X-ray Telescopes

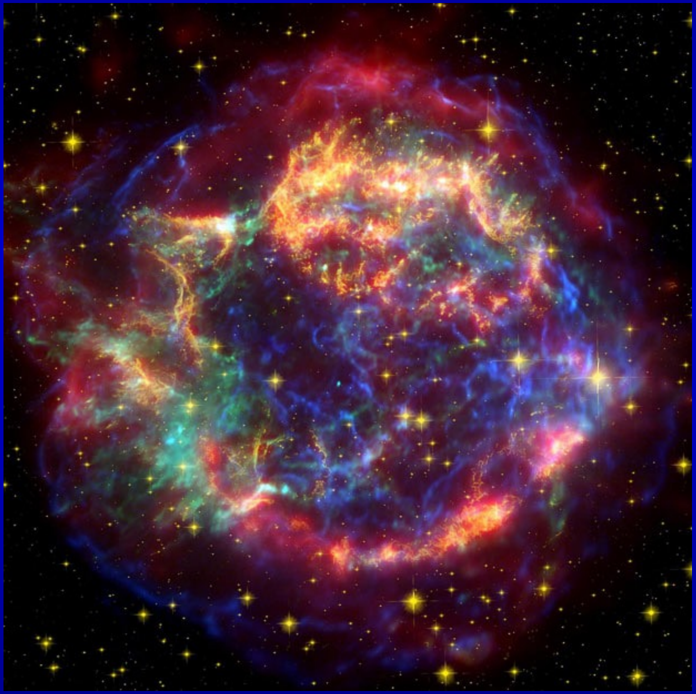
Optics Design, Technology and Performance

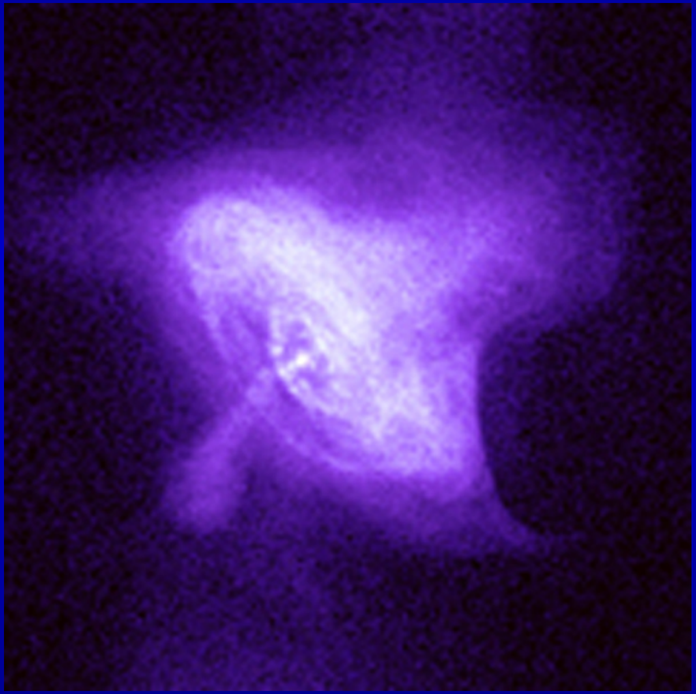
Astroparticle School, OHP, 23-28 May, 2016

Professor Dick Willingale
X-Ray and Observational Astronomy
&
Space Science Instrumentation
University of Leicester
UK

How do they do that?

Soft X-ray (0.3-10 keV) images with ~1″ resolution





Cassiopeia A NASA/CXC/SAO Crab Nebula

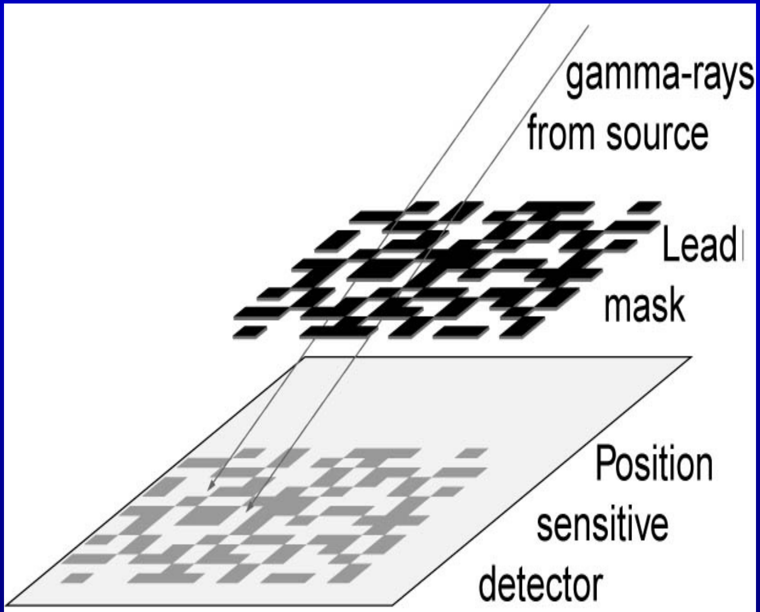
Overview of lecture

- Basic physics for imaging X-rays
- Geometry for imaging X-rays
- Past and present X-ray telescopes
- New X-ray optics technologies
- Future X-ray telescopes
- The diffraction limit…
- Performance and calibration

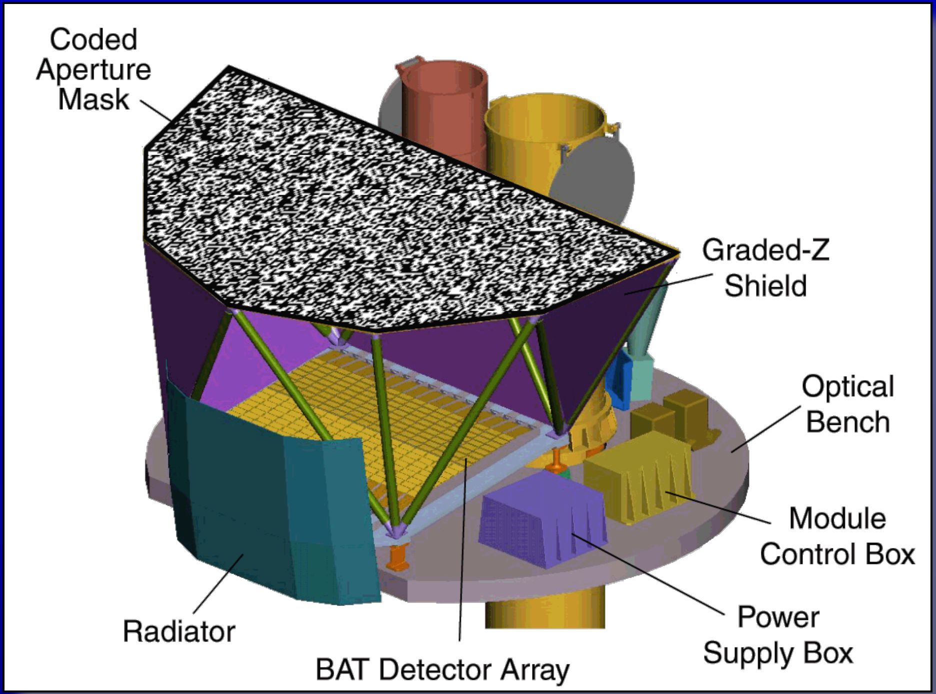
Basic Physics for Imaging X-rays

- Absorption
  - Shadow mask imaging – multiplexing advantage (over pin-hole camera) – each detector pixel sees many sky pixels
  - but no focusing advantage

Source casts gamma-ray shadow on detector - location of shadow yields location of source

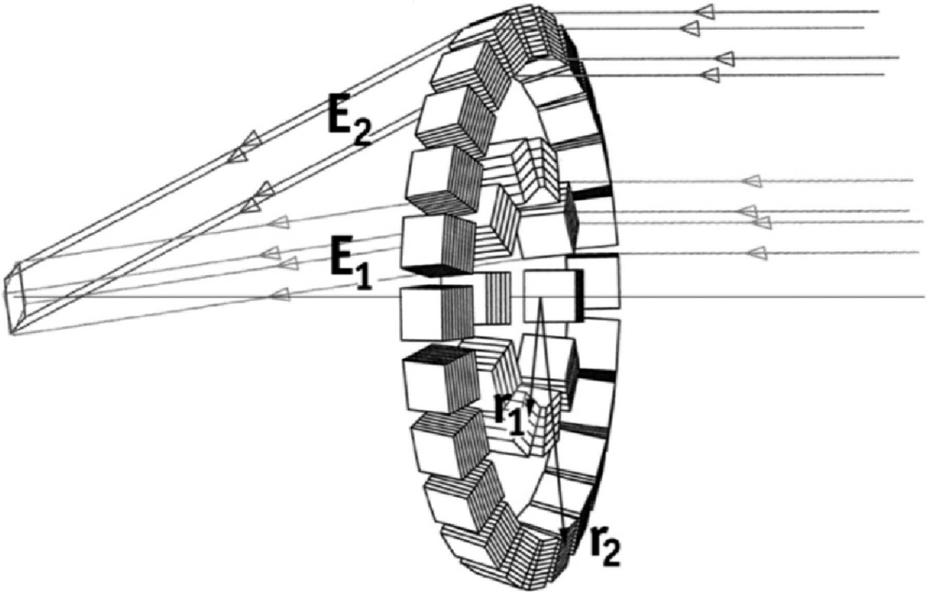


Swift BAT

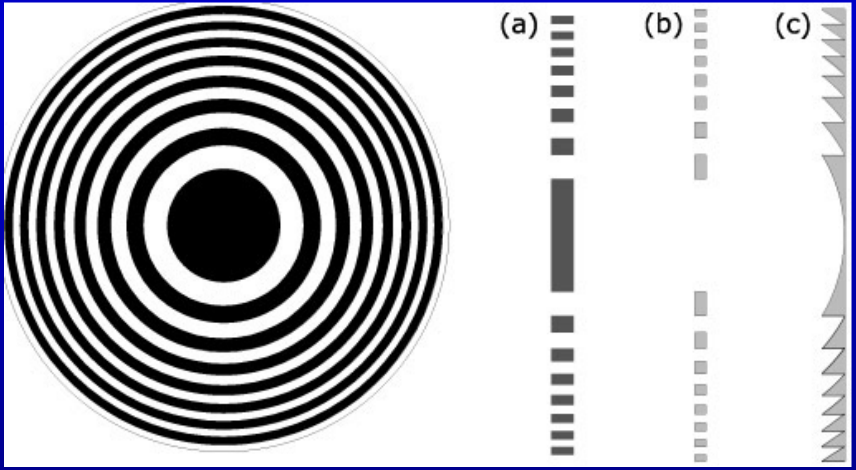


Basic Physics for Imaging X-rays

- Diffraction
  - Imaging using Bragg (crystal) reflection – Laue lens – chromatic
  - Zone plates – chromatic – used for X-ray microscopes
  - Axions and Phase Fresnel Lenses – diffraction gratings with rotational (axial) symmetry – high angular resolution in hard X-ray or Gamma-ray band (Skinner 2004)



Laue lens – narrow band concentrator



Zone plate – narrow band imaging

Basic Physics for Imaging X-rays

- Refraction
  - Fresnel lenses – chromatic and very large focal length
  - Using diffractive-refractive combinations can get achromatic imaging over a restricted energy band (Gorenstein 2005)

Complex refractive index for X-rays in materials

$n=(1-\delta)-i\beta$ δ and β small and +ve

Refraction deviation very small – very long focal lengths

Mass absorption coefficient $\mu=4\pi\beta/\rho\lambda$ dominant – lenses must be very thin

Both δ and β strong functions of λ - chromatic

Basic Physics for Imaging X-rays

- Reflection
  - Fresnel reflection at grazing incidence – achromatic, broad energy band, can give large area combined with high angular resolution - the classical approach for X-ray telescopes
  - Multilayer coatings – high energy reflectivity

Complex refractive index for X-rays in materials

$n=(1-\delta)-i\beta$ δ and β small and +ve

Real part <1 so phase velocity >c

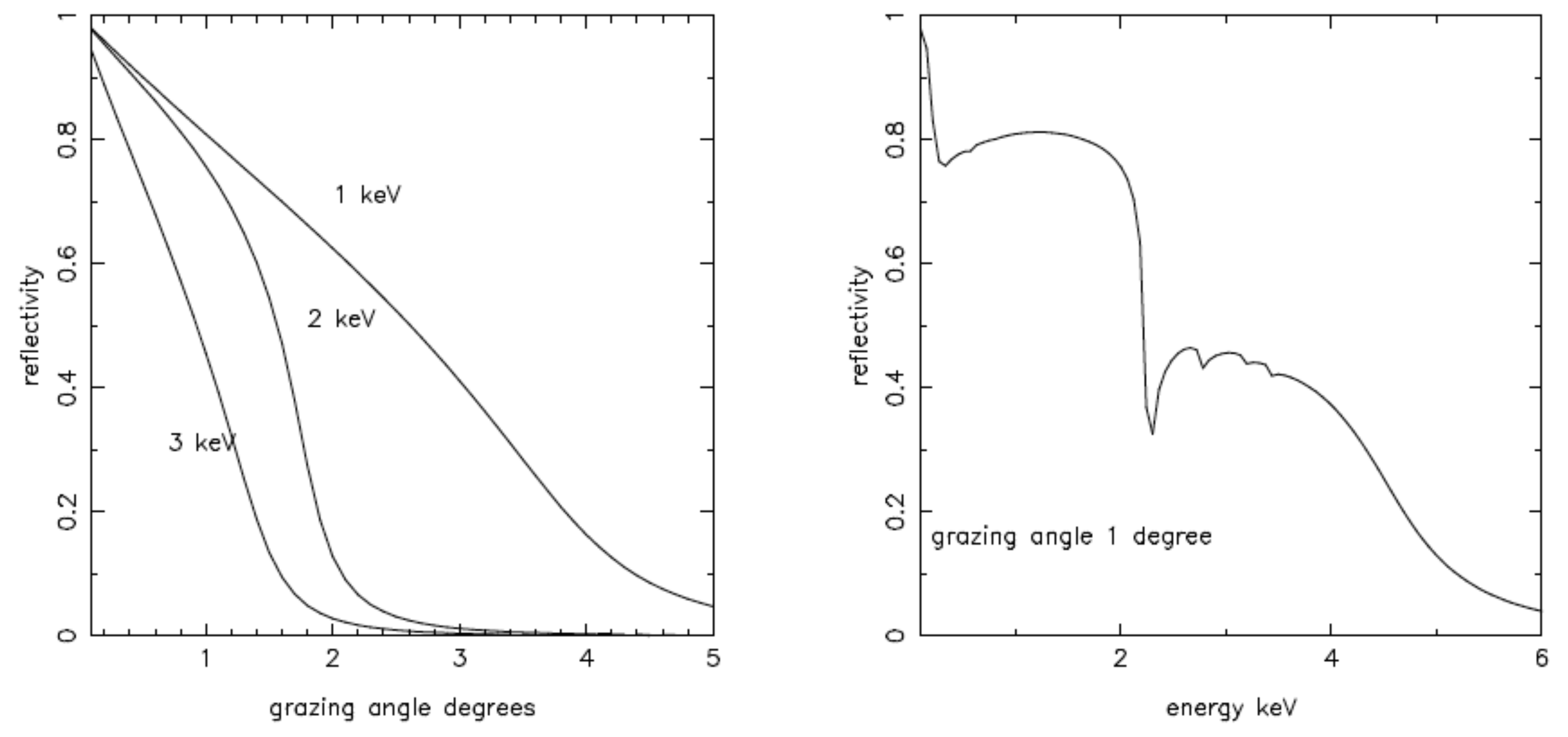
At critical grazing angle $\cos(\theta_t)=1-\delta$ get Total External Reflection

Grazing angles $\theta_t < \sqrt{(2\delta)}$ reflectivity high

X-ray wavelengths λ in Å then $\theta_t \approx 0.1\lambda\sqrt{\rho}$ need Au, Pt, Ir high Z

Basic Physics for Imaging X-rays

Grazing incidence reflectivity from gold

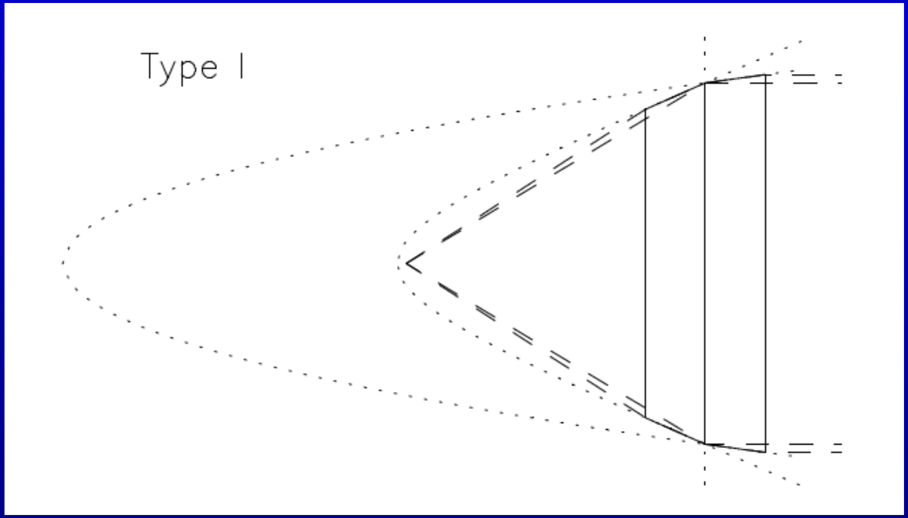


Geometry for Imaging X-rays

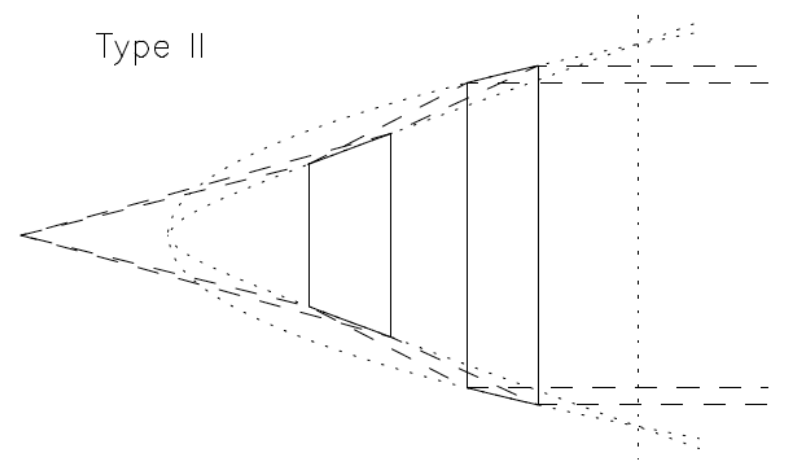
- Shadow projection
  - no focusing advantage but simple geometry
- Focusing advantage
  - must deviate the X-rays in some way using diffraction, refraction or reflection
- Large deviation angles
  - Bragg reflection but highly chromatic and inefficient
- Small deviation angles
  - from diffraction, refraction or reflection – inherently large f-ratio
- Grazing incidence reflection
  - Always require 2 (or even number) grazing incidence reflections to achieve 2 dimensional imaging - reduce/eliminate coma – principal plane perpendicular to optical axis

Geometry for Imaging X-rays

- Wolter I and II (1952)
  - 2 grazing incidence reflections in the same plane
  - Surfaces of revolution with axial symmetry – ubiquitous – Wolter I has been the favoured solution to date
  - 1st surface paraboloid+2nd surface hyperboloid
  - Grazing incidence analogue of classic Cassegrain reflector



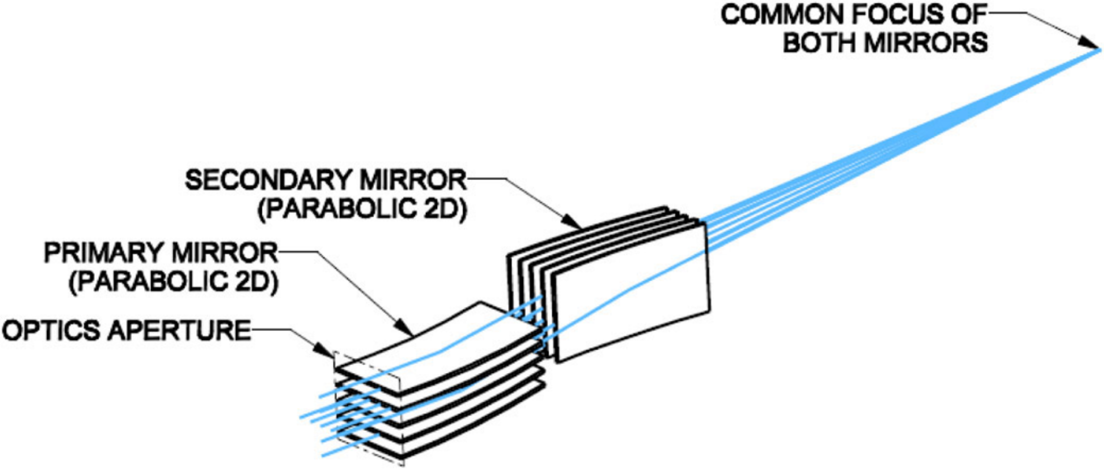
internal+internal reflection



Internal+external reflection

Geometry for Imaging X-rays

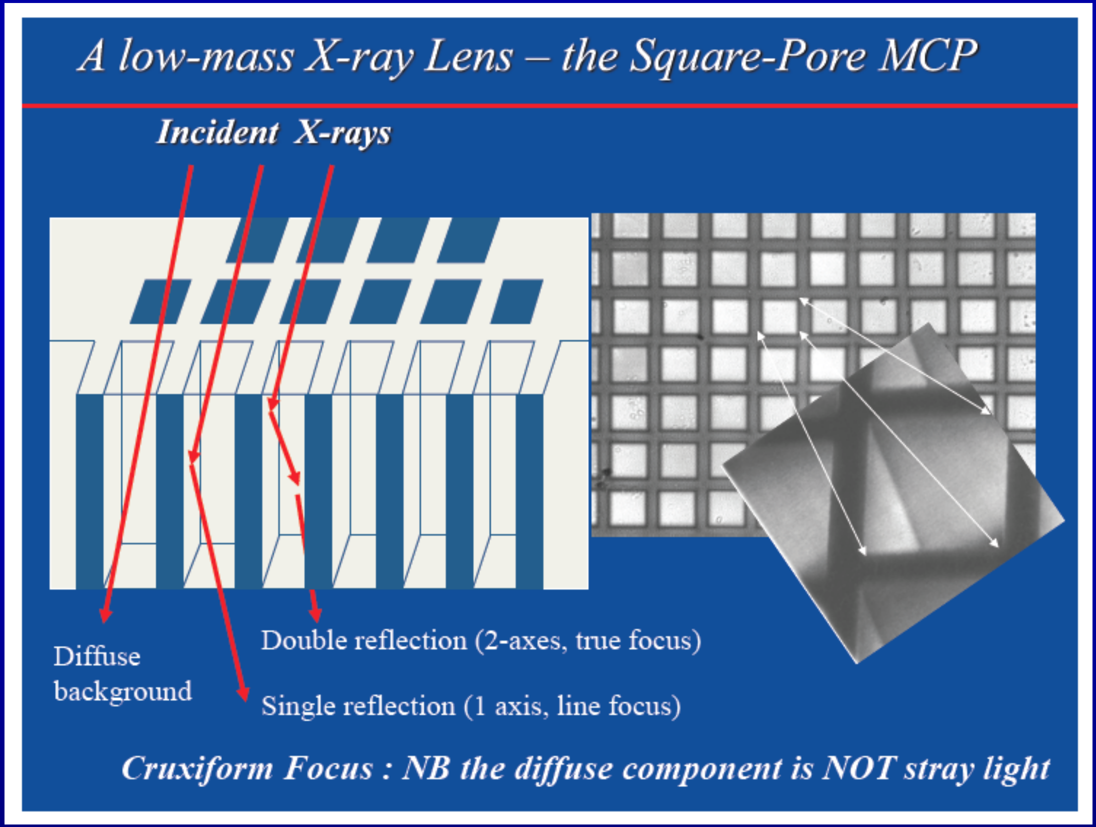
- Kirkpatrick-Baez (1948)
  - 2 grazing incidence reflections in orthogonal planes
  - originally orthogonal spherical surfaces
  - can achieve large collecting areas using many nearly identical plates - parabolic surfaces
  - No lateral inversion - can be used in a wide field configuration



Hudec 2011

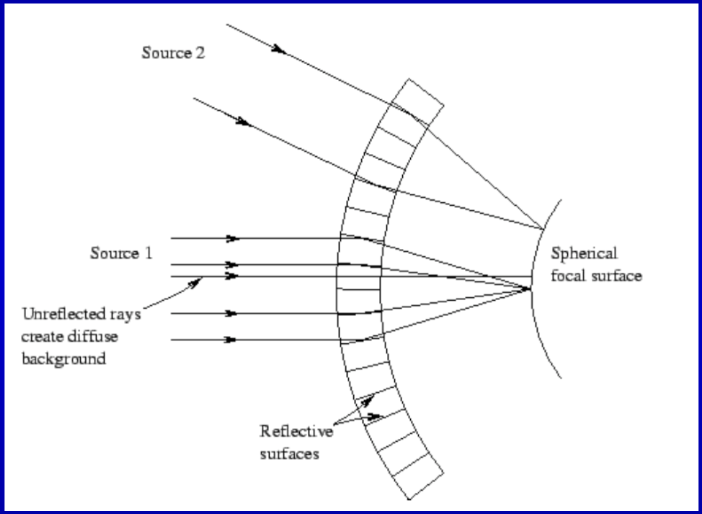
Geometry for Imaging X-rays

- Lobster Eye (Angel 1977)
  - 2 grazing incidence reflections from adjacent sides of small square pores
  - Excellent wide field coverage but small collecting area



A low-mass X-ray Lens – the Square-Pore MCP

Cruxiform Focus : NB the diffuse component is NOT stray light

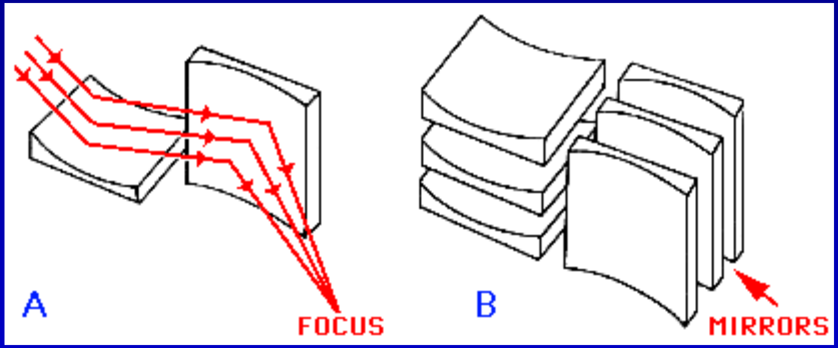


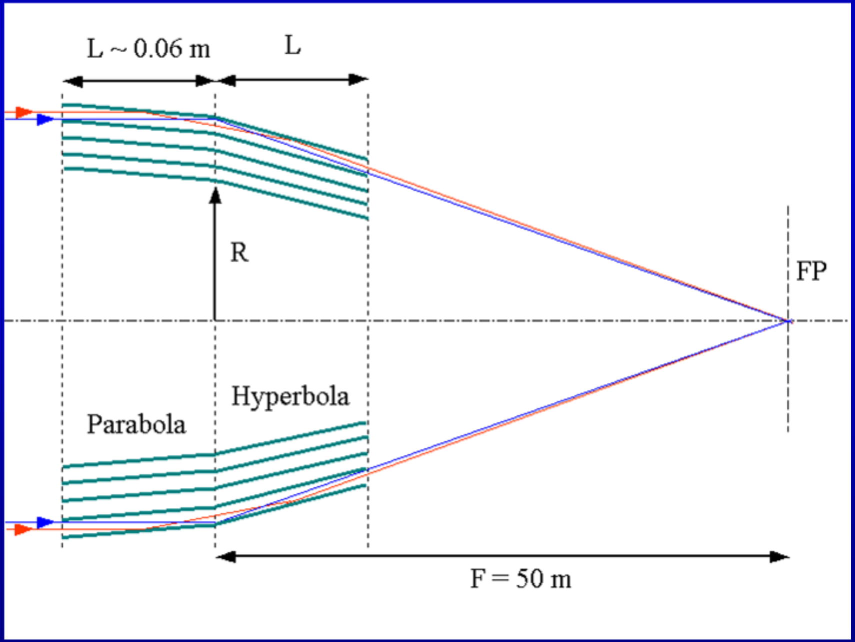
Pores on spherical surface
All point to common centre

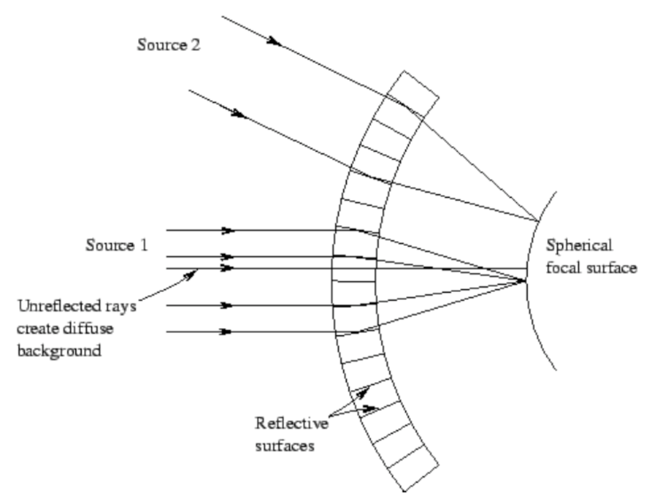
Geometry for Imaging X-rays

Nested grazing incidence mirrors

At grazing incidence the aperture area coverage is low – we must nest many surfaces together
and substrates must be THIN



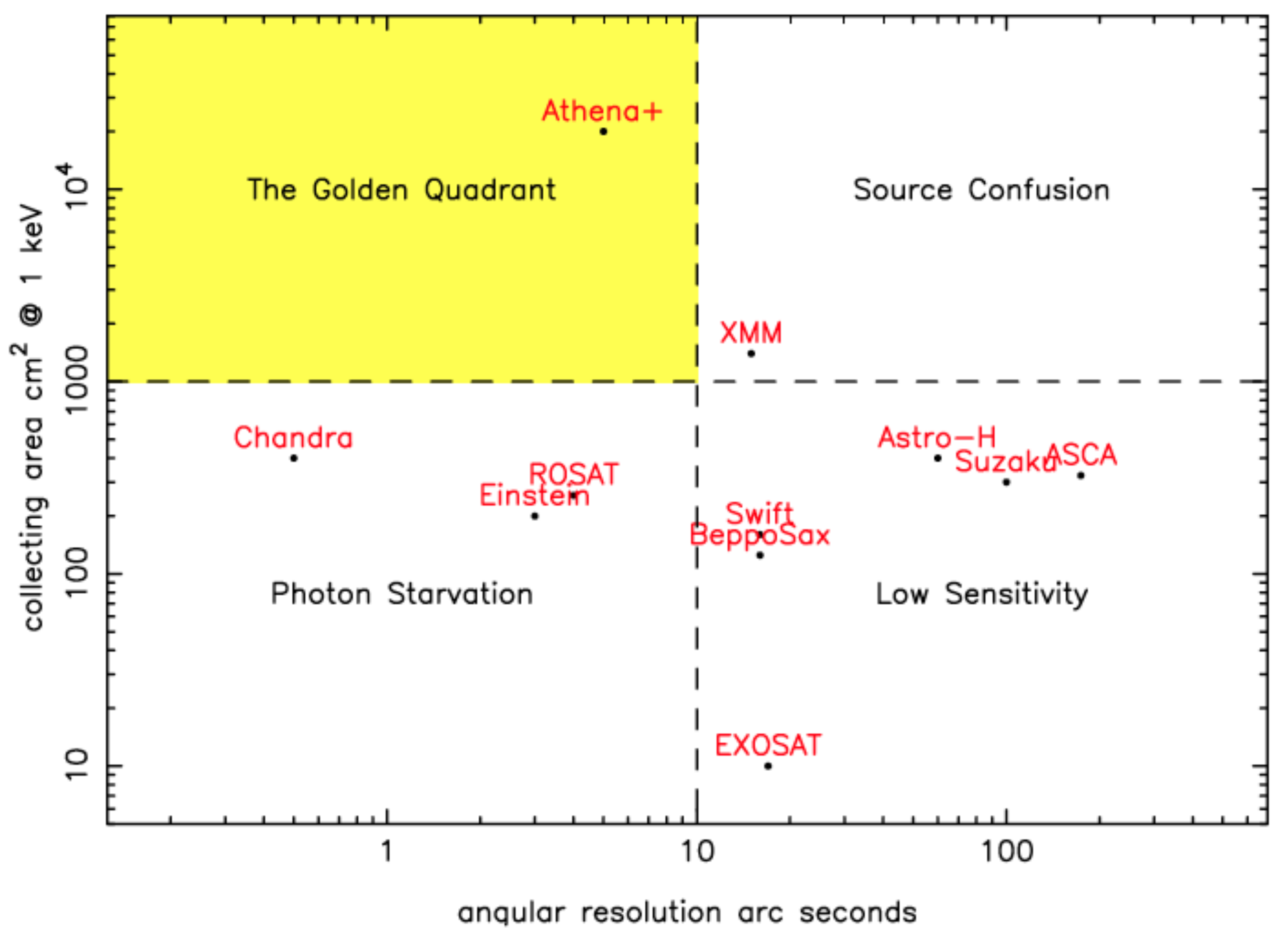




Physics + Geometry
The traditional X-ray telescope

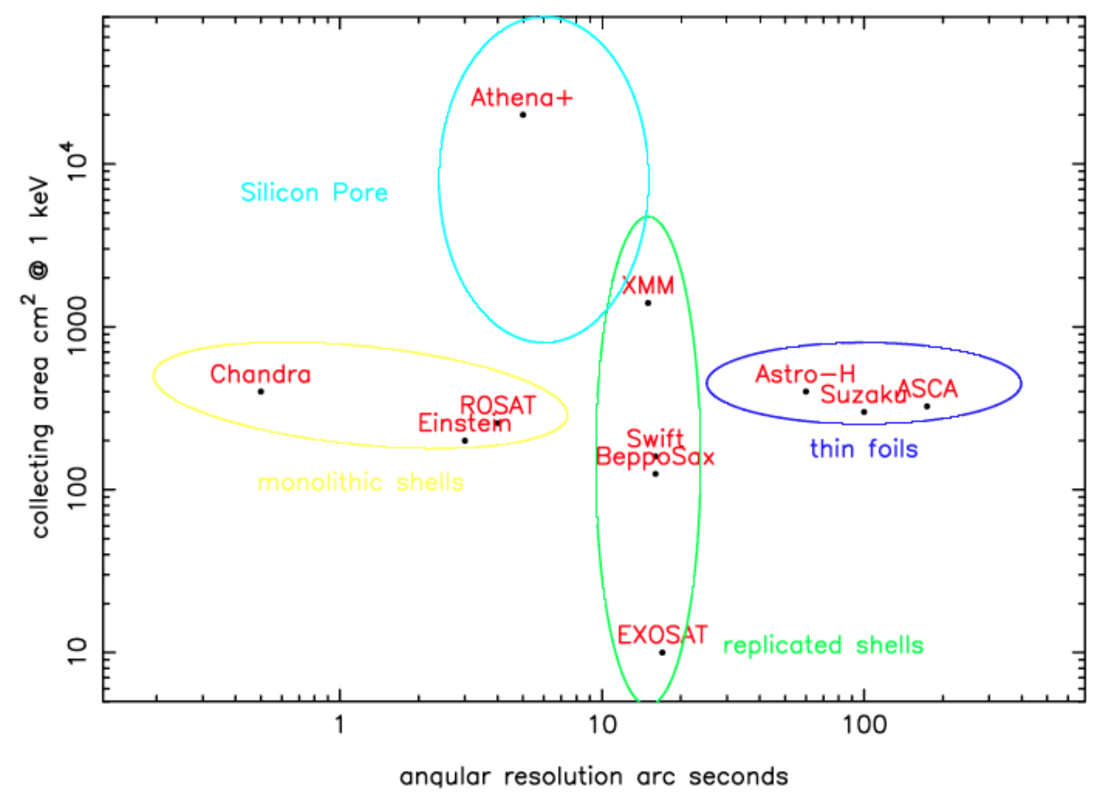
- Fresnel grazing incidence reflection
  - from coating of high-Z material e.g. Au or Ir, super-smooth few Å rms roughness
  - Surface figure gradient errors a few arc seconds or better
- Wolter I
  - minimum grazing angles – best high energy response
- Kirkpatrick-Baez
  - grazing angles √2 larger – compromise hard response for same f-ratio – but wide field of view possible
- Highly modular designs
  - c.f. LAMAR concept (Gorenstein 1986) – many identical or near identical modules to achieve a large collecting area

Wolter I Grazing Incidence Telescopes



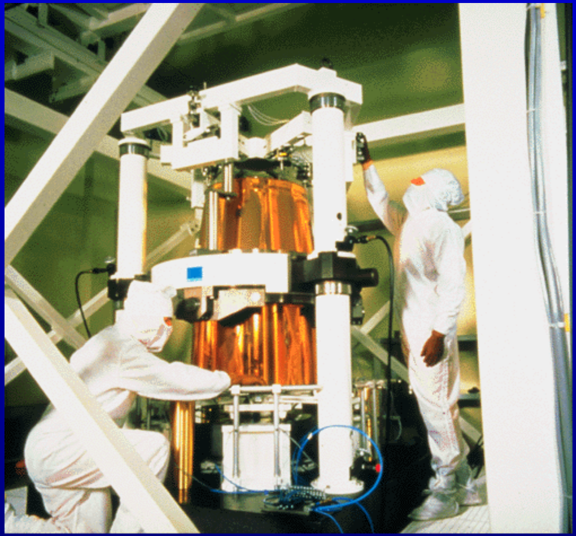
Technology – Grazing Incidence Mirrors

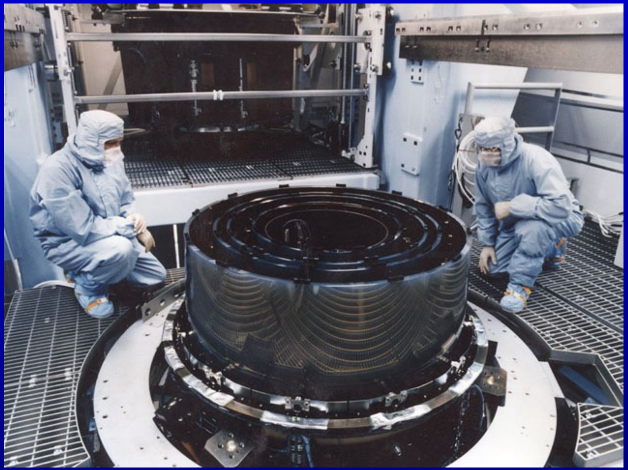
- Thin substrates
  - to maximize the collecting-area-to-mass-ratio
- Support structure
  - to maintain or improve the figure quality and achieve high angular resolution



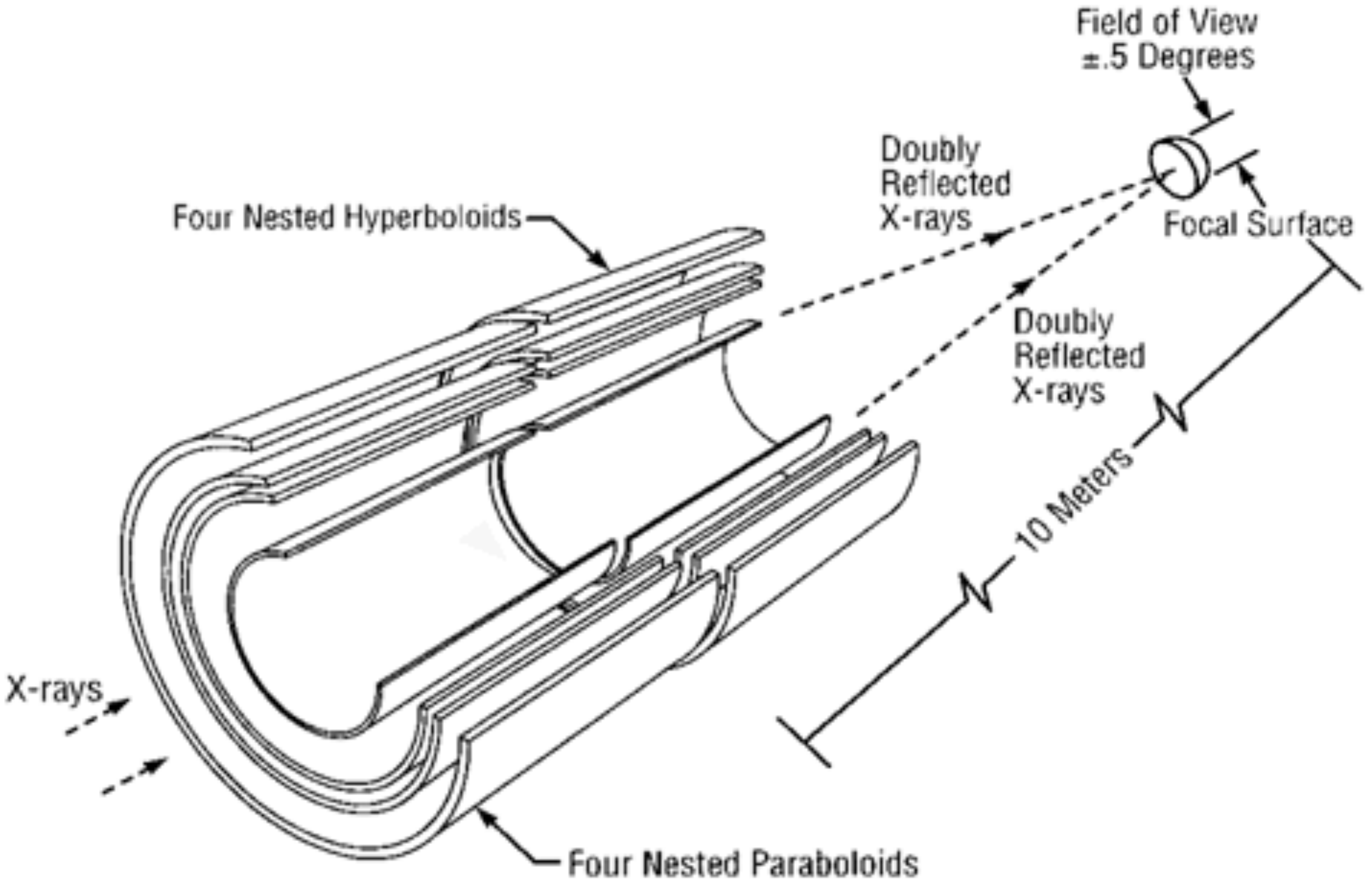
Einstein ROSAT Chandra

- Monolithic shells – thickness 11-20 mm – glass/ceramic
- Low aperture utilization and high mass
- Accurate figure – high angular resolution -> 1 arc sec
- Manufactured by traditional grinding and polishing
- Coated with Au or Ir to give high reflectivity





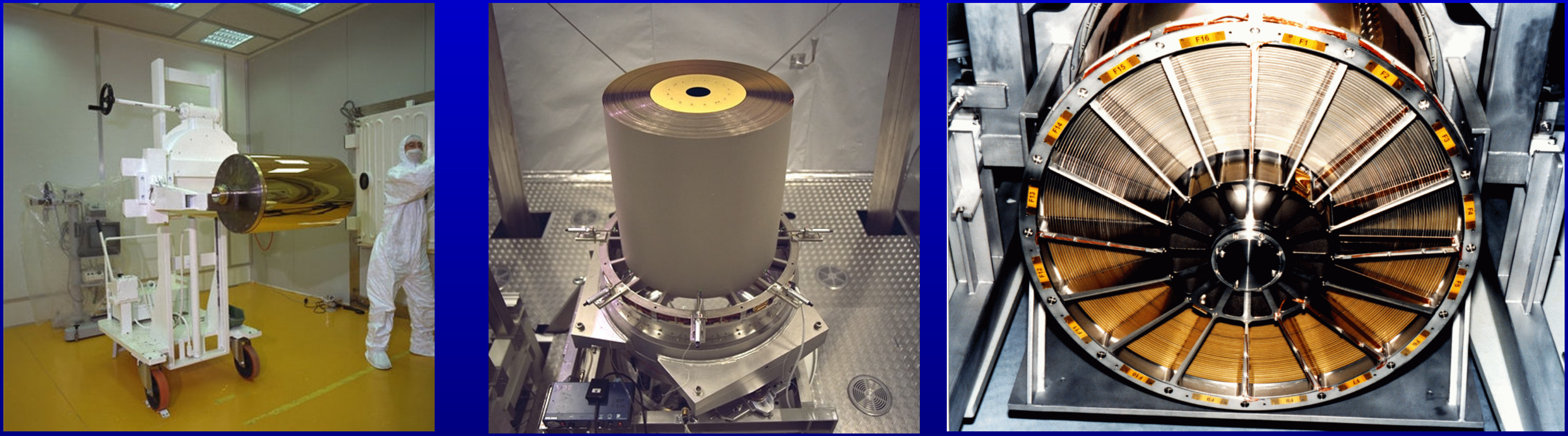
Einstein ROSAT Chandra



Area of polished surface >> aperture coverage

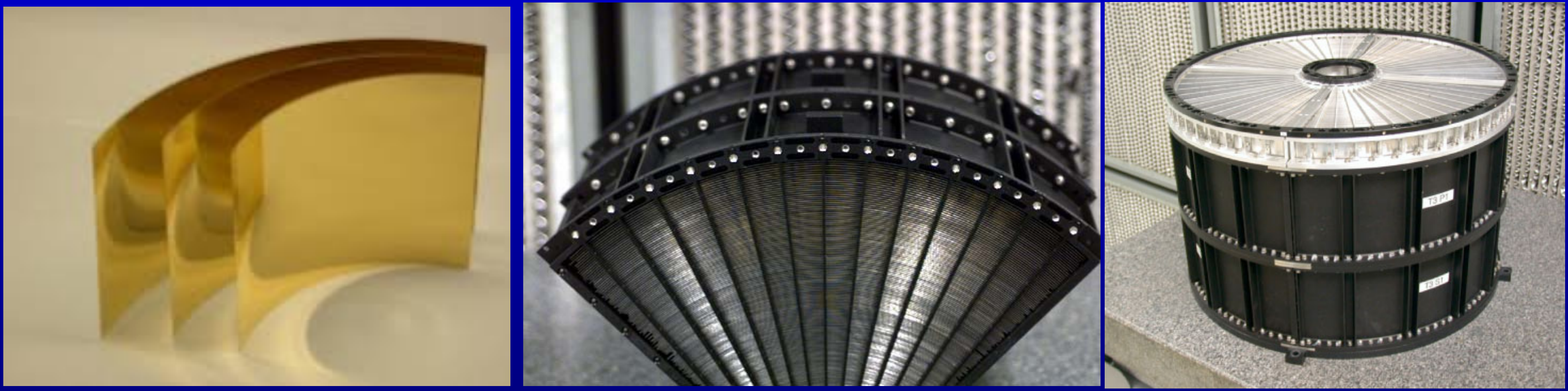
Exosat XMM BeppoSAX Swift

- Thin replicated shells – epoxy or Ni - ~1 mm
- Many nested to increase area – XMM 58 shells
- Mandrels made by traditional grinding and polishing
- Both paraboloid and hyperboloid in 1 shell
- Au used to release shells during replication



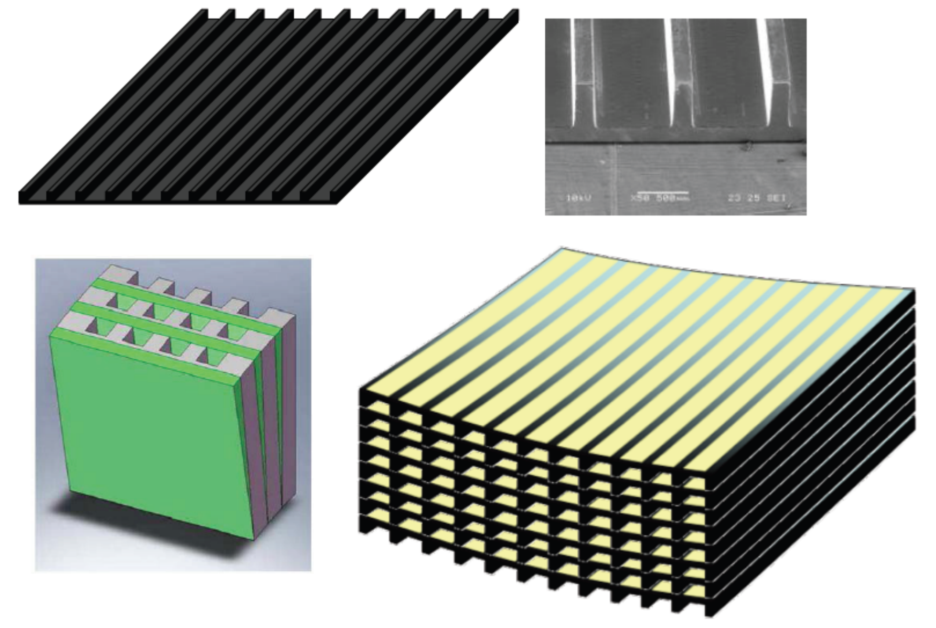
BBXRT ASCA Susaku Astro-H

- Aluminium Foil Mirrors – thin – 0.2 mm
- Introduced by Serlemitsos GSFC in 1980s
- Highly nested conical approximation to Wolter I - sectors
- Well suited to coating with multilayers to provide a low mass high energy response mirror – e.g. Astro-H
- Large area but poor angular resolution 1-2 arc mins

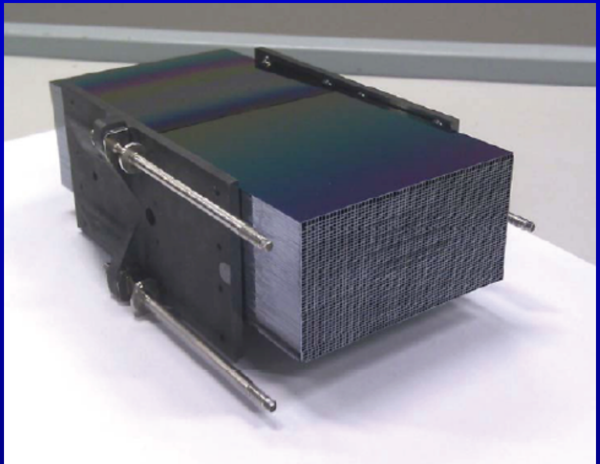


New Technology - SPO

- Silicon Pore Optics (SPO) (Beijersbergen et al. 2004)
- Use Si wafers manufactured for the electronics industry
- Very flat, thickness 0.775 mm and highly polished ~3 Å rms
- Diced, wedged, grooved, coated, cold bonded



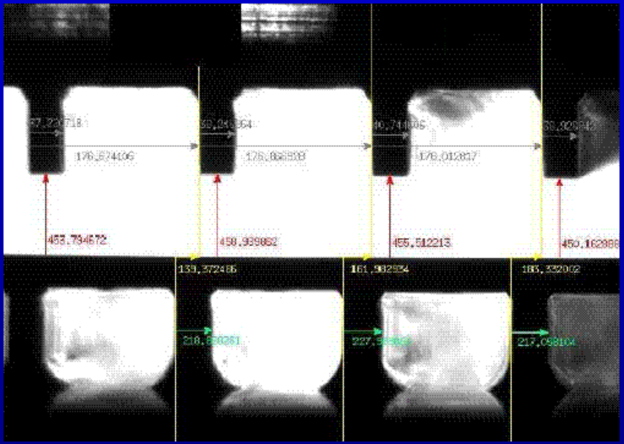
Thin membrane ~0.15 mm
2 stacks -> 1 module



Cosine Research NL

New Technology - SPO

- At present angular resolution limited by conical approximation to Wolter I but true Wolter I possible
- SPO stacks can be made in Wolter I or K-B geometry
- Can be used for either narrow or wide field telescopes

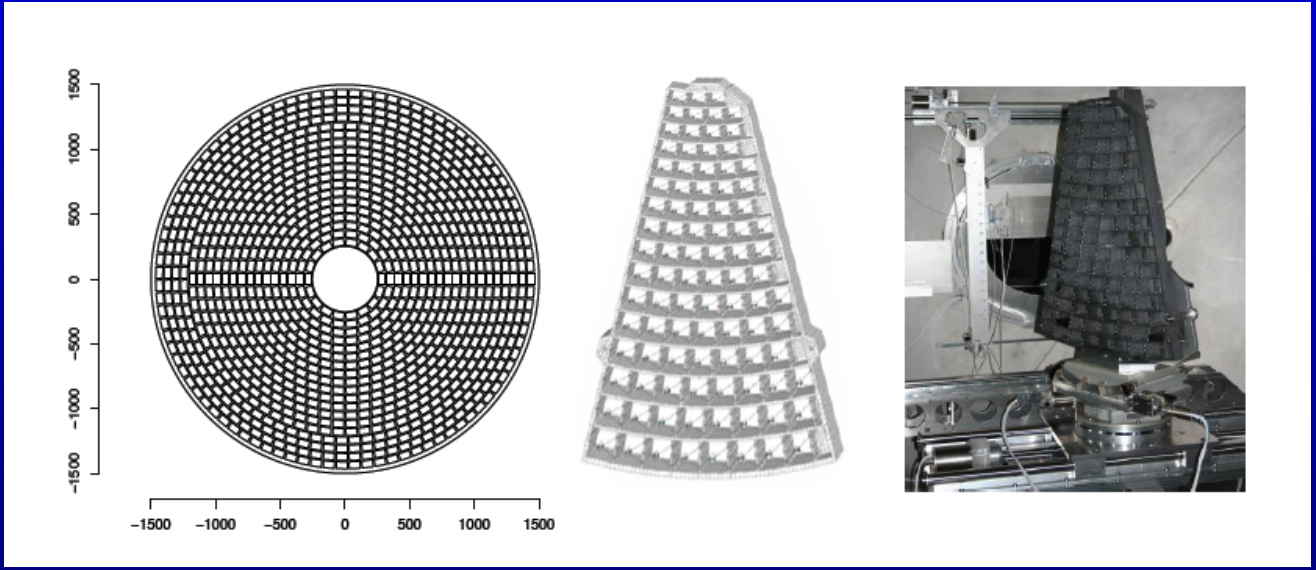


Pores 0.63 x 1-4 mm

Cosine Research NL

Athena – ESA 2028 – SPO?

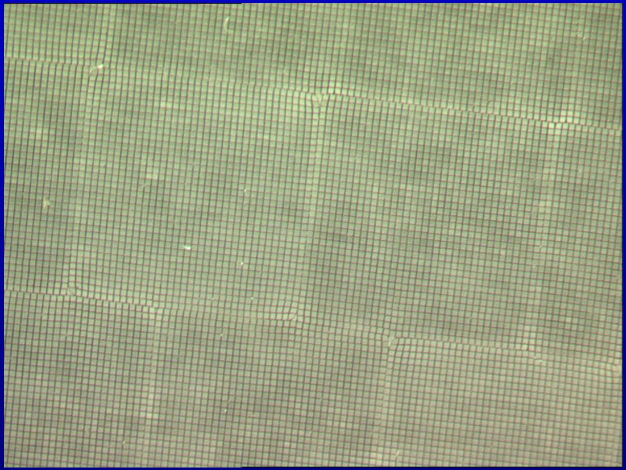
- ~800 SPO modules packed into an aperture 3 m diameter
- Area ~2m^2 at 1 keV
- Angular resolution 5 arc seconds
- Field of view 40-50 arc minutes diameter

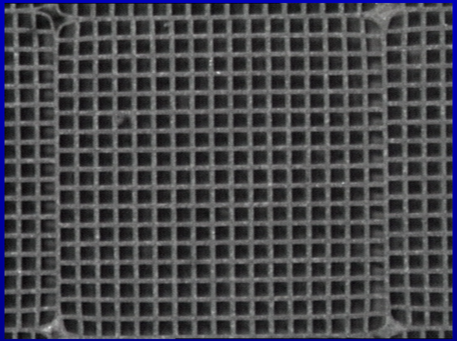


New Technology - MPO

- Square Pore Micro-channel Plate Optics (Micro Pore Optics)
  - Small square glass pores – 10-100 microns – very low mass – alignment of pores achieved in manufacture limits angular resolution to ~1 arc minute
  - Ideally suited to Lobster Eye but can be used in Wolter I configuration if radial packing used – very low mass
  - Bepi Columbo MIXS-T aperture diameter 200 mm gives 50 cm^2 area at 1 keV and angular resolution of 4 arc minutes – total mass only ~2 kg
- Etched Silicon pores or slots created by the MEMS process (Ezoe et al. 2005)
  - could be used as an alternative to glass but difficult to bend

MCP radial packing

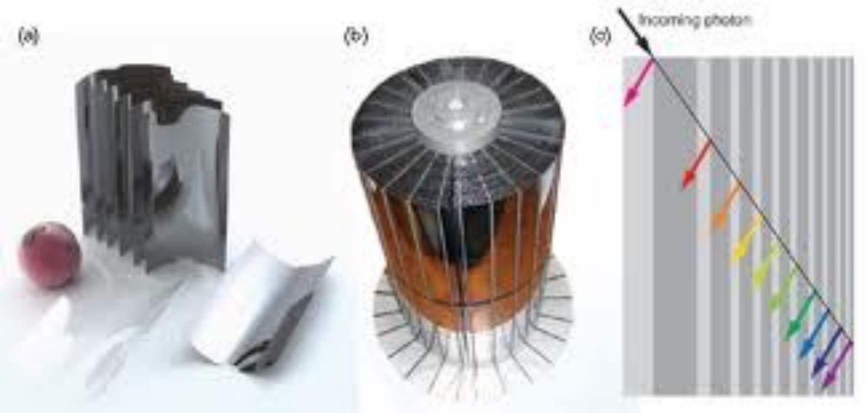


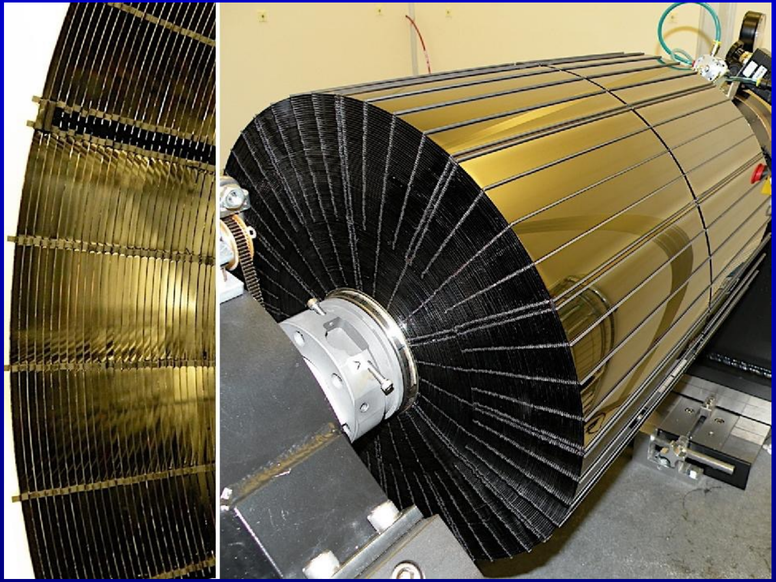


MIXS-T STM

New Technology – SGO - NuSTAR

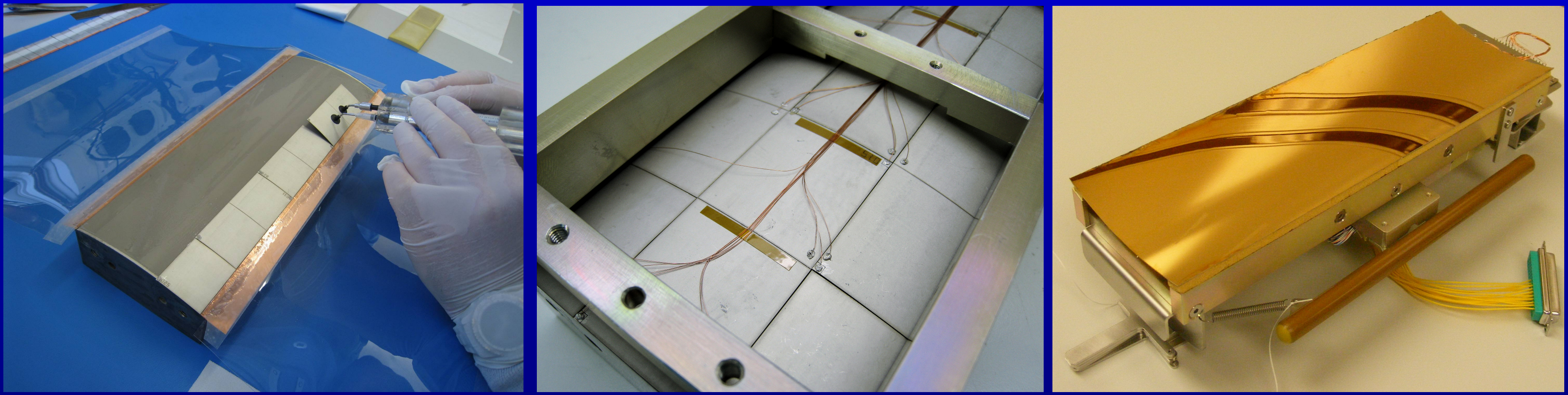
- Slumped Glass shell-sector Optics (SGO)
  - originally developed for HEFT (Hailey et al. 1997) and used to construct the NuSTAR mirrors (Koglin et al. 2009) – angular resolution ~ 1 arc minute
  - Slumping process developed in USA (Goddard) and Europe (INAF-OAB and MPE)
  - Multilayer coatings -> high energy response up to 30-40 keV
  - With clever mounting (in future) -> a few arc seconds resolution





New Technology
Actively adjustable thin shells

- Thin sheet of piezoelectric actuator can be incorporated into the structure of thin shell reflectors
- By adjusting the figure using the actuators can improve the angular resolution – hopefully sub-arcsecond (Feldman et al. 2009, Reid et al. 2009) – GEN-X



The Future of X-ray Telescopes

- Traditional X-ray telescopes
  - Wolter I will continue to dominate for narrow field telescopes
  - SPO and SGO will provide angular resolutions of a few arc seconds or better combined with large area > 1m^2 – Athena- Think big! - wait until 2028
  - Actively adjustable thin shells might push resolution sub-arcsecond and give large collecting areas – GEN-X – Think hi-res! 2035+
  - Foil telescopes will continue to provide the ~1 arc minute low mass and hard response large area optics – Think cheap! (relatively)
  - MPOs will provide a very low mass alternative for ~1 arc minute imaging in the soft band – Think low-mass! - SVOM MXT 2022
- Wide field X-ray monitors
  - Low mass Lobster Eye constructed using MPOs (square pore MCPs)
  - K-B constructed using SPO – better angular resolution and larger area
  - Think wide! All-Sky!
- Ultra high angular resolution – the diffraction limit
  - Great scope for innovation and design - mirrors, lens and diffractive optics
  - 0.1-100 microarcseconds – Think!

Ultra High Angular Resolution X-ray Astronomy

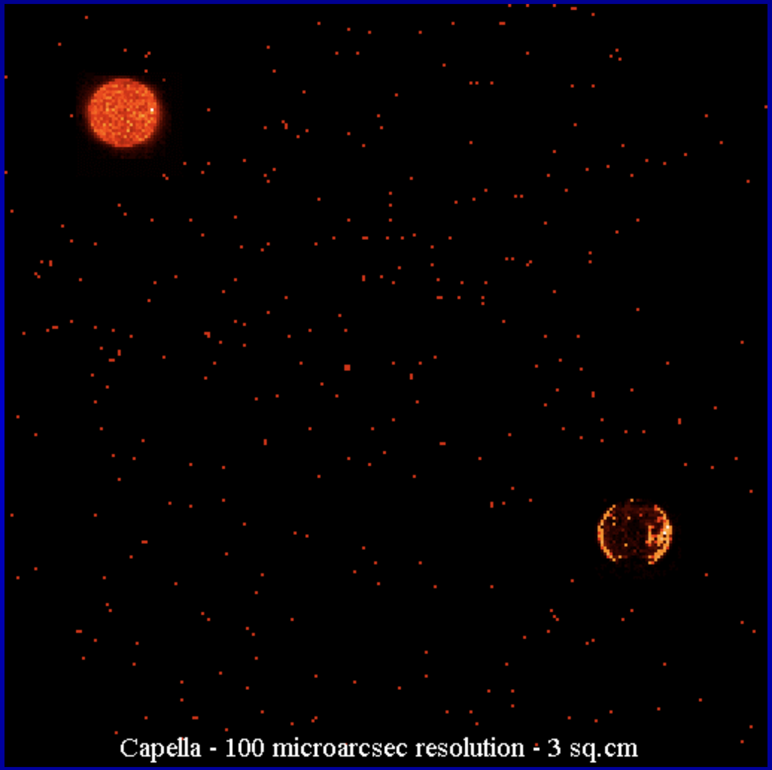
Ultimate aim:
Imaging accretion onto a black hole

But need 0.1 micro arc sec resolution
to image the event horizon

Initial ultra high angular resolution

Starting point
~100 μarcsec in the soft X-ray band 0.5-2.0 keV

20 cm on surface of the Moon
70 m on surface of the Sun
The Solar diameter at 100pc
100 AU at 1 Mpc



Capella – 100 μarcsecs

Wolter I not possible – f too large, surface figure too demanding

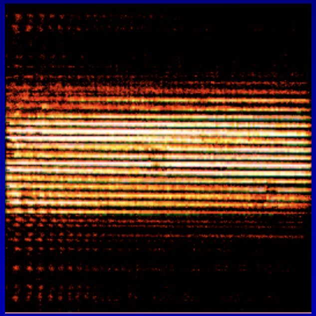
X-ray Diffraction Limit

$\Delta\theta = \lambda / D$ where
D is the aperture diameter or
D is interferometer baseline

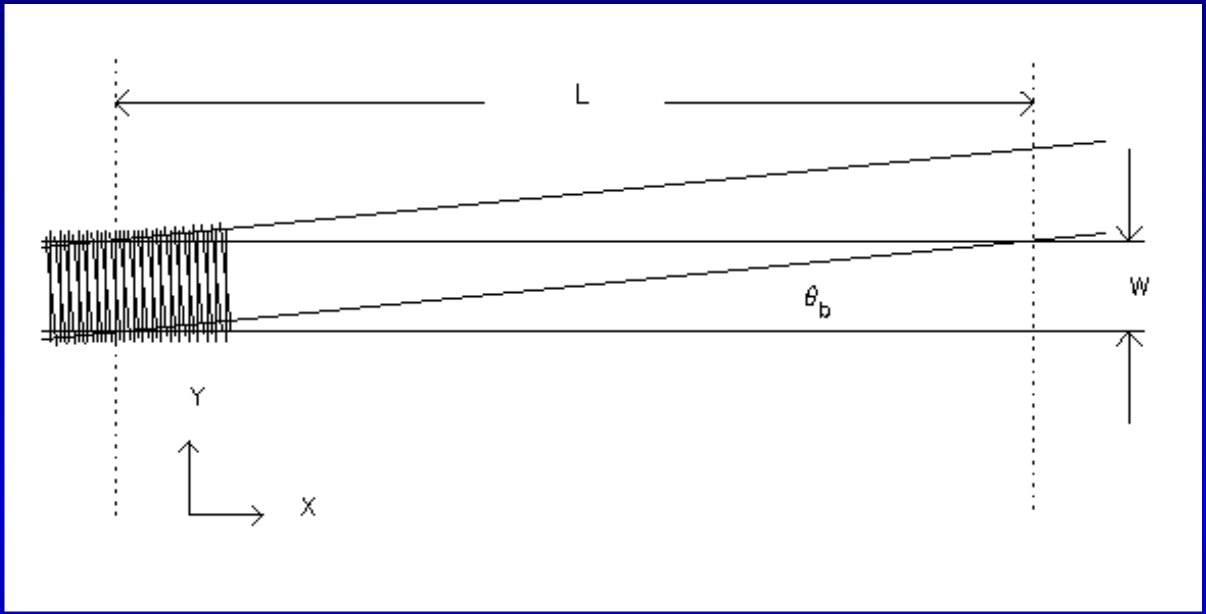
If $\lambda \approx 10$ Å and $D = 2$ m then $\Delta\theta \approx 2\text{x}10^{-9}$ radians

$\Delta\theta \approx 100\ \mu$ arcseconds

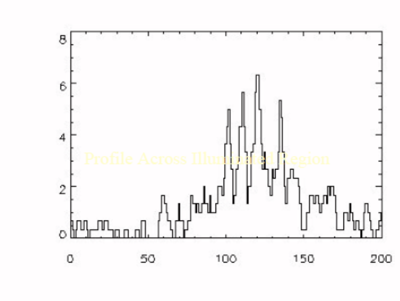
X-ray interference fringes



Optical demo
Willingale et al. 2005



1.25 keV Cash et al. 2000



θ_b is angle between overlapping beams

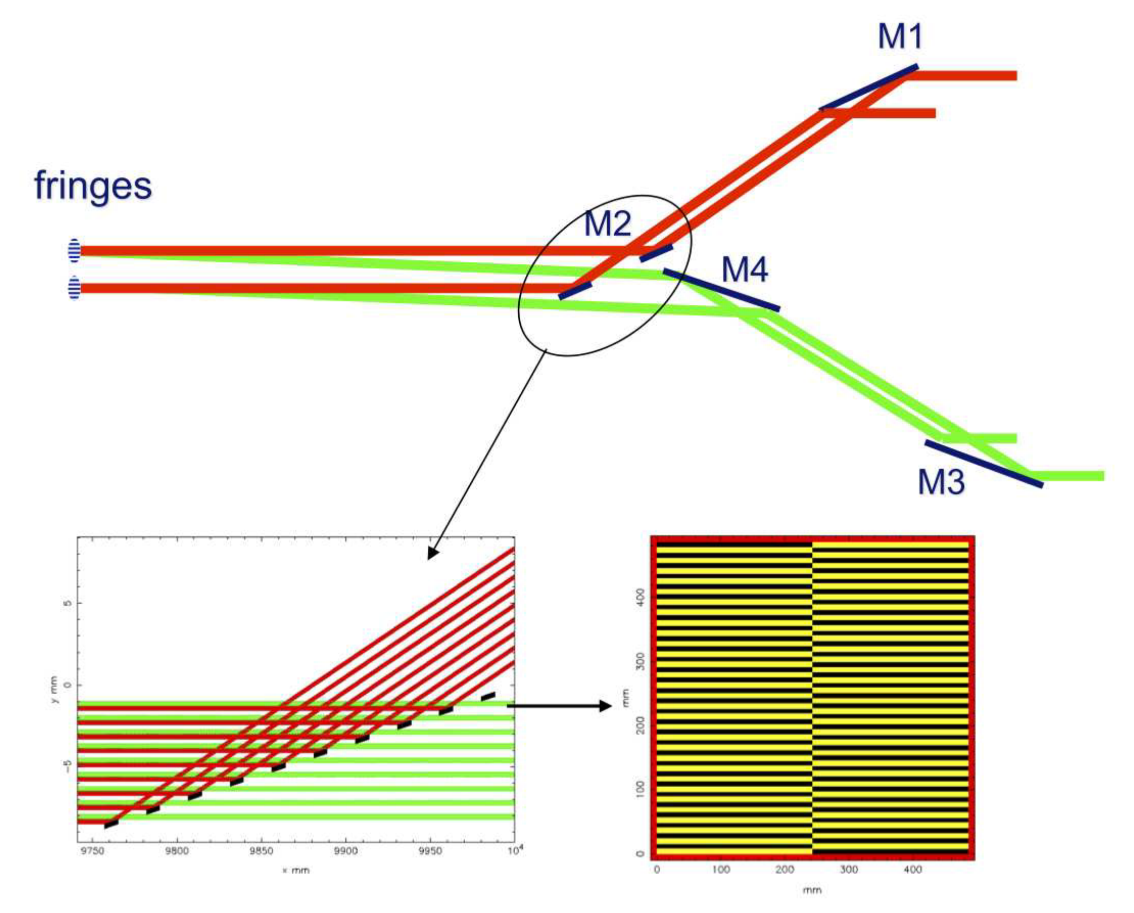
Fringe spacing $\Delta y = 2\lambda/\theta_b$

If $\Delta y \approx 10$ μm, $\lambda \approx 10$ Å, $\theta_b \approx 2\times10^{-4}$ radians

$\theta_b \approx 40$ arc seconds

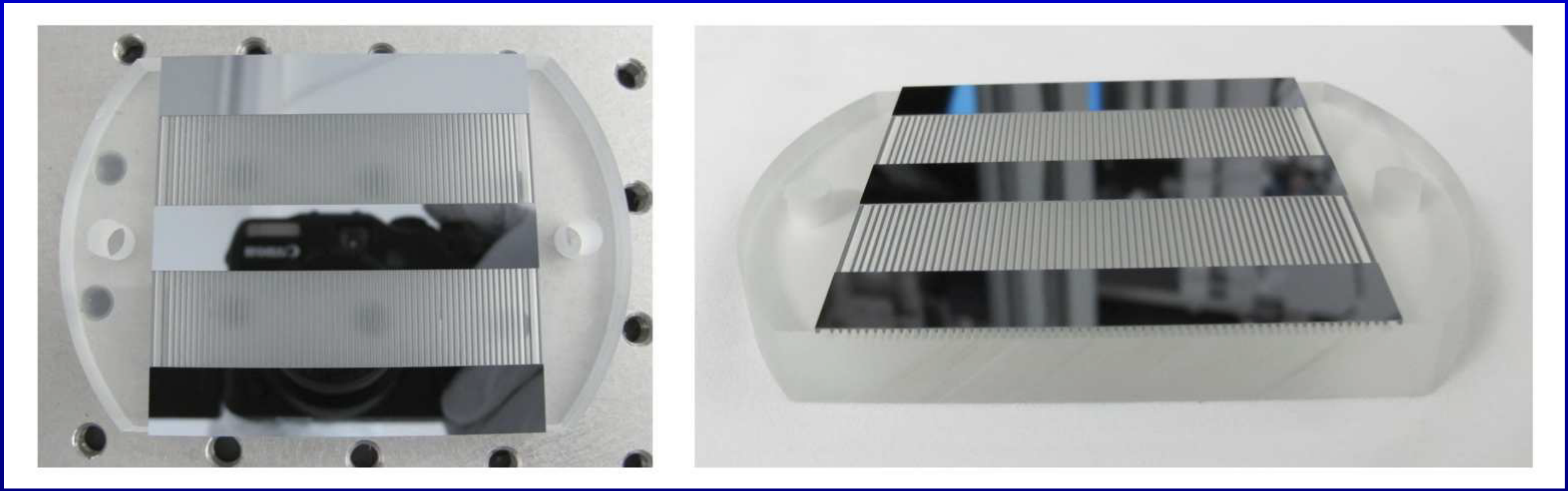
Telephoto geometry with nesting

- Willingale 2004
- 1-D version of the Wolter II
- F >> physical length
- 4 grazing incidence reflections from flats M1, M3, M4 required to produce fringes
- M2 slatted mirror
- Full size 500x500 mm - ~30 slats
- 2 halves off-set to produce a continuous fringe pattern



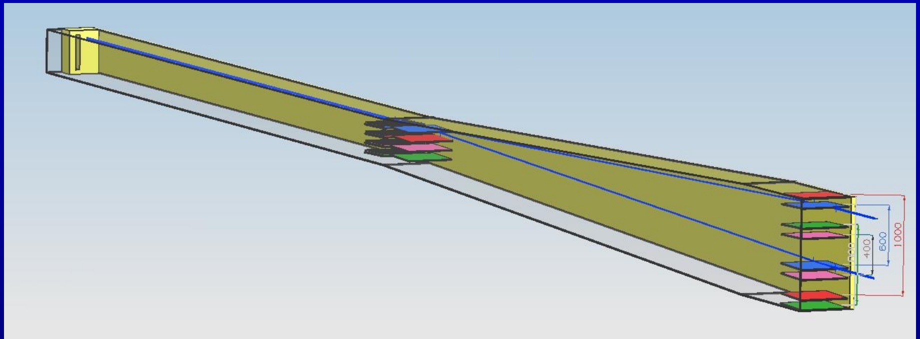
1st prototype slatted mirror

- Made using SPO technology – Cosine Research
- Large areas co-planar to ± 10 nm
- Trapped dust a problem
- We are confident that 2nd prototype will meet spec.



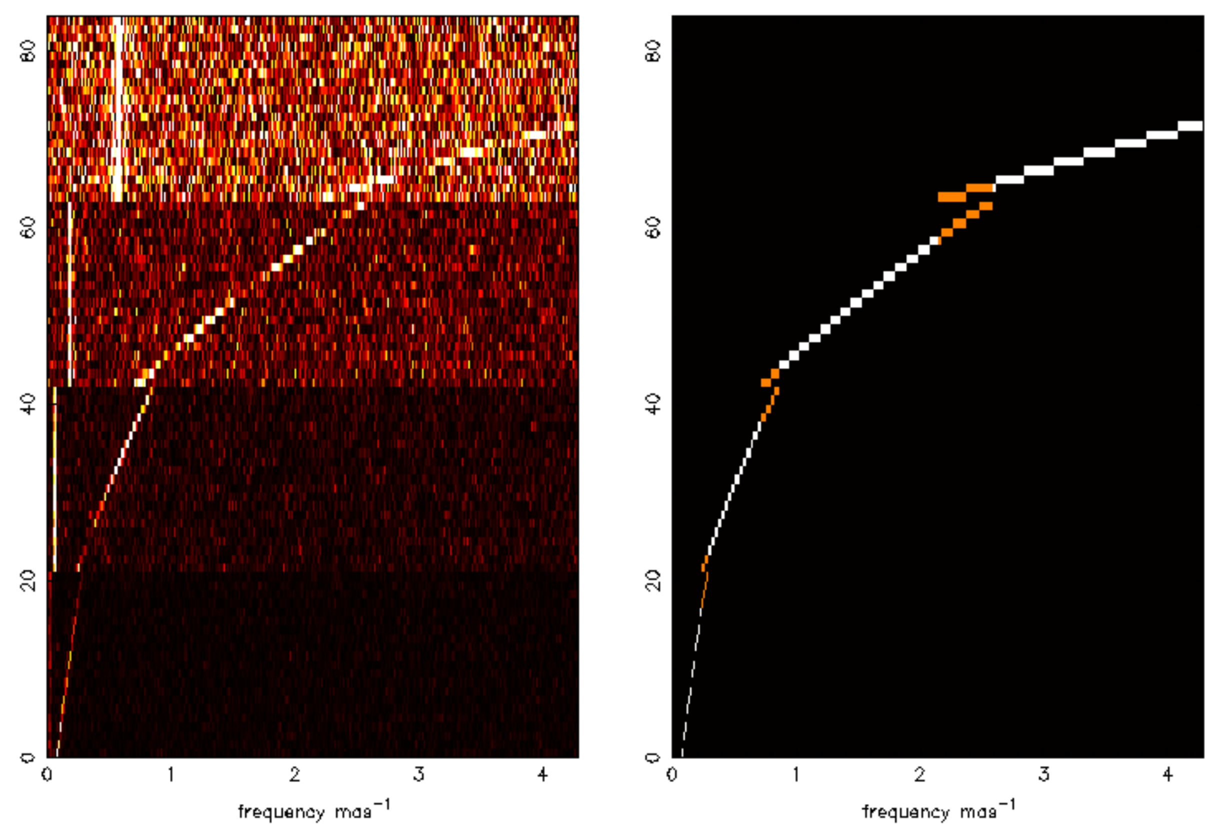
Simulation of 4 parallel systems

- 4 D-spacings: 35, 105, 315 and 945 mm
- Total length ≈ 20 m
- Total collecting area ~80 cm^2 (including gold reflection and detector efficiency)
- Energy band 0.58-2.1 keV
- 21 energy channels, using XMM-Newton EPIC CCD E/ΔE
- Source strength 1 Crab for 1000 secs
- Binary system: 1 extended, 1 unresolved



Simulated Interferograms

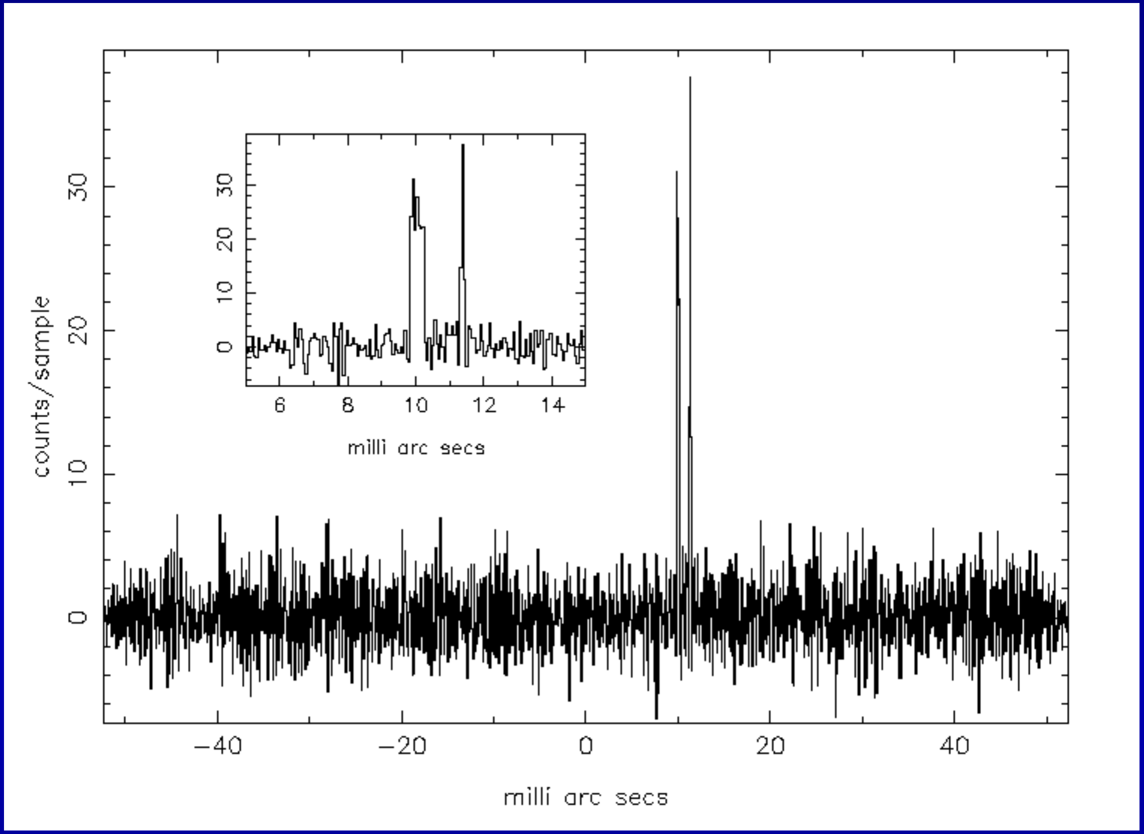
4 Ds
21 Es



Signal
mask

Spatial frequency

Reconstructed binary distribution



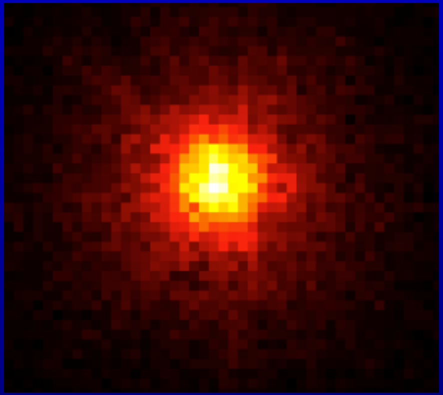
Reaching X-ray diffraction limit is possible…

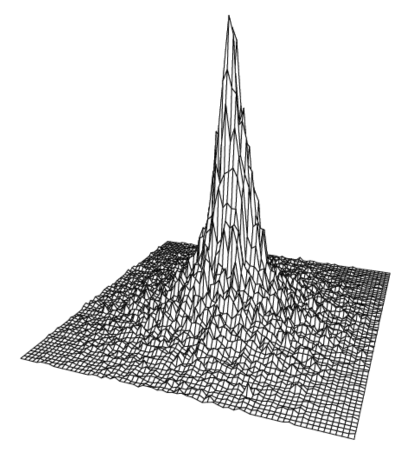
Performance and Calibration

- Properties to be calibrated
  - Point Spread Function
  - Effective area
  - Focal length and plate scale
- As a function of
  - Energy - full band and fine structure over absorption edges
  - Angle - arc second scale for PSF - arc minute scale for area vignetting

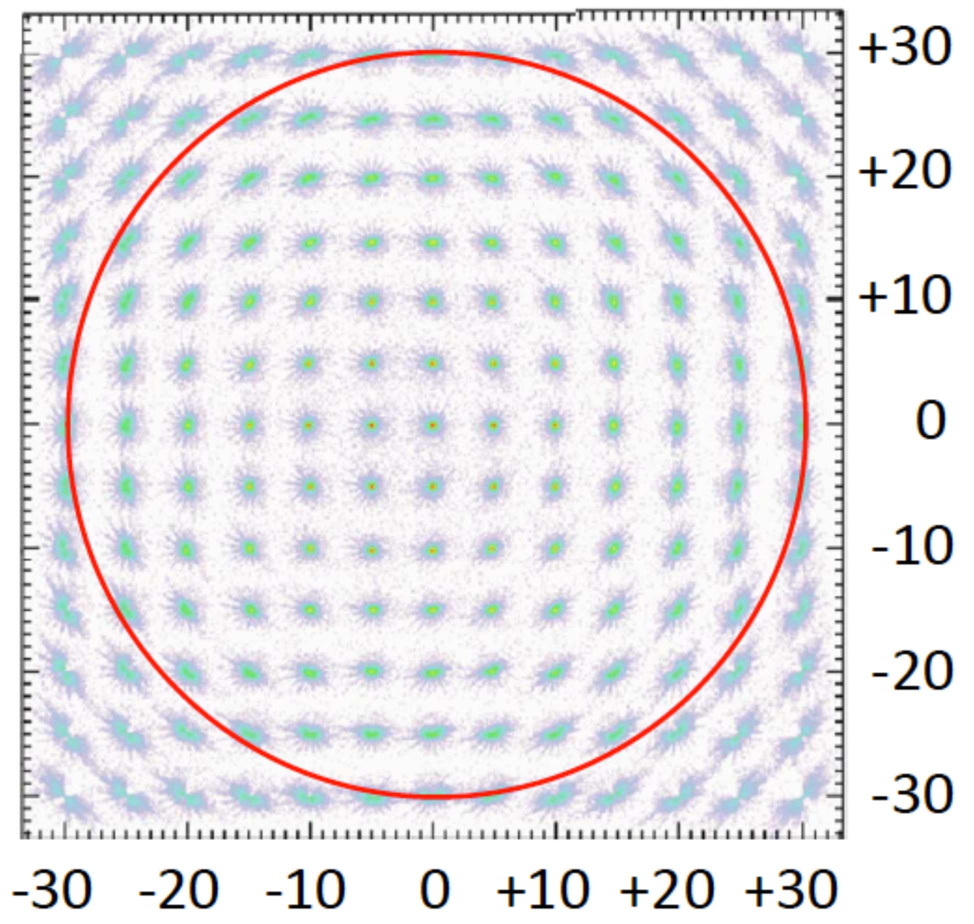
Point Spread Function (PSF)

- The size and shape of the PSF varies as a function of energy and position within the field of view
- Size of beam characterised by the Half Energy Width - HEW is diameter of circle that contains half the focused energy
- The centroid of the PSF is used to specify the best estimate of the position of a point source



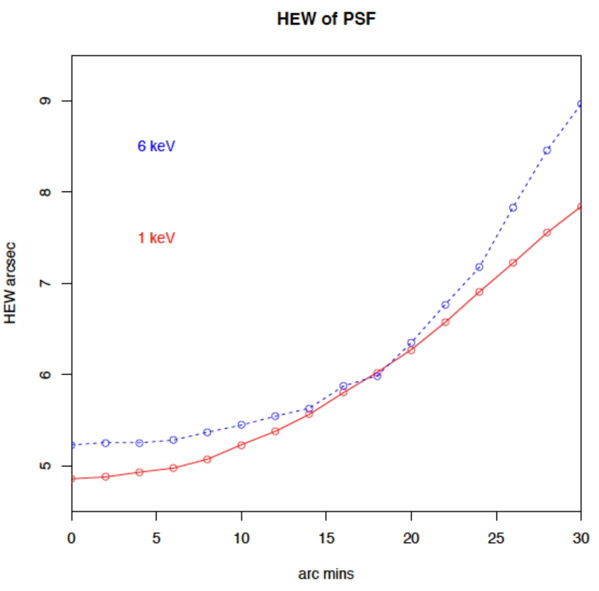


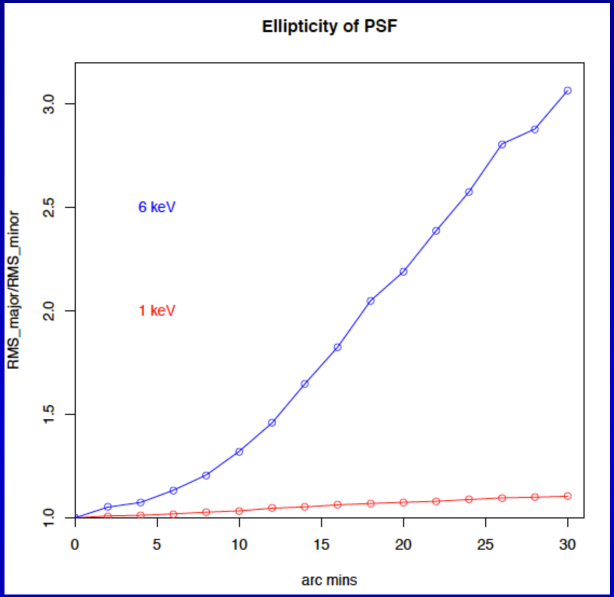
eRosita PSF Calibration



- optimum focal plane is curved - spherical
- CCD detectors flat - PSF degrades off-axis

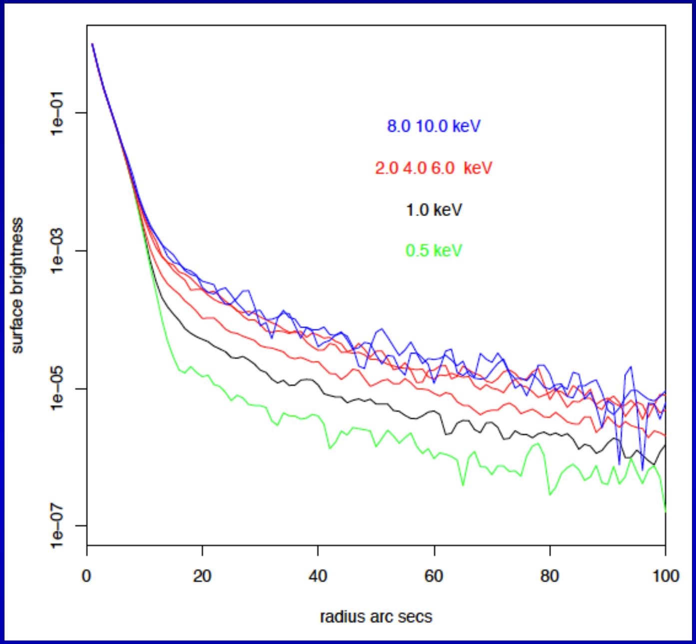
PSF Off-Axis

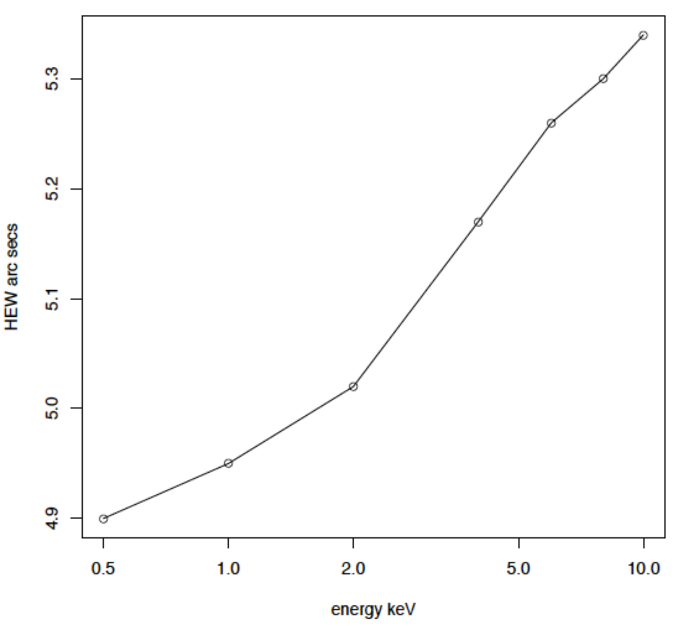

HEW of PSF


Ellipticity of PSF

The width (HEW) and ellipticity (rms_major/rms_minor) vary as a function of off-axis angle

PSF vs. Energy

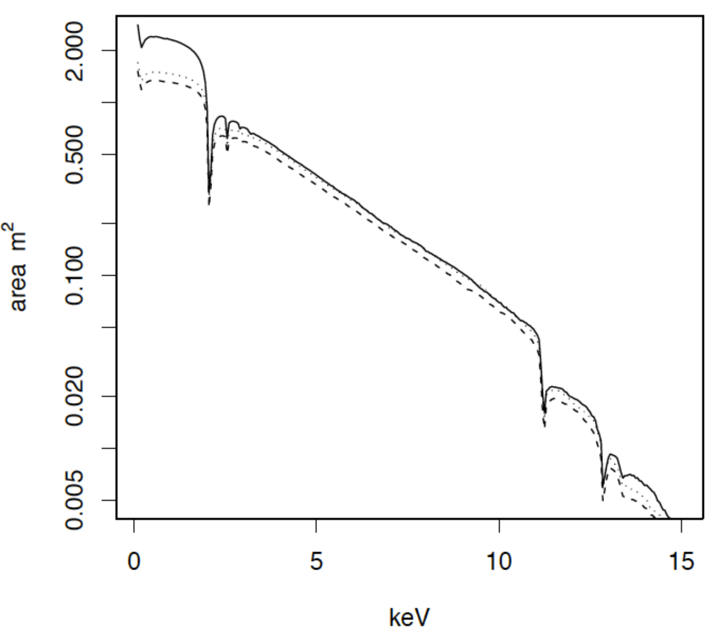


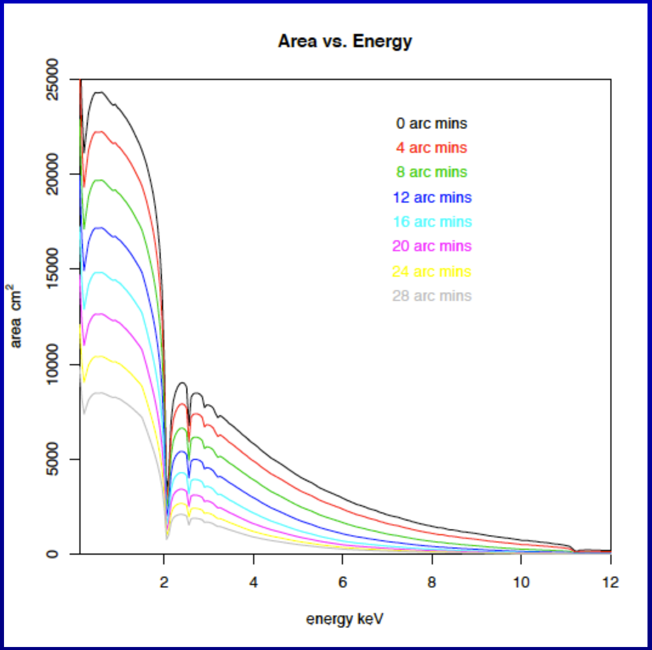


- Scattering from surface roughness increases with energy
- HEW increases with energy

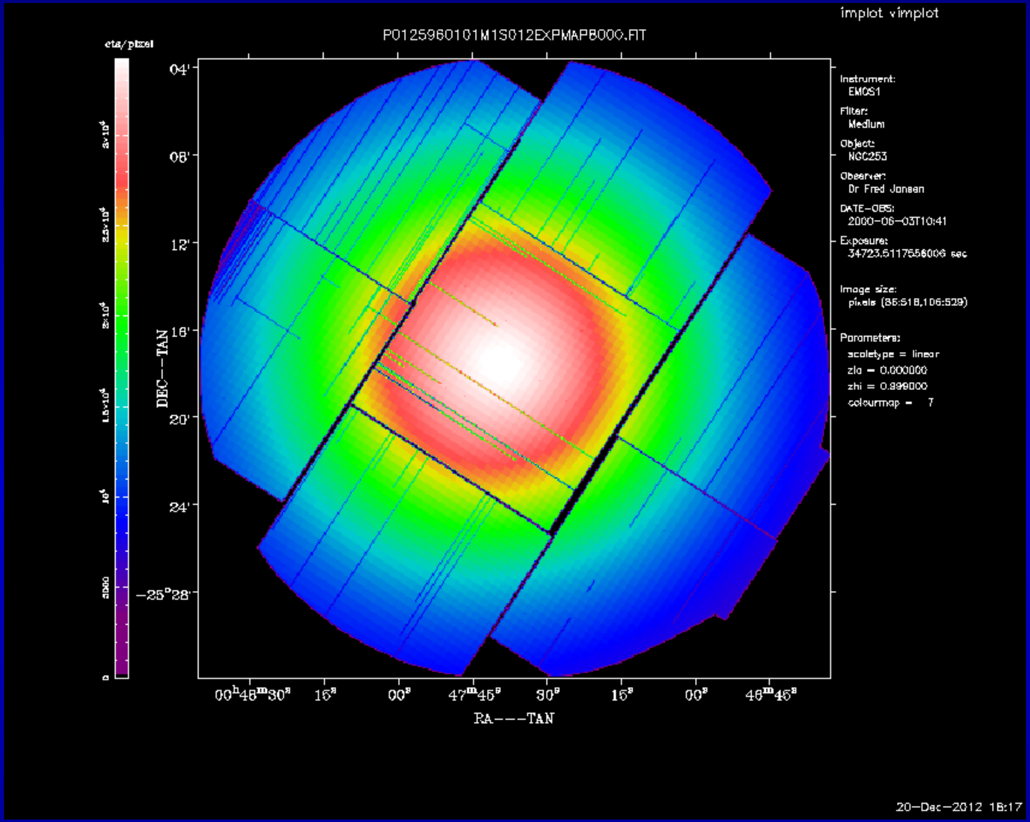
Collecting/Effective Area

- Varies as a function of energy - change in reflectivity of, and absorption edges in, the reflecting coating
- Varies as a function of position in the field of view - vignetting





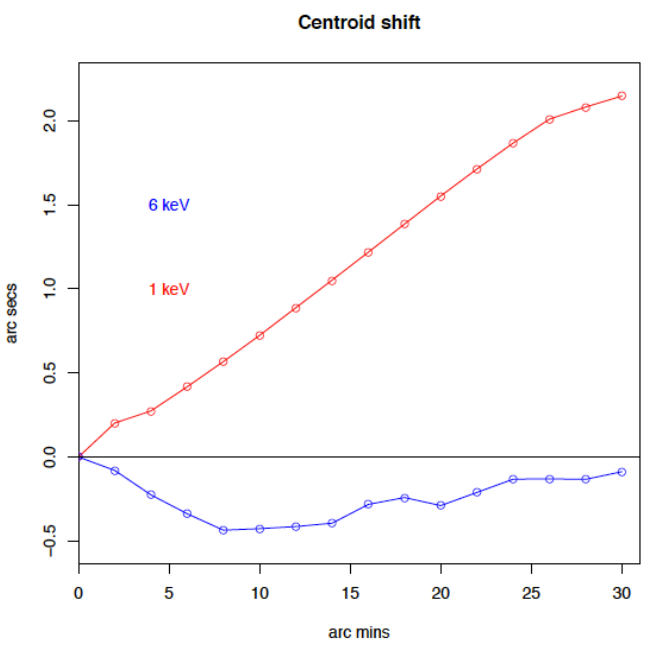
Vignetting - Exposure Matrix



e.g. XMM-Newton EPIC
for NGC 253

- Combine the effective area of the mirror with the coverage and efficiency of the detectors

Plate Scale and Mapping



Mapping $\tan(\theta)=x/F$

- The PSF centroid shifts with respect to the nominal plate scale position off-axis
- This potentially introduces an energy dependent non-linearity in the plate scale