Next Generation X-ray Optics: High-Resolution, Light-Weight, and Low-Cost

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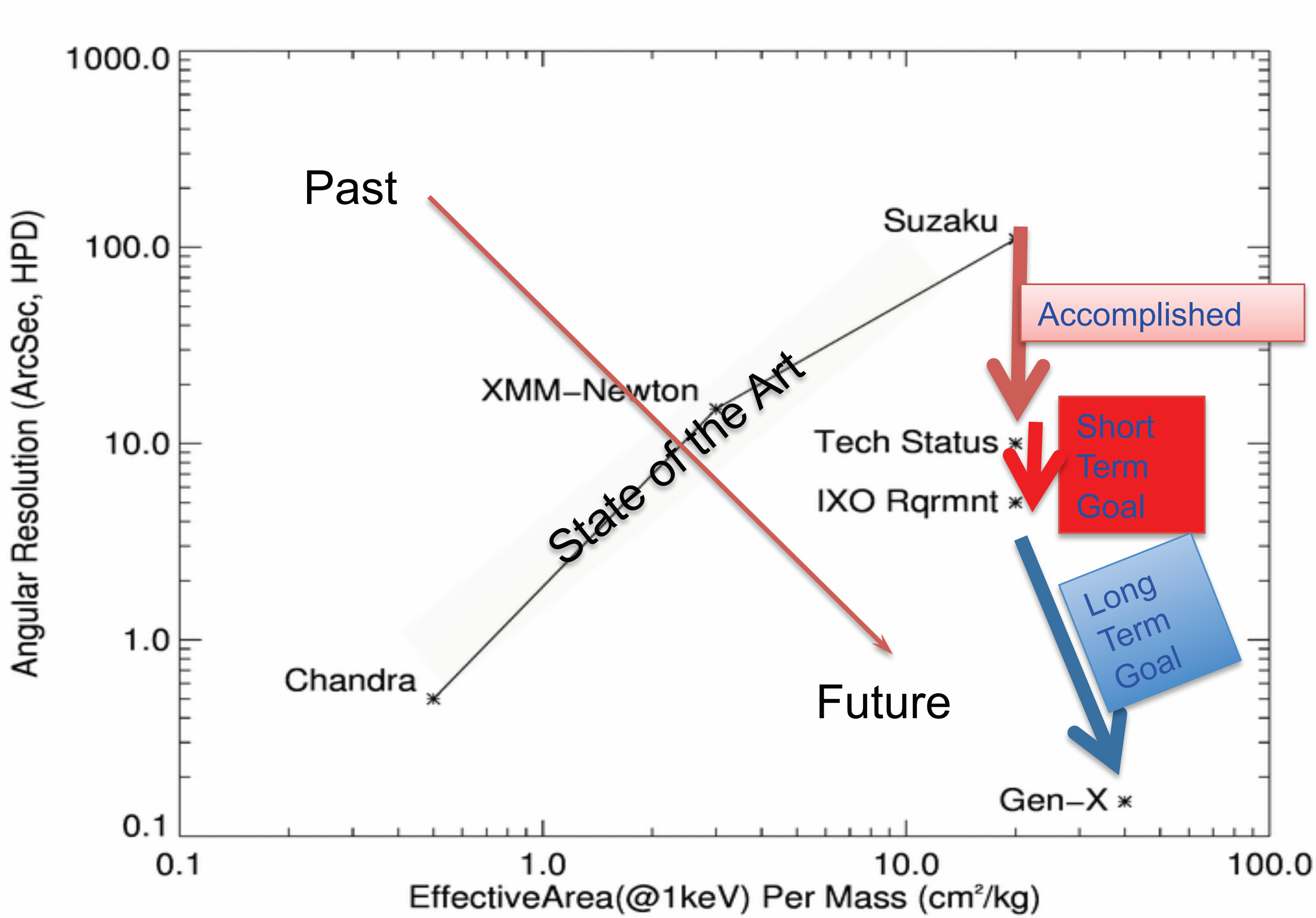
Objectives

- **Short Term (2 – 5 years) Objective: 5”**
  - Precision glass slumping technology, capitalizing on the IXO investment in mirror technology development
  - TRL-5 for 10” by 2012
  - TRL-5 for 5” by 2014
- **Long Term (4 – 10 years) Objective: 0.1”**
  - Precision polishing and light-weighting of mono-crystalline silicon, developing a *game-changing* technology to advance x-ray astronomy in the next two decades
  - TRL-4 for 1” by 2016
  - TRL-5 for 1” by 2018
  - TRL-4 for 0.1” by 2020 (?)
  - TRL-5 for 0.1” by 2021 (?)

The Ideal X-ray Telescope

- Performance Aspects
  - High angular resolution: < 0.5”
  - Large effective area: > 1 m^2
  - Broad band in energy: 0.1 – 100 keV
  - Large field of view: ~1 square degree
- Programmatic Aspects
  - Lightweight: < 1500 kg
  - Low production cost: < $400M
  - Short production schedule: < 4 yrs

Technology Context and Objectives



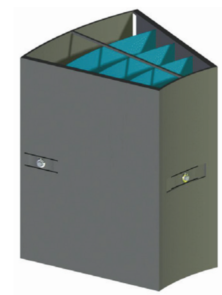
Past, Current, and Future Missions

- 120" – Starting point (Suzaku) in 2002
  - ~60" – Improved aluminum foil optics (EPE, XENIA)
- 53" – Accomplished (NuSTAR) in 2009
- 10" – AEGIS, AXSIO,WHIMEX, HEX-P, BEST
- 5" – SAHARA, WFXT, WFXIS
- 1" – SMART-X or flagship mission in the 2020's
- 0.1" – GEN-X or flagship mission in the 2030's

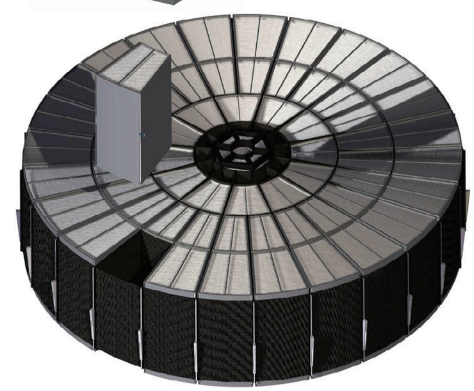
Technology Paradigm

- Segmented Hierarchical Design: ***Scalable to telescopes of all sizes***
  - Mirror segment
  - Mirror module
  - Mirror assembly
- Parallel Developments
  - Mirror fabrication techniques
  - Mirror alignment and integration techniques
  - Systems engineering at both module and assembly levels

Mirror Segment



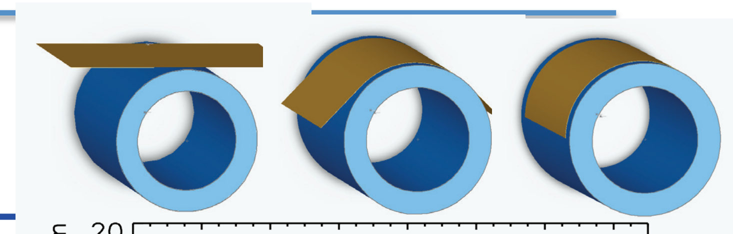
Mirror Module

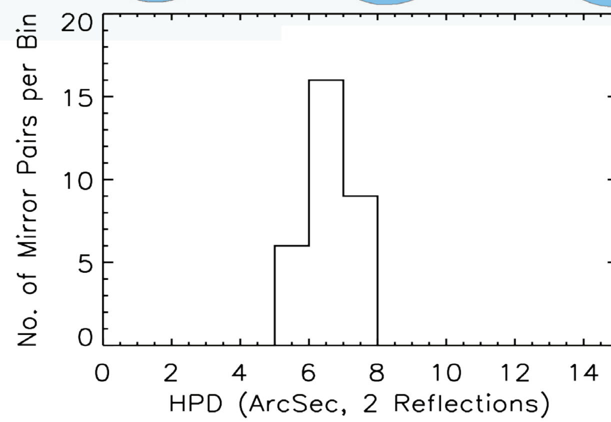


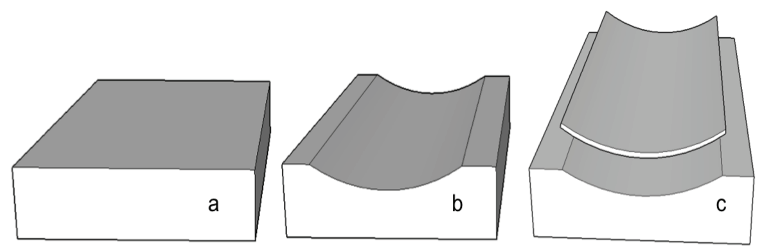
Mirror Assembly

Fabrication of Substrates

- Precision slumping of glass
  - Start with *lightweight* and *low-cost*
  - Seek to improve *angular resolution*
- Precision figuring and light-weighting mono-crystalline silicon
  - Start with excellent *angular resolution* and *light-weight*
  - Seek to reduce *cost*





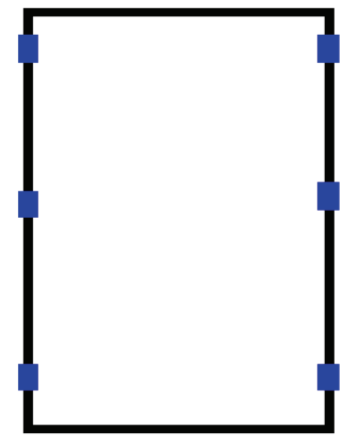


Coating: Sputtering and Atomic Layer Deposition

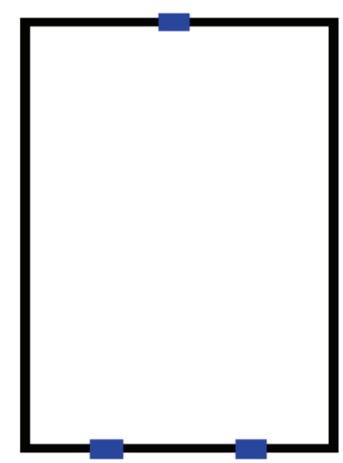
- Soft X-ray (0.1 – 10 keV) Telescopes: single or bi-layer coating
  - Iridium top coating (compressive stress) with chromium under coating (tensile stress)
  - Coating of both concave and convex sides to achieve cancellation of stress
- Hard X-ray (1 – 100 keV) Telescopes: multi-layer coating
  - Detailed balance of stress layer by layer
  - Detailed balance of stress on concave and convex sides

Integration of Mirror Segments

- Mirror segments "over-constrained"
  - Start with a method that already meets mechanical load requirements
  - Reduce distortion caused by over-constraints

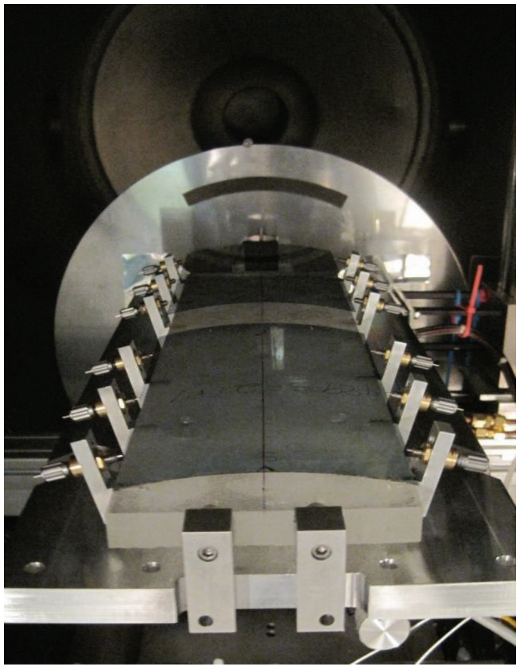


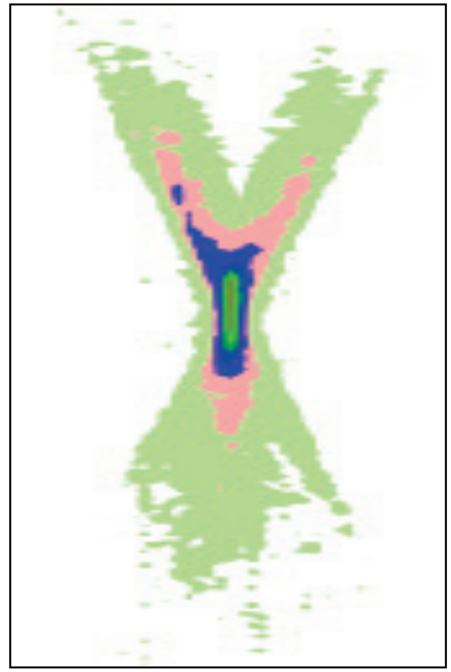
- Mirror segments "kinematically-constrained"
  - Start with a method that meets distortion requirements
  - Develop mechanism to enable the mirror segments to withstand launch load



X-ray Test Result

A pair of mirrors aligned, bonded and placed in a vacuum chamber for x-ray performance test





An X-ray image obtained using 4.5 keV x-rays; the half-power diameter (HPD) is 8.9”, to be compared with IXO’s 5” requirement

Full illumination with 4.5 keV x-rays, 8.9” HPD (two reflections)

Systems Engineering at Module Level

	10"	5"	1"	0.1"
Can a module be tested in a horizontal beam?	Maybe	No	No	No
Can a module with over-constrained mirrors withstand reasonable and realistic launch loads?	Yes	Yes	Yes	Yes
Can a module perform to angular resolution requirements in a reasonable and realistic on-orbit thermal environment?	Yes	Maybe	Yes with silicon mirrors	Not known yet
Alignment and performance long-term stability?	?	?	?	?

Vertical Soft X-ray Beam Line

- Gravity distortion prevents a mirror module from being tested in a horizontal x-ray beam
- A vertical soft x-ray beam operating at ~131 Angstroms is needed to enable the demonstration of high resolution mirror modules
  - A modest 0.5m in diameter parabola
  - With demonstrated multi-layer coating
  - A small vacuum chamber
  - A ~10m vertical pipe

Timeline

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
10" Telescope (Glass)	TRL-3	TRL-4	TRL-5								
5" Telescope (Glass or Silicon)				TRL-3	TRL-4	TRL-5					
1" Telescope (Silicon)		TRL-2	TRL-3	Building and commissioning of a vertical test beam			TRL-4		TRL-5		

1. Basic principles observed and reported
2. Technology concept and/or application formulated
3. Analytical and experimental critical function and/or characteristic proof-of-concept
4. Component and/or breadboard validation in laboratory environment
5. Component and/or breadboard validation in relevant environment
6. System/subsystem model or prototype demonstration in a relevant environment (Ground or Space)

Four Ingredients of Success

- [✔] Clear *short*- and *long-term* objectives
  - Explorer type missions in the short term (2 - 4 yrs)
  - Flagship missions in the long term (5 – 10 yrs)
- [✔] Right approach, paradigm, idea
  - Willingness to change, open to course correction
- [✔] Right people
  - Experience, skill, energy, creativity
- [?] Reasonable funding level: ~$3M a year
  - Maintain personnel skill mix and continuity
  - Procure and maintain facilities and equipment
  - Develop industry partners