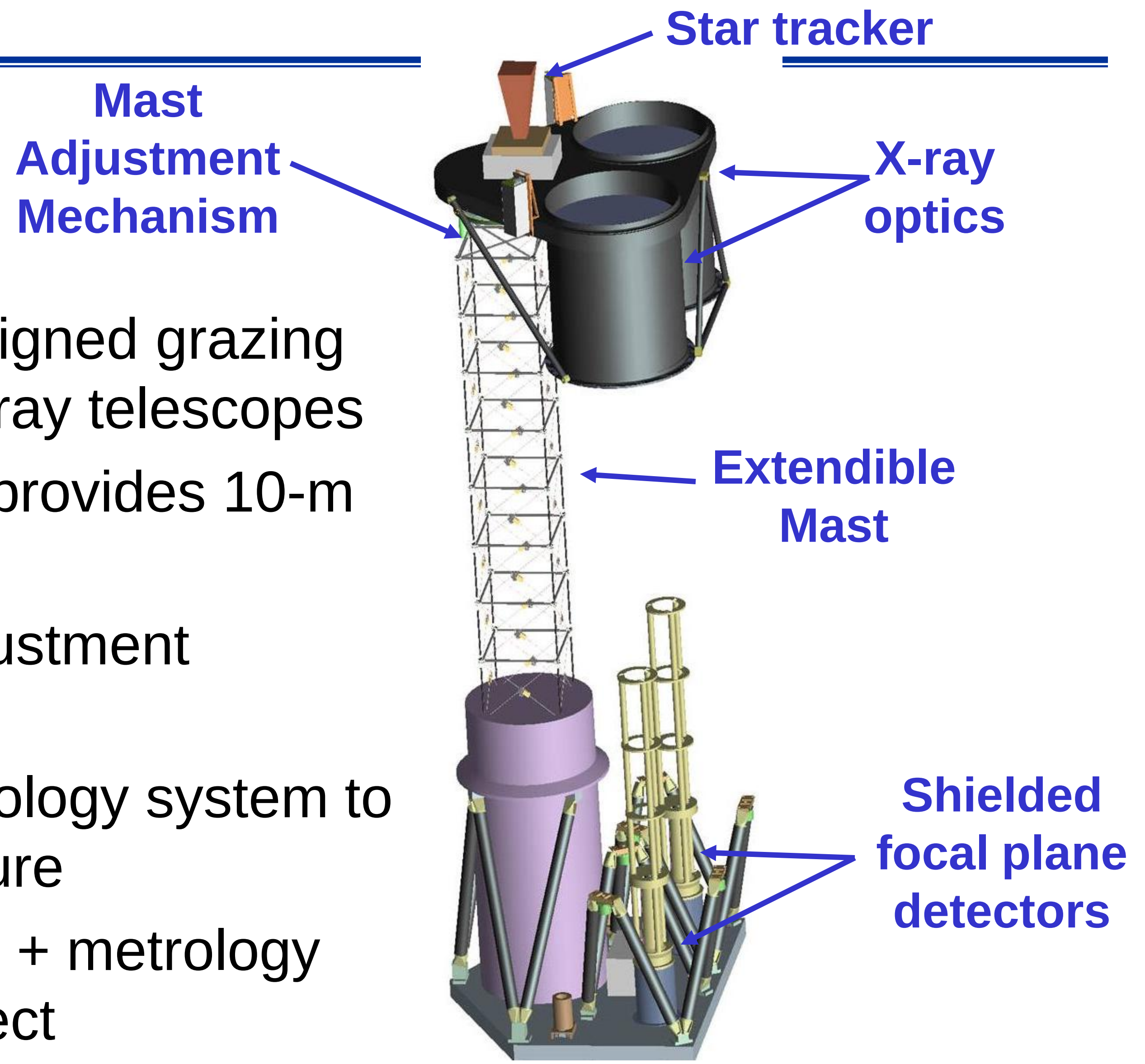
Slumped glass multilayered hard X-ray optics NuSTAR experience and future prospects

Finn E. Christensen

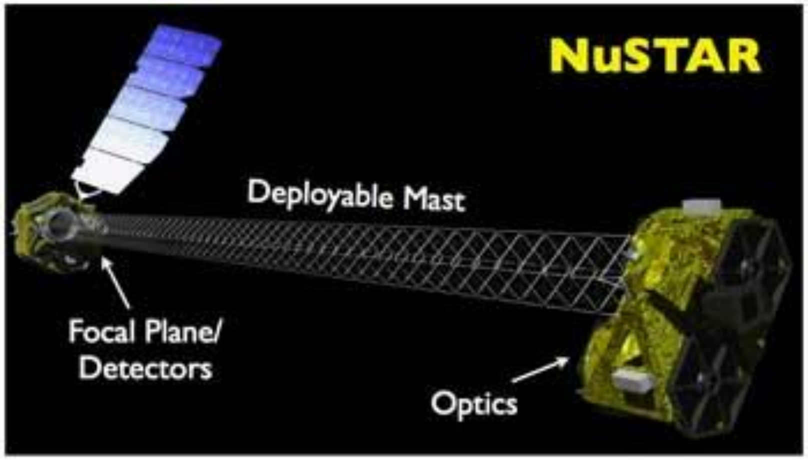
DTU-Space

NuSTAR Payload Description

- Two identical coaligned grazing incidence hard X-ray telescopes
- Extendable mast provides 10-m focal length
  - Single-use adjustment mechanism
- Simple laser metrology system to remove mast flexure
- Star camera head + metrology provides fine aspect



NuSTAR Performance Summary



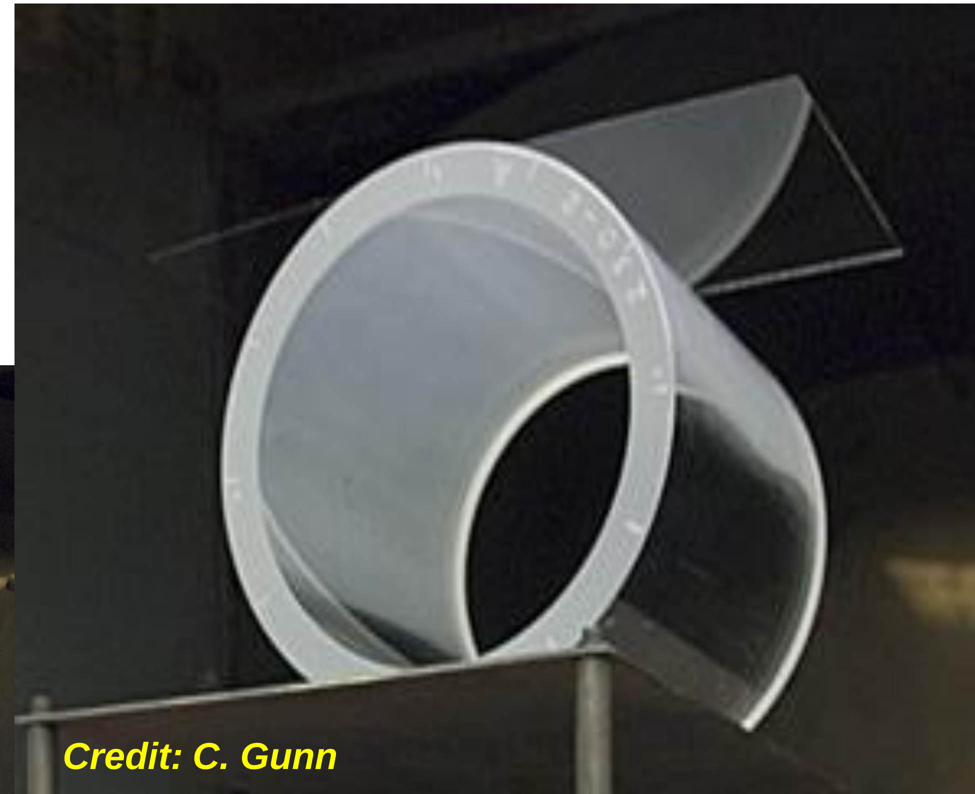
Two co-aligned hard X-ray telescopes

Caltech – PI F.Harrison

Energy Range:	5-80 keV
Angular Resolution:	58 arcsec (HPD) 18 arcsec (FWHM)
Field of View:	12 x 12 arcmin
Spectral Resolution:	1.2 keV at 68 keV 600 eV at 6 keV
Timing Resolution:	0.1 msec (absolute) 2 microsecond (relative)
Sensitivity (3σ, 1 Ms):	2×10^{-15} erg/cm^2/s (6-10 keV) 1×10^{-14} erg/cm^2/s (10-30 keV)
ToO Response:	<24 hr. Can be 3-4 hours

Mirror substrates are thermally formed from 0.21mm thin glass microsheets

- GSFC approach slumps glass directly onto highly polished mandrels



Credit: C. Gunn

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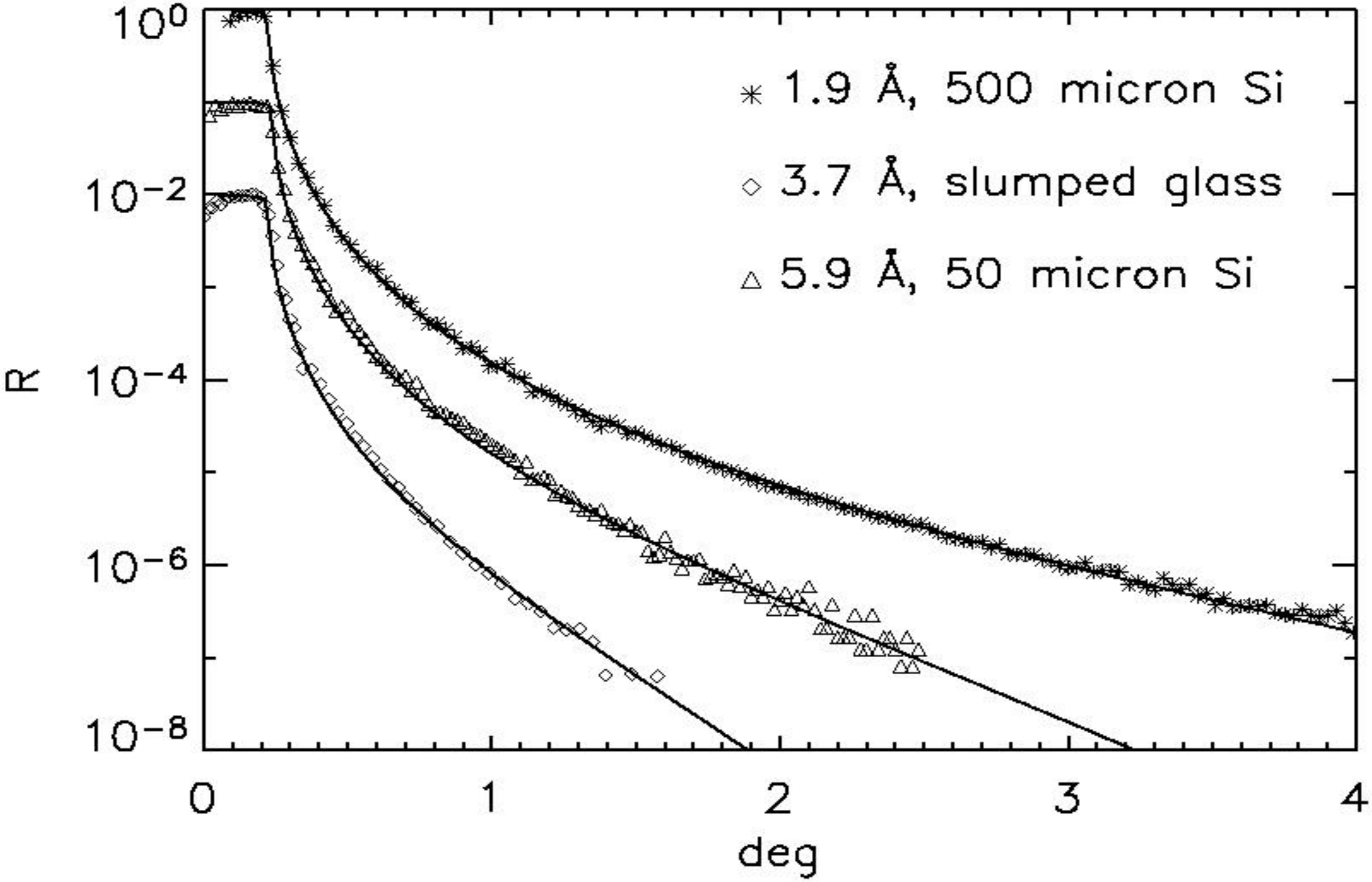
Substrate forming in oven

Cylindrical forming mandrels

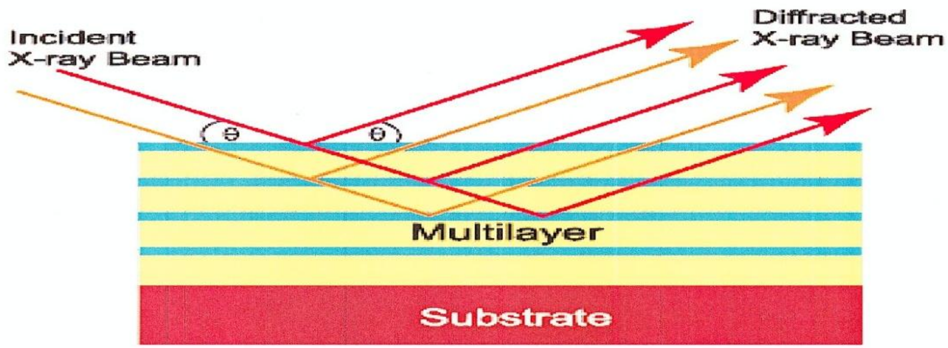
Prospects for slumping

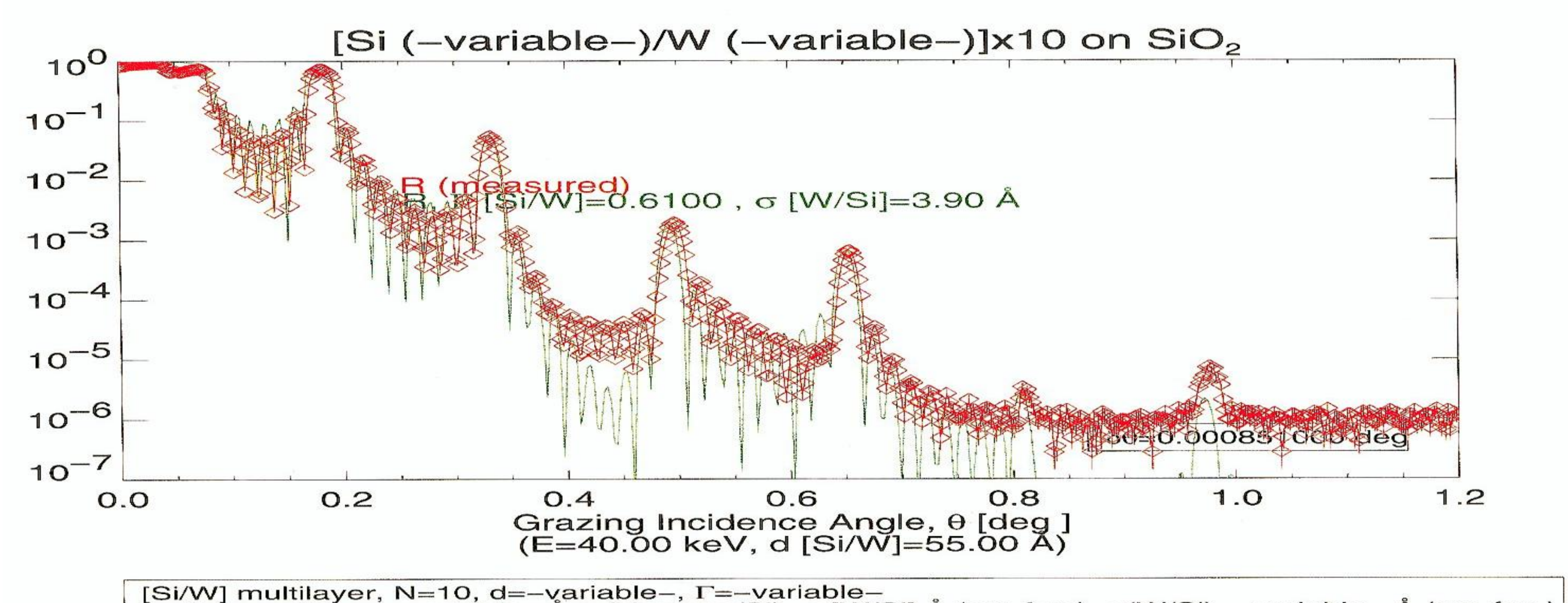
- Average cylindrical figure of flight mirrors from NuSTAR is ca 30 arcsec but improved over time
- Improvements in slumping can probably be improved to 10 -15 arcsec

Substrates - micro roughness



Multilayer structure - Artificial Bragg reflector

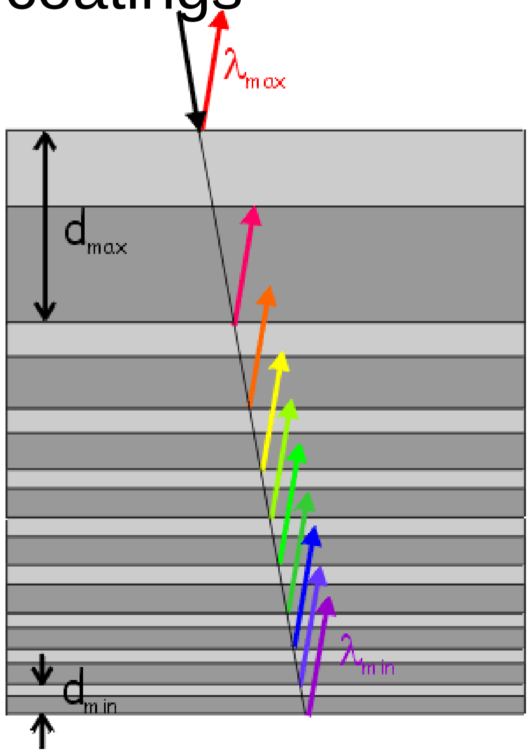


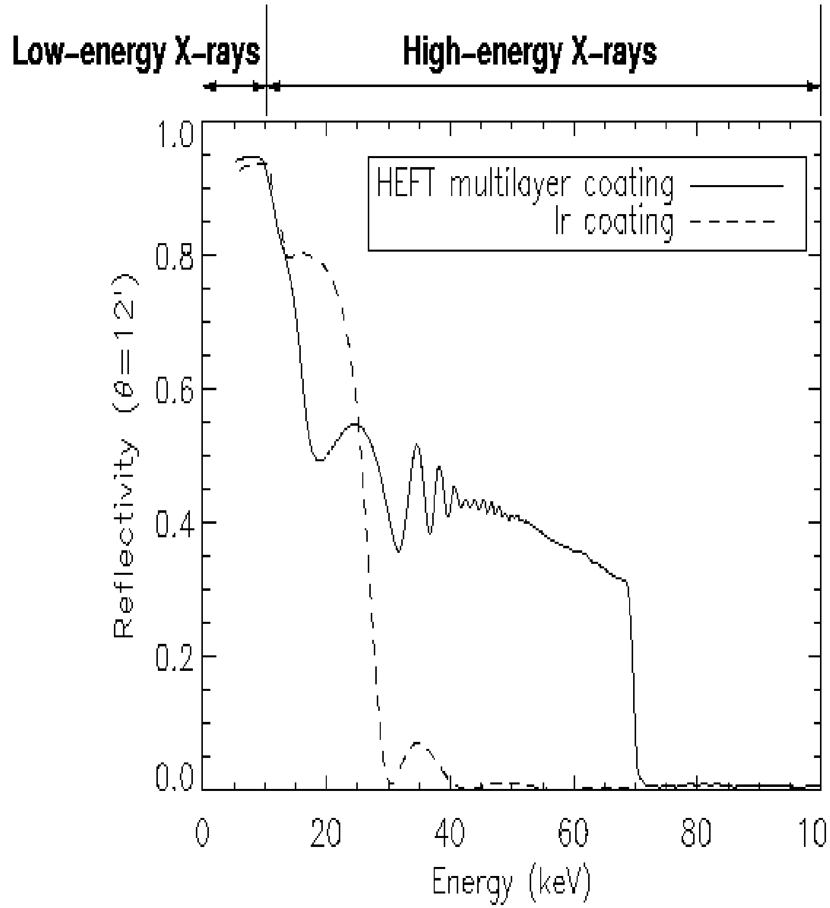


Coatings – depth graded a la neutron supermirrors

Christensen et al , SPIE, Vol 1546 ; 1991

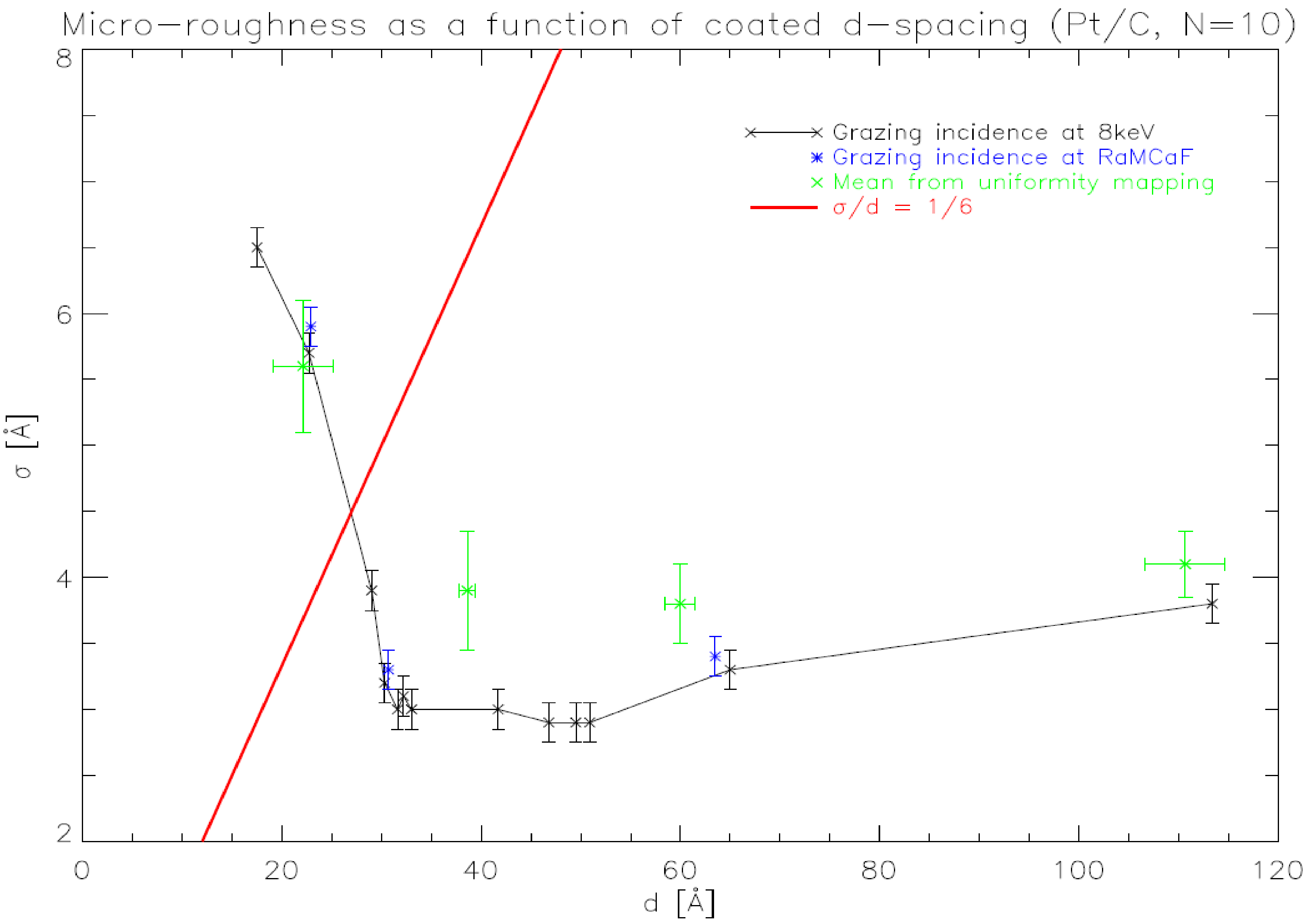
Graded d-spacing coatings





Choice for NuSTAR is to use W/Si and Pt/C – smallest layer spacings on order 1 nm

Roughness versus d for Pt/C ; N = 10



Power law design of d-spacings - K. Joensen Thesis

$$d_i=a\cdot(b-i)^{-c}$$

Must specify a,b,c and number of bilayers N and Γ_i=relative thickness of heavy material in a given bilayer($d_{h,i}$) to d_i. This is assumed independent of i so Γ is constant throughout stack.

Alternatively one can specify

$d_1=d_{max}$ and $d_N=d_{min}$ and c,N,Γ

Design recipes for FM1 and FM2

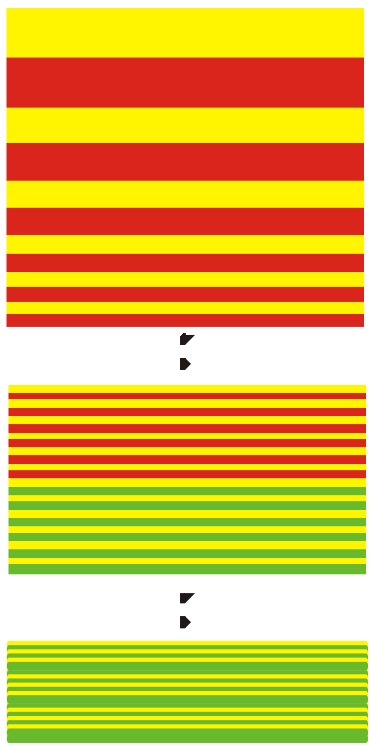
NuSTAR

Group	Material	Angle [mrad]	Layer range	D_{min} [Å]	D_{max} [Å]	N	c	σ [Å]	Γ_{Top}	Γ_{stack}	D_{stack} [μm]
1	Pt/C	1.34 - 1.52	1 - 12	29	133.66	145	0.245	4.5	0.7	0.45	0.558
2	Pt/C	- 1.73	13 – 24	29	131.58	145	0.228	4.5	0.7	0.45	0.547
3	Pt/C	- 1.96	25 – 36	29	129.56	145	0.234	4.5	0.7	0.45	0.551
4	Pt/C	- 2.22	37 – 49	29	121.84	145	0.214	4.5	0.7	0.45	0.537
5	Pt/C	- 2.52	50 – 62	29	109.50	145	0.225	4.5	0.7	0.45	0.541
6	Pt/C	- 2.85	63 – 76	29	107.50	145	0.225	4.5	0.7	0.45	0.541
7	Pt/C	- 3.23	77 – 89	29	102.75	145	0.212	4.5	0.7	0.45	0.534
8	W/Si	- 3.67	90 – 104	25.0	95.228	291	0.238	4.3	0.8	0.38	0.955
9	W/Si	- 4.16	105 – 118	25.0	83.942	291	0.220	4.3	0.8	0.38	0.934
10	W/Si	- 4.72	119 - 133	25.0	74.471	291	0.190	4.3	0.8	0.38	0.902

Prospects for design

- Refine design of top bilayers to smooth out wiggles. Youwei Yao et al
- Use ’novel’ material combinations – Ni/C, NiV/C, Co/C, NiV/B4C, NiV/SiC, W/SiC - All with a minimum d-spacing of ca 25 Å. WC/SiC with a minimum d-spacing of 15 Å
- Use dual stack material designs
- Increase number of bilayers to 1000+
- For NuSTAR absolute values of dmin and dmax was accurate run-to run to +- 5 %. Can relatively easily be improved to +´2 %

DUAL MATERIAL STACKS

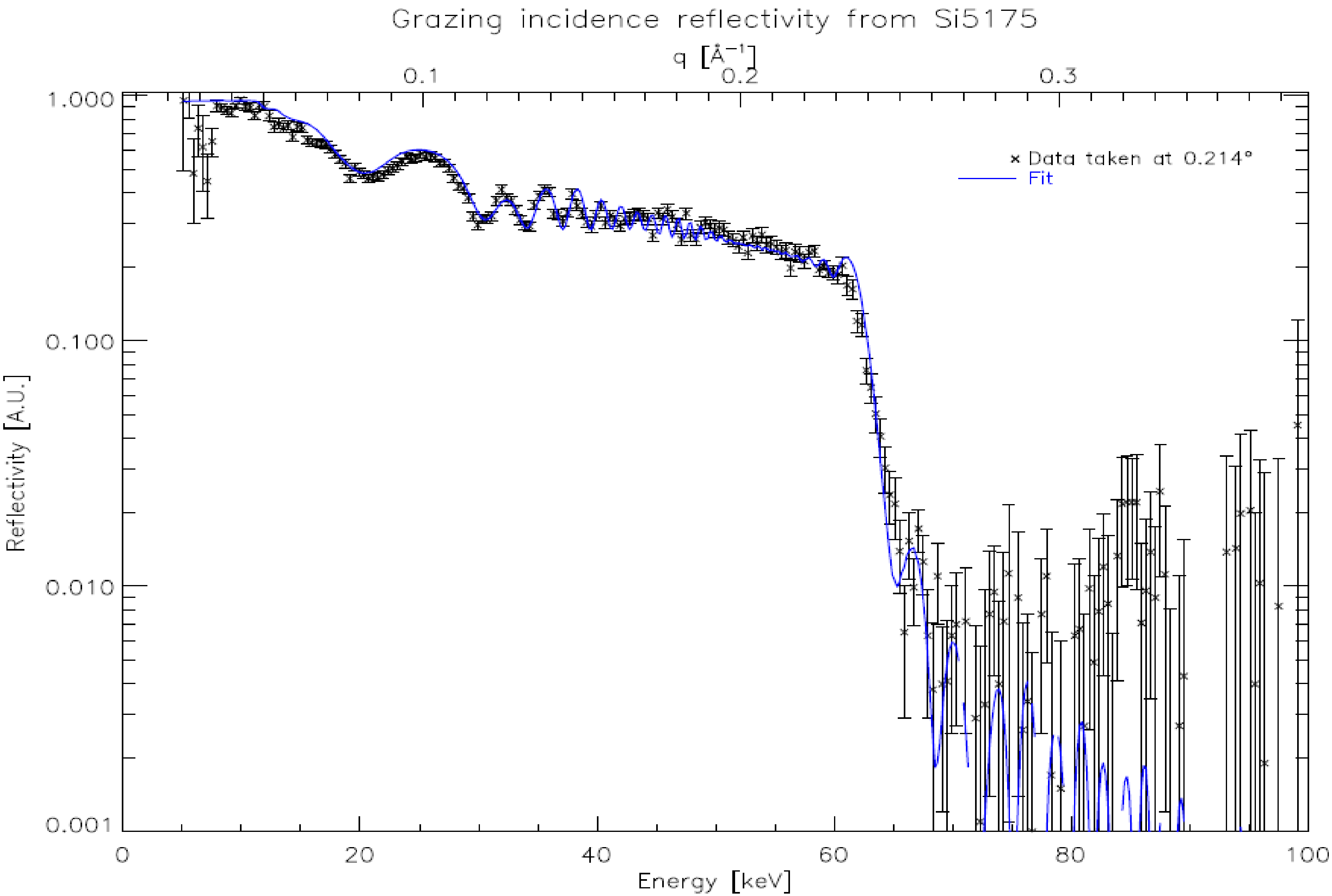


NiV/SiC

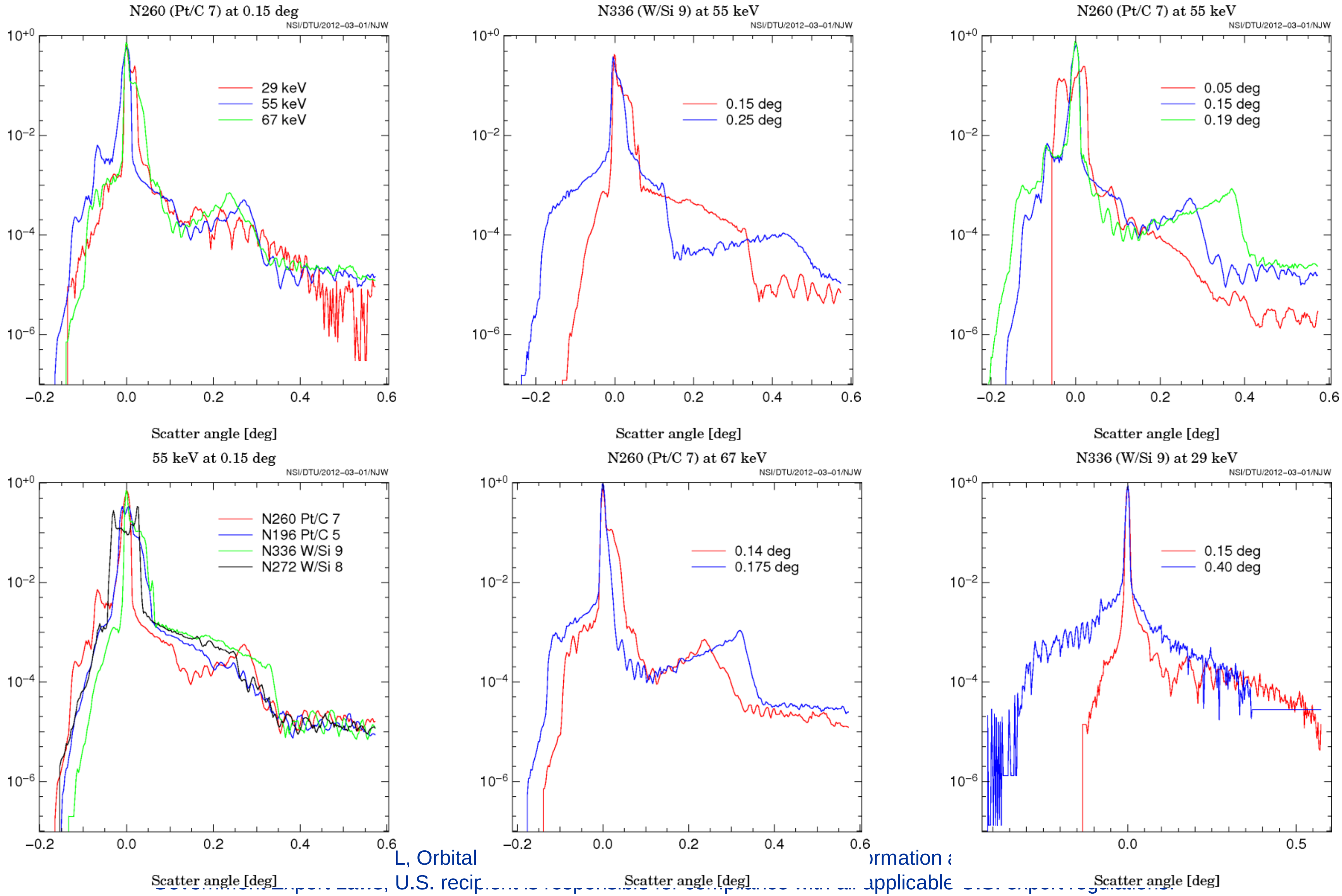
and

small d-spacing
W/SiC

Witness sample - Recipe 6
Pt/C ; σ = 4.4 Å



Scattering – from flight mirrors



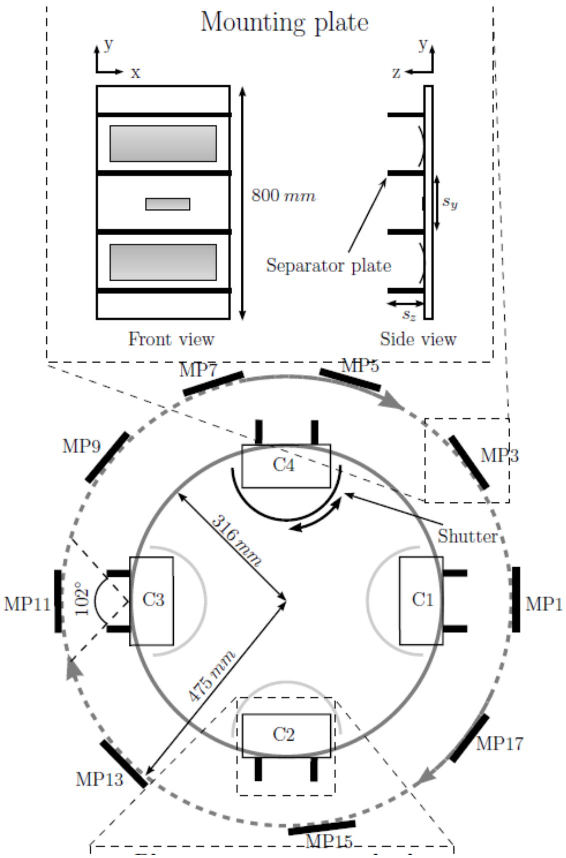
Stress values for W/Si and Pt/C

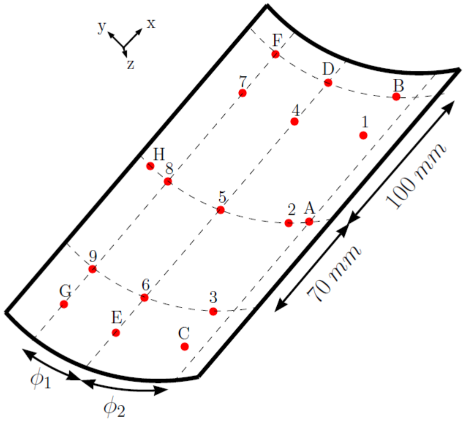
Material	Average stress Compressive	Range
Pt/C	134 Mpa	50-300
W/Si	75 Mpa	10-200

Prospects re stress

- Use novel coating techniques to reduce stress – Nitrogen assisted sputtering – has worked for NiV/C, W/B4C and Co/C

Uniformity campaign





Prospects for improving uniformity

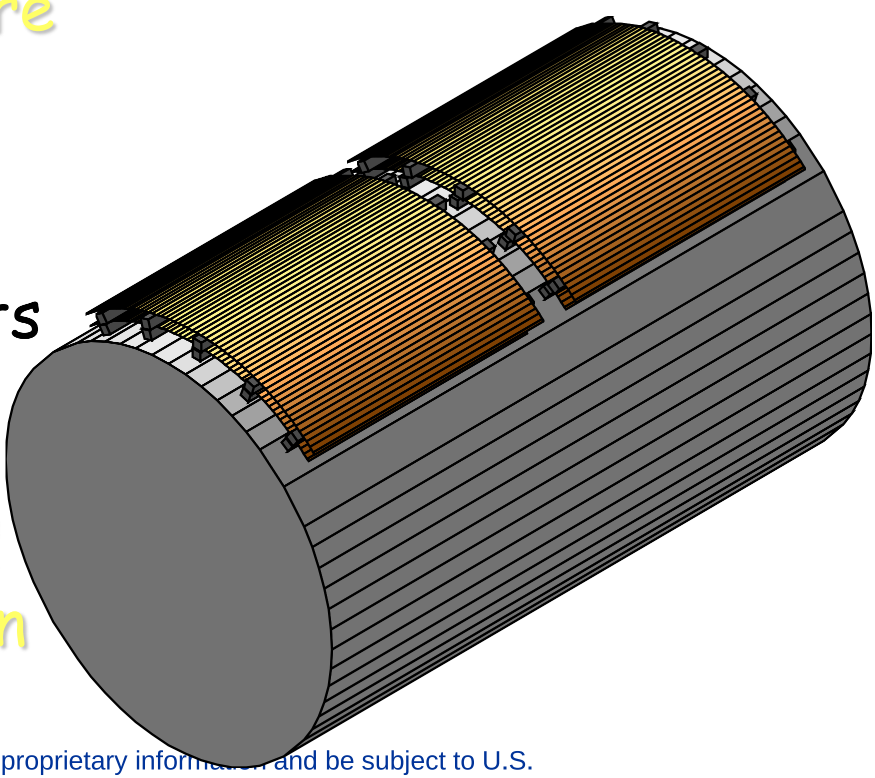
- NuSTAR on order +- 5 % rms
- Can relatively easily be improved to +- 2 %

Assembly & Alignment

NuSTAR

- Each spacer is machined to the precise radius and angle with respect to the optic axis.
  - No stack-up errors are propagated throughout optic build.

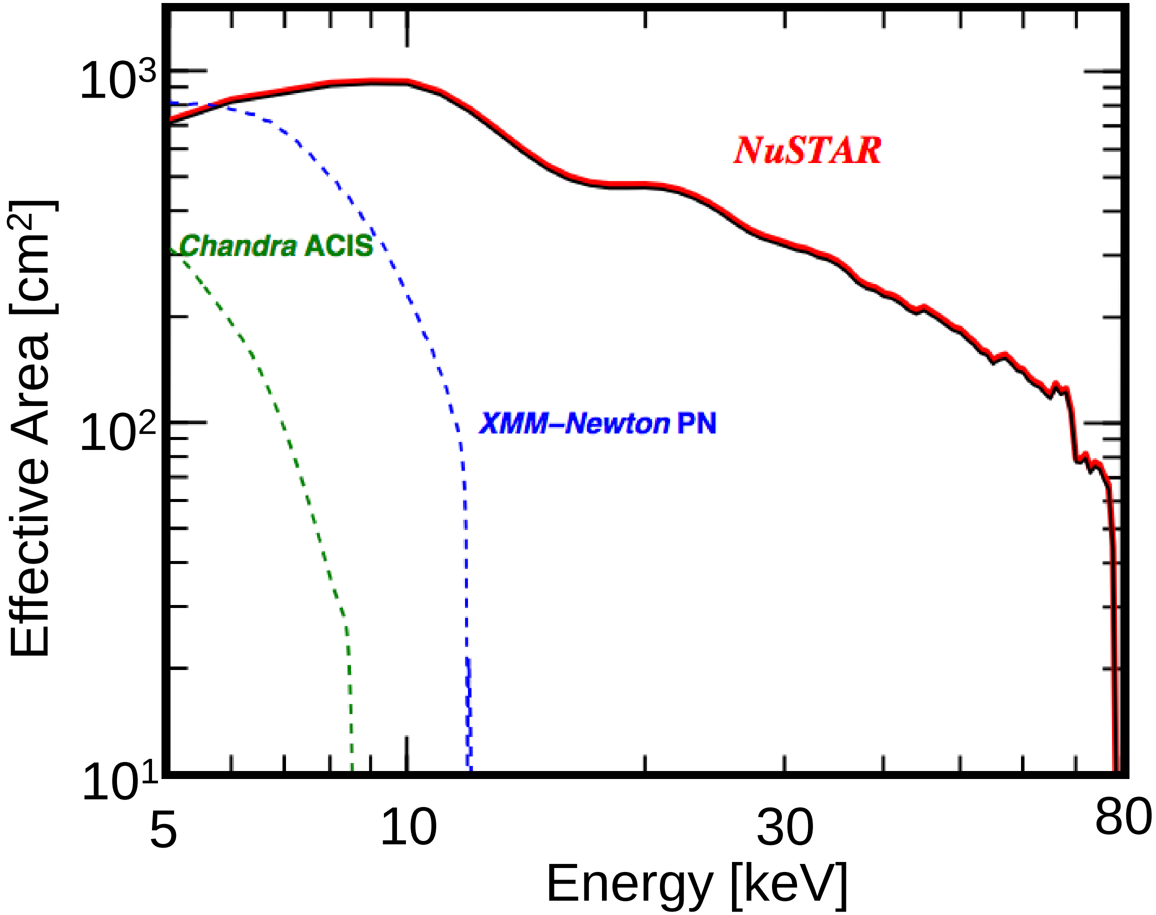
- Multilayer mirror segments are constrained to spacers with epoxy.
  - Only near net shaped shells required to obtain high performance.

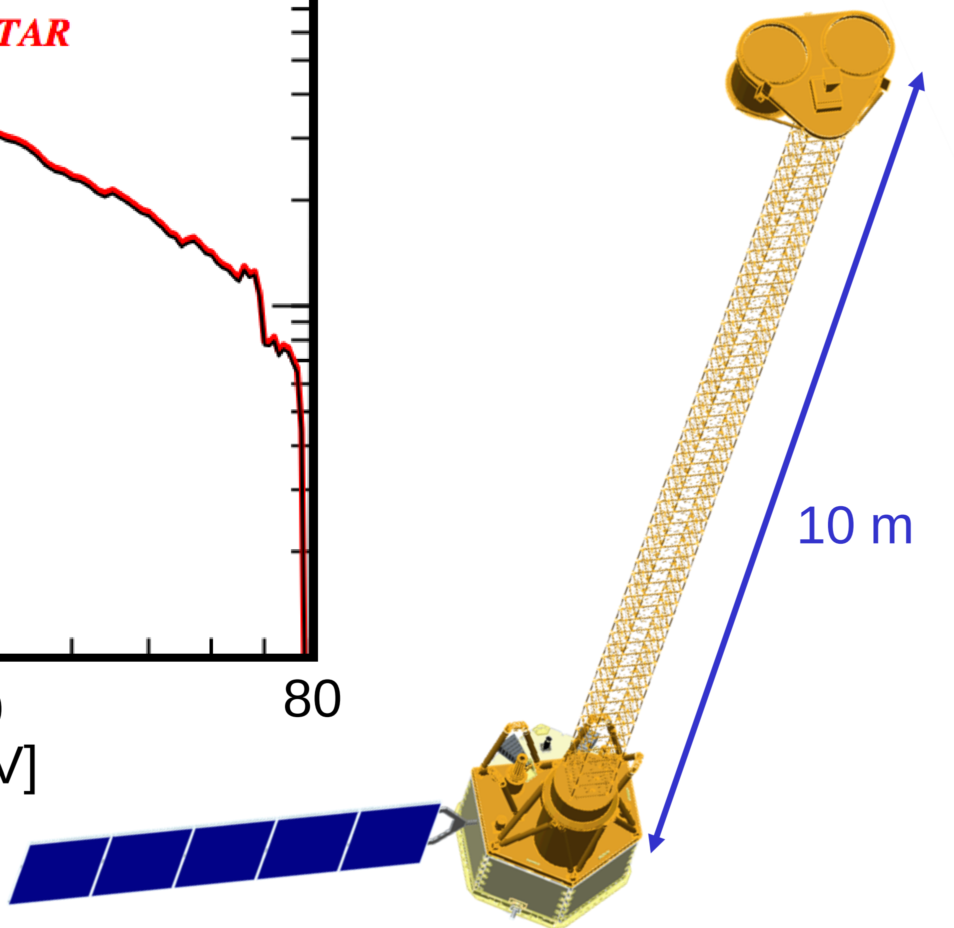


Prospects for slumping and mounting

- Use conical/wolter shapes slumping mandrels
- Improve mounting

NuSTAR extends focusing to high X-ray energies beyond Chandra & XMM



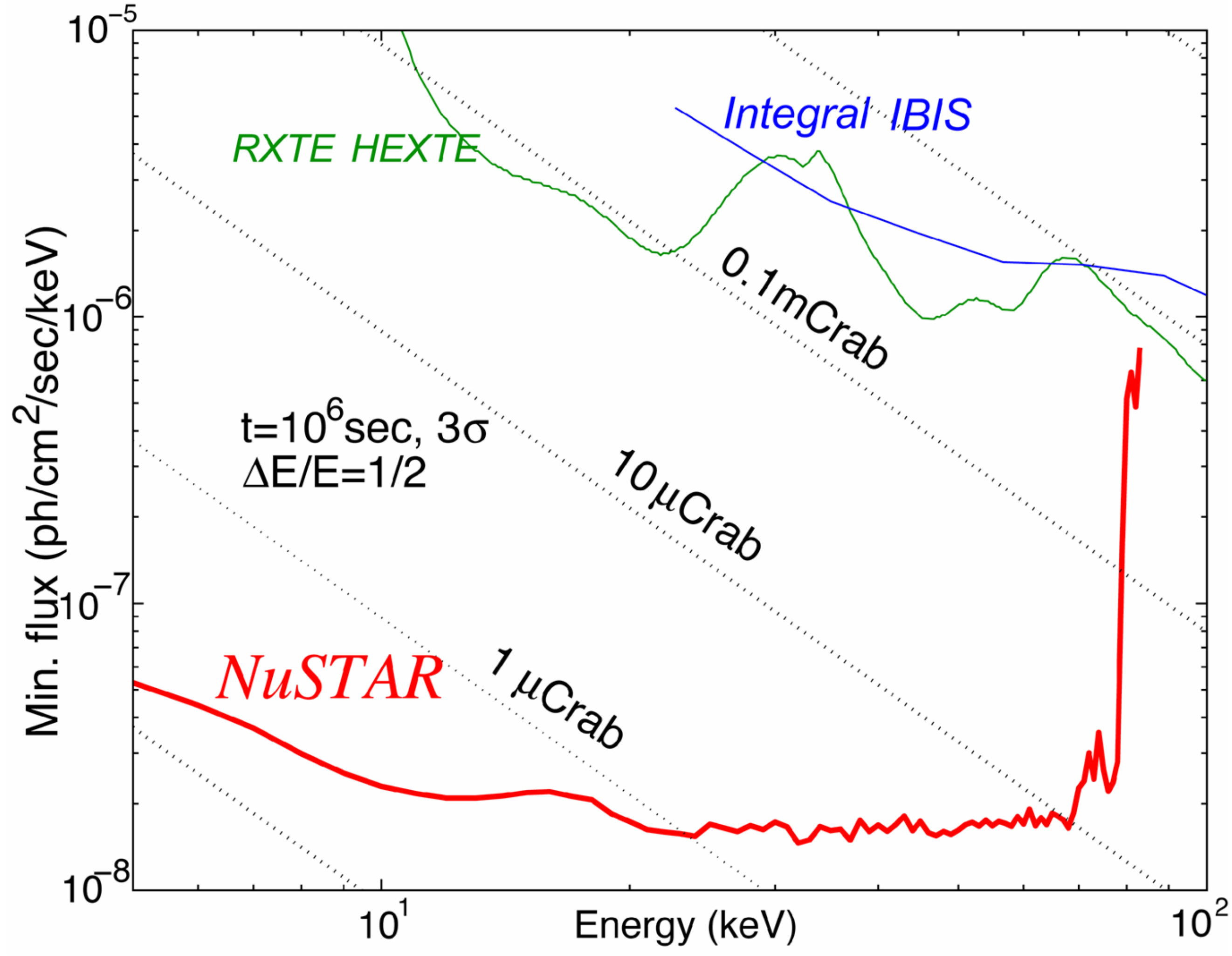


Improves sensitivity by orders of magnitude

NuSTAR

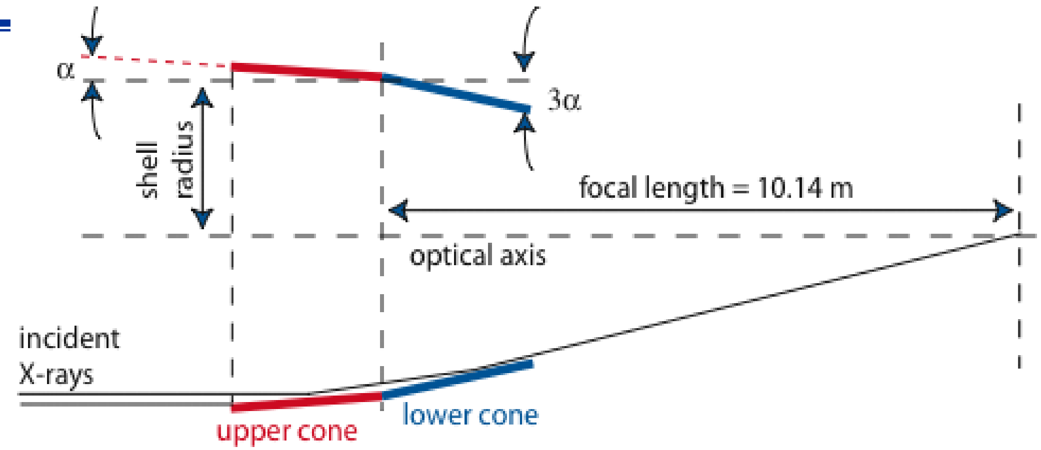
Bringing The High Energy Universe Into Focus

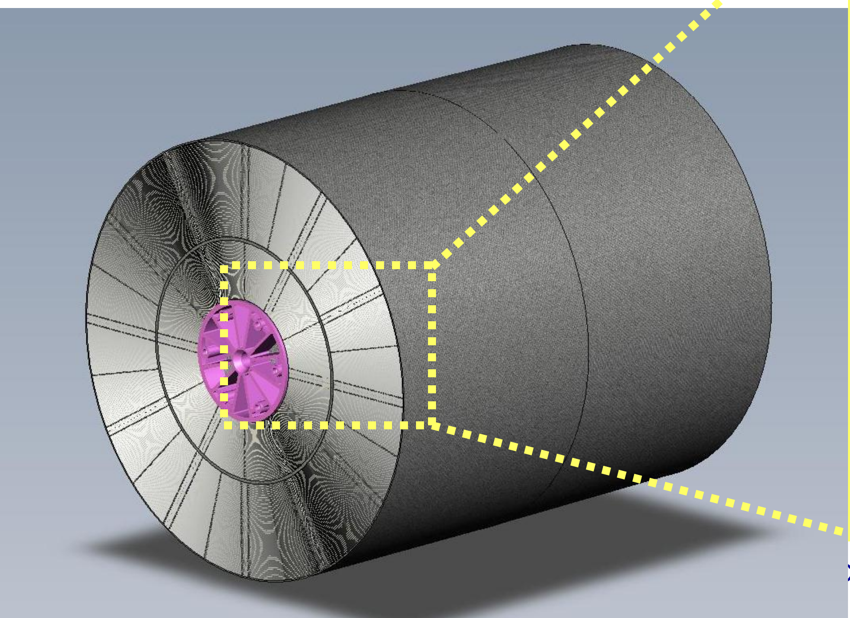
Nuclear Spectroscopic Telescope Array

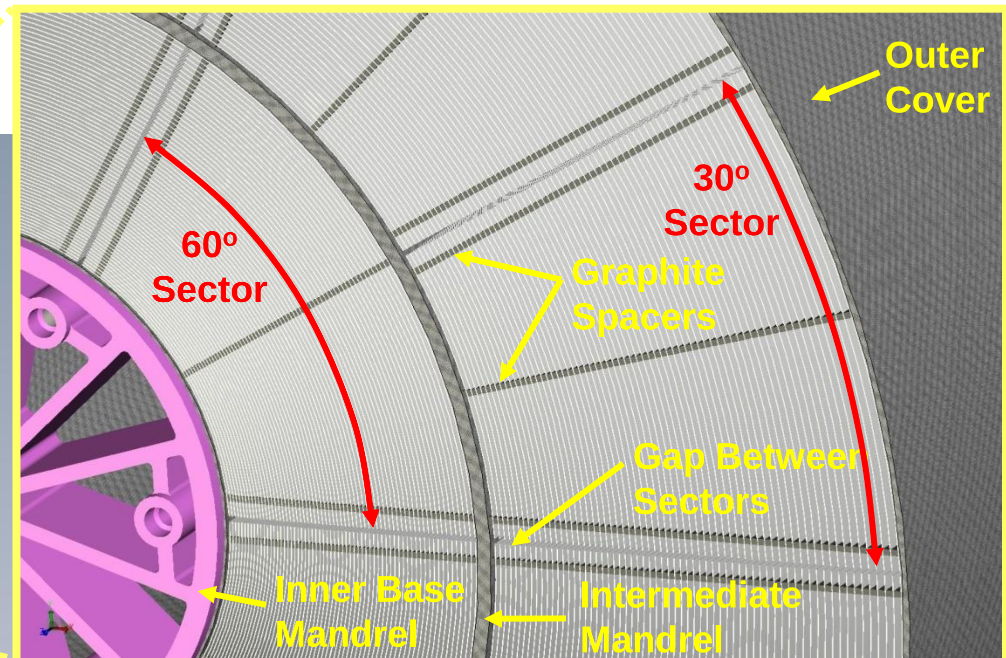


Each NuSTAR optic will be comprised of 130 conic approximation Wolter-I shells

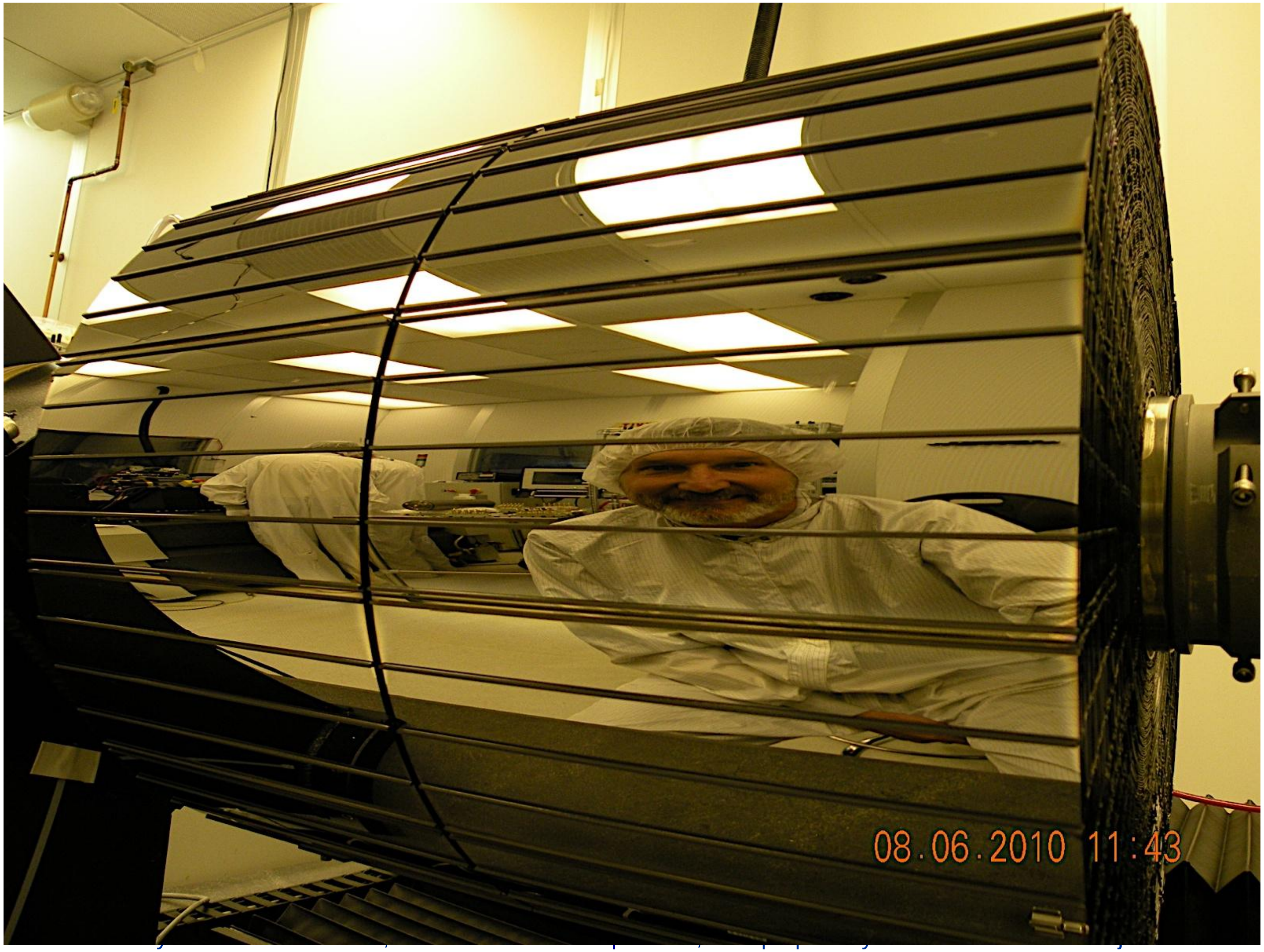
FocalLength	10.14 m
Shell Radii	54-191 mm
Graze Angles	1.3-4.7 mrad
Shell Length	225 mm
Mirror Thickness	0.2 mm
HPD Performance	57″
Total Shells Per Module	130
Total Mirror Segments	4680



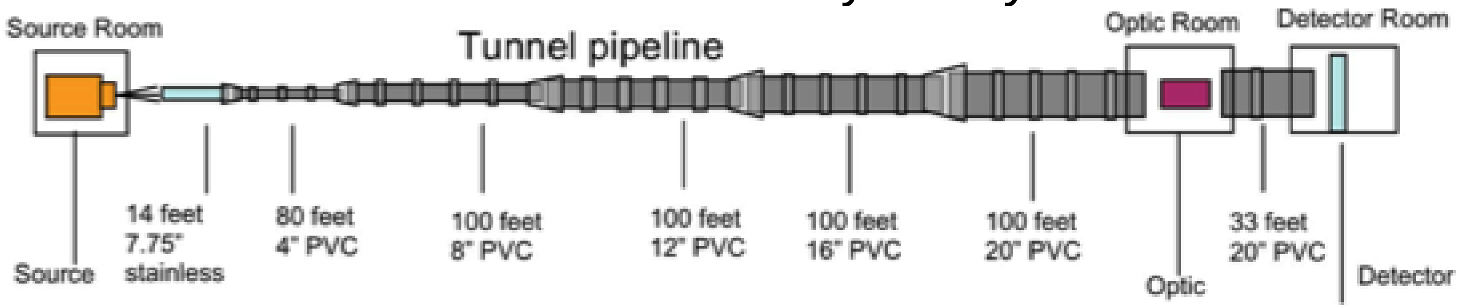




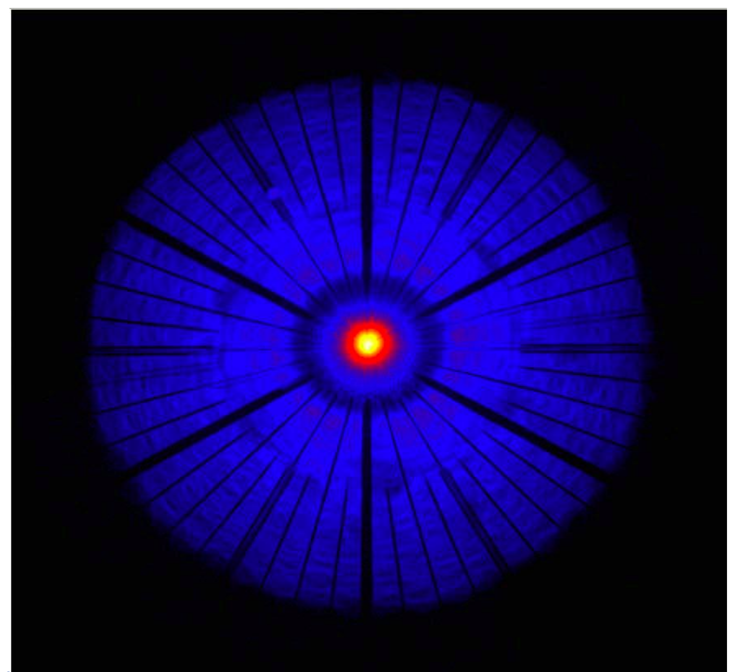
NuSTAR optics completed March 2011



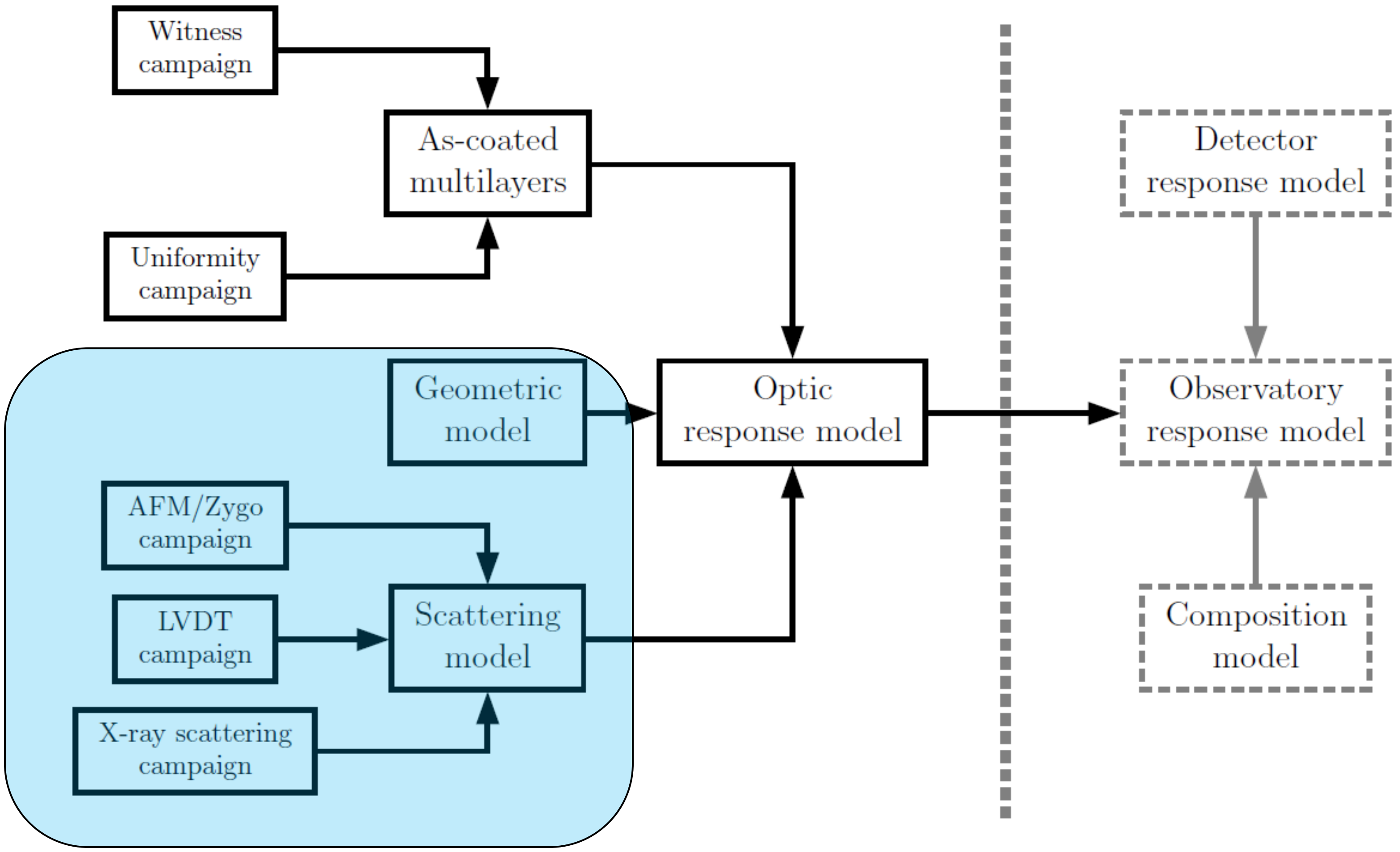
- X-ray full flood illumination (10 – 80 keV) using brehmsstrahlung source at 160 m Columbia University facility



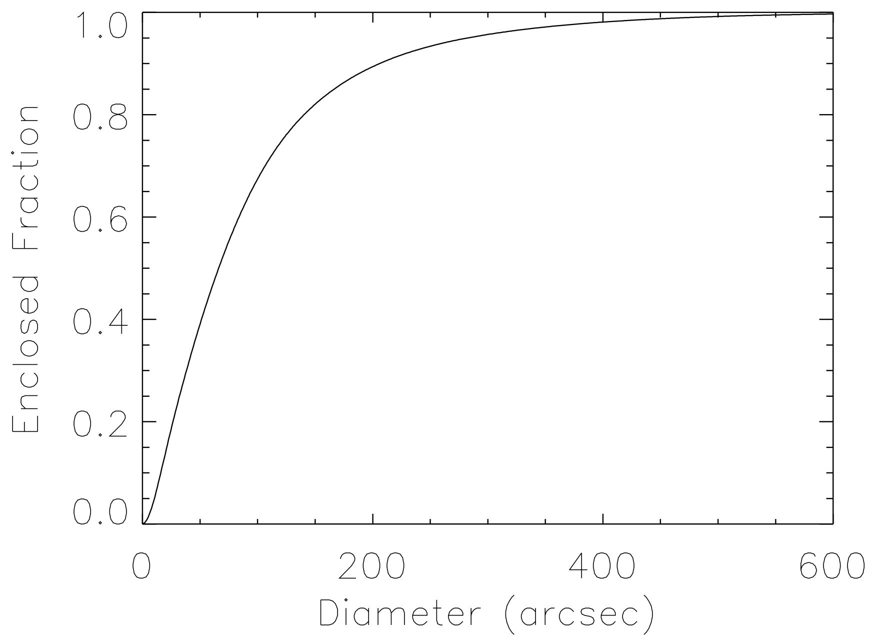
HPD 57 ”

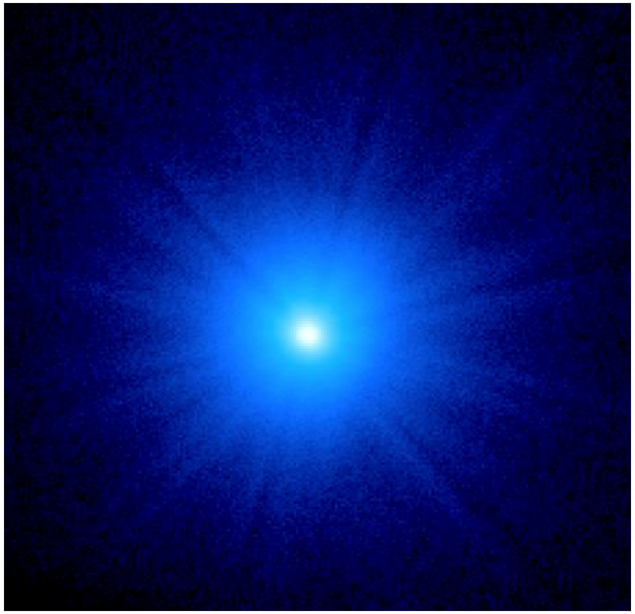


Optics Response model



Point Spread Function





GRS 1915 accreting black hole

Into the Gamma ray range – Compton scattering

Monica Fernandez et al - Accepted for publication in Phys Rev Letters

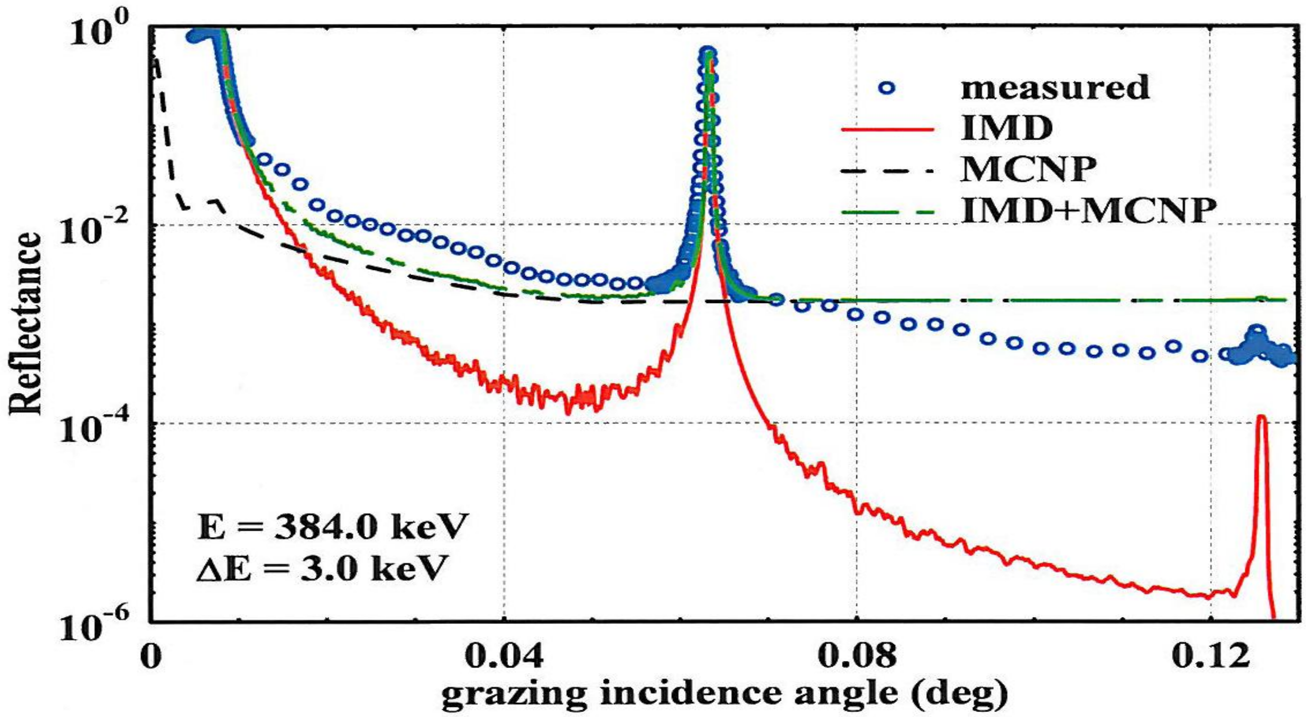


Fig. 3.

WC/SiC ML ; d = 1.5 nm, N= 300, Gamma = 0.4

Challenge going to higher energies

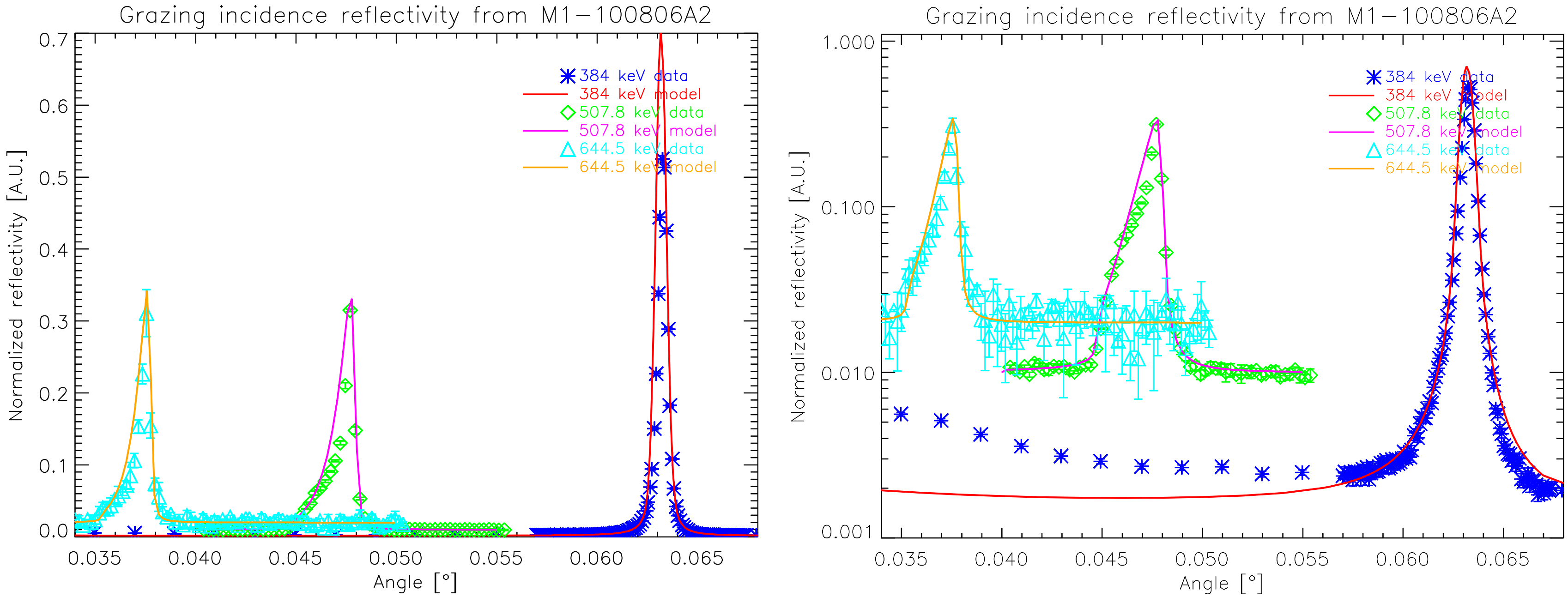
- Evaluate conventional scatter above 100 keV
- Necessary to add Compton scatter above 100 keV

Revisiting INTERFACE and MFC_MODEL

INTERFACE=1, MFC_MODEL=1

Exponential, Nevot-Croce

Ad hoc model: $d_w=e^{\alpha x}$, α=-0.20, x = 0…19, d_{mod}=0-0.0665



LLNL + DTU work to be published