Riccardo's Legacy to the Wide Field X-ray Missions

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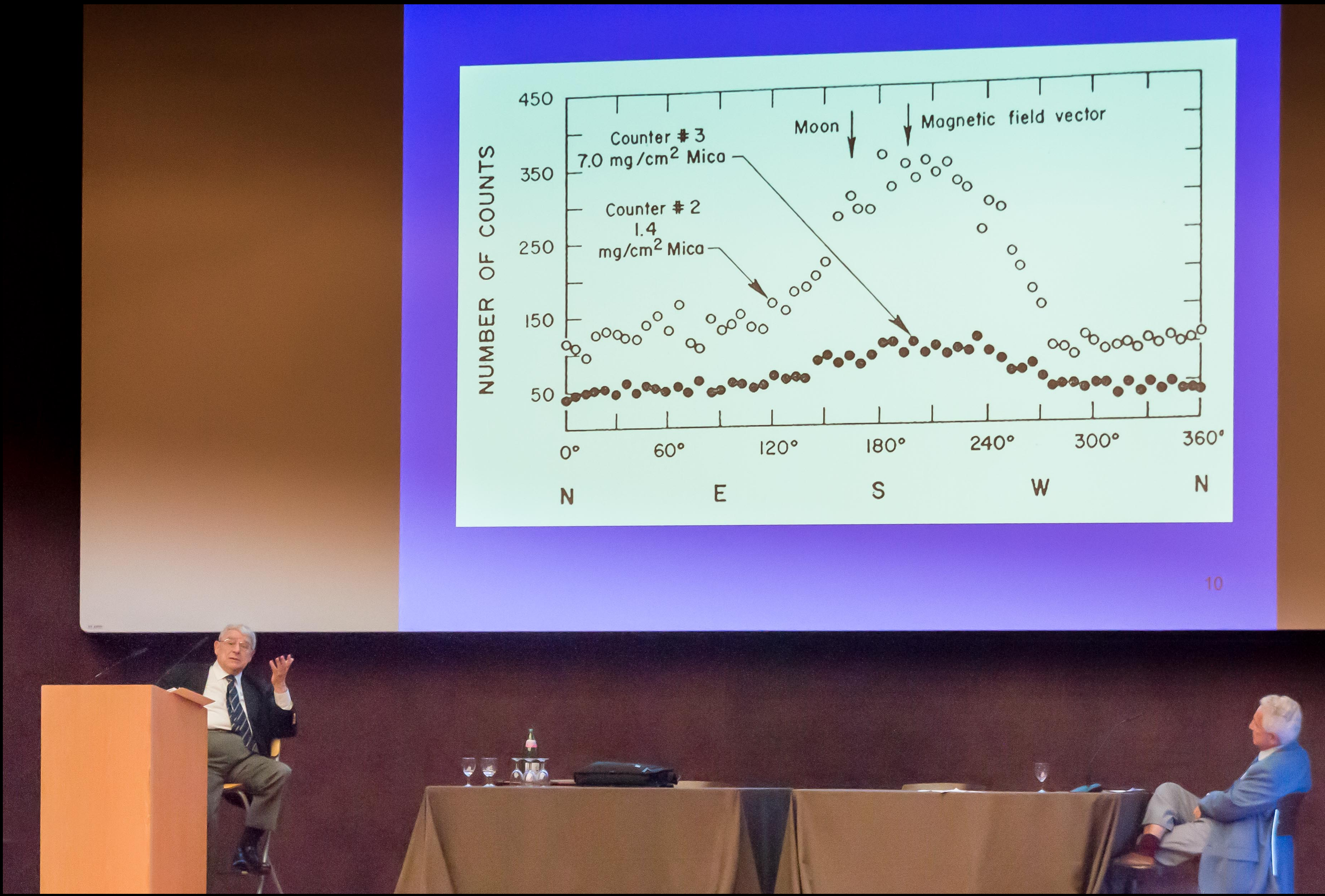


X-ray Astronomy: towards the next 50 years!
Conference in Riccardo's honor, Milano 1- 5 Oct 2012

Memories by...

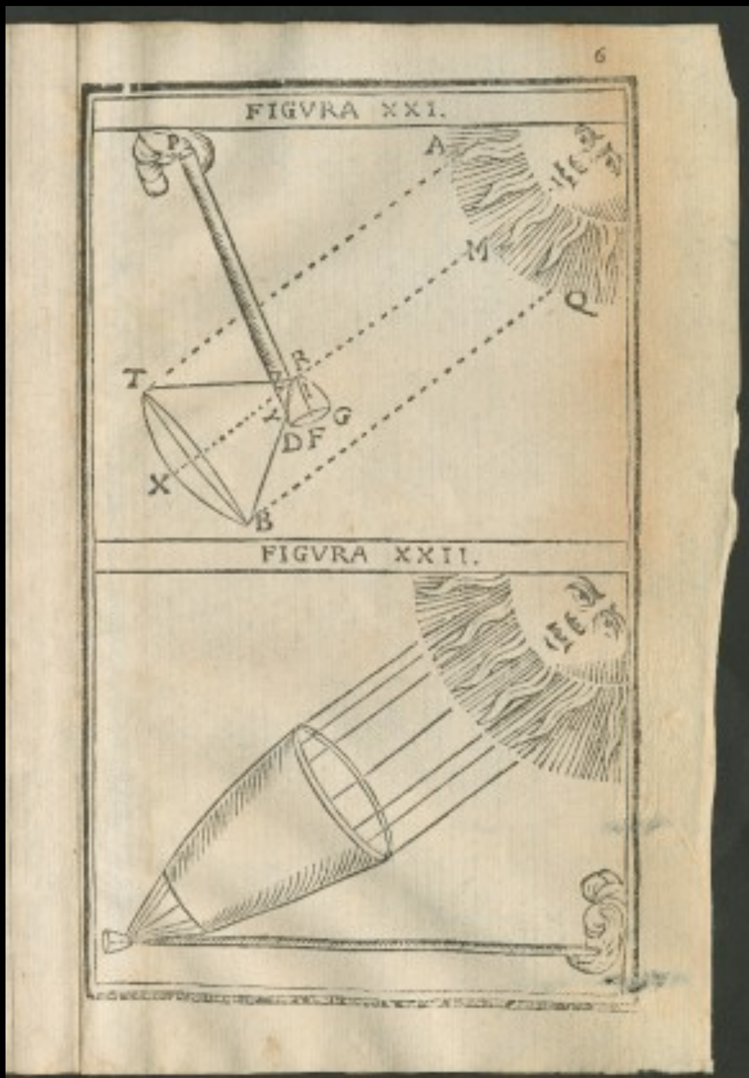
...Anna Wolter

Riccardo was a giant of Astronomy, a great scientist and a great manager. I can't but be honored to have known him. His grand enterprises have already been told and it is not up to me to testify his importance: he not only invented X–ray Astronomy, but also introduced many "best practices" born in the X-ray Astronomy

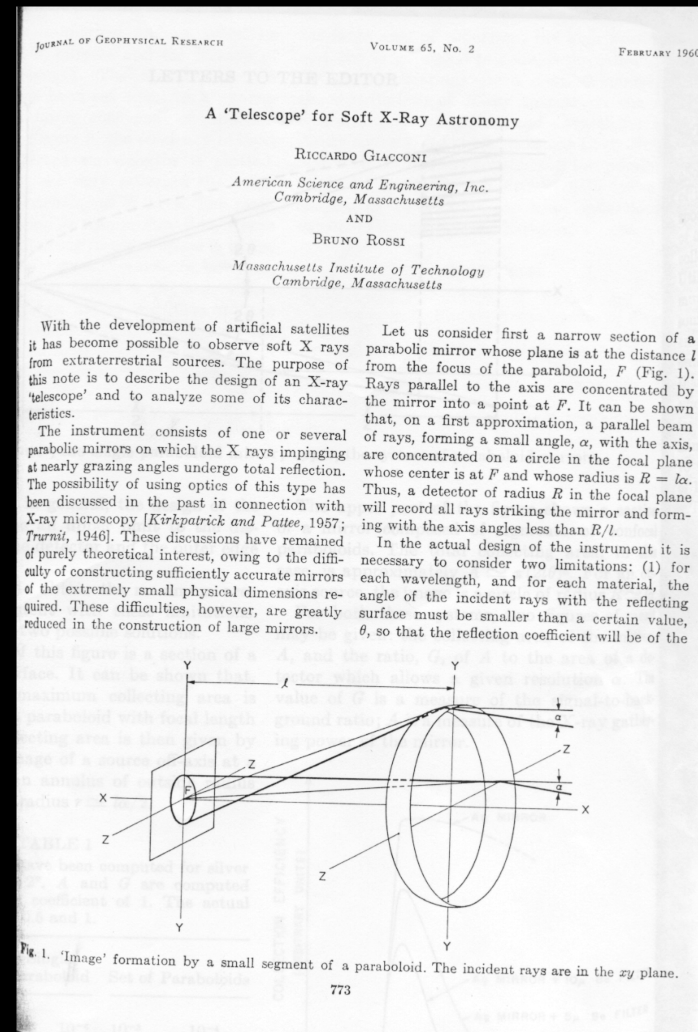
http://edu.inaf.it/index.php/riccardo-giacconi-in-milano/

Anna Wolter, Luigi Stella and contributions by O. Citterio, G. Tagliaferri, A. Renzini. G. Pareschi, G. Trinchieri and the movie of the last interview in Italy with P. Bianucci at the Brera Observatory

First grazing Incidence Mirror …and X-ray astronomical optics concepts!



Bonaventura Cavalieri, 1632



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.

Giacconi & Rossi, 1960

The Attempt to Build a Wide-Field X-Ray Telescope (from "Secrets of the Haory Deep)

"I started thinking whether it might not be possible to dedicate a smaller mission to this one task, and realized that we could make up for the lesser sensitivity of a smaller mirror with wider field optics, which needed only to be invented.

....

I discussed this possibility with STScI staff members Chris Burrows and Richard Burg, and we considered optics systems based on two-reflection grazing incidence, in which the reflecting surfaces could be high-order polynomials rather than conics.

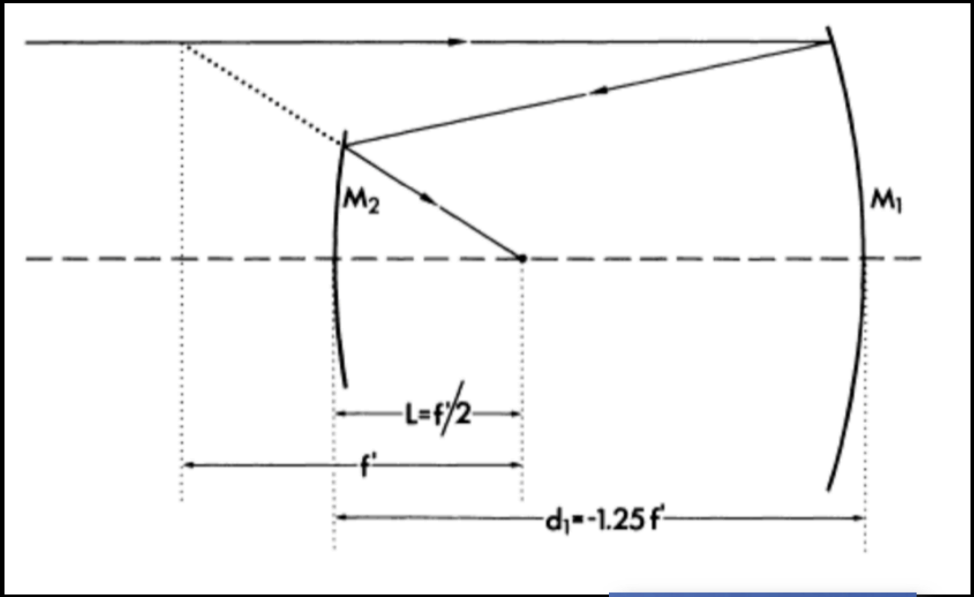
....

Chris was able to obtain solutions that would achieve angular resolutions of 2.5 arcsec over a field of 28 arcmin radius. We submitted these results in April 1990 in a letter to Astrophysical Journal Letters, which was not published until June 1992.

Schwarzschild & Aplanatic Telescopes

1905: Karl Schwarzschild solved the Seidel 's equations for **spherical** aberration and **coma** finding a relation between parameters capable to make a telescope **aplanatic**. (Couder 1926 ➔ also correction of **astigmatism** with corved focal plane)

"For any geometry, 2 aspheric mirrors allow the correction of SI and SII to give an aplanatic telescope"



Schwarzschild telescope

KS: f/3.0
b_{S1}= -13.5 (Hyperbola)
b_{S2}= 1.963 (Spheroid)
FoV:2.8 deg
RMS_{edge}~12''

Technological obstacle: Aspherical Optics manufacturing

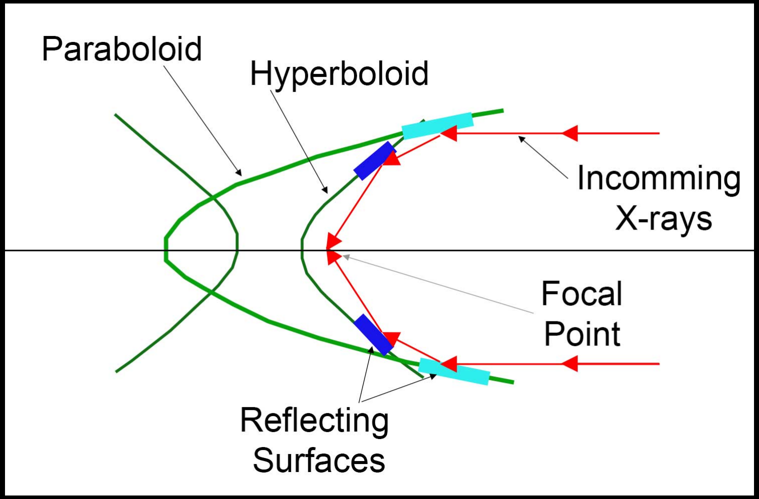
4 m SC ASTRI Cherenkov telescope, Mount Etna, Sicily

Schwarzschild theory first practical application: X-ray telescopes

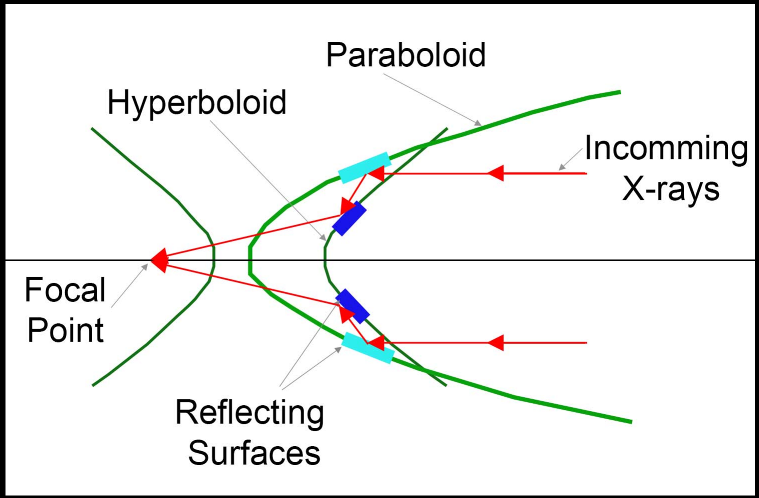
1952a: **Wolter** solved the Abbe condition for grazing incidence angles. Under the assumption that F_P>>L. *Coma is small (but it still suffers from field curvature and astigmatism)*

1952b: H. Wolter solved Schwarzschild condition for grazing incidence angles. **Wolter-Schwarzschild** design → Coma is eliminated (but not *field curvature* and *astigmatism)*

- Perfect on-axis imagery
- Focal length shortening



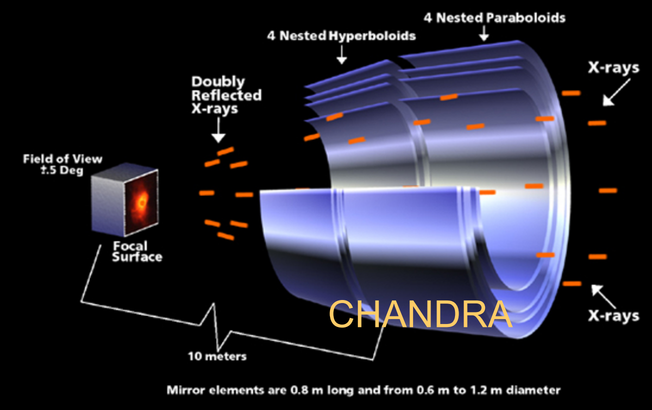
Wolter I:Typical incidence angle < 1 deg
Used for X-rays (E>1 keV) imaging



Wolter II
Typical incidence angle < 10 deg
Used for XUV and UV imaging

X-ray telescopes: Polynomial

1992: Burrow, Burgs, Giacconi proposed to modify the X-ray telescope (CHANDRA) design with Schwarzschild-like **polynomial solution** togeher with the use of **small mirror/focal lengths ratio**



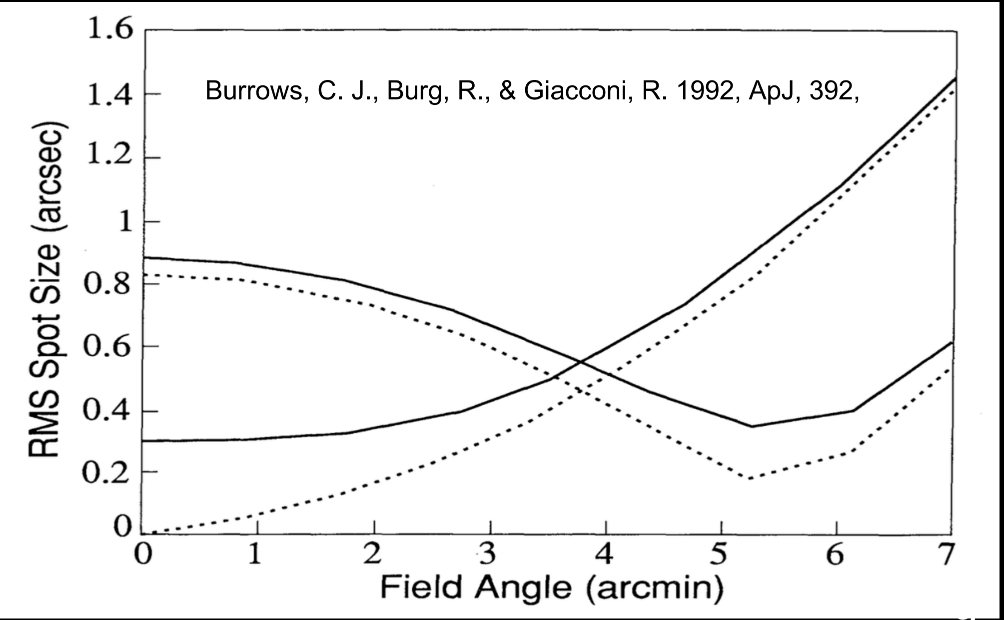
- Defines the surface profile allowing higher order polynomials admitted
- Optimization of the imagery quality is on the FoV

$$M = \sqrt{\frac{\int \theta\sigma^2 \, d\theta}{\int \theta\sigma \, d\theta}}$$

Solving Seidel conditions On axis

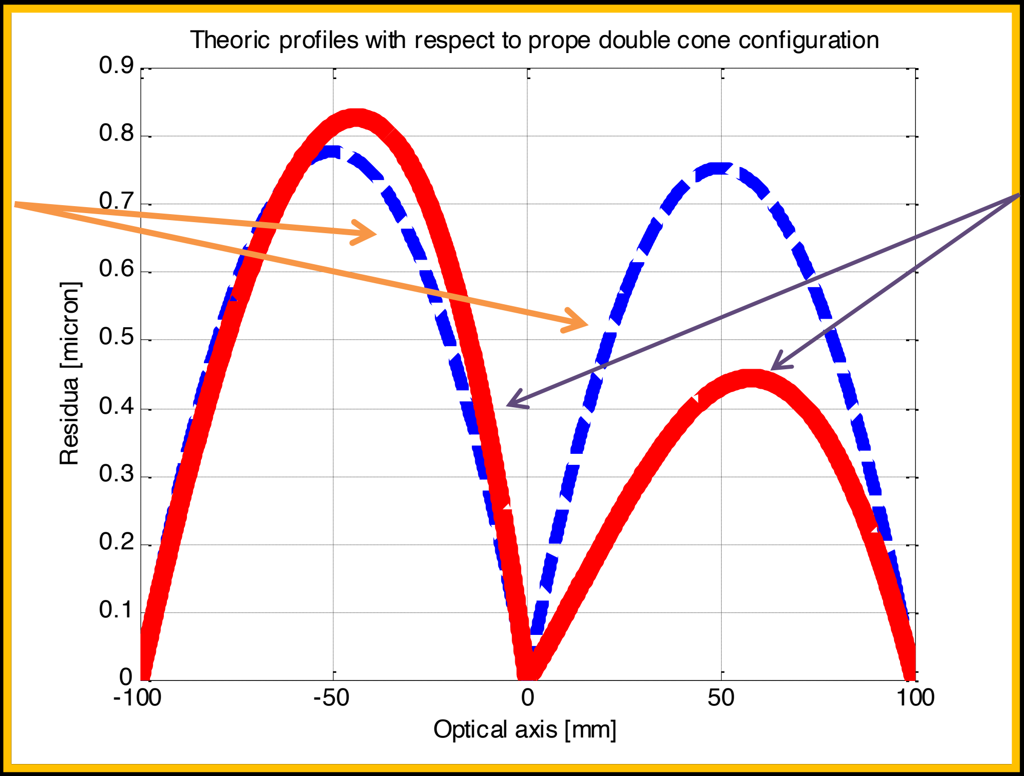
↓

Ray-tracing optimization On the FoV



Polynomial profiles

Mirrors are usually built in the WOLTER-I which provides, in principle, perfect on-axis images
But rapid degradation with increasing off-axis angles



Optimization with POLYNOMIAL profiles increase the angular resolution at large off-axis positions but degrading the on-axis performances

See Burrows, Burgh and Giacconi (1992), Conconi et al. (2010)

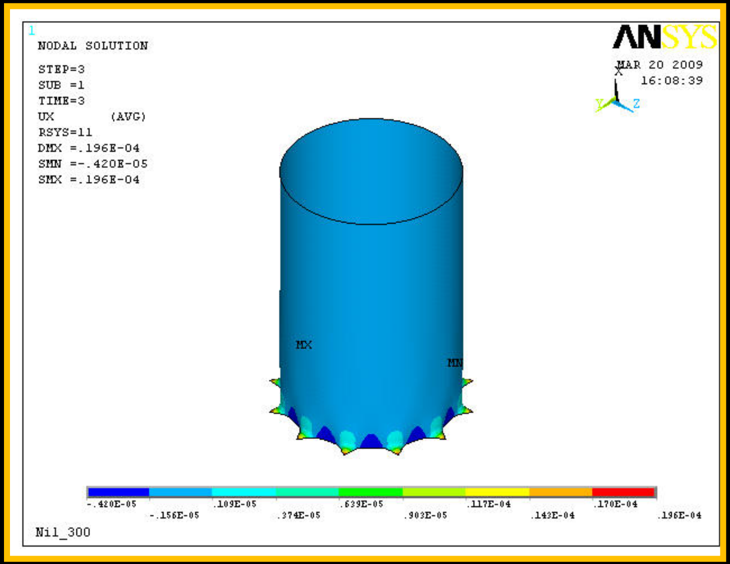
Small aspect ratio optics

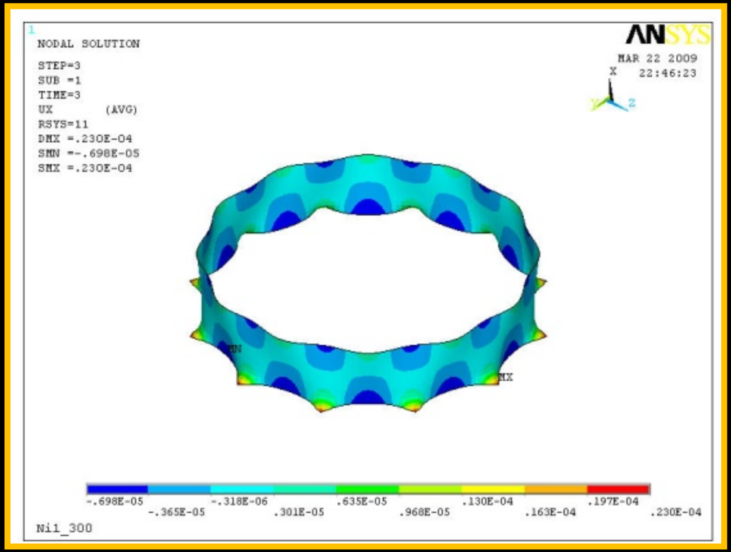
➔Increased difficulty in reaching very good angular resolution

- mechanical behavior closer to a "belt-like" configuration rather than a "tube-like"

- border effect errors with a much higher weight in determining the PSF

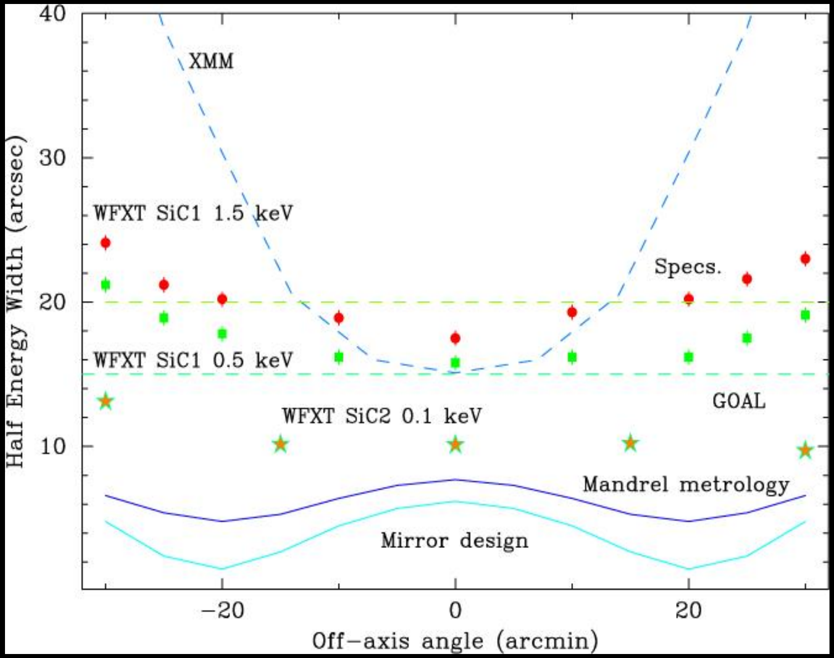
- angular resolution more strongly affected by the slope errors caused by out-of-phase azimuthal errors



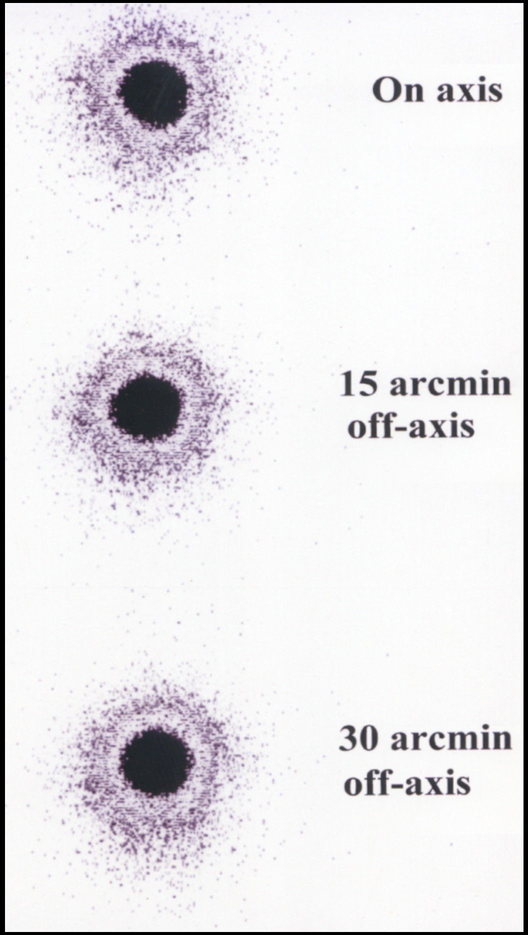


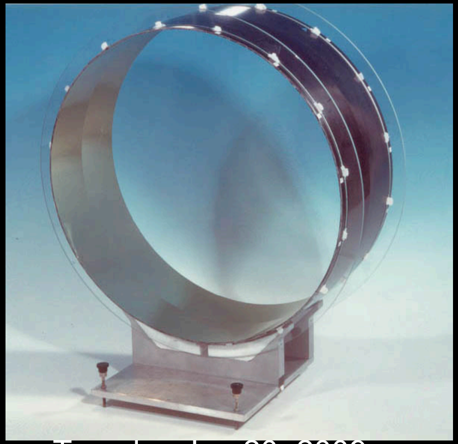
WFXT prototypes in SiC by epoxy replication

Polynomial mirrors developed in Italy for the WFXT mission (1998-2001, see Chincarini et al. '98)



Tests @ Panter-MPE & Marshall XRF





WFXT (epoxy replication on SiC) – Ø = 60 cm

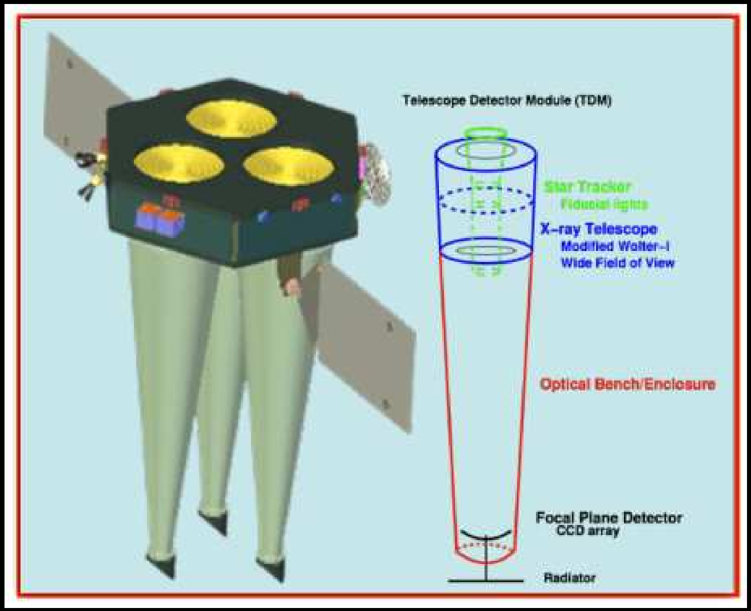
Height = 20 cm

F. L. = 300 cm

HEW = 10 arcsec @ 0.1 keV

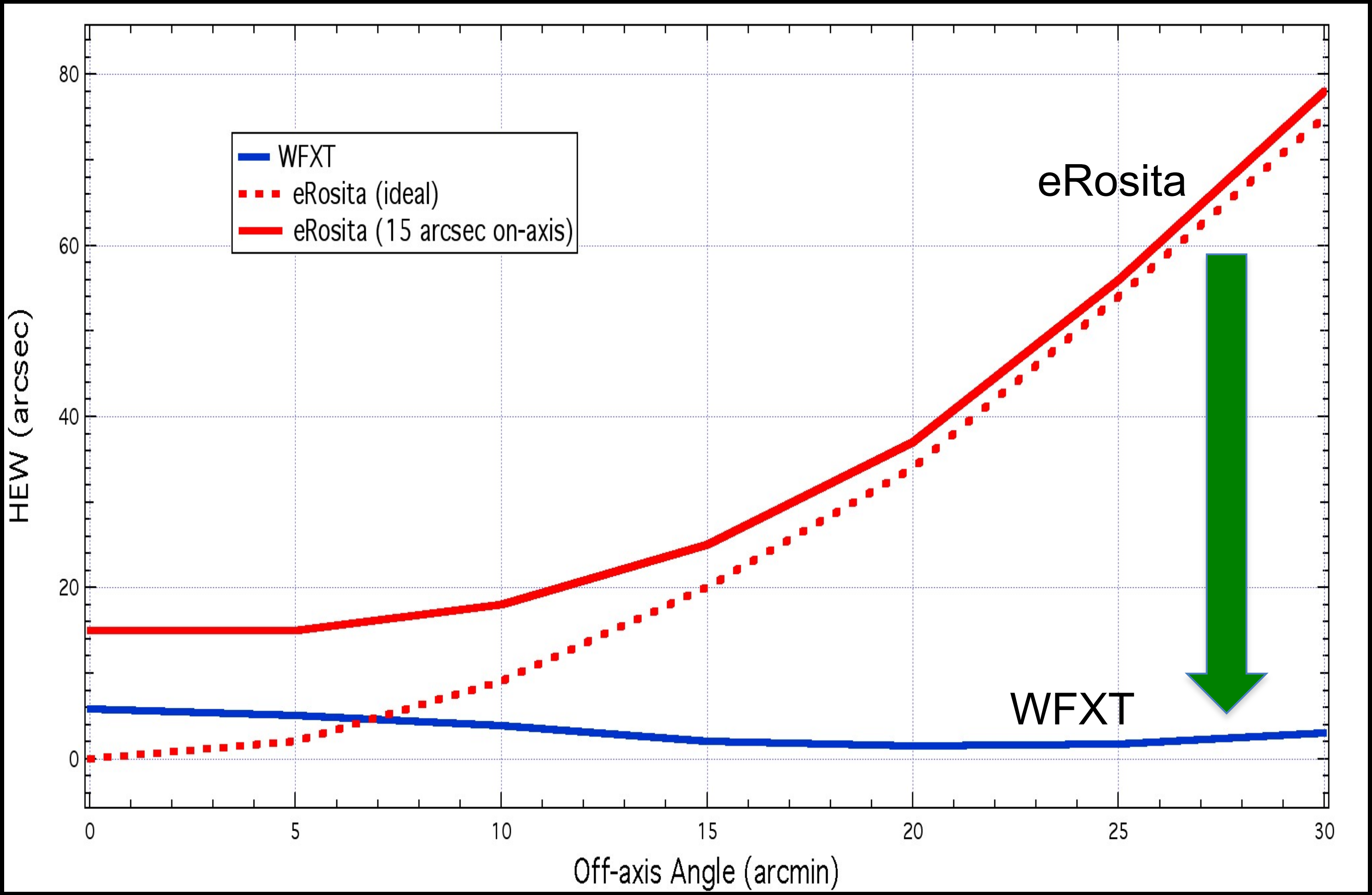
Ref:. O. Citterio, et al., ", *SPIE Proc.*, 3766, 198 (1999)
Ghigo et al., *SPIE Proc.*, 3766, 209 (1999)

WFXT Telescope Configuration (Murray, 2011)



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)

HEW across the FOV: WFXT vs. eRosita



N.B.: Aspect ratio WFXT = 0.07 – Aspect ratio eRosita = 0.16

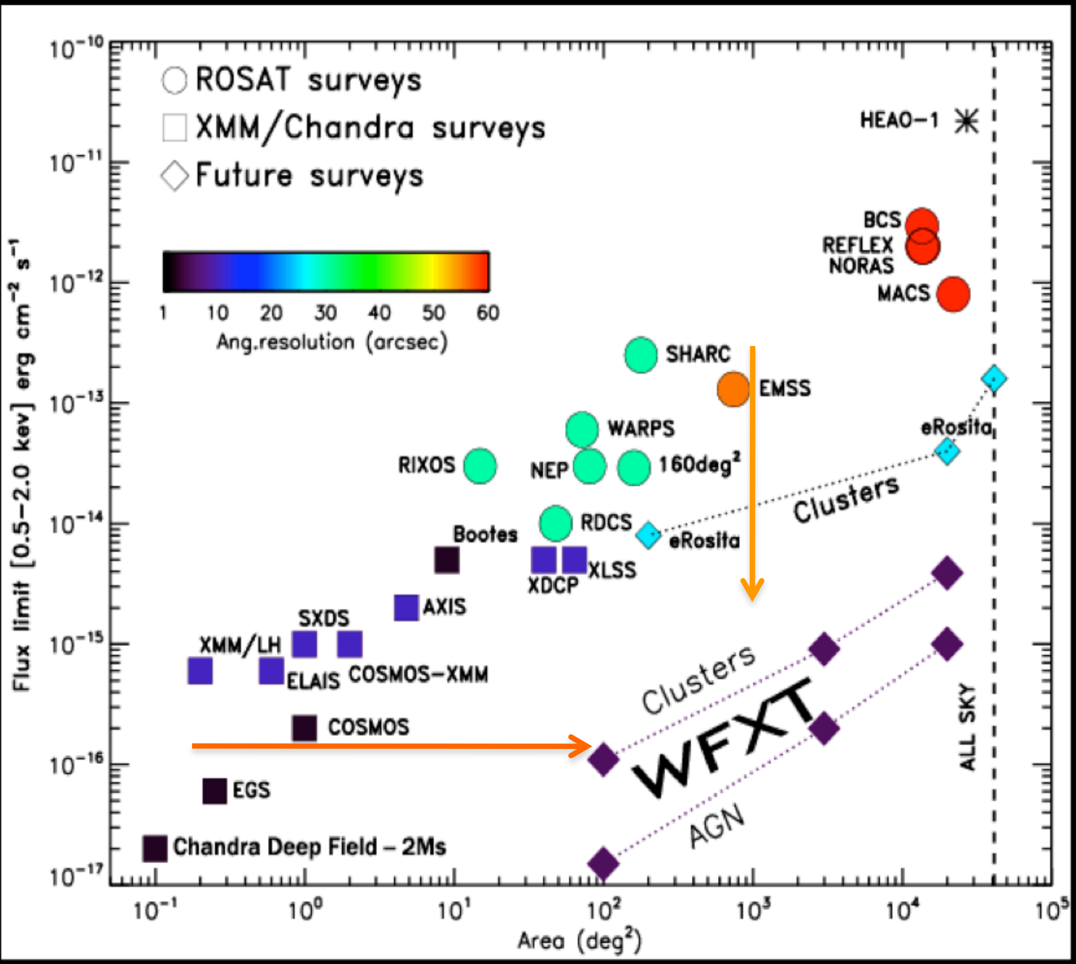
Survey capabilities comparison

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

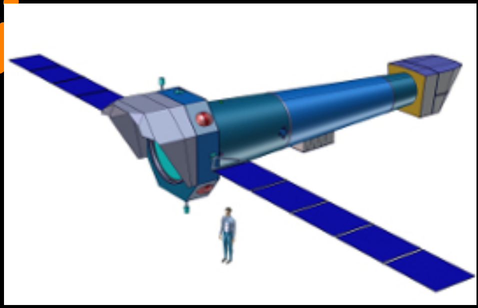
Sensitivity



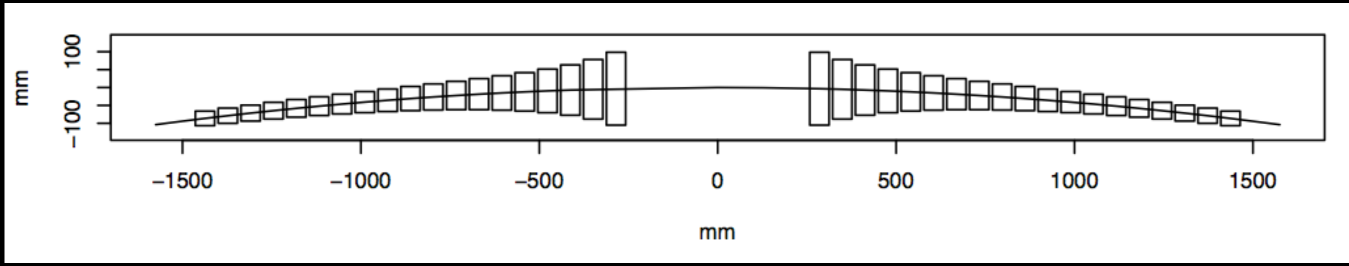
- WFXT sensitivity provides orders of magnitude increase over other missions
- The good angular resolution easily identifies extended sources and avoids confusion

CREDITS: P. Rosati

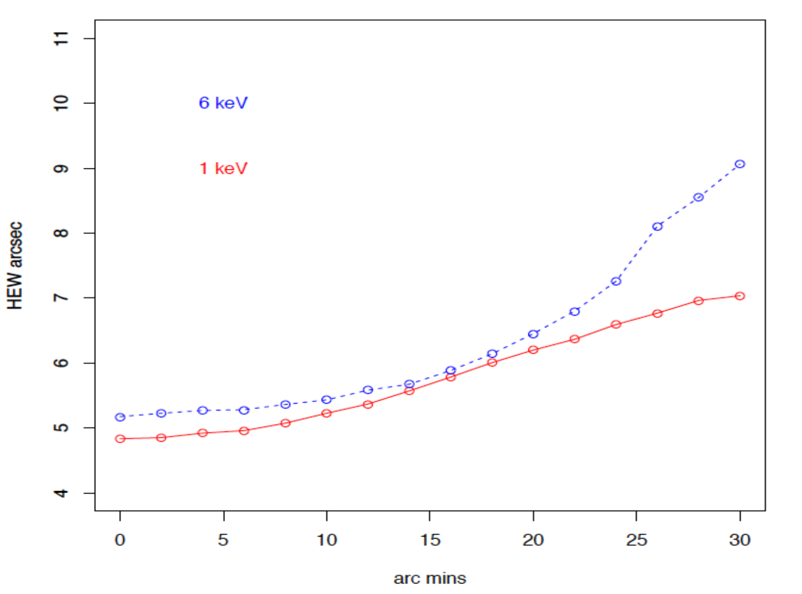
ATHENA: small degradation of the angular resolution off-axis



Wolter-Schwarzschild (W-S) obeys Abbe sine condition

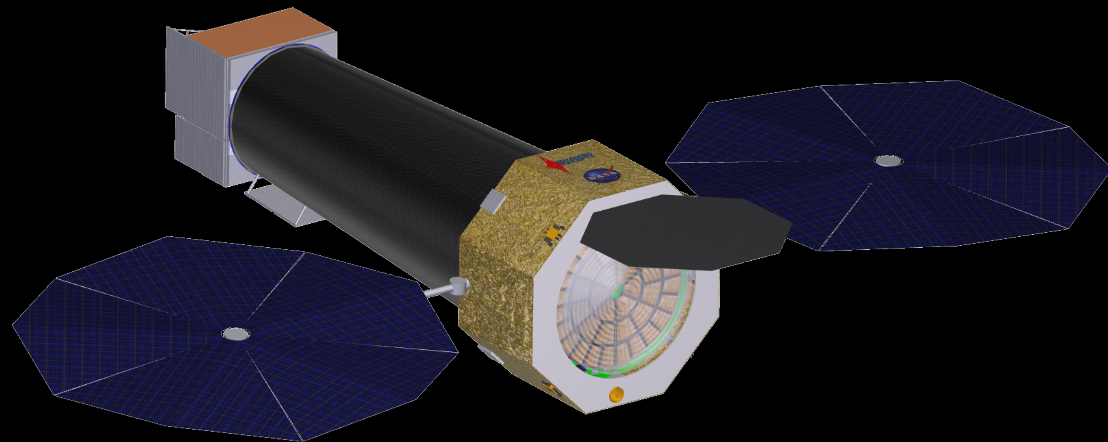


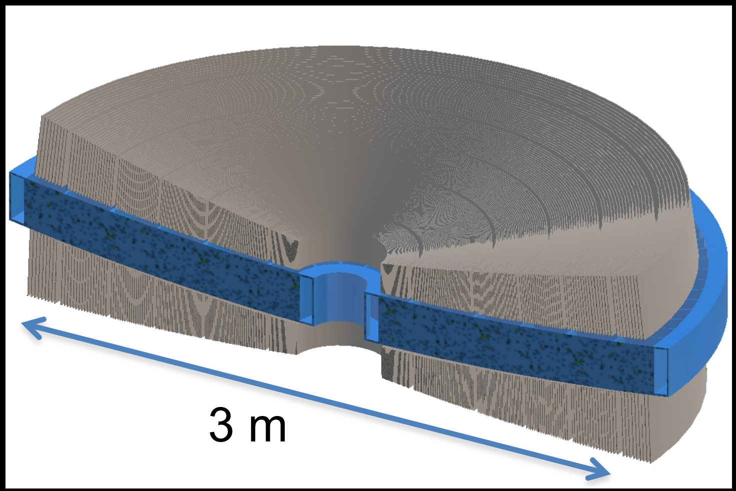
Use of a small mirror/focal length aspect ratio + optimized mirror profile

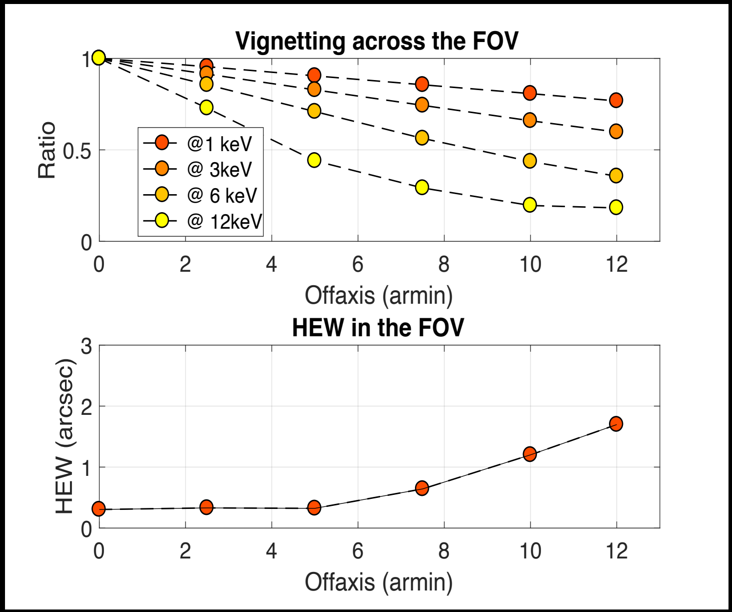


IMAGER with 40 arcmin diameter FOV at 5" arcsec on average

X-RAY OBSERVATORY
LYNX



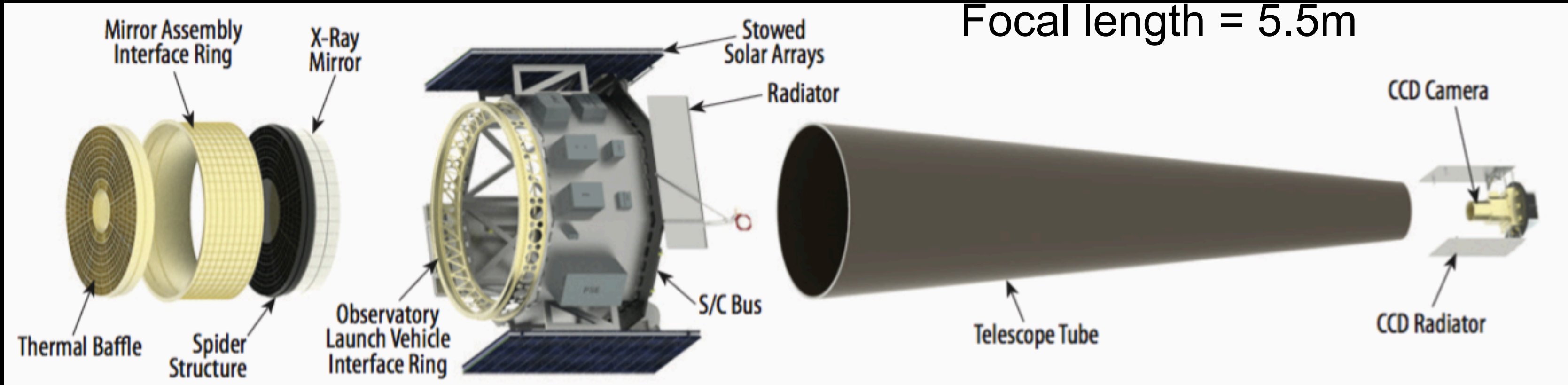




W-S design with HEW on average < 1“ with a 10 arcmin diameter FOV thanks to the small aspect ratio

STAR-X (NASA GSFC, 2017)→ Design directly derived from WFXT 2011

Focal length = 5.5m



X-ray Telescope Assembly	Energy Band	0.5-6 keV				
	Field of View	1.0 deg^2				
	Point Spread Function	5 arcsec half-power diameter over entire FOV				
	Effective Areas (cm^2)	**Energy (keV)**	0.5	1	4	6
		On-axis	1270	1800	250	45
		0.25° off-axis	962	1360	140	17
		0.50° off-axis	706	992	70	7
	Spectral Resolution (FWHM) (eV)		70	80	120	150
Mission	Orbit	5° inclination, 600 km, circular				
	Transient Event Alert	Within 30 sec of on-board detection, through TDRSS (90% of the time)				
	Response to ToO	Within 60 mins of receipt (90% of the time)				
	Slew and Repoint	120° in less than 5 mins; 0.5° in 24 sec				
	Astrometric Knowledge	2 arcsec (3σ)				
	Observing Efficiency	> 66%				

Riccardo's moral testament!

Mem. S.A.It. Vol. 84, 472

Memorie della
Società Astronomica Italiana
1871 Società degli Spettroscopisti

Considerations on X-ray astronomy

A start in X-ray astronomy

R. Giacconi

*"Contrary to the point of view expressed by several astronomers, **I am confident that we still are in a discovery era**. Given that the physical nature of 97% of the matter in the Universe is still unknown, I believe there is ample room for frontline research that will provide as many surprises as have occurred in the last decades.*

*I am therefore certain that in the next 50 years x-ray astronomy will reach new heights. **I hope the new generation of astronomers will have the opportunity to Learn-Think-Plan and Do as we have had**."*