Wave Optics

why focusing ?

- ⊕ sensitivity !
- ⊕ angular resolution and /or precise source identification
- ⊕ smaller detectors give better spectral resolutions
- ⊕ lower mass detectors, cooling systems, shielding
- ⊕ lower data transmission and storage
  (data rate used for signal rather than for noise)

but how ?

reflection

refraction

diffraction

high energy astrophysics : 1/λ irony

The performance of virtually all astronomical instruments is diffraction limited

angular resolution	A	~	d/λ
spectral resolution	R	~	N/λ

In optical astronomy : $d/\lambda \approx 10^6$-10^7. Best angular resolutions are presently achieved in radio astronomy ... because wave properties are actually *used* rather than just presenting a limitation. VLBI over baselines (d) of up to 10^8–10^9 wavelengths => $\Delta\theta \approx$ milliarcsec resolution

In high energy astronomy, even a system with an aperture of a millimeter should produce diffraction limited angular resolutions of the order of > 10^9 (1 MeV), yet present instruments have allowed for

angular resolution (gamma)	$\Delta\theta$	~	0.1° - 5°
spectral resolution (gamma)	R	≤	500

focusing instruments : from *total external reflection* to *Laue diffraction*

total external reflection

Wolter telescopes tradl, replicated,foil optics		0.1- 12 keV
Lobster eye telescopes, Microchannel Plate Optics		0.1-3.0 (+) keV
Capillary Concentrators “polycapillaries”		1 - 60 keV
Multiple reflection optics (4+)		1- 80 keV
Kirkpatrick/Baez Optics		

diffraction

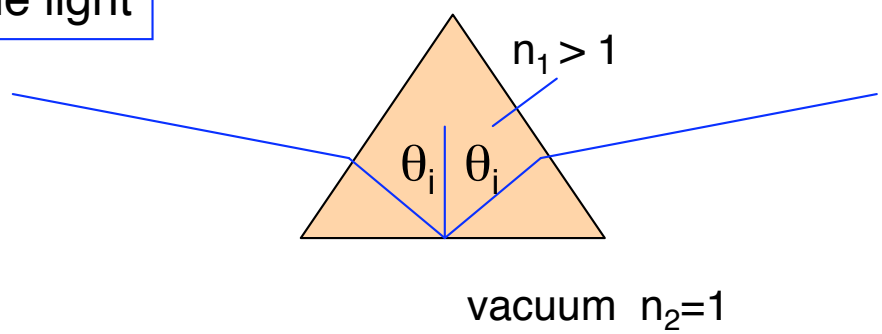
Multilayer mirrors	Unifrom Period Multilayers	
	EBB Multilayers	20 - 100(+) keV
Bragg-Lenses		10 - 200 keV
Laue-Lenses	broadband Laue lens	
	narrowband-, tunable- Laue lens	100 keV - 2 MeV

refraction

Fresnel zone plate		
Phase Fresnel lens		< 1 keV - > 1 MeV

total external reflection

total internal reflection of visible light

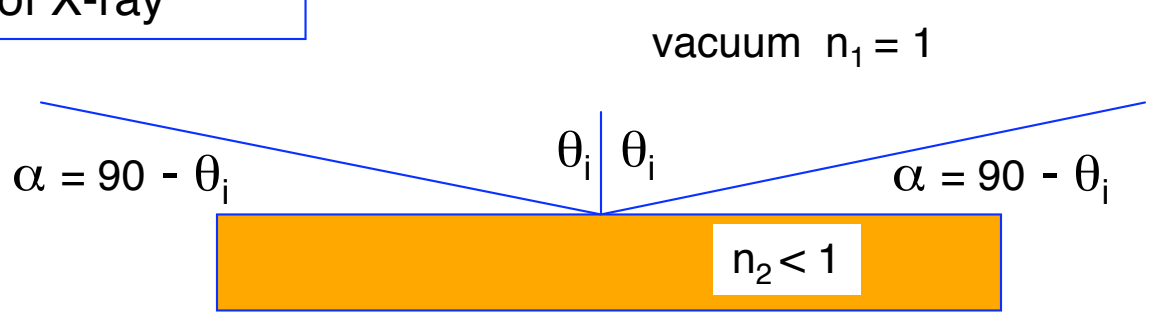


Snell's law

$$\sin\vartheta_2 = \frac{n_1}{n_2}\sin\vartheta_1$$

no solution for $n_2 < n_1 \sin\theta_i$

total external reflection of X-ray



Snell's law

$$\sin\vartheta_2 = \frac{n_1}{n_2}\sin\vartheta_1$$

no solution for $n_2 < n_1 \cos\alpha$

total external reflection

critical grazing angle θ_c

$$\theta_c = (4\pi r_o \lambda^2 n)^{1/2}$$

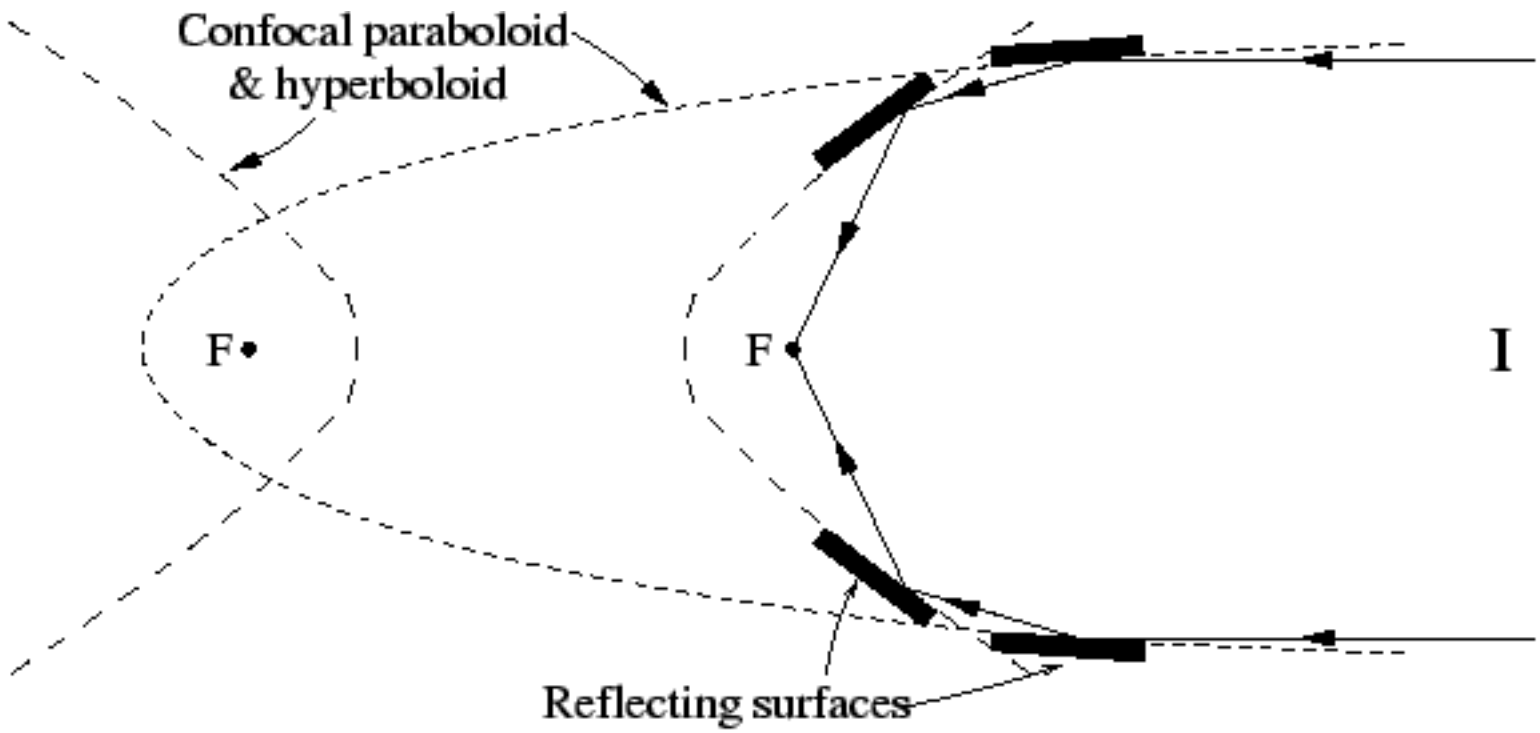
r_o classical e^- radius
n electron density

+ high reflectivities
+ imaging capabilities
+ large bandpass
± small θ_c small (γ-rays) => long focal length
- small projected reflecting surfaces

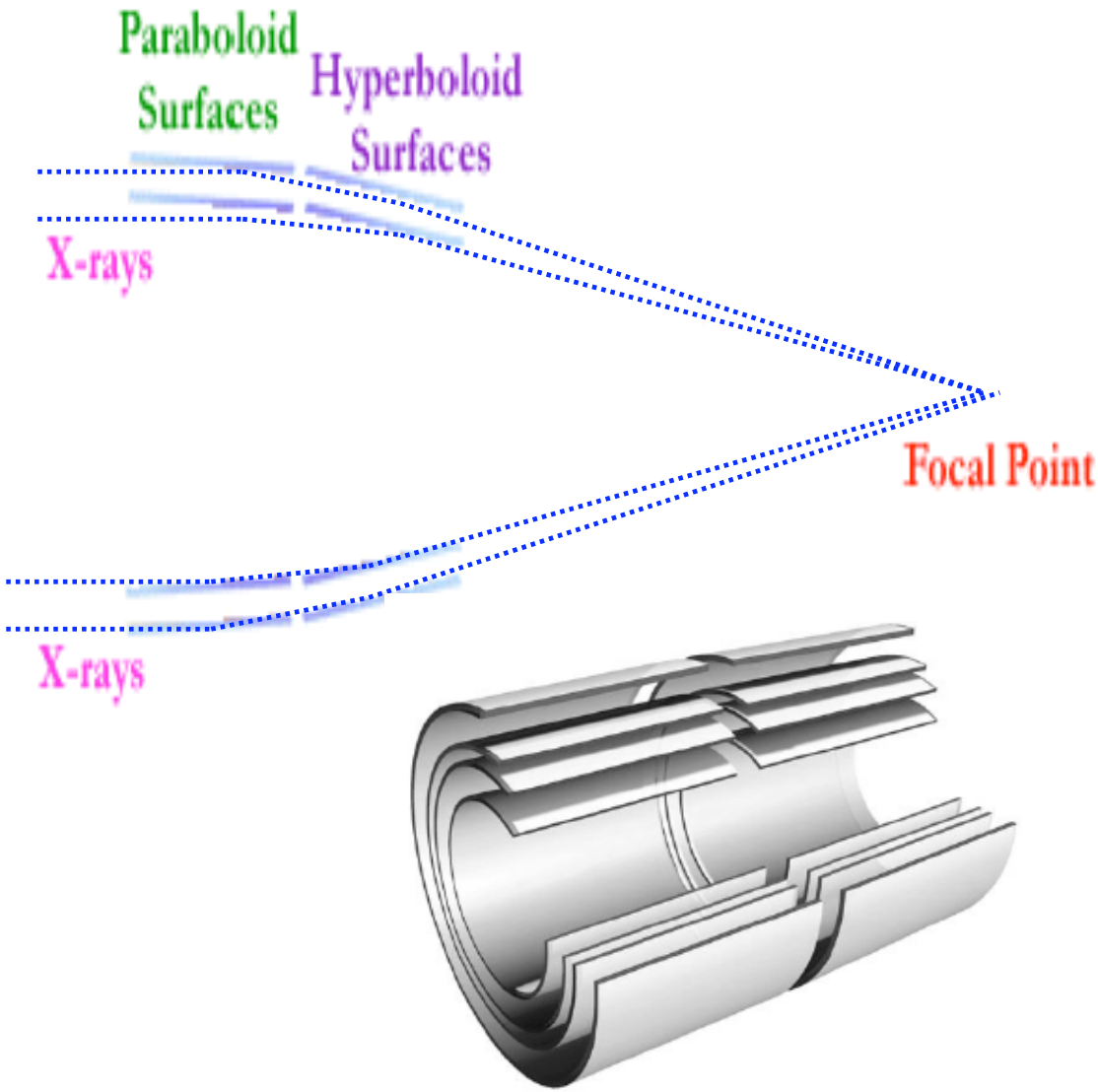
element	Z	δ	β	θ_c (10 keV)
C (diamond)	6	$4.6 \cdot 10^{-6}$	$4.5 \cdot 10^{-9}$	0.173°
Si	14	$4.9 \cdot 10^{-6}$	$7.4 \cdot 10^{-8}$	0.180°
Cu	29	$1.6 \cdot 10^{-5}$	$1.9 \cdot 10^{-6}$	0.326°
Au	79	$3.0 \cdot 10^{-5}$	$2.2 \cdot 10^{-6}$	0.443°

http://www.astro.caltech.edu/~george/ay20/xray-telescopes.pdf

Wolter type I telescope

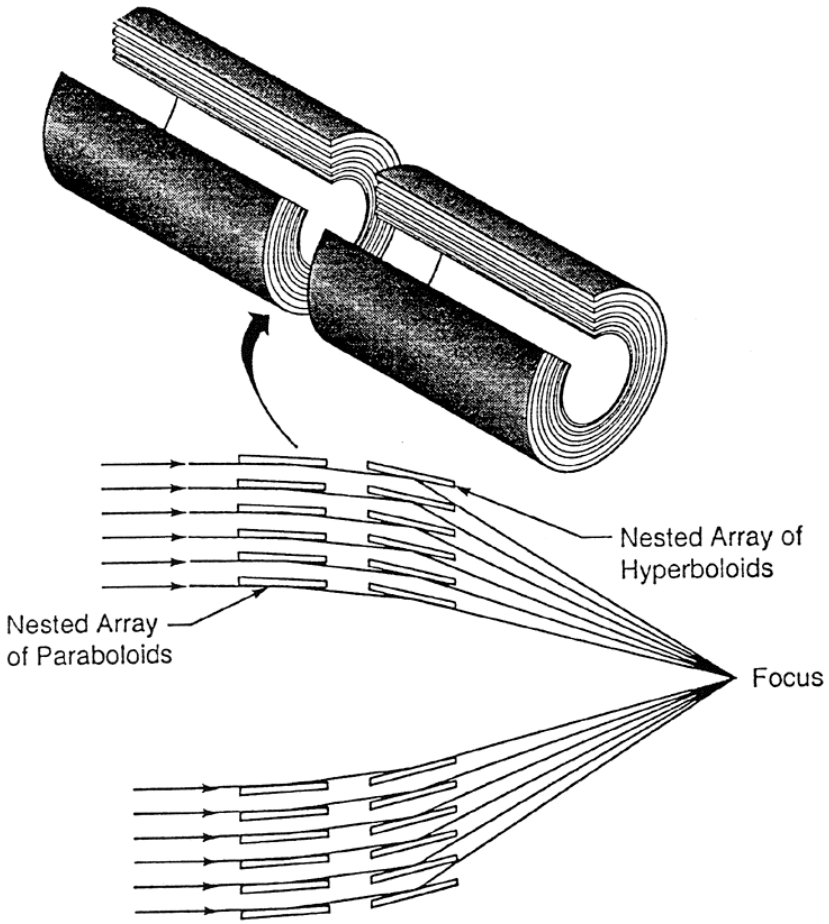


Wolter telescopes



XMM mirror

Wolter telescopes



mission launch	no mirr.	geom area [cm^2]	graz. angles [arcmin]	highest energy [keV]
"traditional" grazing inc. optics (e.g Zerodur)				
Einstein '78	4	412	40-70	5
Rosat '90	4	1140	83-135	2
Chandra '99	4	1100	27-51	10
replicated optics				
Exosat	2	80	90-110	2
Sax*	4*30	176		
Newton '99	58	6000	18-40	10
foil optics				
Asca*	120	4*558	21-45	12
Suzaku/XRT	175	4*873		12

*2 conic sections=approx. Wolter I optic (small θ)

multiple reflection optics (4 or more)

surface imperfection

domain	lambda	$\lambda/10$	
Sub-mm	0.5 mm	50 μm	
NIR	2 microns	0.2 μm	
Visible	0.5 microns	50 nm	
X	1 keV	0.1 nm	(~1 atome)
Gamma	1 MeV	0.1 pm	(10-100 x noyau atomique)

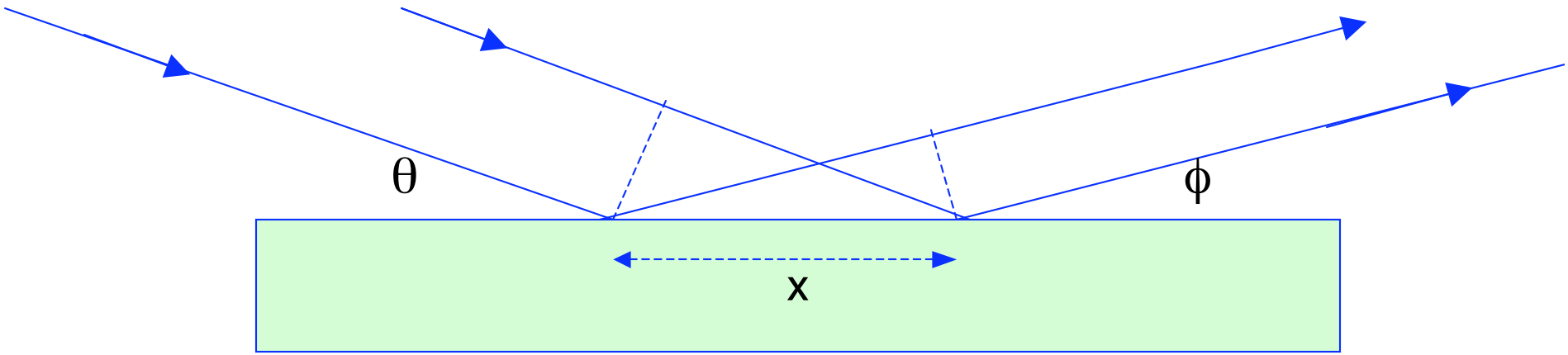
As in an optical telescope, imperfections in the shape of the mirror degrade the resolution.

Good optical surfaces are generally true to about $\lambda/4$ (~400A).

At 10 keV (1 A), a photon has a wavelength comparable to the size of an atom, and a mirror cannot be polished to levels less than a few atomic diameters.

Fortunately, at grazing incidence, the effective wavelength seen normal to the mirror is $\lambda/\sin(\theta)$, so graininess due to individual atoms is not a major concern.

external reflection seen as an interference



$$x \cos\theta - x \cos\phi = n\lambda$$

for all $\lambda \Rightarrow \phi = \theta$

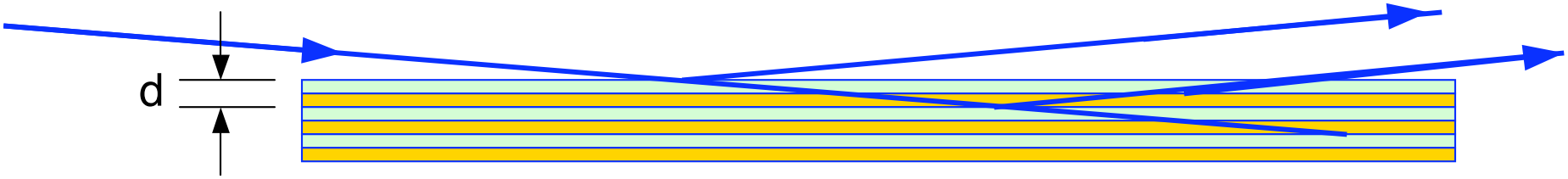
multilayer mirrors at grazing incidence

Wolter-I telescope(parabaloid + hyperboloid)working up to ~ 100 keV

http://infocus.gsfc.nasa.gov/

http://www.srl.caltech.edu/HEFT/index.html

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



several layers, d constant => narrow bandpass

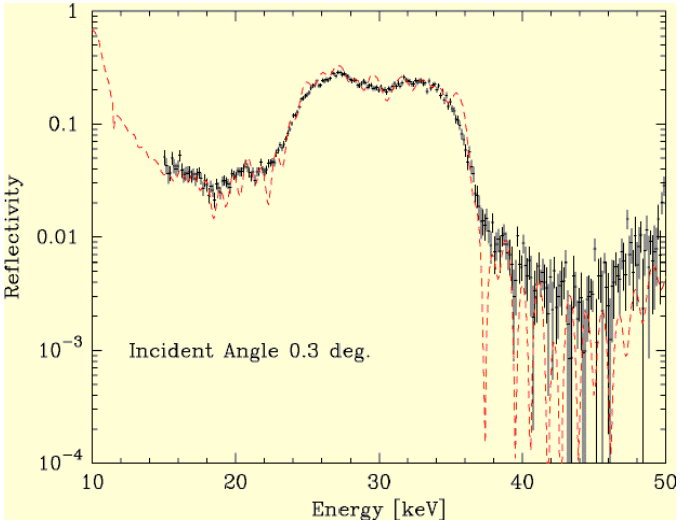
d variable => largers bandpass, reduced efficiency

Example for a multilayer mirror telescope

InFOCuS

Supermirror Hard X-ray Telescope

(GSFC + Nagoya)

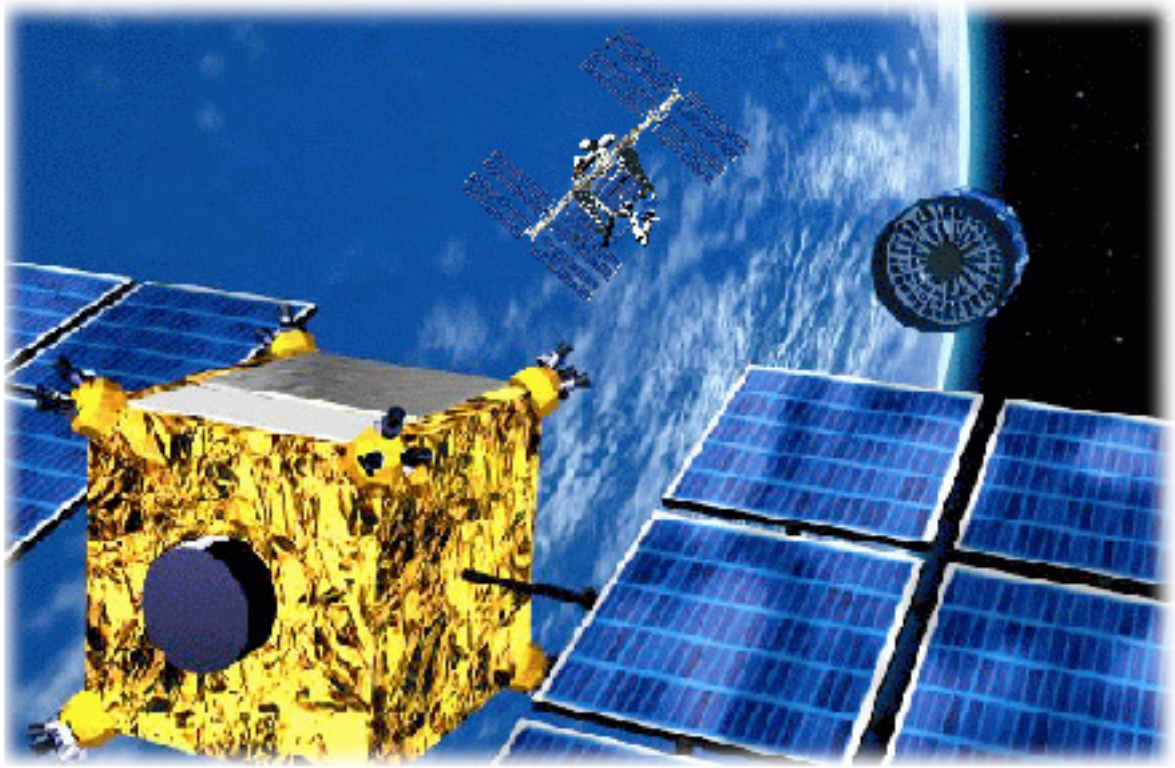


Future : SIMBOLX-X, XEUS

SIMBOLX-X, formation flying mission of CNES (see talk by Ph. Ferrando)

XEUS proposed by/to ESA to succed XMM-Newton (+ 2015).

- 250 times more sensitive than XMM-Newton
- **30 m²** = (50 x RXTE, XEUS-2)
- 0.05-30 keV (nominal)



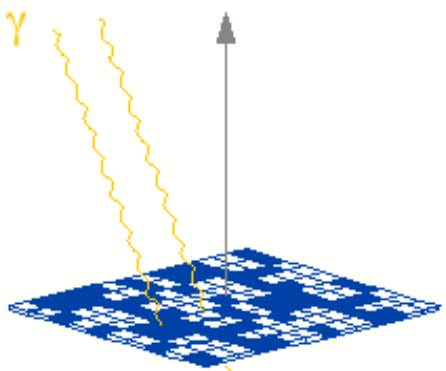
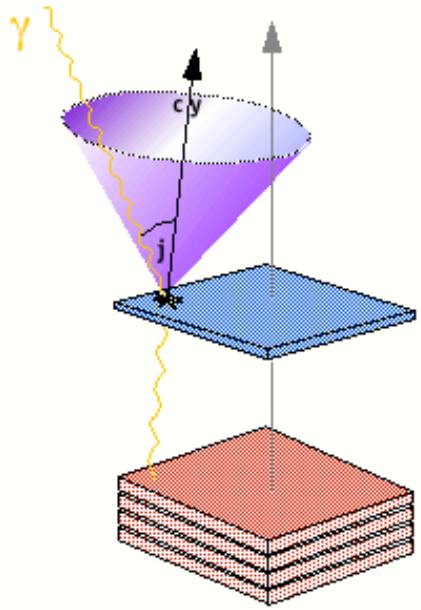
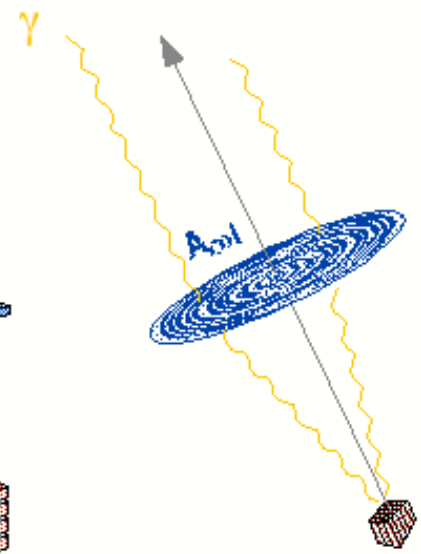
$$N_{\sigma_{qpo}} \propto \frac{S^2}{(S+B)}$$

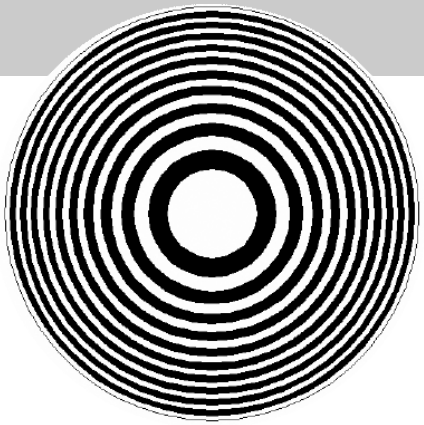
S: Source counts

(∝ collectring surface)

B: background counts

Focusing Gamma-Rays - why ?

aperture / effect	modulating aperture systems geometric optics absorption	Compton telescopes quantum optics incoherent scattering	crystal lens telescopes wave optics coherent scattering
aperture system			
detector	$A_{det} = A_{col}$	$A_{det} = A_{col}$	A_{det}
signal S ~	A_{col}	A_{col}	A_{col}
background B ~	$V_{det} \sim A_{det} = A_{col}$	$V_{det} \sim A_{det} = A_{col}$	$V_{det} \sim A_{det} << A_{col}$
S/B	const (A)	const(A)	A_{col}/A_{det}



I) Refraction / Diffraction in a Fresnel Lens

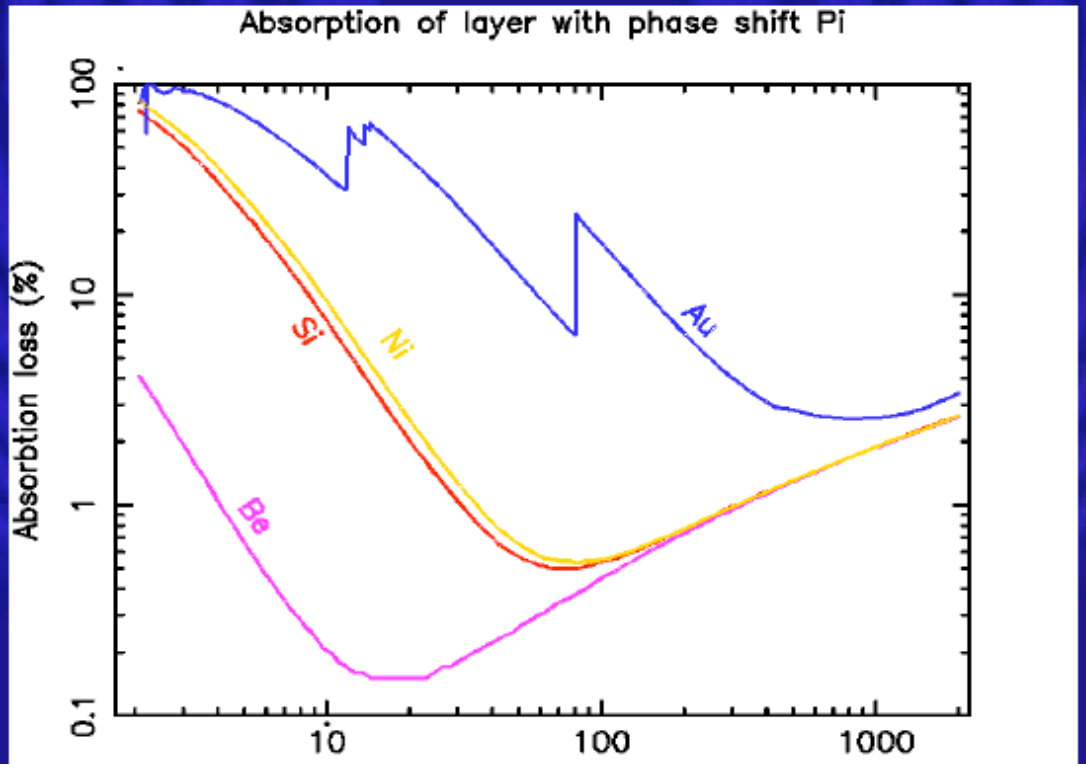
real part of the refraction index for gamma-rays :

$$\mu = 1 - \delta \qquad \text{where} \qquad \delta \approx 2\times10^{-9}\left(\frac{\rho}{10\,g\,cm^{-3}}\right)\left(\frac{E}{1MeV}\right)^{-2}$$

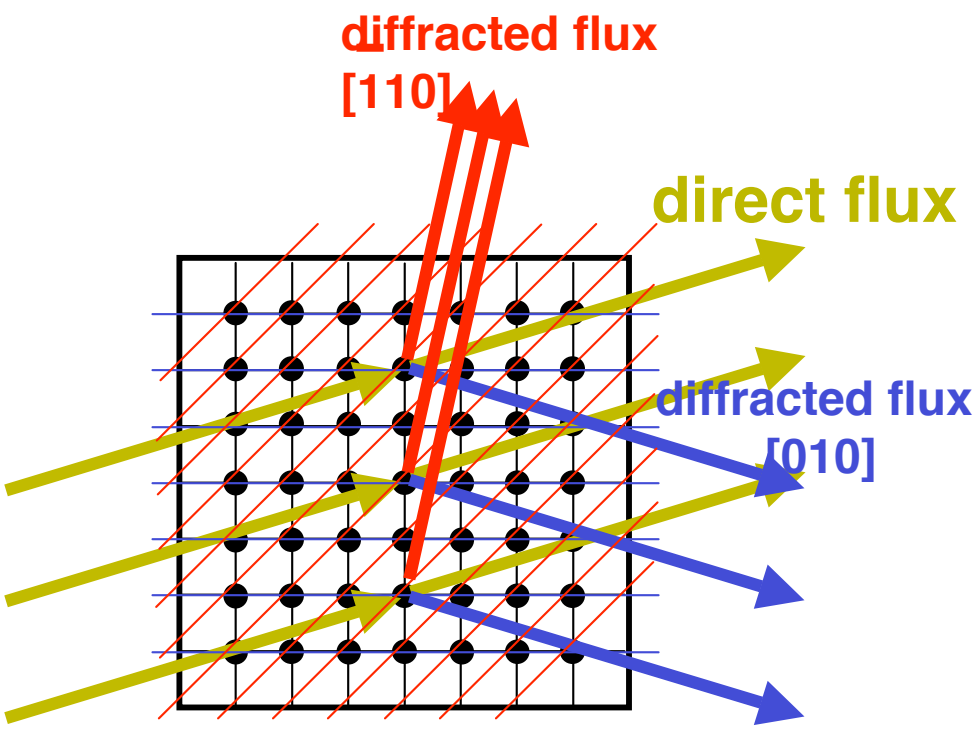
$$t_{2\pi} = \frac{\lambda}{\delta} \approx 0.6\left(\frac{\rho}{10\,g\,cm^{-3}}\right)^{-1}\left(\frac{E}{1MeV}\right) mm$$

Some examples of the thickness necessary for a phase change of 2π :

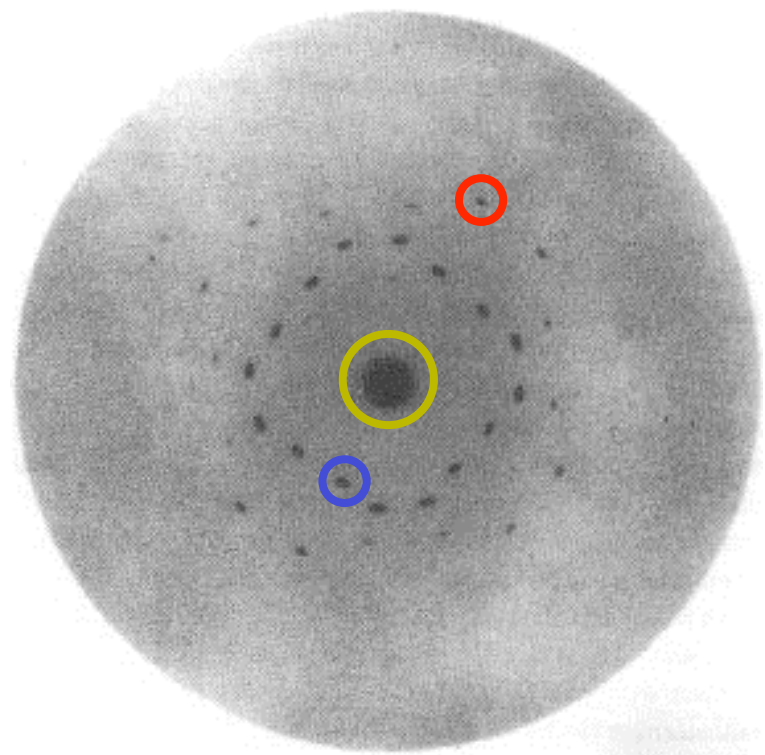
	Energy	$t_{2\pi}$	Transmission
Plastic	6 keV	30 microns	96 %
Aluminium	100 keV	225 microns	99 %
Titanium	500 keV	0.7 mm	97 %



2) Bragg diffraction in a crystal lens

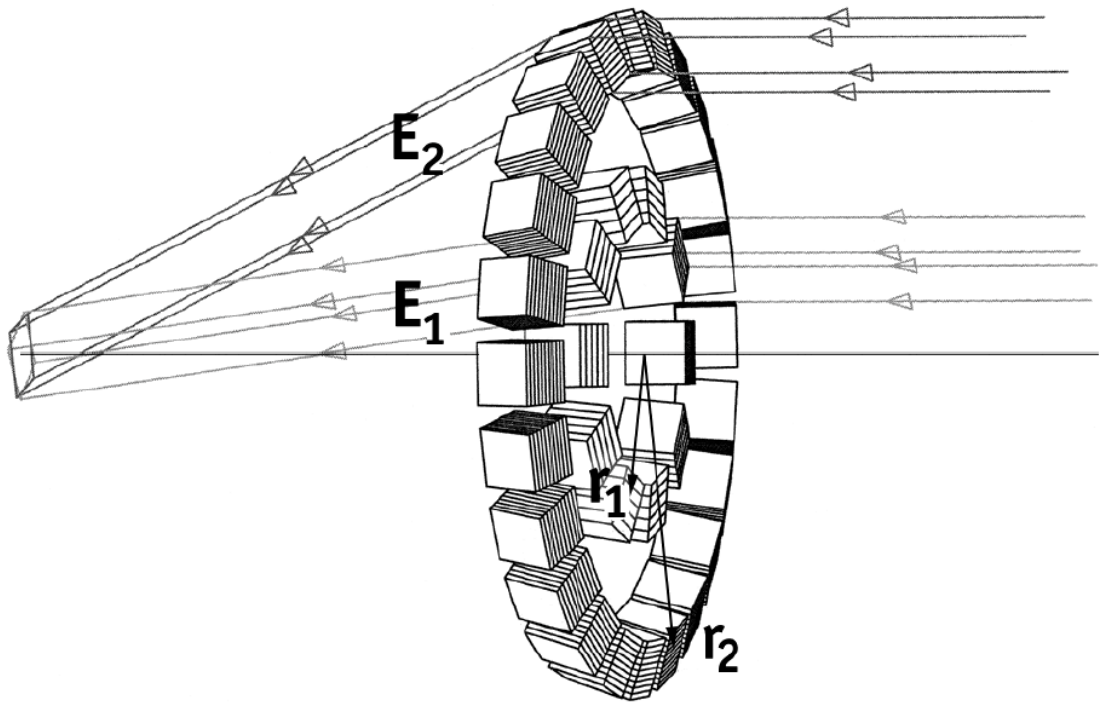


$$2d_{hkl} \sin\theta = n\lambda$$



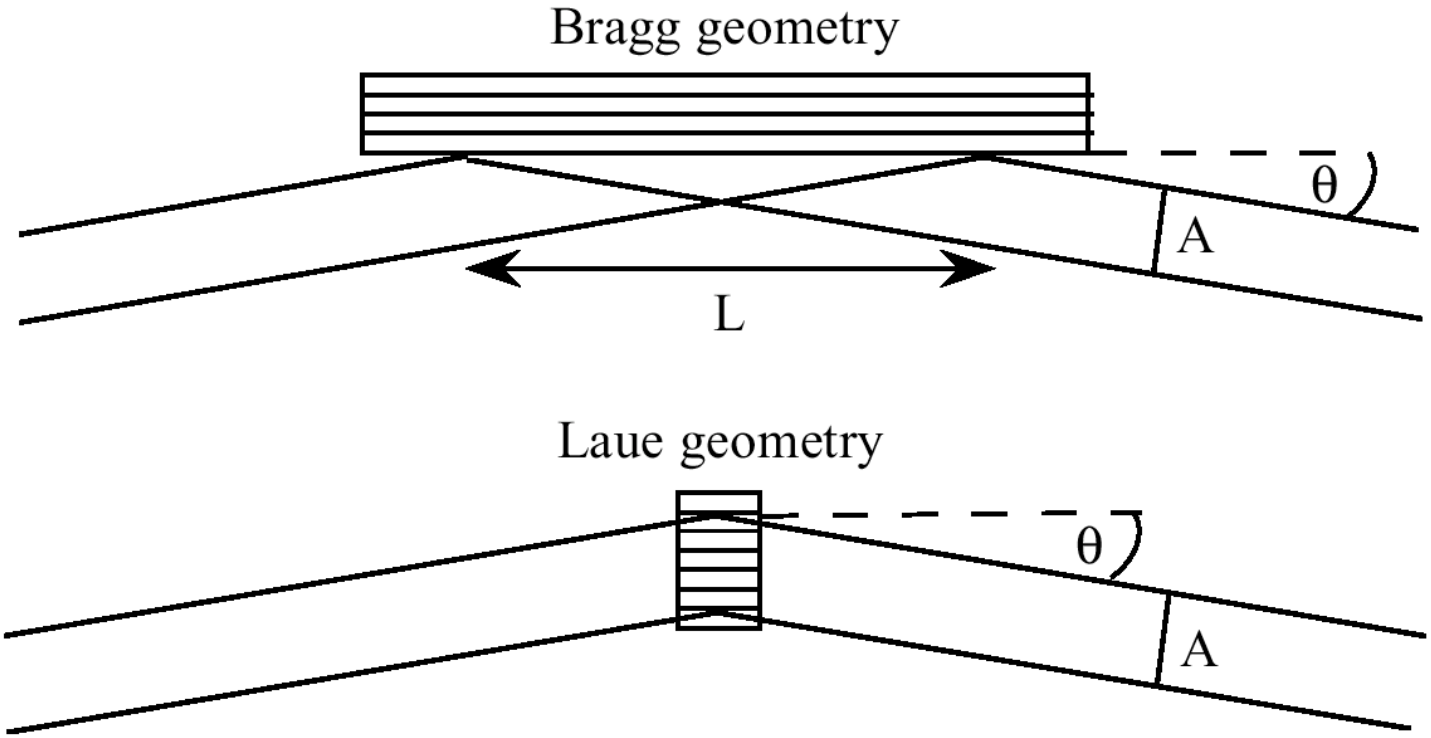
Laue, Friedrich et Knipping, 1912

Lens geometry



$$2d_{hkl}\sin\theta = n\lambda$$

Bragg vs. Laue geometry



Laue geometry uses volume reflection, whereas Bragg geometry uses surface reflection.

Bragg geometry : a beam with cross-section A would require a crystal length L
$L = A / \sin\Theta_B$ e.g. for A=1cm and $\Theta_B = 0.5°$ => L = 114 cm

calculating the reflection efficiency of a Laue lens

simplified calculation using the Darwin mosaic model :

- reflection amplitudes of each microcrystal added incoherently
- absorption is calculated on a macroscopic scale
  (the absorption within each microcrystals is neglected)

The reflection efficiency at the Bragg energy as a function of Bragg angle θ is:

$$r_{th}(\theta) = 0.5(1-e^{-2\alpha T})(e^{-\mu T})$$

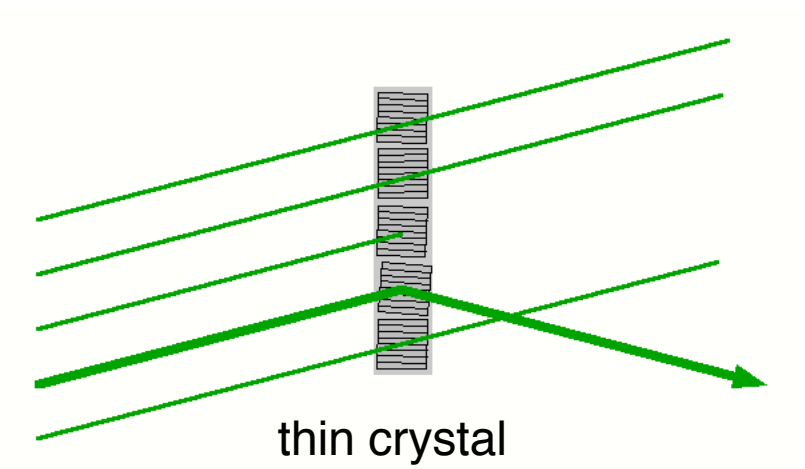
μ Absorption coefficient (T crystal thickness)

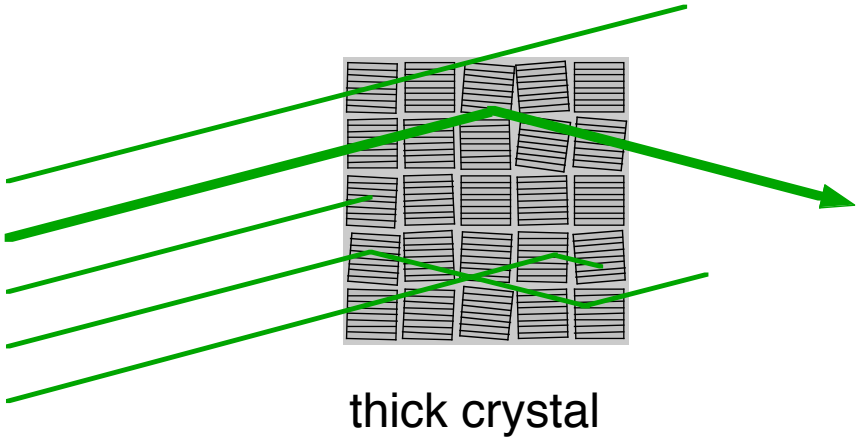
$\alpha(\theta)$ diffraction coefficient : $\alpha(\theta) \sim \frac{F^2\lambda^3}{V^2\sin(2\theta)} \sim \frac{\rho^{5/3}}{E_\gamma^2}$

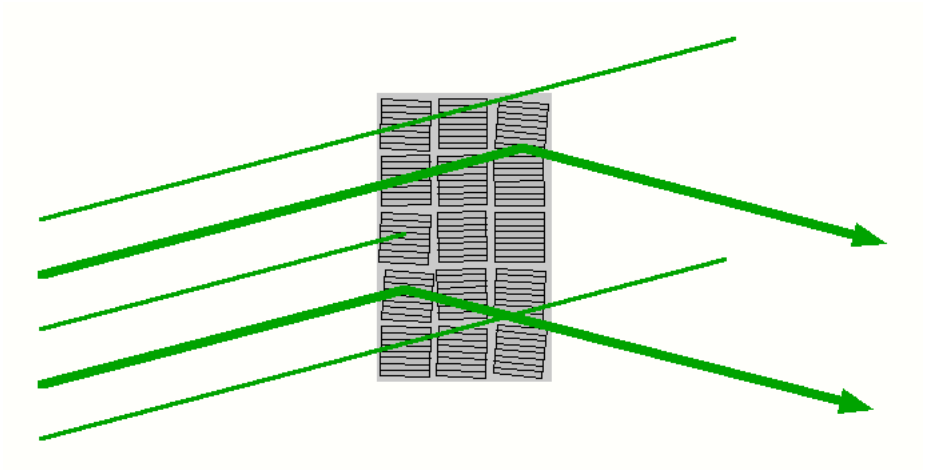
F : structure factor F[hkl=333] << F[hkl=111]

The reflection efficiency decreases with increasing energy and order, and with decreasing structure factor.

the optimal thickness for a diffraction crystal (E)

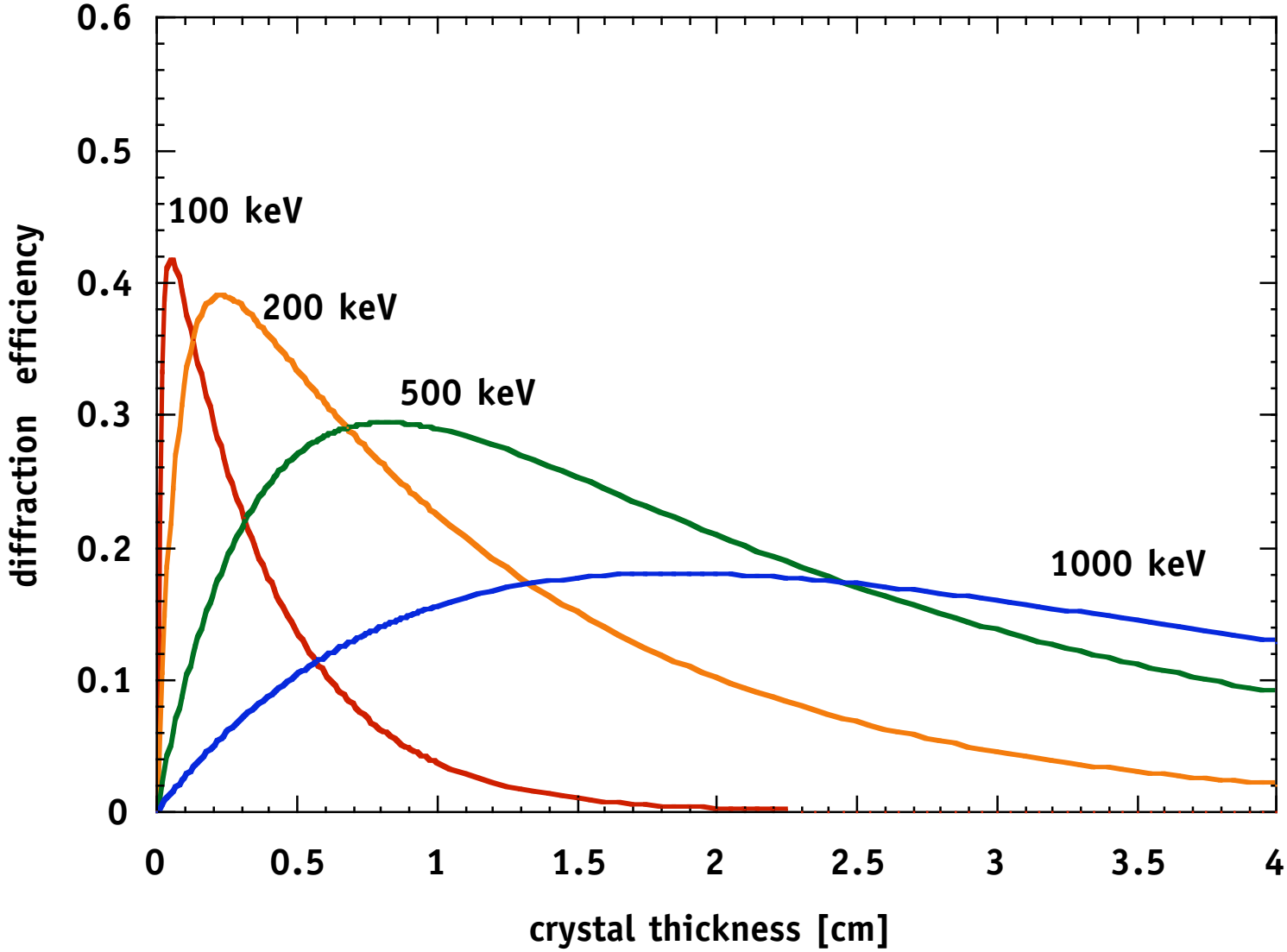




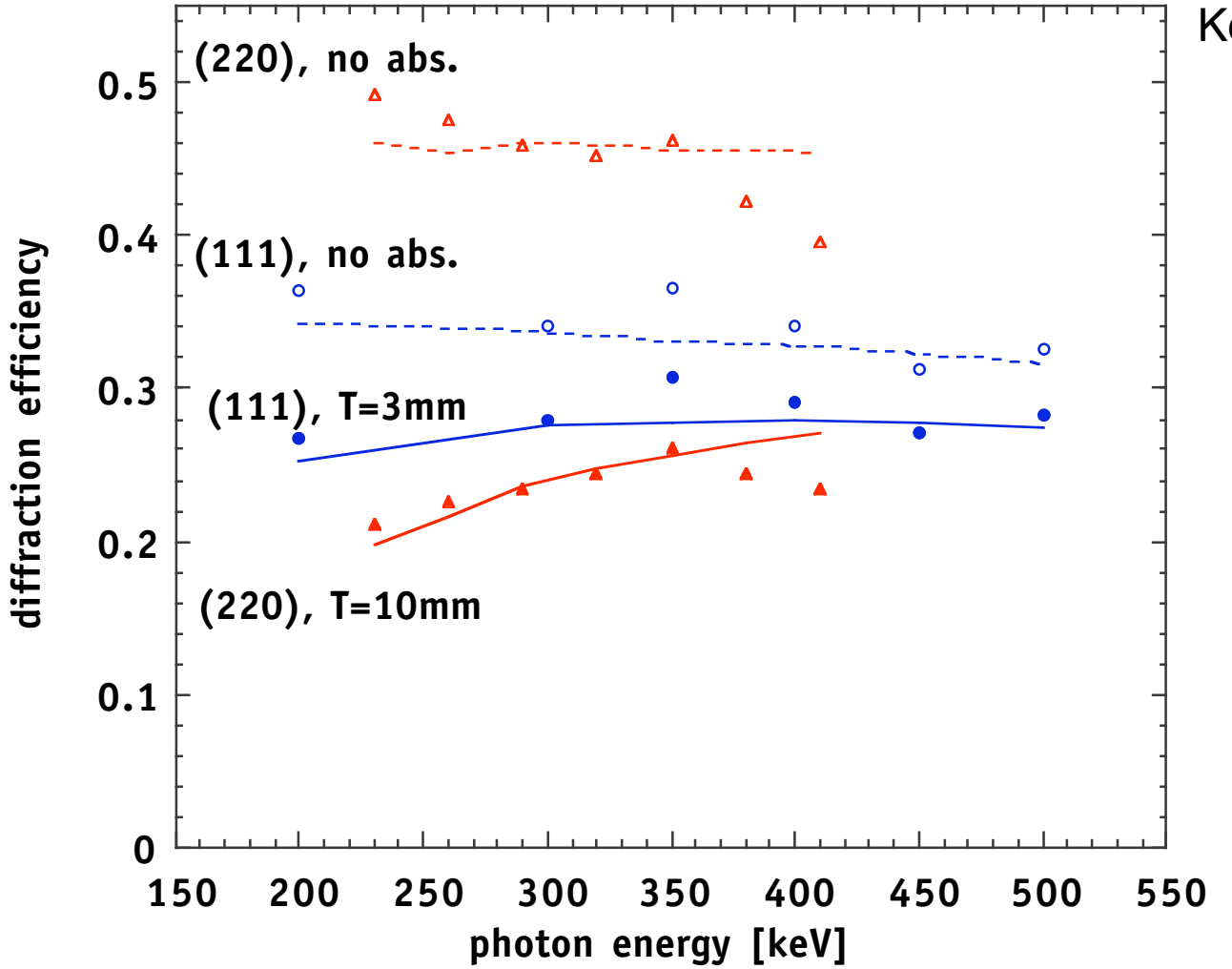


optimal thickness - energy dependent !

the crystal diffraction efficiency for Ge [440] planes



Diffraction efficiency of Ge crystals



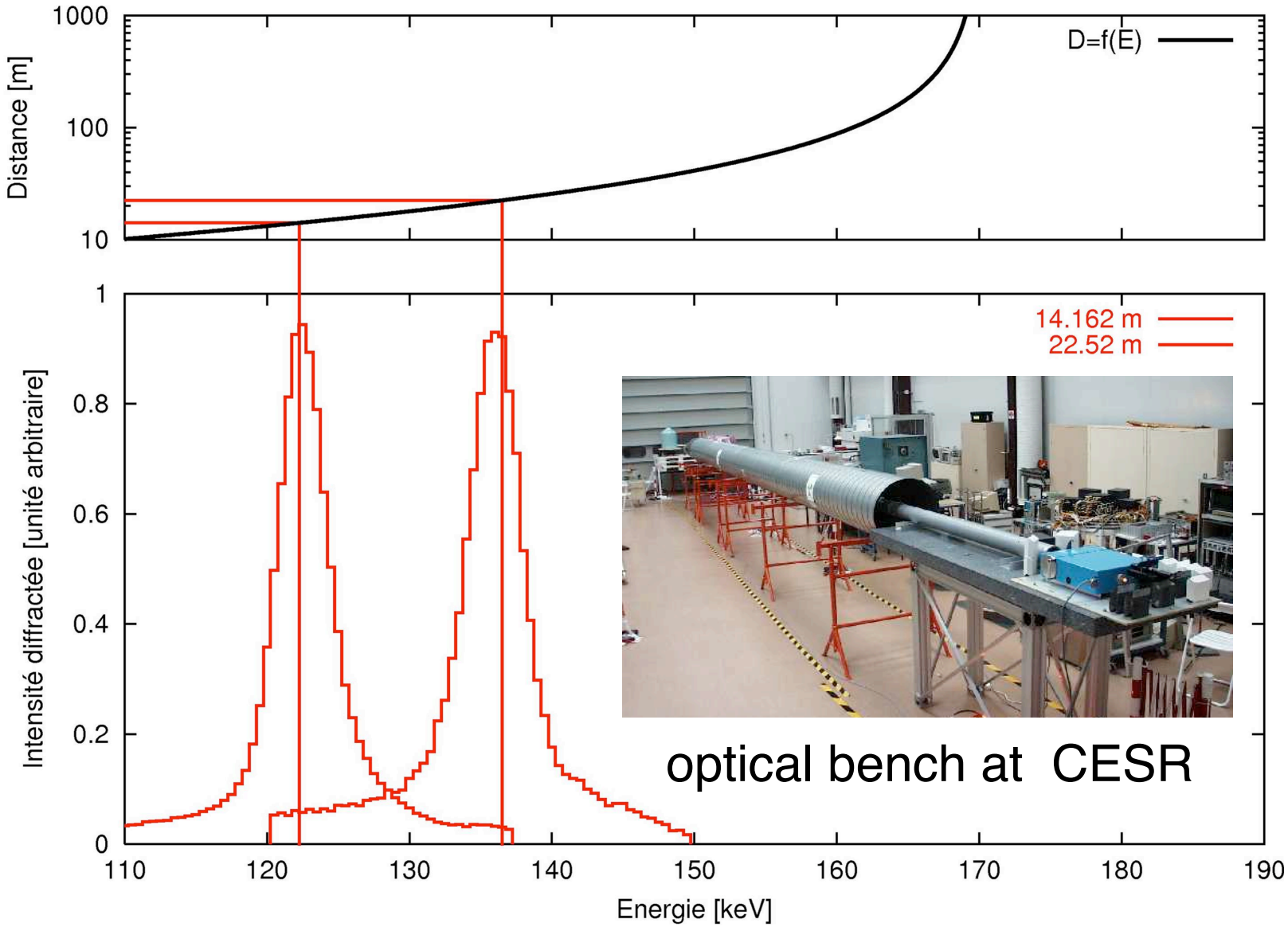
Kohnle et al 1998

APS / ANL synchrotron beam (~ parallel, divergence ≈ 3”)

diffraction efficiency : ratio of doubly diffracted / singly diffrated flux

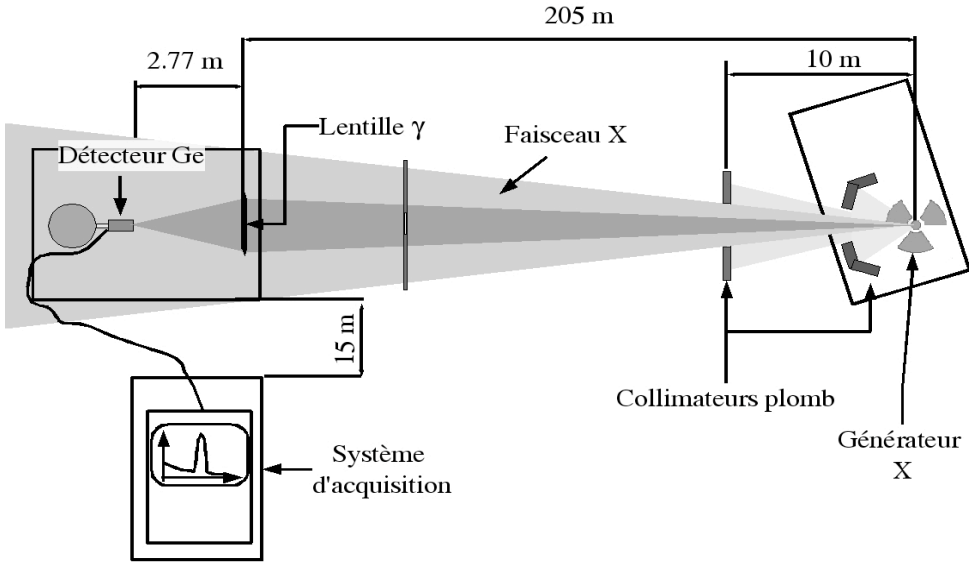
CLAIRE

CLAIRE : tests in the lab ... and beyond

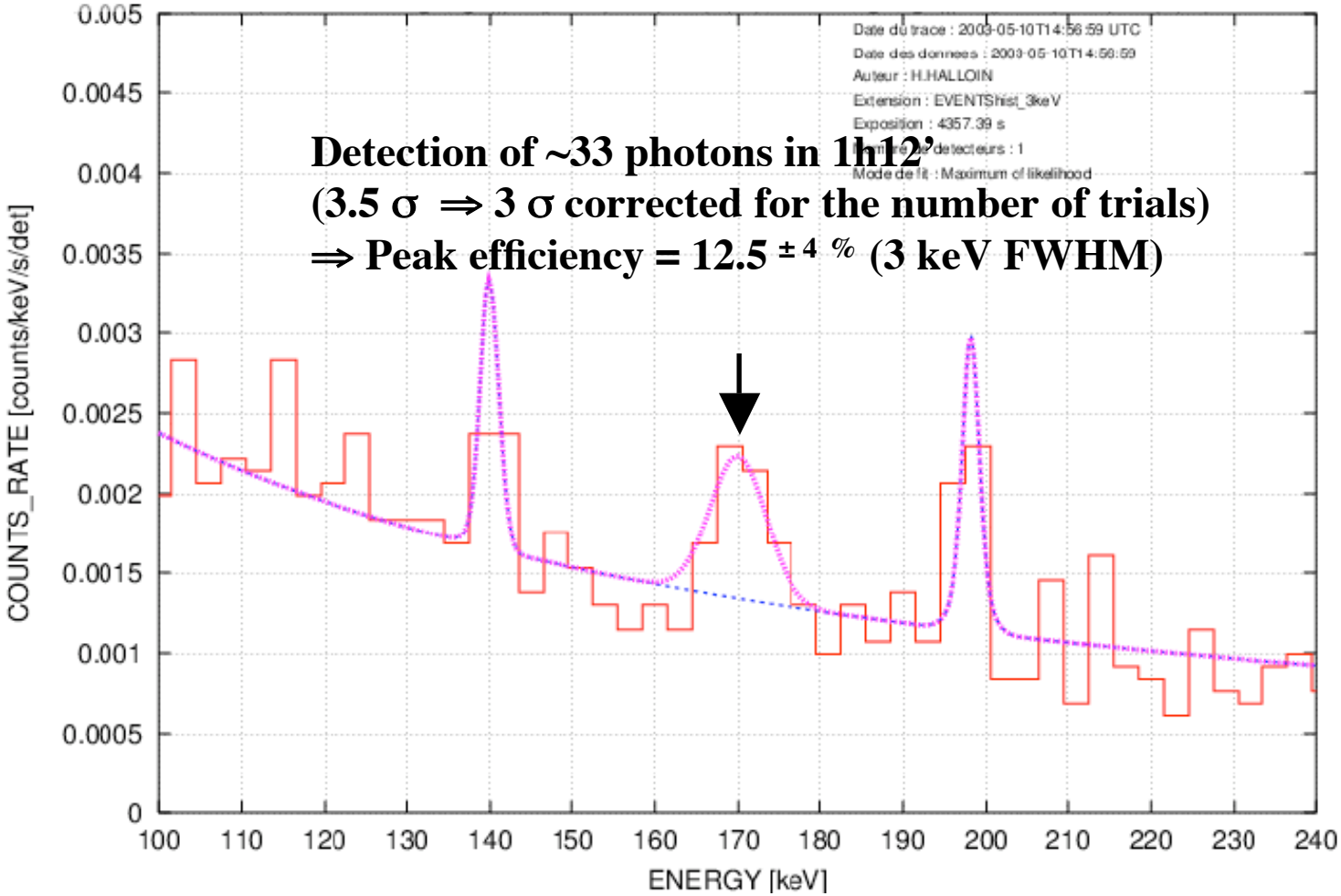


optical bench at CESR

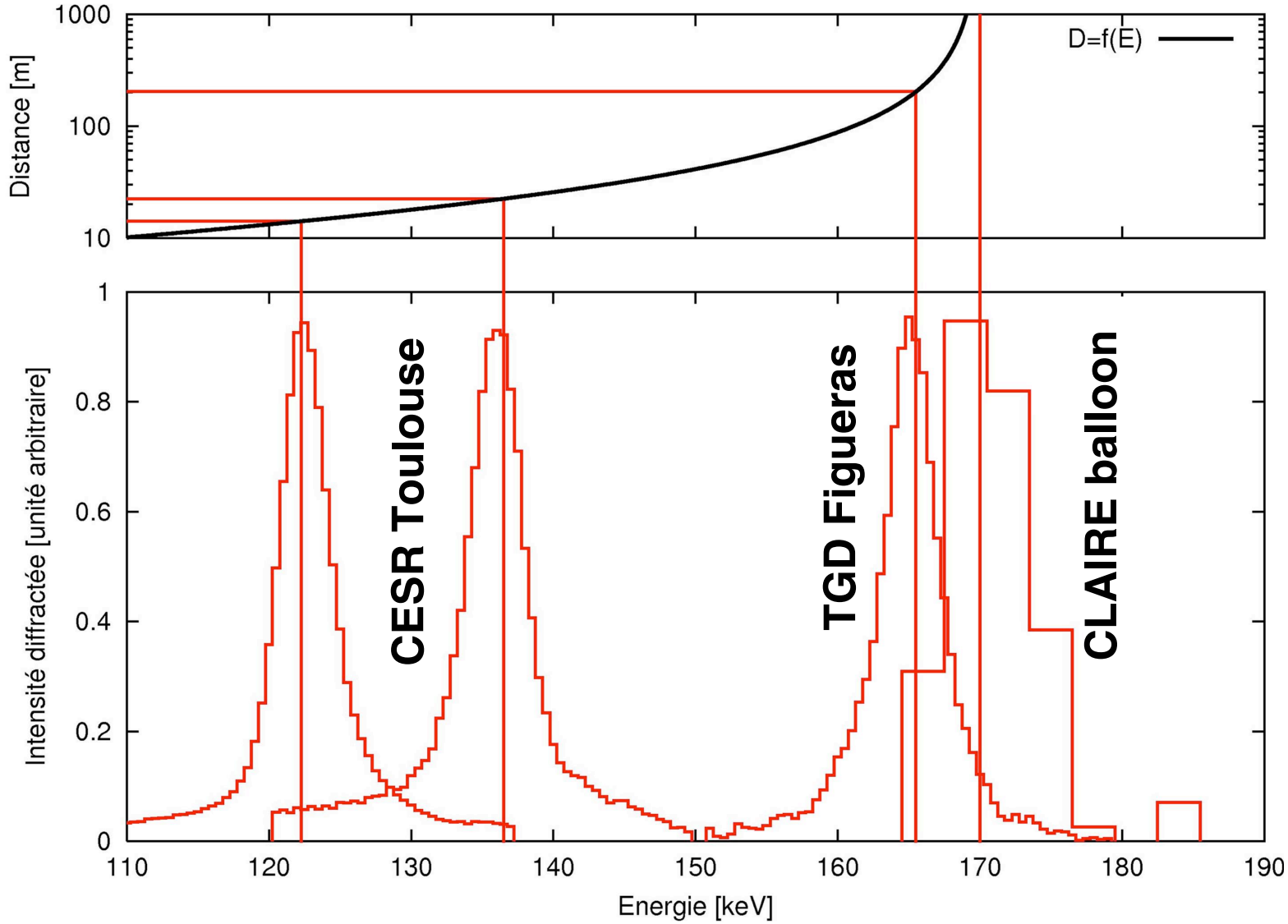
CLAIRE TGD : a source close to infinity ...



CLAIRE 2001 : first light for an astrophysical source

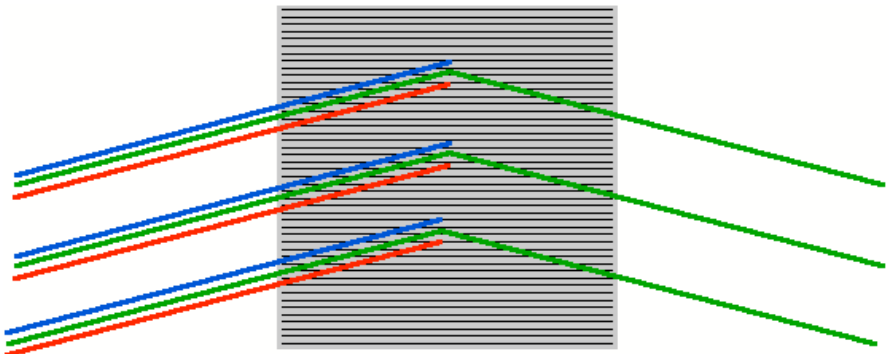


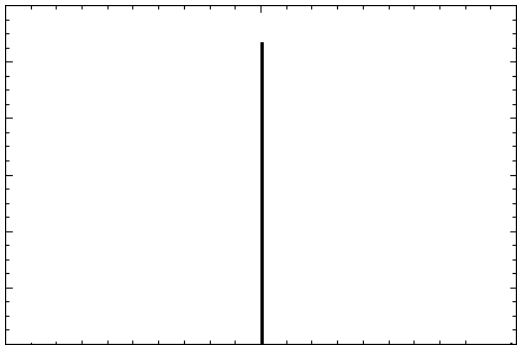
CLAIRE : 14 m, 22.5 m, 205 m ... infinity ! $\varepsilon_{peak,3\ keV} \approx 10\ \%$



the energy bandpass ΔE and field of view $\Delta\theta$

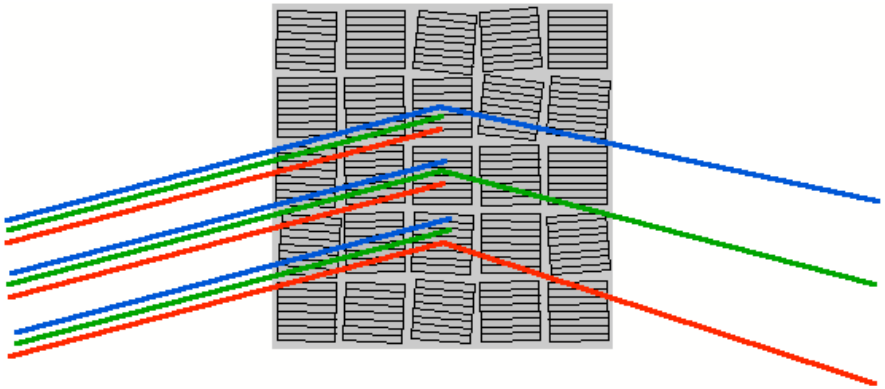
perfect monocrystal

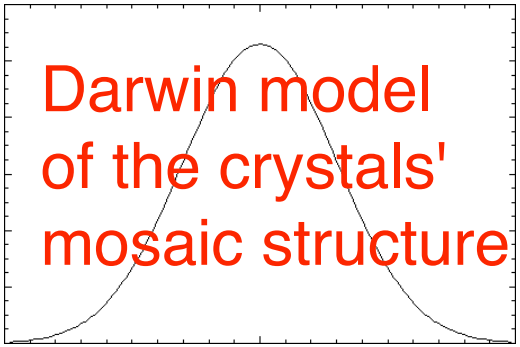




ΔE / $\Delta\theta$

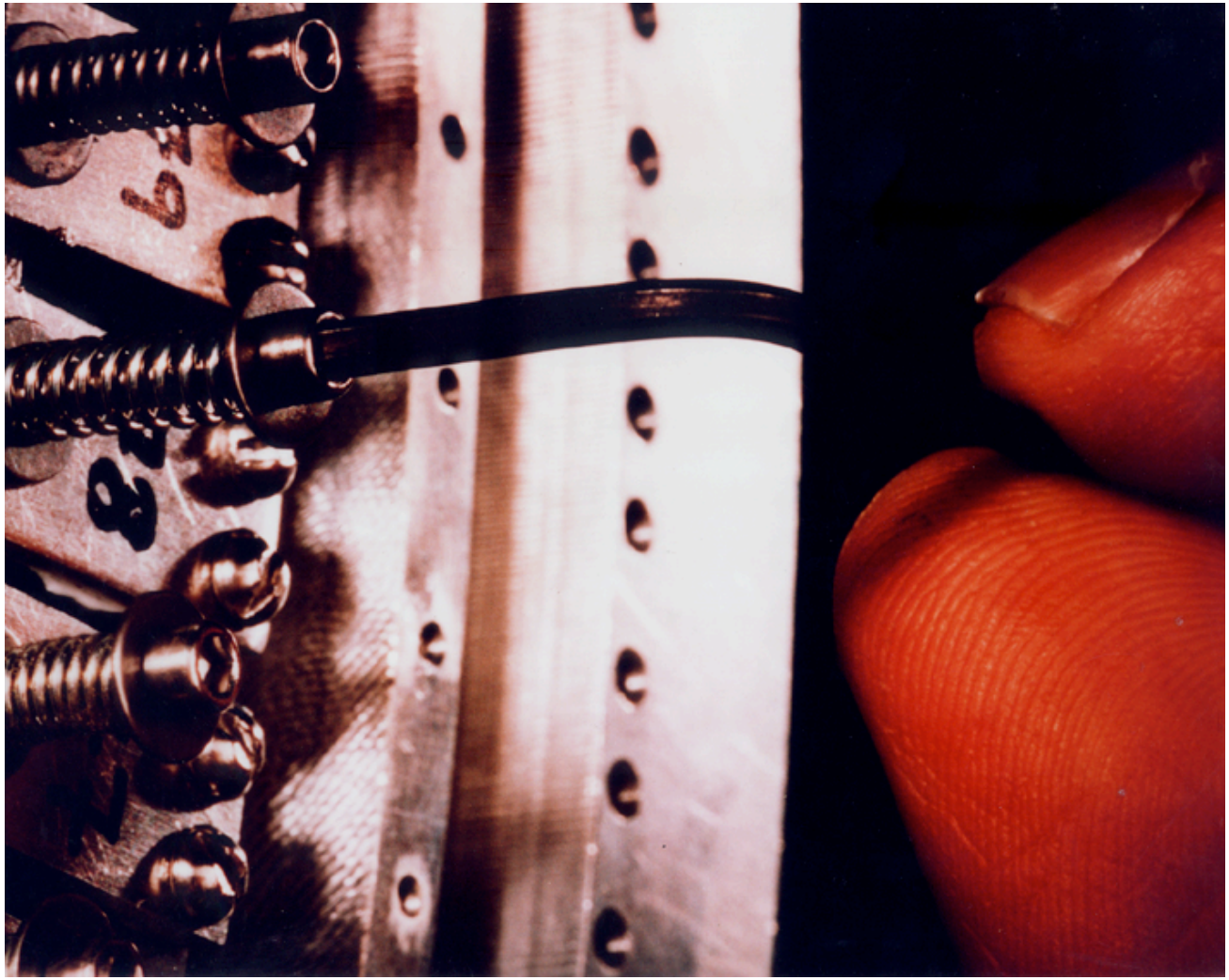
mosaic crystal



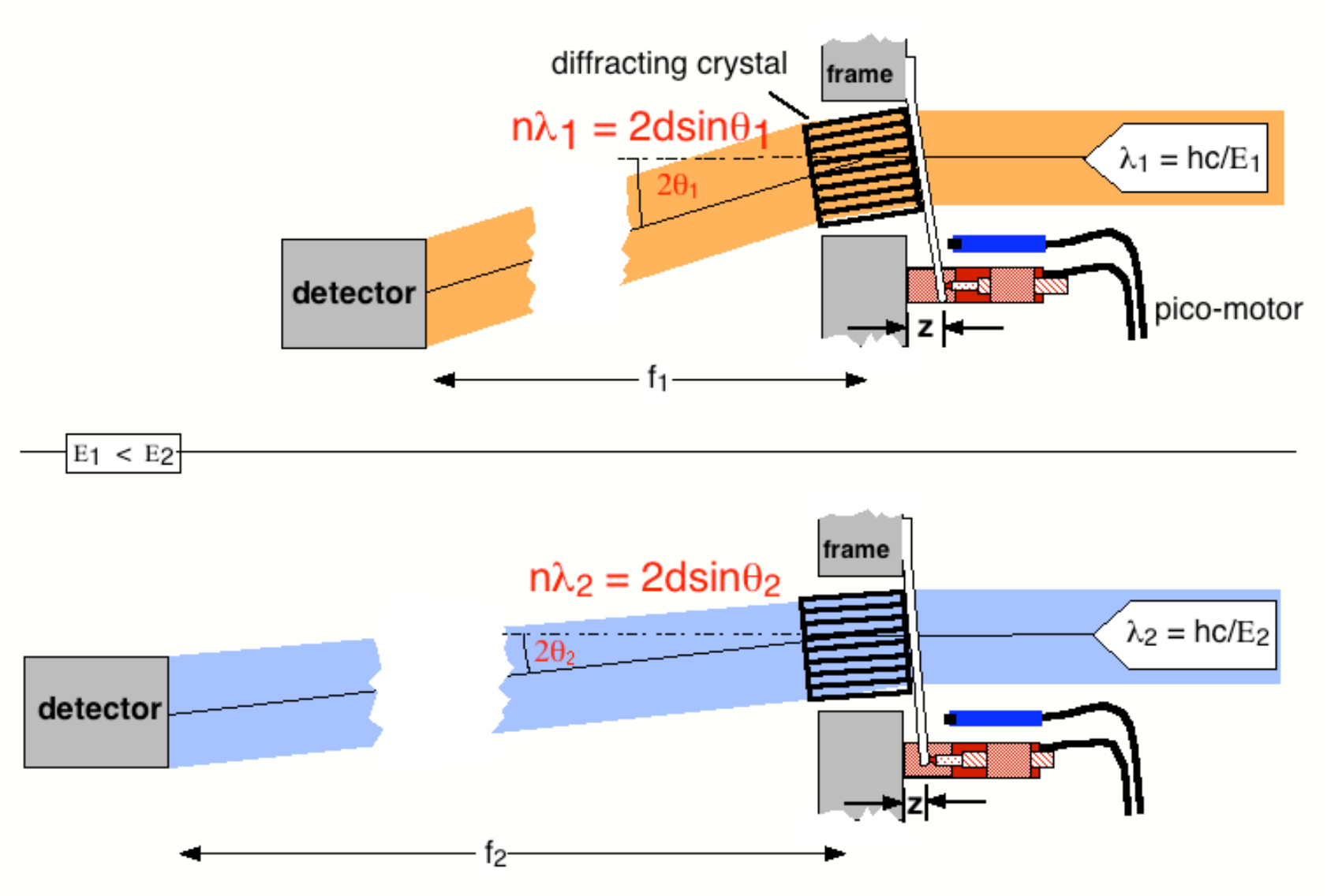


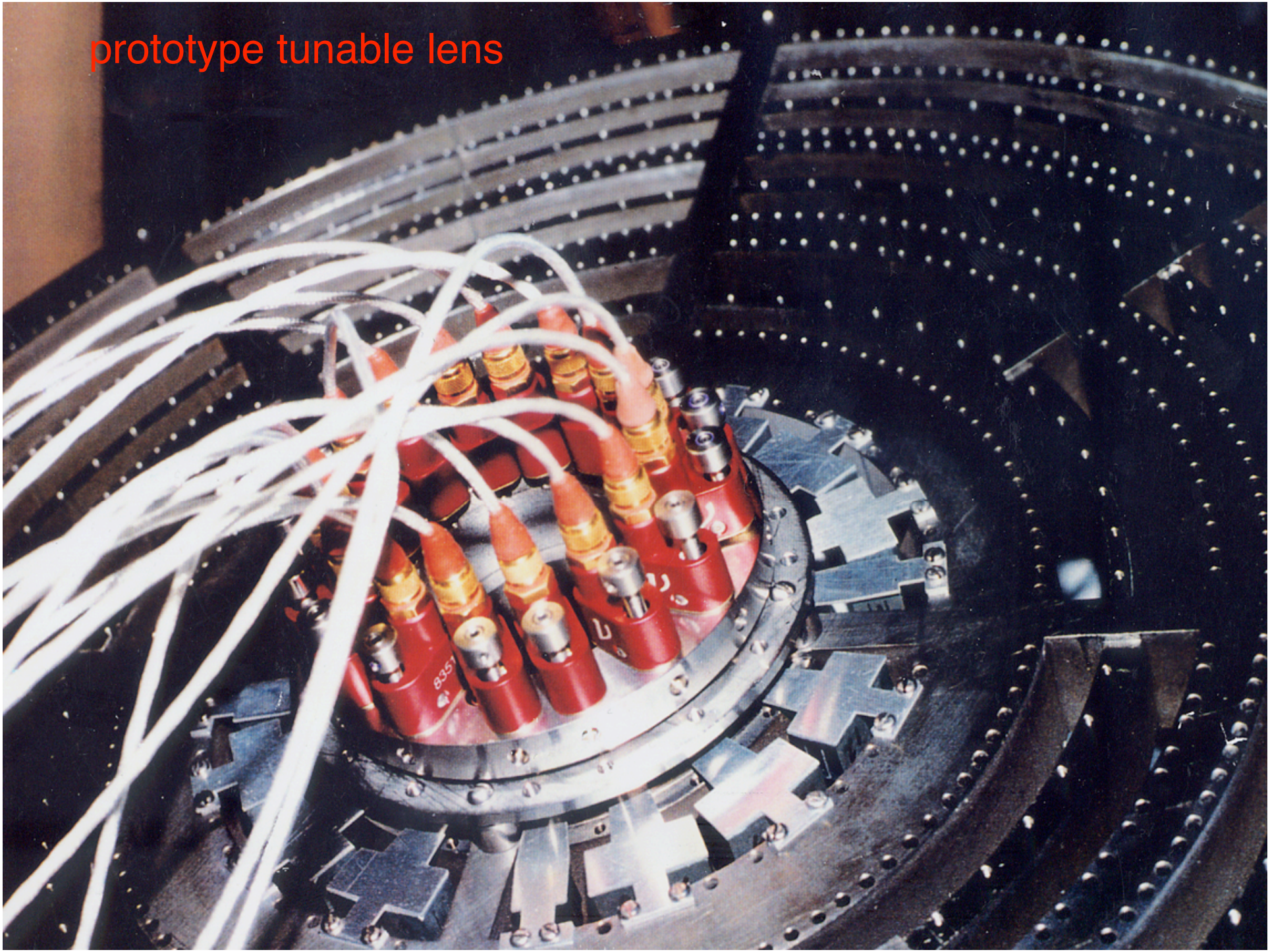
ΔE / $\Delta\theta$

tuning the lens ...



the principle of a tunable Laue Lens




prototype tunable lens

everything about nothing or nothing about everything

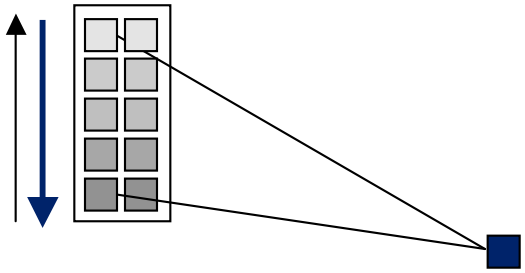
Narrow band Laue Lens :

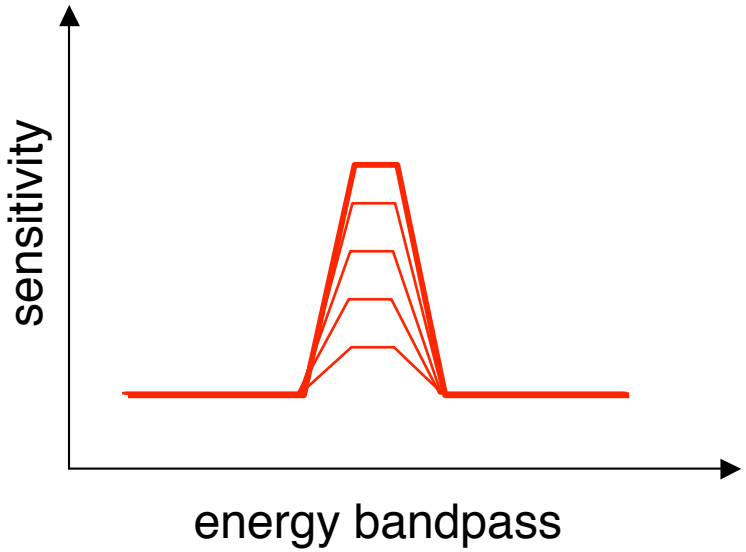
Each ring uses **different set of crystal planes**

radius r

d(r)

E fix





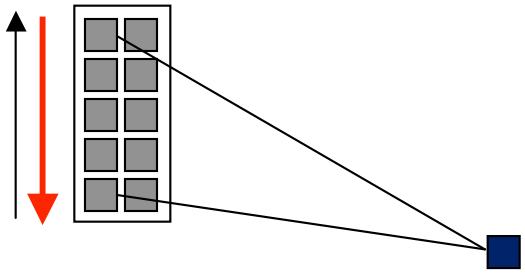
Broad band Laue Lens :

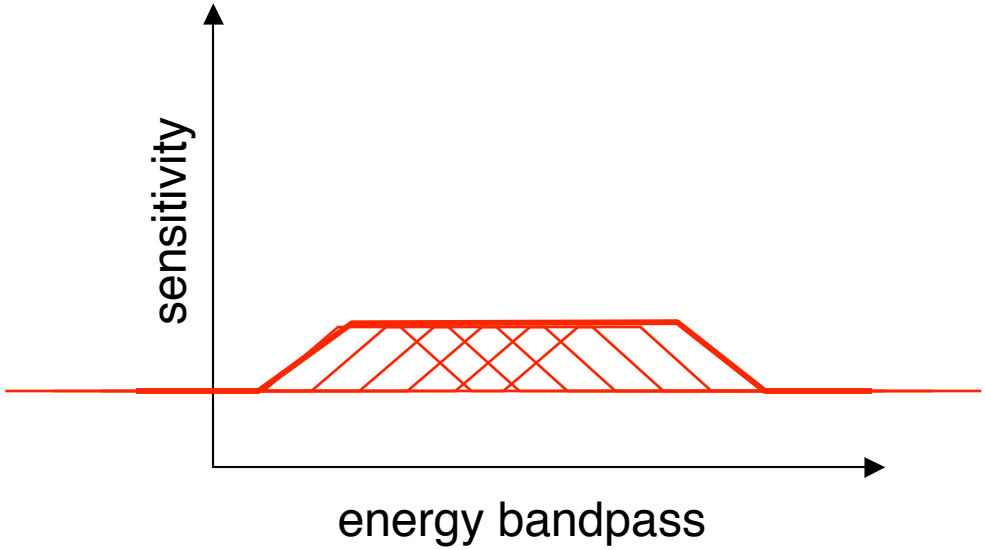
All rings use **same set of crystal planes**

radius r

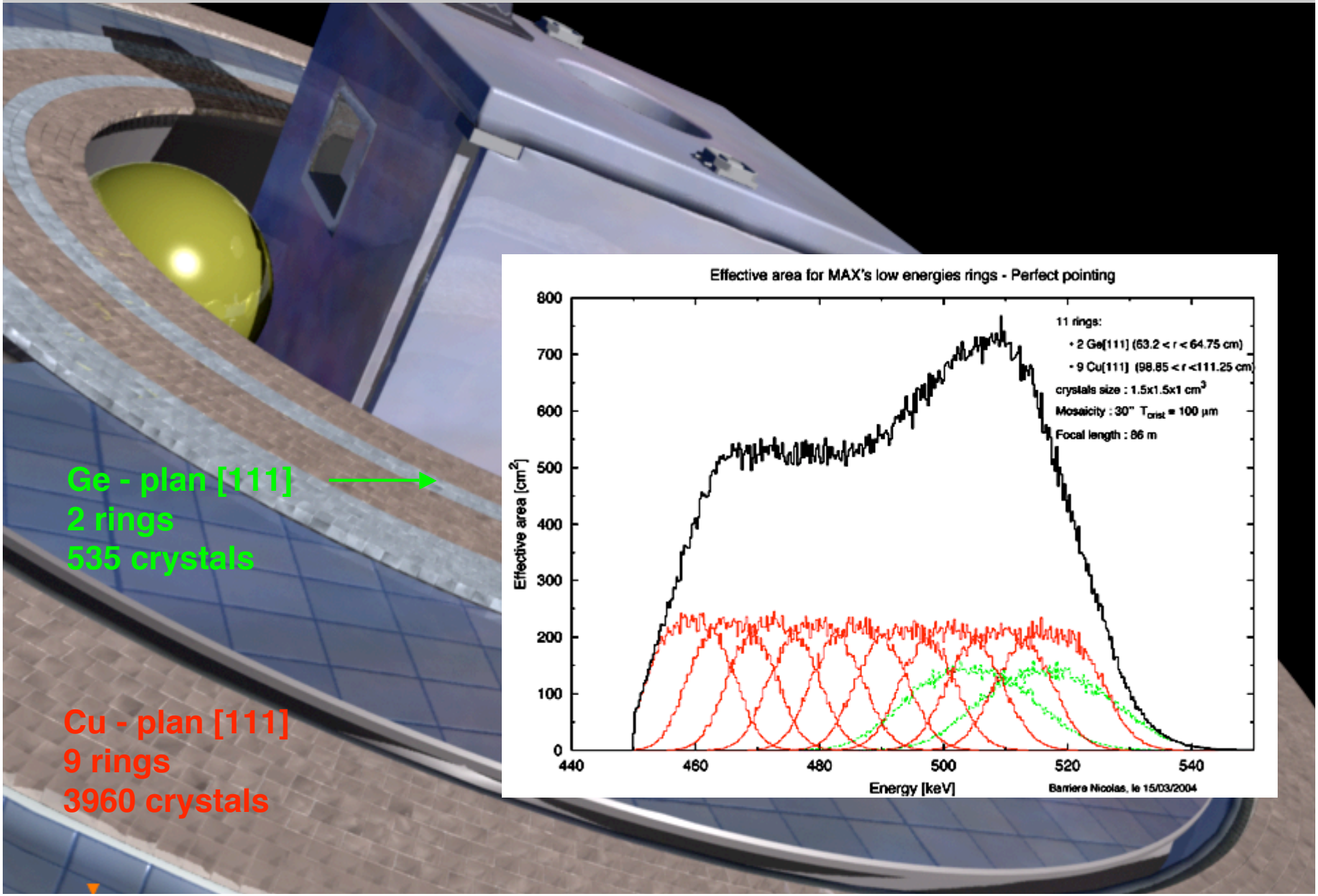
d fix

E(r)

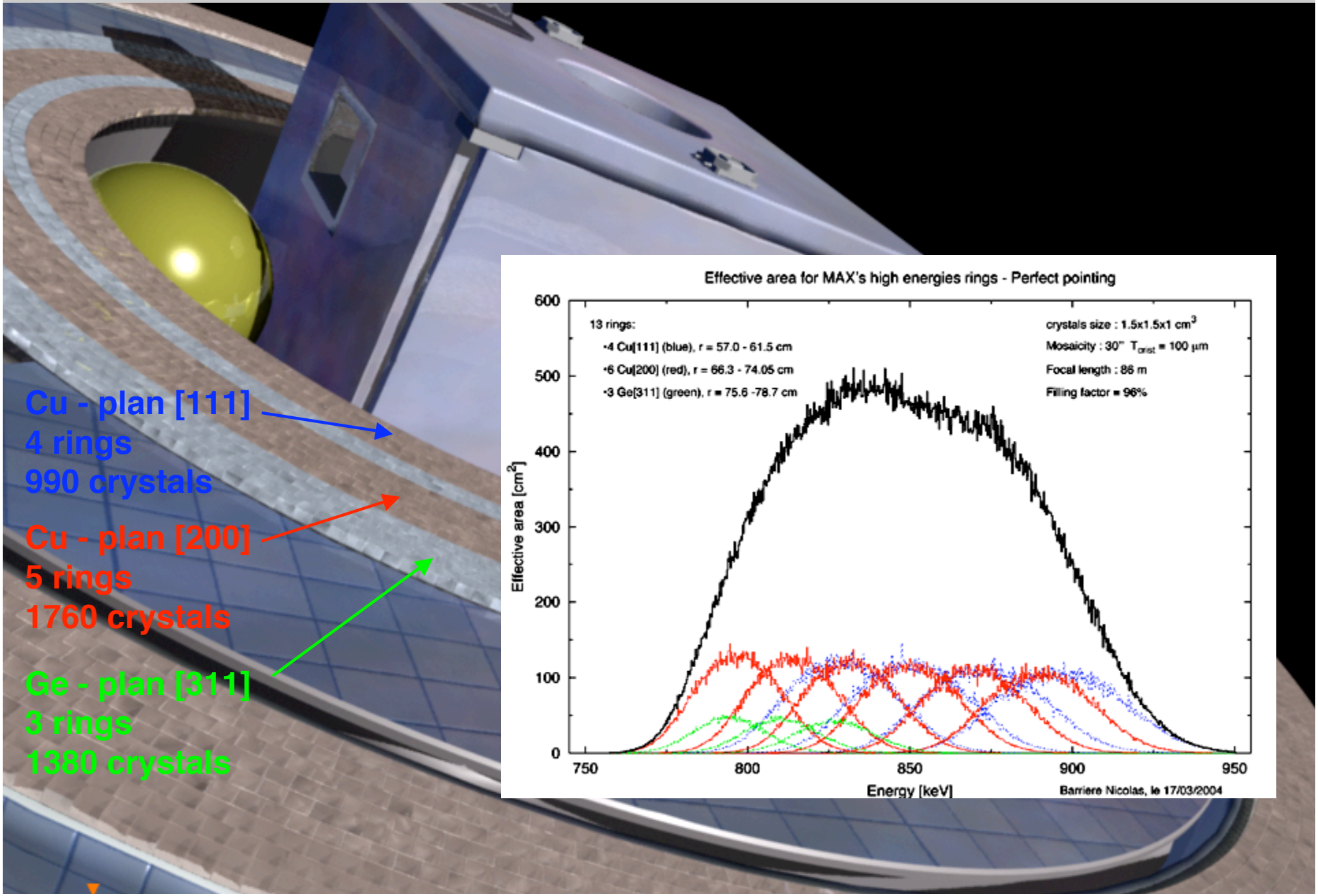


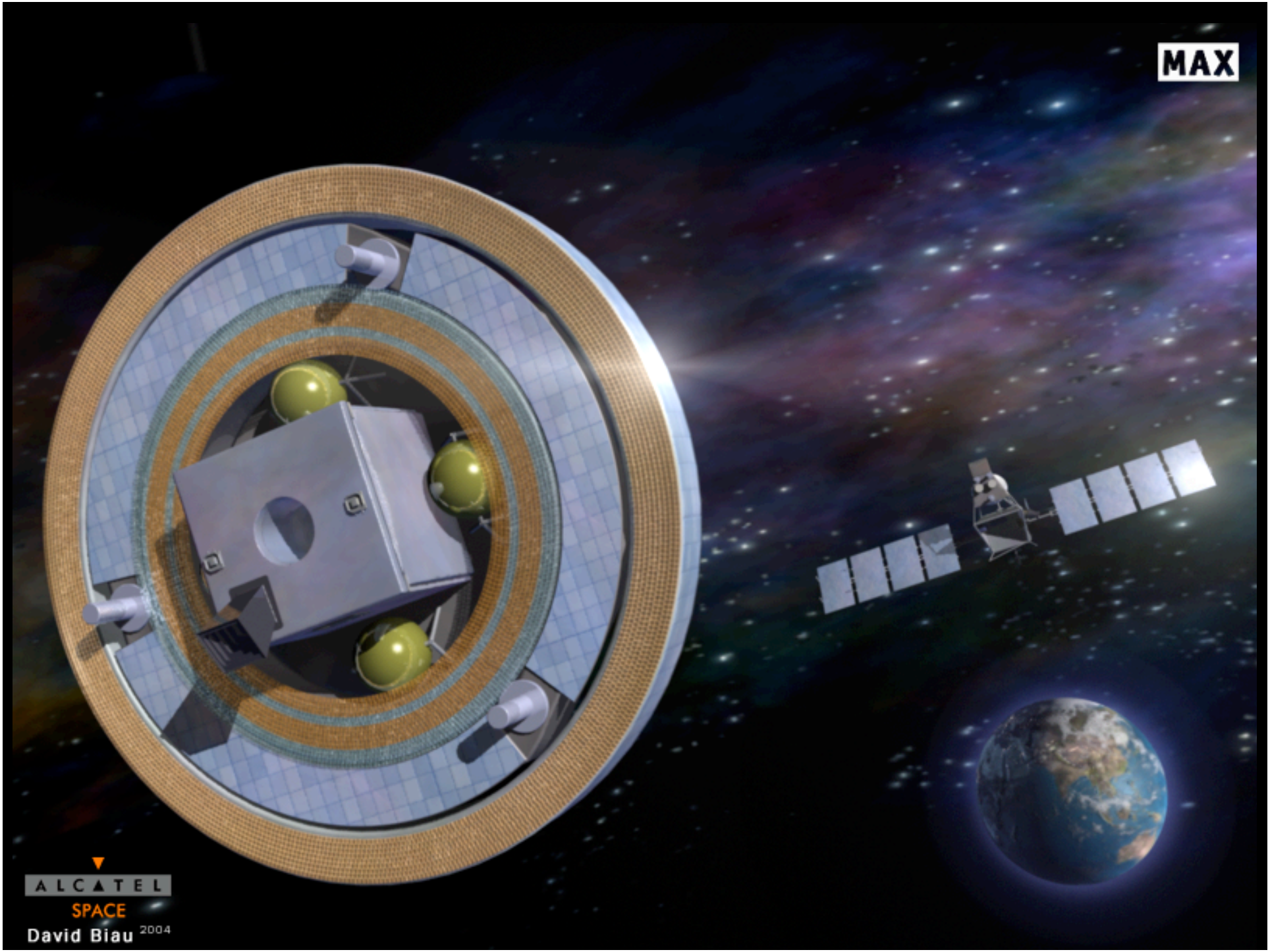


designing a Laue lens telescope - efficient area I

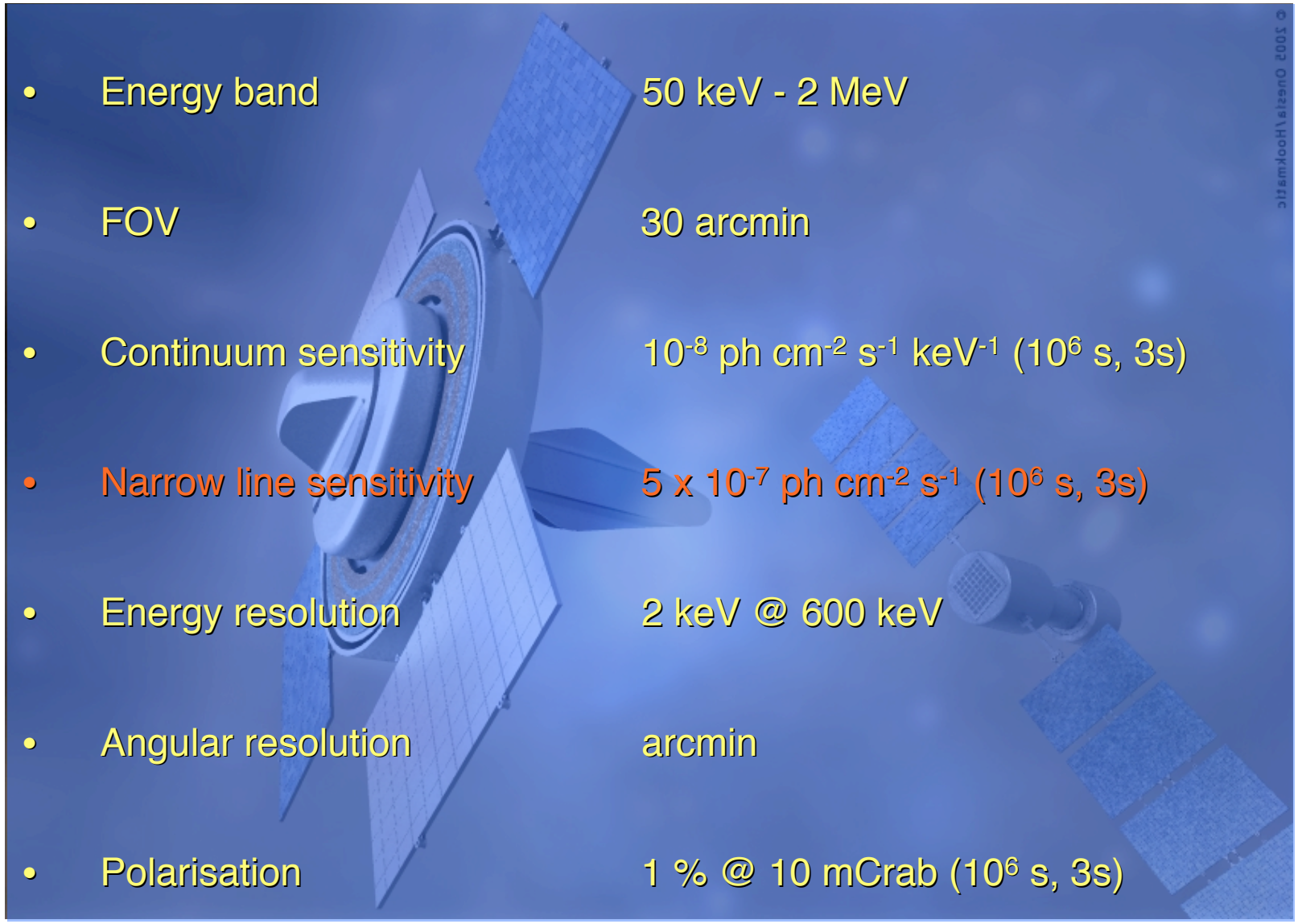


designing a Laue lens telescope - efficient area I




MAX
ALCATEL
SPACE
David Biau 2004

Mission requirements for a Gamma-Ray Imager



• Energy band	50 keV - 2 MeV
• FOV	30 arcmin
• Continuum sensitivity	10^{-8} ph cm^{-2} s^{-1} keV^{-1} (10^6 s, 3s)
• Narrow line sensitivity	5 x 10^{-7} ph cm^{-2} s^{-1} (10^6 s, 3s)
• Energy resolution	2 keV @ 600 keV
• Angular resolution	arcmin
• Polarisation	1 % @ 10 mCrab (10^6 s, 3s)