Optics requirements for the Generation-X x-ray telescope

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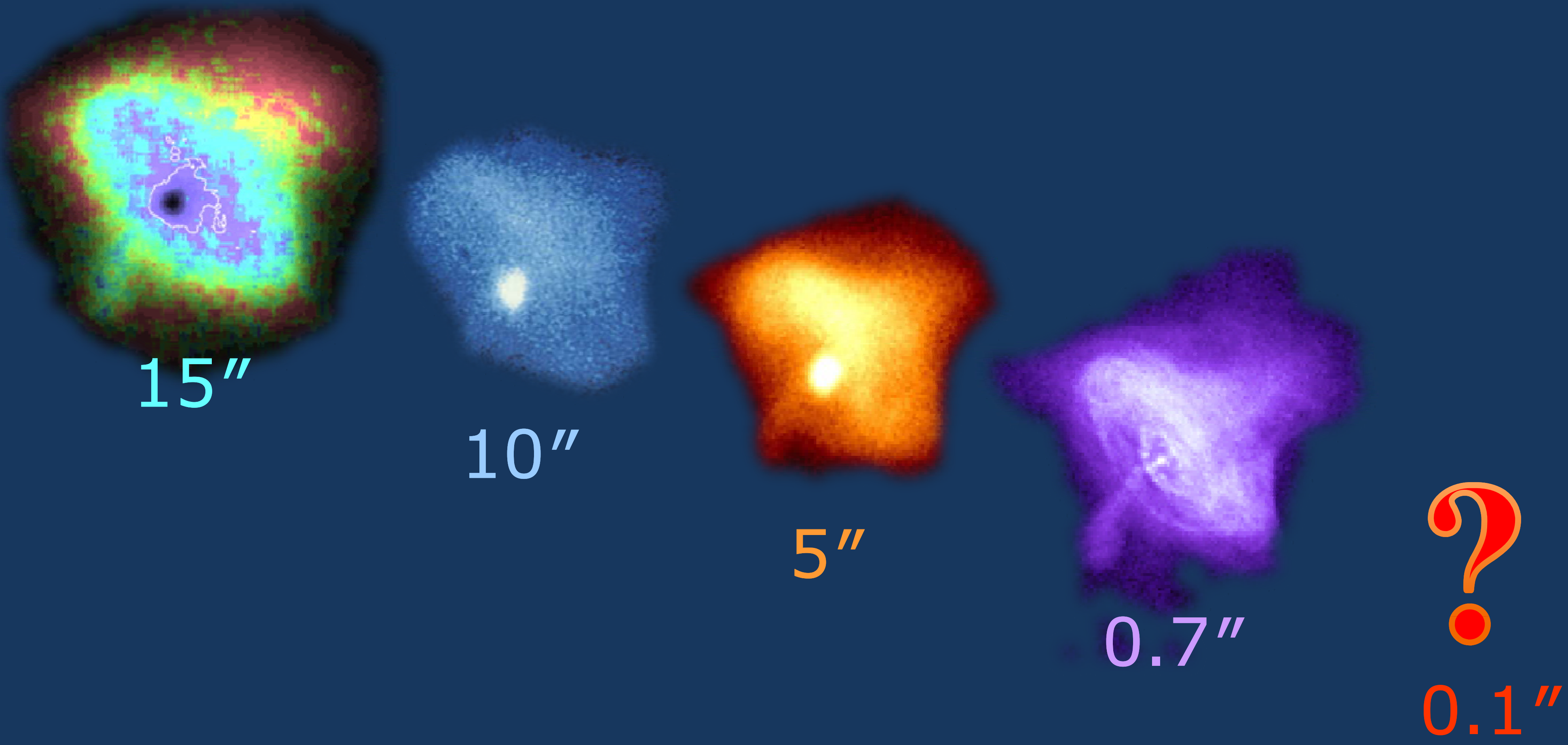
Generation-X Astrophysics Strategic Mission Concept Study is underway.

- Generation-X would launch in 2030+.
  - Largest-area, highest-resolution x-ray telescope
- Purpose of ASCMS
  - Make science case for mission.
  - Identify plausible mission architecture.
    - Aries-V launch to sun–earth L2
  - Lay out technology development plan.
    - Science instruments
    - X-ray optics
      - Identify key technology & manufacturability issues.
      - Formulate a roadmap to bring to technology readiness level TRL6 … and to manufacturing readiness.

Outline

- Fundamental needs for future x-ray telescopes
  - Sharp images ⇒ excellent angular resolution.
  - High throughput ⇒ large aperture areas.
- Generation-X optics technical challenges
  - High resolution ⇒ precision mirrors & alignment.
  - Large apertures ⇒ lots of lightweight mirrors.
- Innovation needed for technical readiness
  - 4 top-level error terms contribute to image size.
  - There are approaches to controlling those errors.
- Innovation needed for manufacturing readiness
  - Programmatic issues are at least as severe.

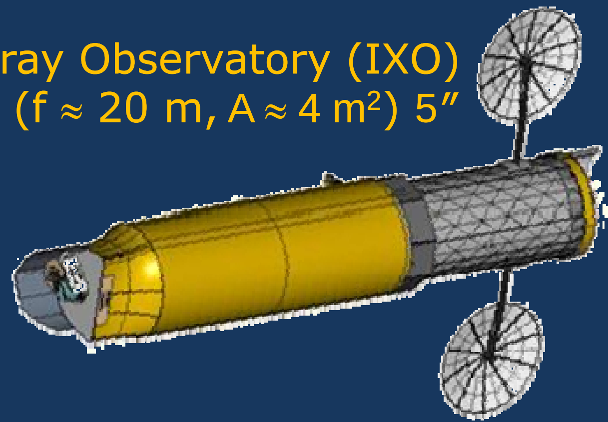
Higher resolution improves both imaging quality and sensitivity (noise reduction).



Aperture area improves sensitivity (signal increase), down to the confusion limit.

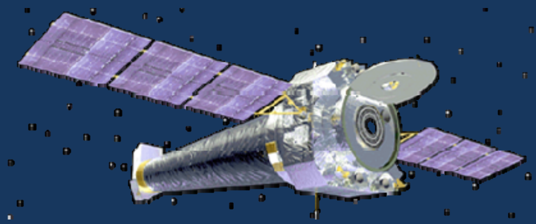
Astronomical x-ray telescopes need large area and high-resolution imaging.

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

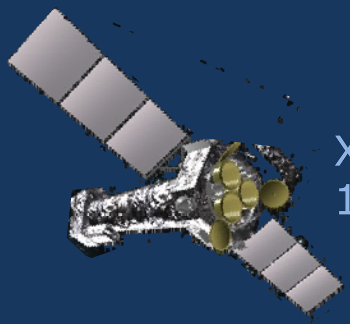


International X-ray Observatory (IXO)
≈2020 (f ≈ 20 m, A ≈ 4 m^2) 5″

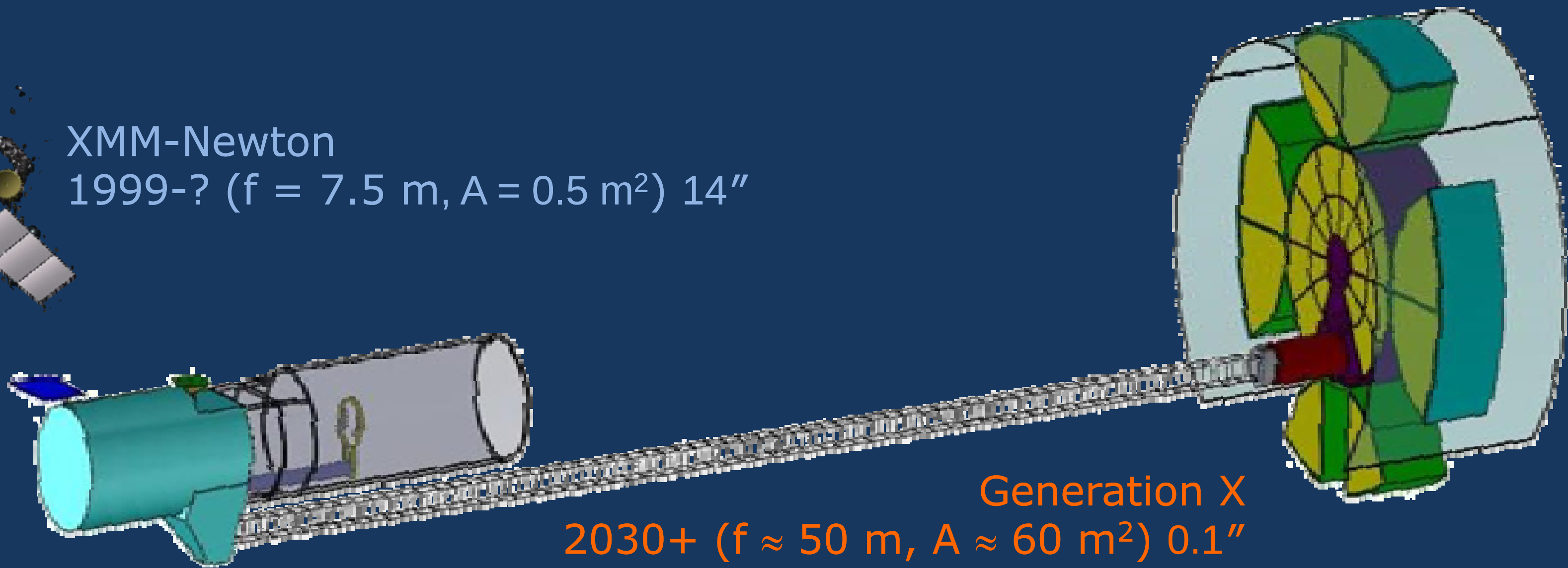
Röntgen Satellit (ROSAT)
1990-1999 (f = 2.4 m , A = 0.10 m^2) 5″



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



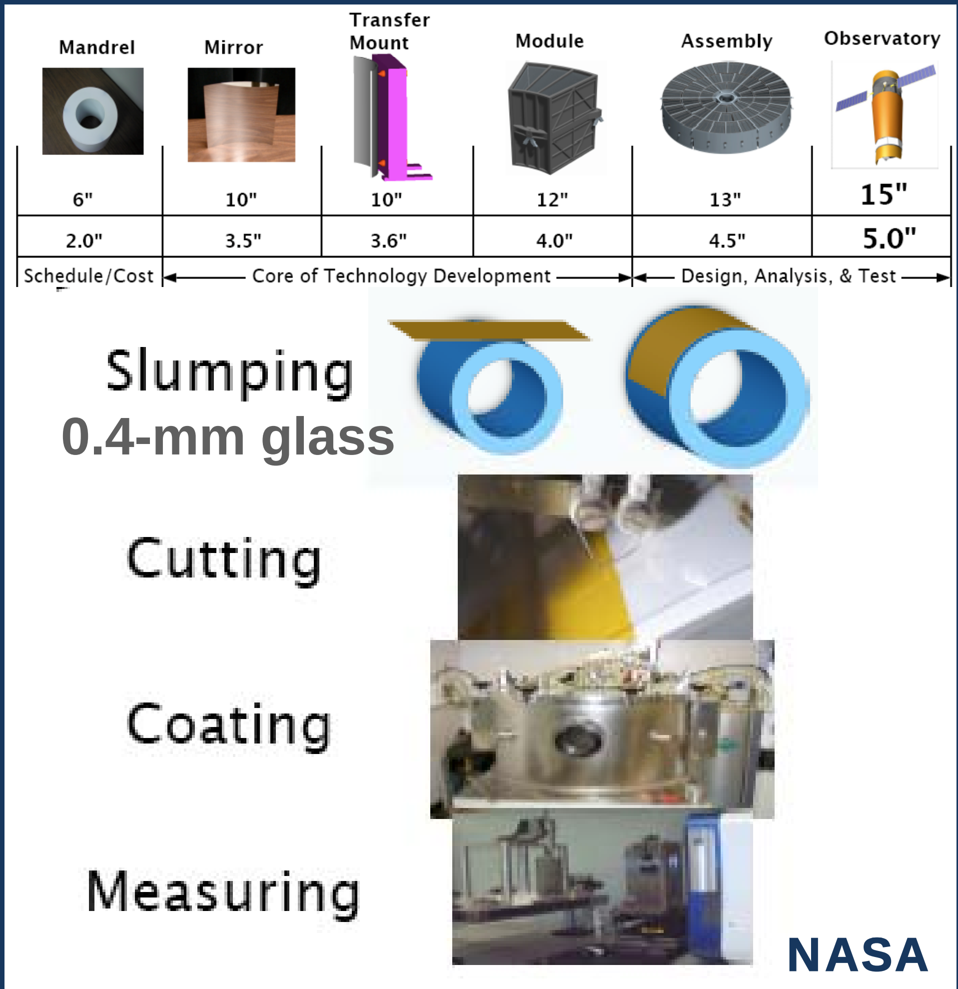
XMM-Newton
1999-? (f = 7.5 m, A = 0.5 m^2) 14″



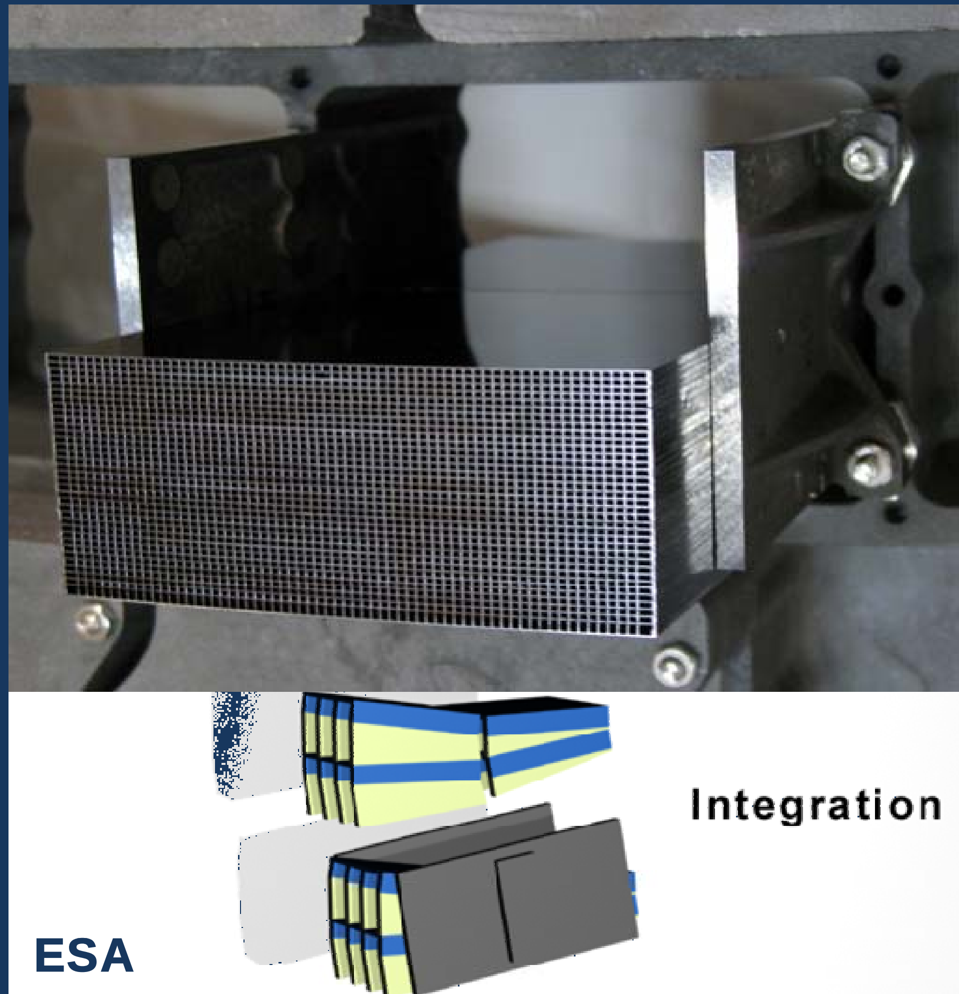
Generation X
2030+ (f ≈ 50 m, A ≈ 60 m^2) 0.1″

NASA, ESA, & JAXA are developing two candidate optics technologies for IXO.

SLUMPED GLASS



SILICON PORE STACKS



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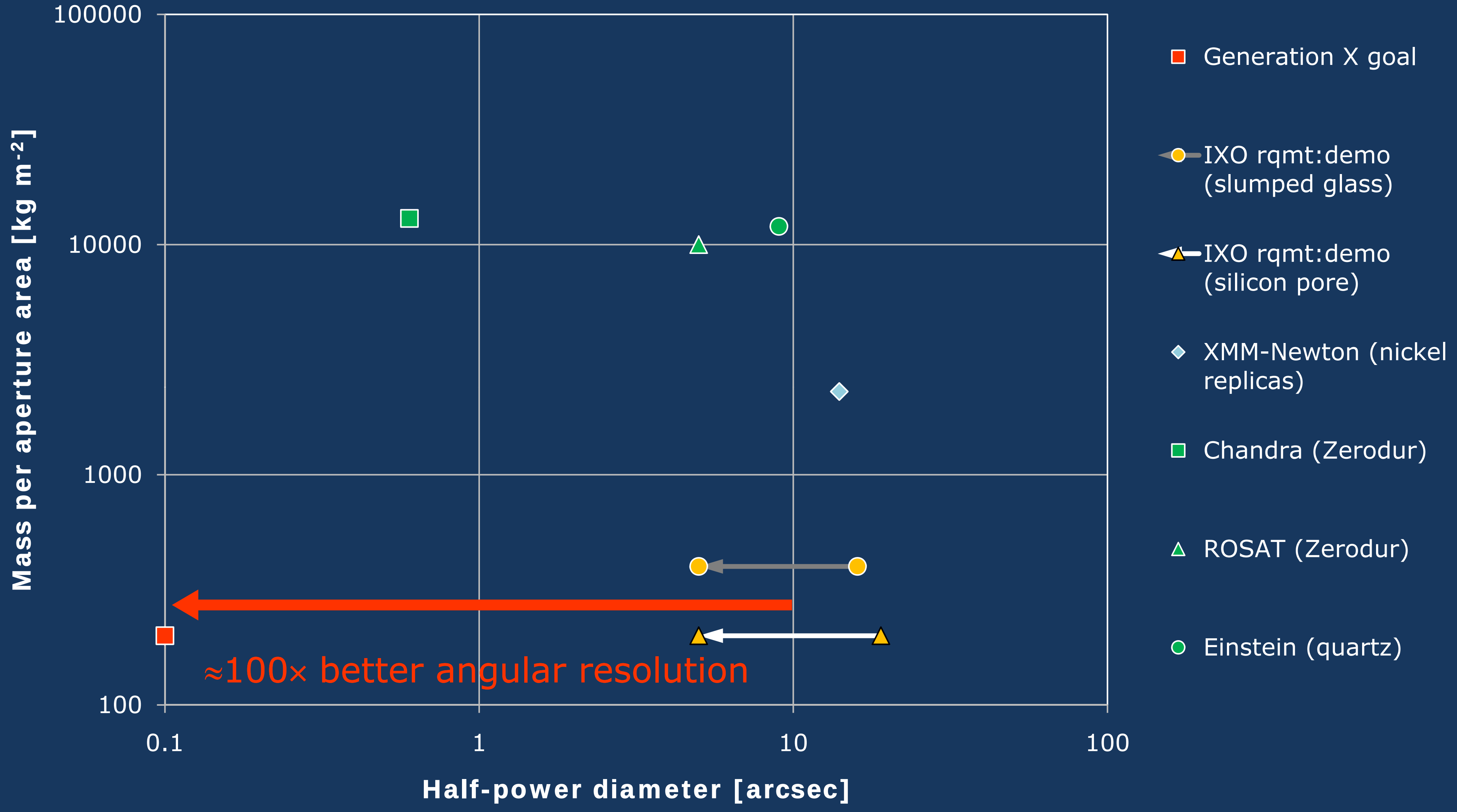
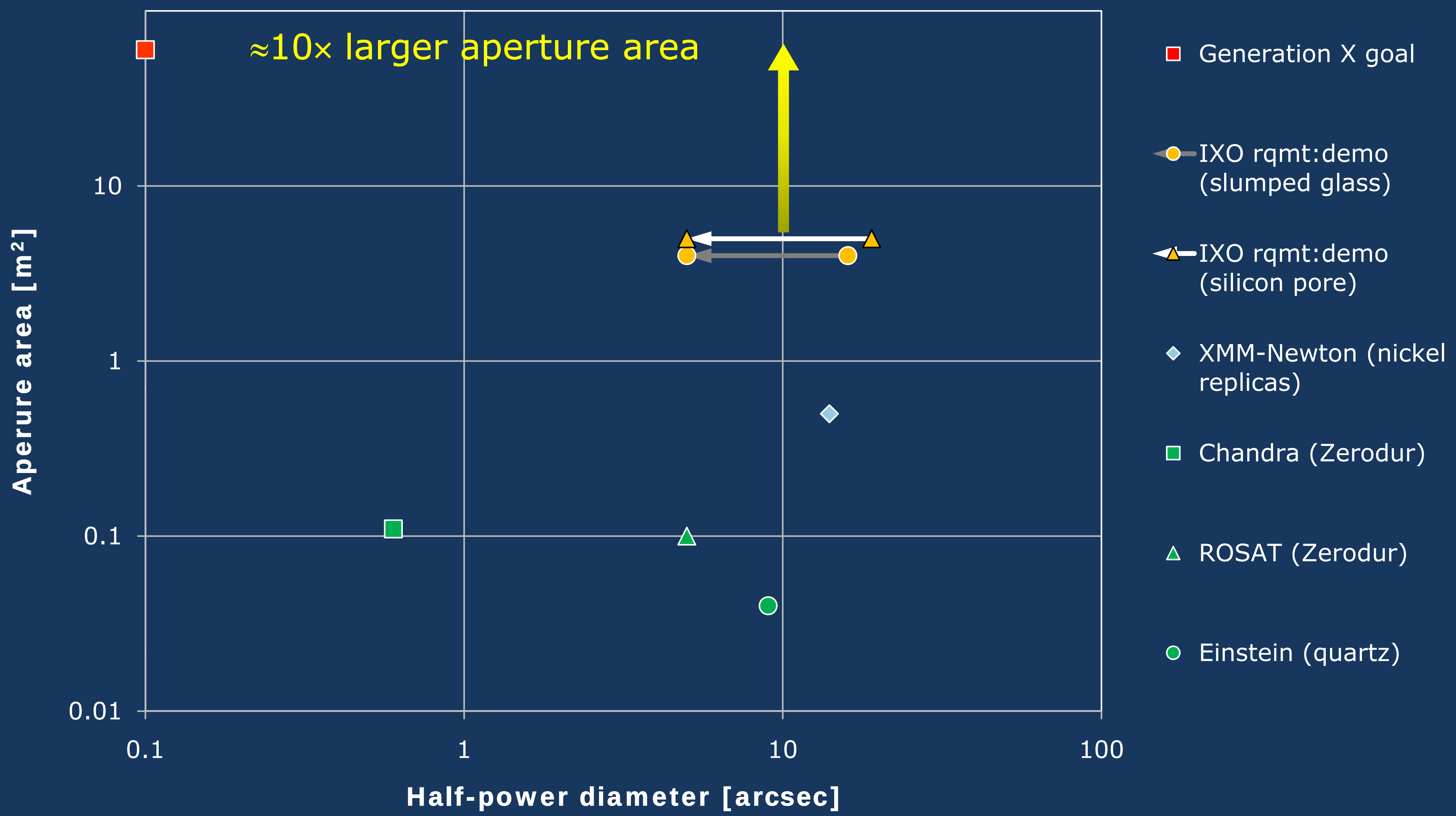
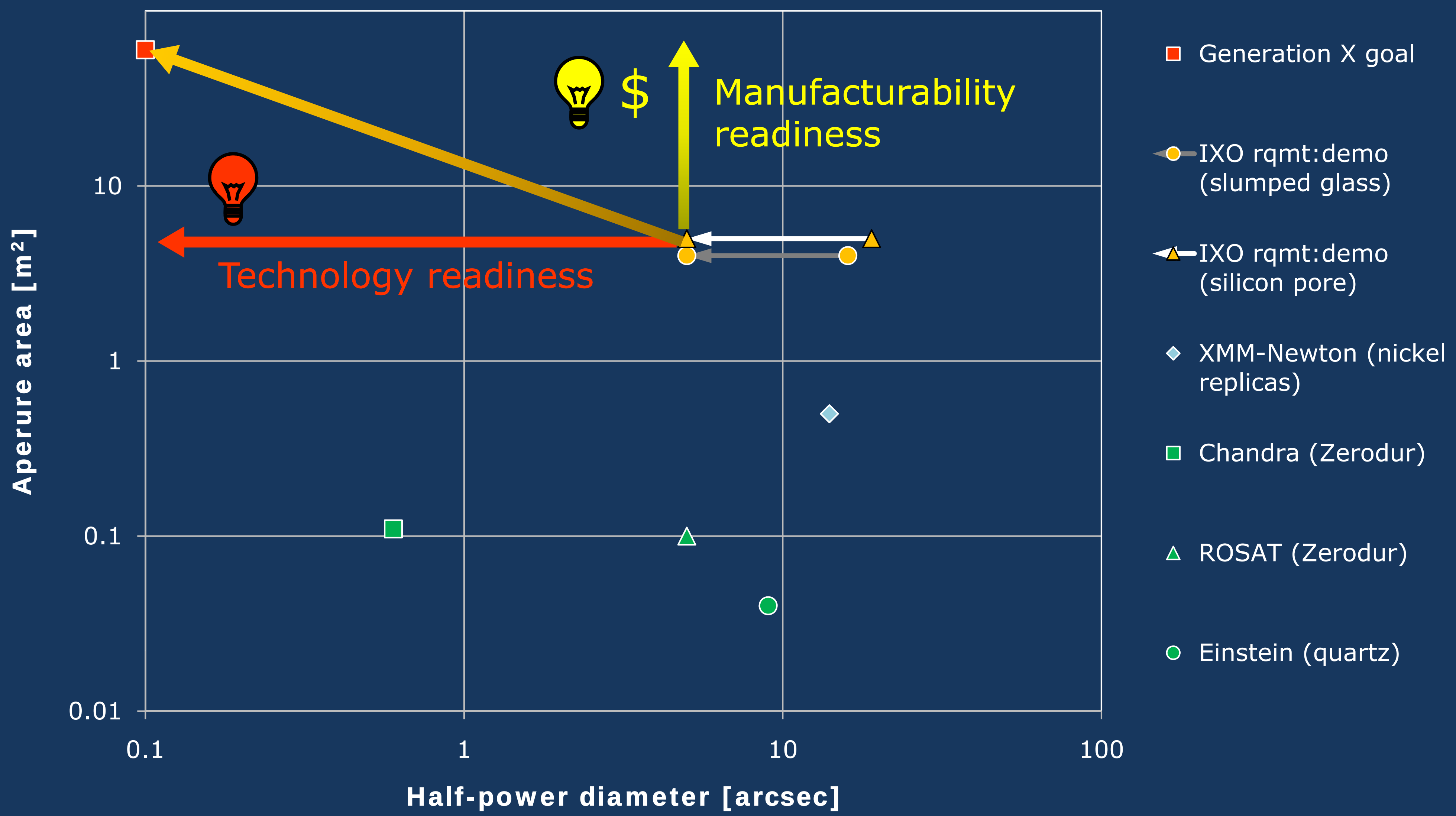
The aperture areal-mass constraint for Generation X is similar to that of IXO.



The aperture-area requirement for Generation X more than 10× that of IXO.



In principle, segmented optics may be scalable to arbitrarily large areas.



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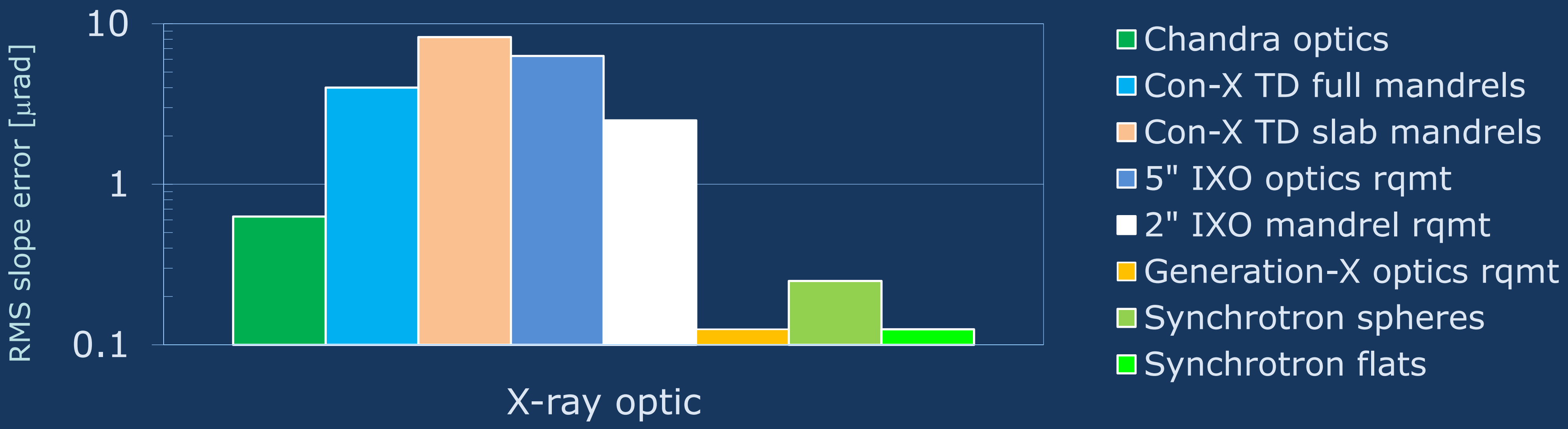
There are 4 top-level terms in the error budget for 0.1″ HPD (0.074″ RMS blur)

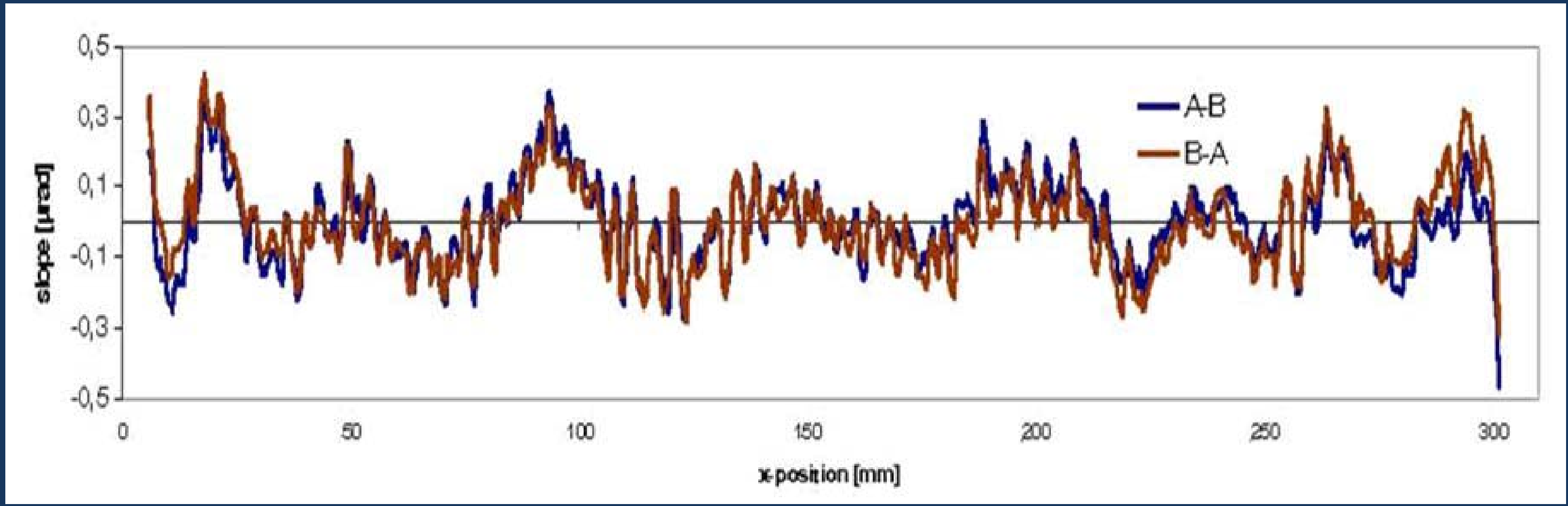
- Mirror surface quality
  - Microroughness scatters far outside 0.1″ ∅.
  - Slope deviations < 0.026″ = 0.125 μrad RMS.
- Mirror mounting
  - Mount must not distort mirror, or
  - Must be able to correct any distortions.
- Mirror-pair (P–S) alignment
  - Accuracy of P–S slope difference < 0.037″ RMS.
- Positioning of aligned mirror pairs
  - Accuracy of co-location < 0.36μ×F RMS.
    - P–S pairs are not sensitive to overall tilt errors.

There are alternative approaches for addressing each error contribution.

- Mirror surface quality
  - Replicate to requirements at >mid-f.
  - Correct >mid-f figure of replica (in situ).
- Mirror mounting
  - Align very stiff mirrors with correct low-f figure.
  - Actively correct low-f figure of flexible mirrors.
- Mirror-pair (P–S) alignment
  - Align separate P and S replicated mirrors.
  - Replicate integral P+S mirror from mandrel.
- Positioning
  - May need rigid-body adjustment on-orbit.

Requirement on axial-slope deviation is near state-of-art, even for thick mirrors.





BESSY flat, figured to 0.12-μrad RMS residual slope, by Zeiss

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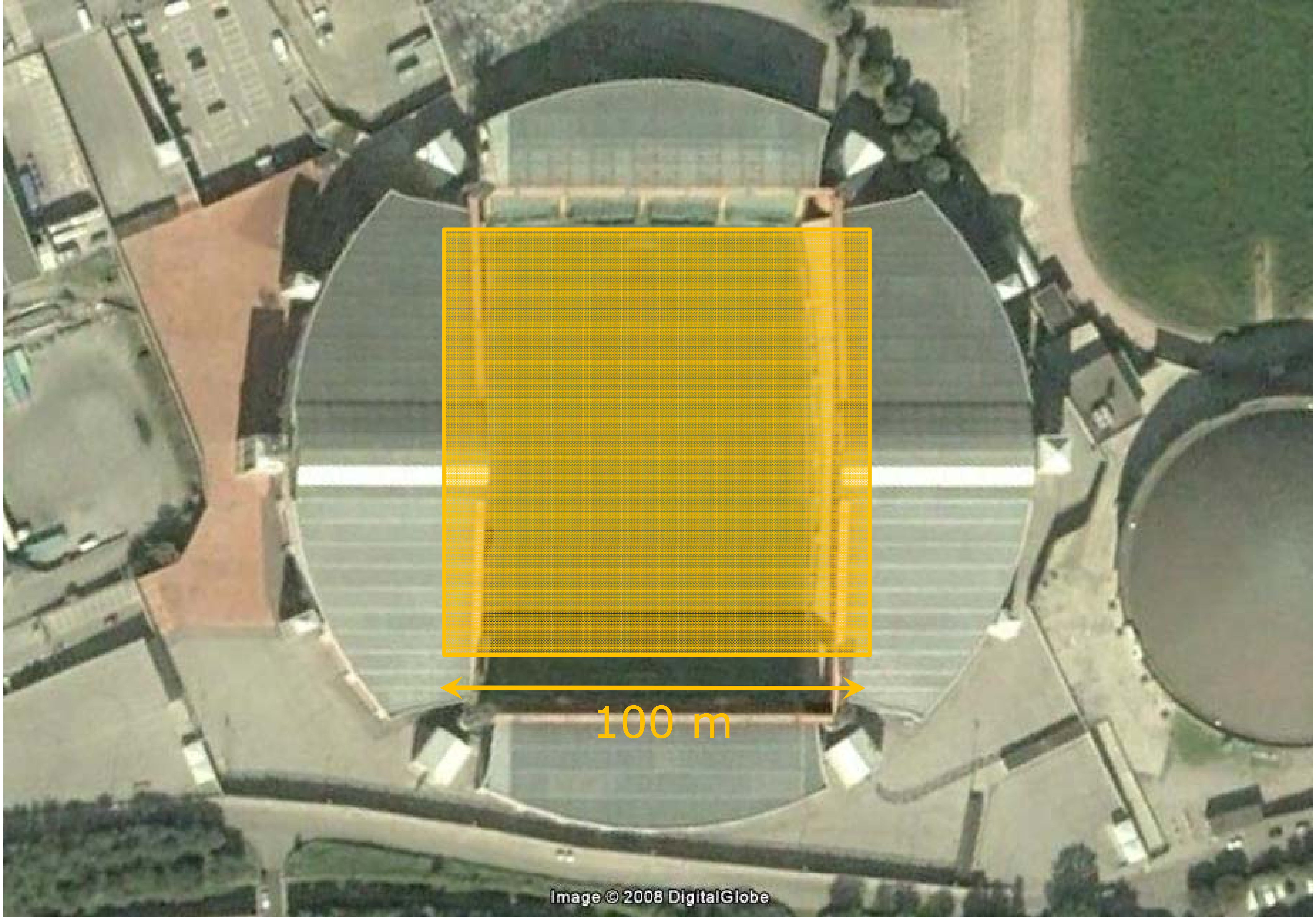
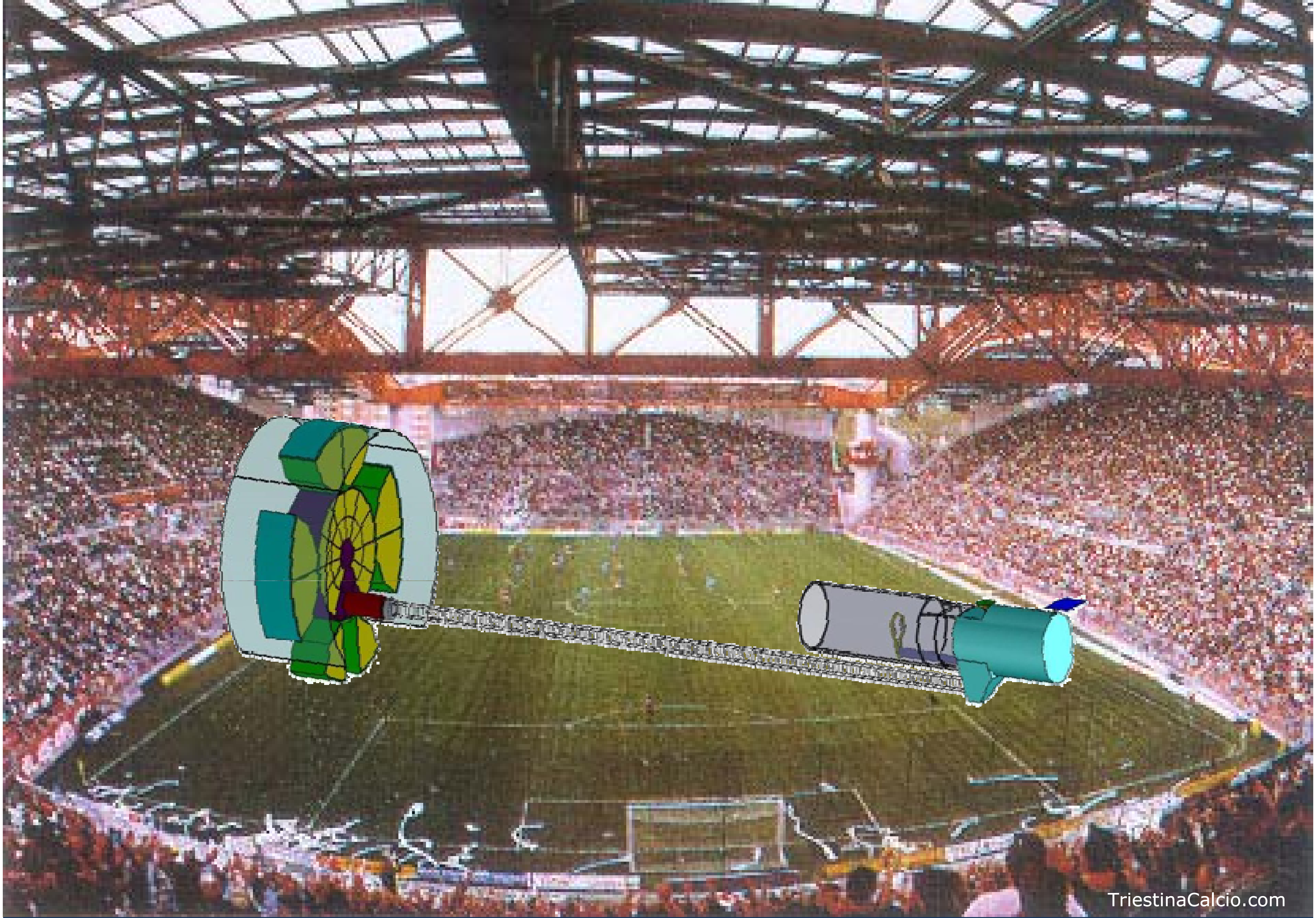
For a typical x-ray band, surface area is about 200 times the aperture area.

- Grazing-incidence imaging requires at least 2 reflections.
  - Area of each secondary mirror is nearly equal to that of its corresponding primary mirror.
- The typical grazing angle ≈ 0.01 radian.
  - $\alpha < \alpha_c = 0.029 \sqrt{(f_1\ \rho/A)} \div E_{keV} \approx 0.018\ (\sqrt{\rho}) \div E_{keV} \rightarrow 0.08 \div E_{keV}$ for typical x-ray coating (Ir, Pt, Au).
  - Energy range $\Rightarrow \alpha = R/(4F) = D/(8F)$: f-number.
- Large apertures ⇒ *very* large mirror areas. $
  - IXO mirror surface area ≈ 1000 m^2.
  - Generation-X mirror surface area ≈ 10000 m^2.


100 m
Image © 2008 DigitalGlobe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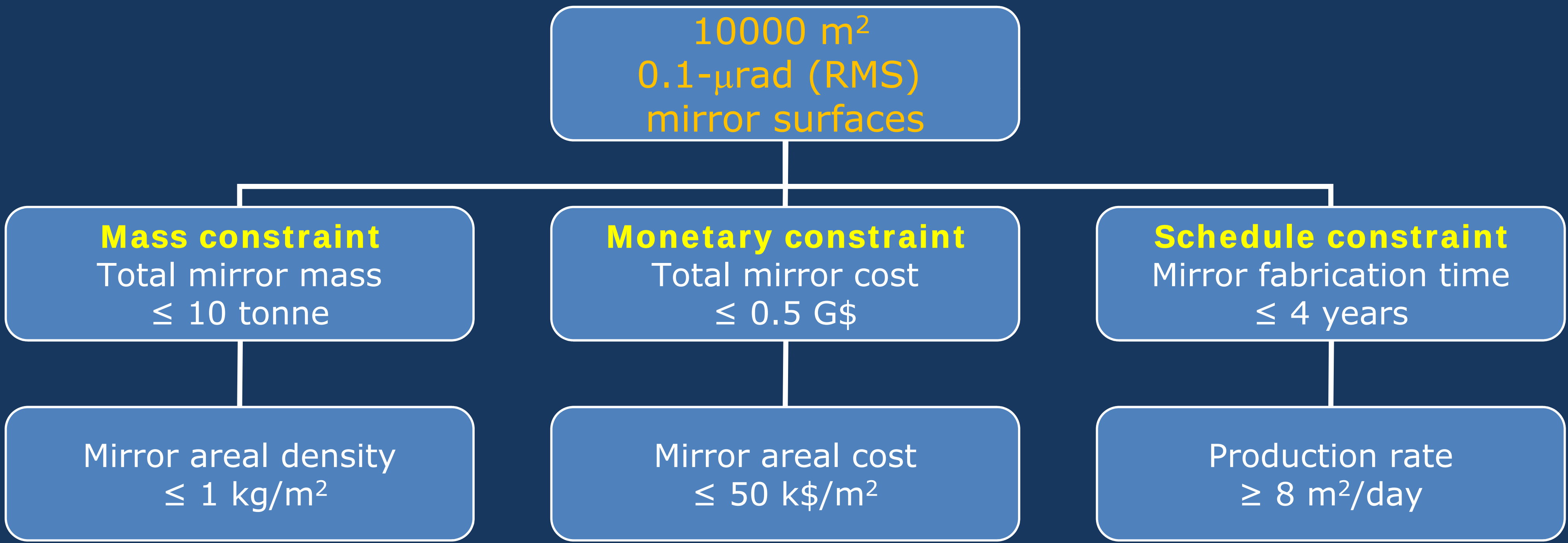
Programmatic constraints require innovation for manufacturing readiness.

- Optimize mandrel fabrication and replication.
  - Minimize post-replication corrections.
- Automate all processes as fully as possible.
  - Implement closed-loop fabrication & metrology.



Summary

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Optical factors favor multiple telescopes over a single one of the same total area.

- N telescopes with individual area $A_N = A_1/N$
  - Other x-ray observatories use this approach.
    - XMM/3; ASCA/4; Suzaku/4; eROSITA/7; HERO/8
  - Leverages the replication approach.
    - Reduces mandrel area and cost by $\sqrt{N}$ to N. $
  - Each telescope is more compact by $\sqrt{N}$.
    - Radius $R_N = R_1/\sqrt{N}$; focal length $F_N = F_1/\sqrt{N}$.
    - Eases handling, alignment, assembly, and testing. $
      - May simplify and reduce risks of deployment. $
  - Sensitivity, detector & mirror area are invariant.
- Trade against multiple focal-plane detectors.