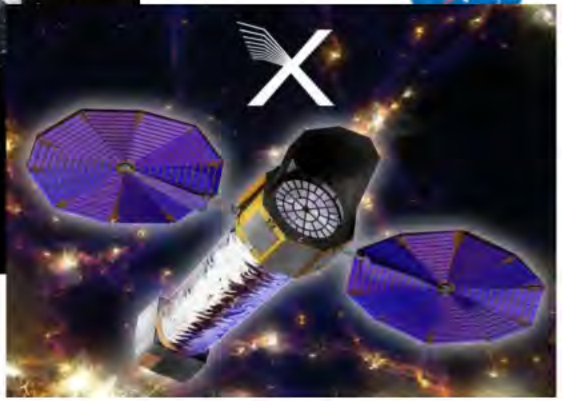
Bond design

- Grazing incidence optics for astrophysics applications are thin and heavily nested to reduce telescope mass/volume (left).
- Gravity sag and epoxy shrinkage significantly affect optical performance. To mitigate these effects during assembly, shells are hung from wire suspension (center). To reduce epoxy effects, bonds are designed as symmetric double lap joints (right).

	Tilt (arcsec)	Centering (µm)	Circularity (RMS µm)	Shape knowledge (arcsec HPD)	Epoxy shrinkage (arcsec HPD)
IXPE (96 shells)	10	16	34	~5	2.3
Sub-arcsec optics	<10	<5	<10	<1	<1

X-ray Mirror Coatings at MSFC

Danielle Gurgew

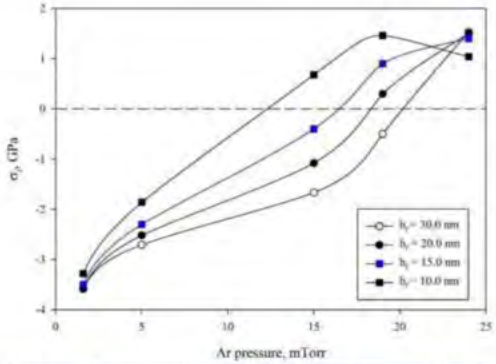


Motivation

- Develop advanced low stress x-ray optical coatings enabling future missions such as *Lynx* and *HEX-P*
- Low stress coatings are key for achieving energy bandpass and angular resolution requirements

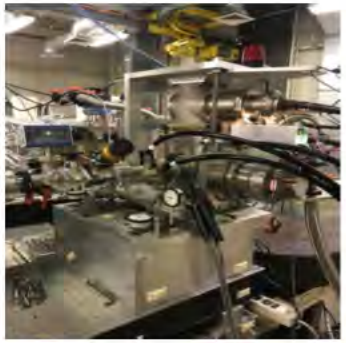
Areas of Coating Development

- Next generation multilayer coatings for broadband X-ray imaging
- Extend coating capability of DC sputtered films to full shells and segments
- Low stress coatings: single layer and multilayer



Facilities and Capabilities

- RF and DC magnetron sputtering
- Single layer + multilayer coatings
- In-situ stress measurements
- Precision adhesion test system
- Metrology labs
- X-ray reflectometer



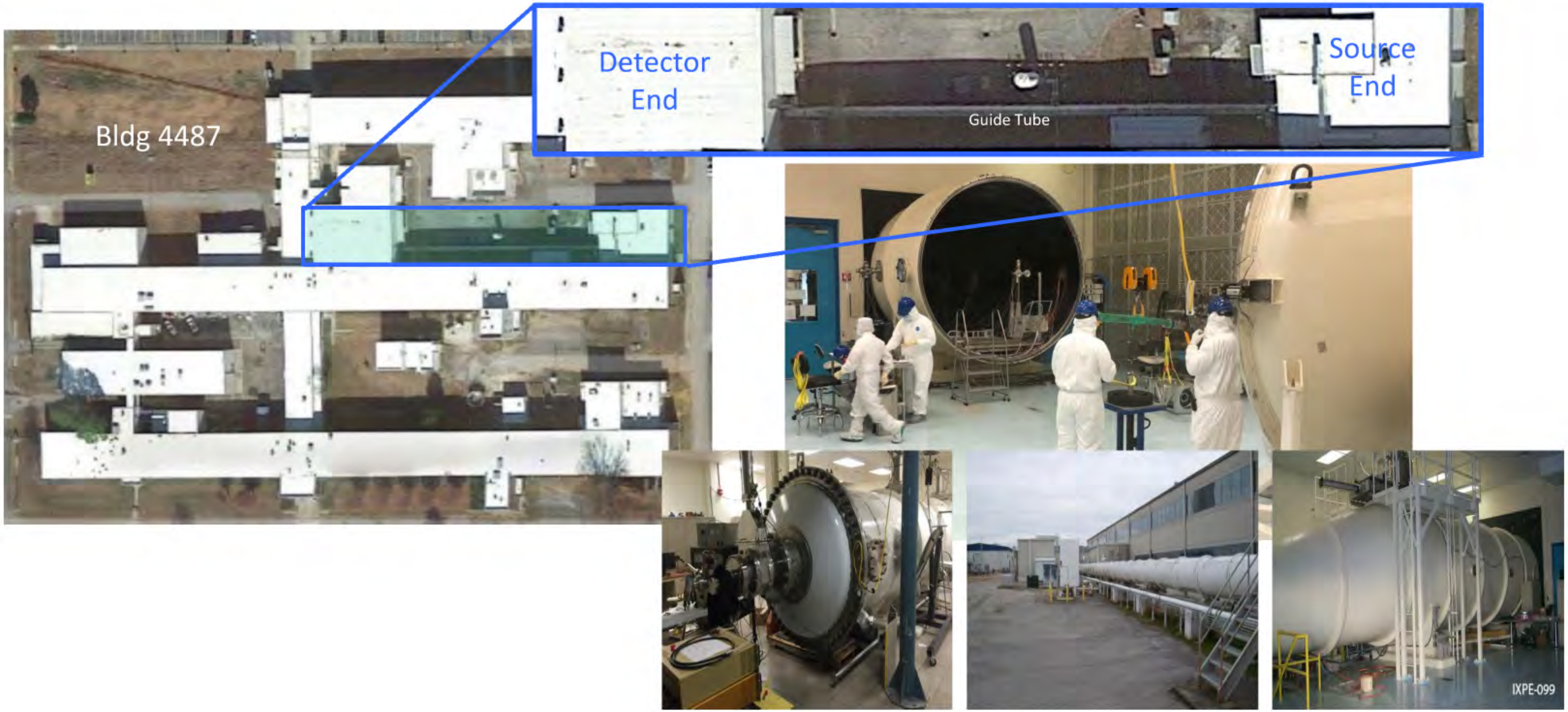
World Class Test and Calibration Facilities

MSFC 100-m Test Facility

X-Ray and Cryogenic Facility

The Marshall 100-Meter X-ray Beamline

The user-friendly Marshall Space Flight Center X-ray optical test facility



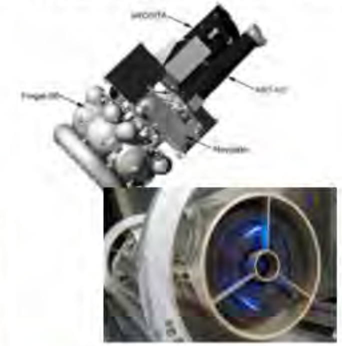
Background: The Marshall 100-m X-ray Beamline

Providing trusted expertise and solutions for high-energy telescopes and instrumentation test and calibration

- **User-based facility for X-ray optic calibration and instrument testing.**
- **Normal incidence stray-light and environmental testing.**
- **Essential tool utilized for MSFC internal grazing incident, replicated shell, development activities.**
- **The MSFC 100-m is advertised to all APRA funded projects.**
- **Support provided to other NASA Centers, Universities, and Industry.**

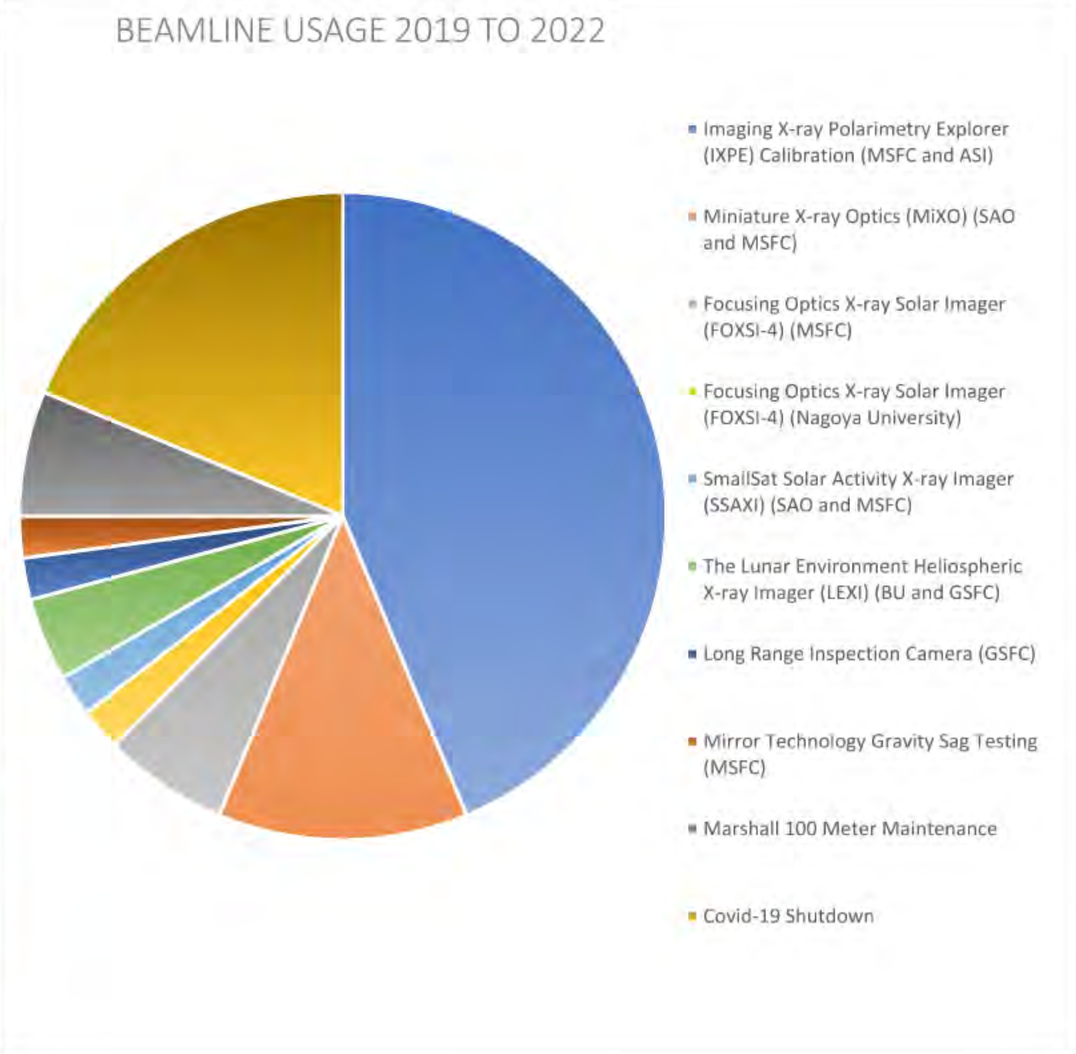
HERO/HEROES (balloon)
8 Modules, 13/14 shells

ART-XC (satellite)
8 Modules, 28 shells, qualified



FOXSI (rocket)
7 Modules, 7/10 shells

IXPE (SMEX)
3 Modules, 24 shells

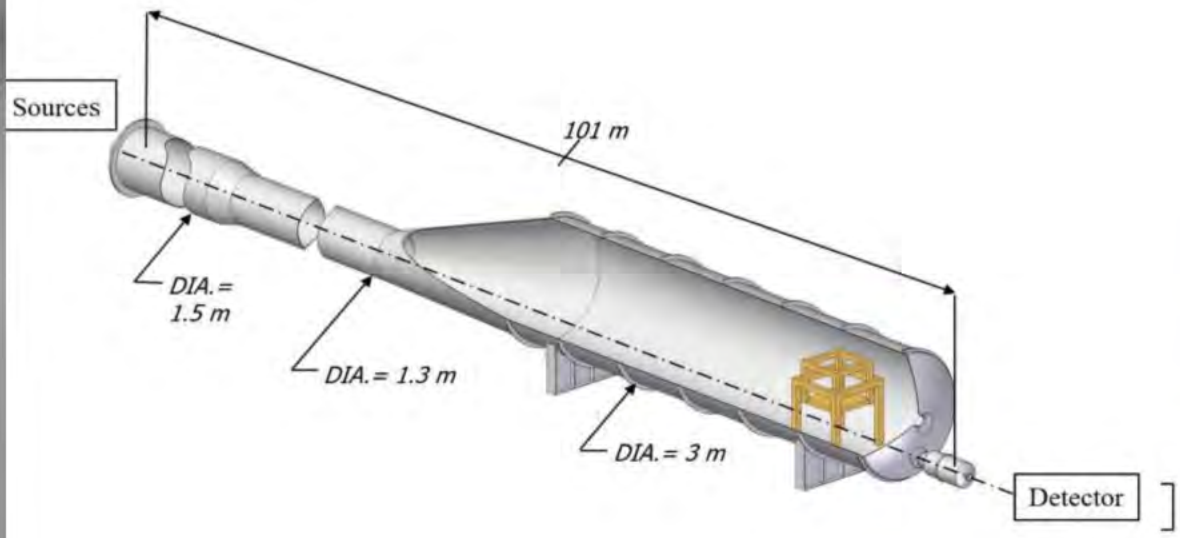


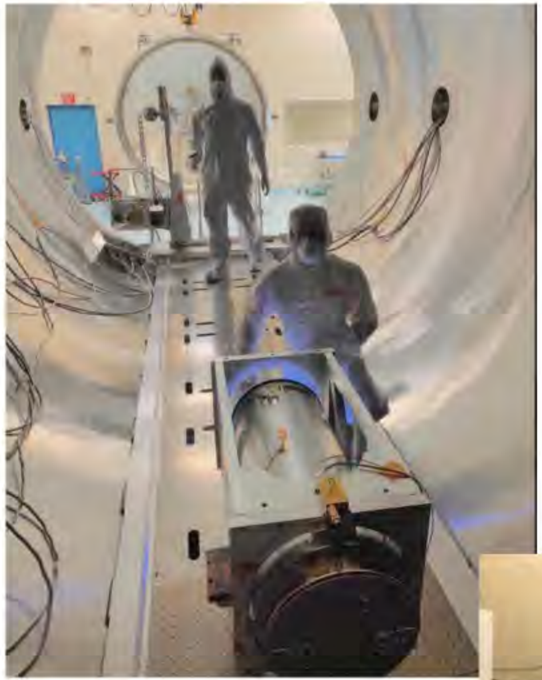
Marshall 100 Meter

General facility information

Nominal operation - chamber can be pumped to:

- **Low 10^{-5} Torr in less than 4 hours**
- **10^{-6} Torr in approx. 4-6 hours**
- **10^{-7} Torr in approx. 6-8 hours**





- Total facility: 101 meters long
- Beamtube: 1.3 meter-wide
- Detector chamber: 3 meter-wide, 8 meters long

- Cleanrooms
  - 10K instrument chamber
  - 100K work/staging area
  - Gowning facility
- Loading dock accessible

Marshall 100 Meter

Source Room

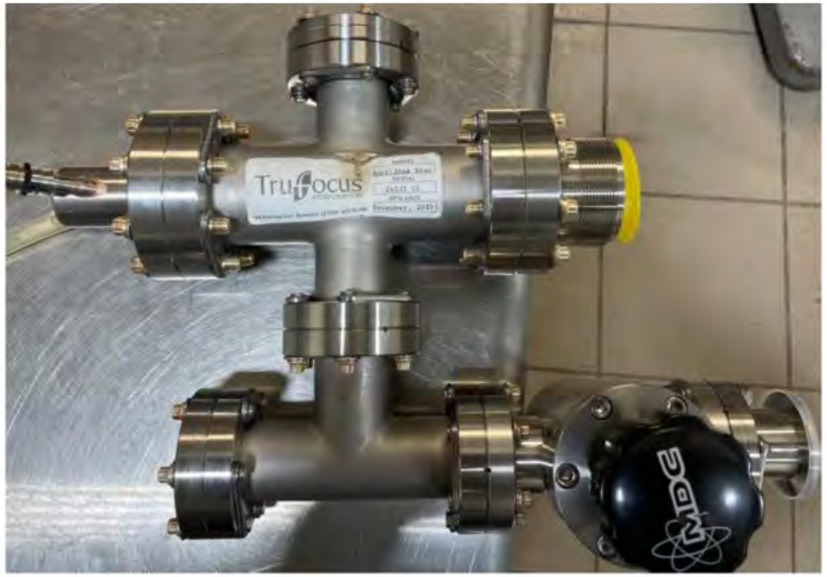
- Sub arcsecond sources
- Flange alignment stage
- Controlled from detector room
- Filters and OBF available

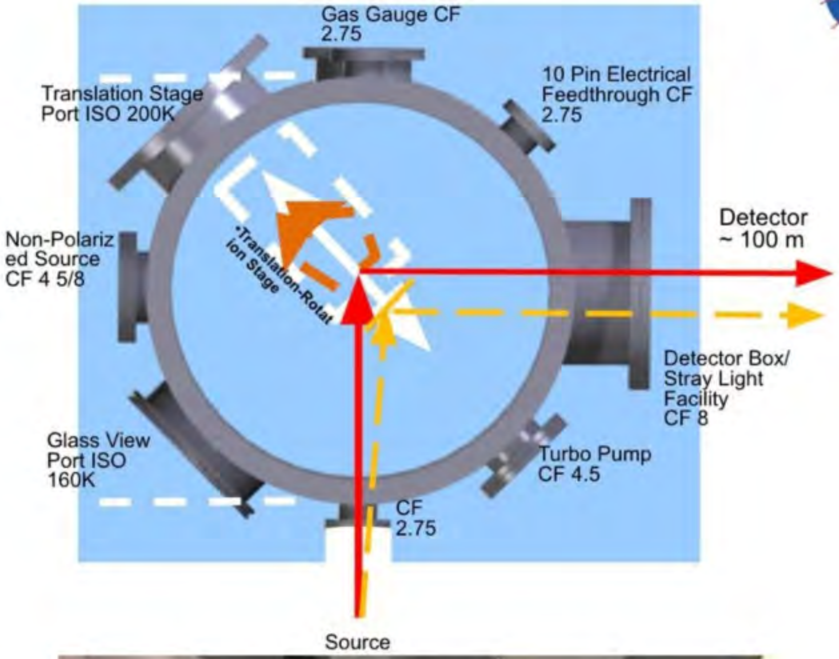
Tube Brand	Anode	Line (keV)	Max Voltage (kV)	Max Current (mA)
TruFocus 6050	Mo	2.2 (l)	50	1
(Be window)	Rh	2.7 (l)	50	2
	Ti	4.5 (ka)	50	2
	Fe	6.4 (ka)	50	1
	Cu	8.1 (ka)	50	1
TFX3110EW	W	8.4(l),59(ka)	110	2.5
TruFocus-10-2-AL	Al	1.49 (ka)	8.5	0.5
Manson Source	var	var	10	1

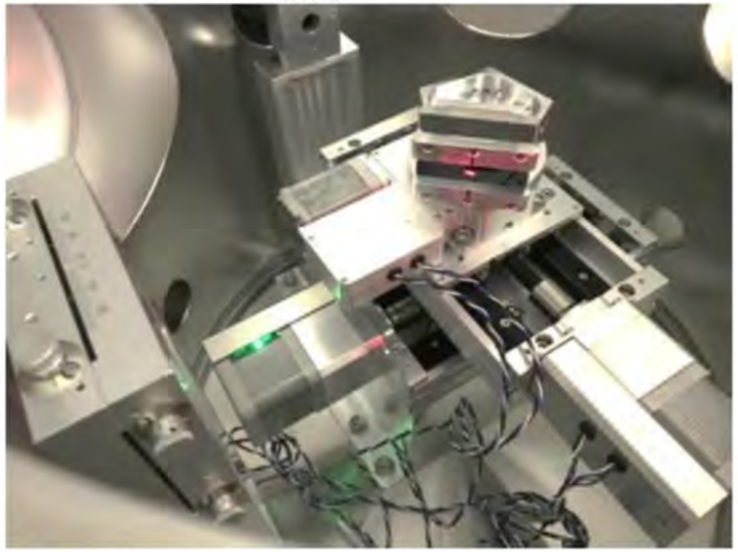
Marshall 100 Meter

Source Room

Trufocus
30kV/30mA
X-ray Source







Anode	Line (keV)	Max Voltage (kV)	Max Current (mA)	Crystal
Rh	2.7	30	30	Ge(111)
Ti	4.5	30	30	Si(220)
Fe	6.4	30	30	Si(400)

Marshall 100 Meter

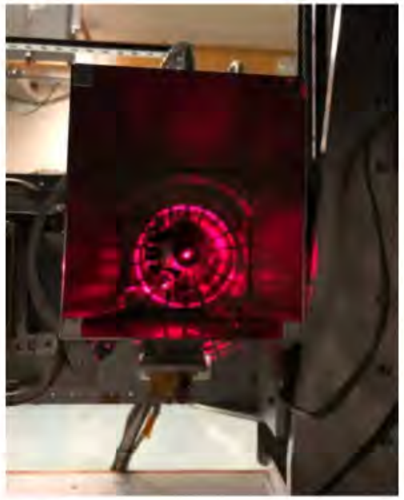
Facility Detectors

- **CCD**
  - Andor DW436, SN 10513
  - 2048 X 2048 array of 13.5 um pixel
  - Optical blocking filter and shutter
  - Operates at -45 deg C
  - Characterize point spread function of beam.
- **SDD**
  - Amptek Fast-SDD (50 mm^2)
  - 12.5 um Be window
  - Si3N4 ‘C-II’ window
  - Fast count rate/low deadtime
  - Effective Area
    - Two detectors mounted both on focal plane and near optical node
- **CdTe**
  - Amptek XR-100 CdTe (25 mm^2)
  - For hard X-ray experiments (< 20 keV)

Marshall 100 Meter

Laser alignment

- Laser reflected off retractable mirror at source end.
- Diffuses to ~ 1 m diameter at detector end
- Allows for rough focus and alignment of X-ray optic

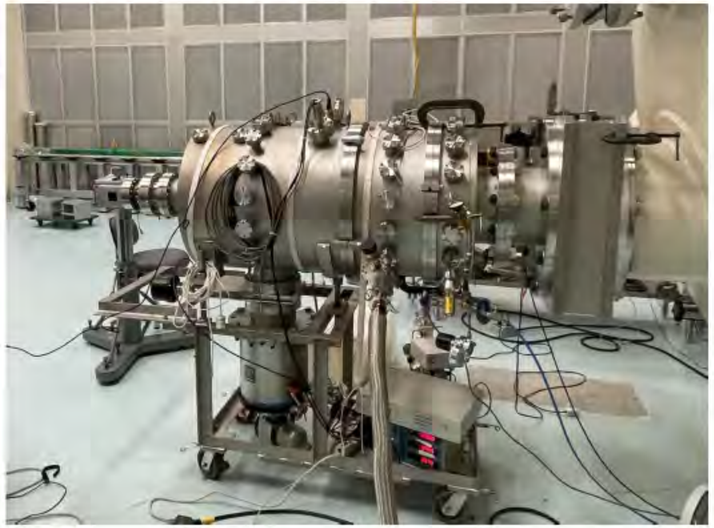


Hexapod (H-850)

- Load: 80 kg
- Range: +/- 30 degrees
- Optic/Collimator stage
- Programable motion

The Bell Housing

- External vacuum chamber, co-linear to the beamline
- Quick turnaround on test optics
- Internal Tip, Pan, and linear Z-stage
- External Andor CCD camera
- Be window allows for SDD measurements
- Additional tubing added for longer focal length optics



Parker X-Y Stage

- Load: 100 kg
- XY Travel: 36 in by 30 in (Res 0.1μm)

Summary

- The Marshall 100 Meter X-ray Beamline (*aka The Stray Light Test Facility*) is a world class X-ray optic test facility. It is capable of calibrating projects ranging from student lead experiments all the way to Explore size missions.
- The Marshall 100 Meter is advertised to all successful APRA funded projects. For additional community support (NASA Centers, Universities, and Industry) please contact:

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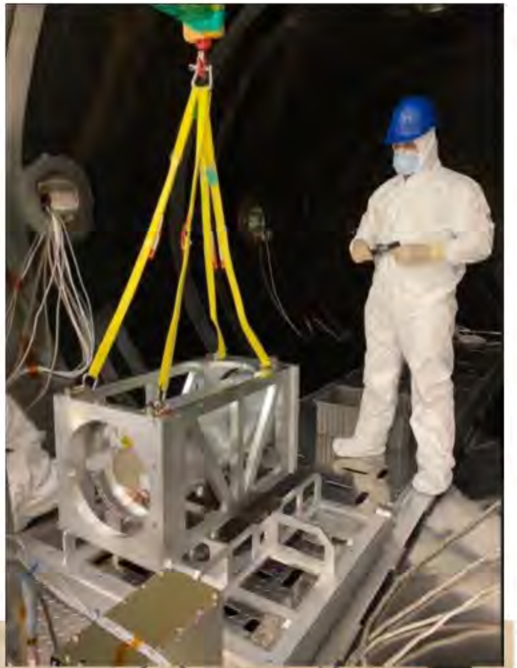

MSFC X-Ray & Cryogenic Facility (XRCF) Aerial View

Contact: **Jeff Kegley** for more information and facility use. **jeff.kegley@nasa.gov**

A brief history of the MSFC XRCF

the world's largest X-Ray calibration facility and the Agency's premier cryo-optical test facility

- 1989-1991 MSFC XRCF constructed to meet Chandra requirements
- 1991 Chandra's largest diameter mirror TRL verified
- 1992-1996 Modification to meet full Chandra requirements
- 1997 Chandra Mirror Acceptance Test and Telescope Calibration
- 1998-2005 X-Ray telescopes - including Hinode + addition of cryo/optical capability
- 2005-2008 Modifications & Tech Maturation for James Webb Space Telescope
- 2008-2011 JWST Flight Mirror Manufacturing Data and Pre-flight Verification
- 2012-2013 JWST Backplane Structural Deformation Measurement
- 2015-2020+ Advanced Normal Incidence Mirror Development activities
- 2019-2020 Marshall Grazing Incidence X-Ray Spectrometry telescope alignment & verification
- 2021+ ESA's ATHENA Engineering, Qualification, and Flight Mirrors, and ultimately for future observatories – Probe-class and New Great Observatories

X-Ray & Cryogenic Facility Overview

- MSFC Flagship class X-ray beamline facility.
- 538 m source to detector with 518 m beam tube that is 1.5 m diameter.
- 23 m detector chamber, 7 m in diameter.
- Detector chamber opens to 1 K cleanroom. Additional 10 K cleanroom with gowning room.
- Operates down to 10^{-7} Torr. Thermal shroud range: 20K to 320K.
- Electron Impact Point Source, Rotating Anode Source, in situ filter wheel.
- Flow proportional counter and SDD beam monitors. CCD, SDD, and flow proportional counter focal plane.

Top Take Away Points

1. Most of the Universe is invisible to the naked eye.

2. Need to observe all wavelengths to truly understand the Universe.

3. To observe X-rays from space, we need to get above most of the atmosphere. This can be done with high-altitude balloons, sounding rockets, and spacecraft.

4. NASA MSFC has extensive capability regarding the design, fabrication, test, and calibration of Full-Shell X-ray Optics - which are critical to exploring the X-ray Universe.