Making Mirrors
(for Wolter-like)

Manufacturing techniques utilized so far

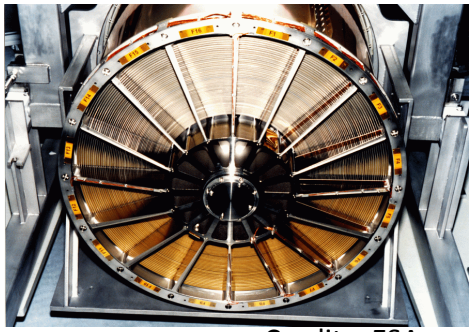
Credits: NASA

1. Classical precision optical polishing and grinding

Projects: *Einstein, Rosat, Chandra*

Advantages: *superb angular resolution*

Drawbacks: *high mirror walls ➔ ➔ small number of nested mirror shells, high mass, high cost process*



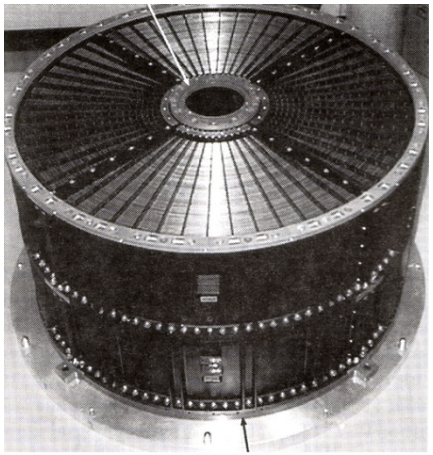
Credits: ESA

2. Replication

Projects: *EXOSAT, SAX, JET-X/Swift, XMM, ABRIXAS (➔ examples follow hereafter)*

Advantages: *good angular resolution, high mirror "nesting" the same mandrels for many modules*

Drawbacks: *relatively high cost process; high mass/geom. area ratio (if Ni is used).*



Credits: ISAS

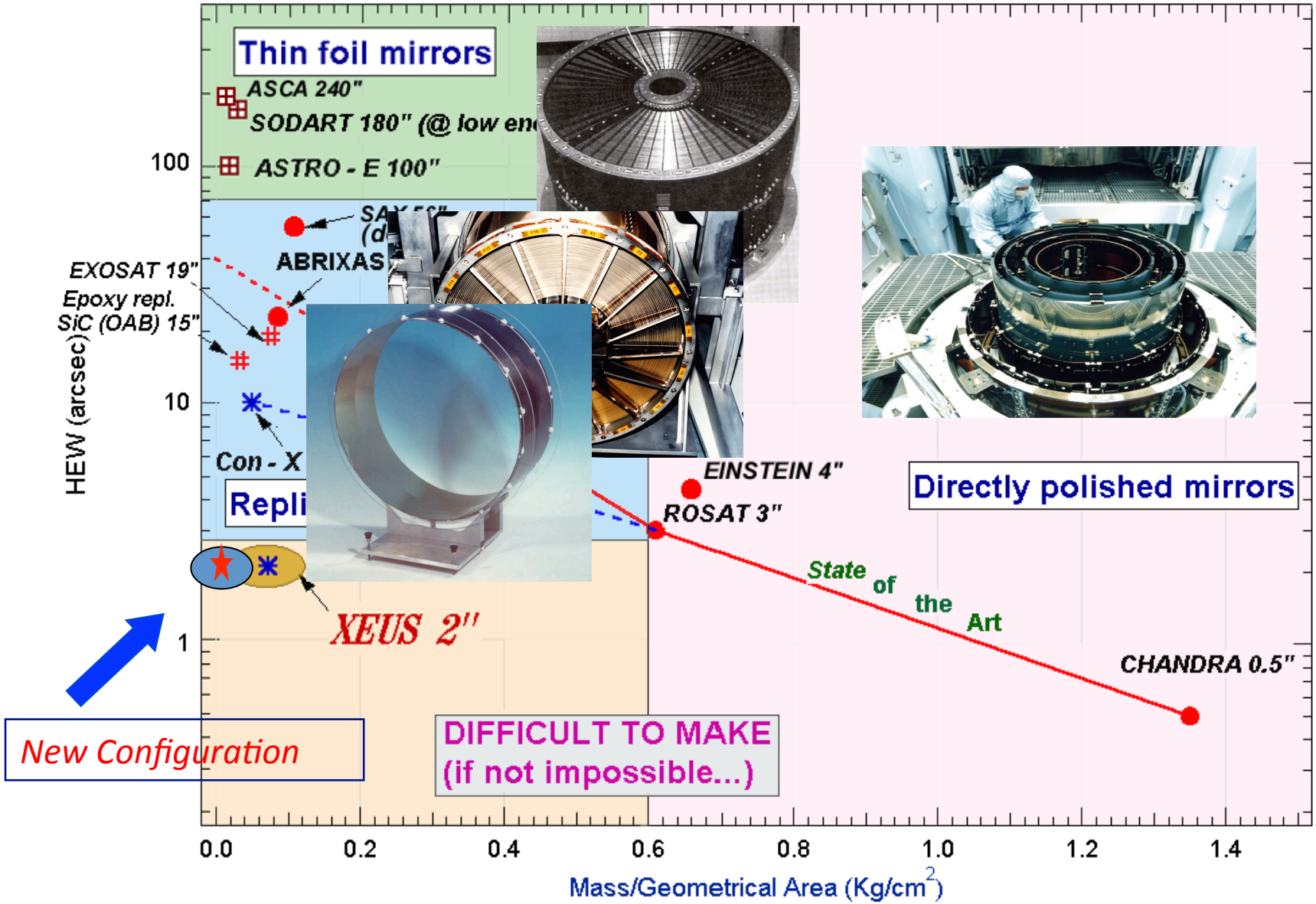
3. "Thin foil mirrors"

Projects: BBXRT, *ASCA, SODART, ASTRO-E*

Advantages: *high mirror "nesting" possibility, low mass/geom. area ratio (the foils are made of Al), cheap process*

Drawbacks: *until now low imaging resolutions (1-3 arcmin)*

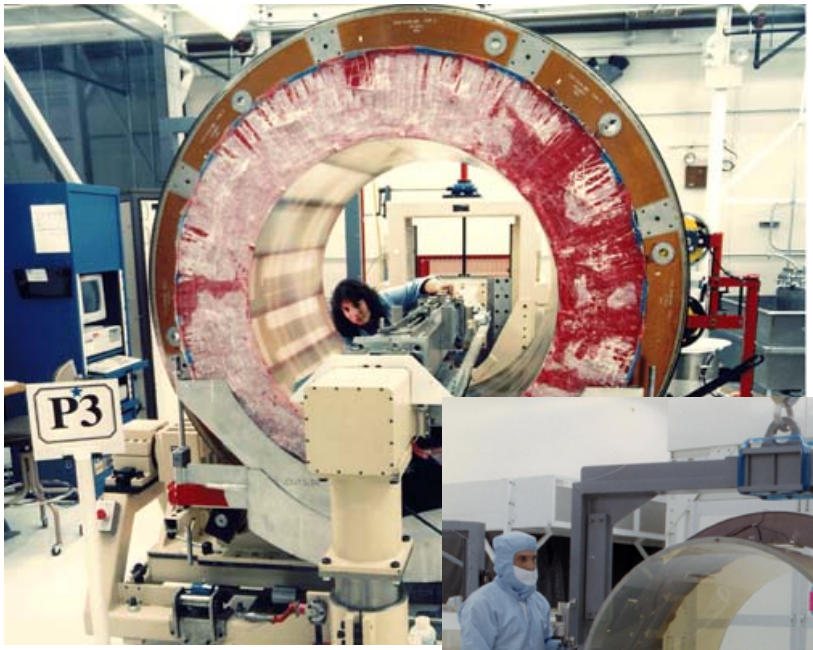
Present Astronomical optics technologies: HEW Vs Mass/geometrical area



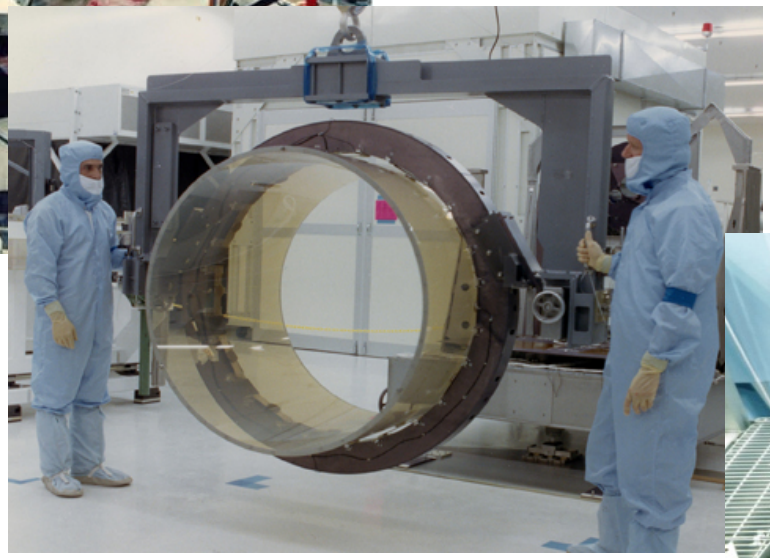
Chandra

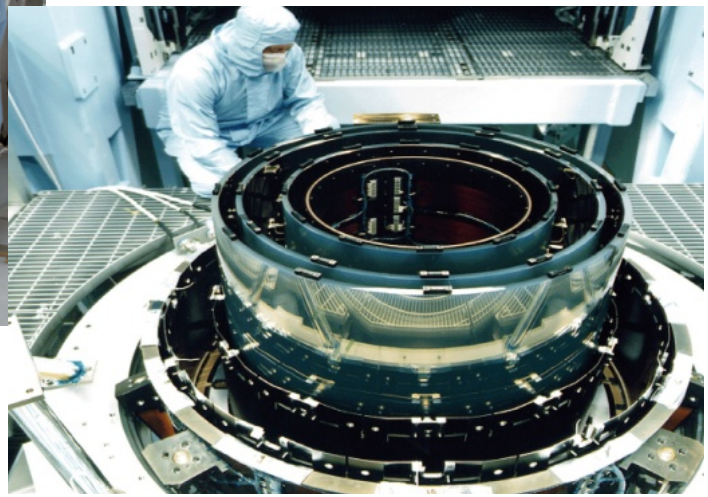
- *Focal length = 10 m*
- *1 module, 4 shells*
- *Coating = Iridium*
- *Angular Resolution = 0.5 arcsec HPD*

Polishing of the Chandra shells

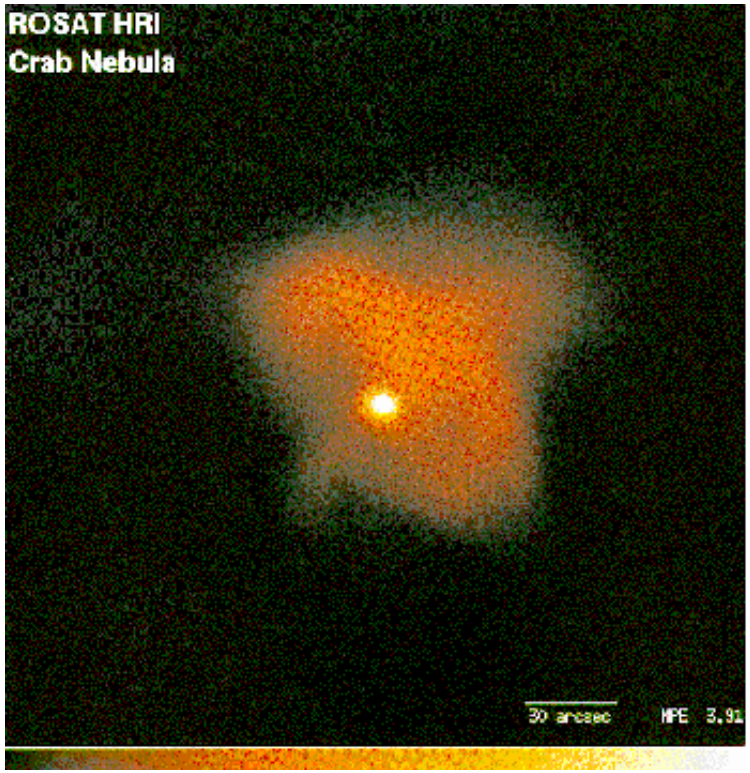


20 mm thick shells !

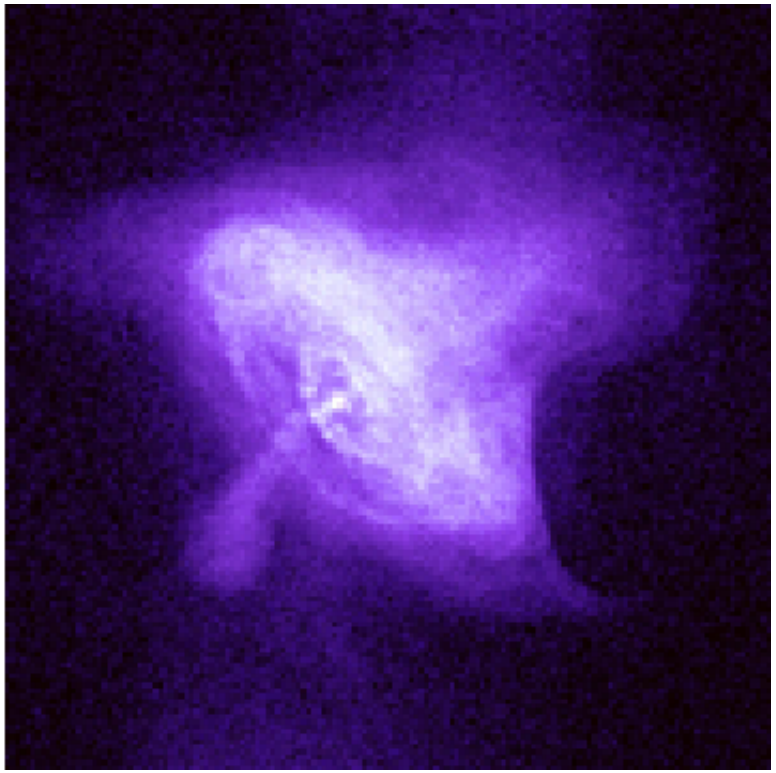




Chandra: a fantastic angular resolution

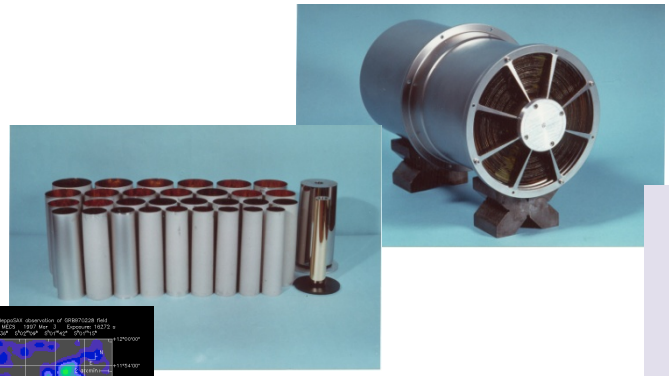


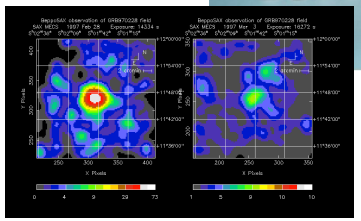
Rosat: HPD = 3 arcsec



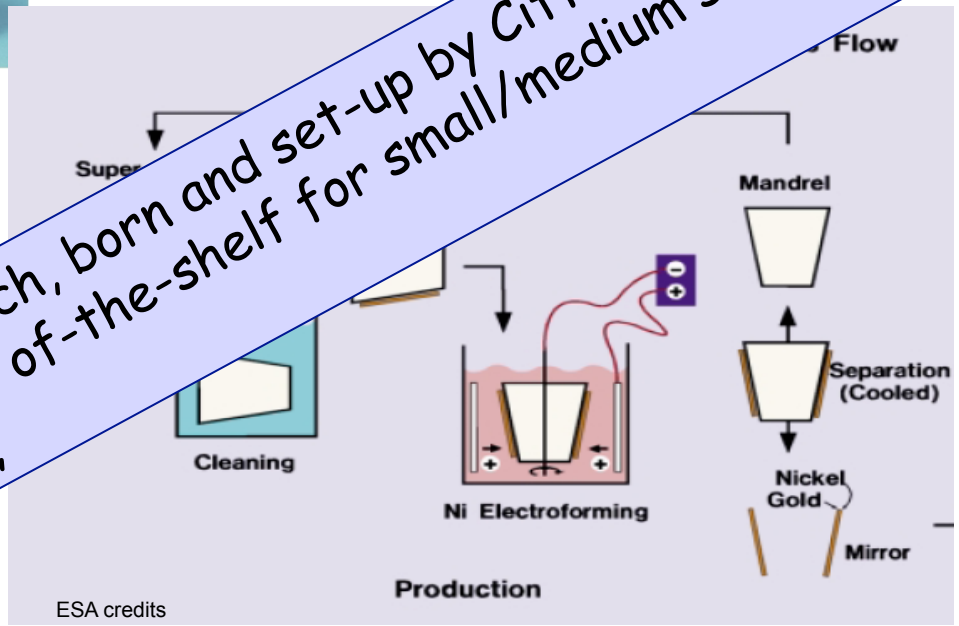
Chandra: HPD = 0.5 arcsec

X-ray optics by Ni electroforming replication



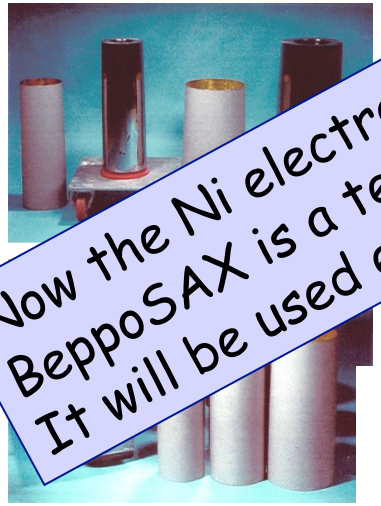


BeppoSAX

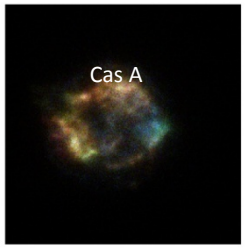


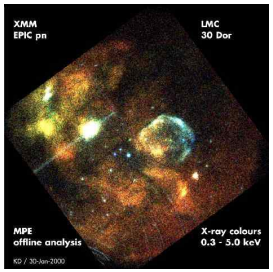
ESA credits

Now the Ni electroforming approach, born and set-up by Citterio et al. For BeppoSAX is a technology almost of-the-shelf for small/medium size missions. It will be used e.g. for e-Rosita,



Jet-X/Swift

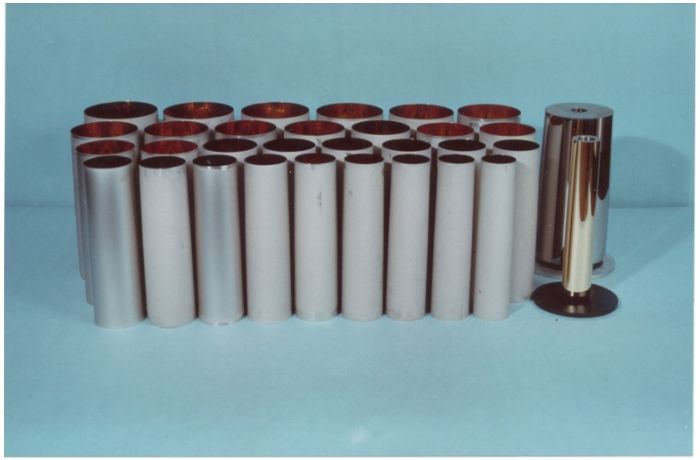


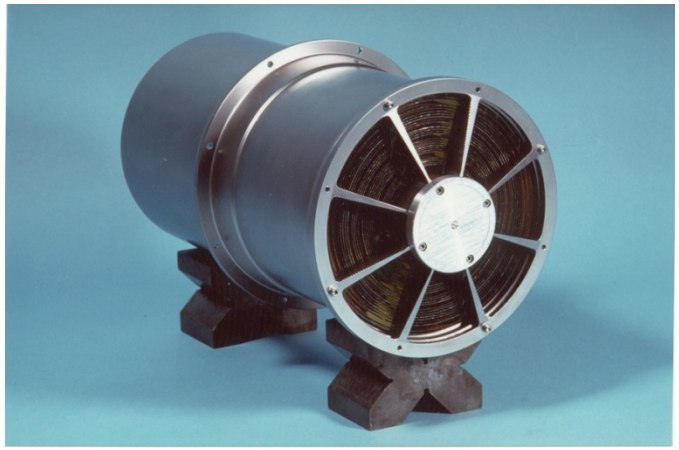


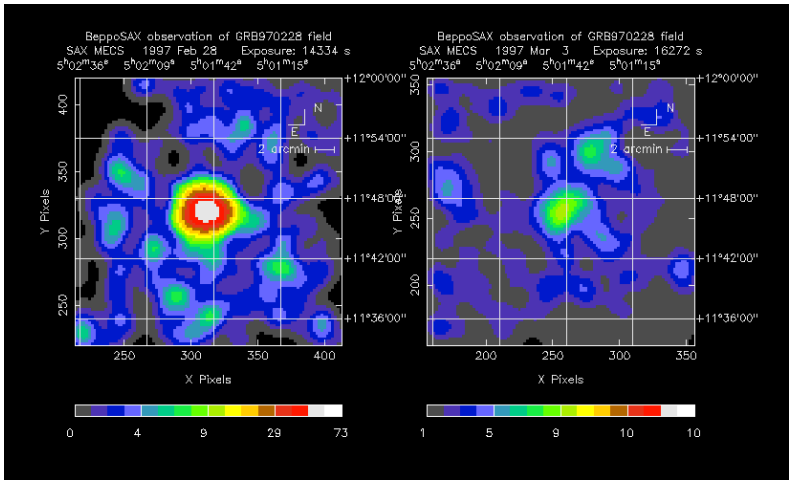
XMM-Newton

Beppo-SAX soft X-ray (0.1 – 10 keV) concentrators

- *Wolter I double-cone approx. – Au coating*
- *4 modules – 30 shells/mod.*
- *F.L. = 180 cm Max diam = 16.1 cm*
- *A_{eff} @ 1 keV = 85 cm^2 /module*
- *HEW= 60 arcsec (corresponding to the two-cones geom. aberration!)*

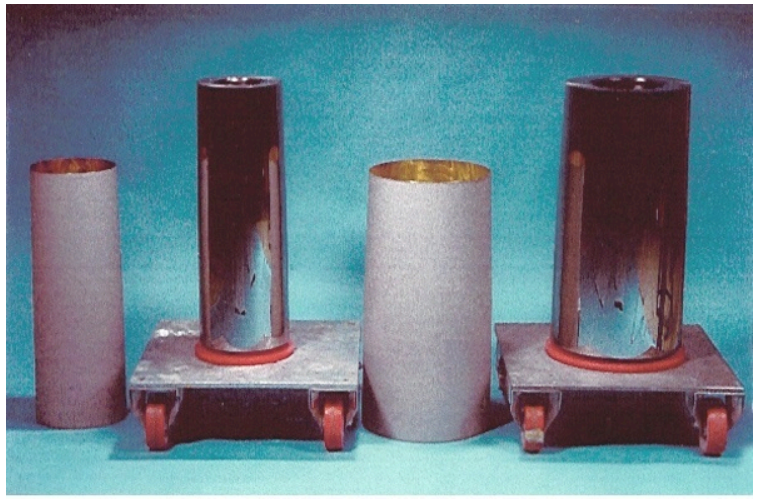


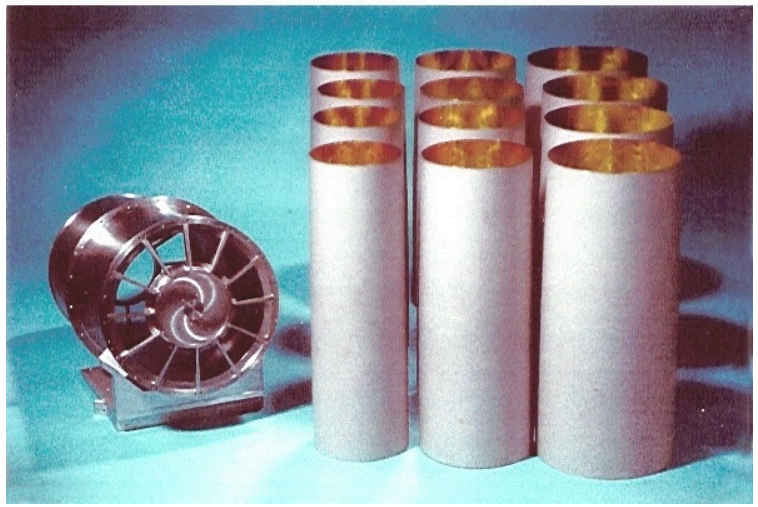




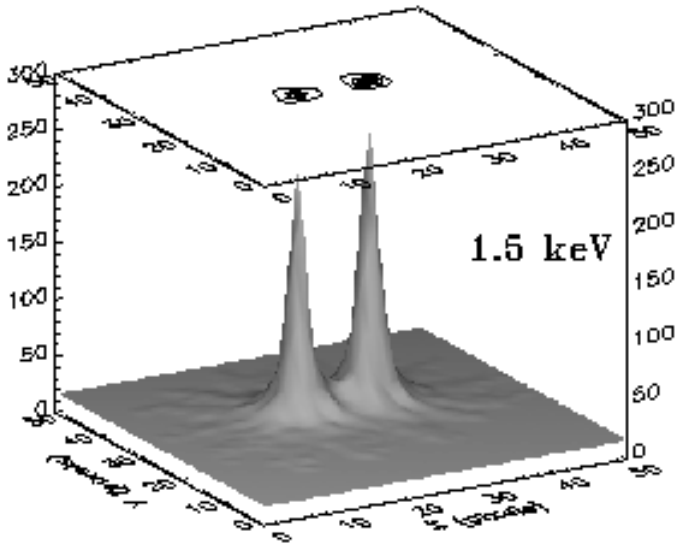
GRB970228

JET-X (optics ready since1996) / SwiftXRT(2004) optics





- *Wolter I profile – Au coating (pathfinder of XMM)*
- *2 mod. (JET-X) / 1 mod (Swift) – 12 shells/mod.*
- *F.L. = 350 cm - Max diam = 30 cm*
- *A_{eff} @ 1 keV= 150 cm^2 /module*
- *HEW= 15 arcsec*

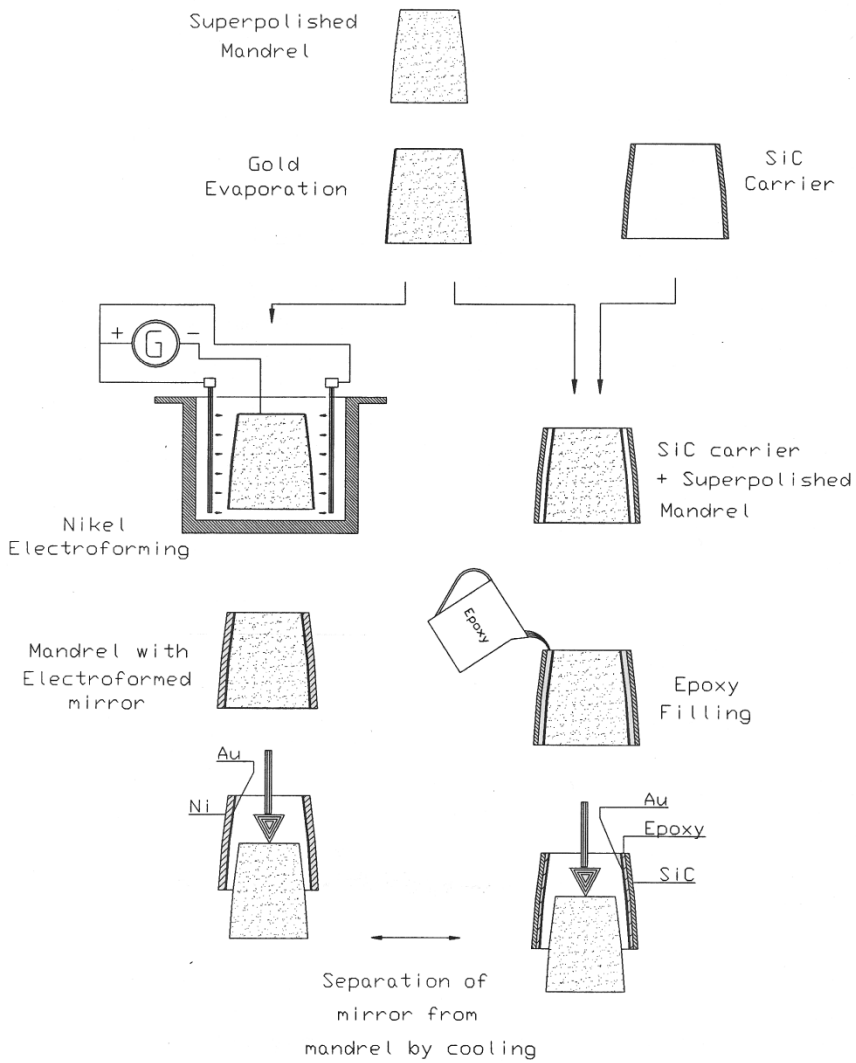


Source separation: 20”

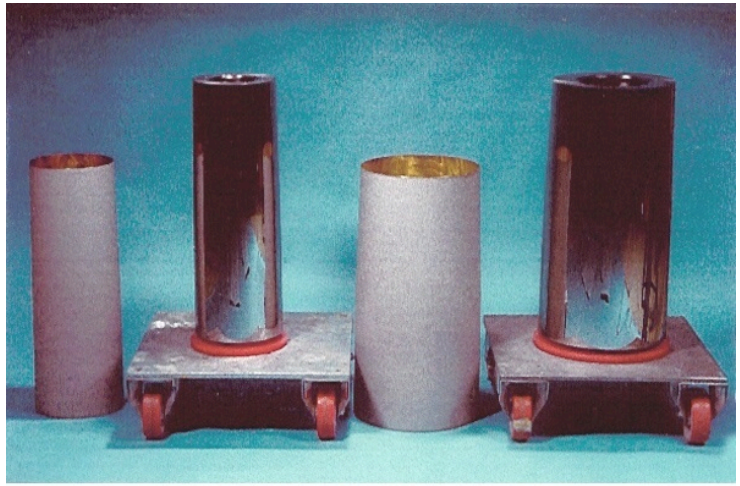
Replication methods

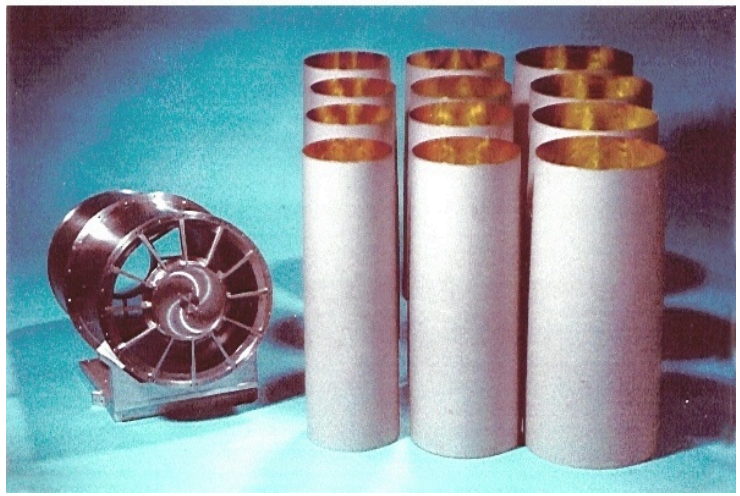
- Ni electroforming replication (SAX, JET-X/Swift, XMM, ABRIXAS, e-ROSITA, SIMBOL-X, SVOM/XIAO)

- *epoxy replication*: EXOSAT (Be), WFXT (Alumina & SiC prototypes), EDGE/XENIA?

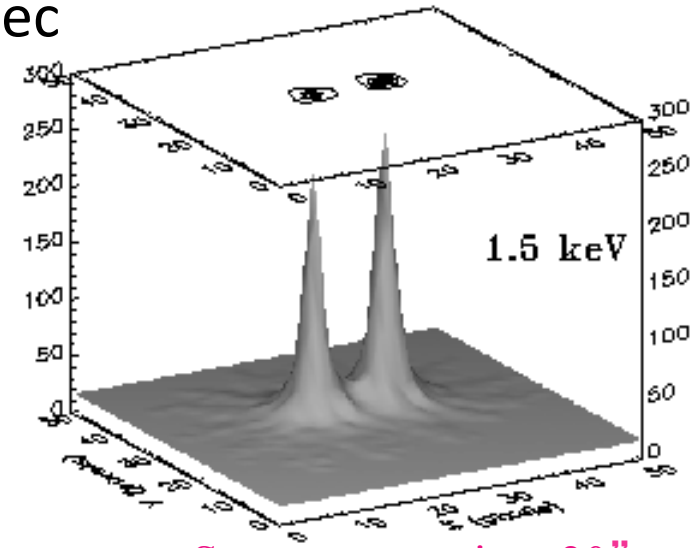


JET-X (optics ready since 1996)

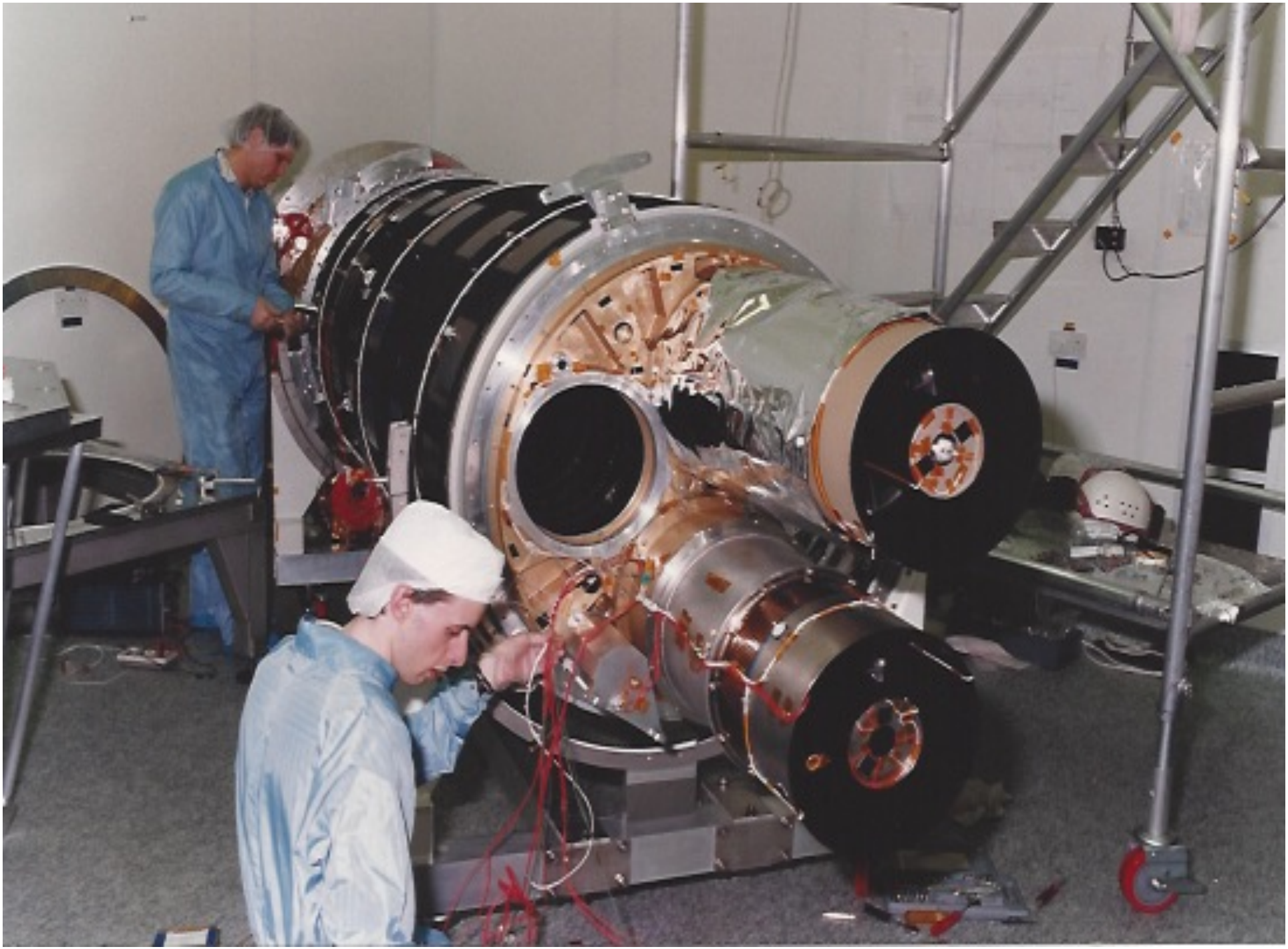


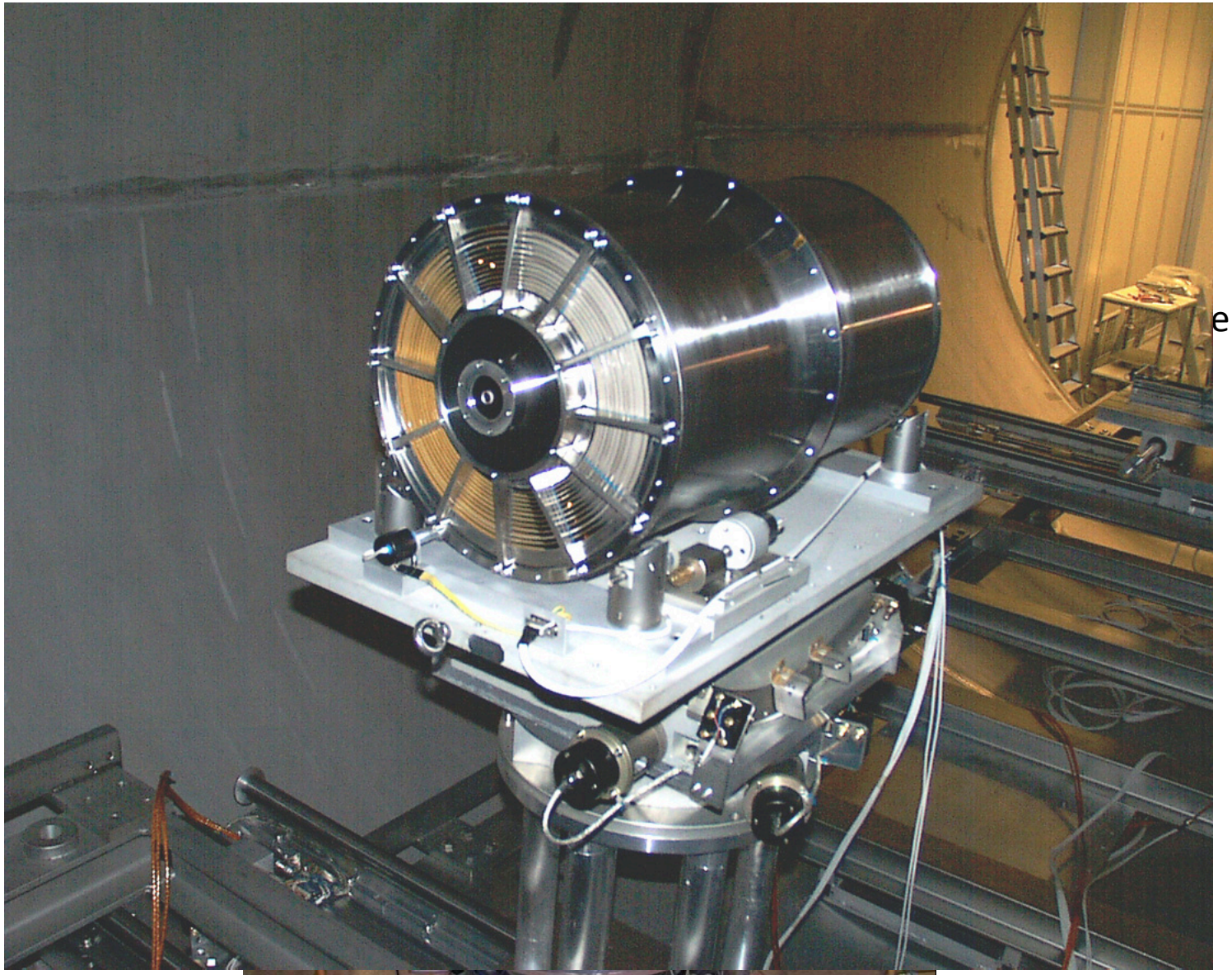


- Wolter I profile – Au coating (pathfinder of XMM)
- 2 mod. (JET-X) / 1 mod (Swift) – 12 shells/mod.
- F.L. = 350 cm - Max diam = 30 cm
- A_{eff} @ 1 keV= 180 cm^2 x 2 = 360 cm^2
- HEW= 15 arcsec

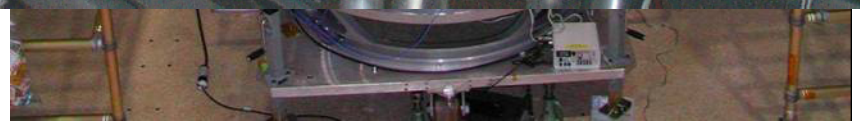


Source separation: 20”





elescope



Swift Observatory

Burst Alert Telescope (BAT)
- 32,000 CdZnTe detectors
- 2 sr field of view

X-Ray Telescope (XRT)
- CCD spectroscopy
- Arcsec GRB positions

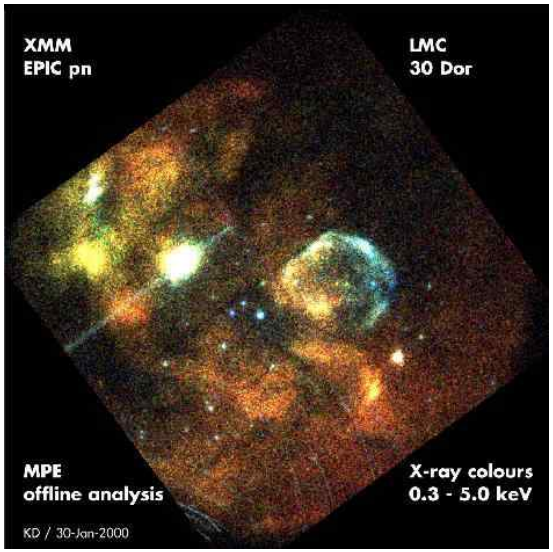
UV-Optical Telescope (UVOT)
- Sub-arcsec position
- 22 mag sensitivity

Spacecraft slews XRT & UVOT to GRB in <100 s

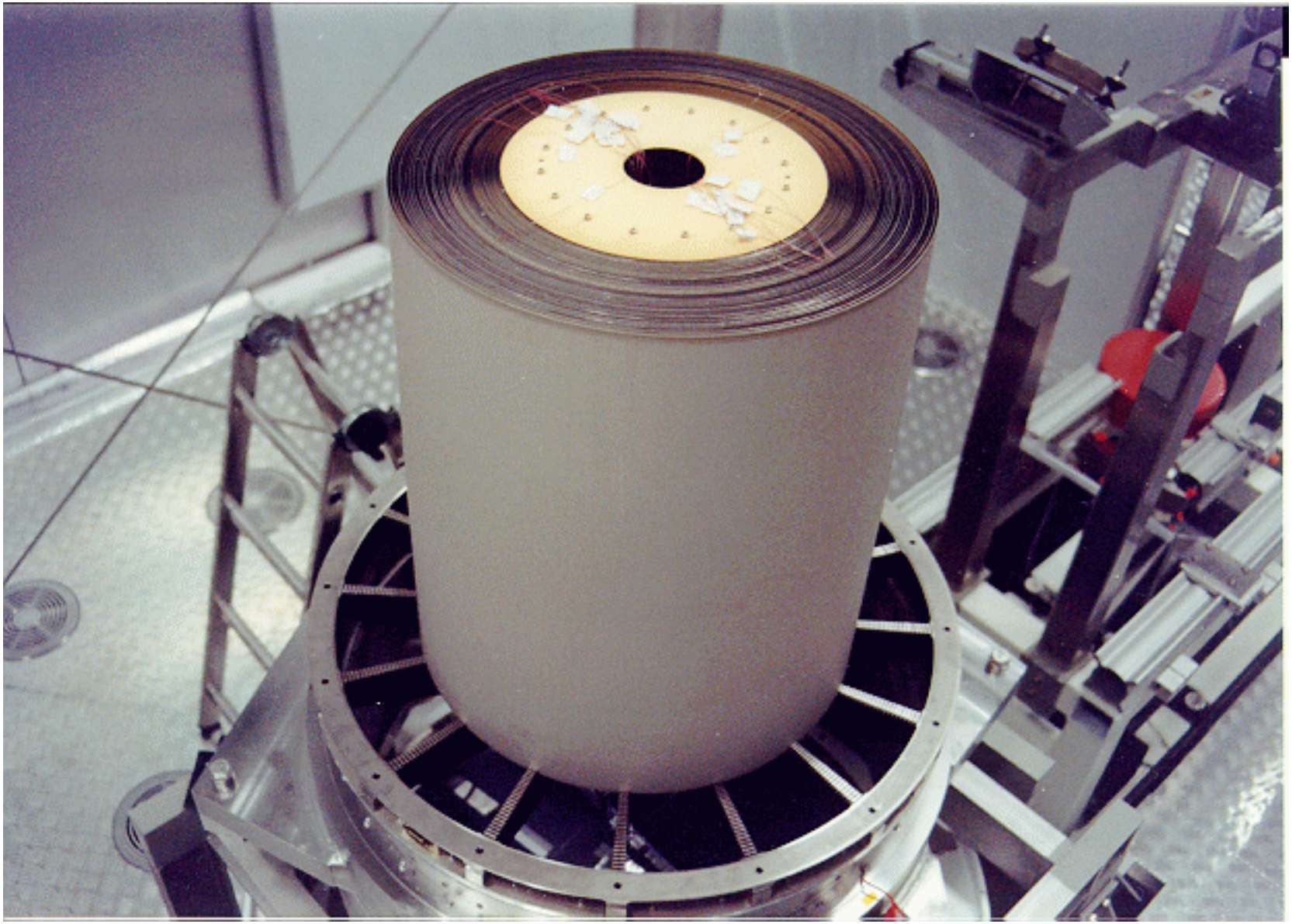
XMM Mirror Modules under integration on the spacescraft

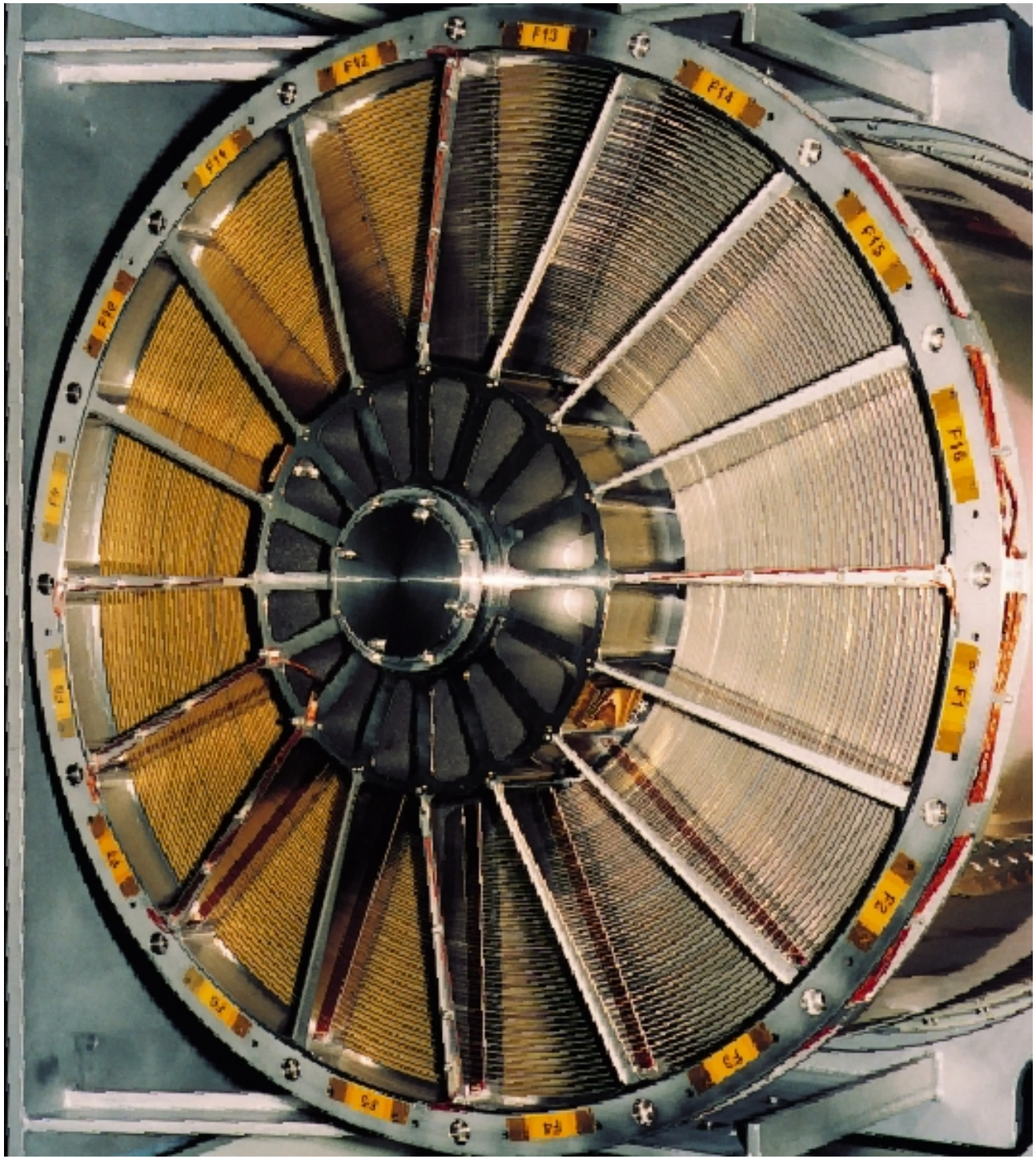
XMM-Newton (operational since dec. 1999)

- *Wolter I profile – Au coating*
- *3 mod. - 58 shells/mod.*
- *F.L. = 750 cm - Max diam = 70 cm*
- *A_{eff} @ 1 keV= 1500 cm^2 /module*
- *HEW= 15 arcsec*



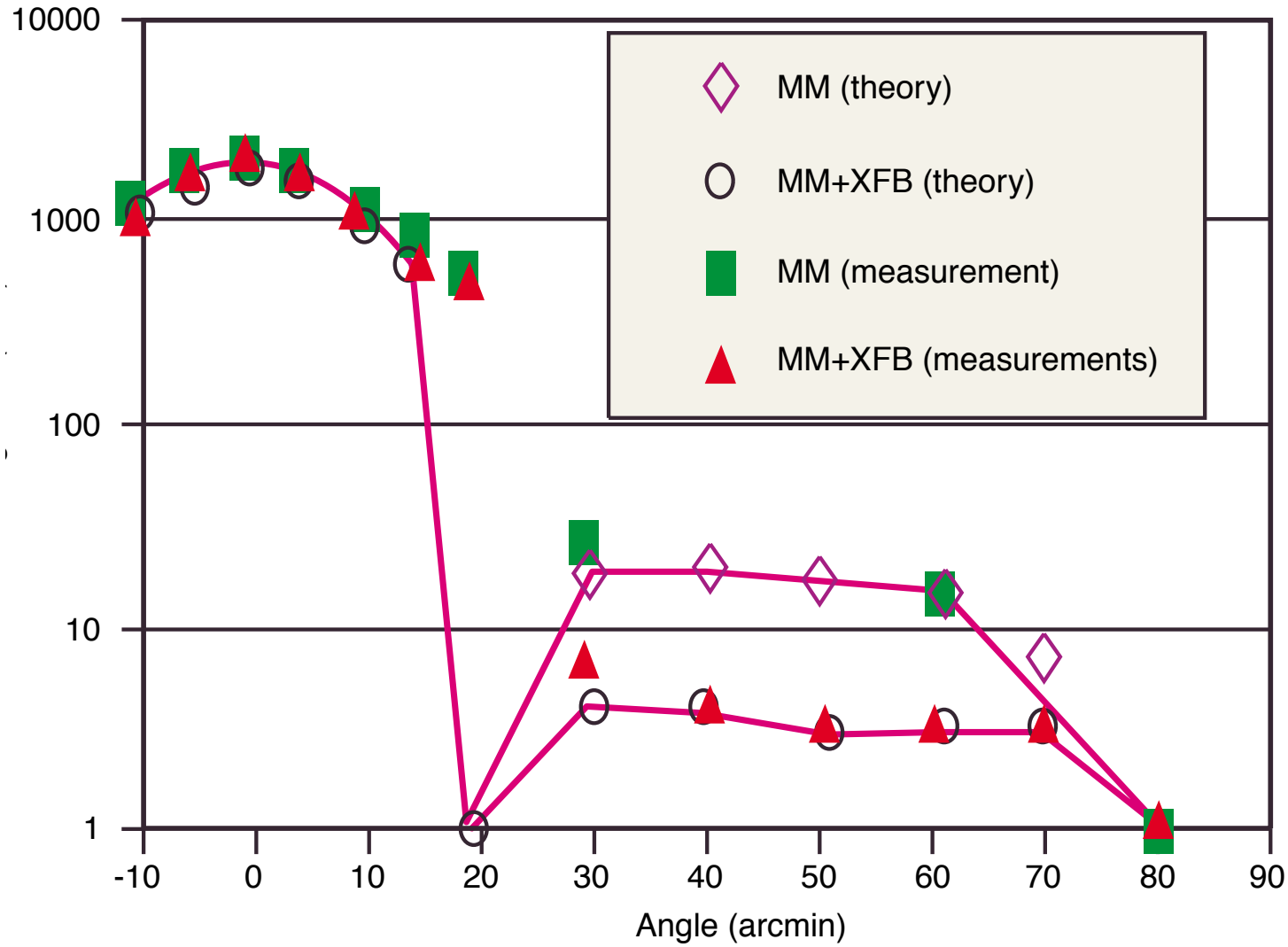
Credits: ESA



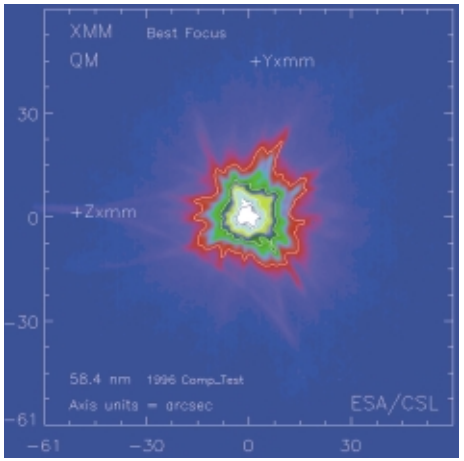


A complete XMM mirror module

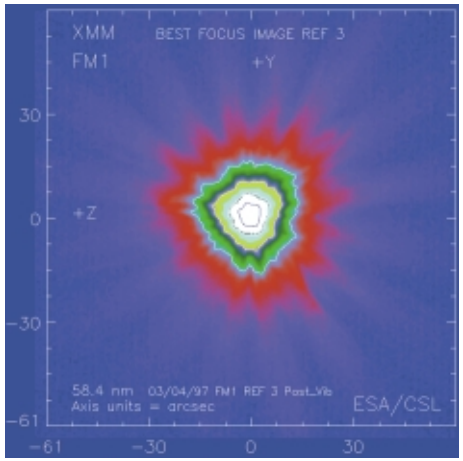
XMM Mirror Module
R1
reflectivity
0.8
0.6
0.4
0.2
0
8.05 keV
350
300
250
200
150
shell radius [mm]
R. Egger 10/97
Foto: Kayser-Threde


10000
1000
100
10
1
-10
0
10
20
30
40
50
60
70
80
90
Angle (arcmin)
MM (theory)
MM+XFB (theory)
MM (measurement)
MM+XFB (measurements)

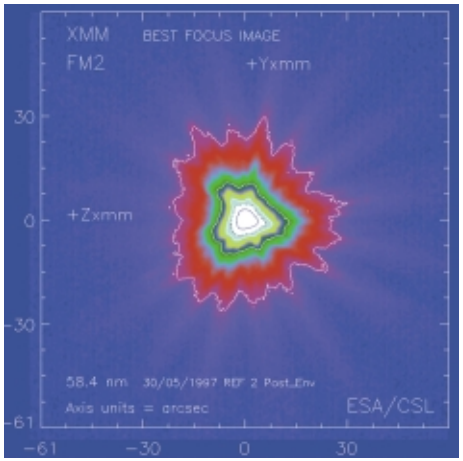
XMM Mirror Flight-Modules: PSF measuread @ Panter/MPE



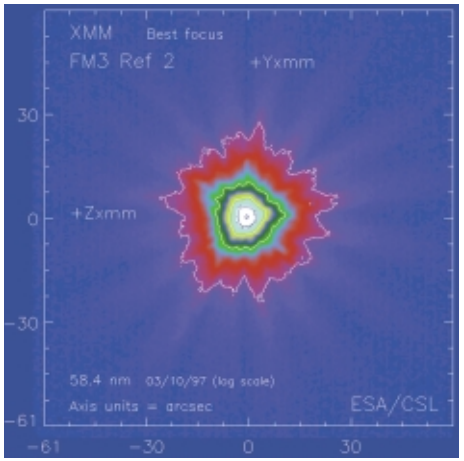
MM QM



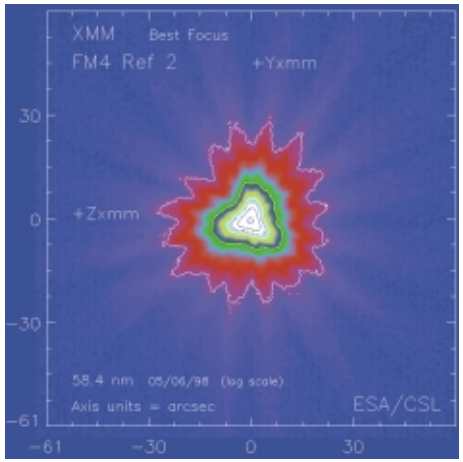
MM FM1



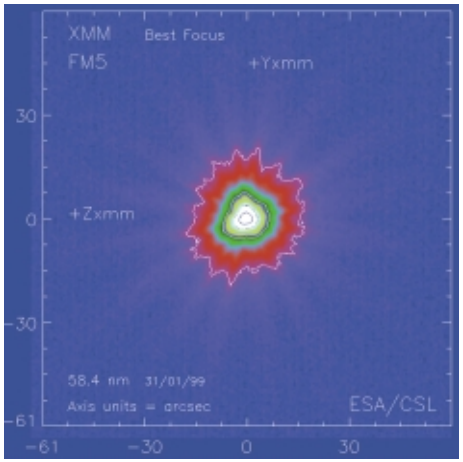
MM FM2



MM FM3



MM FM4

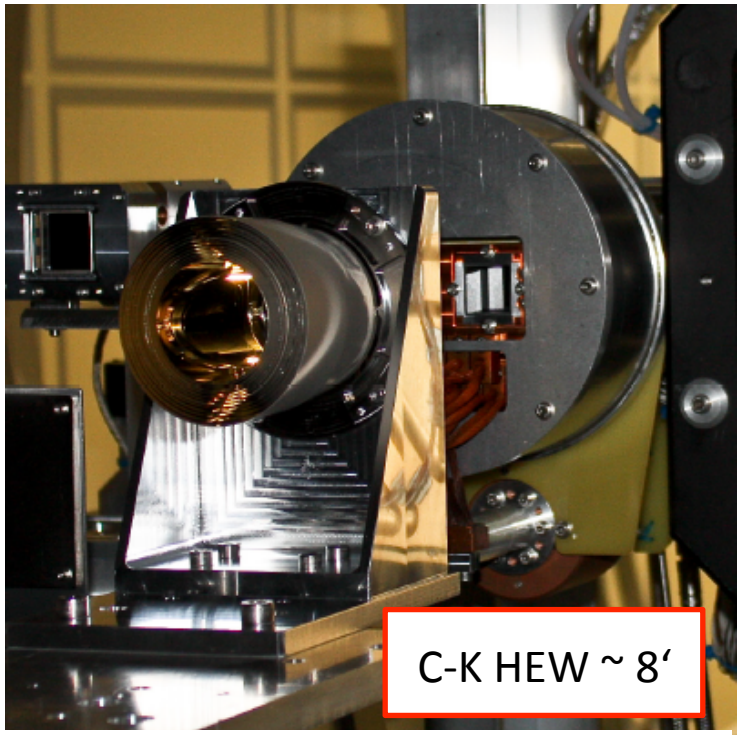


MM FM5

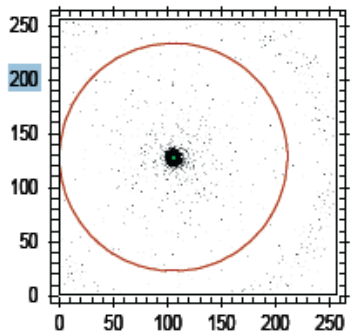
The „Max-Valier“ High School Satellite

- School Satellite Project Setup/develop
  - 2 Ground Stations
  - Electric Power power supply for satellite
  - Attitude control for satellite
  - CMOS Camera
  - Radio communication experiments
- Projekt Partners
  - Technical High School Bozen, Italy
  - Technical High School Meran, Italy
  - OHB, Bremen, Germany → Piggyback launch, funding, AIS (ship ID signals) tests
  - MPE, Garching, Germany → X-ray telescope
- Launch 04/2014 from Plesestk on a VEGA
- Sun-synchronous Orbit 700km

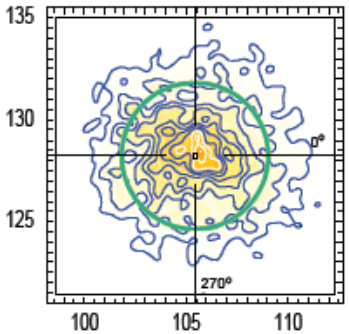
Complete Mirror Module X-Ray Test



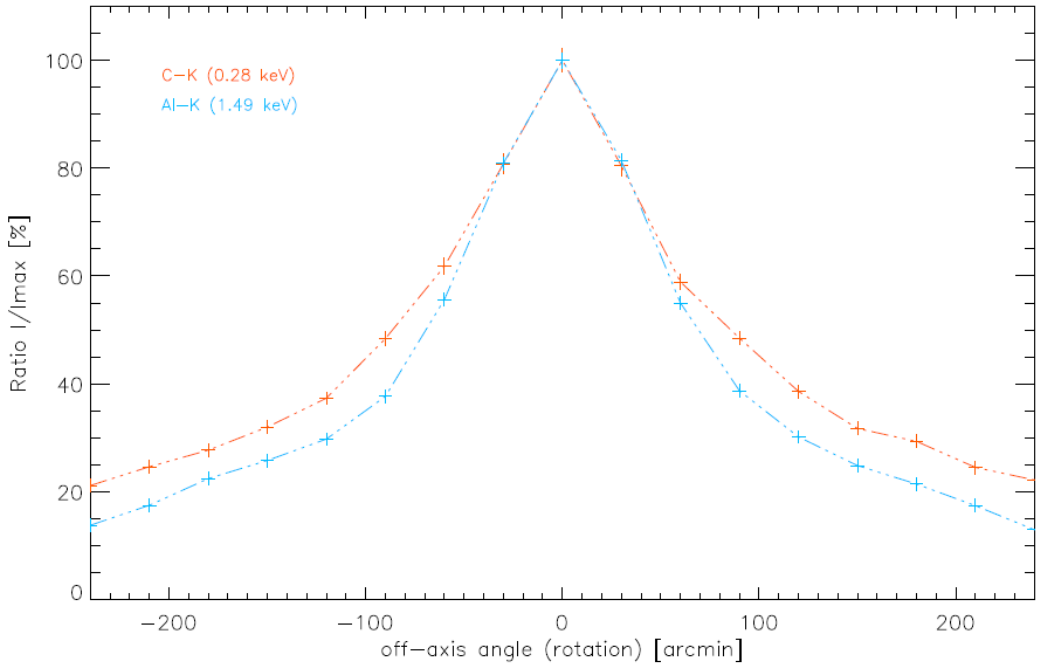
Energy [keV]	Effective area [cm^2]	Error ($\pm 3\,\sigma$) [cm^2]
0.28	7.463	0.344
0.93	5.056	0.202
1.25	4.449	0.141
1.49	3.710	0.141
2.98	0.067	0.003



(a) Complete CCD area



(b) Zoomed region



New Mid-size missions:

- hard X-rays
- wide field

The X-ray optics of the past (..but also current…) decades

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

PS: now also NUSTAR, see later

Frontiers for the X-ray telescopes of the new decade(s) based on optical systems

- imaging on wide field of views
  - ✓ e-Rosita

- Spectroscopy & Hard X-ray high angular resolution optics

  - ✓ NUSTAR ➔ GOAL ACHIEVED
  - ✓ ASTRO-H

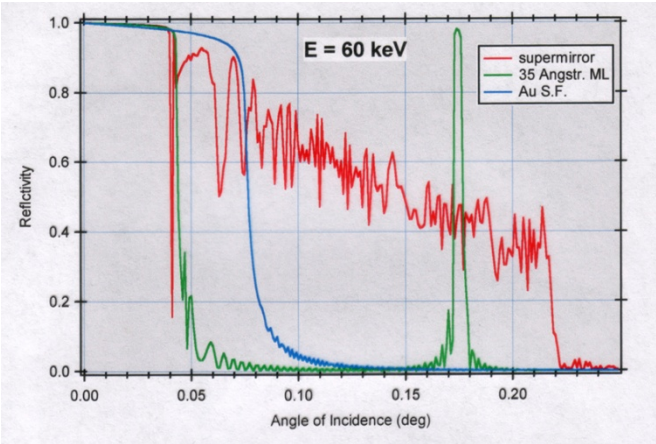
- ATHENA+: Very high effective area with a high angular resolution for imaging spectroscopy

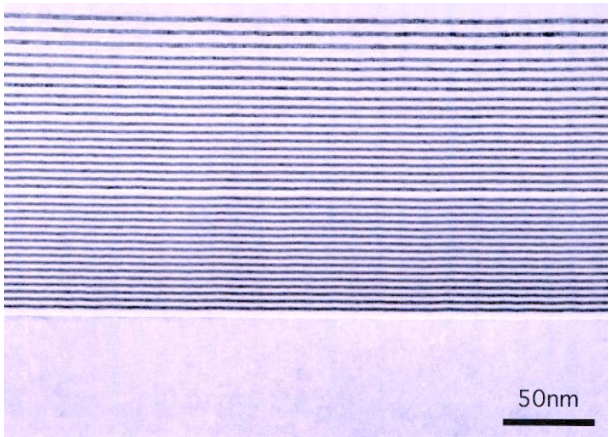
- AXSIO: Very high effective area with a high angular resolution for imaging spectroscopy

- SuperChandra, WFXT…..

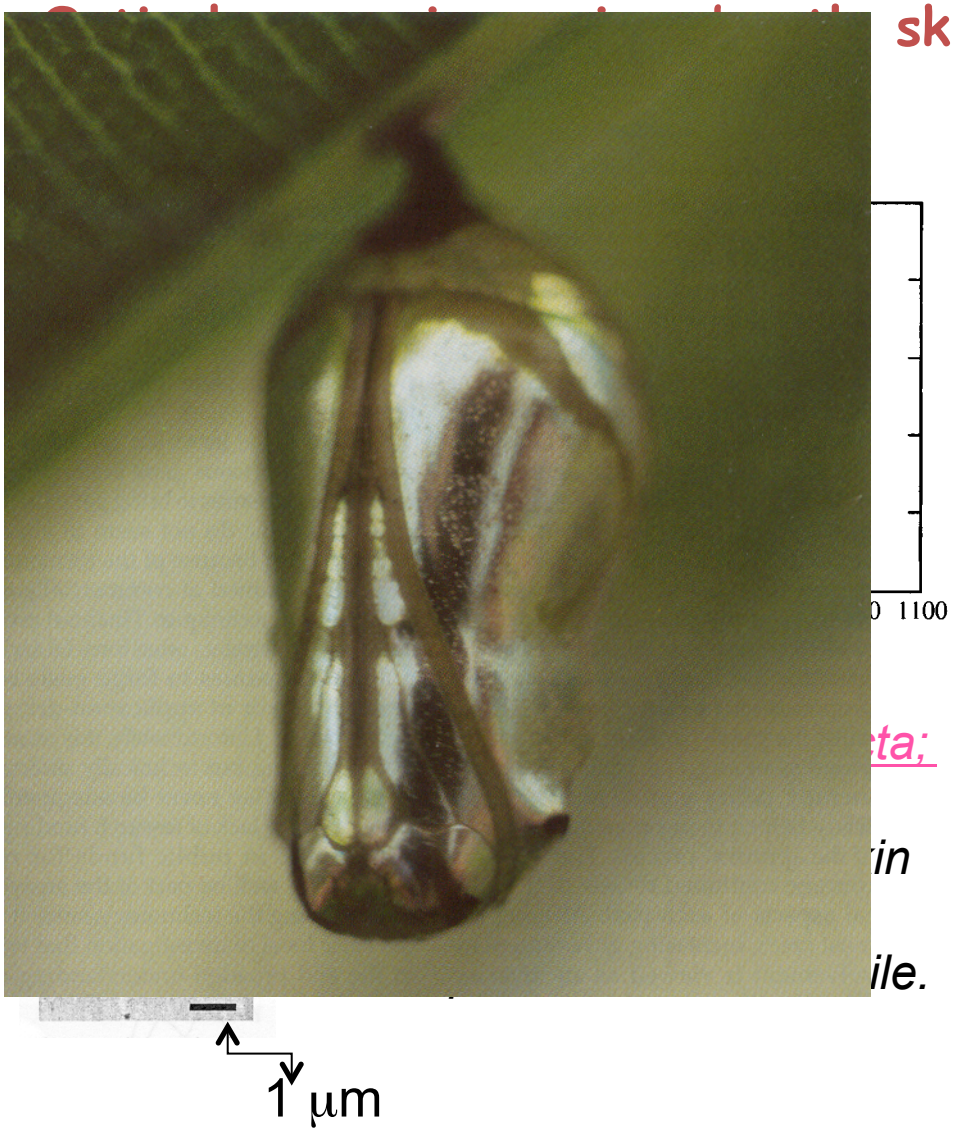
Wide band multilayers

X-ray supermirrors





skin



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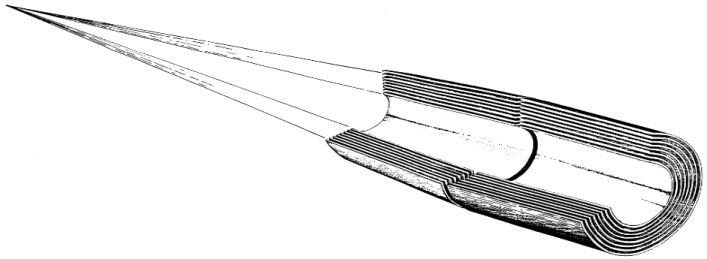
Focusing in the hard X-ray region (> 10 keV)



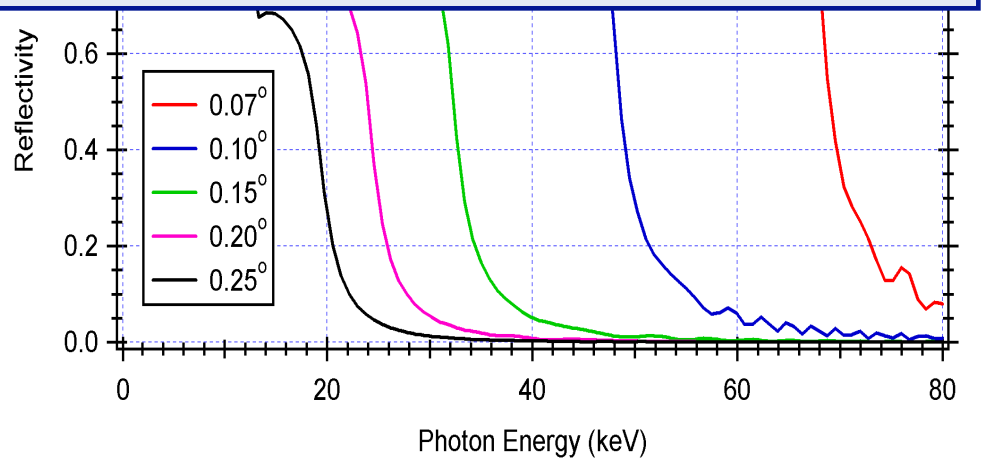
$$A_{eff} \approx F^2 \times \theta_c^2 \times R^2$$

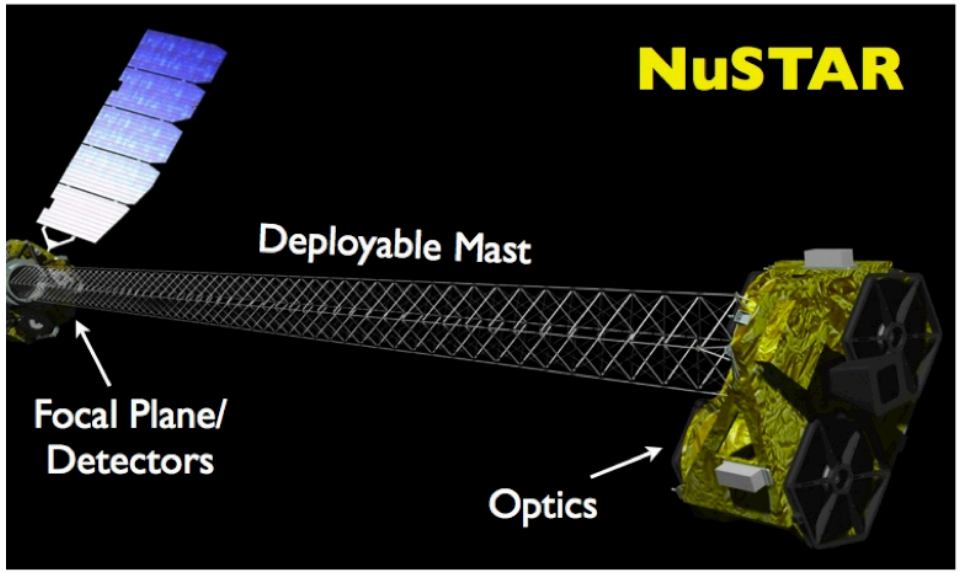
At photon energies > 10 keV the cut-off angles for total reflection are very small also for heavy metals

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

but

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

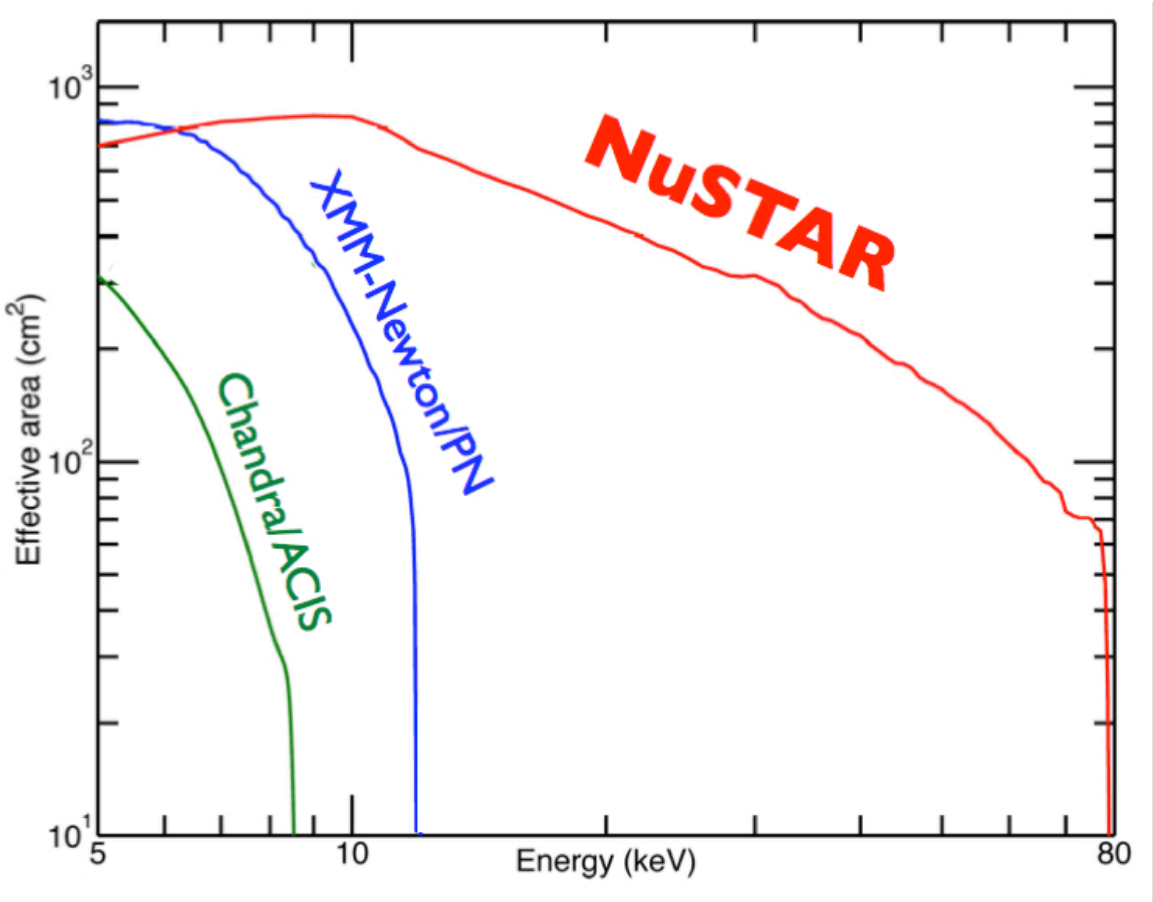




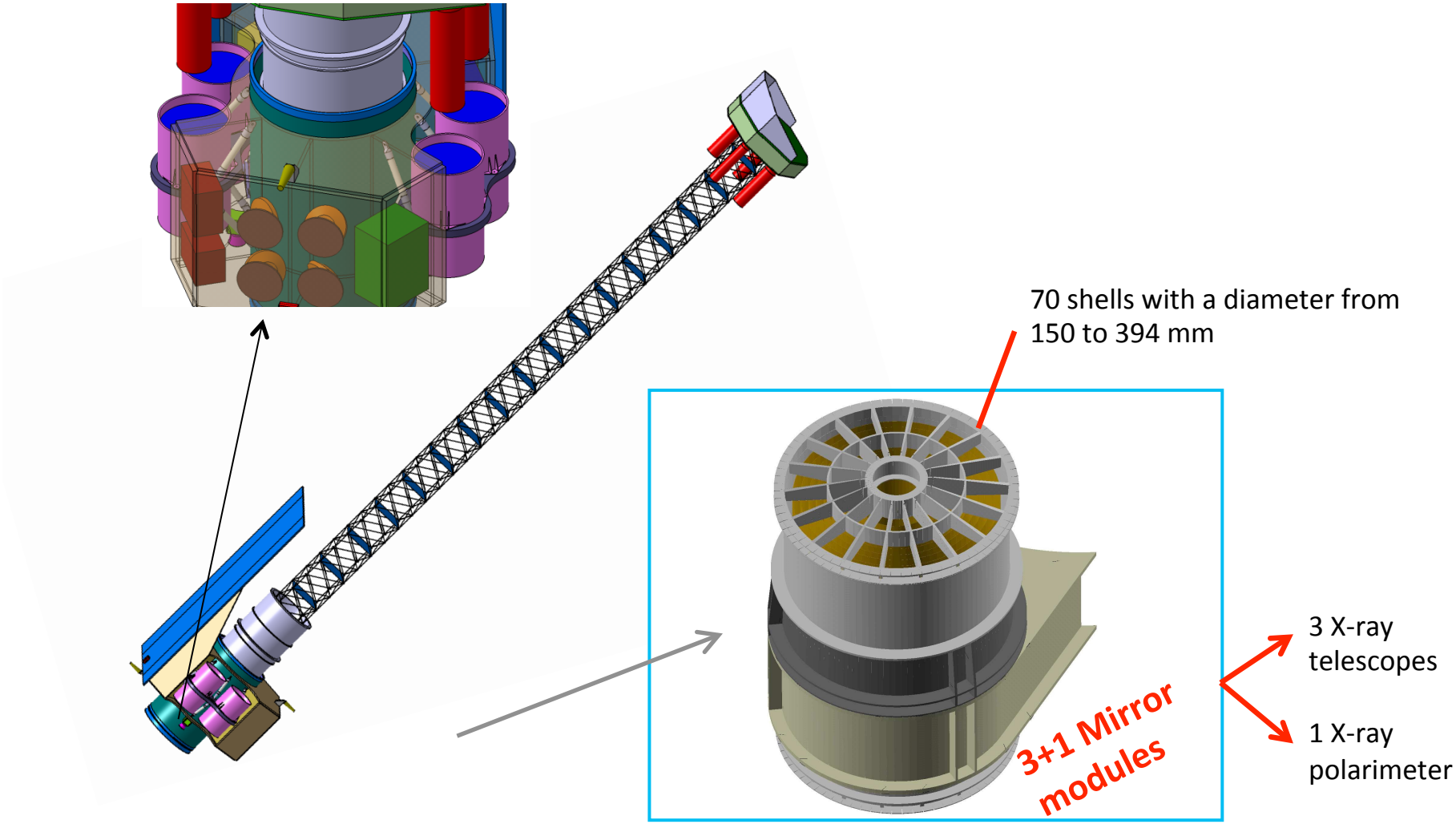
NUSTAR

- **Energy Band:** 5 - 80 keV
- **Angular Resolution:** ~50" (HPD), ~10" (FWHM)
- **Field of View:** 13' x 13'
- **Energy Resolution:** 0.5 keV at 6 keV, 1.0 keV at 60 keV (FWHM)
- **Maximum Flux Measurement Rate:** 10,000 cts/s
- **ToO response:** < 48 hours
- **Launch date:** February 2012
- **Orbit:** 550 km x 600 km, 6 degree inclination

Nustar effective Area



The NHXM mission



Two mirror modules

- 133 layers of grazing incidence shells with multilayer coating
- the inner 66 layers are comprised of 6 segments with 12 pieces of glass per layer
- while the outer 67 layers are comprised of 12 segments with 24 pieces of glass per layer
- Each unit is 47.2 cm) long and, upon completion, will be 19.1
- weigh 31 kg

About 5000 segments produced via hot slumping at Goddard and coated at DTU

First light images of Cygnus X-1 on June 28th, 2012

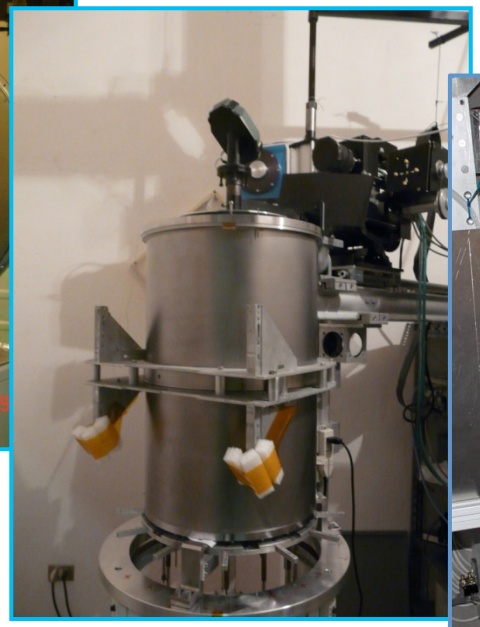
HEW compliant with grond calibrations (≈ 55 arcsec)

Technology Demonstrator of SIMBOL-X/NHXM

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

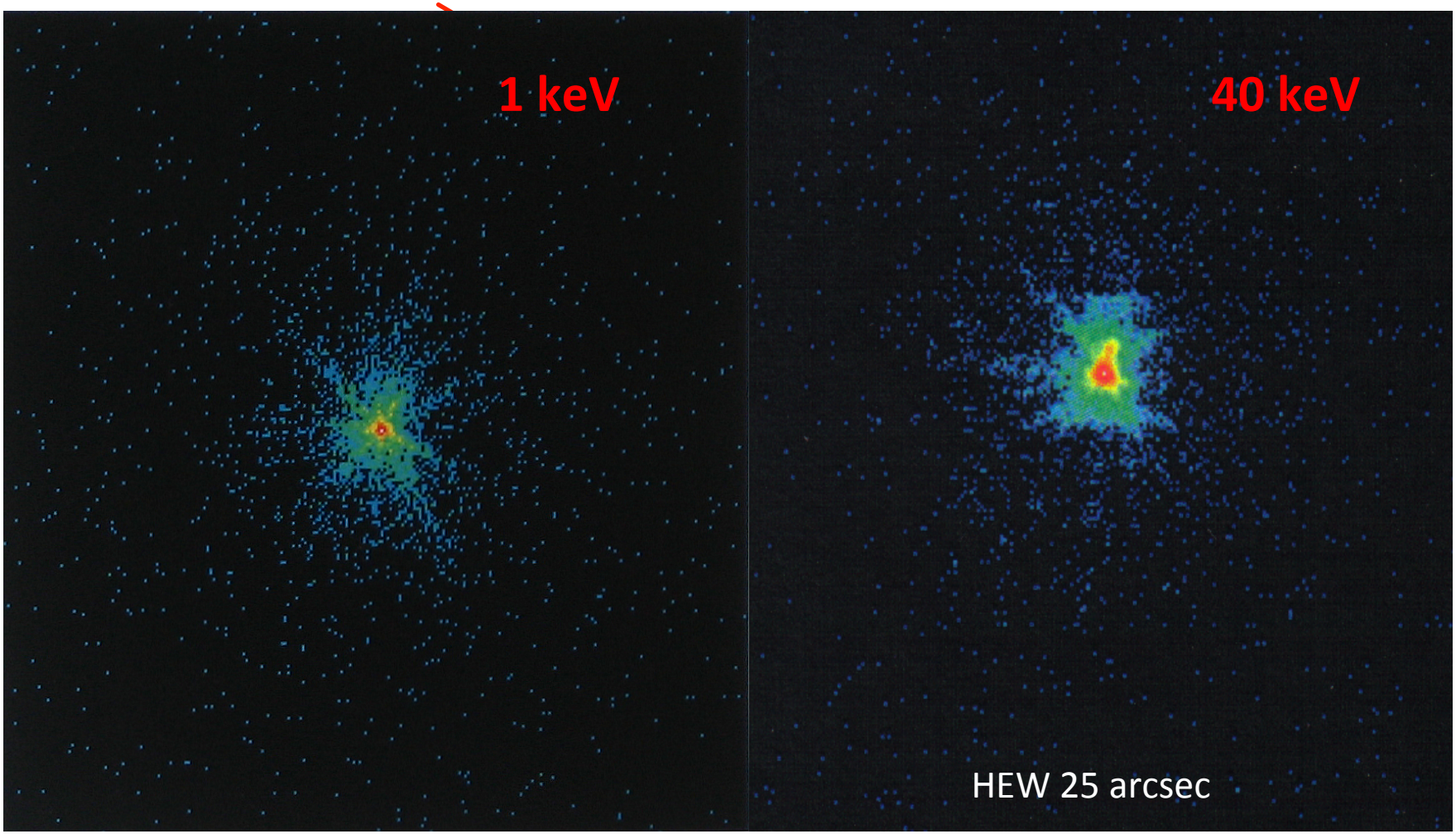
Mechanical structure: 2 spiders with 20 spokes



Integration of three mirror shell

PANTER tests

Optics calibration @ Panter/MPE



Angular resolution for Hard X-ray Experiments & Telescopes

Experiment - Telescope	Year	"Imaging" technique	Angular resolution
SAX-PDS	1996	Rocking collimator	> 3600 arcsec (collimator pitch)
INTEGRAL-IBIS	2002	Coded mask	720 arcsec (mask pitch)
NUSTAR	**2012**	**Multilayer Wolter I mirrors**	**55 arcsec HEW**
NHXM/ SIMBOL-X-like?	?	Multilayer Wolter I Optics	> / >> 20 arcsec HEW

SKYLAB X-ray telescope

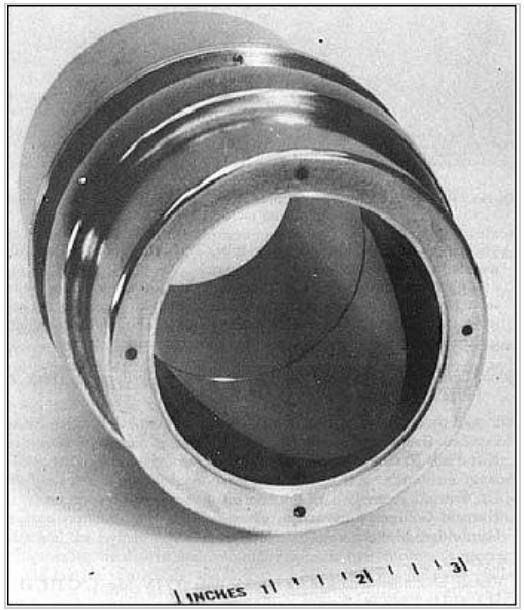
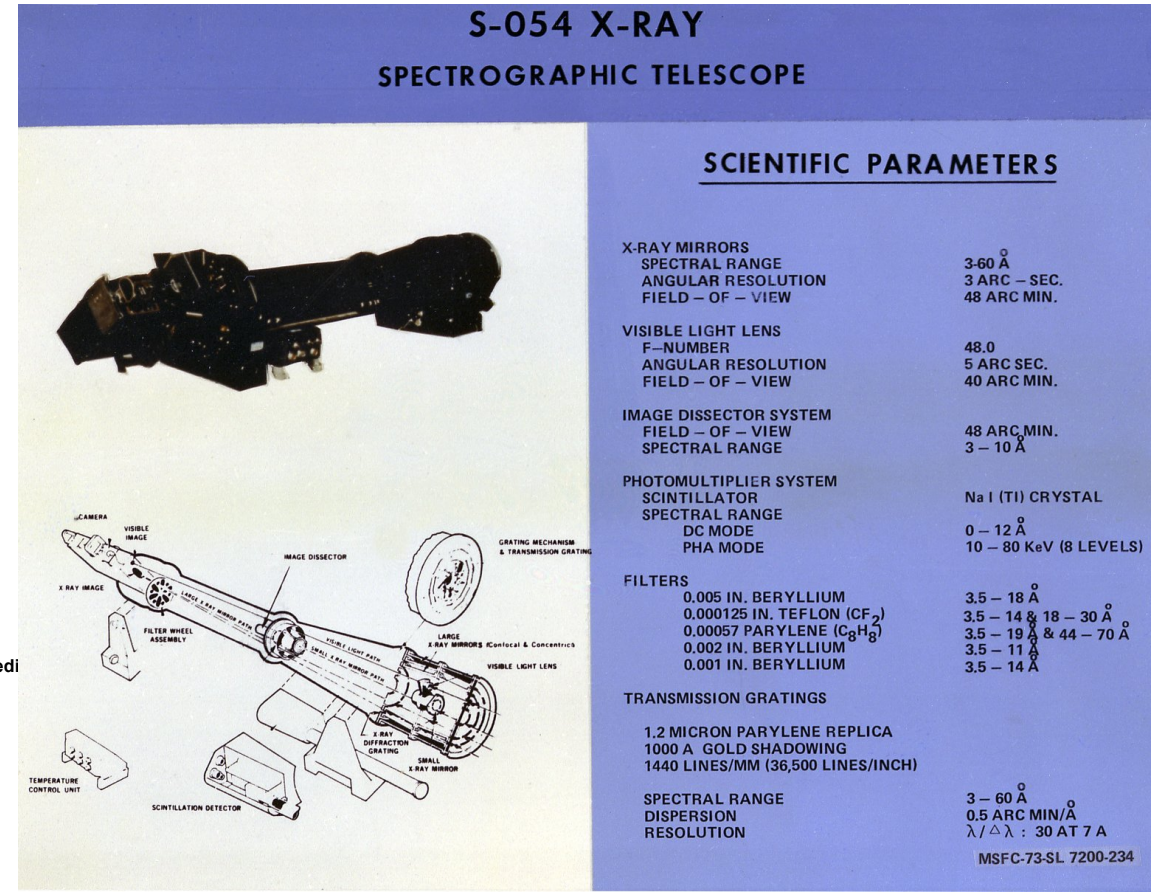
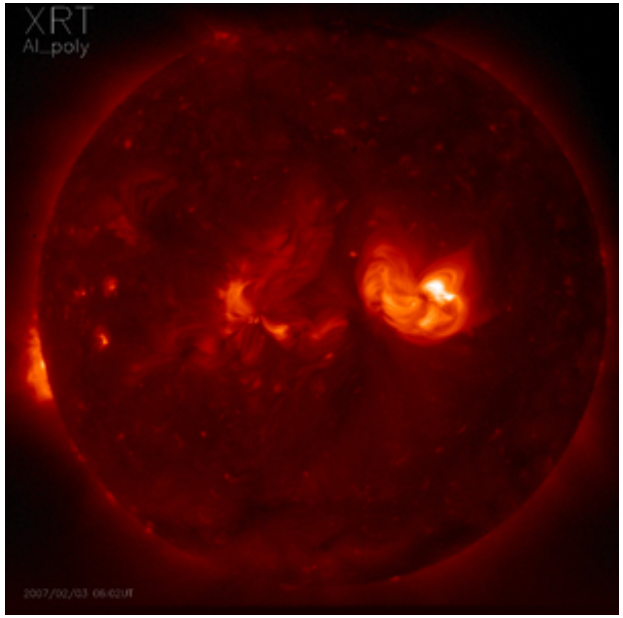


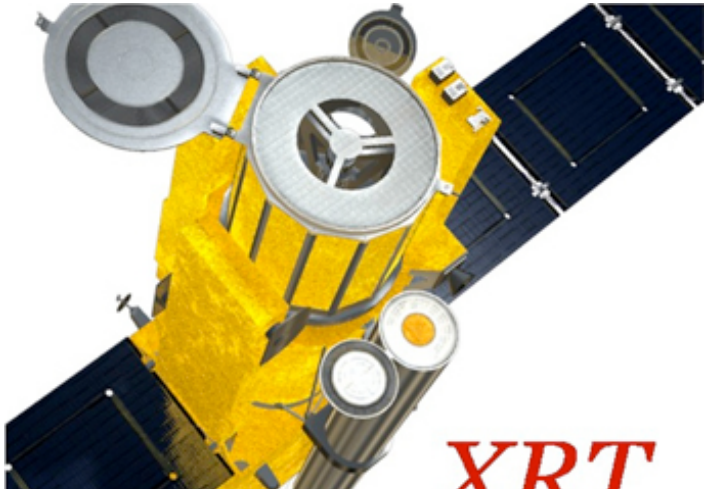
Figure 26: Photo of the cylindrical mirror for X-ray imaging telescope (image credi

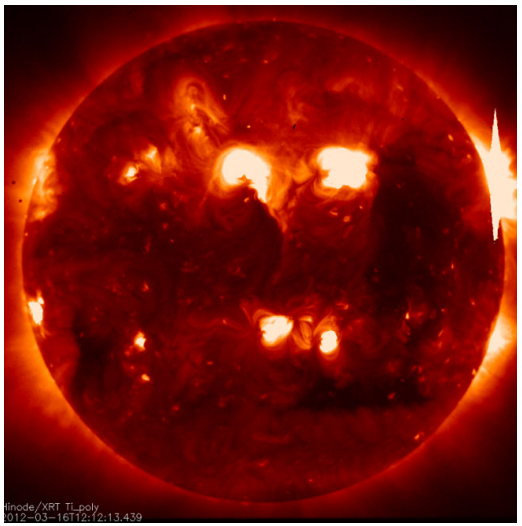


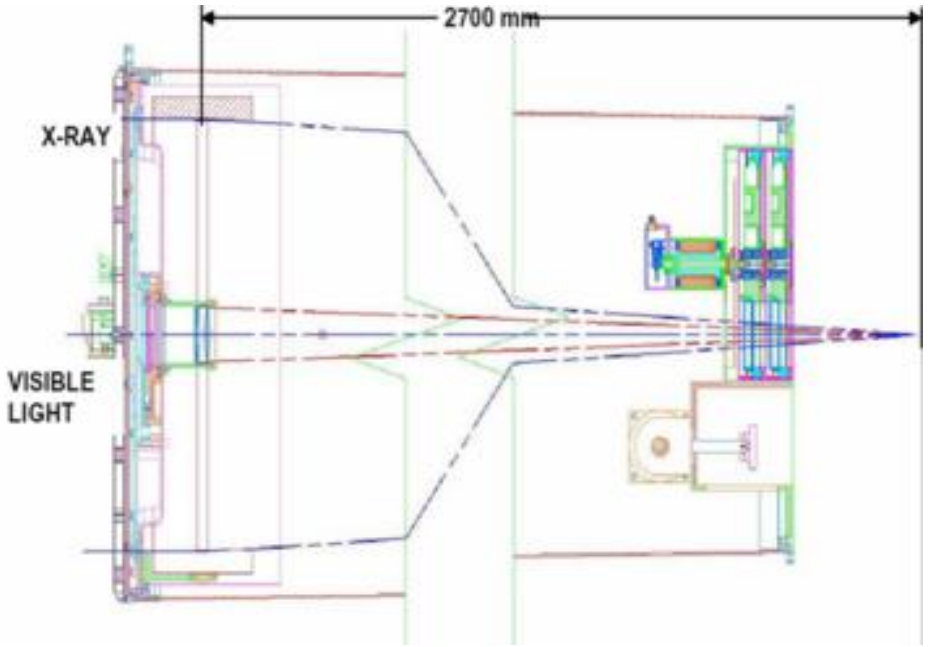
See Vaiana et al. 1977

Hinode X-ray telescope









Solar and non-Solar soft X-ray telescopes (< 5 keV)

- Solar
  - The X-ray flux is very high ➔ a single shell THICK is sufficient
  - Need of a very good angular resolution (a few arcsec)
  - Moderate focal length

- non-Solar
  - The flux of the X-ray source is very week ➔ need of a high effective area
  - Thin nested multiple shells
  - Often long focal length
  - The angular resolution / throughput trade-off

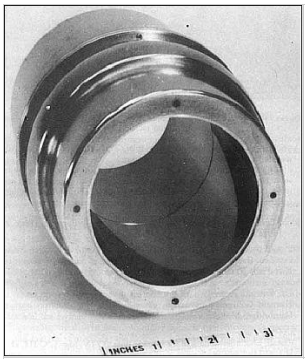
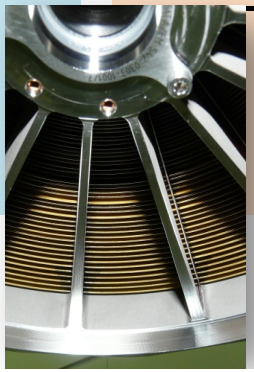


Figure 26: Photo of the cylindrical mirror for X-ray imaging telescope (image credit: NASA)



Needs for future Solar X-ray telescopes

(opinion from a dummy!)

- Hard (> 5 keV) X-ray detectors have been so far based on indirect imaging techniques e.g. Rotation modulation collimators
  - Focusing optics may become a valid alternative to provide a better imaging capabilities, higher dynamic range and better sensitivity ➔ FOXSI and friends

- Broad band telescopes, from 0.5 KeV up to 60 keV…ù
  - New Solid State detectors with enhanced capabilities

- In the soft X-ray regime, the use of low cost multiple mirrors may enhance spectroscopic and polarimetric studies but the have to be ccomplinat with….
  - Low cost & small size

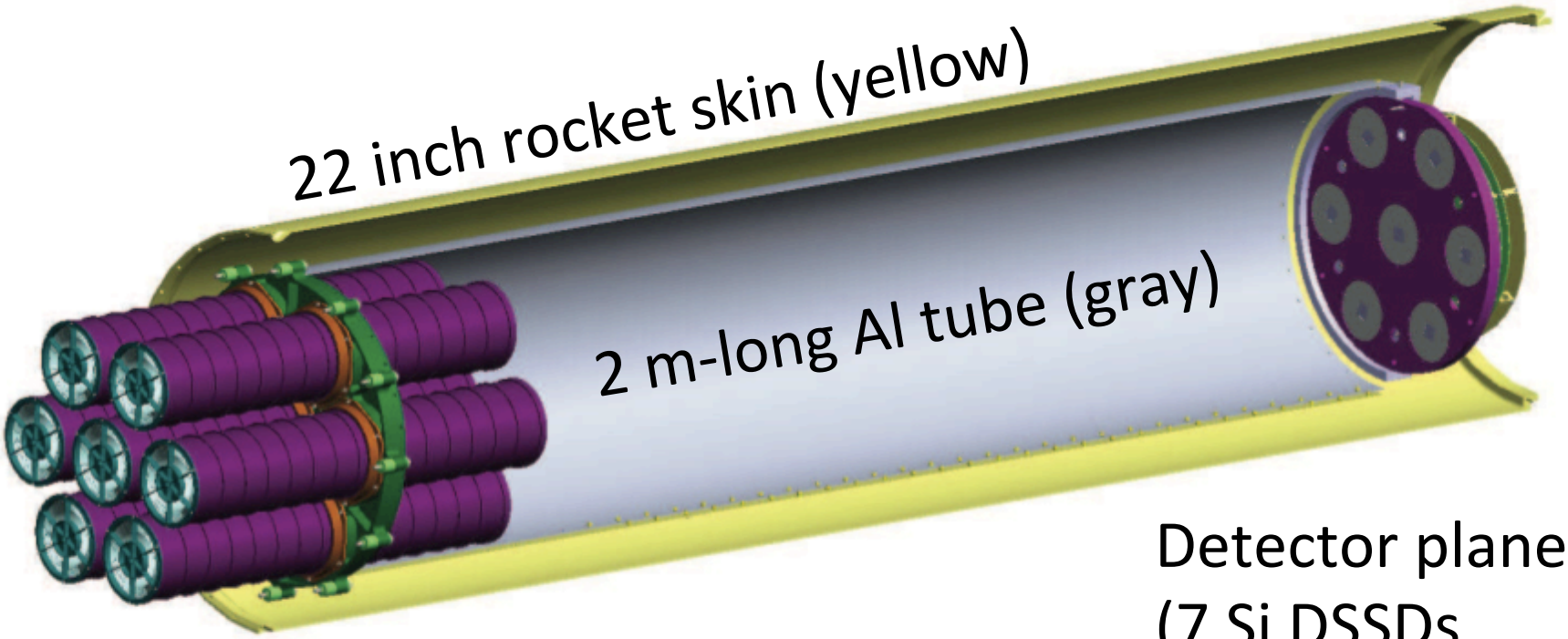
FOXSI Optics Details

- Focal Length: 2 m
- Number of modules: 7
- Number of shells: 7 (10)
- Optics Type: Wolter I
- Outer shells radius: 52 mm
- Inner shell radius: 38 mm (32 mm)
- Shell length: 60 cm.
- Energy range: 4 – 15 keV

* Values in parenthesis are for FOXSI2.

FOXSI Payload Overview

Telescope modules (B. Ramsey, MSFC)
(7 modules with 7 shells each)



Full moment cantilever connection (green)

Credits: Krucker et al.

Detector plane (7 Si DSSDs, T. Takahashi, ISAS/JAXA)

FOXSI X-ray optics assembly

FOXSI optics

- Focal Length: 2 m
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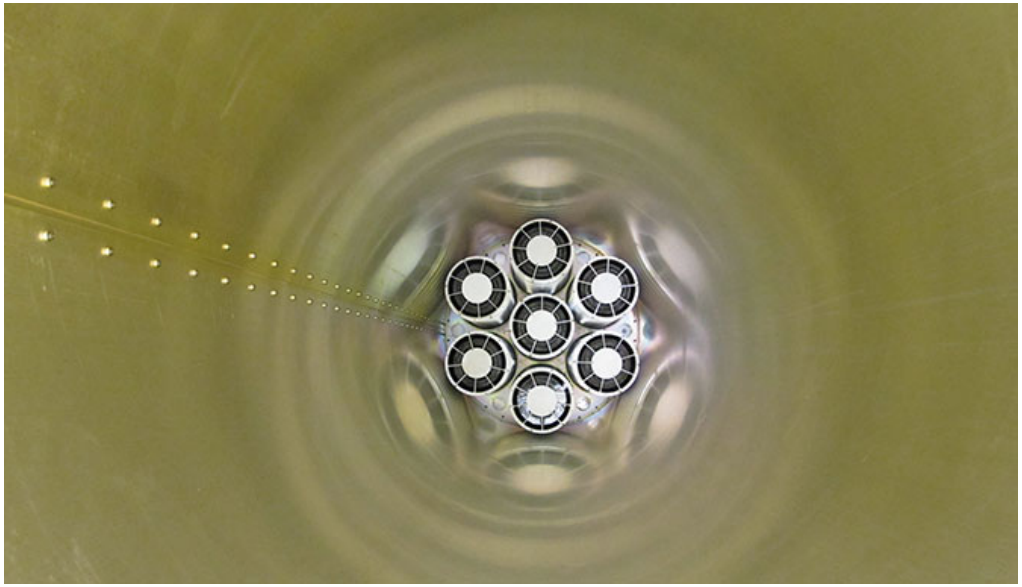
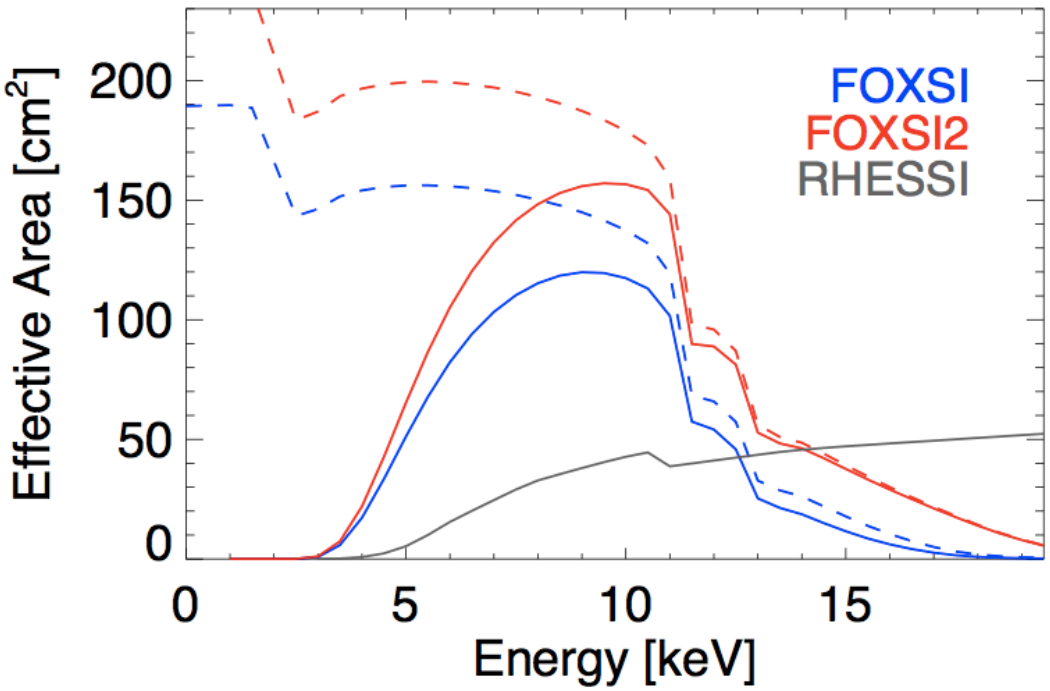


Looking down the telescope tube on FOXSI the Focusing Optics X-ray Solar Imager reveals state-of-the-art optics that will help focus hard x-rays, which usually simply pass right through telescope mirrors. Credit: NASA/S. Christe

Field-of-View ➔ 16 x 16 arcsec ^{2}

FOXSI Effective area



The dashed line represent the area provided by the optics.
The solid line is taking the entrance window and detector efficiency into account.

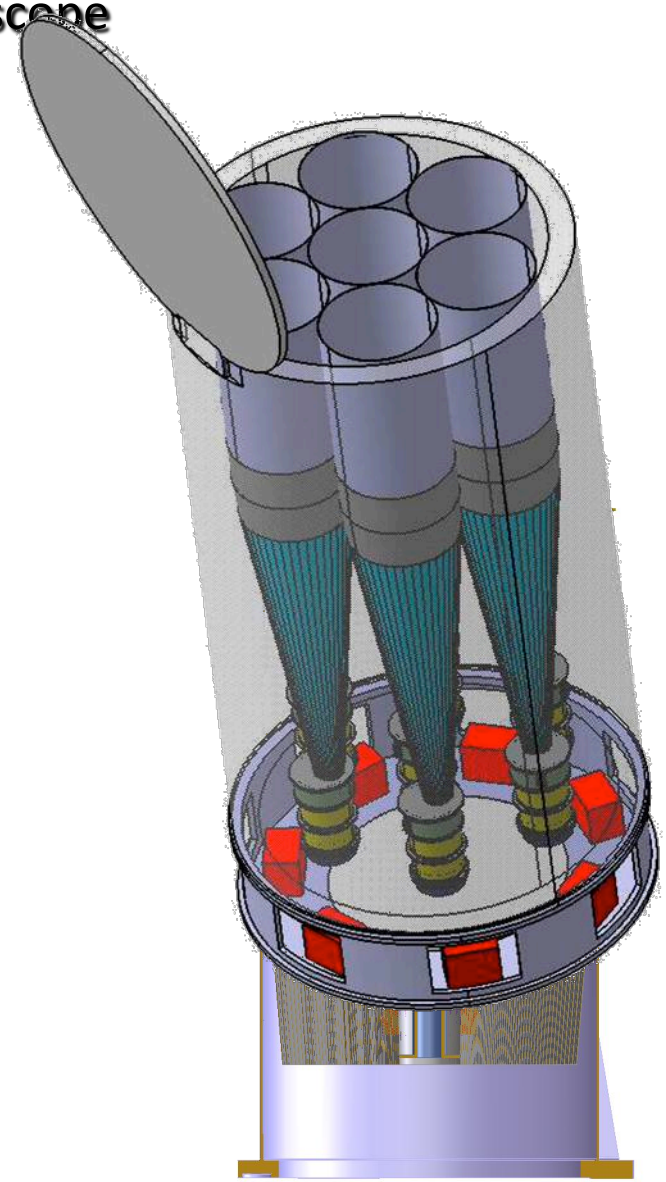
- FOXSI's effective area
  - Blue represents the current configuration for the flight in 2012
  - Red represents an upgraded configuration for a flight in 2014
- Due to increased area and smaller detectors, FOXSI will be **~50** times more sensitive than RHESSI (in this energy range).

Credits: Krucker et al.

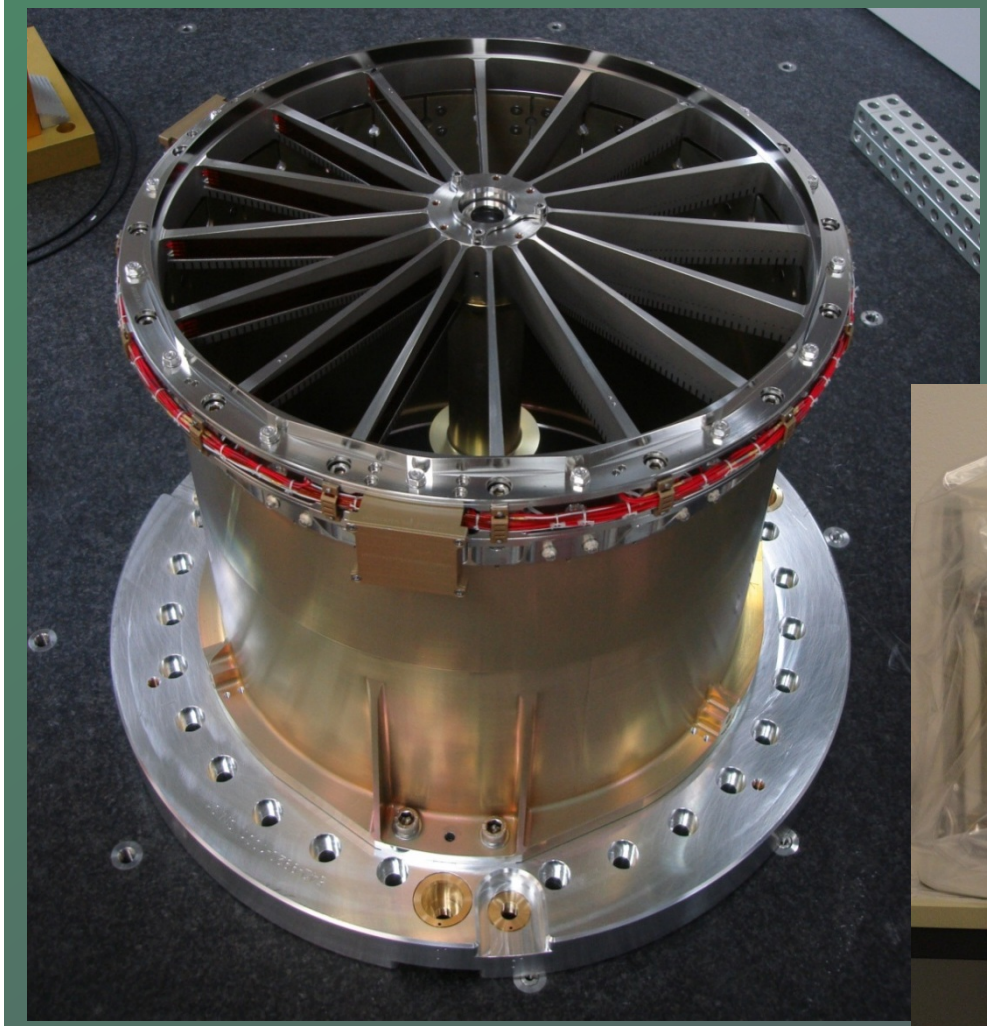
E-Rosita Mirror Design

Basic Data of the eROSITA Telescope

Mirror Type	Wolter 1
Number of mirror modules	7
Orientation of mirror modules	parallel
Degree of nesting	54
Focal length	1600 mm
Largest mirror diameter	365 mm
Smallest mirror diameter	76 mm
Micro-roughness	<0.5 nm
Energy range	~0.2 – 10 keV
Coating	Gold (> 50 nm)
Field-of-view	61' ∅



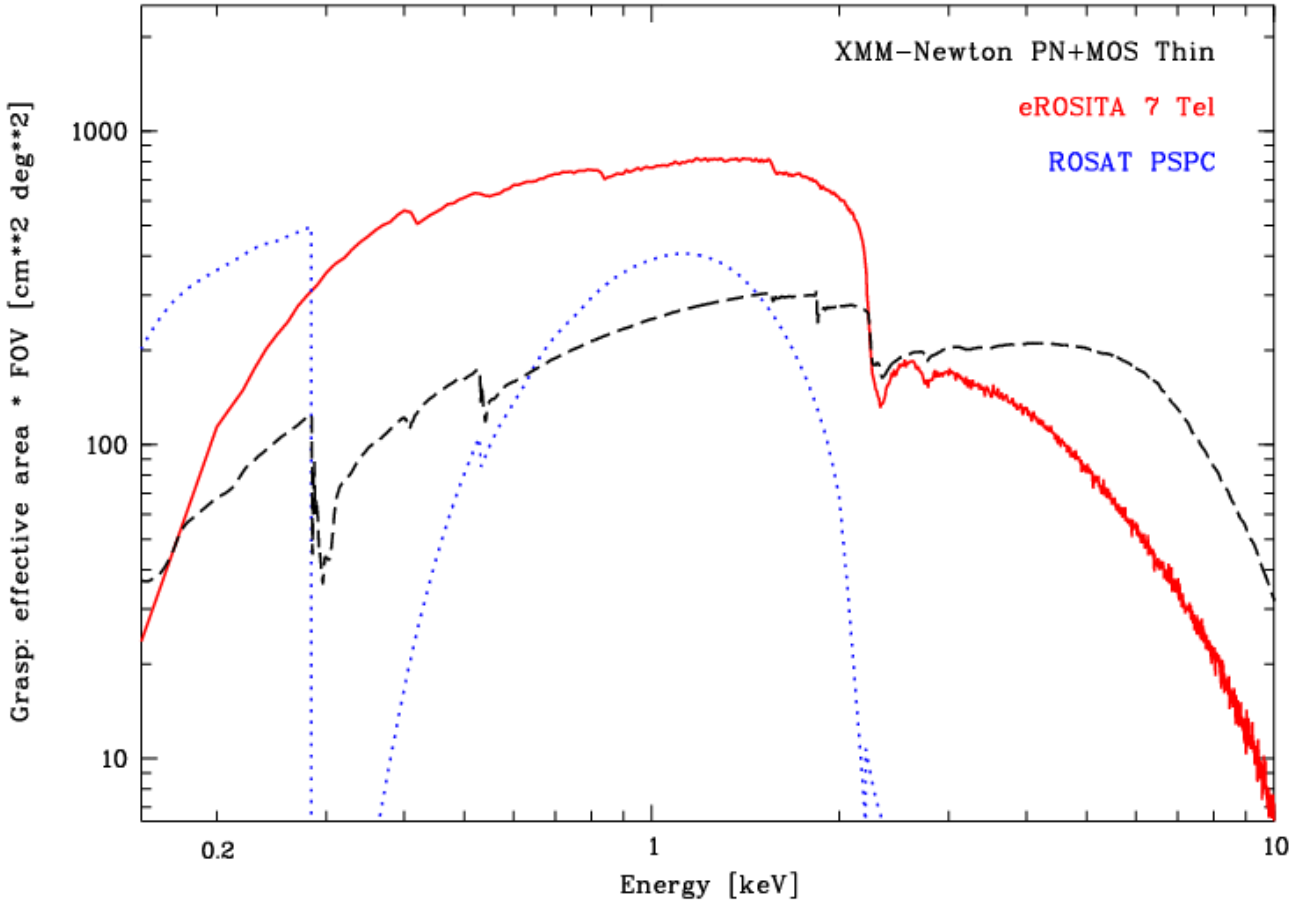
Mirror Module Structure



KAYSER-THREDE

e-Rosita: Grasp

Grasp [cm^2 deg^2]



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

E-Rosita: Mirror Design

Basic Data of the eROSITA Telescope

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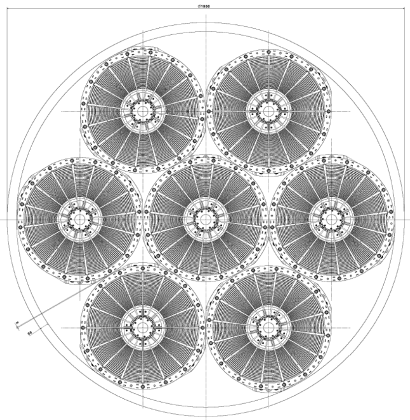
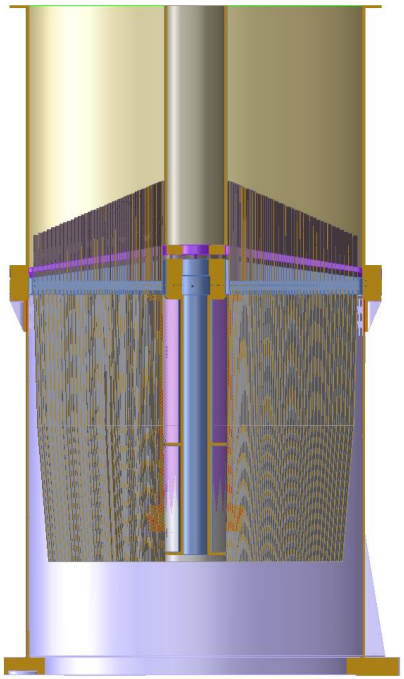
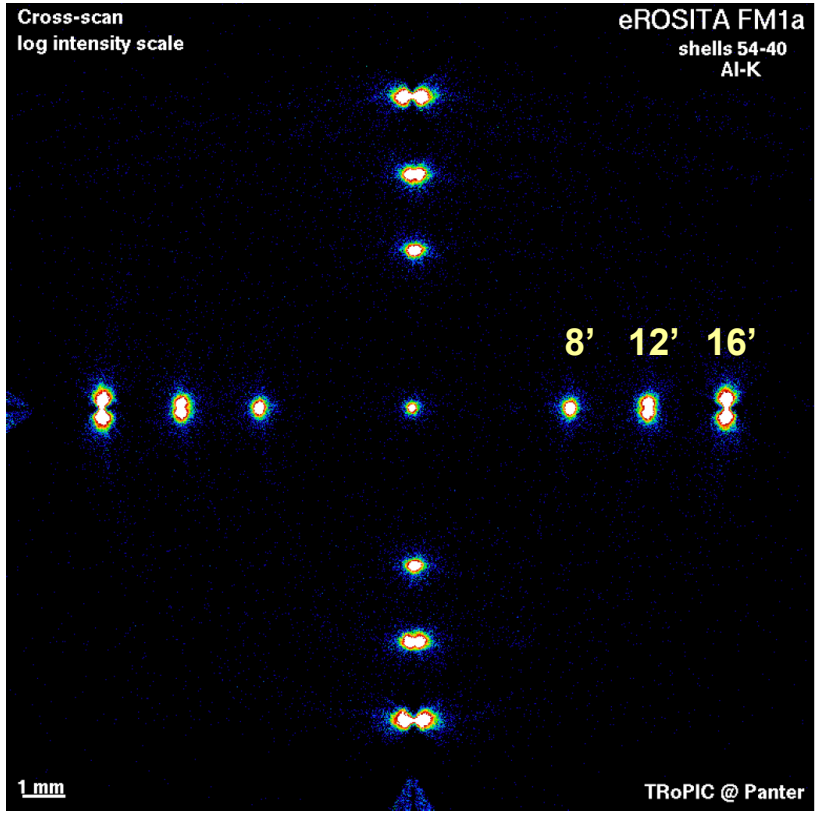
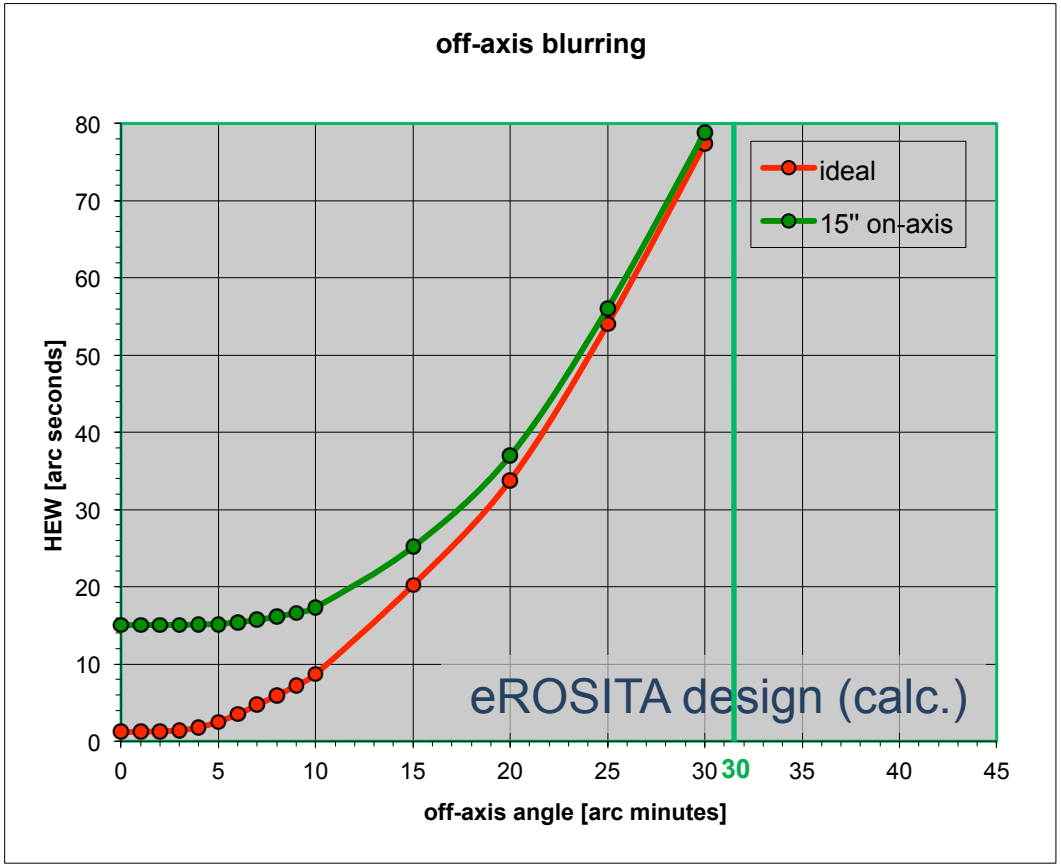




E-Rosita: Point Spread Function (PSF)



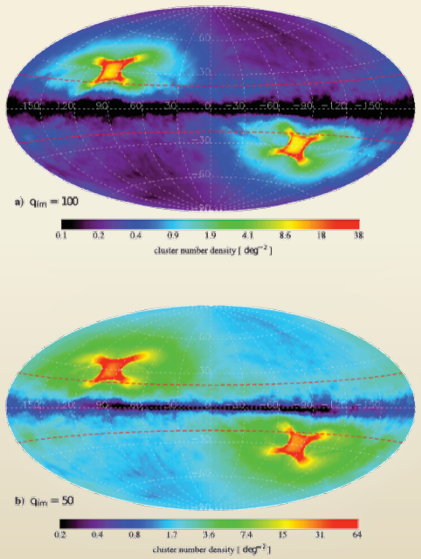


Clusters of Galaxies

100.000 GCs in eRASS

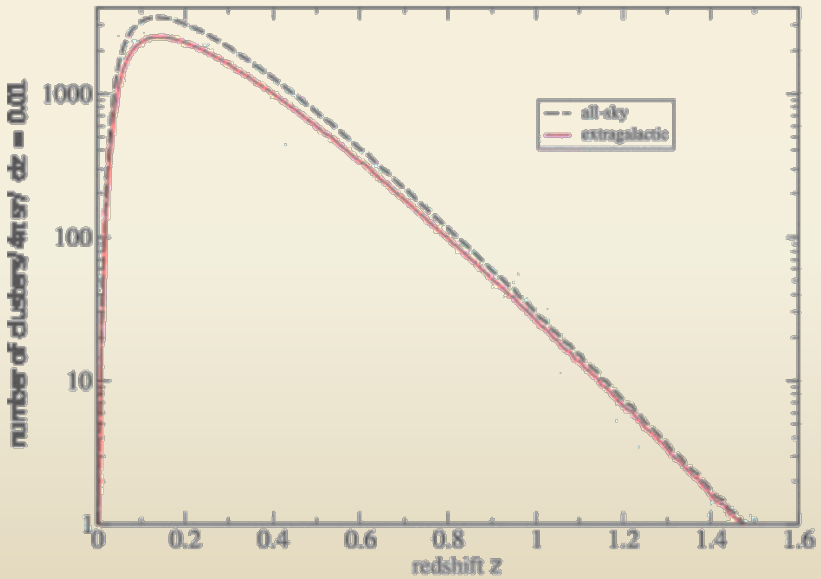
- Core Science of eROSITA -

- Cluster mass function evolution with redshift for different cosmologies
  → constraints on Ω_m, Ω_λ, σ_8



Nphot.	all sky	extragal sky
30	393810	293767
50	236503	176946
100	113227	85139
500	17272	13159
1000	7191	5514

M. Mühlegger Ph.D. thesis



X-ray optics with polynomial profile: general remarks

- 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,

➔ **rapid degradation with increasing off-axis angles**

- More general mirror designs than Wolter's exist

➔ **the primary and secondary mirrors are expanded as a power series**

- Optimization of polynomials

➔**increase the angular resolution at large off-axis positions but degrading the on-axis performances**

See Burrows, Burgh and Giacconi (1992)

Why short mirror lengths for WFXT

- The aspect ratio mirror shell length / focal length plays a very important role; in general the height of the shells should be kept as short as possible

- With short mirror shells the *spherical aberration* contribution to the PSF is reduced; moreover a better control of the *curvature of the field* is achieved

spherical abberation coma

$$\sigma \approx k \frac{\tan^2\theta}{\tan\alpha}\left(\frac{L}{F}\right) + 4\tan\theta\tan^2\alpha$$

α = on-axis incidence angle
θ = angular off-set
L = mirror height
F = focal length

Van Speybroeck & Chase, Appl. Opt., 1971

- A typical aspect ration between focal length and mirror shell of **14 - 15** must has to be taken (this was for the old WFXT design), but it should change in the interval **10 – 30**, depending on the f-number.

N.B.: short mirror shells ➔ increase of the manufacturing problems!

Optimization of the Single Mirror Shell

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

Best merit function for optimization of surveying telescopes

f = Focal Length / Shell Entrance Radius

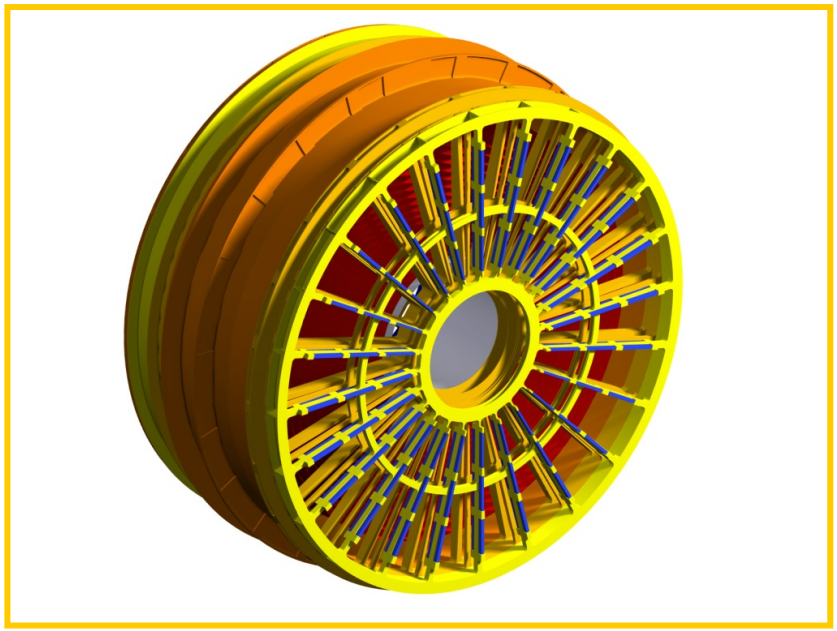
l = (100 x Total Mirror Length / Focal Length)

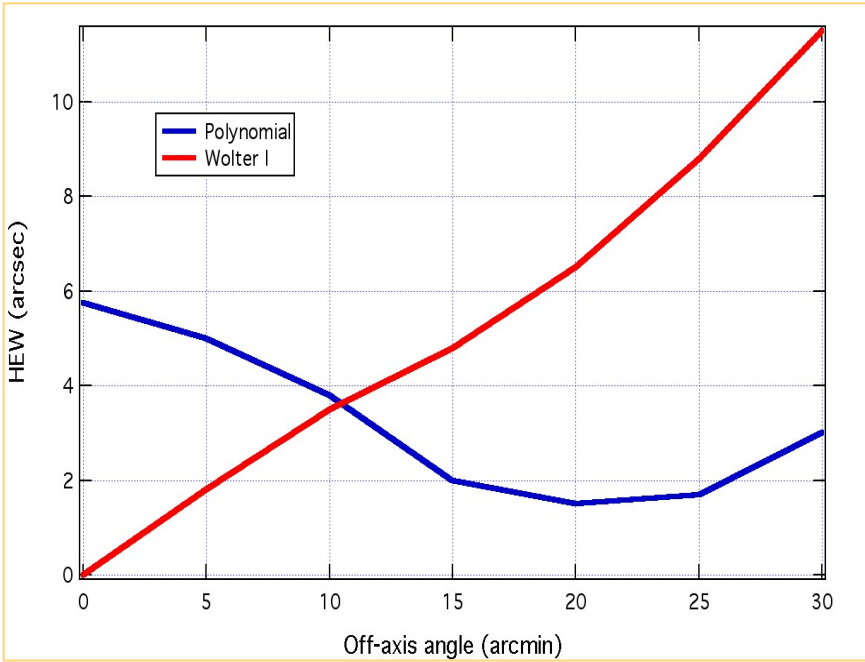
$$\text{HEW}(1\text{keV},\ f,\ l) \simeq 0.075 \times f \times l - 0.3 \text{ arcsec}$$

Simplified formula for the HEW of a polynomial optics (BBG, 1992) weighted over the FOV coming from the optimizations (Conconi et al., Applied Optics , 2009, submitted)

Thin glass shell oriented to Wide Field X-Ray Telescope

(P.I. S. Murray; Sen. Scient. R. Giacconi)





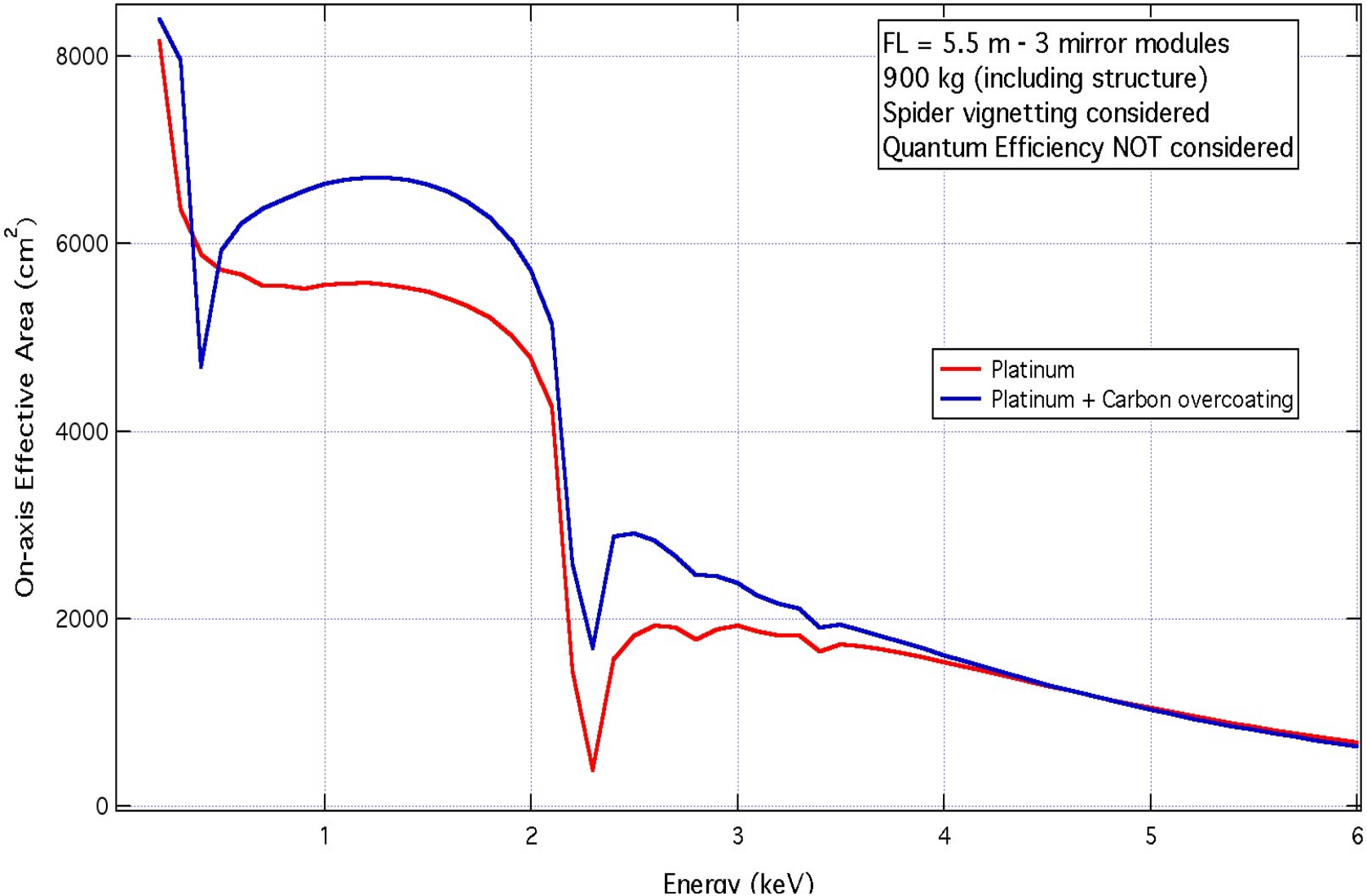
N.B.: same mirror height/FL aspect ratio =0.07

WFXT being proposed to NASA in the context of the RFI call (Sept 2011)- P.I. S. Murray

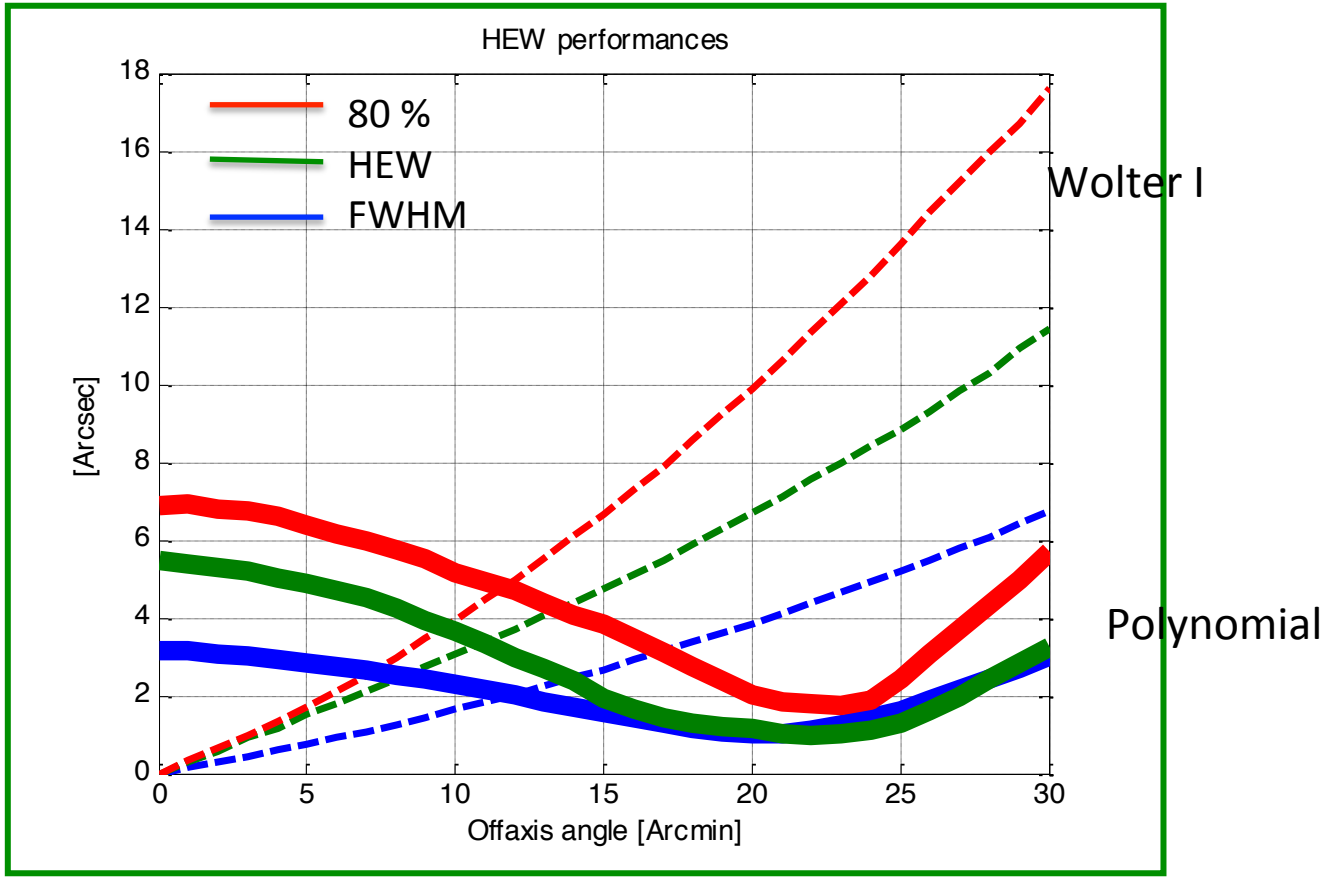
WFXT Telescope Configuration

Parameter	Design
Number of Modules	3
Material	Fused Silica
Configuration	Polynomial Profile
Focal Length	5.5 m
MAX & min top diameters	0.36 & 1.1 m
MAX and min mirror Length (2 reflections)	408 & 220 mm
Coating	Pt + C overcoating
Wall Thickness	3 – 1.7 mm
Number of mirror shells /module	55
Total Weight	900 kg (3 modules including structure)

WFXT On-axis effective area



Angular resolution from the design (not including fabrication errors)



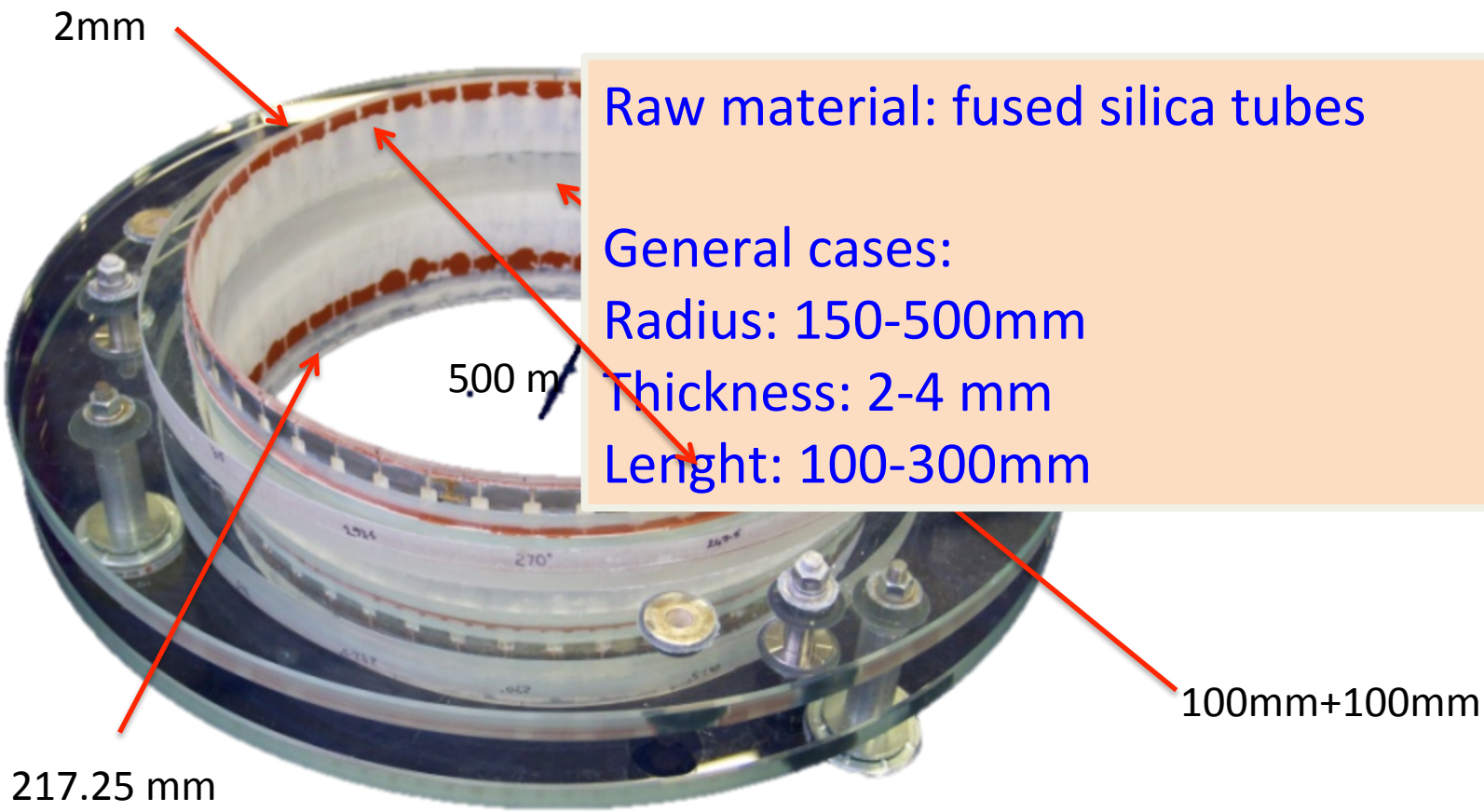
Survey capabilities comparison

GRASP = on-axis A_{eff} x 0.75 * FOV

MERIT FACTOR FOR SURVEY= GRASP / HEW^2

	ROSAT	CHANDRA	XMM	eROSITA	WFXT*
GRASP @1 keV (cm^2 deg^2)	300	50	240	750	4400
HEW @2/3 FOV (arcsec)	30	3	20	30	5
MERIT FACTOR (cm^2 deg^2 / $arcsec^2$)	0.3	5.5	0.6	0.83	176

Thin glass shells

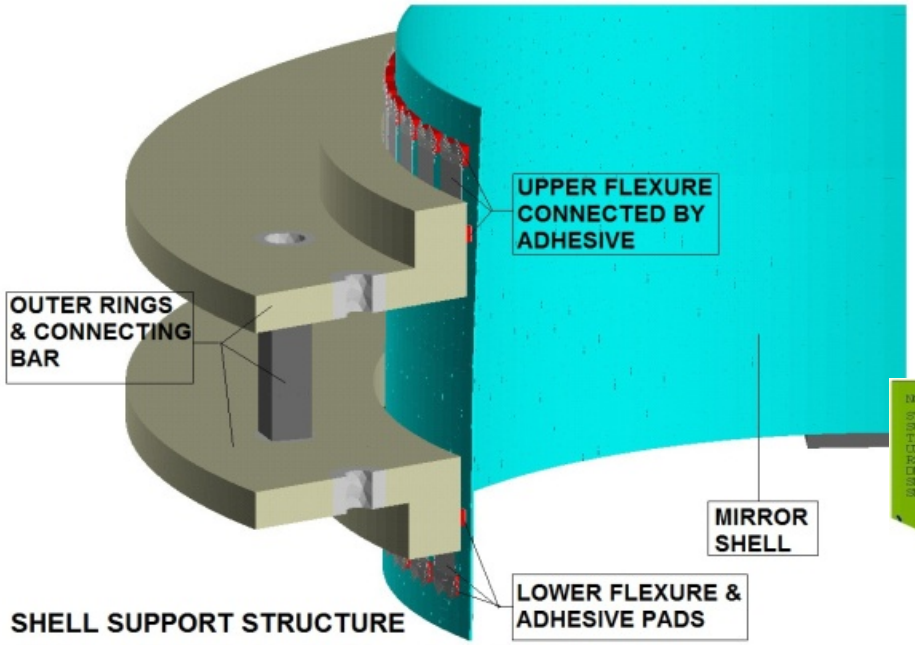


Raw material: fused silica tubes

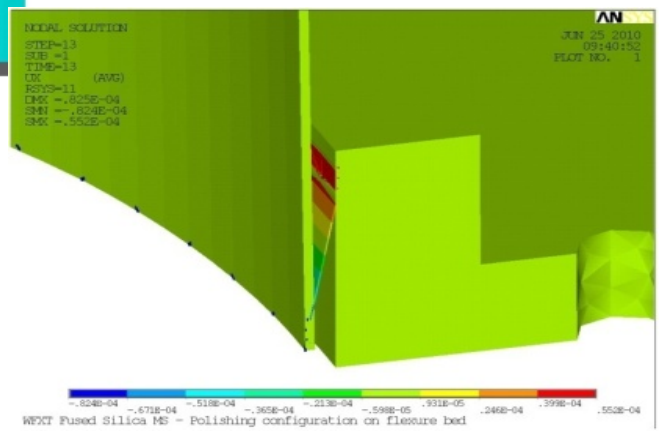
General cases:
Radius: 150-500mm
Thickness: 2-4 mm
Lenght: 100-300mm

Need of astatic support to sustain the mirror shell during the polishing and figuring process

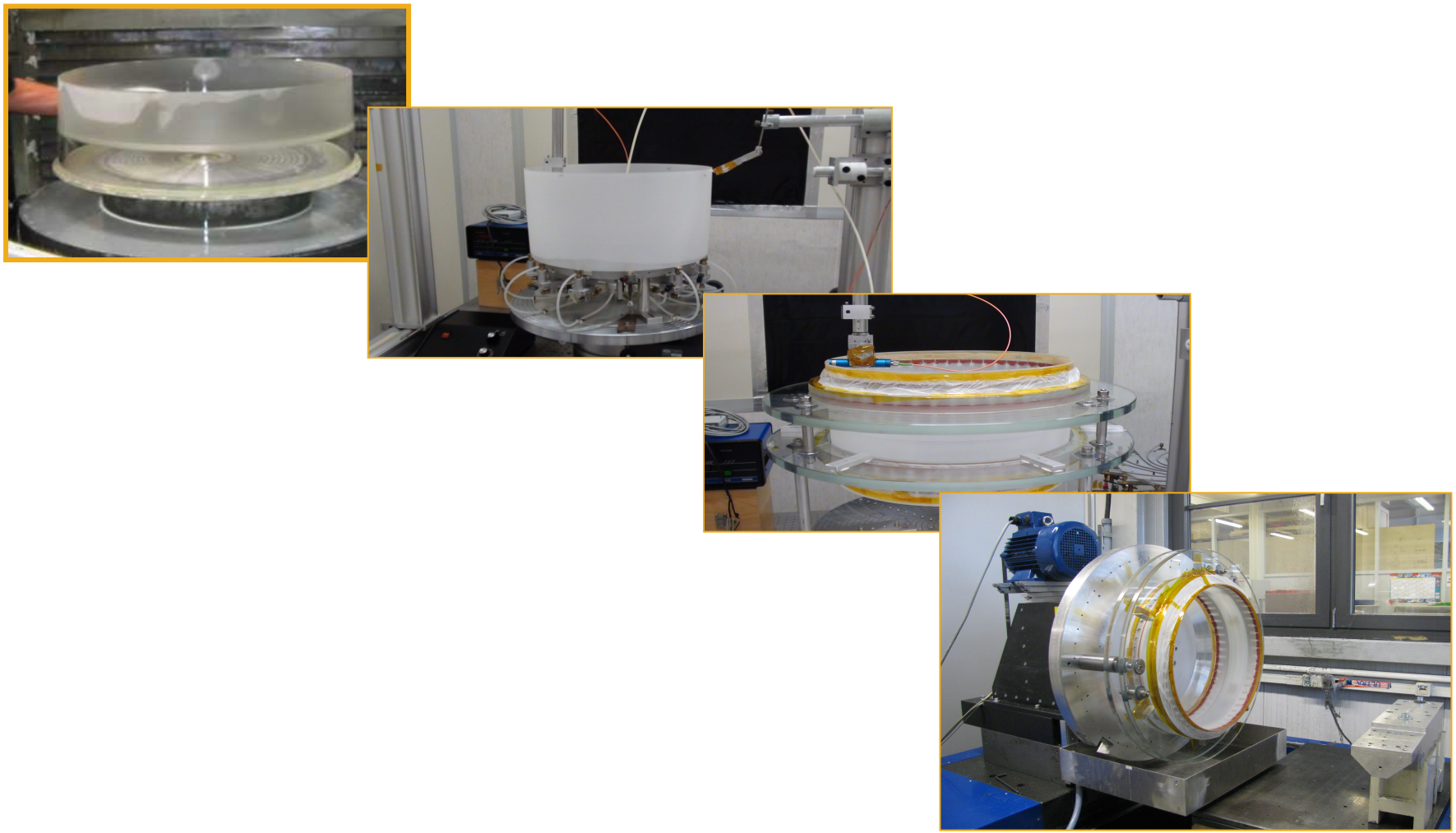
How to handle a thin glass shell: the Shell Supporting System (SSS)



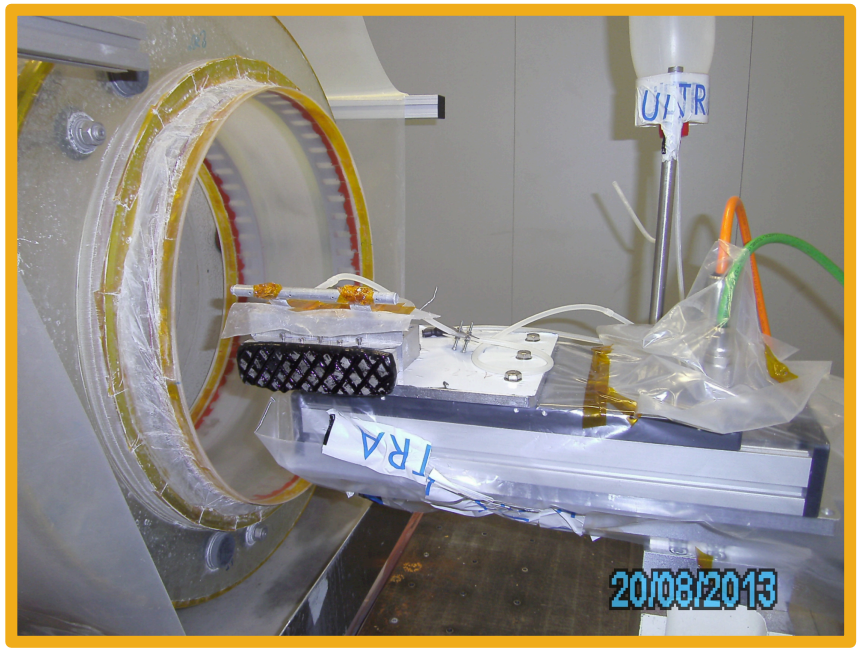
-Temperature effects
-Gravity effects
-Integration errors



Process flow (I)



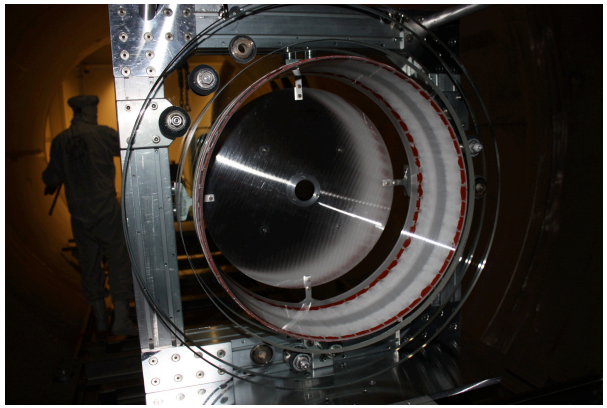
Process flow (II)

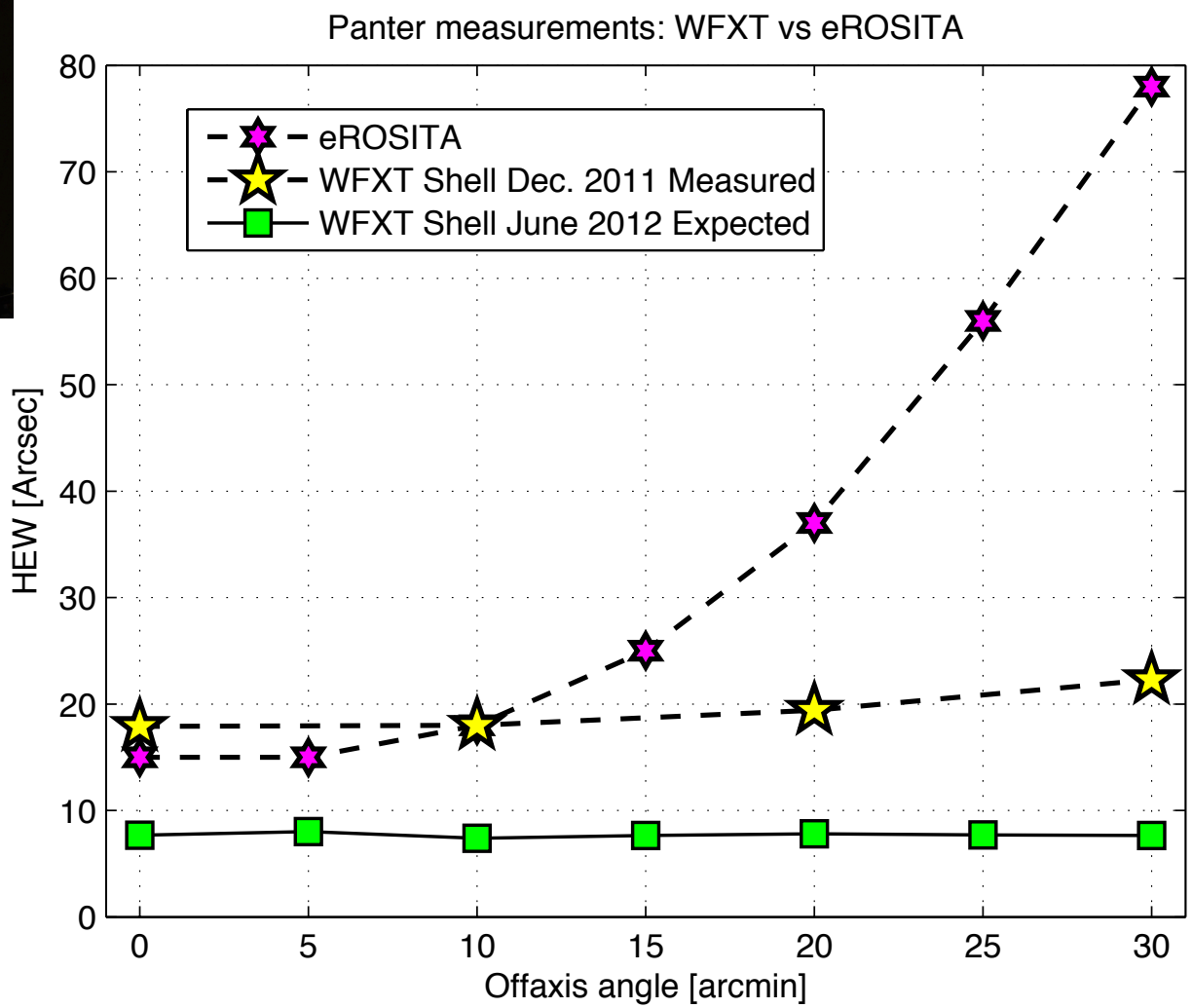


No polishing machine, but Pitch tool directly mounted on the grinding lathe

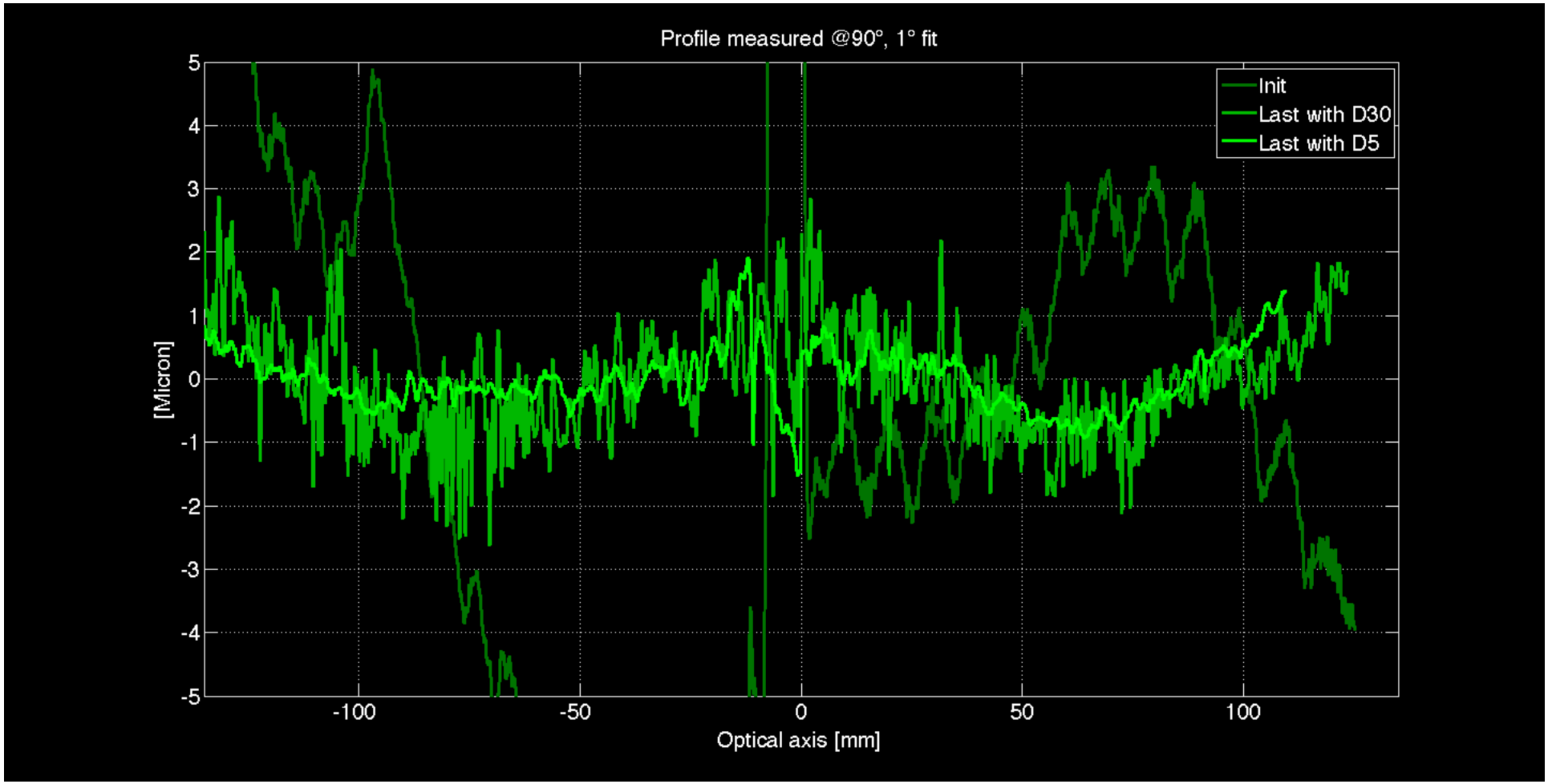
Final Ion Beam Correction of residual low frequency longitudinal and OOR errors

Preliminary Result after calibration @ PANTER

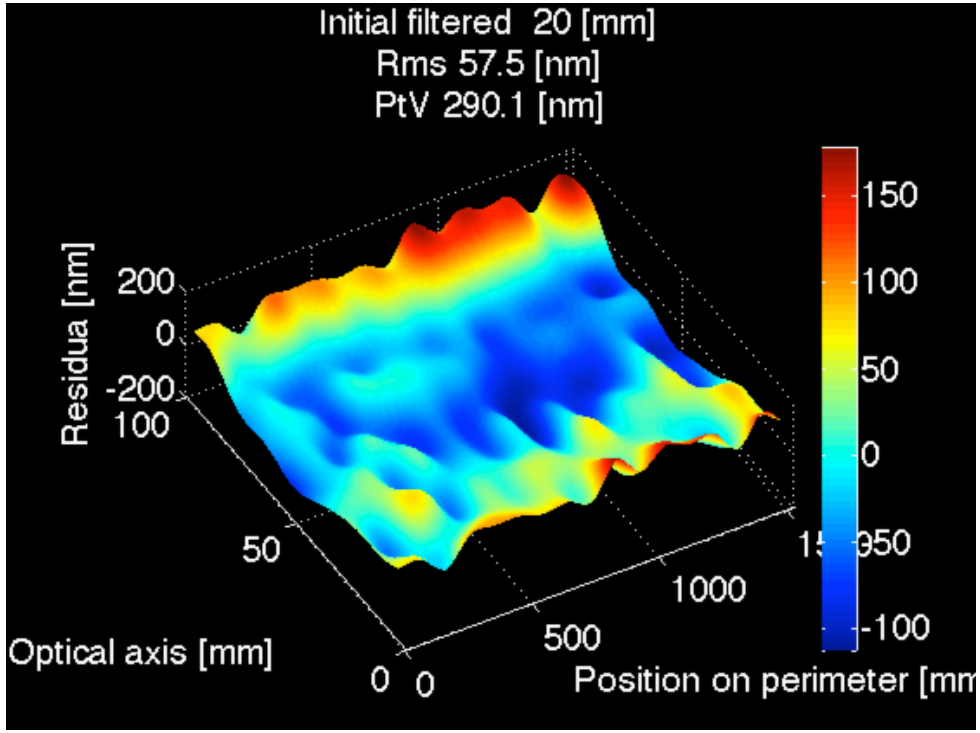


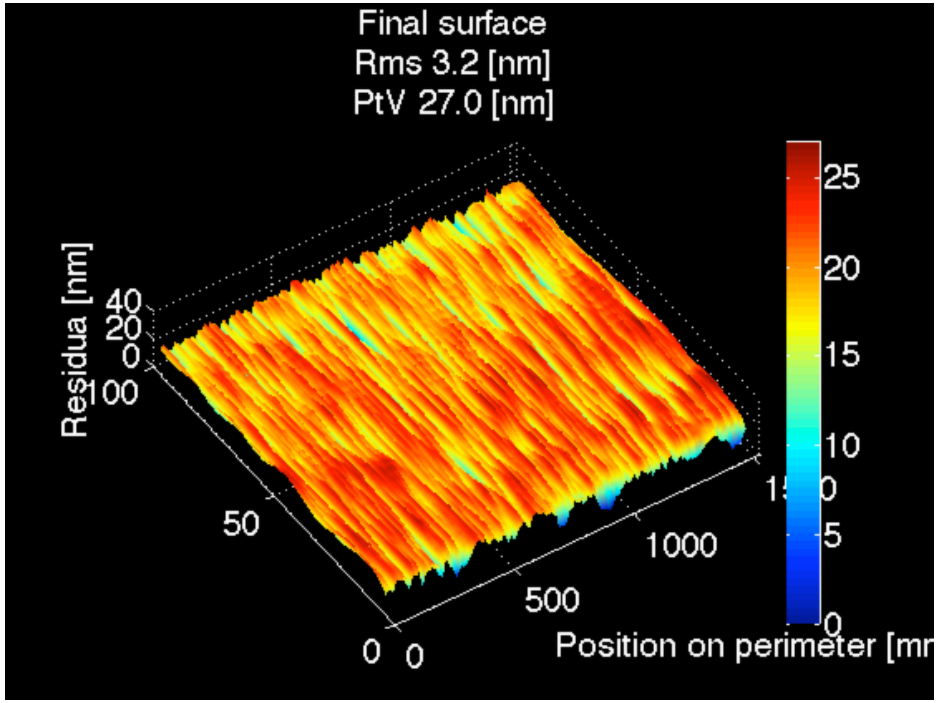


Longitudinal Profile: evolution of residuals



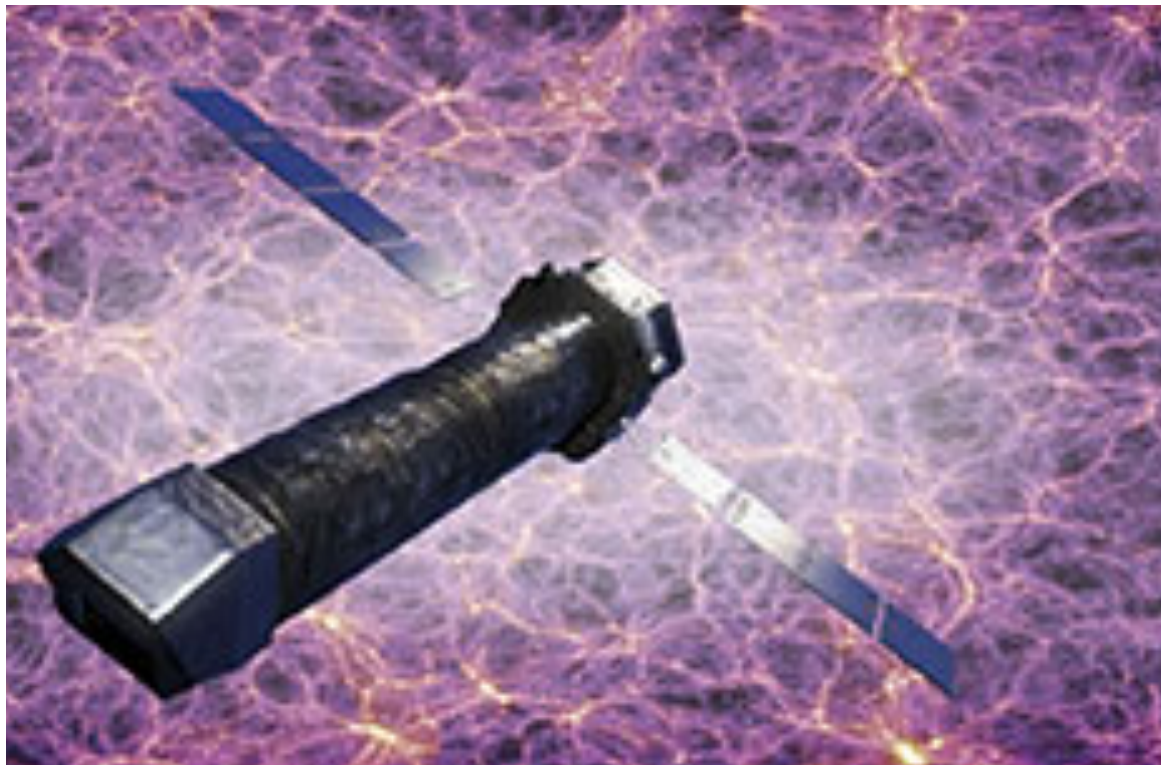
Ion beam: expected results from simulation





Simulations show that ideally the Ion beam process is able to converge toward a mathematical solution with final rms of around 3nm, removing completelly low frequency errors in both longitudinal and azimuthal directions. (residual error <<1’’).

ATHENA – ESA approved large mission (2028)

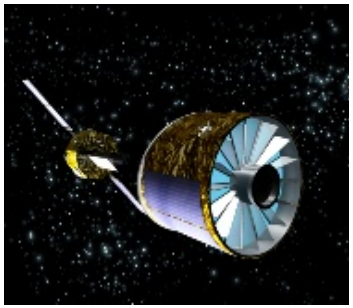


Angular resolution requirements

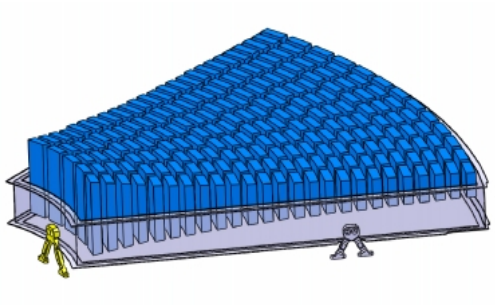
- Elaborated by the Athena+ working groups

Topic	Goal	Comment
Cluster core physics	Mapping with at least 3 to 5 independent radial bins within the cluster core regions in clusters of up to z~1 and beyond.	The goal angular resolution would enable to extend the z range
Cluster outskirts	Mapping cluster outskirts (low surface brightness) after removing point source emission from background objects in a representative sample of objects out to z~1 and beyond	Cosmic background suppression >80% for baseline angular resolution.
Cluster feedback	Resolve the velocity and thermodynamic structure in cavity rims to understand the energetics of AGN feedback in clusters. Resolving fine structures (X-ray filaments, weak shots) and cavities in distant clusters	Reaching the goal angular resolution will enable to see feedback in action at higher z
High z survey	Deep imaging for black hole demographics from a multi-tired survey, providing arcsec positions and million object catalogs including hundreds of objects at z>5	Trade-off space in the FOV average point source sensitivity HEW=f(OAA)
Obscured accretion	Measure the luminosity function of CT AGNs down to z~4 (sub-L*) thanks to an increased survey speed compared eg to Chandra	Set by the need to have 100s of objects between z~1-2
Observatory science	Star forming region, Solar system bodies, galaxy survey, galactic center, ...	Solid justification for the baseline angular resolution

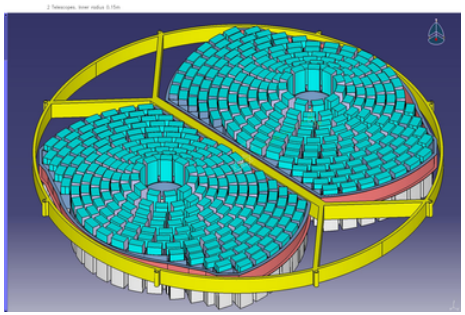
Some historical remarks



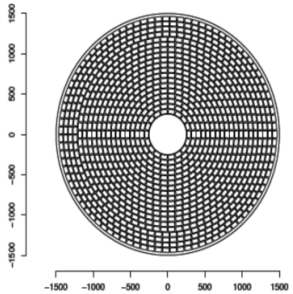
XEUS



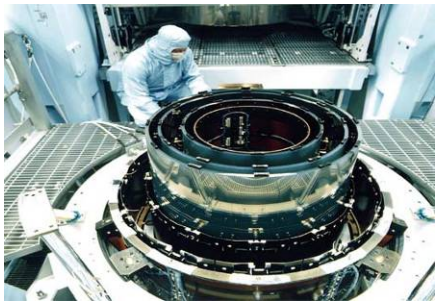
IXO



ATHENA L1



ATHENA L2

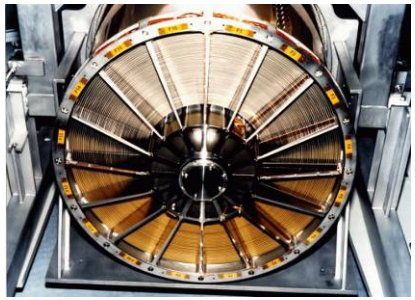


CHANDRA

0.5 arcsec

Aeff = 0.078 m²

18500 kg/m²
Aeff @ 1 keV

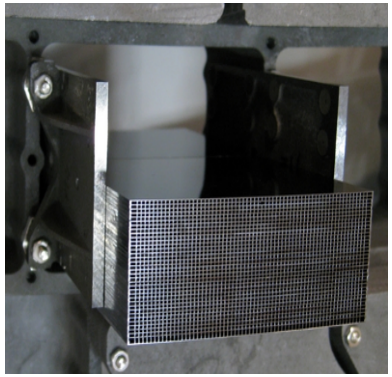


XMM-NEWTON

14 arcsec

Aeff = 0.43 m²

2300 kg/m²
Aeff @ 1 keV



Silicon Pore Optics

5-10 arcsec

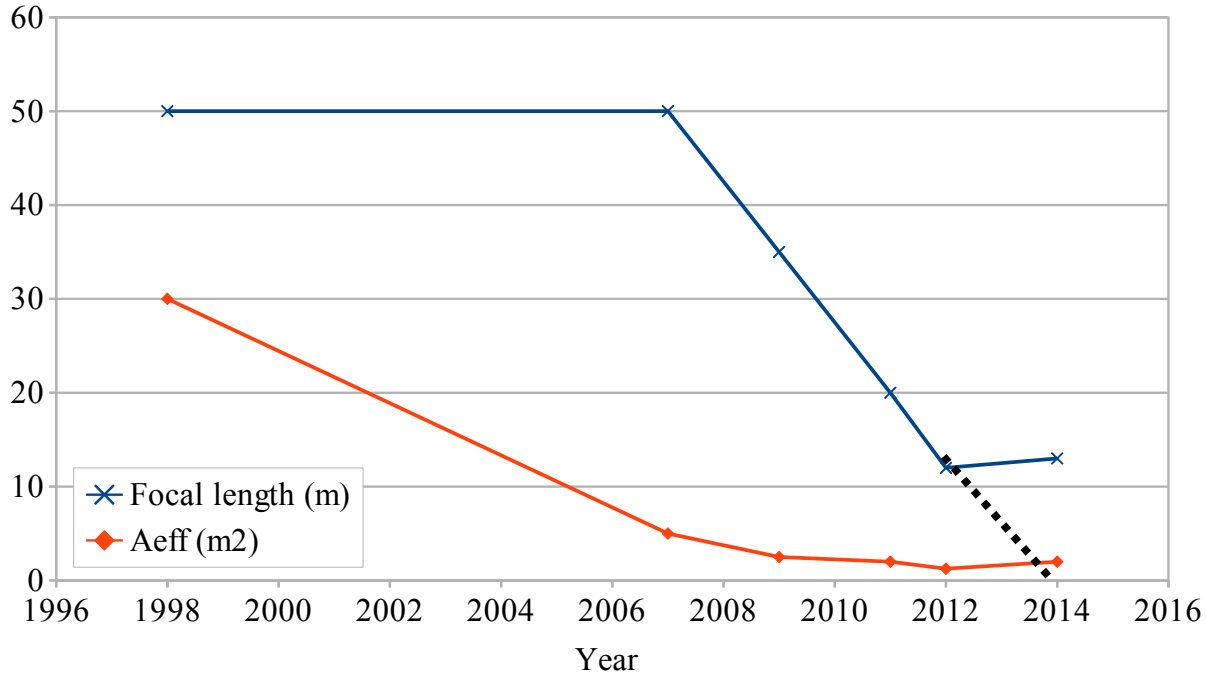
Aeff = 1 m²

<240 kg/m² (mirror module)
Aeff @ 1 keV

ATHENA baseline

From 1998 to 2014 – technology has to adapt continuously

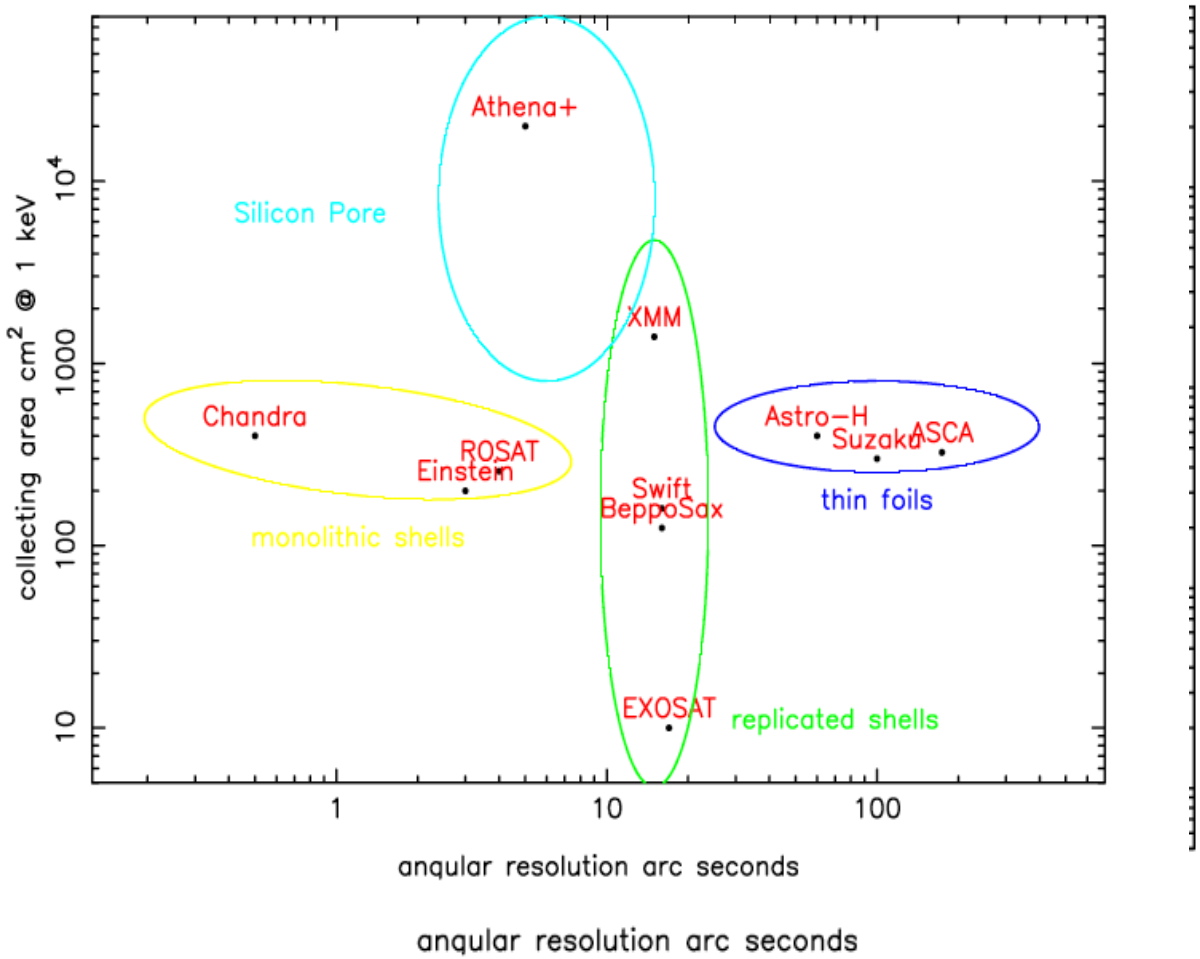
XEUS	IXO	ATHENA -	+
Proof of principle	1st robot f=50 m / r=2 m	2nd robot f=20 m / r=0.74m	



Next Robot: FL 12 m

Athena Telescope

Collecting Area vs. Angular Resolution

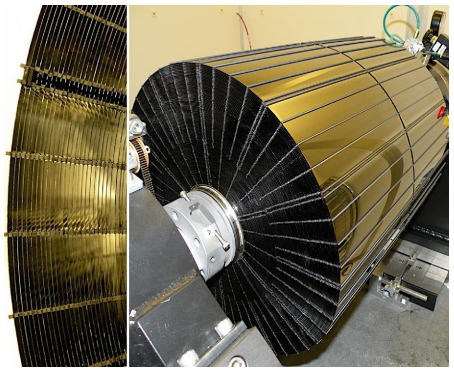


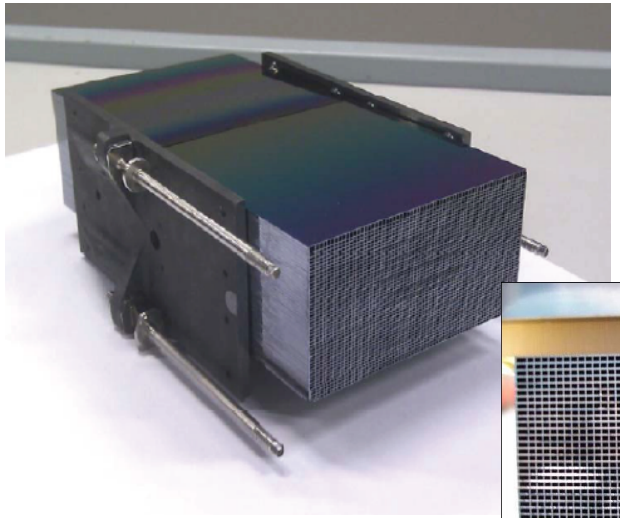
angular resolution arc seconds

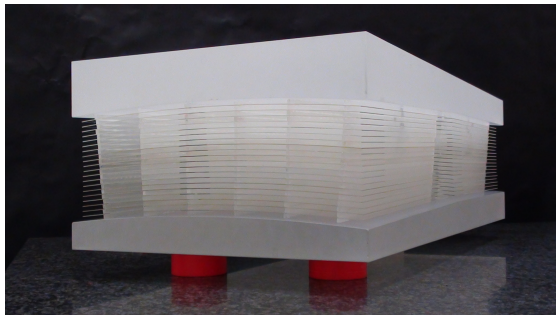
Technologies for mirrors

- Baseline:
  Silicon Pore Optics (SPO) – ESA/Cosine

- Alternative:
  Slumped Glass Optics (SGO)
  INAF/Brera, MPE, GSFC







ATHENA will be large (2 m^2 A_{eff} @ 1 keV)

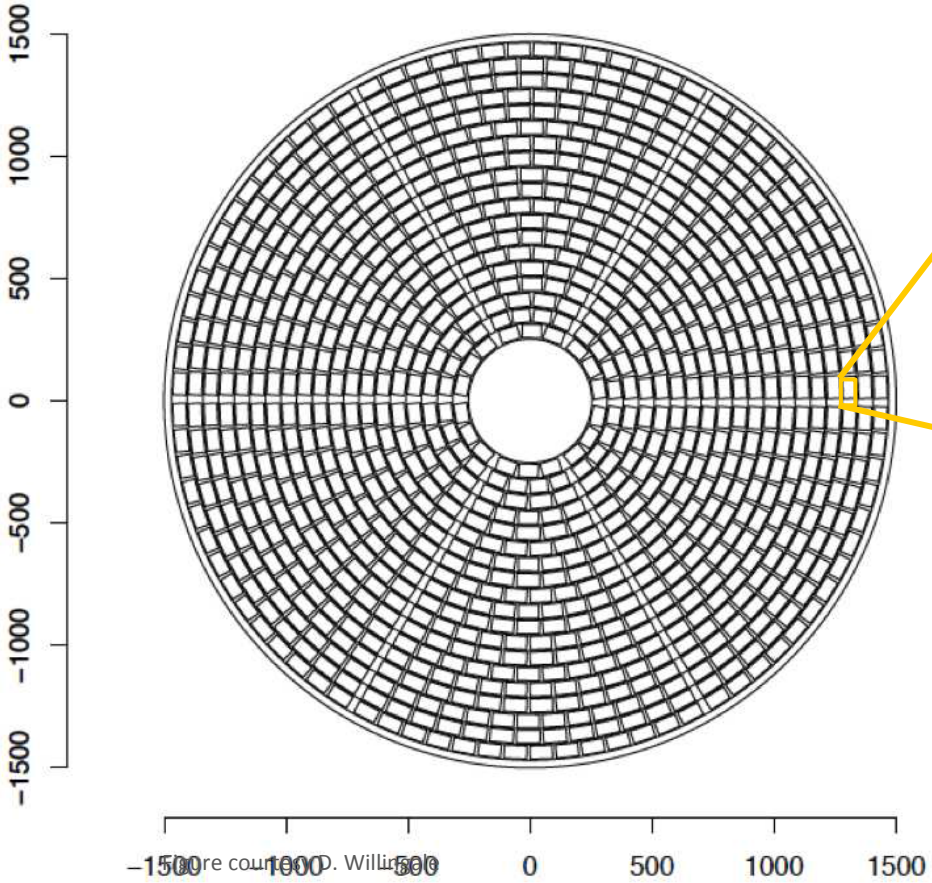
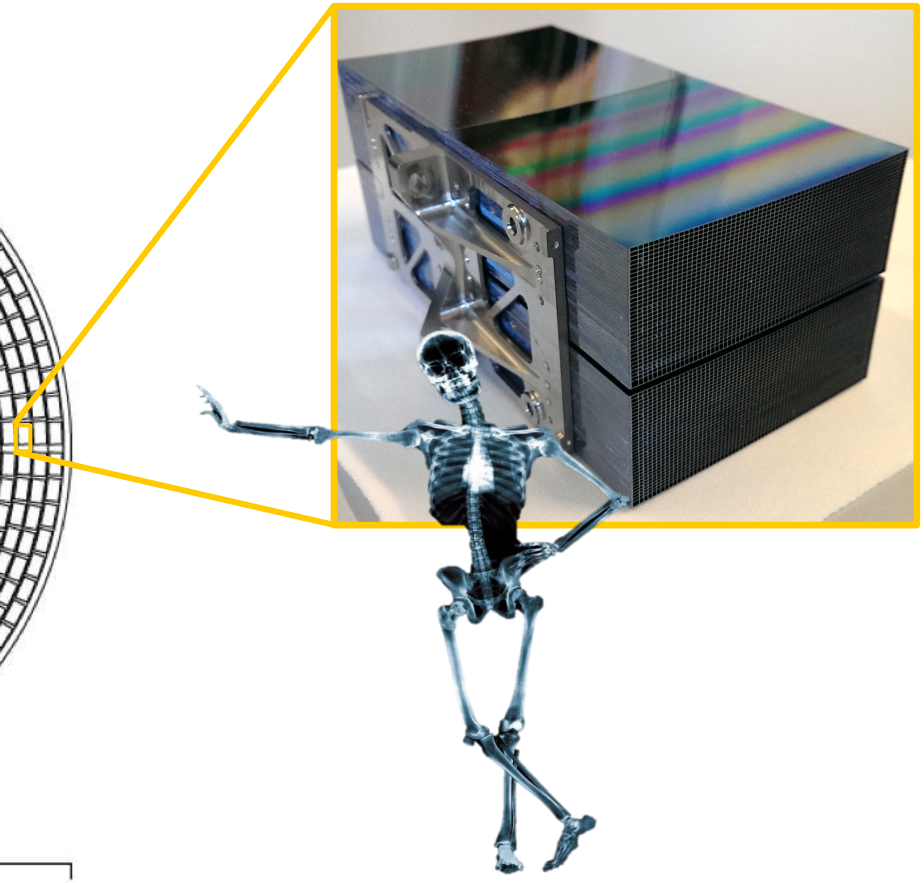
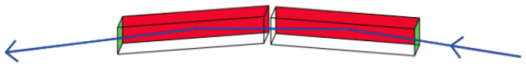


Figure courtesy D. Willingale



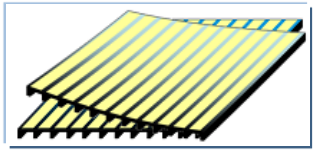
ATHENA: Telescope concept & baseline technologies

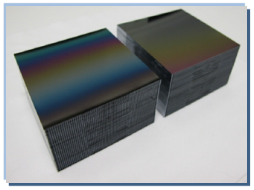
Single pore



Fundamental brick of ATHENA+ telescope is the Woltjer-I pore optic composed by two sections corresponding to the parabolic and hyperbolic surfaces

Silicon Pore Optics stacks

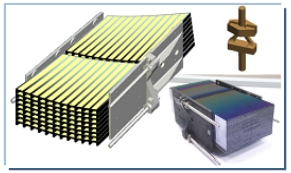


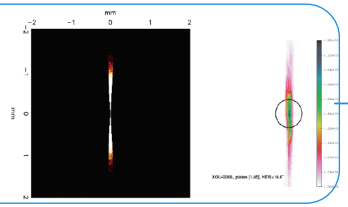


Silicon Pore Optic (SPO) are obtained by stacking of Silicon Wafer. Two different stacks are need:

- For Parabolic surfaces => SPO-P stacks
- For Hyperbolic surfaces => SPO-H stacks

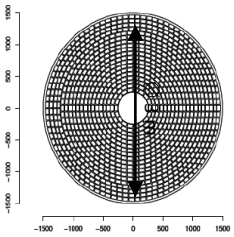
Mirror Module

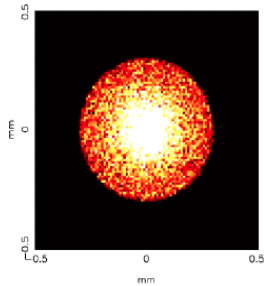




A complete SPO module (or Mirror Module – MM) comprising the SPO-P and SPO-H stacks. The kink angle between the front and back stack is set accurately and secured by gluing the stacks between the mounting plates. MM PSF is distributed along a line

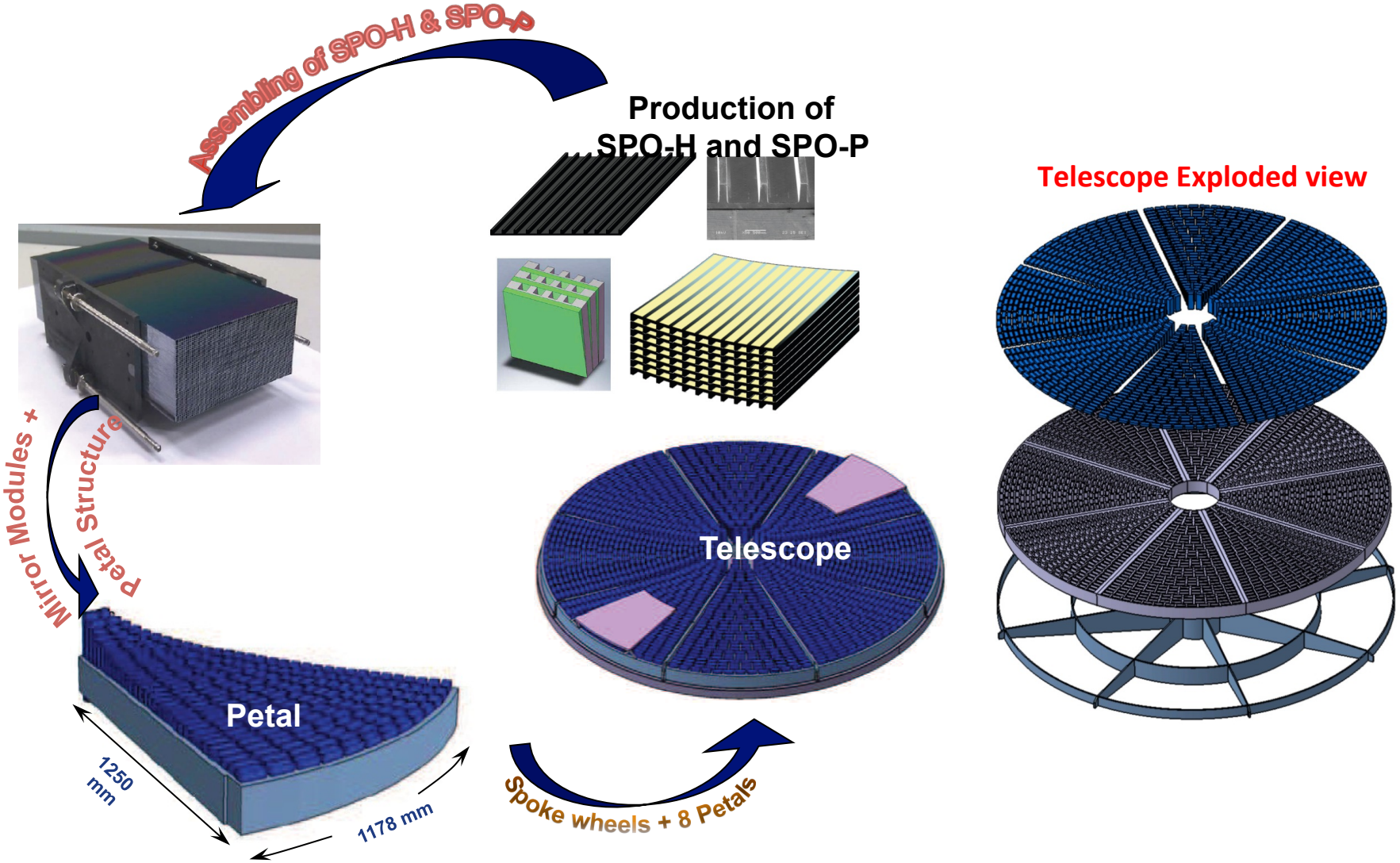
Telescope



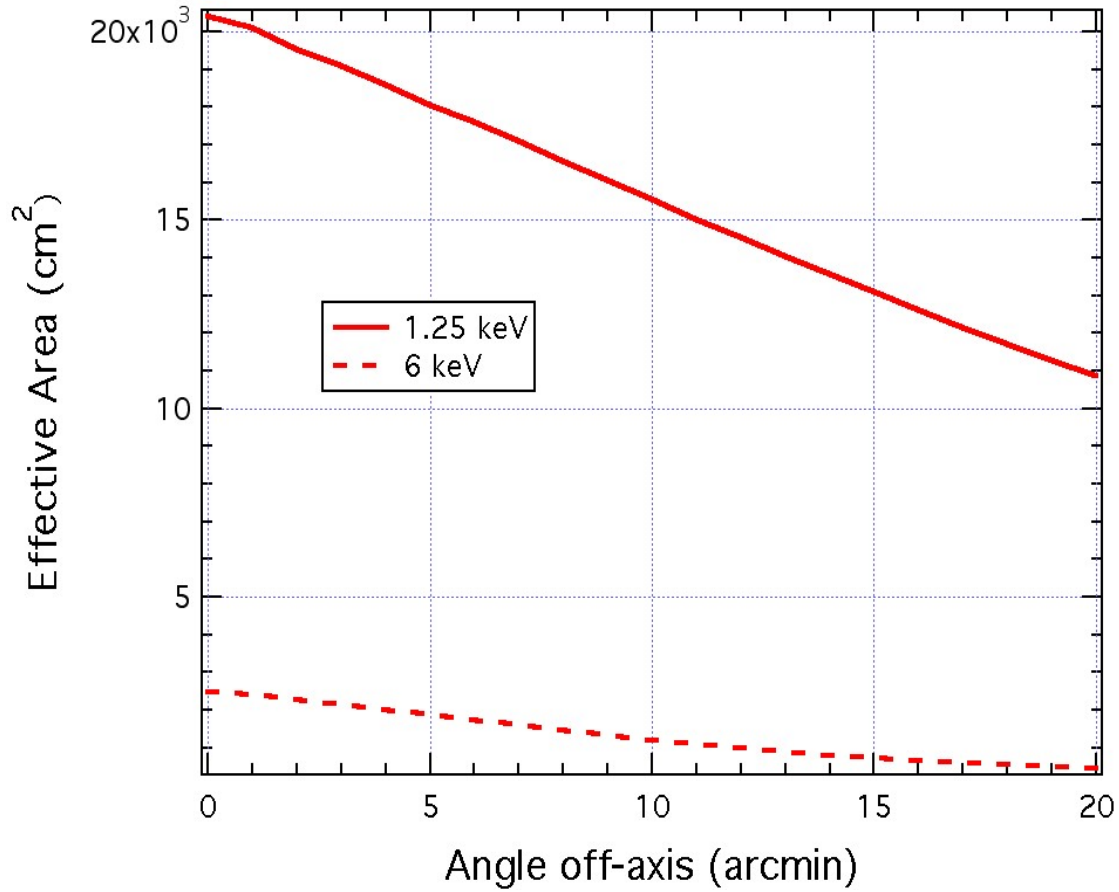


In order to create a mirror with a diameter of 3 meters the MM are arranged in a mosaic to populate the aperture. For integration convenience the aperture is subdivided in eight identical petals. The MM are hosted in a panel structure and the petals are mounted on a spoke wheel structure. Providing all the modules are correctly aligned the line foci from the combination of millions of pores across the full aperture will overlap to form a PSF with circular symmetry.

From Silicon basic material to Telescope

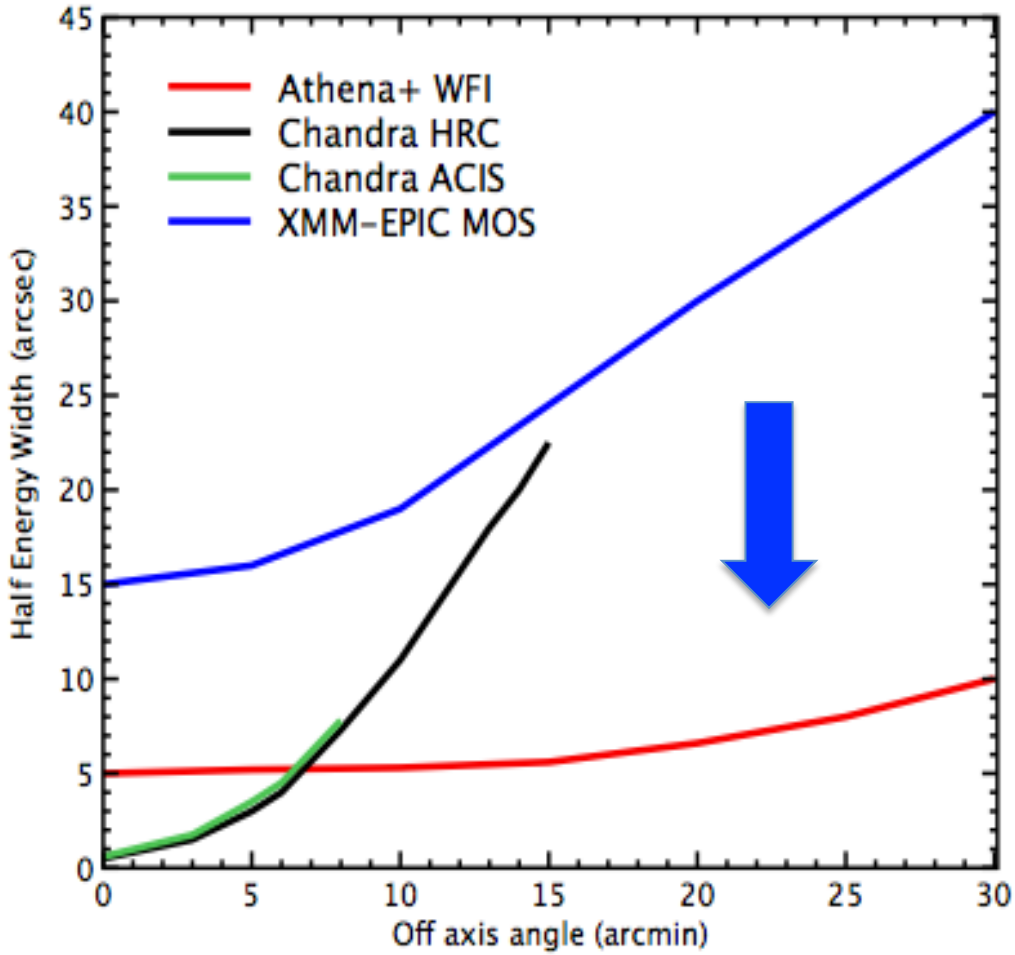


Effective Area



September 2014 – INAF/OABrera contribution within the
AO7819 ESA contract for demonstration of the inner ring SPO stackin

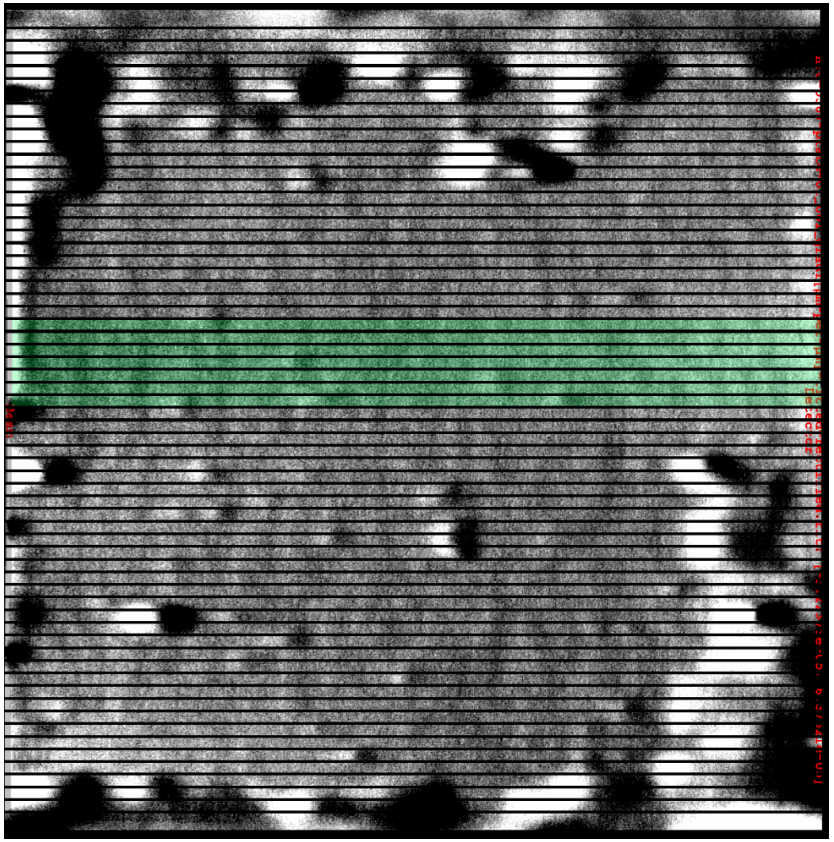
Angular resolution Vs. FOV for AHENA (and past missions)



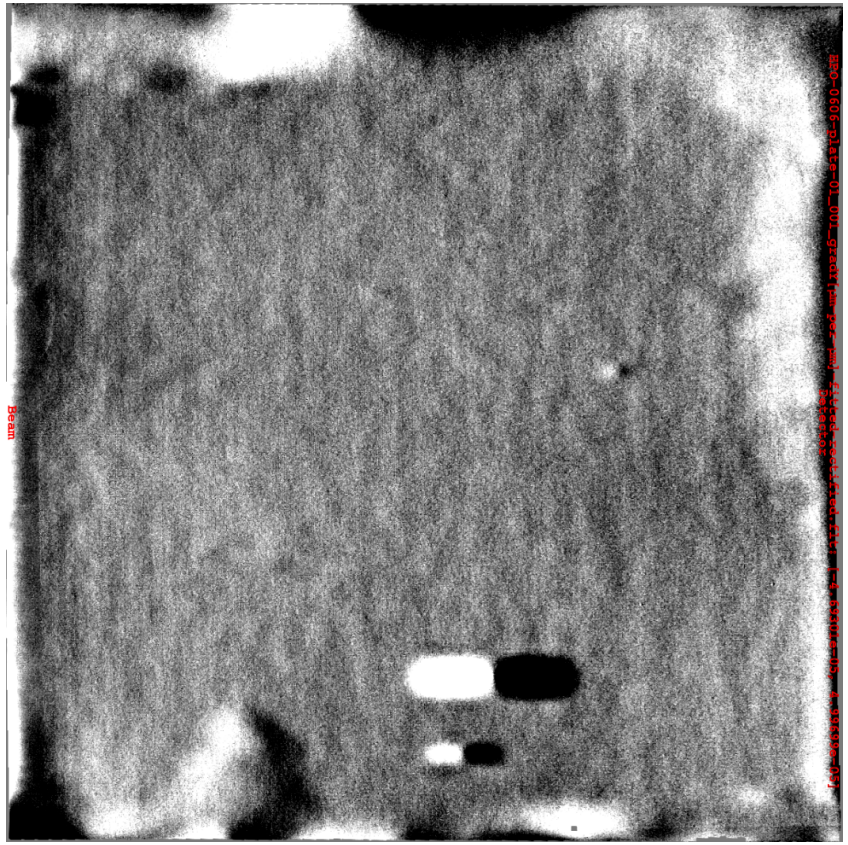
Silicon Pore Optics Developments

- Developments of the SPO technology have and are focused in three areas:
  - ✓ Demonstration of the environmental qualification of the SPO mirror modules
  - ✓ Further improvement of the angular resolution (from 20 arcsec to 3 arcsec per module)
  - ✓ Evaluation and preparation of the industrialization phase.
- Further activities regard the development of elements like:
  - ✓ Baffling systems and coatings
  - ✓ Accommodation matters
  - ✓ Required special test facilities

Current work area – increasing the yield

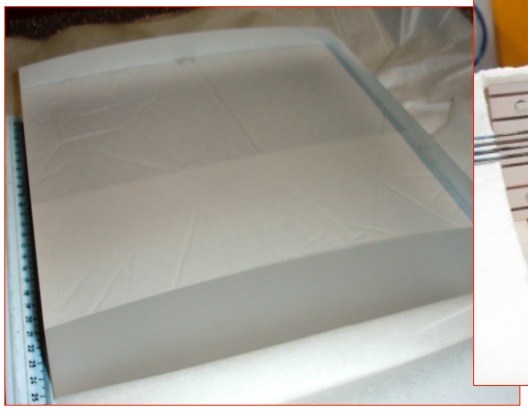


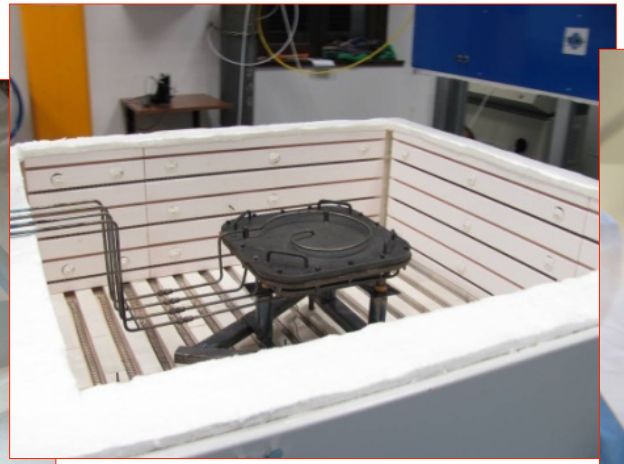
March 2014

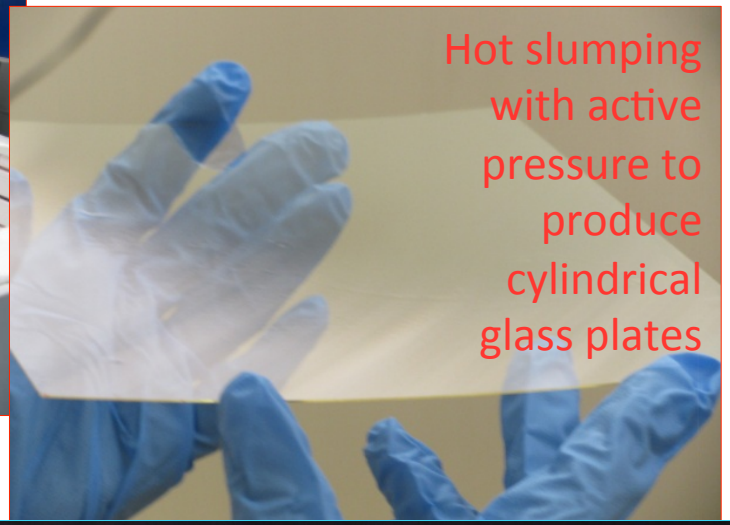


June 2014

IXO/ATHENA: production process at present

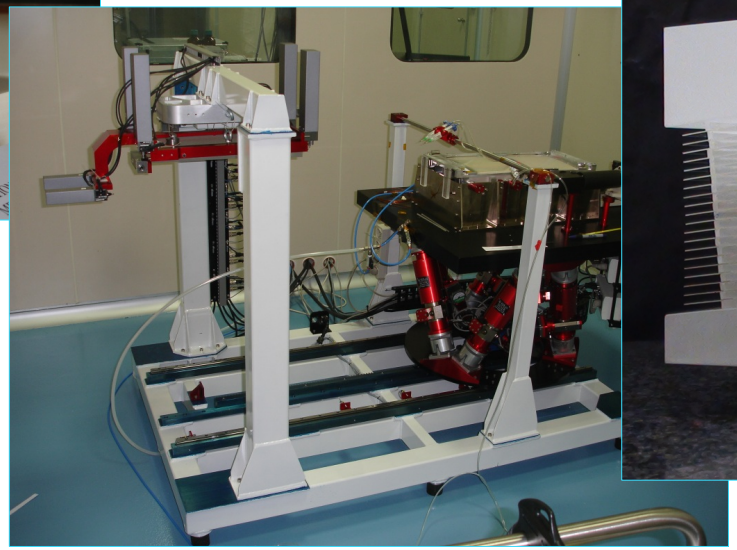


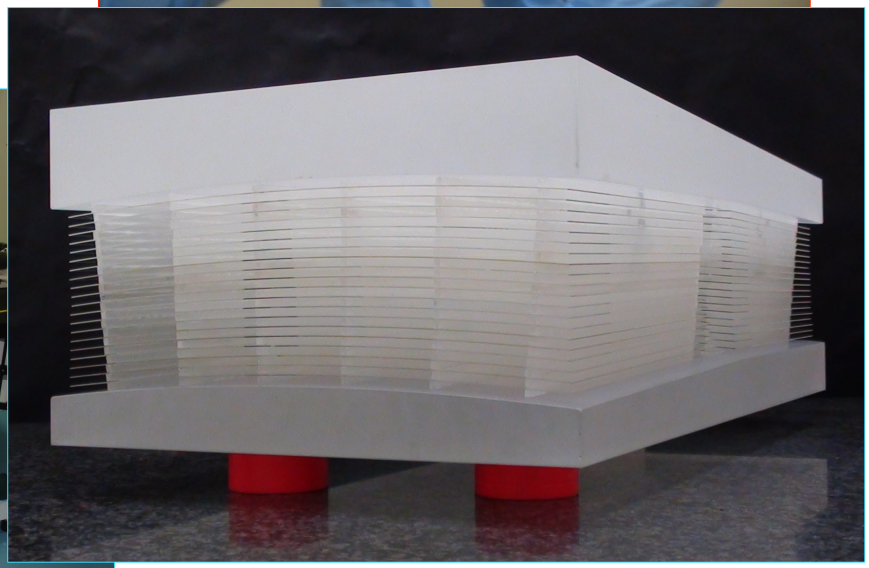




Hot slumping with active pressure to produce cylindrical glass plates

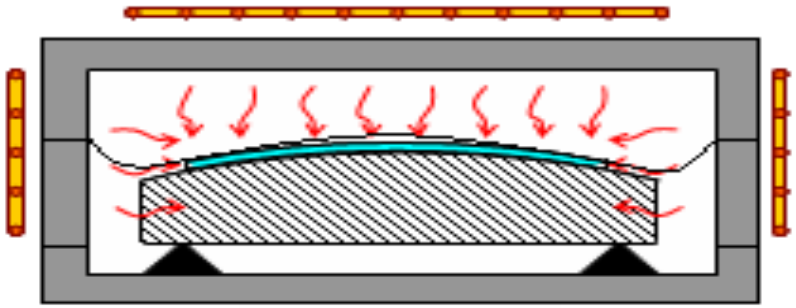
Cold slumping for plates shaping to Wolter I & alignement



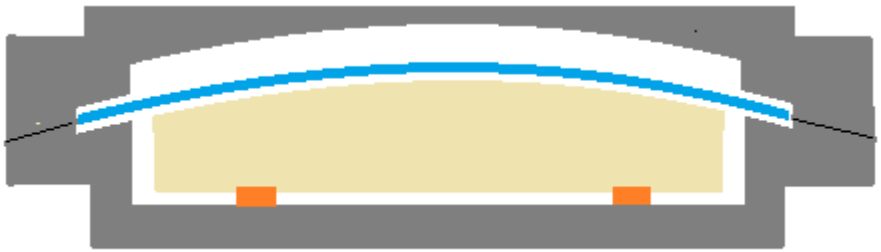


M.M. Civitani et al. [SPIE 2014, 9141-41]

Application of pressure during slumping



Previous approach



Technique patented by INAF

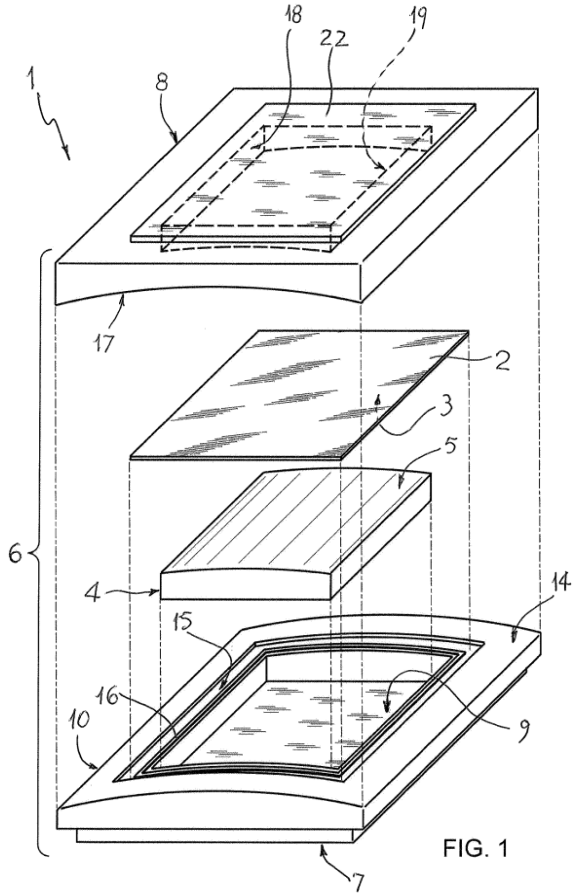
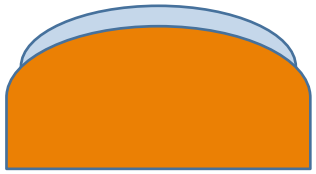


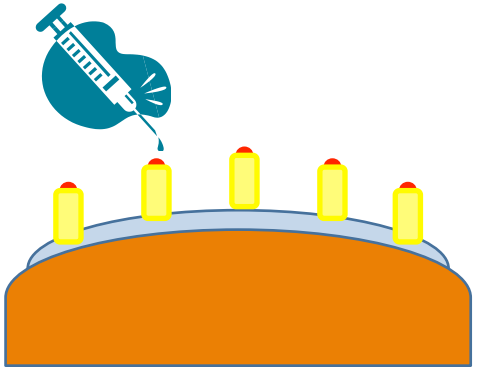
FIG. 1

The Integration MAchine

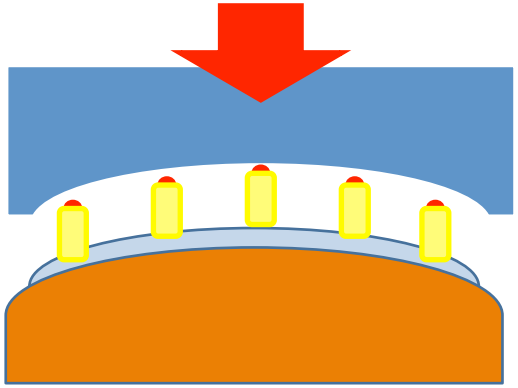
Mould integration process



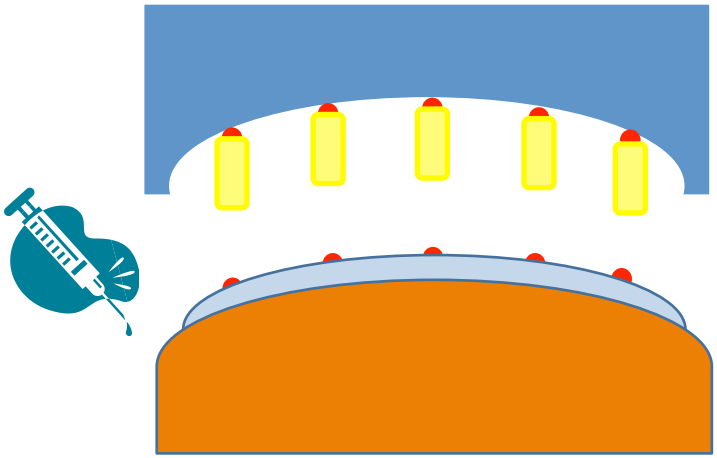
Glass fixed
To the mould



Ribs aligned on the glass
And glue dispensed



Ribs glued to backplane



Backplane with ribs glued to glass fixed on mould

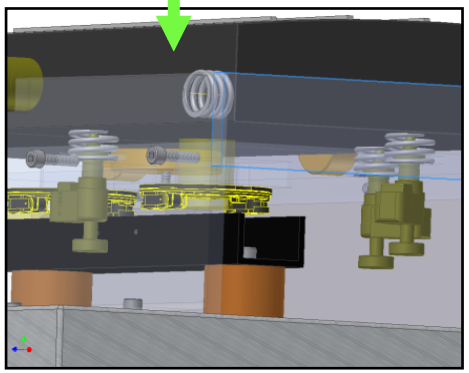
- Glass plate has the SAME SHAPE of the mould
- Glass plate shape is FROZEN with ribs
- The mould can be taken as a REFERENCE

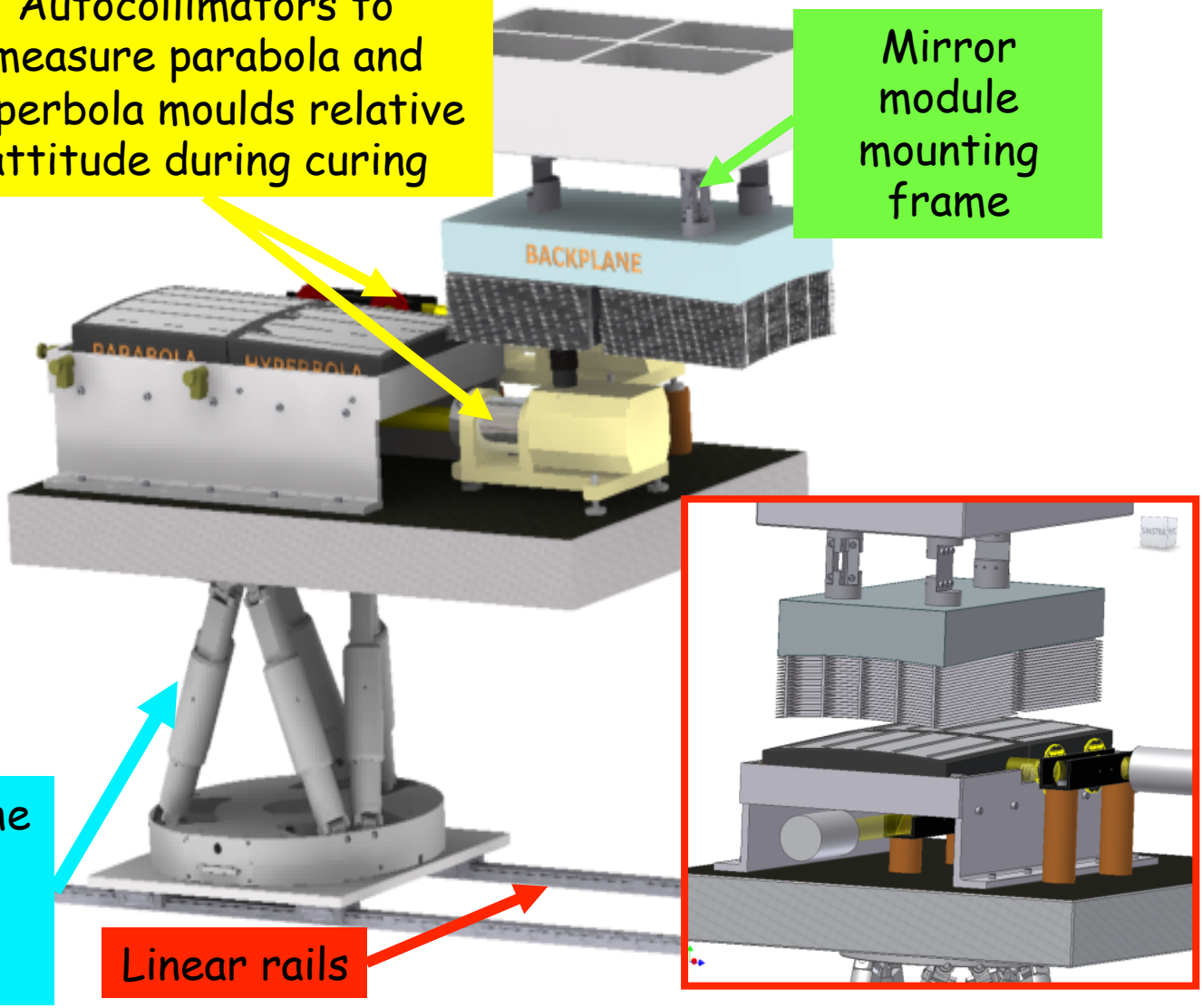
Integration Machine (IMA) Past contract on Glass slumping

The relative alignment of the two plate has to be controlled with high accuracy: 6 PICOMOTORS

Autocollimators to measure parabola and hyperbola moulds relative attitude during curing

Mirror module mounting frame



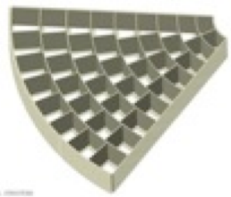
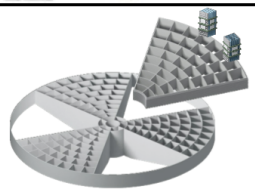


The alignment of the PP couple has lower requirements-> HEXAPOD

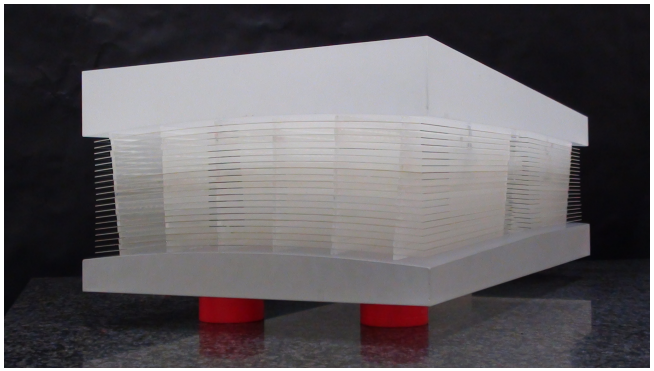
Linear rails

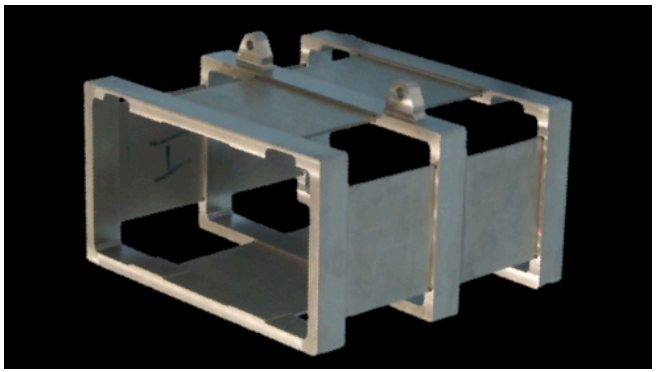
Hierarchical Concept Of IXO Telescope

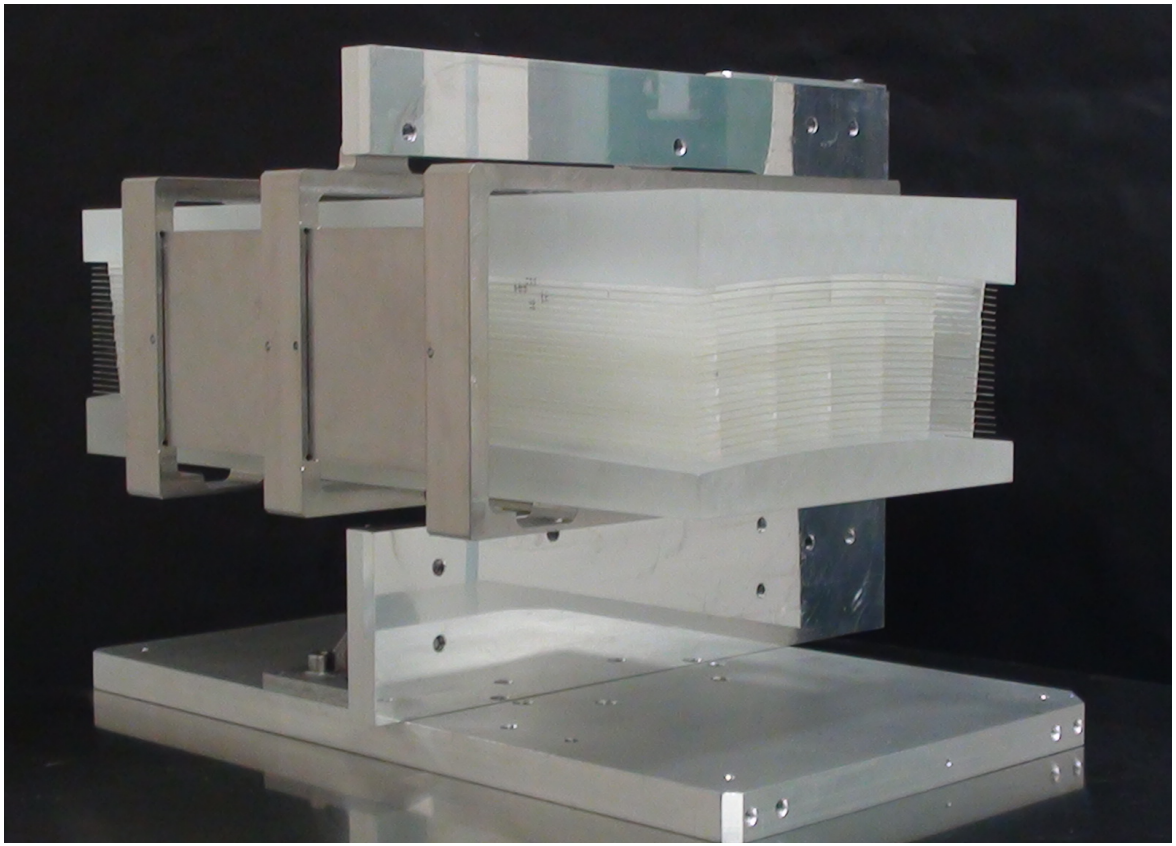
(➔ ESA contract on glass slumping)

Mirror Plate (MP)	Glass foil which are slumped and will be integrated according to the Wolter-I optical scheme and assembled to form the X-Ray Optical Unit .	
Plate Pair (PP)	Pair of Mirror Plates, one parabolic and one hyperbolic.	
X-Ray Optical Unit (XOU)	Elementary optical unit composed of stack of glass Plate Pairs connected each other by glued ribs. An outer structure allows handling, calibration and connection to the Mirror Petal Structure.	
Mirror Petal Structure (PS)	Intermediate Level Structure containing a number of XOUs. Several PSs are needed to azimuthally cover the entire aperture of the IXO Telescope.	
IXO Mirror Assembly	The entire optics assembly of the satellite, comprising optical and structural parts, i.e. PSs populated with the XOUs made by stacks of MPs .	

XOU_BB







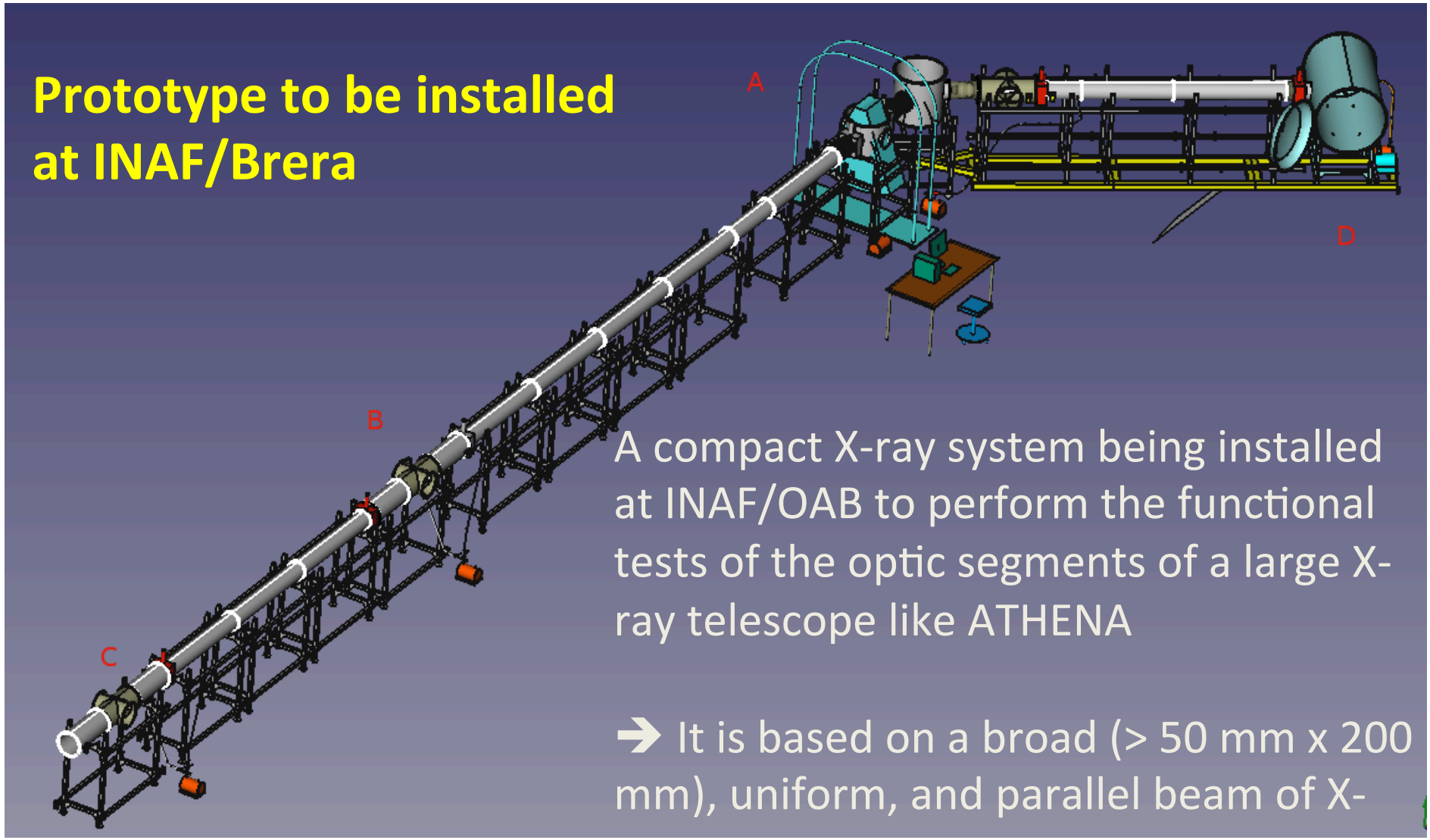
A completely integrated unit populeted with 20 plate pairs

Testing X-ray Focusing Modular Elements

- For Athena: ~1200 focusing XOUs

- We need to. At the site of production:
  - 1) precisely align in X-rays the parabolic and the hyperbolic stacks in each XOU
  - 2) operate a selection of the most performing XOUs.
  - 3) optical alignment in X-rays of the XOU in the petal

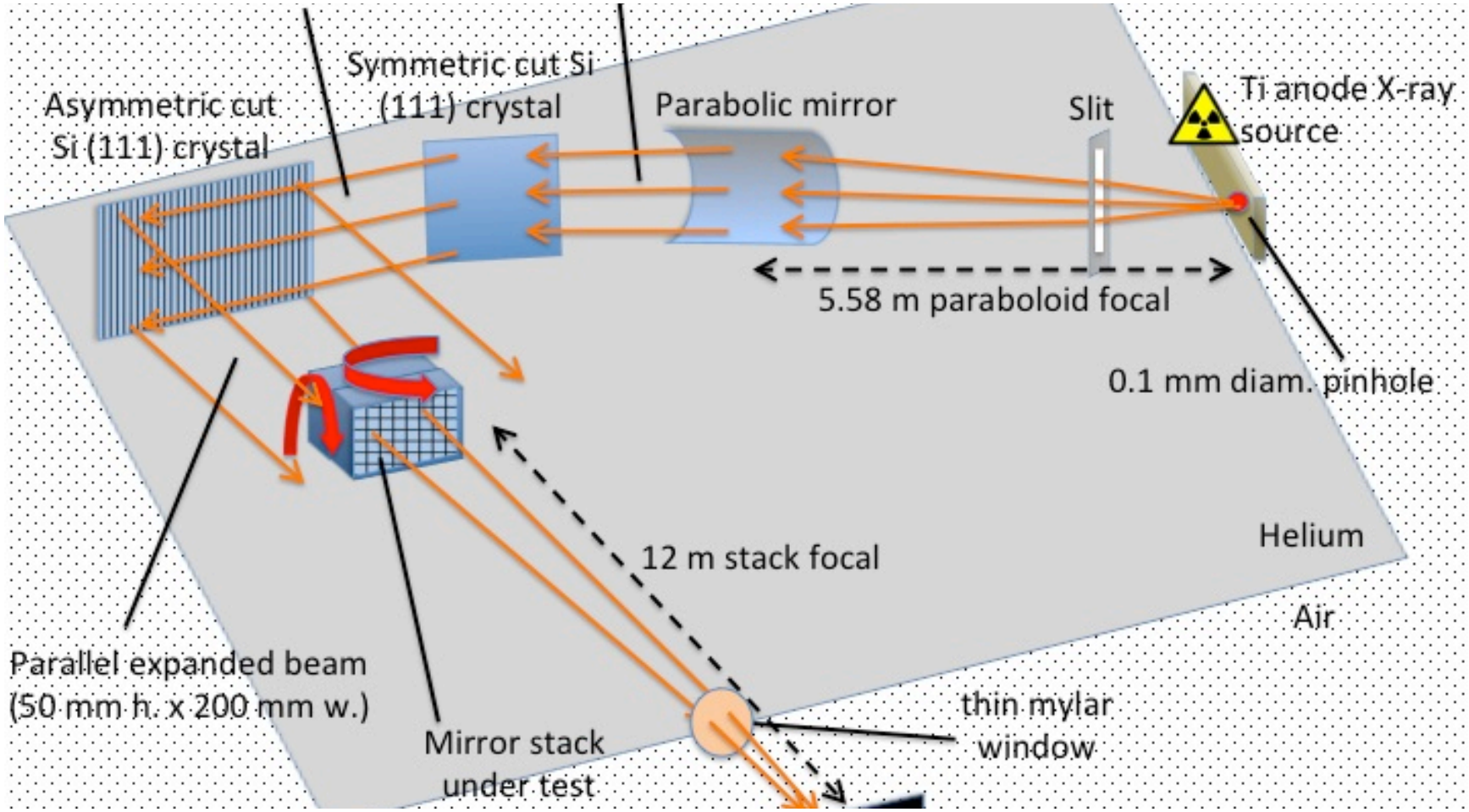
BEaTriX, Beam Expander Testing X-ray facility



A compact X-ray system being installed at INAF/OAB to perform the functional tests of the optic segments of a large X-ray telescope like ATHENA

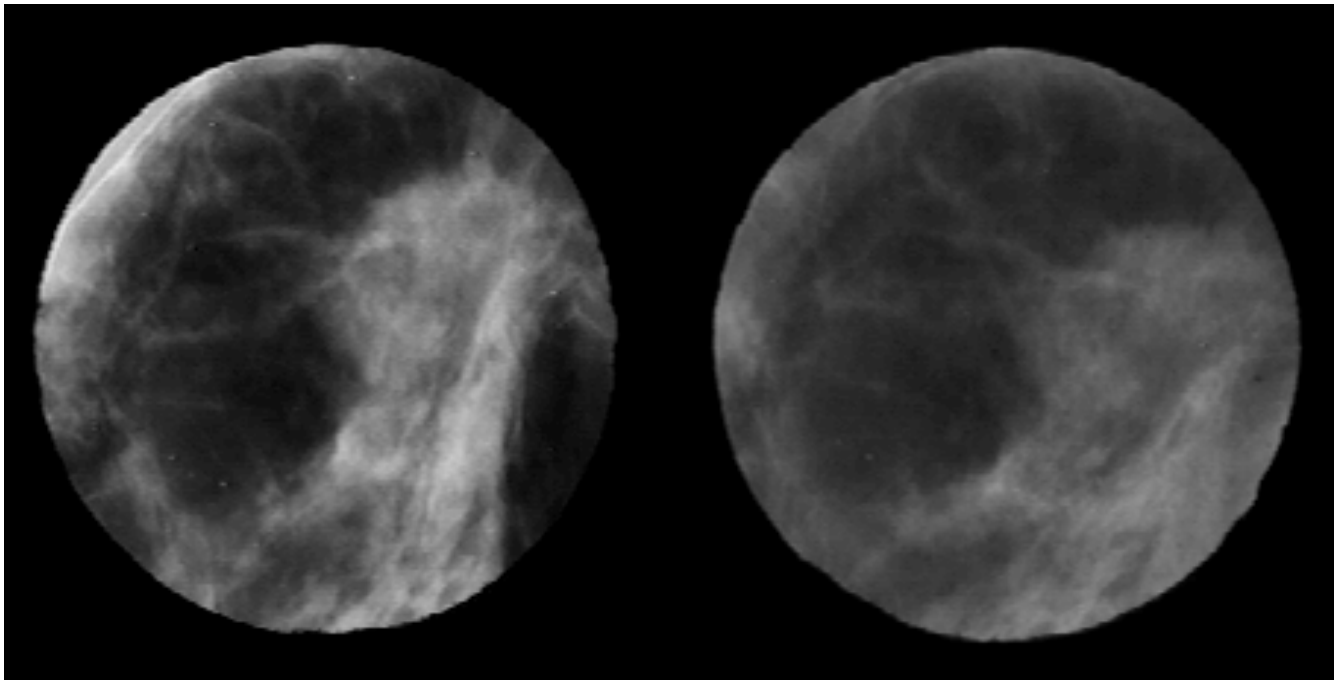
➔ It is based on a broad (> 50 mm x 200 mm), uniform, and parallel beam of X-rays

BEATRIX-X optical layout



Spin-Off Applications from X-ray astronomical optics

Mammography application



Monocromatic X-ray source (sinchrotron at 17 keV)

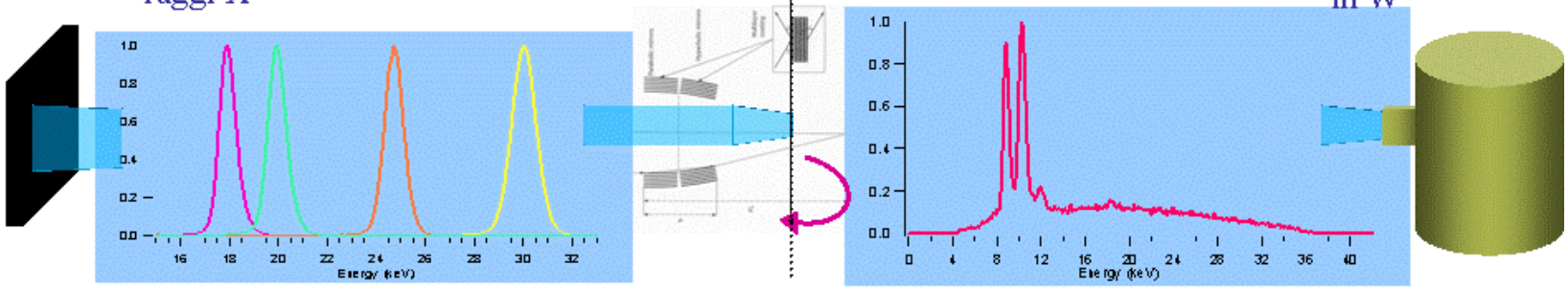
Conventional X-ray source (peak at 17 keV)

Collimazione & Monocromatizzazione: schema per una possibile implementazione con sorgenti convenzionali

Rivelatore digitale per raggi X

Ottiche a multistrato per collimazione e monocromatizzazione dei raggi X tramite diffrazione alla Bragg

Tubo per raggi X convenzionale con anodo in W



Risoluzione Energetica (FWHM) ≈10 %

Credito: M. Gambaccini – Univ. di Ferrara

Incident Spectrum

- W anode
- 35 kVp
- Filtro = 1 mm Be
- $\Phi_{mAs} = 1.24 \times 10^6$ fotoni/(mm^2 × mA × s)

Schema di un possibile sistema radiologico basato su un rivelatore digitale insieme ad un sistema di ottiche per raggi X (un insieme di molti specchi confocali in radenza) per la collimazione e monocromatizzazione del fascio da una sorgente convenzionale

Ophthalmic application

- 300 mm, highly aspheric, elliptical mirror enables 200° retinal inspection exams.
- Replication by electroforming is best suited for cost-effective, mid-volume series production of accurate high-aspheric mirrors, which would be impossible or too expensive to realize with traditional optics manufacturing techniques.

Replication by electroforming enables new optical diagnostic equipment

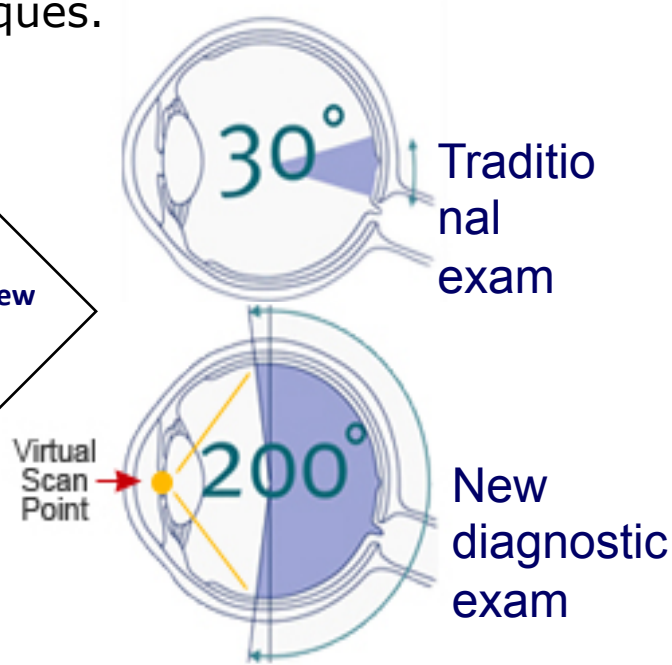
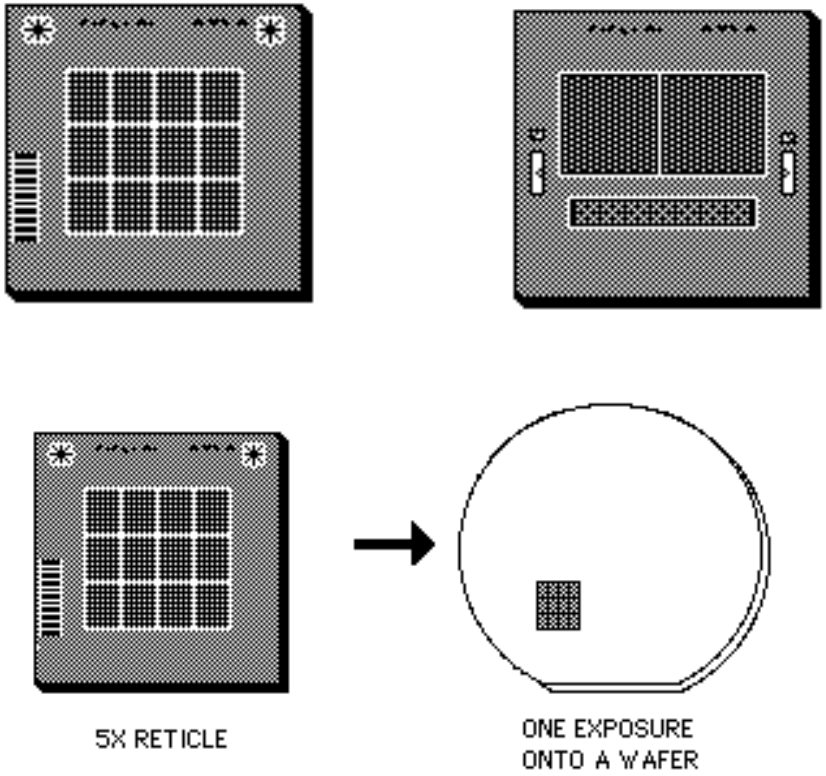
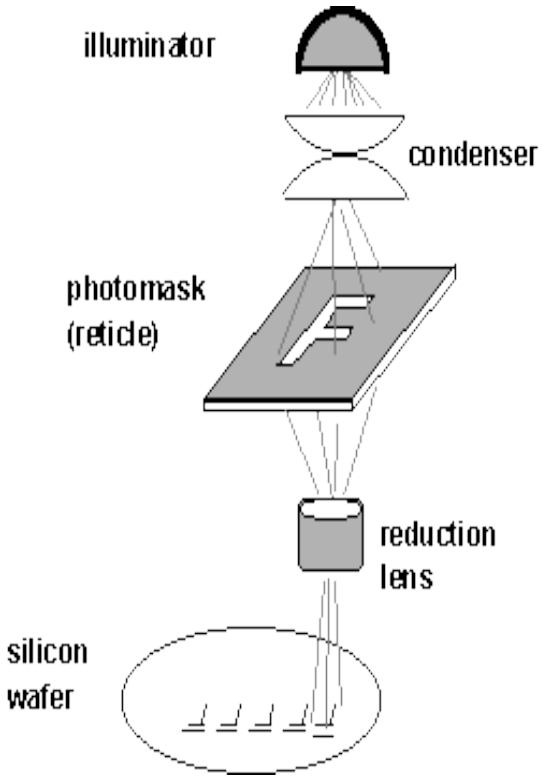


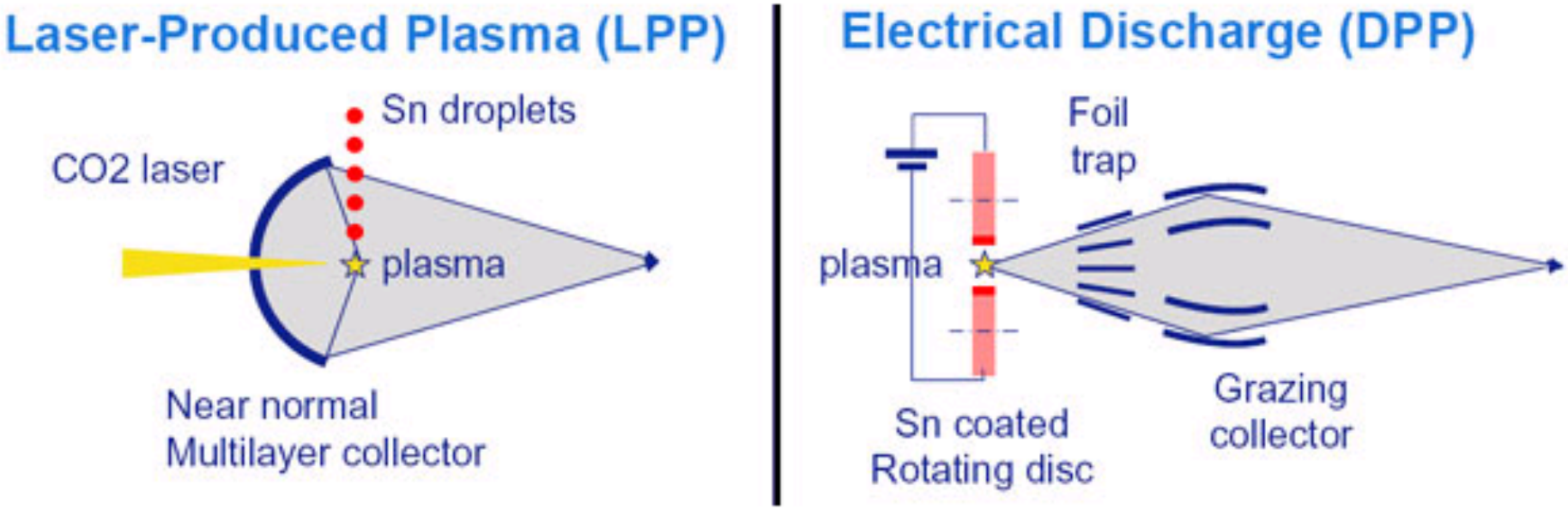
Photo-lithograpy

Masks and Gratings



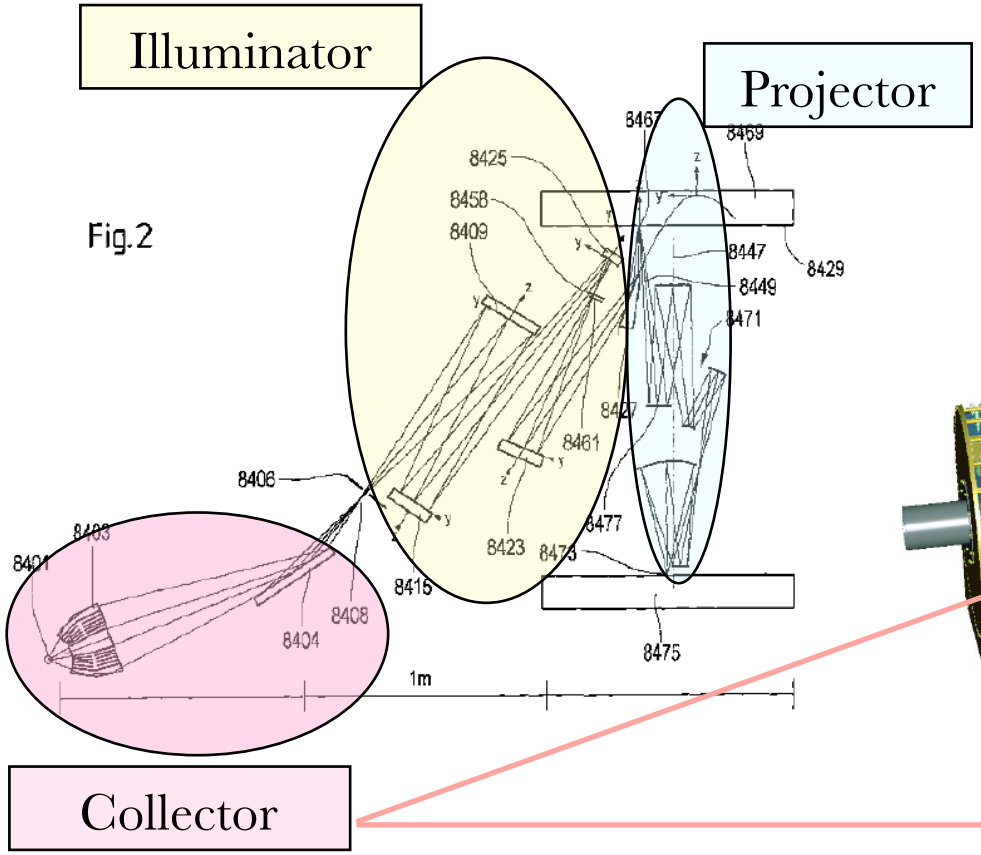


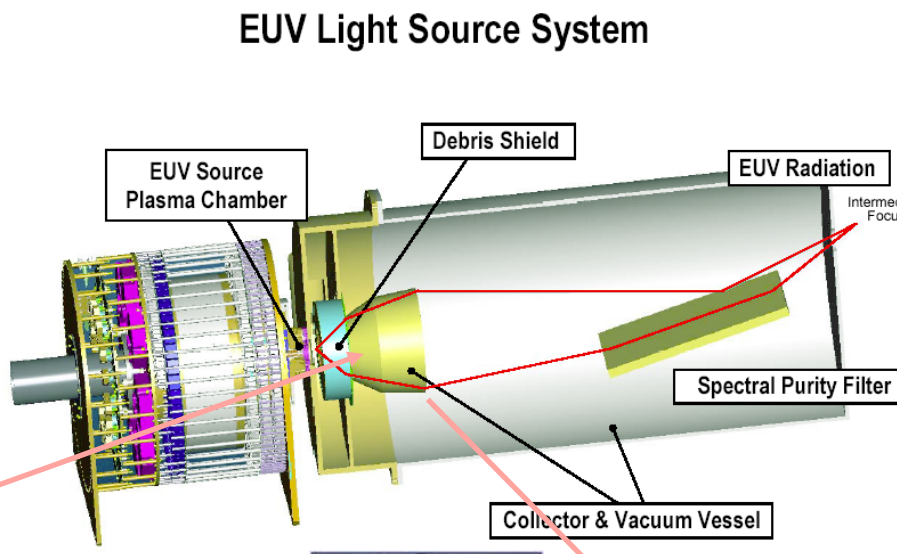
LPP versus DPP

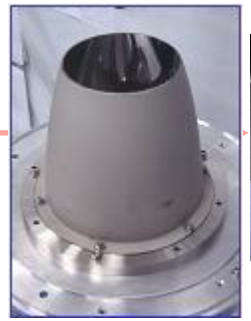


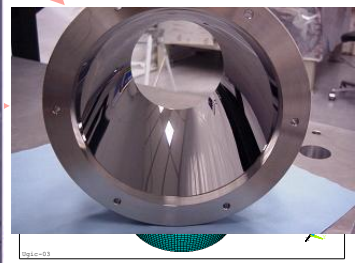
The question still remains whether laser- or discharge-produced plasma sources will prove the most effective for high-volume EUV lithography. (Source: ASML)

Optics for EUV Lithography (13.5 nm)

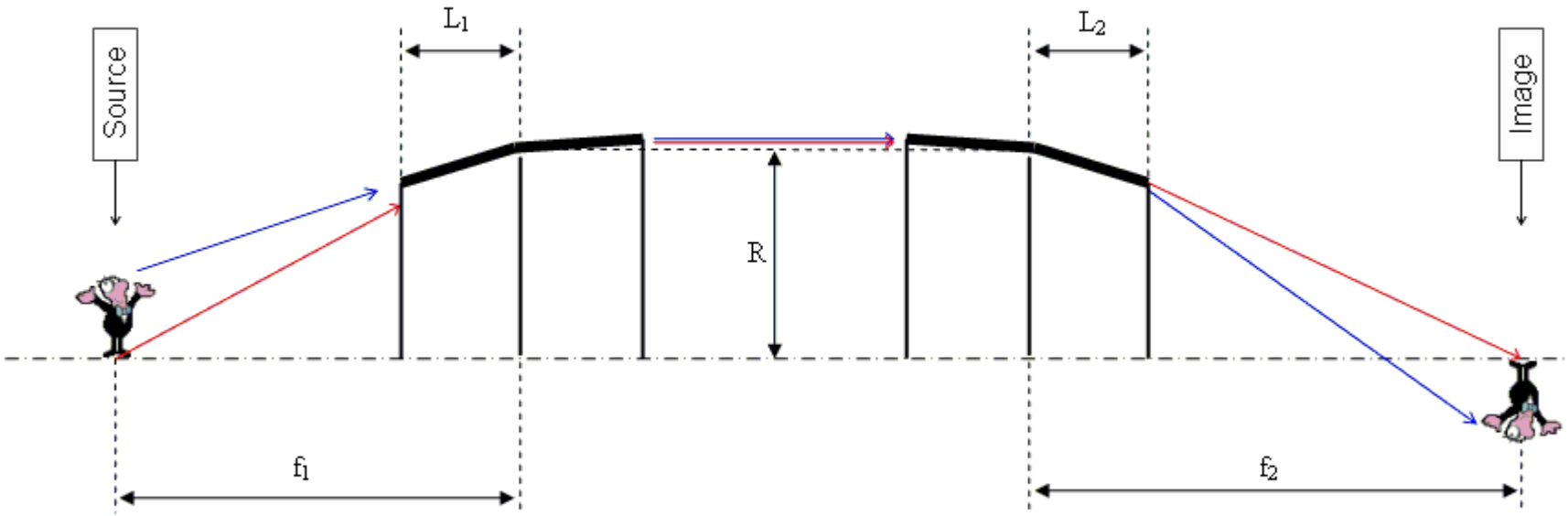








Imaging and magnification of X-ray sources



$f = R / \tan 4\alpha$ $\quad$ $f = 28.6\ R$ $\quad$ $(\alpha = 0.5°)$

Magnification = f_2 / f_1 $\quad$ $(L_1 / f_1 = L_2 / f_2)$

FOV <= 1° $\quad$ (E <= 3 KeV)