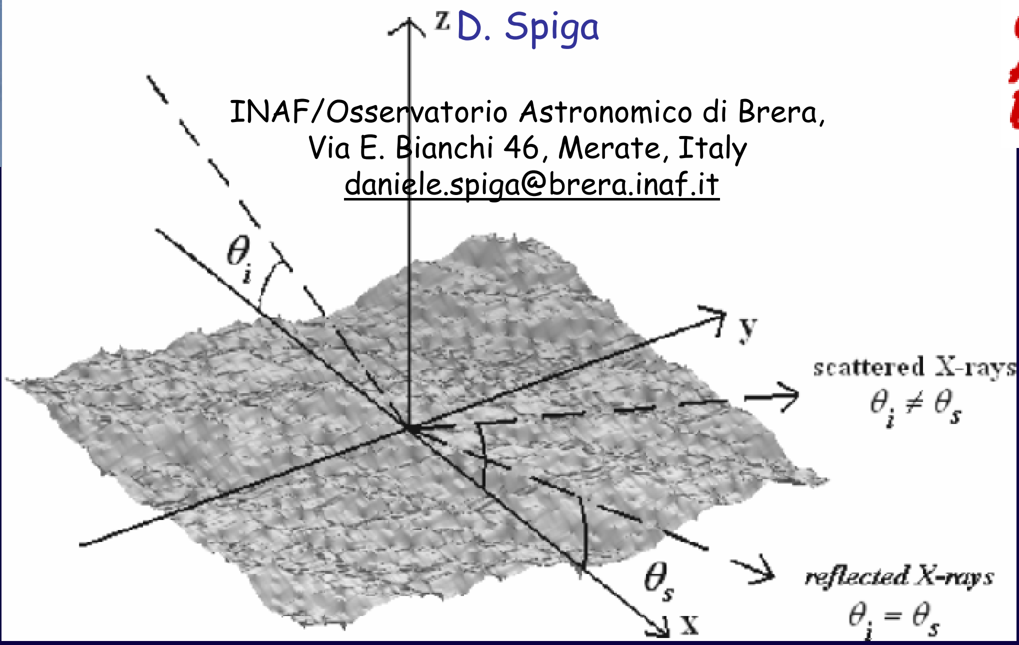
X-ray imaging telescopes: prediction of the expected image of the expected image quality from surface roughness metrology data



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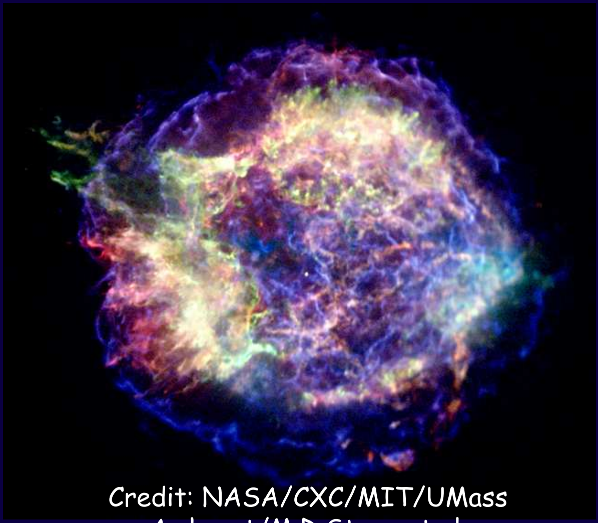
WHAT X-RAY ASTRONOMERS WANT: HIGH ANGULAR RESOLUTION...



Credit: NASA/CXC/MIT/UMass Amherst/M.D.Stage et al.

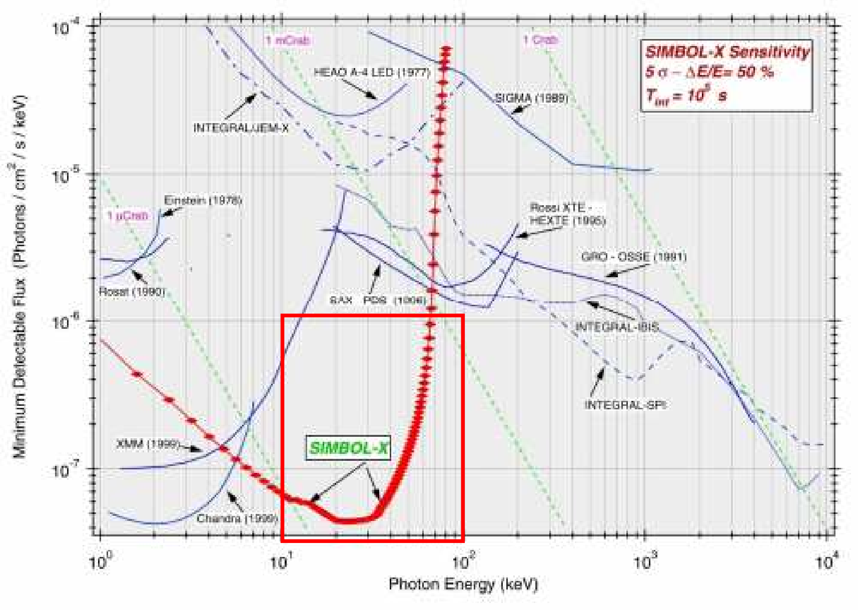
Credit: NASA/Swift-XRT

Chandra image, res. = 0.5 arcsec HEW

Swift XRT image, res. = 15 arcsec HEW

The angular resolution of X-ray telescopes is a fundamental requirement to resolve the details of celestial sources

… AND LARGE EFFECTIVE AREAS

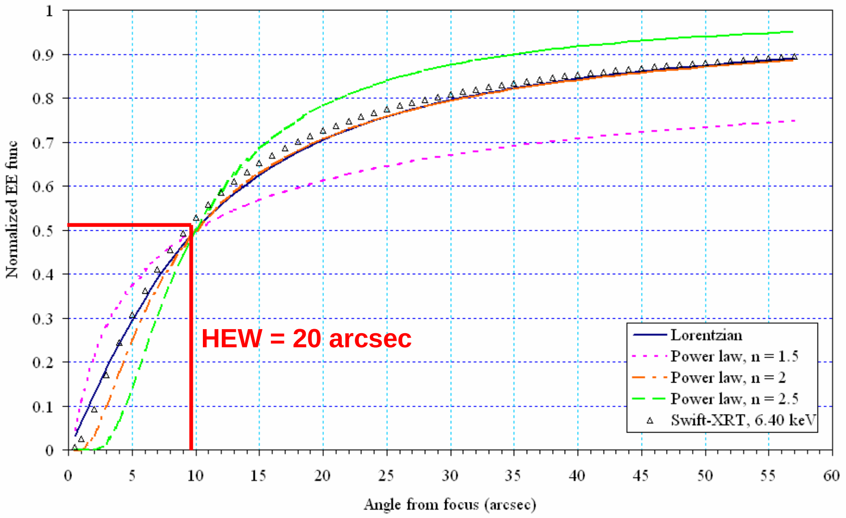


- Most X-ray sources are faint, large collecting areas (~ 1000 cm^2) are needed to increase the sensitivity.
- A limited mass (~ 300 kg) for the telescope to fly…!
- High stability in orbital environment (variations of temperature, cosmic rays, micrometeoroids, …)

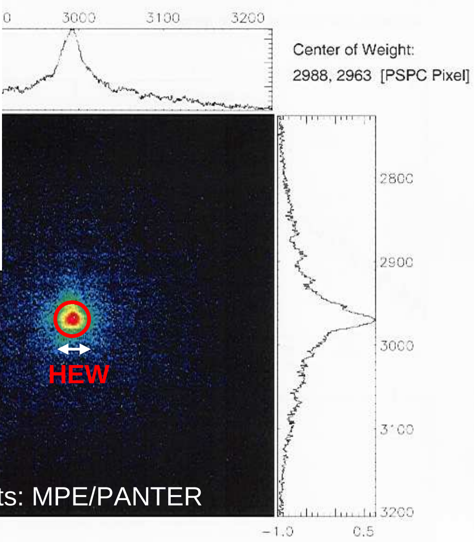
X-ray telescopes must have the capability to detect *extremely weak fluxes* (down to 10^{-8} ph/s/cm^2/keV).

To date, the energy range 10 – 100 keV has still to be explored with *direct imaging* telescopes.

ASTRONOMERS LIKE USING THE HEW (= Half Energy Width)



HEW (or HPD, Half Power Diameter) = the angular diameter in arcsec including 50% of focused photons

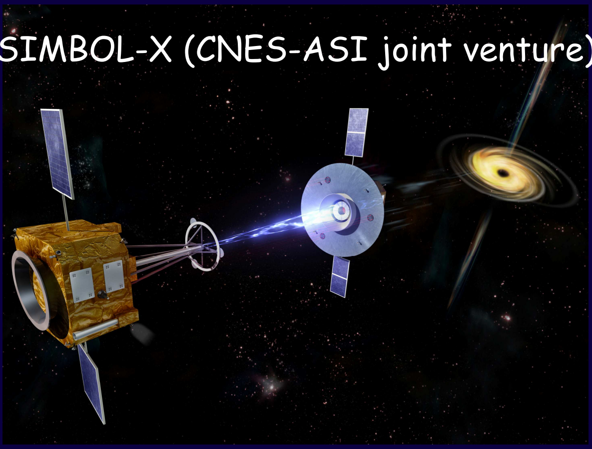


Credits: MPE/PANTER

Other parameters (like FWHM) would be, in general, non-representative of the optical performances (exception: nearby sources)

A NEW HARD X-RAY MISSION

SIMBOL-X (CNES-ASI joint venture)



Focal length	20 m
Min diameter	300 mm
Max diameter	700 mm
Min incidence angle	0.11 deg
Max incidence angle	0.25 deg
Energy band	0.5 – 80 keV
Number of shells	100
Effective area (1 keV)	~ 1400 cm^2
Effect. area (30 keV)	~ 450 cm^2
Field of View	12 arcmin
Required HEW *	15 arcsec (1 keV) 20 arcsec (40 keV)

SIMBOL-X will allow the extension of imaging capabilities to the hard X-ray band by adopting:

- Very shallow incidence angles (0.1-0.25 deg), made possible by a 20 m focal length, managed with the formation flight configuration.
- Graded **multilayer coatings** to enhance mirrors' reflectivity up to 80 keV

G. Pareschi, P. Ferrando, "*The SIMBOL-X hard X-ray mission*", Exp. Astron. 20, 139-149 (2006)

CONTRIBUTIONS TO IMAGING DEGRADATION

1) An energy-independent term H_0, caused by the
   a) single mirror figure errors
   b) alignment of mirrors

→ Ray tracing from profiles, UV bench measurement

2) An energy-dependent term H(λ), caused by surface roughness X-ray scattering (XRS)

→ Physical optics

$$HEW^2(\lambda) \approx H_0^2 + H^2(\lambda)$$

Correction with active optics

not effective if this term prevails (in hard X-rays)

Accurate roughness metrology urge!

METROLOGICAL INSTRUMENTATION FOR MIRROR DIAGNOSTIC AT INAF-OAB

Long-Trace profilometer – suitable for stress-induced deformations

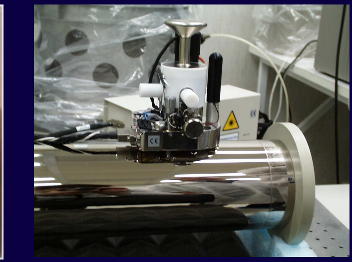
WYKO profilometer

1D surface profiles

2.5, 0.6 mm wide scans

Nomarski Phase Contrast microscope

5x – 100 x



2 Atomic Force Microscopes

2D surface maps (plane and curved substrates): 100, 10 1 µm wide scans

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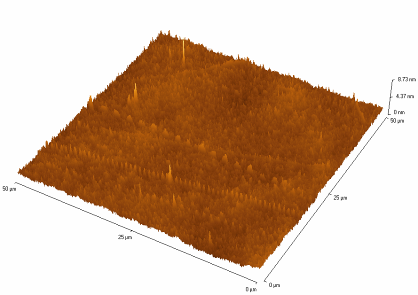
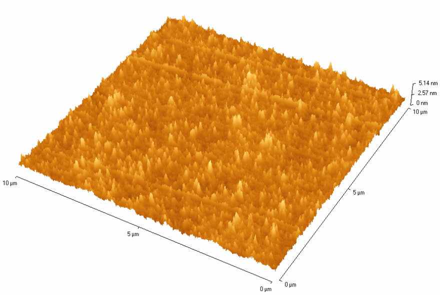
X-RAY MIRROR SURFACE ROUGHNESS MEASUREMENTS

- Each instrument is sensitive only to a particular window of spatial frequencies.



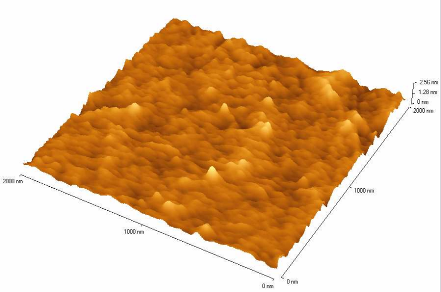
AFM, 100 µm – 0.4 µm

σ = 2.9 Å



AFM, 10 µm – 40 nm

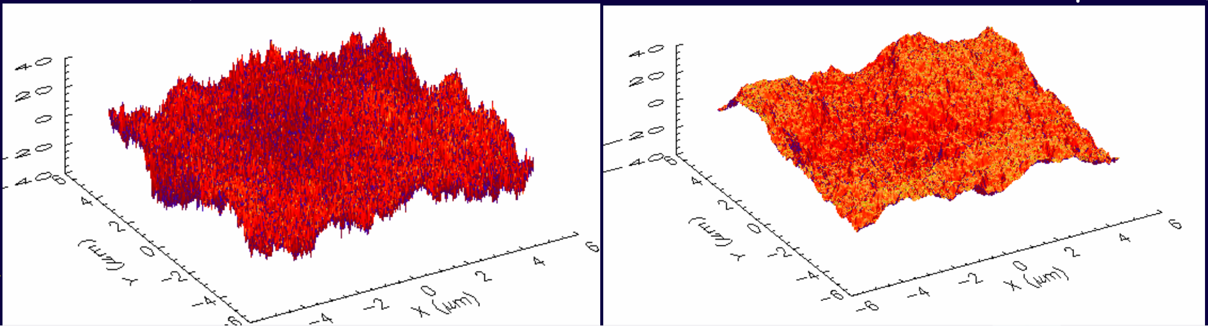
σ = 2.6 Å



AFM, 1 µm – 4 nm

σ = 1.4 Å

- Also in the same bandwidth, surfaces with the same rms can be VERY different (see below: same rms = 10 Å, 10 µm wide, but different spectrum)



REPRESENTATION IN TERMS OF POWER-SPECTRAL DENSITY

Representing the roughness in terms of PSD (Power-Spectral-Density) has several advantages (and at least a disadvantage):

$$P(f) = \frac{1}{L}\left|\int_0^L z(x)e^{-2\pi i f x}dx\right|^2$$

height $$\sigma^2_{\Delta f} = \int_{\Delta f} P(f)\,df$$

slope $$m^2_{\Delta f} = \int_{\Delta f} (2\pi f)^2 P(f)\,df$$

curvature $$c^2_{\Delta f} = \int_{\Delta f} (2\pi f)^4 P(f)\,df$$

- ☺ PSDs from different instruments are (in general) mutually-consistent
- ☺ PSDs in the same bandwidth can be averaged to reduce sampling effects
- ☺ The PSD returns a complete description of the statistical properties of roughness
- ☺ It directly involves the X-ray scattering and, therefore, the image degradation!
- ☹ It provides little or no information for ray-tracing…

DIRECT DERIVATION OF THE H(λ) FROM A SURFACE PSD

PSD → H(λ)

Spiga D., 2007, *"Analytical evaluation of the X-ray scattering contribution to imaging degradation ingrazing-incidence X-ray telescopes"*. Astronomy and Astrophysics, vol. 468, 775-784

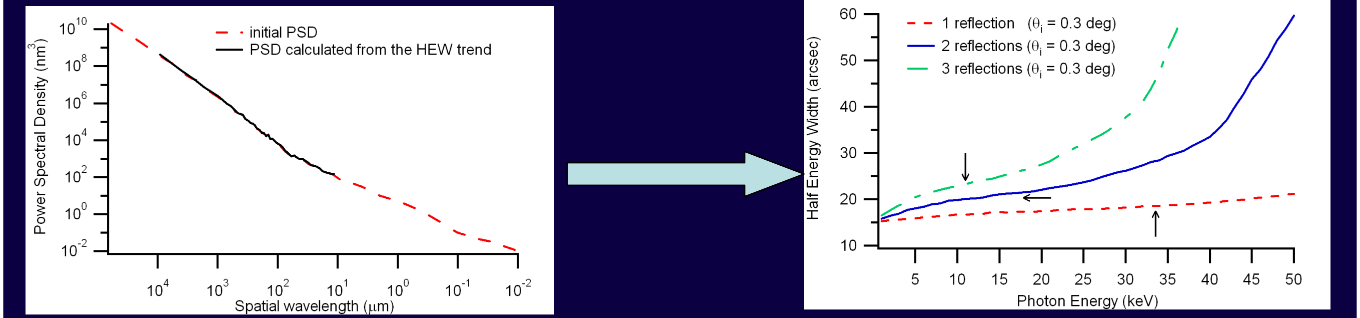
$$\int_{f_0}^{2/\lambda} P(f)\,df = \frac{\lambda^2}{16\pi^2 \sin^2 \vartheta_i}\ln\left(\frac{2N}{2N-1}\right) \rightarrow \text{derive } f_0 \rightarrow H(\lambda) = \frac{2\lambda f_0}{\sin \vartheta_i}$$

N : number of identical reflections

θ_i : grazing incidence angle

λ : photon wavelength

f : surface spatial frequency



DIRECT DERIVATION OF THE H(λ) FROM A SURFACE PSD

For a fractal surface

Spiga D., 2007, *"Analytical evaluation of the X-ray scattering contribution to imaging degradation ingrazing-incidence X-ray telescopes"*. Astronomy and Astrophysics, vol. 468, 775-784

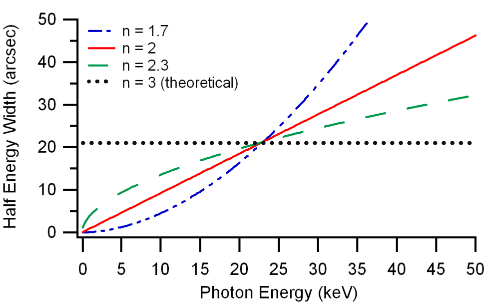
$$P(f)=\frac{K_n}{f^n}\xrightarrow{\text{1 reflection}}H(\lambda)=2\left[\frac{16\pi^2 K_n}{(n-1)\ln 2}\right]^{\frac{1}{n-1}}\left(\frac{\sin\vartheta_i}{\lambda}\right)^{\frac{3-n}{n-1}}$$

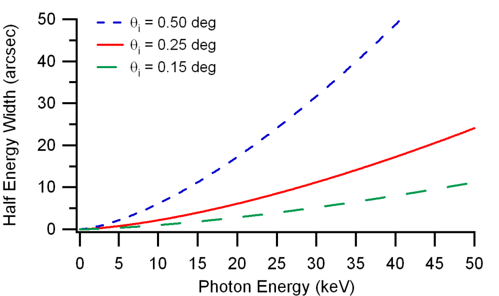
The H(λ) function is also a **power-law**, with a spectral index

$$\gamma=\frac{3-n}{n-1}$$

1) γ > 0, because fractal **surfaces** have 1 < n < 3 !!!

2) For a fixed K_n: the steeper the PSD, the better!!





DIRECT DERIVATION OF THE PSD FROM A H(λ) FUNCTION

PSD → H(λ)

Spiga D., 2007, *"Analytical evaluation of the X-ray scattering contribution to imaging degradation ingrazing-incidence X-ray telescopes"*. Astronomy and Astrophysics, vol. 468, 775-784

$$\frac{P(f_0)}{\lambda}\frac{d}{d\lambda}\left(\frac{H(\lambda)}{\lambda}\right)+\frac{1}{4\pi^2\sin^3\vartheta_i}\ln\left(\frac{2N}{2N-1}\right)\approx 0$$

At the frequency

$$f_0=\frac{H(\lambda)}{2\lambda}\sin\vartheta_i$$

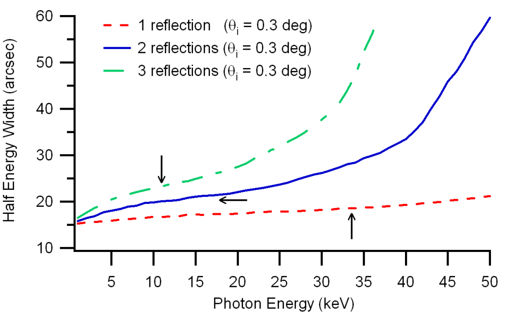
N : number of identical reflections

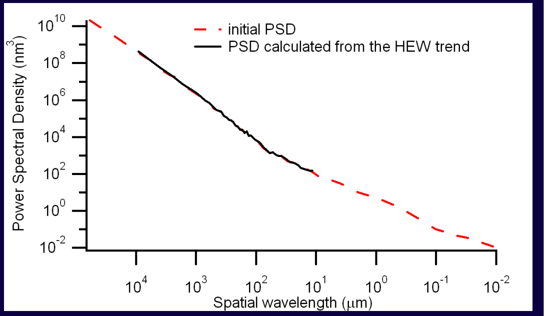
θ_i : grazing incidence angle

λ : photon wavelength

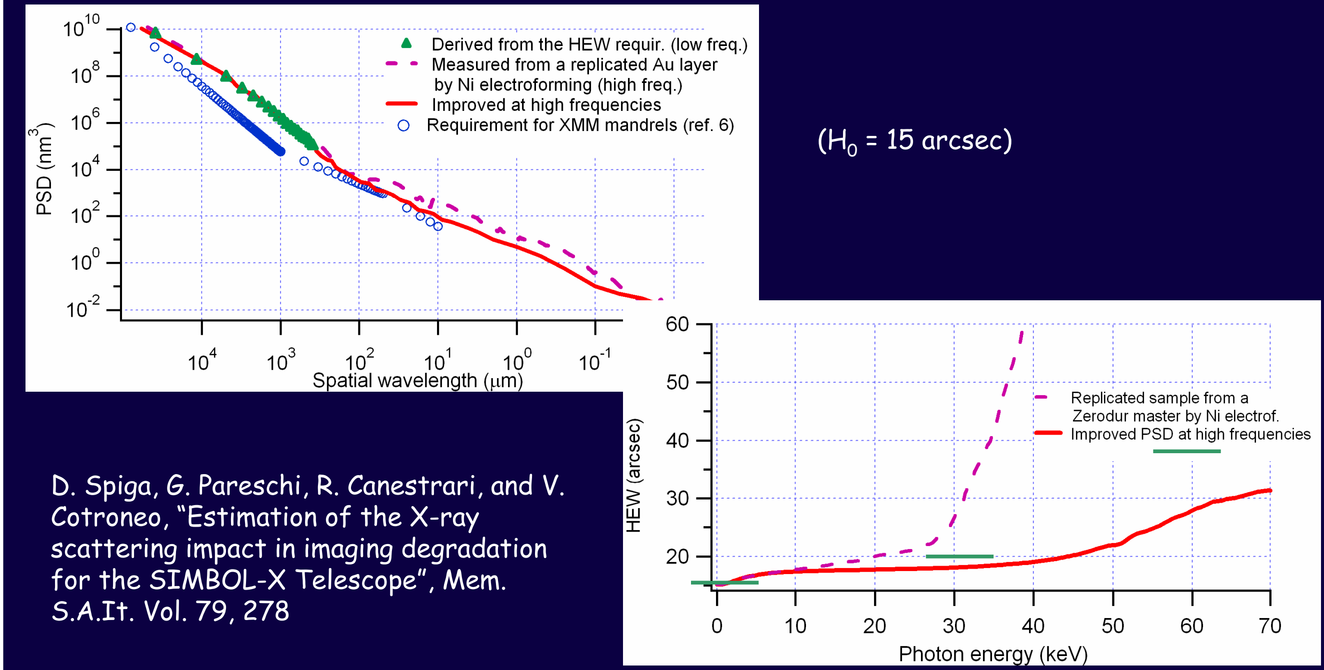
f : surface spatial frequency

These formulae can be useful to translate HEW requirements into PSD tolerances !!!!





ROUGHNESS TOLERANCES FOR SIMBOL-X



(H_0 = 15 arcsec)

D. Spiga, G. Pareschi, R. Canestrari, and V. Cotroneo, "Estimation of the X-ray scattering impact in imaging degradation for the SIMBOL-X Telescope", Mem. S.A.It. Vol. 79, 278

PSD	1 mm > ℓ > 100 µm	100 µm > ℓ > 10 µm	10 µm > ℓ > 1 µm	ℓ < 1 µm
violet	10.2 Å	3.6 Å	2.5 Å	1.8 Å
red	9.3 Å	2.2 Å	1.3 Å	1.0 Å

FINAL REMARKS

- Active optics for X-rays can correct the mirror profiles, but what if X-ray scattering due to roughness degrades the image?

- X-ray scattering seems to pose the main threat to the telescope angular resolution. Clear roughness tolerances should be established from scientific requirements of the telescope.

- Treatment of roughness in terms of PSD allows to relate it PSD to the expected HEW trend, as a function of λ (and vice versa).

- Application of simple formulae allows determining the surface finishing tolerances for focusing mirrors in soft and hard X-rays.

FUTURE WORK

- Extending the formalism to any multilayer coating.

- Apply the method to explain the angular resolution of existing X-ray telescopes like Swift/Jet-X.