X-ray Optics for the new decade

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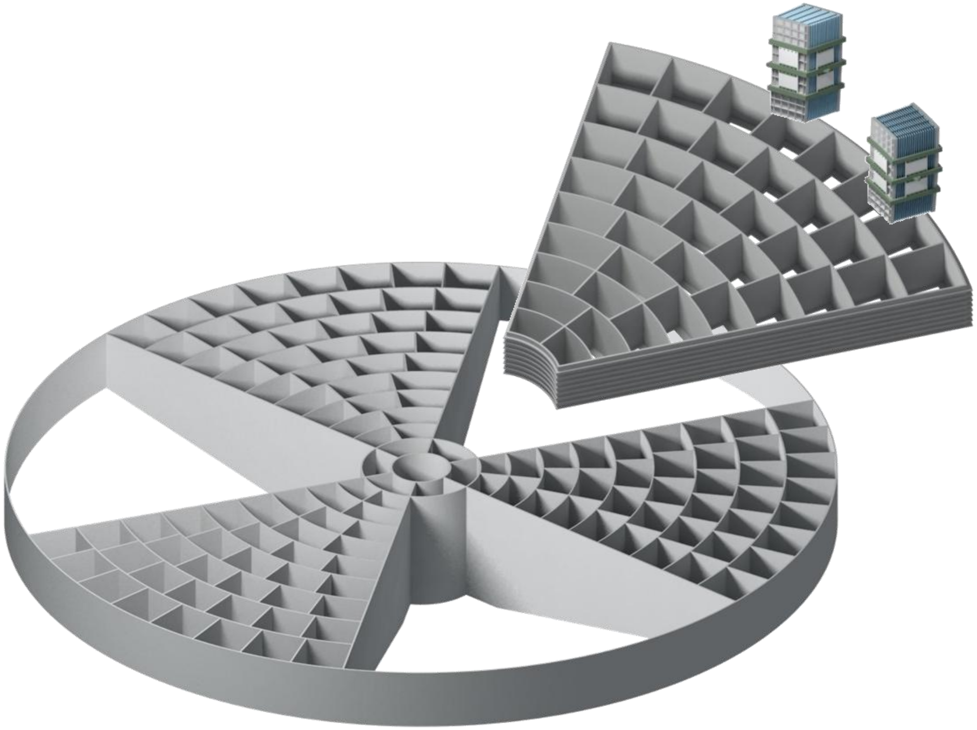
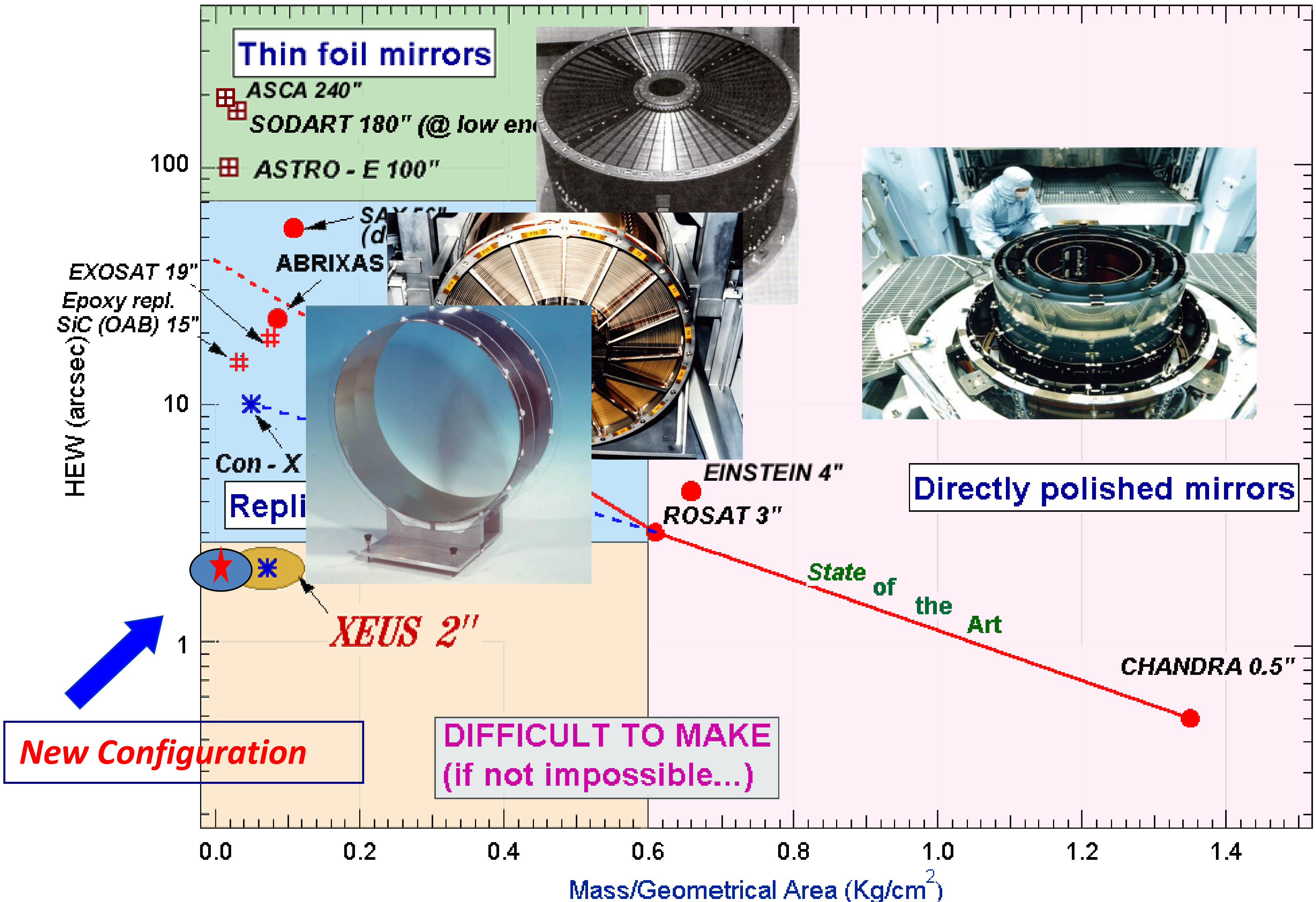


The X-ray optics of the current decade

Mission	Energy Band (keV)	Foc. Length (m)	Coll. Area (cm^2)	Diam . Max (cm)	FOV (arcmin)	HEW (arcsec	Techn.
XMM	0.2 - 12	7.5	1450 x 3	70	30	15 - 25	Ni repl.
Chandra	0.2 - 8	10	400	120	16	0.5	Direct Polishing
Swift	0.2 - 8	3.5	150	30	16	18	Ni repl.
Suzaku	0.2 - 12	4.7	450	40	17	120	Al foils

Present Astronomical optics technologies: HEW Vs Mass/geometrical area



Frontiers for the X-ray telescopes of the new decade

- enhanced imaging on wide field of views
  - e-Rosita
  - WFXT

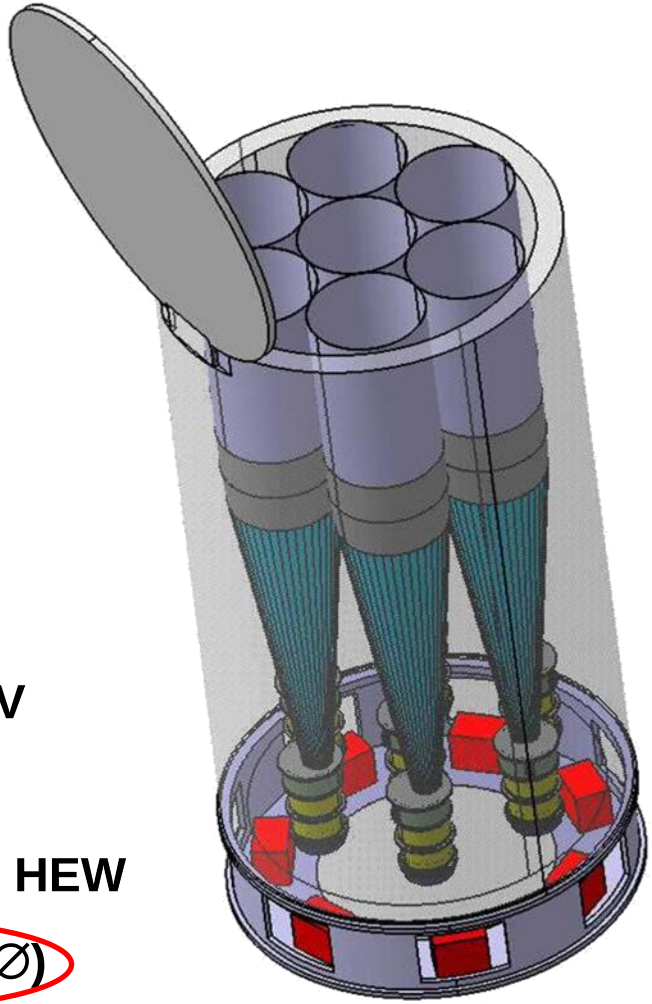
- Hard X-ray high angular resolution optics
  - NHXM

- IXO: Very high effective area with a high angular resolution for imaging spectroscopy

Basic Data of the eROSITA Telescope

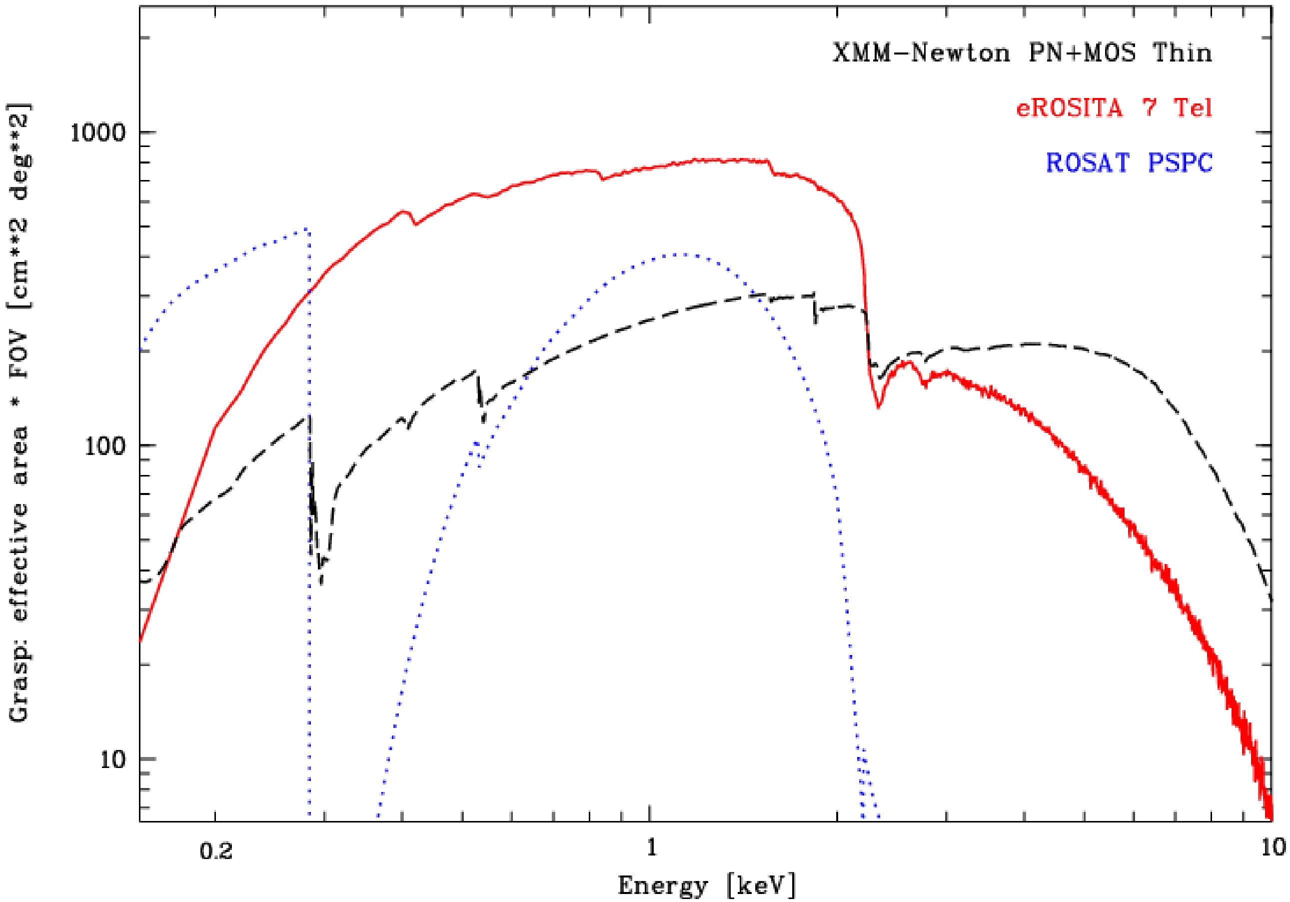
Baseline configuration

Number of mirror modules	**7**
Degree of nesting	**54**
Focal length	**1600 mm**
Largest mirror diameter	**365 mm**
Smallest mirror diameter	**76 mm**
Wall material	**Ni**
Micro-roughness	**0.5 nm**
Energy range	**~0.2 – 10 keV**
Coating	**Gold**
Angular Resolution	**15-30 arcsec HEW**
Field-of-view	**41′×41′ (61’ ∅)**
Mass per module	**< 60 kg**



e-Rosita: Grasp

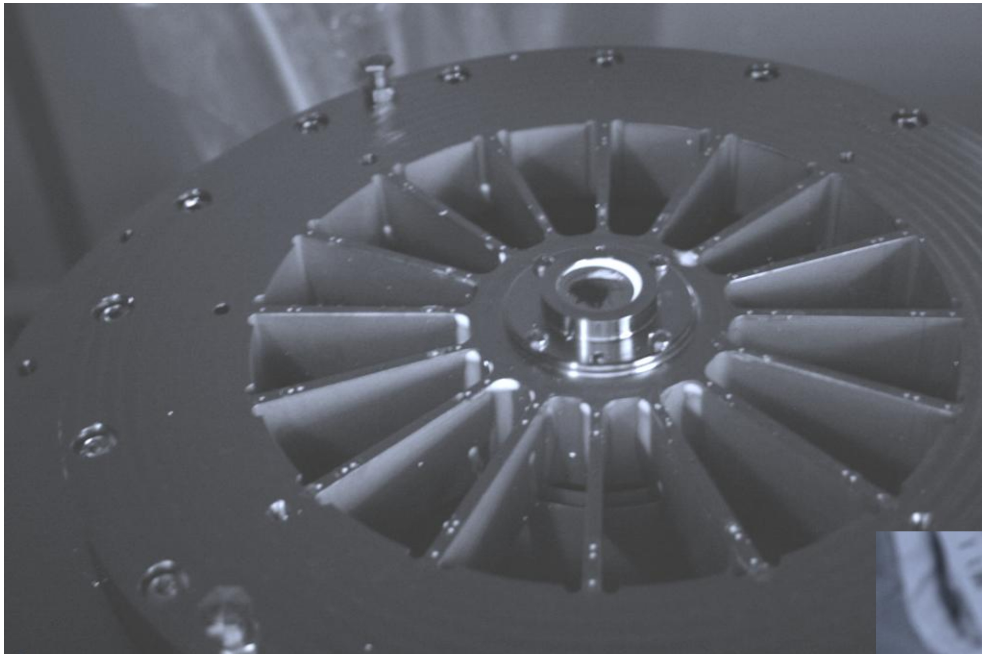
Grasp [cm² deg²]



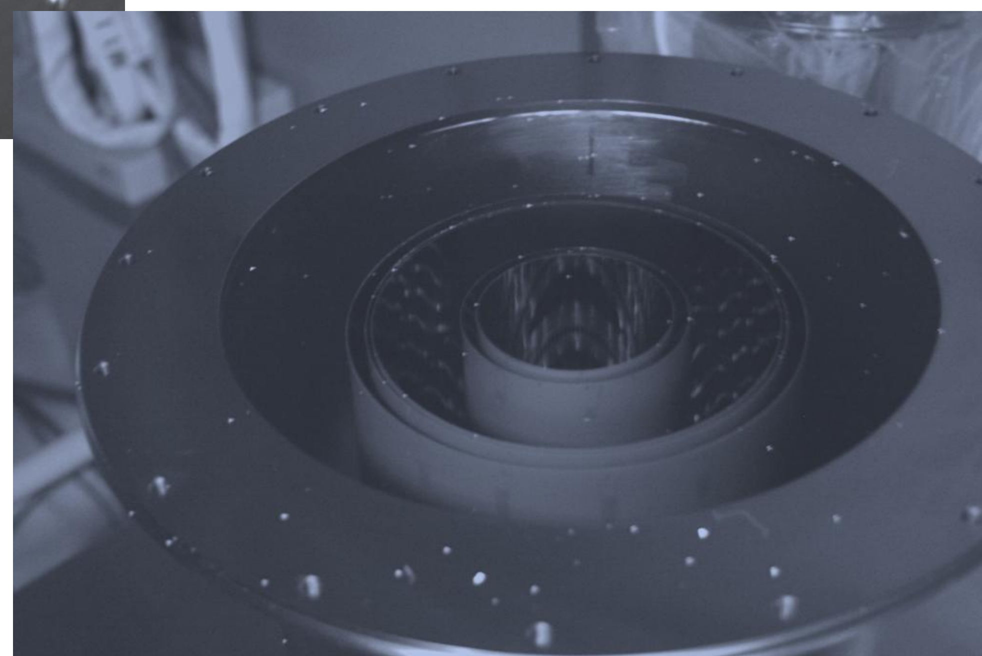
Grasp of 7 e-ROSITA telescopes is 3-4 x higher than 3 XMM-Newton telescopes in the energy range 0.3-2 keV!

EROSITA MULTI SHELL DRUM X-RAY TEST RESULTS

(16/17 DECEMBER) 2009



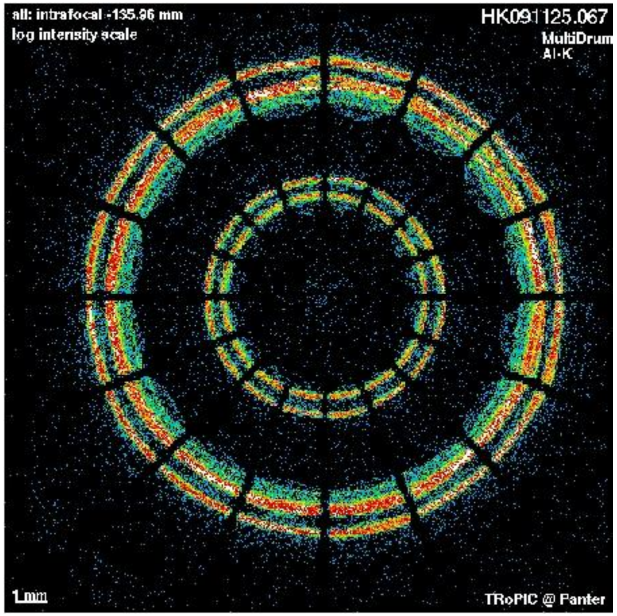
An e-ROSITA Mirror Module demonstrator composed by 5 shells has been tested for process qualification at PANTER facilities

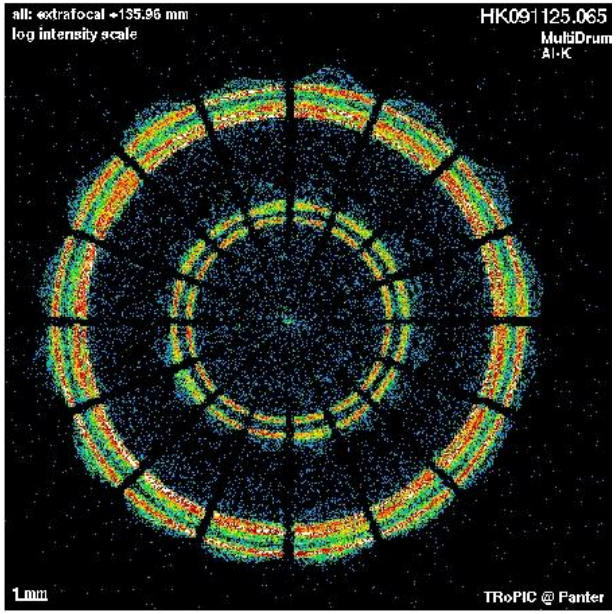


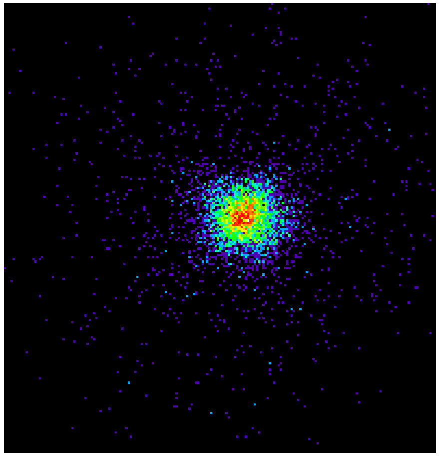
Mirror shells produced via Ni-electroforming and integrated by Media Lario Technologies, Italy

CREDITS: MPE

e-ROSITA MULTI SHELL DRUM CALIBRATIONS

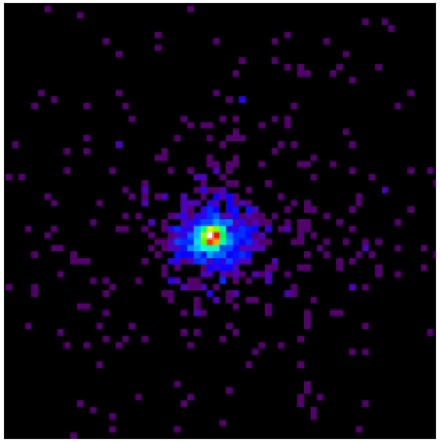






Al-K

	HEW	W90	scattering
1.49 keV	14.8''	89''	3.0%
8.04 keV	13.9''	157''	10.0%

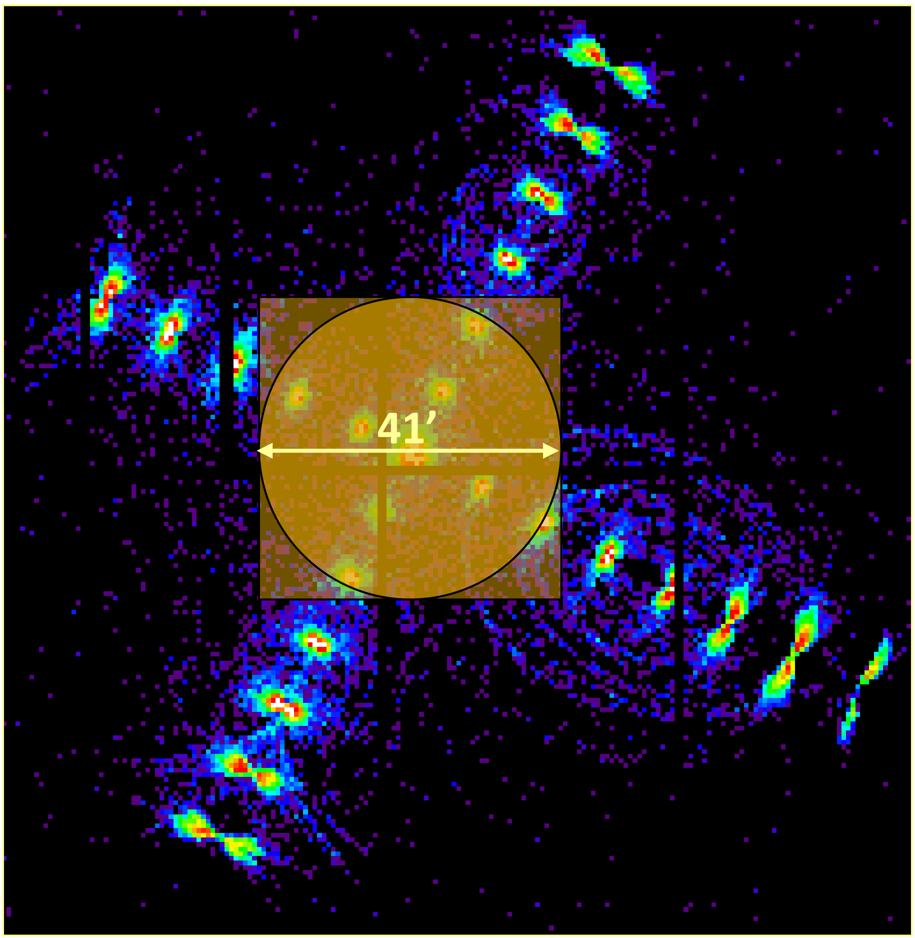


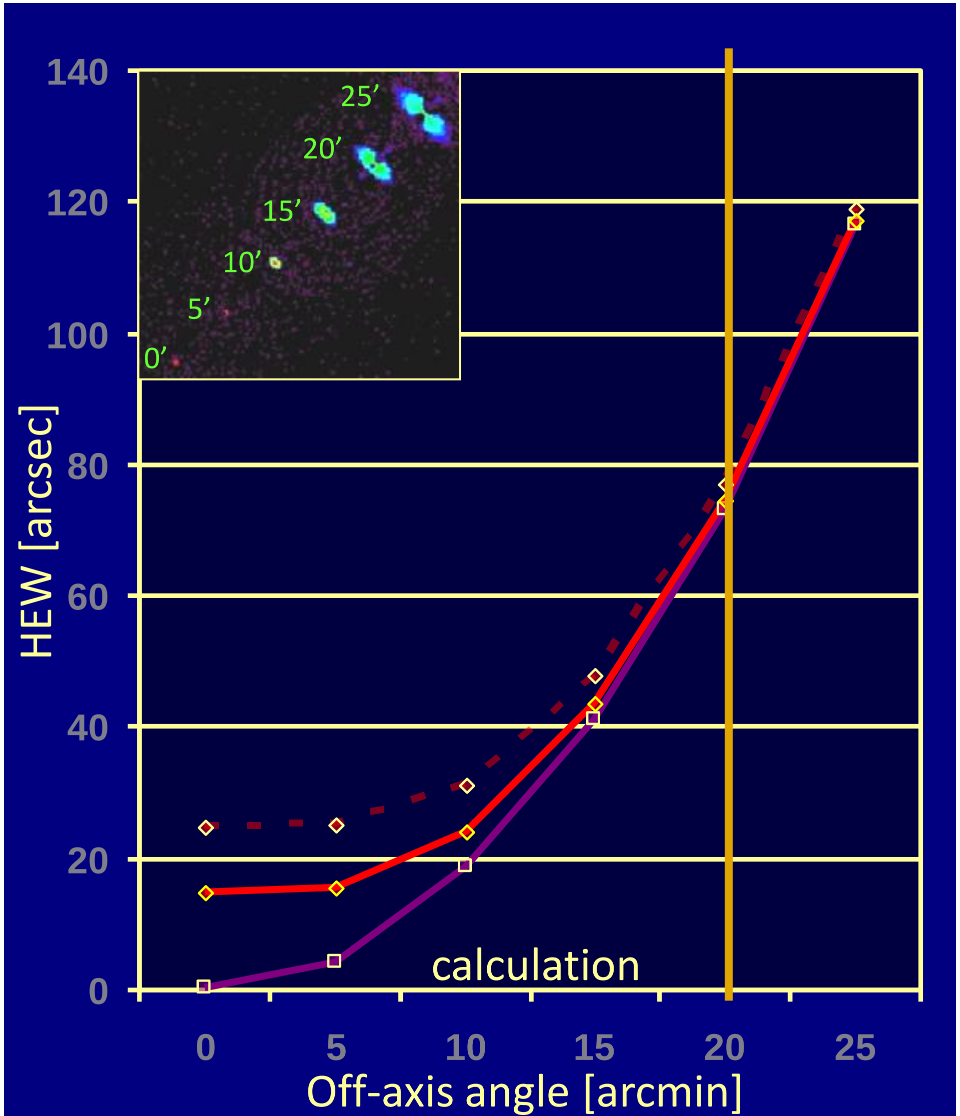
Cu-K

CREDITS: MPE

e-Rosita: Wolter I Point Spread Function (PSF)

(affected by off-axis aberrations)





Credits: MPE

X-ray optics with polynomial profile

- Mirrors are usually built in the Wolter I (paraboloid-hyperboloid) configuration which provides, in principle, perfect on-axis images.

- This design exhibits no spherical aberration on-axis but suffers from field curvature, coma and astigmatism, which make the angular resolution to degrade rapidly with increasing off-axis angles.

- More general mirror designs than Wolter's exist in which the primary and secondary mirror profiles are expanded as a power series;

- These polynomial solutions are well suited for optimization purposes, which may be used to increase the angular resolution at large off-axis positions, degrading the on-axis performances (Burrows, Burgh and Giacconi 1992)

In the design also the length of each mirror element, the shift among intersection-planes and the curvature of the focal plane system must be optimized (see Conconi et al., 2010)

Optimization of the Single Mirror Shell

$$M_{\mathrm{single}} = \sum_{j=0}^{n} (\mathrm{HEW}(\Theta_j) + \mathrm{EEF}_{80}(\Theta_j))/2 \times \Theta_j d\Theta_j$$

Best merit function for optimization of surveying telescopes

f = Focal Length / Shell Entrance Radius

l = (100 x Total Mirror Length / Focal Length)

$$\mathrm{HEW}(1\mathrm{keV},\ f,\ l) \simeq 0.075 \times f \times l - 0.3\ \mathrm{arcsec}$$

Simplified formula for the HEW of a polynomial optics (BBG, 1992) weighted over the FOV coming from the optimizations (Conconi et al., 2010)

Grasp

Grasp = A_{eff} x FOV → measured at 1.5 keV in cm^2 deg^2

- Grasp measures the speed in which a survey can cover an area of the sky down to a given flux limit.

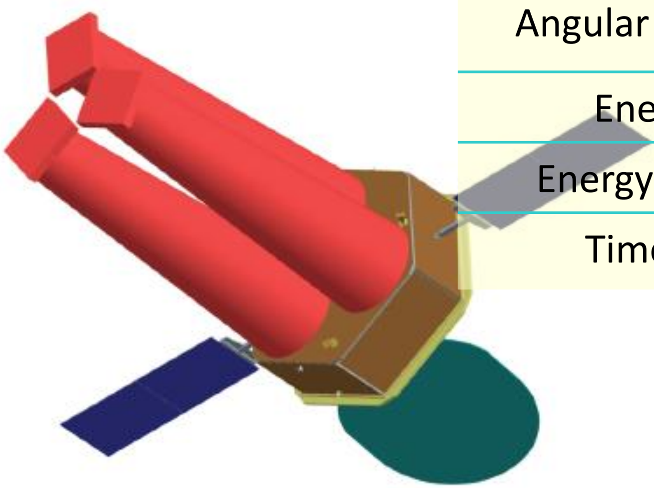
- Better angular resolution results in better efficiency and source identification.

	WFXT	eROSITA	XMM	ROSAT	IXO	Chandra
Grasp (cm^2 deg^2)	9000	1150	900	630	1500	50
HEW across the FOV (arcsec)	5/10	15-30	15-25	15-40	5	1-5

WFXT Scopes and Requirements

- medium class mission proposed to the Decadal Survey 2010
- Sky Surveys in X-ray for the discovery of high red-shift AGN and clusters of galaxies

Parameter	Requirement	Goal
Area at 1 KeV (cm^2)	6000	10000
Area at 4 KeV (cm^2)	2000	3000
Field of View diam.(degrees)	1	1.25
Angular Resolution (arcsec)	< 10 (HEW)	< 5 (HEW)
Energy Band (keV)	0.2 – 4	0.1 – 6
Energy Resolution ($\Delta E/E$)	> 10	> 20
Time Resolution (s)	< 3	< 1



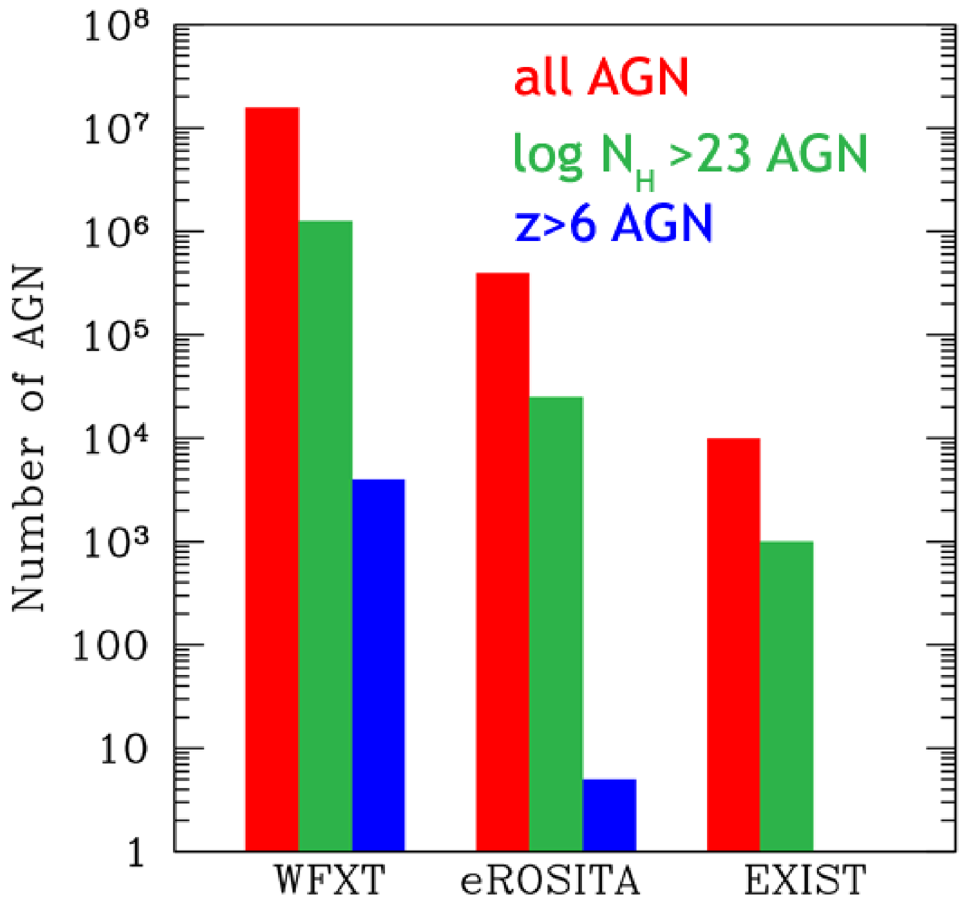
The Wide Field X-ray Telescope (WFXT) Mission, Stephen S. Murray et al. [7732-67] on Friday

2-order-of-magnitude more sensitive than any previous X-ray mission for large area survey

XMM: area 4500 cm^2 @ 1 keV, HEW 15”

CHANDRA: area 800-400 cm^2 @ 0.25-5 keV, HEW 0.5”

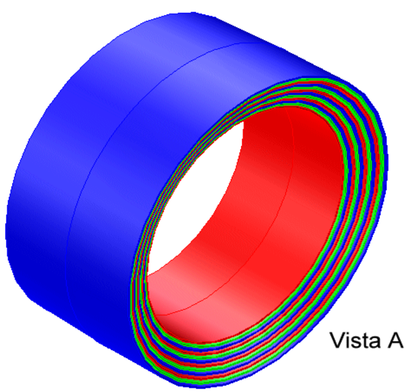
Science Highlights: AGN and Galaxies

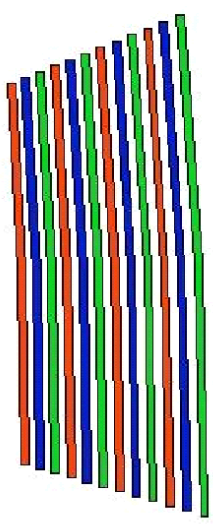


- *WFXT* will be an "X-ray *GALEX*", detecting $>10^7$ AGN, $>10^5$ galaxies
  - Luminosity function
  - Minimal bias
  - Environment and evolution
- Variability in AGN, galaxies (XRB and tidal captures)
- Deep survey will reach CDF depths

WFXT Optical Design

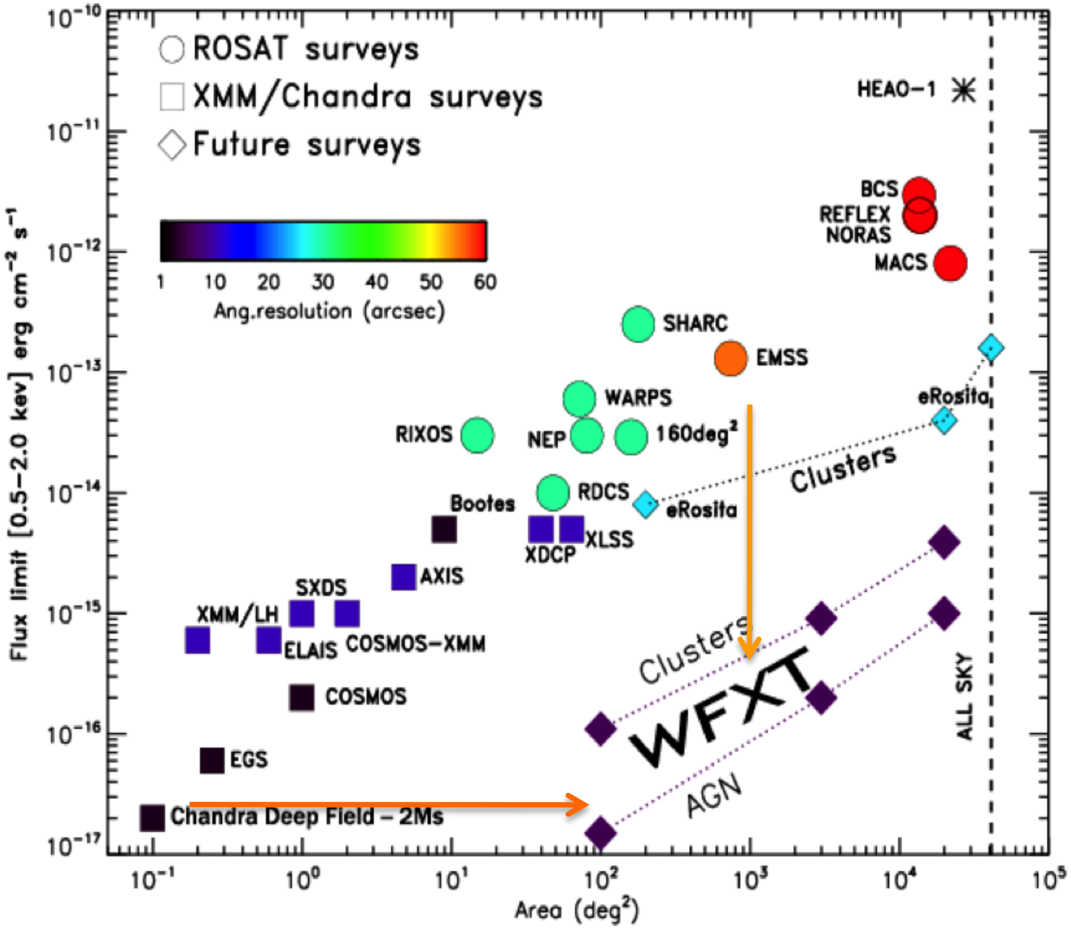
Focal Length	5500 mm
Number of Optics Modules	3
Numbers of Shells	78
Radius [min – Max]	165 – 550 mm
Total length [min – Max]	235 – 440 mm
Thickness [min – Max]	1.2 – 2.2 mm
Total on-axis Effective Area* (1 keV)	9236 cm^2
Total on-axis Effective Area* (4keV)	2565 cm^2
Total Weight (3 modules)**	780 kg





Chandra t 20 mm, XMM t 0.5-1 mm

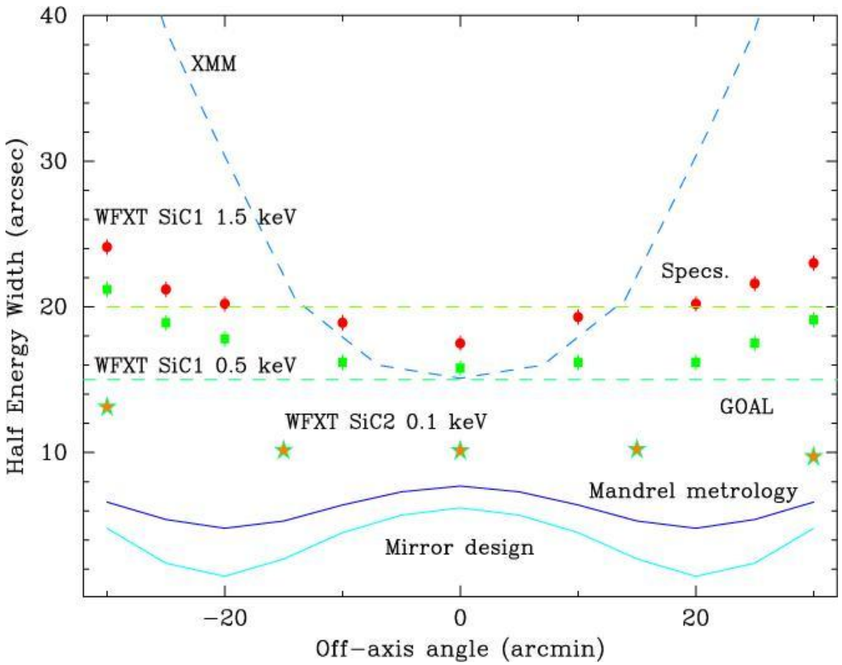
Sensitivity

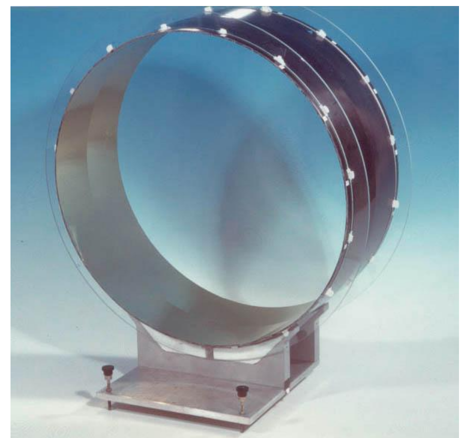


- WFXT sensitivity provides orders of magnitude increase over other missions
- The good angular resolution easily identifies extended sources and avoids confusion

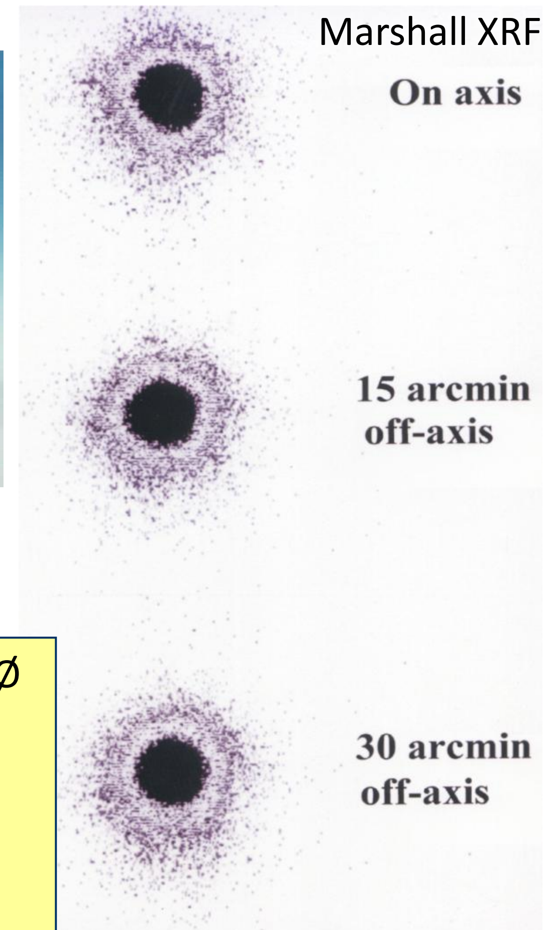
WFXT heritage (SiC by epoxy replication)

see O. Citterio, et al., ", SPIE Proc., 3766, 198 (1999) Ghigo et al., SPIE Proc., 3766, 209 (1999)





Tests @ Panter-MPE & Marshall XRF



WFXT (epoxy replication on SiC) Ø = 60 cm

Height = 20 cm

F. L. = 300 cm

HEW = 10 arcsec @ 0.1 keV

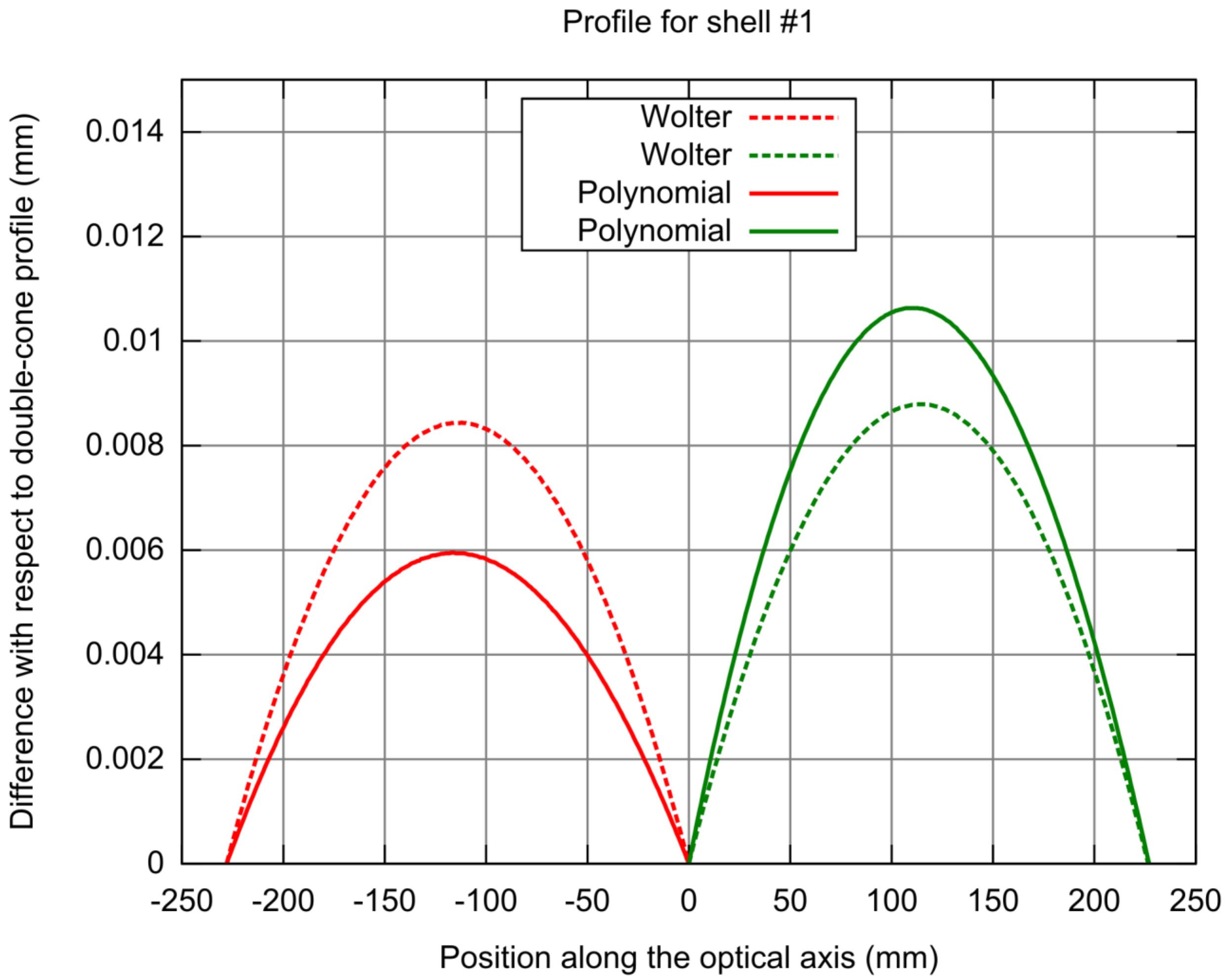
Ni replication with same mandrel Ø = 60 cm

Height = 20 cm

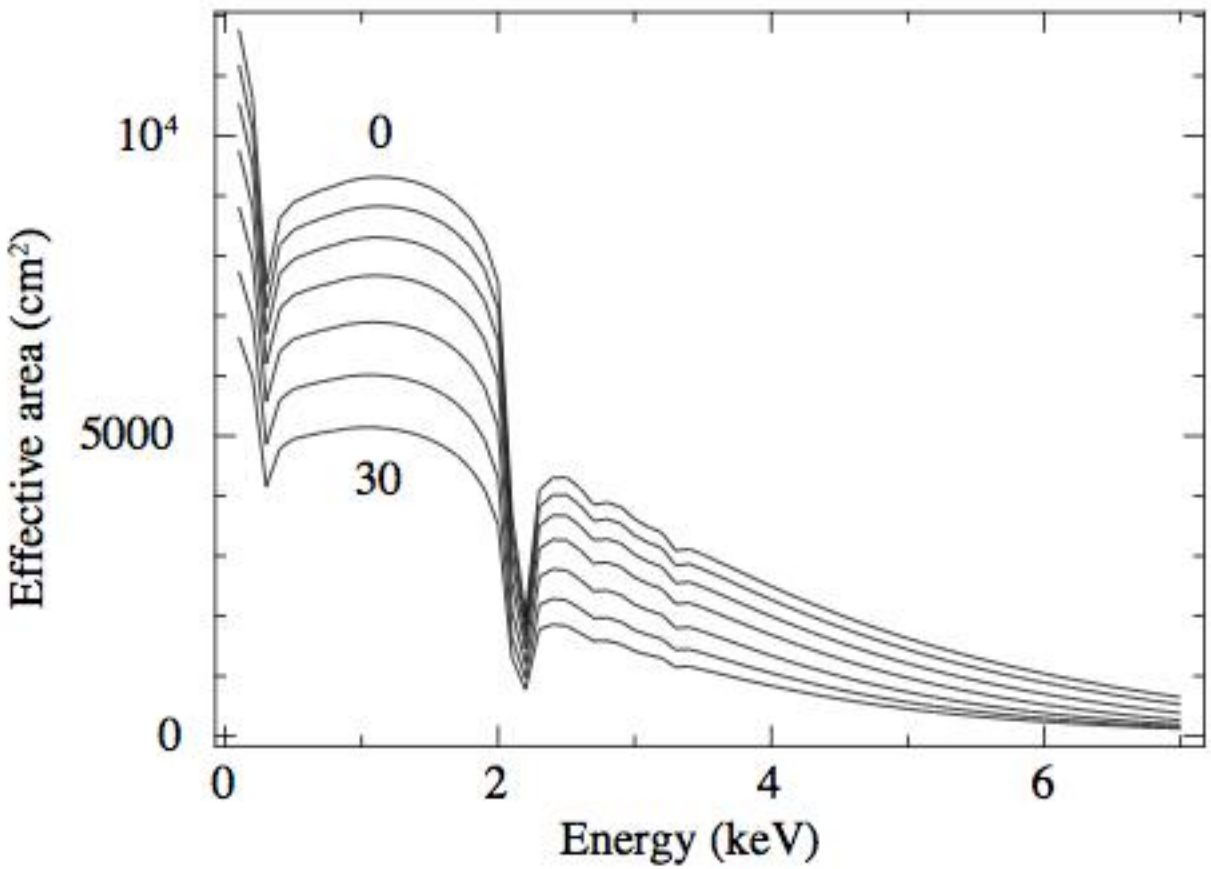
F. L. = 300 cm

HEW = 35 arcsec @ 0.28 keV

Sag of the first polynomial mirror wrt a Wolter I

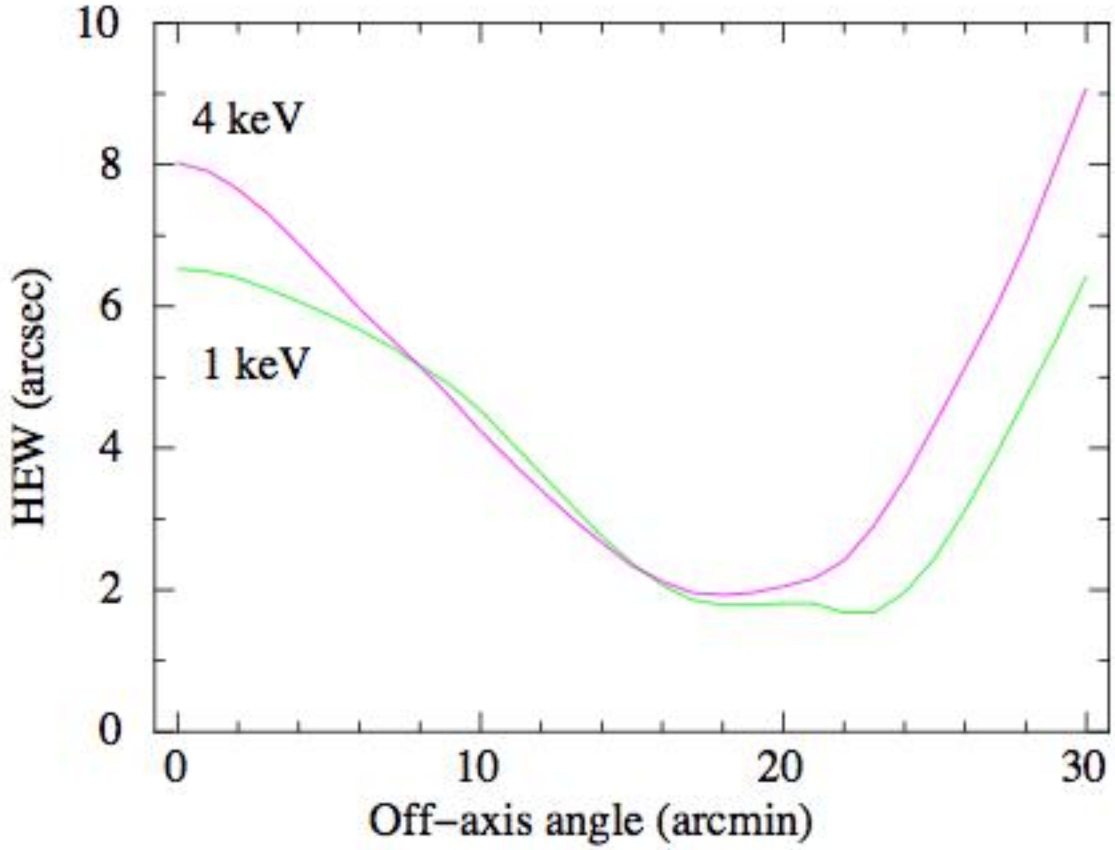


Effective area for Glass



Coating: Pt + C overcoating

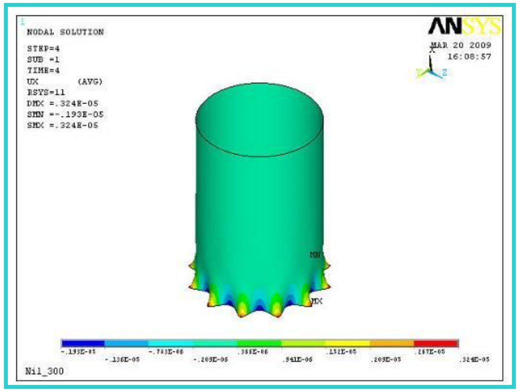
HEW for the mirror module (theoretical design)



N.B.: Manufacturing and integration errors not yet included

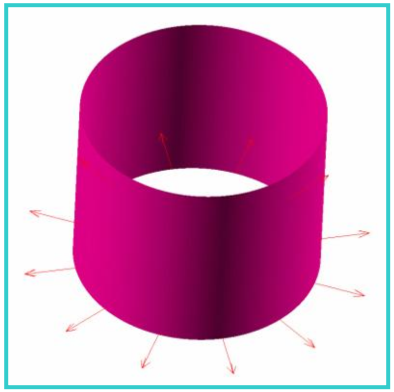
Challenge of thin shells with small aspect ratio

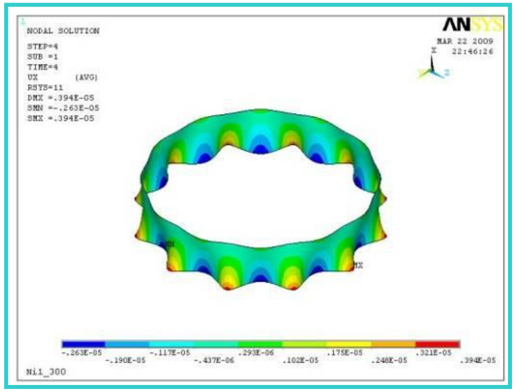
Small aspect ratio ➔ difficulty in reaching good angular resolution because they are **more sensitive to perturbing effects related to edges loads**:



- mechanical behavior closer to a “belt-like” configuration rather than a “tube-like”
- border effect errors with a much higher weight in determining the PSF
- angular resolution more strongly affected by the slope errors caused by out-of-phase azimuthal errors

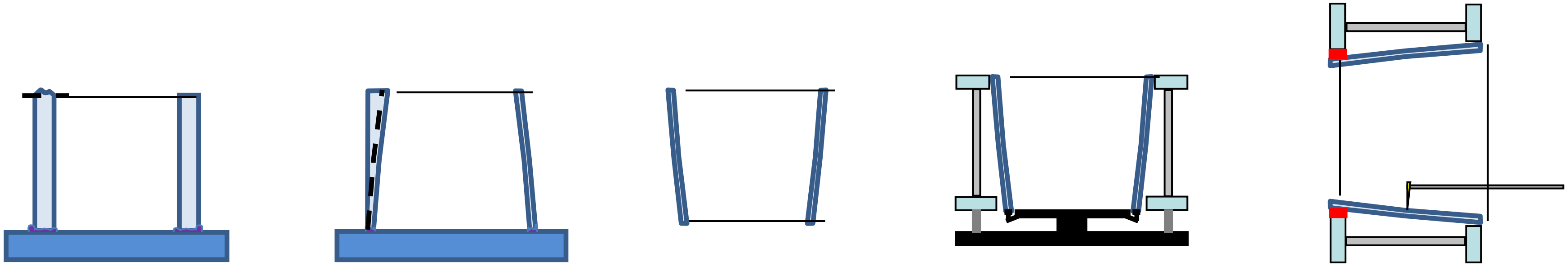
12 r F 0.1N in 12 front section points 30°



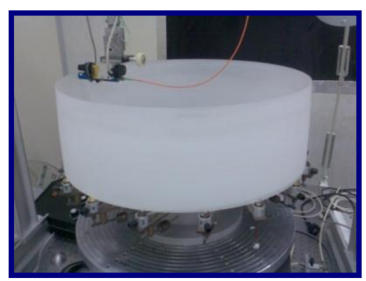


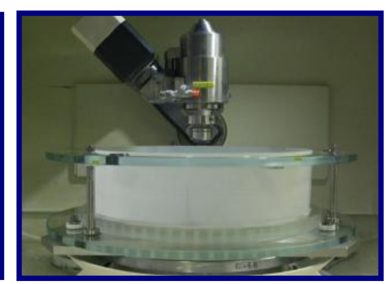
very short MSs show degradation 6-16 times larger with respect to long MS

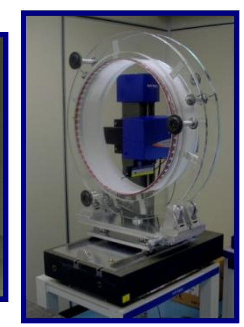
Quartz Direct Polishing Approach



Raw material is a Quartz tube available on the market	**Grinding of the quartz tube**	**Delivery of the carrier**	**Integration on a suitable interface structure by means of an astatic support**	**Polishing and last manufacturing steps until final integration in the mirror structure**







Grinding RESULTS

Grinding run	Shell #	Out of Roundness [µm]	Profile error (peak to valley) [µm]	Lesson learned
1	1	76	/	•Feasibility of the grinding process. •Definition of metrology and support systems. • no astatic support (large uncertainties)
1a	2	73	/	
2	3	45	11	•Analysis of the grinding process. •Improvement in SSS and fixation procedure.
	4	61	10	
	5	61	16	
	6	305	16	
2a	3	/	/	•Broken during re-grinding tests to improve the fixation
C.E. 3 sss3	7	9	8	•Improvement in the fixation of the shell during grinding
	8	5	6	

Polishing Step

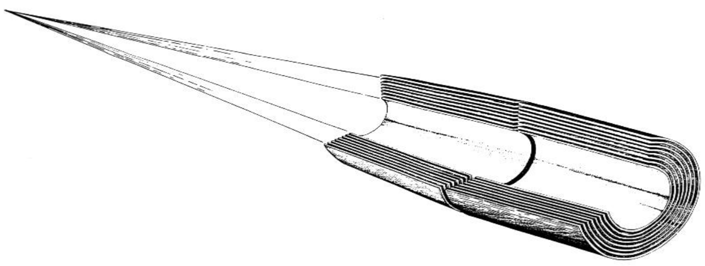
- IRP 600 Machine developed by ZEEKO (UK)
- 7 axis CNC machine tool controller
- Bonnet tool can be used for:
  - Grolishing (grinding/polishing) coarser-higher removal rate
  - Polishing

Test @ Panter/MPE by winter 2010?

Shell on IRP 600 machine during a grolishing phase

High energy optics (an imaging!)

Focusing in the hard X-ray region (> 10 keV)



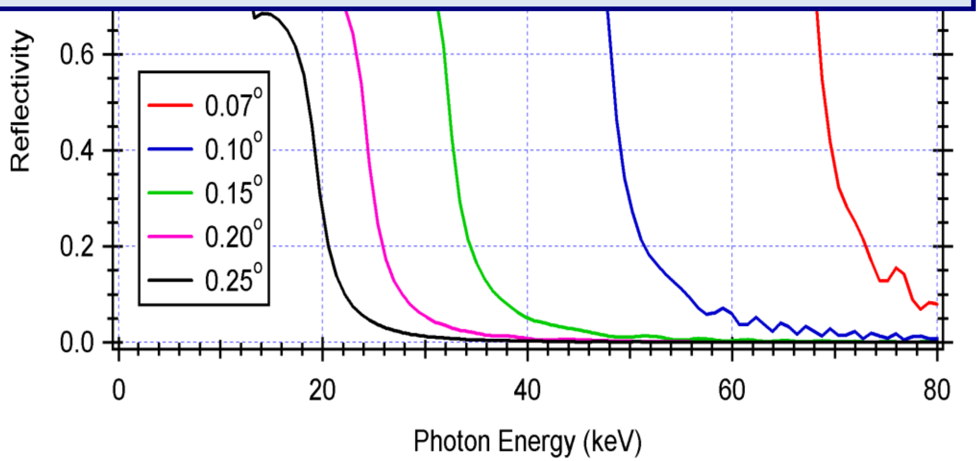
$$A_{eff} \approx F^2 \times \theta_c^2 \times R^2$$

At photon energies > 10 keV the cut-off angles for total reflection are very small also for heavy metals

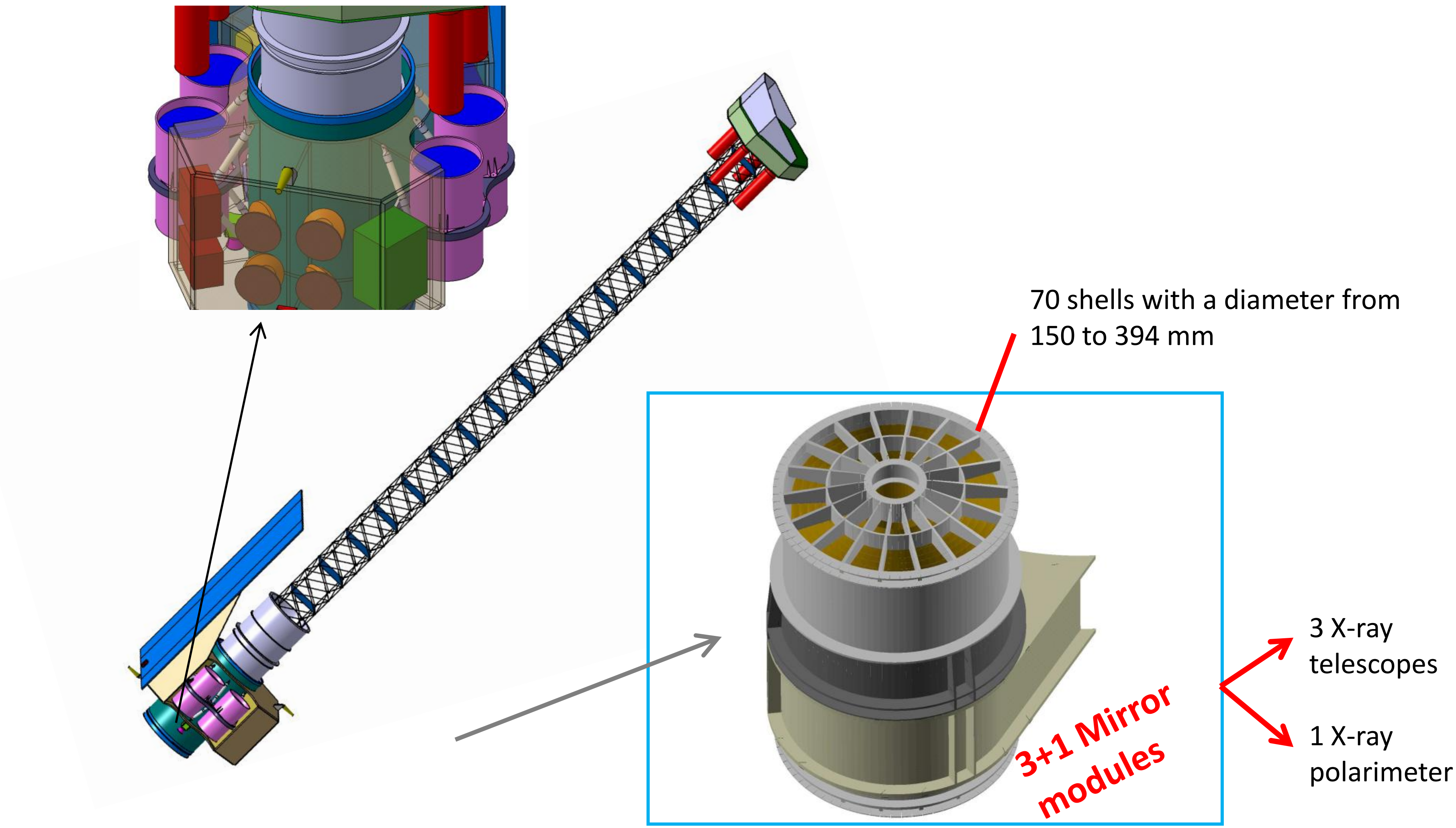
➔ **the geometrical areas with usual focal lengths (> 10 m) are in general <u>negligible</u>**

but

$$\vartheta_{crit} \propto \frac{\sqrt{\rho}}{E}$$



The NHXM mission



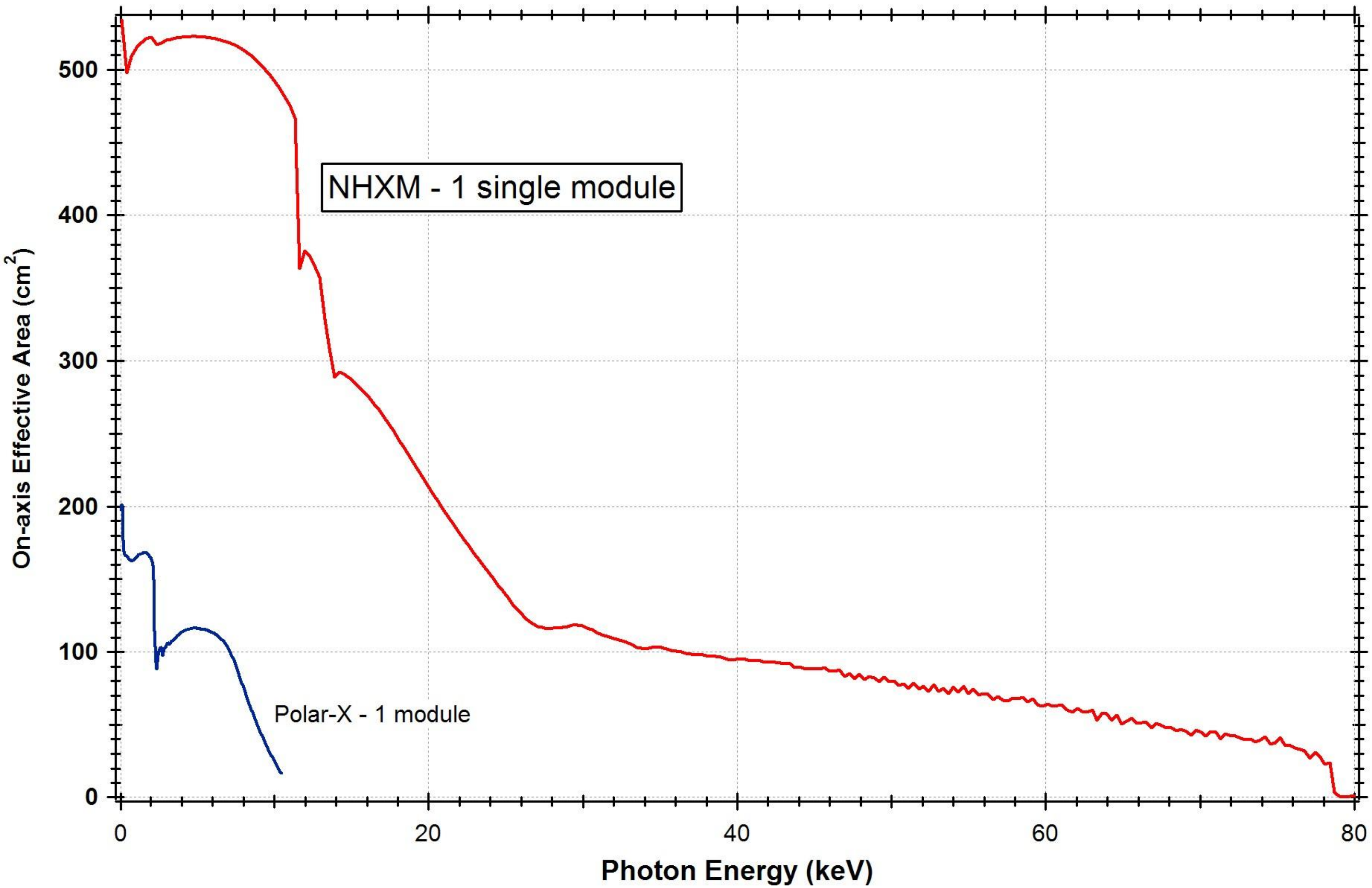
NHXM Optics Requirements

# of Telescopes		3+1
Energy band (keV)		0.5 ÷ 80
Effective area (for 3 MM) (cm^2)	at 30 keV	350
	at 5 keV	1000
Focal Length (meters)		10
Field of View diameter (50% E.A. @30keV) (arcmin)		12
Half Power Diameter at 30 keV (arcsec)		20

Angular resolution for past & future Hard X-ray Experiments

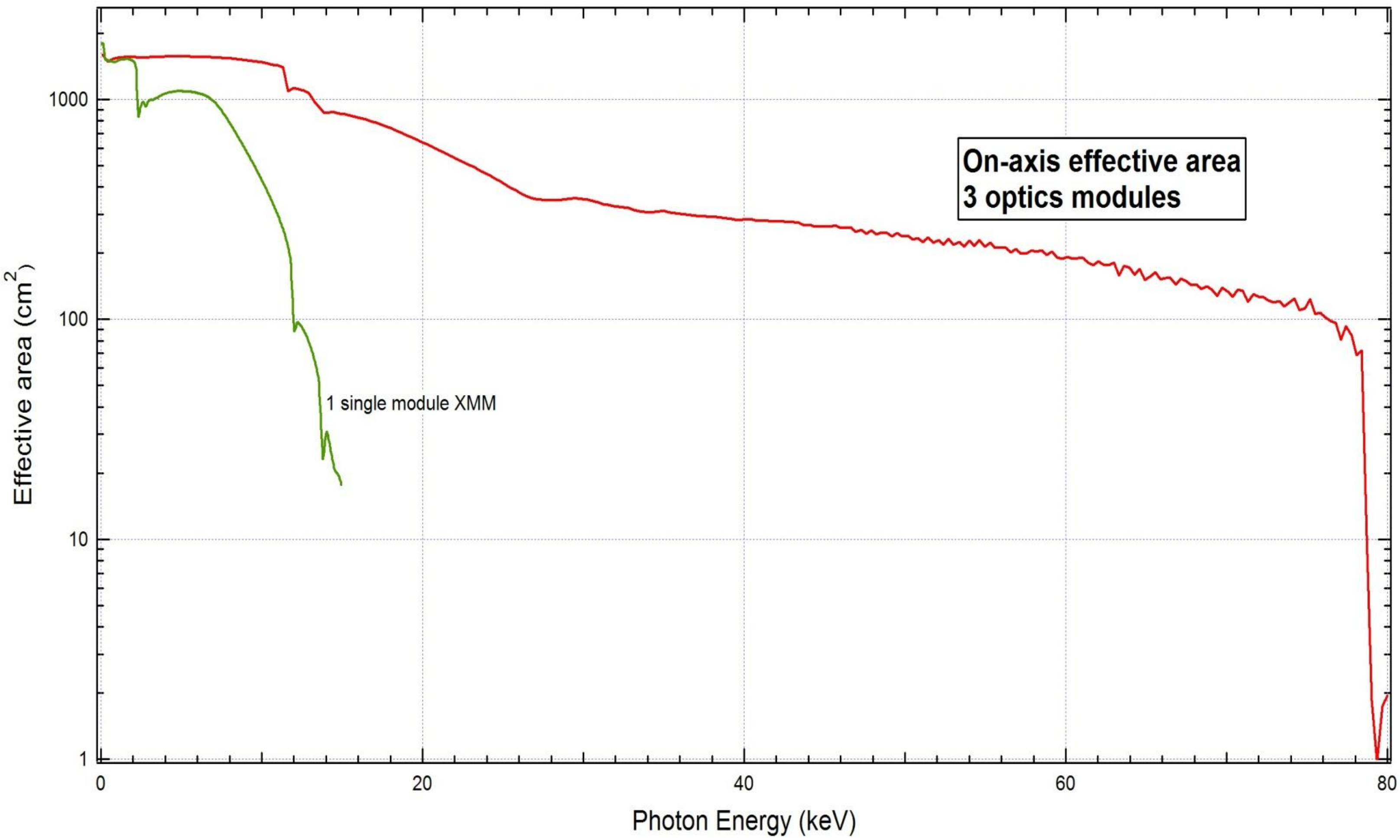
Experiment	Year	"Imaging" technique	Angular resolution
SAX-PDS	1996	Rocking collimator	> 3600 arcsec (collimator pitch)
INTEGRAL-IBIS	2002	Coded mask	720 arcsec (mask pitch)
HEFT (baloon)	2005	Multilayer Wolter I mirrors	> 90 arcsec HEW
NUSTAR	2012	Multilayer Wolter I mirrors	60 arcsec HEW
ASTRO-H	2016	Multilayer Wolter I mirrors	120 arcsec HEW
NHXM	**2017**	**Multilayer Wolter I Optics**	**20 arcsec HEW**

Effective Area (1 module)

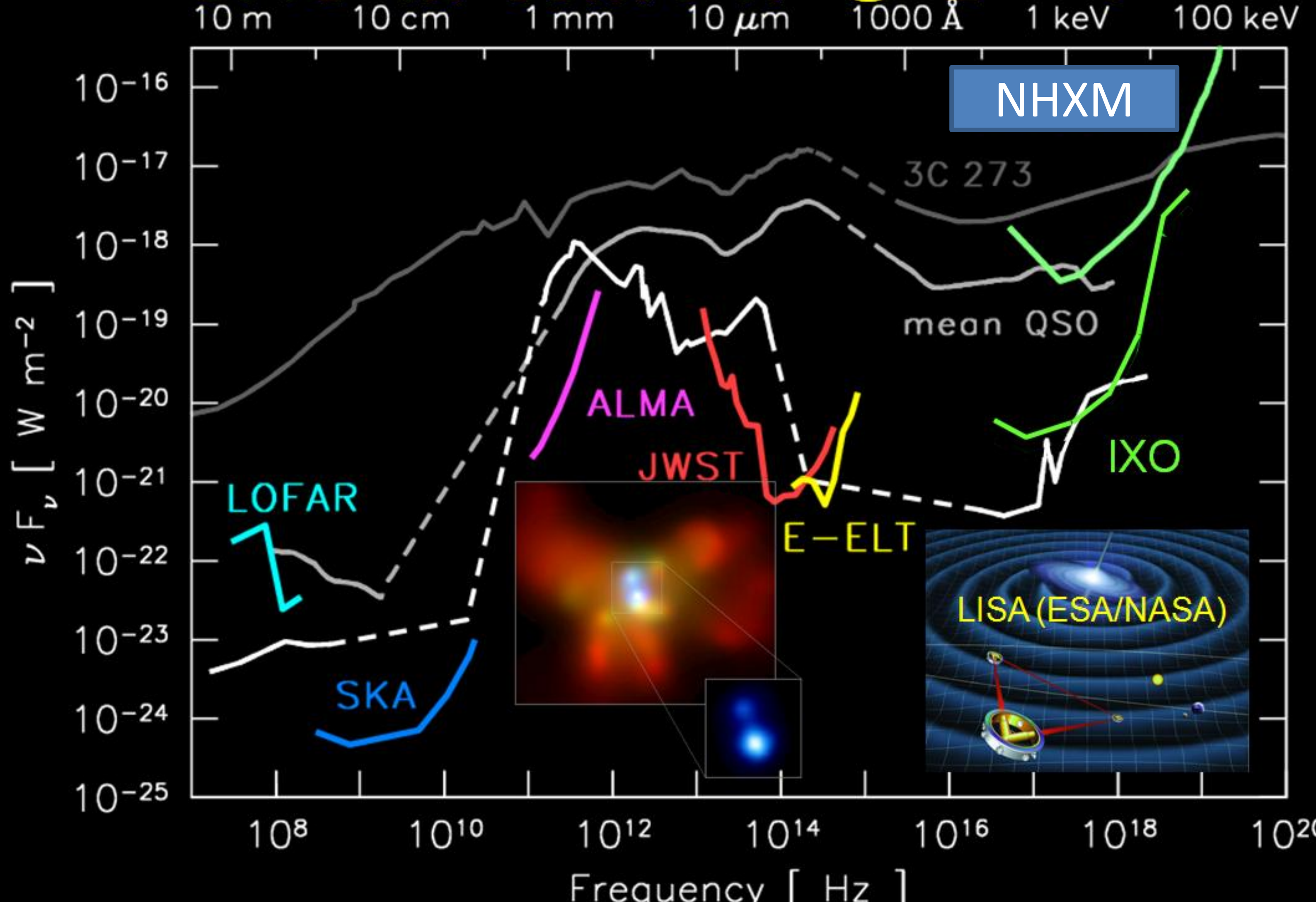


12 arcmin FOV (diameter, 50% vignetting @ 30 keV)

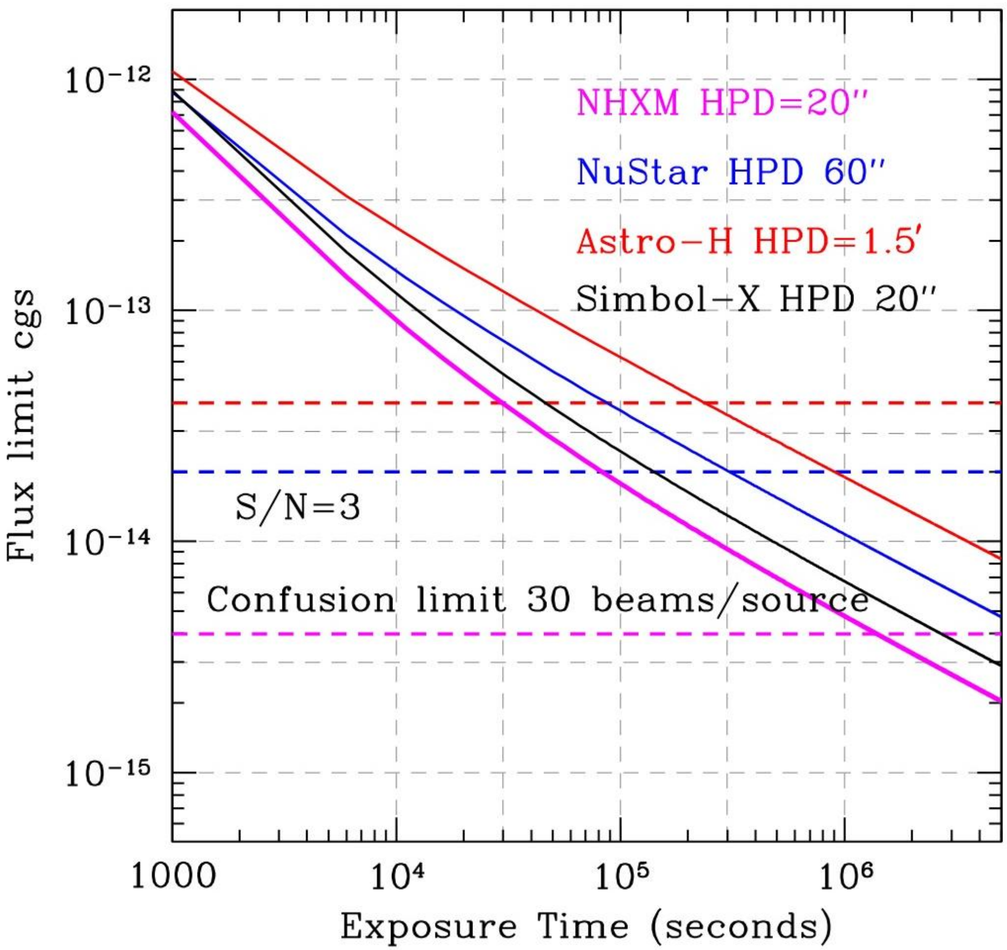
Effective Area (3 modules)



IXO in context @ z=10



Flux sensitivity



Sources per field (10 – 40 keV):

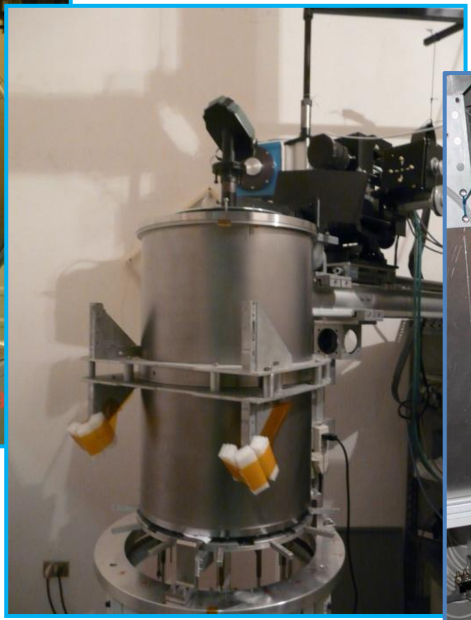
- **Nustar → 6**
- **Astro-H → 1**
- **NHXM → 40**

Tecnology Demonstrator Model 1 (TDM1)

3 mirror shells,
600 mm length,
10m focal length:

	#1	#2	#3
Diameter	286	291	297
thickness	0.25	0.25	0.25
Multi-layer	90 W-Si	200 W-Si	200 W-Si

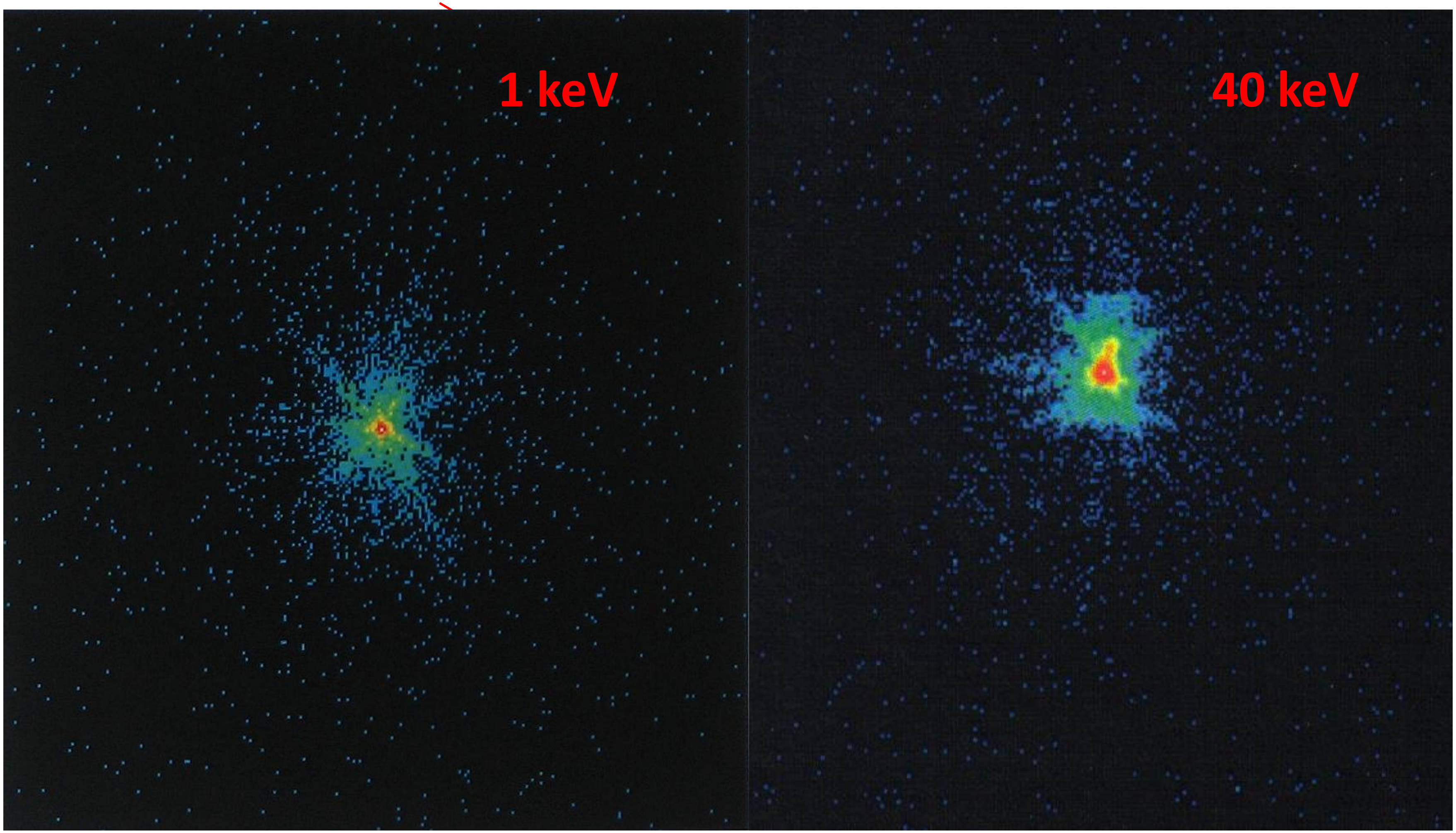
Mechanical structure: 2 spiders with 20 spokes



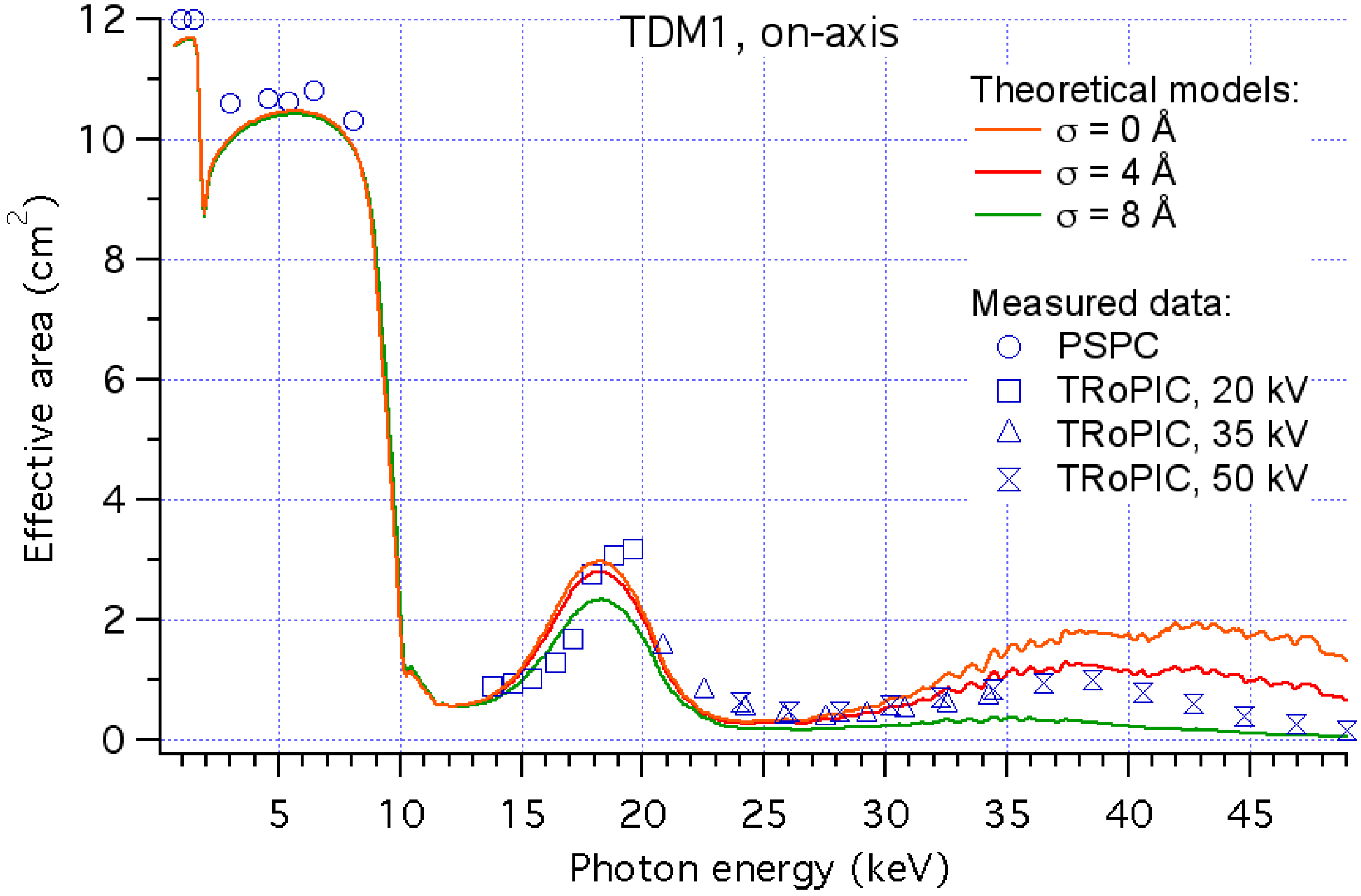
Integration of three mirror shell

PANTER tests

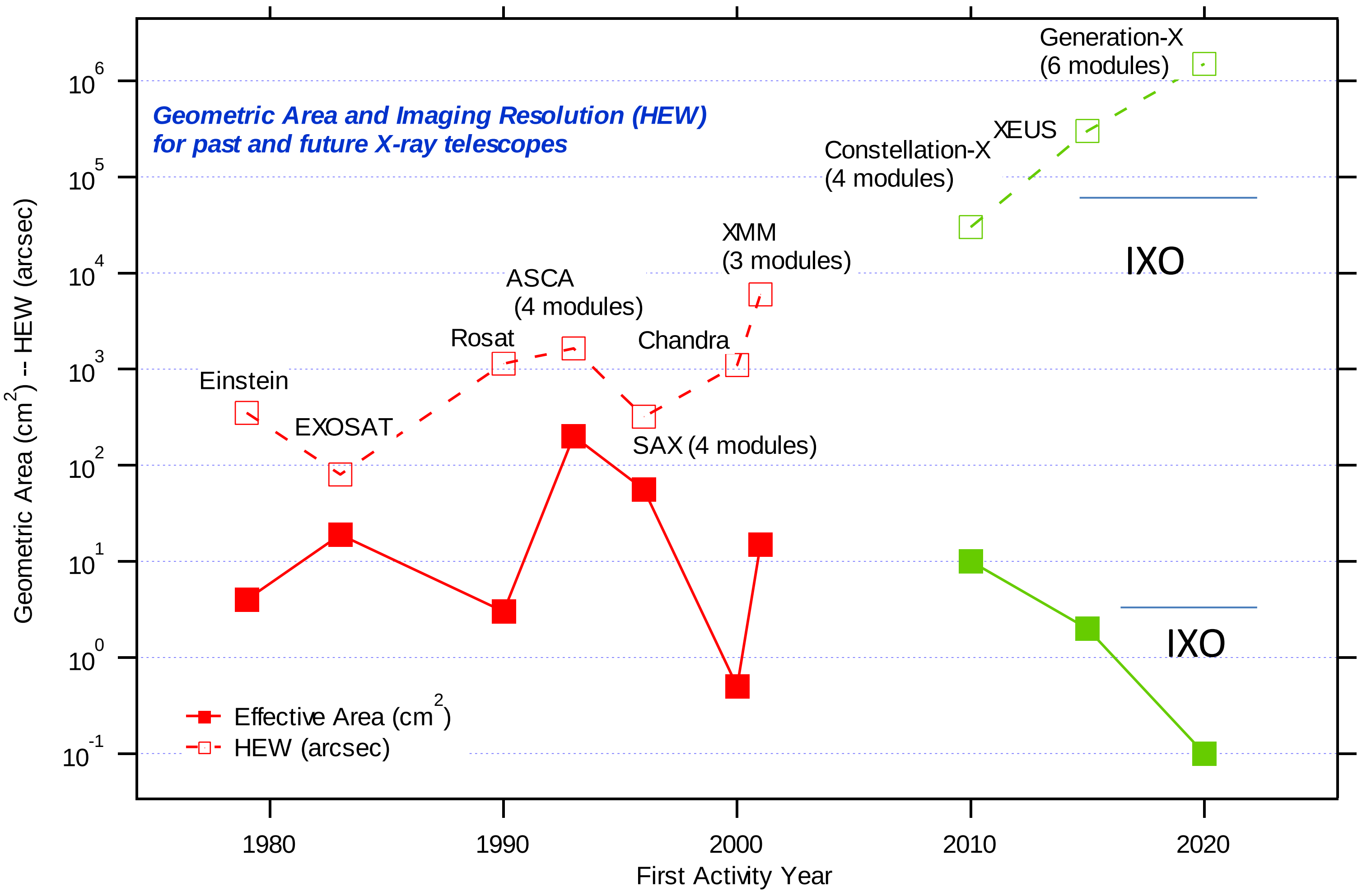
Optics calibration @ Panter/MPE



Tecnological Demonstrator Model 1 (TDM1)



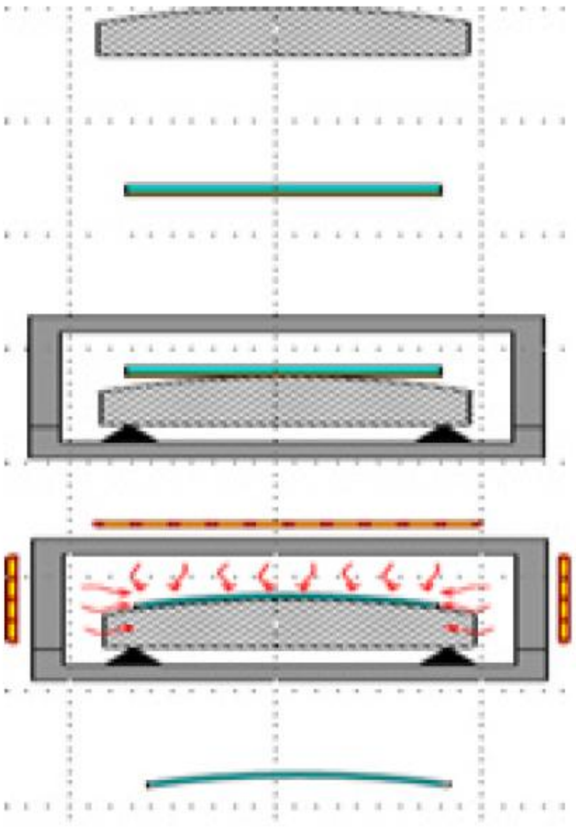
Geometric Area and Angular resolution for past and future X-ray telescopes



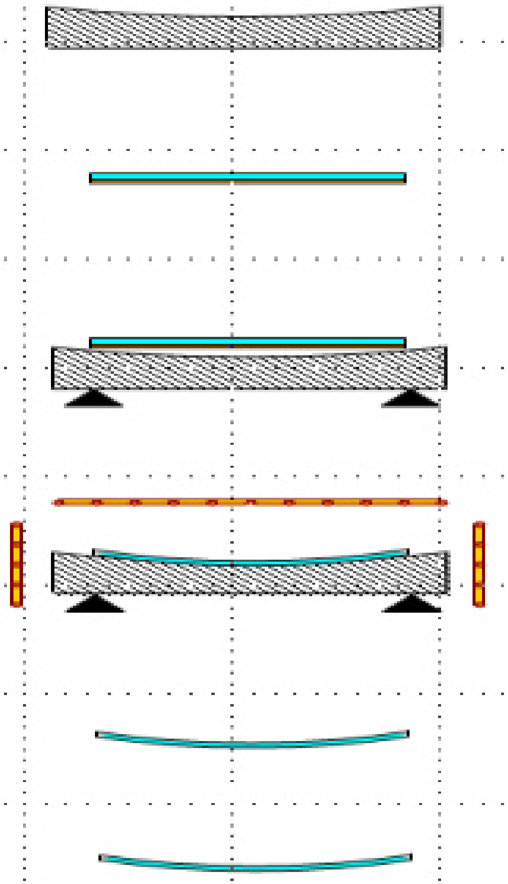
BACK-UP IXO (FORMER XEUS) OPTICS TECHNOLOGY PHASE 1

Direct & Indirect slumping processes

DIRECT



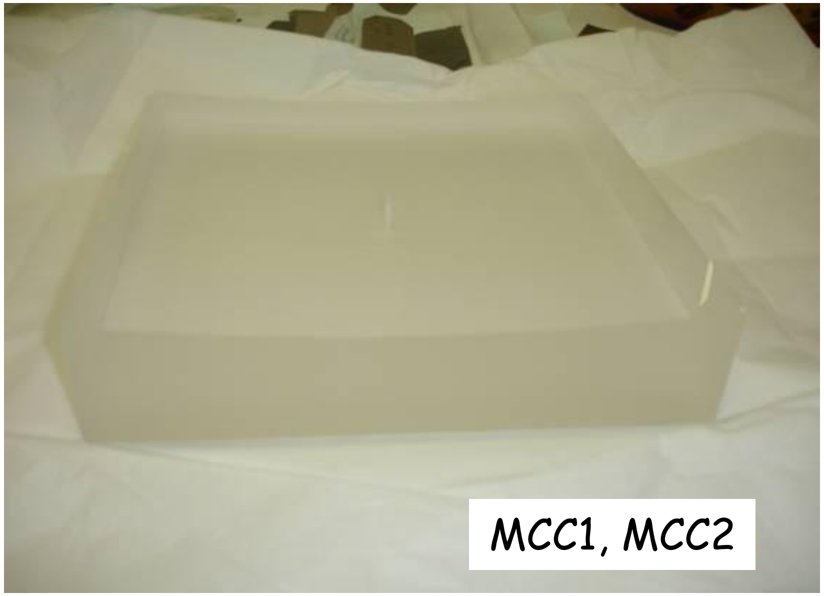
INDIRECT



Introduction: Materials and Definitions

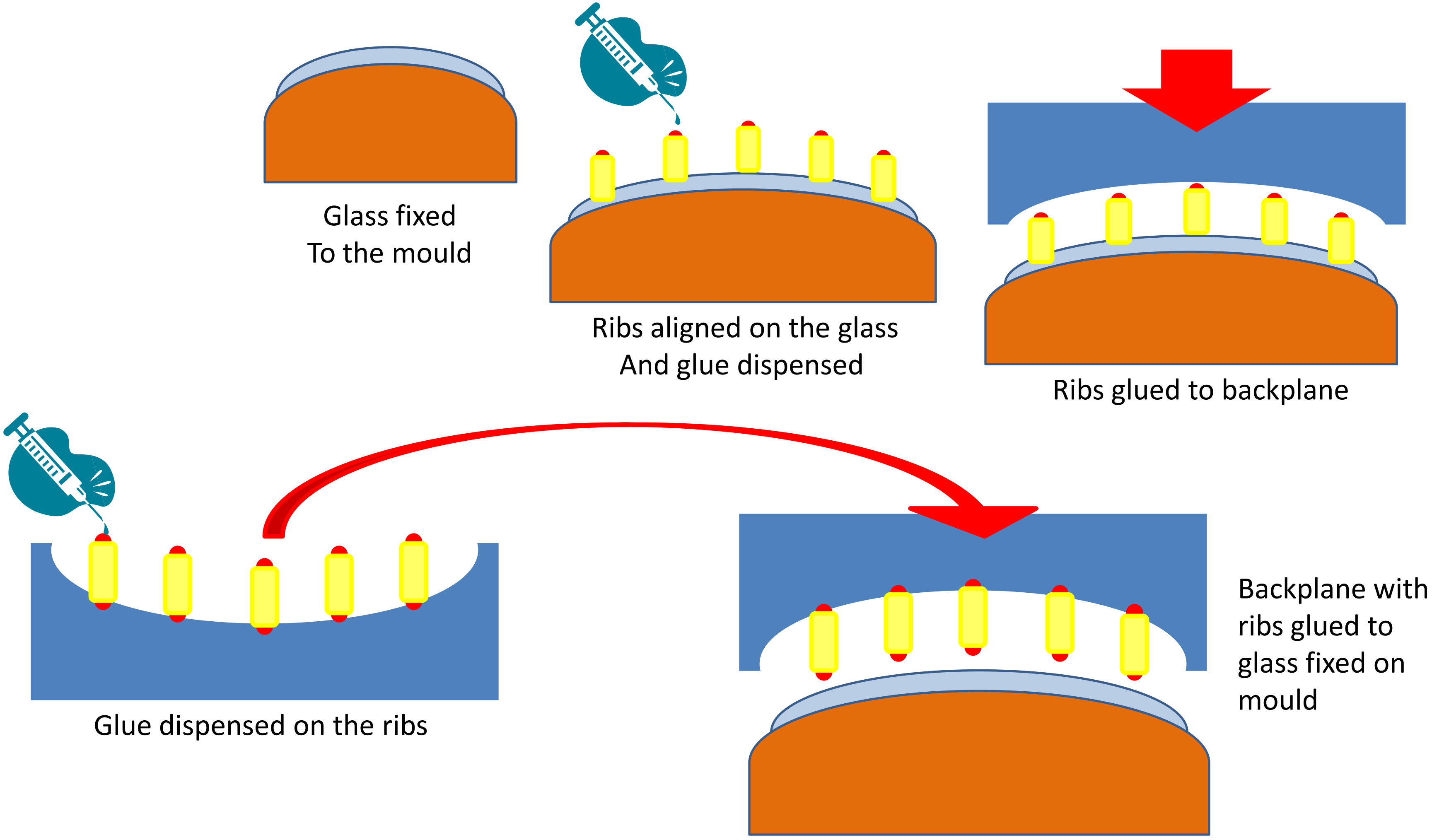
Fused Silica Cylindrical moulds,
250x250x50mm,
Radius of Curvature = 1 m,
Pt coated / Cr-PT coated

Selected for cost and delivery time constrain

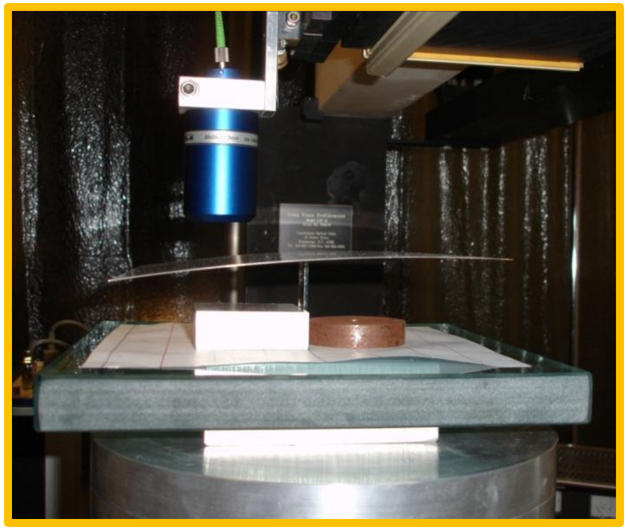


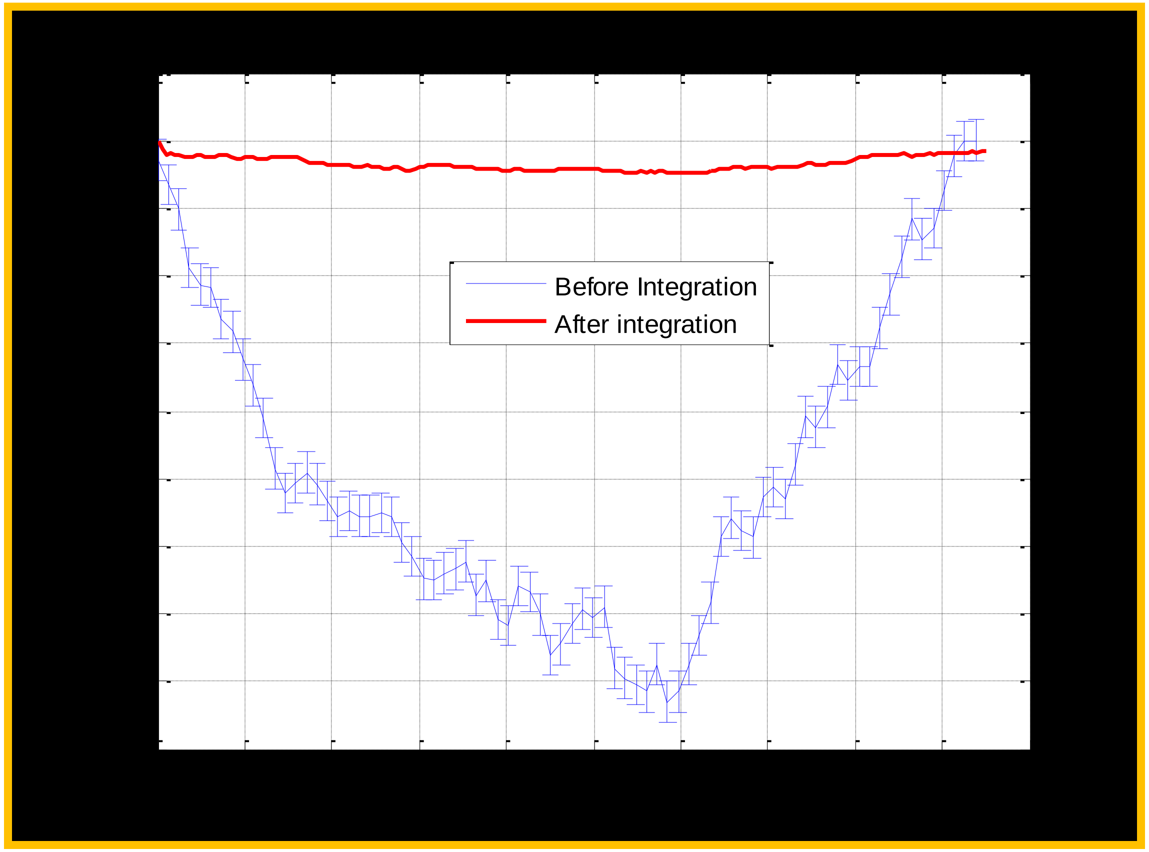
Convex and Concave cylindrical **moulds** as delivered by Hellma Optik

Slumped glass integration



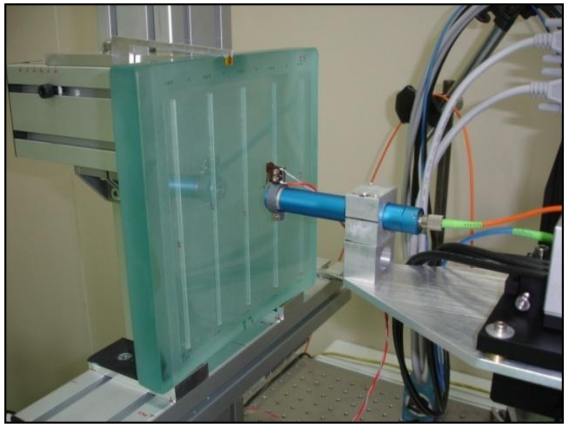
Longitudinal profile before/after integration

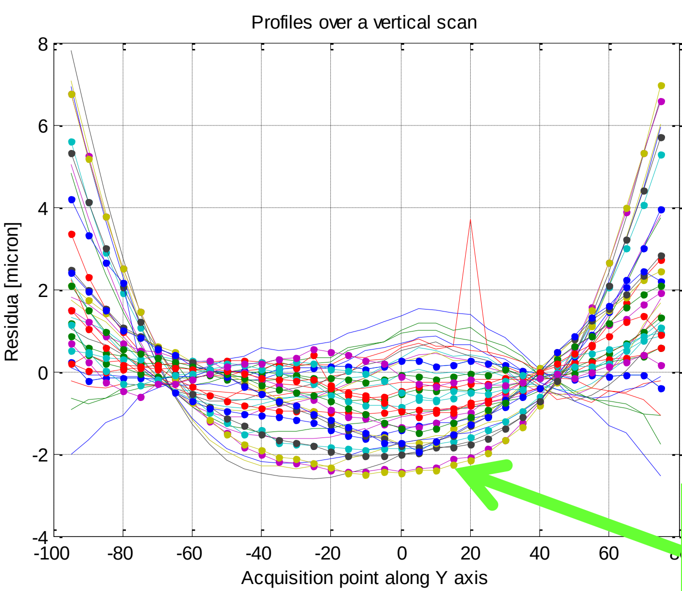




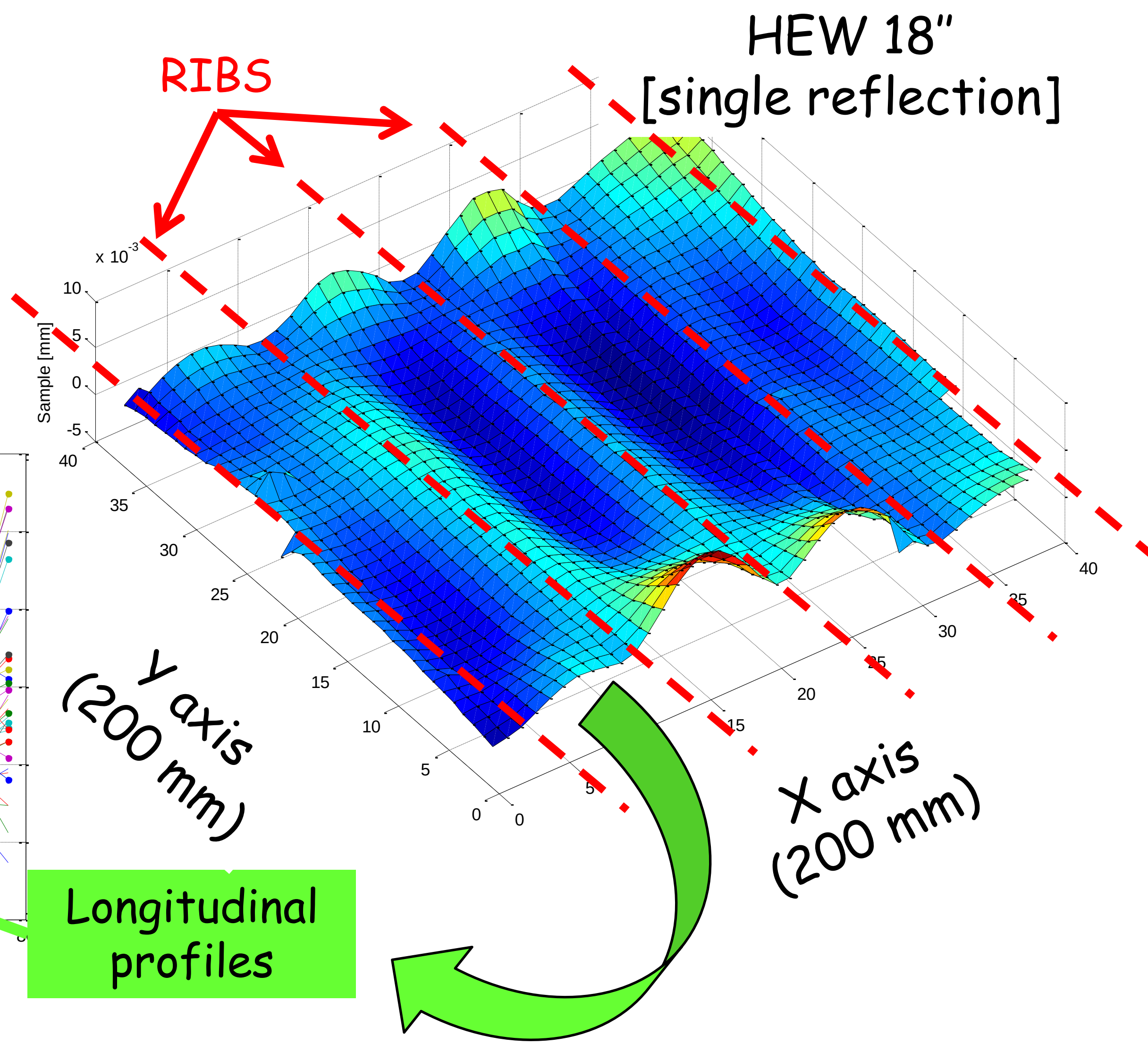
Possible error due to Incorrect positioning of the sample

Integrated sample results

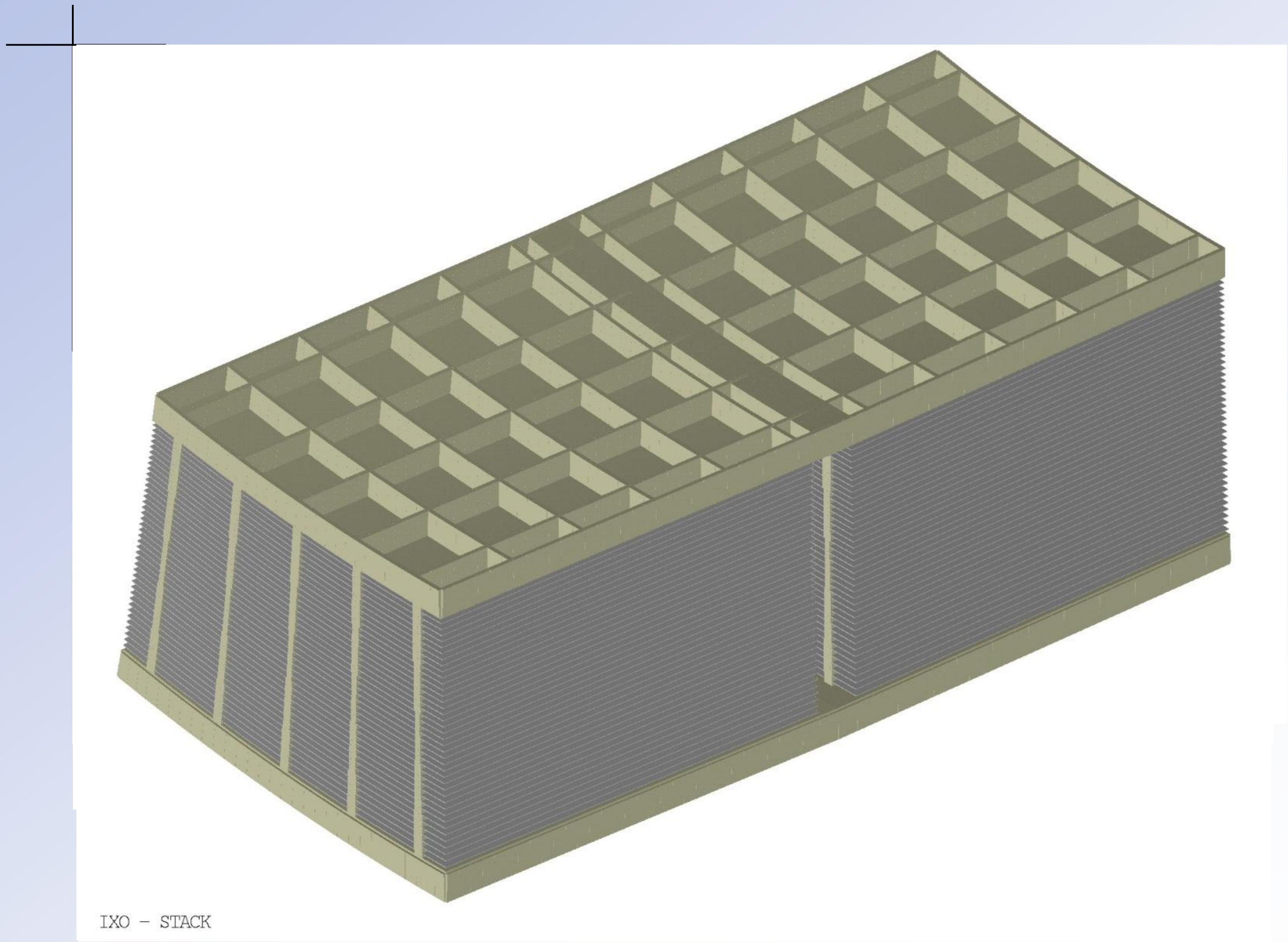




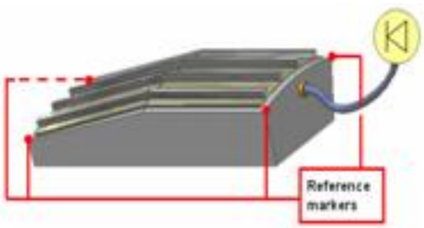
Longitudinal profiles

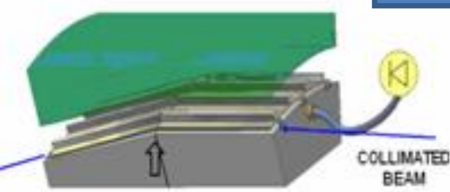


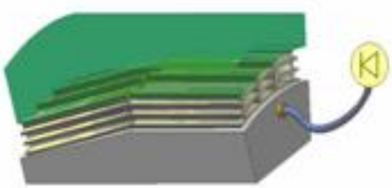
THE INTEGRATION CONCEPT

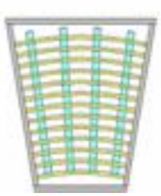


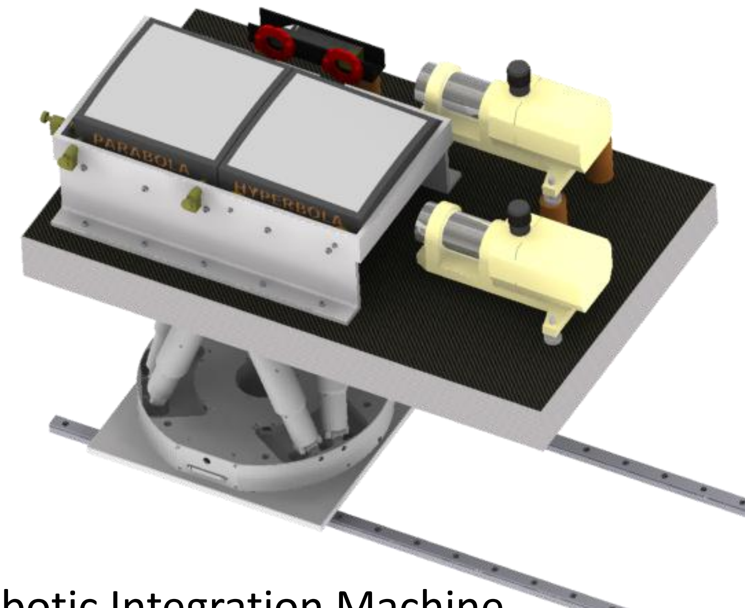
Integration concept based on the use of connecting/reinforcing ribs



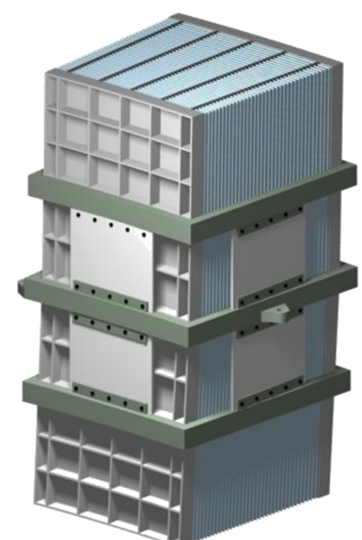








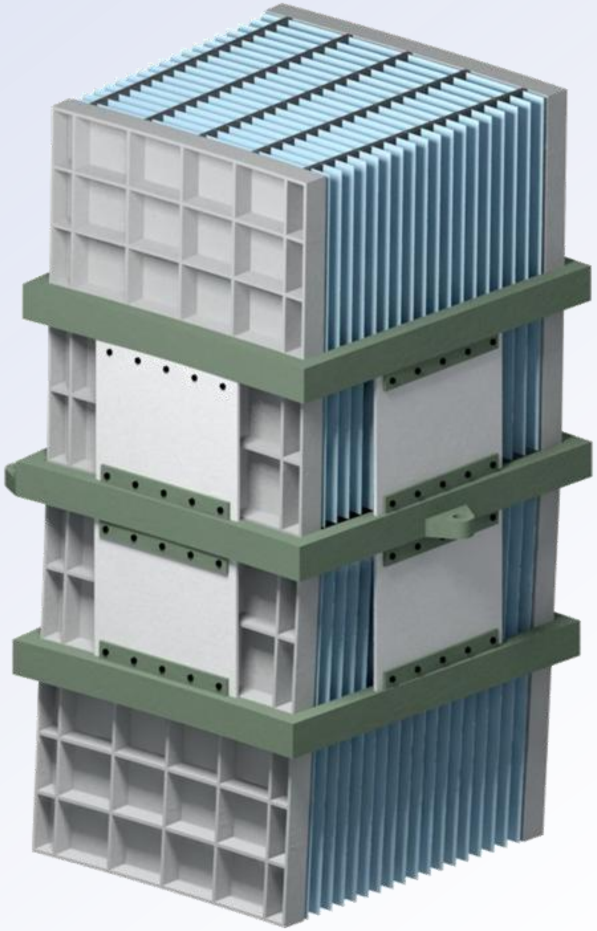
Robotic Integration Machine



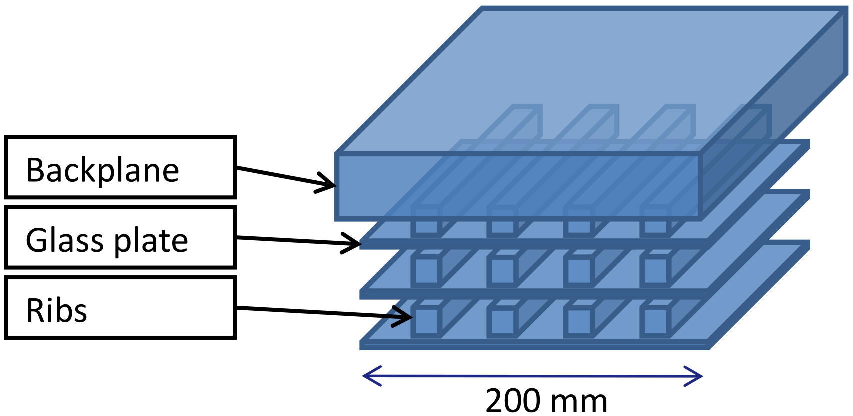
Integrated unit

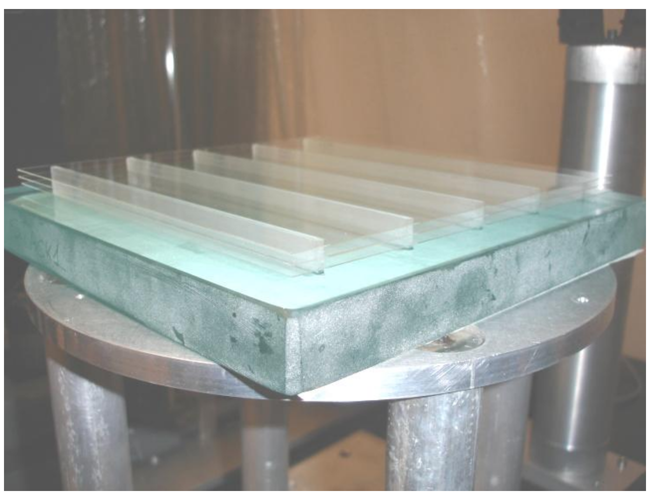
BASELINE XOU CONFIGURATION

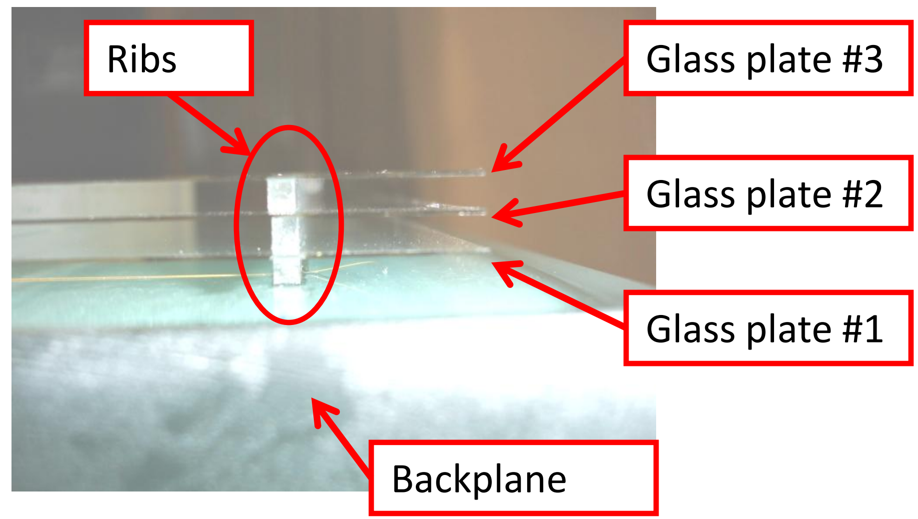
- External Titanium frame with system of flexures decoupling module deformation from FMA primary structure (or petal) deformation.
- Simple supporting substructure
- Simple I/F frame with decoupling flexures



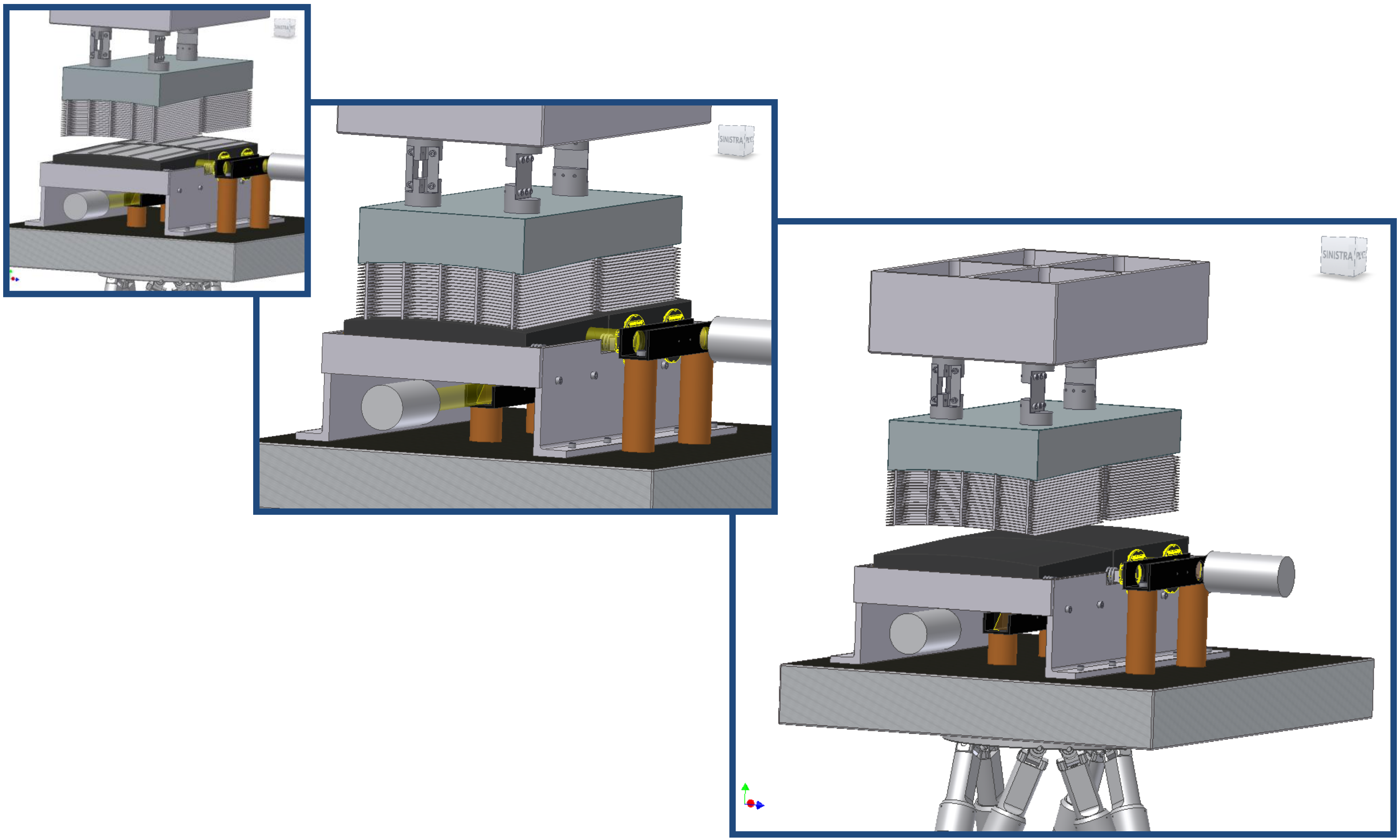
Subsystem	Number	Material	Size (L x W x H)
Backplane	1	Float glass	230 x 230 x 24.5
Ribs	5 x 3	BK7	190 x 3.0 x 2.6
Glass plates	3	D263 ECO	200 x 200 x 0.38
Glue	-	EP30-2	-



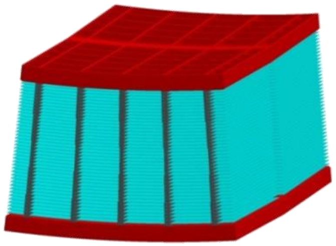


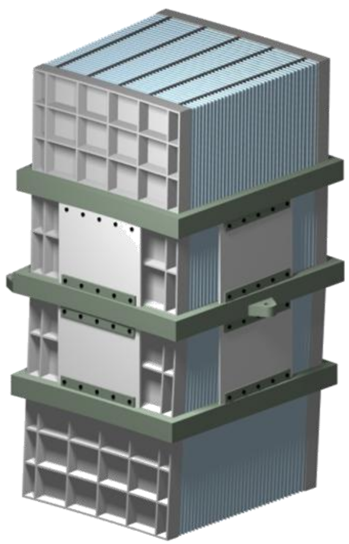


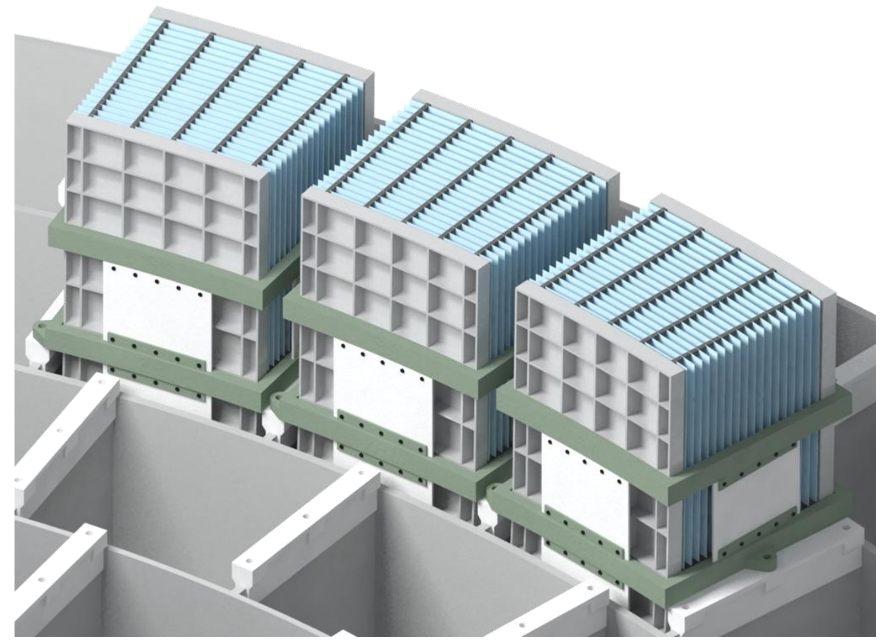
PP Integration steps with IMA



From the double plated stack (with ribbed glass back-plates) to the optics module assembly



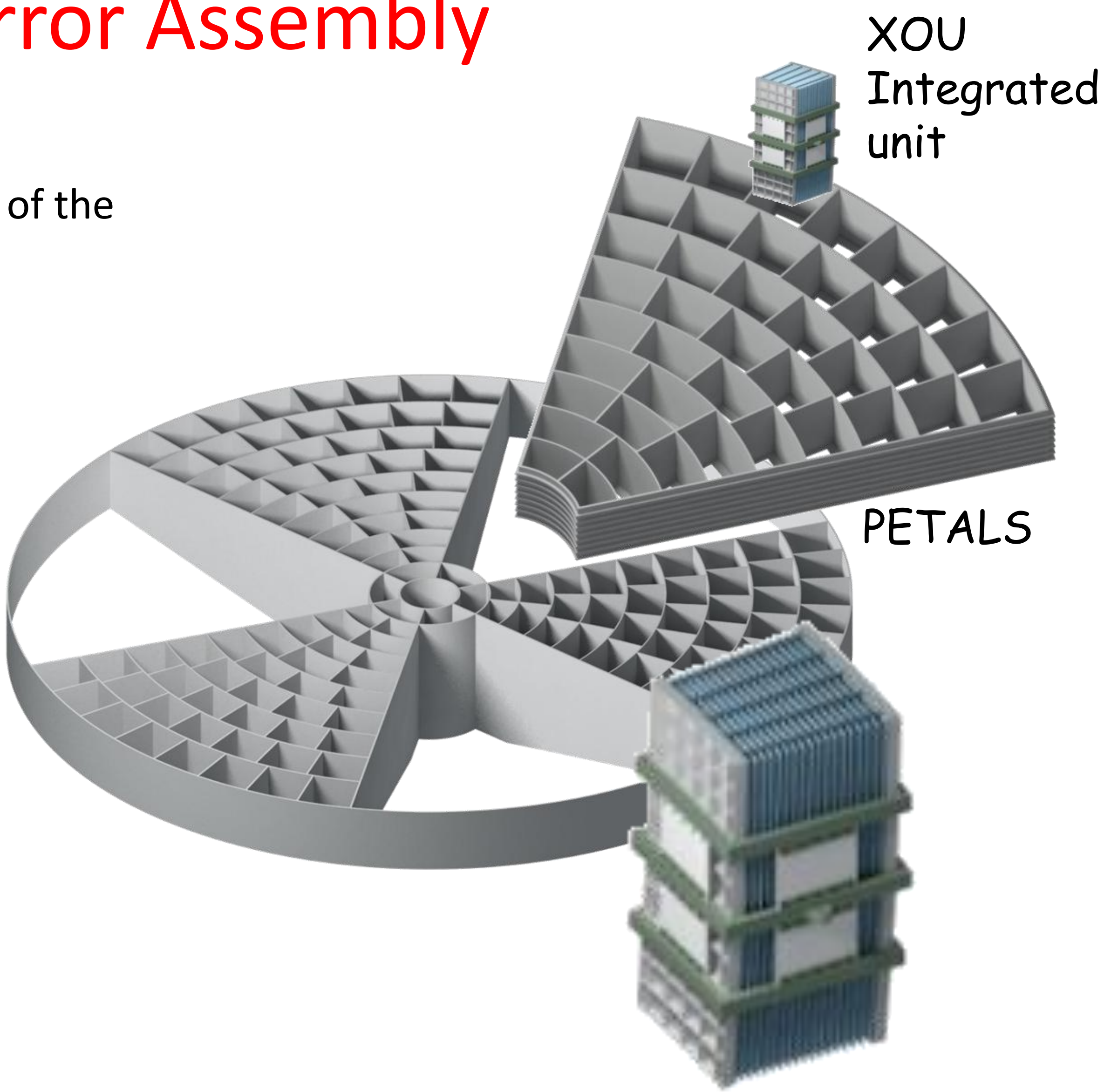




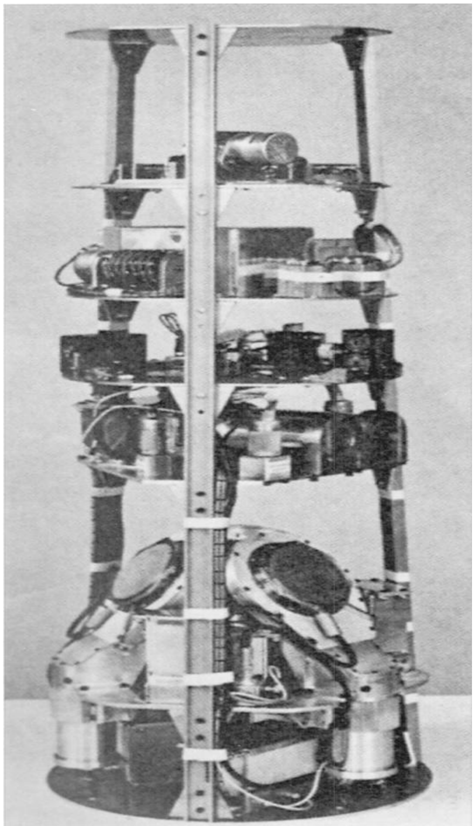
Flight Mirror Assembly

Hierarchy principle for fabrication of the complete mirror assembly

Main Parameters for the Telescope Configuration	
Number of MS per XOU	35-60
Number of Rings	9
Number of XOUs	246
MS thickness	0.4mm
Ribs average thicknes	4.2mm
Average XOU mass	~ 10.5 Kg



1962: discovery of the first extrasolar X-ray source



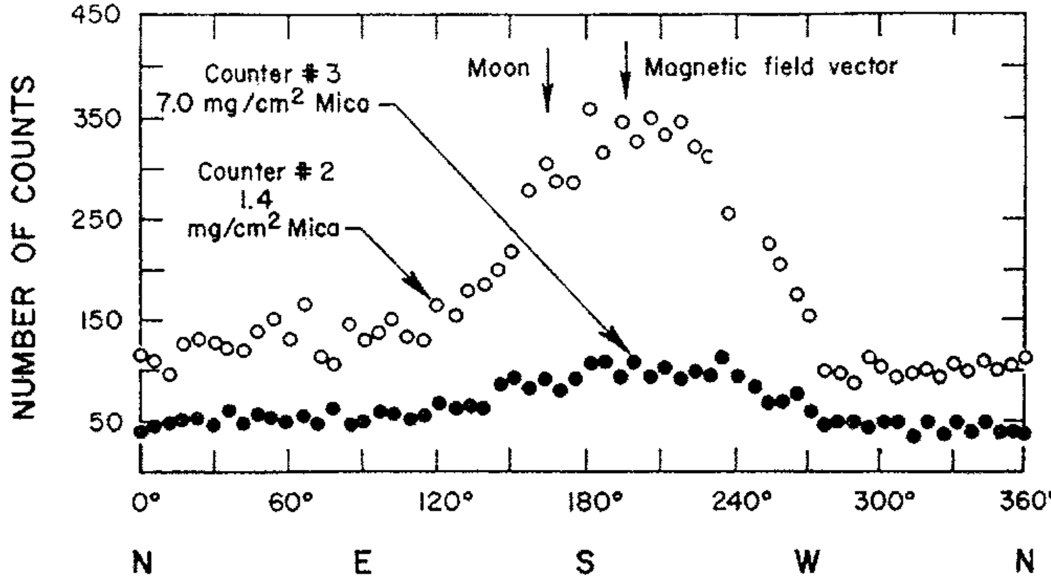
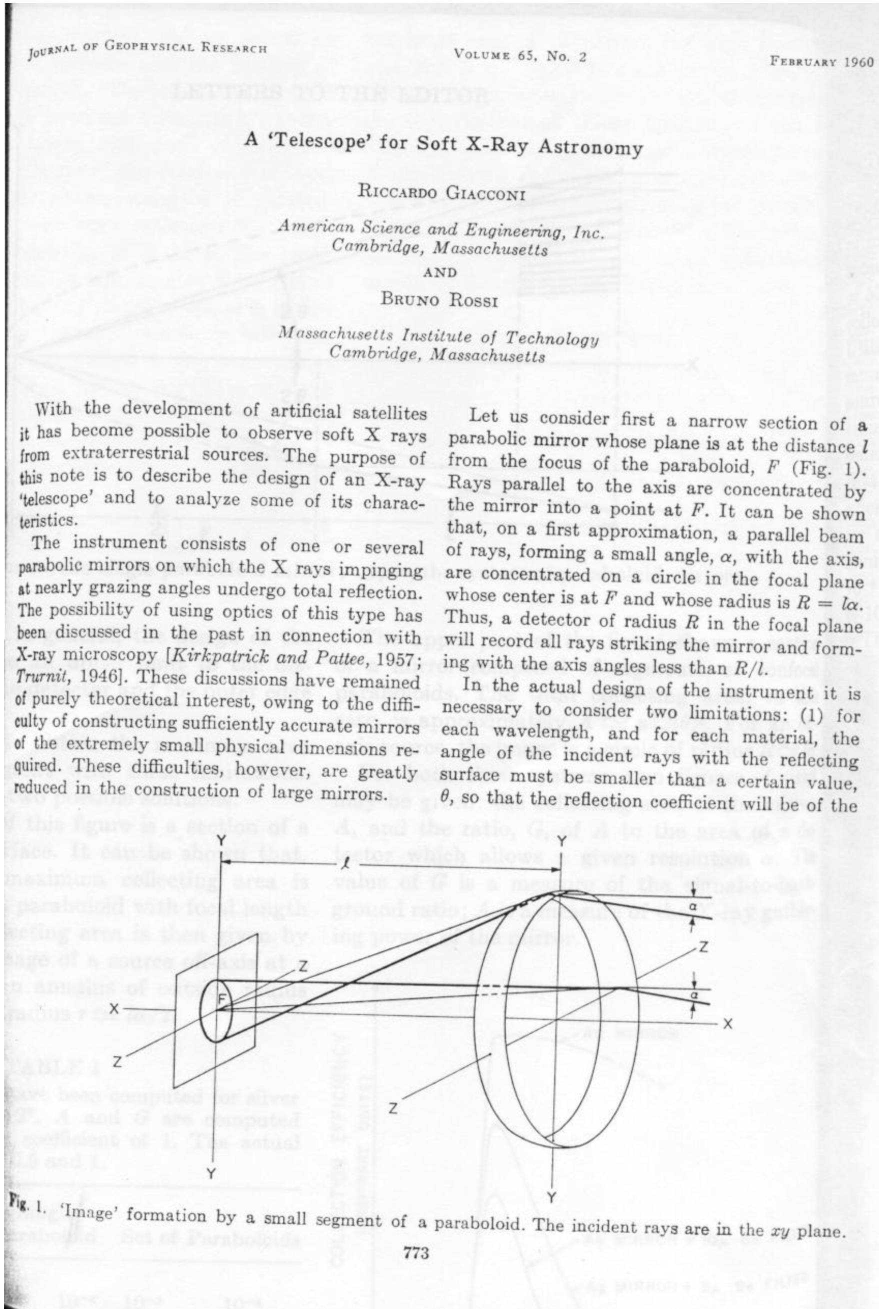


FIG. 2. The first observation of Sco X-1 and of the x-ray background in the June 12, 1962, flight. From Giacconi, Gursky, Paolini, and Rossi, 1962, Phys. Rev. Lett. **9, 439**.



Journal of Geophysical Research Volume 65, No. 2 February 1960

A 'Telescope' for Soft X-Ray Astronomy

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and

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With the development of artificial satellites it has become possible to observe soft X rays from extraterrestrial sources. The purpose of this note is to describe the design of an X-ray 'telescope' and to analyze some of its characteristics.

The instrument consists of one or several parabolic mirrors on which the X rays impinging at nearly grazing angles undergo total reflection. The possibility of using optics of this type has been discussed in the past in connection with X-ray microscopy [*Kirkpatrick and Pattee*, 1957; *Trurnit*, 1946]. These discussions have remained of purely theoretical interest, owing to the difficulty of constructing sufficiently accurate mirrors of the extremely small physical dimensions required. These difficulties, however, are greatly reduced in the construction of large mirrors.

Let us consider first a narrow section of a parabolic mirror whose plane is at the distance l from the focus of the paraboloid, F (Fig. 1). Rays parallel to the axis are concentrated by the mirror into a point at F. It can be shown that, on a first approximation, a parallel beam of rays, forming a small angle, α, with the axis, are concentrated on a circle in the focal plane whose center is at F and whose radius is $R = l\alpha$. Thus, a detector of radius R in the focal plane will record all rays striking the mirror and forming with the axis angles less than R/l.

In the actual design of the instrument it is necessary to consider two limitations: (1) for each wavelength, and for each material, the angle of the incident rays with the reflecting surface must be smaller than a certain value, θ, so that the reflection coefficient will be of the

Fig. 1. 'Image' formation by a small segment of a paraboloid. The incident rays are in the xy plane.

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2010: 50 years of X-ray astronomical optics!

Happy birthday!