Telescopes & Mirrors

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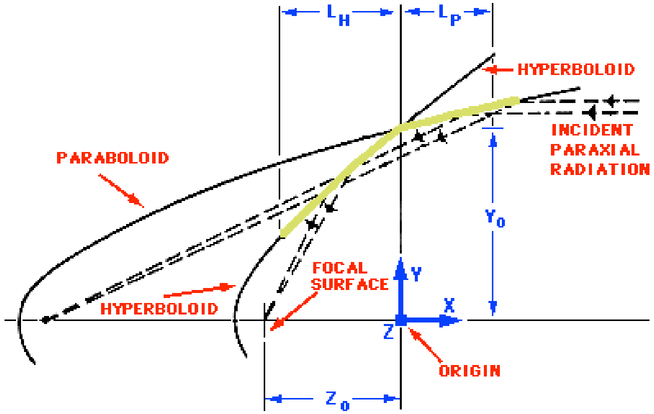
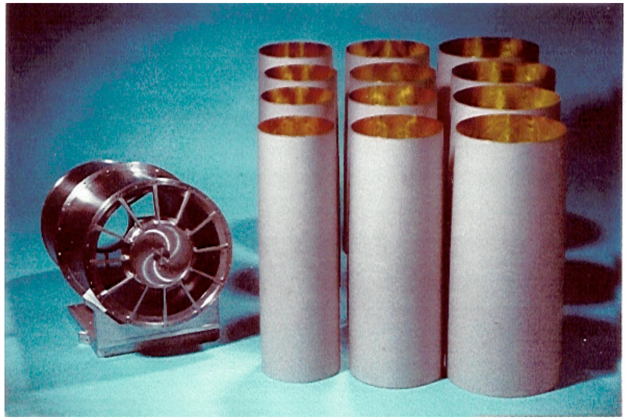
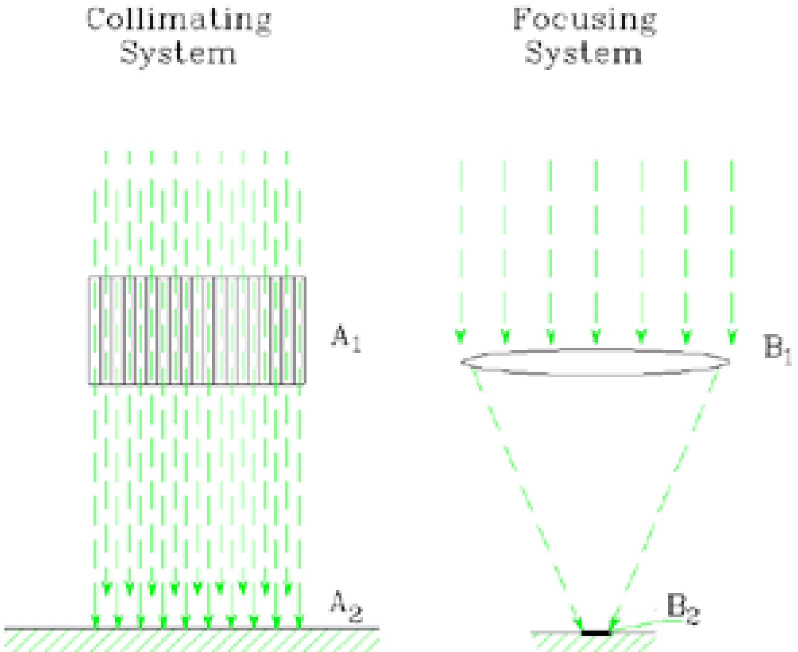




Outline

- ✓ remarks on grazing – incidence for X-ray astronomy
  - ○ why grazing incidence reflection
  - ○ optical configurations for grazing-incidence mirrors
- ✓ making mirrors
  - ○ *the replication method*
- ✓ examples of past and future X-ray telescopes
- ✓ remarks on Gamma ray focusing telescopes and optics

Advantages of focusing optics versus direct-view detectors



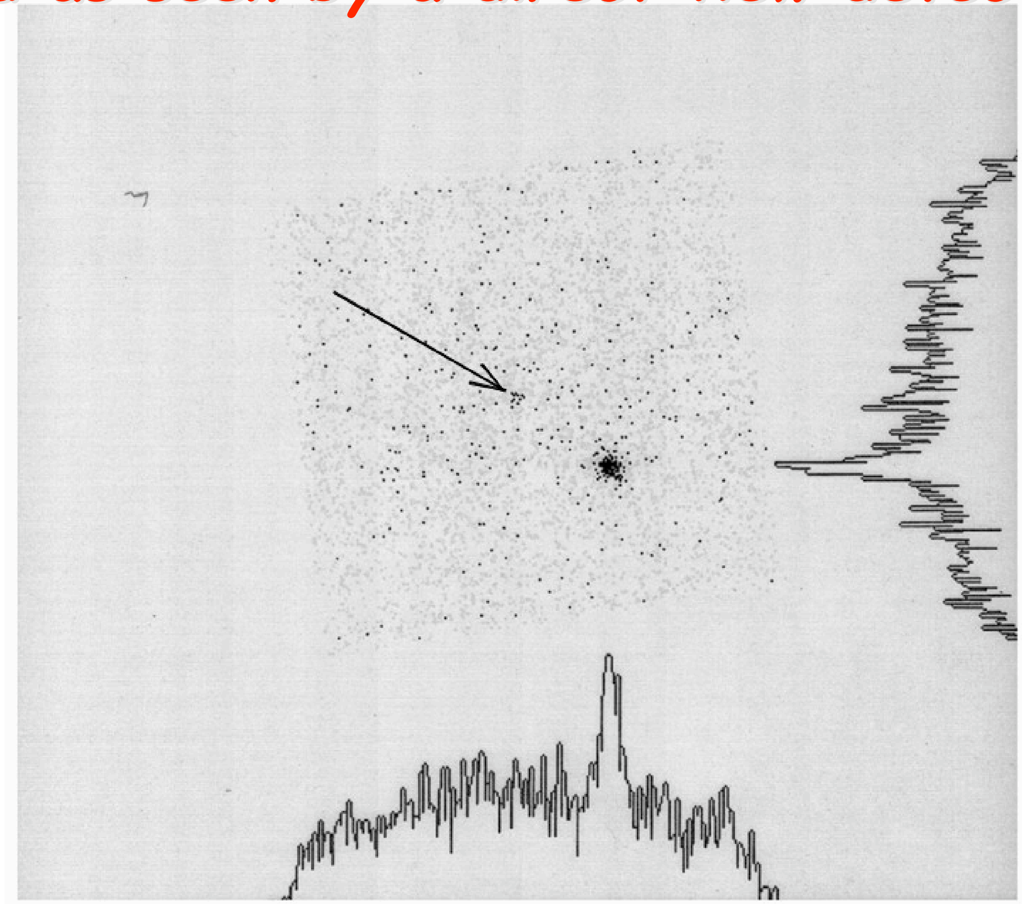
$$F_{\min} = n_\sigma \frac{\sqrt{2B}}{\sqrt{A_{eff} T_{\text{int}} \Delta E}}$$

$$F_{\min} = n_\sigma \frac{\sqrt{BA_d}}{A_{eff}\sqrt{T_{\text{int}} \Delta E}}$$

B =background flux, Tint = integration time, ΔE = integration bandwidth

Moreover: much better imaging capabilities!

Simulation of two sources in a "Einstein" field as seen by a direct view detector



With the direct vie detector the second "weak" sources is lost in the background

X-ray astronomical optics history in pills (I)

- 1895: Roentgen discovers "X-rays"
- 1948: First succesfull focalization of an X-ray beam by a total-reflection optics (Baez)
- 1952: H. Wolter proposes the use of two-reflection optics based on conics for X-ray microscopy
- 1960: R. Giacconi and B. Rossi propose the use of grazing incidence optics for X-ray telescopes
- 1962: discovery by Giacconi et al. of Sco-X1, the first extra-solar X-ray source
- 1963: Giacconi and Rossi fly the first (small) Wolter I optics to take images of Sun in X-rays
- 1965: second flight of a Wolter I focusing optics (Giacconi + Lindslay)
- 1973: SKYLAB carry onboard two small X-ray optics for the study of the Sun

X-ray astronomical optics history in pills (II)

- 1978: Einstein, the first satellite with optics entirely dedicated to X-rays

- 1983: EXOSAT operated (first European mission with X-ray optics aboard)

- 1990: ROSAT, first All Sky Survey in X-rays by means of a focusing telescope with high imaging capabilities

- 1993: ASCA, a multimudular focusing telescope with enhanced effective area for spectroscopic purposes

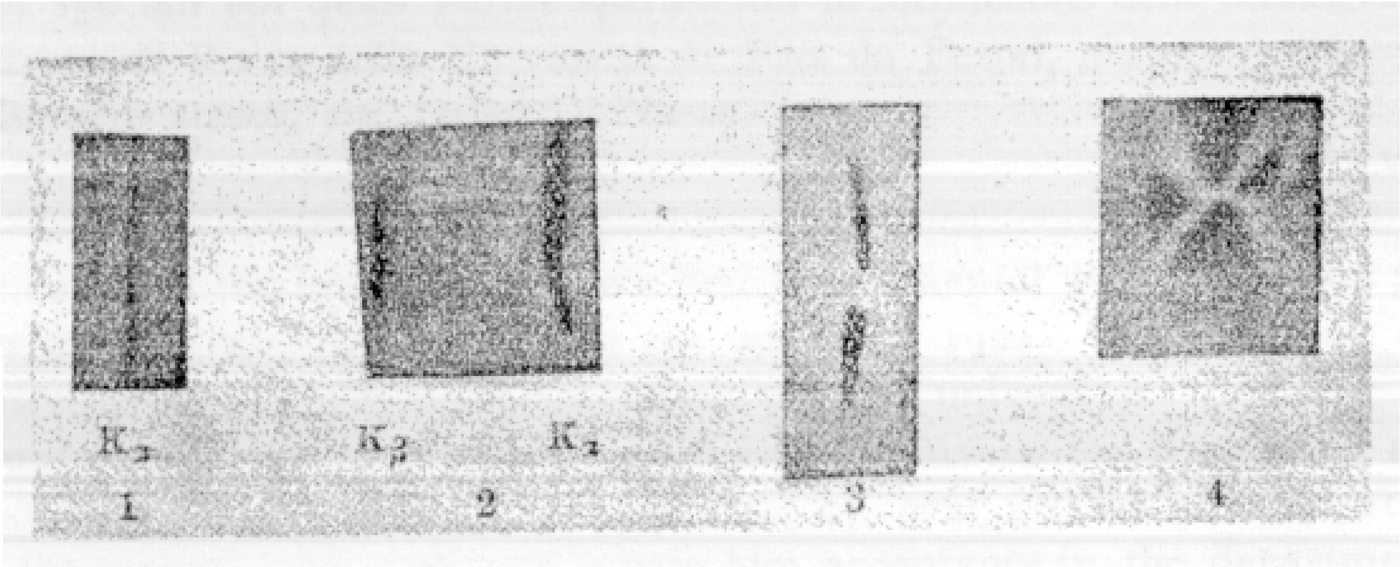
- 1996: BeppoSAX, a broad-band satellite with Ni electroformed optics

- 1999: launch of Chandra, the X-ray telescope with best angular resolution, and XMM-Newton, the X-ray telescope with most Effective Area

- 2004: launch of the Swift satellite devoted to the GRBs investigation (with aboard XRT)

- 2005: launch of Suzaku with high throughput optics for enhanced spectroscopy studies with bolometers

Imaging experiments using Bragg reflection from "replicated" mica pseudo-cylindrical optics



E. Fermi – Thesis of Laurea, "Formazione di immagini con i raggi Roentgen" ("Imaging formation with Roentgen rays"), Univ. of Pisa (1922)

Thanks to Giorgio Palumbo!

X-ray optical constants

- complex index of refraction to descrive the interaction X-rays /matter:

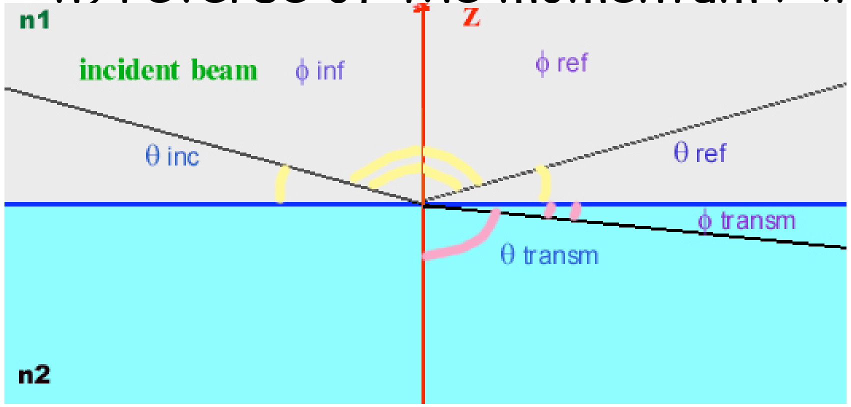
δ → changes of phase

β → absorption

$$\boxed{\begin{array}{l}\tilde{n} = n + i\beta = 1 - \delta + i\beta \\ (\mu = 4\pi\beta/\lambda \;\; cm^{-1})\end{array}}$$

Linear abs. coeff.

- at a boundary between two materials of different refraction index n_1, n_2 reverse of the momentum P in the z direction:



$$\boxed{\vec{p}_1 = \frac{h}{2\pi}\vec{k}_1}$$

$$\left|\vec{k}_1\right| = \frac{2\pi}{\lambda} n_1$$

$$\Longrightarrow \quad \boxed{2p_z \propto \tfrac{4\pi}{\lambda} n_1 \sin\theta_{inc}}$$

momentum transfer

- the amplitute of reflection is described by the Fresnel's equations:

$$r_{12}^{s} = \frac{n_1 \sin\theta_1 - n_2 \sin\theta_2}{n_1 \sin\theta_1 + n_2 \sin\theta_2} \qquad r_{12}^{p} = \frac{n_1 \sin\theta_2 - n_2 \sin\theta_1}{n_1 \sin\theta_2 + n_2 \sin\theta_1}$$

Total X-ray reflection at grazing incidence

- if vacuum is material #1 ($n_1 = 1$) ➔ the phase velocity in the second medium increases ➔ beam tends to be deflected in the direction opposite to the normal.

- Snell's law (n1 cosθ_1 =n2 cosθ_2) to find a critical angle for total reflection:

$$\theta_{crit} \approx \sqrt{2\delta} = \sqrt{\frac{r_0 \lambda^2 \rho N_{Av} f_1}{A\pi}}$$

λ = wavelenght ρ = density

A = atomico weight f_1 = scattering coeff.

r_0 = classical electron radius

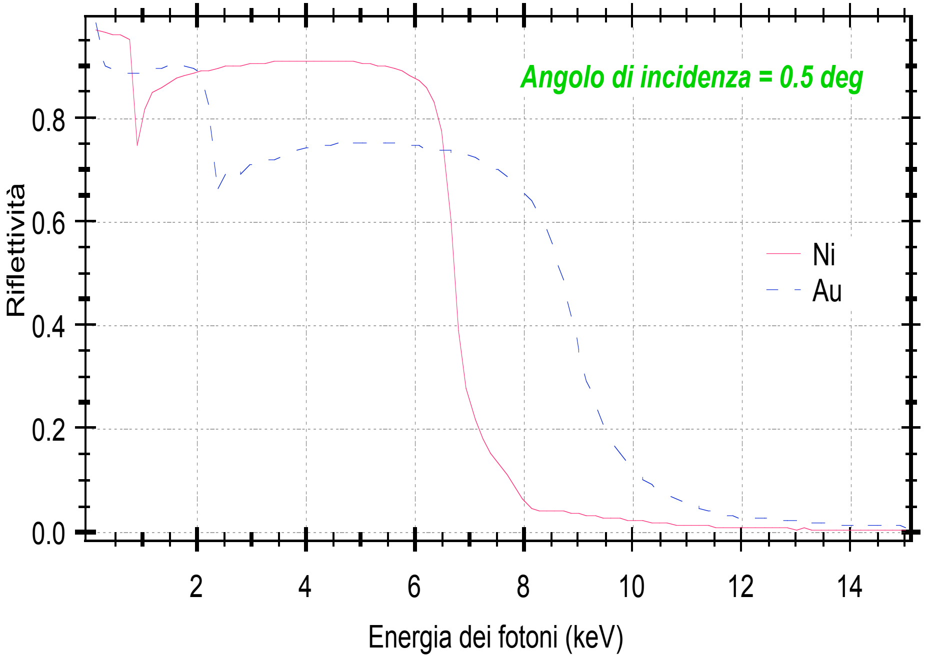
- far from the fluorecence edges $f_1 \approx Z$ and for heavy elements $Z/A \approx 0.5$:

$$\theta_{crit}(arc\min) \approx 5.6\lambda(A)\sqrt{\rho}$$

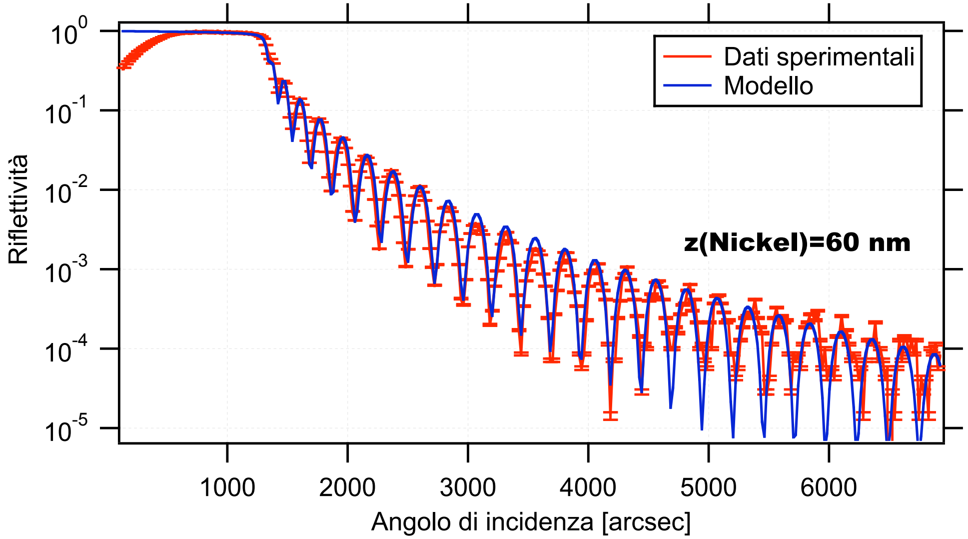
- reflectivity loss due to scattering:

$$I_R = I_0 \exp\left[-\left(\frac{4\pi\cdot n\cdot\sigma\cdot sin\theta}{\lambda}\right)^2\right]$$

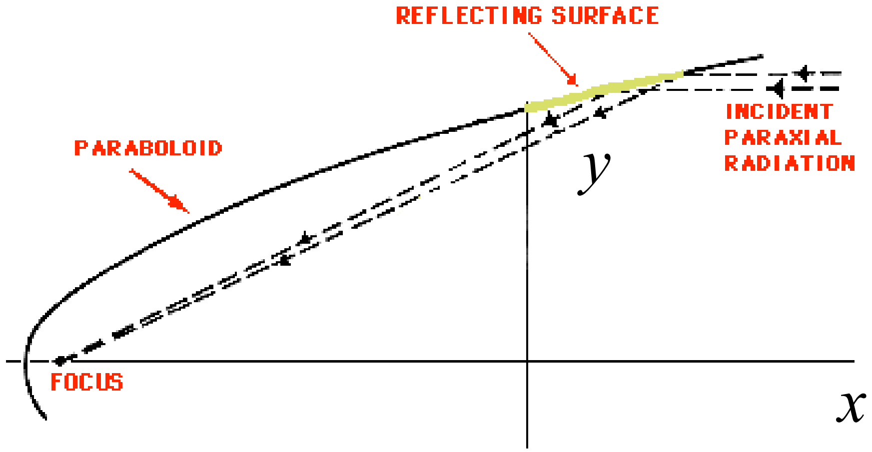
σ = rms microroughn. level



Other examples: C, Ni, Au



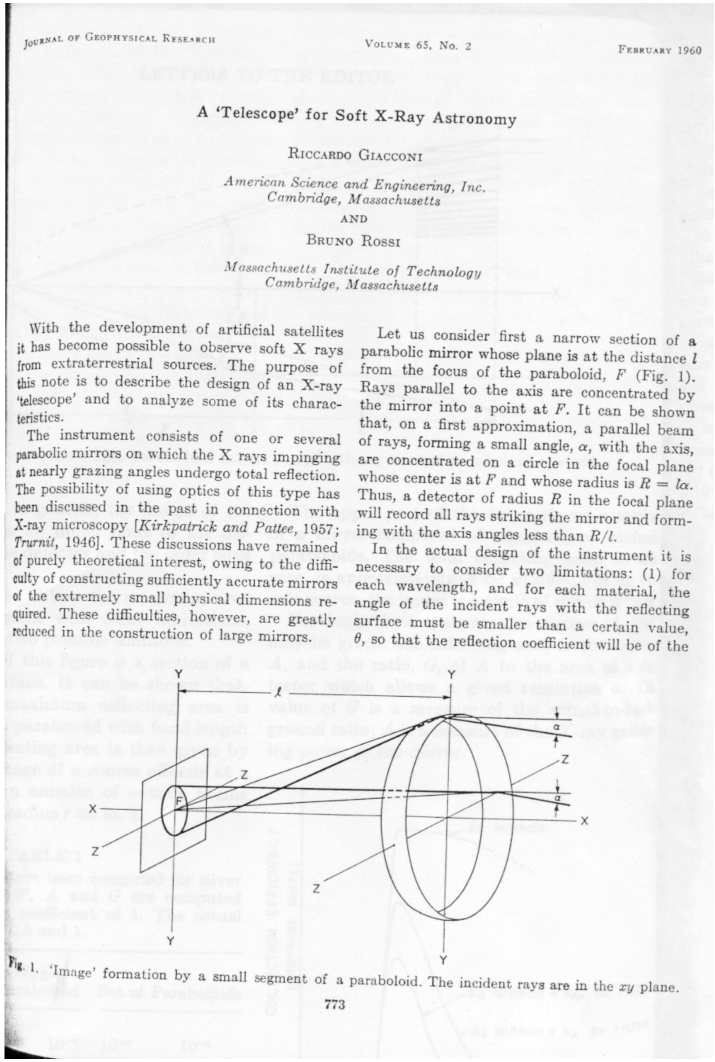
X-ray mirrors with parabolic profile



$$y^2 = 2\,p\,x$$

$$p = 2 * \mathit{dist.\ focus\text{-}vertex}$$

- perfect on-axis focusing
- off-axis images strongly affected by **coma**



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

A 'Telescope' for Soft X-Ray Astronomy

Riccardo Giacconi

American Science and Engineering, Inc.
Cambridge, Massachusetts

and

Bruno Rossi

Massachusetts Institute of Technology
Cambridge, Massachusetts

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.

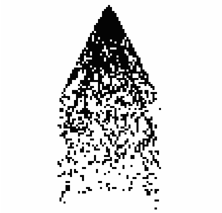
Let us consider first a narrow section of a parabolic mirror whose plane is at the distance l from the focus of the paraboloid, F (Fig. 1). Rays parallel to the axis are concentrated by the mirror into a point at F. It can be shown that, on a first approximation, a parallel beam of rays, forming a small 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.

The Abbe sine condition to have coma-free focusing mirrors

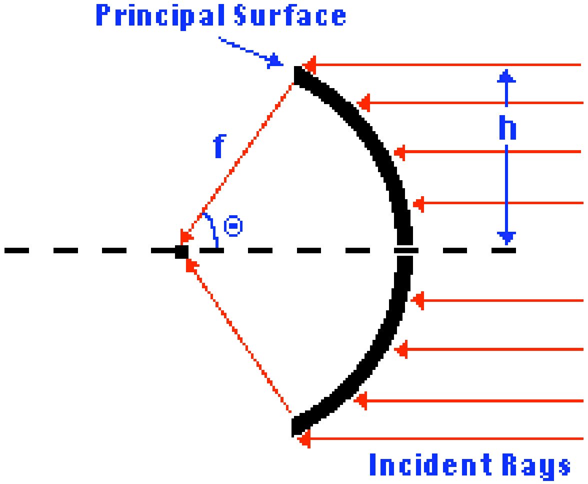
Coma: *off-axis abberation caused by a different magnification of reflected rays, depending on the hitting position at the mirror surface*



Typical blurring of a focal spot due to coma

- Coma free mirrors must satisfy the Abbe sine condition:

The surface defined by the intersection of each input ray with its corresponding output ray ***(principal or Abbe surface)*** *must be a sphere around the image, i.e.:*

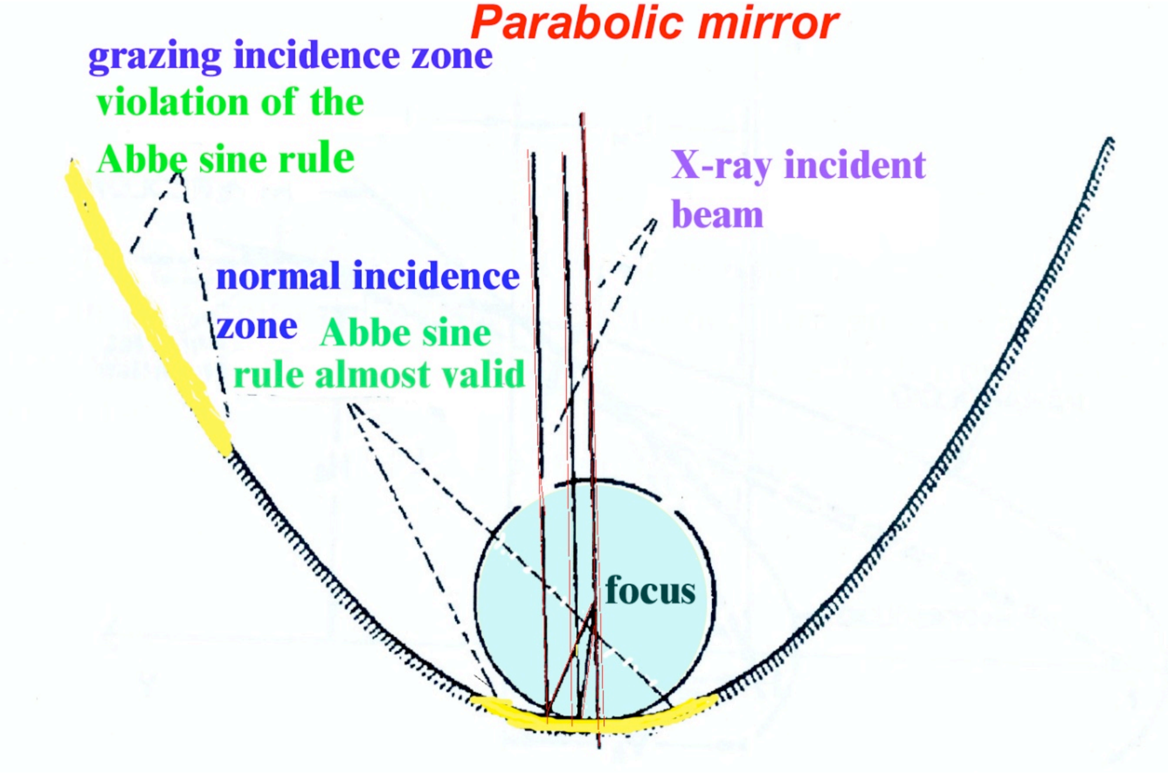


$$\boxed{\frac{h_1}{\sin\theta_1} = \frac{h_2}{\sin\theta_2} = const.}$$

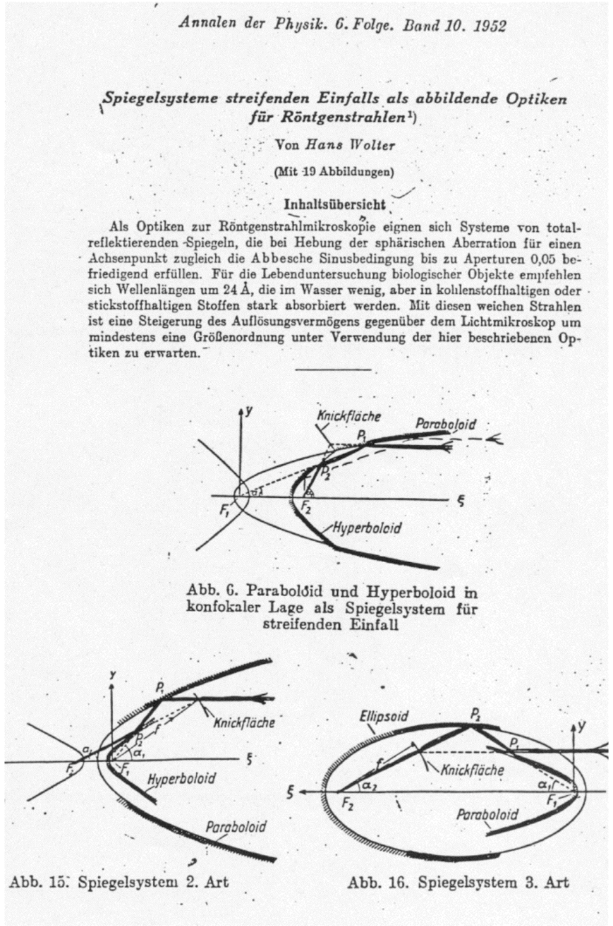
Parabolic mirrors & the Abbe sine condition

The parabolic profile approximately obeys to the Abbe rule only near the vertex, i.e. at normal incidence but not for grazing incidence angles

➔ <u>the parabolic geometry is not optimal for X-ray telescopes</u>



Wolter's solution to the X-ray imaging



Annalen der Physik. 6. Folge. Band 10. 1952

***Spiegelsysteme streifenden Einfalls als abbildende Optiken für Röntgenstrahlen*[1])**

Von *Hans Wolter*

(Mit 19 Abbildungen)

Inhaltsübersicht

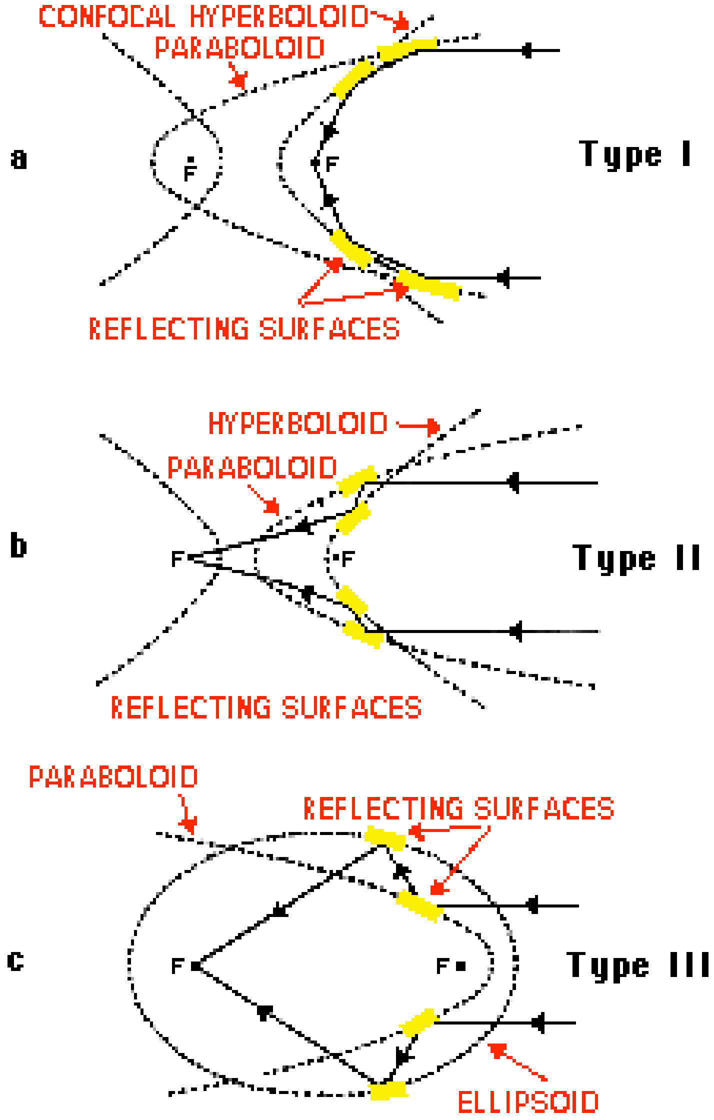
Als Optiken zur Röntgenstrahlmikroskopie eignen sich Systeme von totalreflektierenden Spiegeln, die bei Hebung der sphärischen Aberration für einen Achsenpunkt zugleich die Abbesche Sinusbedingung bis zu Aperturen 0,05 befriedigend erfüllen. Für die Lebenduntersuchung biologischer Objekte empfehlen sich Wellenlängen um 24 Å, die im Wasser wenig, aber in kohlenstoffhaltigen oder stickstoffhaltigen Stoffen stark absorbiert werden. Mit diesen weichen Strahlen ist eine Steigerung des Auflösungsvermögens gegenüber dem Lichtmikroskop um mindestens eine Größenordnung unter Verwendung der hier beschriebenen Optiken zu erwarten.

Abb. 6. Paraboloid und Hyperboloid in konfokaler Lage als Spiegelsystem für streifenden Einfall

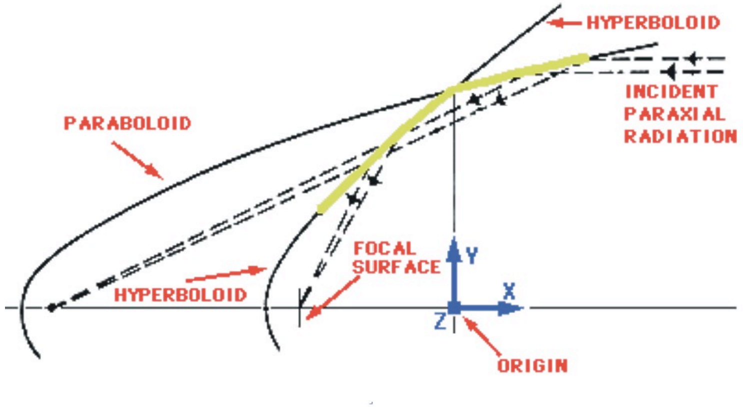
Abb. 15. Spiegelsystem 2. Art

Abb. 16. Spiegelsystem 3. Art

H. Wolter, Ann. Der Phys., NY10,94



The Wolter I mirror profile for X-ray astronomy applications



- it guarantees the minimum focal length for a given aperture

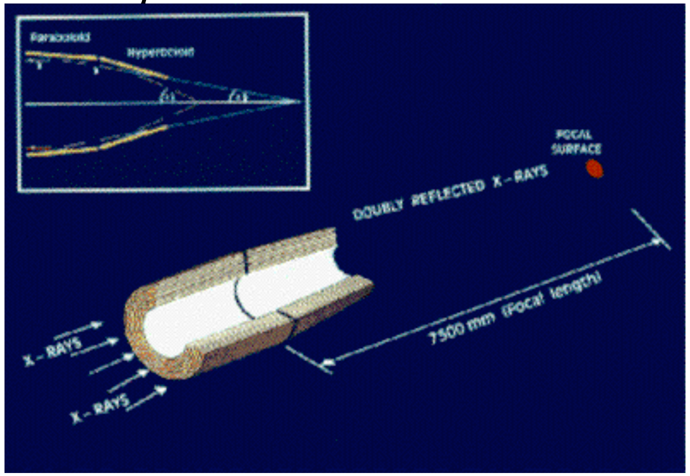
- it allows us to nest together many confocal mirror shells

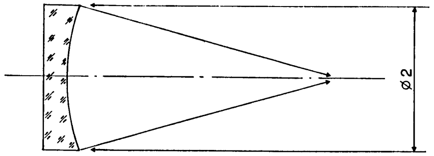
- Effective Area: $8 \pi F L \theta^2 \mathrm{Refl.}^2$

F= focal length = R / tan 4θ

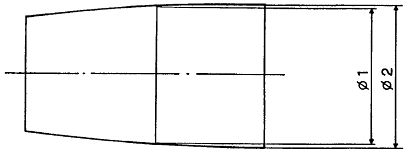
θ= *on-axis incidence angle*

R = aperture radius

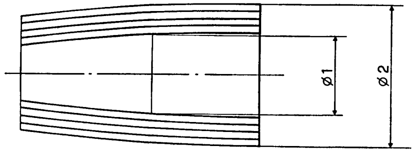




$$S_V = \frac{\pi \varnothing_2^2}{4}$$

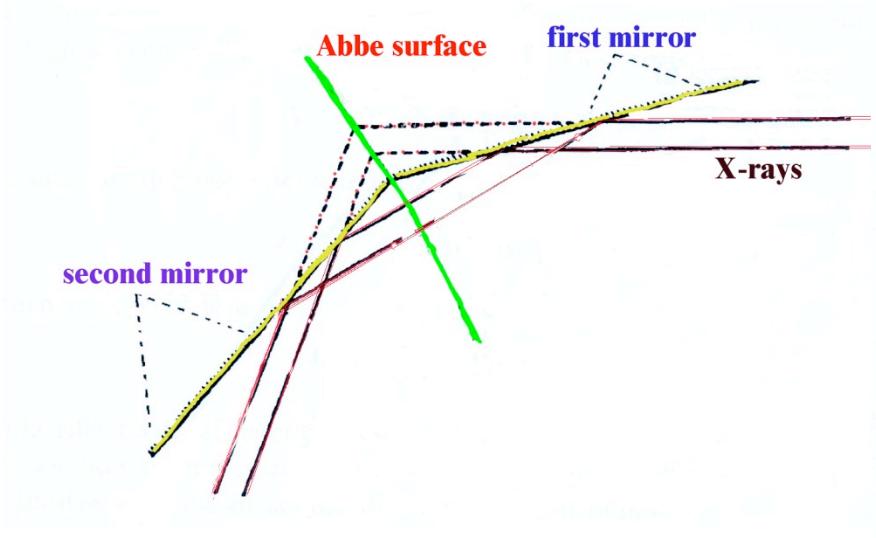


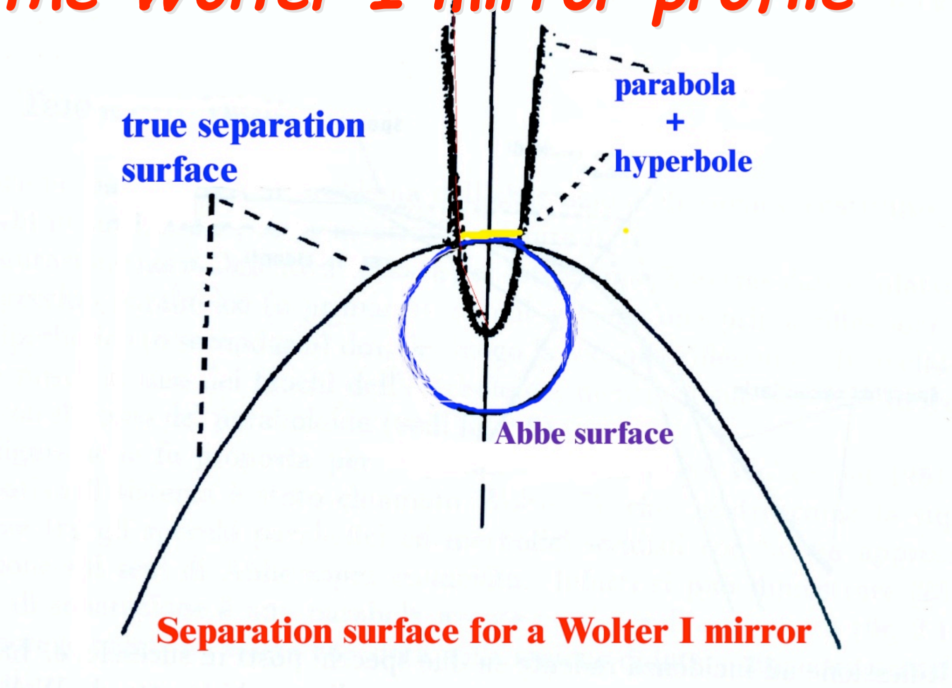
$$S_1 = \frac{\pi (\varnothing_2 - \varnothing_1)^2}{4}$$



$$S_X = \frac{\pi (\varnothing_2 - \varnothing_1)^2}{4}$$

The Abbe condition and the Wolter I mirror profile





Separation surface for a Wolter I mirror

Spherical aberration term

$$\boxed{\sigma_{rms} = 0.2\frac{\tan^2\gamma}{\tan\theta}\left(\frac{L}{F}\right) + 4\tan\gamma\tan^2\theta}$$

Residual coma term

σ_{rms} = rms blur circle

θ = incidence angle

γ = off-axis angle

L = mirror height

F= focal length

NOTE:

the optimal focal plane is not flat: $\delta_{flat} \propto r^2 \frac{L}{F^2}\frac{1}{\tan^2\theta}$ *r = focal plane radius*

Alternative profiles derived from Wolter I

- **Wolter-Schwarzschild** profile: *it exactly satisfies the Abbe sine condition and it has been adopted for the Einstein mirrors; is coma free but it strongly affected by spherical aberration*

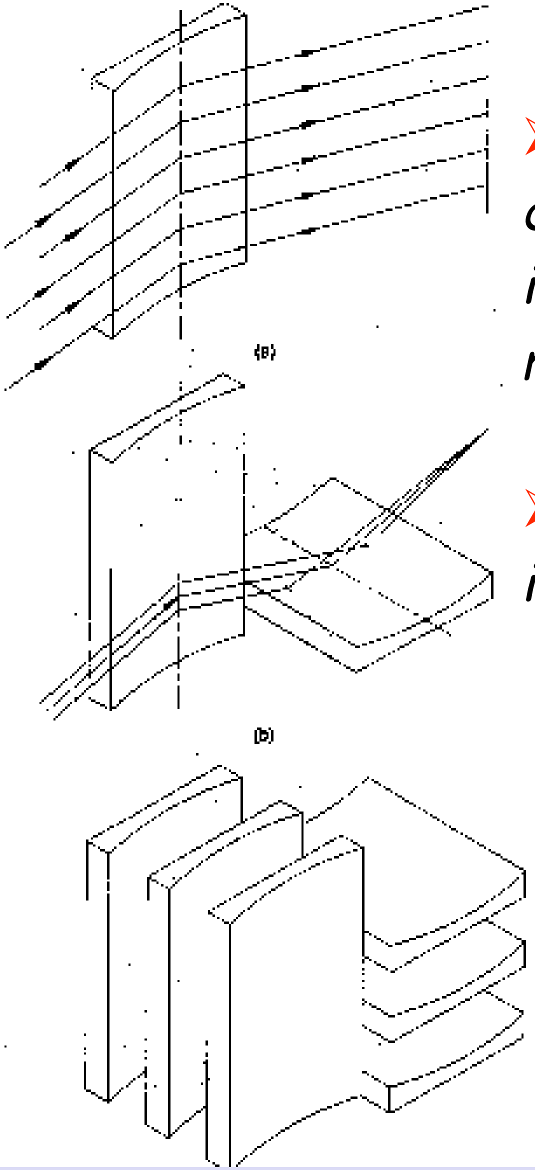
- **double-cone** profile: *it better approximates the Wolter I at small reflection angles: It is utilized for practical reasons (- cost + effective area). Intrinsic on-axis focal blurring given by:*

$$\boxed{HEW \propto \frac{LR}{F^2}}$$

- **polynomial** profile: *parameters have been specifically optimized to maintain the same HEW in a wide field of view*

(introducing small aberration on-axis the off-axis imaging behavior is improved ➔ same principle of the Ritchey-Chretienne normal-incidence telescope in the optical band)

Kirpatrick-Baez Telescopes

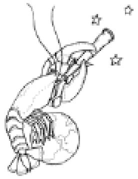


- *parabolic-profile curved mirrors in just one direction ➔ to focus a beam in a single point another identical mirror has to be orthogonally placed with respect to the first one;*

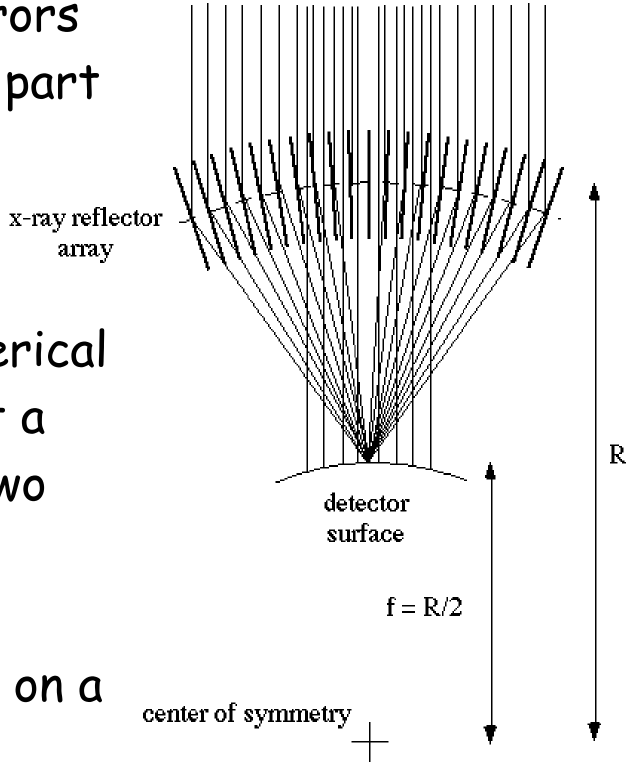
- *it is possible to nest many confocal mirrors to increase the effective area;*
    - *compared to a Wolter I system with same focal length and same incidence angle (on-axis), angles are two time larger;*
    - *imaging capabilities result to be limited by some inherent aberration;*

NB: by means of a K-B optics was performed the first successful attempt of the focalization of an X-ray beam in total-reflection regime (1948)

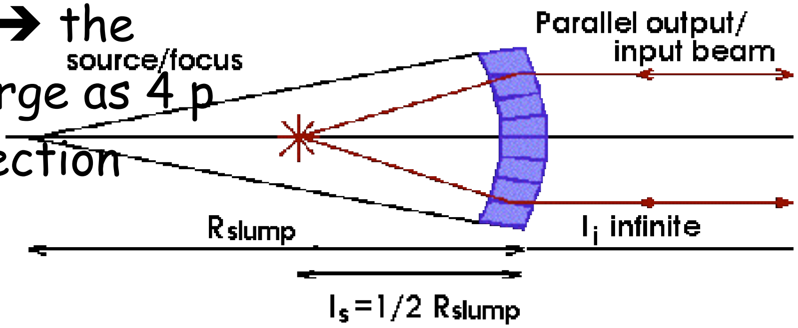
Lobster-Eye optics



Lobster-Eye Optics Geometry (1-dimensional)



- system similar to spherical normal-incidence mirrors but, in this case, the beam impinges on the convex part of the entrance pupil;
- the pupil is formed by a system o channels with square section uniformly distributed around a spherical surface of radius R. To be focused in a single point a collimated beam has to sustain the reflection by two orthogonal walls of a same channel;
- the photons are focused onto points distributed on a spherical surface of radius R/2;
- a preferential optical axis does not exist ➔ the system field of view can be in principle as large as 4 p with the same Effective Area for every direction



Manufacturing techniques utilized so far

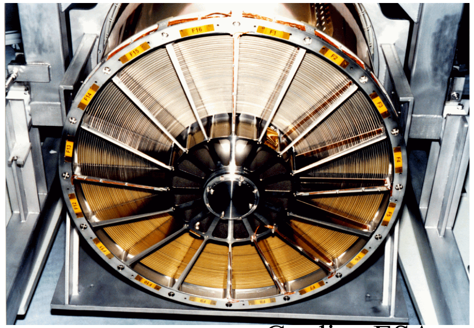
Credits: NASA

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*



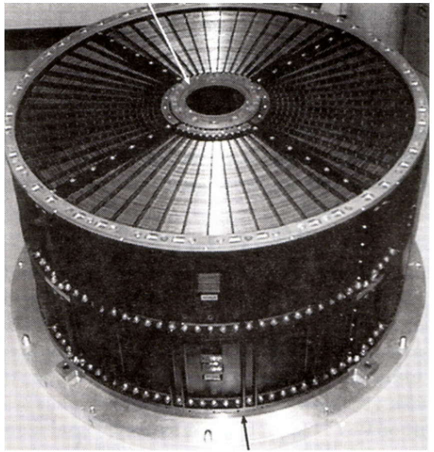
Credits: ESA

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

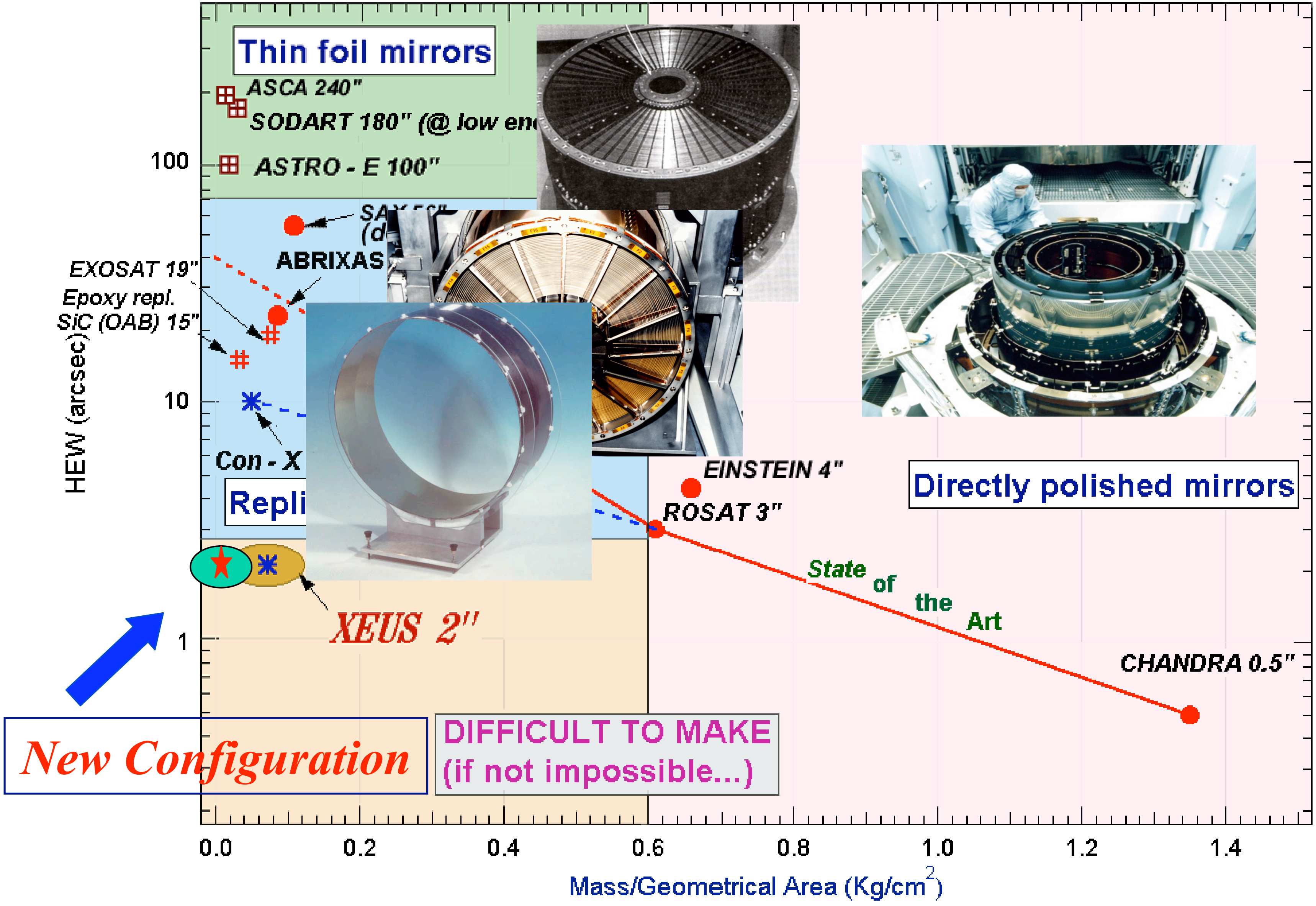
3. "Thin foil mirrors"

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



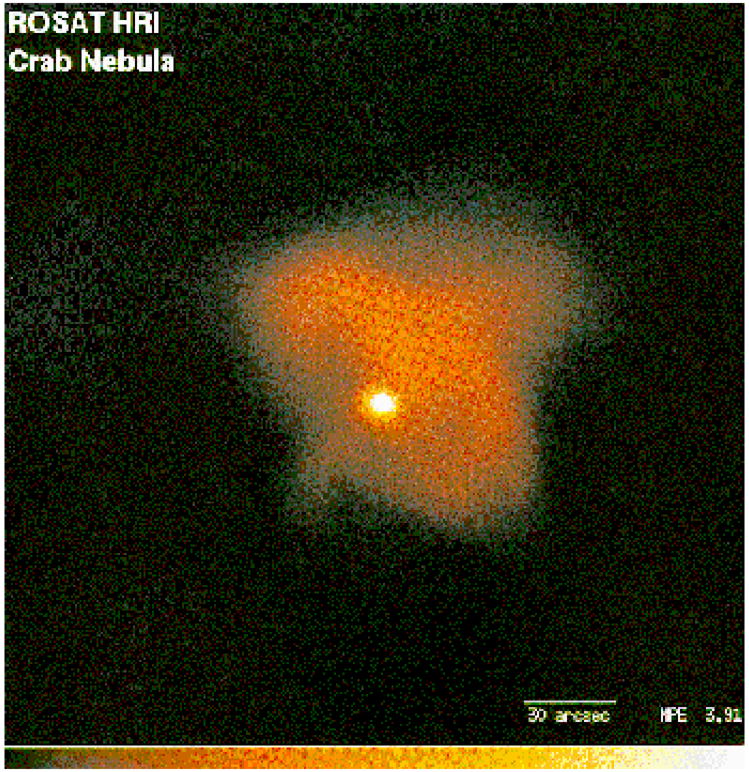
New Configuration

DIFFICULT TO MAKE
(if not impossible...)

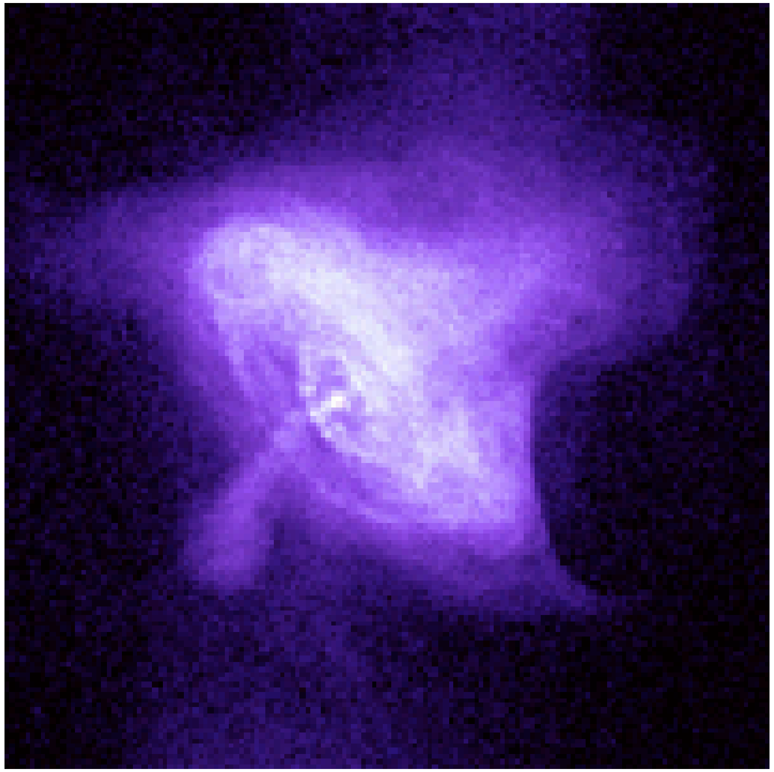
Chandra

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

Chandra: a fantastic angular resolution



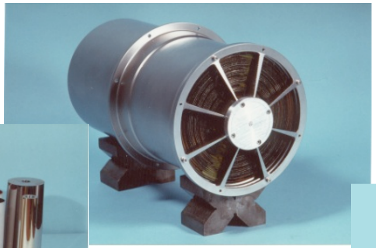
Rosat: HPD = 3 arcsec

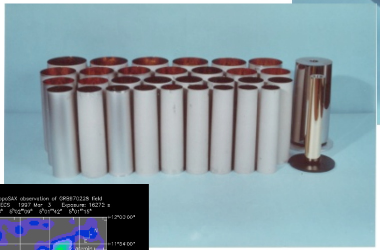


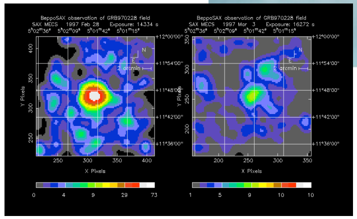
Chandra: HPD = 0.5 arcsec

X-ray optics by Ni electroforming replication

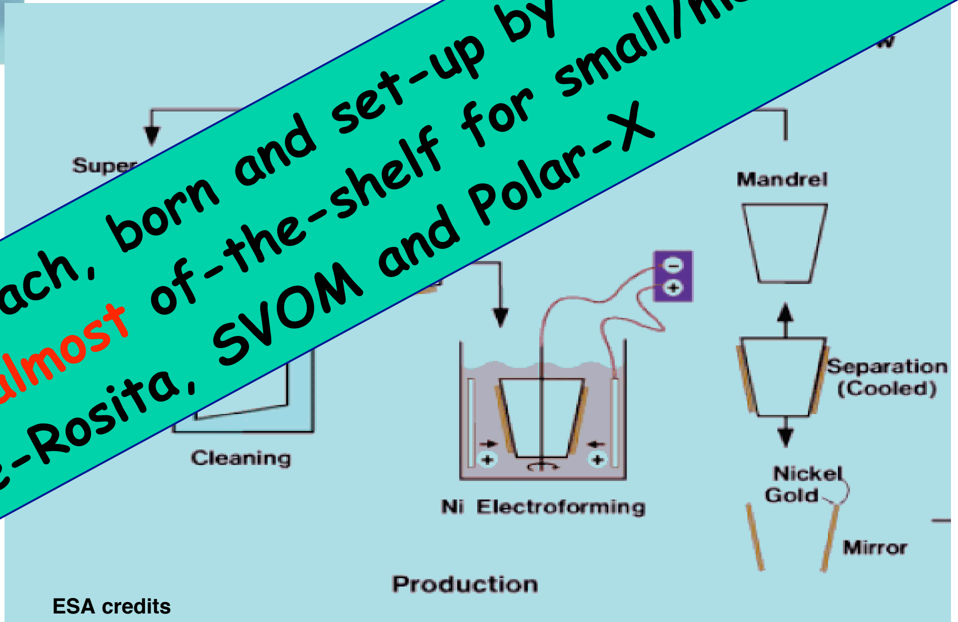
Now the Ni electroforming approach, born and set-up by Citterio et al. For BeppoSAX is a technology almost of-the-shelf for small/medium size missions. It will be used for e-Rosita, SVOM and Polar-X





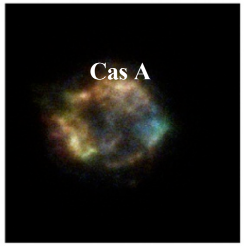


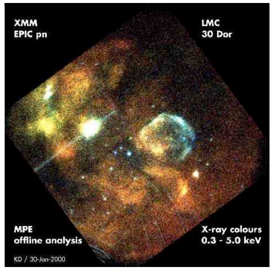
BeppoSAX



ESA credits

Jet-X/Swift

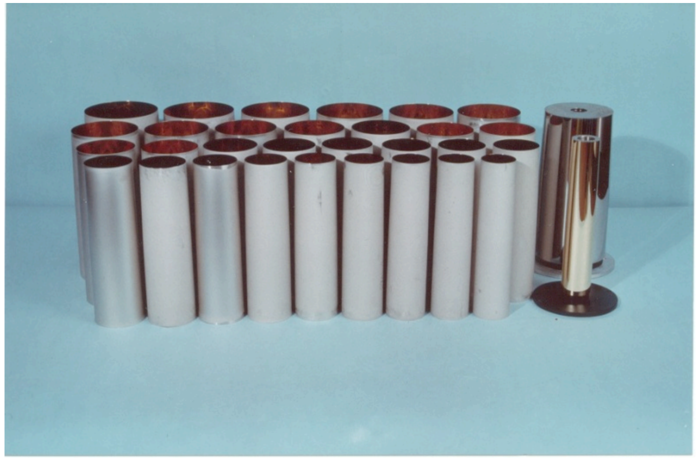


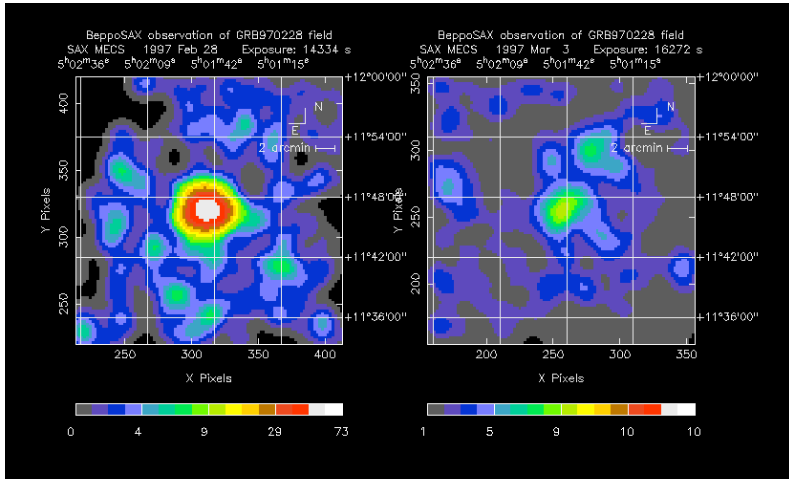


XMM-Newton

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!)





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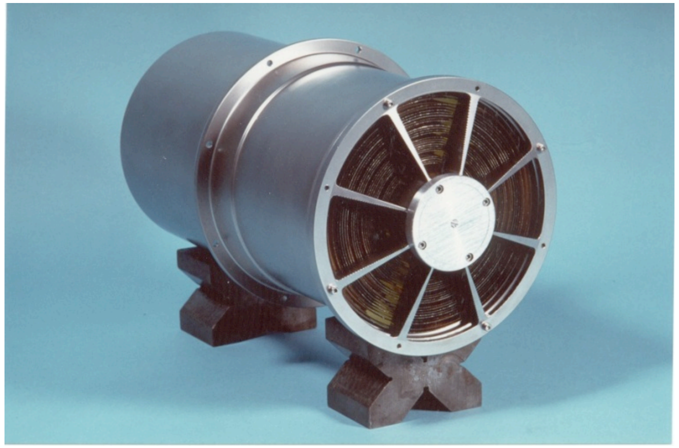
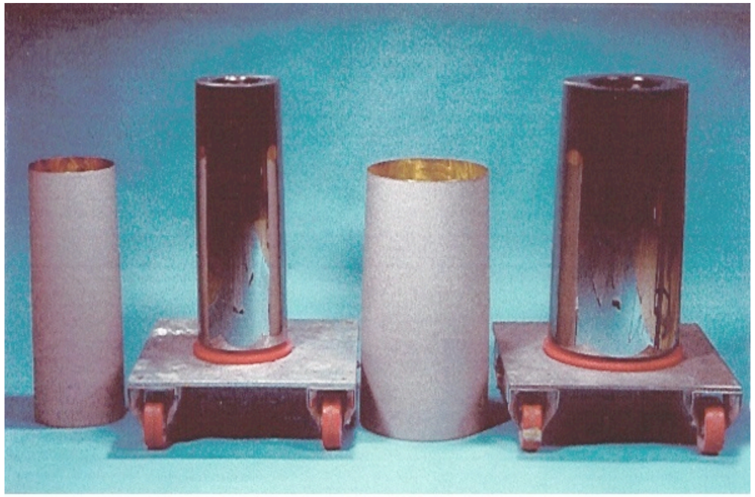
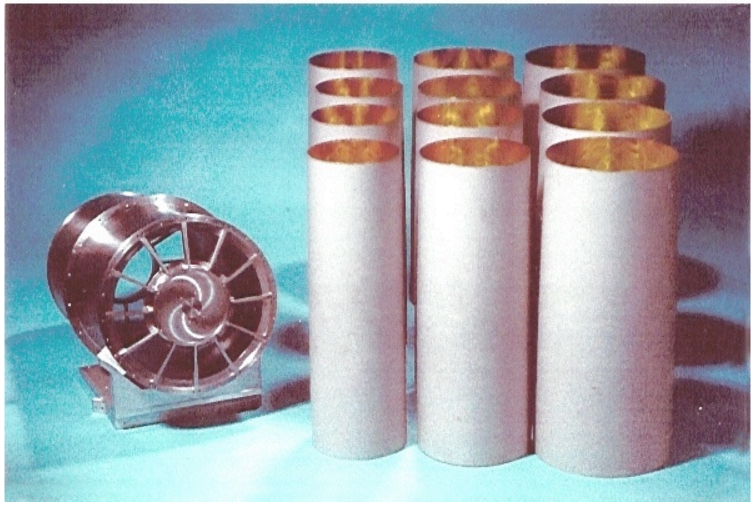
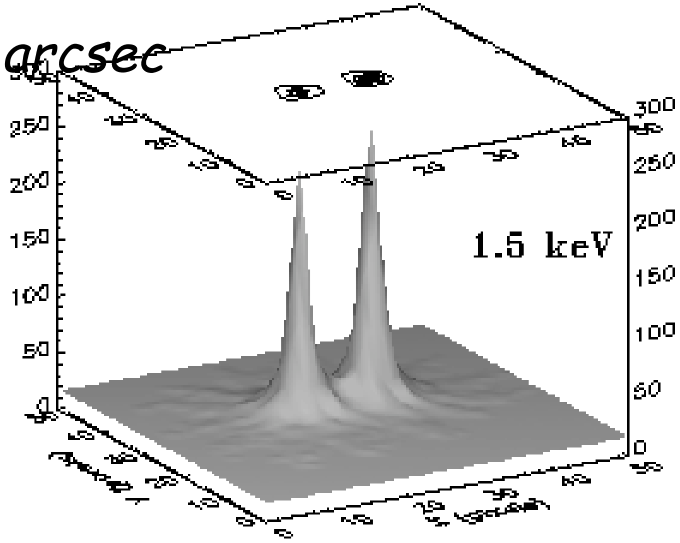


JET-X (optics ready since1996) / SwiftXRT(2004) optics





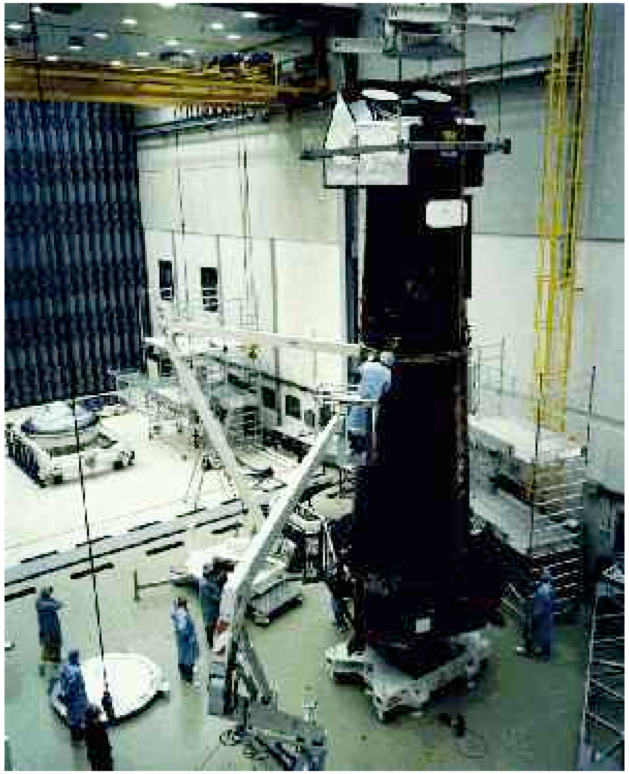
- Wolter I profile – Au coating (pathfinder of XMM)
- 2 mod. (JET-X) / 1 mod (Swift) – 12 shells/mod.
- F.L. = 350 cm - Max diam = 30 cm
- A_{eff} @ 1 keV= 150 cm^2 /module
- HEW= 15 arcsec

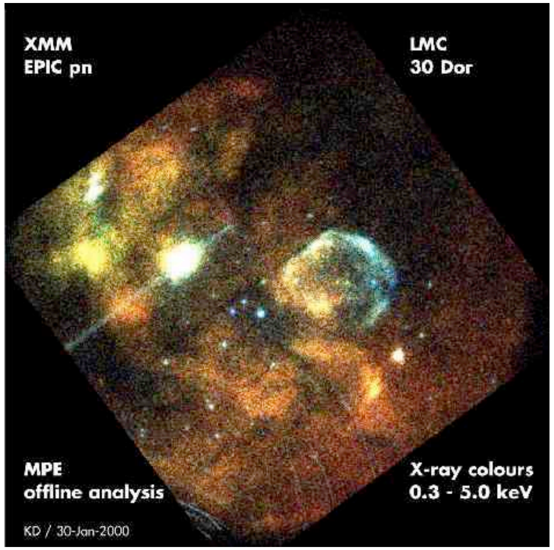


Source separation: 20”

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



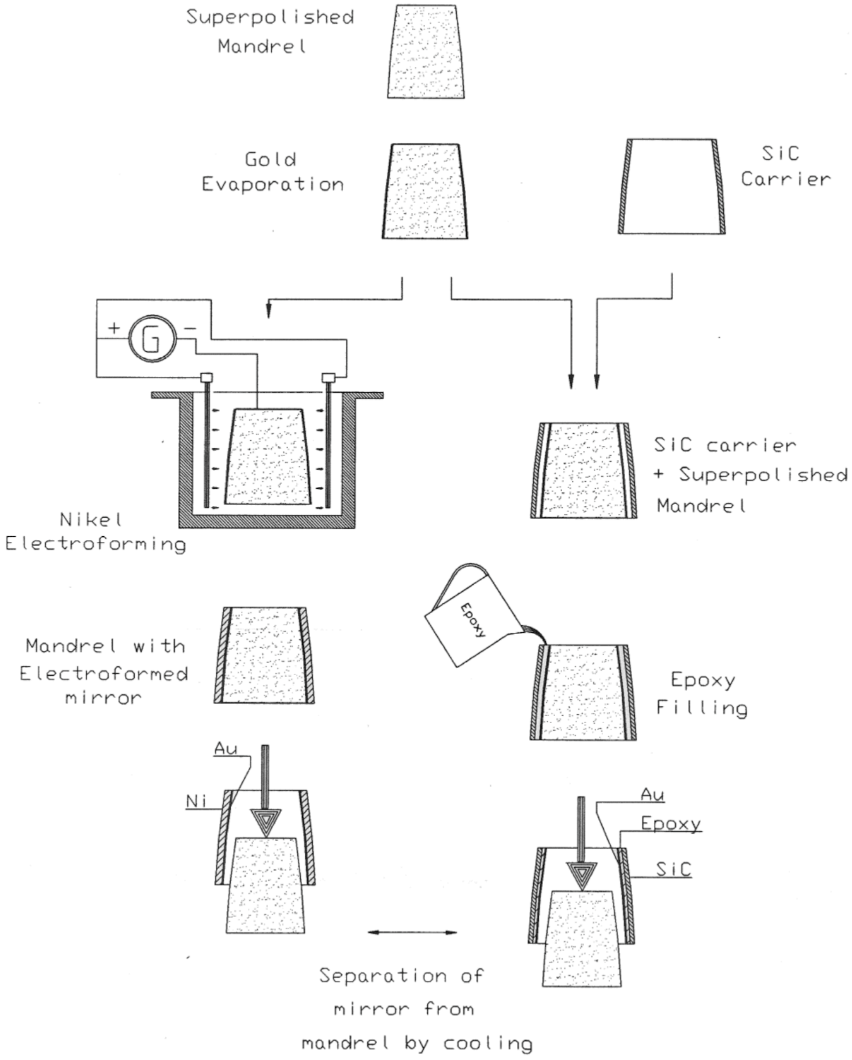


Credits: ESA

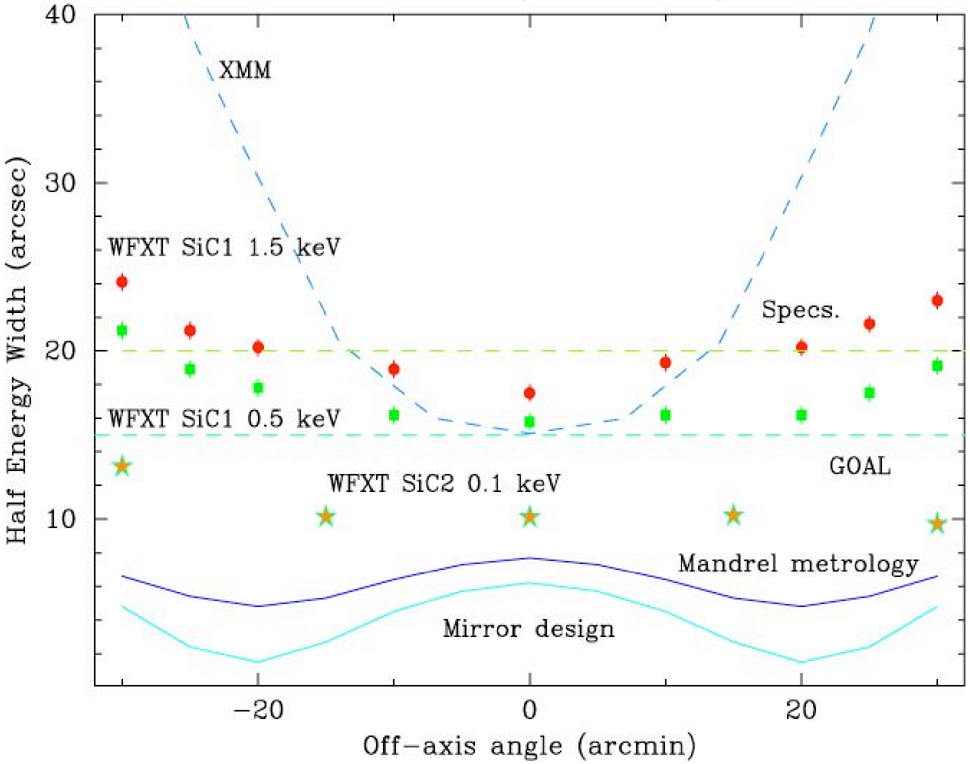
Replication methods

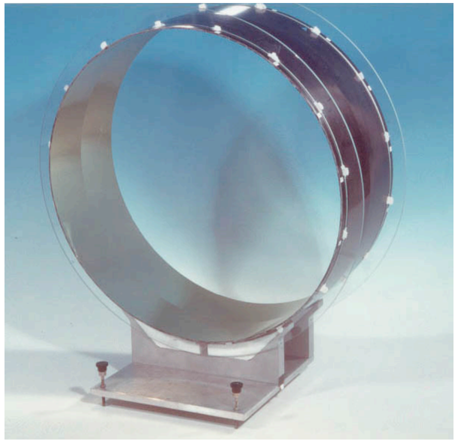
- Ni electroforming replication (SAX, JET-X/Swift, XMM, ABRIXAS, e-ROSITA, SIMBOL-X, SVOM/XIAO)

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



WFXT (feasibility study 1997-1998) – Polynomial mirrors

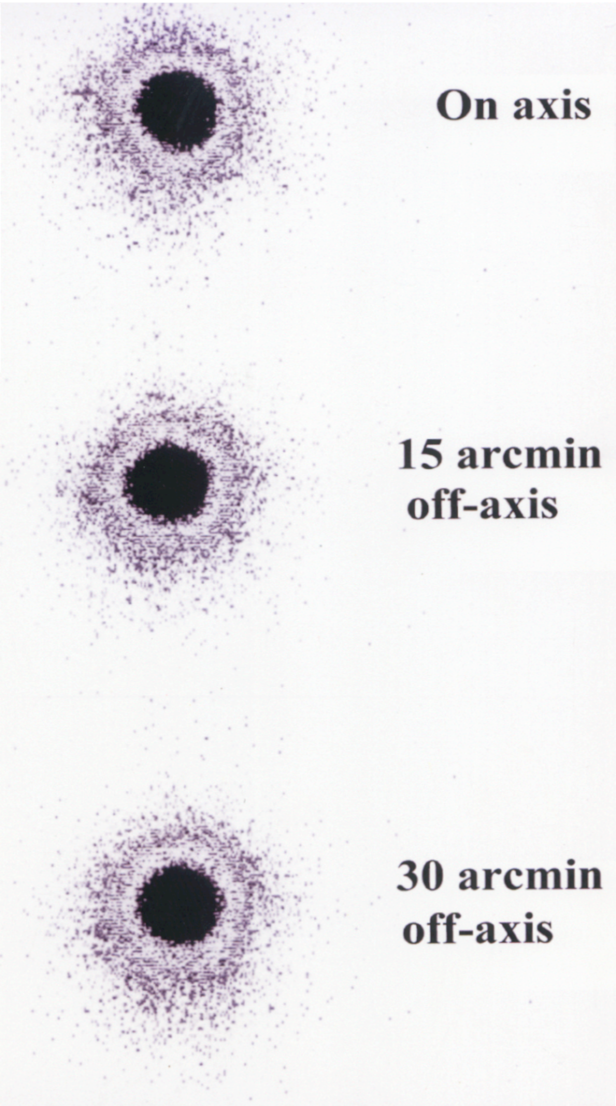




WFXT (epoxy replication su carrier in SiC) – Ø = 60 cm

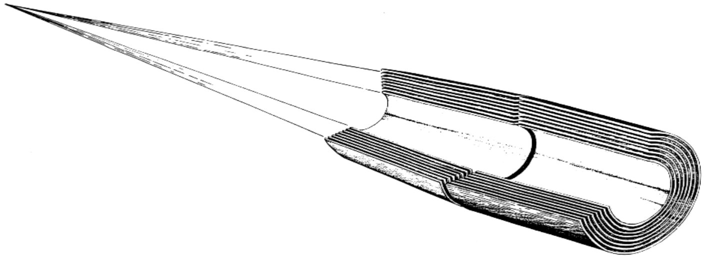
F. L. = 300 cm

HEW = 10 arcsec



Test @ Panter-MPE

The focusing problem in the hard X-ray region (> 10 keV)



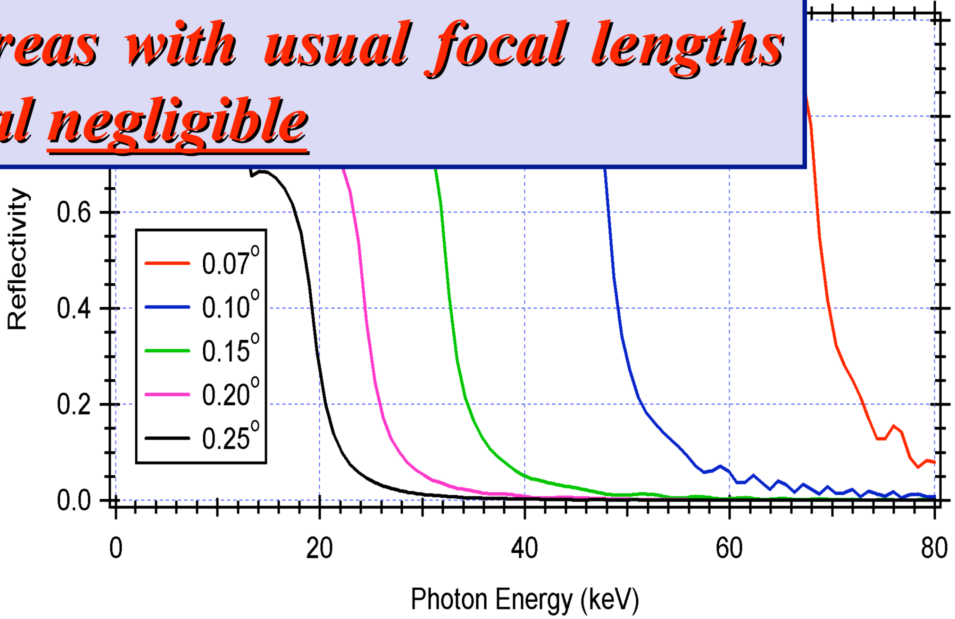
$$A_{eff} \approx F^2 \times \theta_c^2 \times R^2$$

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

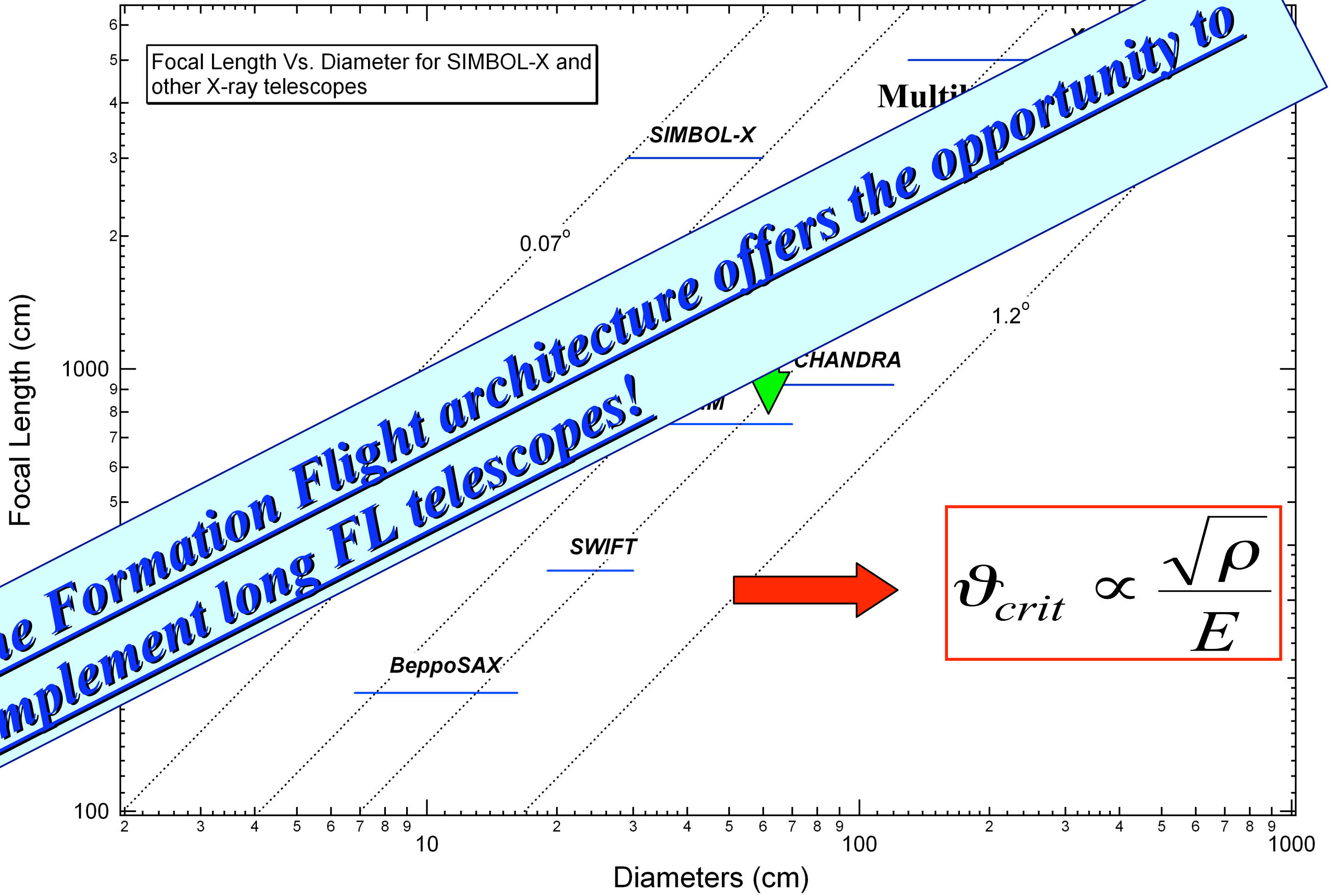
➔ *the geometrical areas with usual focal lengths (> 10 m) are in general negligible*

but

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



Focal Length Vs. Diameters for SIMBOL-X and other X-ray telescopes

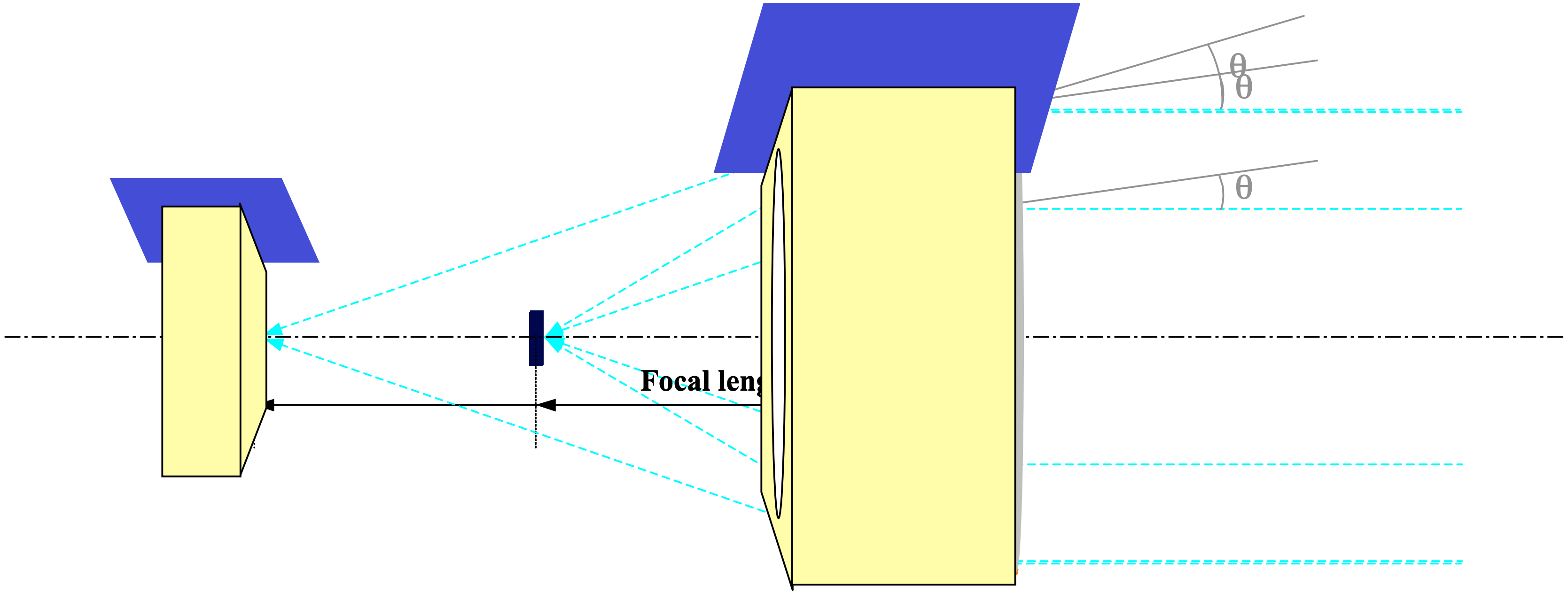


The Formation Flight architecture offers the opportunity to implement long FL telescopes!

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

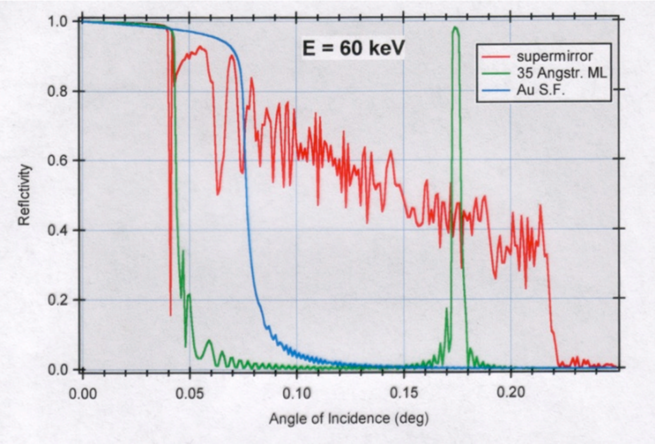
$$A_{eff} \approx F^2 \times \theta_c^{\,2} \times R^2$$

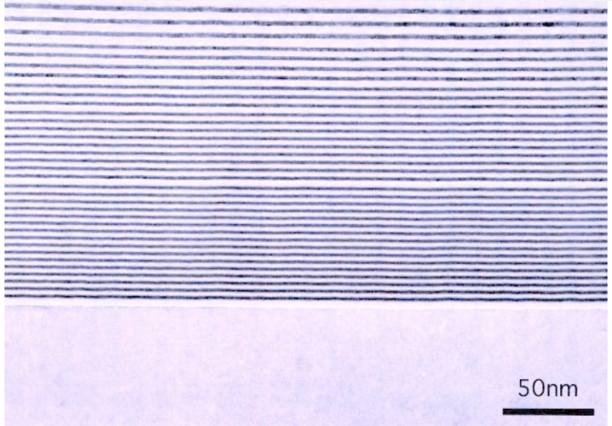
The formation flight contribution



Wide band multilayers

X-ray supermirrors





Optical supermirrors in a beetle skin

Top-level scientific requirements

Energy band:	**~0.5 – ≥ 80 keV**
Field of view (at 30 keV):	**≥ 12’ (diameter)**
On-axis effective area:	≥ 100 cm^2 at 0.5 keV ≥ 1000 cm^2 at 2 keV ≥ 600 cm^2 at 8 keV ≥ 300 cm^2 at 30 keV ≥ 100 cm^2 at 70 keV ≥ 50 cm^2 at 80 keV (goal)
Detectors background	$< 2\times10^{-4}$ cts $\mathrm{s^{-1}cm^{-2}keV^{-1}}$ HED $< 3\times10^{-4}$ cts $\mathrm{s^{-1}cm^{-2}keV^{-1}}$ LED
On-axis sensitivity	**≤ 10^{-14}c.g.s.(~0.5 μCrab), 10-40 keV band, 3σ, 1Ms,**
Line sensitivity at 68 keV	$< 3\times10^{-7}$ ph $\mathrm{cm^{-2}\ s^{-1}}$ (3σ, 1Ms)
Angular resolution	**≤ 20”*(HPD)*, E < 30 keV** **≤ 40”*(HPD)* @ E = 60 keV (goal)**
Spectral resolution	**E/ΔE = 40-50 at 6-10 keV** **E/ΔE = 50 at 68 keV (goal)**
Absolute timing accuracy	**100 μs (50 μs goal)**
Absolute pointing reconstruction	**~ 3″ (radius, 90%) (2” goal)**
Mission duration	**3 years including commissioning and calibrations (2 years of scientific program) + provision for a possible 2 year extension**
Total number of pointings	**> 1000 (first 3 years, nominal mission)** **500 (during the possible 2 year mission extension)**

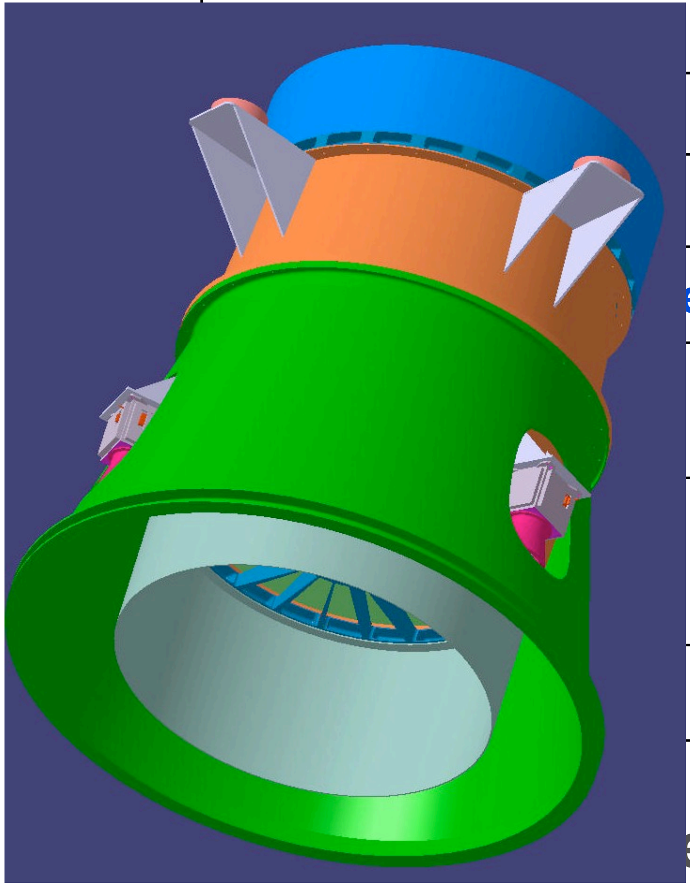
Simbol-X Optical Design

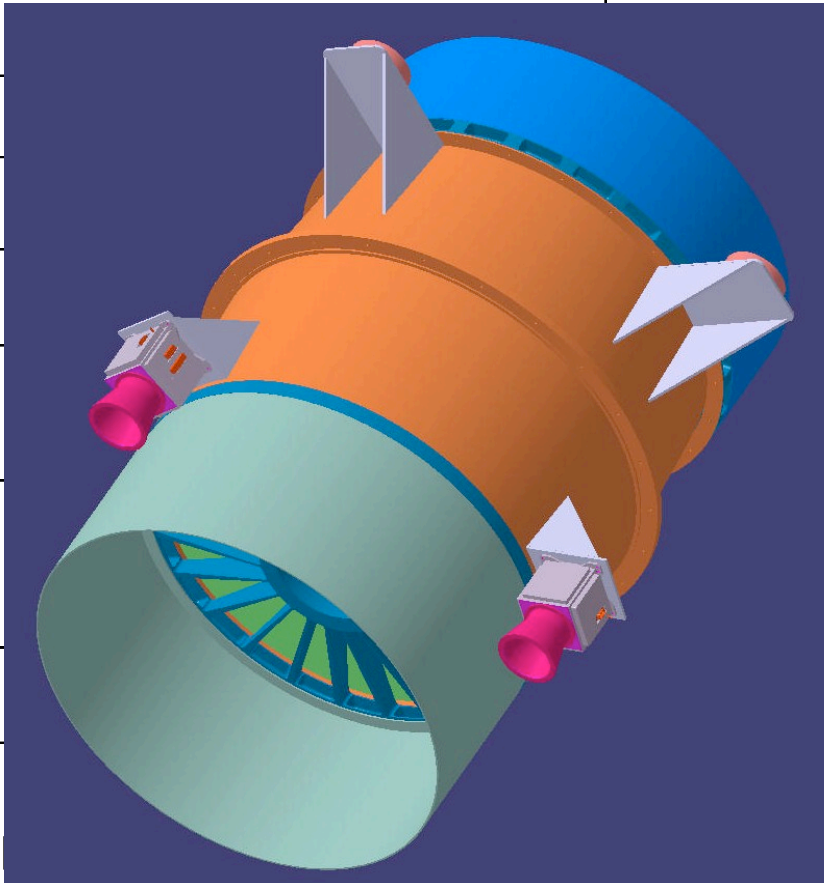
Min-Max Diameter	250 - 650 mm
Focal Length	20000 mm
Mirror Height	600 mm
Configuration	Wolter I
Number of Mirror shells	100
Min-Max incidence angles	0.1° - 0.25°
Min-Max wall thickness_	0.25 - 0.55 mm
Total Mirror Mass	287 kg

_ NB: thickness trend 2 times less XMM-Newton

Simbol-X Optical Design

Min-Max Diameter	**250 - 650 mm**
ells	





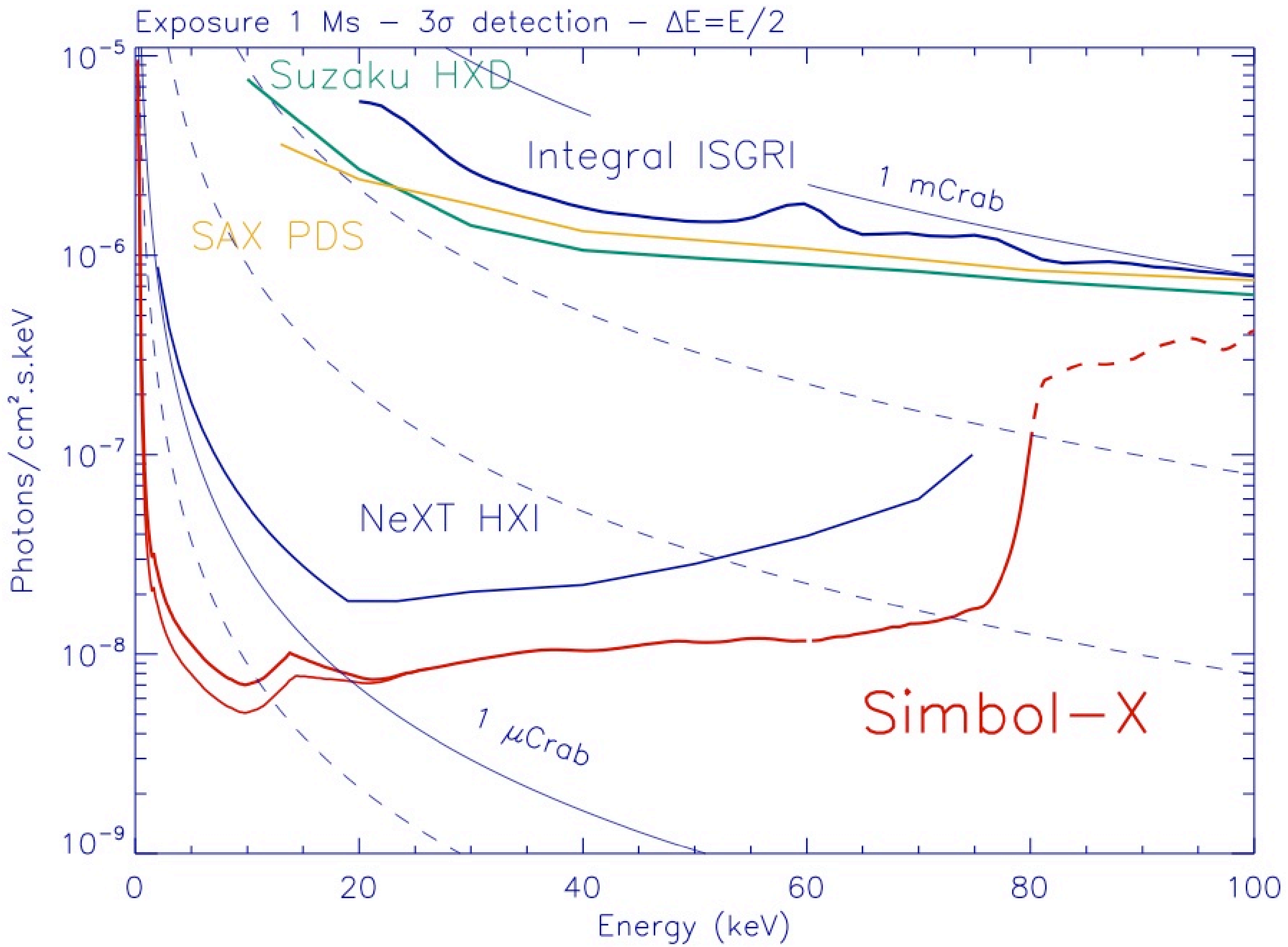
ess t

Newton

Angular resolution for past & future Hard X-ray Experiments

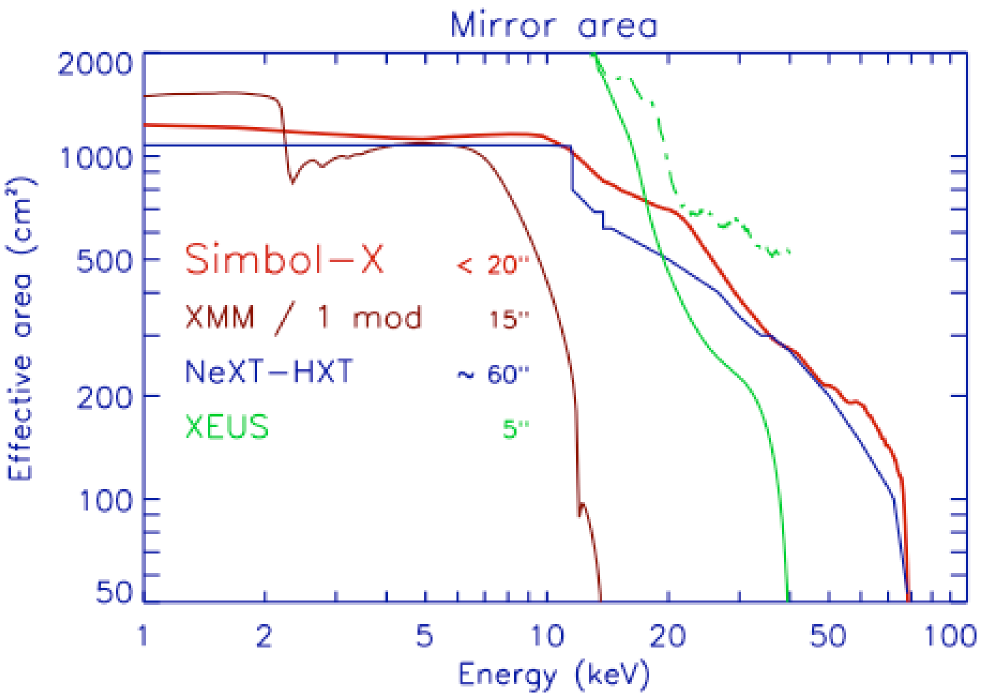
Experiment	*Year*	*"Imaging" technique*	*Angular resolution*
SAX-PDS	1996	Rocking collimator	> 3600 arcsec (collimator pitch)
INTEGRAL-IBIS	2002	Coded mask	720 arcsec (mask pitch)
HEFT (baloon)	2005	Multilayer optics	> 90 arcsec HEW
NUSTAR	2011	Multilayer Optics	40-60 arcsec HEW
SIMBOL-X	***2014***	***Multilayer Optics***	***15-20 arcsec HEW***

Expected Flux Sensitivity



Simbol-X Optics

- **Heritage from XMM-Newton : nickel shells obtained by electroforming replication method; low mass obtained via a reduced thickness of shells**
- **Coating : multi-layer Pt/C needed for requirement on large FOV and on sensitivity up to > 80 keV**

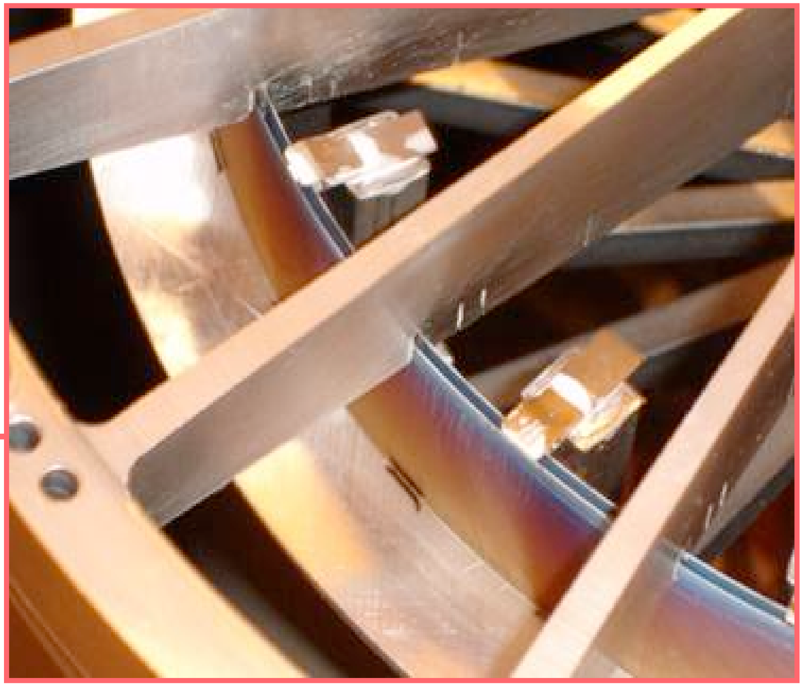


Focal length : 20 m
Shell diameters : 30 to 70 cm
Shell thickness : 0.2 to 0.6 mm
Number of shells : 100

N.B. I: The optics module will have both sides covered with thermal blankets

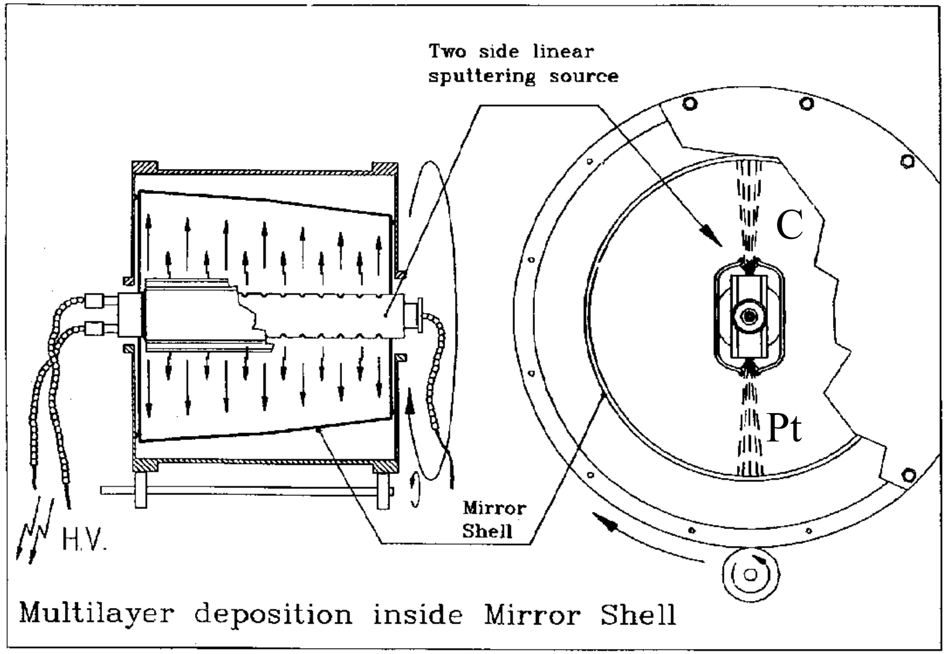
N.B. II: a proton diverter will be implemented

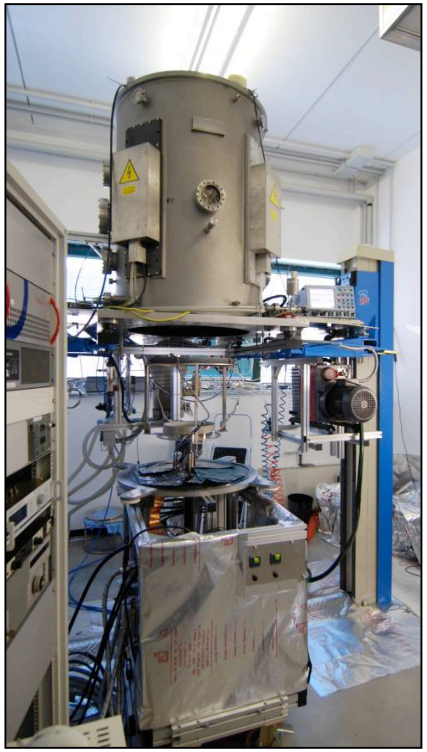
Integration of thin mirror shells



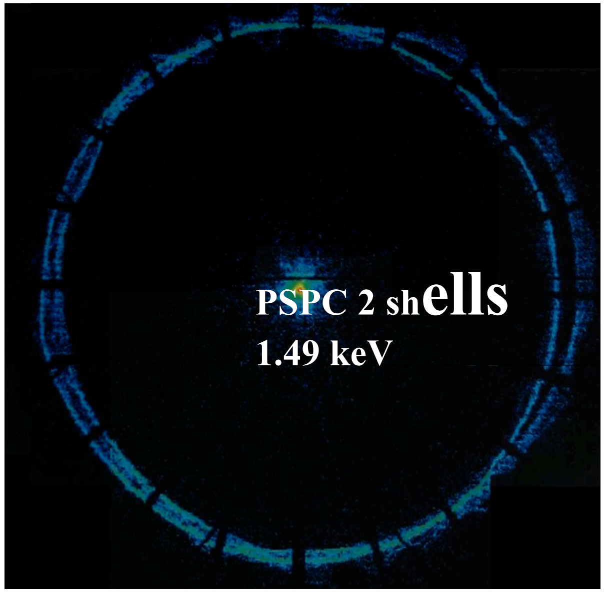
Integration of thin mirror shells

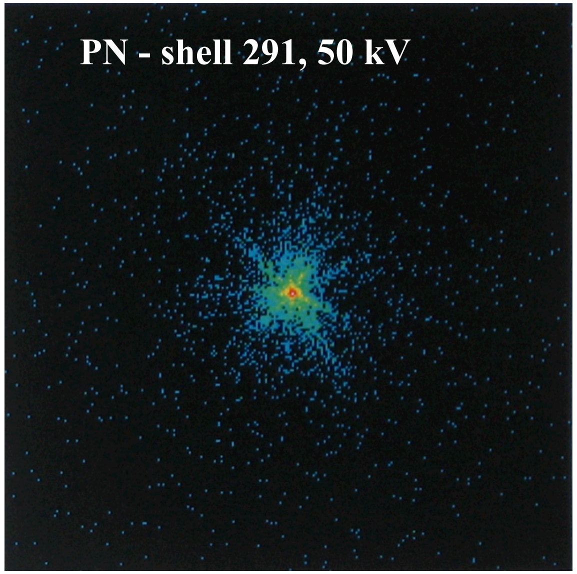
Multilayer deposition concept

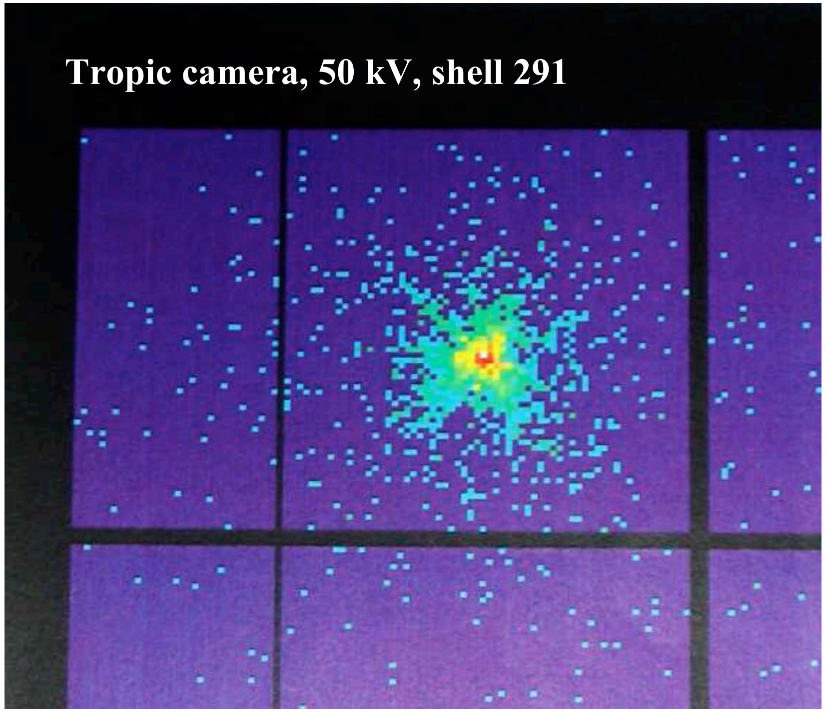




Calibration of the 2 mirror shell prototype at Panter MPE



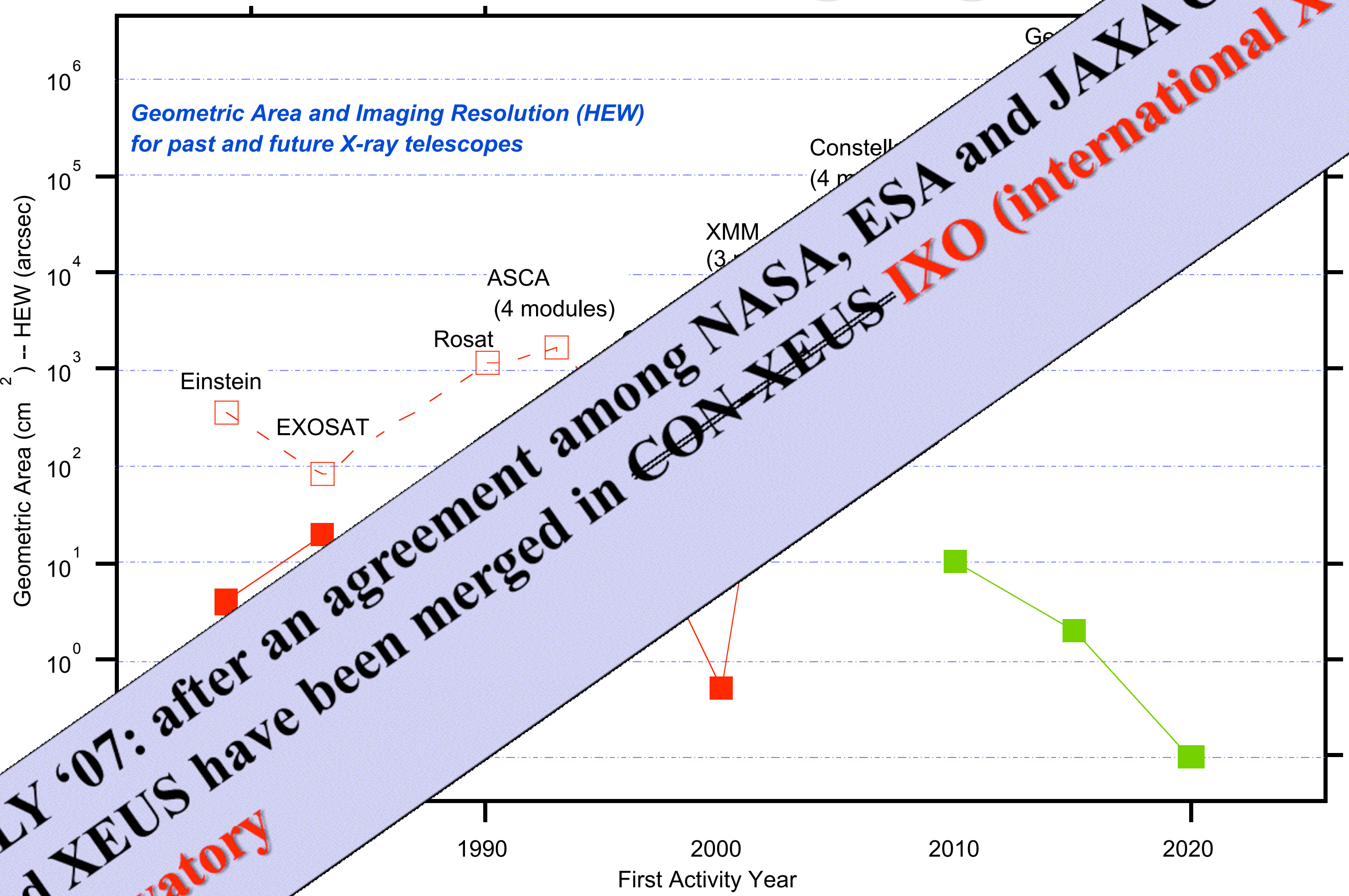




Calibration of 2 mirror shell prototype at Panter MPE

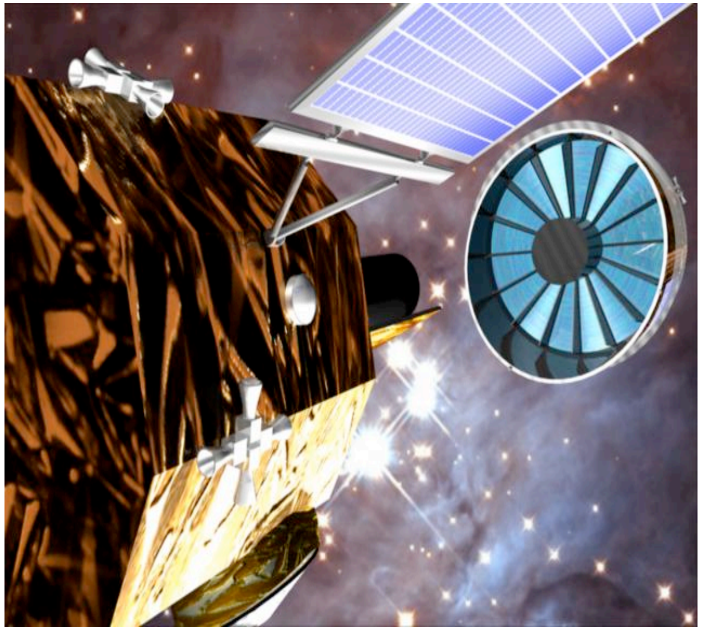
Energy (keV)	HEW (arcsec) 291 shell	HEW (arcsec) 295 shell
1.5	23	22.5
8	24	27.5
20	27	29
35	31	49
50	33	49

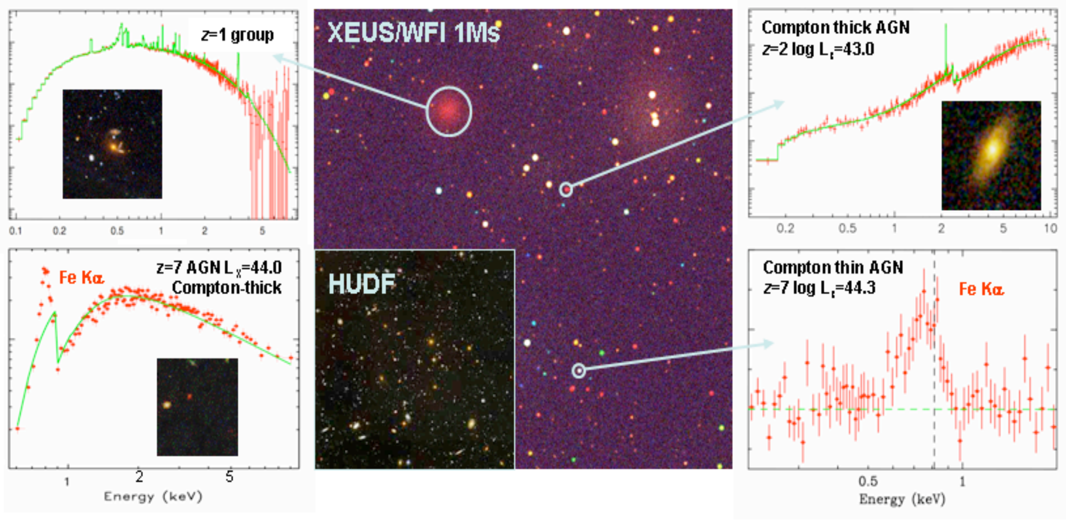
Where are we going?



JULY ‘07: after an agreement among NASA, ESA and JAXA Con-X and XEUS have been merged in ~~CON-XEUS~~ IXO (international X-ray Observatory

XEUS





Sensitivity (cgs) (3 x10^{-18}) @ 0.2–8 keV; 4_

Effective Area

- 1 (1.5) m^2 @ 0.2 keV
- 5 m^2 @ 1 keV
- 2 m^2 @ 7 keV
- 1 m^2 @ 10 keV
- (0.1) m^2 @ 30 keV

Angular Resolution

5 (2) arcsec @ < 10 keV

10 arcsec @ 40 keV

Field-of-View

7 (10) arcmin diameter: WFI, HXI

1.7 arcmin diameter: NFI

XEUS X-ray optics requirements

ITEM	*Requirement*	*Goal*
Angular Resolution (HEFW)	5 arcsec	2 arcsec
Collecting Area @ 1 keV	5 m^2	5 m^2
Collecting Area @ 7 keV	2 m^2	2m^2

N.B. data from the proposal document

Optics mass budget

Mirrors	Support	ancillary	Total
882 kg	176 kg	238 kg	1296 kg

N.B. data from the proposal document

Optics error budget

Specification (arcsec)	*Inherent*	*Intrinsic*	*Extrinsic*	*Enviro nment*	*Total*
Goal	1.4	1.2	0.5	0.5	2
Requirement	1.8	3.7	2	2	5

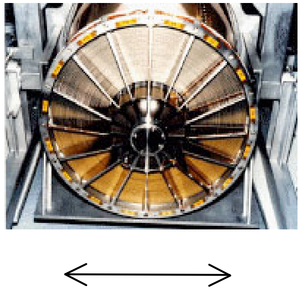
N.B. data from the proposal document

Optics Characteristics

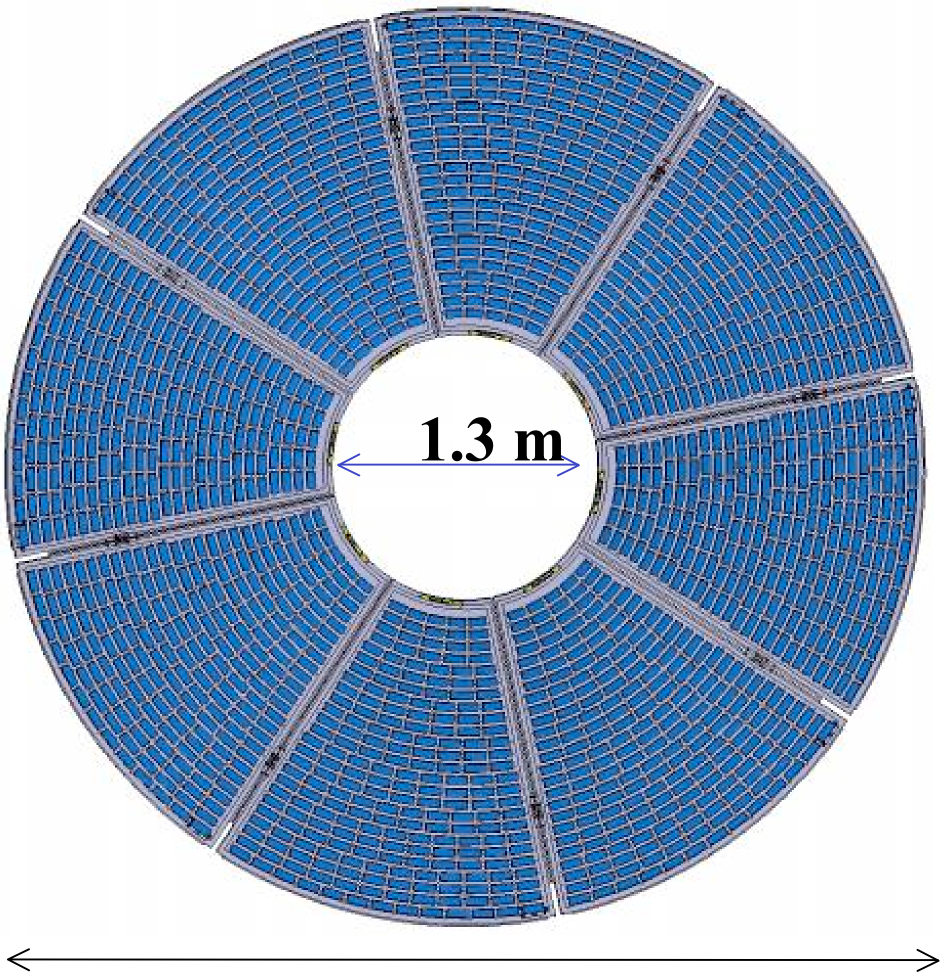
Characteristic	Value
Pore size	0.6 x 1.5 mm^2
Aperture radii	0.67–2.1 m
Grazing reflection angles	0.27–0.86 degrees
Focal length	35 m
Plate scale	170_m/arcsec

N.B. data from the proposal document

XMM

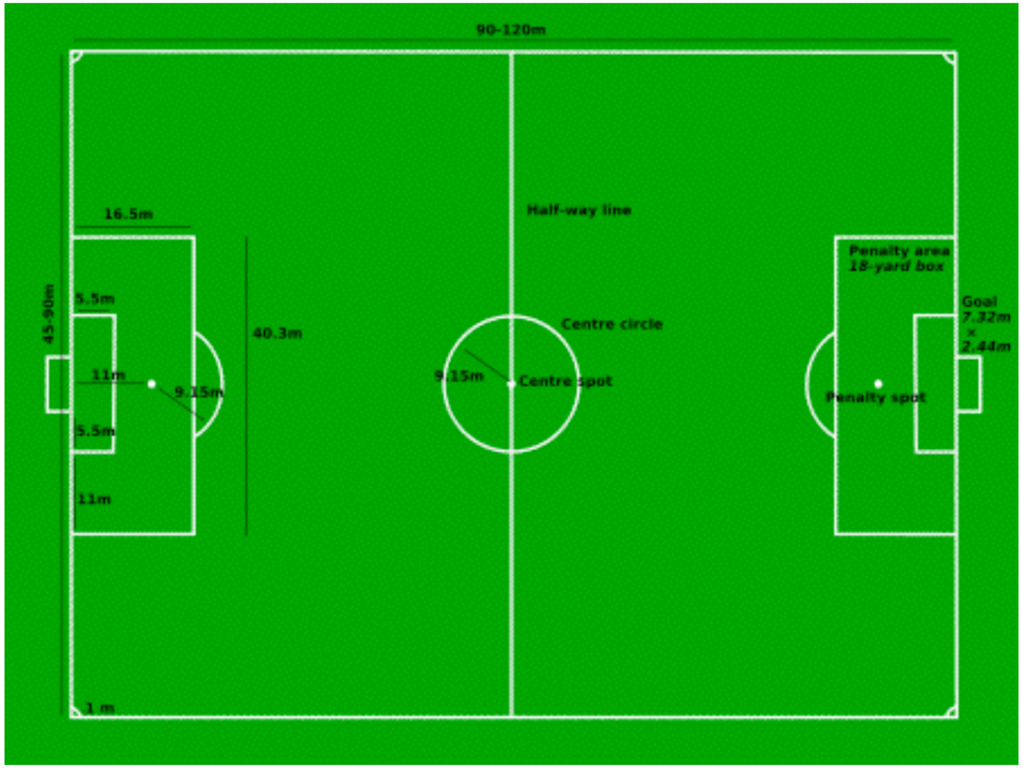


XEUS



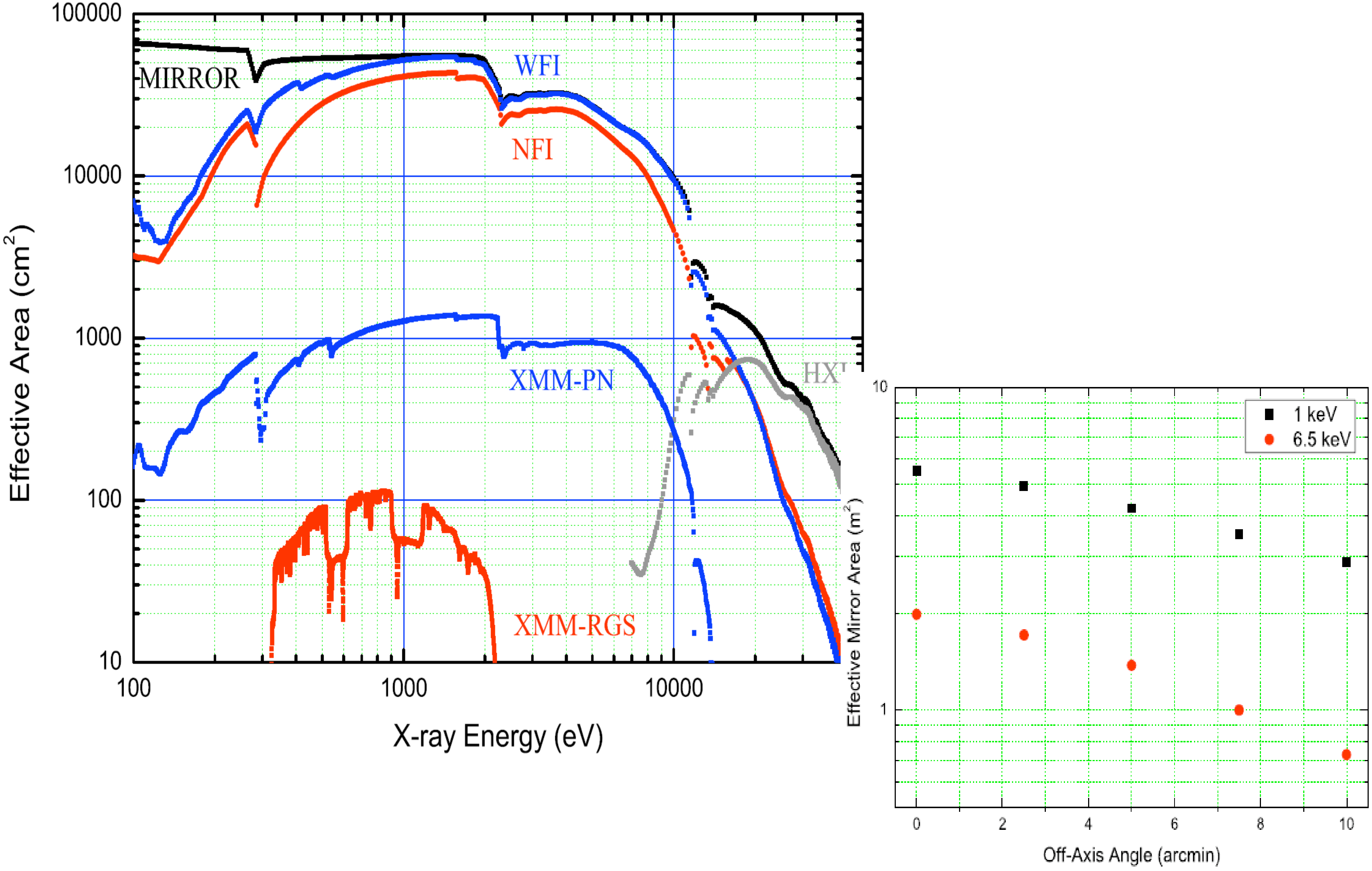
Total reflecting surface to be produced

2.5 x



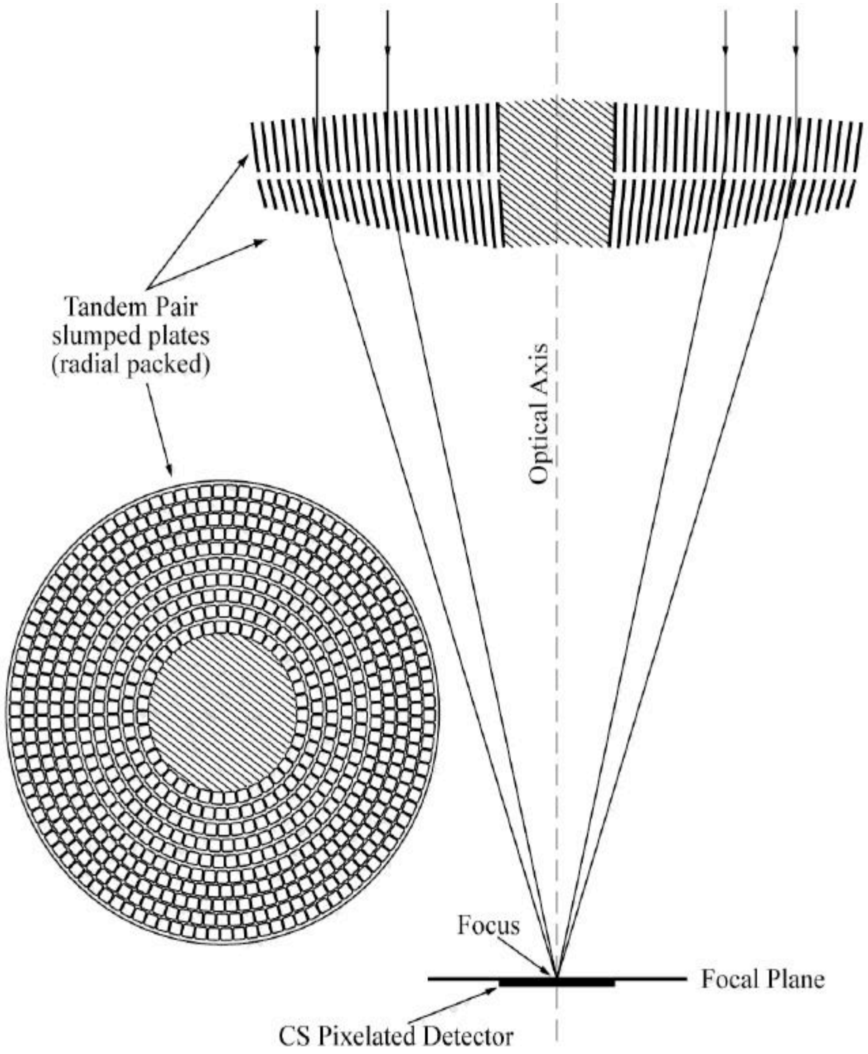
Need of a manufacturing process scalable at a high volume production industrial level!

XEUS Effective Area



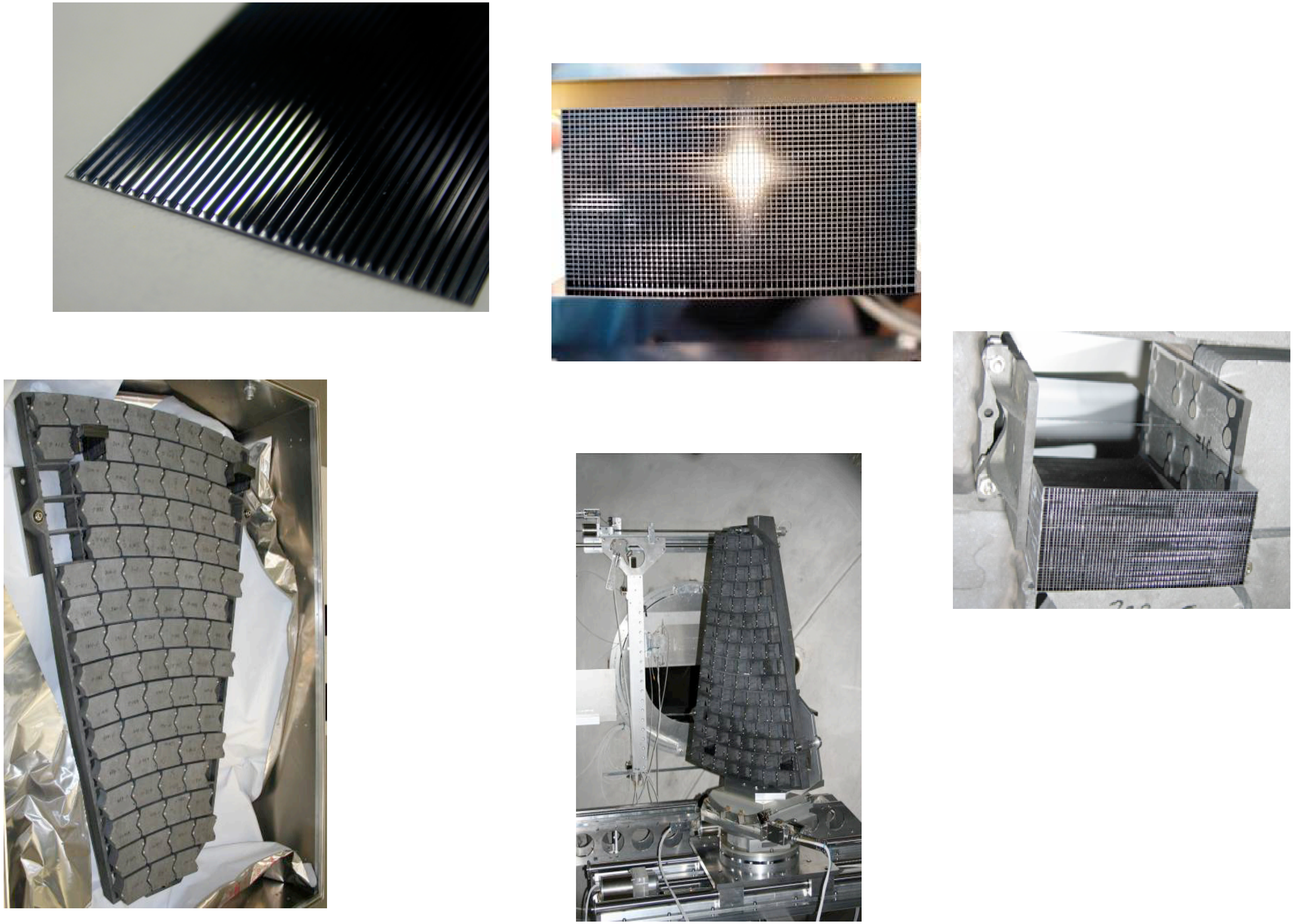
X-ray Pore Optics System

Double-Cone approximation



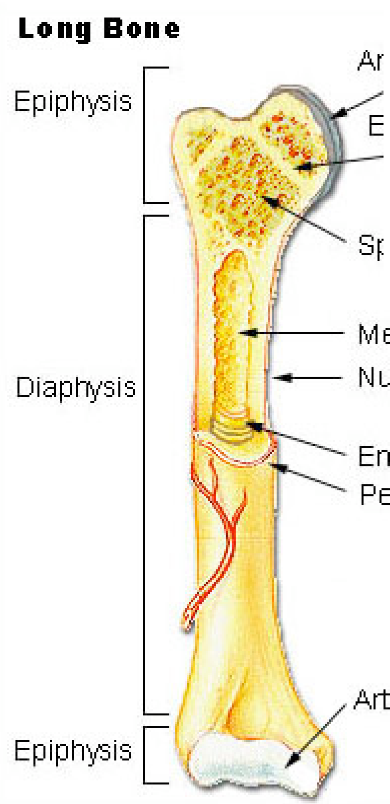
N.B.:concept introduced by D. Willingale et al, Capri 1994

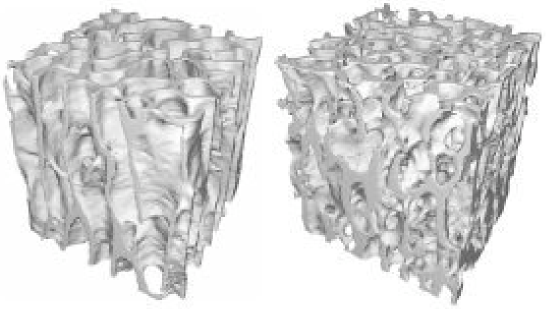
Pore Optics technology



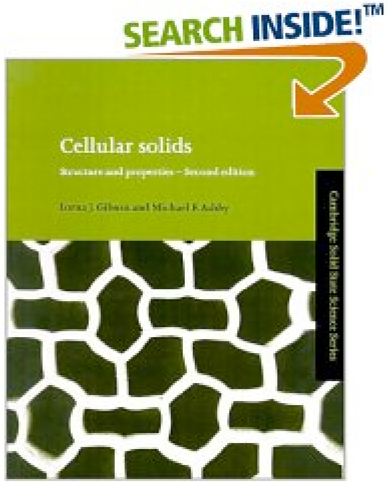
Credits: ESA & Cosine

Cellular solids: light weight structures with a very high stiffness





Foamed



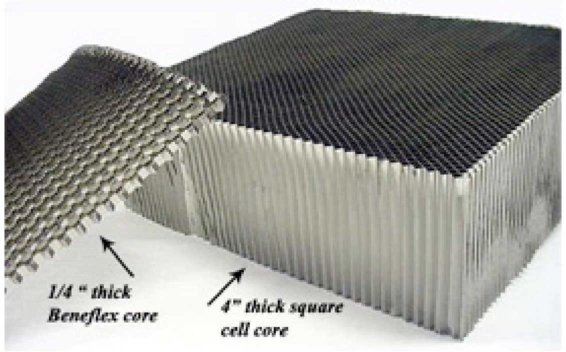
Cellular solids

Structure and properties – Second edition

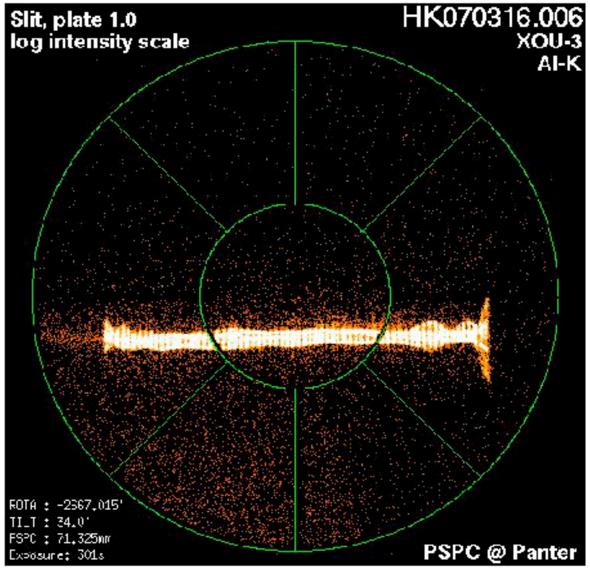
Lorna J. Gibson and Michael F. Ashby

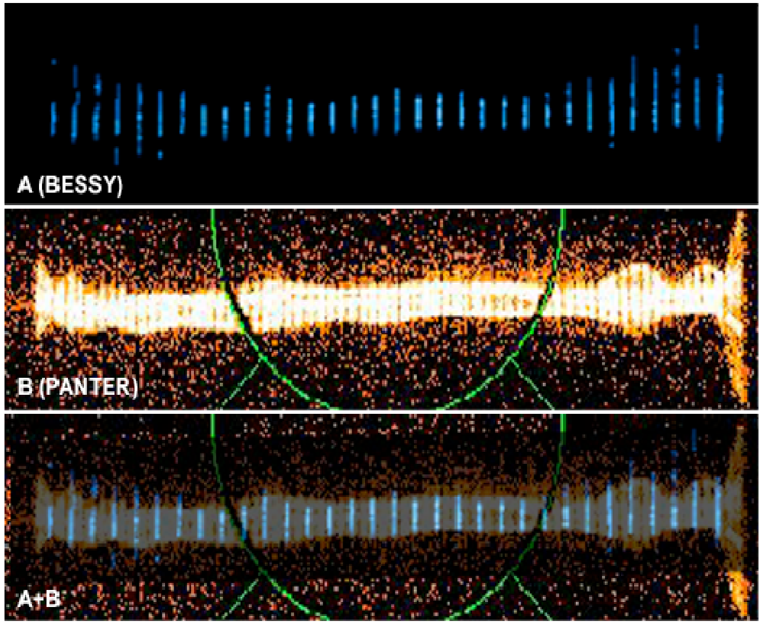
Cambridge Solid State Science Series

Regular cellular structures



Preliminary imaging tests onto two-reflection optics (I)

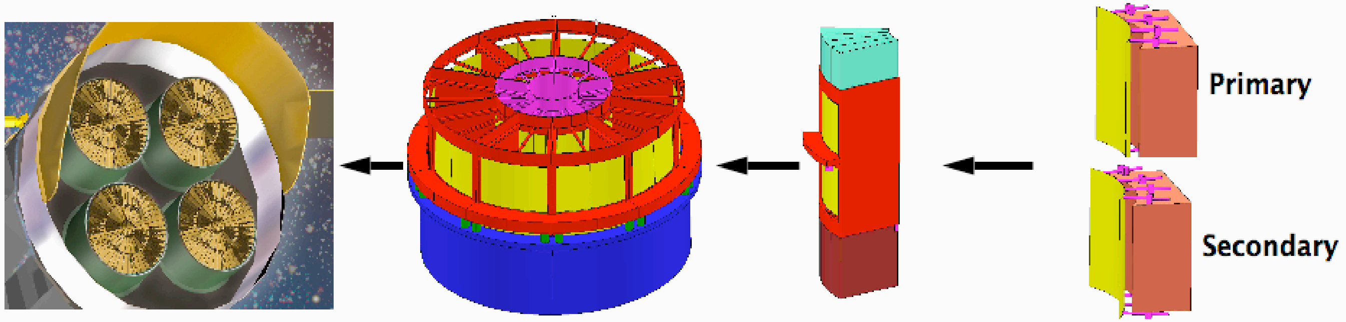




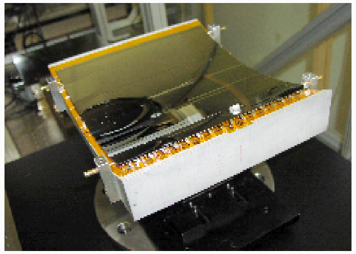
Credits: ESA, Cosine, MPE

Collon et al, SPIE Proc 67898, in press (2007)

Alternative approach: hot sluping of thin glass segments



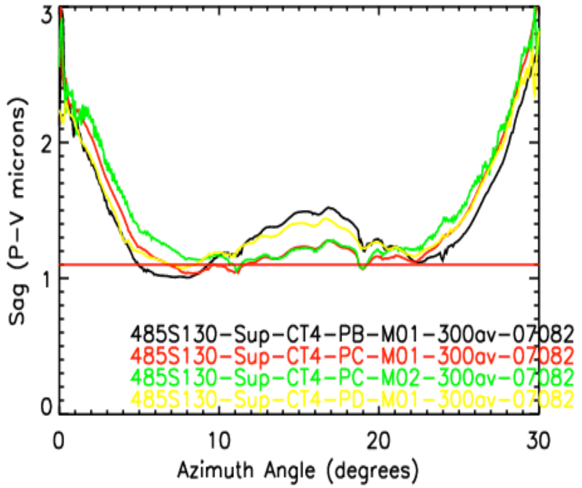
(a) Observatory (b) Mirror Assembly (c) Mirror Module (d) Mirror Segment



Mattress

Cantor Tree

Suspend & Bond

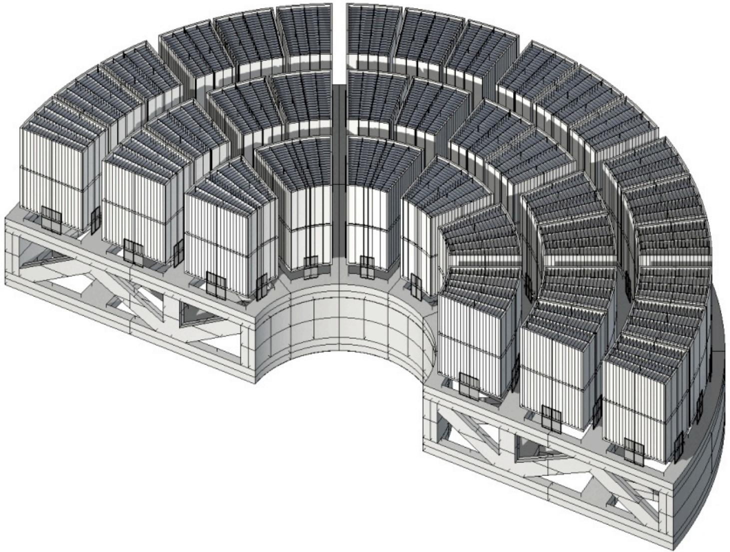


0.4 mm thick segments 1 tandem (without integration)
HEW = 13 arcsec

Wolter I preliminary design for XEUS (I)

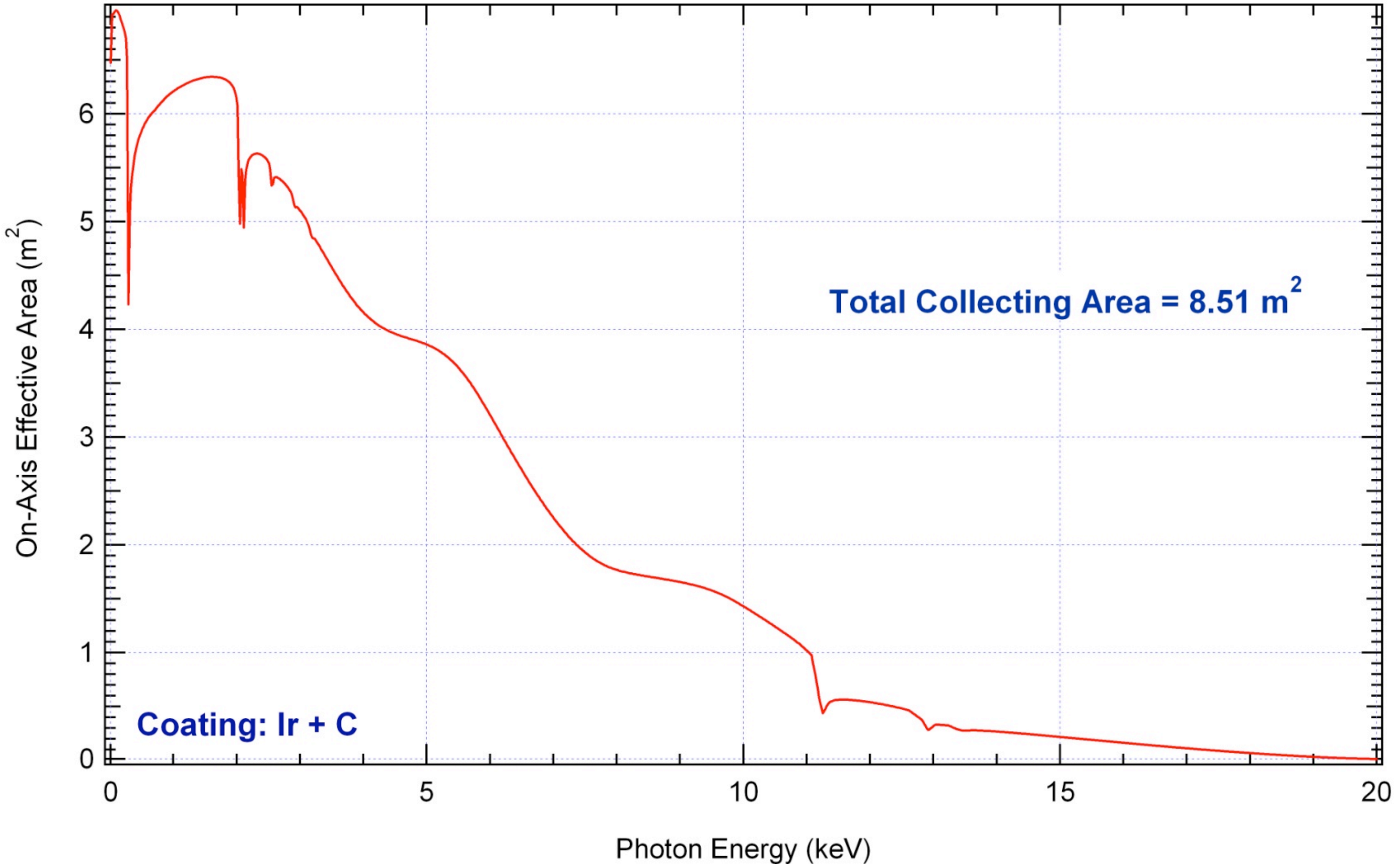
- 3 petal rings, respectively composed by 12 -24 - 36 petals, arranged on the supporting structure;
- Wolter 1 with focal length 35m; Parabola and hyperbola are 0.6m long (0.3+0.3); 2 mm x 0.15 mm ribs every ~75 mm;
- The total number of mirror shells is 403 made of slumped glass with constant thickness (0.15 mm);

Petal Ring #	Rmin [mm]	Rmax [mm]	Mirror Shells number
1	610	988	192
2	1130	1508	123
3	1660	2027	88

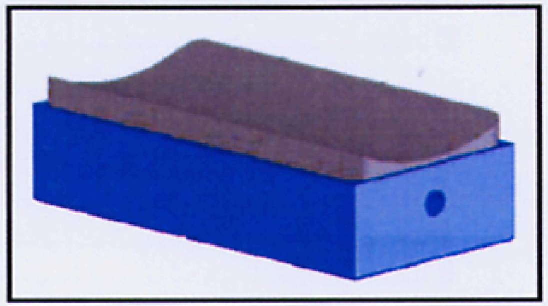


Weight including CFRP Structure ~ 2 tons

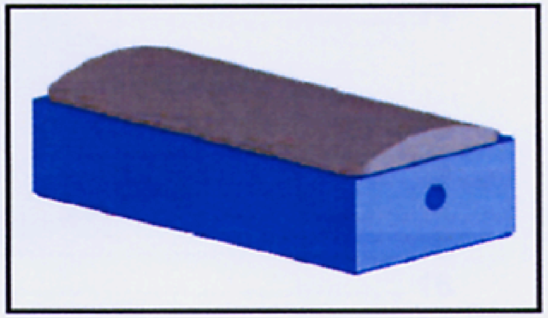
Wolter I design effective area



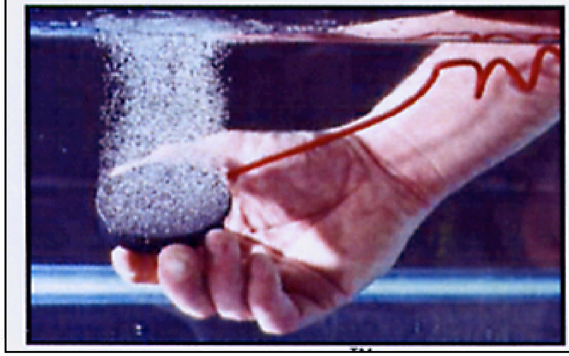
Cold slumping glass approach



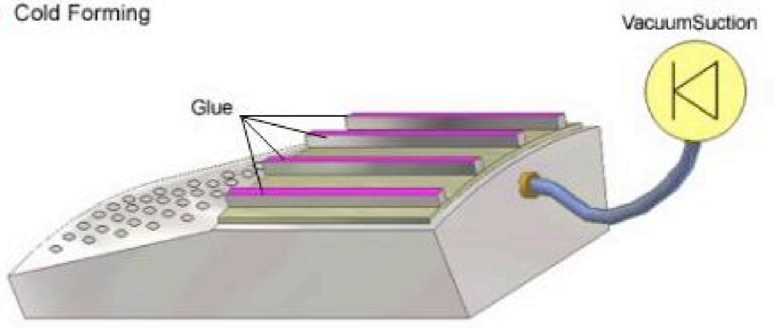
Concave Radial Air Bearing – 'W' Configuration



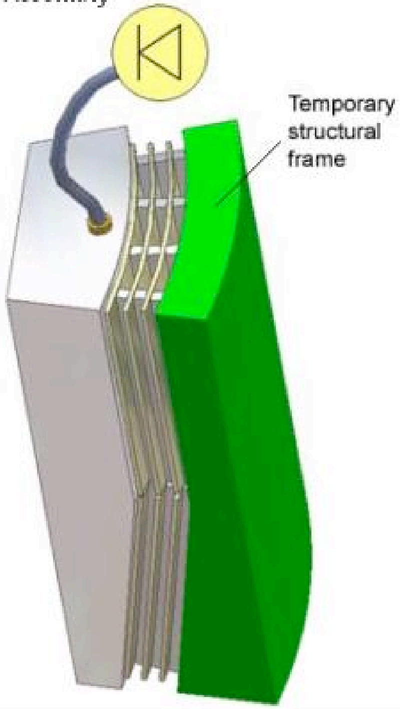
Convex Radial Air Bearing – 'W' Configuration



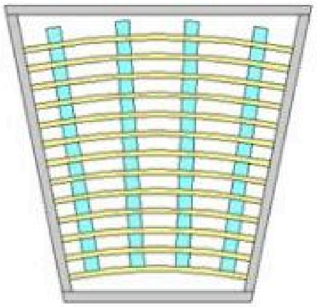
4 Cold Forming



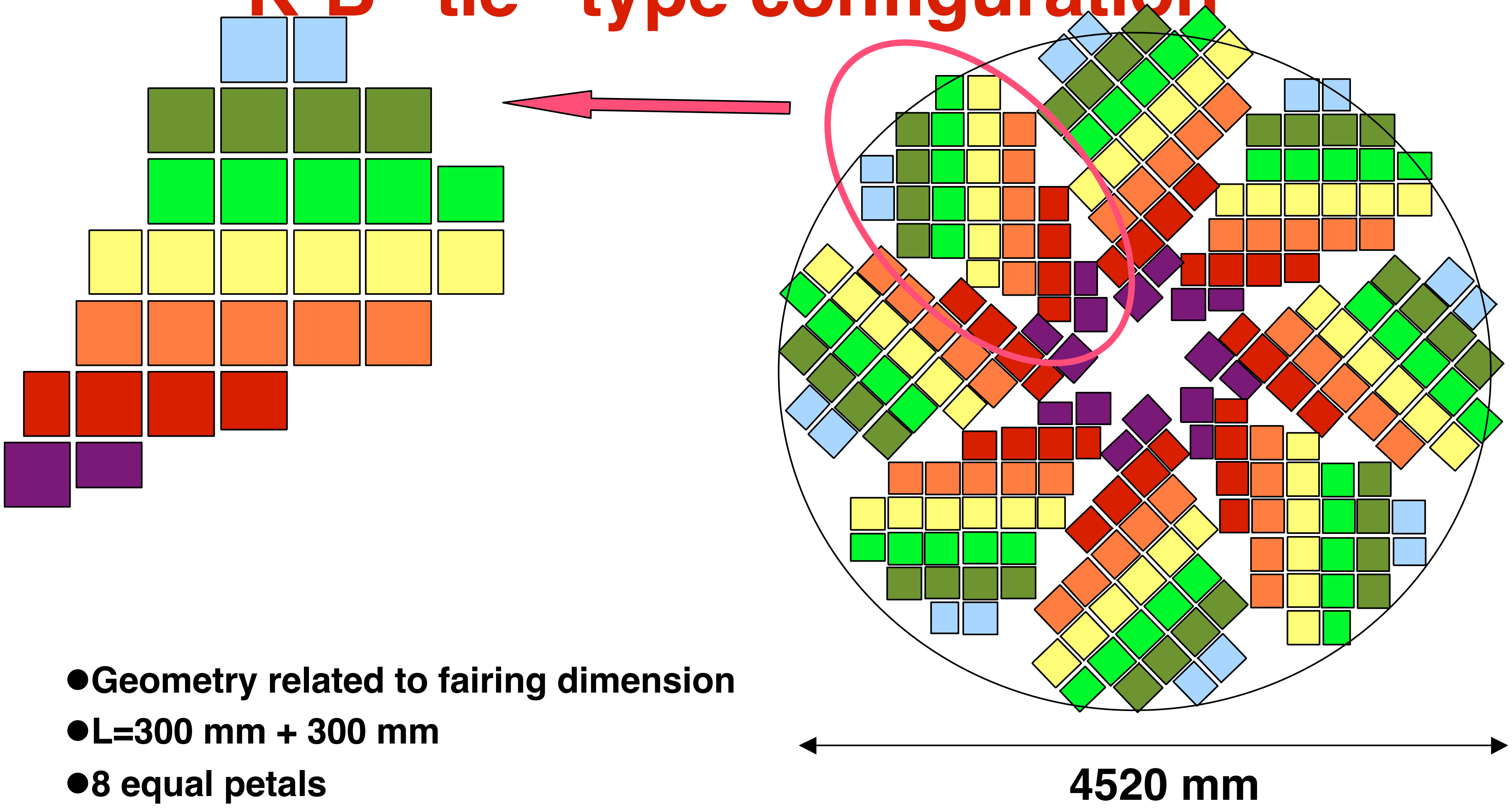
5 Assembly



6 Petal

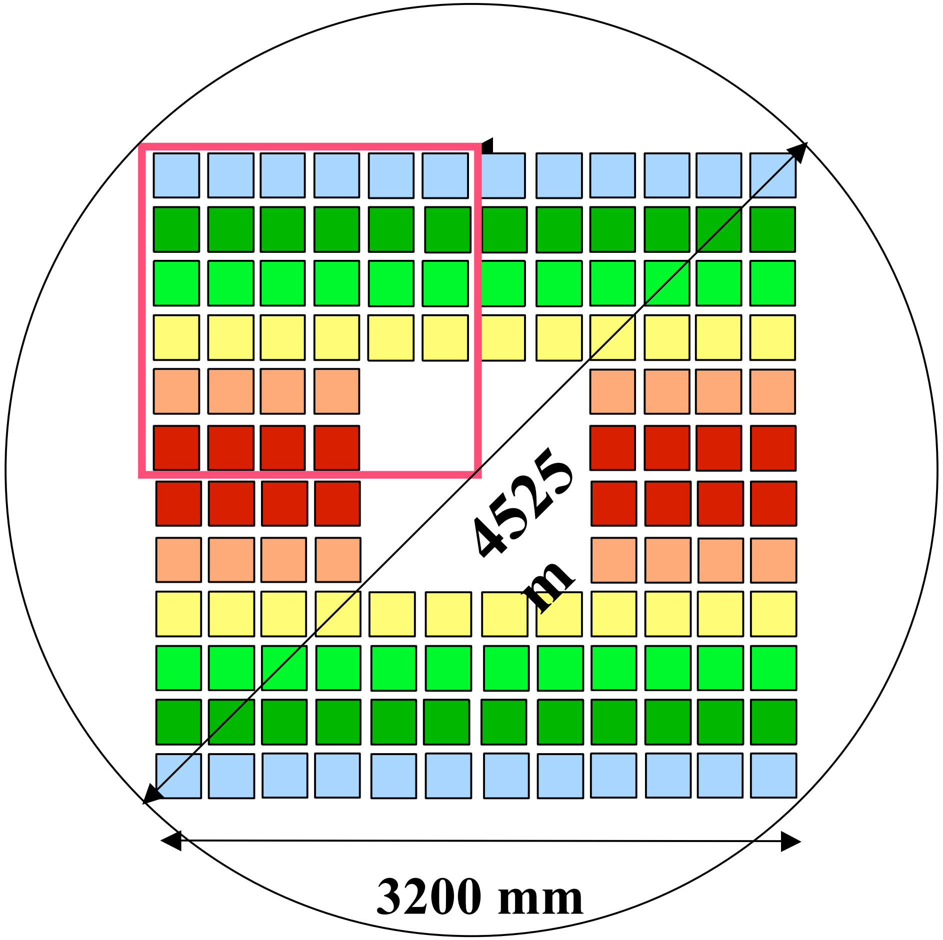


K-B "tie" type configuration



- Geometry related to fairing dimension
- L=300 mm + 300 mm
- 8 equal petals
- 7 sets of equal blocks for each direction (x, y)_
- F=35 m: N1=247 N2=243 _=0.0228 rad
- F=25 m: N1=180 N2=176 _=0.0365 rad
- F=20 m: N1=146 N2=141 _=0.0455 rad

K-B “chocolate” type configuration



- Possibility to use vacant space
- 4 equal modules
- 6 sets of equal blocks for each direction
- F=35 m
  - N1=260 N2=258
  - _=0,023 rad
- F=25 m
  - N1=190 N2=185
  - _=0,032 rad
- F=20 m
  - N1=151 N2=153
  - _=0,04 rad

*LAMAR telescope (1988)_*

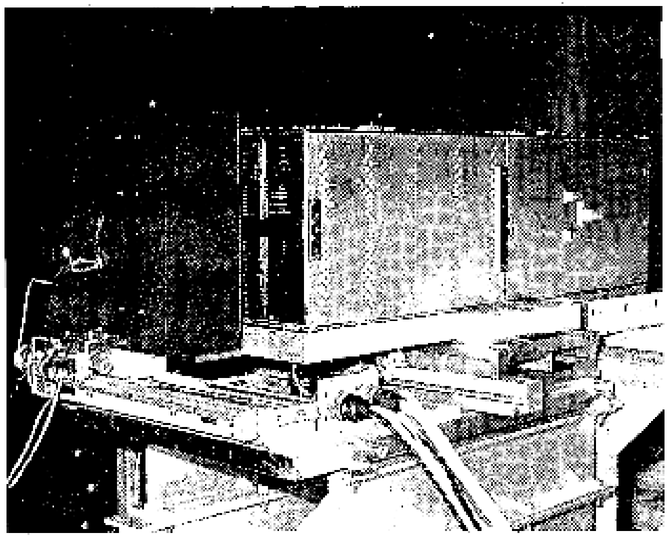


Fig. 2. View of the complete mirror (front and rear modules) in a vacuum chamber at the MSFC X-Ray Calibration Facility. A 2.64-cm slit (which is not opened to its full height) defines a fixed direction for the x-ray beam.

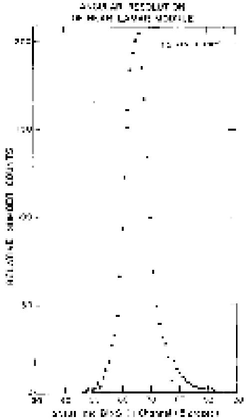


Fig. 3. Angular resolution function of the rear section of the mirror at 1.5 keV as measured with the HRI detector. This is the 1-D image projected along a horizontal axis.

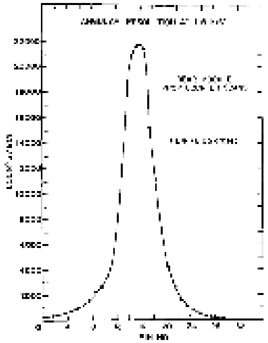


Fig. 4. The 1.5-keV 1-D angular resolution (projected along a horizontal axis) of the rear section measured with a scanning small aperture proportional counter.

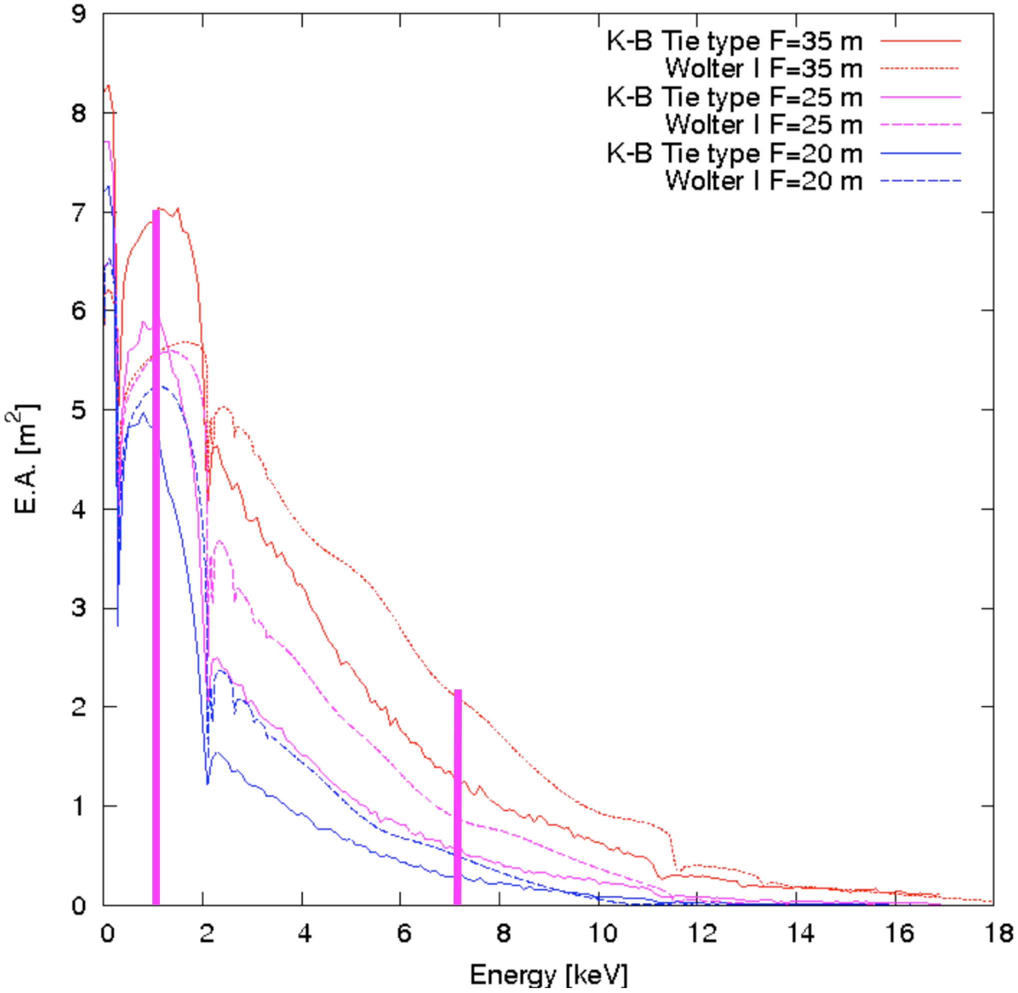
1450 APPLIED OPTICS / Vol. 27, No. 8 / 15 April 1988

- D. Fabricant, L.M. Cohen, P. Gorensrein
- Mechanical cold shaping technology

- Mirror mudule 20 X 30 cm
- F = 3,4 m
- Effective Area at 1,49 keV 82,2 cm^2
- Effective Area at 8,01 keV 9,2 cm^2
- HEW 30 arcsec at 1,5 keV

Effective area

- Effective area: K-B vs Wolter I for diffent focal lenght
- Pt+C coating



Hard X-ray Focusing by mosaic crystals

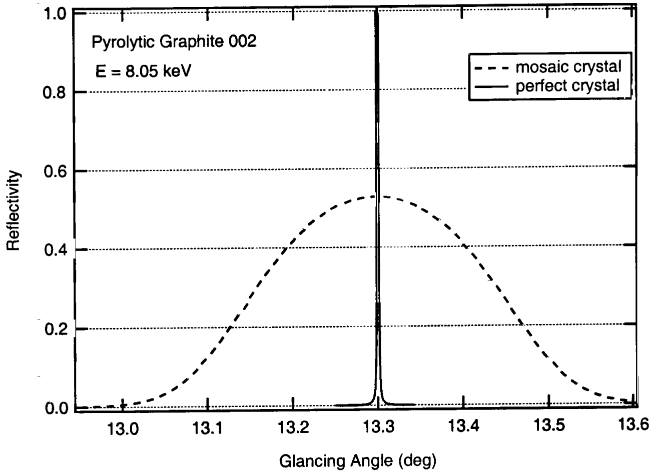
- Bragg diffraction from a crystal lattice ➔ reflectivity peaks at:

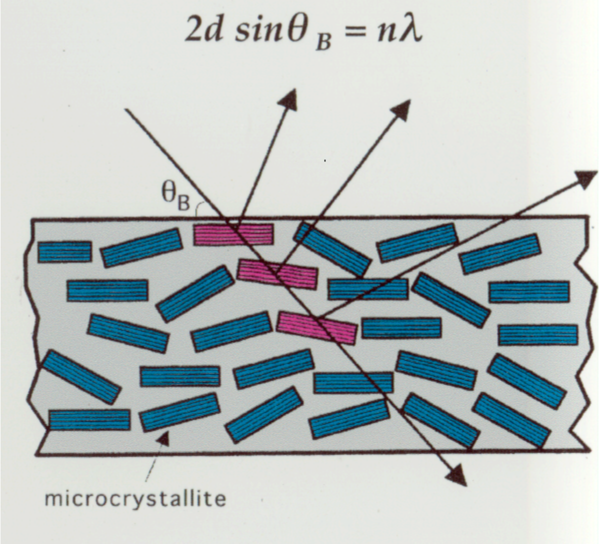
$$2\ d\ \sin\theta = n\lambda$$

d typical value of a few Angstroms

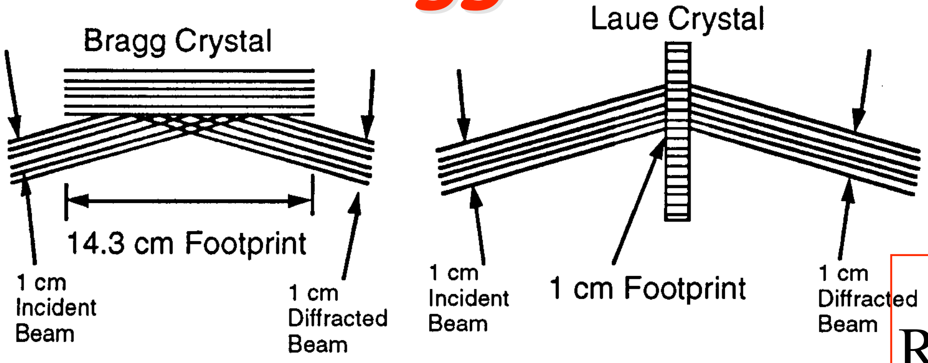
- mosaic crystals: at microscopic level a structure of microcrystals almost-parallel to the external crystal surface. The distribution of the crystallites normals is described by a Gaussian law

- each crystallite reflects in an independent way (without any interferometric coupling with the beams reflected from the other crystallites) ➔ the integrated reflectivity results to be much larger (>100) than for a perfect crystal case





“Bragg” & “Laue” Configurations



Bragg

$$\mathrm{Re}f_{\mathrm{int}\,eg} \propto \left(\frac{F}{V}\right)^2 \lambda^3 \frac{1}{\mu} \times FWHM_{Gauss}$$

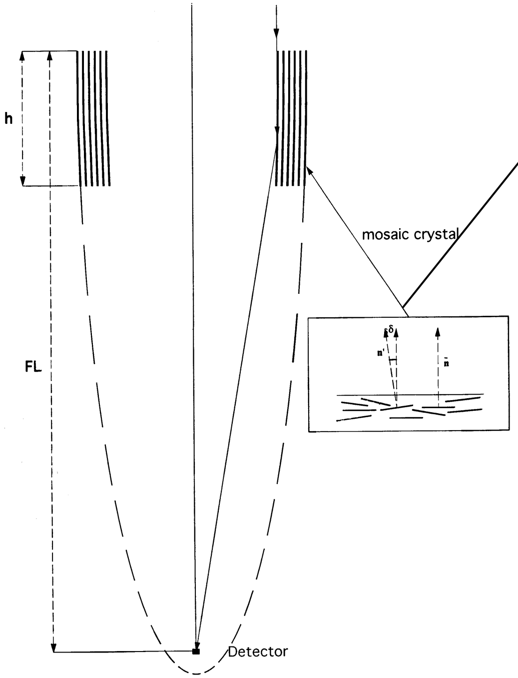
Laue

$$\mathrm{Re}f_{\mathrm{int}\,eg} \propto \left(\frac{F}{V}\right)^2 \lambda^3 \frac{T}{\sin\theta} \times FWHM_{Gauss} \times e^{-\mu\frac{T}{\sin\theta}}$$

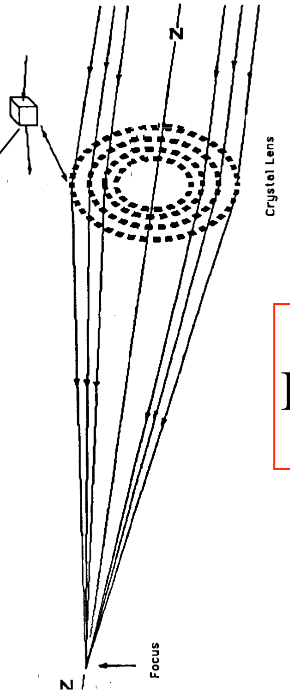
F = Structure Factor

V = Volume of the lattice element

μ = lin. absorb. coeff



Bragg

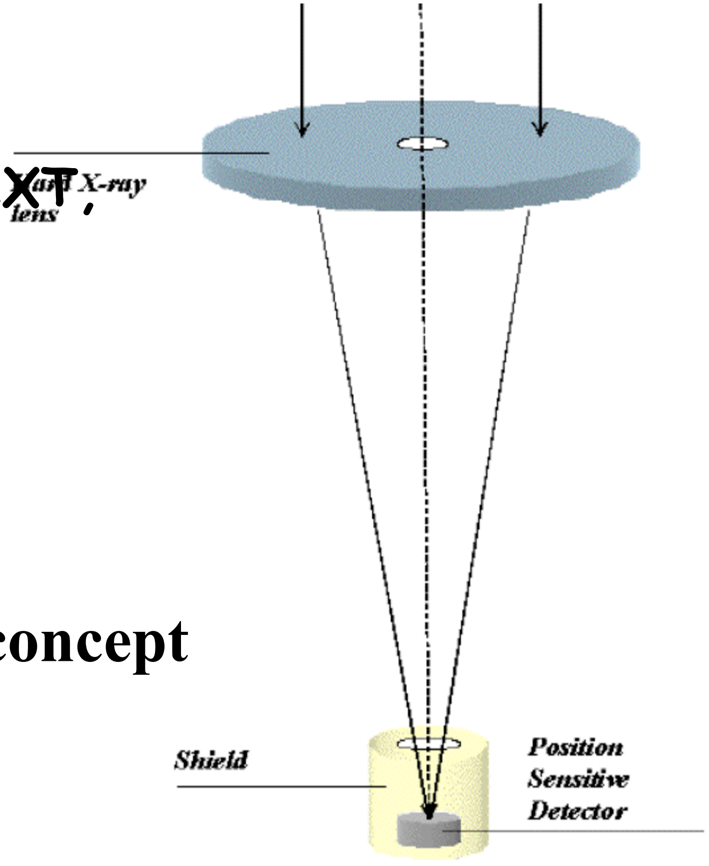


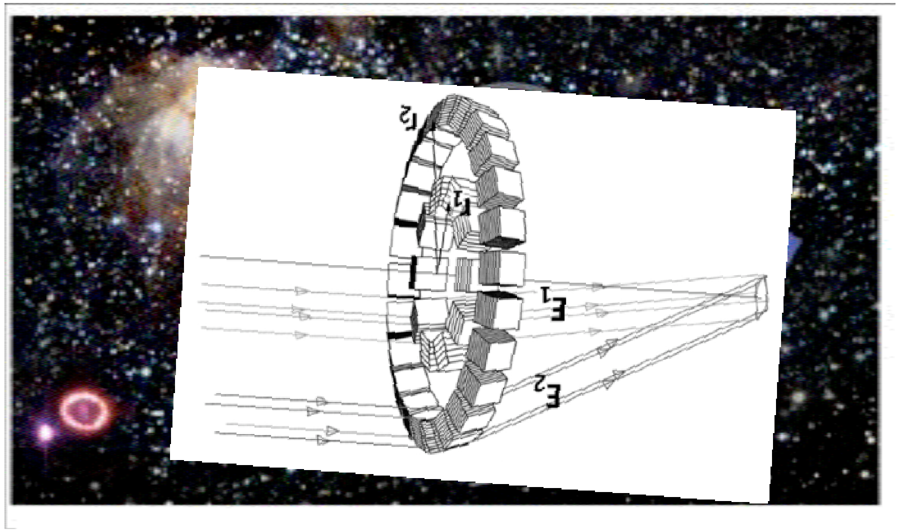
Laue

Why crystal diffraction for high energy telescopes

- Focusing optics in the hard X-/soft gamma-ray band is crucial for a significant leap

- The hard X-ray band (E<80 keV) can be covered with multilayer mirrors (NuStar, NeXT, Simbol-X) .
- The higher energy band (>80 keV) can be efficiently covered with Laue lenses.

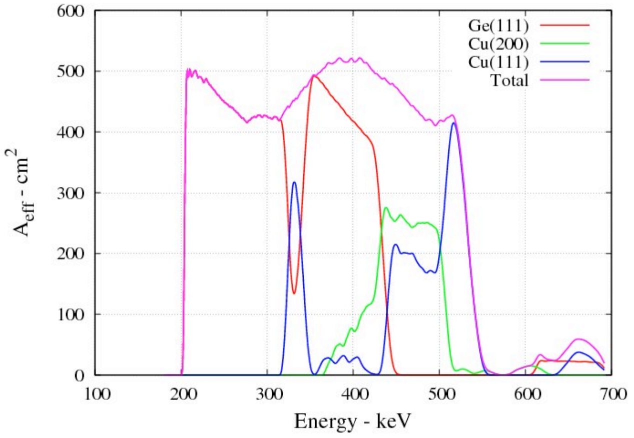


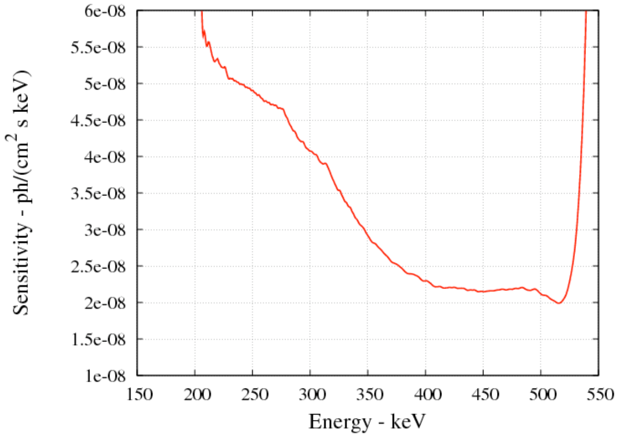


GRI concept

Example of configuration suitable for GRI low energy lens (200-550 keV)

Parameter	
Focal length (m)	100
Nominal passband (keV)	200–530
Inner radius (cm)	88
Outer radius (cm)	185
Crystal material	Ge[111], Cu[111], Cu[200]
Mosaic spread (arcmin)	0.5
Tile cross section (mm^2)	15 × 15
Tile thickness (mm)	optimized
Number of crystal rings	61
No. of tiles	17661 (Ge[111]), 3254 (Cu[200]), 3386 (Cu[111])
Crystal weight (kg)	155
Effective area (cm^2) @ 200 keV	500
Effective area (cm^2) @ 400 keV	530
Effective area (cm^2) @ 511 keV	430
Half power radius(mm)	12



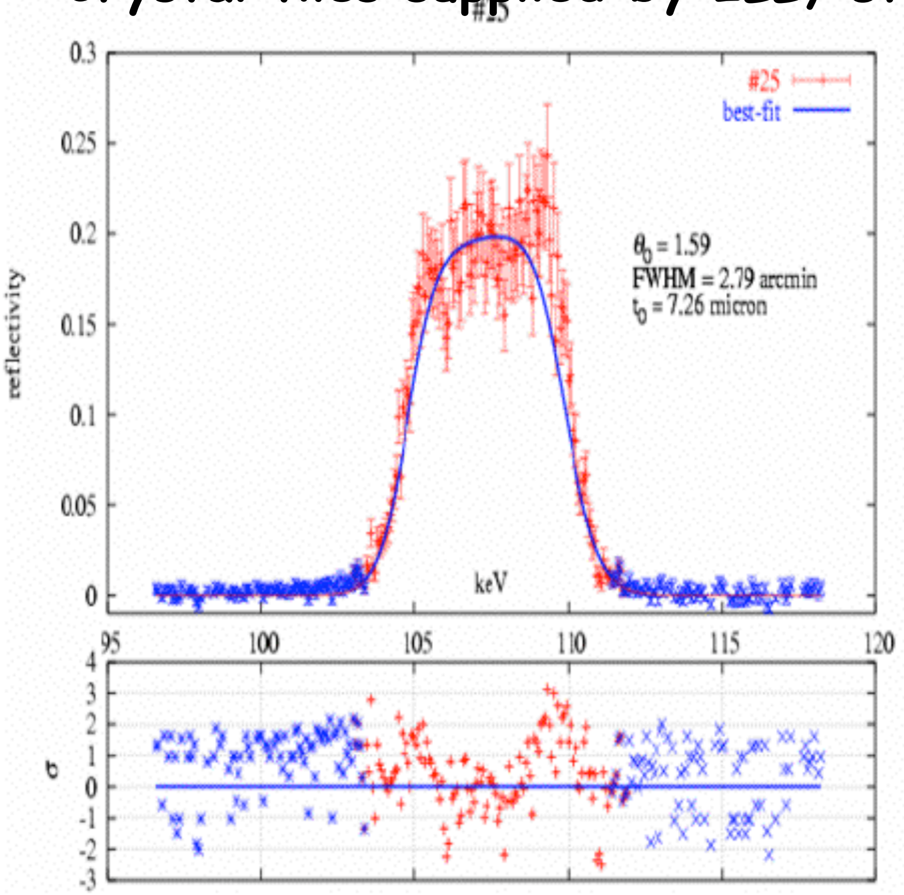


3 sigma sensitivity, _T= 10^6 s

- Crystal material: Cu(111)

- Available mosaic spread: 3-4 arcmin(now also available with lower spread);

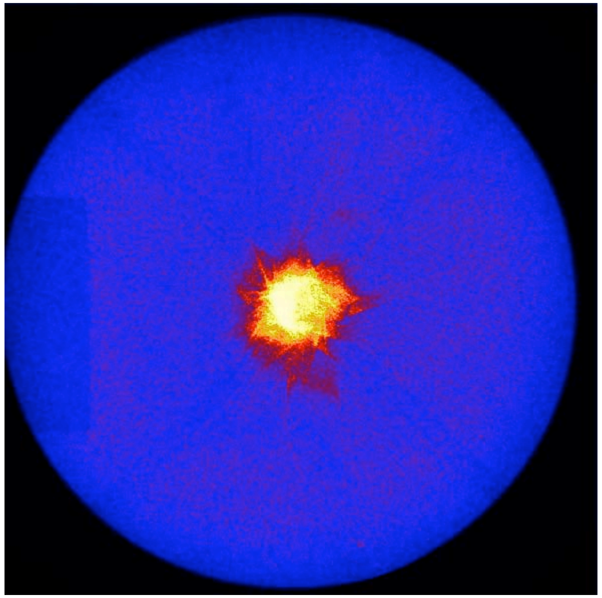
- Crystal tiles supplied by ILL, Grenoble.

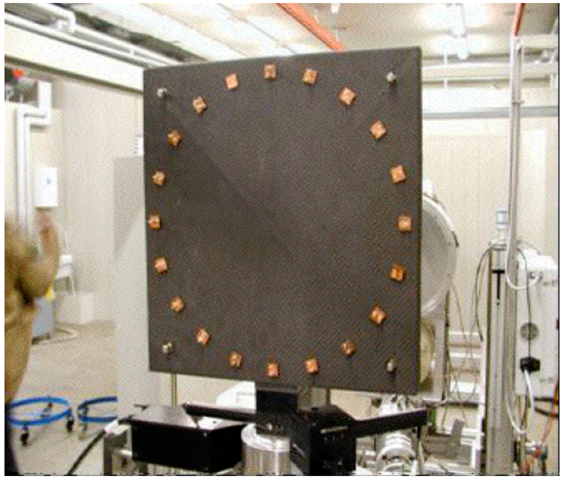


Credits;: F. Frontera – University of Ferrara

First lens prototype & light

- Tile size: 15x15x2 mm3
- Mosaic spread: 3-4 arcmin
- Lens support: carbon fiber
- Focal length: 6 m





HEW of 15 arcmin at 200 keV

Credits;: F. Frontera – University of Ferrara

Chrenkov Atmospheric Telescopes

- Atmospheric Cherenkov Telescopes permit to perform observations of astronomical objects emitting in gamma-rays with energies from 50 GeV up to several TeV.

- The showers extend over many kilometers in length and few tens to hundreds of meters in width and have their maximum located at around 8-12 km altitude. Electrons and positrons in the shower core, moves with ultra-relativistic speed and emits Cherenkov light.

- This radiation is mainly concentrated in the near UV and optical band and can therefore pass mostly unattenuated to ground and detected by appropriate instruments.

- Light flashes from showers have a very short duration, typically 2-3 ns in case of a g shower.

Chrenkov Atmo

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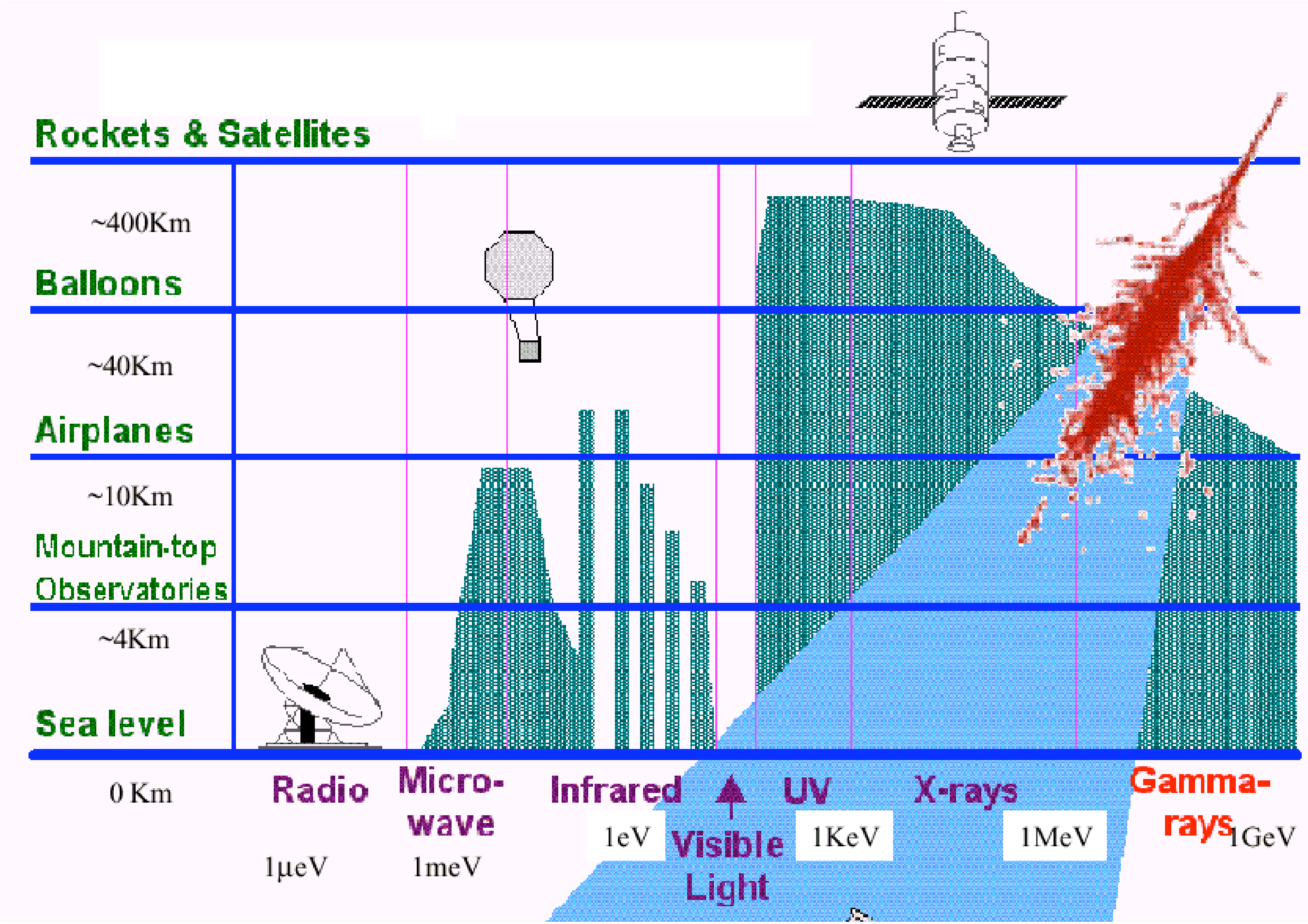
Rockets & Satellites
~400Km
Balloons
~40Km
Airplanes
~10Km
Mountain-top Observatories
~4Km
Sea level
0 Km
Radio
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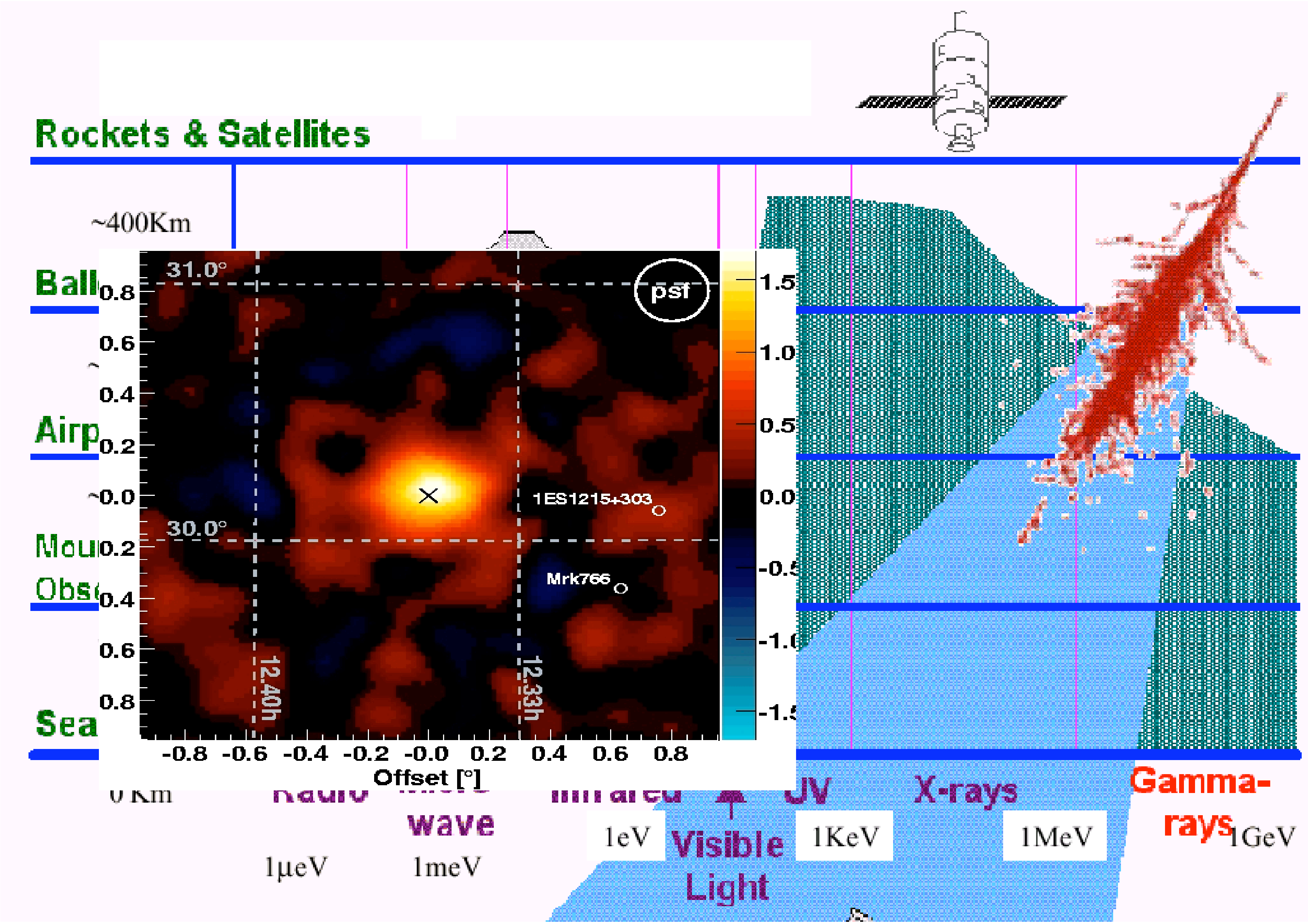
Infrared
Visible Light
UV
X-rays
Gamma-rays
1μeV
1meV
1eV
1KeV
1MeV
1GeV


Rockets & Satellites
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Gamma-
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1KeV
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1GeV
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30.0°
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12.33h
1ES1215+303
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0.4
0.2
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-0.8 -0.6 -0.4 -0.2 -0.0 0.2 0.4 0.6 0.8
Offset [°]
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5

The MAGIC Telescope Configuration

- Davies-Cotton reflector, which is the most commonly used configuration for TeV telescopes, is used also for Magic

- Originally, the Davies-Cotton telescope was developed as a solar concentrator and as such, it does not satisfy the rigorous requirements of astronomy in the visible wavelength range

- A large reflector composed of many small, identical, spherical facets is relatively inexpensive to build. The alignment of the optical system is easy.

- A Davies-Cotton telescope consists of a primary mirror with parabolic approximated configuration, formed by several coronas of spherical mirrors each at different radii; the half of central radius coincides with the Focal Length of the primary

- For Magic the focal length is 34 m and the diameter is 17 m; the primary is formed by 240 panels of ~ 1 m^2 each

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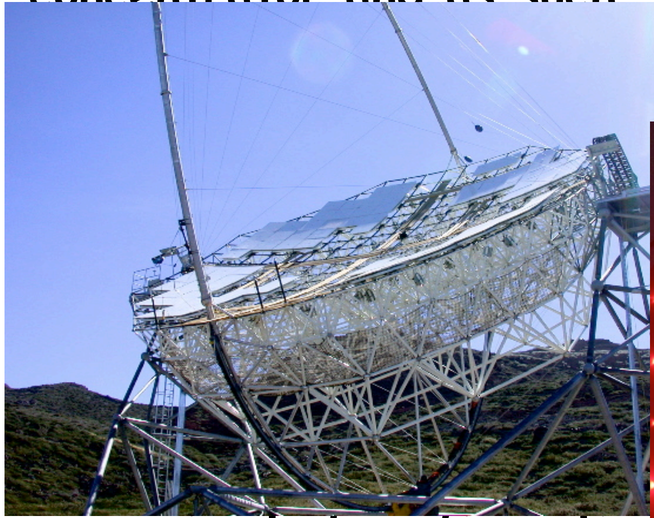
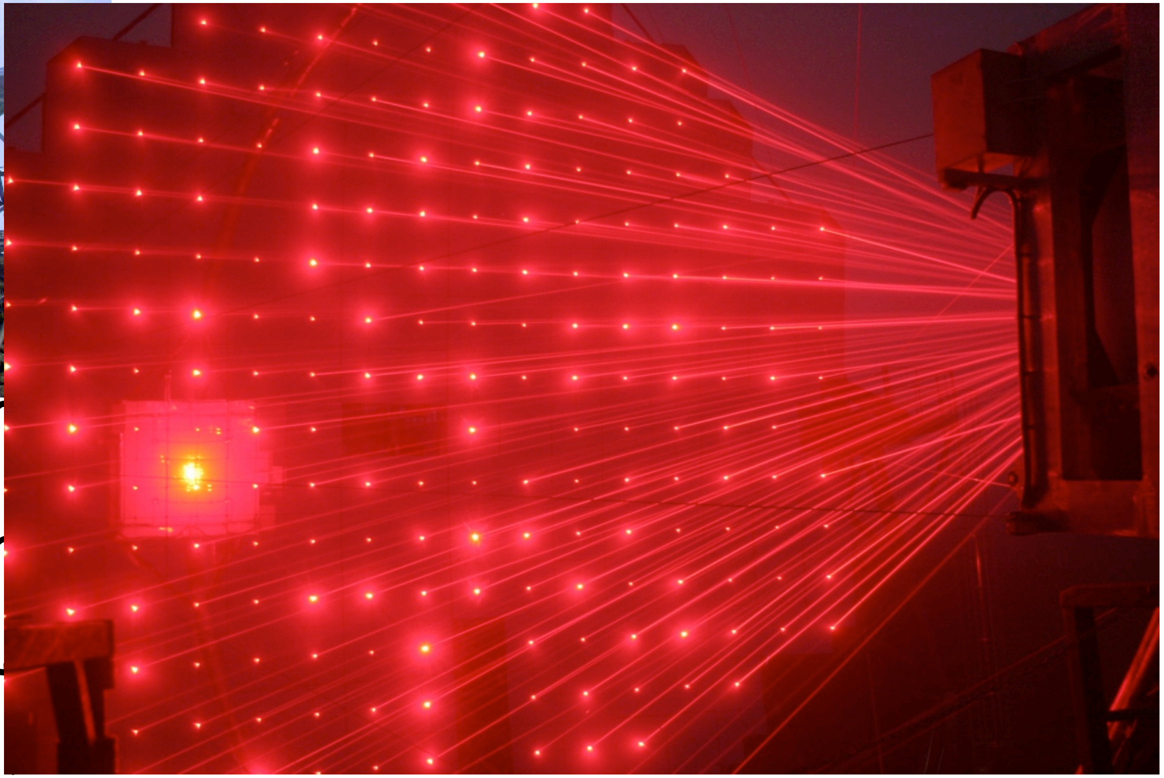




approximated configuration

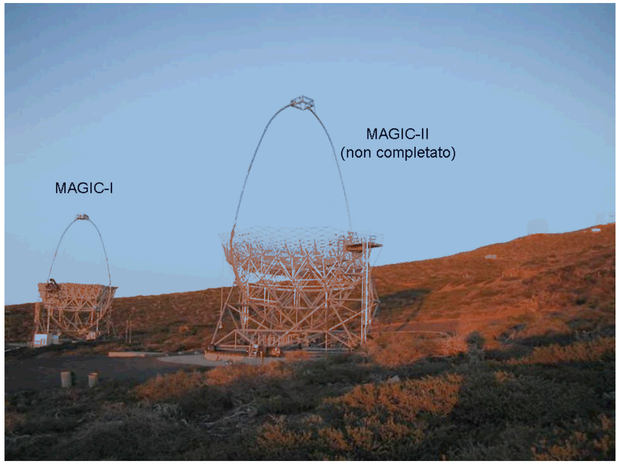
mirrors each at different

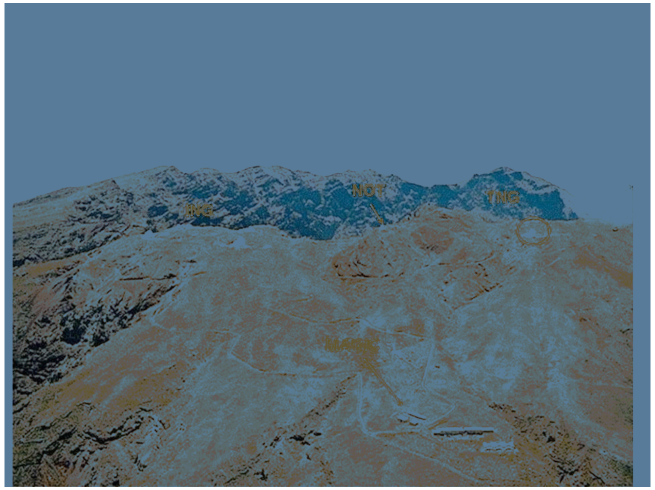
the Focal Length of the pr

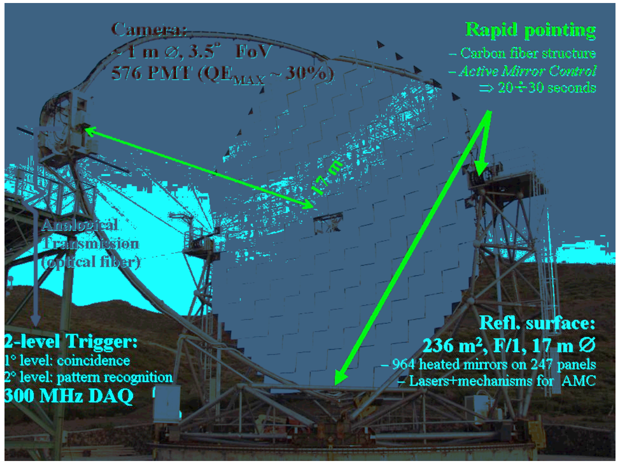
- For Magic the focal leng

primary is formed by 240

MAGIC Telescope System







Geometry:	**Parabolic**
Diameter:	**17m**
Collecting Area:	**240 m^2**
F-number (f/D):	**1**
FOV:	**3.8 deg**
Slew time:	**20 s**
Angular resolution:	**< 3 arcmin**
Energy Resolution:	**30%**
Operating Band:	**50 GeV – 50 TeV**
Sensitivity (@1 TeV):	**30 mCrab (1 single telescope)** **20mCrab (2 telescopes)**
Sensitivity @ 50 GeV:	**0.1 Crab (1 single telescope)** **0.05 Crab (2 telescopes)**

Glass Mirror Manufacturing

- Derived from a similar technique proposed by for the manufacturing of X-Ray optics (XEUS)

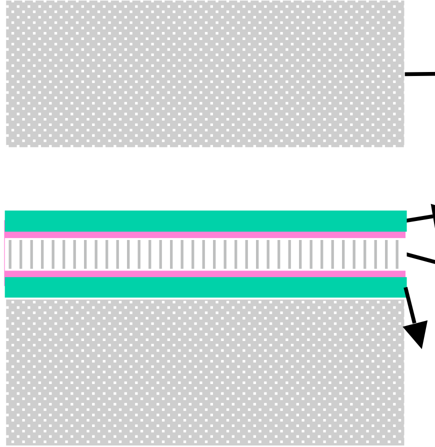
- A thin glass sheet (1-2 mm) is elastically deformed so as to retain the shape imparted by a master with convex profile. If the radius of curvature is large, the sheet can be pressed against the master using vacuum suction

- On the deformed glass sheet (under vacuum force) one glues a honeycomb structure that provides the needed rigidity

- Then a second glass sheet is glued on the top in order to obtain a sandwich

- After releasing the vacuum, on the concave side one deposits a reflecting coating (Aluminum) and a thin protective coating (Quartz)

Glass Panel Manufacturing flow

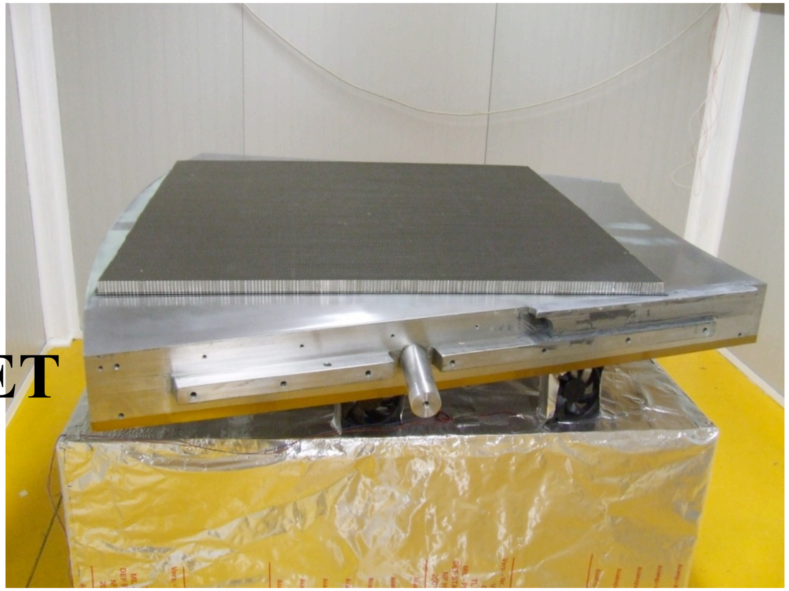


MASTER

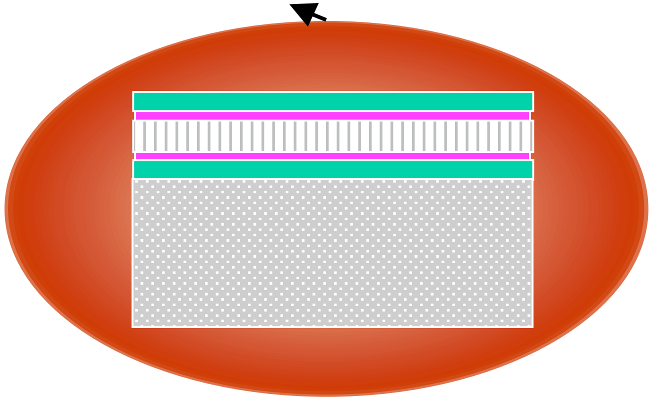
BACKING SHEET

HONEYCOMB

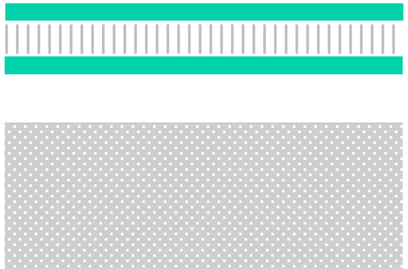
REFLECTING SHEET

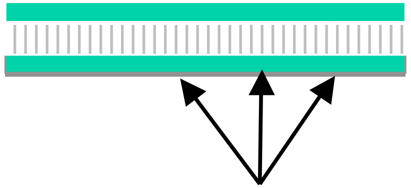


CURING CHAMBER



RELEASE

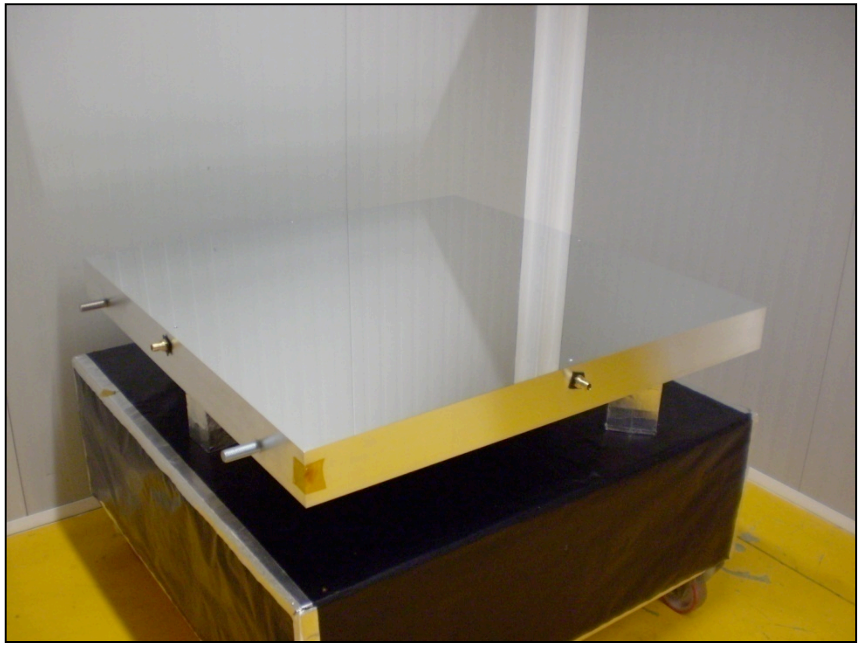




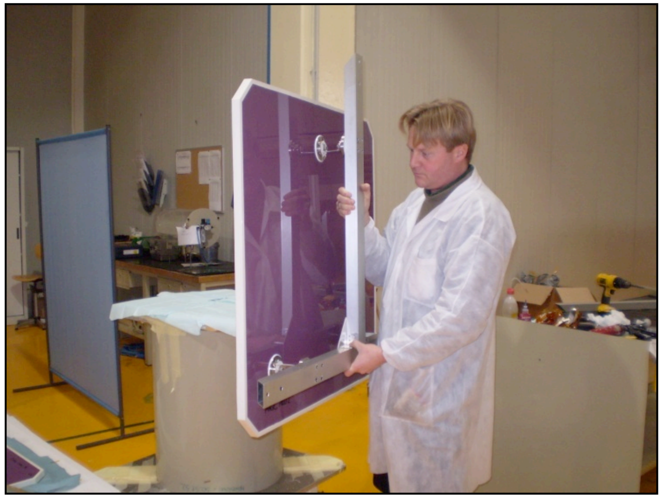
PVD COATING

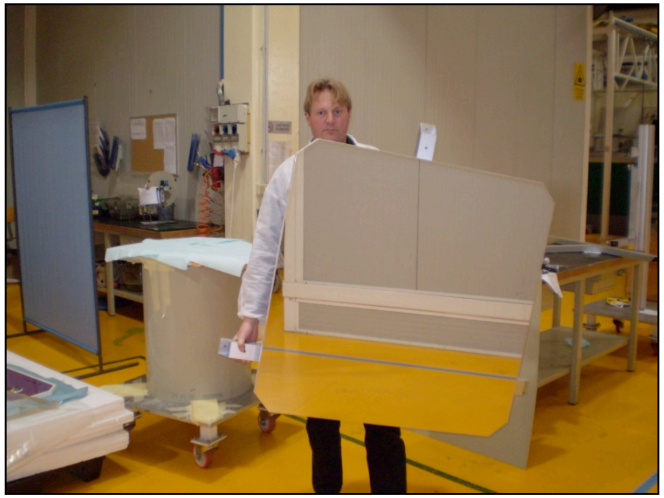
AL + SiO_2

Master and panel in the making



Aluminum master 1040 x 1040 mm





Front and rear of a segment

Size = 985 x 985 mm Weight = 9.5 Kg.

Nominal curvature radius= 35 m

All 240 panels successfully produced, being installed right now!