Recent advances in reflective hard x-ray / soft gamma-ray optics and Prospects for Soft Gamma-ray Focusing Optics

Future Space-Based Gamma-ray Observatories Workshop, NASA GSFC

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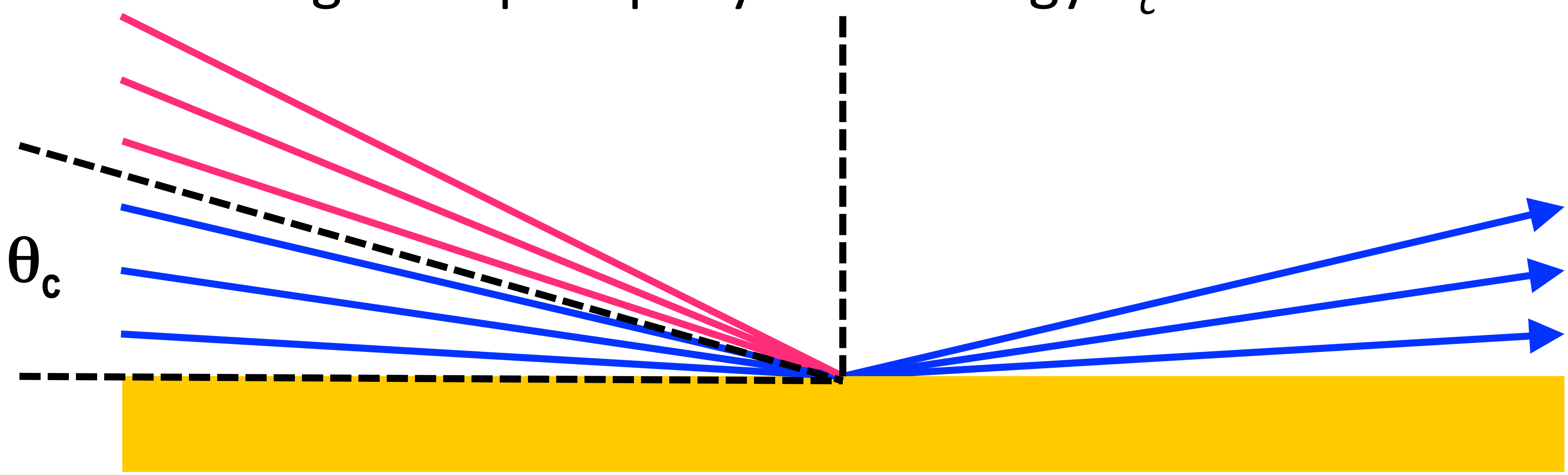
Overview

- Reflective (multilayer-coated) x-ray optic primer
- Soft γ-ray optics
  - Motivation: Non-destructive assay of spent nuclear fuel
  - Results
- Space-based missions
  - Prior efforts (NuSTAR)
  - Considerations
  - Preliminary concepts

X-RAY OPTICS PRIMER

Reflective x-ray optics

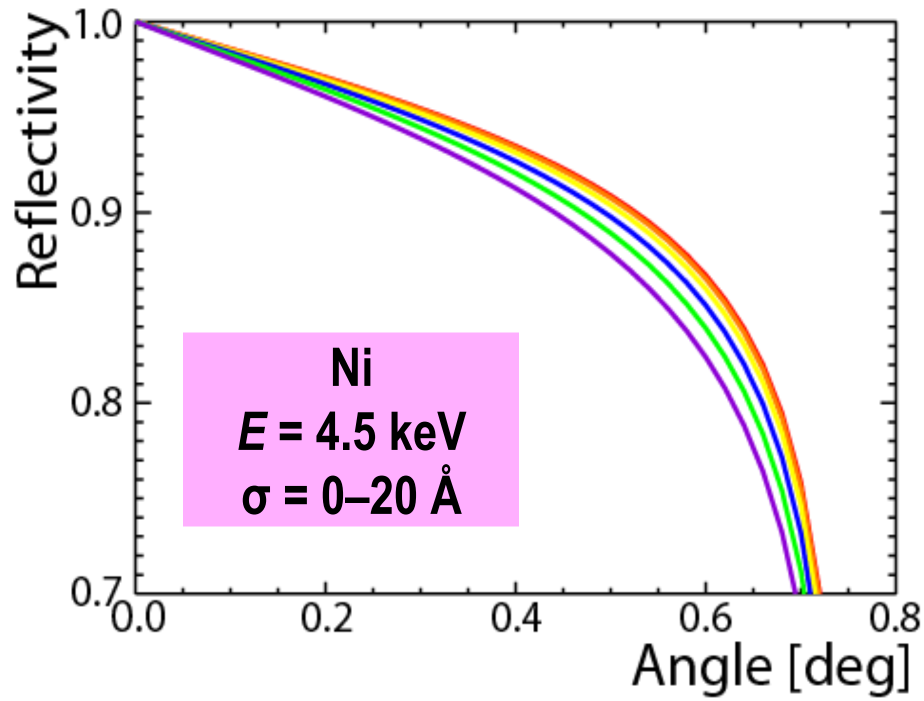
- Compton first discovered X-rays incident at small glancing angles are totally reflected
  - "The Total Reflexion of X-rays", *Philosophical Magazine*, **45**, 1121, (1923)
- Index of refraction for high energy photons $n = 1 - \delta - i\beta$
- Total external reflection of light occurs when the incident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

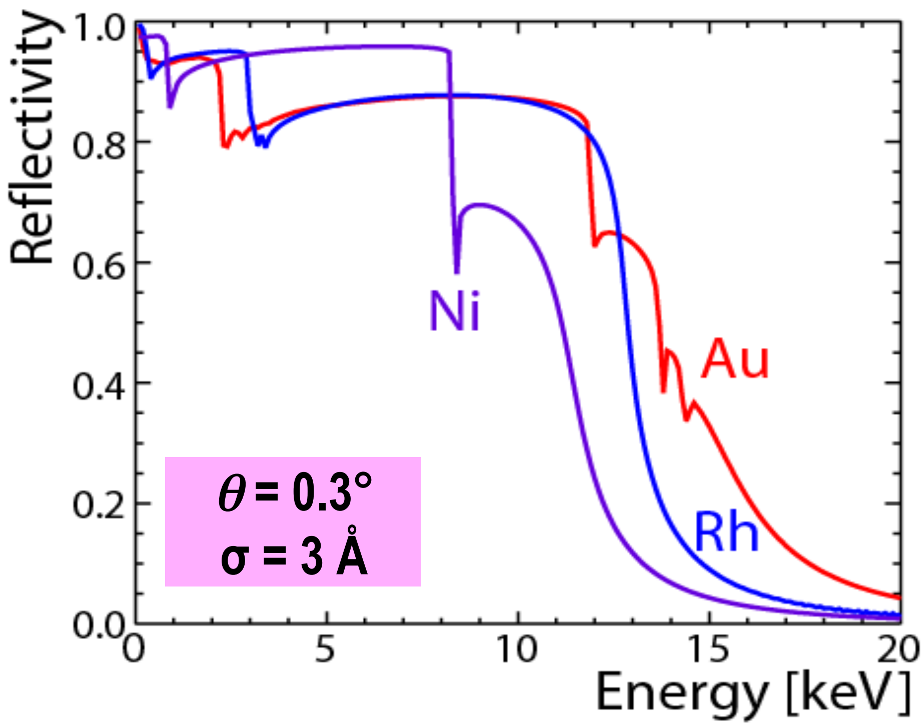


X-ray reflectivity

Limited to materials that:

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





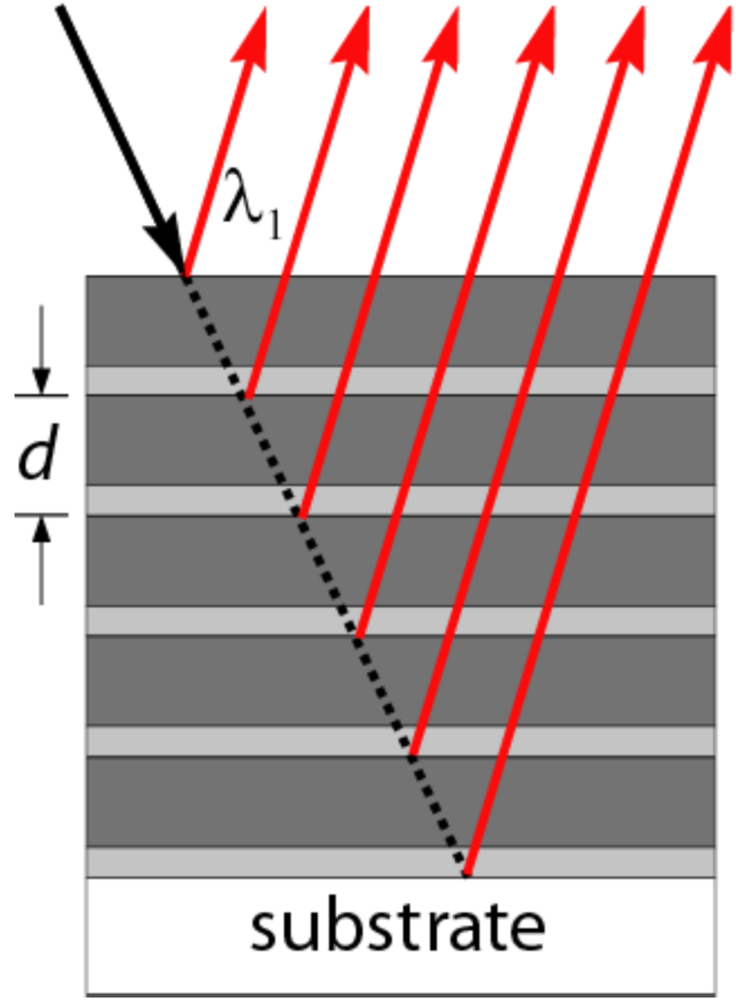
- Reflectivity depends not only on material, but also its high-spatial frequency errors (*i.e.,* surface roughness or finish)

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

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

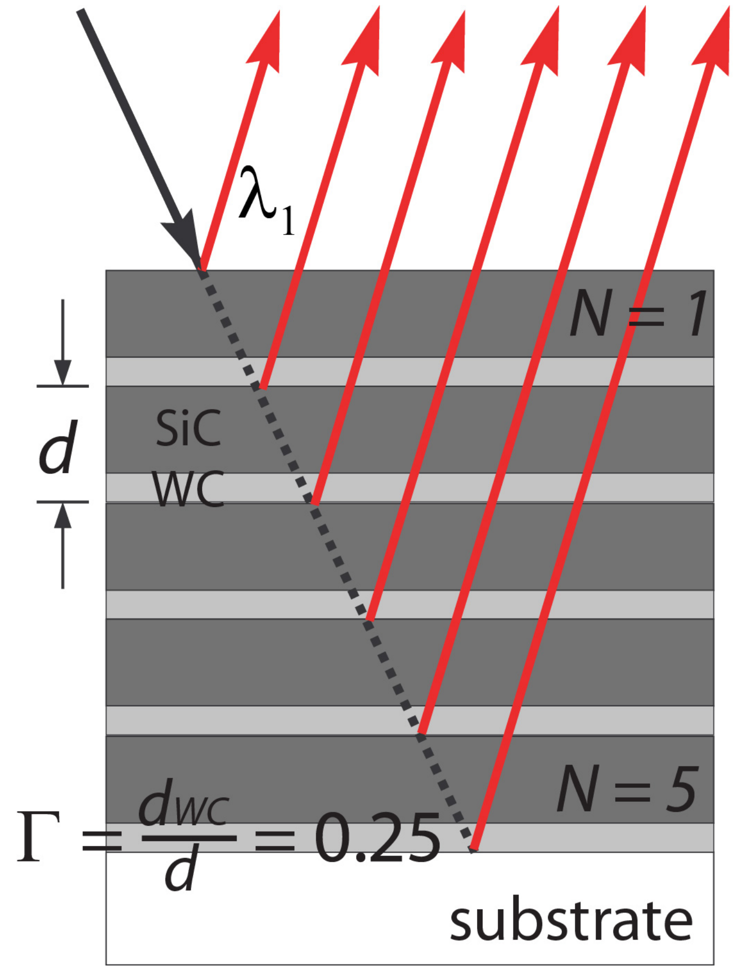
- Theory described in 1920s-1930s
- First proposed for X-ray applications in early 1970s by Spiller *et al.*
- Initially, constant-*d* designs used for high reflectivity for particular bands



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

Multilayer considerations

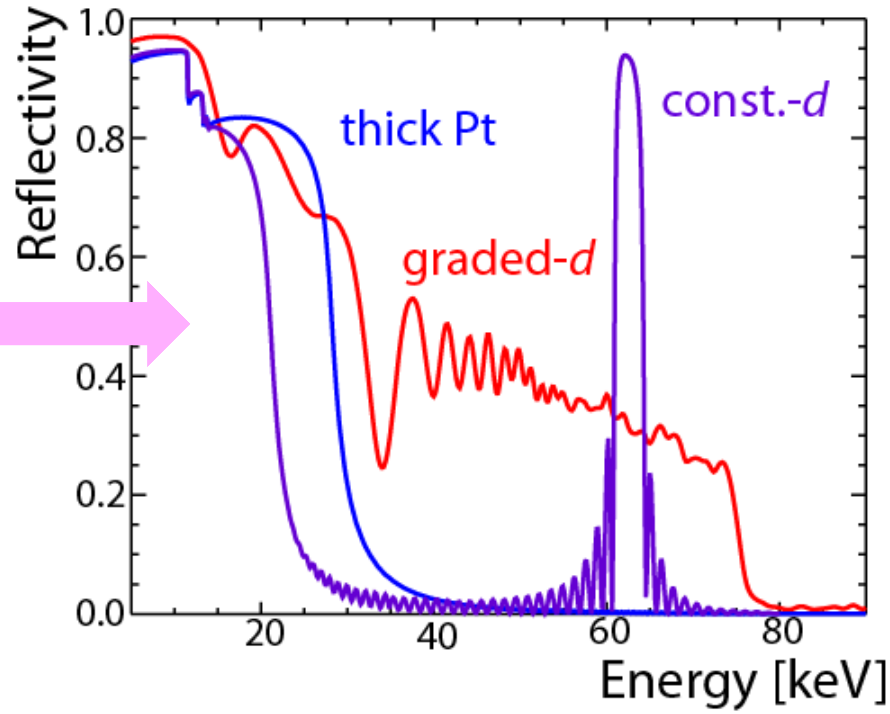
- Our films/coatings/multilayers created via DC magnetron sputtering
  - Ions of material accelerated from guns onto substrates in alternating fashion in a (mostly) evacuated chamber
  - “Turntables” allow spinning and rotation to precise control film thickness on aspheric substrates
- Knobs
  - Chamber gas and density, gun power, substrate biasing, material system
- Performance & characteristics
  - Reflectivity
  - Stress
  - Roughness (scattering)
  - Cost (materials & time)

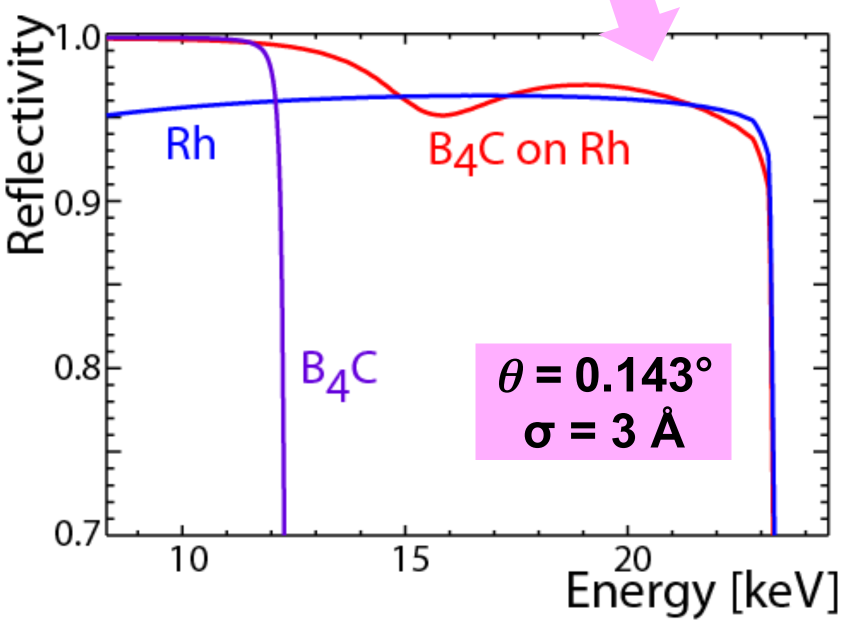


- *N*, number of bi-layers
- *d*, period of bi-layers
- Γ, ratio of absorber material to period

Sample performance

- Recipes can be tuned for specific applications
- Systems can consist of
  - Hundreds to thousands of bilayer pairs
  - Tens to a single bi-layer pair (e.g, an “overcoating”)





Three curves

- 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

SOFT γ-RAY OPTICS & NUCLEAR NON-PROLIFERATION

Improving the accuracy of Safeguards techniques

- ***Directly*** and ***non-destructively*** measure the content of U and Pu isotope (e.g., ^{235}U and ^{239}Pu) in spent fuel through gamma-ray spectroscopy MJ Pivovaroff et al. *NIM A* **743: 109** (2014)
  - With just a detector, lines of interest are overwhelmed due to
    - High count rates
    - Low intensity of nuclear lines with respect to other radioisotopes

Isotopic emission lines

Isotope	E [keV]	Activity [$\gamma\ g^{-1}s^{-1}$]
^{235}U	143.8	8.4×10^3
^{235}U	185.7	4.3×10^4
^{239}Pu	129.3	1.4×10^5
^{239}Pu	375.0	3.6×10^4
^{239}Pu	413.7	3.4×10^4
^{240}Pu	160.3	3.4×10^4

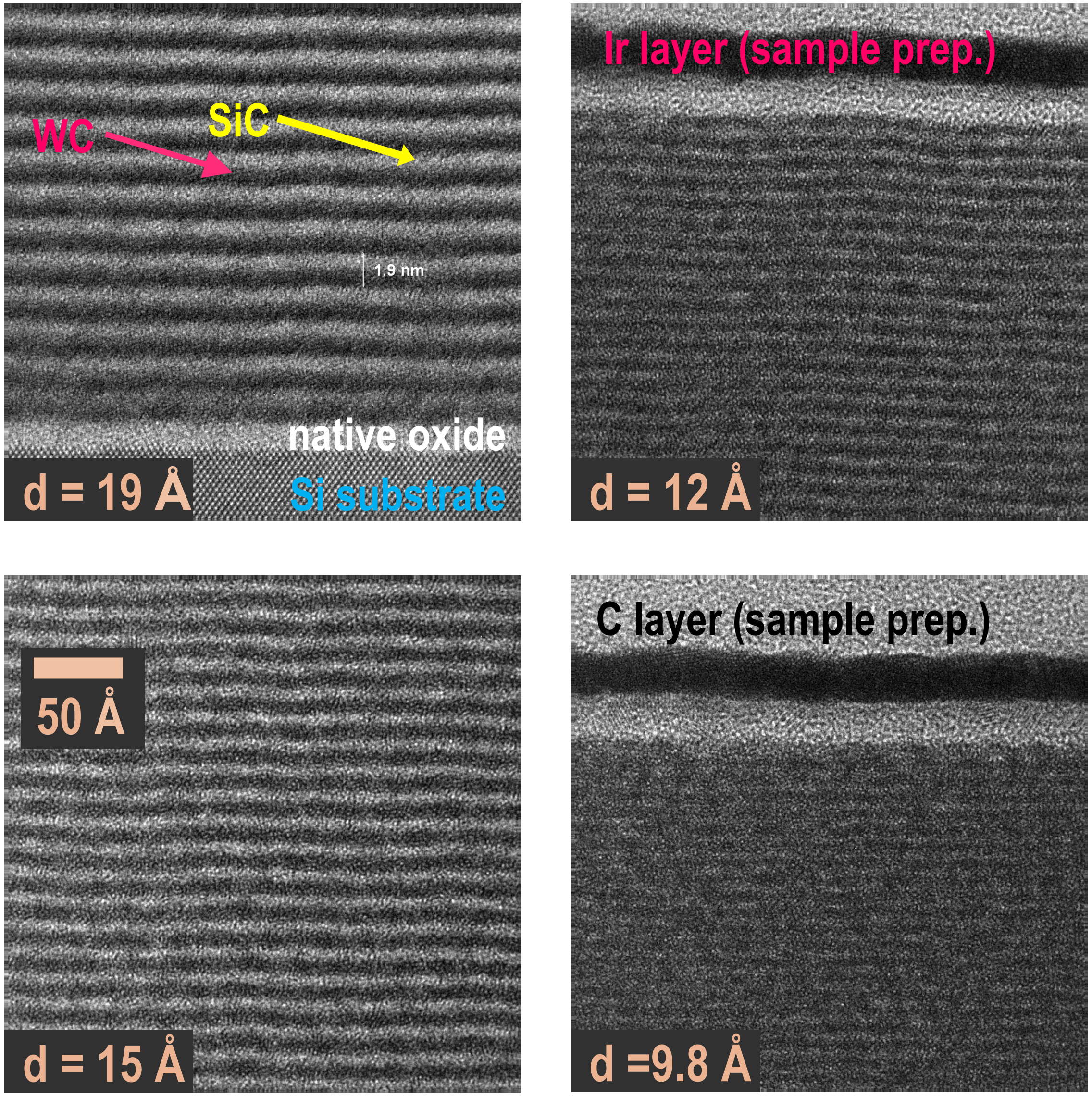
Characteristic emission lines

Line	U [keV]	Pu [keV]
$K_{\alpha1}$	98.4	103.7
$K_{\alpha2}$	94.7	99.6
$K_{\beta1}$	111.3	117.3
$K_{\beta2}$	114.5	120.6
$K_{\beta3}$	110.4	116.3

Understand your material system

- Determine density and stochiometry of the material systems
  - RBS + XPS + XRR
  - Use this information and atomic scattering factors to compile optical constants—no evidence for disagreement
- Study evolution of stress and roughness as a function of
  - deposition parameters
  - multilayer composition (Gamma and N)
- Examine if films are crystalline or amorphous
  - LAXRD
  - TEM

TEM studies



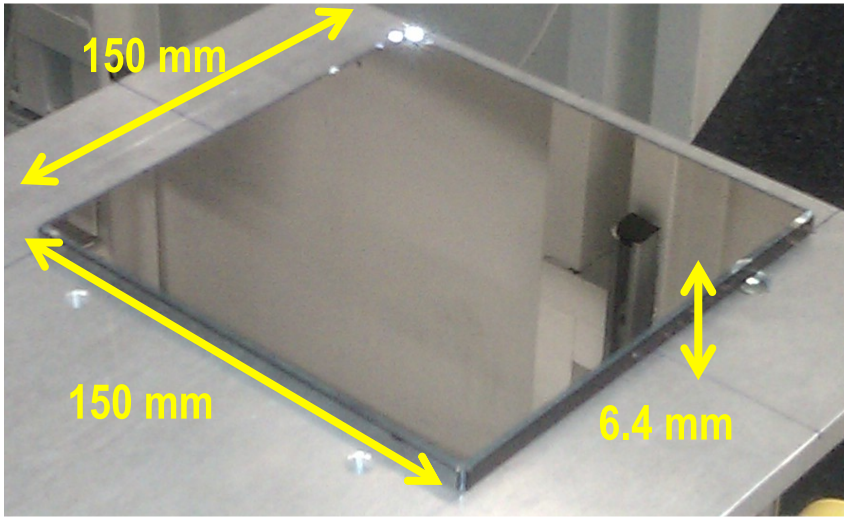
- Microscopy reveals continuous, amorphous films down to *d* = 12 Å
- Instrument resolution makes it too difficult to interpret *d* = 10 Å

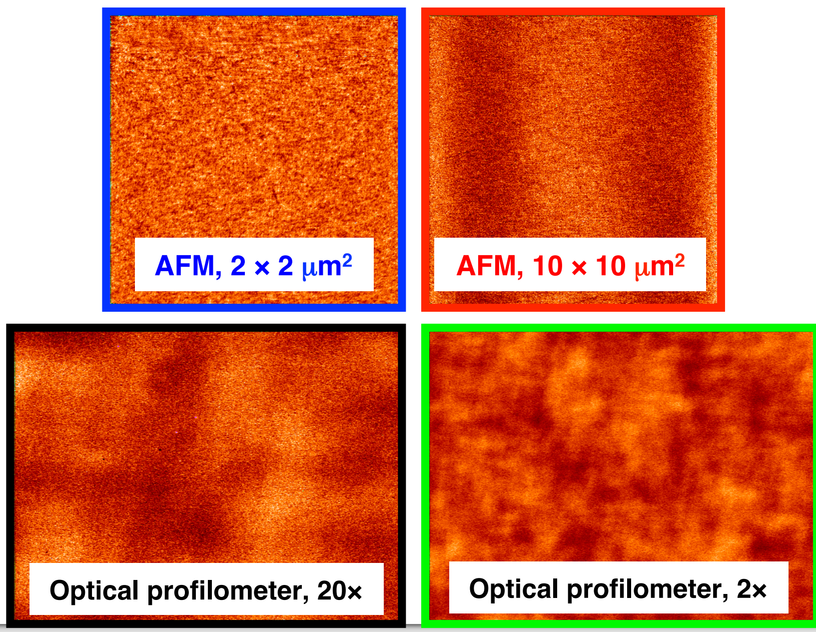
Understand your substrates, pre- and post-deposition

- Perform surface characterization at low-, mid- and high-frequency spatial scales using metrology tools that have absolute calibrations and/or validated cross-calibrations
  - "Figure": Full-aperture interferometer (or long-trace profilometer)
  - "Mids": Visible wavelength microscope
  - "Finish": Atomic force microscope (AFM)

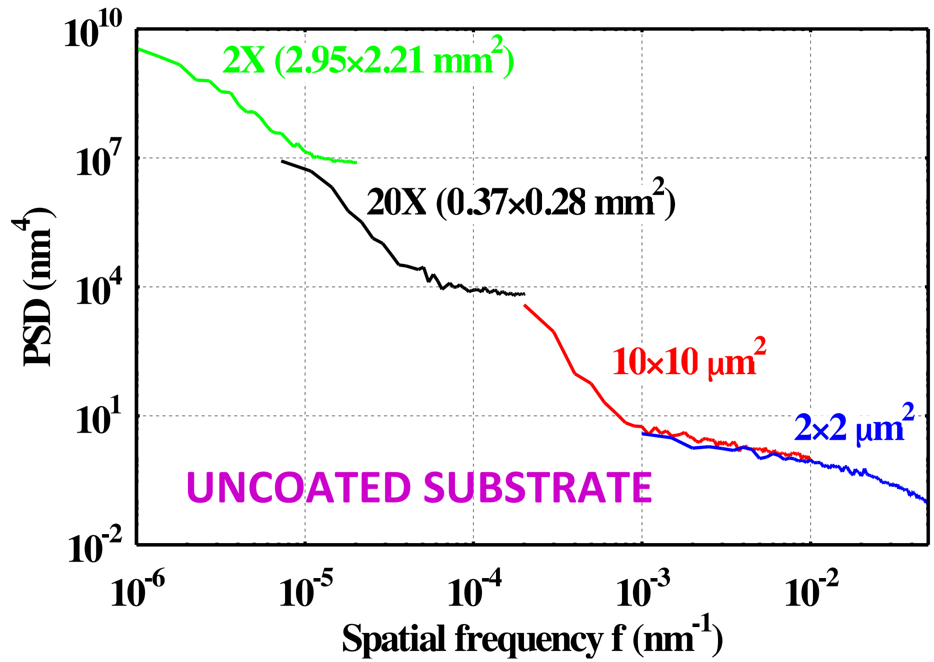
- Construct 1D and 2D PSDs
  - Integrate over PSD (and higher-order moments) to determine slope/figure errors and roughness

Si wafers are not appropriate for high energies studies because of large figure errors





- Super-polished EUV lithography mask blanks made of fused silica were selected as substrates based on their extremely **smooth and flat surface.**



Slope = < 1 μrad = 0.2 arcsec
MSFR = 2.6 Å rms
HSFR = 0.5 Å rms

X-ray reflectivity measurements

Facility & beamline	Date	Energy [keV]	Footprint, width ×length [mm²]	Purpose
BNL/NSLS; X17B1	Aug 2010	62; 186	1×16 1×40	Reflectivity
DTU; custom reflectometer	Jun 2011	8	3×6	Reflectivity; uniformity
ESRF; ID15a	Sep 2011	370-390	2.5×30	Reflectivity
ESRF; ID15A	Apr 2013	380; 500; 650	2.5×60 …. 2.5×100	Reflectivity
LBNL/ALS; 6.3.2	Jun 2013	0.8	0.05×0.15	Reflectivity; uniformity

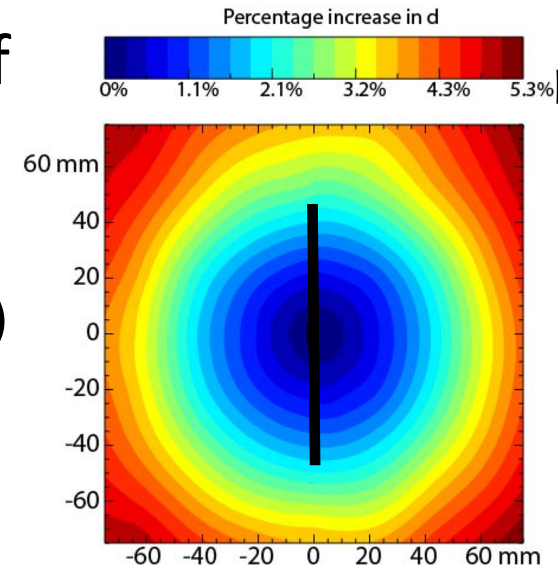
Develop a model of optics response based on low energy calibration that predicts high energy performance

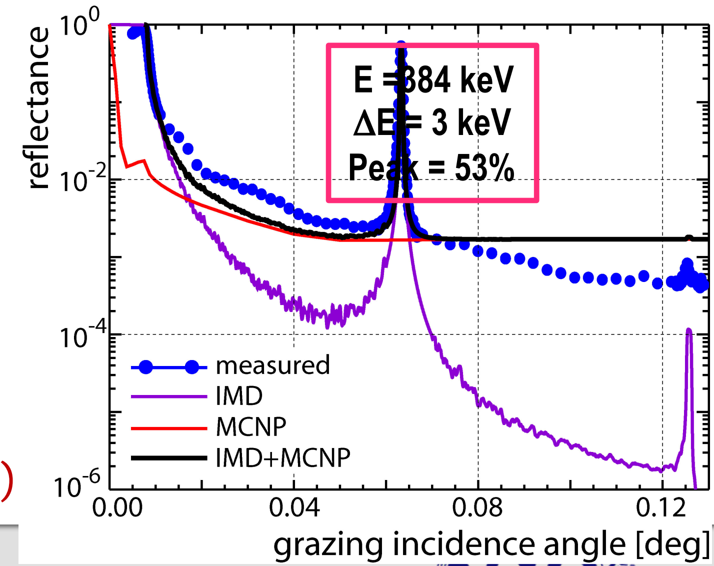
- Account for small amount of variation in *d*
  - Estimate "depth grading" (8 keV)
  - Map d-spacing uniformity (0.8 keV)

Beam footprint size makes uniformity increasingly important at higher energies/lower grazing incidence angles

- Include Photon transport in experimental set-up for E >100s keV

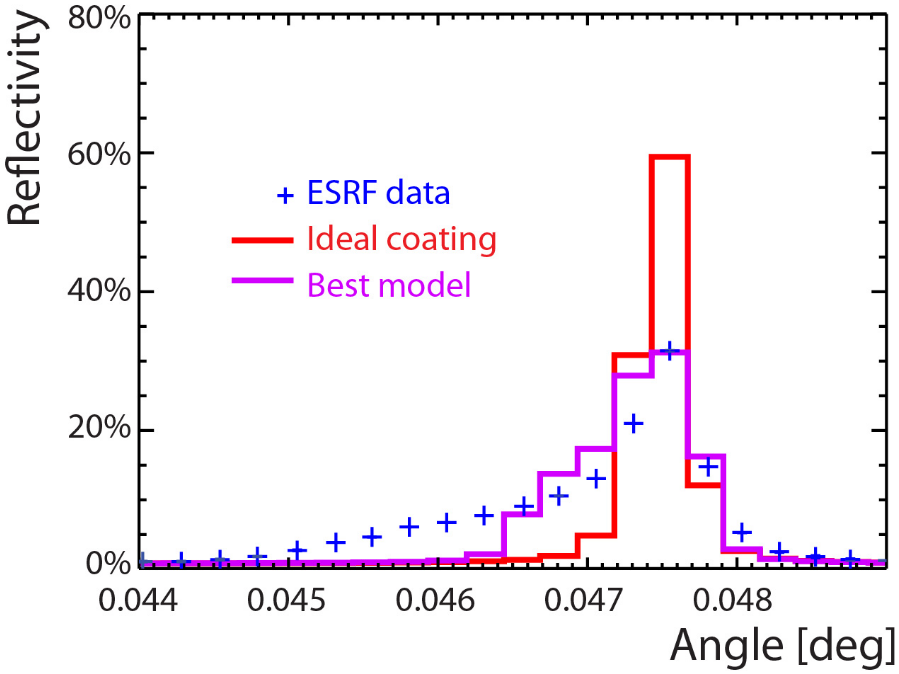
M. Fernandez-Perea et al. *NIM A* **710**:114 (2013)
M. Fernandez-Perea et al. *PRL* **111**:027404 (2013)



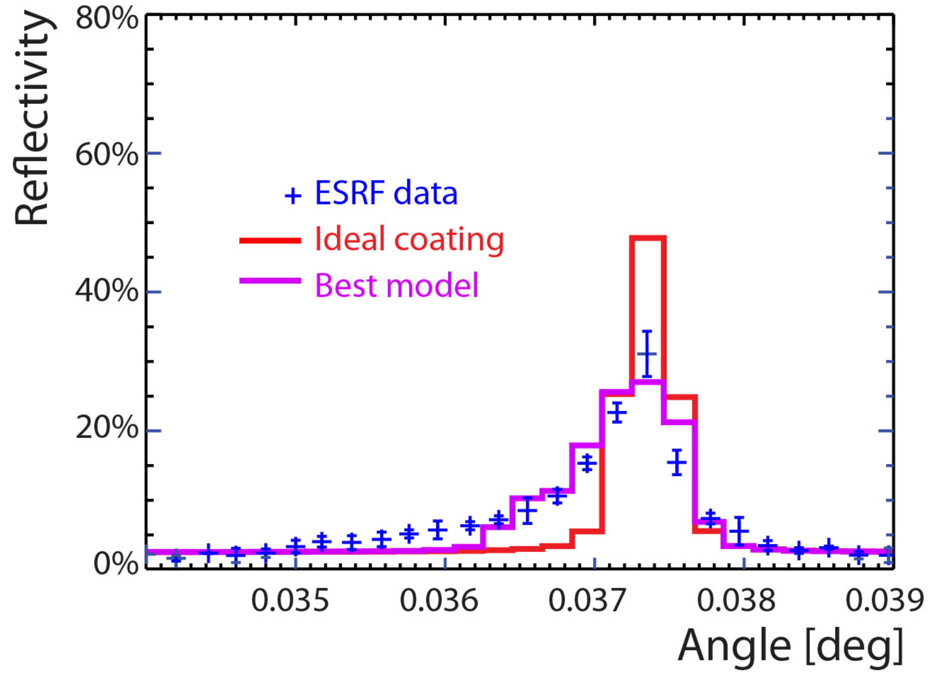


Demonstrated reflectivity above 0.5 MeV

508 keV



645 keV

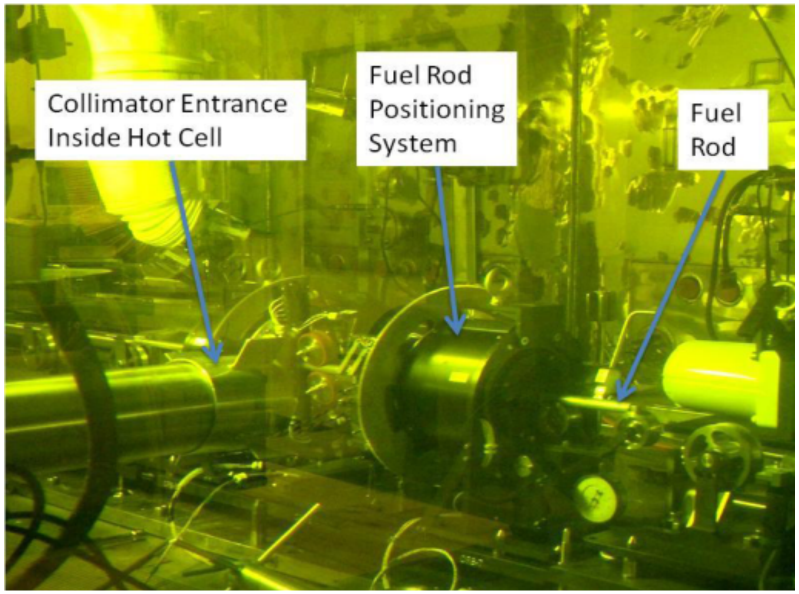


N. Brejnholt et al. *Optics Express* ***22:15364*** (2014)

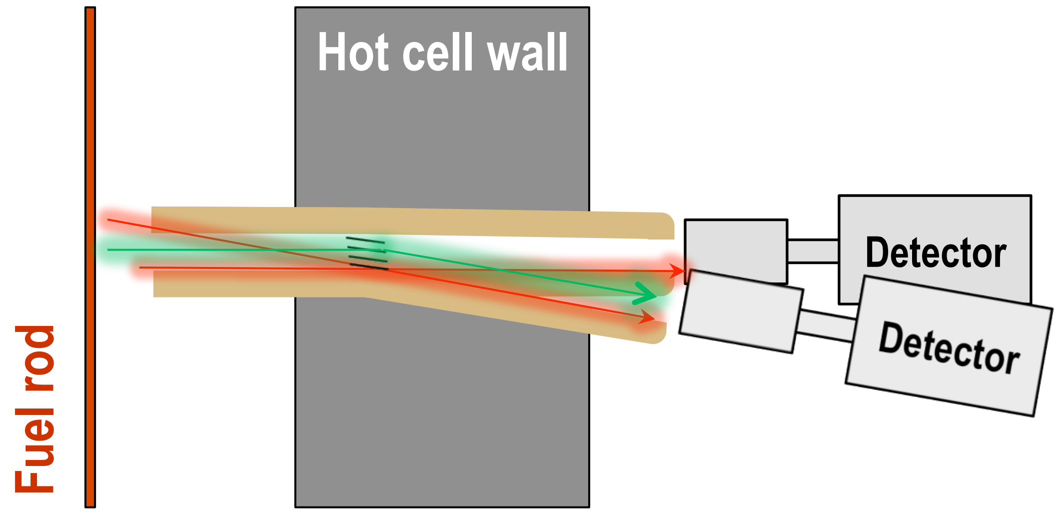
- > 30% reflectivity at 511 keV
- Mirror optimized for 186 keV—theoretical limit for constant-*d* multilayer recipe is >80%

γ-RAY MIRRORS IN ACTION

Experimental concept

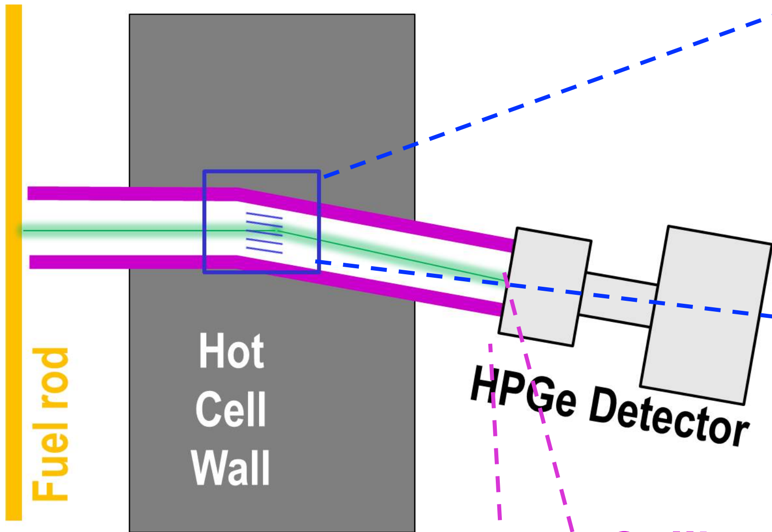


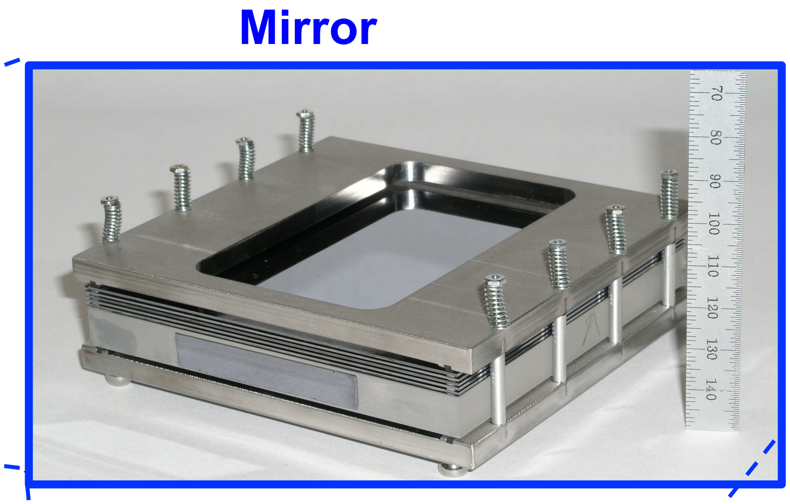
Irradiation Fuel Examination Lab, ORNL

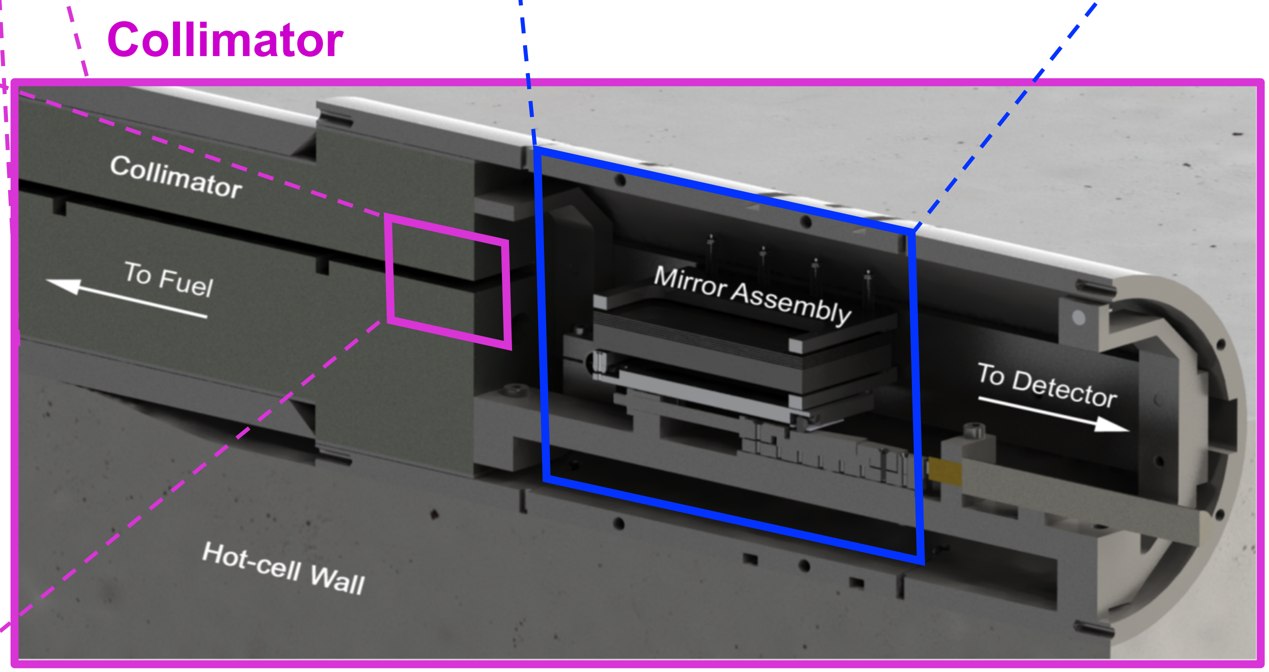


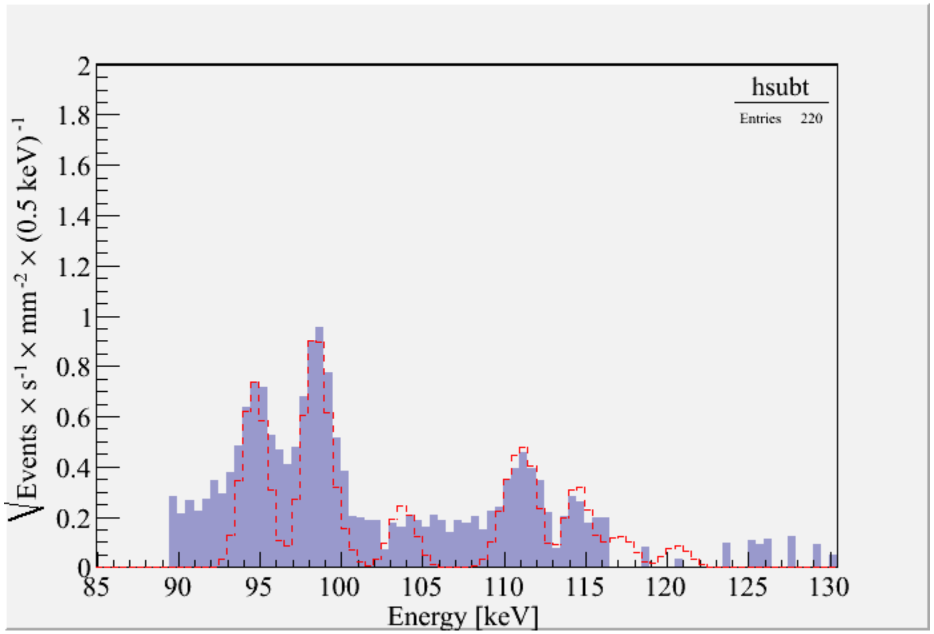
- Use multilayer mirrors as a pass-band filter
  - Rely on multilayers to only transmit emission lines of interest to the detector
- Low-cost (LLNL) version of silicon pore optics
  - Substrates are multi-layer-coated square Si wafers
  - Use precision ground rods as spacers
  - Optics consists of a 5 nested, parallel mirrors

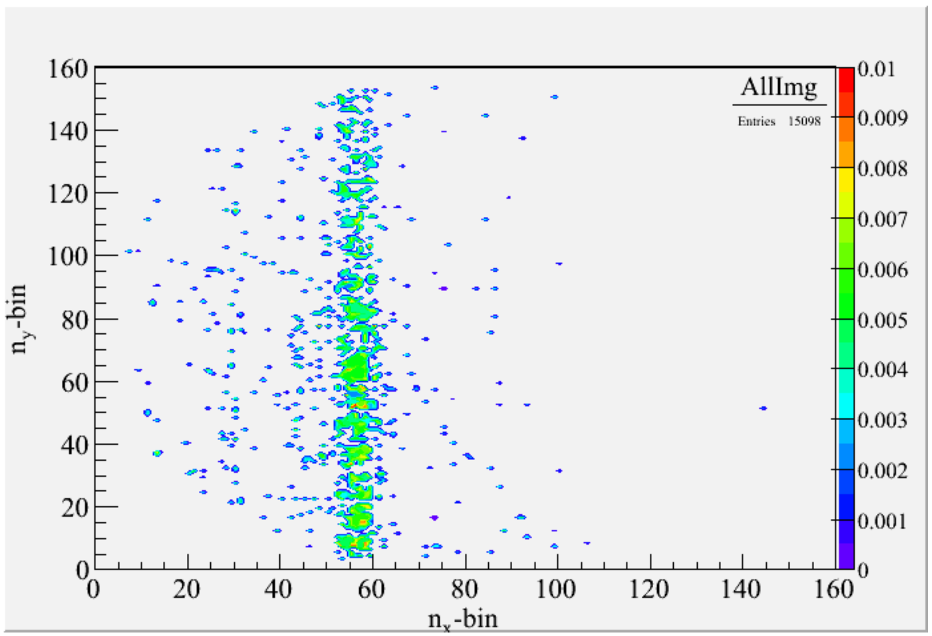
Experimental design











Fuel rod measurements: TMI AG616E

- The mirror is moved systematically from 2.5 mrad to 5.0 mrad, in 0.1 mrad steps
- Around 3.0 mrad, Bragg's law is satisfied around 100±20 keV
- The reflected beam "walks" across the detector face and the intensity in the U K-shell emission lines varies
  - Analogous to a rocking curve response

J. Ruz et al. *NIM A* **777:15** (2015)
J. Ruz et al. App Opt, submitted (2016)

STATE-OF-THE-ART HARD X-RAY OPTICS

Wolter optics for x-ray astronomy

- Wolter design: Even number of conic surfaces of revolutions
- Idea later adopted by Giacconi *et al.* for astronomy
- Key innovation: nested mirrors to increase collecting area (solid angle)

"Spiegelsysteme streifenden Einfalls als abbildende Optiken für Röntgenstrahlen," H Wolter. *Phys Ann* **10:94** (1952)

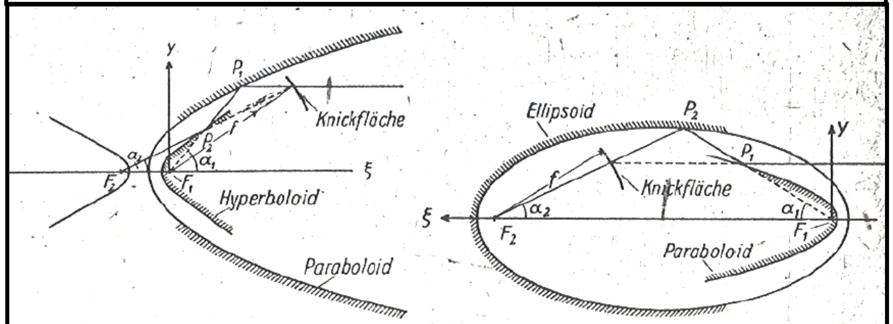
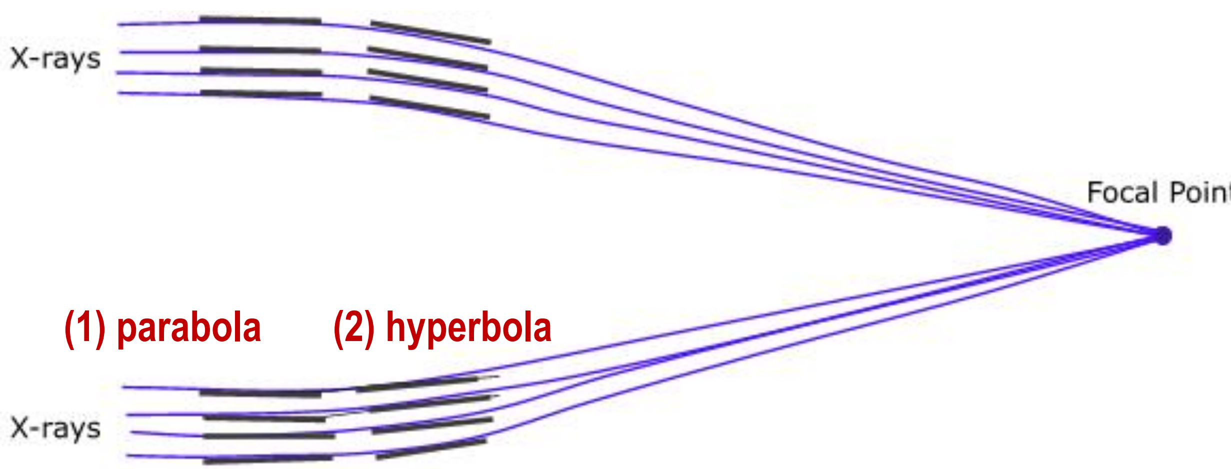


Abb. 15. Spiegelsystem 2. Art

Abb. 16. Spiegelsystem 3. Art

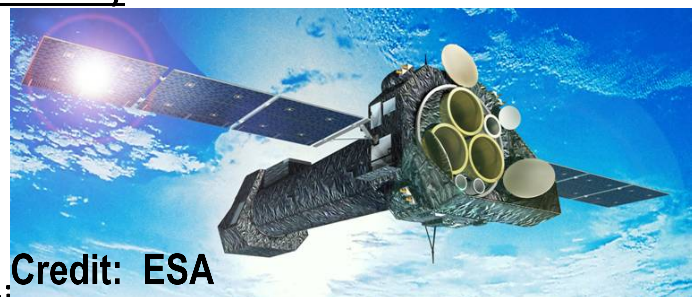
Wolter telescope (1952)



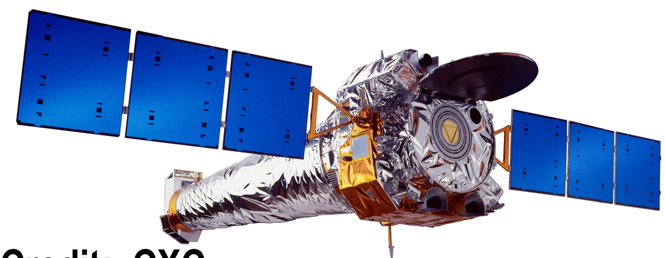
NuSTAR: the transition from soft to hard x-rays

XMM-Newton; ESA (2000)

- 15″ HPD
- 3 telescopes,
  58 nested shells
- 120 m^2 surface area
- Replicated from precision mandrels



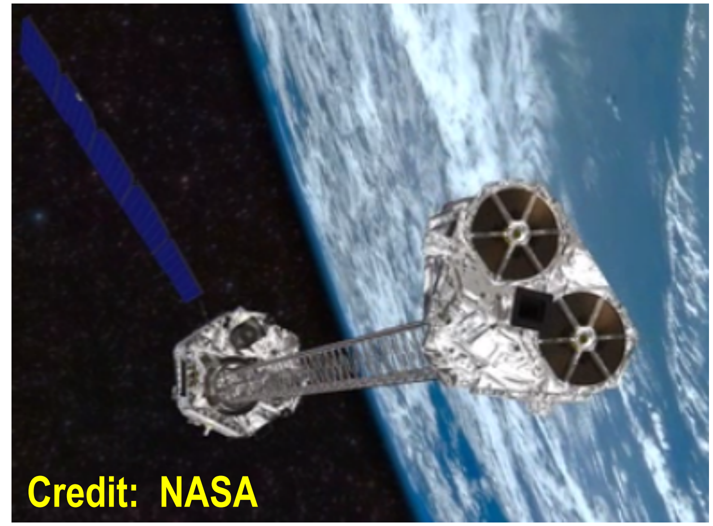
Credit: ESA



Credit: CXC

Chandra; NASA (1999)

- 0.5″ HPD
- 1 telescope,
  4 nested shells
- 10 m^2 surface area
- Polished monolithic blanks



Credit: NASA

NuSTAR; NASA (2012)

- 60″ HPD
- 2 telescopes,
  130 nested shells
- 80 m^2 surface area
- First focusing x-ray optics > 10 keV order of magnitude more sensitivity than previous missions
- **Thermally-formed, segmented glass, multilayer-coated mirrors**

Satellite (instrument)	Sensitivity
INTEGRAL (ISGRI)	~0.5 mCrab (20-100 keV) with >Ms exposures
Swift (BAT)	~0.8 mCrab (15-150 keV) with >Ms exposures
NuSTAR	~0.8 μCrab (10-40 keV) in 1 Ms

FA Harrison et al. *Proc SPIE* **7732:7732-0S** (2010)
FA Harrison et al. *Ap J* **770:103** (2013)

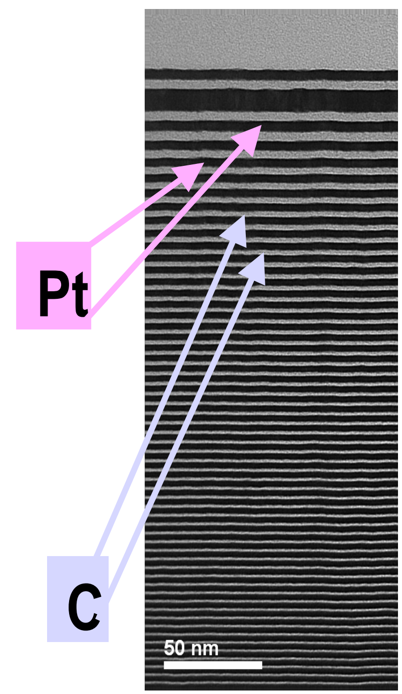
NuSTAR enabling technologies

Thermally-formed glass substrates):

- Good thickness uniformity and excellent surface finish (roughness with σ = few Å)
- Flat pieces of glass slumped directly onto highly polished mandrels and turn into cylindrical shapes
- Excellent figure (10–20″ HPD) has been demonstrated

Depth-graded multilayer coatings optimized for broad-band response)

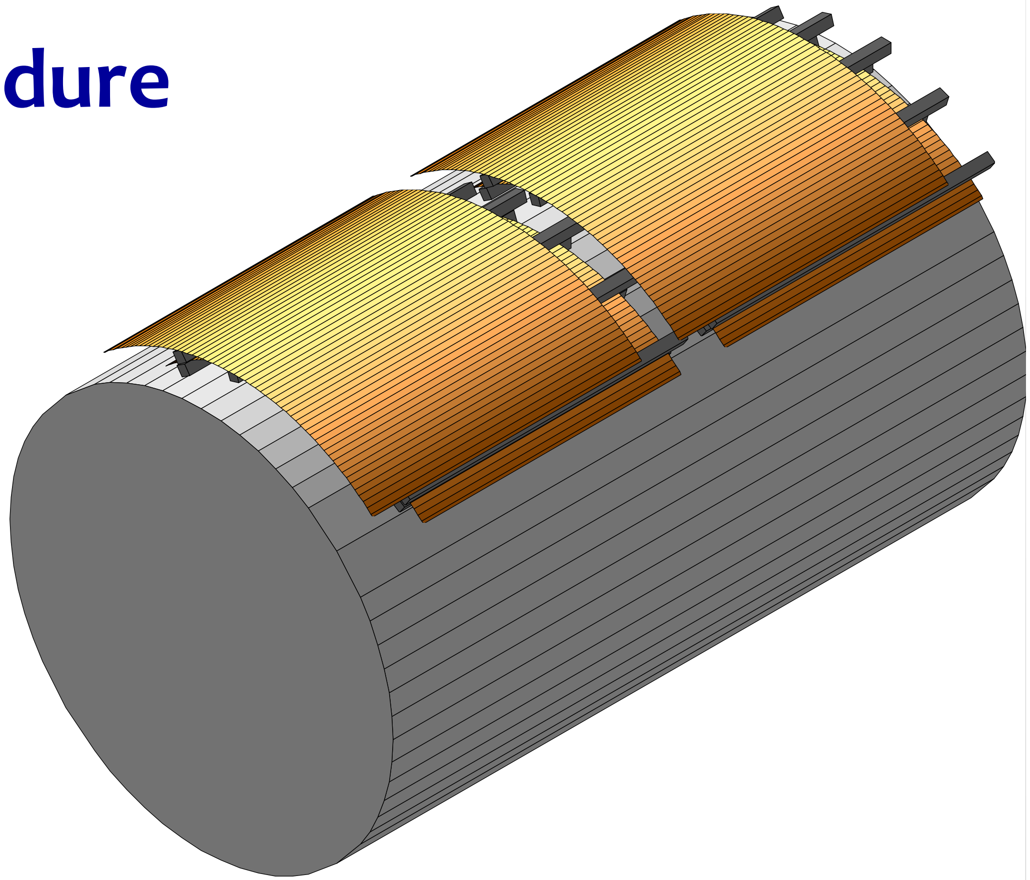
- Pt/C; W/SiC material systems used, driven by need to detect Ti-44 lines at 68 & 78 keV
- X-ray testing to optimize coatings and understand performance
- Extensive metrology to validate models (TEM, roughness,..)
- High throughput magnetron sputtering chamber



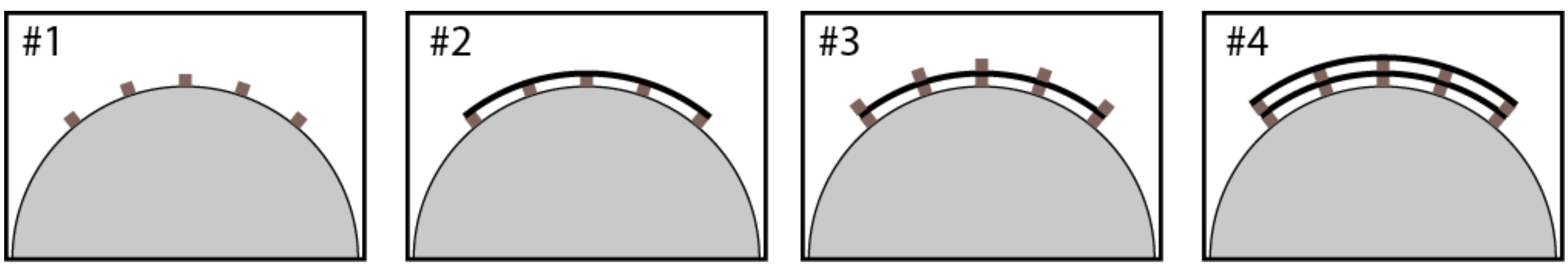
Team includes: Columbia U., DTU-Space, NASA GSFC, LLNL

Optics assembly procedure

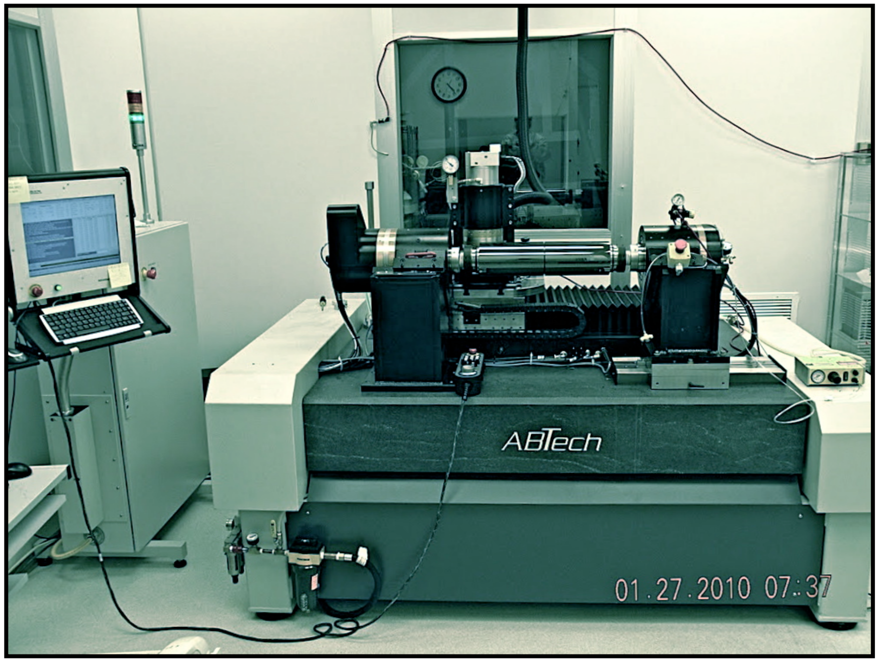
- Epoxy graphite spacers onto a mandrel and machined to the correct radius & angle (#1)
- Epoxy ML-coated substrates to spacers (#2)
- After epoxy cures, epoxy next layer of spacers to previous layer of glass (#3)
- Machine these spacers, epoxy another layer of glass into place (#4)



*JE Koglin et al. Proc. SPIE, **4851:607** (2003)*



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

JE Koglin et al. Proc. SPIE ***8147:8147-0J*** (2011)
WW Craig et al. Proc. SPIE ***8147:8147-0H*** (2011)

Glass is positioned and clamped for overnight cure of epoxy

Flight optic with more than 100 layers

γ-RAY OPTICS FOR SATELLITE MISSIONS

What will it take to move to ~0.5 MeV (and beyond) ?

- Knowledge of material system
- Knowledge of sputtering system(s)
- Knowledge of substrates
- Knowledge of experimental facilities

- Suggested approach when building the telescopes
  - Exhaustive testing at lower energies → build model of reflective optics response
  - Comprehensive particle-physics modeling of entire optics structure in particle transport code (MCNP or GEANT)
  - Selective testing at highest energies → verify model of optics reflectivity and off-diagonal terms from inelastic scattering in structure

Several motivations for gamma-ray telescopes

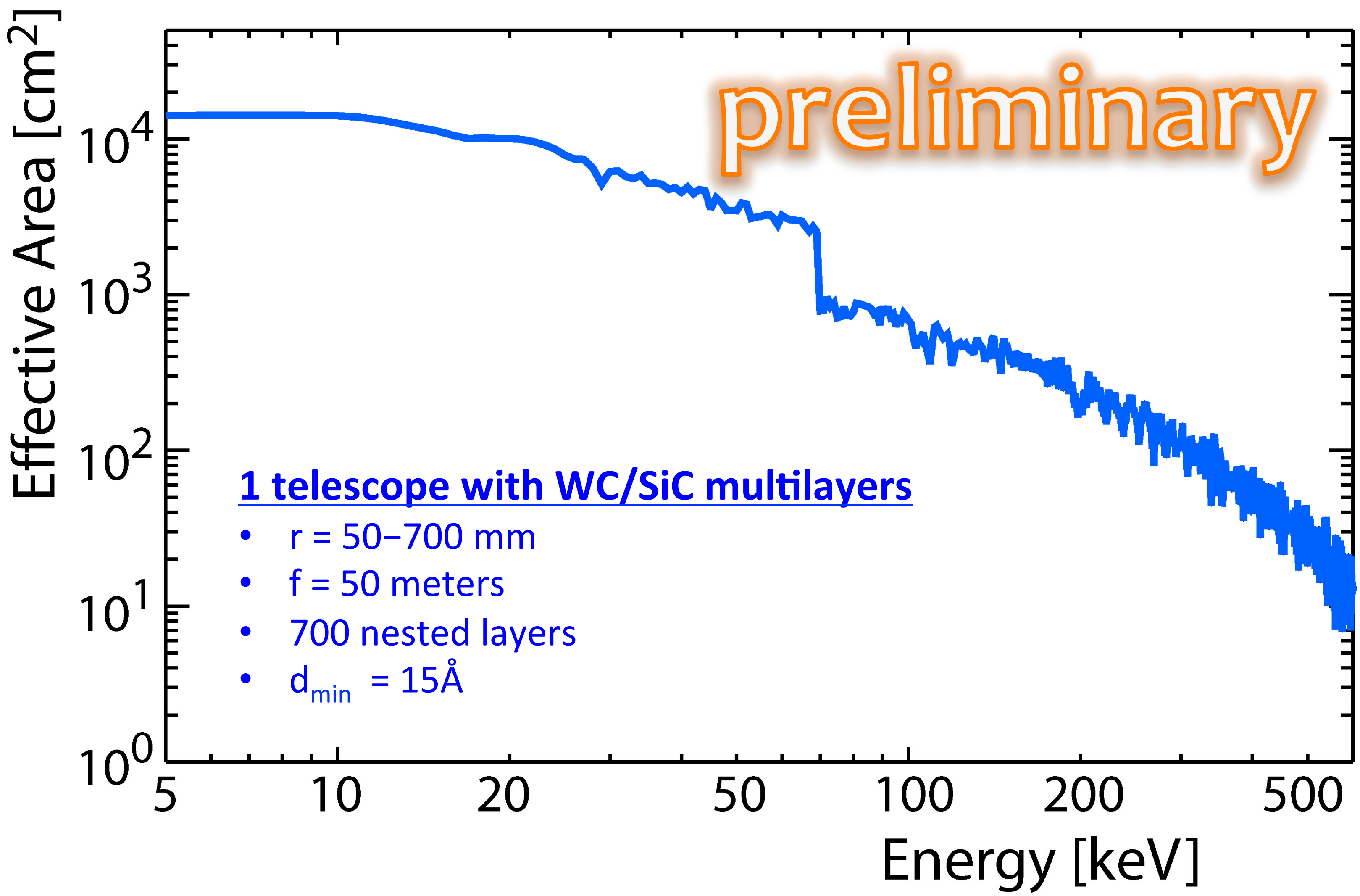
- Sub-disciplines include
  - Traditional astrophysics
    - Galactic and extra-galactic sources
    - Line emitters and broad-band
  - Dark matter
  - Cosmic ray studies
- An imager optimized to image 511 keV emission in the Galaxy could simultaneously address important questions in multiple fields

Required improvements in capability (partial list)

Capability	NuSTAR	Other developments	Future mission
Deployable mast [Length, accuracy]	10 meters, 1-3 mm accuracy	SRTM: 60 meters, 15 cm accuracy	50 meters, 5-10 mm accuracy
Multilayers: d_{min}	25 Å	LLNL: 15 Å	10 Å
Multilayers: recipe	Power-law	Nagoya: Aperiodic	Aperiodic
Multilayers: thickness control on square meters of substrates	5-30%	LLNL: VLOC < 1%	< 2%
Highly nested optics	133 layers	------	600-1000 layers
PSF, segmented glass [core,HPD]	Core: 25 arcsec HPD: 60 arcsec	GSFC: Core: 5 arcsec HPD: 10 arcsec	Core: 10 arcsec HPD: 15 arcsec

This list focuses on telescope issues: significant system engineering remains!

One possibility: broad-band 5 keV to 500 keV mission



D. Della Monica Ferreira et al. Proc. SPIE ***8861:8861-16*** (2013)

Another possibility: annihilation line imager

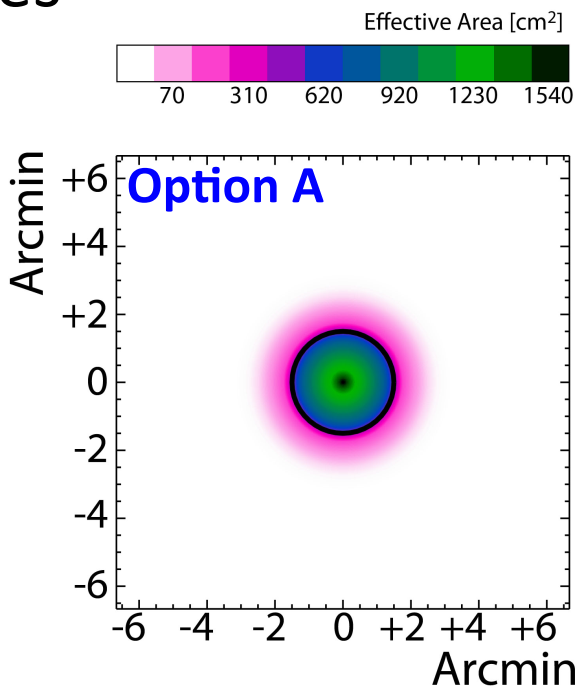
- Optimize multilayer designs to obtain spectral response around 511 ± 50 keV

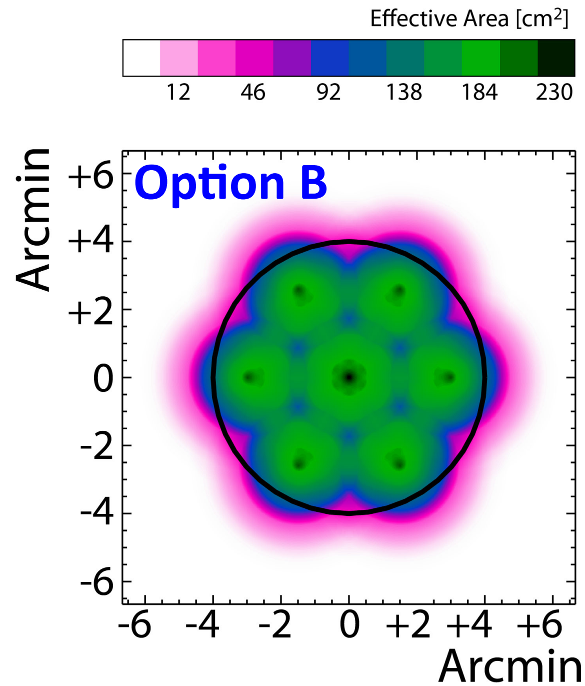
7 telescopes, WC/SiC multilayers

- r = 50–500 mm 495 nested layers
- d_{min} = 10Å f = 35 meters

- Build seven telescopes

- Option A
  - Co-align all optics
  - Maximum area, ideal for point sources
  - 3 arcmin FOV (where Eff.Area drops to 50% of max)
- Option B
  - Cant optical axis of each telescope by 4 arcmin
  - Ideal for surveys
  - 8 arcmin FOV (same definition as above)





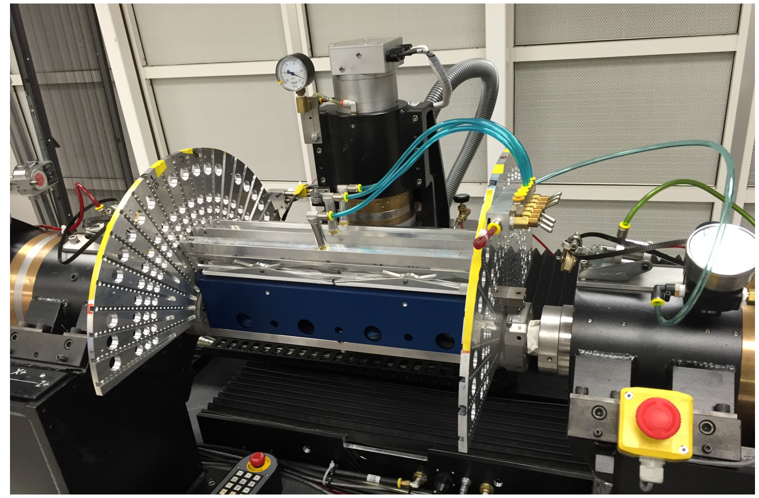
preliminary

On-going research

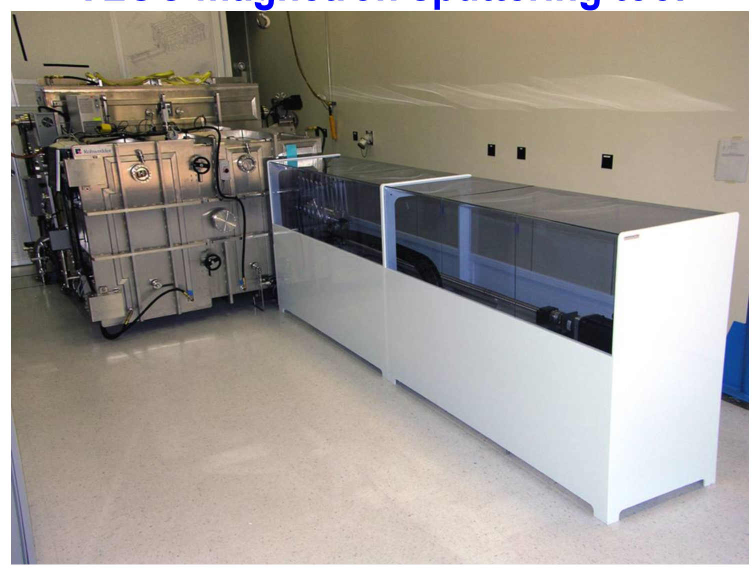
- Using a NuSTAR assembly machine to make optics at LLNL
  - Just completed first 90-140 keV optic for non-proliferation
  - Used to make an optic for the CERN Axion Solar Telescope (CAST)
- Studying use of our large deposition tool (1.5×1.5 m^2) to coat scores of substrates simultaneously

All techniques will help us build prototype γ-ray focusing optics

Very-hard x-ray optic, completed Feb'16



VLOC magnetron sputtering tool



Conclusions

- We have demonstrated that multilayer-coated optics can work well above 0.5 MeV
  - We have developed an approach that uses low-energy calibration to accurately predict high-energy performance
  - Building *E* > 100 keV prototypes right now for non-proliferation
- Although there are risks and challenges, we can consider true focusing optics for future soft γ-ray missions
  - Multilayers can be tuned to achieve broad-band response or maximum sensitivity near lines of interest
- We can begin serious design efforts/trades **now** … provided we have sound scientific goals on which to optimize