Lobster-Eye Hard X-Ray Telescope Mirrors

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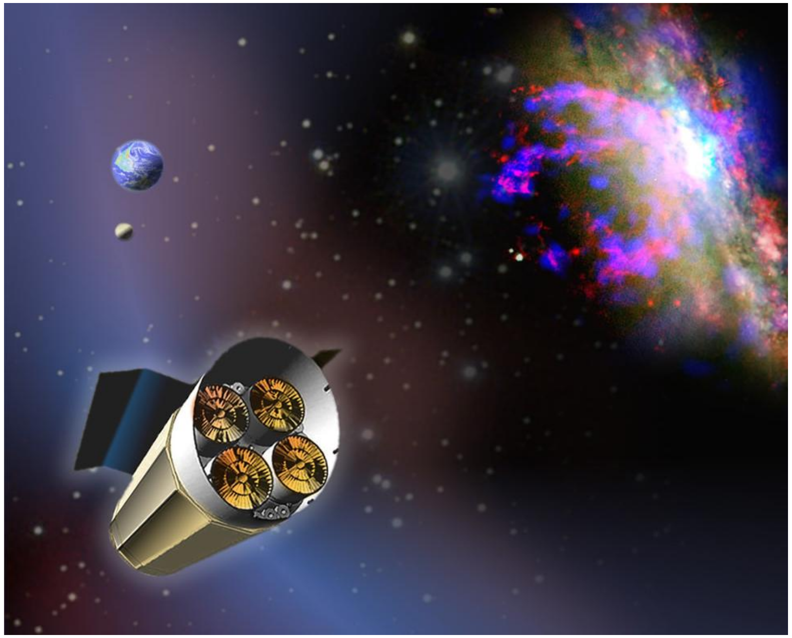
NASA is developing a hard X-ray telescope (HXT) for Constellation-X mission

HXT Goals:

1. Study of black hole evolution
2. Investigation of the Cosmic X-ray Background (CXRB)
3. Detection of hard X-rays in stellar flares
4. Observation of nuclear transition lines



Baseline Constellation-X HXT requirements

Band Pass: 10 - 40 keV

Minimum effective area: 150 cm^2 @ 40 keV

Minimum angular resolution: 30”

Field of View: 5’ X 5’ (10’ X 10’ goal)

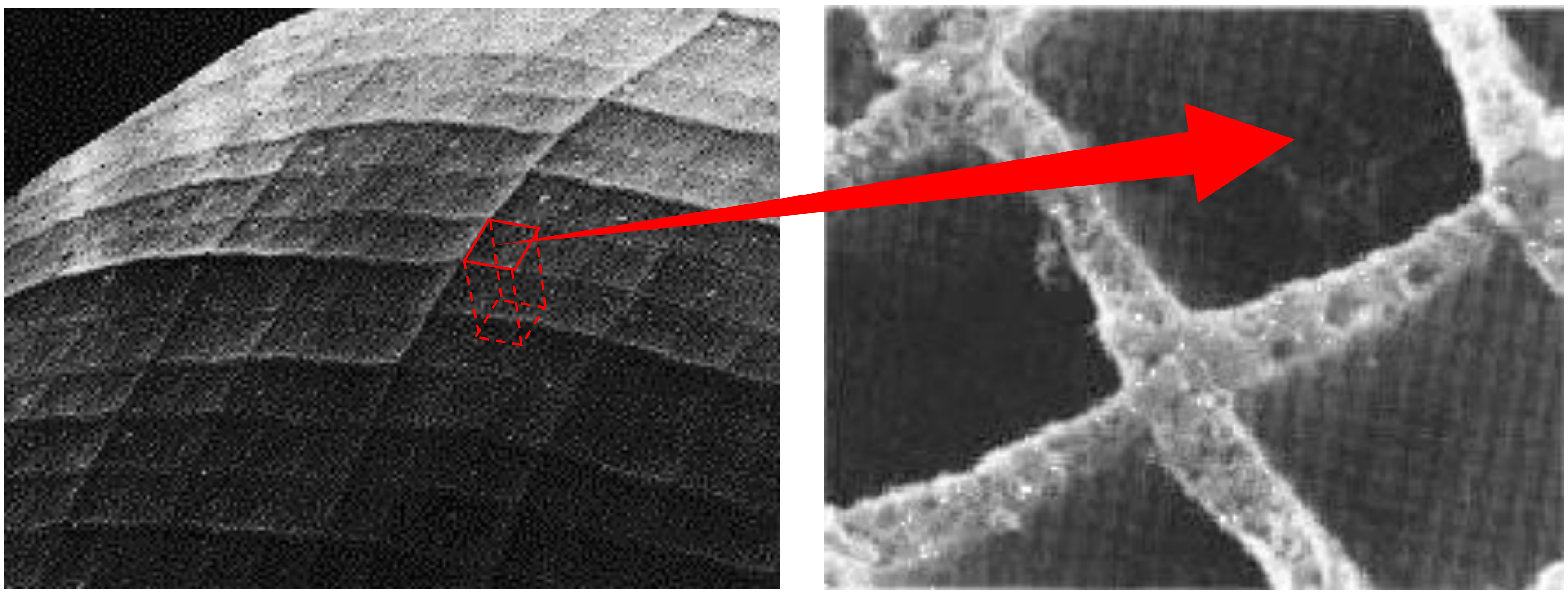
Conventional X-ray telescopes employ nested parabolic mirrors (Wolter I geometry)

Disadvantages of this technology:

- Hard to achieve high surface quality
- Each mirror element has to individually manufactured (expensive!)
- Requires expensive multilayer coatings to achieve high collection efficiency (Ni is not an efficient hard X-ray reflector)

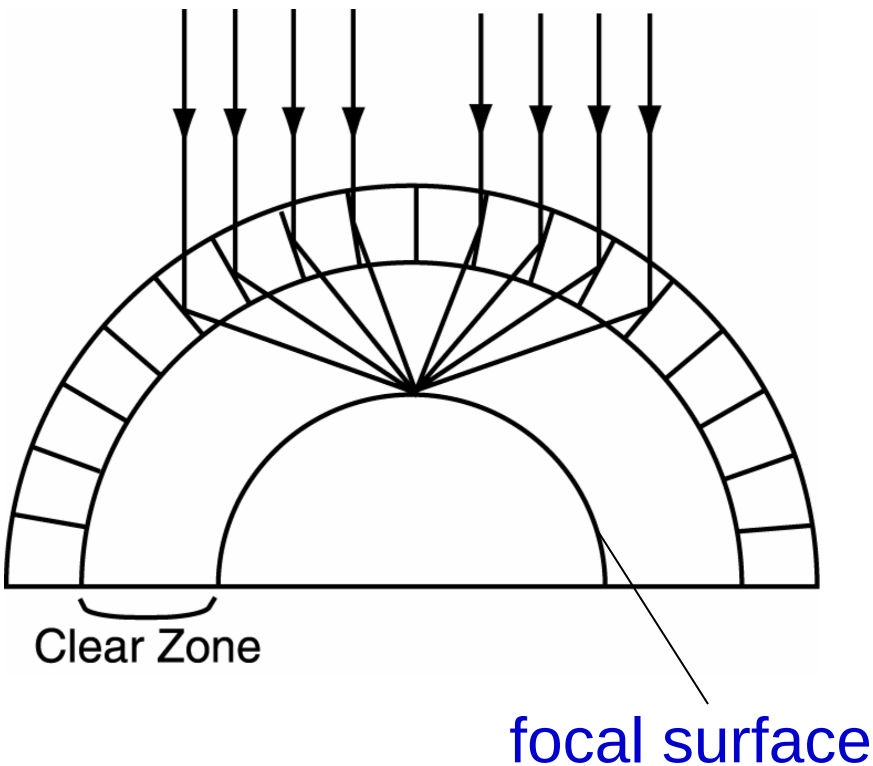
POC is developing a hard X-ray telescope based on the optical principle of a lobster eye

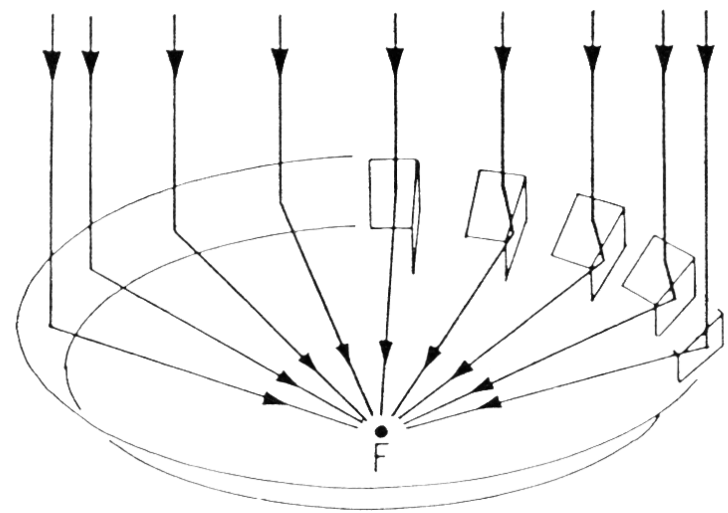
Lobster eye developed for efficient light detection in dark deep-sea environment

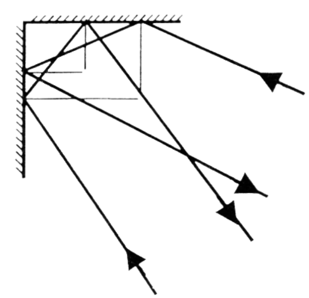


Lobster eye consists of square channels (~30x30x60 μm in size) with reflecting walls

Image is formed by corner reflections from adjacent channel walls

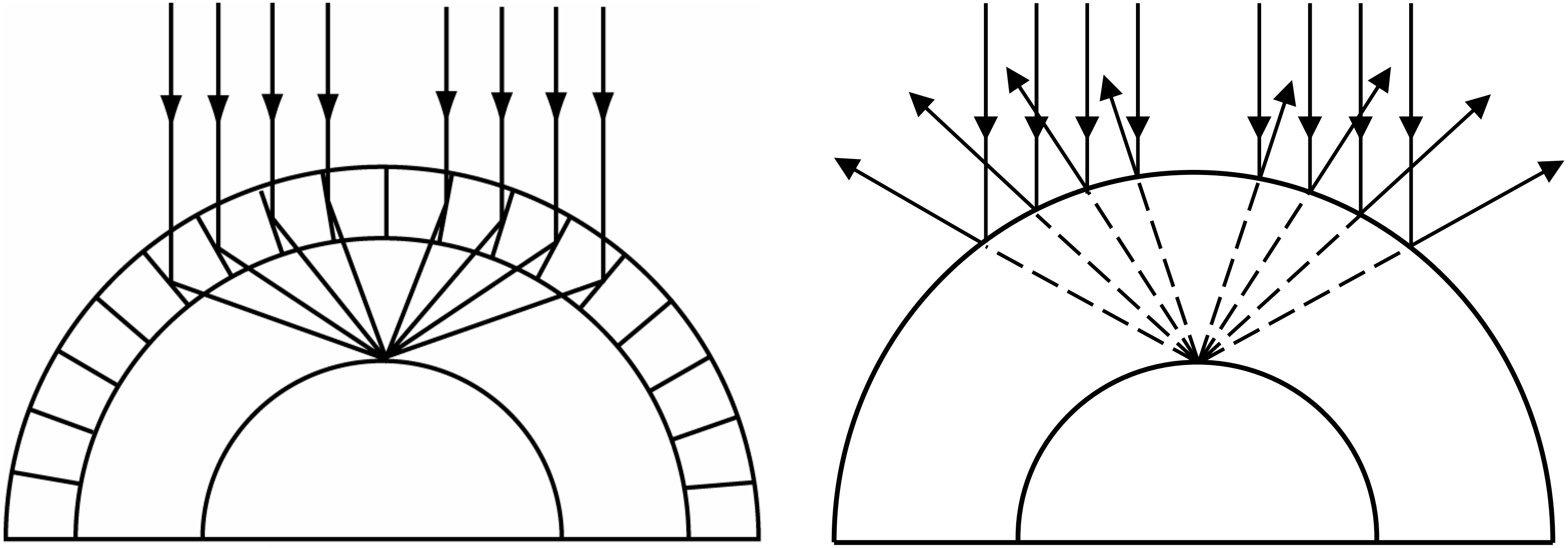






M.F. Land & D-E Nilsson, *Animal Eyes*

Lobster eye resembles a spherical mirror



Important difference:

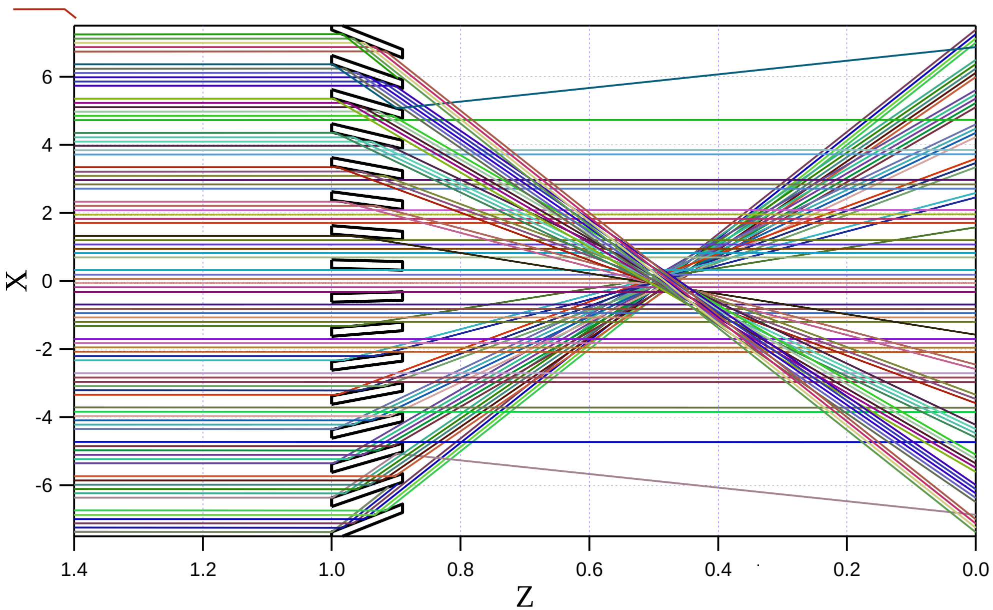
Lobster eye produces real image

Spherical mirror produces virtual image

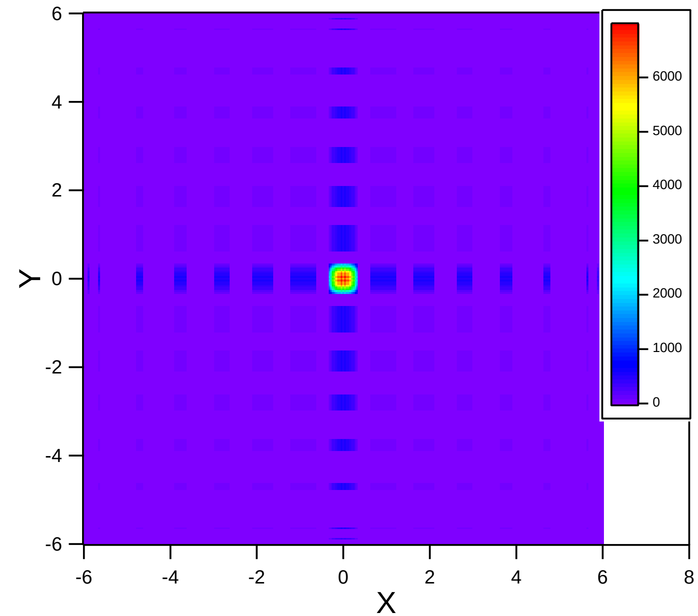
Natural lobster eye uses multilayer organic reflective coatings, which are perfectly suited for working in visible light.

To adopt this technology for focusing hard X-rays, we need to make the following modifications:
1) Use very flat mirrors with excellent surface quality;
2) Apply a coating made of a material with high X-ray reflectivity (high-density, high-Z metals).

Numerical simulation of an X-ray Lobster Eye lens



One-dimensional ray-tracing for a parallel beam incident on the lens



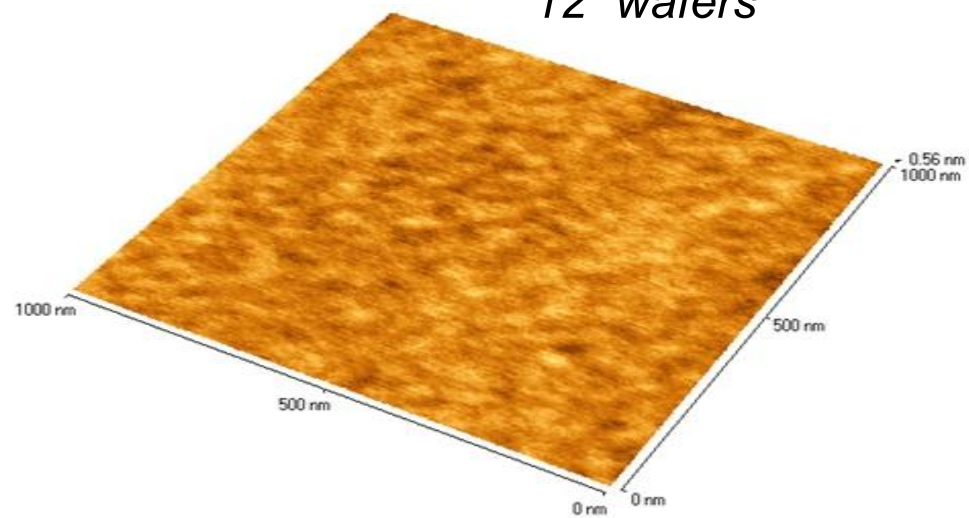
Two-dimensional view of the focal plane intensity distribution shows a characteristic "cross" pattern

Simulation parameters: E = 40 keV, R = 2 m, channel angle γ_0= 0.25 mrad, Au mirrors

Lobster-Eye lenses are manufactured out of semiconductor-grade silicon wafers

Commercial 12” double-side-polished Si substrate

AFM surface profiling of 12” wafers

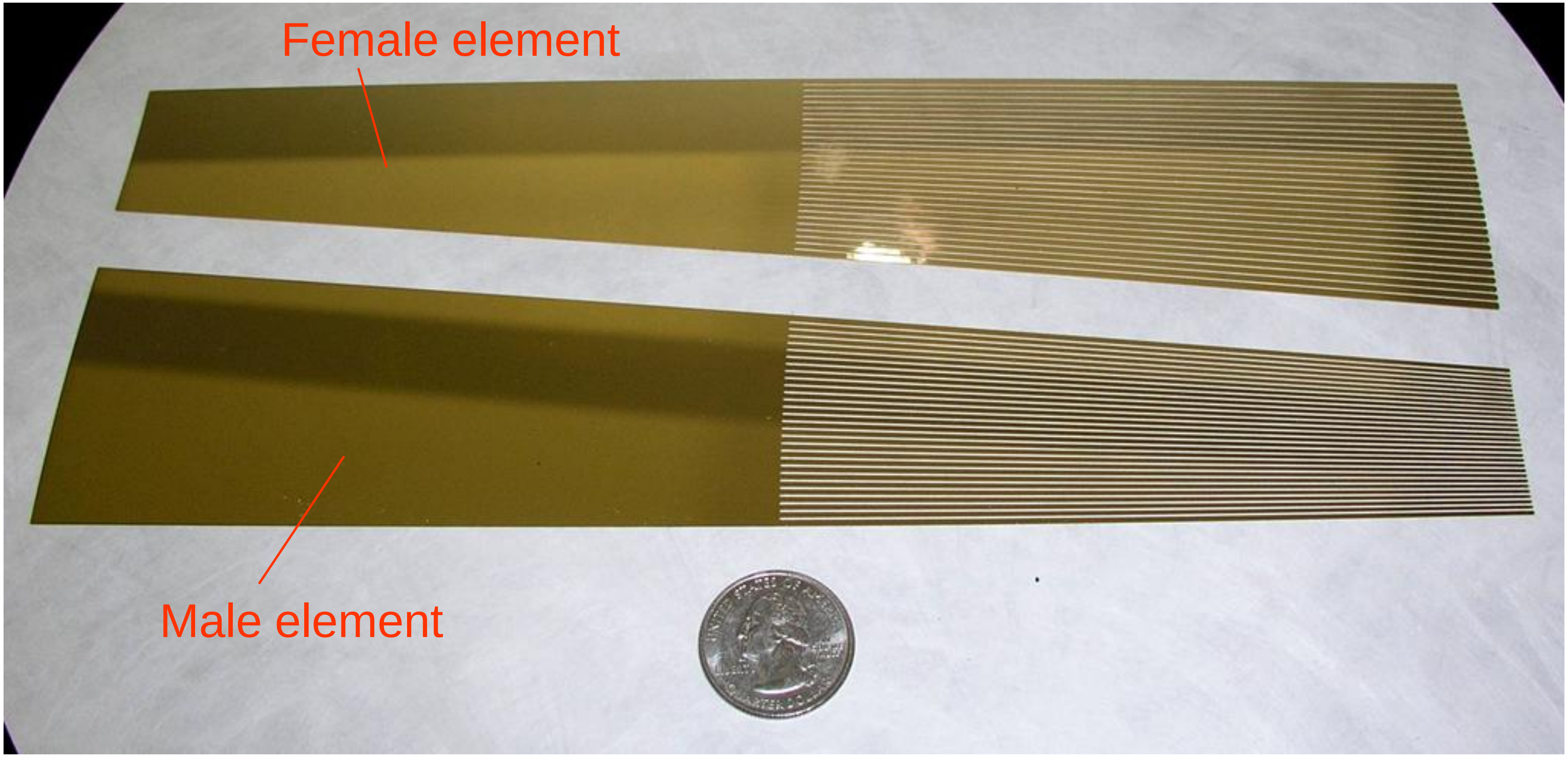


Typical surface parameters:

RMS roughness ~ **5 Å**

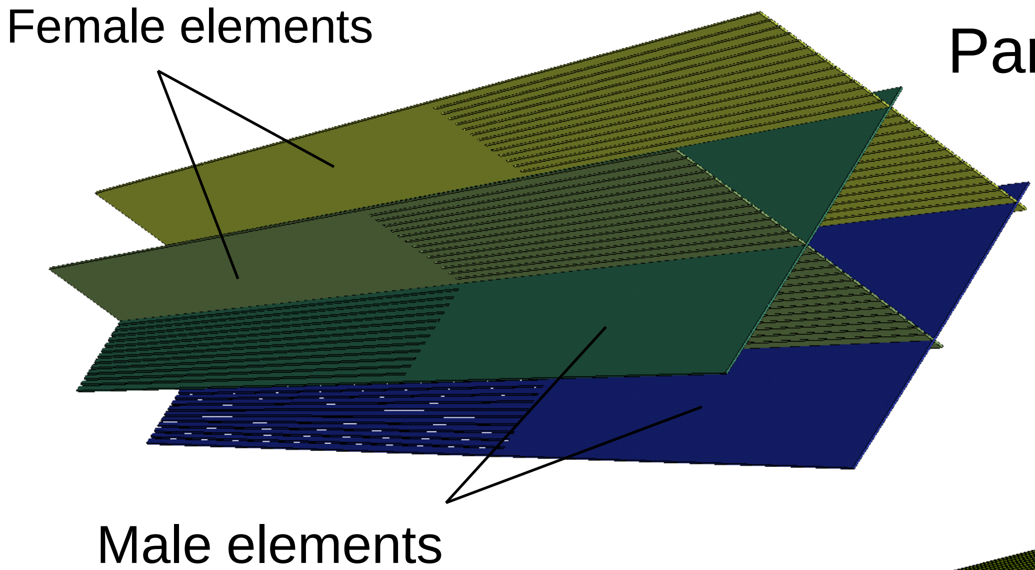
Bow/Warp < 30 μm (possible to achieve ~ 5 - 10 μm)

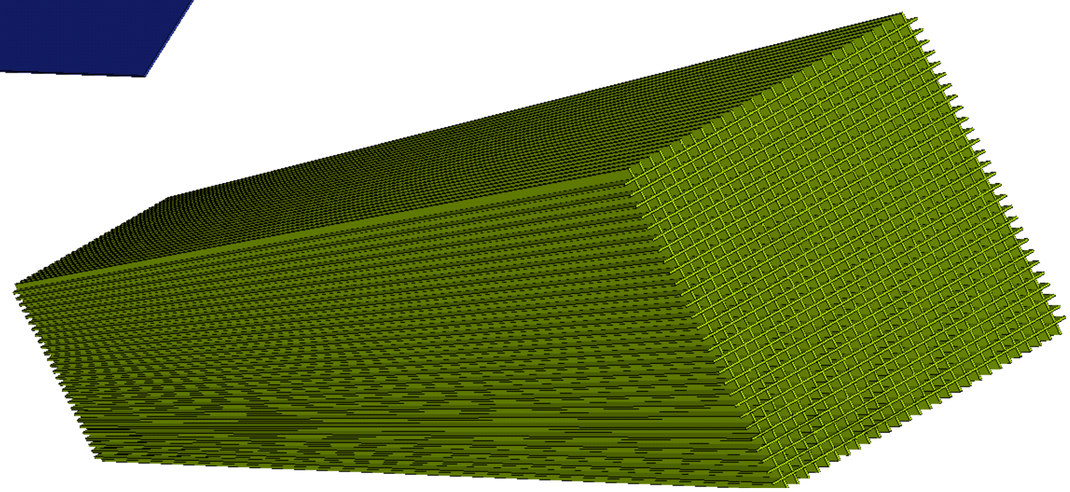
Lobster-eye lenses are assembled from pairs of male and female elements



Au coating is applied to Si substrates for enhancing X-ray reflectivity

Male and female elements are inserted into each other to produce the square channel structure of a lobster-eye lens

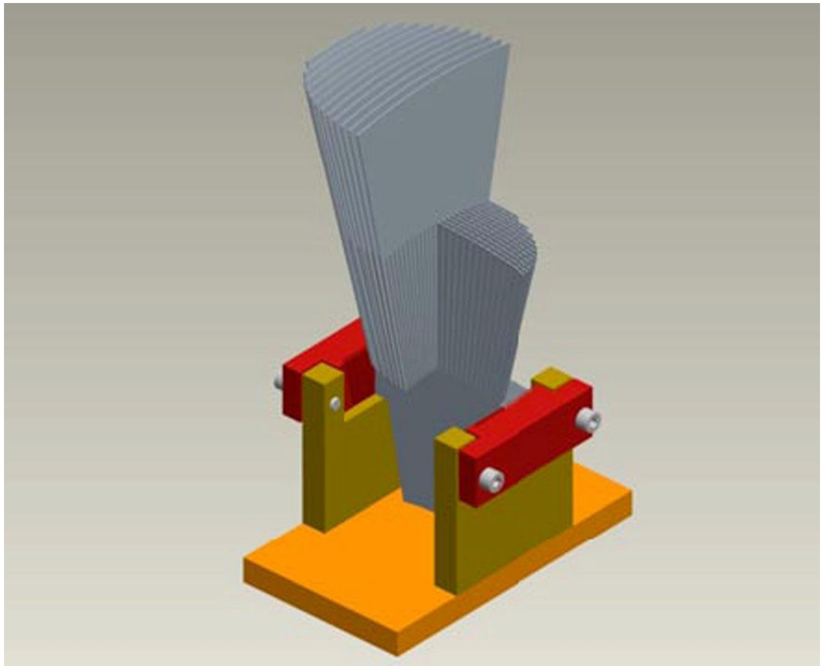




Partial assembly

Full assembly

Lobster-eye lens assembly station



Simulation in Pro/E

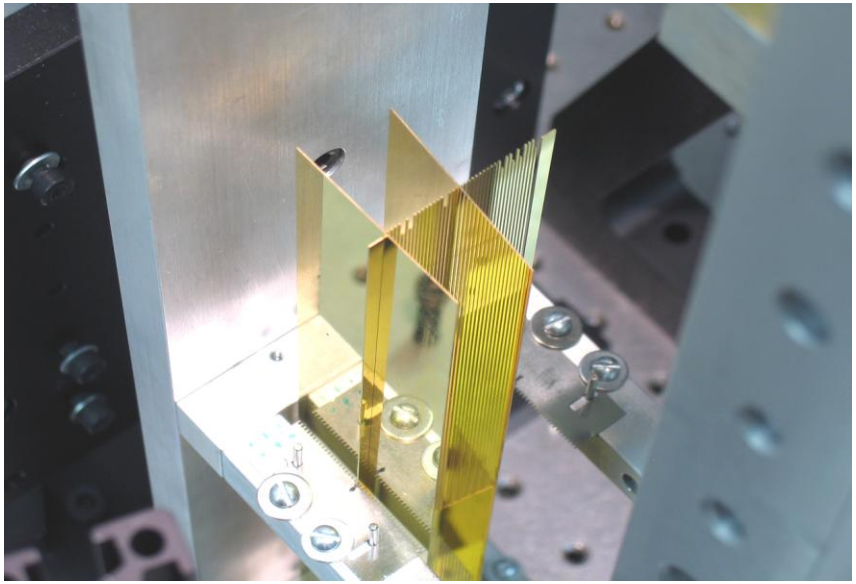
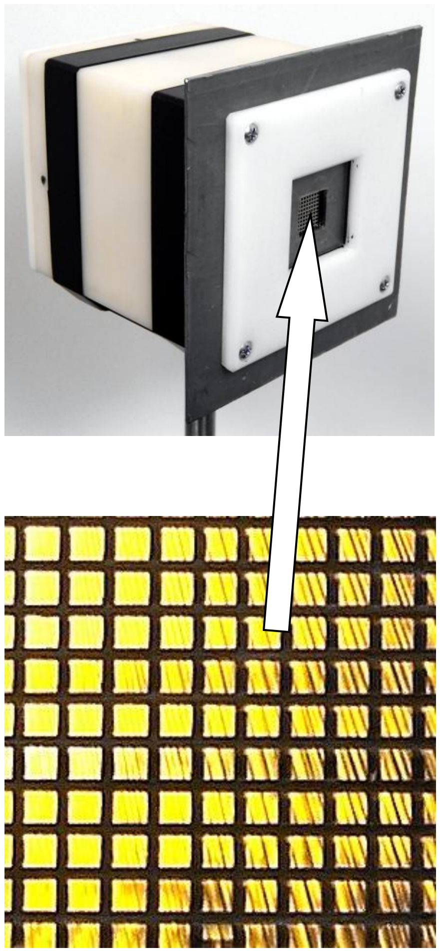


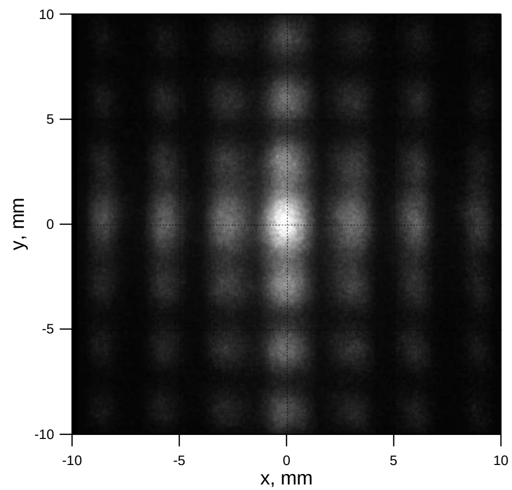
Photo of the assembly process

Experimental X-ray focusing demonstration using a parallel-channel lens

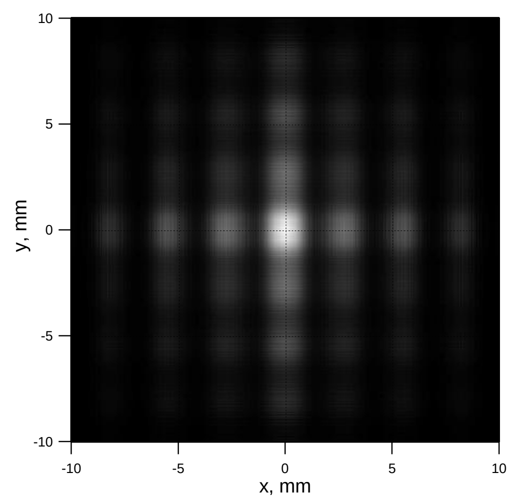
POC X-ray Lobster-Eye lens made of Au-coated Si wafers



Channel width = 0.9 mm

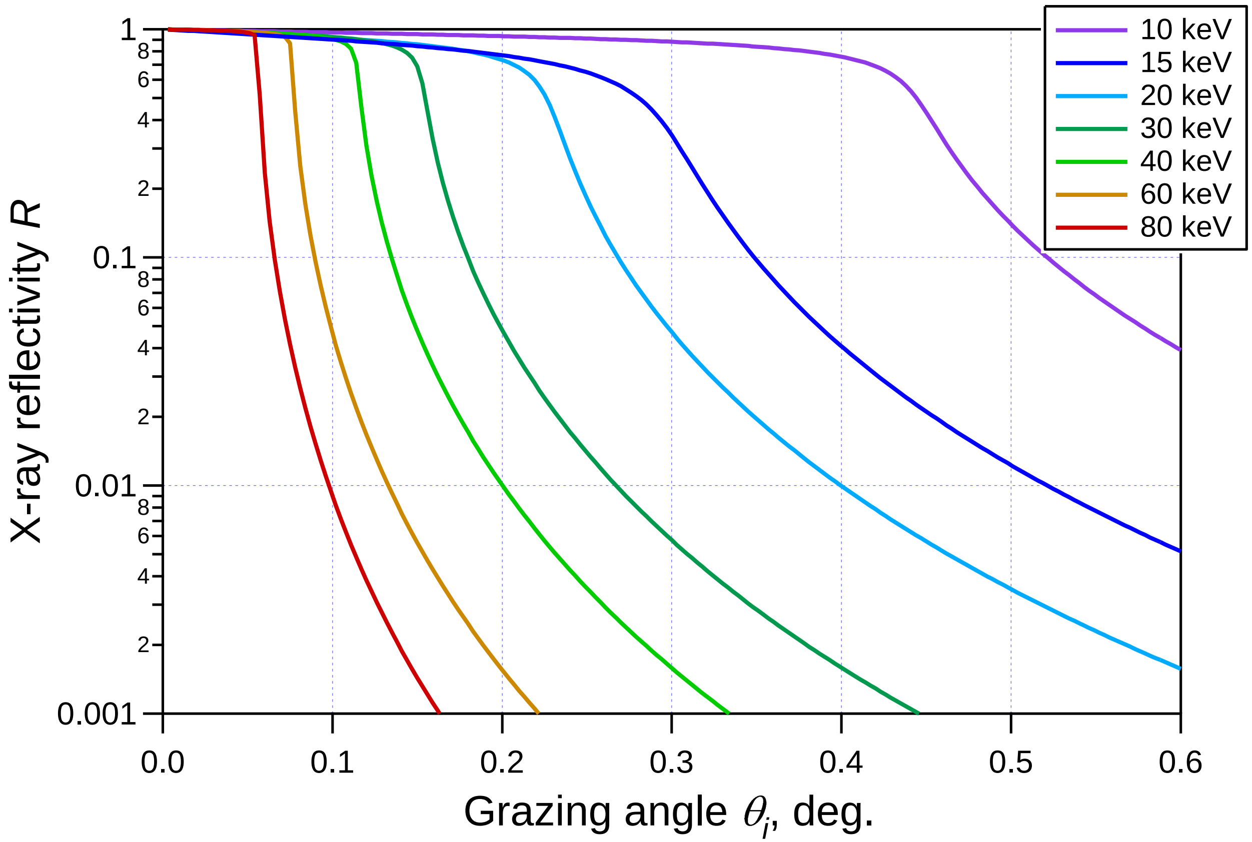


Measured image of the X-ray point source produced by this lens for 10-20 keV photons



Simulated image

Theoretical X-ray reflectivity of gold mirrors for various X-ray energies

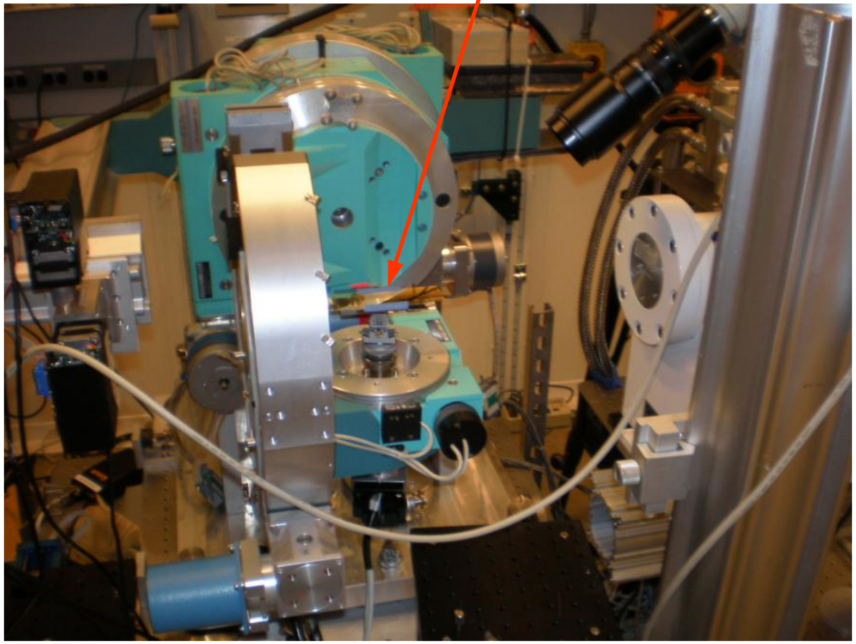


$R \sim 1$ only for $\theta_i \le \theta_c$, where θ_c – critical grazing angle.

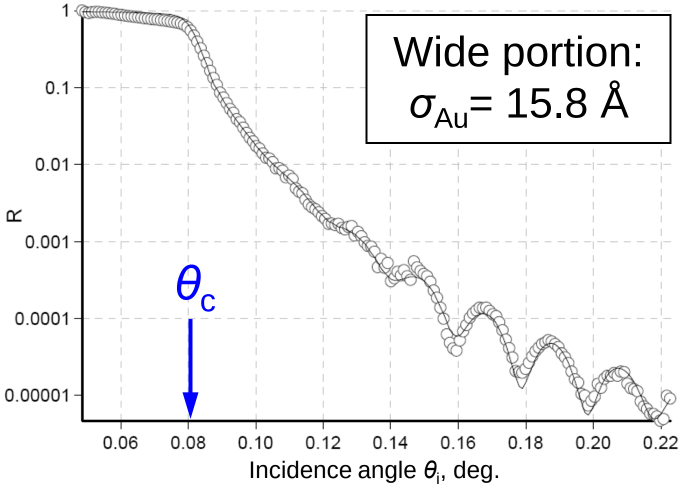
θ_c decreases with photon energy $\left(\theta_c \sim \frac{1}{E}\right)$

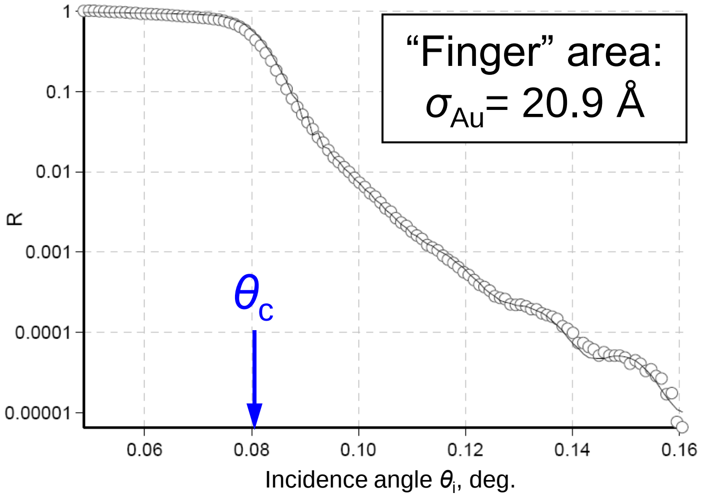
POC successfully tested Lobster-eye lens elements at Argonne National Lab

Gold-coated silicon lens element



Experimental setup for measuring hard X-ray reflectivity of lens elements





Demonstrated R>90% for θ_i<θ_c @55 keV!

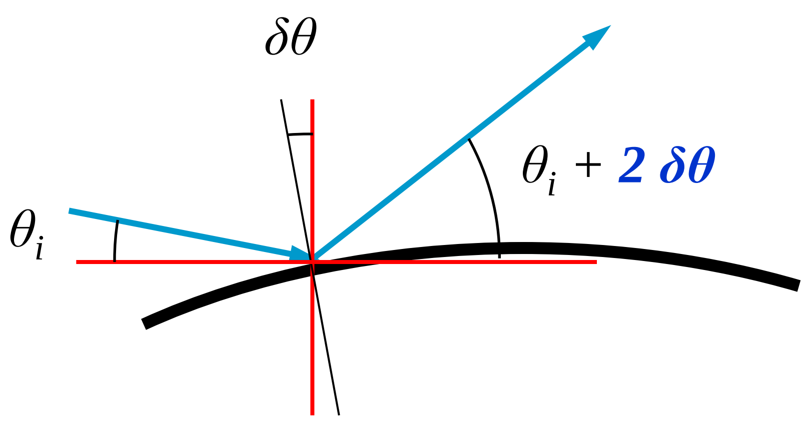
Coatings for hard X-ray mirrors

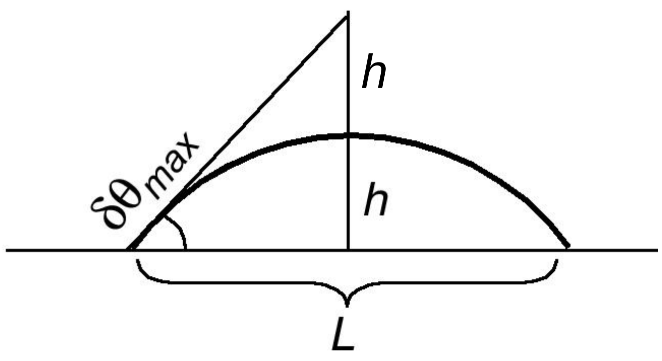
Element	Z	Density g/cm^3	Critical angle @30 keV, deg.	Effective coll. area (rel. to Au)*	Price, US$ /troy ounce
Rhenium	75	21.0	0.160	1.09	5950
Osmium	76	22.6	0.165	1.16	380
Iridium	**77**	**22.4**	**0.164**	**1.15**	**425**
Platinum	78	21.5	0.161	1.11	1312
Gold	79	19.3	0.153	1.00	667
Nickel	28	8.9	0.114	0.56	Negligible
Uncoated silicon	*14*	*2.3*	*0.059*	*0.15*	

*Effective collecting area is proportional to θ_c^2.

Iridium-coated mirrors will provide the best combination of performance, material price, and deposition cost.

Flatness of mirror substrates is crucial for achieving sharp X-ray focusing





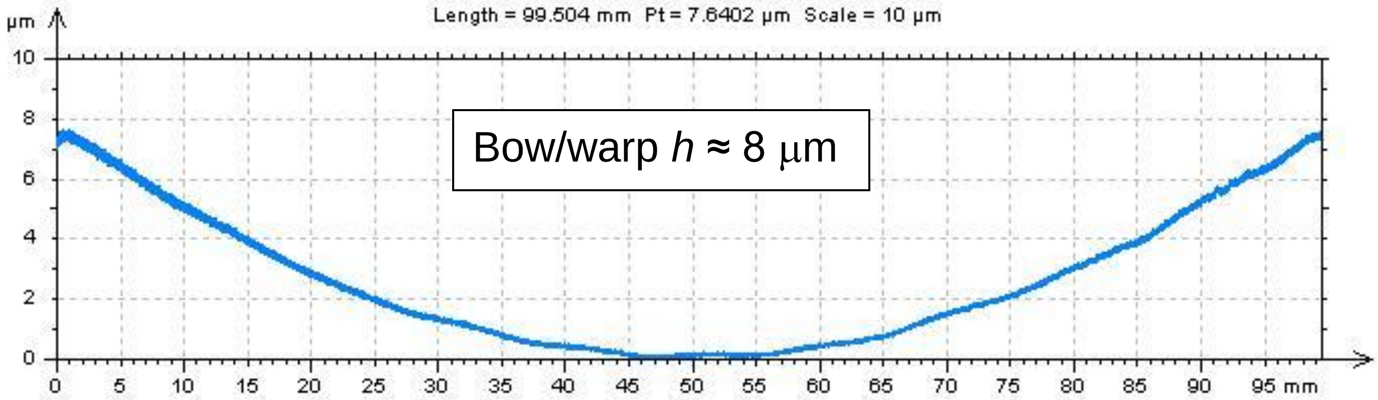
Bow and warp of the silicon substrates distorts the directions of X-ray reflections, which can significantly reduce the angular resolution of a Lobster-eye telescope.

Angular “blurring” due to the bow and warp:

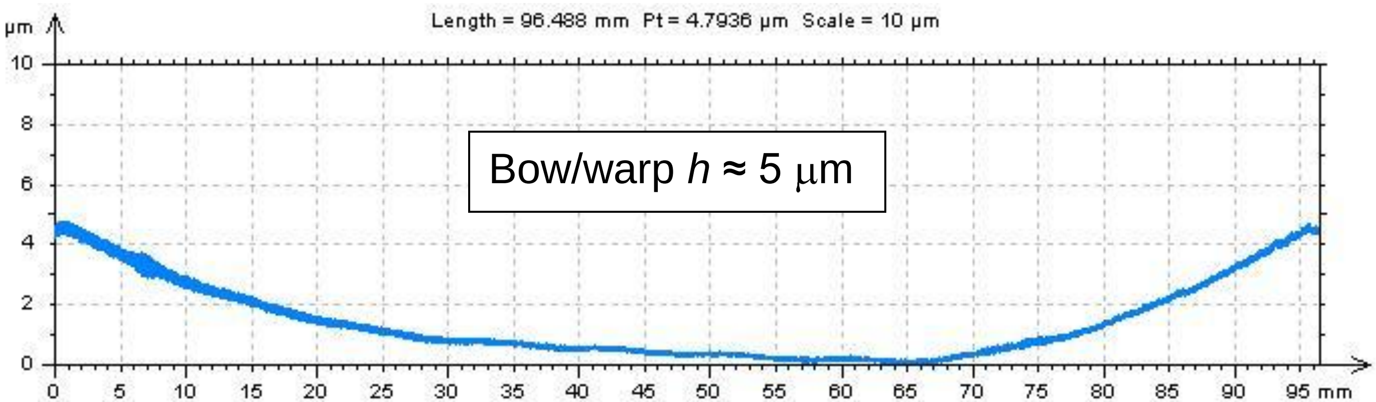
$$\boxed{\delta\theta_{ref} \approx \frac{6h}{L}}$$

Profilometry measurements on 100-mm wafers

Scan along X-axis:

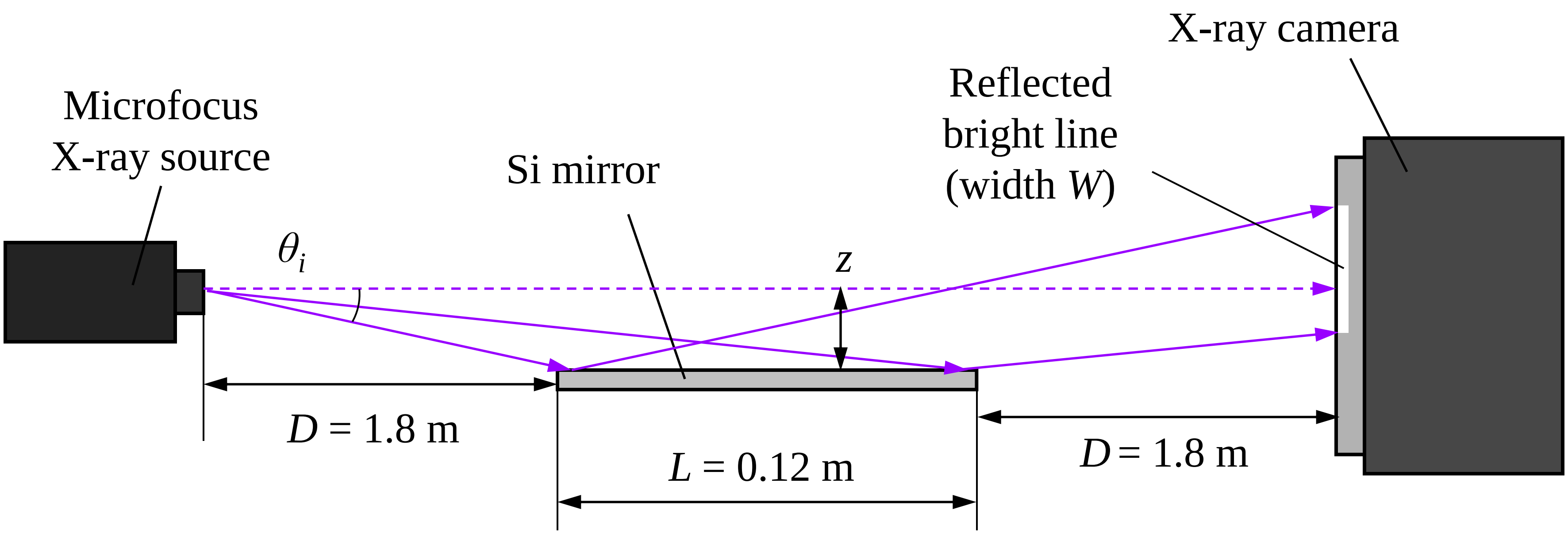


Scan along Y-axis:



$$\text{Expected angular resolution} \sim \frac{6h}{L} = \frac{6 \times 0.008\,\text{mm}}{100\,\text{mm}} \approx 0.5\,\text{mrad} = 1.7\,\text{arcmin}$$

Characterization of silicon mirror flatness



Reflection line width for a perfectly flat mirror:

$$W_{ideal} = 2L\tan\theta_i \approx \frac{2Lz}{D + L/2}$$

Surface waviness will typically produce a broader line: $W_{measured} > W_{ideal}$

We define flatness parameter:

$$\varepsilon = \frac{W_{measured}}{W_{ideal}} - 1$$

ε > 0: de-focusing
ε < 0: focusing
Good mirror will have |ε| << 1

Relationship between *ε* and bow/warp *h*

$$\text{Angular blurring} = \frac{|\varepsilon| W_{ideal}}{D + L/2} = \frac{|\varepsilon| 2Lz}{\left(D + L/2\right)^2} = \frac{6h}{L}$$

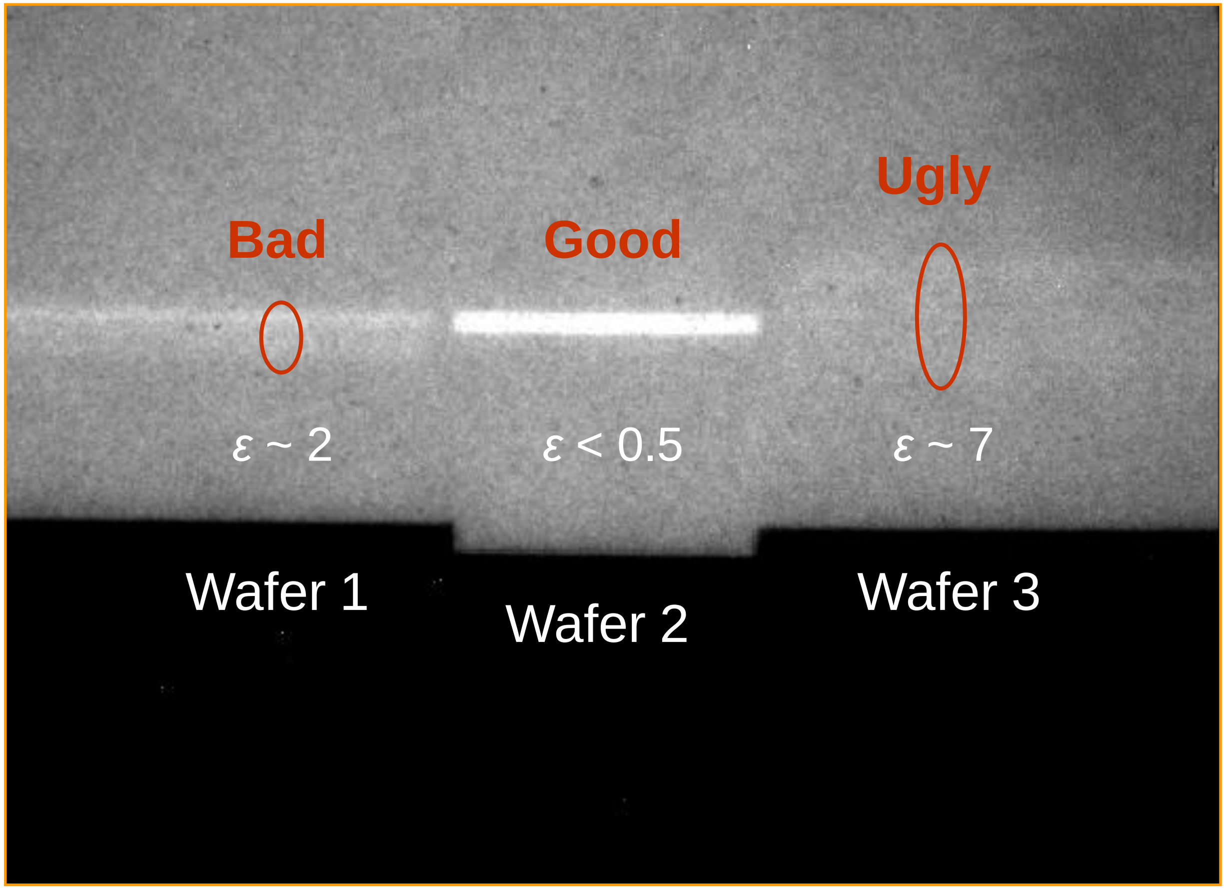
$$|\varepsilon| = \frac{3h\left(D + L/2\right)^2}{2L^2 z}, \qquad h = \frac{2L^2 z}{3\left(D + L/2\right)^2}|\varepsilon|$$

For example, for D = 1800 mm, L = 120 mm, and z = 3.5 mm, we get:

$$\boxed{h = |\varepsilon| \times 9.7\,\mu\text{m}}$$

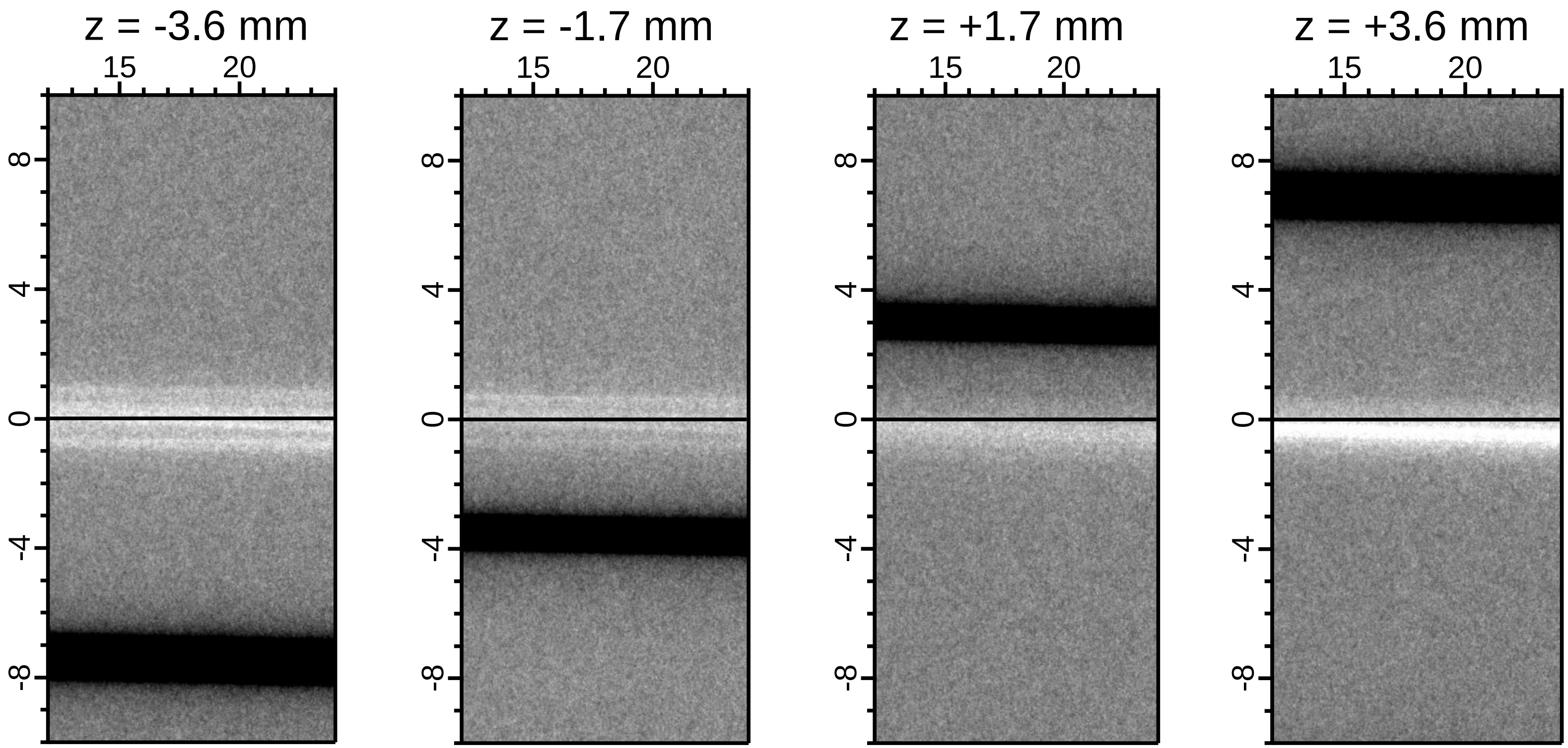
Reflections from three wafers: The Good, the Bad, and the Ugly

~20 mm



All wafers have the same length (12 cm)

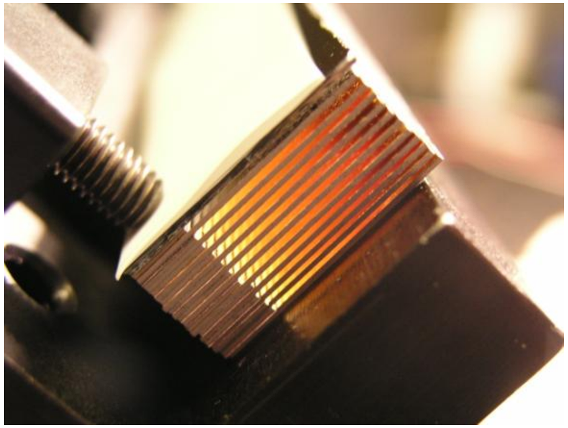
Typical X-ray reflection images for various vertical positions of a wafer

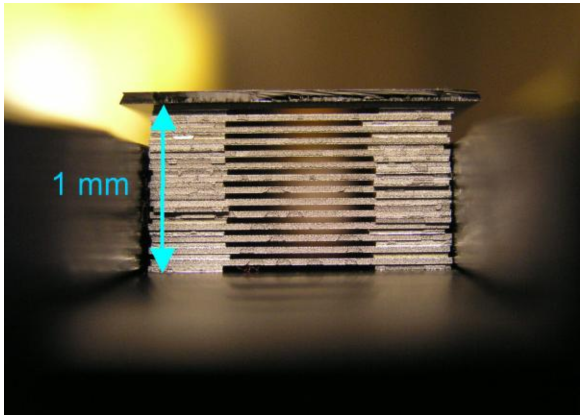


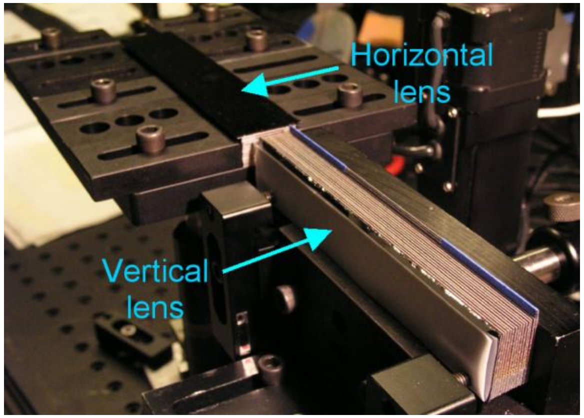
ε = 1.25 ε = 2.75 ε = -0.13 ε = 0.25

Focus broadening is almost 3X its natural width → BAD!

Fabrication of LE telescope prototype with two Si mirror stacks

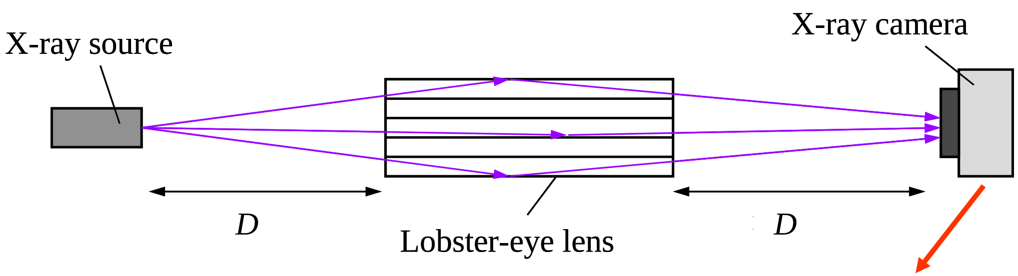


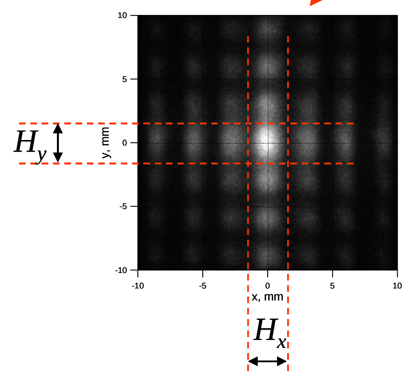




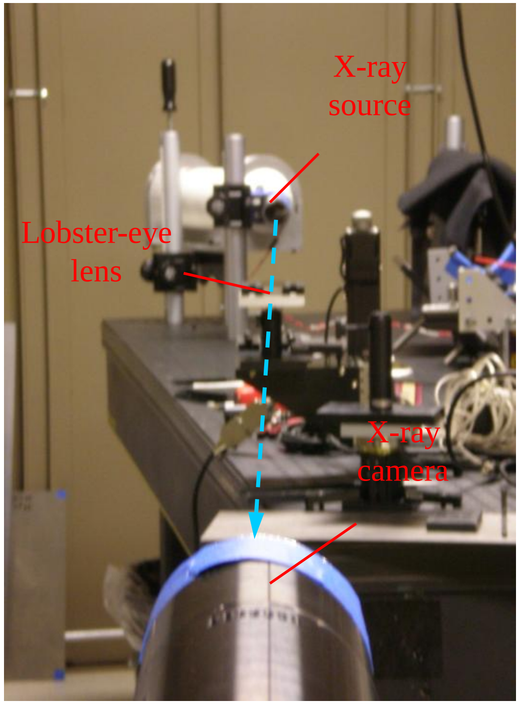
Si mirror thickness = Spacer thickness = 400 μm

Experimental setup for testing LE lenses

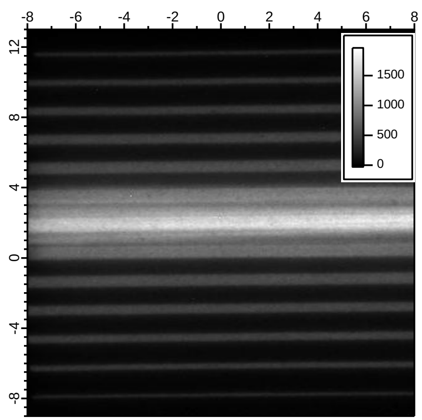




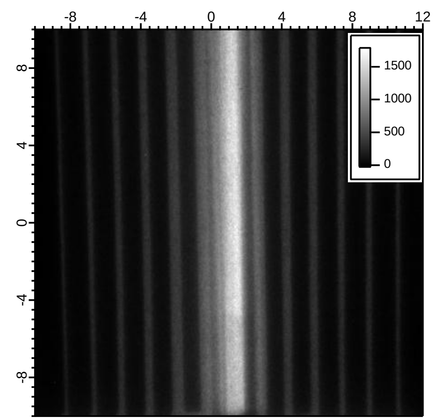
Angular resolution ~ $H_{x,y}\,/D$



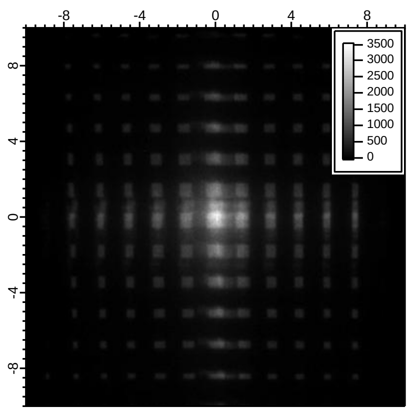
Images of a point source produced by the prototype lobster-eye lens



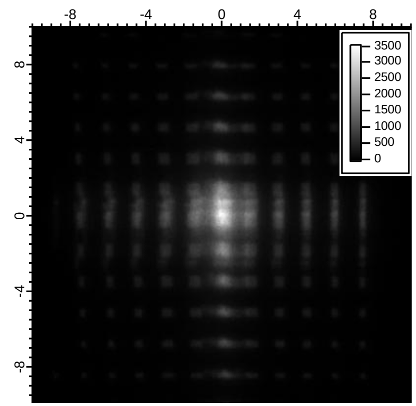
Horizontal stack, 20 kV



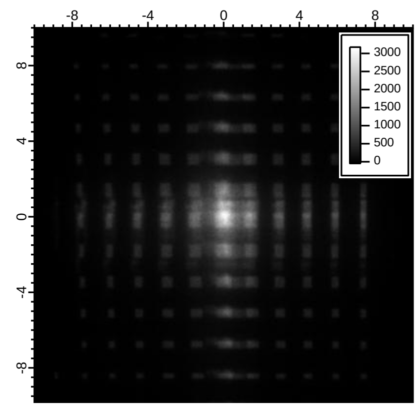
Vertical stack, 20 kV



Combined, 20 kV



Combined, 50 kV



Combined, 90 kV

Measured FWHM of the peak = 1.2 mm, theoretical FWHM = 0.4 mm

Blurring of the focal spot is due to the mirror waviness

$$\text{Teoretical resolution} \approx \frac{\text{Channel width}}{D} = \frac{0.4\,\text{mm}}{1800\,\text{mm}} \approx 0.7\,\text{arcmin}$$

$$\text{Measured resolution} = \frac{FWHM\ \text{of peak}}{D} = \frac{1.2\,\text{mm}}{1800\,\text{mm}} \approx 2\,\text{arcmin}$$

$$\text{Bow/warp resolution limit} \approx \frac{6h}{L} = \frac{6 \times 0.015\,\text{mm}}{120\,\text{mm}} \approx 2.6\,\text{arcmin}$$

(assuming a typical bow/warp of 15 μm across a 120-mm mirror)

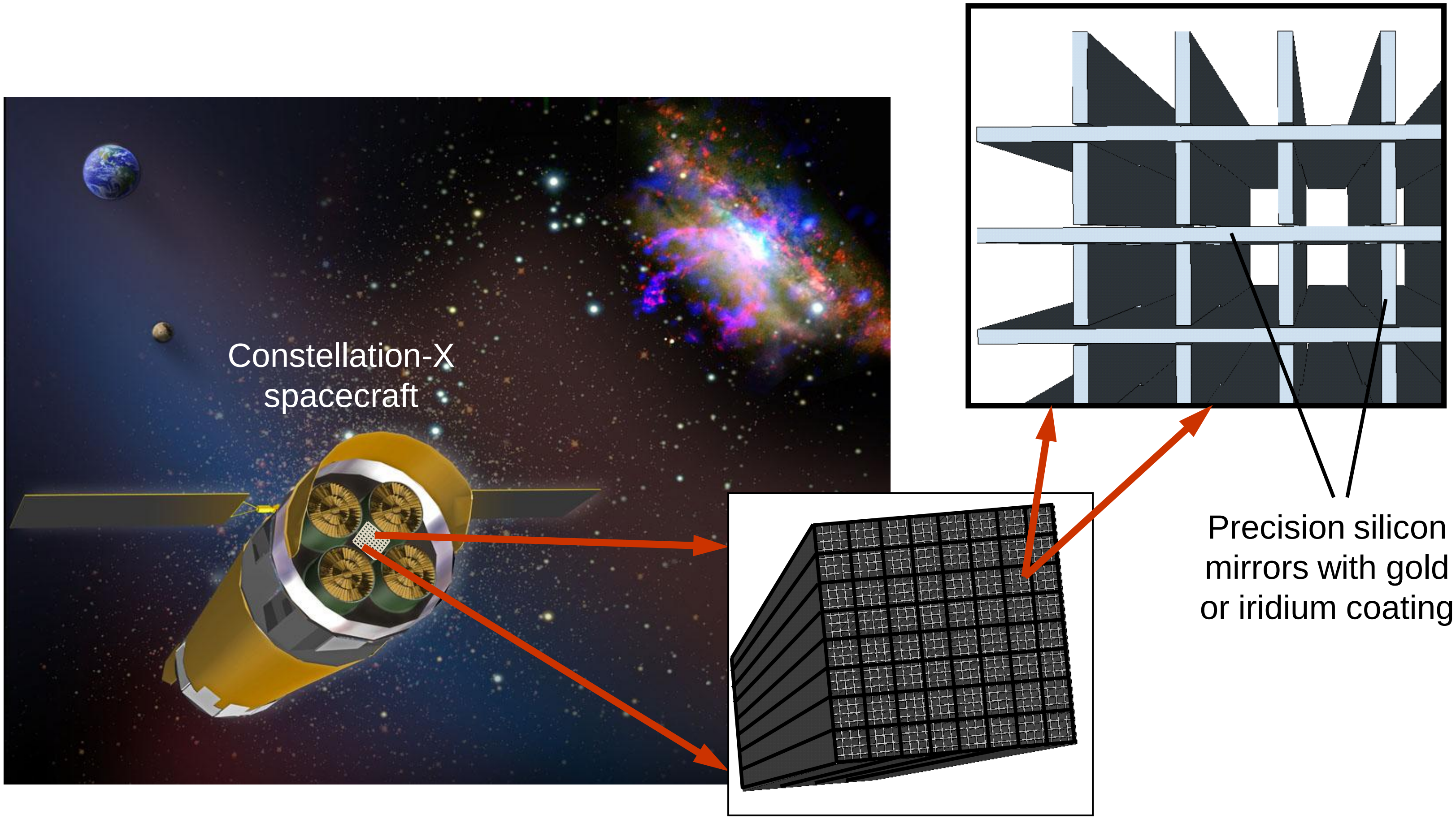
Measured angular resolution is in good agreement with theoretical estimates

Mirror waviness has to be reduced in order to achieve better performance

- **Common semiconductor silicon wafer bow/warp spec:** 30 μm across a 300-mm wafer → Angular resolution of 2 arcmin
- **Available high-quality silicon polishing:** 5 μm across a 300-mm wafer → Angular resolution of 20 arcsec
- Further improvements: mirror segmentation, MRF polishing, material selection by inspection→ Angular resolution of <5 arcsec

Lobster-eye hard X-ray telescope for NASA's Constellation-X mission

ALEX module detail



8x8 array of adjustable lobster-eye modules

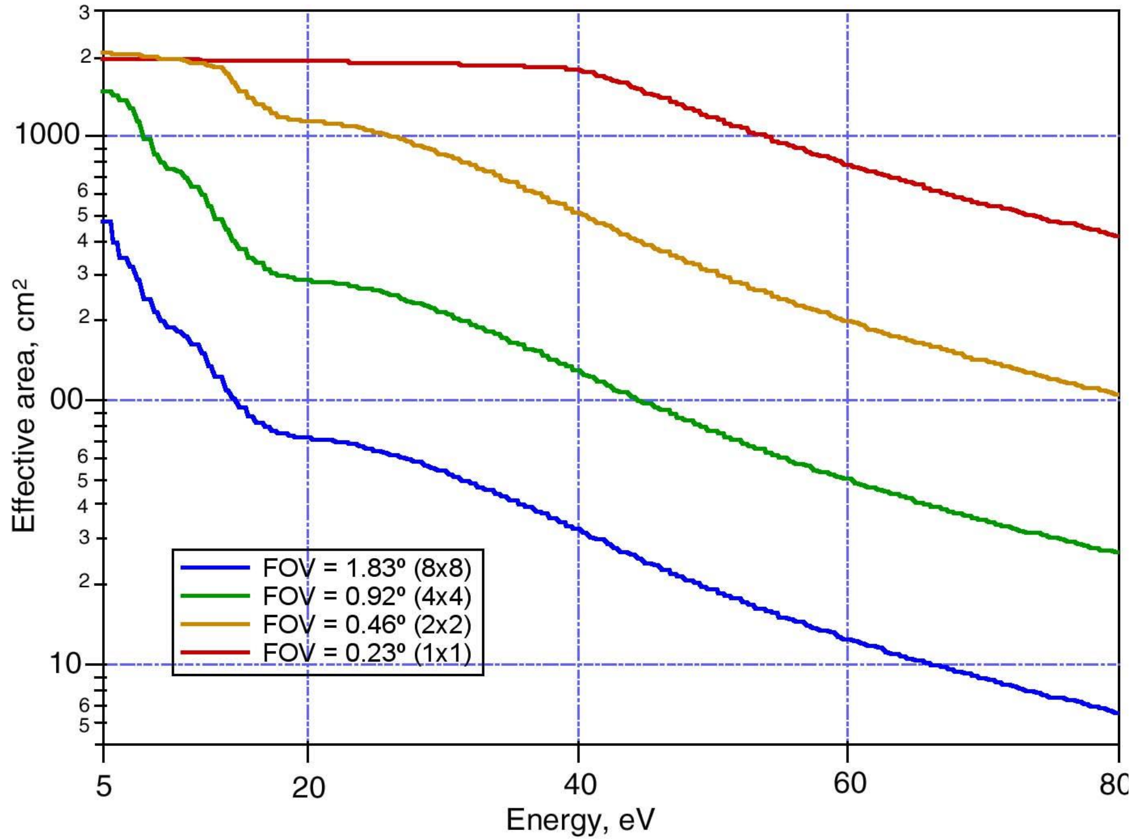
Future hard X-ray telescope will be an adjustable 8x8 array of Lobster-Eye lenses

Parameters of each lens:

- Radius of curvature R = 20 m
- Number of channels N = 115×115
- Channel angle $\gamma_0 = 3.3\times10^{-5}$ = 7"
- Channel spacing Λ = 700 μm
- Mirror length l = 28 cm
- Mirror thickness d = 100 mm
- Lens dimensions = 8 cm × 8 cm × 28 cm
- Lens weight = 1.1 kg.

- Overall dimensions = 64 cm × 64 cm × 28 cm
- Overall weight = 70 kg

Effective area of the telescope in four different FOV/sensitivity configurations



Use of Au-coated Si mirrors is assumed

Timeline of lobster-eye hard X-ray telescope development

Lobster-Eye Telescope Parameter	July 2007	2008	2009	2010-2012	NASA HXT Requirement
Number of channels	13 × 13 (parallel)	30 × 30	111 × 111	888 × 888	N/A
Angular resolution	120 arcsec	30 arcsec	7 arcsec	7 arcsec	<30 arcsec
Field of view	~20 arcmin	15 arcmin	15 arcmin	120 arcmin	5 arcmin
Effective collecting area @ 40 keV	~0.5 cm^2	2 cm^2	>25 cm^2	2000 cm^2	>150 cm^2
Size, cm	1 × 1 × 12	2 × 2 × 20	8 × 8 × 28	64 × 64 × 28	
Weight	~10 g	~150 g	~1 kg	70 kg	<250 kg

POC telescope performance will exceed NASA HXT specs

Advantages of POC's lobster-eye technology over conventional X-ray telescopes

- **Higher performance:** Higher resolution, wider FOV, larger collecting area
- **Simplicity of manufacturing:** All telescope optics can be assembled from only 2 parts: male and female mirror elements
- **Proven technology:** Lobster-eye components will be manufactured using standard materials and techniques of the optical and semiconductor industries
- **Lower weight:** Lobster-eye telescope will be manufactured out of lightweight silicon wafers, resulting in two- to threefold weight reduction
- **Lower cost:** POC technology does not need substantial material R&D because we use standard materials and methods.

Conclusion

1. We demonstrated a technology for fabricating lobster-eye hard X-ray optics based on assembling the lens from semiconductor-quality silicon wafers coated with gold.
2. A prototype lens demonstrated hard X-ray focusing (~30-40 keV) with angular resolution ~2 arcmin.
3. Further improvements in performance can be achieved by fabricating larger optics using high-quality silicon material with reduced waviness.
4. We designed a hard X-ray telescope (HXT) for NASA Constellation-X mission with expected performance exceeding NASA specs.

Acknowledgements

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