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Novel x-ray optics for CAST and astrophysics applications

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The CAST collaboration

3rd Joint ILIAS-CERN-DESY Axion WIMPs Training Workshop, June 22, 2007, University of Patras, Greece

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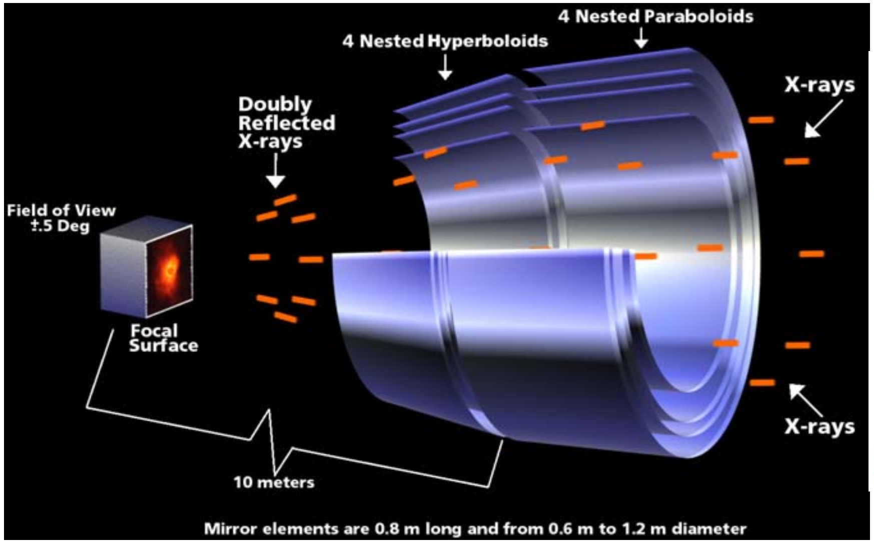
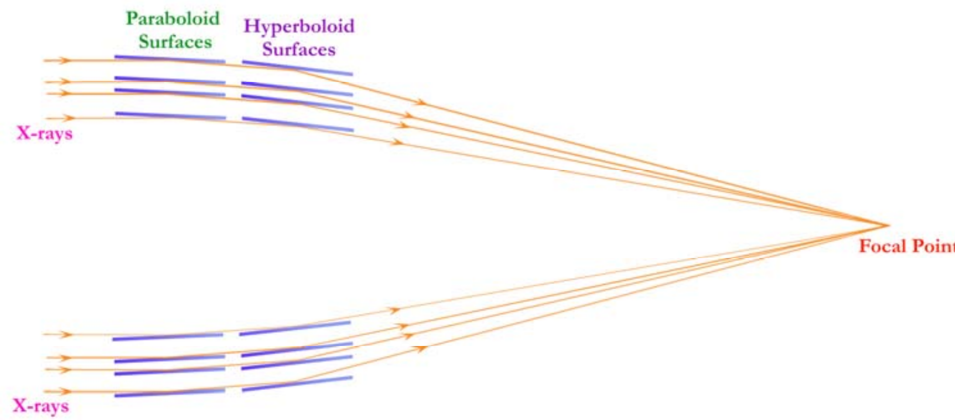
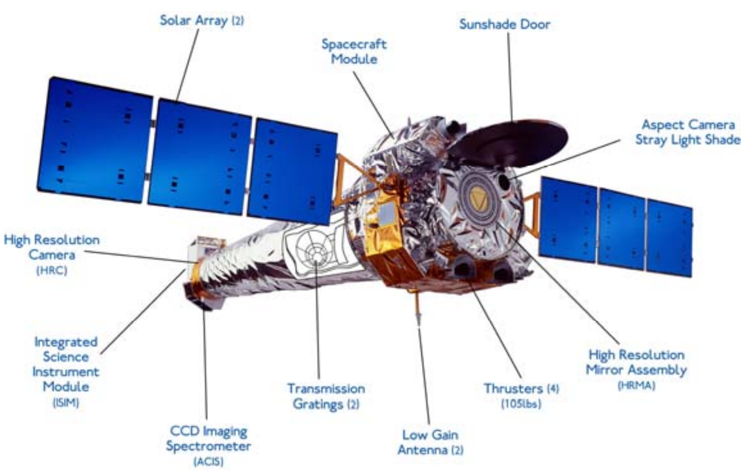
Ultra-high resolution x-ray optics require extremely precise, smooth substrates and reflective thin films







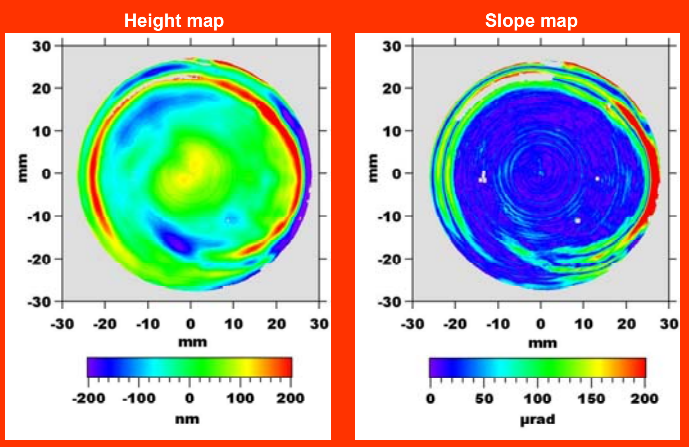
NASA's Chandra X-ray Observatory, High-Resolution Mirror Assembly:

- 0.08 eV – 10 keV, eff. area = 400 cm^2 @ 1 keV
- Wolter I design, 0.5 arcsec resolution
- Zerodur substrates
- 300 Å Ir reflective coatings with a 50 Å Cr binding layer

D. E. Graessle, R. Soufli, A. J. Nelson, C. L. Evans, A. L. Aquila, E. M. Gullikson, R. L. Blake, A. J. Burek, SPIE 5538, 72-83 (2004).

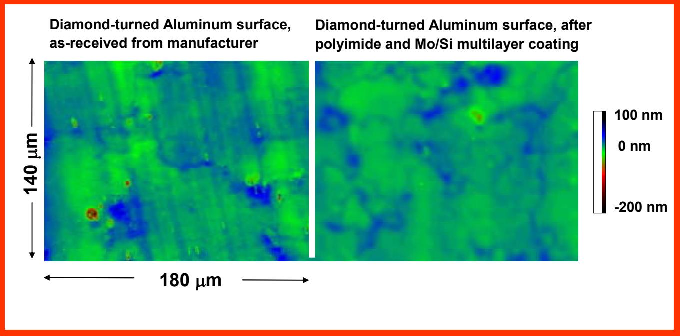
The main challenge is to demonstrate and maintain the required optical surface quality in the figure, mid- and high- spatial frequencies

Visible light interferometry results from multilayer-coated, diamond-turned condenser mirror

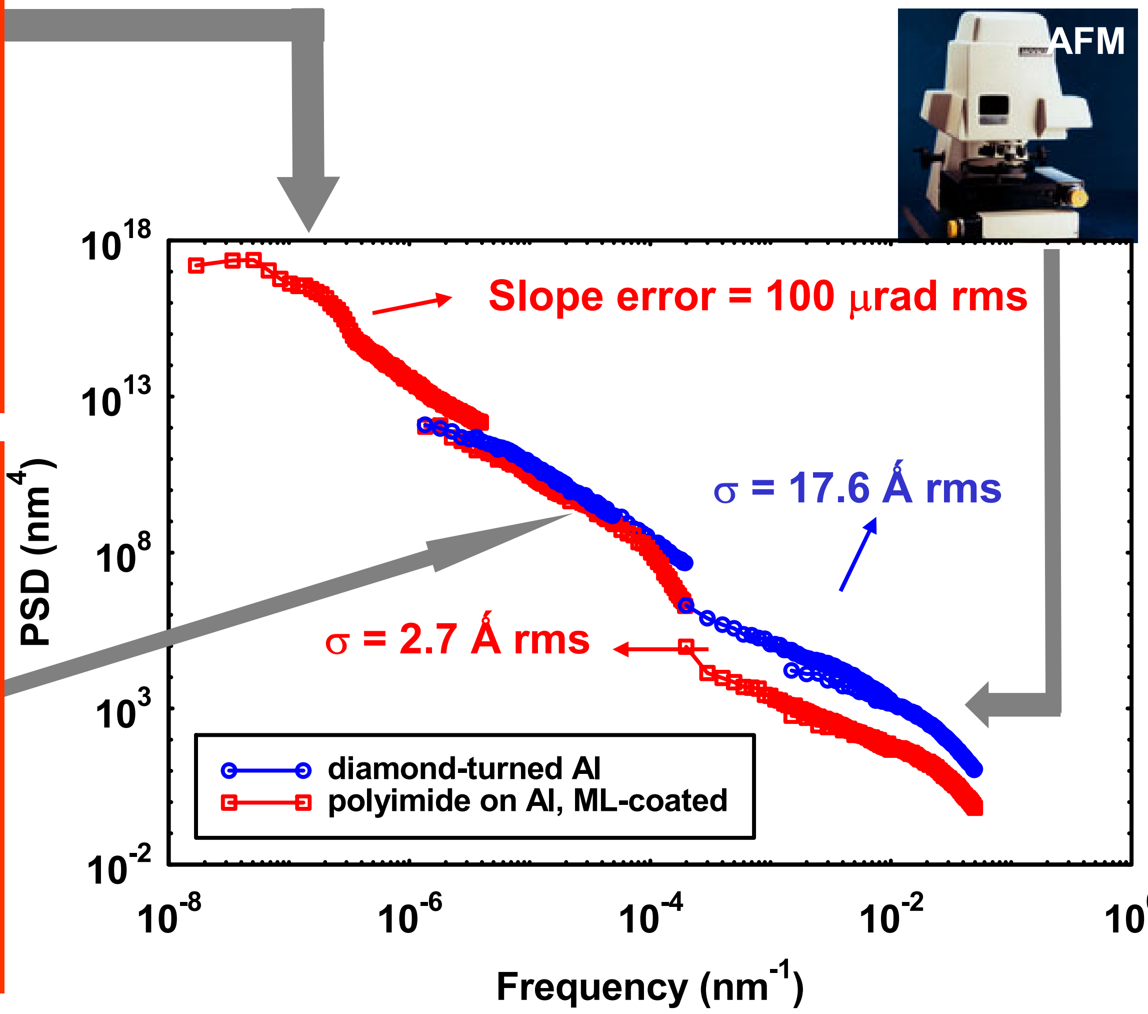


R. Soufli, E. Spiller, M. A. Schmidt, J. C. Robinson, S. L. Baker, S. Ratti, M. A. Johnson, E. M. Gullikson, Opt. Eng. 43(12), 3089-3095 (2004).

Polyimide smoothes high spatial frequency roughness, including 10 µm-range diamond turning marks



Measurements obtained with a Zygo New View™ optical profiling microscope operated at 40× objective lens magnification



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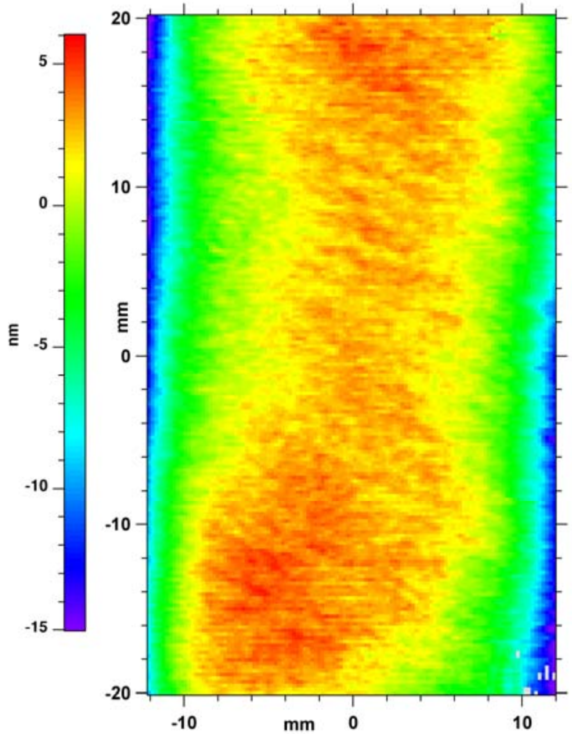
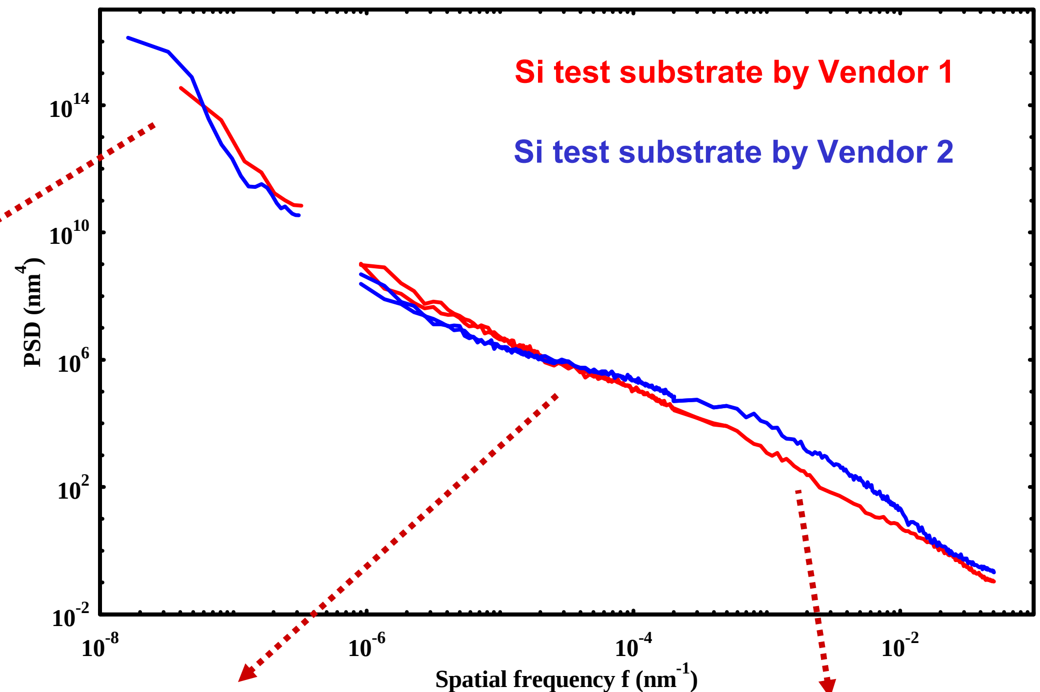
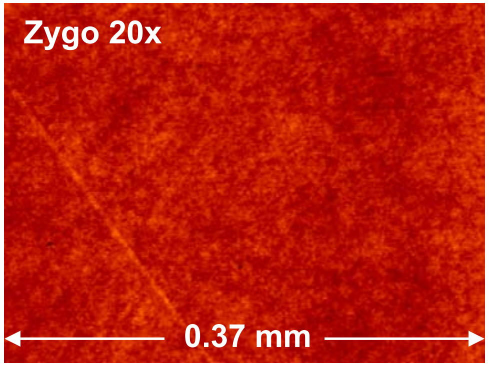
Physics / performance requirements determine the specifications in each spatial frequency range

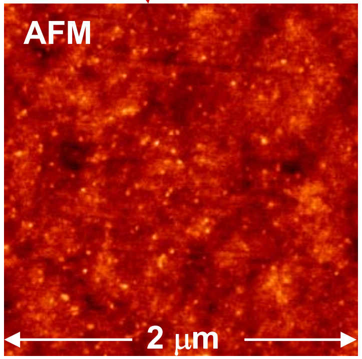
Precision surface metrology at LLNL on candidate Si substrates for the x-ray optics beamline at the LCLS free-electron laser

Full-aperture interferometry





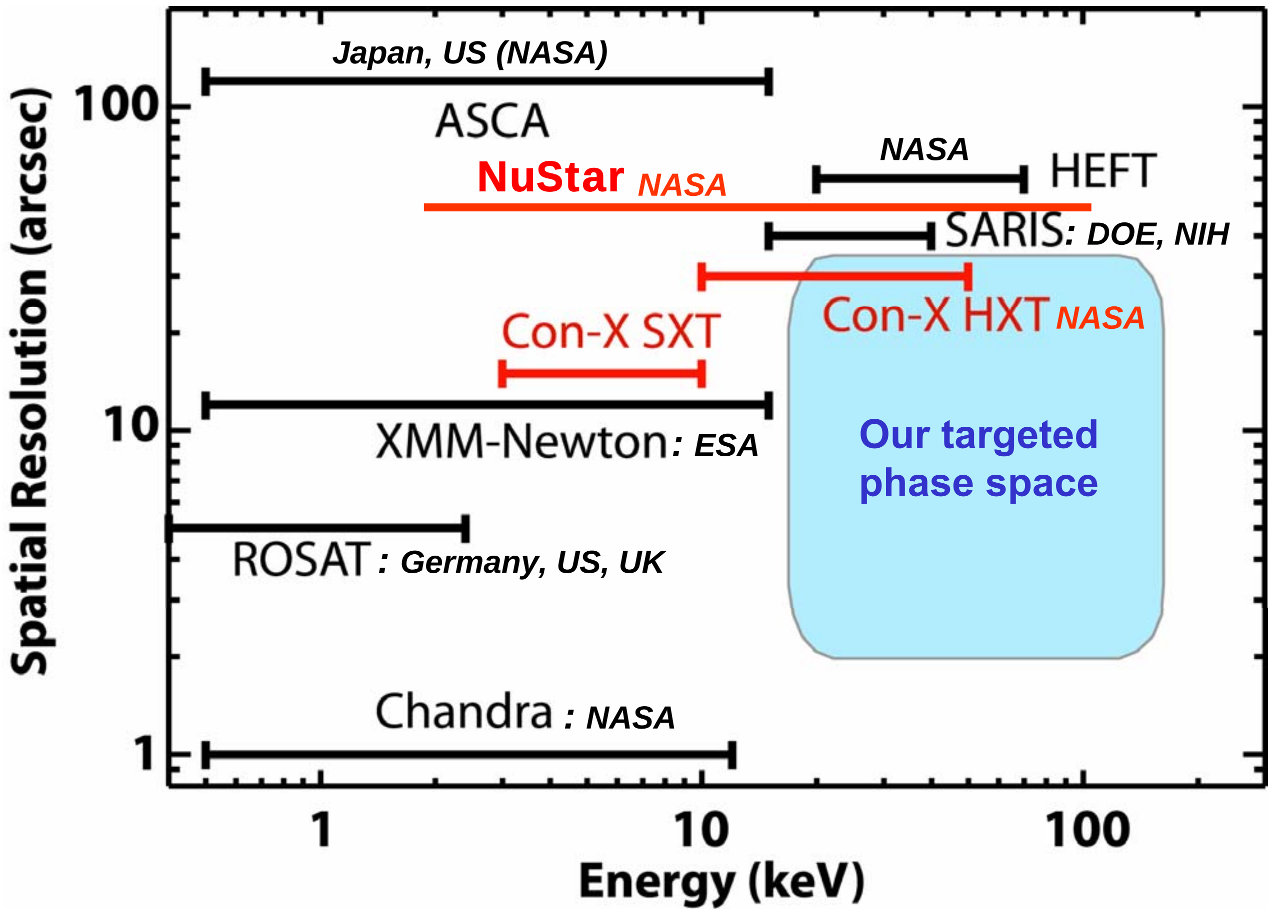




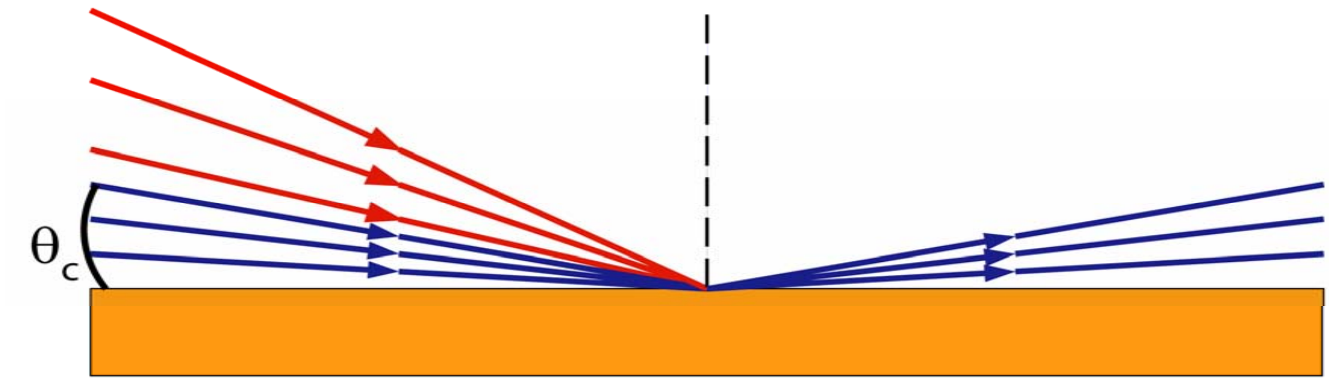
Acknowledgement:
Michael A. Johnson
(LLNL)

Our group at LLNL has been developing next generation x-ray optics for plasma physics, astronomy and medical applications

Resolution vs. energy comparison of high-efficiency reflective X-ray systems

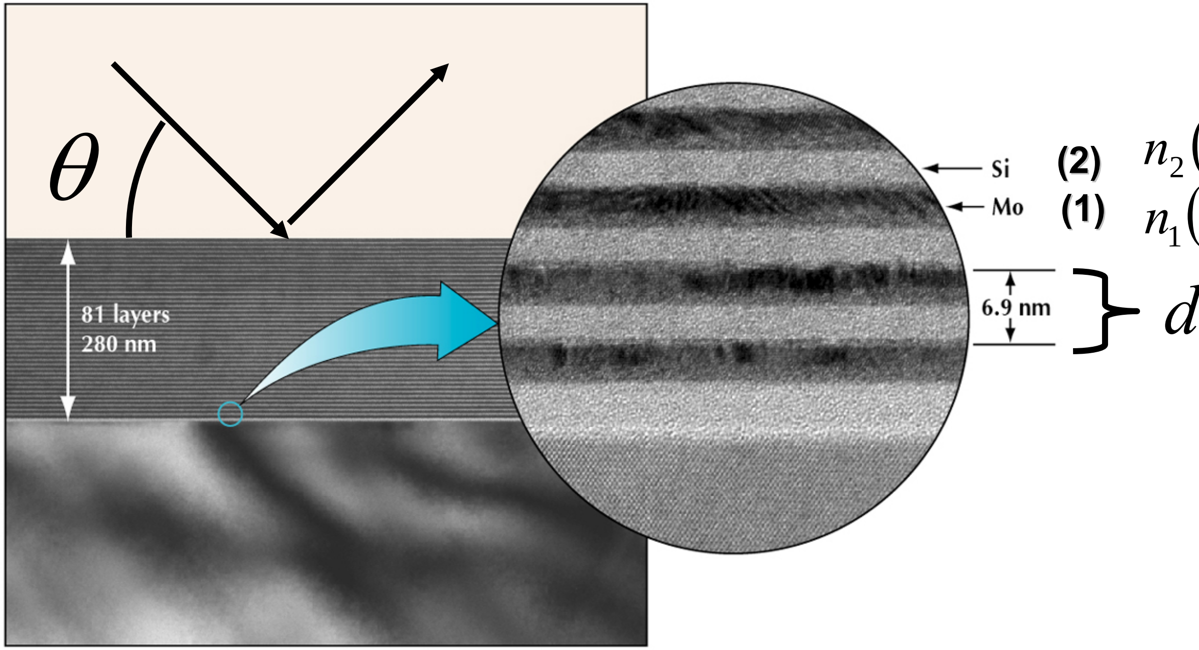


Hard x-ray mirrors: the need for reflective multilayer coatings



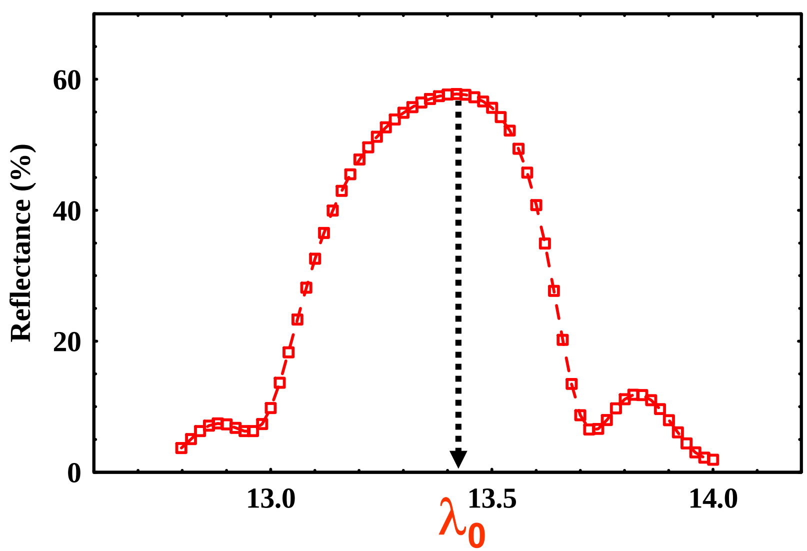
- Index of refraction for high-energy photons is given by
  $n = 1 - \delta + i\beta$.
- Total external reflection of light occurs when the incident angle is less than the critical angle $\theta = \sqrt{2\delta}$
- Critical angle drops rapidly with energy $\theta_c \sim E^{-2}$.
- Incredibly difficult to achieve significant effective area above 10 keV with single layers of any material.
- Instead, rely on multilayers to achieve high-reflectivity beyond θ_c.

Multilayer interference coatings



(2) $n_2(\lambda) = 1 - \delta_2(\lambda) + i\beta_2(\lambda)$

(1) $n_1(\lambda) = 1 - \delta_1(\lambda) + i\beta_1(\lambda)$



Bragg equation for multilayers:

$$m\lambda_0 = 2d\sin\theta\sqrt{1 - \frac{2\bar{\delta}}{\sin^2\theta}}$$

$m = 1, \theta \to 90°$ **(near-normal incidence)**

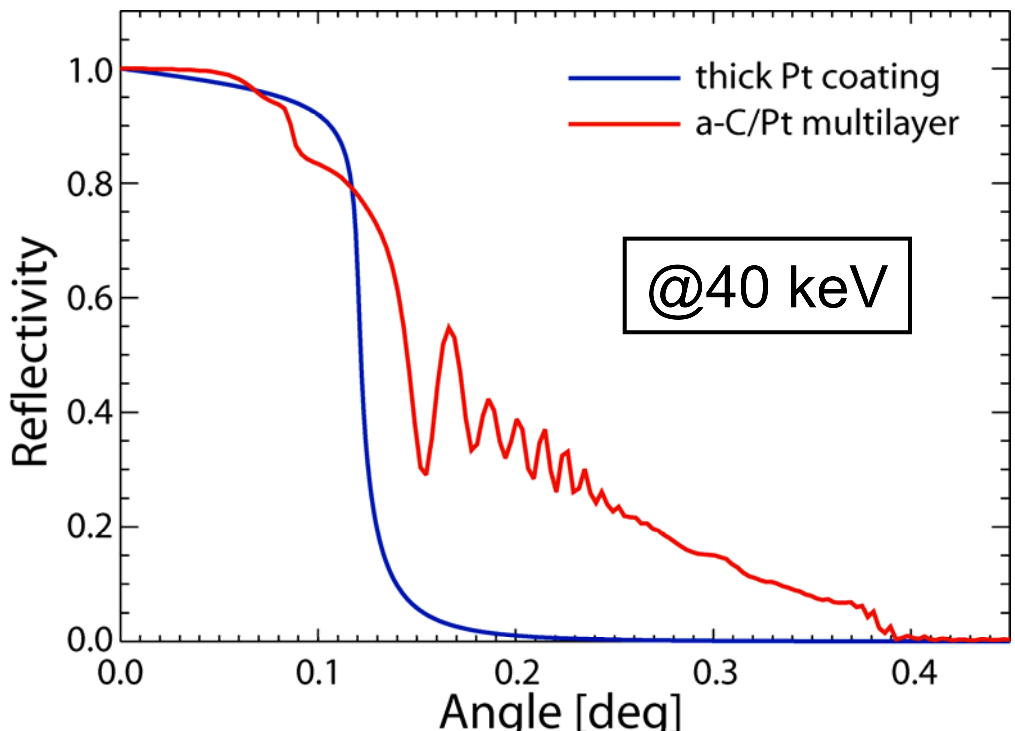
$$\lambda_0 \approx 2d$$

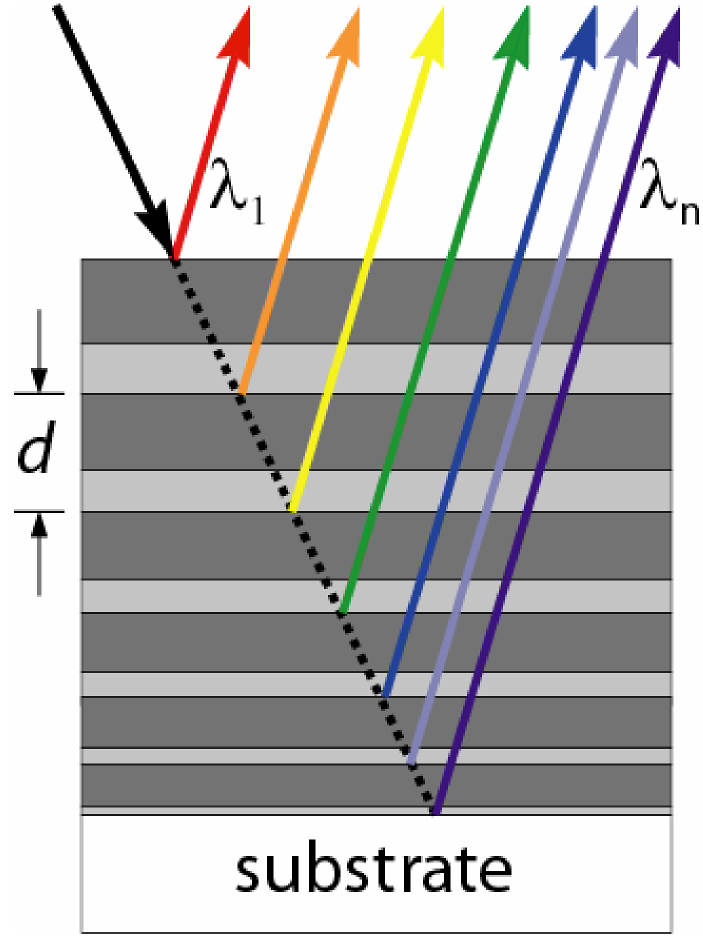
Depth-graded multilayers at grazing incidence greatly extend the efficiency / energy range of hard x-ray optics

- **Bragg's law:** $m\lambda = 2d \sin\theta$

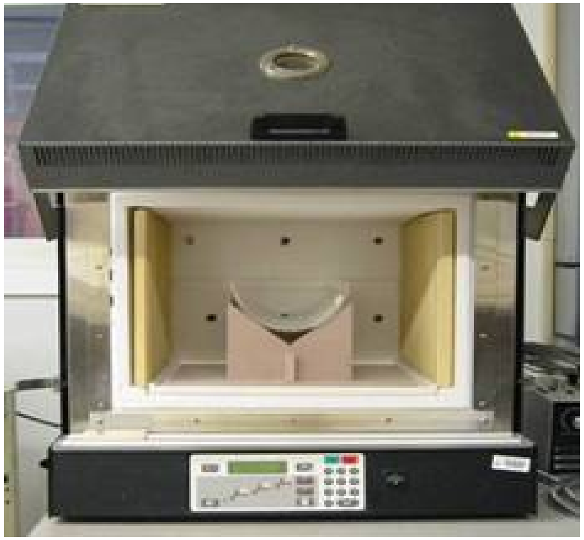
  $$m\Delta\lambda = 2\Delta d \sin\theta$$

- **Allow *d* to vary as a function of depth, satisfying the Bragg equation over a range of λ**





Thermally formed, segmented glass substrates have been developed at LLNL



Slump 0.2mm-thick flat panel display glass in ovens

Coat glass with ~ few hundred layers (2.5-10nm each) of W/SiC, Pt/SiC to extend energy band

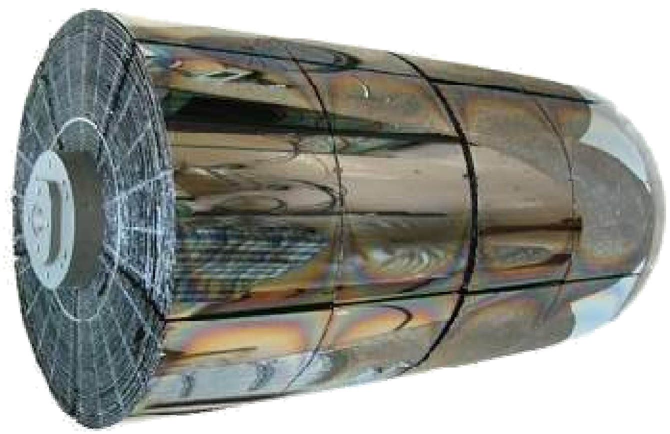
Segmented glass substrate approach is:

- Inexpensive
- Has convenient geometry for reflective coating
- Demonstrated 2–4 Å high-spatial frequency roughness, ~60 arcsec figure

Acknowledgements: Caltech University, Columbia University, DNSC

Thermally formed, segmented glass substrates have been implemented successfully in the HEFT hard x-ray telescope

Assemble the glass into an optic using graphite and epoxy.



A completed HEFT optic with 72 layers made up from 1440 individual mirrors (20-70 keV)

• W. W. Craig et al, "Development of thermally formed glass optics for astronomical hard X-ray telescopes," *Opt Express*, 7, 178-185, (2000).

• J. E. Koglin; C. M. H. Chen; J. C. Chonko, F. E. Christensen, W. W. Craig, T. R. Decker, C. J. Hailey, F. A. Harrison, C. P. Jensen, K. K. Madsen, M. J. Pivovaroff, M. Stern, D. L. Windt, E. Ziegler, "Hard x-ray optics: from HEFT to NuSTAR", SPIE 5488, 856-867 (2004).

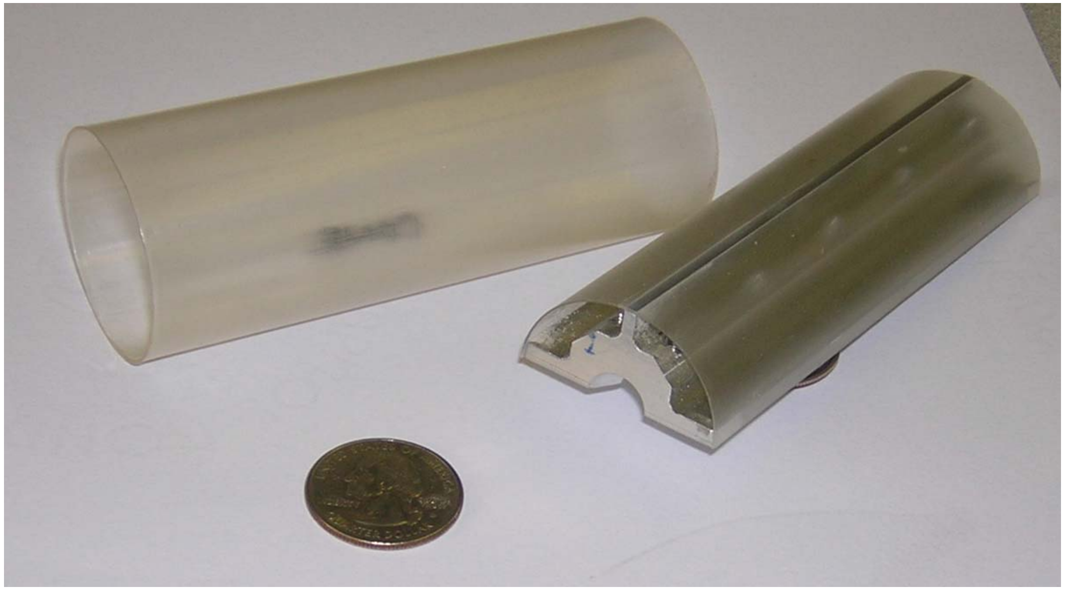
Acknowledgements: Caltech University, Columbia University, DNSC

Thermally formed, full-revolution polycarbonate substrates have been developed at LLNL

Polycarbonate substrate approach:

• Enables fabrication of x-ray substrates with small radius

• Inexpensive, lightweight, versatile

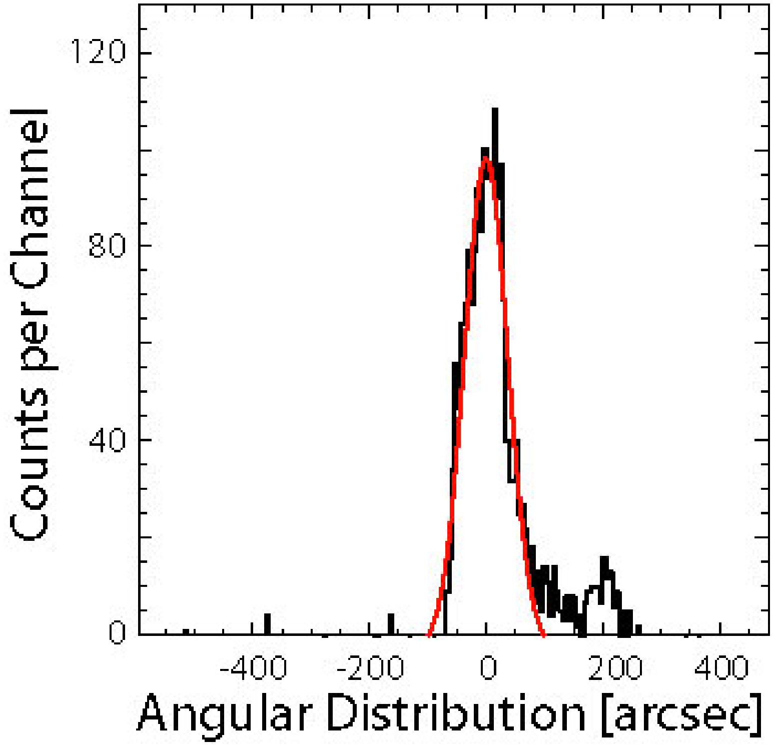


• For soft x-ray applications: Full-revolution shells (Combined with appropriate reflective coating process) greatly ease alignment, allow simple integration into highly-nested system

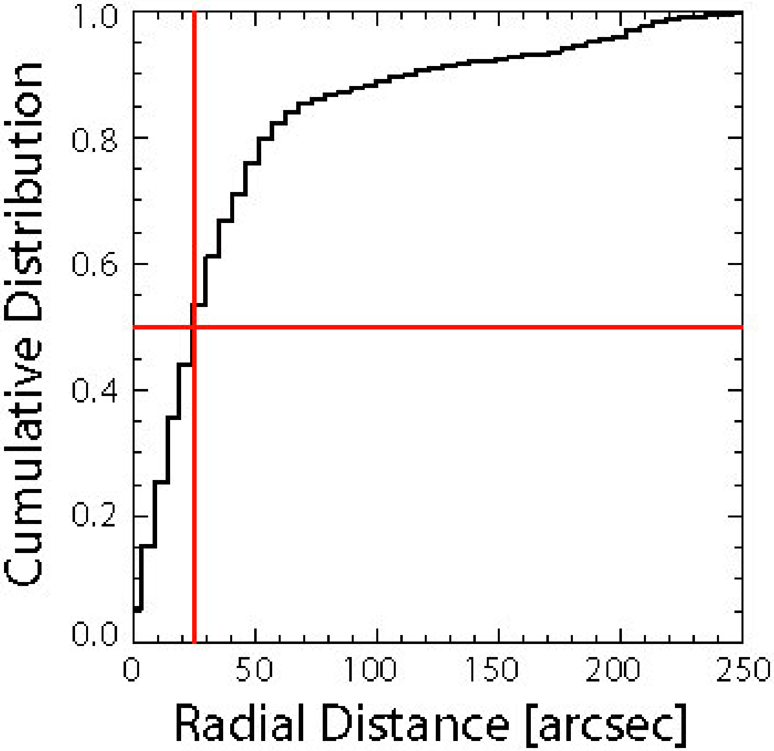
•For hard X-ray applications: Segment shells into smaller pieces for multilayer deposition and integration into optics using established techniques

Polycarbonate integral shells demonstrate 50’’ figure

FHWM: 87″

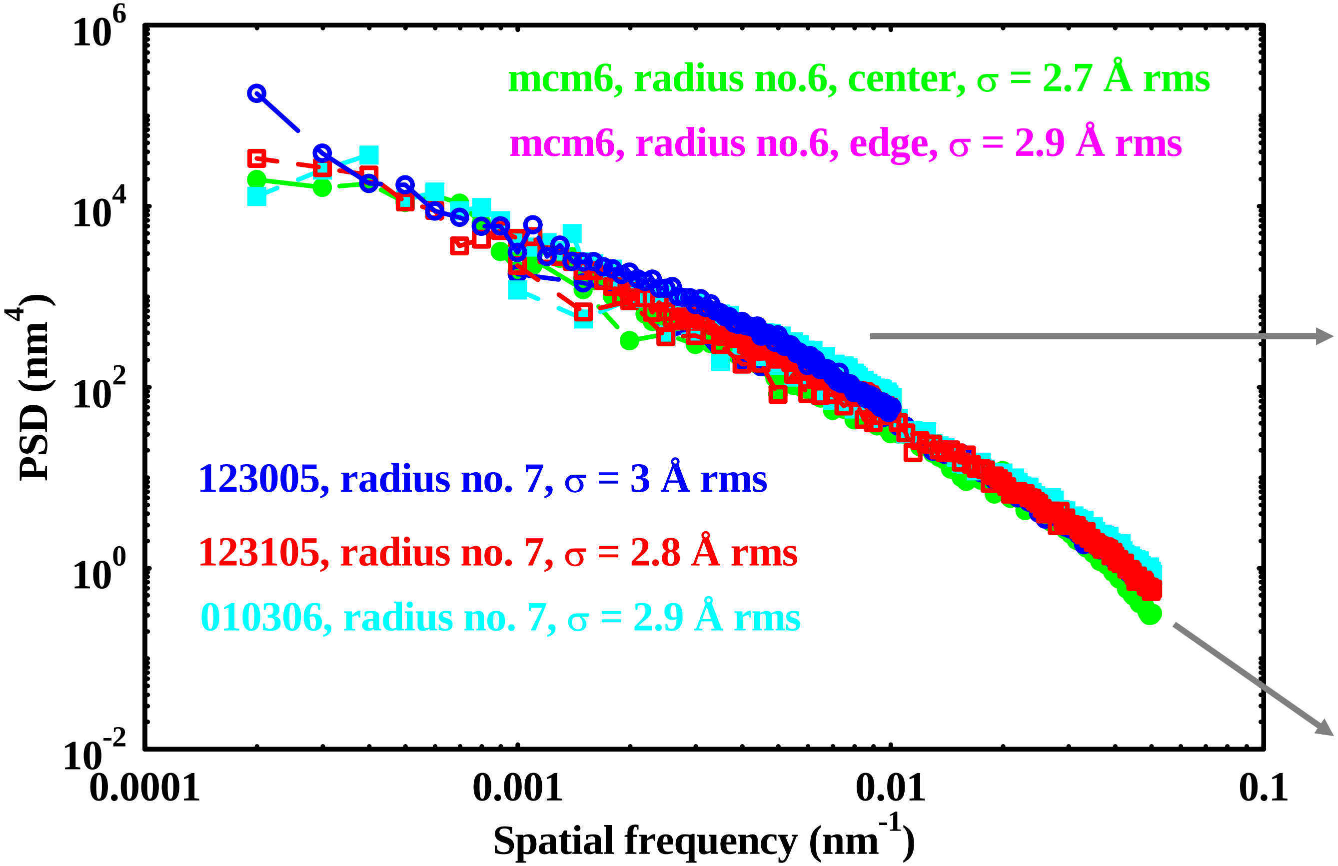


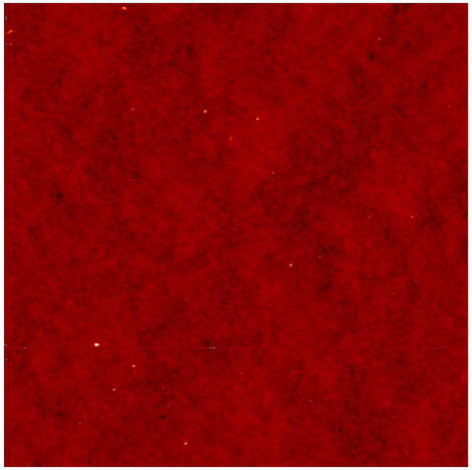
HPD: 50″



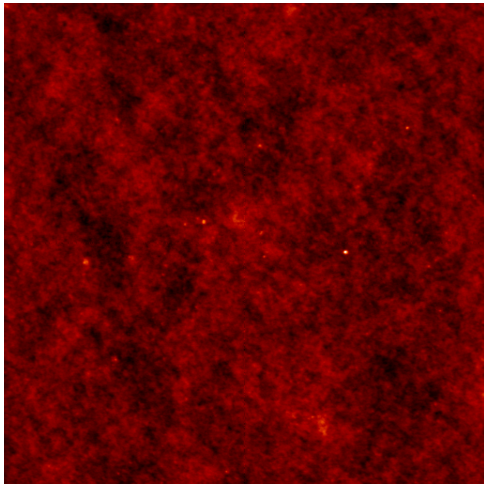
Measurements performed at 8.05 keV (Cu Kα) at DNSC

Polycarbonate substrates demonstrate high-spatial frequency roughness < 3 Å





10×10 μm² AFM image, 123105



2×2 μm² AFM image, 123105

$$\sigma^2 = \int_{f_1}^{f_2} 2\pi f S(f) df$$

where S(f) ≡ PSD (nm^4), f_1 = 10^{-3} nm^{-1}, f_2 = 5×10^{-2} nm^{-1}

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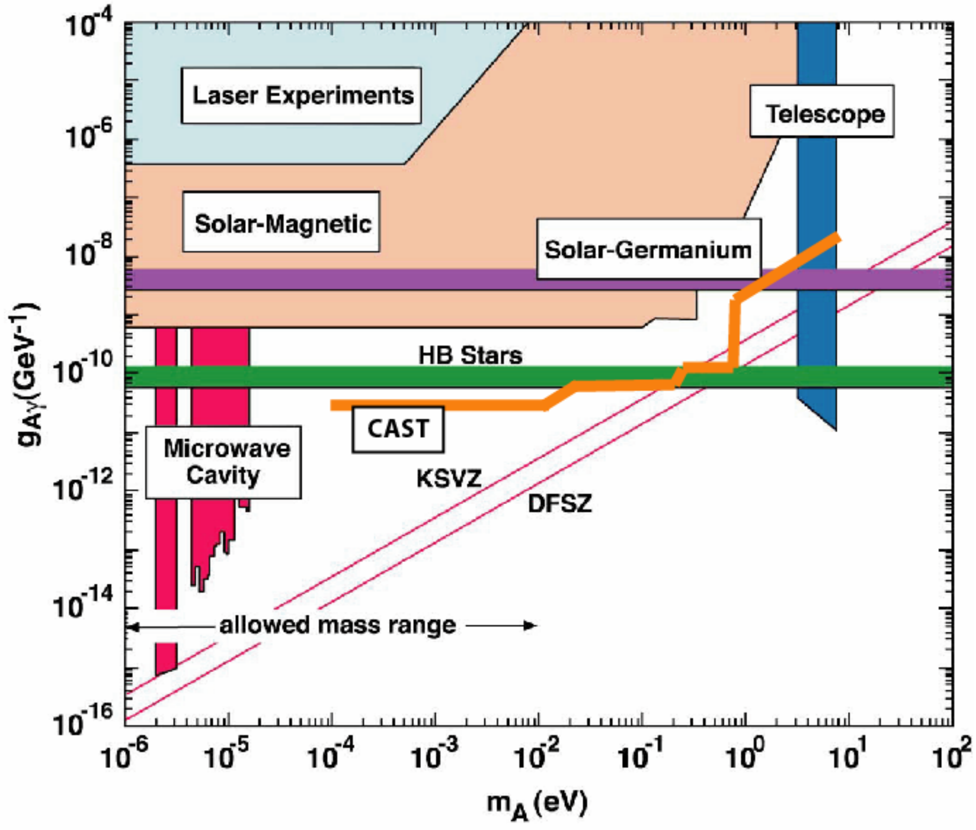
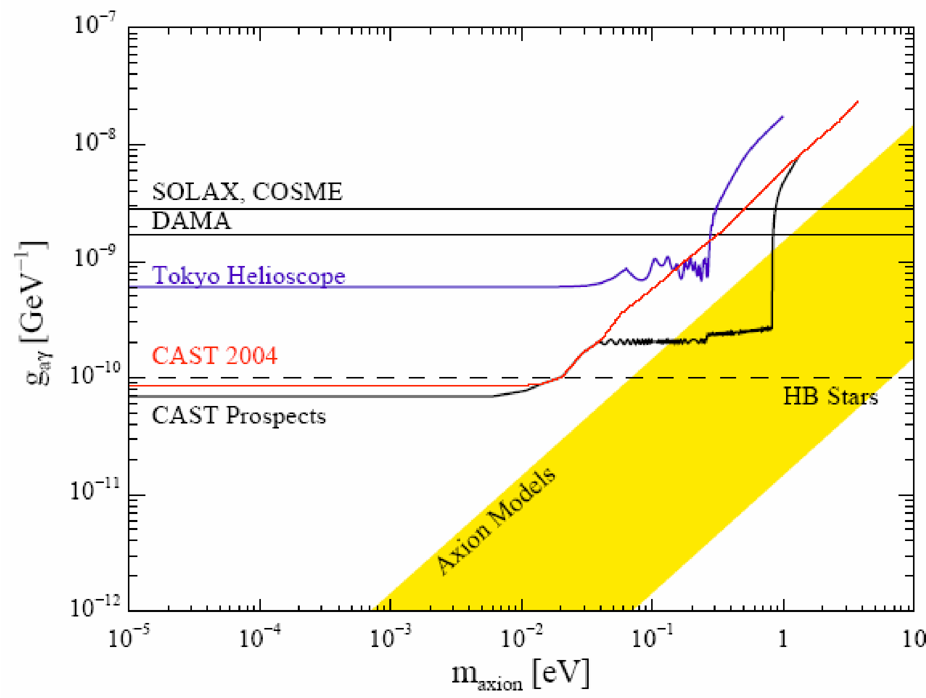
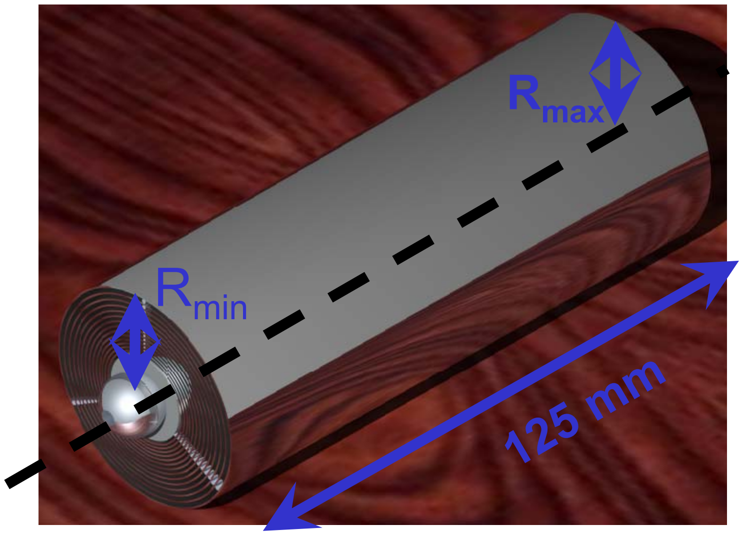
An x-ray collimator can improve the sensitivity of the CAST experiment

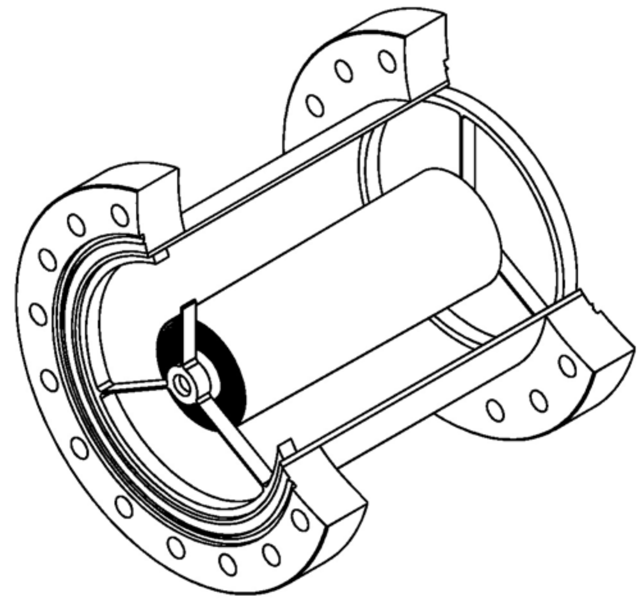


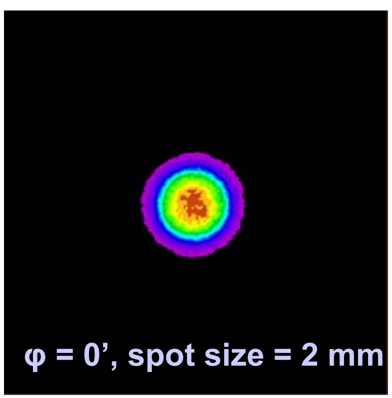
LLNL optic improves sensitivity to $g_{\alpha\gamma\gamma}$ by factor of 2



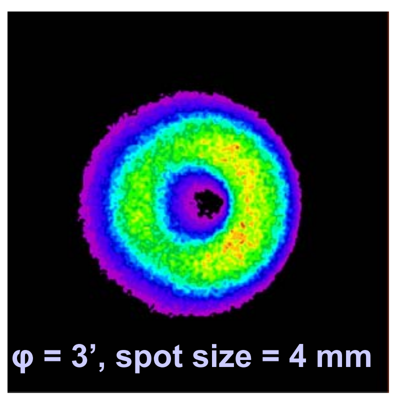
Design of LLNL x-ray collimator based on novel polycarbonate substrates for CAST Micromegas detector







φ = 0', spot size = 2 mm



φ = 3', spot size = 4 mm

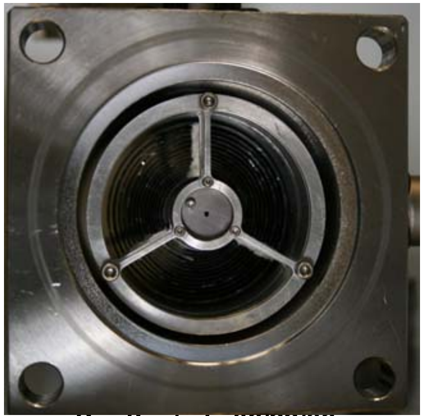
- Conical approximation of Wolter I (no imaging needed, only concentration of x-rays)
- 14 nested shells, each 125 mm long
- θ_i = 0.22°, R_{min} = 9.4 mm, R_{min} = 9.9 mm
- θ_i = 0.53°, R_{min} = 22.3 mm, R_{min} = 23.5 mm
- Each shell interior coated with ~ 300 Å Ir
- Distance from front of optic to detector is 1.3 m
- Outer shell is larger than magnet bore to allow for error in alignment.

Optic completed in August 2006

11 (out of 14) Ir-coated polycarbonate shells in LLNL cleanroom lab, prior to assembly

Assembled optic

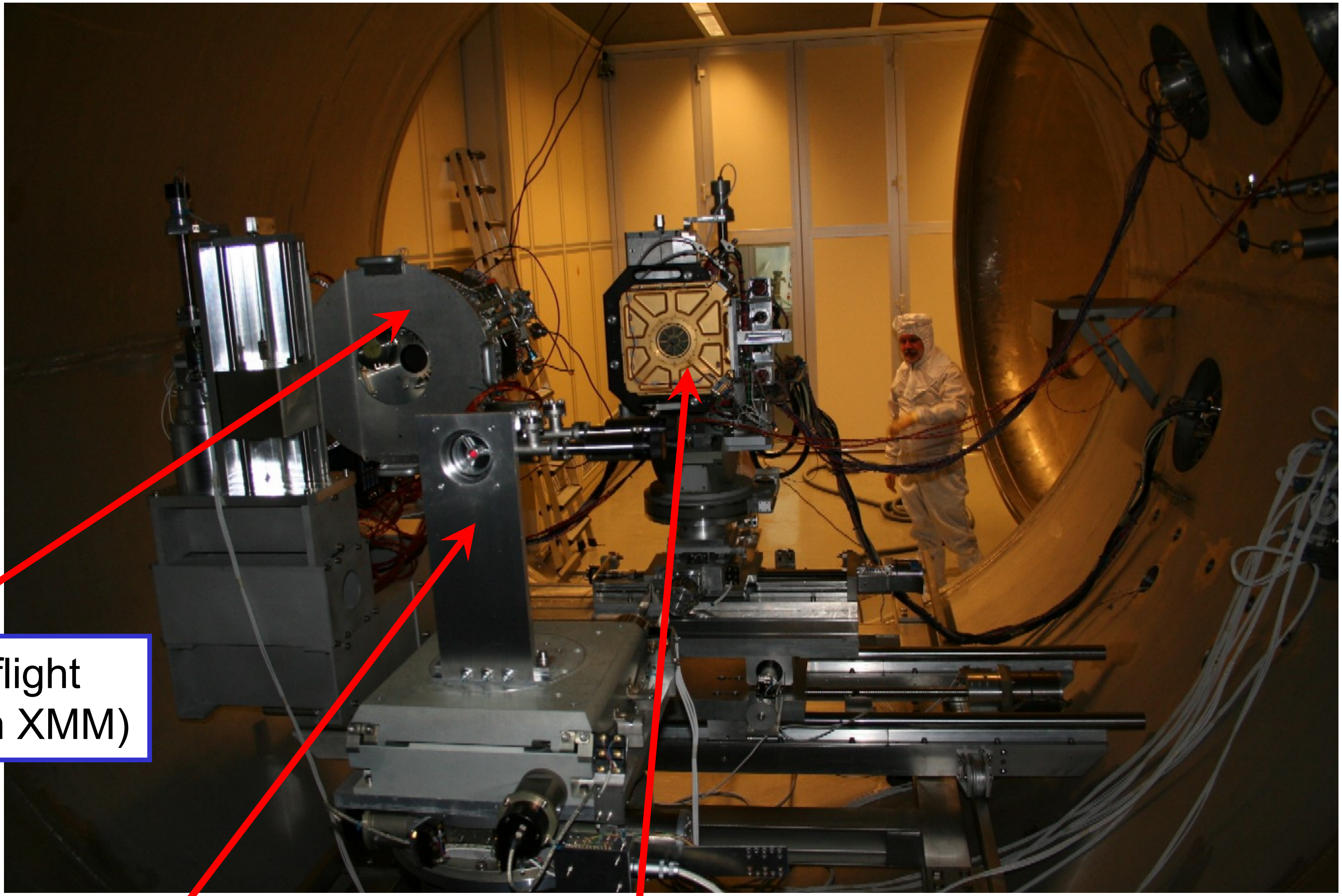
Entrance aperture



Exit aperture

Vacuum pipe with adjustment mechanisms

Optic installed at PANTER



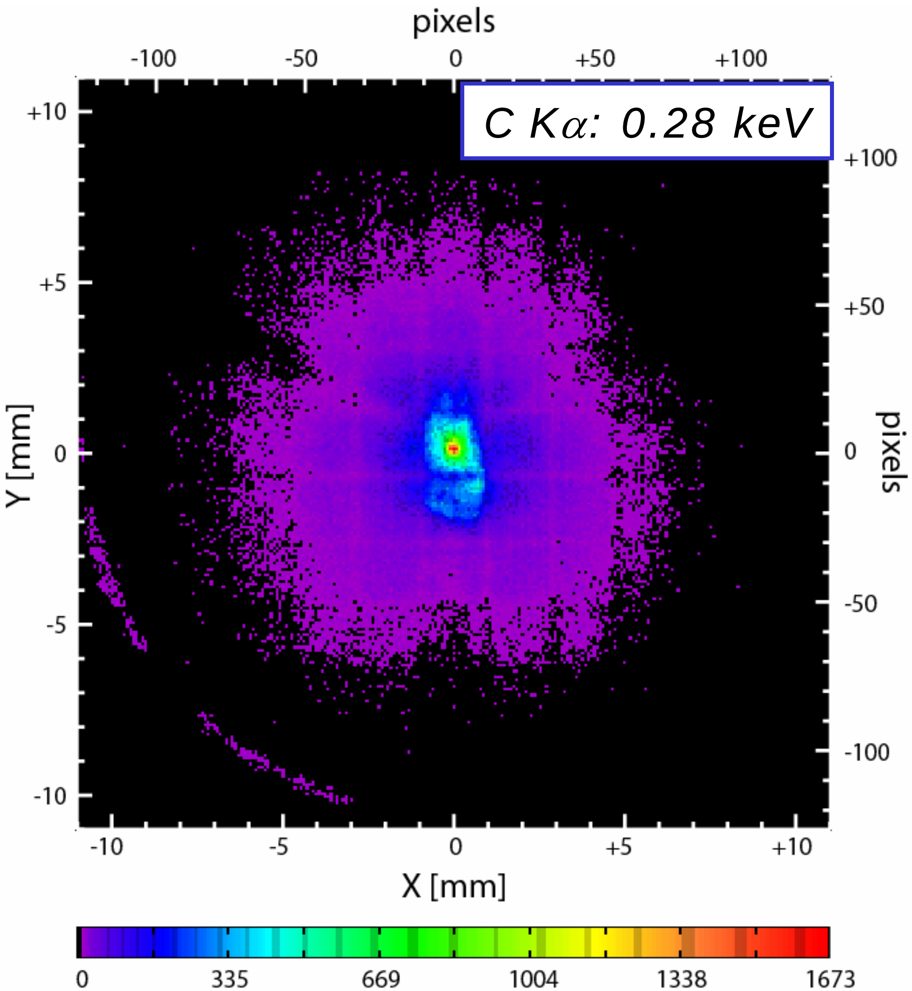
PN CCD (flight spare from XMM)

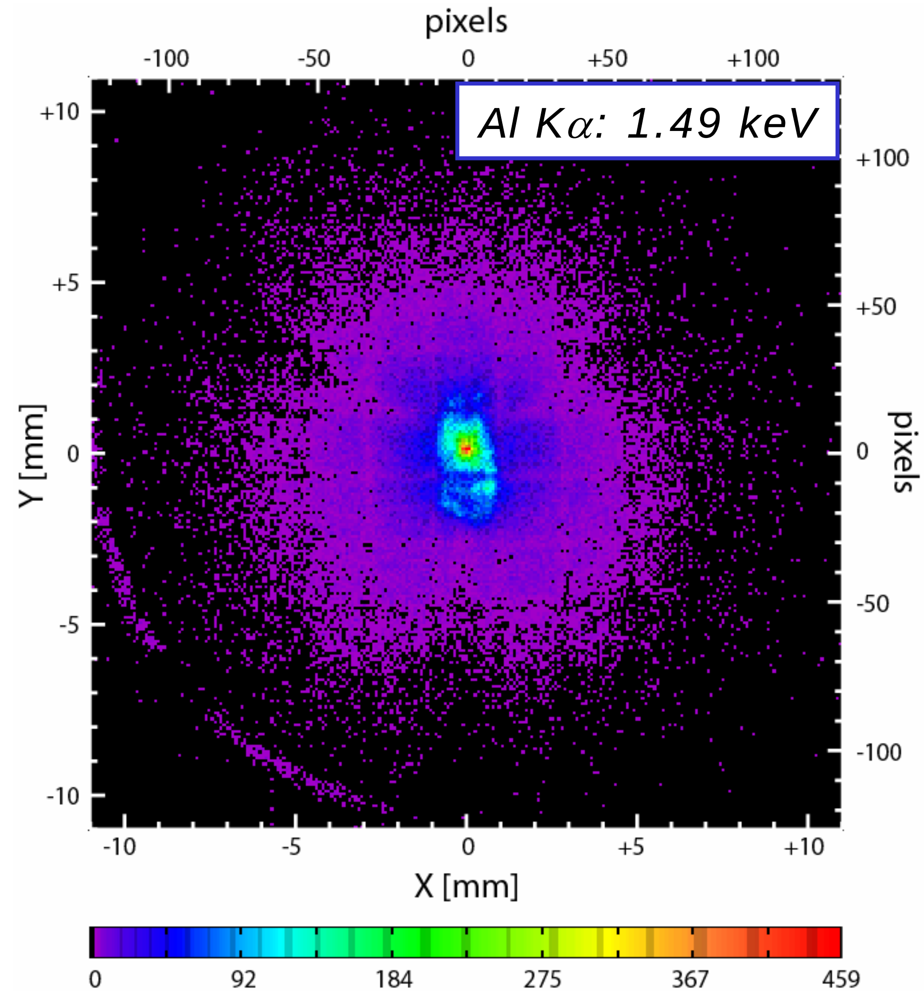
Test stand that holds optic

PSPC gas detector (flight spare from ROSAT)

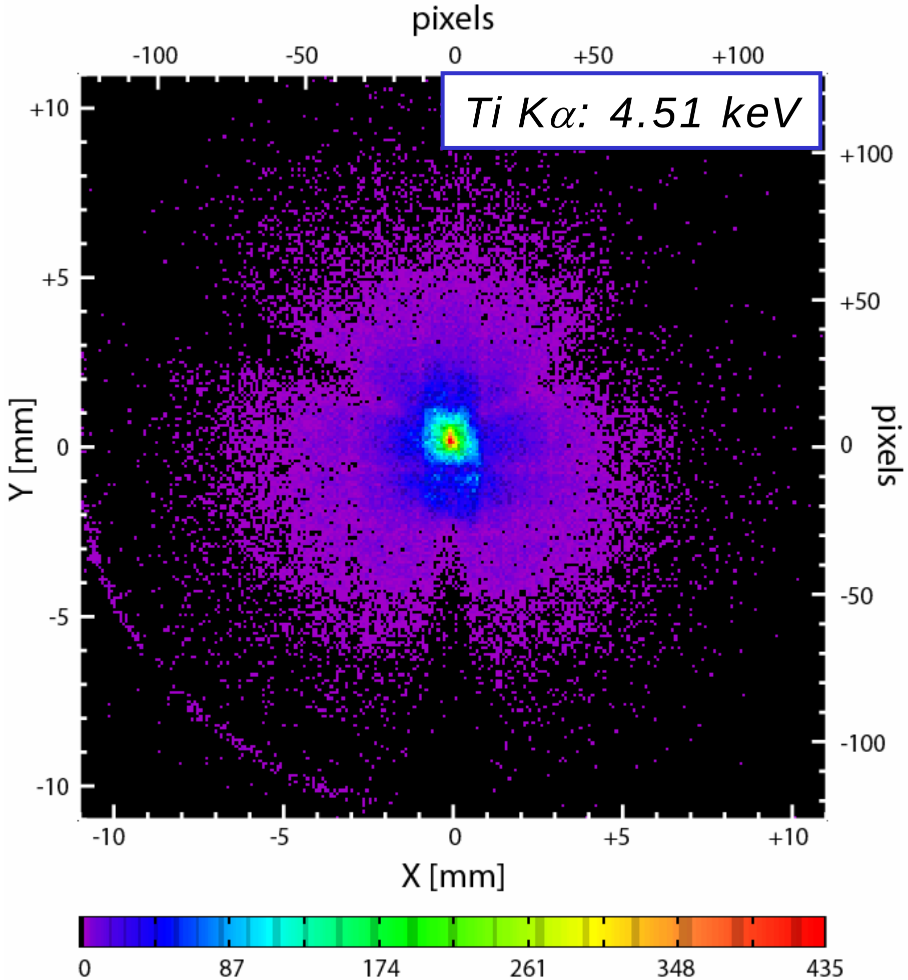
PSF measurements at PANTER (1)

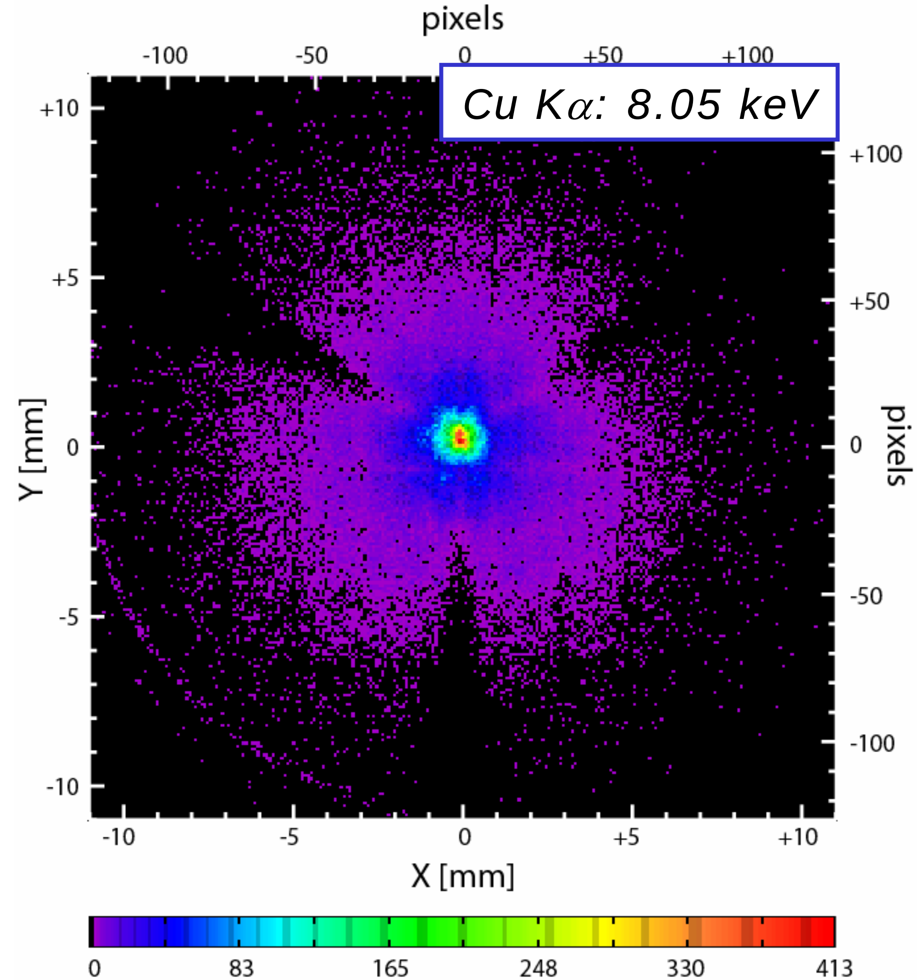
Once we know the optimal position for the focal plane, study PSF at five energies





PSF measurements at PANTER (2)





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PSF analysis

- Scattering more pronounced at higher energies, as expected from theory ($1/\lambda^2$ dependence)
- Core sharpens at higher energies
- Outer shells have low efficiency at higher energies
  - Indicates these shells have different properties that inner portion of optic
  - Consistent with properties inferred from focal length measurements

Encircled energy analysis

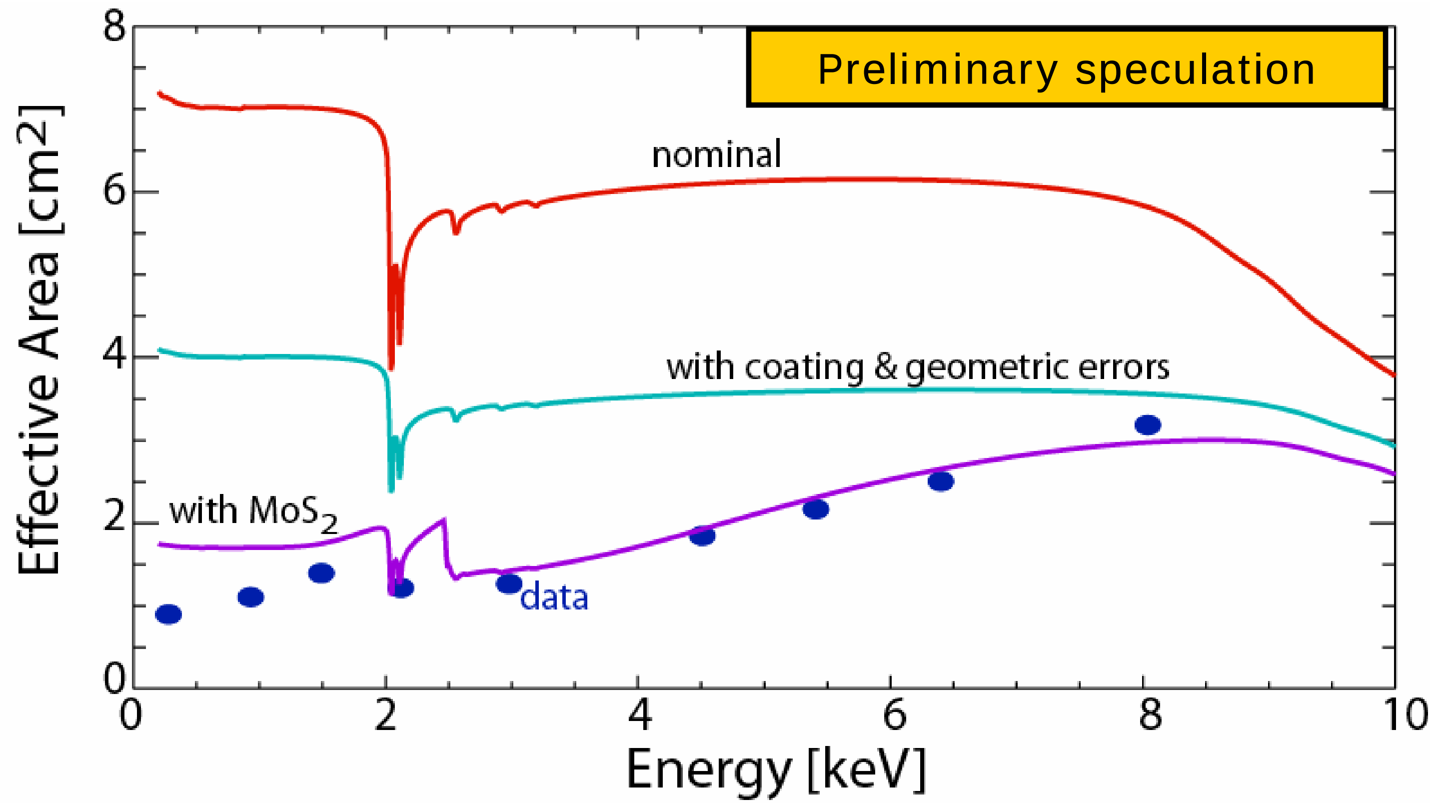
- Scattering (higher energies) and geometric errors (lower energies) balance each other
  - Spot size is essentially independent of energy

Energy [keV]	0.28	0.93	1.49	4.51	8.05
50% diameter	3.9 mm	3.8 mm	3.9 mm	3.8 mm	3.9 mm
75% diameter	6.8 mm	6.7 mm	6.8 mm	6.6 mm	6.8 mm
90% diameter	12.1 mm	11.9 mm	12.0 mm	11.9 mm	12.1 mm

- HPD is about 2.5× larger than original predictions, 90% energy circle 3× larger
- Three factors at play:
  - Different focal lengths (geometric errors)
  - Mid-spatial frequency errors (coatings process)
  - Misalignment of shells (±30 arcsec) with respect to one another (fabrication process)

Effective area analysis

- Factors that contribute to losses
  1. Geometric errors reduce area at all energies
  2. Rougher and non-ideal coating reduces area across entire band pass
  3. Putative contamination layer primarily absorbs low energy photons



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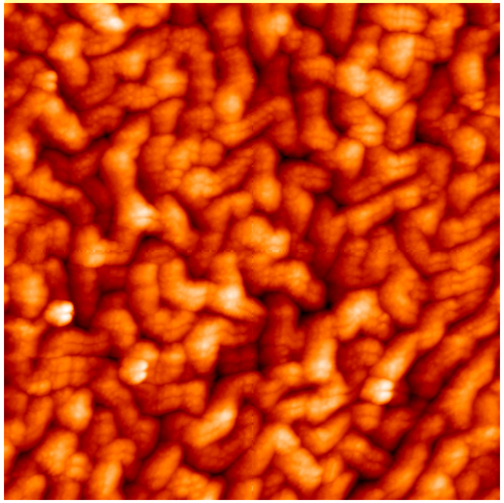
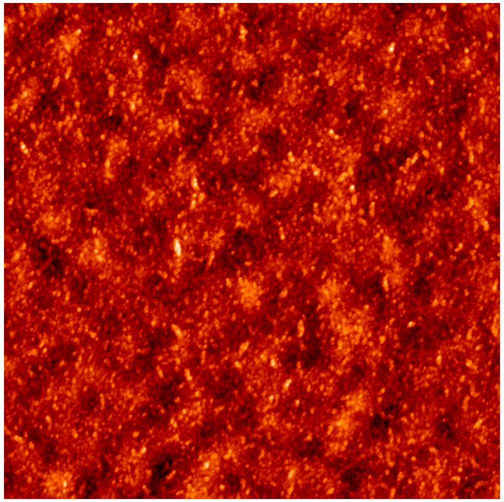
Coating the interior surface of small-radius, full-revolution x-ray substrates is a very challenging task

Before optimization



Ir-coated CAST radius no. 7
$2\times2\ \mu m^2$, <u>σ =47 Å rms</u>

After optimization



Ir-coated CAST radius no. 4,
2x2 μm^2, edge1, <u>σ = 11.6 Å rms</u>

- Ir coating was performed by outside vendor using Pulsed Laser Deposition (PLD), guided by surface characterization at LLNL (AFM, SEM, optical profilometry)
- Even after roughness optimization, coating quality varied among shells and across length of a single shell
- Sensitivity of polycarbonate material to thermal effects during Ir deposition is difficult to manage

Performance of x-ray optic with Micromegas detector

- Optic was successfully integrated into new beamline
- Optic did focus light on Micromegas
- **Exercise was incredibly valuable learning experience:** learned several lessons that will be integrated into future efforts

Follow-on analysis to understand and improve optic performance

- X-ray Photoelectron Spectroscopy (LLNL, CERN) to determine composition of surface contamination
  - Already have results from witness coupons prepared during Ir coating
  - Complete interpretation requires results from additional samples, including actual optic
  - Iridium film contains IrO_2, hydrocarbons, nitrogen compounds and trace amounts of Si
- Precise measurements of substrates to design new tooling to correct geometric errors

Plans forward

- Complete metrology of prototype CAST x-ray optic
  - Study contamination and quantify geometric errors in detail
- Develop work plan to correct geometric errors
- Consider and pursue other coating options to improve surface finish (roughness)

Conclusions

- We understand behavior of x-ray optic
- Confident we can build a 2nd x-ray optic that will behave much closer to expected (and needed) performance
- Our resources are limited, but we are continuing our development