

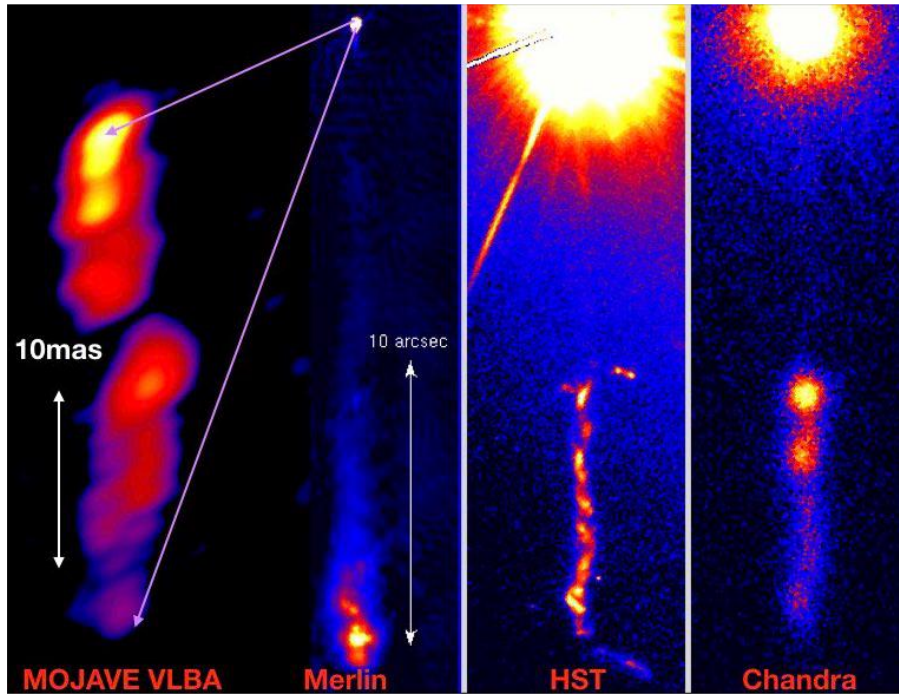
Diffraction-Limited Milli-arcsecond X-ray Imager

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Milli-arcsecond soft X-ray imaging



- Hi-ReX SAG identified about 9 science cases for ~ 5 mas resolution imaging*
- mas-scale structure and separations visible in other bands, but not yet in X-ray.
- **True imaging:** sensitivity scales with resolution, no rotation to cover u-v plane.
- Concept extendable to micro-arcsecond resolution.

*Summary paper from Hi-ReX SAG:

H. L. Marshall, K. Weaver, M. L. Schattenburg, B. Binder, et al.,
“Science of High Resolution X-ray Imaging,” arXiv:2606.28138 (2026)

Chalifoux, et al., Milli-arcsec X-ray imager

A coherence-expanding path to μ as imaging

Incoherent

Capable of $\sim$ arcsec resolution

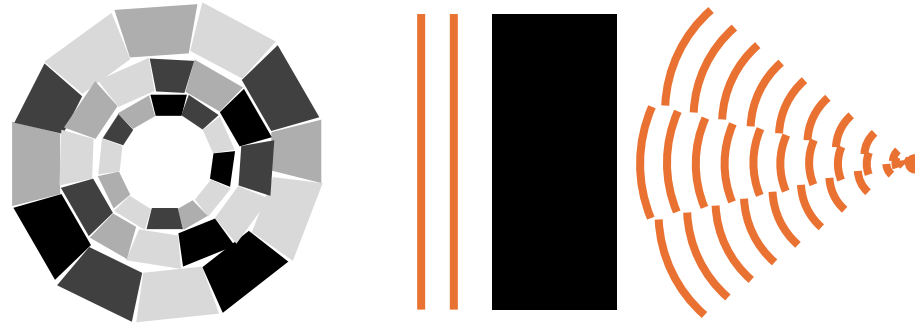
$$f \sim px / \theta \sim 10 \text{ m}$$



Partially coherent

Capable of $\sim$ milli-arcsec resolution

$$f \sim 100 - 1000 \text{ m}$$



Fully coherent

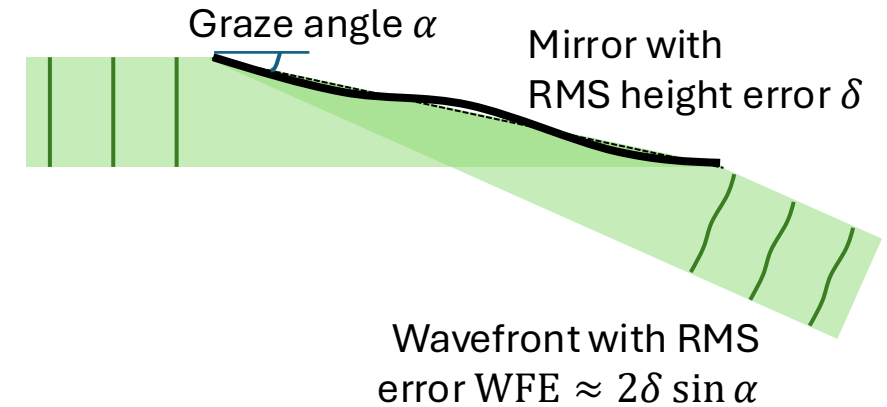
Capable of $\sim$ micro-arcsec resolution

$$f \sim 100 - 1000 \text{ km}$$



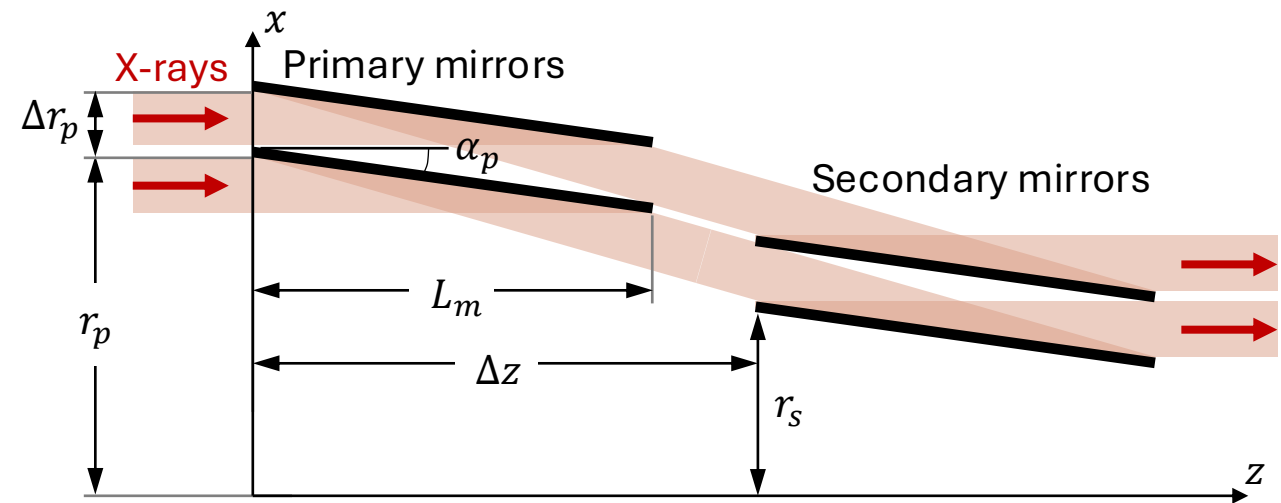
X-rays are waves

- Grazing-incidence reflection attenuates wavefront error.
- Surface accuracy requirements independent of resolution:
 - At 2 keV and $\alpha = 1^\circ$, for $WFE \sim \lambda/20$ RMS, $\delta \sim 1$ nm RMS.
 - Arcsecond-resolution already requires $\delta \sim 10$ nm RMS.
- Resolution driven by region of coherence, D
 - $\theta \sim \lambda/D$
 - 5 mas resolution at 2 keV requires $D \sim 25$ mm
 - One ~ 150 mm-long mirror at $\alpha = 1^\circ$ has $D \sim 2.6$ mm



Phased X-ray mirror shells

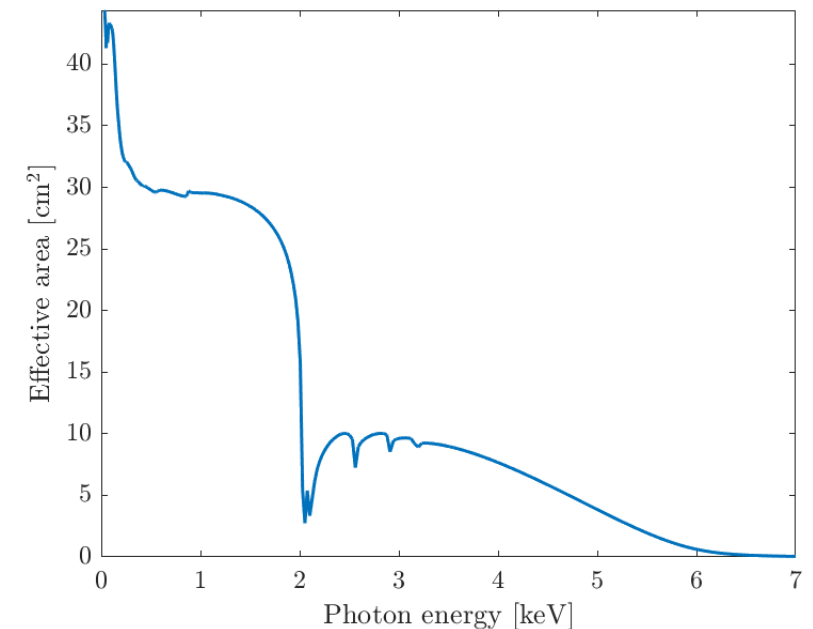
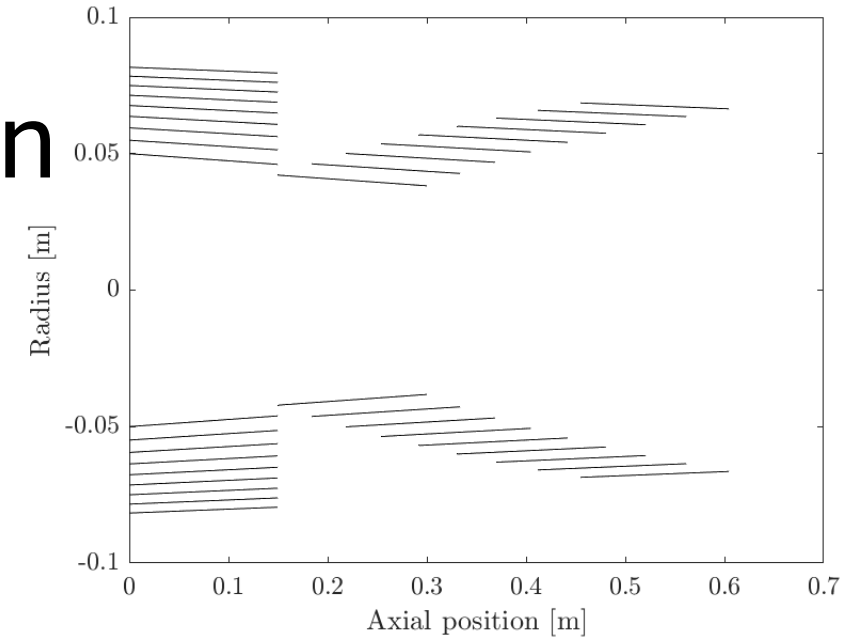
- Region of coherence is expanded by phasing multiple nested shells.
- Optical pathlength can be matched between shells in a Wolter Type 2 telescope.
- Axial spacing and graze angle adjusted throughout a module.
- Mirrors are curved, not flat.



B. D. Chalifoux, R. K. Heilmann, H. L. Marshall, and M.L.Schattenburg:
Appl.Optics, 59, 4901 (2020)

Module size defines resolution

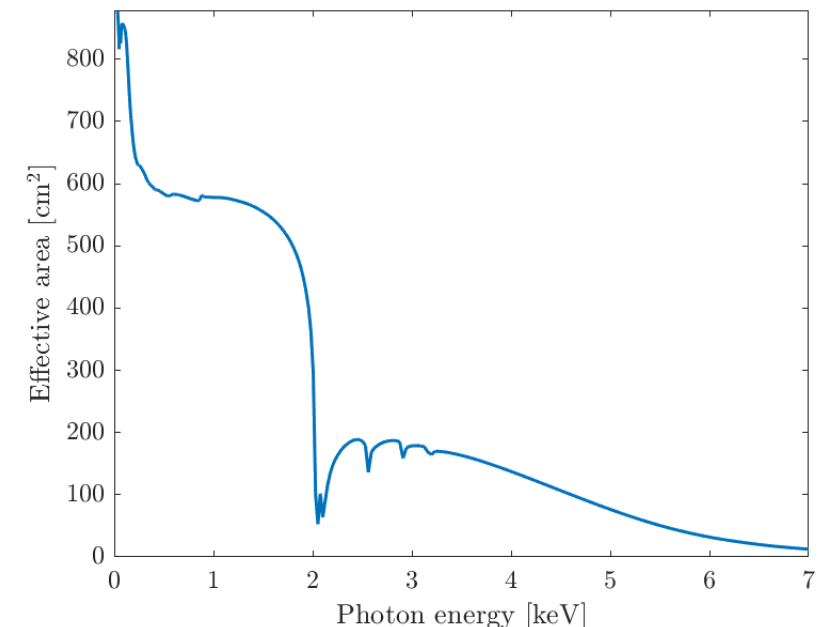
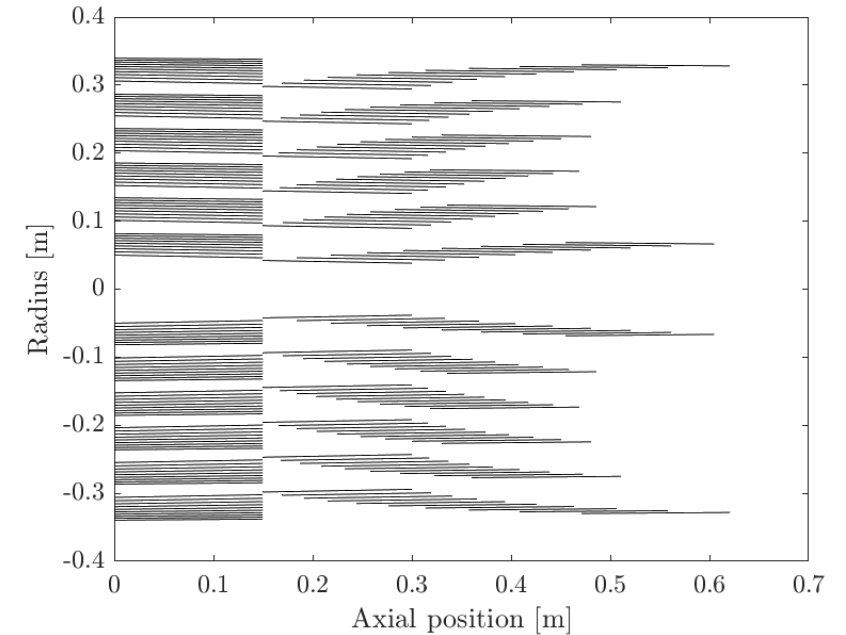
- A single ring of 7 modules, each with internally-matched pathlength.
- Each module has a 31 mm × 31 mm aperture, 9 mirror-pairs
- Segments: 150 mm × 31 mm × 1 mm
- Graze angle around 1.5°
- Coating: iridium



Increasing effective area

- Six rings of modules, with each module having internally-matched pathlength.
- Each ring has different field curvature, but depth of focus is ~ 19 mm. FOV of 1 arcmin is plausible.

Focal length, f	100 m
Diffraction limited angular resolution, 2 keV	5 mas
Pixel size, d_{px}	$2.9 \mu\text{m}$
FPA size	10k x 10k pixels
Angular full FOV	1 arcmin

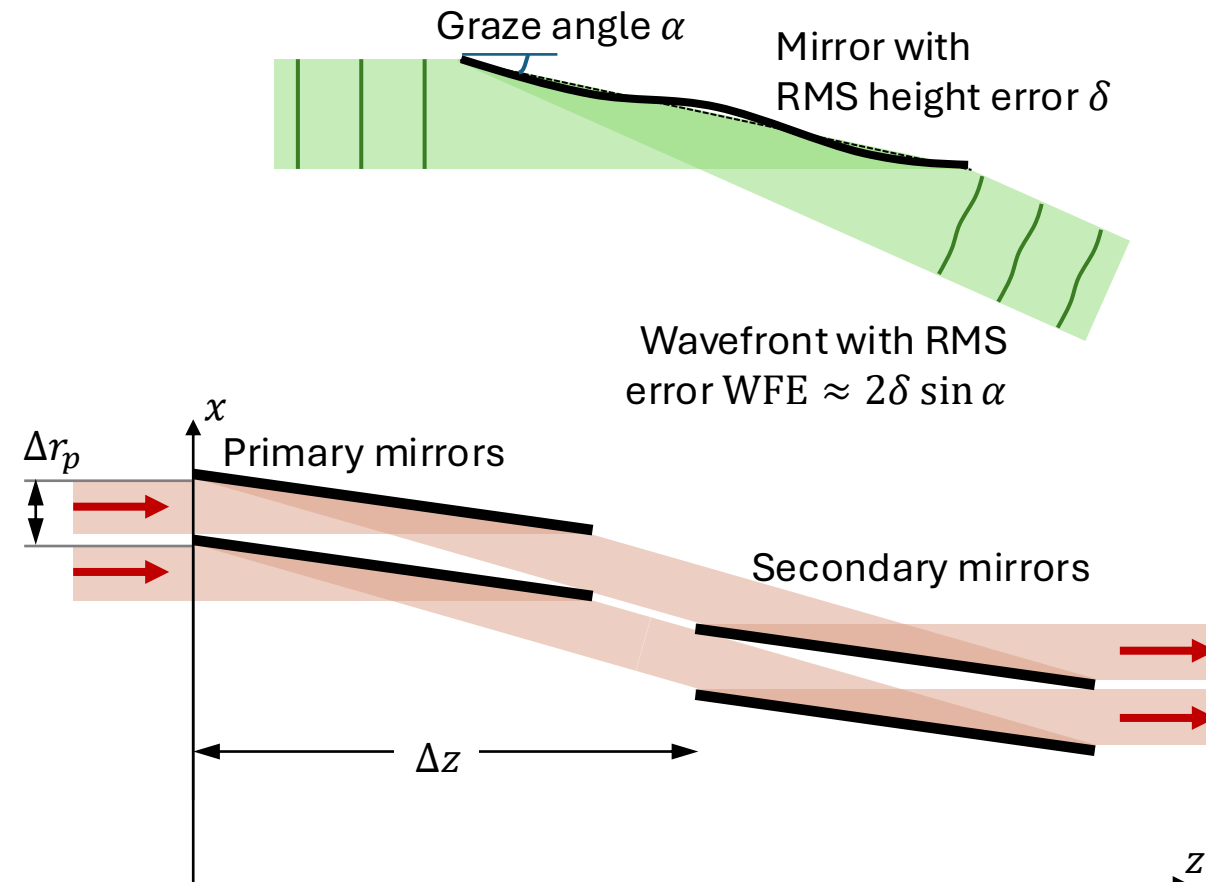


Technology development needs

1. **Mirror modules:** nm-accurate manufacturing and assembly
2. **Ground testing:** bright μm -scale X-ray sources and metrology methods
3. **Long focal lengths:** arcsec-stable, ~ 100 m-long architectures
4. **Attitude knowledge:** $\sim \text{mas}$ line of sight accuracy
5. **Detectors:** large-area, $\sim \mu\text{m}$ spatial resolution, and ~ 100 eV energy resolution

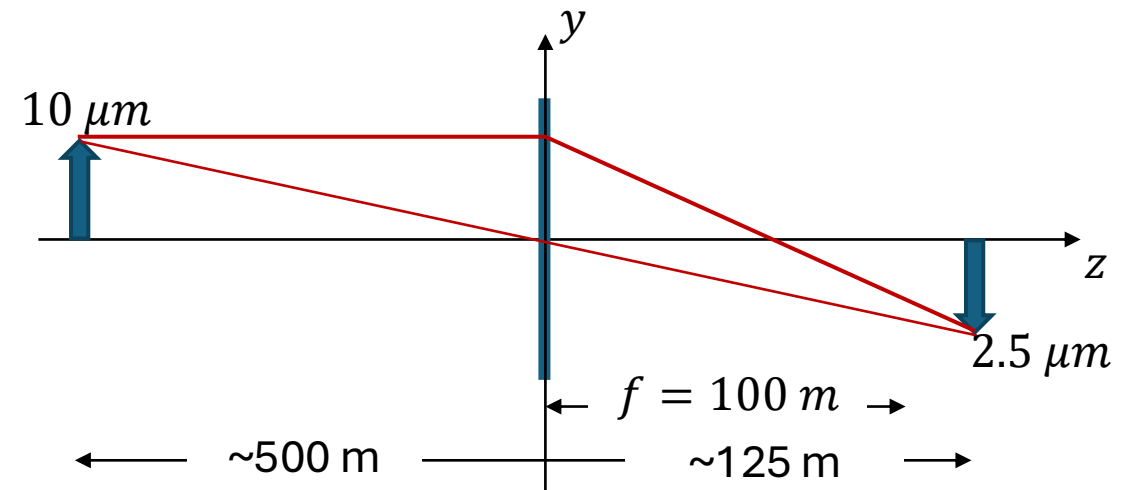
Mirror modules: nm-accurate manufacturing and assembly

- Surface accuracy and phasing requirements:
 - ~1 nm RMS per mirror (~10× tighter than an arcsecond-resolution telescope).
 - Axial gap tolerance <50 nm RMS
 - Radial gap tolerance ~1 nm RMS
 - Pairwise pitch ~1 mas
- New developments:
 - Accuracy similar to synchrotron mirror state-of-the-art.
 - Accuracy much lower than EUV lithography.
 - Silicon carbide (~2-3× stiffer than silicon) is proliferating.
 - Laser processing is maturing*.



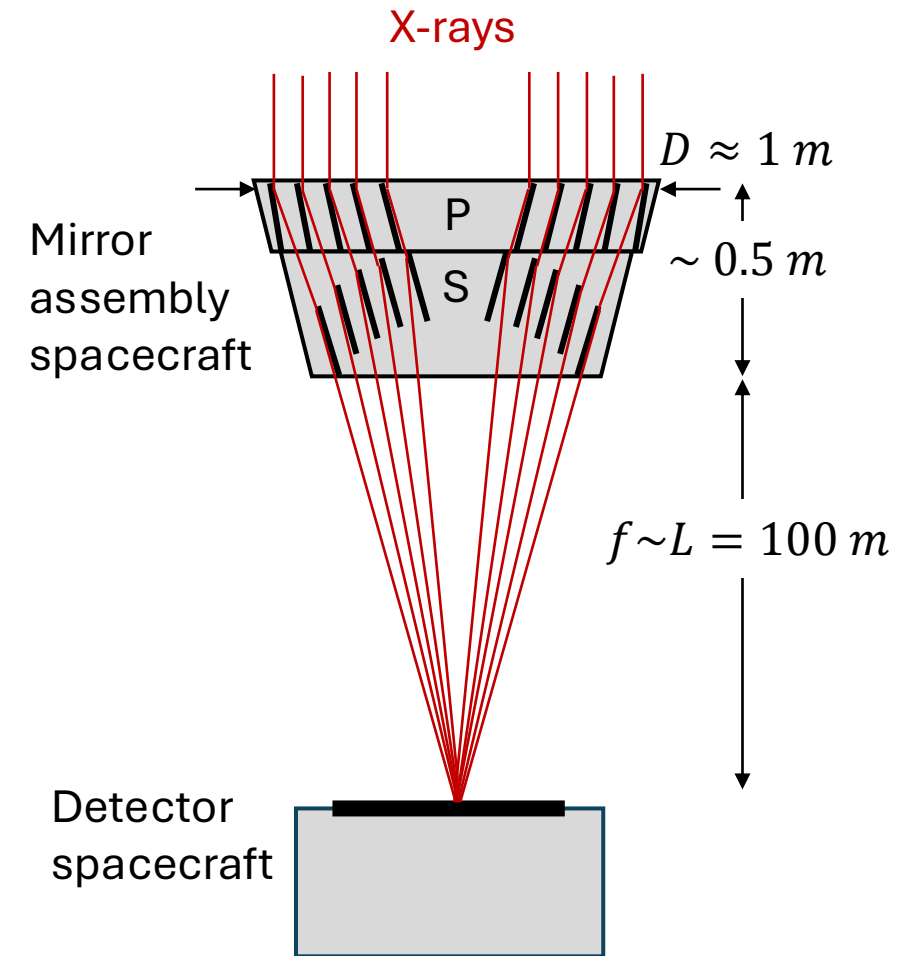
Ground testing: bright μm -scale X-ray sources and metrology methods

- A $10\ \mu\text{m}$ source at $500\ \text{m}$ range yields a $2.5\ \mu\text{m}$ image.
- Need for spatial coherence pushes source size lower.
- Bright sources at *multiple wavelengths* are critical to tune and verify phasing.
- Semiconductor industry is spurring need for bright EUV/Soft X-ray lab sources.



Needs common to any high-resolution X-ray imager or interferometer

- **Long focal lengths:** arcsec-stable, ~100 m-long architectures (formation flying or booms)
- **Attitude knowledge:** ~mas line of sight accuracy
- **Detectors:** large-area, ~ μm spatial resolution, and ~100 eV energy resolution



Summary

- Milli-arcsecond imaging enables science unachievable through other means.
- Coherence-expanding path to increasingly higher resolution.
- Technology development needs:
 1. Mirror modules
 2. Ground testing
 3. Long focal lengths
 4. Attitude knowledge
 5. Detectors