X-ray optics for axion physics

Vistas in Axion Physics

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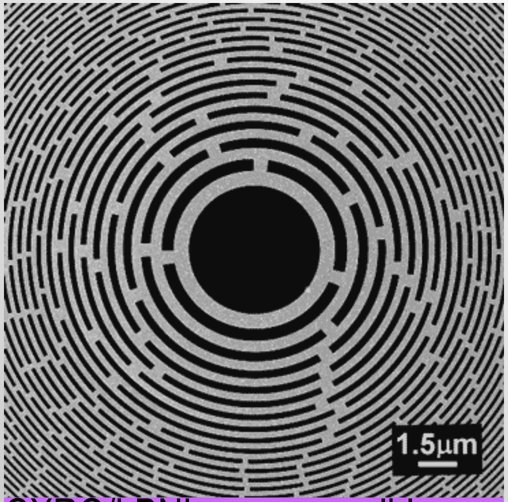
X-RAY OPTICS PRIMER

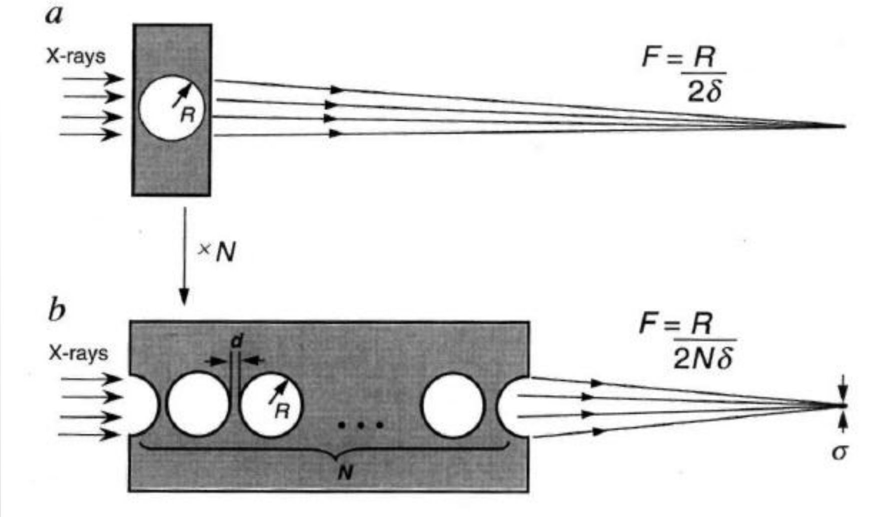
X-ray optics rely on a wide range of phenomena

Diffraction

- Gratings
- Fresnel zone plates



CXRO/LBNL www.cxro.lbl.gov



A Snigirev et al. *Nature*, **384**, 49, (1996)

Refraction

- Compound refractive lens

Absorption

- Pinholes
- Anger cameras
- Coded apertures

KP Ziock et al. Proc IEEE NSS, (2003)

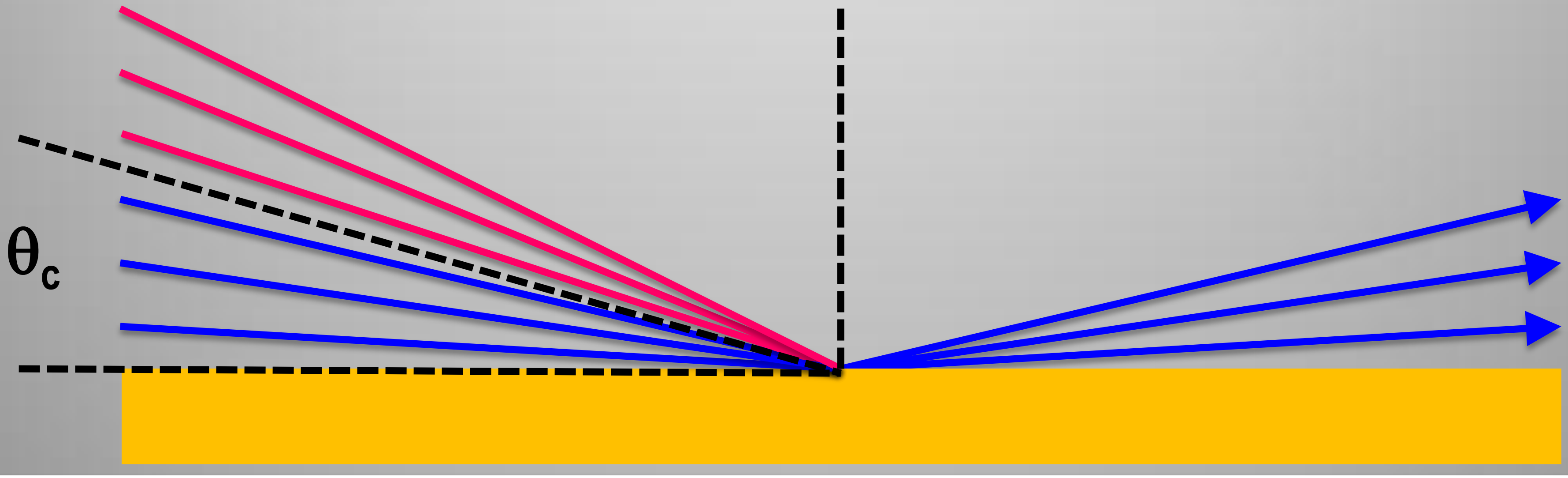
Reflection

- Capillary optics
- Mirrors

Today's talk

Reflective x-ray optics

- Compton first discovered X-rays incident at small glancing angles are totally reflected
  - "The Total Reflexion of X-rays", *Philosophical Magazine*, **45**, 1121, (1923)
- Index of refraction for high energy photons $n = 1 - \delta - i\beta$
- Total external reflection of light occurs when the incident angle is less than the critical angle $\theta_C = \sqrt{2\delta} \propto \sqrt{Z} / E$.
- Critical angle drops rapidly with energy $\theta_c \sim E^{-1}$.



Original reflective x-ray optic concepts

“Formation of Optical Images by X-rays”
P Kirkpatrick, AV Baez
***J Opt Soc Amer*, 38, 766, (1948)**

“Spiegelsysteme streifenden Einfalls als abbildende Optiken für Röntgenstrahlen”
H Wolter, *Phys Ann* 10, 94, (1952)

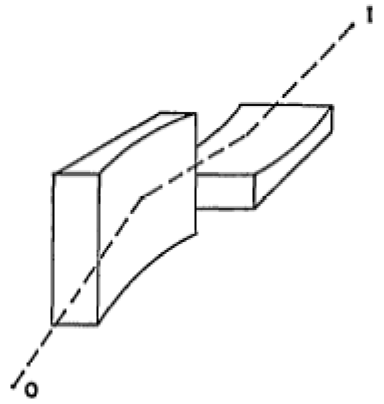


FIG. 11. Arrangement of concave mirrors to produce real images of extended objects with incidence at small grazing angles.

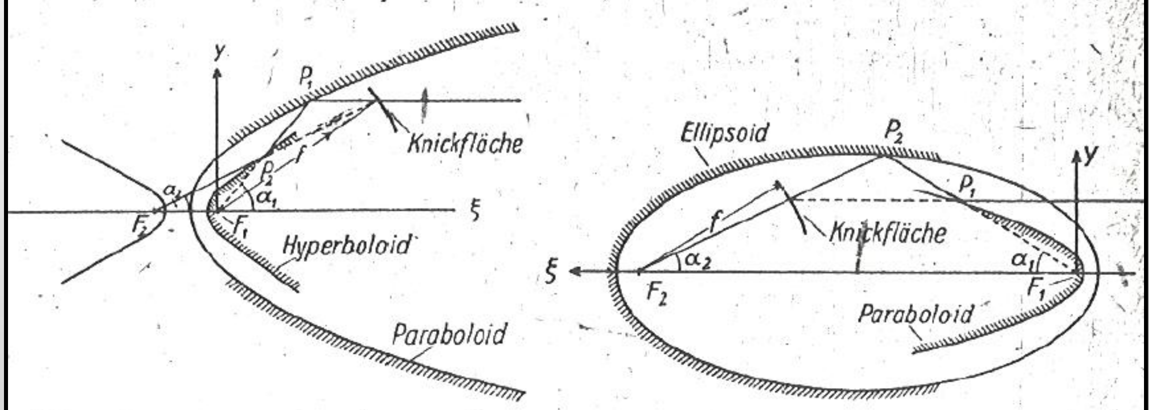


Abb. 15. Spiegelsystem 2. Art

Abb. 16. Spiegelsystem 3. Art

- Two (or more) concave, spherical mirrors
- Does not meet the Abbe sine rule

- Even number of conic surfaces of revolutions (hyperbola+parabola, hyperbola+ellipse, etc.)
- Nearly satisfies Abbe sine rule
- Significant increase in solid angle (compared to KB)

Wolter optics for x-ray astronomy

- Wolter originally proposed his designs for an x-ray microscope for biology
  - Not possible to fabricate in the 1950s
- Idea later adopted by Giacconi *et al.* for astronomy
  - Nobel prize in 2002

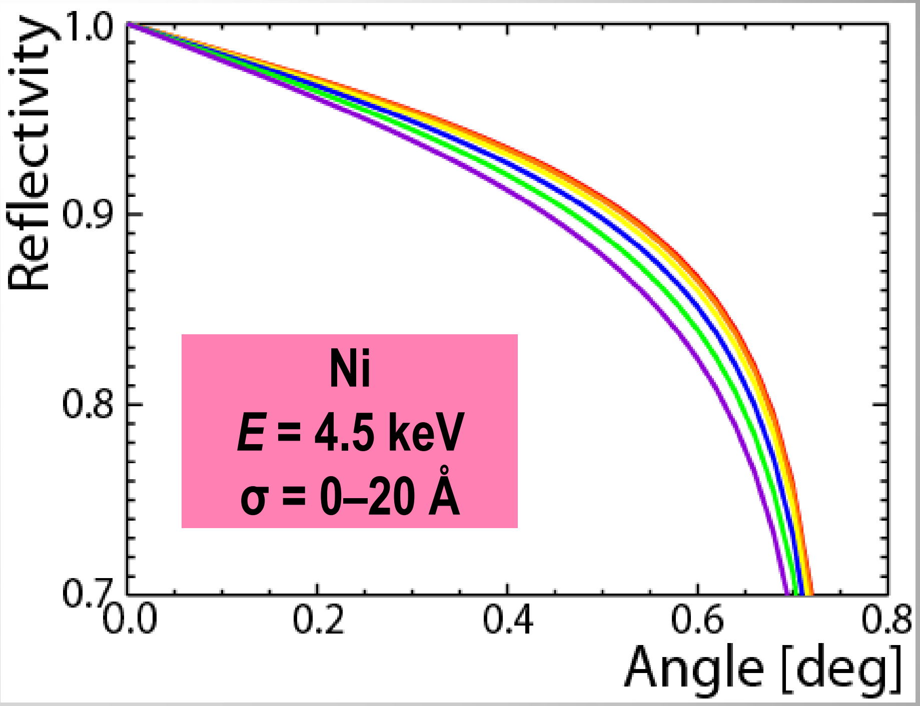
Credit: NASA

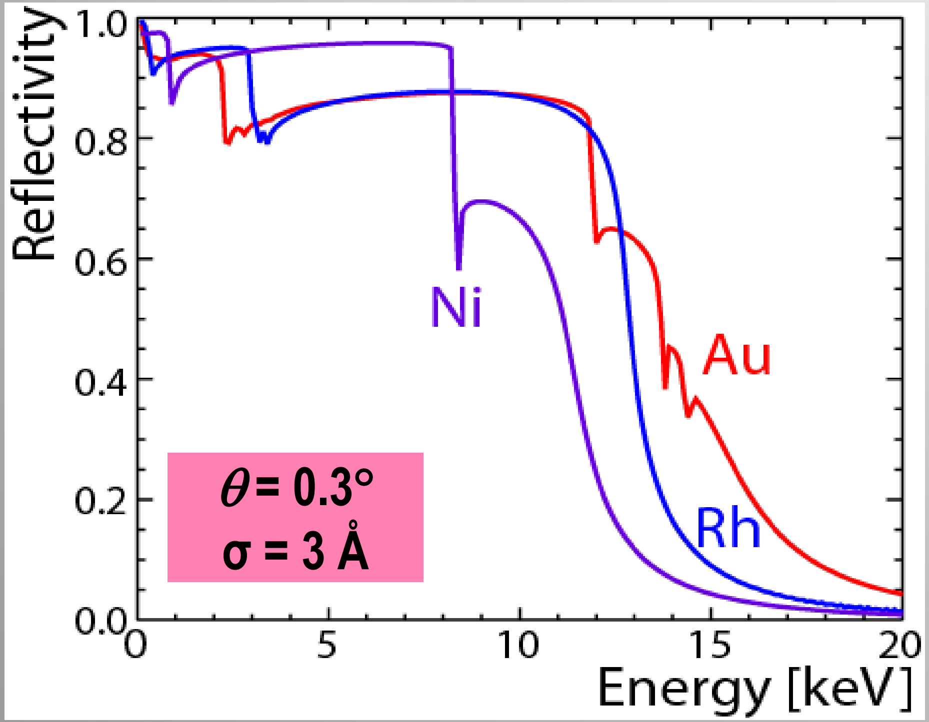
- Key innovation was the realization that mirrors could be nested inside one another to increase collecting area (solid angle)

X-ray reflectivity

Limited to materials that:

- can be polished well or deposited smoothly (*e.g.*, Ni, Rh, Au, Ir)
- (ideally) do not have absorption edges in operational band

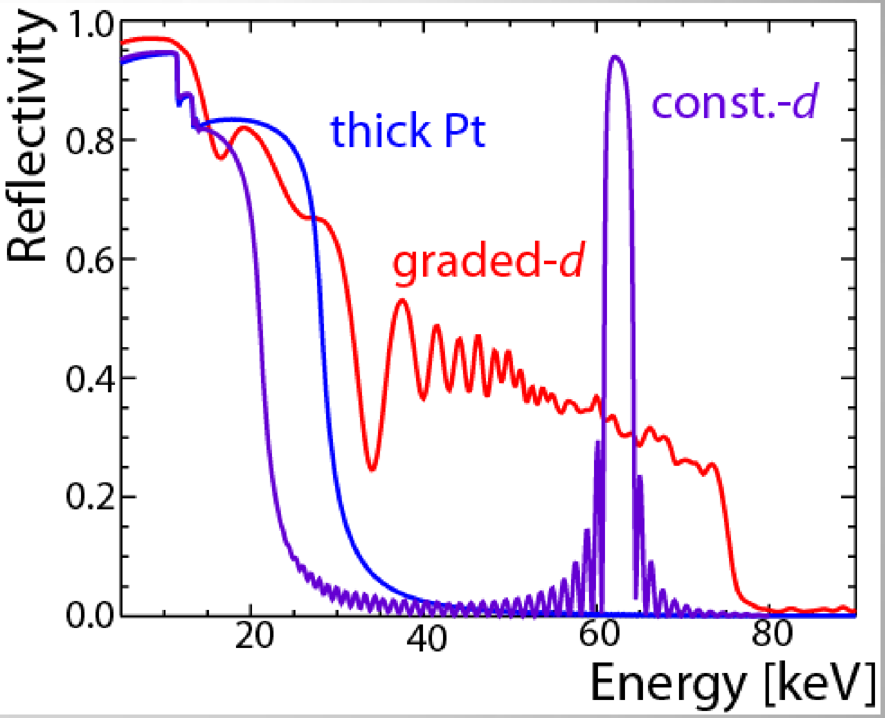




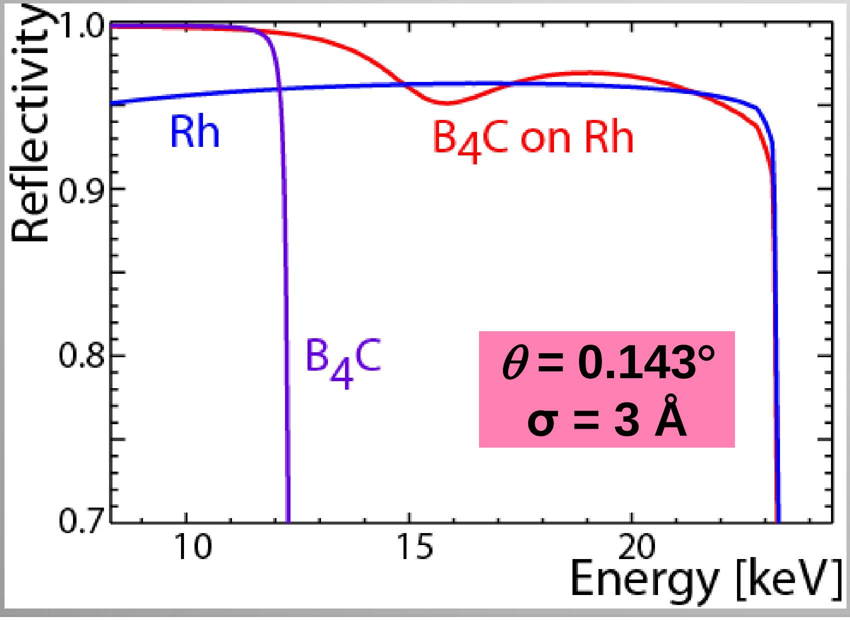
- Reflectivity depends not only on material, but also its high-spatial frequency roughness (*i.e.*, finish)

Multilayer performance

- Recipes can be tuned for application; tremendous versatility
- Systems can consist of 1000's of bilayers to just a few layers ("overcoatings")
- Practically, limited by absorption, stress, absorption, material properties and other constraints (cost, time)



- Semi-infinite Pt coating with σ=3Å
- Constant-d: Pt/SiC, σ=3.0Å, N=90, d=35Å Γ=0.56
- Graded-d: Pt/SiC, σ=4.5 Å, N=566

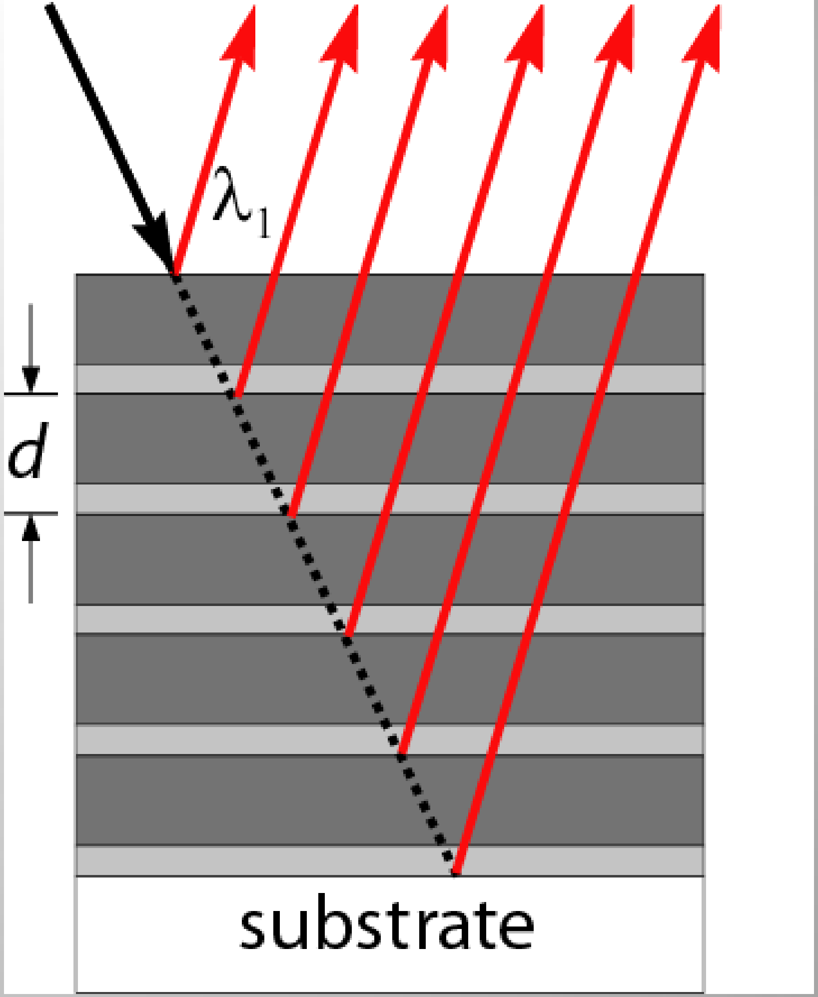


X-ray multilayers

- At high energies, graze angles (θ_c) become too shallow for efficient optics: switch to multilayers
- Alternating layers of high- and low-Z materials act as reflecting interfaces, following Bragg's law

$$m\lambda = 2d\sin\theta\sqrt{1-\frac{2\bar{\delta}}{\sin^2\theta}}.$$

- Theory described in 1920s-1930s
- First proposed for X-ray applications in early 1970s by Spiller *et al.*
- Initially, constant-*d* designs used for high reflectivity for particular bands



- Later, Christensen *et al.* proposed [*Proc SPIE*, **1736**, 229, (1992)] varying *d*, to satisfy the Bragg equation over a range of θ and λ *(~1/E)* at high energies.

TELESCOPES FOR RECENT ASTROPHYSICS MISSIONS

Moving from the soft x-ray band …

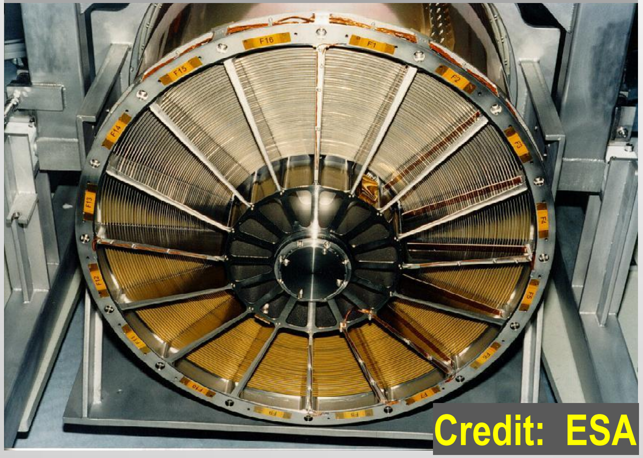
XMM-Newton; ESA

- 15″ HPD
- 3 telescopes, 58 nested shells
- 120 m² surface area
- Mirrors: 200M DM ($120M US)
- Total: $700M US
- Replicated from precision mandrels

Chandra; NASA

- 0.5″ HPD
- 1 telescope, 4 nested shells
- 10 m² surface area
- Mirrors: $700M US
- Total:$1600M US
- Polished monolithic blanks

***XMM* telescope**

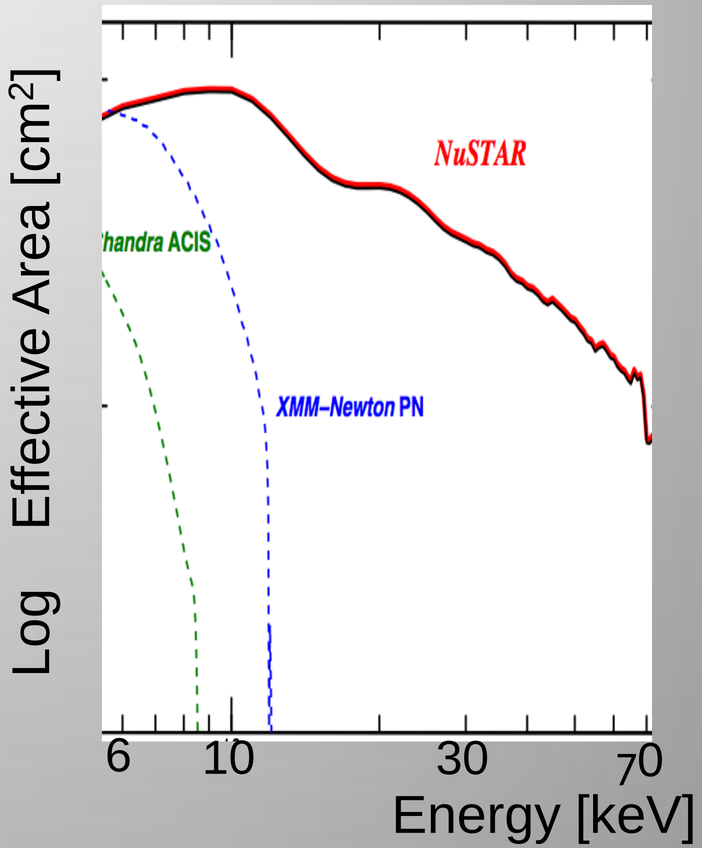


Credit: ESA

***Chandra* Zerodur substrate**

Credit: NASA

NuSTAR, a NASA SMEX satellite scheduled for launch in June 2012



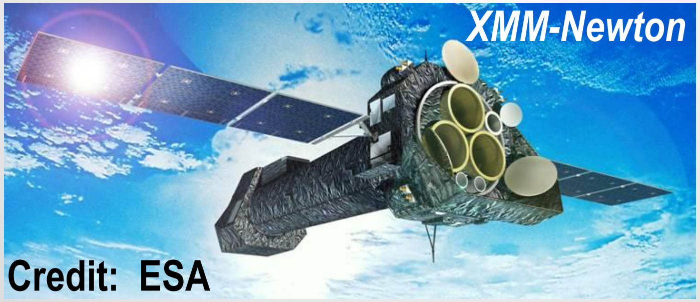
… into the hard x-ray band

XMM-Newton; ESA

- 15″ HPD
- 3 telescopes,
  58 nested shells
- 120 m^2 surface area
- Mirrors: 200M DM ($120M US)
- Total: $700M US
- Replicated from precision mandrels

Chandra; NASA

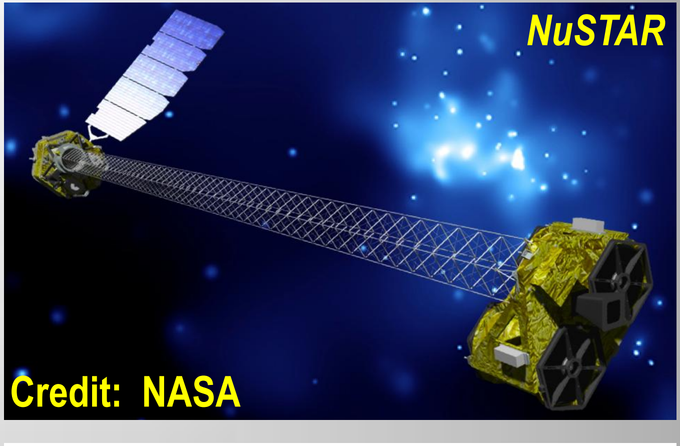
- 0.5″ HPD
- 1 telescope,
  4 nested shells
- 10 m^2 surface area
- Mirrors: $700M US
- Total:$1600M US
- Polished monolithic blanks


XMM-Newton

Credit: ESA


Chandra

Credit: CXC


NuSTAR

Credit: NASA

NuSTAR

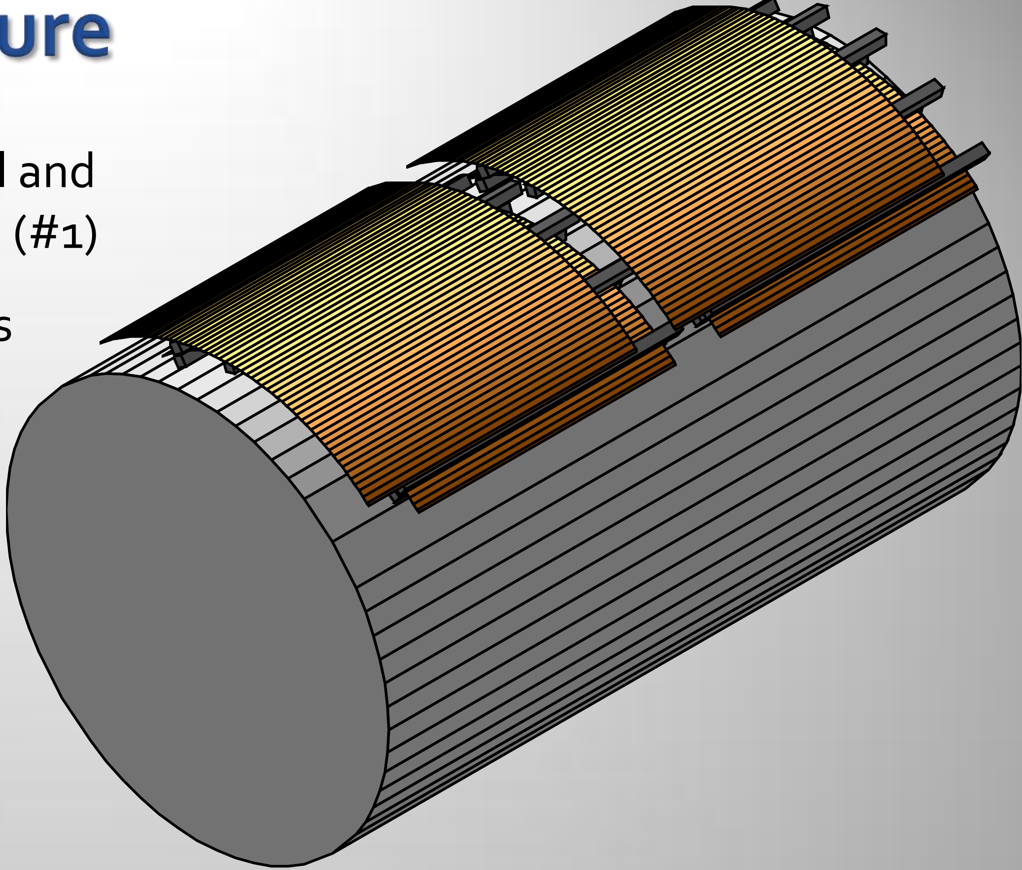
- 45″ HPD goal
- 2 telescopes, 130 nested shells
- 80 m^2 surface area
- Mirrors: $10–15M US
- Total: $100M US
- **Thermally-formed, multilayer-coated mirrors**

Solution: glass substrates

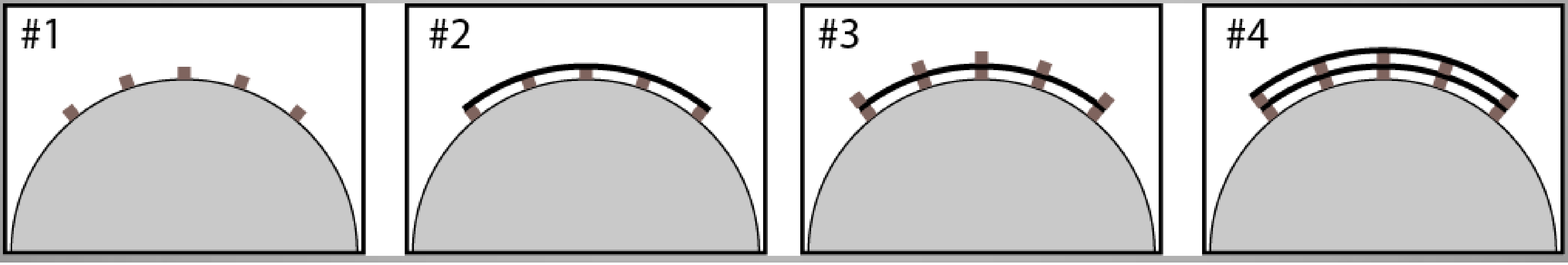
- Work dates back as far as 1988
  - Labov, *Applied Optics*, **27**, 1465, (1988).
- Columbia/DTU/LLNL starts in earnest in late 1990's for the High Energy Focusing Telescope (HEFT) balloon mission
- Start with flat panel float glass (Schott and Corning) which has nice thickness uniformity and excellent surface finish (roughness σ = few Å)
- Thermally form ("slump") into near net shape
  - Take flat pieces of glass and turn into cylindrical shapes
- Coat with appropriate reflective coatings
- Assemble into an optic

Optics assembly procedure

- Epoxy graphite spacers onto a mandrel and machined to the correct radius & angle (#1)
- Epoxy ML-coated substrates to spacers (#2)
- After epoxy cures, epoxy next layer of spacers to previous layer of glass (#3)
- Machine these spacers, epoxy another layer of glass into place (#4)
- Repeat until entire optic is assembled

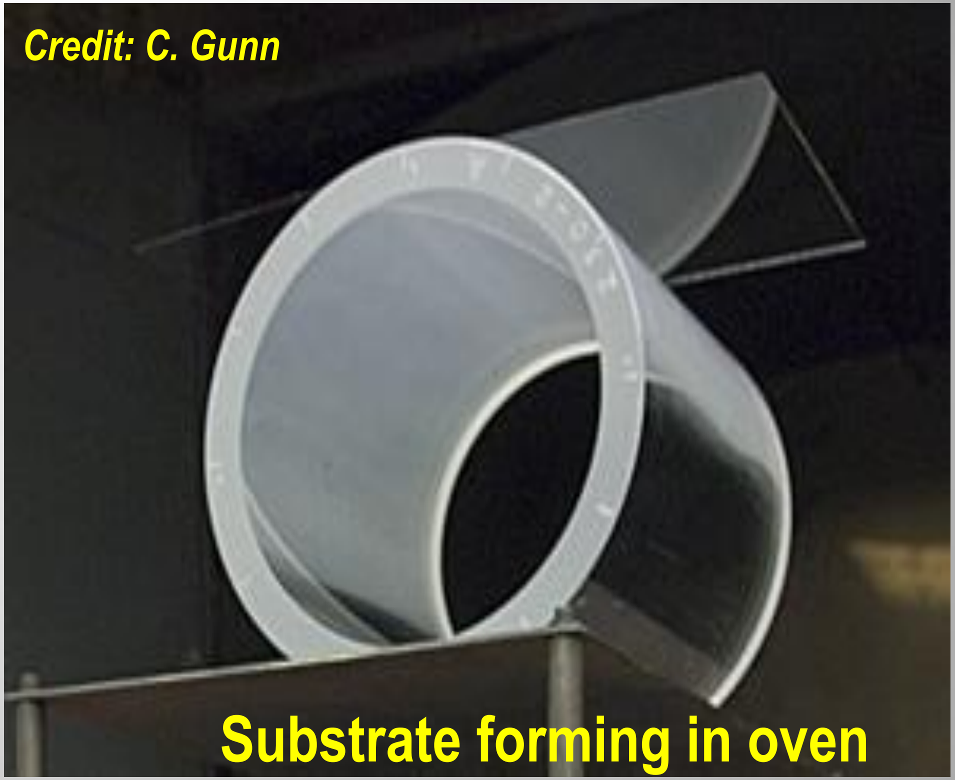


J.E. Koglin *et al.*, *Proc. SPIE,* **4851,** 607, (2003)



Optics start with thermally forming substrates

- Optics PI, Charles Hailey, Columbia University
- Team includes: Columbia U., DTU-Space, NASA GSFC, LLNL



Credit: C. Gunn

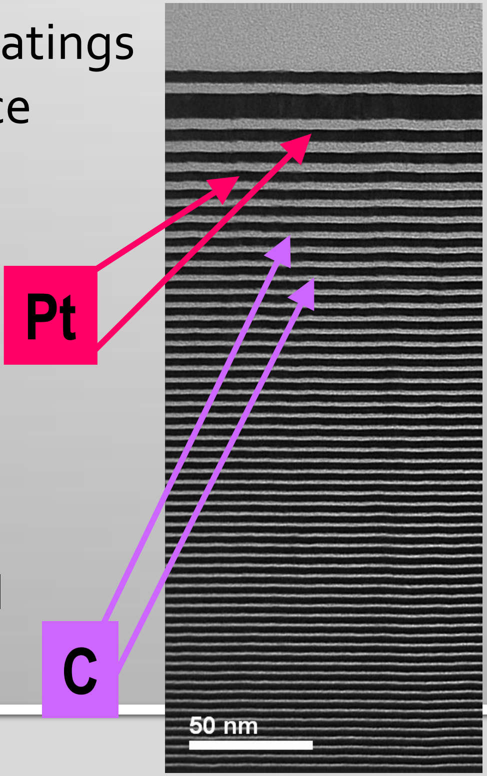
Substrate forming in oven

Credit: C. Gunn

- GSFC approach slumps glass directly onto highly polished mandrels
- Excellent figure (10–20″ HPD) has been demonstrated

Depth-graded multilayer coatings provide broad band response

- Two material systems used, driven by need to detect Ti-44 lines at 68 & 78 keV
  - Pt/C provides highest response
  - W/Si less expensive and smoother
- 10 different multilayer recipes used
- X-ray testing to optimize coatings and understand performance
  - 8 keV (DTU)
  - 60 keV (NSLS)
  - 10-90 keV (RaMCaF)
- Extensive metrology to validate models
  - Surface roughness, TEM compositional studies

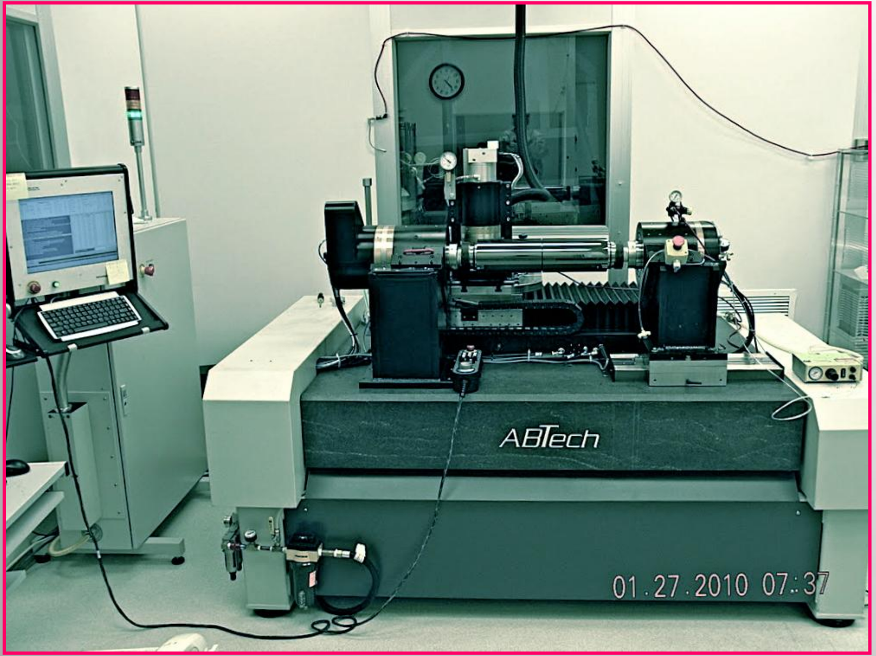



High throughput magnetron sputtering chamber

Danish Technical University-Space Coating Facility

F Christensen *et al.*, *Proc SPIE*, **8147**, (2011)

NuSTAR telescopes assembled at the Nevis Laboratories, Columbia University



Two custom-built assembly machines are used to precisely mount the glass segments at Columbia's Nevis Laboratory

J Koglin *et al., Proc SPIE*, **8147,** (2011)
W Craig *et al., Proc SPIE*, **8147,** (2011)

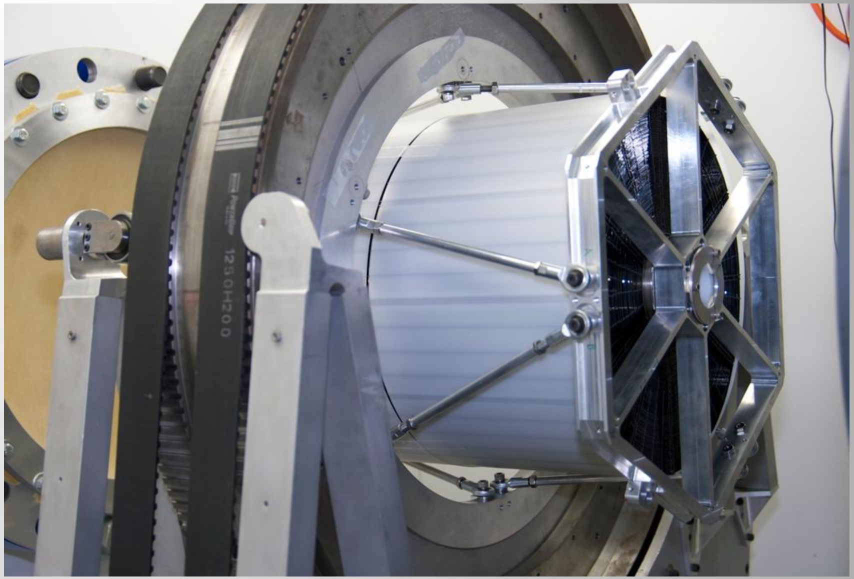
Glass is positioned and clamped for overnight cure of epoxy

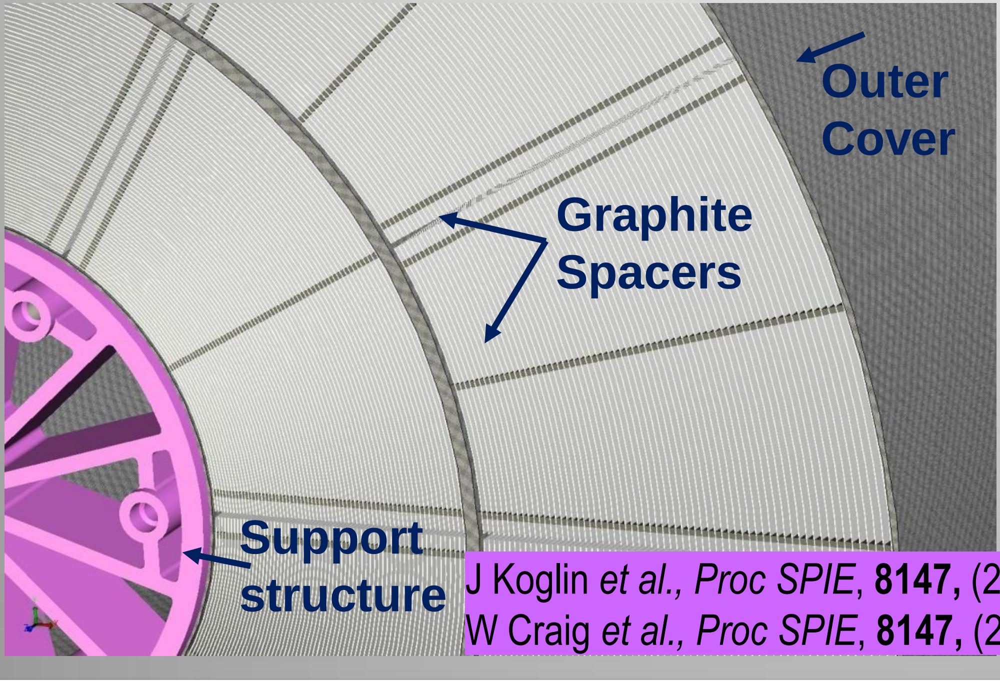
Optic with more than 100 layers

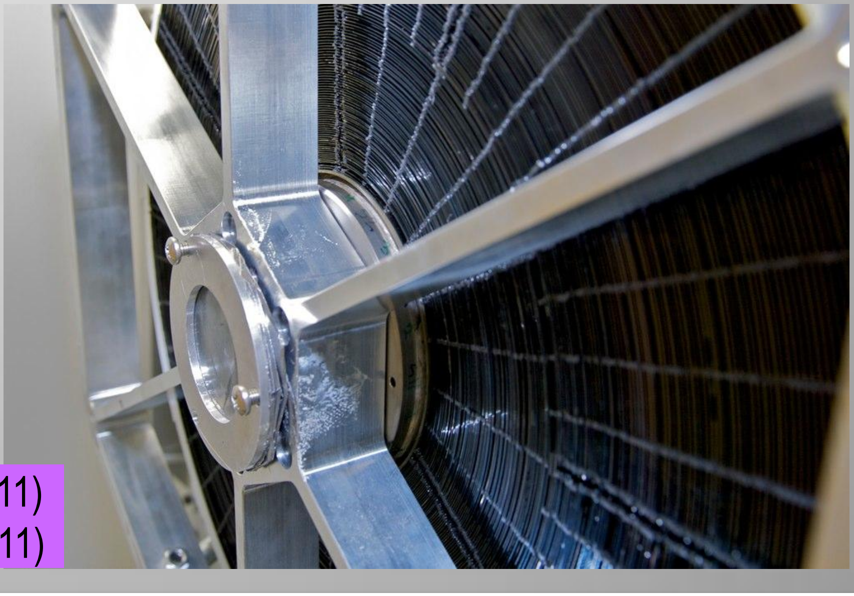
NuSTAR telescope details

Focal Length	10.15 m
Shell Radii	51–191 mm
Graze Angles	0.074–0.224°
Shell Length	225 mm
Mirror Thickness	0.2 mm
Shells Per Module	130
Mirror Segments Per Module	2340

C Hailey *et al. Proc SPIE* ,**7732**, (2010)







J Koglin *et al., Proc SPIE*, **8147,** (2011)
W Craig *et al., Proc SPIE*, **8147,** (2011)

X-RAY OPTICS FOR SOLAR AXION PHYSICS

Guiding philosophy for an axion experiment

$$g_{a\gamma}^{4} \propto \underbrace{b^{1/2}\varepsilon^{-1}}_{\textbf{detectors}} \times \underbrace{s^{1/2}\varepsilon_0^{-1}}_{\textbf{optics}} \times \underbrace{(BL)^{-2}A^{-1}}_{\textbf{magnet}} \times \underbrace{t^{-1/2}}_{\textbf{exposure}}$$

b = background
ε = efficiency

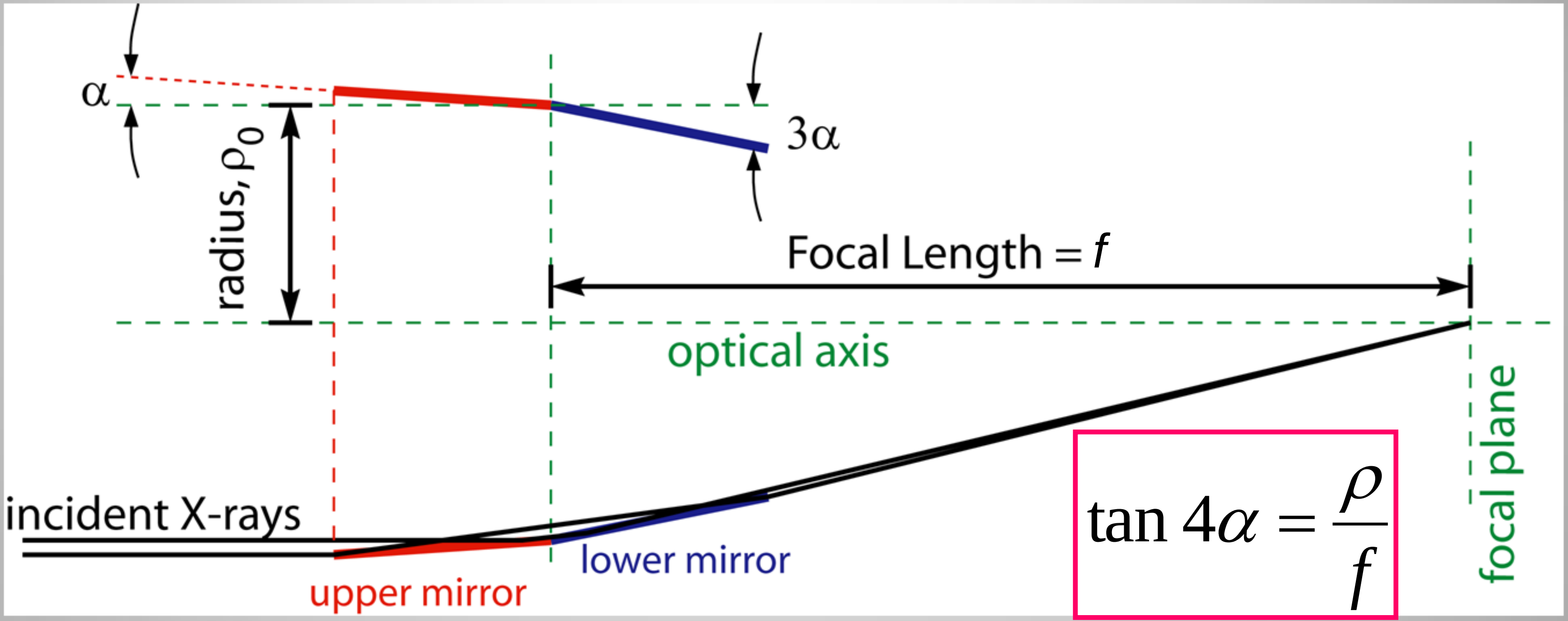
s = spot size
ε_o= efficiency

B = magnetic field
L = magnet length
A = cross-sectional area

t = time

- Optics are needed, primarily, because detectors have non-zero backgrounds (***s*** above)
  - Optics “squeeze” x-ray beam from a size equal to the diameter of the magnet bore to something much smaller
- Spectral response and effective area are also important (ε_o above)
  - Both of these properties influence the throughput of the optic
- Practical constrains
  - Size (e.g. focal length), cost

Wolter basics



$$\tan 4\alpha = \frac{\rho}{f}$$

- Usually, start with maximum allowable graze angle α
- Next, use constraints (e.g., $f < 1.6$m for CAST or minimum allowable substrate radius ρ_{min})

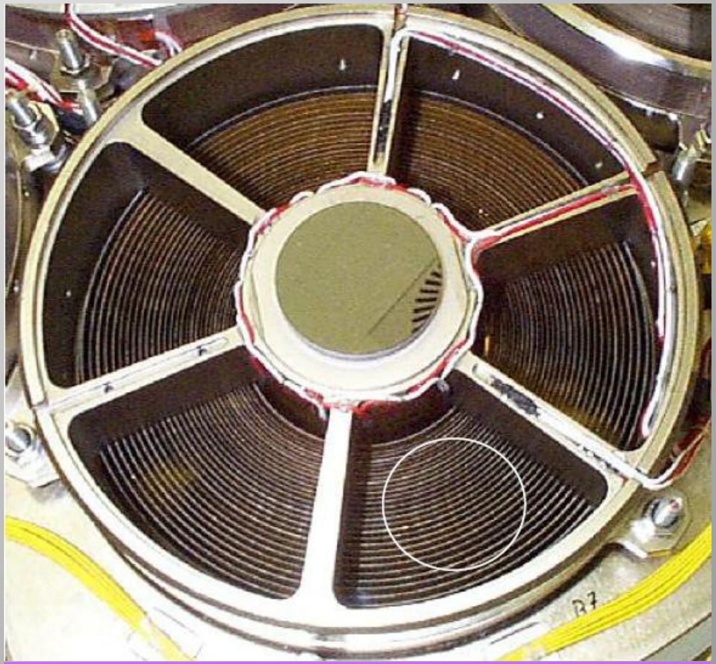
How small can you go?

- Optics are usually specified in terms of angular resolution
- The source may also have angular extent
- State-of-the-possible today
  - Optics: 10-60 arcsec half-power diameter (HPD)
  - Sources: Solar axions come from the central 180″ of the Sun
- CAST, *ABRIXAS* x-ray telescope
  - Spot size

    $180'' \times f = 0.87 \text{ mrad} \times 1600 \text{ mm}$

    $= 1.4$ mm diameter (theory)

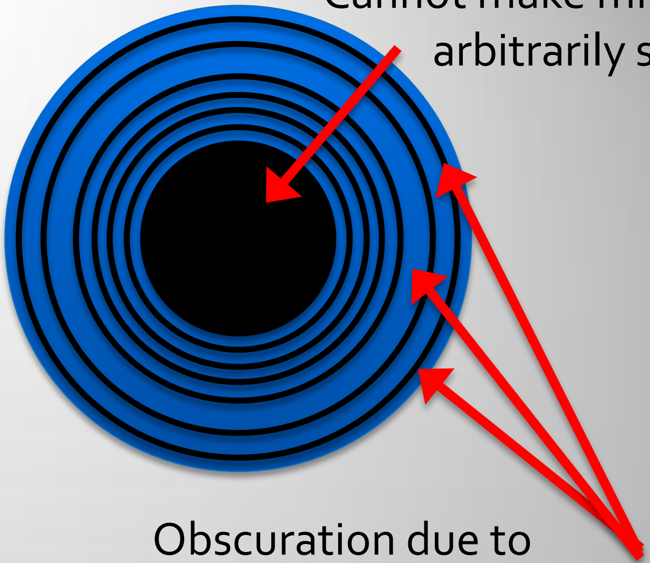
    $= 3.4$ mm diameter (actual)
  - CAST Magnet bore = 43 mm diameter
  - Reduction in area $=(43/3.4)^2 \approx 150$



M. Kuster *et al*., *New J. Phys*, **9**, 169, (2007)

Considerations for IAXO

- 8 magnet bores → at least this many telescopes
- Large areas, ρ = 300 mm
  - Cannot be asymmetric (like CAST)
- Need *NuSTAR*-like approach to fabrication to keep costs down
- Notional focal length
  - $\alpha_{max} \approx 0.8°$
  - $f_{min} \approx \rho_{max}/\tan(4\alpha_{max}) \approx 5.4$ m
- Complex trade required to optimize spot-size and spectrally-matched throughput



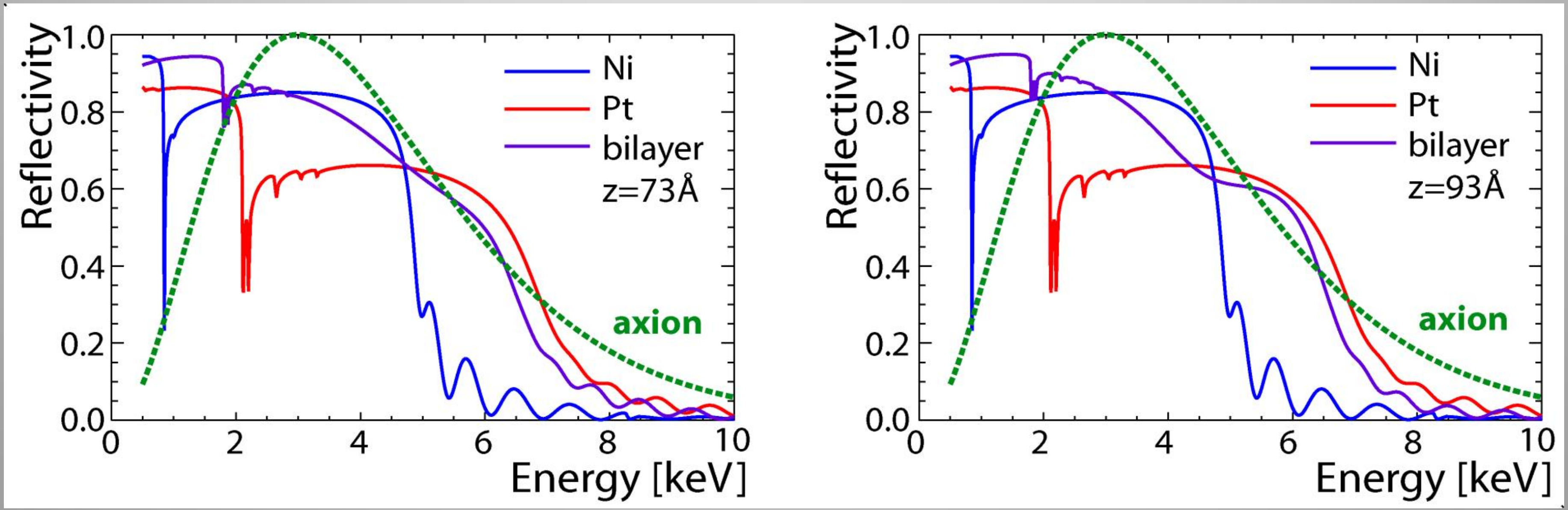
Cannot make mirrors arbitrarily small

Obscuration due to substrate edge blocking light

Optimal coatings depends on several factors

- Must worry about total system throughput:
  - d$\Phi(E) \otimes \mathrm{QE}(E) \otimes \mathrm{EffArea}(E)$ (axion spectrum, detector efficiency and telescope area)
- Fix $\alpha = 0.7^\circ$ and QE is unity from (a) 2-5 keV or (b) 1-10 keV
- Compare pure Ni and Pt coatings with a simple bi-layer, B_4C on W

(a) 2-5 keV **(b) 1-10 keV**



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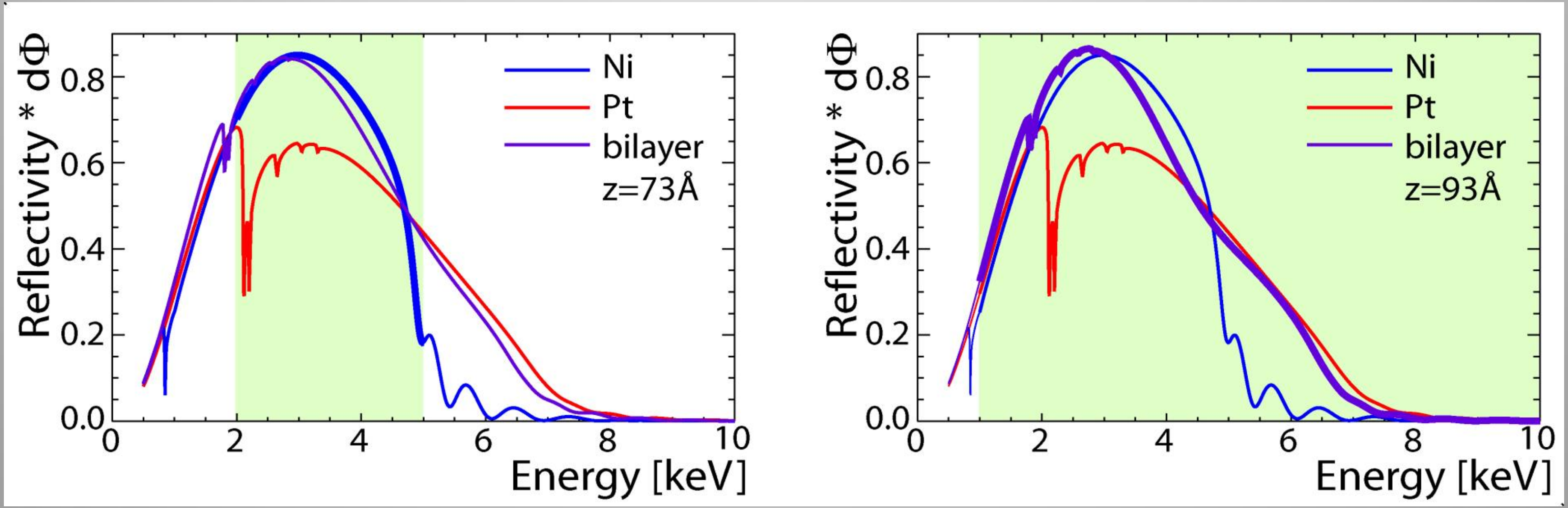

(a) 2-5 keV **(b) 1-10 keV**

Ni best, Pt: 80%, bilayer: 99%

bilayer best, Pt: 88%, Ni: 87%