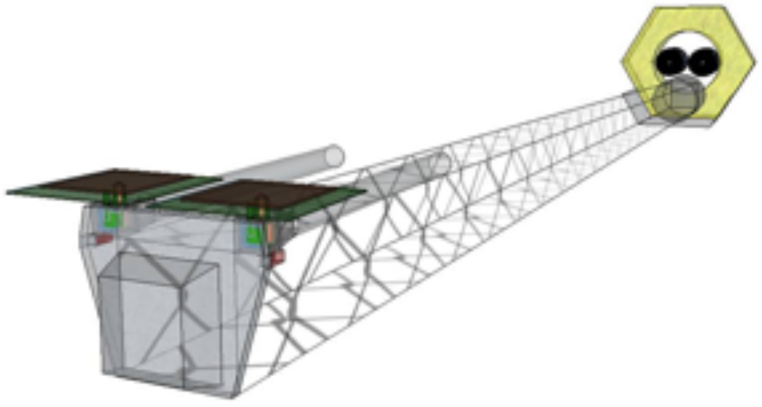
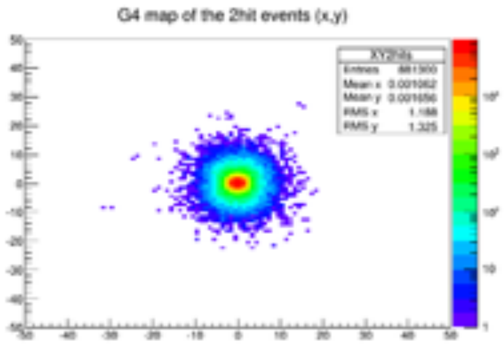
Hard X-ray telescopes

simulation and design



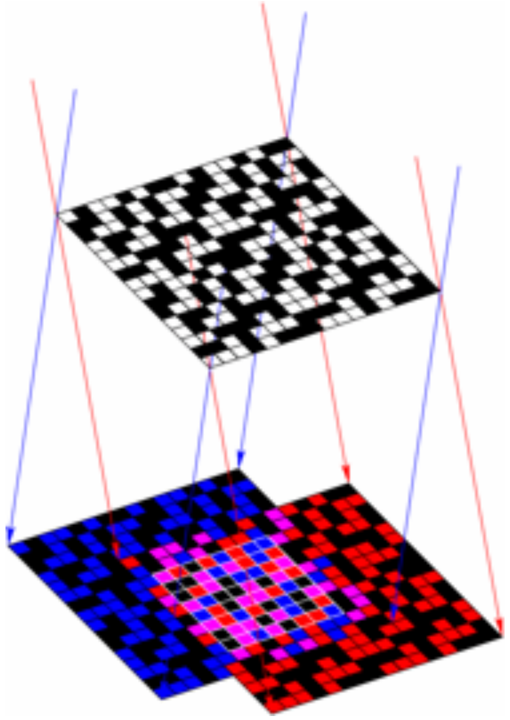


Maxime Chauvin - KTH/Sweden
maxime@particle.kth.se

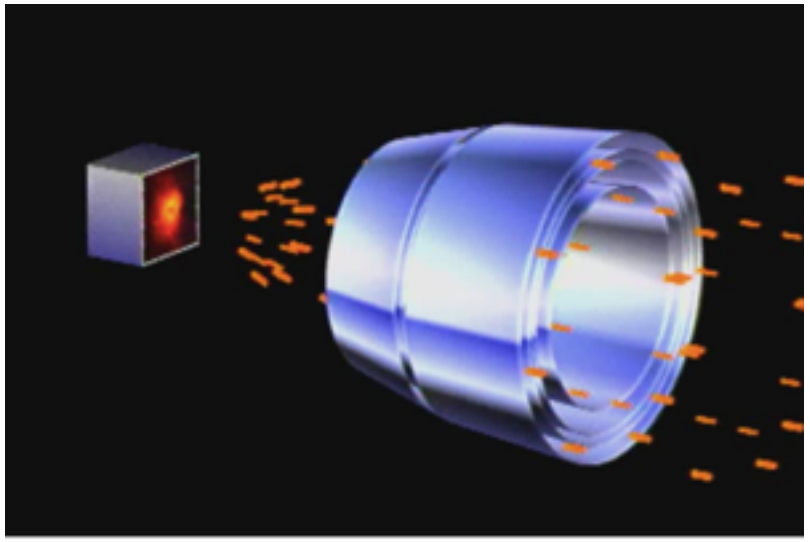
The Future of Hard X-ray Astrophysics (1-500 keV): Science and Instrument Prospects, 13-14th January, Paris

Hard X-ray telescopes simulation and design

- Detection techniques, coded mask vs focalisation



INTEGRAL coded mask (credit ISDC)



Chandra mirrors (credit NASA)

+ no energy limit
+ large FoV
+ simple system

- collecting area = detection area
- indirect imaging
- angular resolution

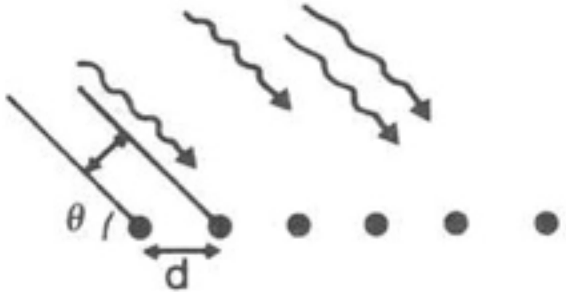
+ large collecting area
+ little detection area
+ good angular resolution

- complexe system
- small FoV
- mass, cost

Hard X-ray telescopes simulation and design

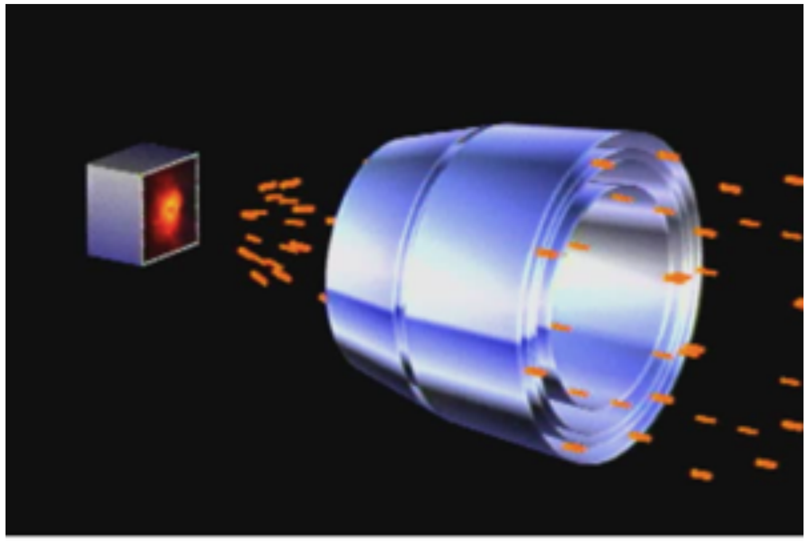
- How to focus hard X-rays?

1. Long focal length for grazing incidence



$$\theta c = \left(N_0 \frac{Z r_e}{A\pi} \rho\right)^{1/2} \lambda$$

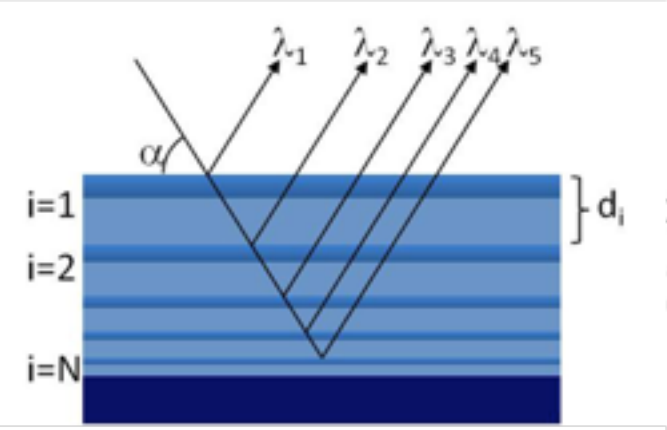
$$d_f = r / \tan(4\theta)$$

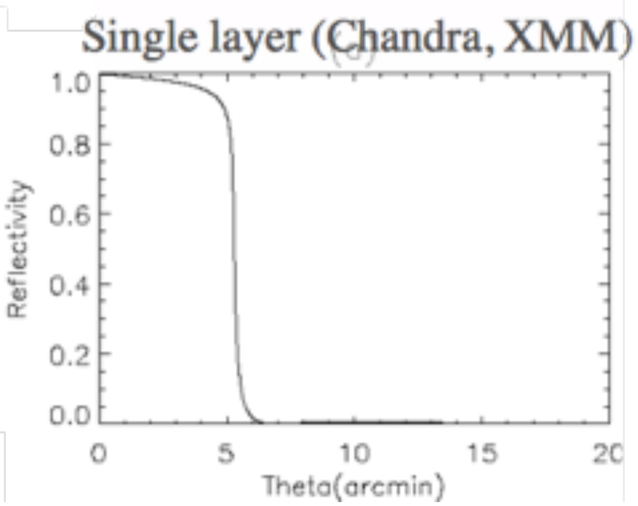


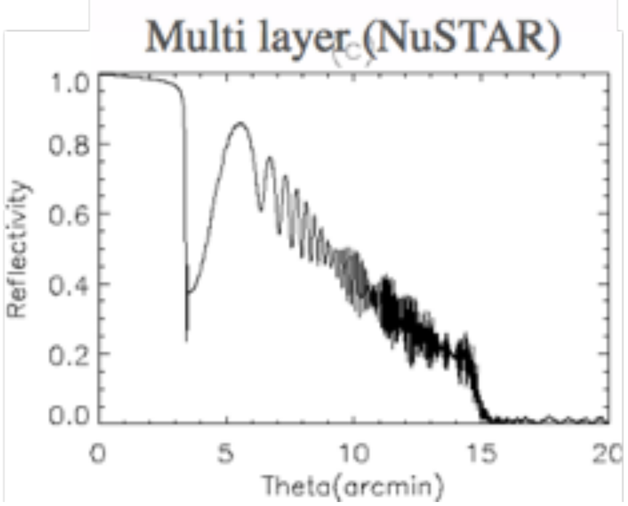
Chandra mirrors (credit NASA)

$E_{max} \sim 1/\theta c \sim d_f$ (focal length) E > 100 keV, $d_f > 10$ m

2. Special mirror coating





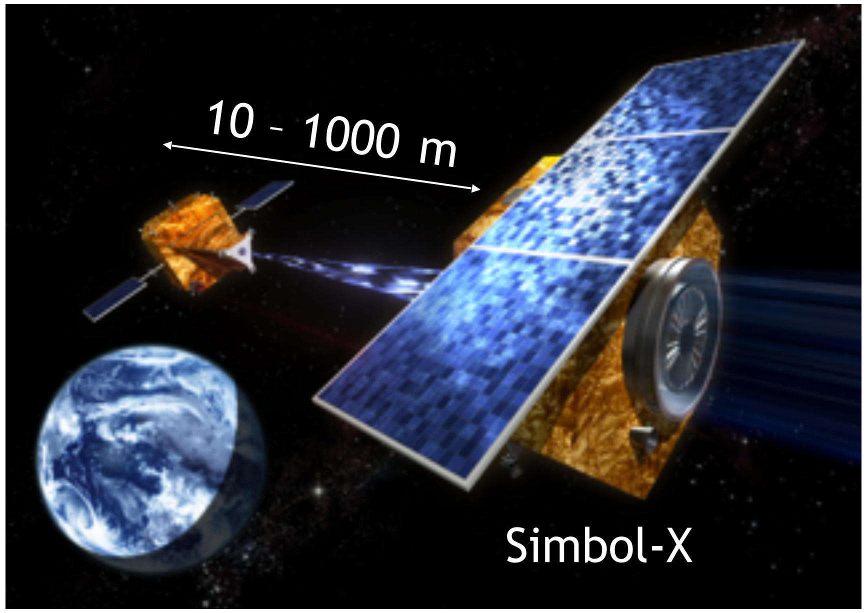


Reflectivity @ 60keV

Hard X-ray telescopes simulation and design

- Solutions for long focal length?

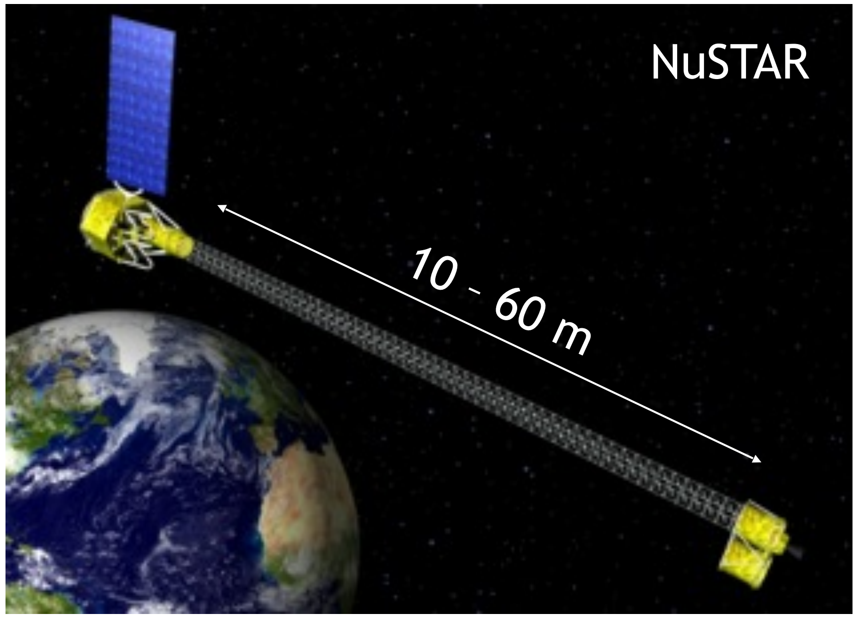
Formation flight



- focal length: 10 - 1000 m
- stability ∝ attitude control

- high mass
- complex system
- two spacecrafts
+ unlimited focal length

Deployable mast

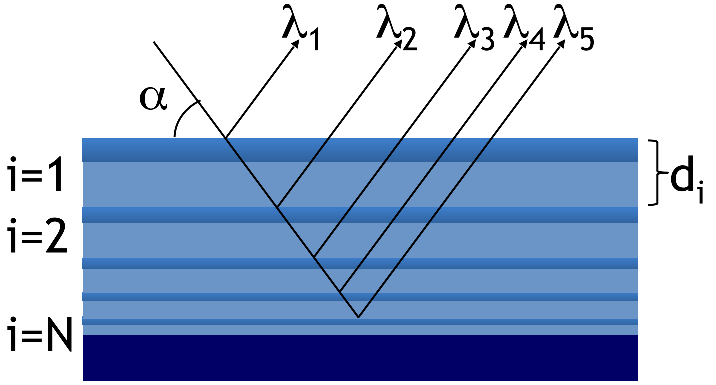


- focal length: 10 - 60 m
- stability ∝ mast length

+ low mass
+ simple system
+ only one spacecraft
- limited focal length

Hard X-ray telescopes simulation and design

- New mirror coatings



$$d_i = \frac{a}{(b+i)^c}$$

Reflectivity at the surface R(E,α):

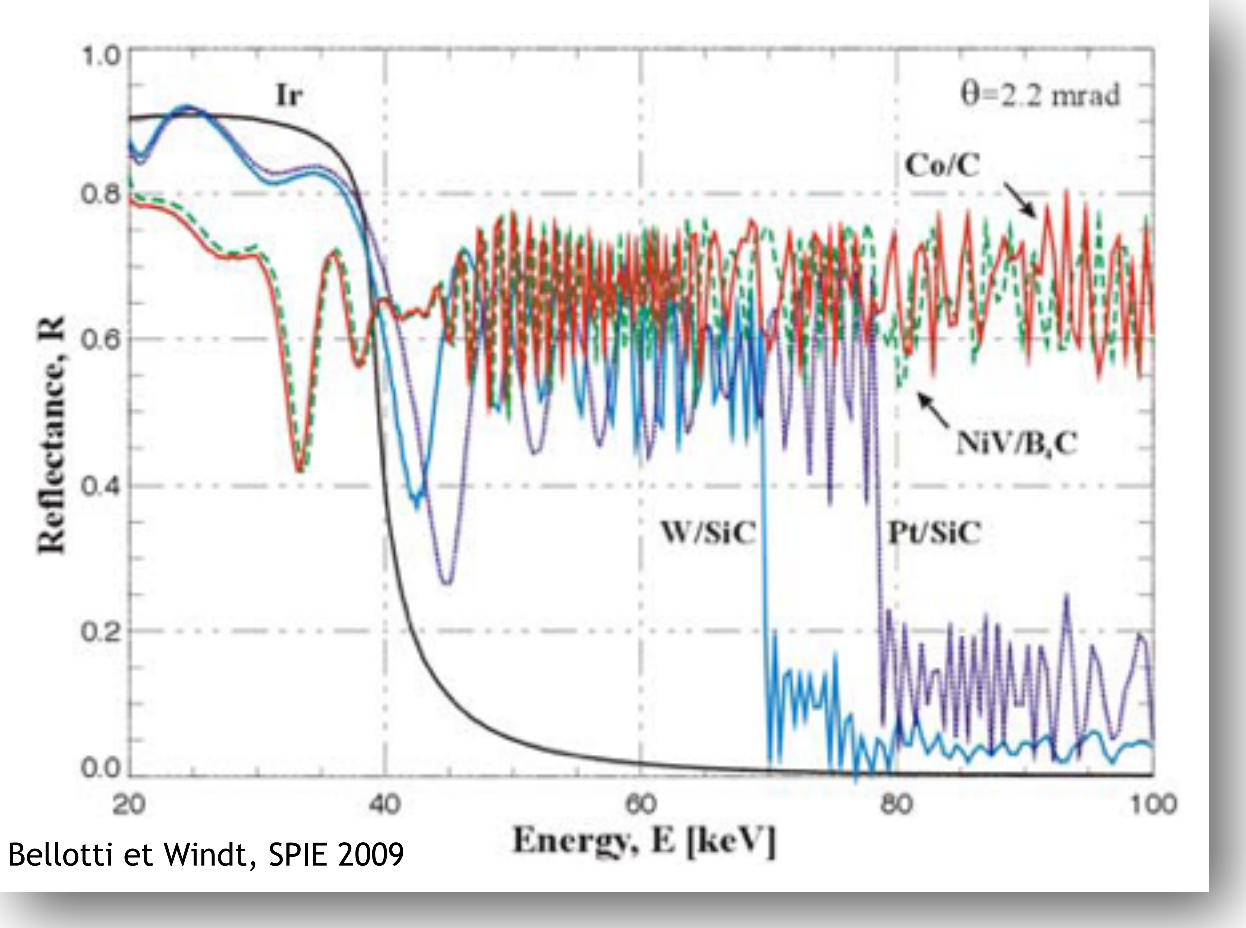
$$R = |R_0|^2$$

$$R_j = a_j^4 \left(\frac{R_{j+1} + r_j}{R_{j+1} \times r_j + 1} \right) \text{with} \quad a_j = \exp\left(-i \frac{\pi}{\lambda} g_j d_j \right), \quad g_j = \left(n_j^2 - \cos^2 \theta \right)^{\frac{1}{2}}$$

(Joensen et al., applied optics, 1995)

Pt/C coating:
- 100 layers
- thickness d = 3.55 - 14.14 nm
- a = 3.55, b = 0, c = 0.3

Co/C coating:
- 1100 layers
- thickness d = 2.75 - 29.19 nm
- a = 6.33, b = -0.91, c = 0.25



Bellotti et Windt, SPIE 2009

Hard X-ray telescopes simulation and design

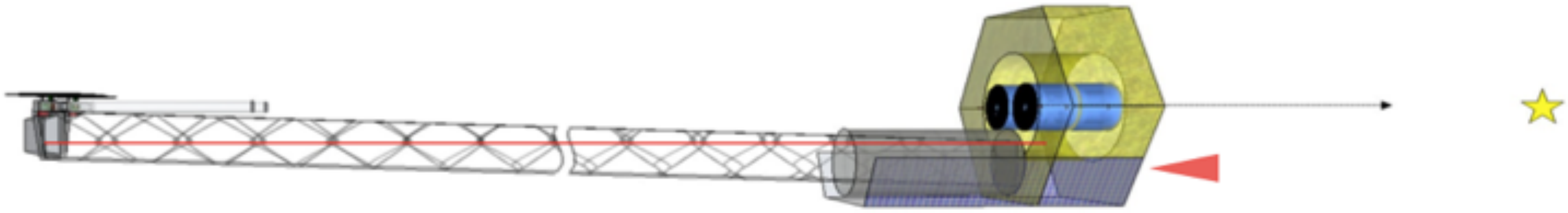
- DynamiX: a Simulation Tool for the Next-gen Hard X-ray Telescopes

Objectives

- predict the telescope performance: deformations, sensors accuracy (image reconstruction), mirrors parameters

- optimize the performance: structure control, metrology system, mirror coating

Characteristics



Detectors
Si, CdTe & Ge
N pixels
Multiple detector planes
TCP/IP sockets

Structure
Deployable mast
Formation Flight
9 degrees of freedom

Metrology
2 star trackers
2 optical sensors
(bias + noise)

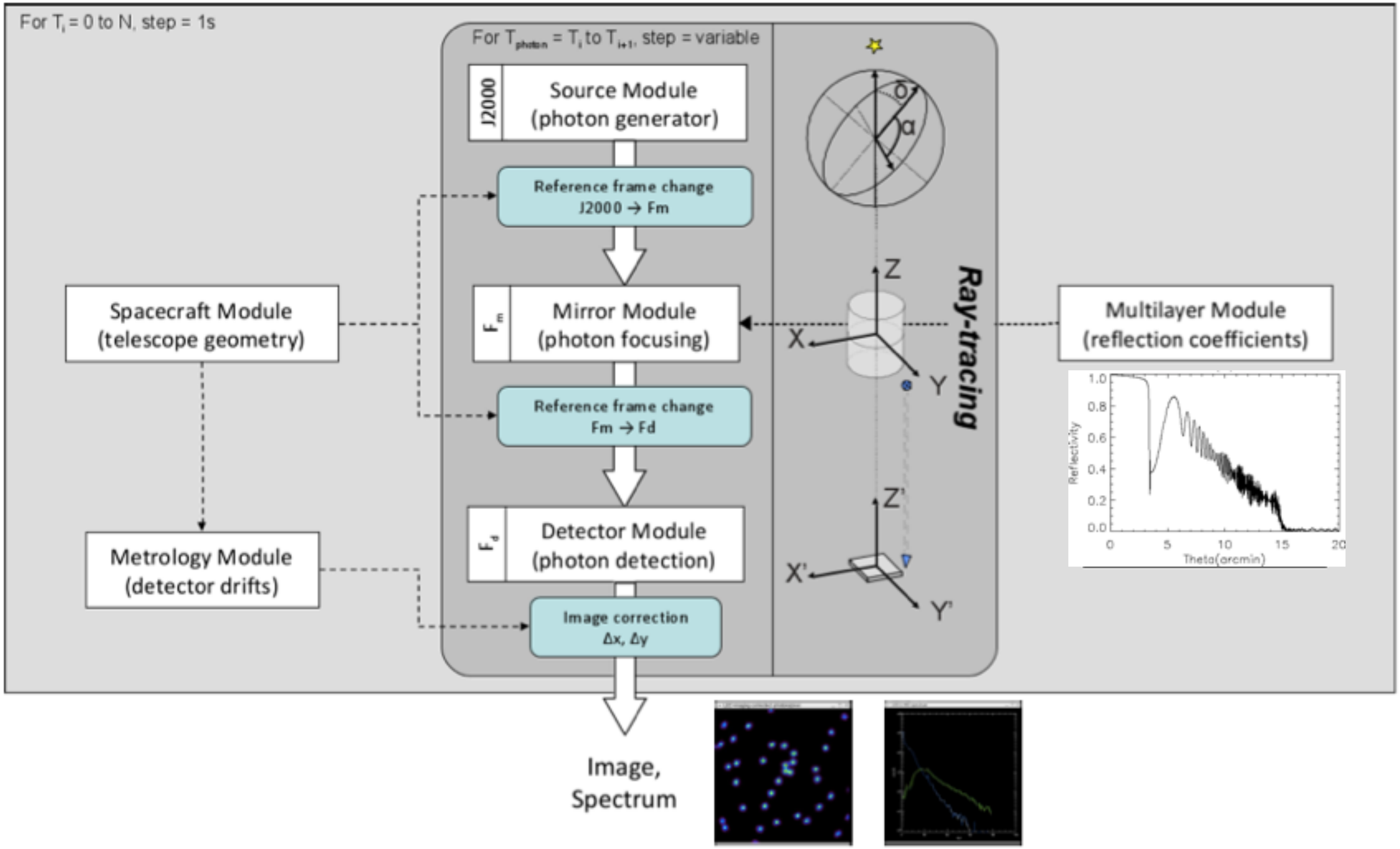
Optics
N mirrors
Radius, length
Focal length
Surface roughness
Multilayer coating

Sources
N point sources
RaDec coordinates
Spectral shape

Chauvin, M., Roques, J.P., "DynamiX, numerical tool for design of next-generation X-ray telescopes", Appl. Opt., 49, 4077 (2010)

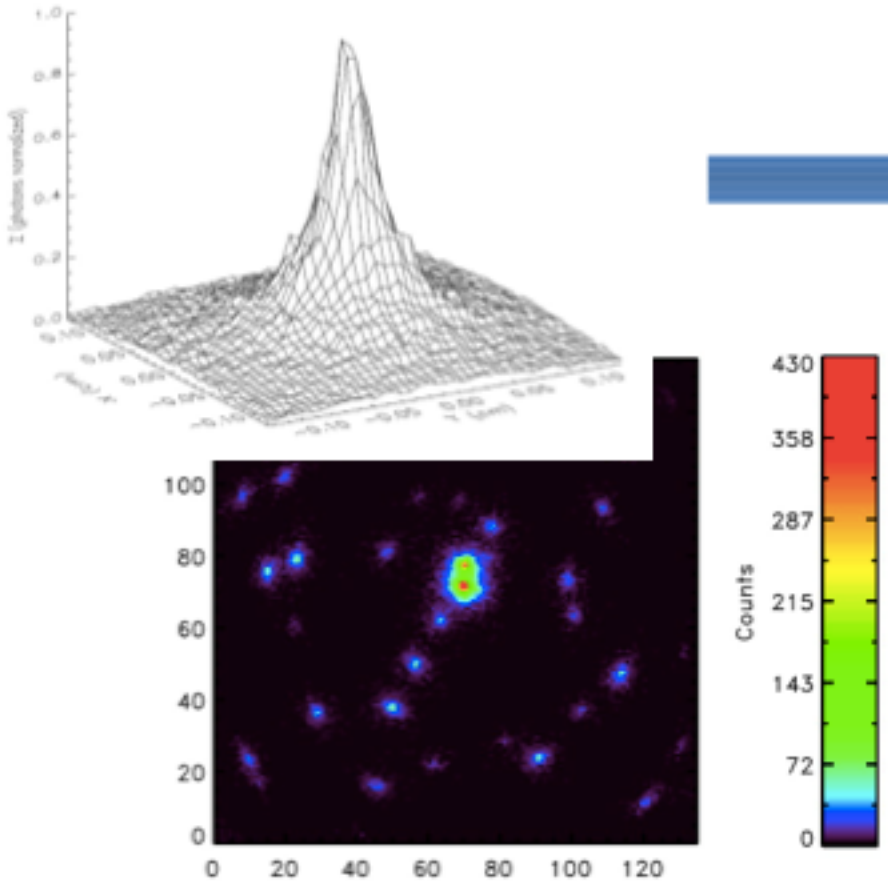
Hard X-ray telescopes simulation and design

- **DynamiX: a Simulation Tool for the Next-gen Hard X-ray Telescopes**

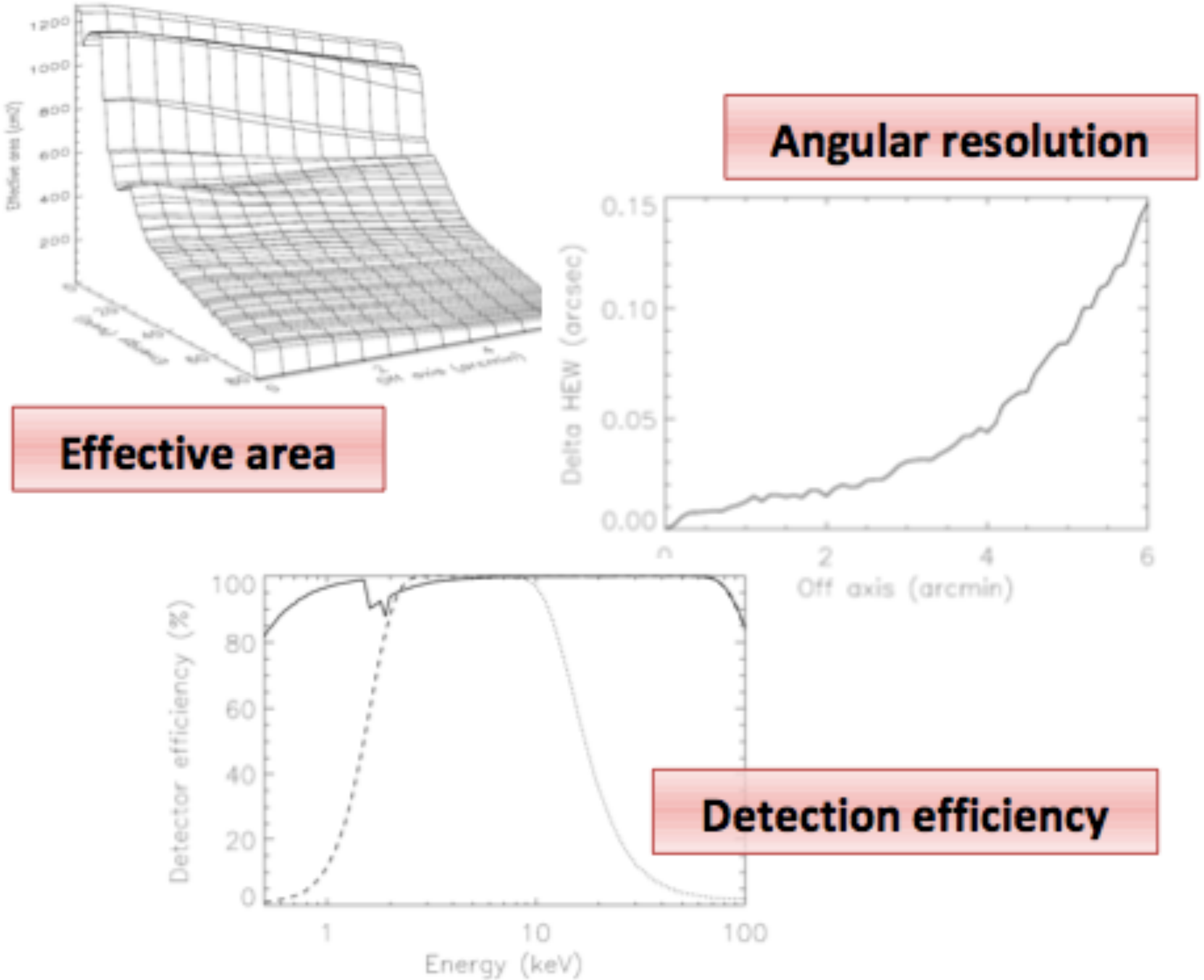


Hard X-ray telescopes simulation and design

- DynamiX: a Simulation Tool for the Next-gen Hard X-ray Telescopes
  - Outputs: positions, times, energies.
  - Features: coating reflectivity, effective area, FoV, angular resolution, optic alignments, detection efficiency, sensitivity, formation flight, deployable mast, metrology, image reconstruction.
  - Calculation time: 13000 ph/s on a single 2.4GHz processor



Images: positions, times, energies



Effective area

Angular resolution

Detection efficiency

Hard X-ray telescopes simulation and design

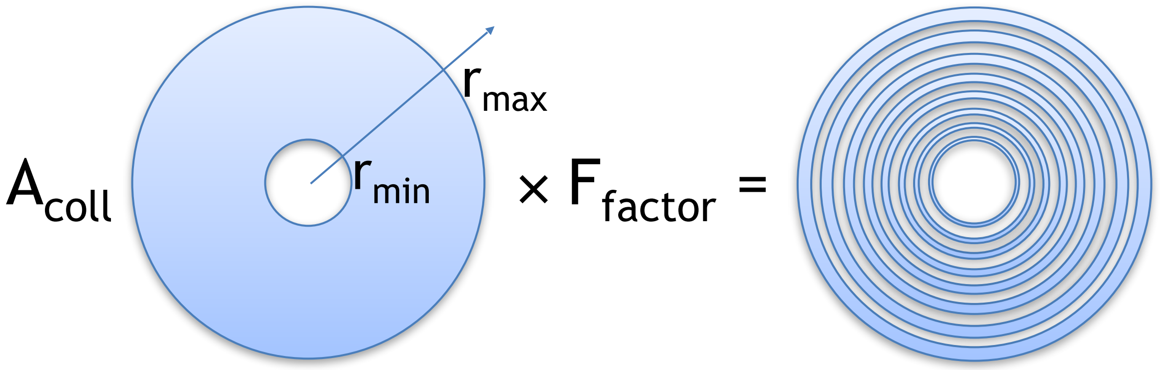
- What do we want?

  - ***Effective area:***

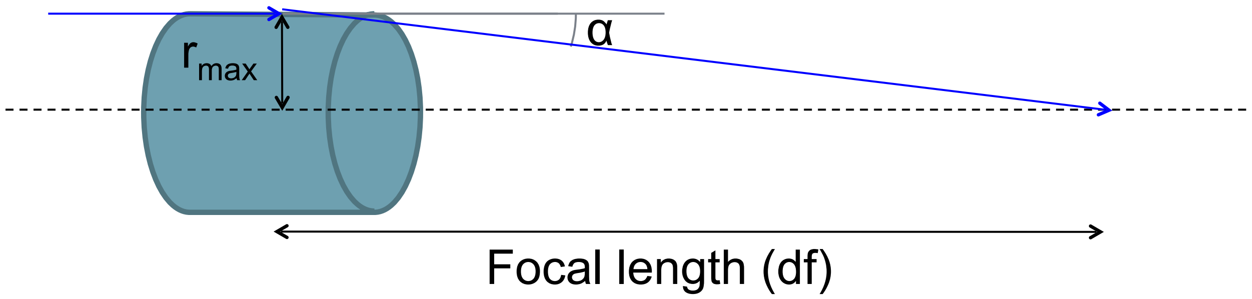
$$A_{eff} = A_{coll} \times R^2_{(\alpha,E)}$$

$$A_{eff} = \pi\left(r^2_{\max} - r^2_{\min}\right) \times F_{factor} \times R^2_{(\alpha,E)}$$

$$A_{eff} \propto r^2_{\max} \propto d_f{}^2$$



$$r_{\max} = d_f \times \tan(4\alpha) \propto d_f$$



  - ***Sensitivity:***

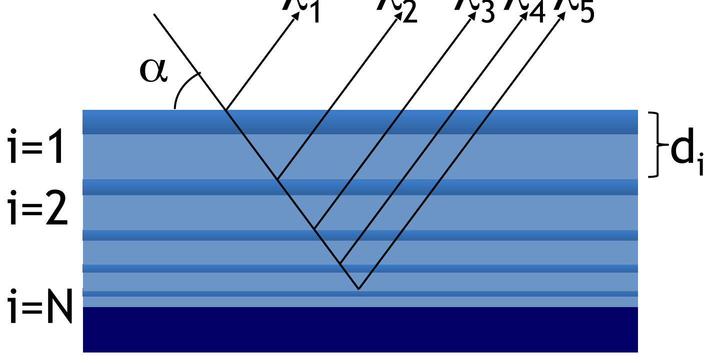
$$\frac{S}{N} \propto \frac{A_{eff}}{\sqrt{B \times A_{psf}}} \propto focal$$

$$A_{PSF} = \pi\left(\tan(HEW) \times d_f\right)^2 \propto d_f^2$$

  - ***Angular resolution:***
    -> good mirror quality
  - ***Field of View:***
    FoV ~ 1/α ~ 1/df

Hard X-ray telescopes simulation and design

- Mirror coatings design



$$d_i = \frac{a}{(b+i)^c}$$

Reflectivity at the surface R(E,α):

$$\begin{cases} R = \left|R_0\right|^2 \\ R_j = a_j^4\left(\dfrac{R_{j+1}+r_j}{R_{j+1}\times r_j+1}\right) \end{cases} \text{with} \quad \begin{aligned} a_j &= \exp\left(-i\frac{\pi}{\lambda}g_j d_j\right) \\ g_j &= \left(n_j^2-\cos^2\theta\right)^{\frac{1}{2}} \end{aligned}$$

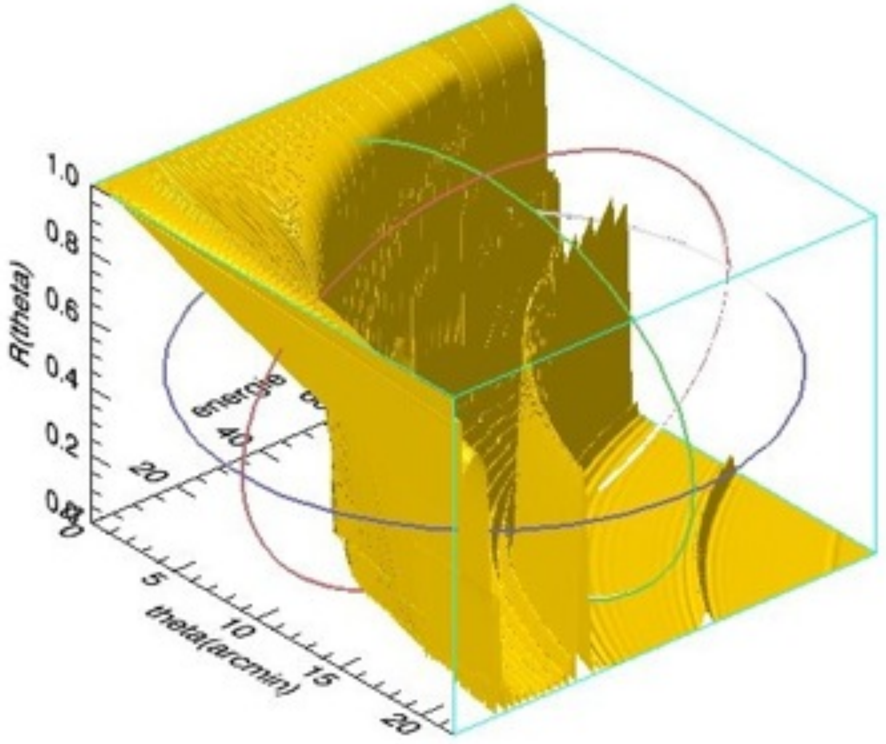
(Joensen et al., applied optics, 1995)

Simulation inputs:

- high Z material (Pt)
- low Z material (C)
- number of layers (100)
- 100 layers
- thickness range (d = 3.55 – 14.14 nm)
- distribution parameters
  (a = 3.55, b = 0, c = 0.3)

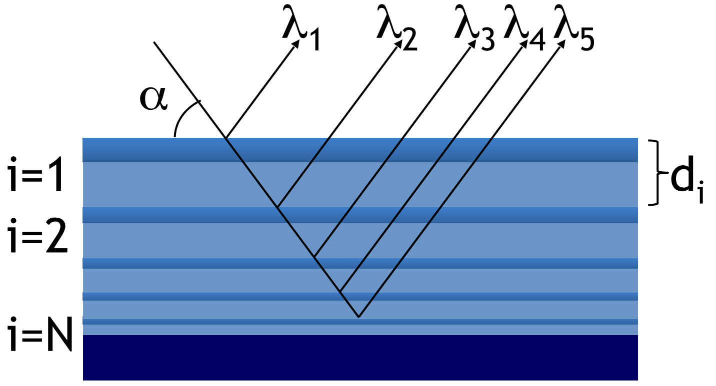
Simulation outputs:

- Reflection coefficient matrix R(E,α)



Hard X-ray telescopes simulation and design

- Mirror coatings design



$$d_i = \frac{a}{(b+i)^c}$$

Reflectivity at the surface R(E,α):

$$R = |R_0|^2$$

$$R_j = a_j^4 \left(\frac{R_{j+1} + r_j}{R_{j+1} \times r_j + 1} \right) \text{with} \quad a_j = \exp\left(-i \frac{\pi}{\lambda} g_j d_j \right) \quad g_j = \left(n_j^2 - \cos^2 \theta \right)^{\frac{1}{2}}$$

(Joensen et al., applied optics, 1995)

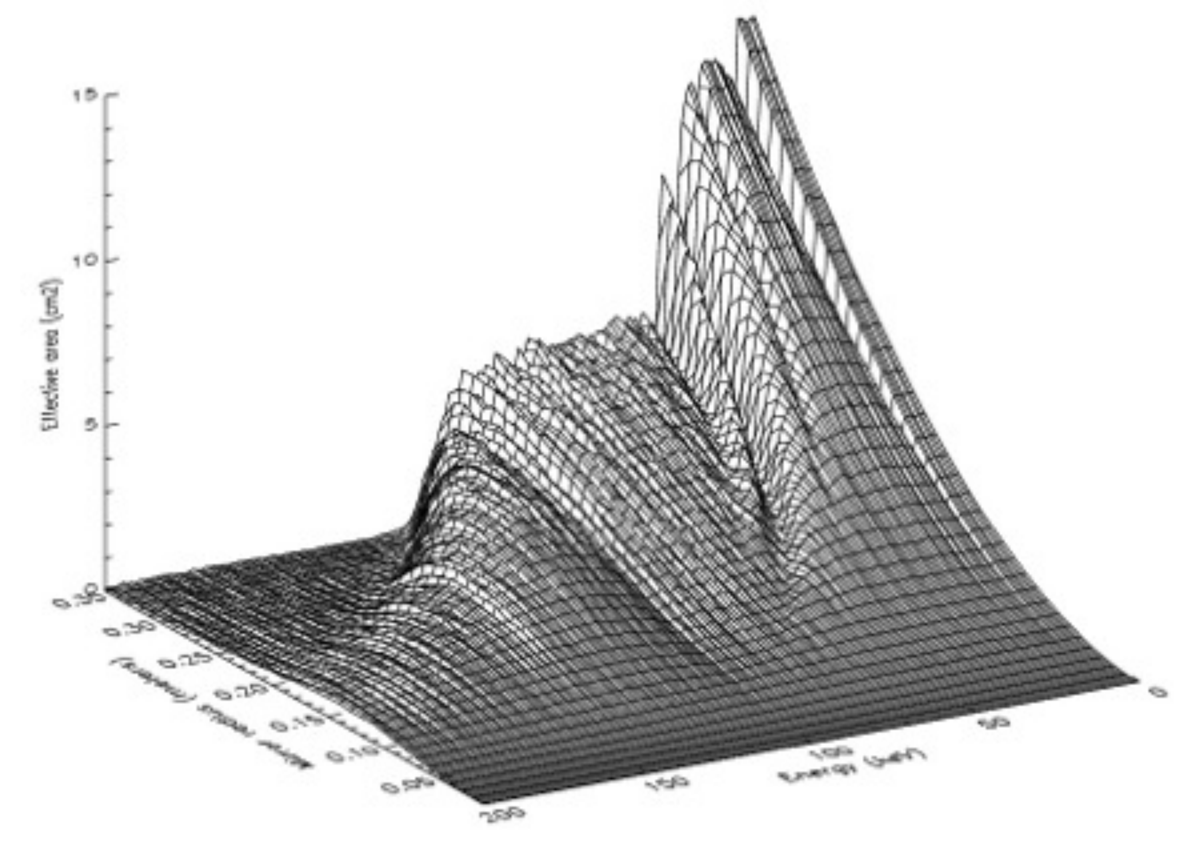
Simulation inputs

Mirror Coating:
- material Co/C
- 1100 layers
- thickness d = 2.75 – 29.19 nm
- a = 6.33, b = -0.91, c = 0.25

Mirror parameters:
- 300 Wolter-I mirrors
- radius: 5 – 35 cm
- focal length: 40 m
- mirror length: 100 cm

Simulation outputs:

- Effective area for one mirror:



Hard X-ray telescopes simulation and design

- Focal length choice

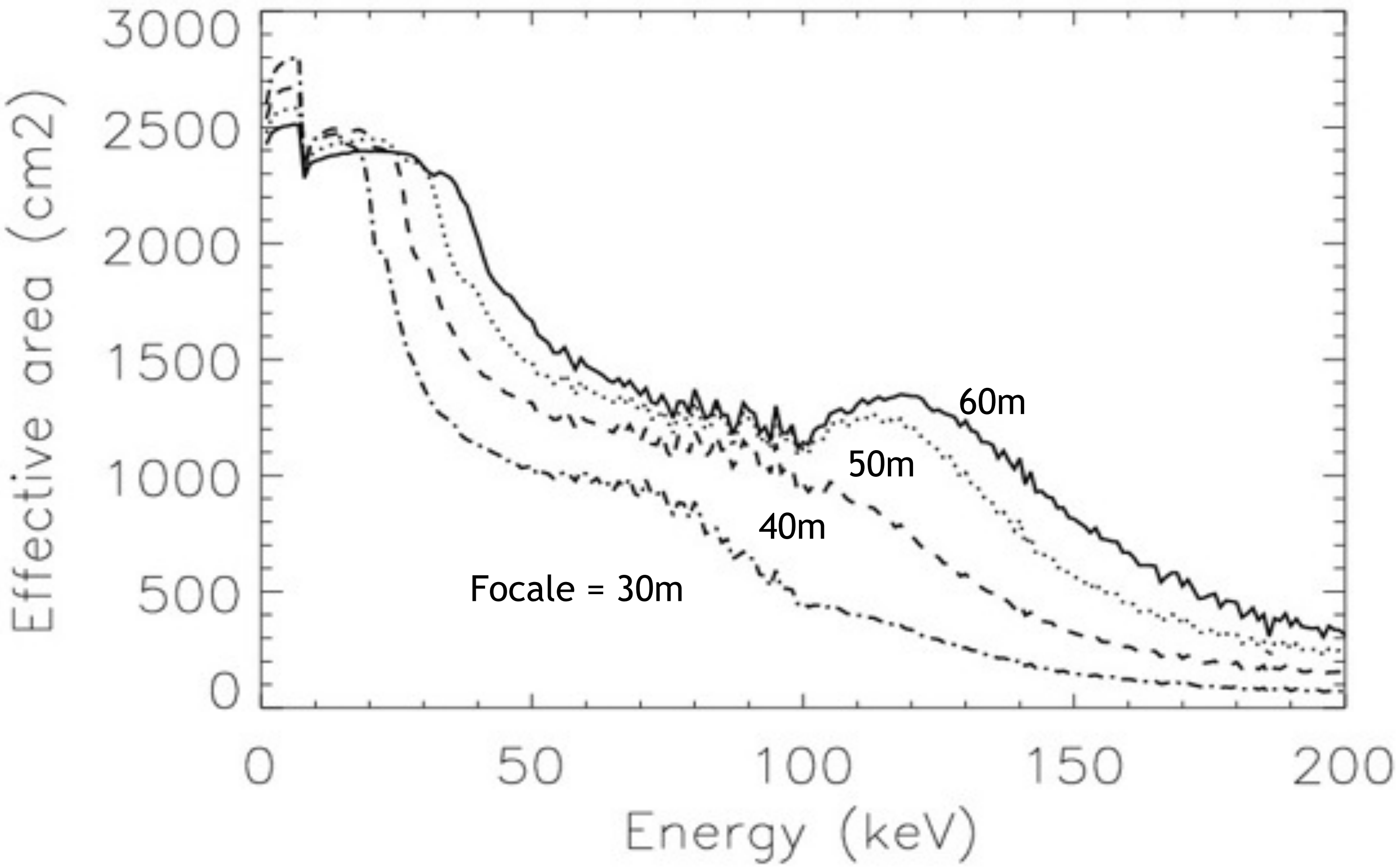
Simulation inputs

Mirror Coating:

- material Co/C
- 1100 layers
- thickness d = 2.75 – 29.19 nm
- a = 6.33, b = -0.91, c = 0.25

Mirror size:

- 300 Wolter-I mirrors
- radius: 5 – 35 cm
- focal length: 30 - 60 m
- mirror length: 100 cm



Hard X-ray telescopes simulation and design

- Mirror radius and mass

Simulation inputs

Mirror Coating:

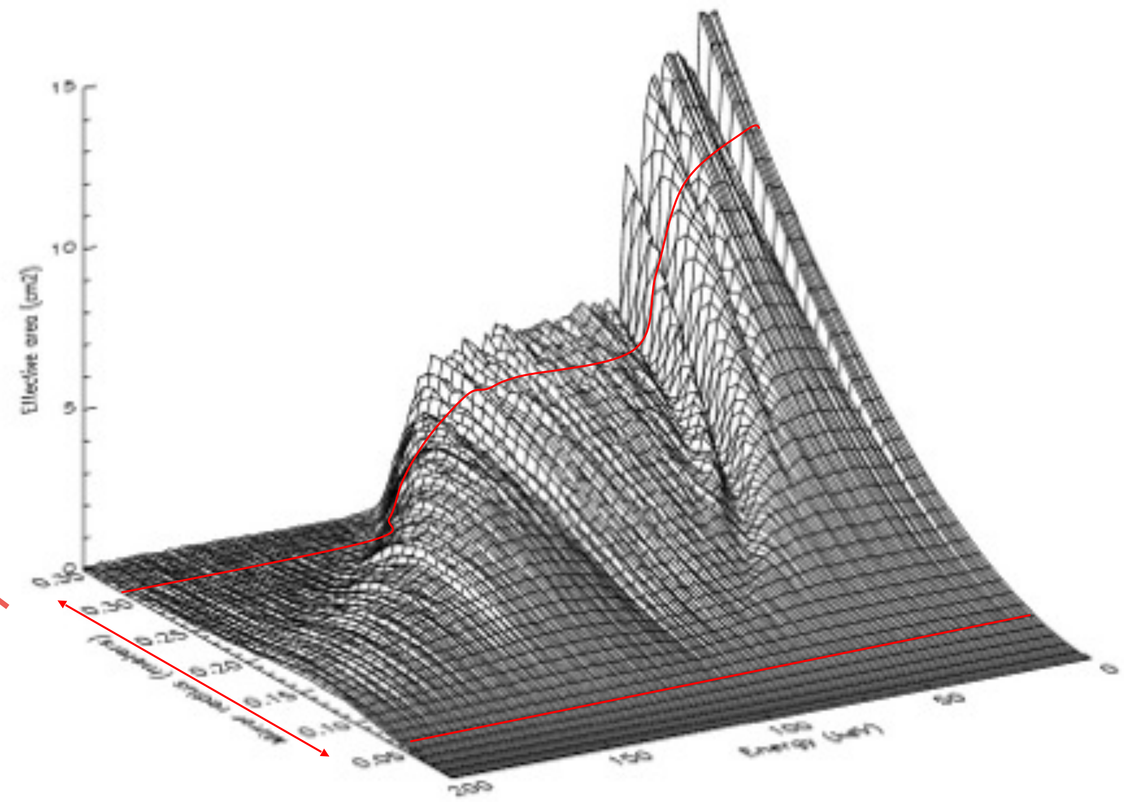
- material Co/C
- 1100 layers
- thickness d = 2.75 – 29.19 nm
- a = 6.33, b = -0.91, c = 0.25

Mirror size:

- 260 Wolter-I mirrors
- radius: 5 – 31 cm
- focal length: 40 m
- mirror length: 100 cm

Simulation outputs:

- Effective area for one mirror:



To reduce mass -> remove the outer mirrors

Hard X-ray telescopes simulation and design

- Number of mirror modules

+ More effective area $A_{total} = A_{eff} \times n$

+ More sensitivity $S_{total} = S \times \sqrt{n}$

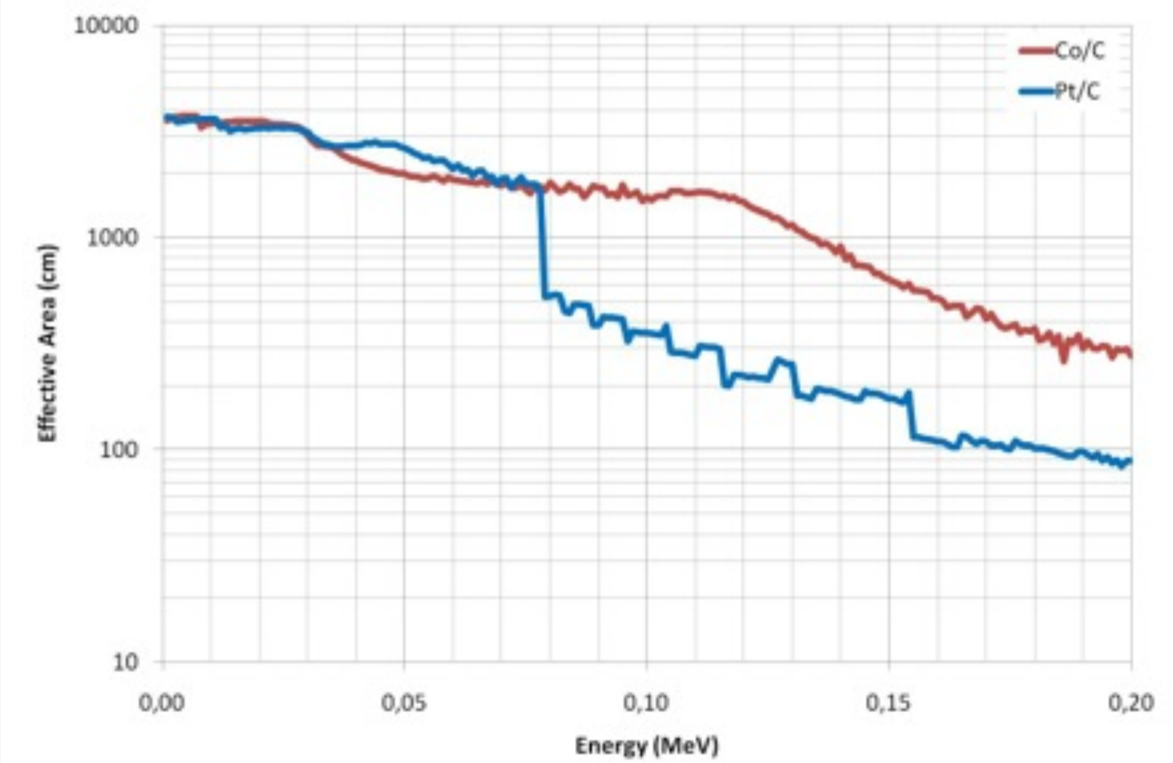
+ Redundancy

- More mass $M_{total} = M_{\mathrm{module}} \times n$

Simulation inputs

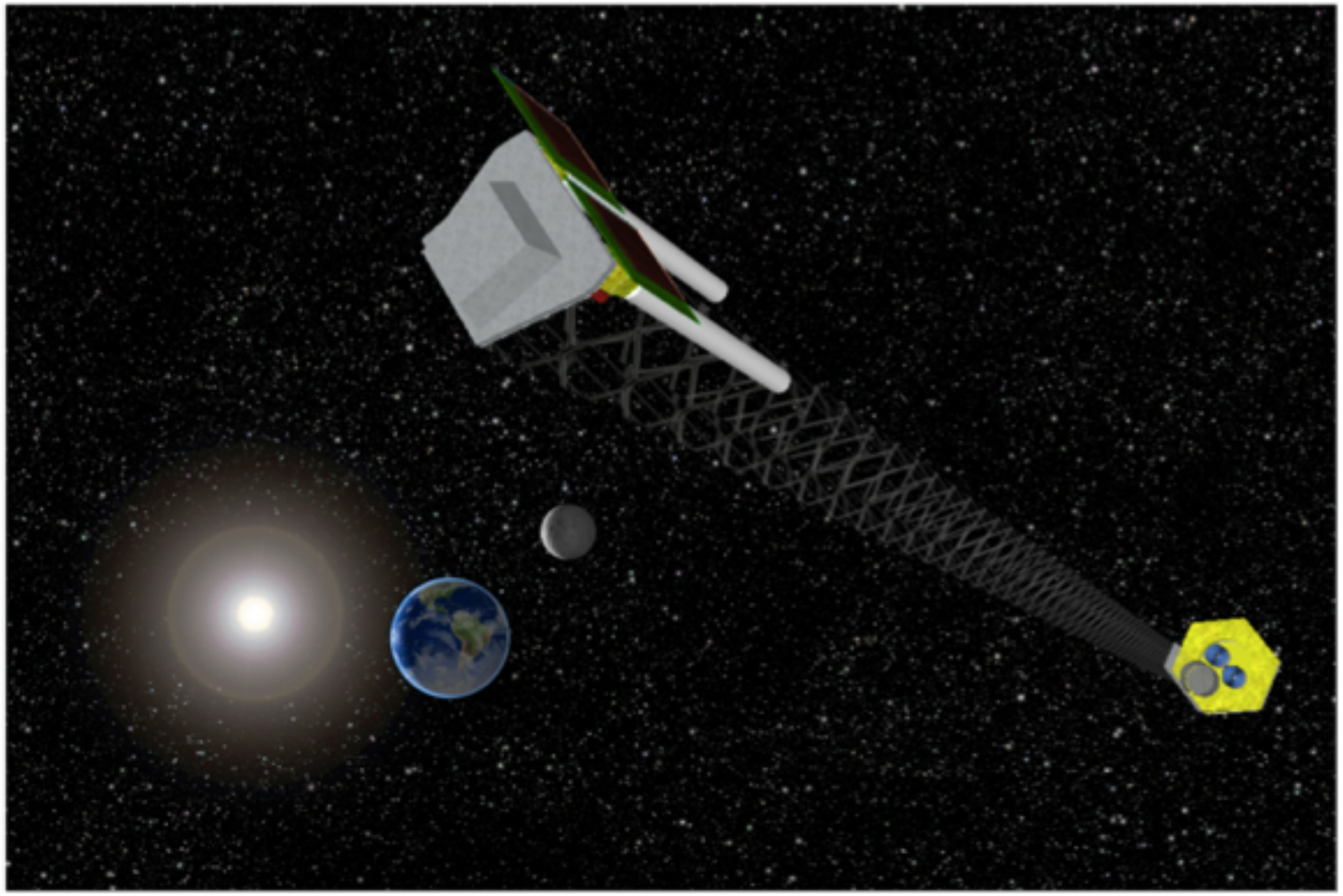
Mirror Coating:
- material Co/C
- 1100 layers
- thickness d = 2.75 – 29.19 nm
- a = 6.33, b = -0.91, c = 0.25

2 mirror modules:
- 260 Wolter-I mirrors
- radius: 5 – 31 cm
- focal length: 40 m
- mirror length: 100 cm



Hard X-ray telescopes simulation and design

- Extending Focalization to 200 keV with PheniX

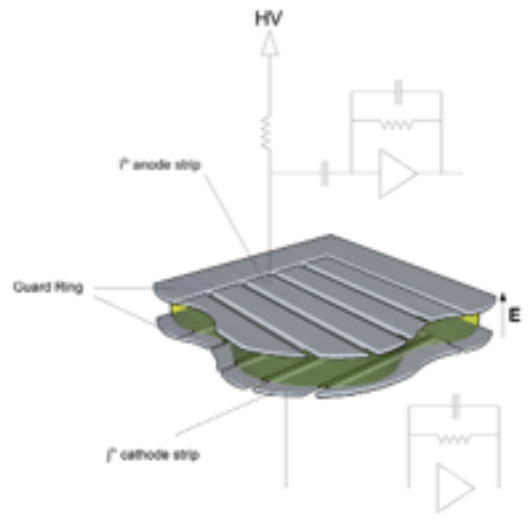


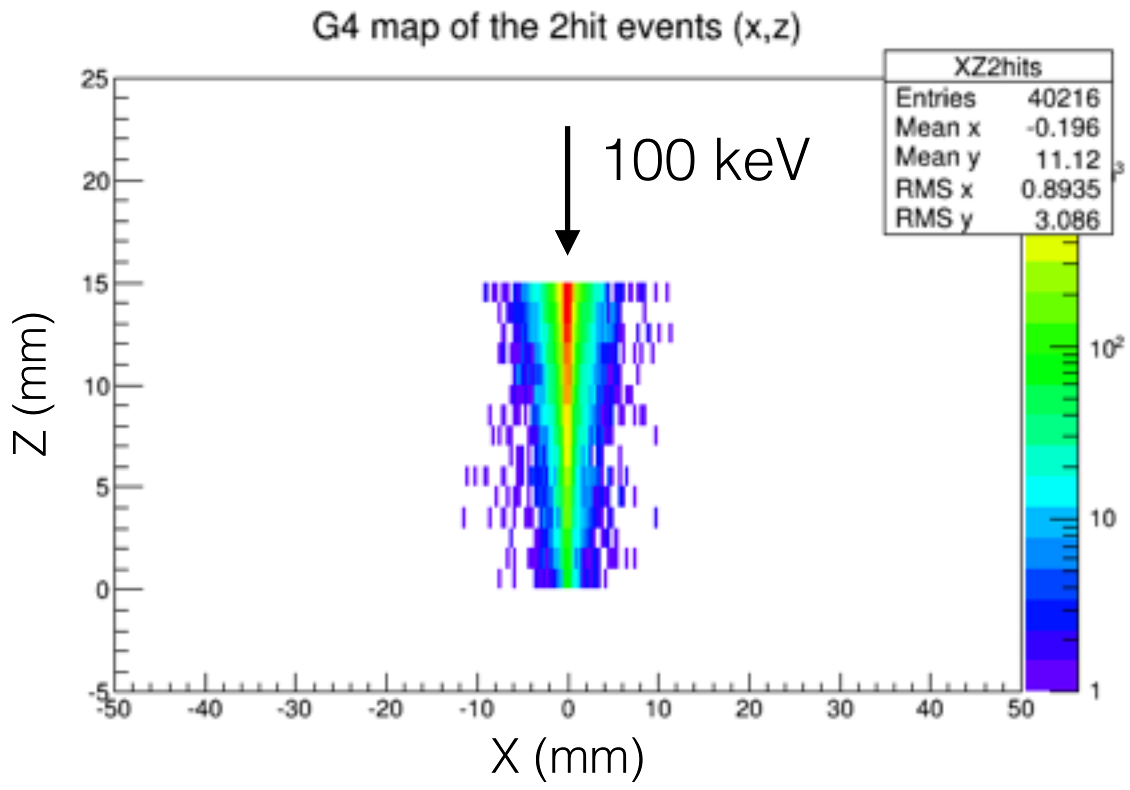
Mission proposal to ESA in the framework of the 2011 M3 call:
Roques, J.P. et al., "PheniX: a new vision for the hard X-ray sky", Exp. Astron., DOI 10.1007/s10686-011-9236-3 (2011)

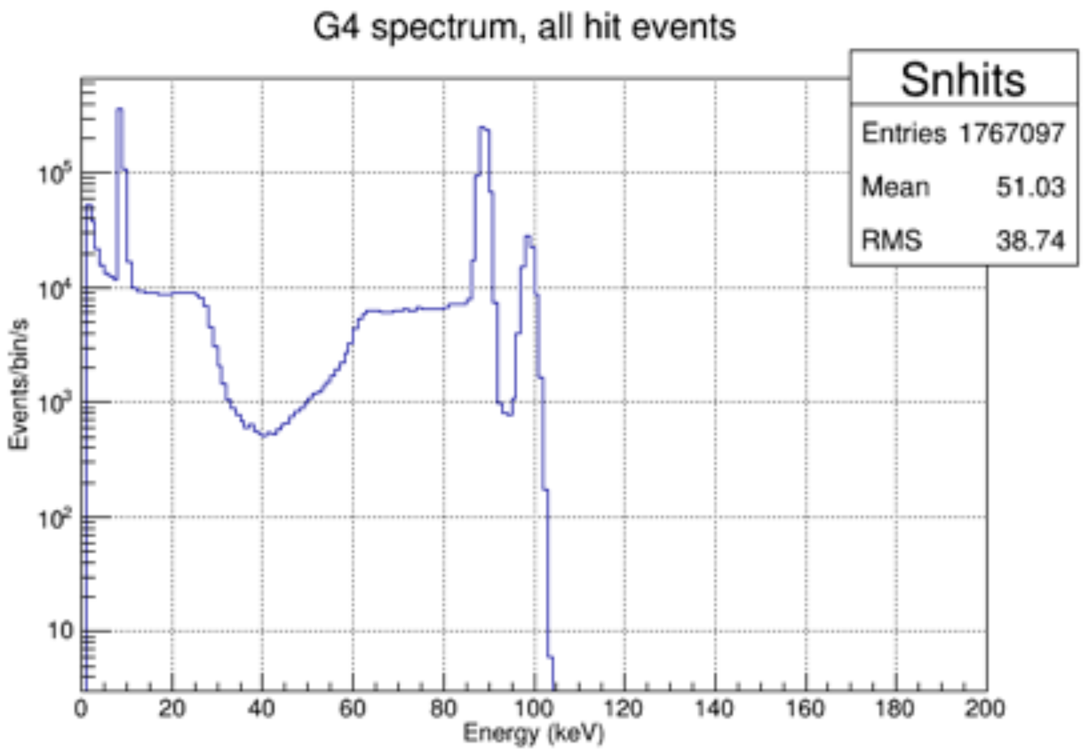
Hard X-ray telescopes simulation and design

- **Extending Focalization to 200 keV with PheniX**
  - Detector design: Geant4 simulation

Energy range	1 - 200 keV
Size	*8cm × 8cm × 1.5cm*
Strips	*160 × 2*
3D resolution	*0.4 mm × 0.4 mm × 1 mm*
Timing resolution	*< 100 ns*
Energy resolution	*400 eV @ 100 keV*



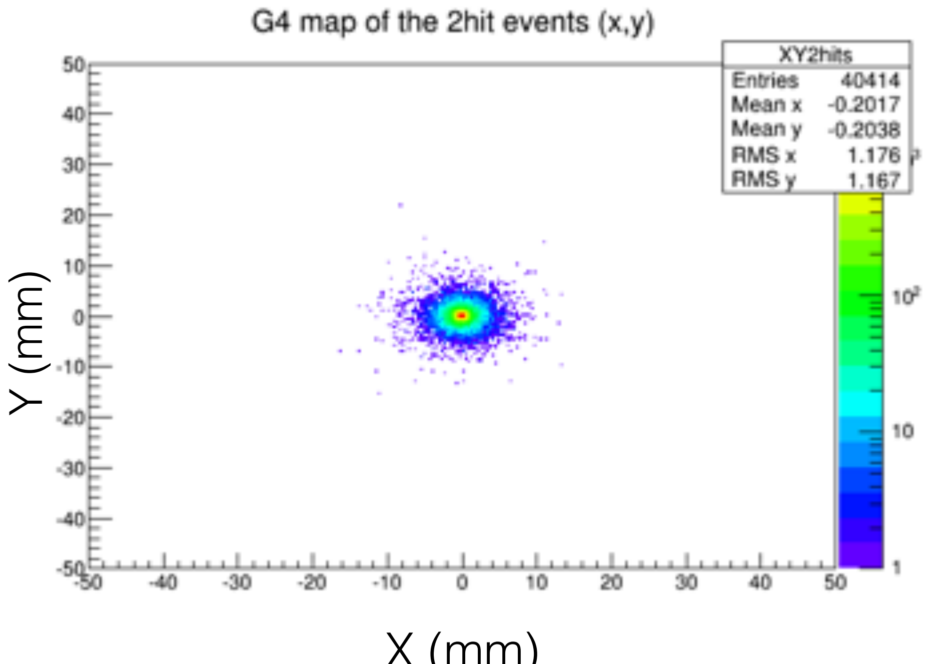


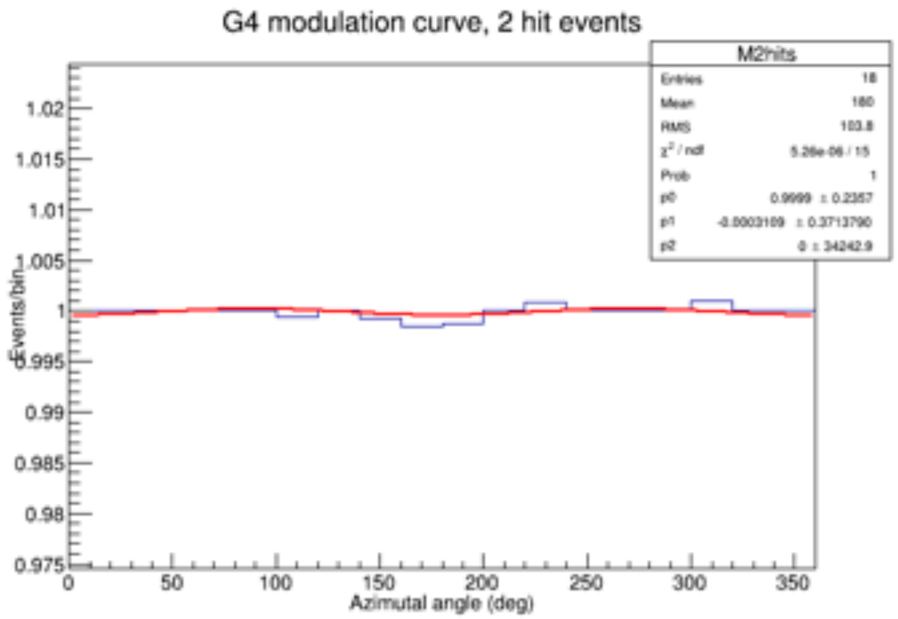


Hard X-ray telescopes simulation and design

- **Extending Focalization to 200 keV with PheniX**
  - Detector design: Geant4 simulation

100 keV
0% polarised

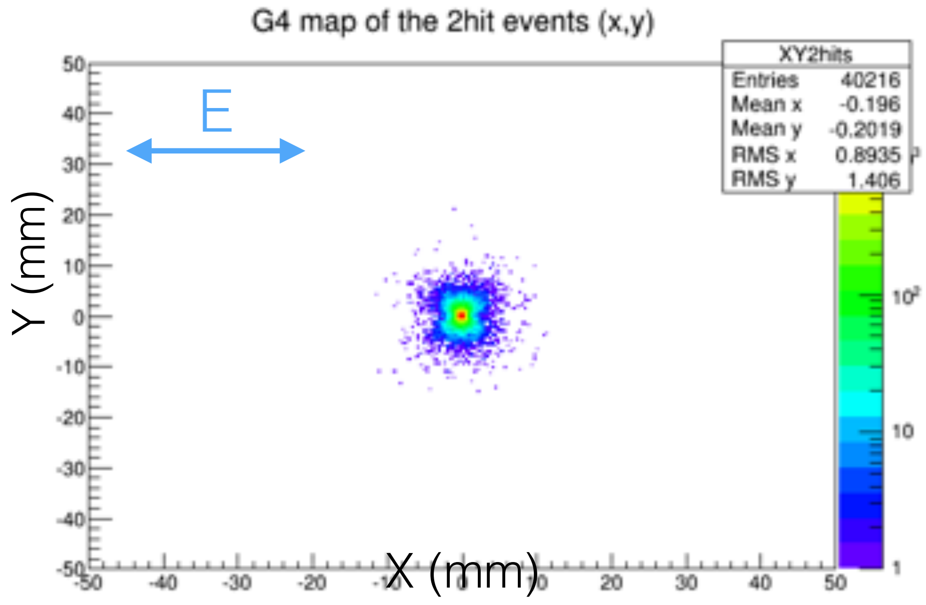


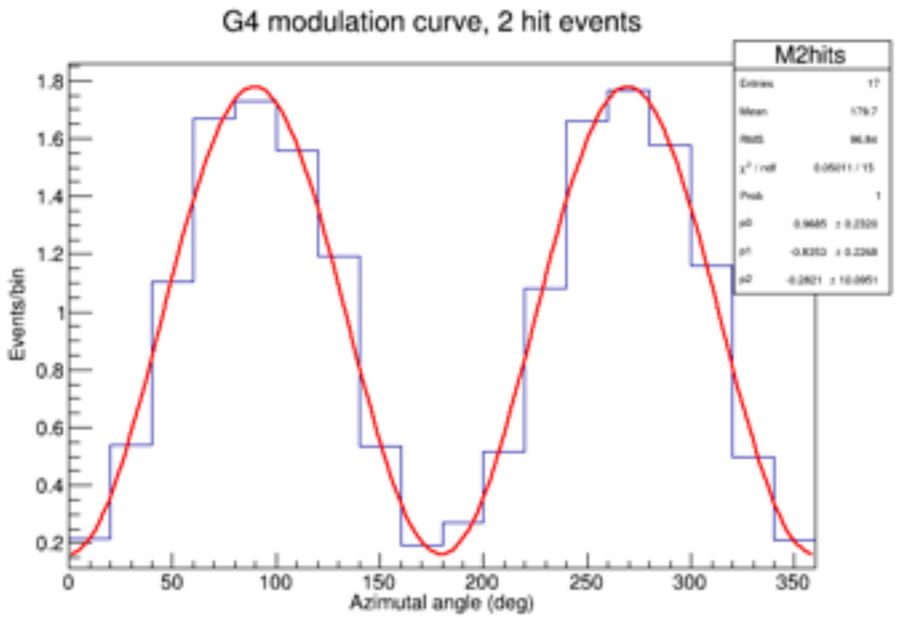


MF
0%

assuming a 3D positioning of 0.4 * 0.4 * 1 mm
selecting events scattering at 90°

100 keV
100% polarised

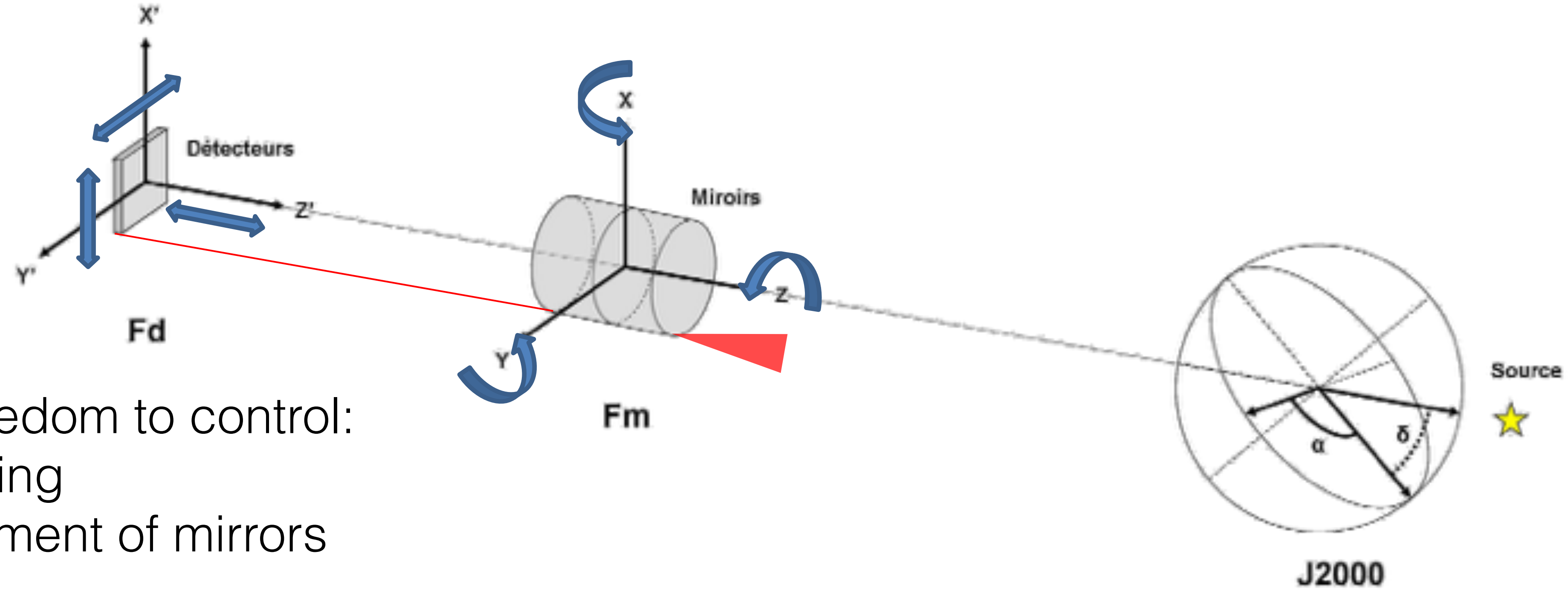




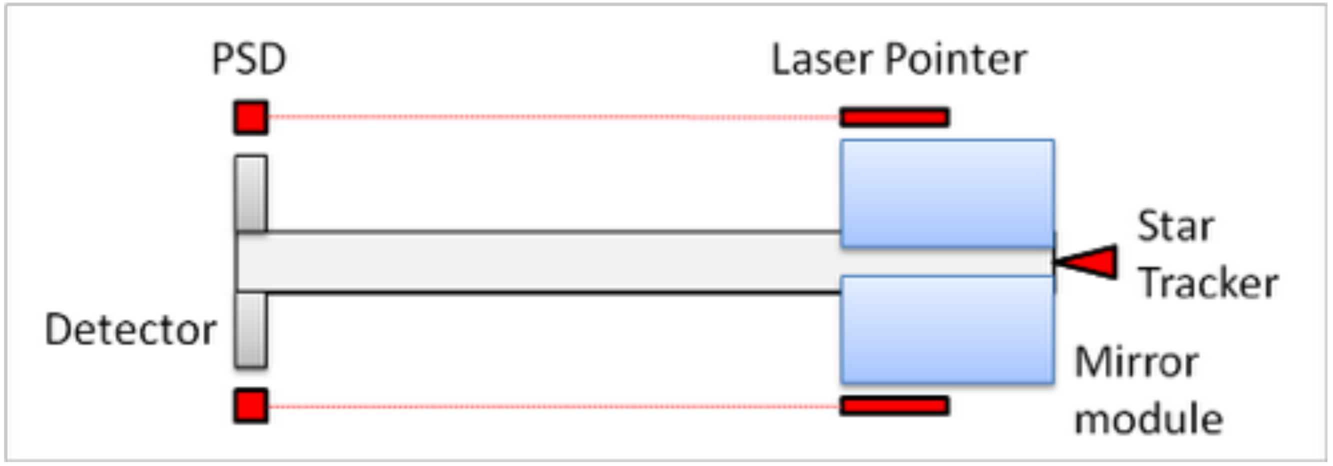
MF
83.5%

Hard X-ray telescopes simulation and design

- Extending Focalization to 200 keV with PheniX
  - Structure control and metrology



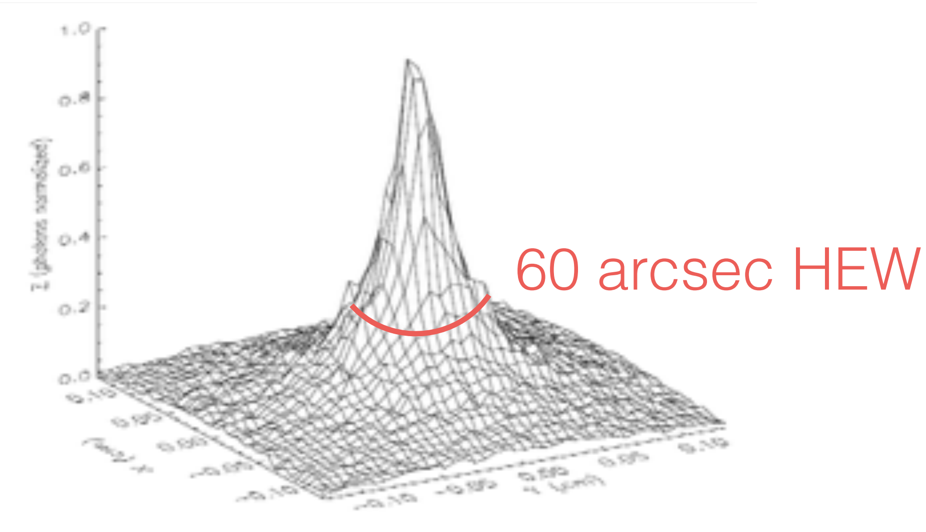
6 degrees of freedom to control:
- 3 for the pointing
- 3 for the alignment of mirrors and detectors

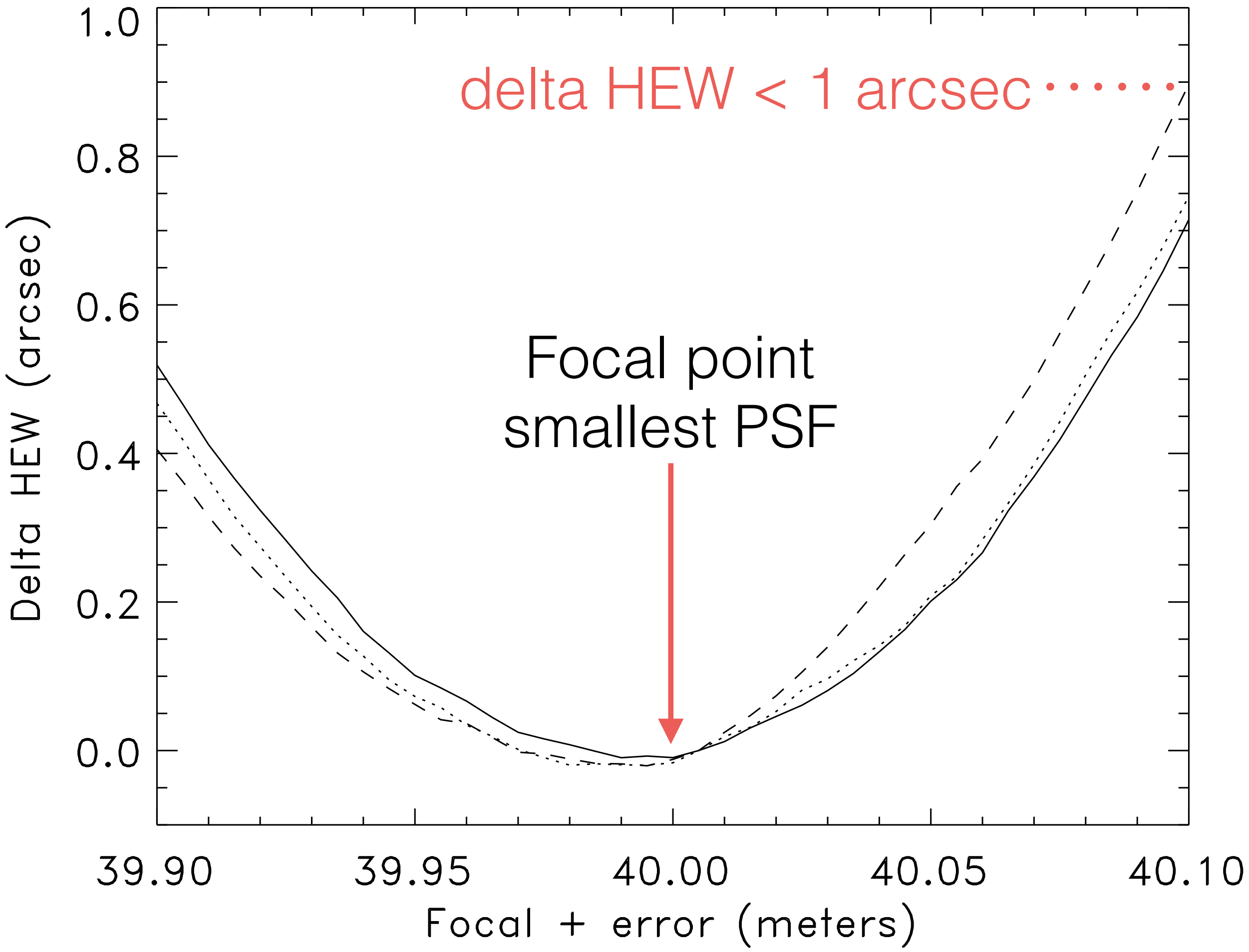


Metrology:
- 1 star tracker
- 1 simple non imaging sensor for alignment

Hard X-ray telescopes simulation and design

- **Extending Focalization to 200 keV with PheniX**
  - Structure control and metrology

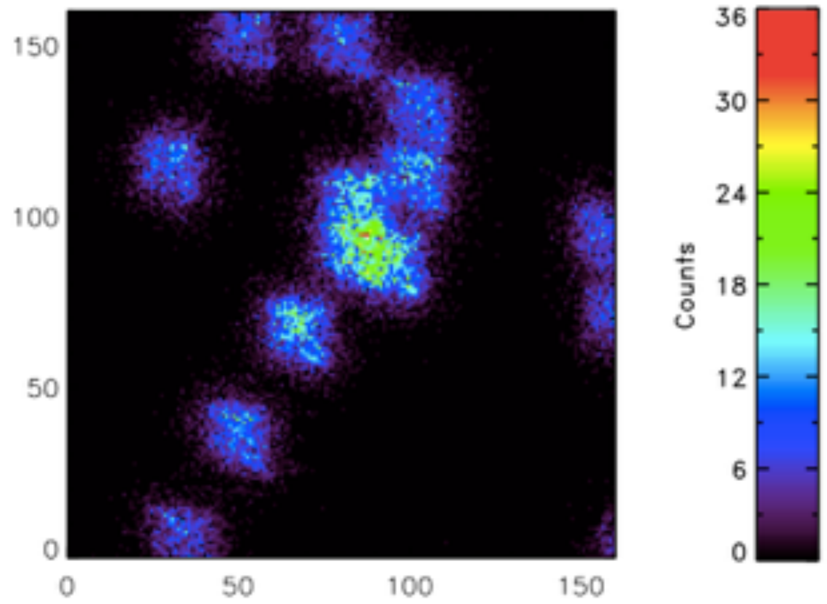




	Control	Metrology
Pointing	*±20 arcsec*	*< 10 arcsec*
Z alignment (focus)	*±10 cm*	*-*
X and Y alignment	*±0.5 cm*	*0.1 mm*

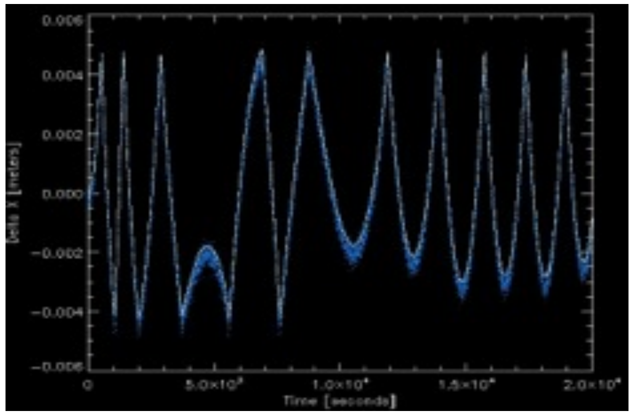
Hard X-ray telescopes simulation and design

- **Extending Focalization to 200 keV with PheniX**
  - Structure control and metrology



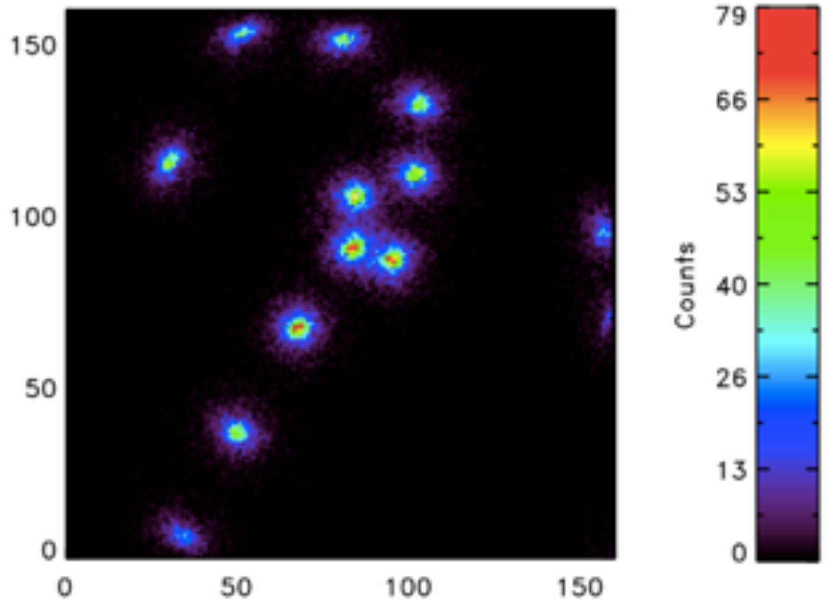
Live image with 0.5cm x y drifts

+



Simulated x y drift measurement

=

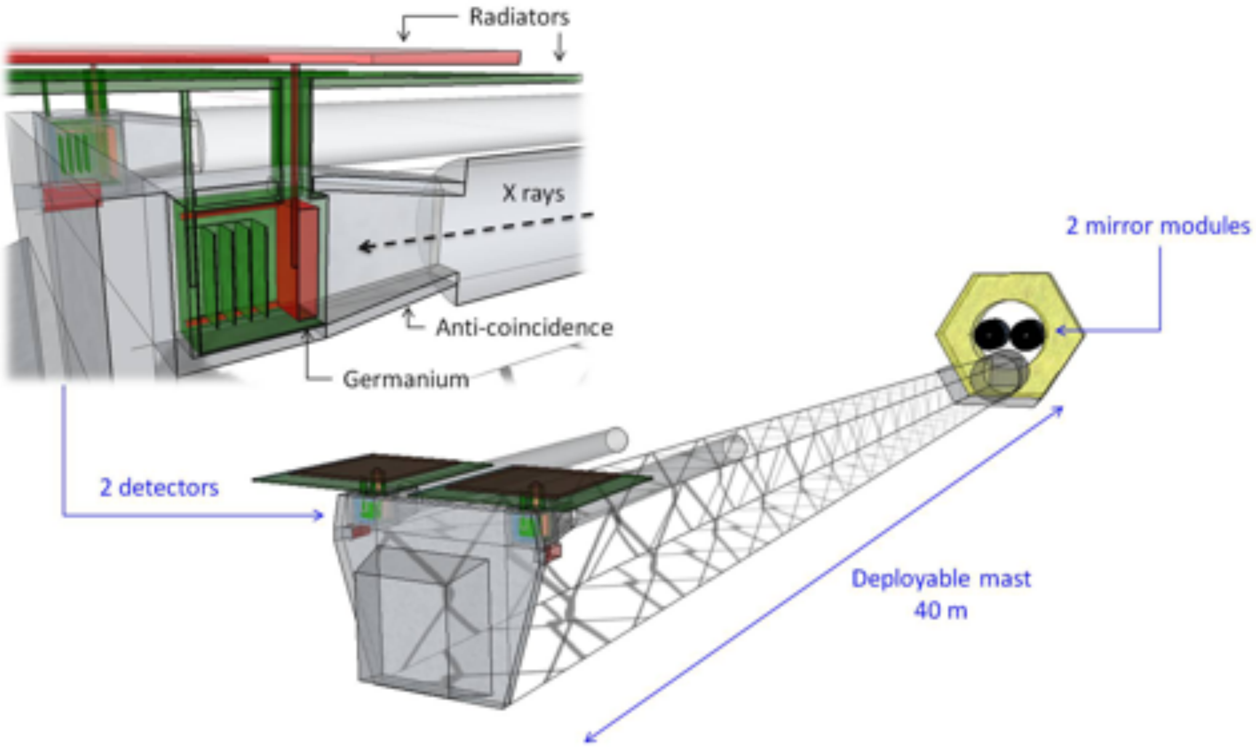


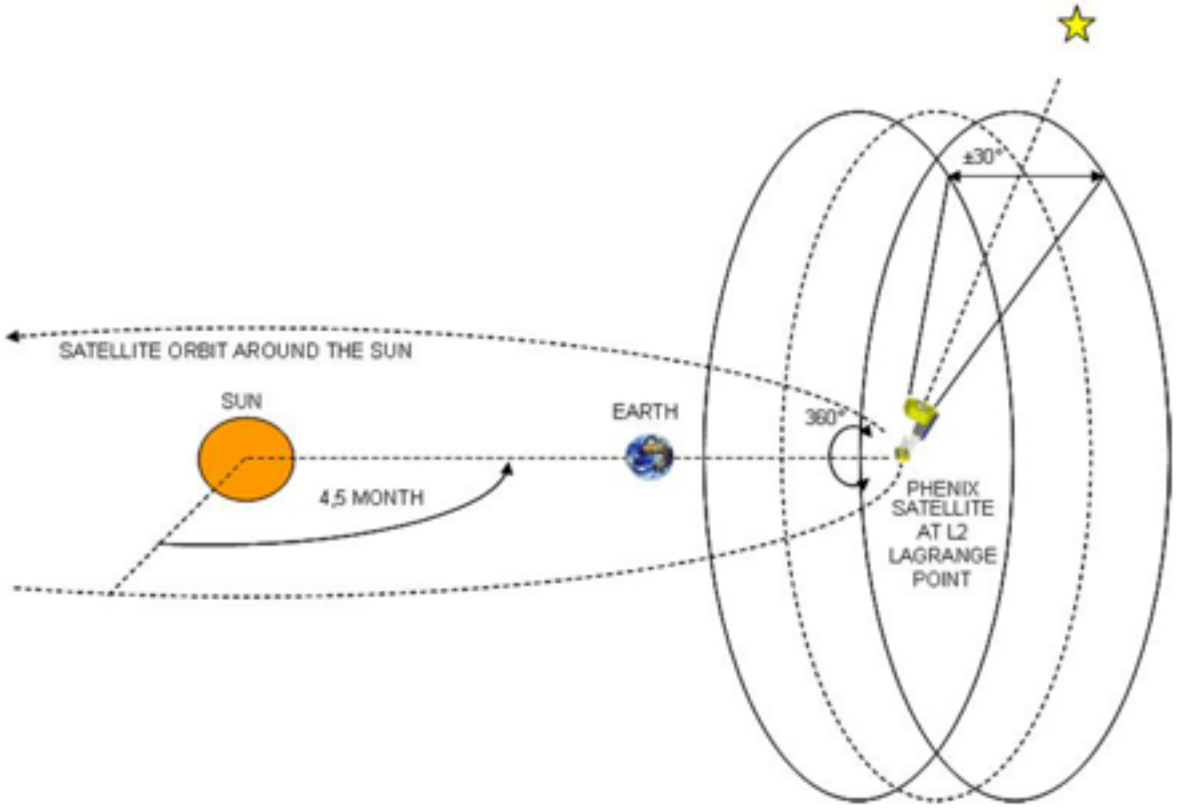
Corrected image

	Control	Metrology
Pointing	*±20 arcsec*	*< 10 arcsec*
Z alignment (focus)	*±10 cm*	*-*
X and Y alignment	*±0.5 cm*	*0.1 mm*

Hard X-ray telescopes simulation and design

- **Extending Focalization to 200 keV with PheniX**
  - Overview

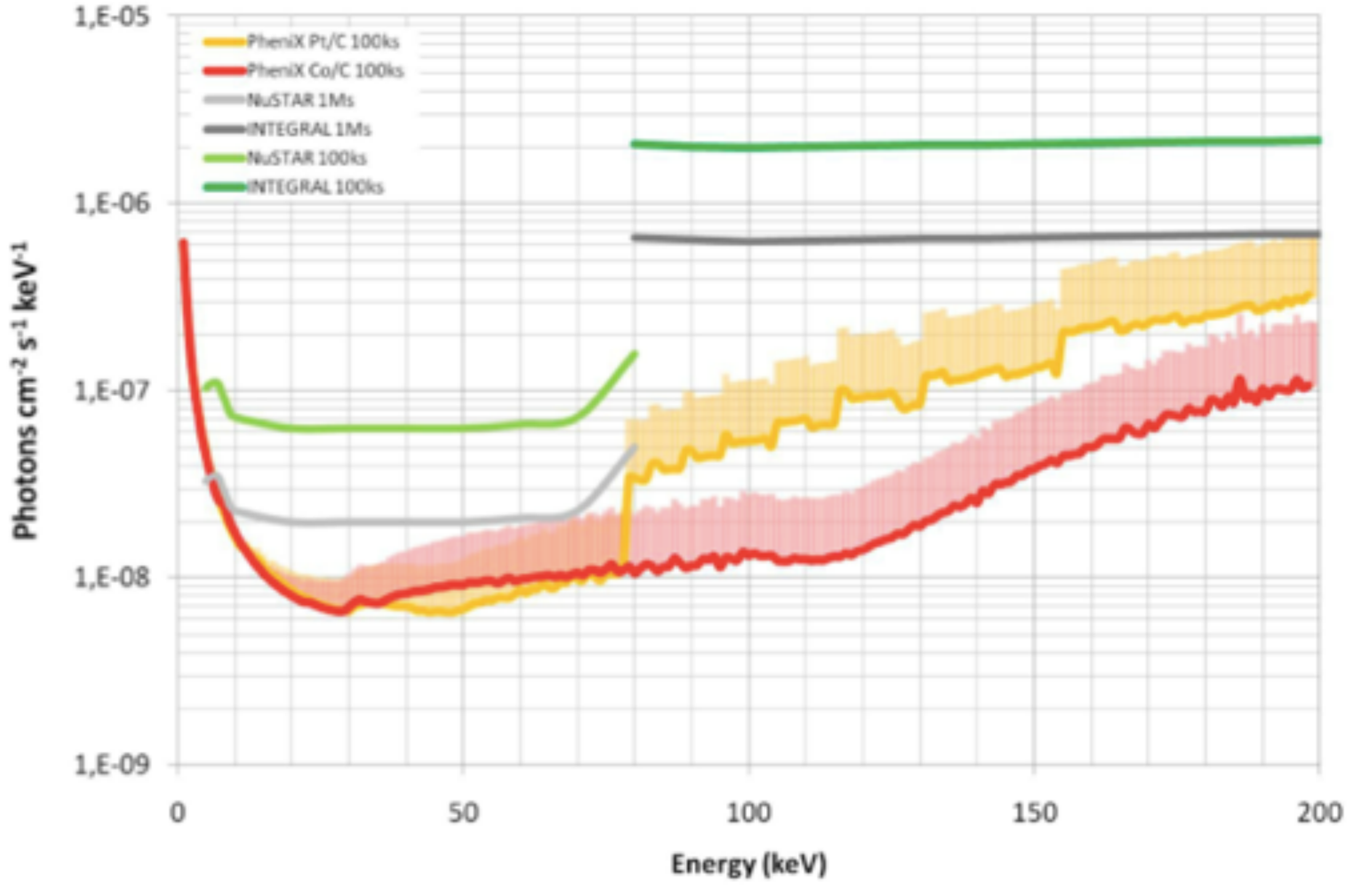




Hard X-ray telescopes simulation and design

- Extending Focalization to 200 keV with PheniX
  - Expected performance

Energy range	1 – 200 keV
Sensitivity	10-8 ph/cm2/s/keV
Angular resolution	20 arcsec @ 30 keV 80 arcsec @ 100 keV
Energy resolution	150 eV @ 6 keV 400 eV @ 100 keV
Polarization	1% 0.1Crab in 100ks



The continuum sensitivity of PheniX for 100 ks observations, based on a 3σ detection with dE/E = 0.5 and an internal background of ~1e–5 c cm–2 s–1 keV–1. The shaded area demonstrates the sensitivity if the background is greater at ~5e–5 c cm–2 s–1 keV–1. For comparison the INTEGRAL and NuSTAR sensitivities are plotted for 100 ks and 1 Ms

Hard X-ray telescopes simulation and design

- Extending Focalization to 200 keV with PheniX
    - Expected performance

Energy range	1 – 200 keV
Sensitivity	10-8 ph/cm2/s/keV
Angular resolution	20 arcsec @ 30 keV 80 arcsec @ 100 keV
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