Optics Requirements for X-Ray Astronomy and Developments at NASA / Marshall Space Flight Center

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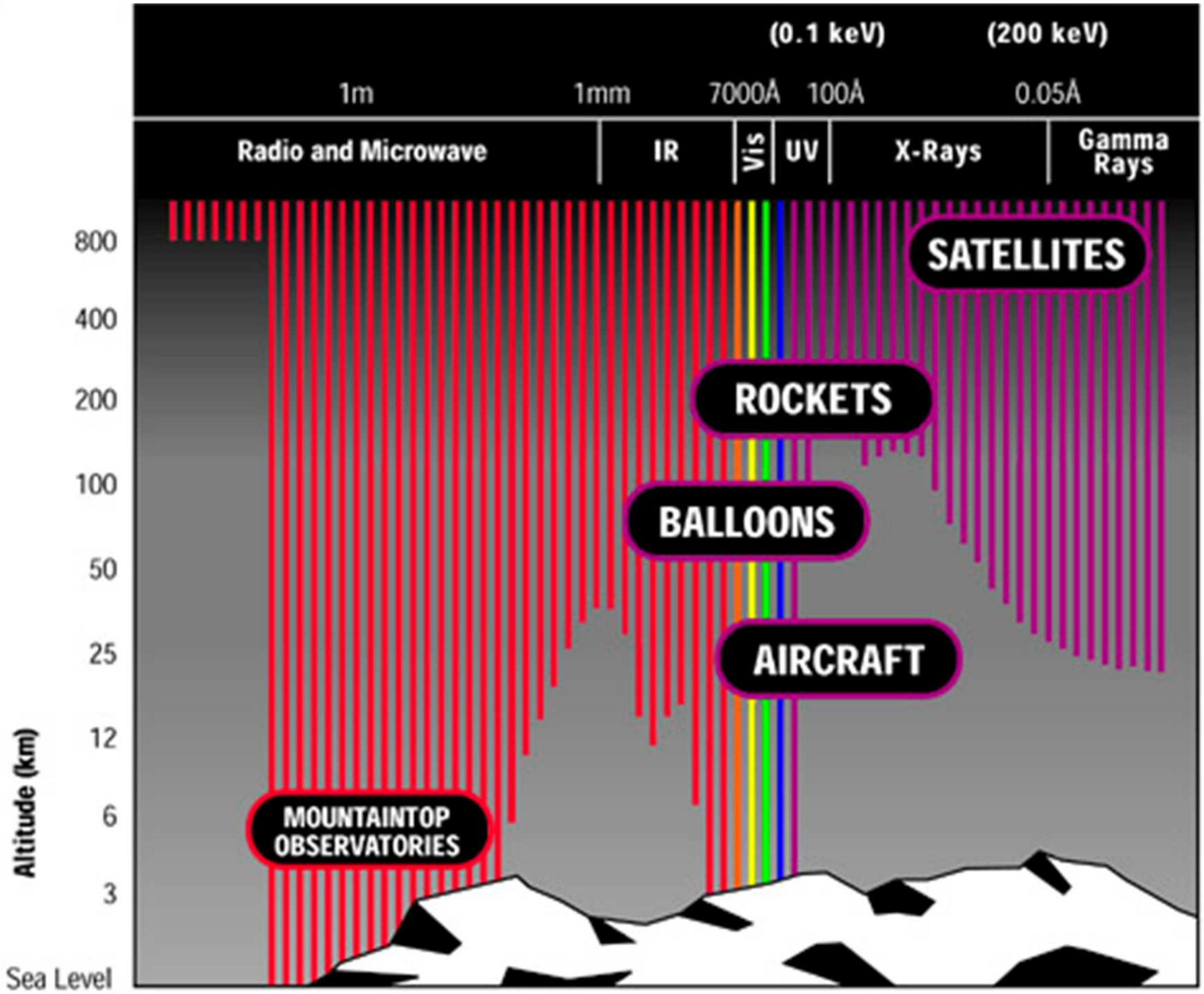
Atmospheric Attenuation

Altitude (km)



X-Ray Astronomy

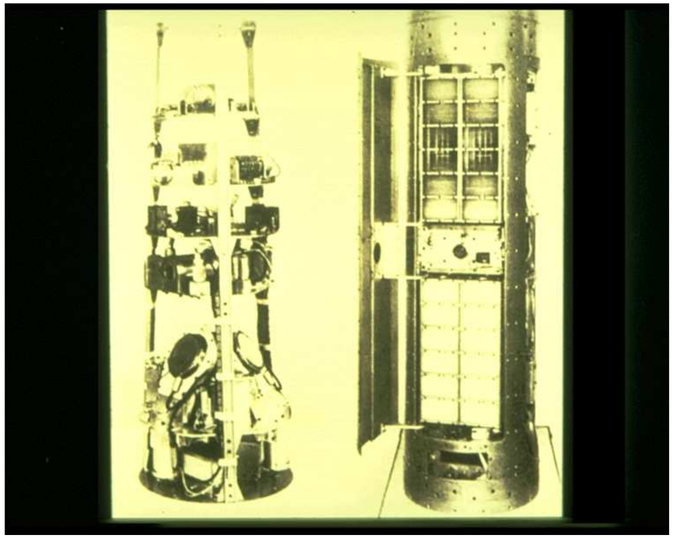
Birth of X-Ray Astronomy

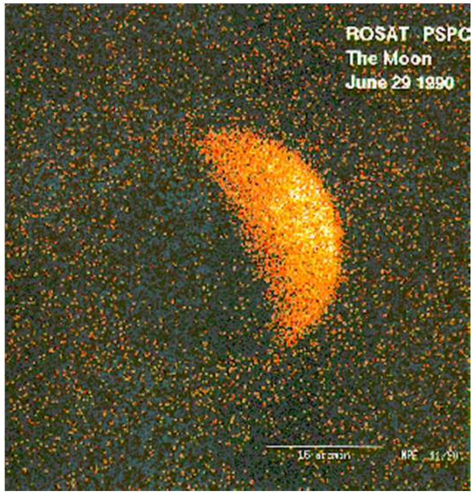
- In 1962, Riccardo Giacconi and colleagues at AS&E flew sounding rocket to look at x-ray fluorescence from the moon

- Lunar signal was overshadowed by very strong emission from the Scorpious region

- Discovered the first extra-solar x-ray source, Sco X-1, and pervasive x-ray background

- This was the effective birth of x-ray astronomy



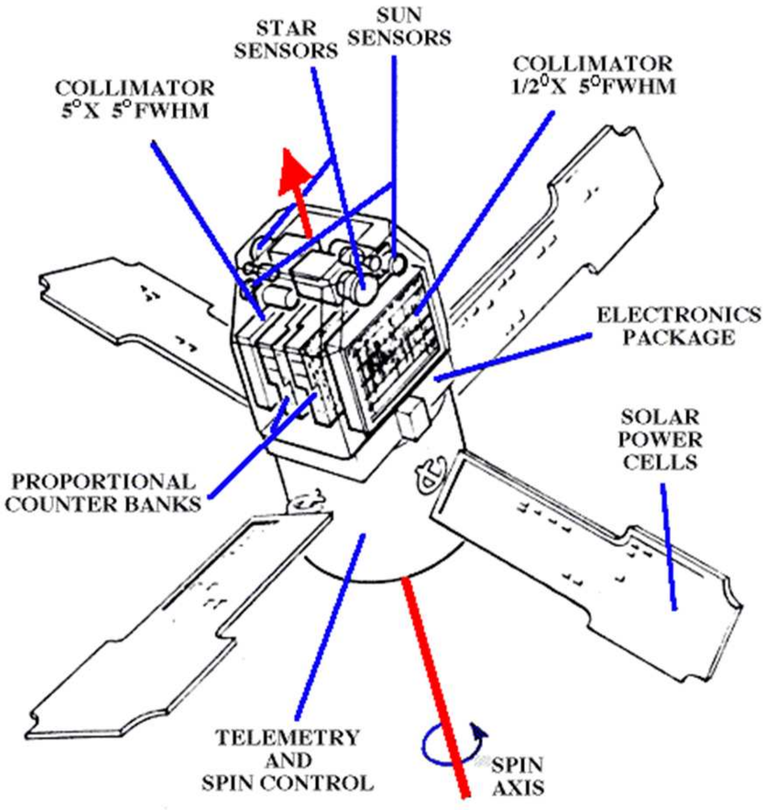


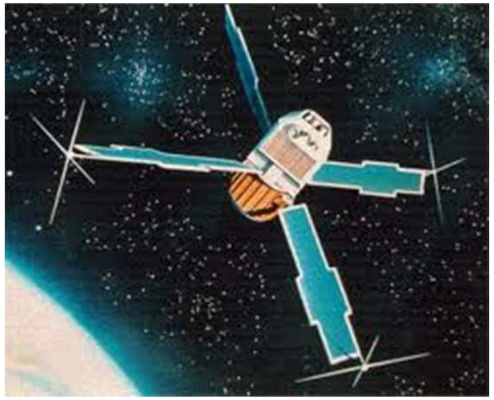
X-Ray Astronomy

First X-Ray Satellite

The UHURU spacecraft was launched in 1970

It weighed just 140 pounds, not much more than the rocket experiment



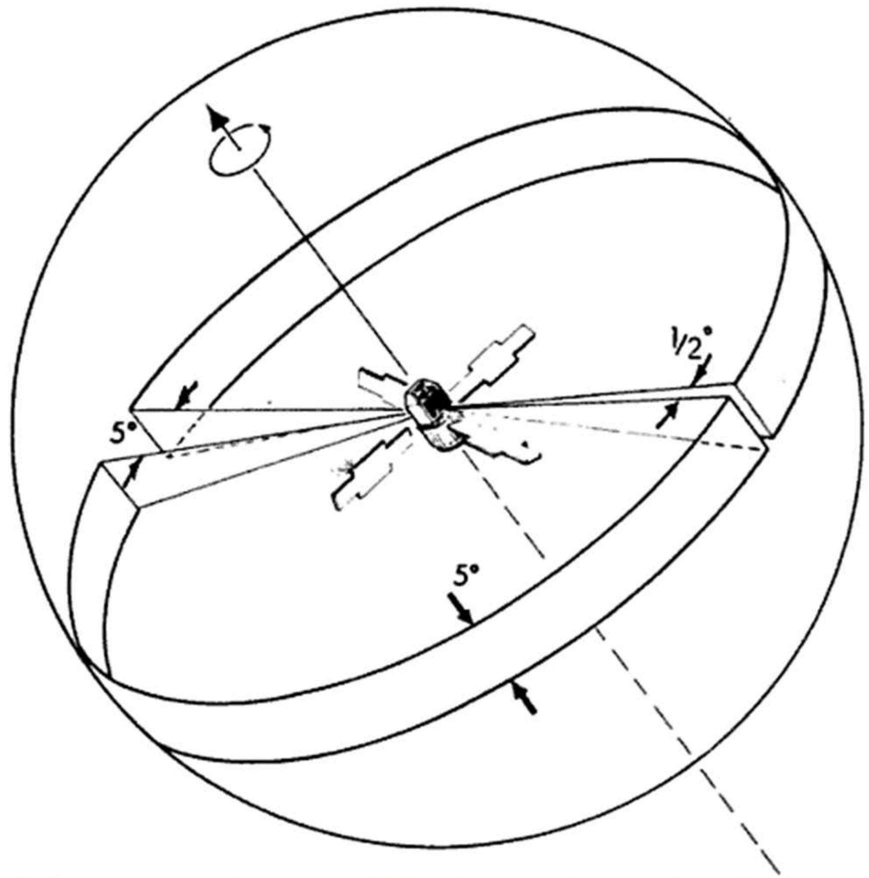


X-Ray Astronomy

UHURU

Used a simple collimator system, to locate x-ray sources in sky

It operated for 3 years and discovered 339 sources in the whole sky



5. Scan geometry of the UHURU X-ray detectors shown as the projection on a
. As the satellite rotates the X-ray detectors view in a 5° band, 90° from the spin axis.

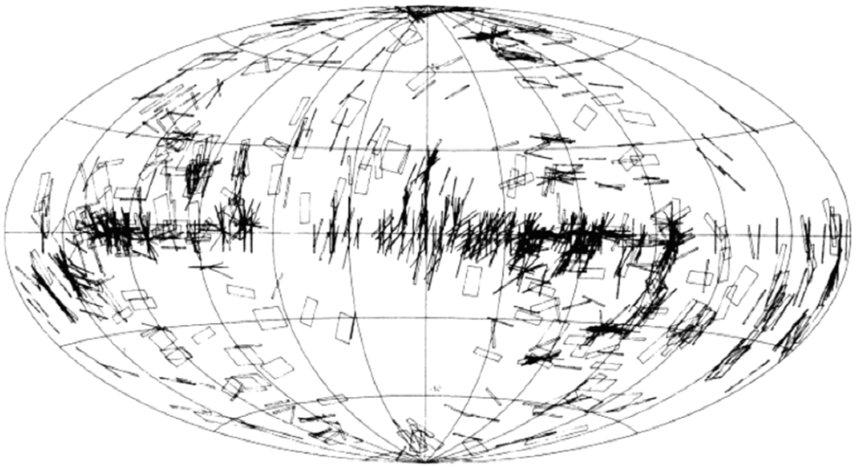
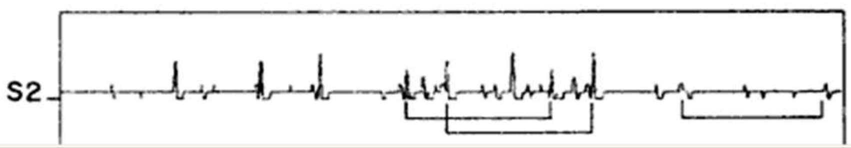


FIG. 3.—Lines of position which result from the computer scan of superposed data are plotted on an equal area projection of the sky in galactic coordinates. The line widths are $\pm 1\ \sigma$ as determined by the minimum χ^2 fits. There are 1171 lines on the plot.



X-Ray Astronomy

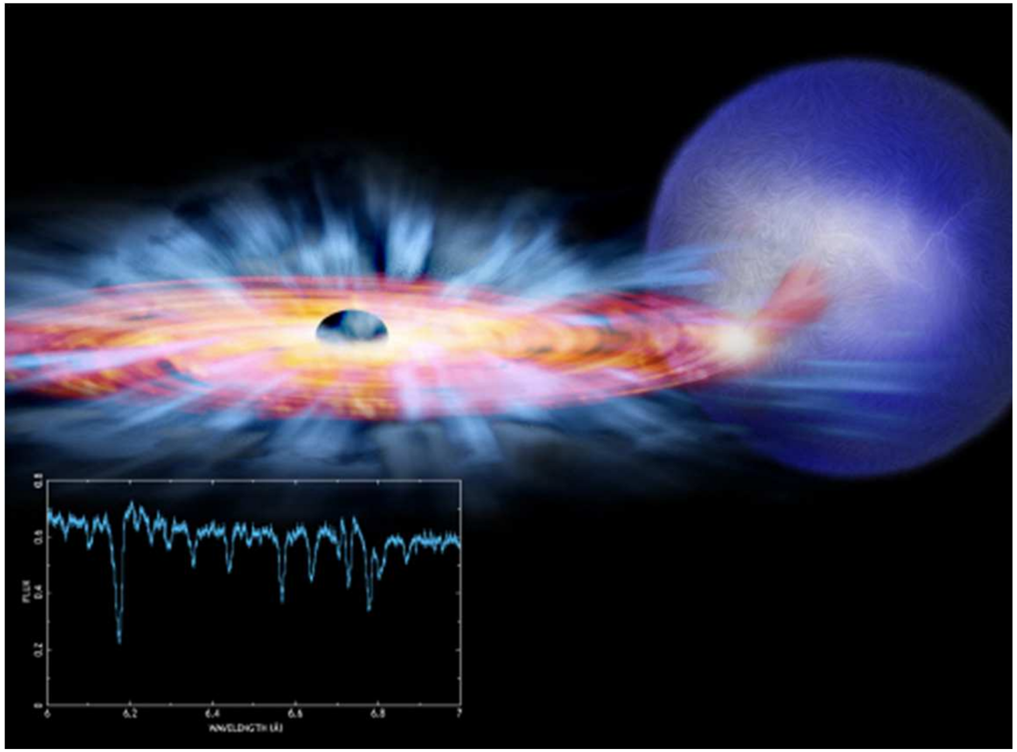
Early observations

From these early observations a picture emerged of a typical x-ray source:

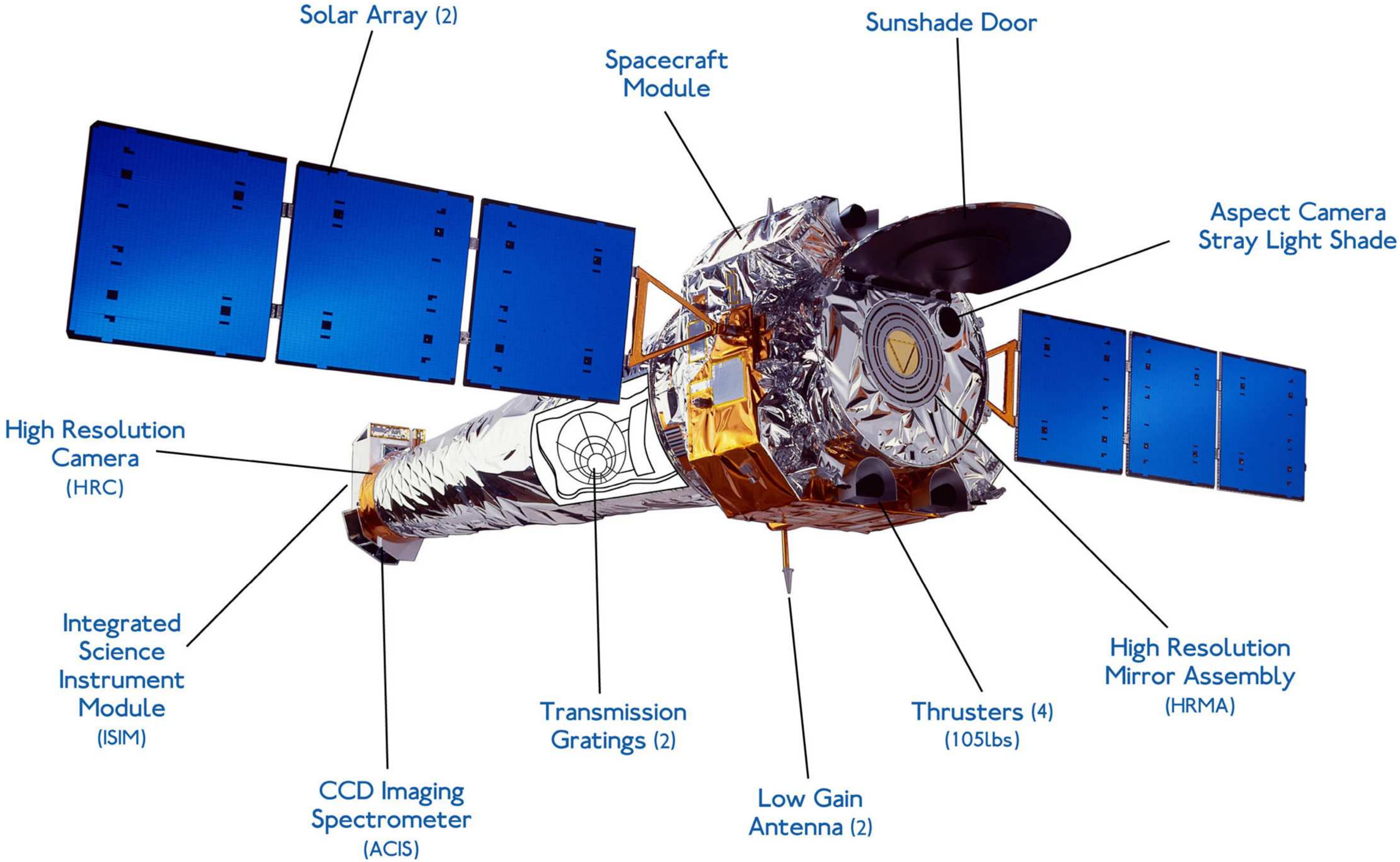
A compact object (neutron star, black hole, white dwarf) orbiting around a normal star

Matter streams down on to the compact object forming an accretion disk

As the matter spirals down and is compressed it gets very hot and emits x rays

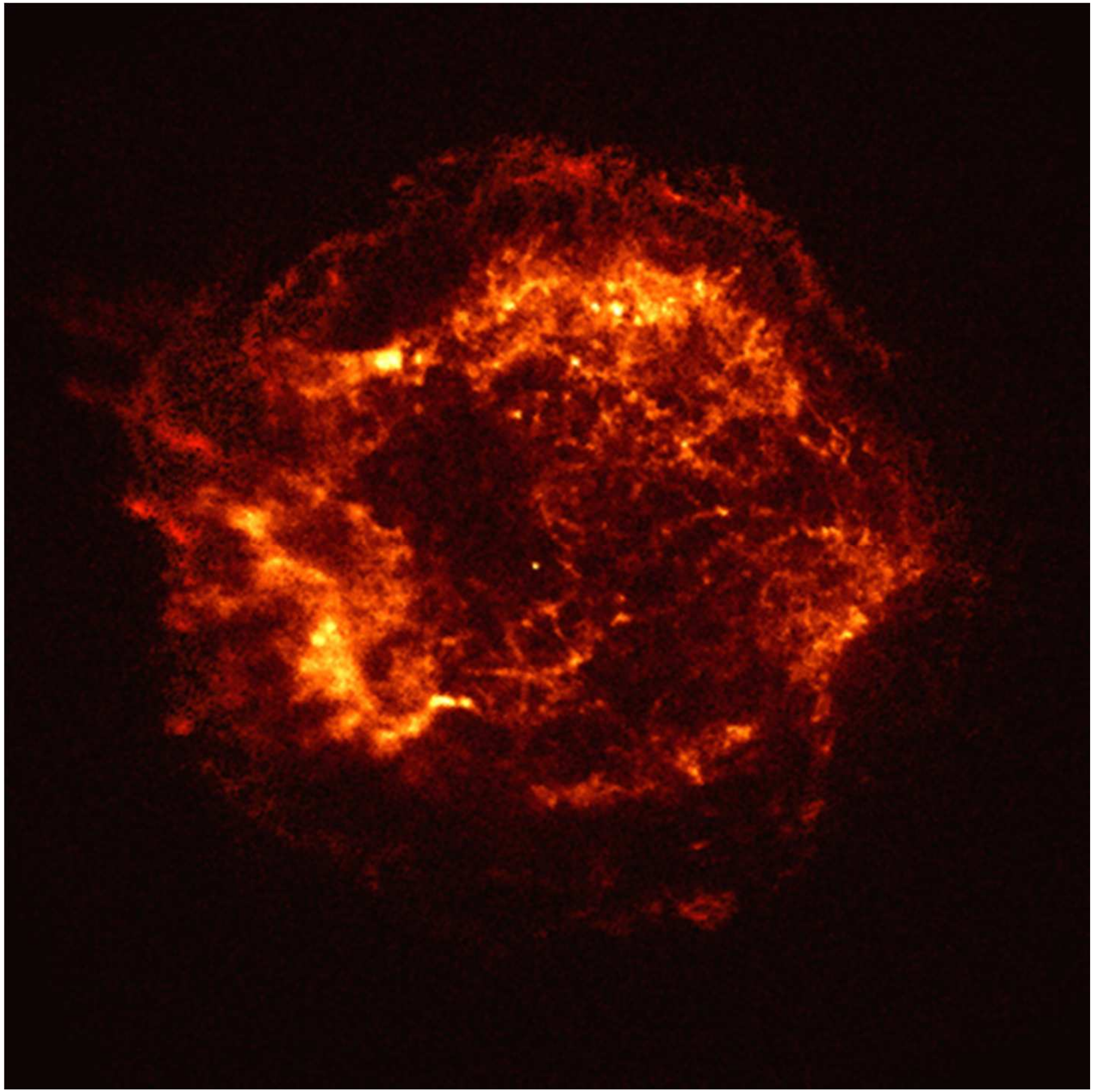


Today .. The Chandra Observatory

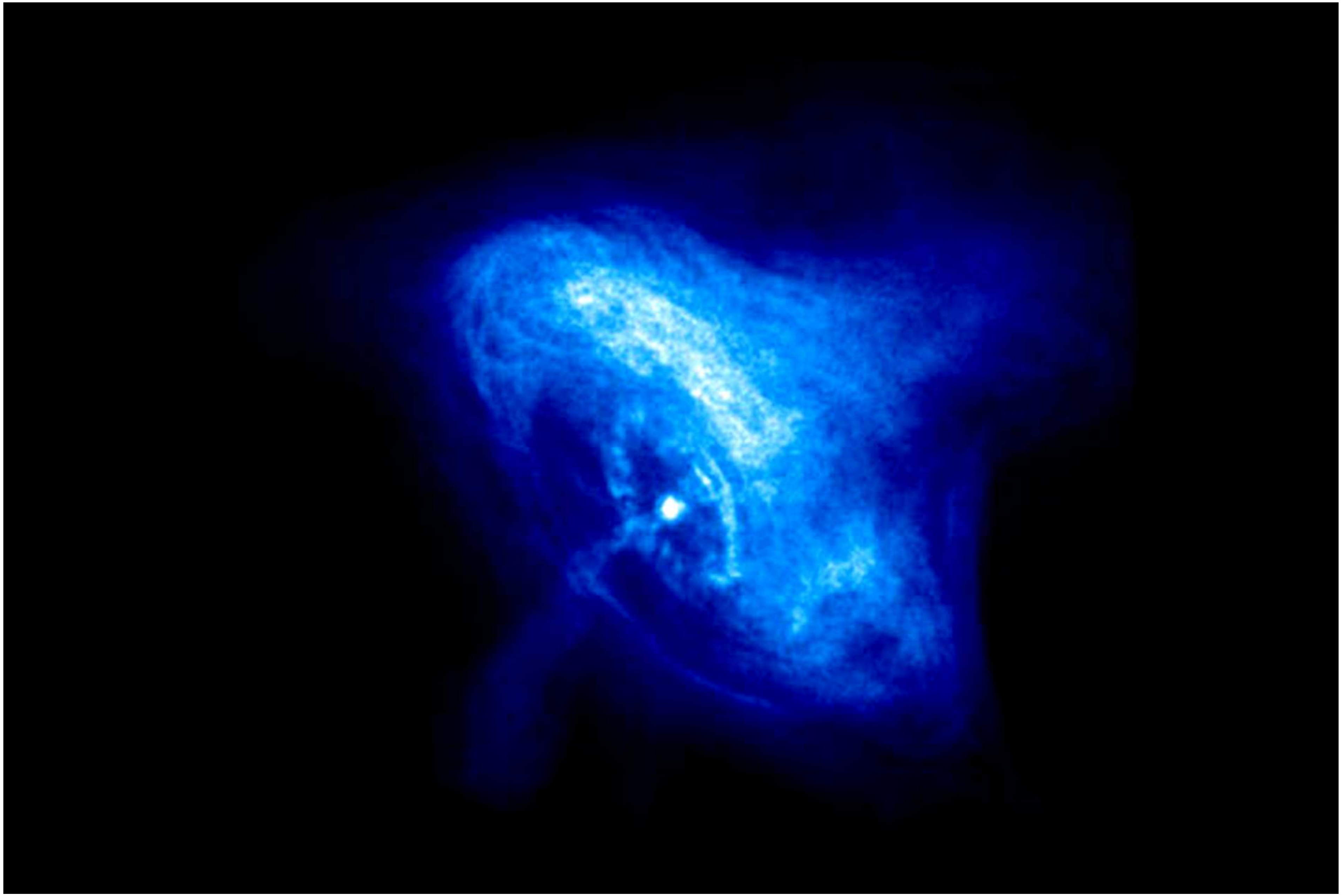


Today .. The Chandra Observatory

Chandra Images : Cas-A Supernova Remnant



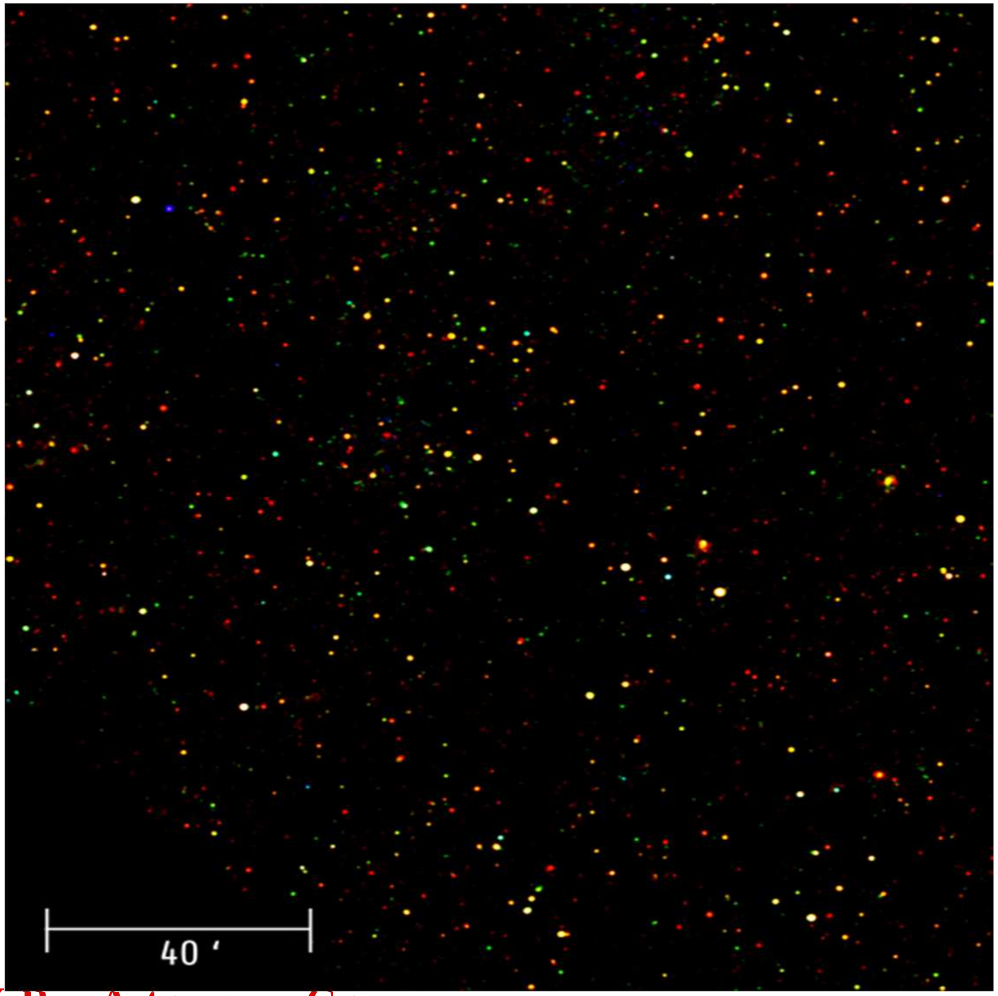
The Crab Nebula and its Pulsar



Deep fields resolve background into discrete sources—mostly active galaxies.

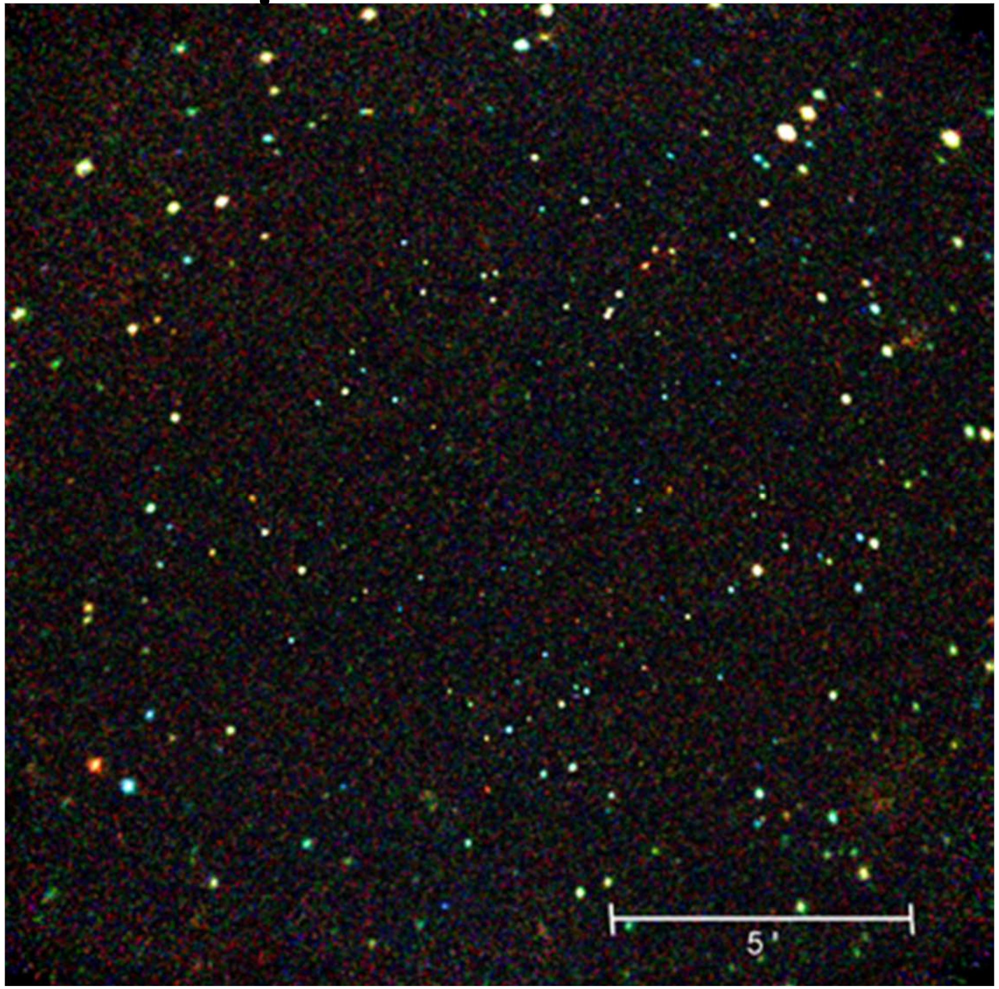
X-ray colors: NASA/CXC/CfA/Hickox et al.

Bootes Medium Field



X-ray flux: NASA/CXC/JHU/AUI/Giacconi et al.

Deep Field South



X-Ray Optics

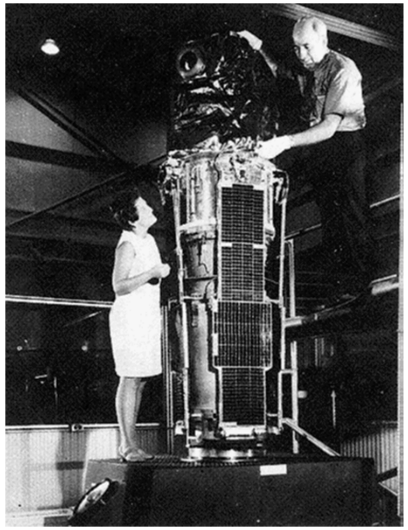
Why focus x rays ?

1) Imaging - obvious

2) Background reduction

- Signal from cosmic sources very faint, observed against a large background
- Background depends on size of detector and amount of sky viewed
  - Concentrate flux from small area of sky on to small detector

$\Rightarrow$ *enormous increase in sensitivity*



First dedicated x-ray astronomy satellite – UHURU →

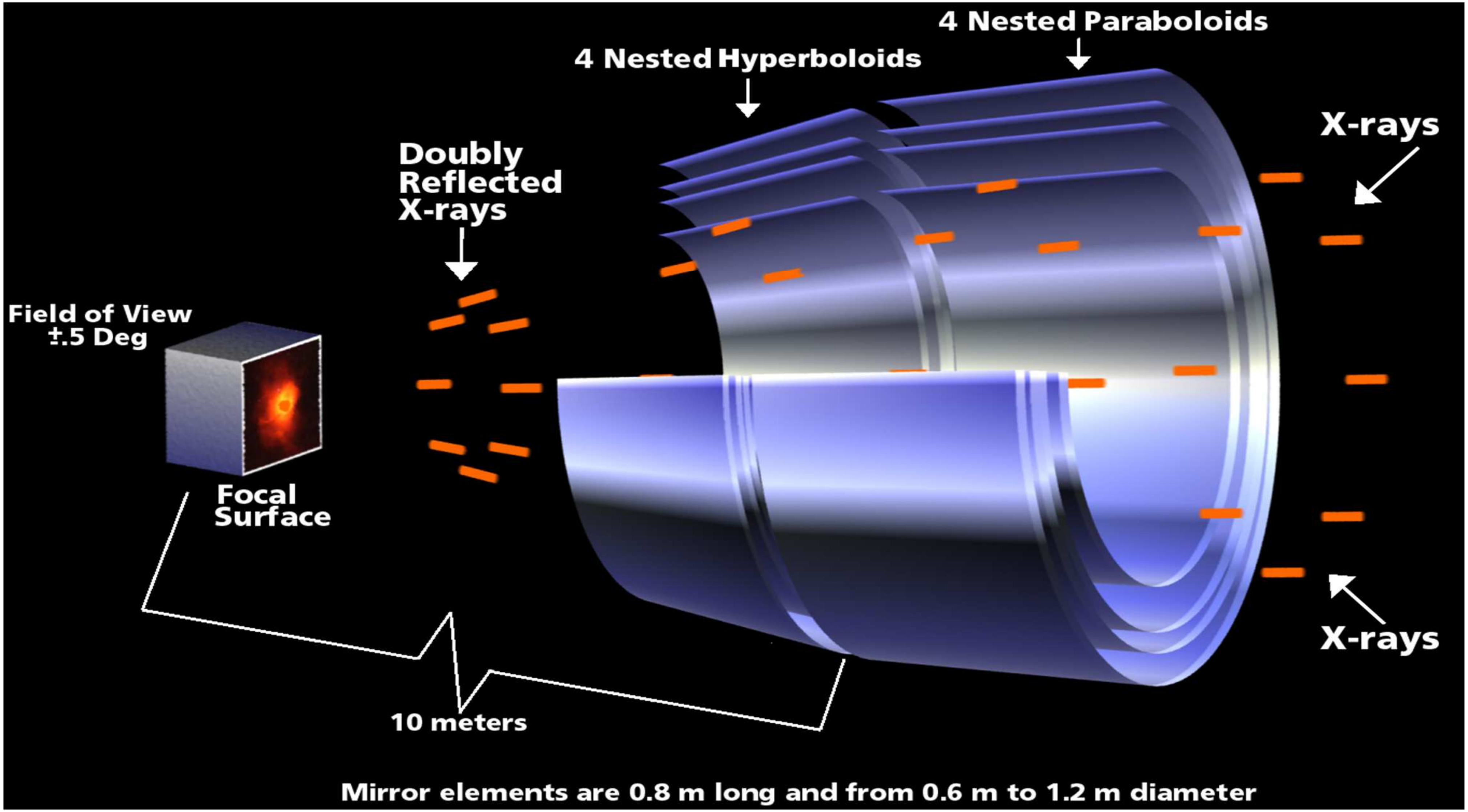
mapped 340 sources with large area detector (no optics)

Chandra observatory - ~ same collecting area as UHURU

- ***5 orders of mag more sensitivity --- 1,000 sources / sq degree in deep fields***
- ***1 background count / keV year !***

X-Ray Optics has revolutionized x-ray astronomy

Chandra X-ray Optics



Chandra Optics

Approaches: Chandra

- Fabricated using thick ceramic, which is meticulously polished and figured, one shell at a time.

- Obtain superb angular resolution ------ 0.5 arcsecond HPD

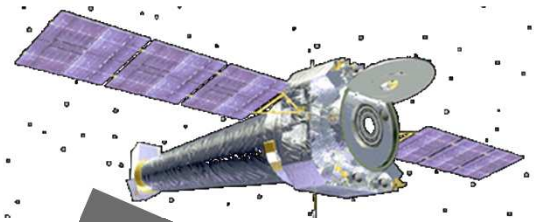
- But very costly to fabricate ($500M) and very heavy (1000 kg)

- *BUT …. How do we follow on from Chandra … need 10-100 x area and similar or better resolution ?*
- *Need thinner (to nest), much lighter (to launch) optics, while preserving or improving resolution ….and all somehow affordable !*

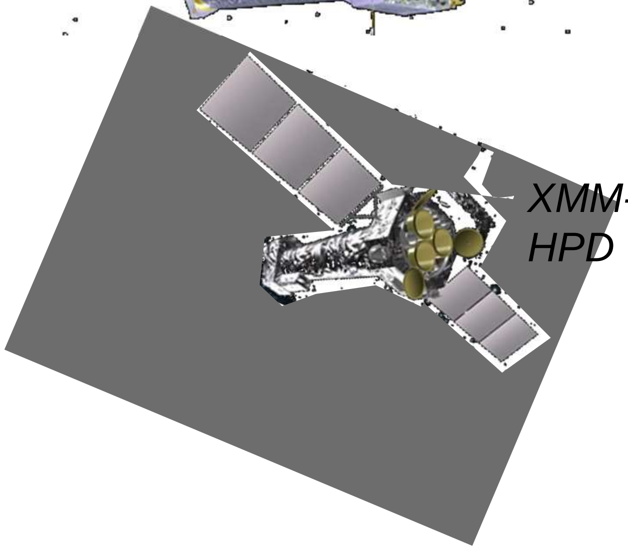
Mission Requirements / Future Challenges

Einstein Observatory (1978-1981)
HPD =10″, A = 0.04 m^2 (f = 3.3 m)

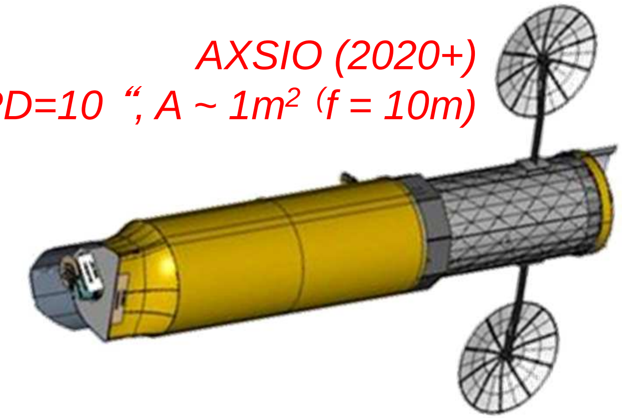
ROSAT (1990-1999)
HPD = 5″, A = 0.10 m^2 (f = 2.4 m)



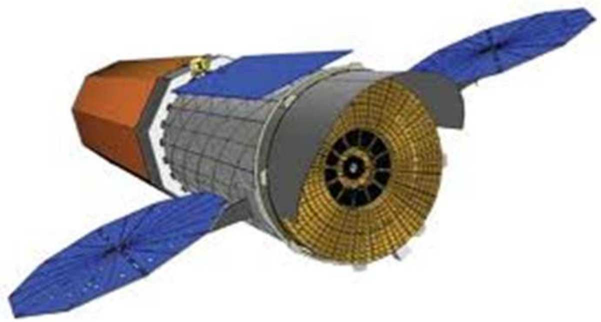
Chandra X-ray Observatory (1999-?)
HPD = 0.6″, A = 0.11 m^2 (f = 10 m)



XMM-Newton (1999-?)
HPD = 14", A = 0.43 m^2 (f = 7.5 m)

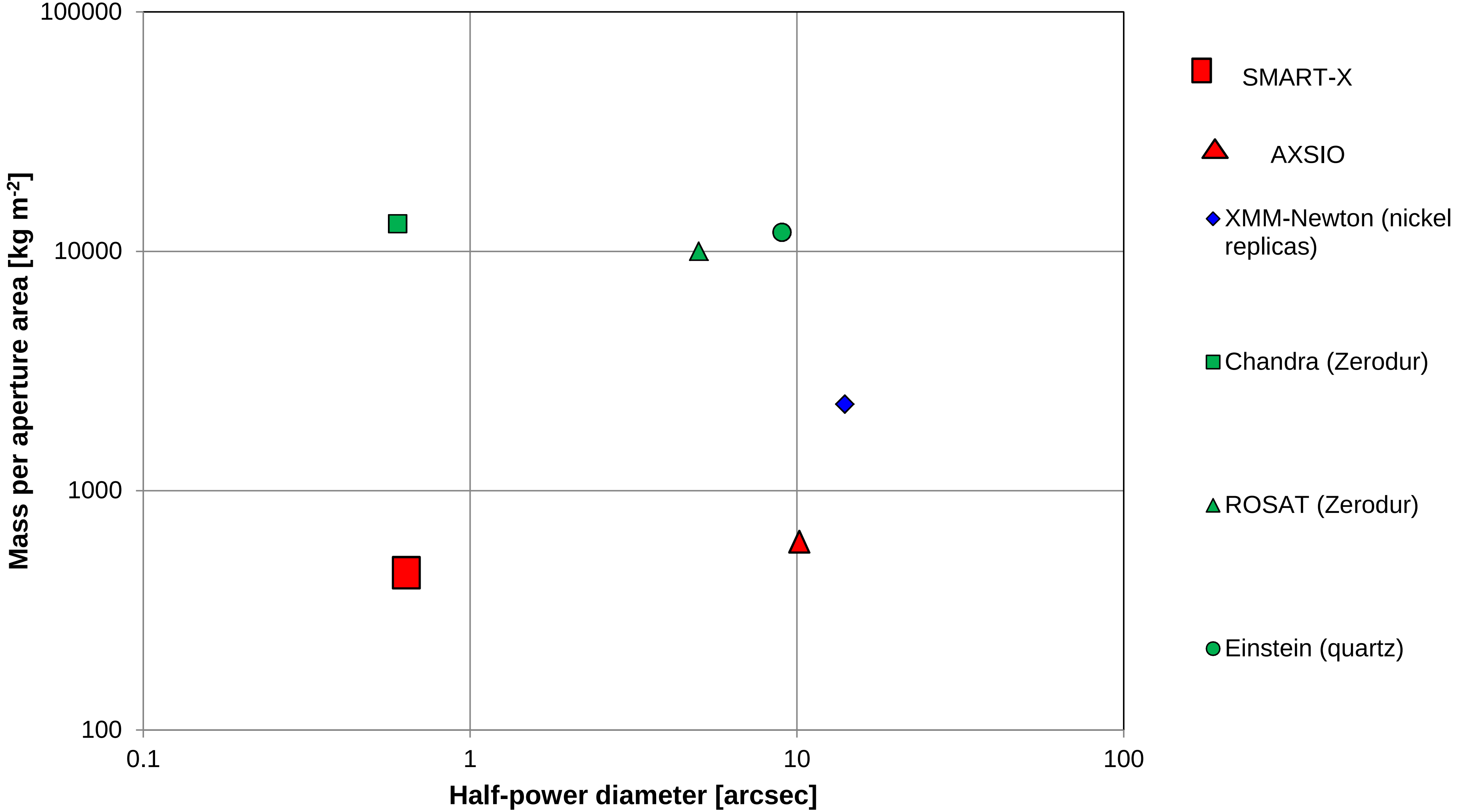


AXSIO (2020+)
HPD=10 ", A ~ 1m^2 (f = 10m)



SMART-X (2030)
HPD = 0.5", A ~ 2.3 m^2 (f = 10 m)

Aperture areal-mass constraints



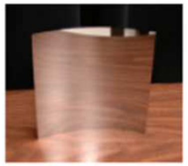
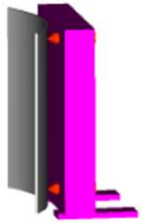
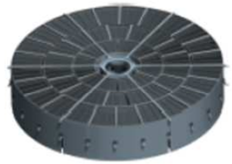
Mirror Fabrication for (near) Future Missions

Slumping
0.4-mm glass

Cutting

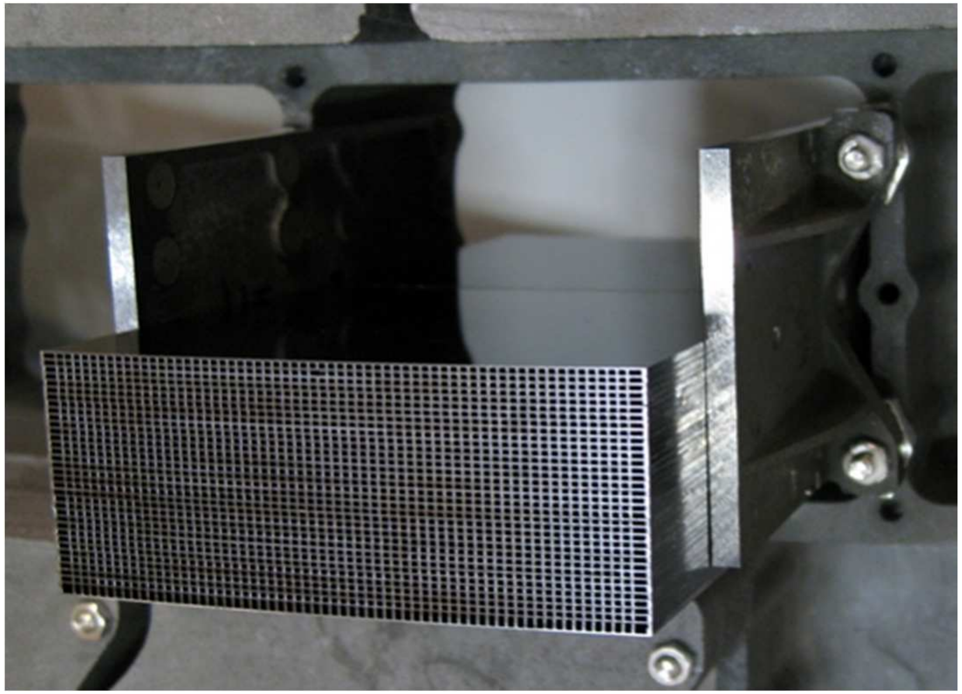
Coating

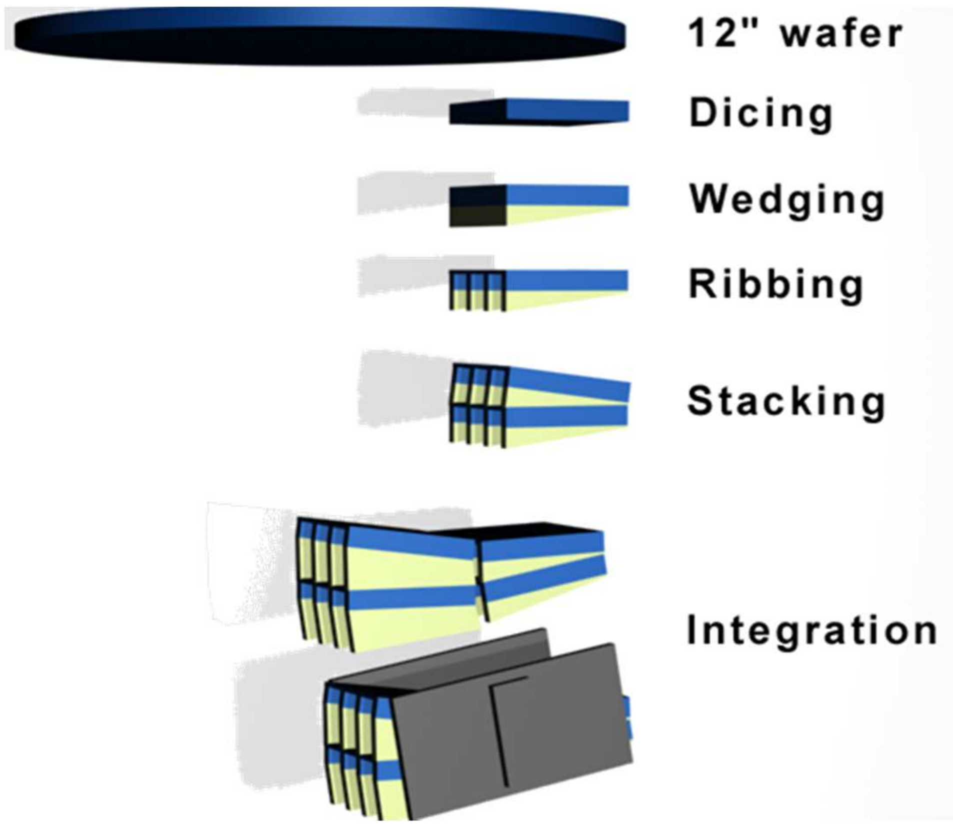
Measuring

Mandrel	Mirror	Transfer Mount	Module	Assembly	Observatory
					
6"	10"	10"	12"	13"	15"
2.0"	3.5"	3.6"	4.0"	4.5"	5.0"
Schedule/Cost	← Core of Technology Development →			← Design, Analysis, & Test →	

In Europe

Silicon Pore stacks

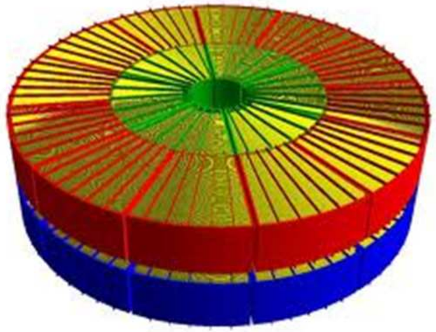




Possible paths to <1″ telescopes

- **Stiff optics**
  - All <10″ x-ray telescopes have used (thick-walled) stiff optics.
  - Large x-ray telescopes require *lightweight* stiff optics.
    - Low-density materials for thick-walled mirrors
    - Integrated structures for mirrors
- **Active optics**
  - Large normal-incidence telescopes (ground-based & JWST) use active optics.
    - Segment positioning
    - Curvature correction
  - Large x-ray telescopes require different active-optics technologies.
    - Reaction structures for surface-normal actuation are too massive and bulky.

Challenges for active optic implementation



- **Required mirror surface area is a couple orders of magnitude larger than the aperture area.**
  - At grazing angle α, mirror surface area $A_{surf} \approx (2/\alpha)A_{ap}$.
  - E.g., for SMART-X $A_{ap} \approx 2.4\ m^2 \Rightarrow A_{surf} \approx 500\ m^2$.
- **Launch considerations limit mass and volume.**
  - Mass constraints $\Rightarrow$ very lightweight mirrors.
  - Volume constraints $\Rightarrow$ many hundreds of highly nested (few mm), thin mirrors (0.4 mm).
- **These constraints preclude use of surface-normal actuation and reaction structures to correct figure.**
  - Mirror alignment would probably use this technology.
  - Figure correction calls for surface-tangential actuation: e.g., piezoelectric/mirror bimorphs.

Challenges for Active Optic Implementation

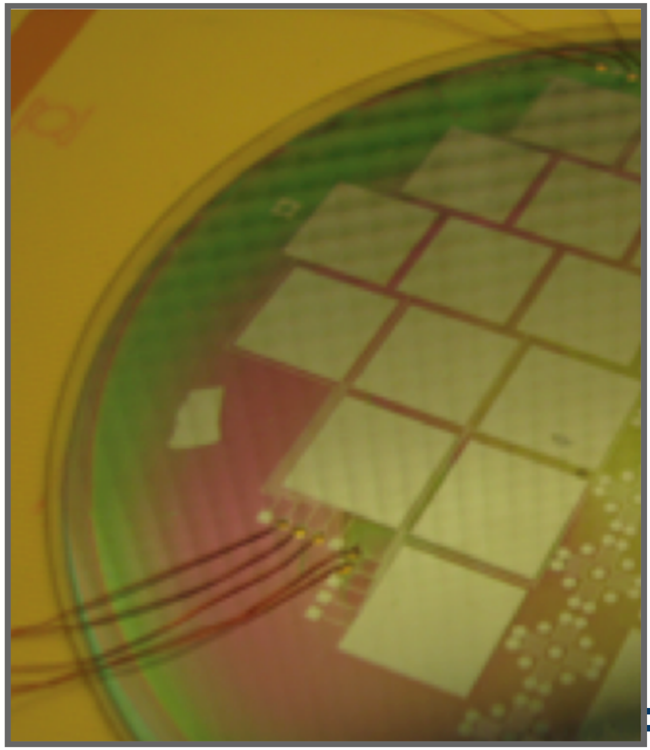
- **Other issues:**
  - Very large number of actuators to fit in and control (10^6)
    - Correction strategy to converge
  - Thermal effects
  - Voltage stability
  - Radiation damage sensitivity

Some current (US) activities shown in next slides

Adjustable Bimorph Mirror: a path to large area, high-resolution X-ray telescopes

- *Thin (~ 1.5 µm) piezoelectric film deposited on mirror back surface.*
- *Electrode pattern deposited on top of piezo layer.*
- *Energizing piezo cell with a voltage across the thickness produces a strain in piezo parallel to the mirror surface (in two orthogonal directions)*
- *Strain produces bending in mirror — **No reaction structure needed***
- *Optimize the voltages for each piezo cell to minimize the figure error in the mirror.*

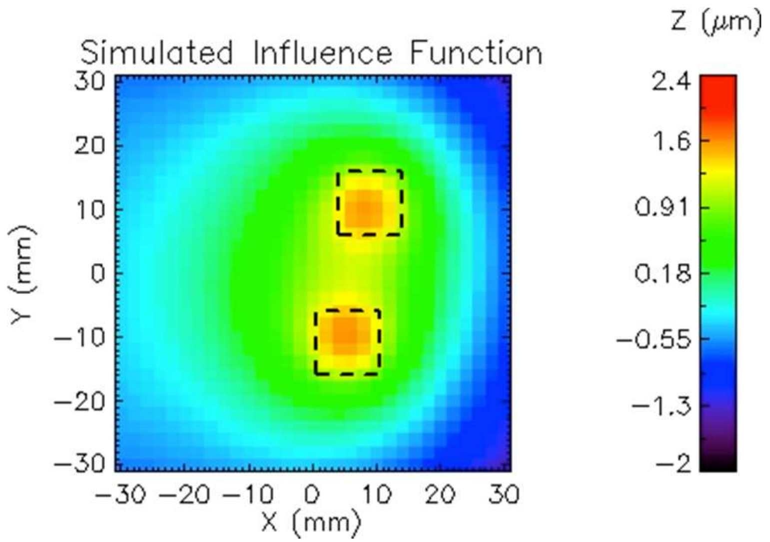
Major accomplishment:
•Deposition of piezos on glass (Penn State Materials Lab).
•First time PZT deposited on glass for such large areas.

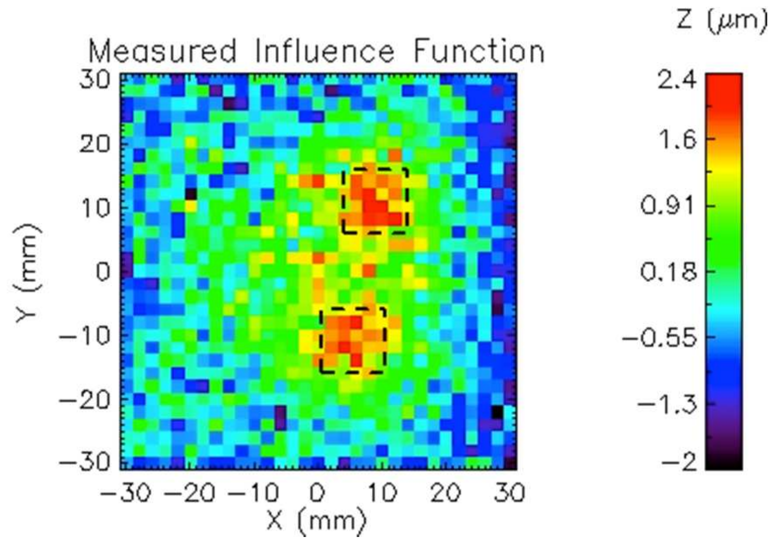


Flat test mirror – 100 mm diameter 0.4 mm Corning Eagle glass with 1.6 µm PZT and 1 cm^2 electrodes Also shows pattern of strain gauges (lower right) deposited on PZT.

Courtesy of Paul Reid / SAO

Proof of Concept

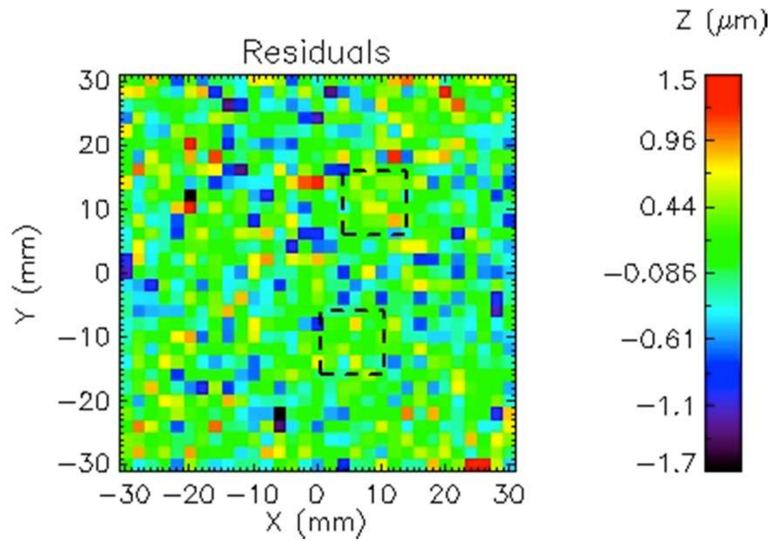




Test using Corning Eagle™ flat glass, 0.4 mm thick, 100 mm diam., 1 cm^2 piezo cells

Deflection at 10V is equivalent to 700 ppm strain — meets SMART-X 500 ppm requirement.

Residual (measured minus modeled) is the same amplitude as metrology noise.

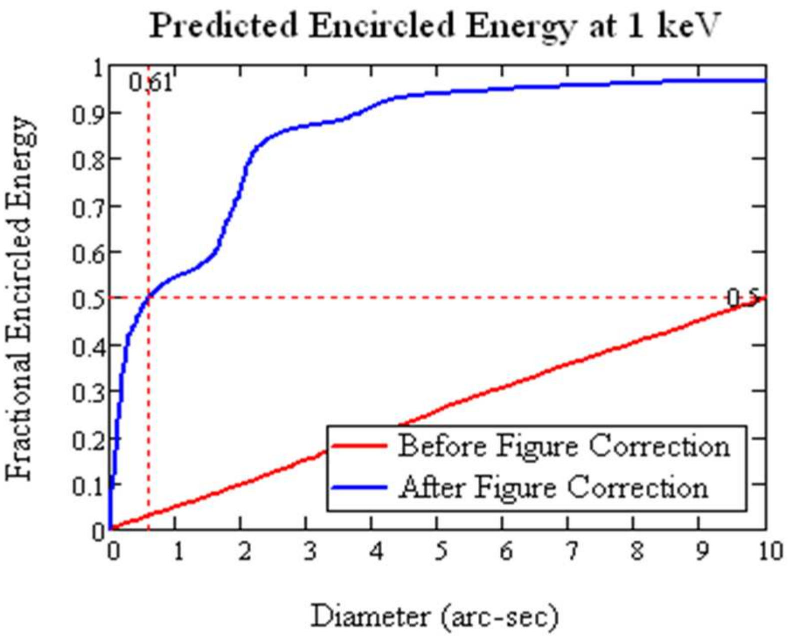


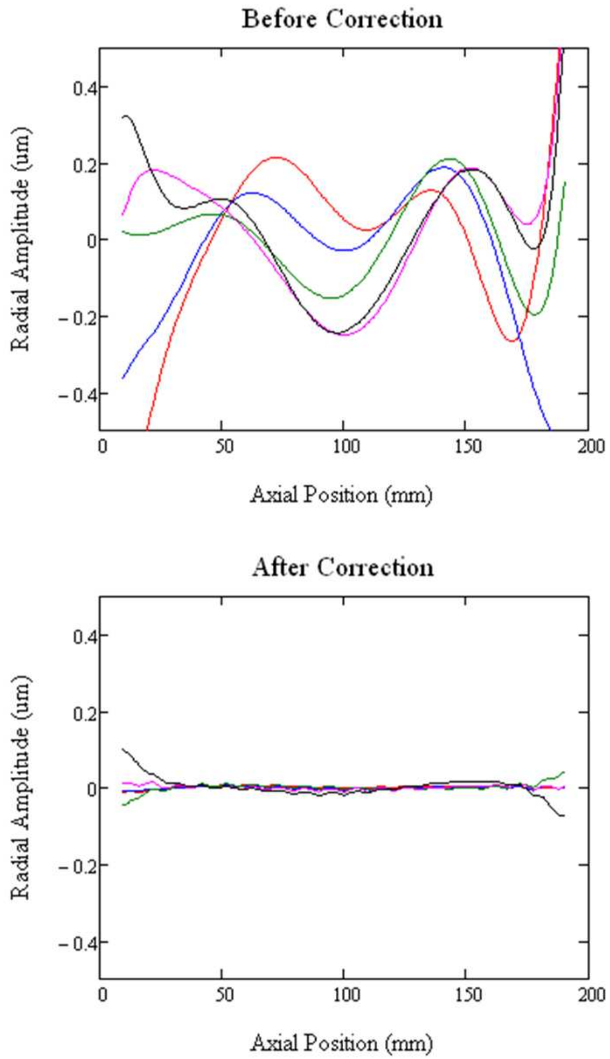
Courtesy of Paul Reid / SAO

Simulated correction of measured data yields 0.6 arc sec HPD for initial 10 arc sec mirror pair

Use modeled influence functions to correct representative data:

- 'Before Correction' = interferometer measurement of mounted IXO mirror (ca. 2008).
- 'After Correction' = residual after least squares fit of ~ 400 influence functions.
- Compute PSF using full diffraction calculation:





Courtesy of Paul Reid / SAO

Summary

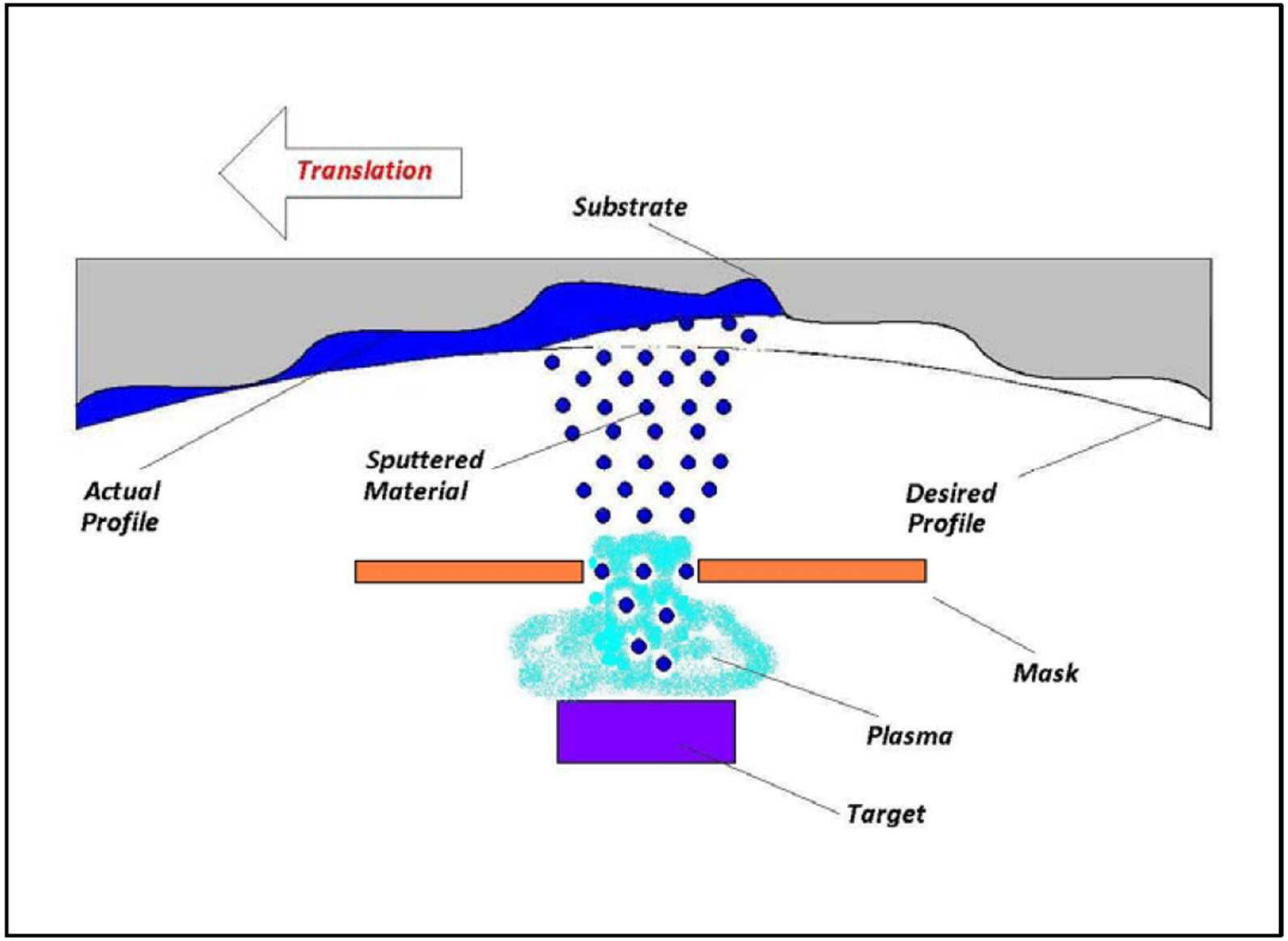
1. **Extremely challenging requirements for future x-ray astronomy missions**
    1. Requirement for large area implies highly nested very thin mirror shells
    2. Requirement for sub-arcsecond resolution necessitates very stiff structures or active control
2. **Active control in its infancy for x-ray astronomy. Many issues to work out**
    1. Large net area to effecticve area means extremely large number of actuators (10^6-10^7) to control precisely
        1. Convergence ? Stability in hostile environment, etc
    2. Estimate of development cost ~ $100M
3. **Other ideas for sub-arcsecond optics ?**

MSFC Developments

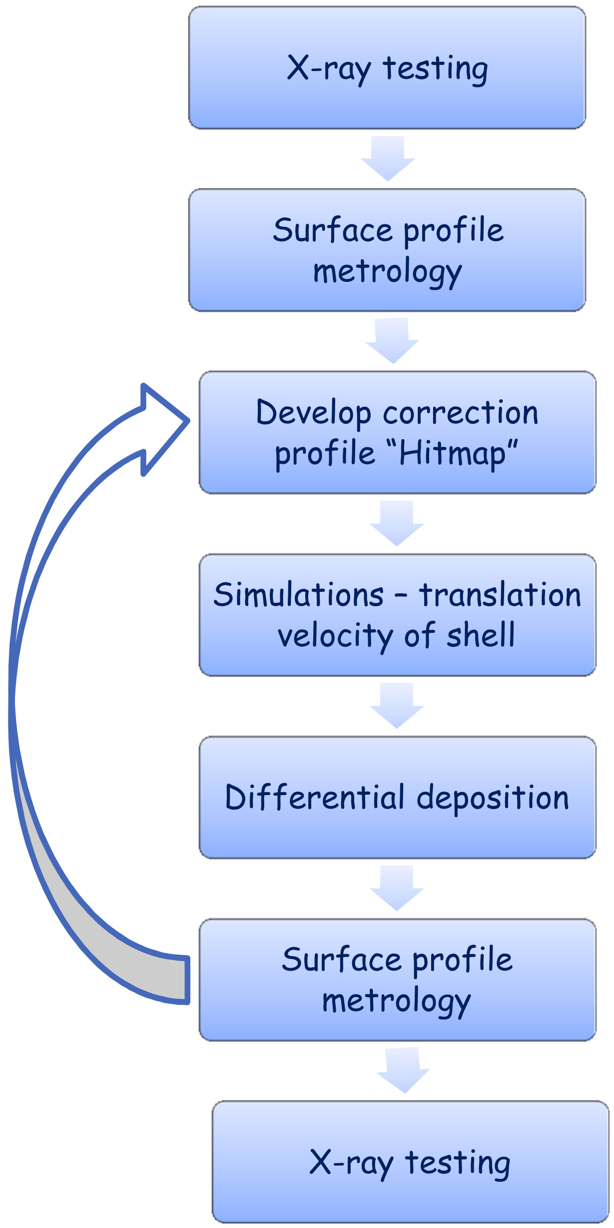
Mirrors for Future Missions – Differential Deposition

Vacuum deposit a filler material to compensate for figure imperfections

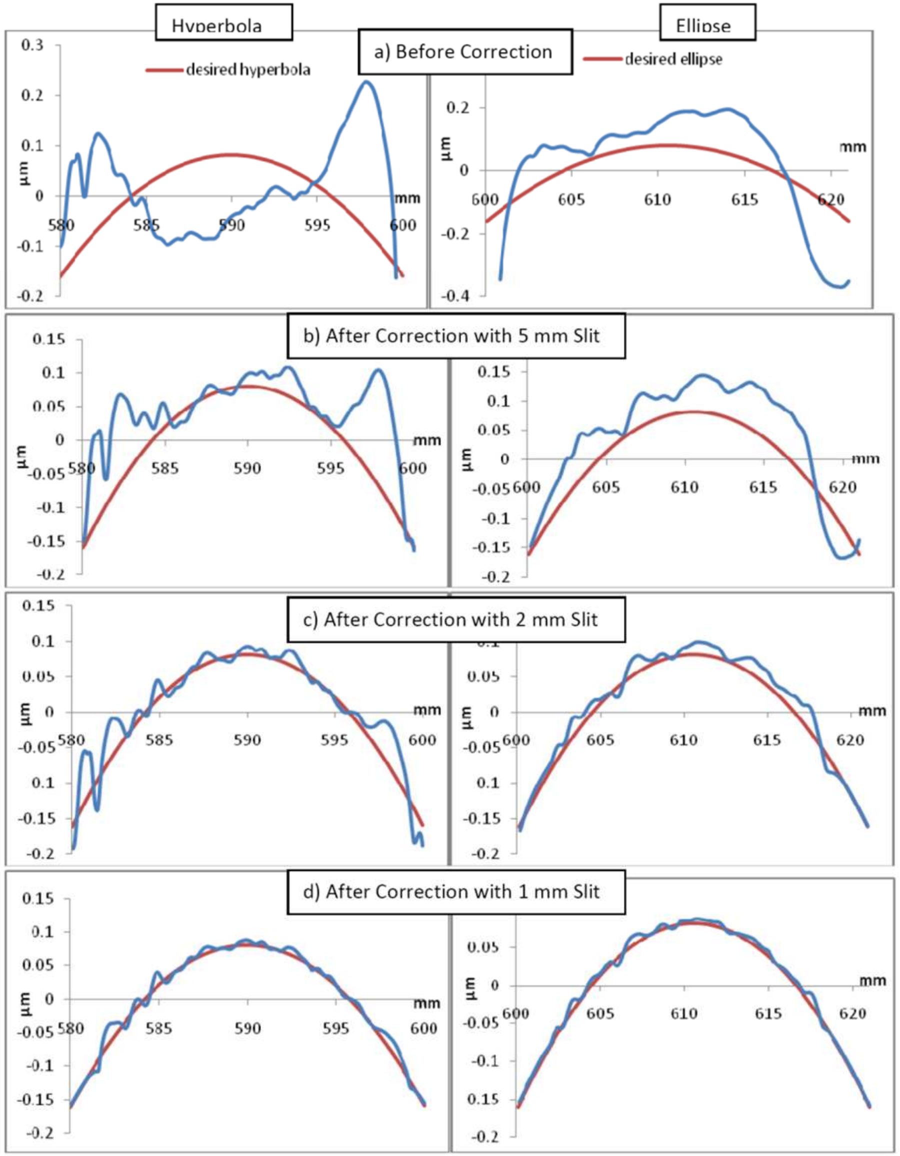
Proof of concept work with Wolter-1 optics underway at MSFC



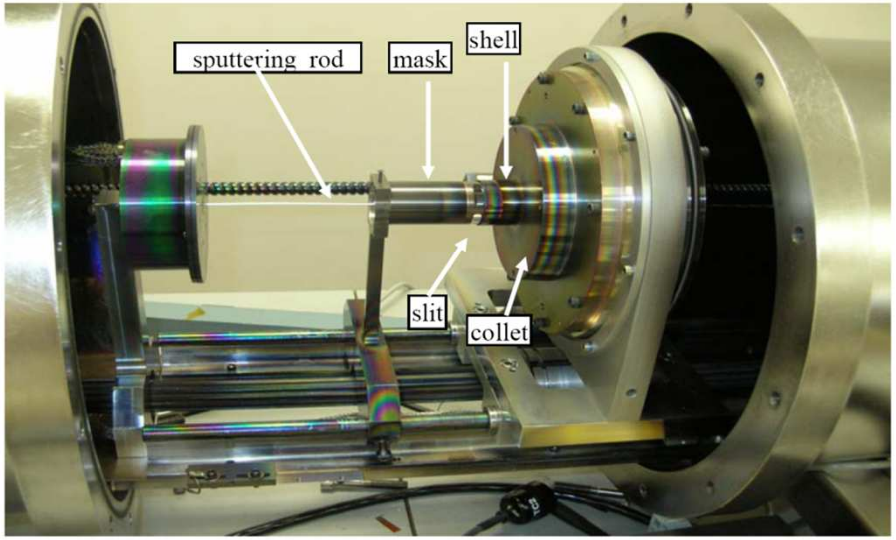
Process sequence – differential deposition



Mirrors for Future Missions – Differential Deposition



Correction stage	Average deposition amplitude (nm)	Slit-size (mm)	Amplitude uncertainty (nm)	Angular resolution (arcsec)
1	300	5	± 0	3.6
			± 10	3.6
			± 50	7.3
2	40	2	± 0	0.6
			± 1	1.0
			± 5	2.0
			± 10	3.5
3	4	1	± 0	0.2
			± 0.5	0.2
			± 1	0.5
			± 2	0.8



Possible practical limitations

- Variation of sputtered beam profile along the length of mirror – particularly for short focal length mirrors
- Deviation in the simulated sputtered beam profile from actual profile, beam non-uniformities, etc
- Positional inaccuracy of the slit with respect to mirror
- Stress effects
- Metrology uncertainty

Proof of concept on few-cm-scale medical imaging optics

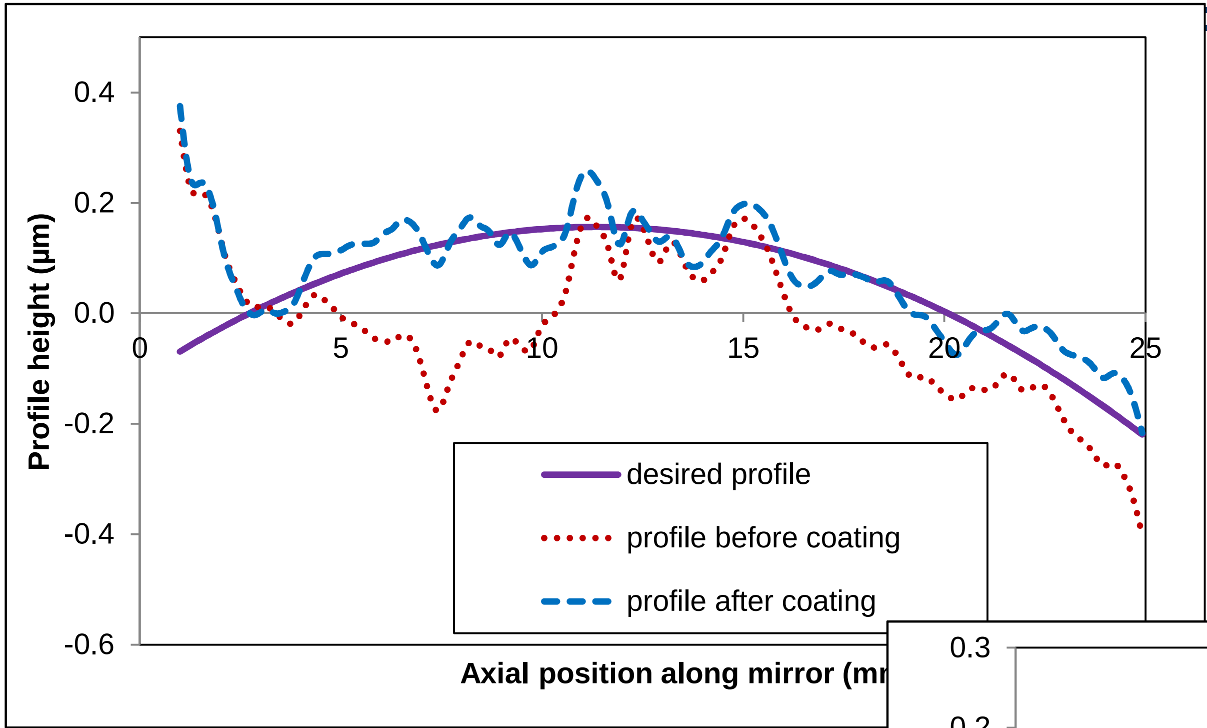
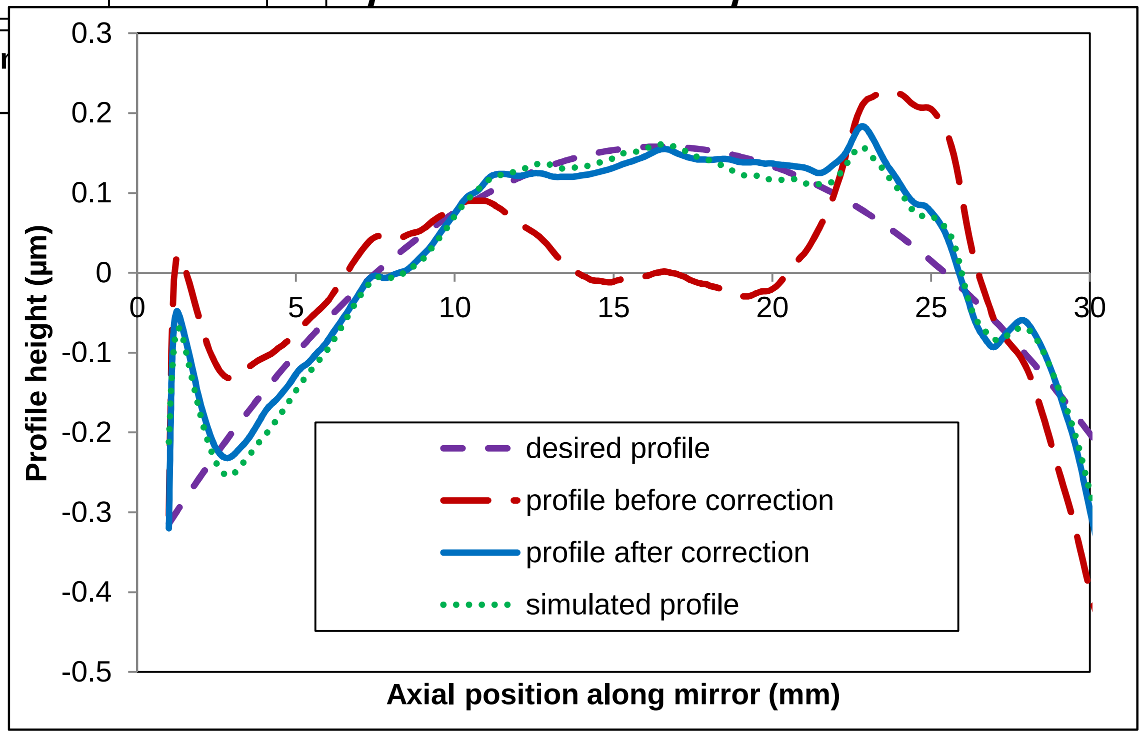


Figure error improvement from 0.11 µm to 0.058 µm rms



Slope error improvement from 12 arc sec to 7 arc sec rms

Current Status

- MSFC has received funding for larger coating chambers for astronomical-size full shell and segmented optics
- Work has started on chamber fabrication
- 3-year program

Development of a Multi-beam Long Trace Profiler

Existing VLTP at the MSFC

The VLTP is adequate for the 0.5 arc sec optics development, but too slow for large effective area optics - Time taken to measure is about 5 mins for 300 mm sample length

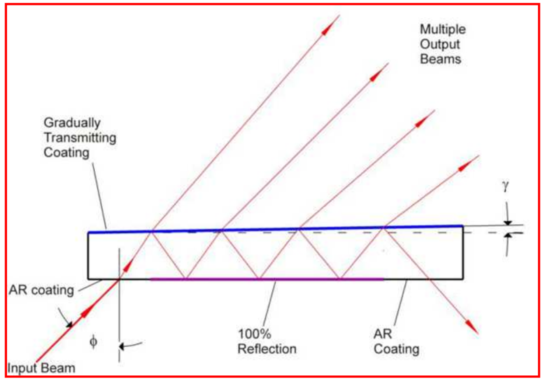
Further improvements:

- Make use of advanced technology
- Higher resolution and faster 2D detectors
- Stable optical sources
- Increase the speed & accuracies of measurements - **Multiple beams**

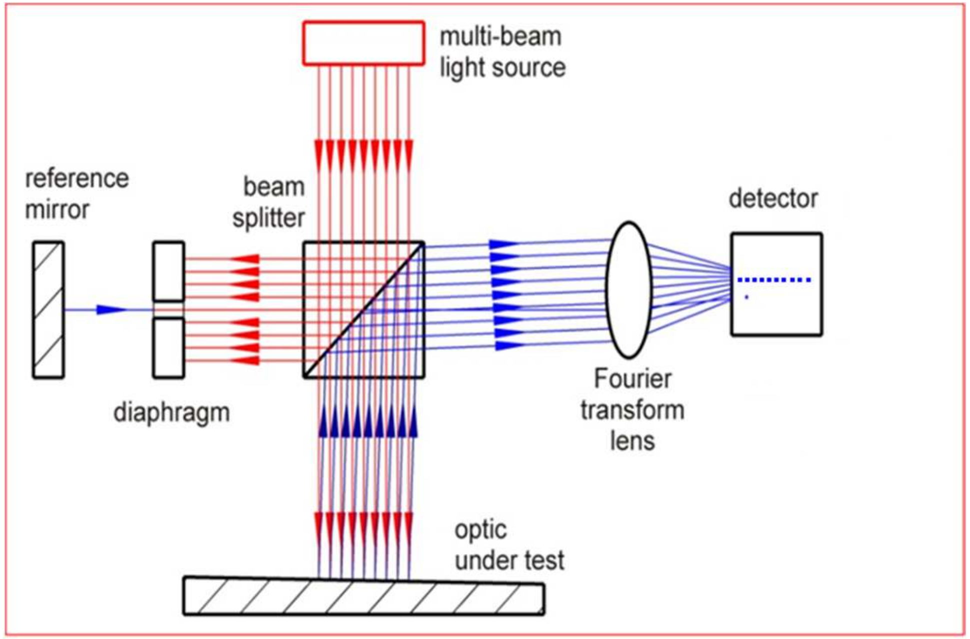
Internal funding, so approach is to order off-shelf optics for proof-of-concept. Then, select the best and define the goals for optical elements quality improvements

Etalon, designed in collaboration with Valeriy V. Yashchuk(LBNL) :

- *Number of beams –10; almost equal intensity*
- *Spatial and angular separation of beams – 2.4 mm and 250 μrad*
- *Dimension – 50 x 50 x 3 mm*
- *Wedge – 60 μrad*
- *11 fabricated, 8 usable, 2 best (intensity uniformity)*



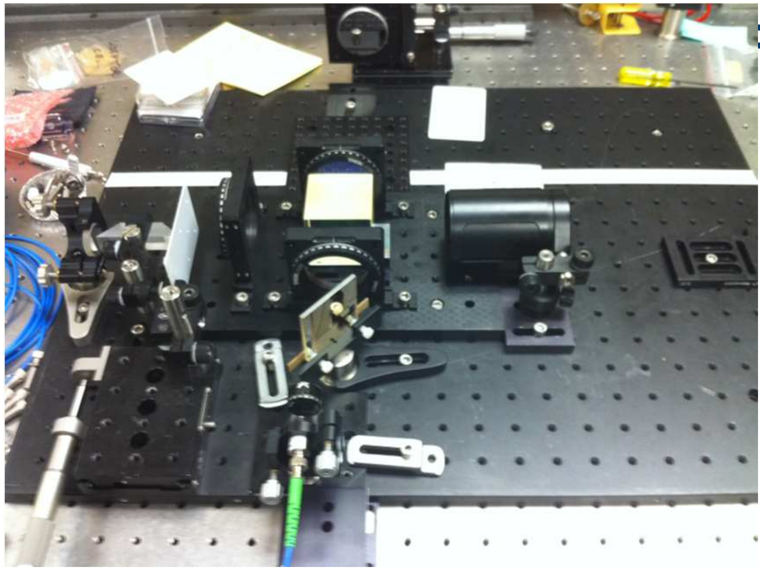
Etalon Schematic



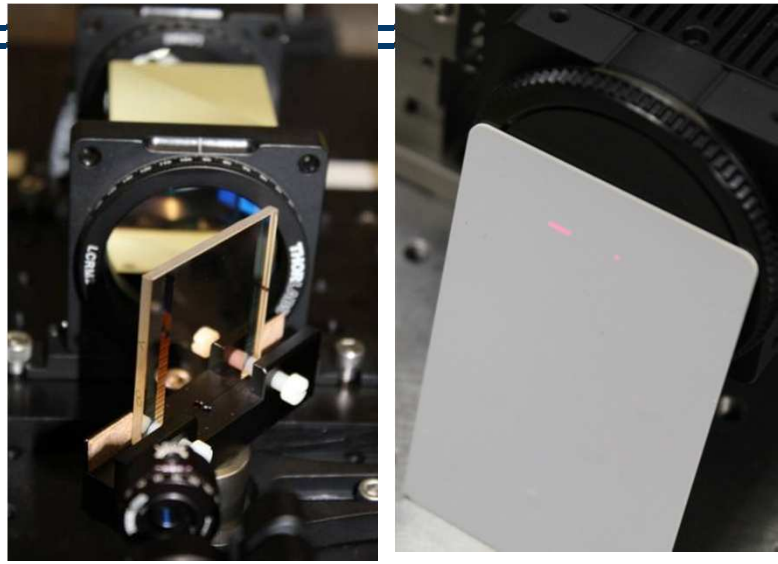
MBLTP Schematic

X-Ray Astronomy Group

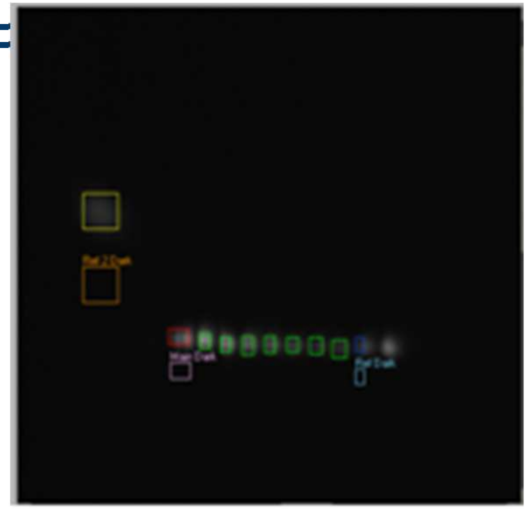
Development of a Multi-beam Long Trace Profiler



MBLTP breadboard, the detector is not shown (on right)



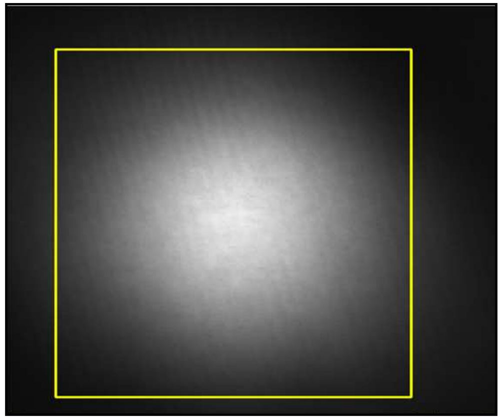
Etalon beamsplitter (left), ten signal beams and reference beam focused on the detector (right)



Screenshot of the detector window. Reference beam is on top left.

- Detector -36 mm x 24 mm area, 7.4 x 7.4 µm pixel size, *1.3 fps for partial frame of 4872x800*
- Custom designed FT *lens (Peter Z. Takacs*(BNL)!) – air-spaced doublet lens, 500 mm focal length, 50 mm diameter, Low distortion – to minimize the effects of lens on systematic errors, three sets fabricated. Working with Peter to define the metrology to detect the best combination
- *The system resolution due to the detector-lens pair is estimated to be ~ 0.23 microrad.*
- *Breadboard is assembled, preliminary testing is being done using regular detector; UV version (no front cover) was procured.*
- Berkeley National Labs (Valeriy) has provided software code, we have adapted it

  for new detector and ten beams
- *In parallel with calibration we are working with Peter and Valeriy to tune the FT lens sets.*



Reference beam on detector, secondary interference fringe pattern is due to the cover plate on the detector