Imaging with Synchrotron Light

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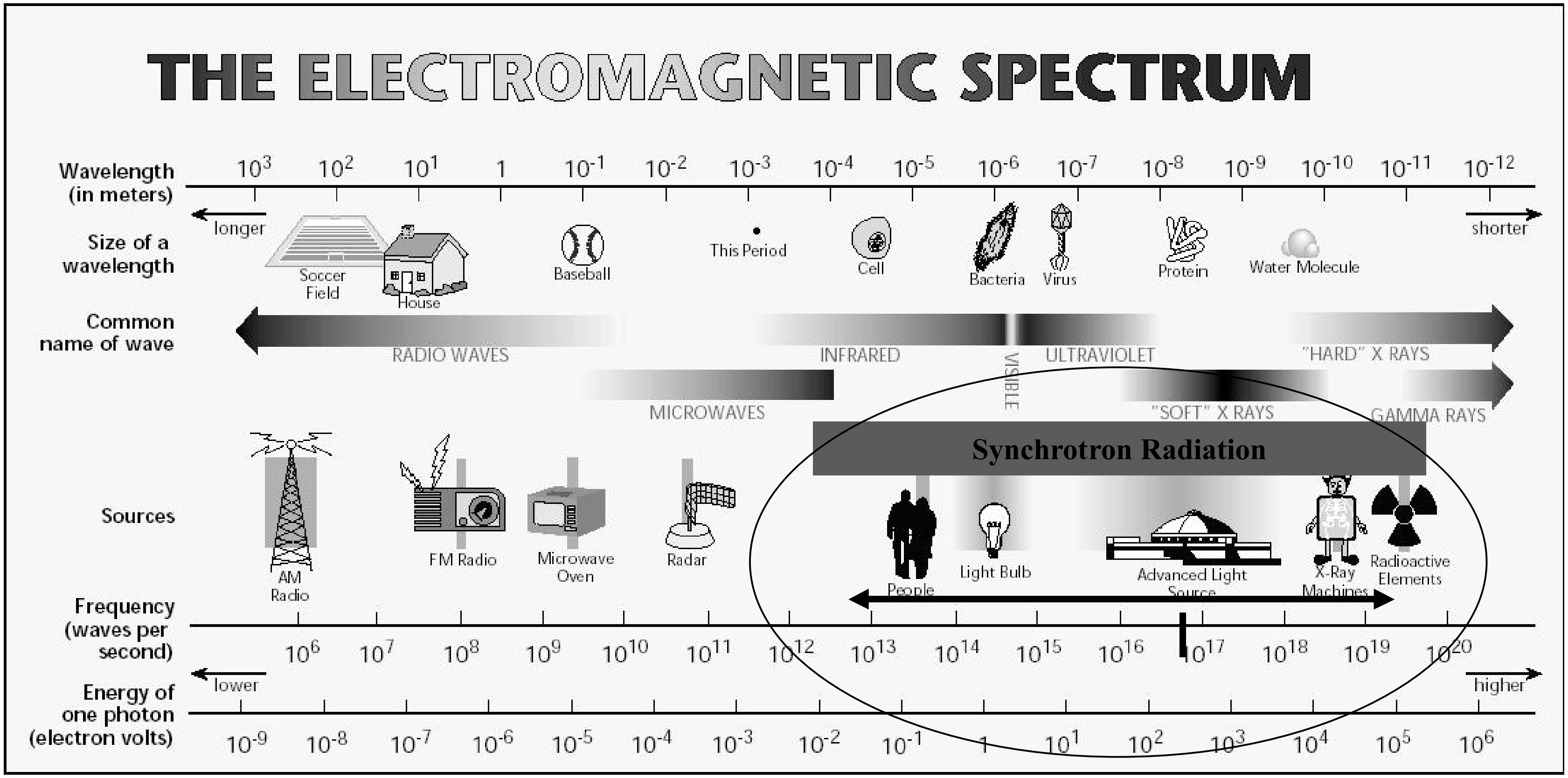
Imaging

- What is an image?
- **im·age** (ǯmôǯ) *n.*
  - ï ñAn optically formed duplicate or other representative reproduction of an object, especially an optical reproduction of an object formed by a lens or mirror.ò

Digital image

- Nowadays most likely to be represented by a 2-D array of sample points (pixels) with orthogonal axes.
- Images are often stored in a compressed form. When used for órealô data this compression process must be lossless.

The EM spectrum



Images made with SR light are usually made with photons.

(In some cases electron images are made.)

SR light for imaging

- Terahertz
  - ï 0.1 ï 1 x 10^{12} hertz frequency
  - ï 1 mm ï 15 microns wavelength
  - ï 0.001 eV ï 0.08 eV

- Infra-red
  - ï 0.5 ï 1 x 10^{14} hertz frequency
  - ï 10 ï 1 microns wavelength (1000 ï 10,000 cm^{-1})
  - ï 0.1 eV ï 1.0 eV

SR light for imaging

- Optical
  - ï Small range: 0.7 ï 0.4 microns
  - ï $4x10^{14}$ ï $7x10^{14}$ Hertz
  - ï 1.8 eV ï 3.1 eV

- Ultra violet
  - ï 0.4 ï 0.05 microns (400 ï 50 nm)
  - ï $7x10^{14}$ ï $6x10^{15}$ Hertz
  - ï 3 eV ï 25 eV

SR light for imaging

- Soft x-rays
  - ï 50 ï 0.4 nm
  - ï $6x10^{15}$ ï $7x10^{17}$ Hertz
  - ï 25 eV ï 3000 eV

- Hard x-rays
  - ï 0.4 nm ï 0.01 nm
  - ï $7x10^{17}$ ï $3x10^{19}$ Hertz
  - ï 3,000 ï 124,000 eV

Where does the synchrotron score?

It is a versatile and very bright source of light

Its characteristics are important for high fidelity imaging:

ÅFlux

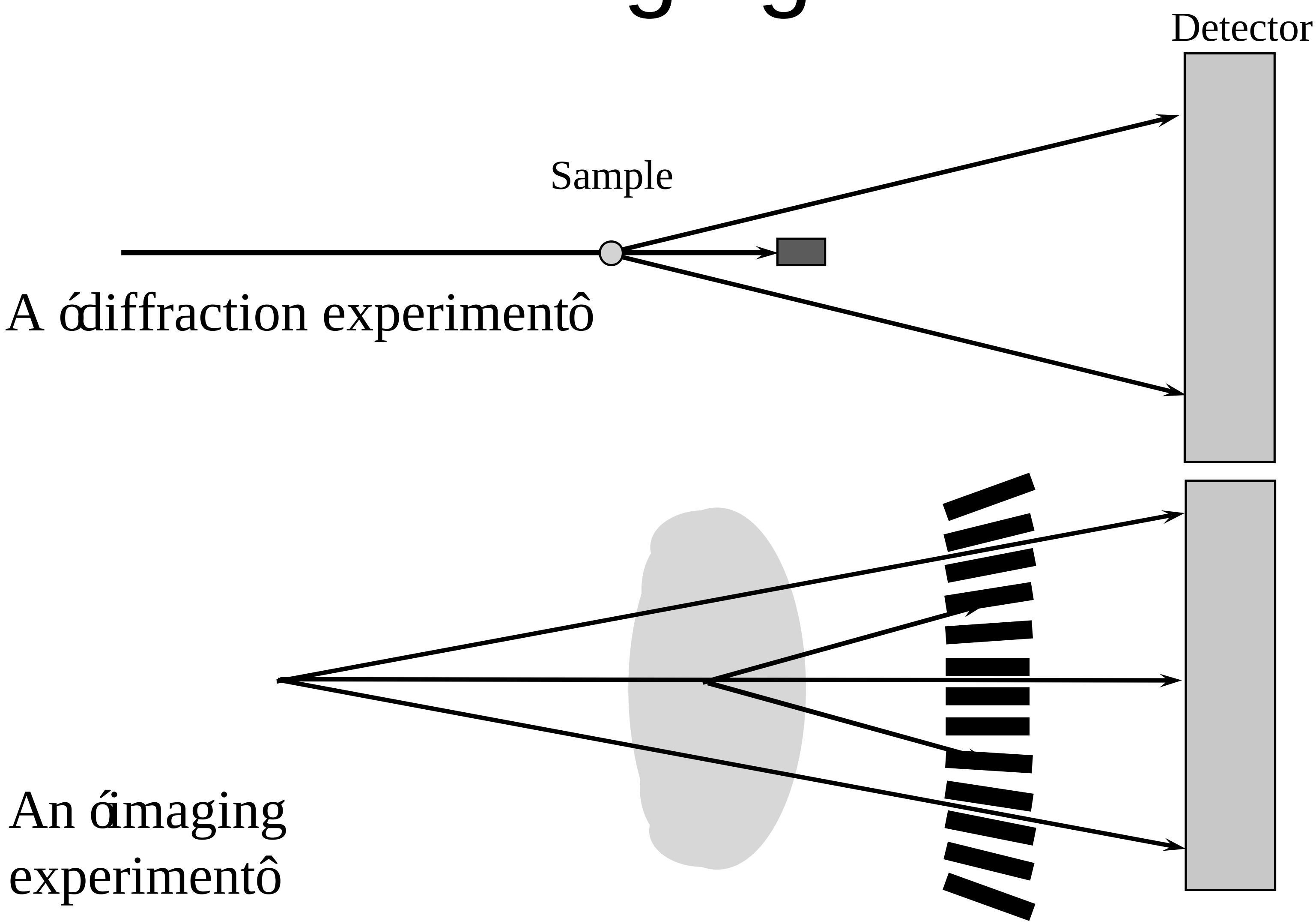
ÅSpectral range and purity

ÅStability

ÅTime structure

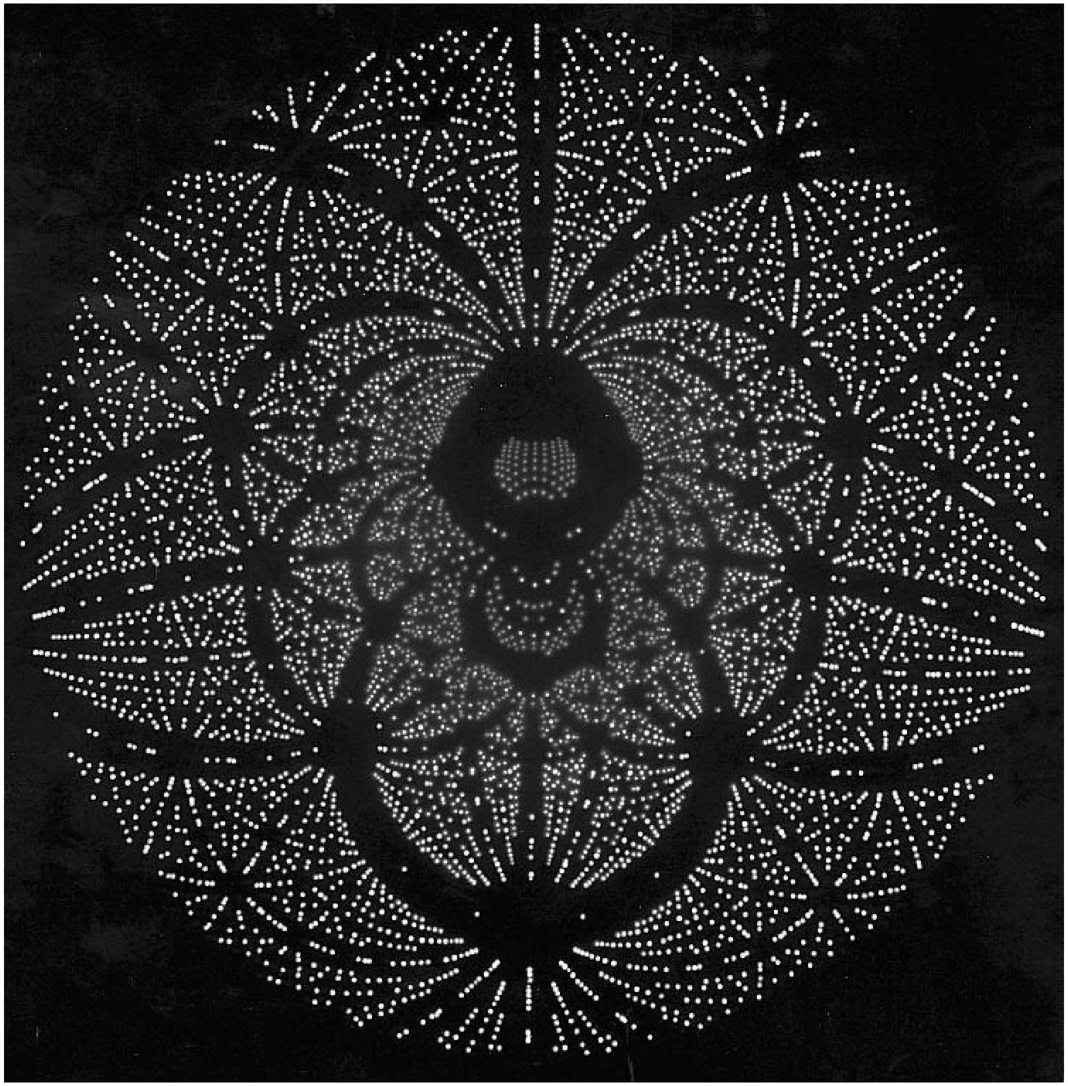
ÅPolarisation

Diffraction or Scattering, and Imaging

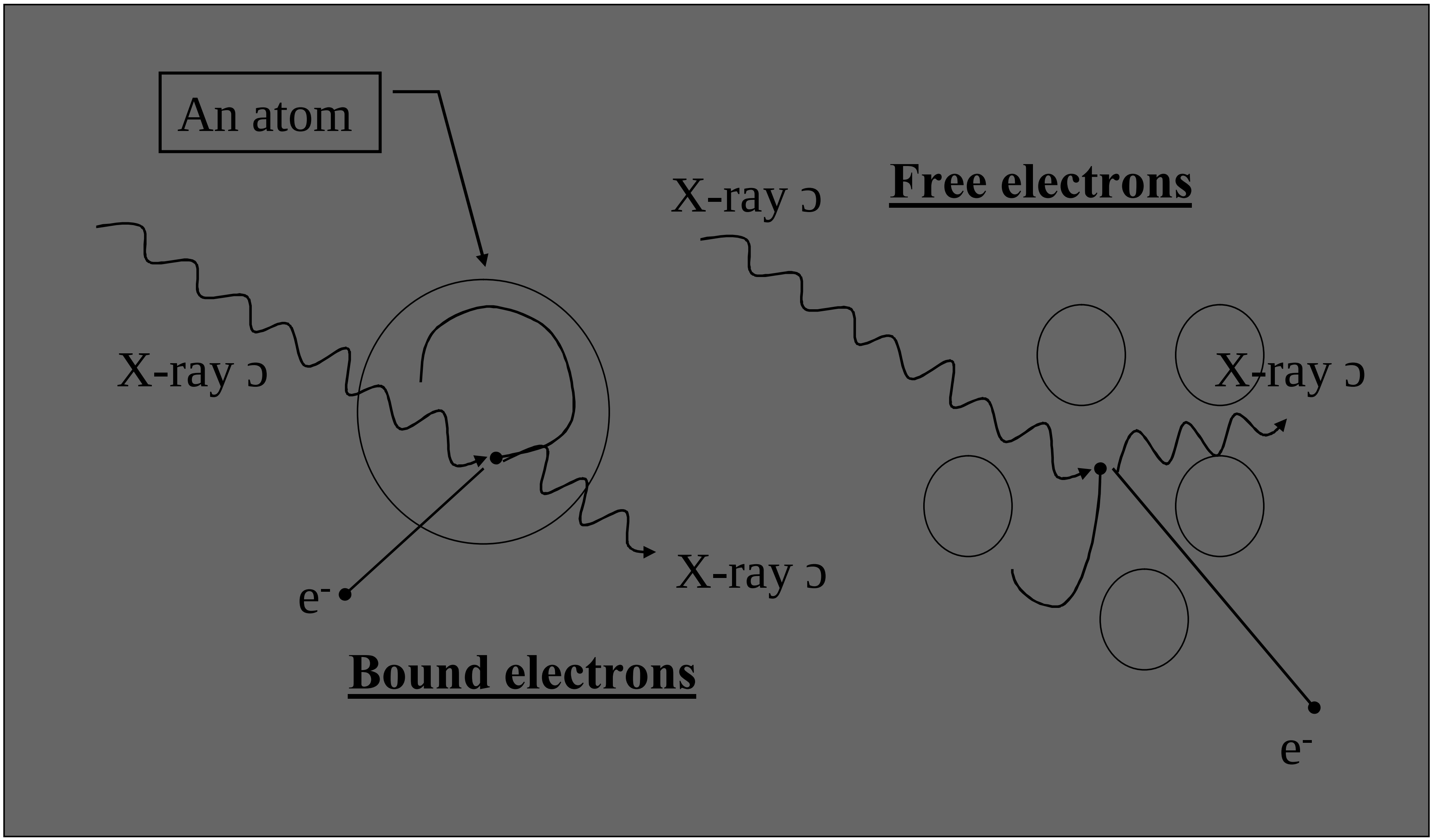


ĩ The imaging sciences (-ographies and ï oscopies)

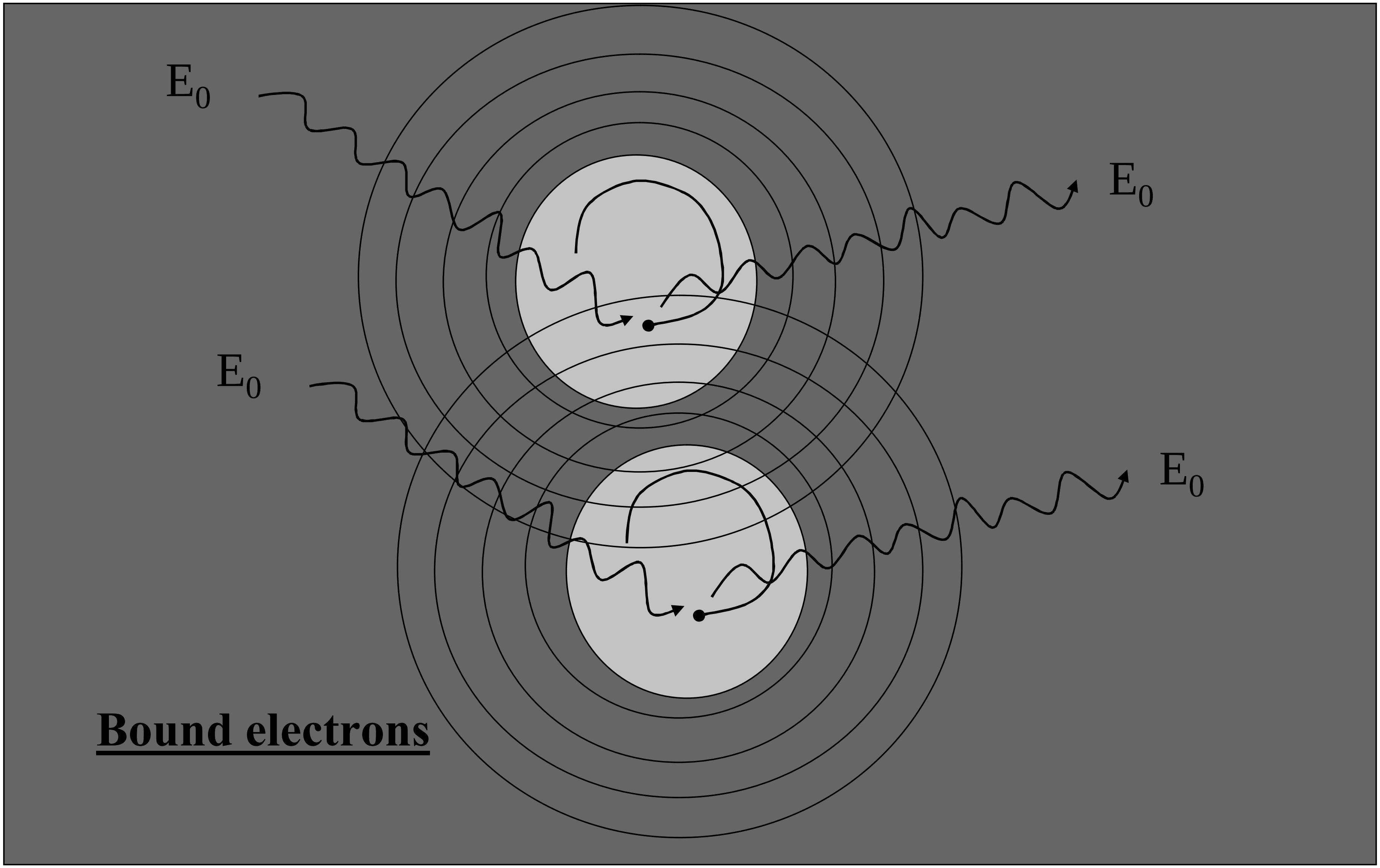
- Crystallography
  - ï Images in crystallography contain inverse spatial data.



How x-rays interact with electrons in matter



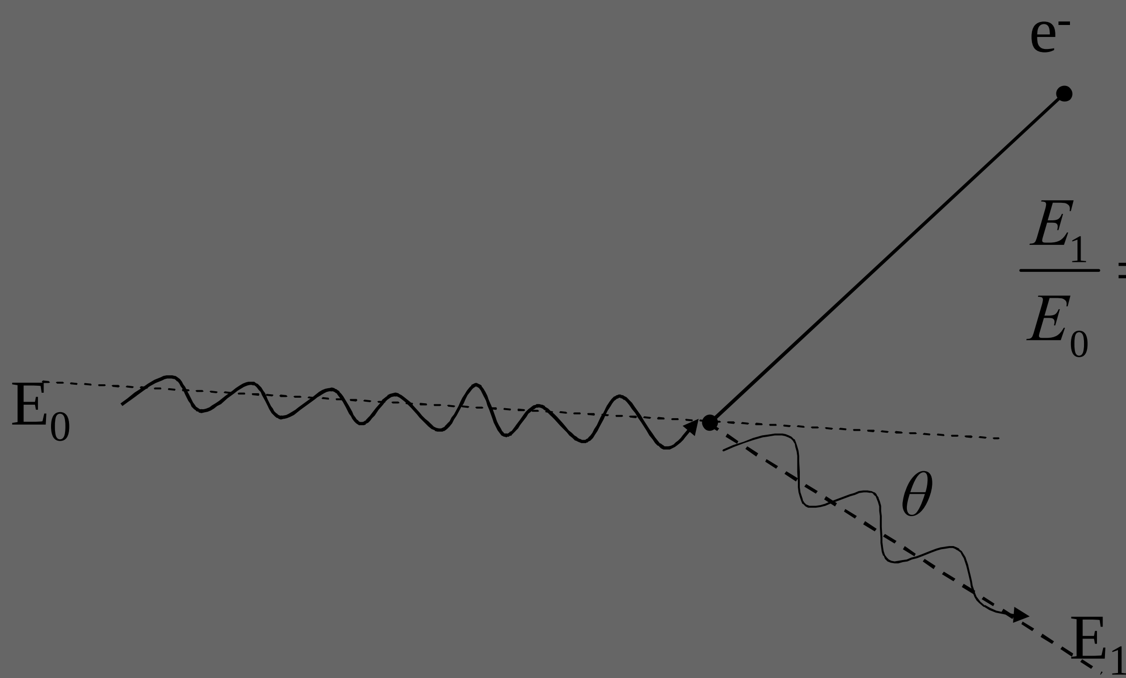
Rayleigh (coherent) scattering



No change in energy (wavelength, frequency)

Compton (incoherent) scattering

Change in energy (wavelength, frequency)

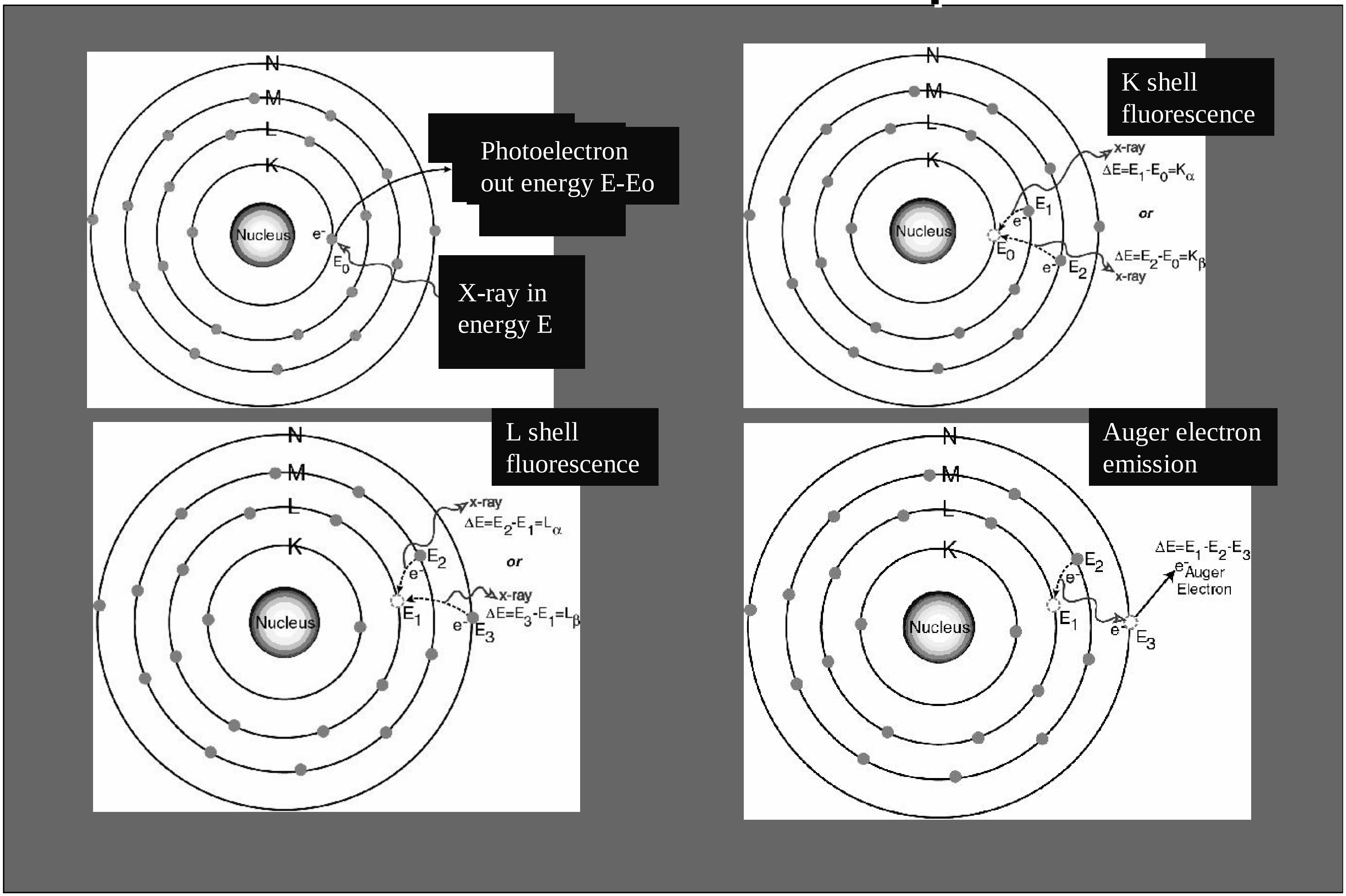


$$\frac{E_1}{E_0} = \frac{1}{1+\alpha(1-\cos(\theta))}$$

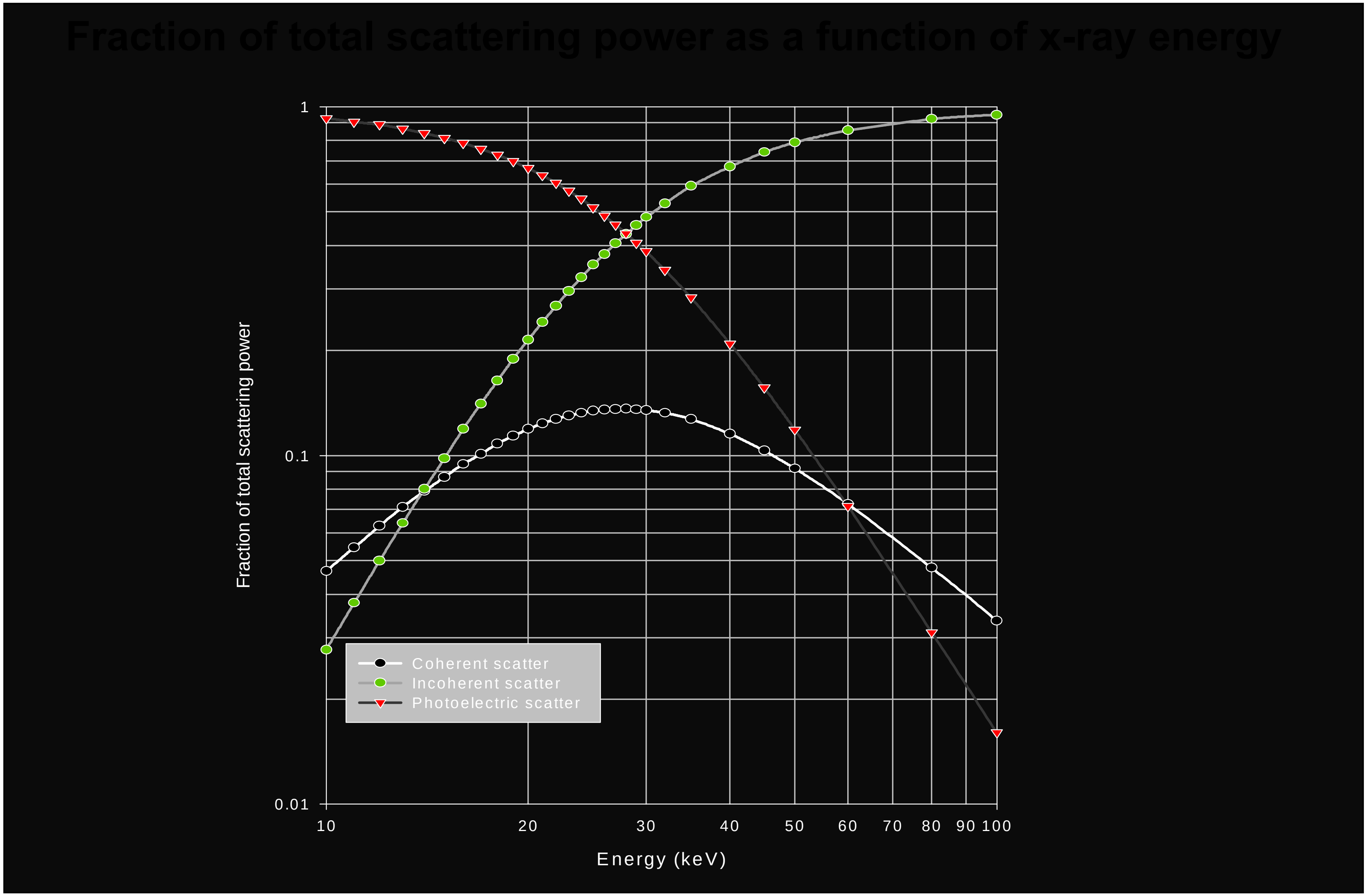
$$\alpha = \frac{E_0}{m_0 c^2}, \equiv \frac{E_0}{511keV}$$

<u>Free electrons</u>

Photoelectric absorption

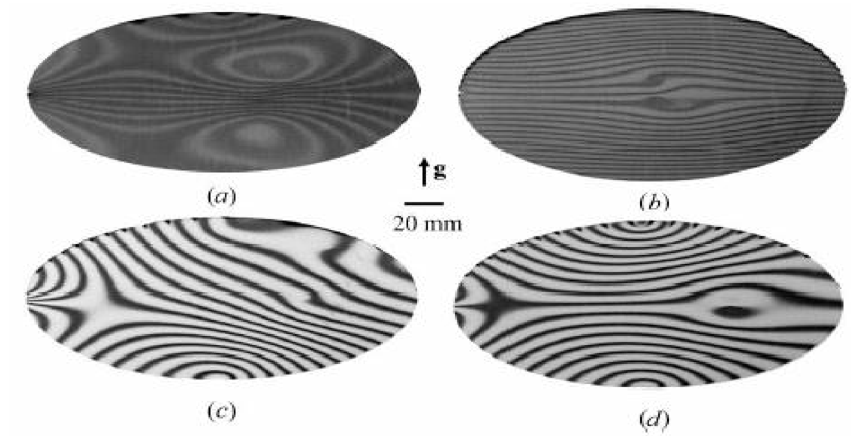


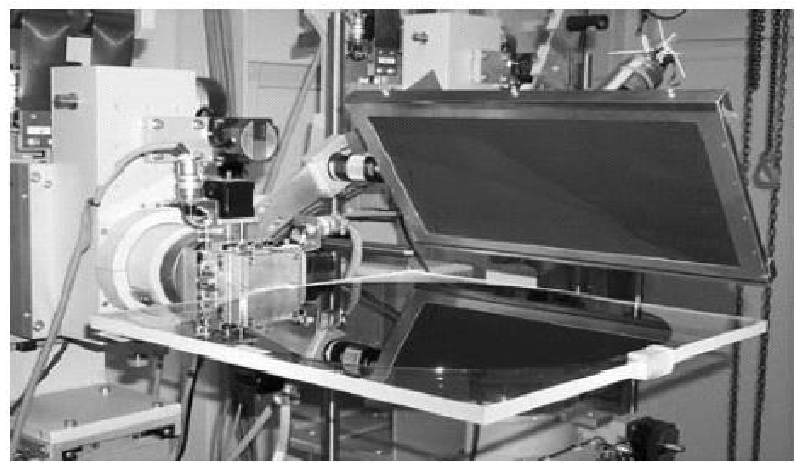
Scatter processes in biological tissue



The imaging sciences (-ographies and ï oscopies)

- Topography
  - ï Maps the intensity of a diffracted beam across the surface of a crystal.
  - ï Used to image strain and imperfections.

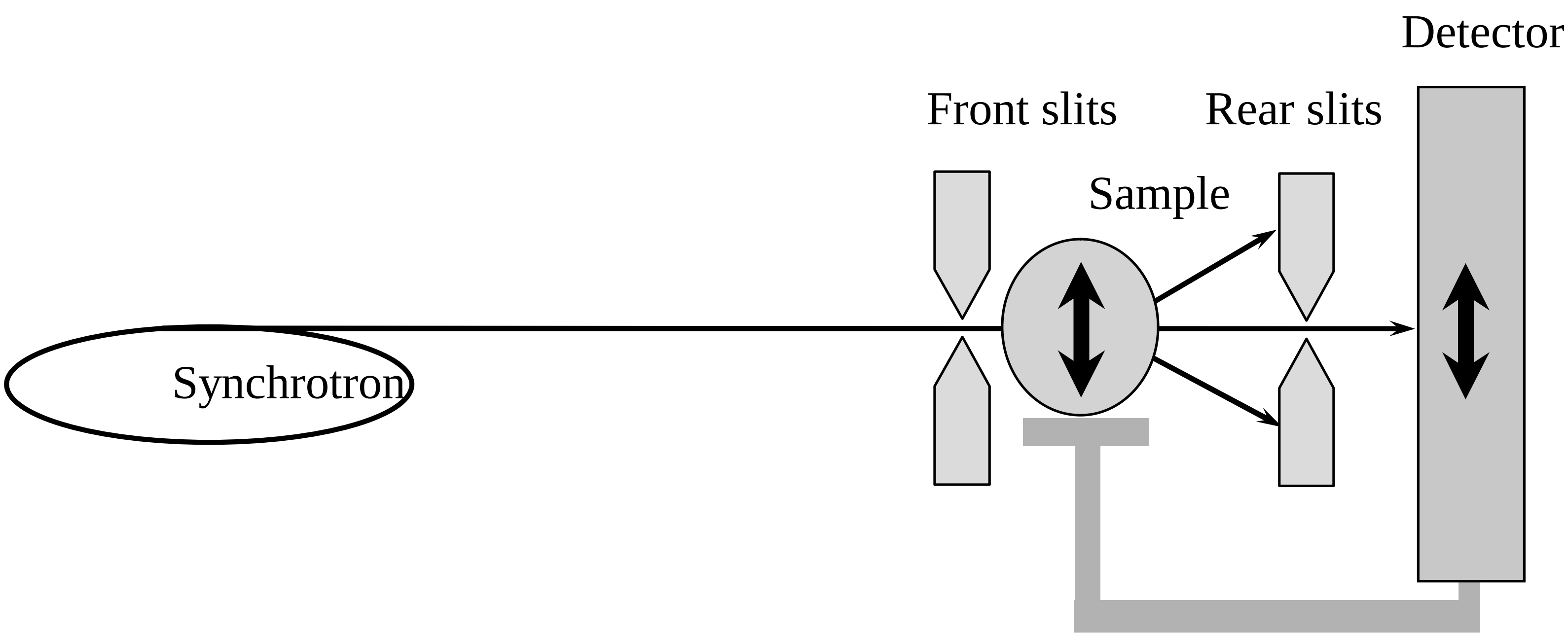




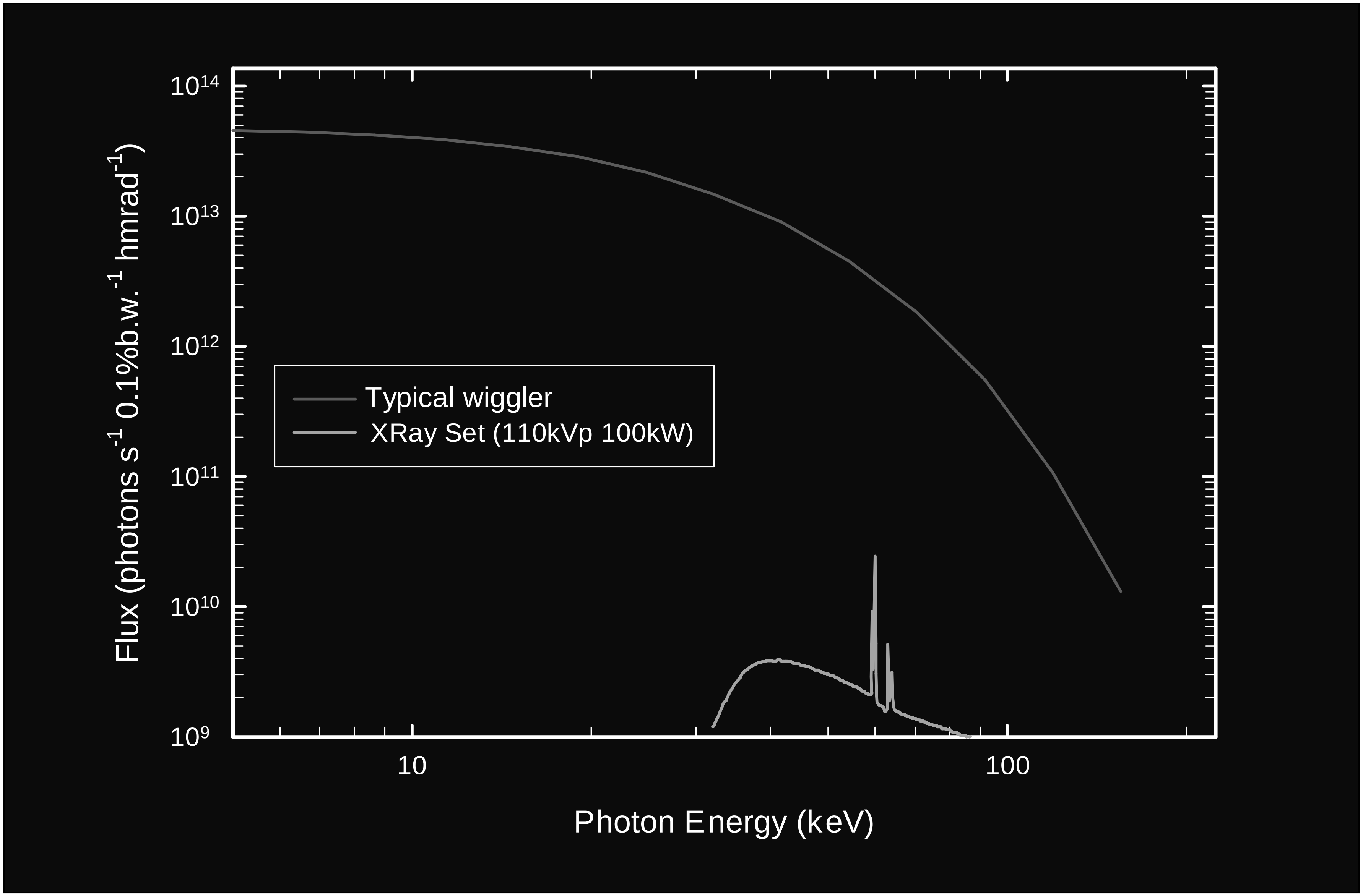
The imaging sciences (-ographies and ï oscopies)

- Radiography
  - ï The most straightforward x-ray imaging technique
  - ï Images are śhadowsô containing information about the absorption of the x-radiation by the object.

SR Radiography Using the SRS

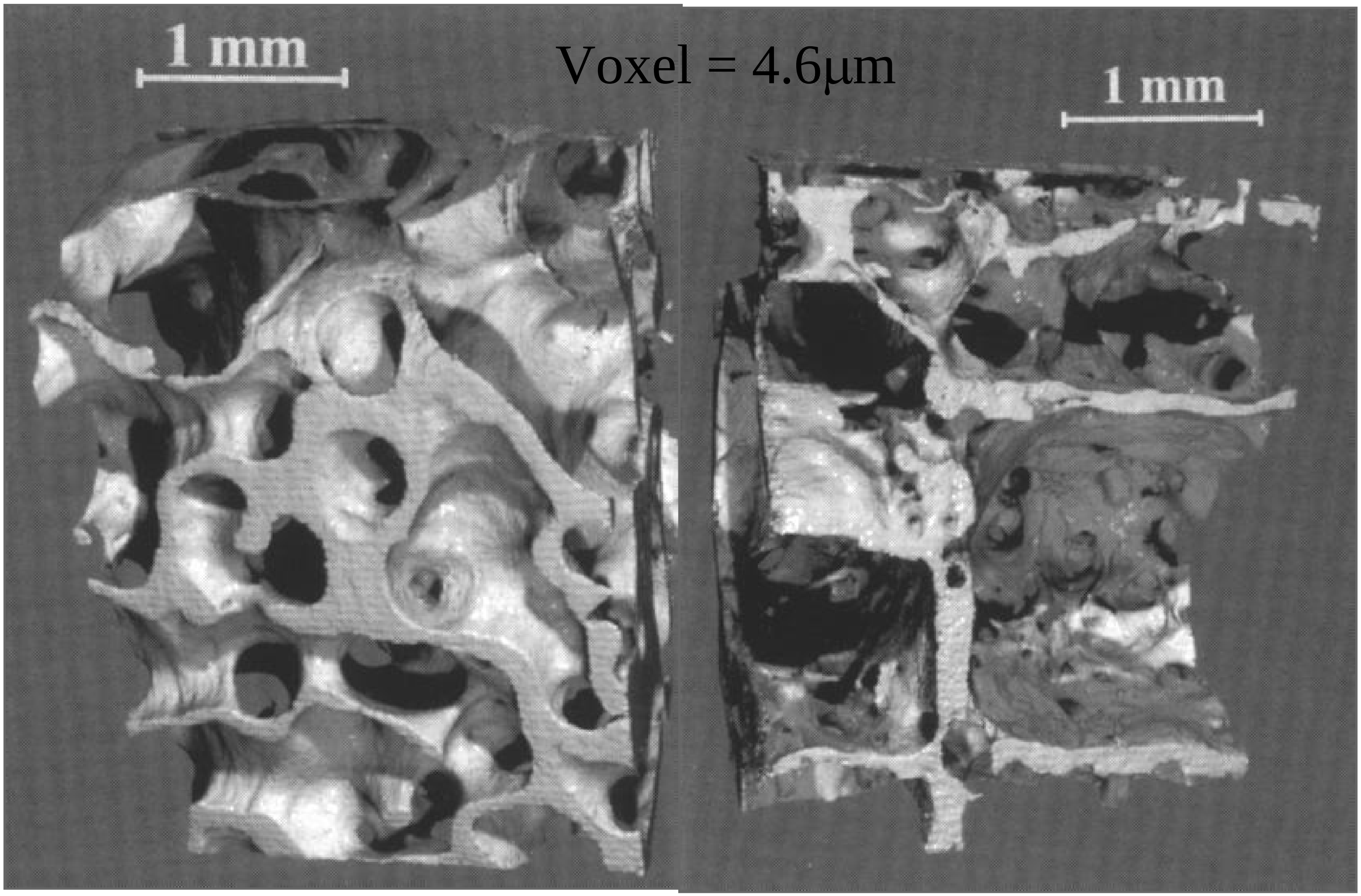


Comparative X-Ray Brilliance



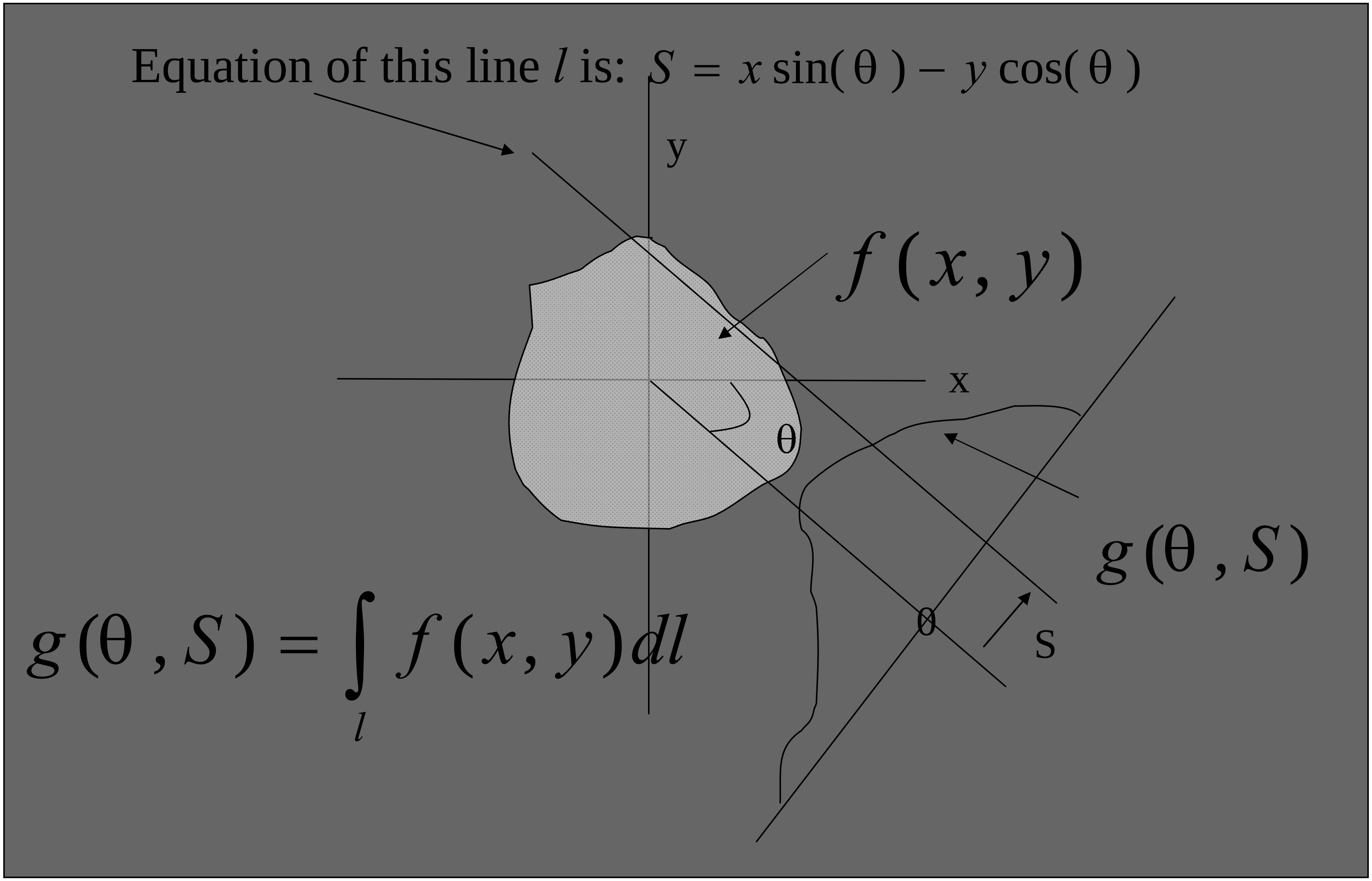
INTERMISSION

Computed tomography



U. Bonse, F. Busch, O. Gunnewig, F. Beckman, G. Delling, M. Hahn & A. Kvick

Projection and the Radon transform



Fourier slice theorem

$$g(\theta, S) = \int\int f(x, y)\delta(x\sin(\theta) - y\cos(\theta) - s)dxdy$$

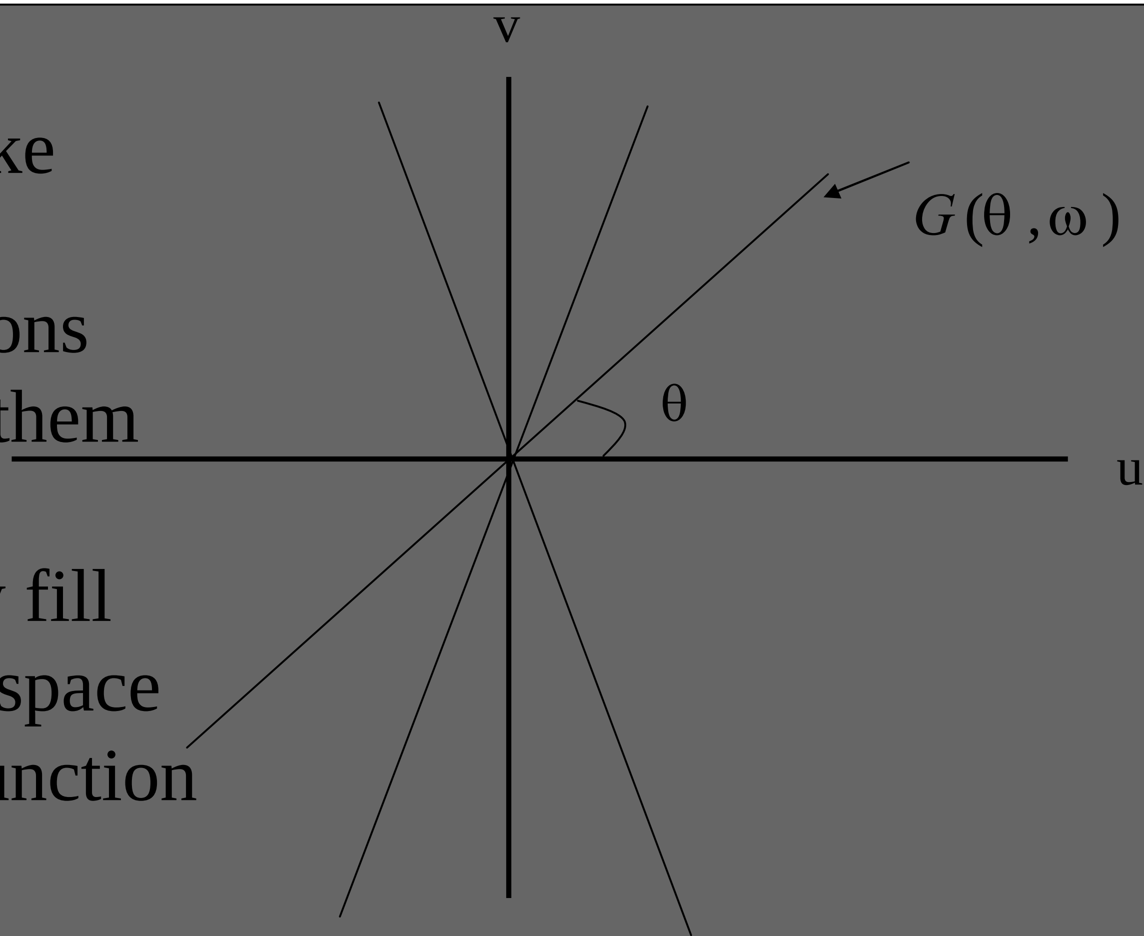
If we take the FT and simplify

$$G(\theta, \omega) = \int\int f(x, y)e^{-i\omega(x\sin\theta - y\cos\theta - s)}dxdy$$

This is the equation of a 1D FT of *f*(x,y) evaluated along a line at angle θ to the origin.

Fill the Fourier space from the project FTs

If we take many projections and FT them we can partially fill Fourier space of the function f(x,y)



Filtered back projection

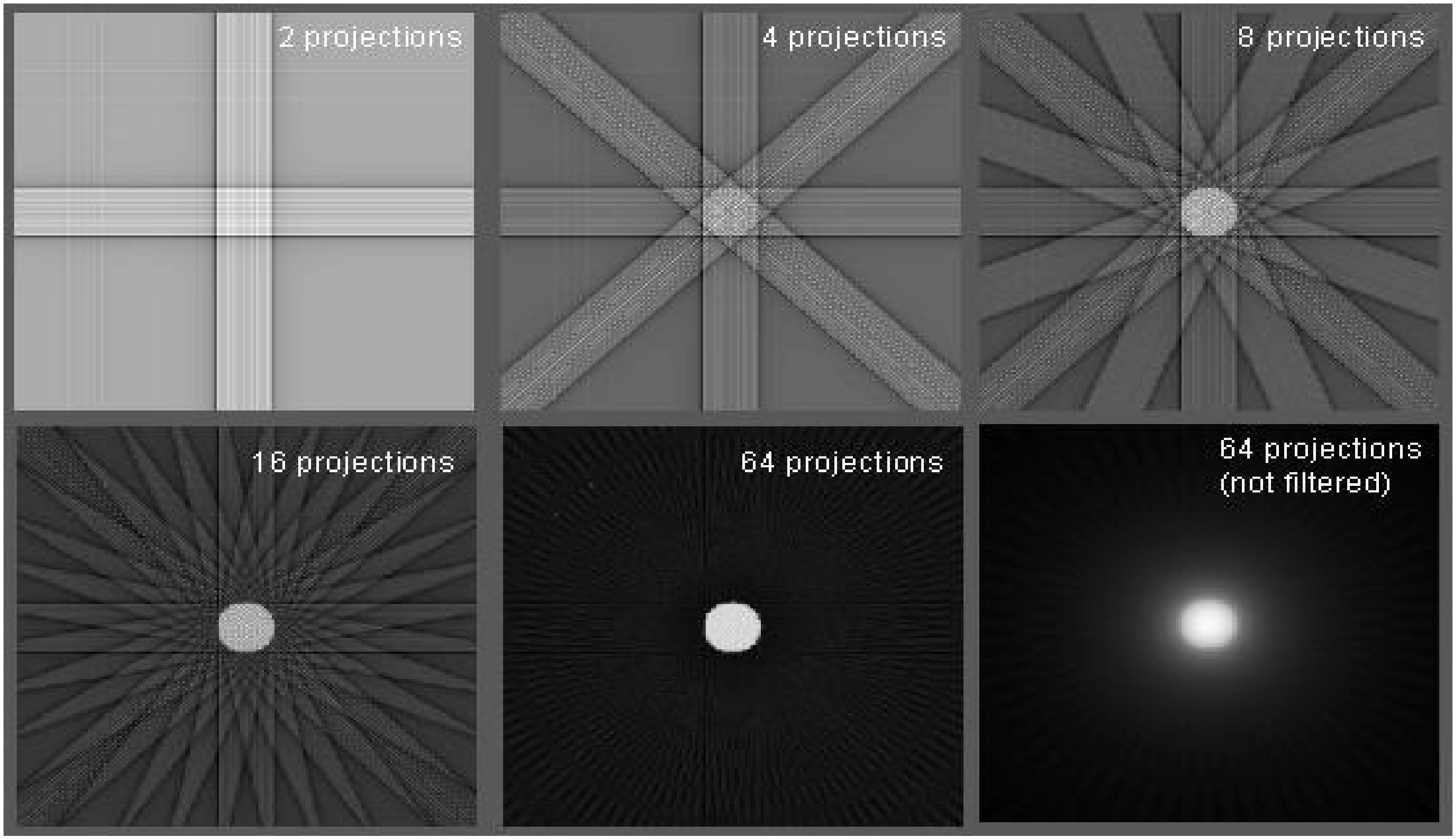
To regain f(x,y) from the Fourier space fill.
Remember in general the inverse FT is:

$$f(x,y) = \frac{1}{4\pi^2}\int\int F(u,v)e^{i(ux+vy)}dxdy$$

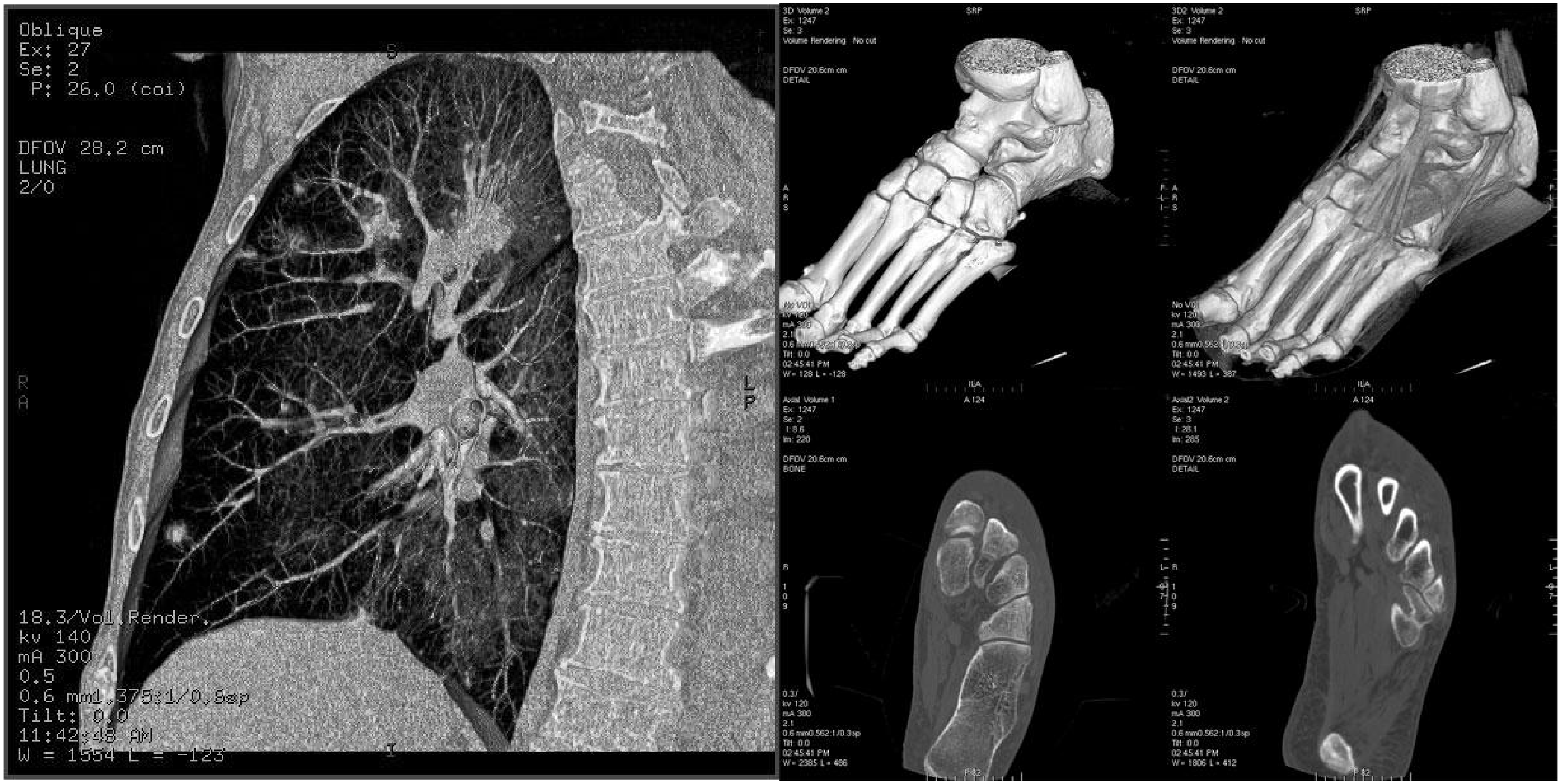
It will drop out that:

$$f(x,y) = \frac{1}{4\pi^2}\int\int G(\theta,\omega)e^{i(x\sin(\theta)-y\cos(\theta))}|w|dxdy$$

FBP in practice

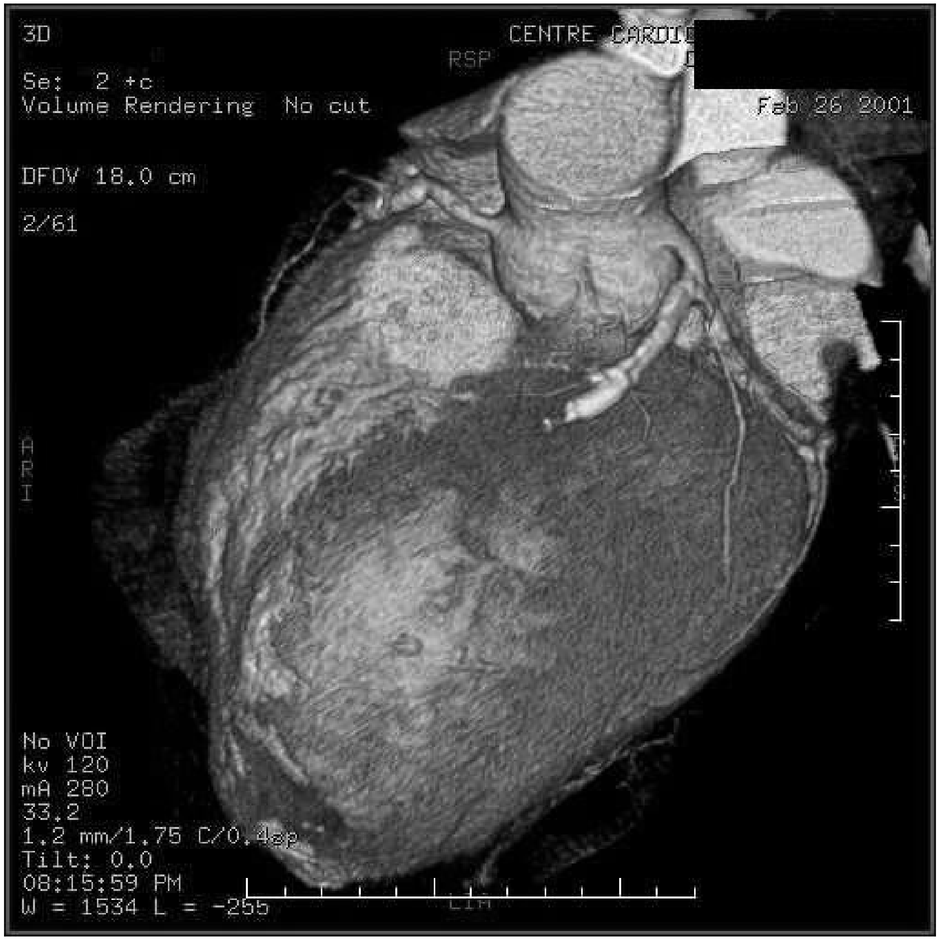


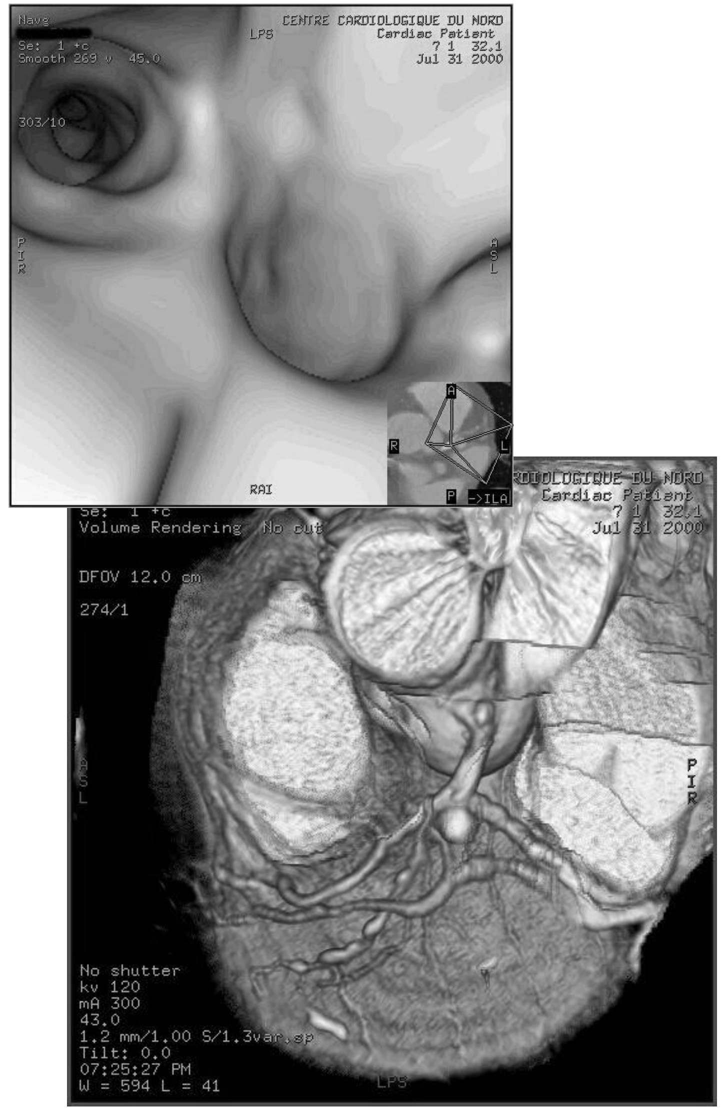
Computed tomography



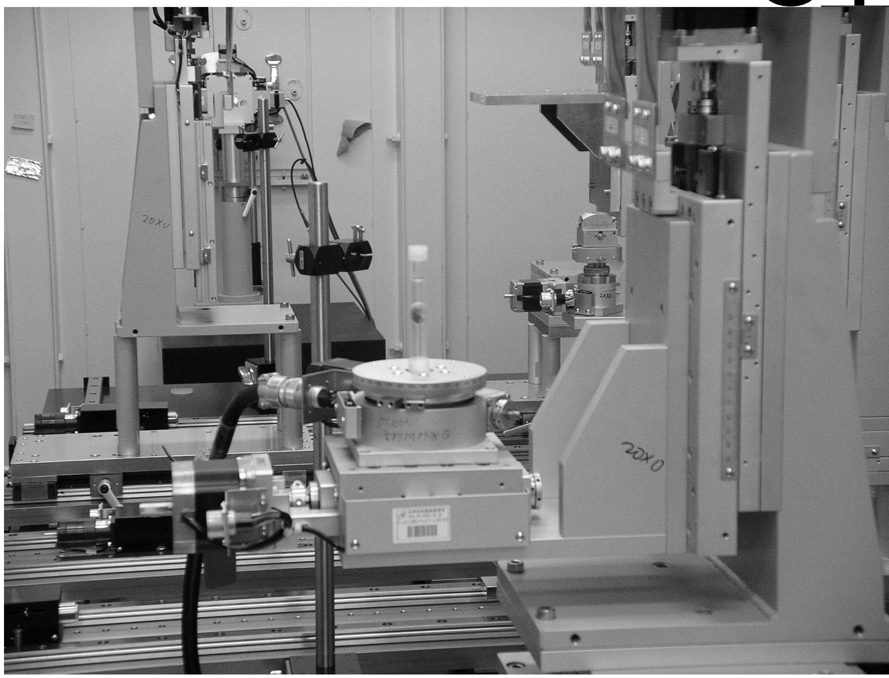
Modern multi-slice CT scanners give superb anatomical detail in 3-D images

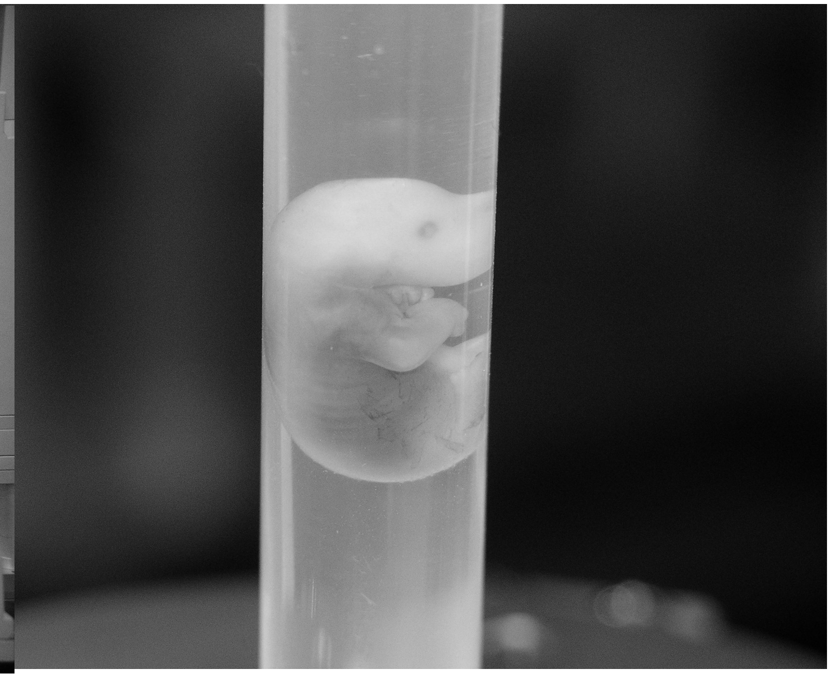
Computed tomography





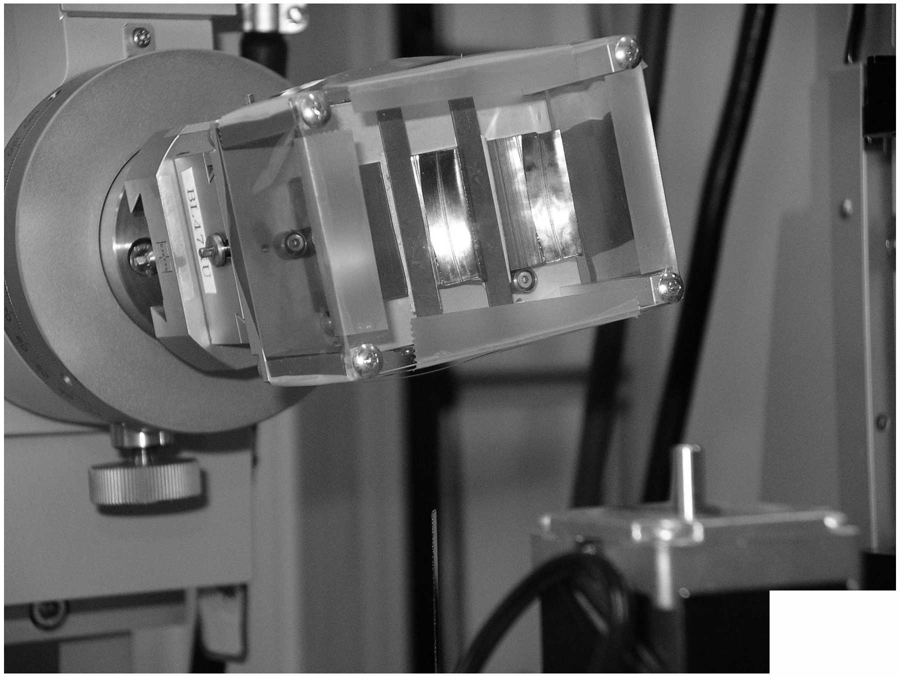
Lung development study with SR CT

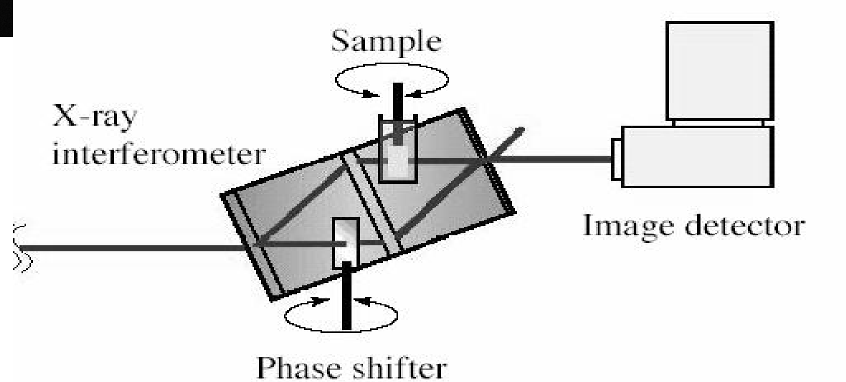




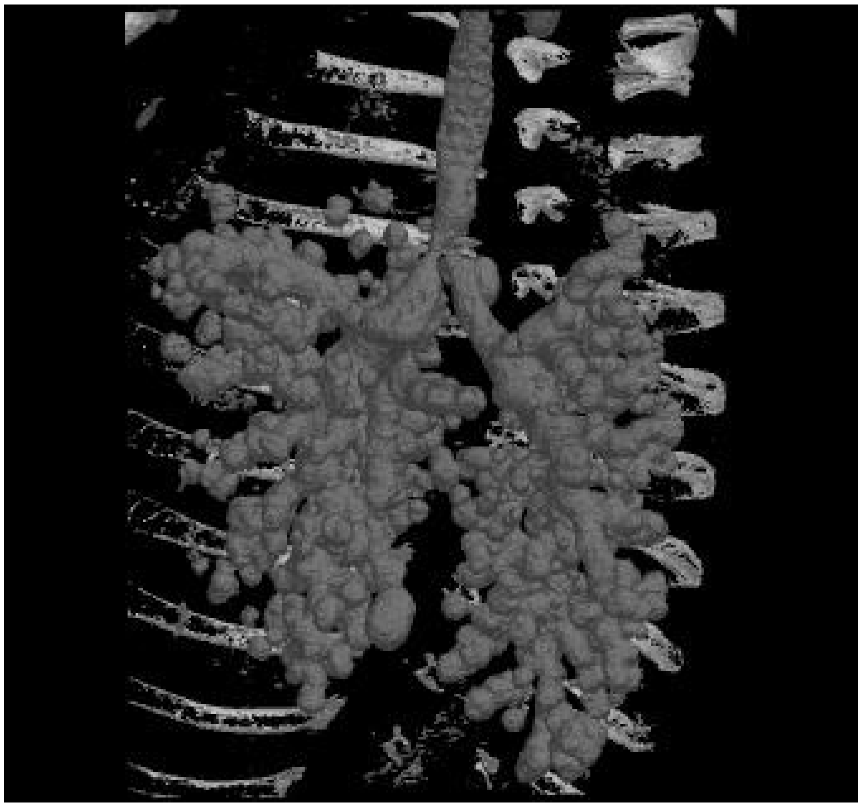
- Wallabies lungs were imaged using SR CT at Spring 8.

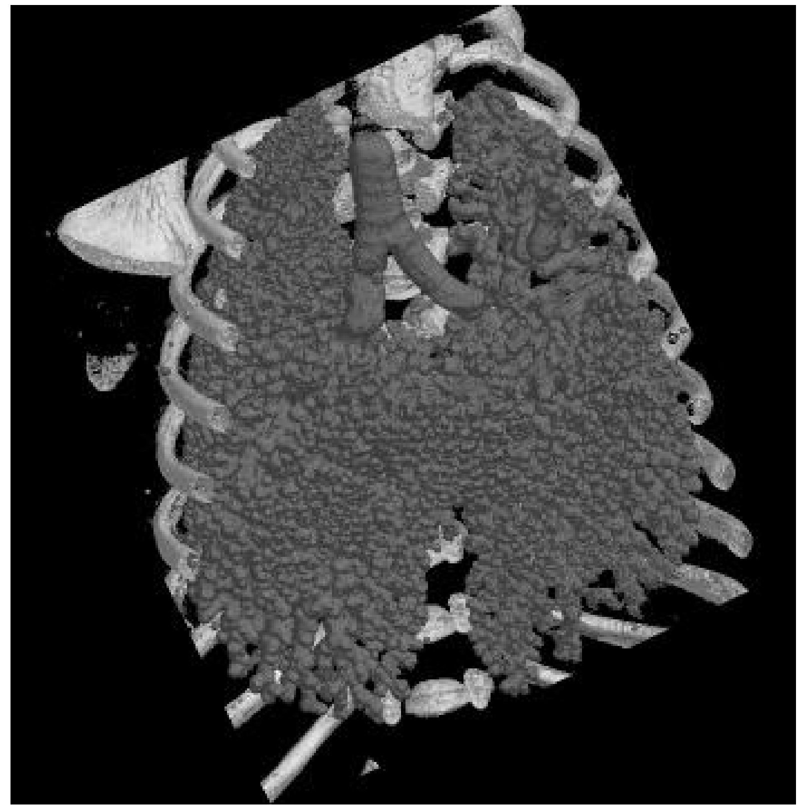
An x-ray interferometer



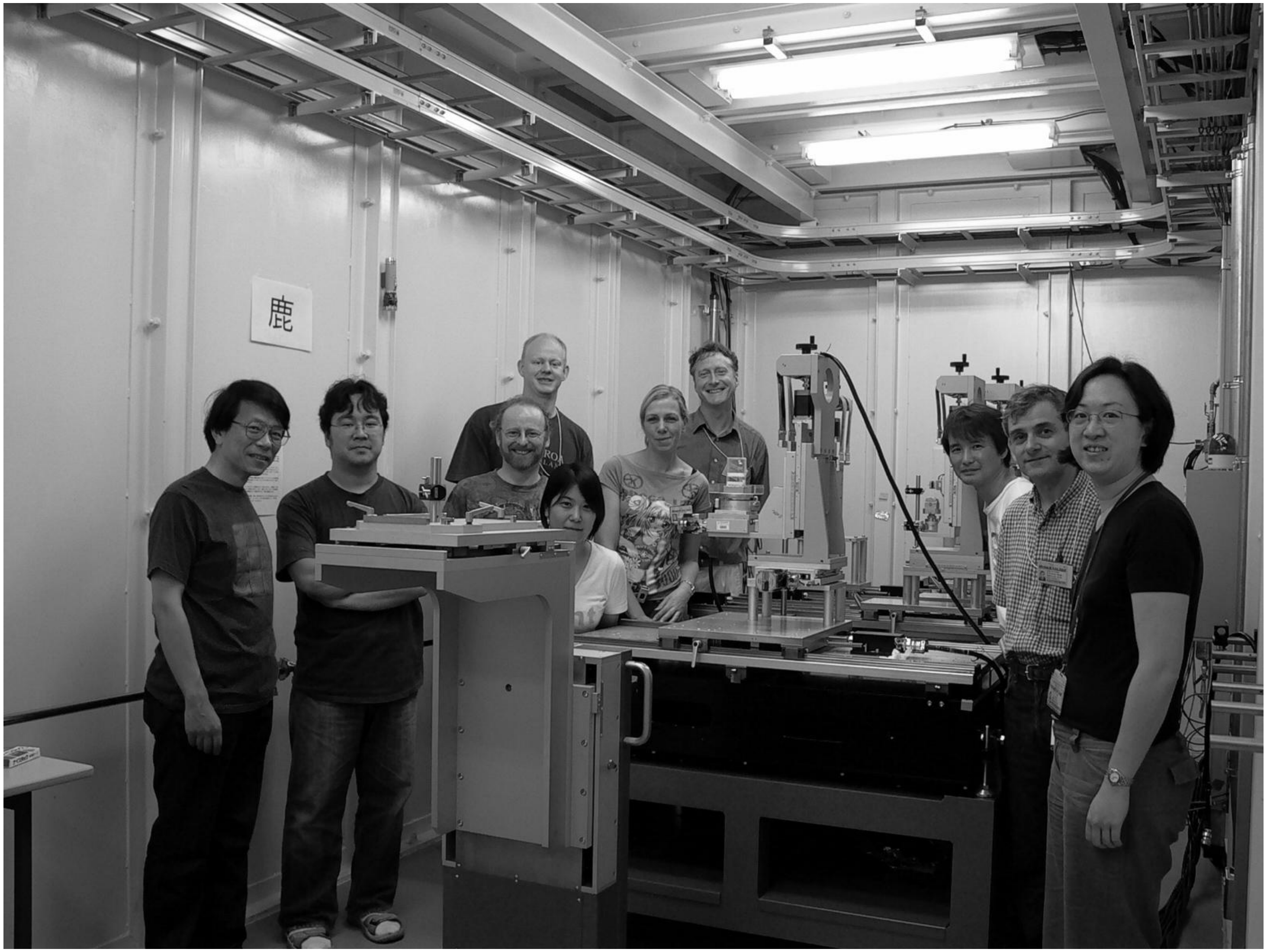


Wallaby lungs in CT





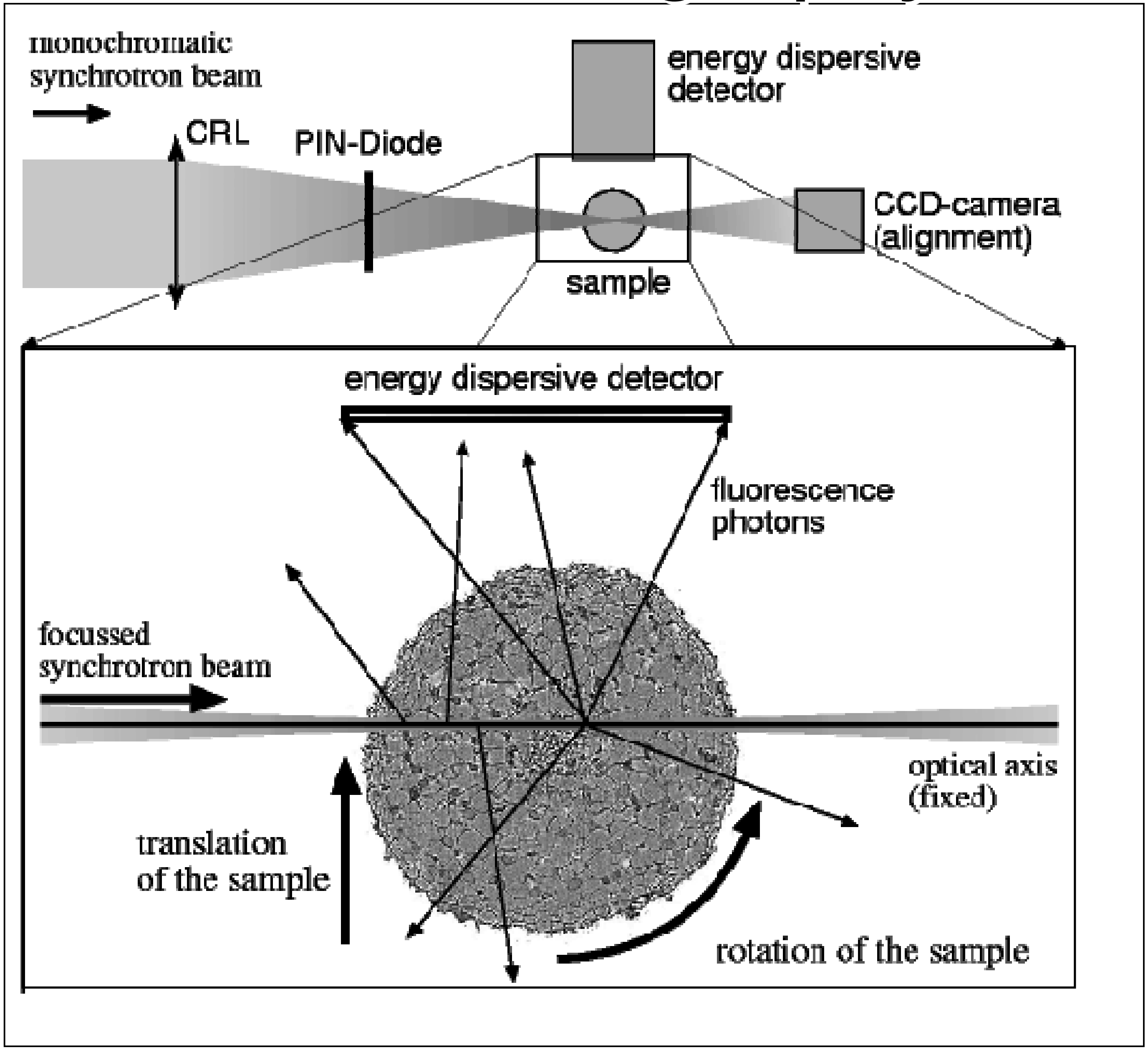
How many people does it take to make a CT of a wallaby?



Fluorescence Tomography

Incident Beam

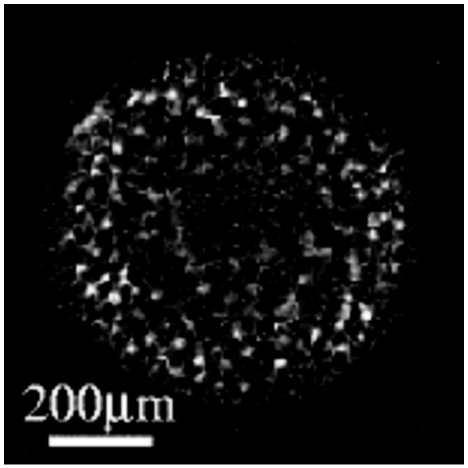
Energy	19.5 keV
Horizontal size	6 µm
Vertical size	1.6 µm
Flux	1.1×10^{10} photons/s.



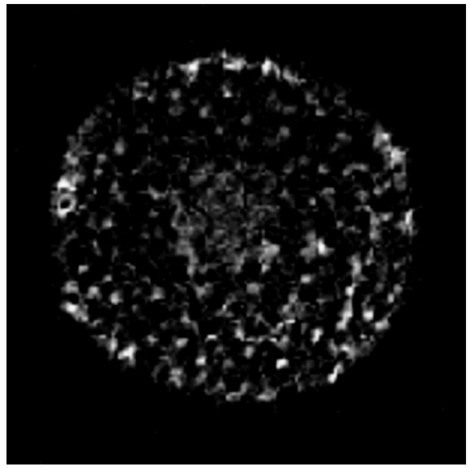
W. Schroder et al
work done at ESRF

Fluoresence Tomography

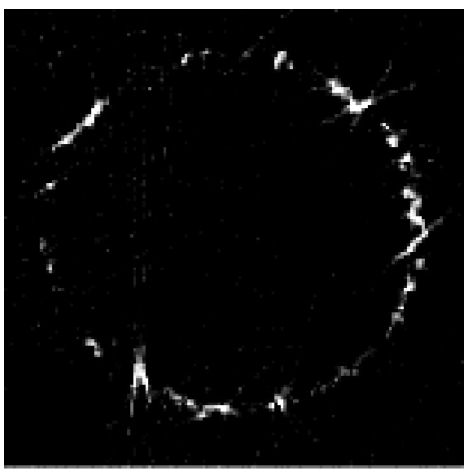
Cl Kα



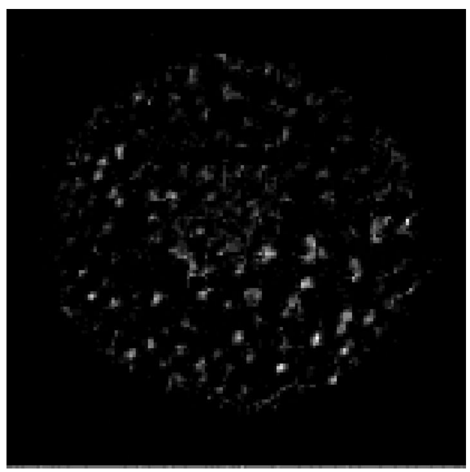
K Kα



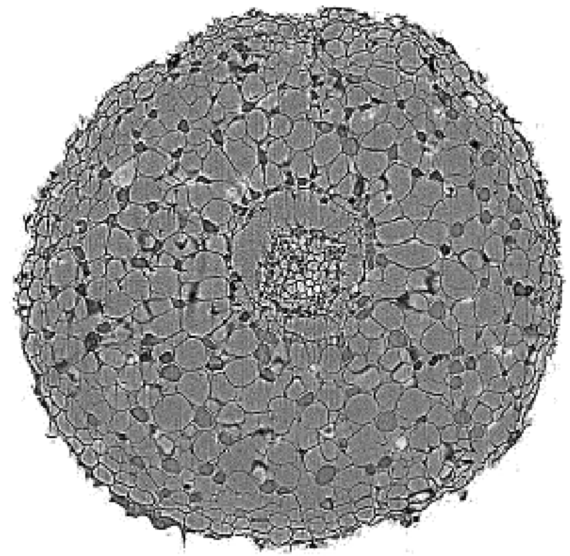
Fe Kα



Rb Kα



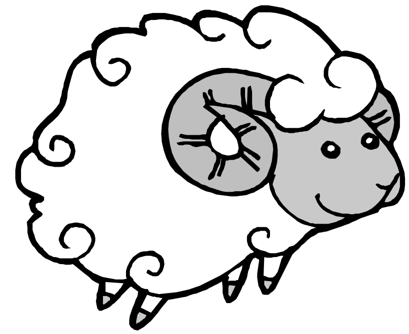
Phase contrast



200μm

W. Schroder et al
work done at ESRF

Vetinary imaging



Proposal for a BioMedical Imaging Beamline on the Canadian Light Source (BMIT).

Prof. Gregg Adams, University of Saskatchewan, Reproductive Science and Medicine Group.

Date: January 24, 2002
Supersedes: January 22, 2002

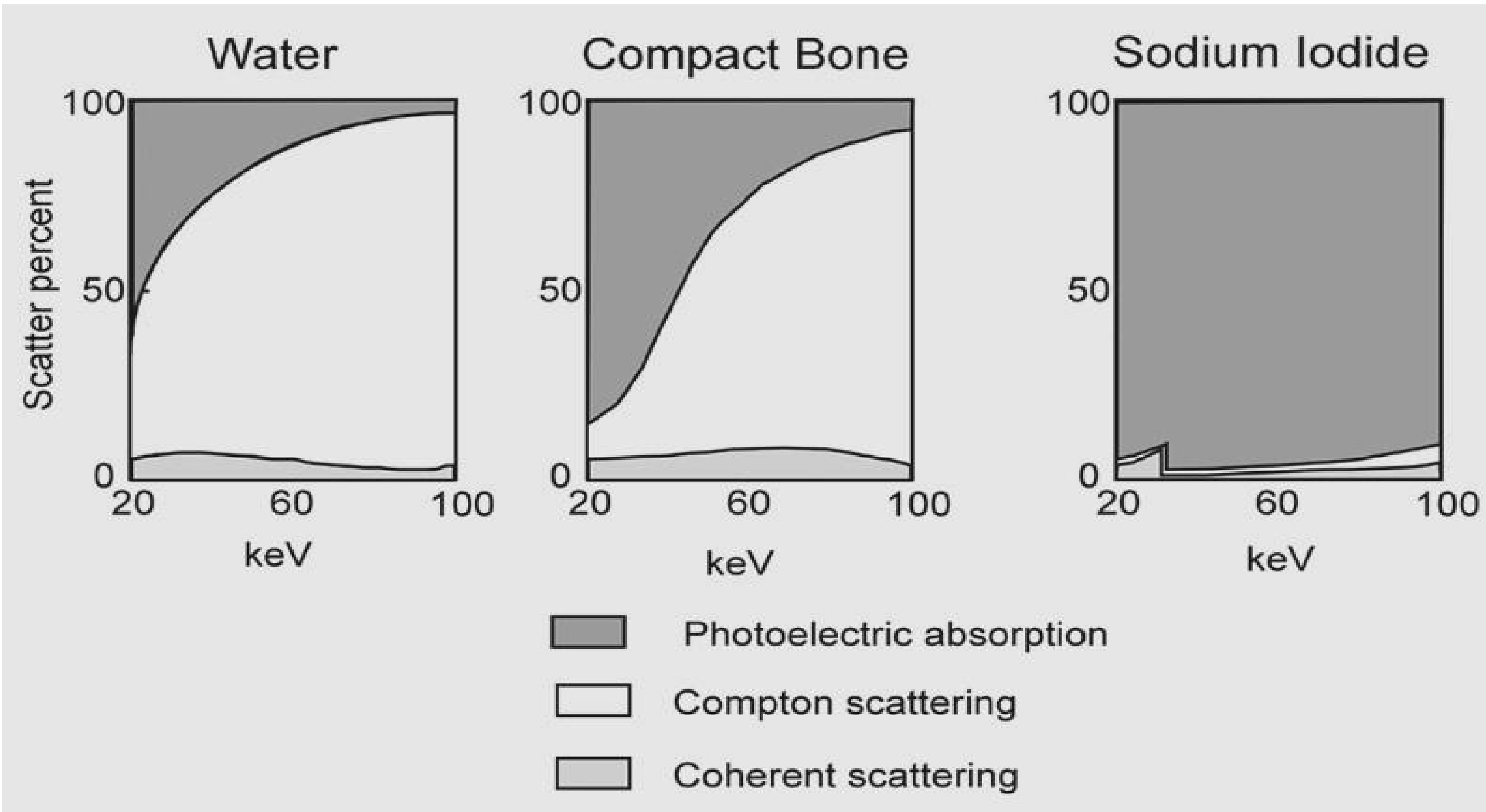
CONFIDENTIAL

Experimental approach The overriding goal is to develop synchrotron techniques for imaging ovarian structures in vivo. The bovine model of ovarian function is perhaps the best developed and most broadly applicable to animal and human studies; ultimately then, we wish to be able to obtain serial images of the $\boxed{\text{ovaries of cows } \textit{in situ}.}$ This raises the obvious challenge of physical size that has rendered conventional radiographic techniques useless ted genitalia. Initially, however, we intend to

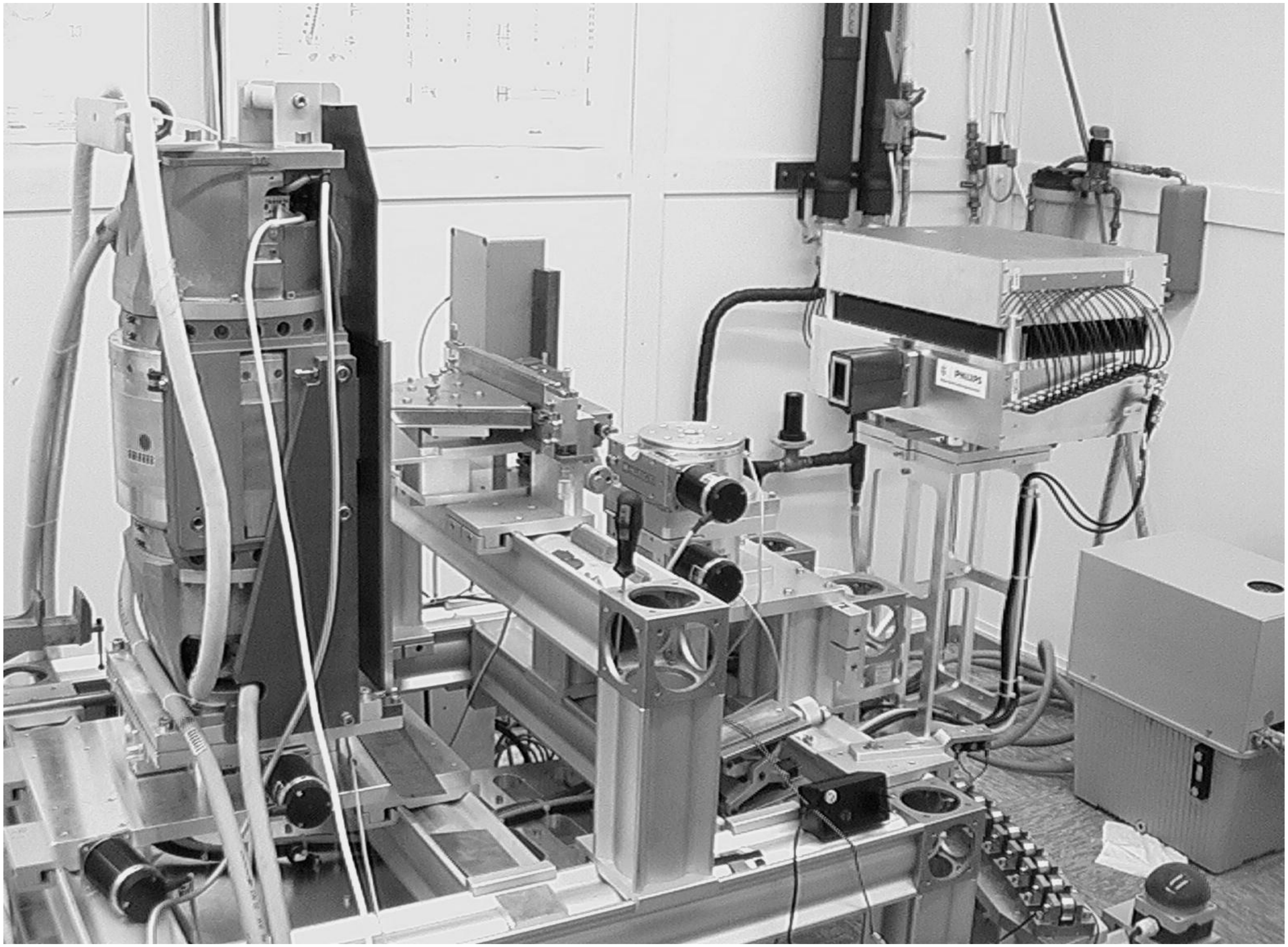
The imaging sciences (-ographies and ï oscopies)

- Coherent scatter imaging
  - ï A map of the object from a particular scatter phase space forms the image.

Scatter fraction in different materials

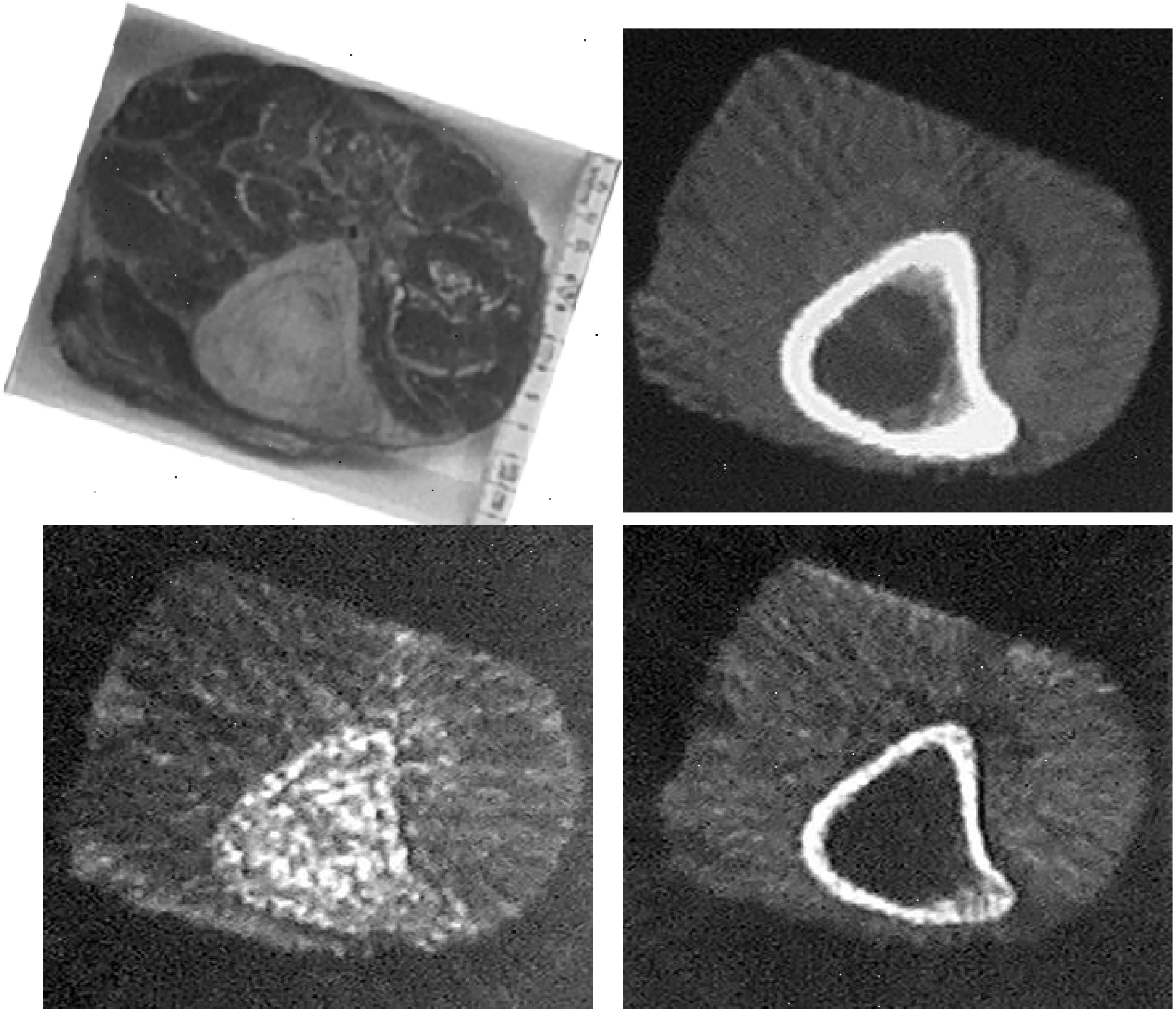


CSCT at Philips in Hamburg



J-P. Schlomka, Philips Research, Hamburg.

CSCT



0.3mm slits

115 × 32 pixels

3 × 1.5 mm pitch

72 projections

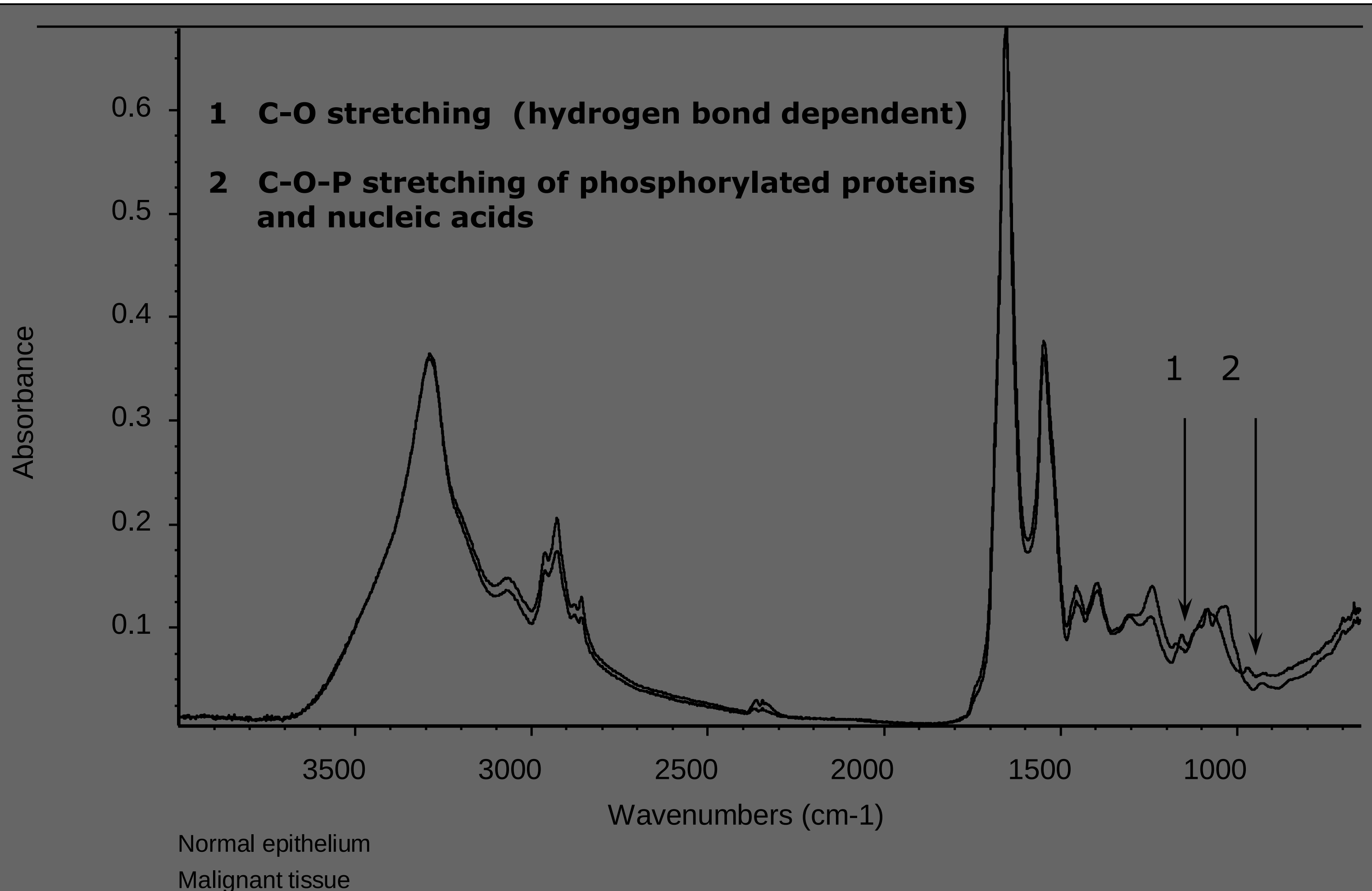
1 sec / projection @
150kV, 30 mA
(2mm Al + 1mm Cu)

J-P. Schlomka, Philips Research, Hamburg.

The imaging sciences (-ographies and ï oscopies)

- Microscopy (IR)
  - ï IR microscopy with SR makes use of the qualities of the SR source with highly developed lab based instruments.

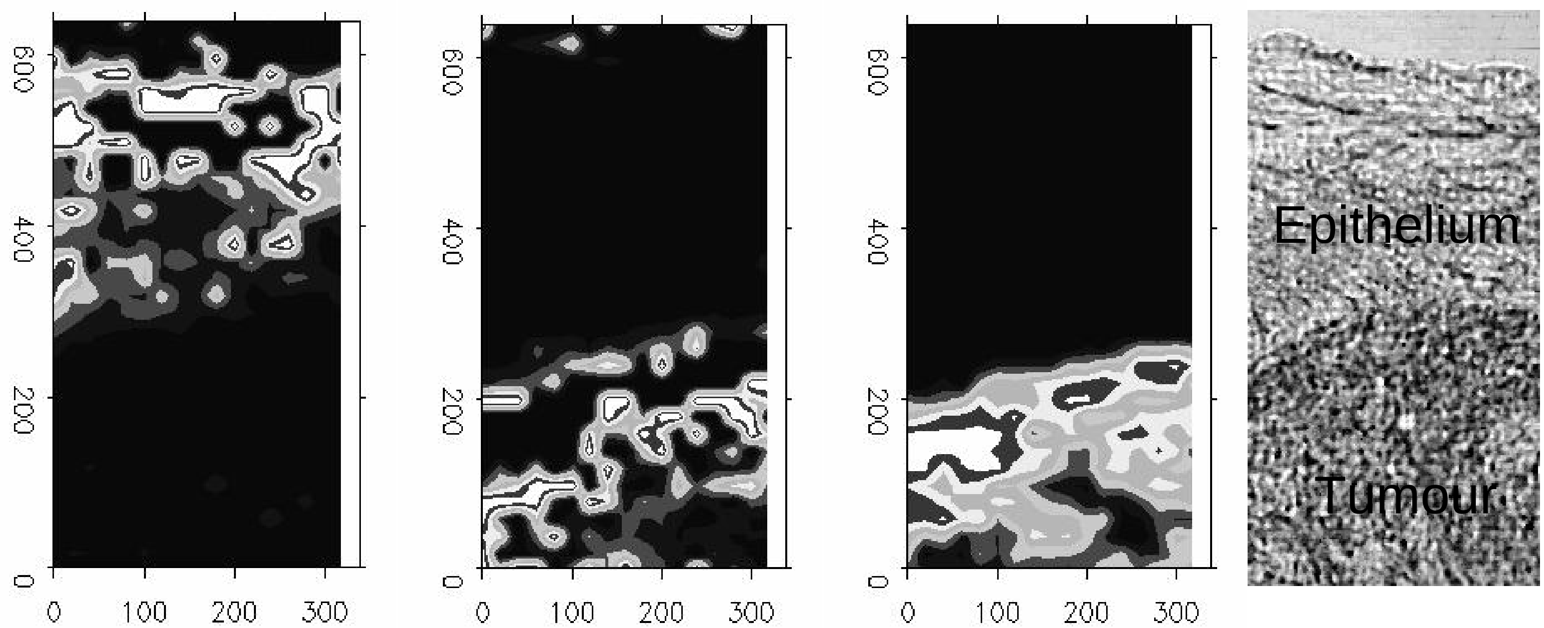
Comparison of normal epithelium IR spectrum with malignant tissue



Mark Tobin, Australian Synchrotron

FTIR Microspectroscopy of Malignant Tumour

1155 / 1170 cm^{-1} | 1170 / 1155 cm^{-1} | 970 cm^{-1}



Bright points show non-malignant IR profile

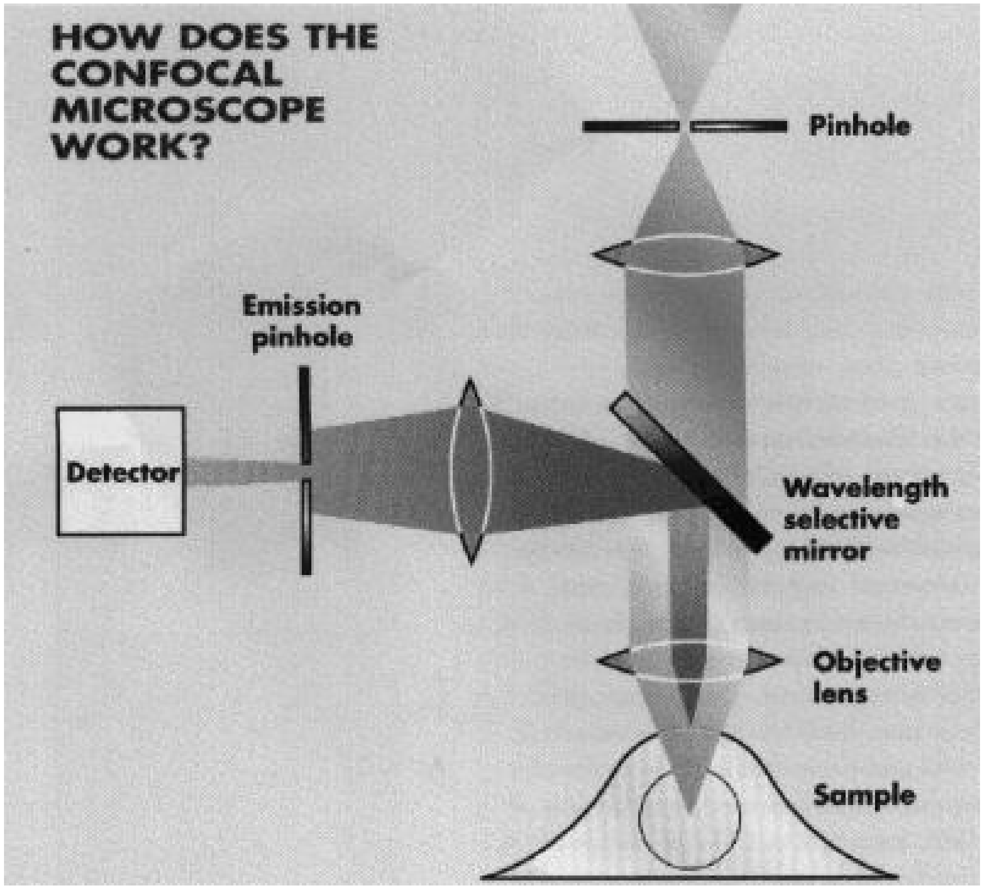
Bright points show malignant IR profile

Bright points show malignant IR profile

The imaging sciences (-ographies and ï oscopies)

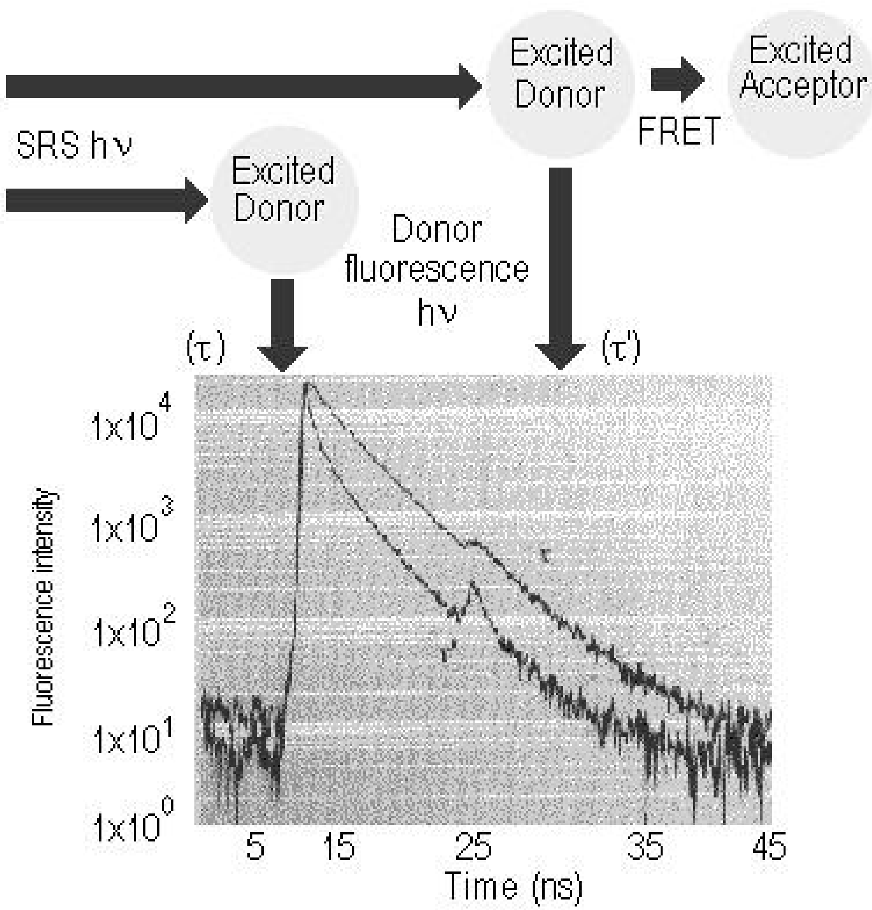
- Microscopy (metavisible)
  - ï The rapid repetition of the SR source flux is exploited in Fluorescence imaging.

Optical microscopy



Two techniques used: Fluorescence Resonant Energy Transfer (FRET) and Fluorescence Lifetime Imaging (FLIM)

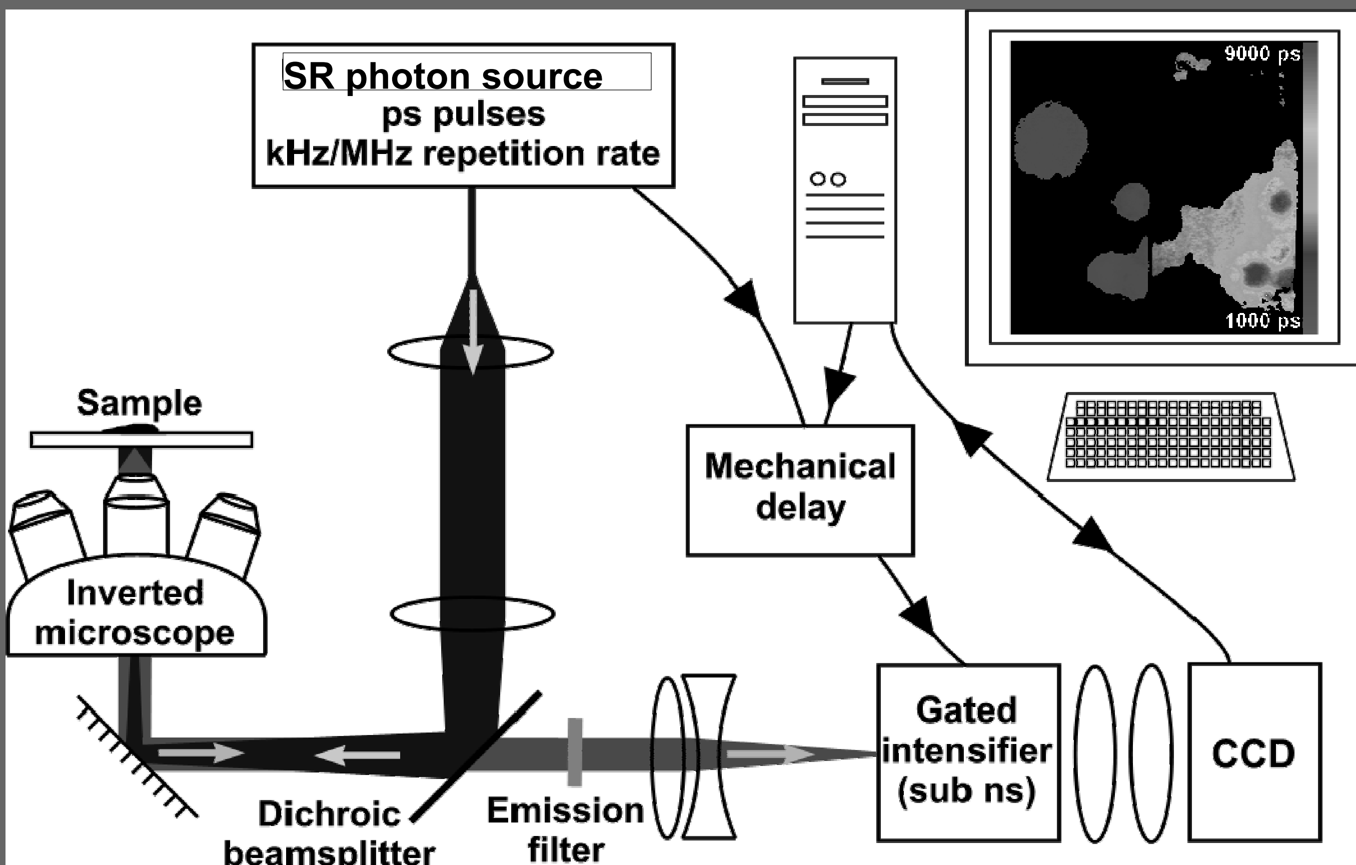
Optical Microscopy - FRET

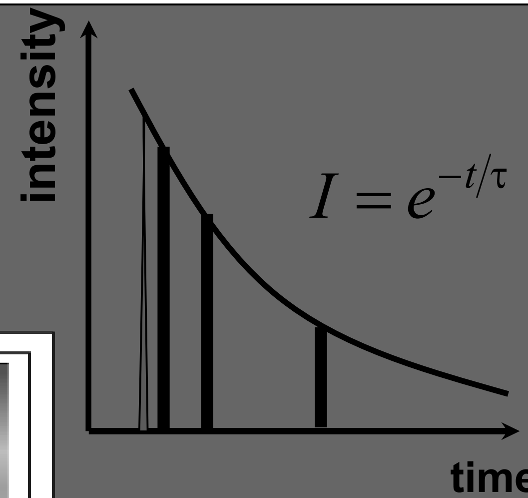


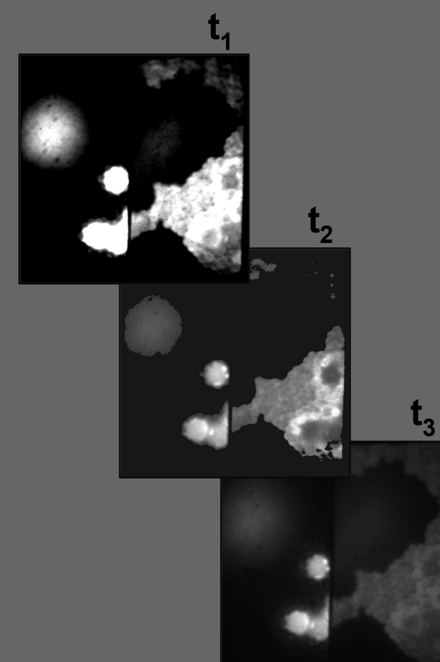
- On excitation, a donor fluorophore emits fluorescence photons with a characteristic lifetime.
- The close proximity (**5 to 10 nm**) of a second fluorophore (acceptor) with an absorption band which overlaps with the emission band of the donor leads to its excitation at a rate which is inversely proportional to the **sixth power** of the distance between them.
- The donor fluorescence and its lifetime are dependent on donor-acceptor distance. Measurement of the donor fluorescence lifetime, gives FRET data free of artifacts which may arise from measuring intensity.

Widefield time-domain FLIM

ÅPicosecond pulses from synchrotron
ÅPicosecond image intensifier gating

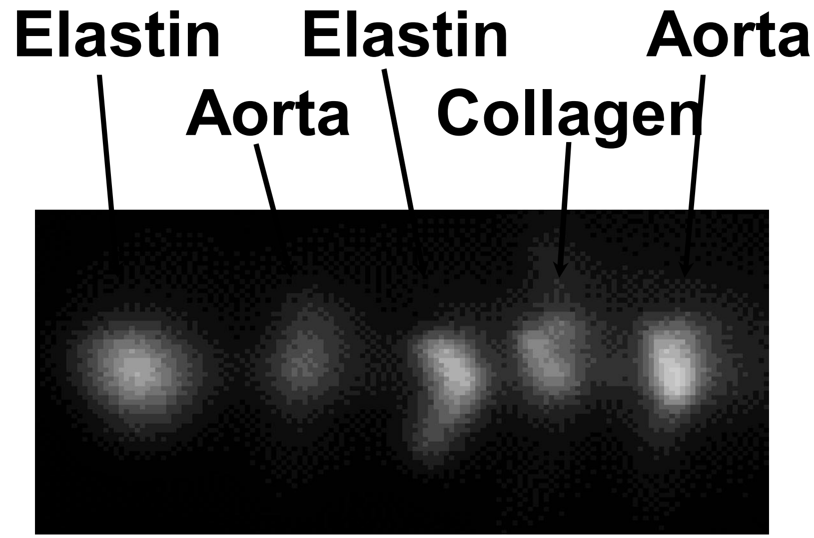




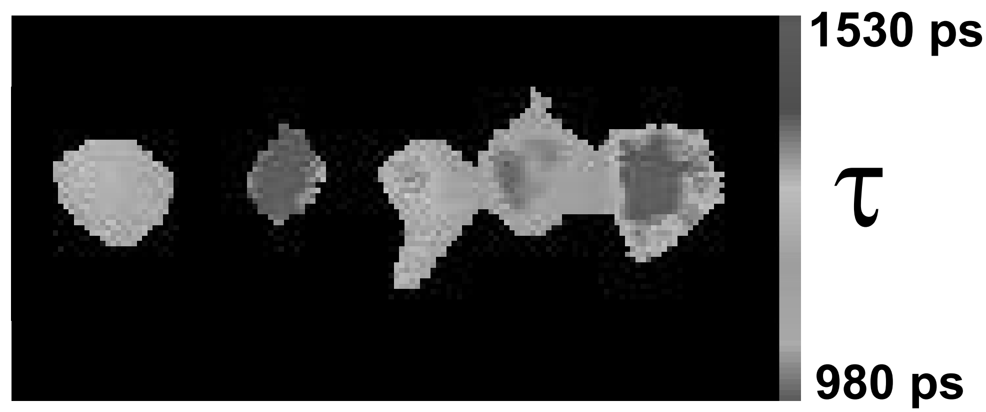


FLIM of tissue constituents

Time-gated intensity image at t = 0



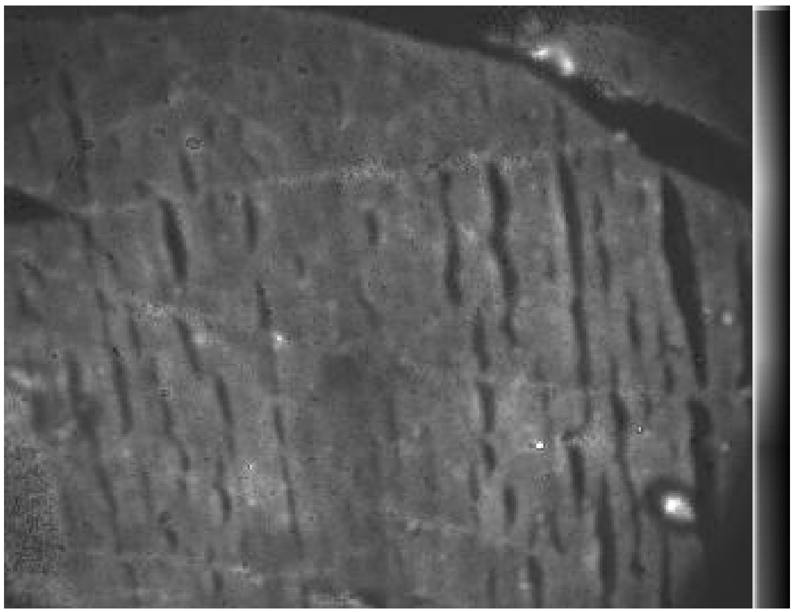
FLIM map (stretched exponential fit)



Change in environment ⇒ change in lifetime

Courtesy Steven Webb, Daresbury Laboratory, s.e.d.webb@dl.ac.uk

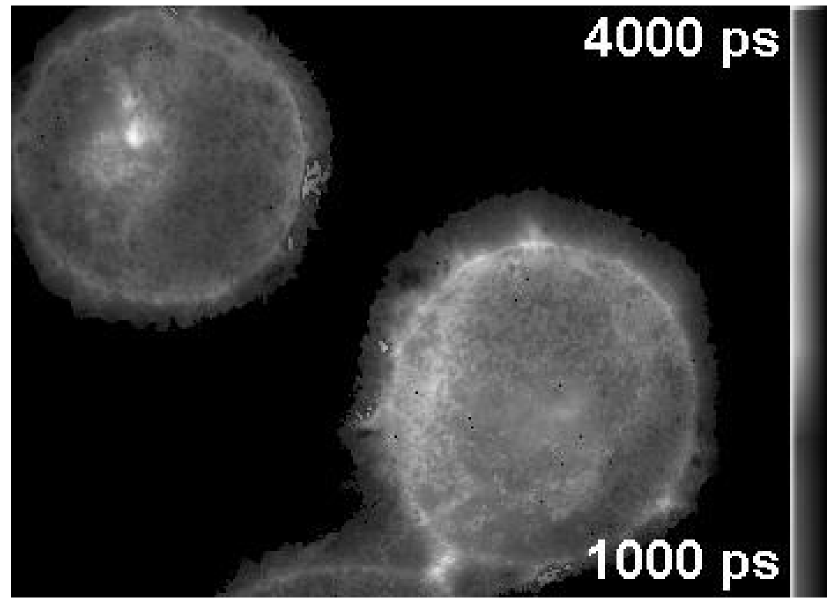
FLIM - Applications



1700 ps

500 ps

Medicine: **FLIM of tendon using auto fluorescence of collagen.**

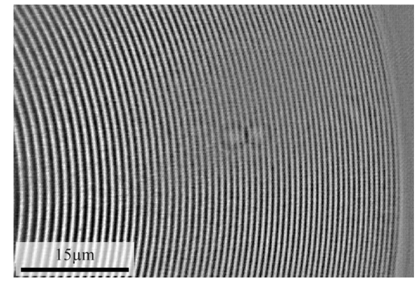


Biology: **cells expressing EGFP**

The imaging sciences (-ographies and ï oscopies)

- X-ray microscopy
  - ï At ćsoftô x-ray wavelengths fresnel optics can be used.
  - ï Harder x-ray lenses can be made using refraction.
- Why use an X-ray microscope?
  - ï Specimen is fully hydrated in solution
  - ï Specimen has high contrast without staining
  - ï Resolution is (30 nm), greater than in light microscopy
  - ï Specimen imaged at atmospheric pressure
  - ï Specimen can be several microns thick (up to 10 µm)

X-ray Lenses



Zone plates

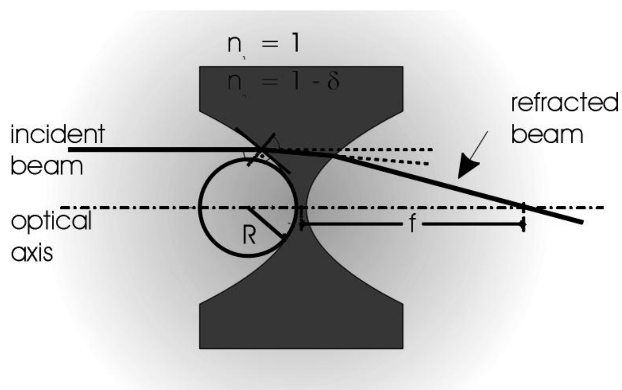
ï nm tolerances. Restricted to Soft x-rays

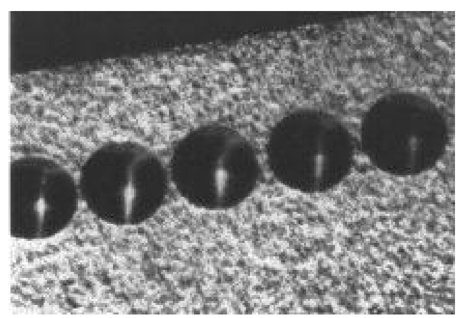
Capillary lenses

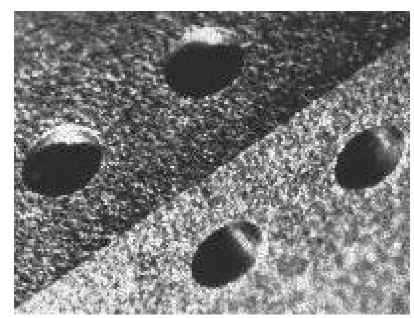
ï Manufacture difficult. Long focal length

Refractive lenses (CRL)

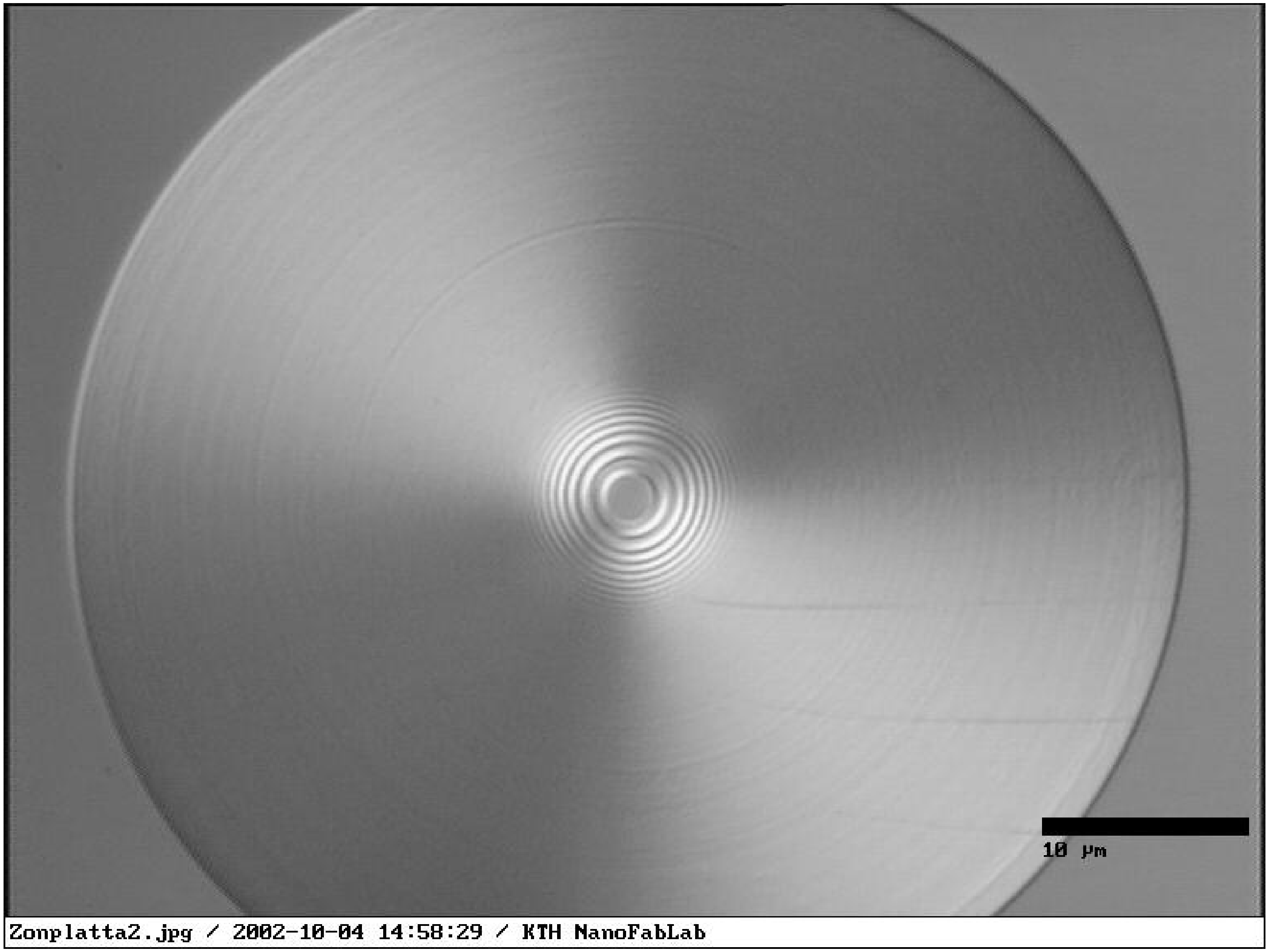
ï Refractive index ~$1\text{-}10^{-6}$





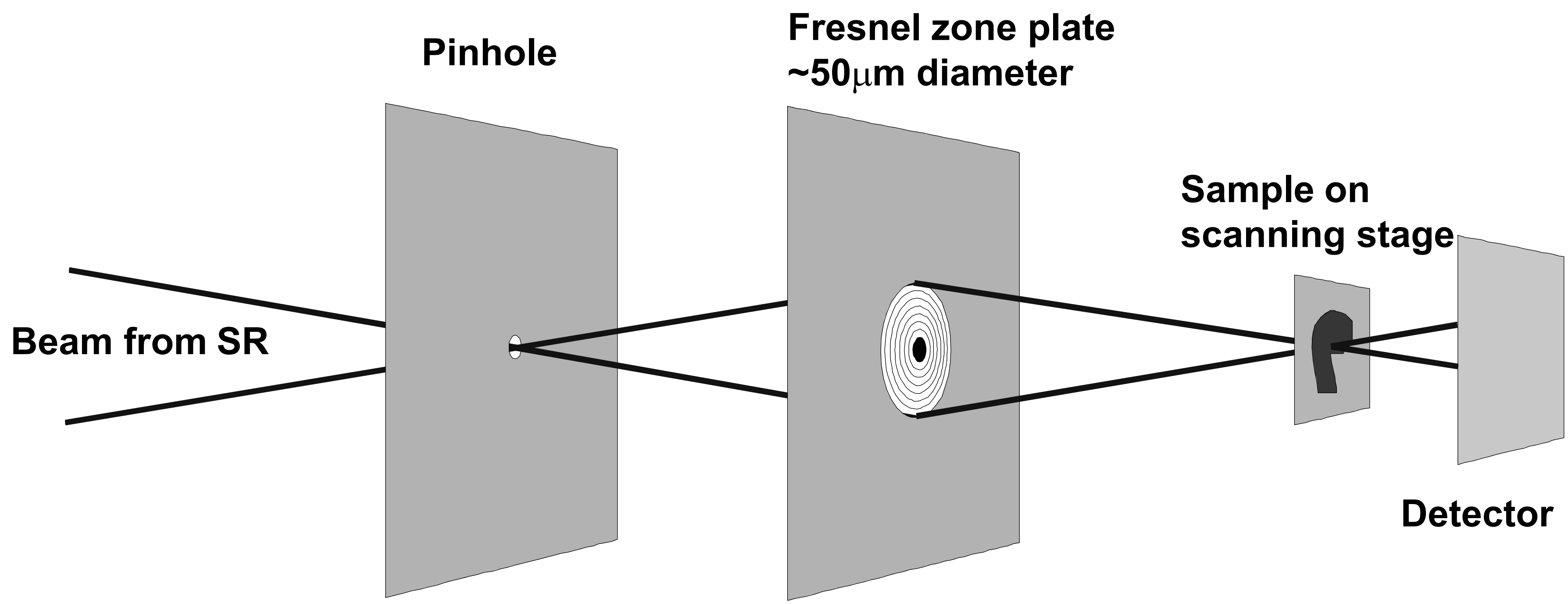


Zone plates

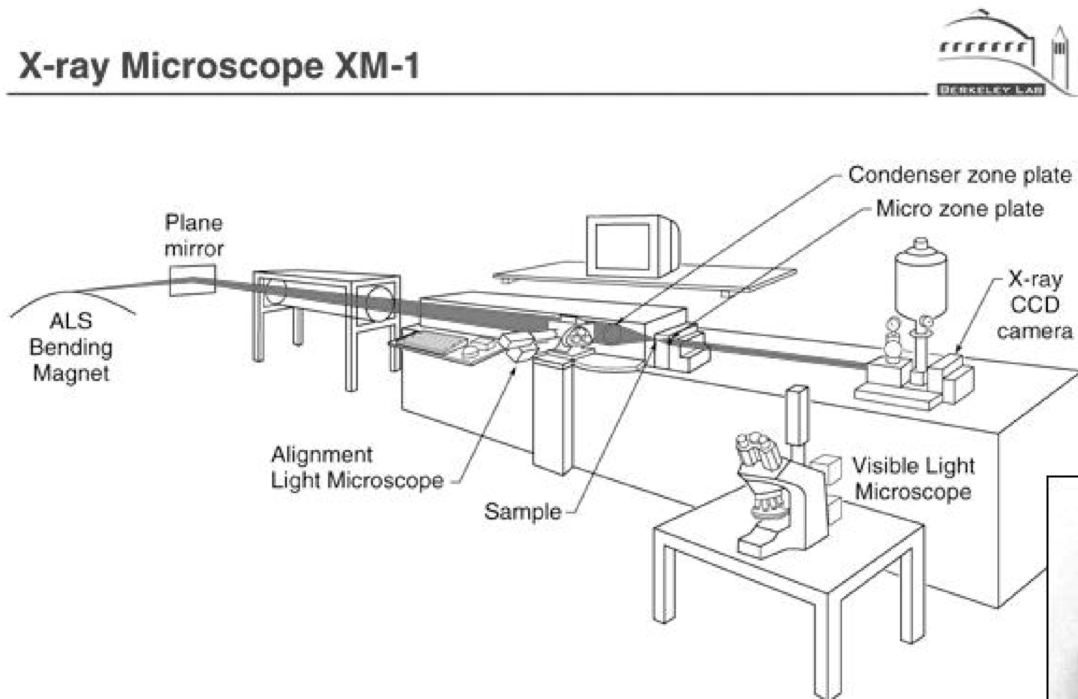


Courtesy KTH, Stockholm, Sweden

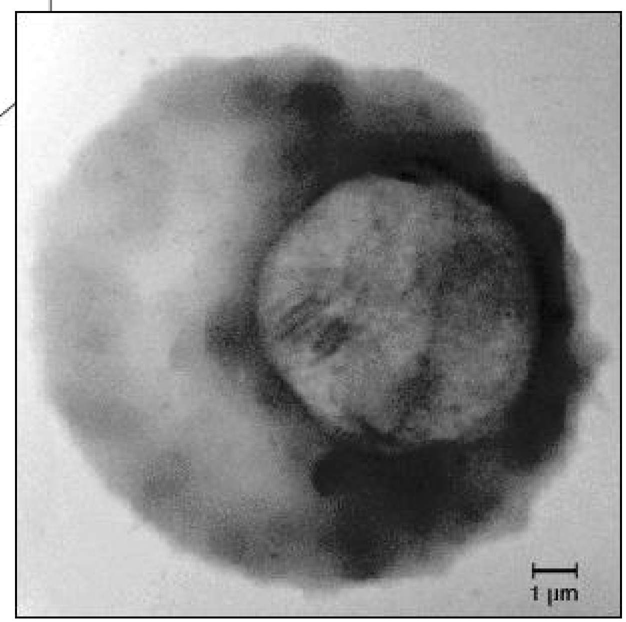
X-Ray Microscopy



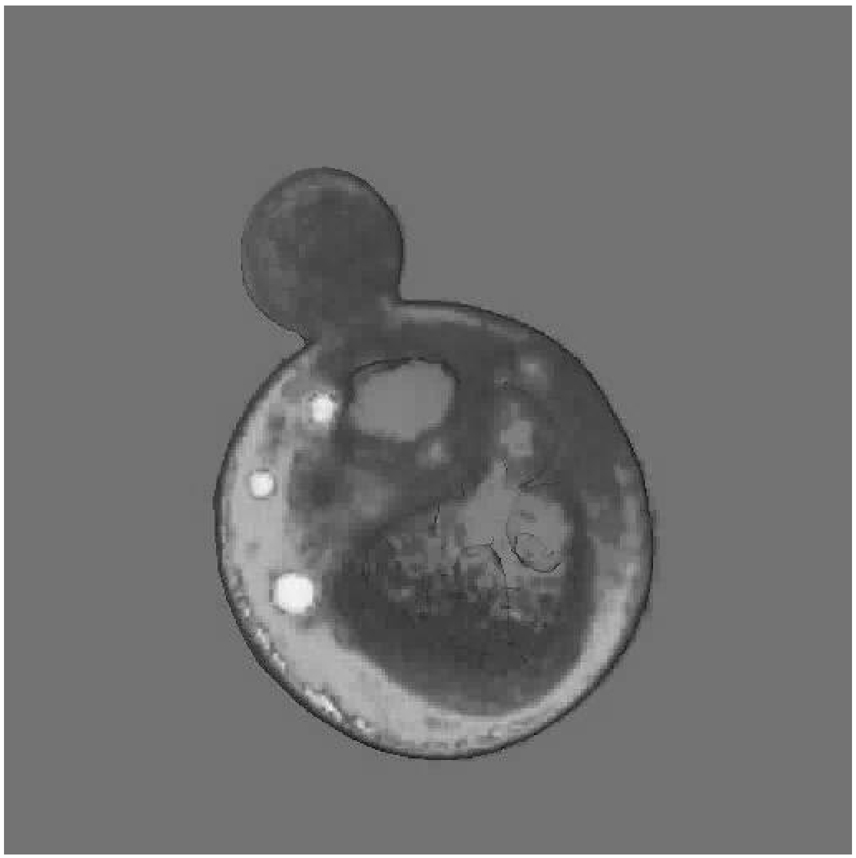
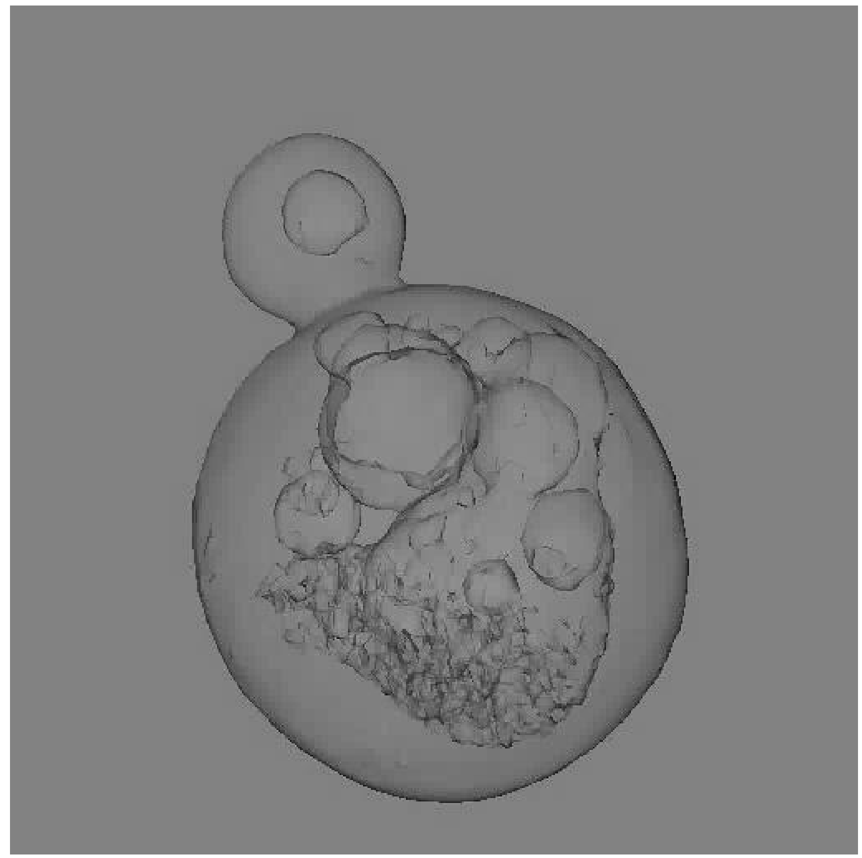
X-ray microscope at the ALS



Malaria parasite inside a red blood cell



X-ray Micro CT

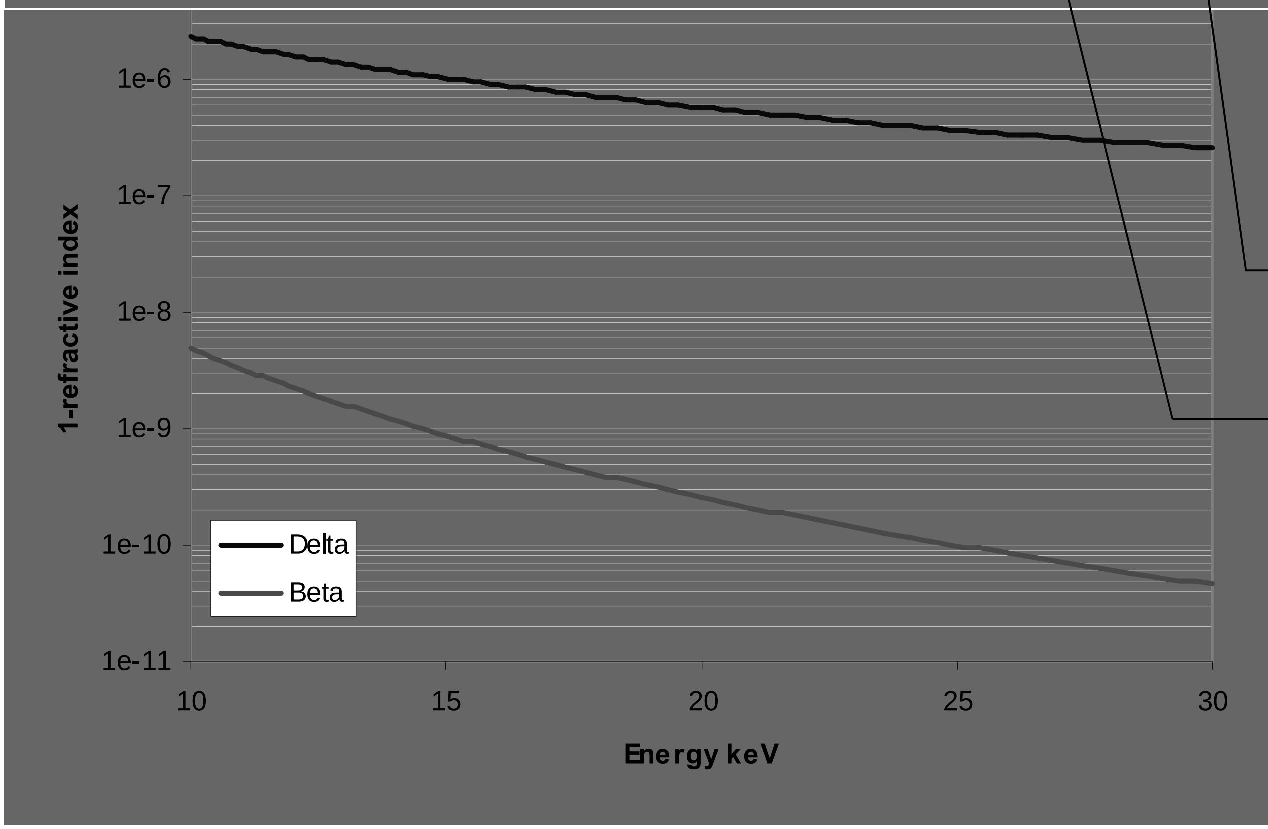
INTERMISSION

Using SR light characteristics

- Coherence
  - ï The coherence length is less than a micron on older sources but at third generation sources gets up to 100ÿs of microns.
  - ï This opens up potentials for several coherence imaging techniques.

Refractive Index at X-ray Wavelengths

$$\eta = 1 - \frac{n r_0 \lambda^2}{2\pi}(f_1 + i f_2) = 1 - \delta - i\beta$$



Note:

$\delta \sim 1000\ \beta$

$\delta \propto E^{-2}$

$\beta \propto E^{-4}$

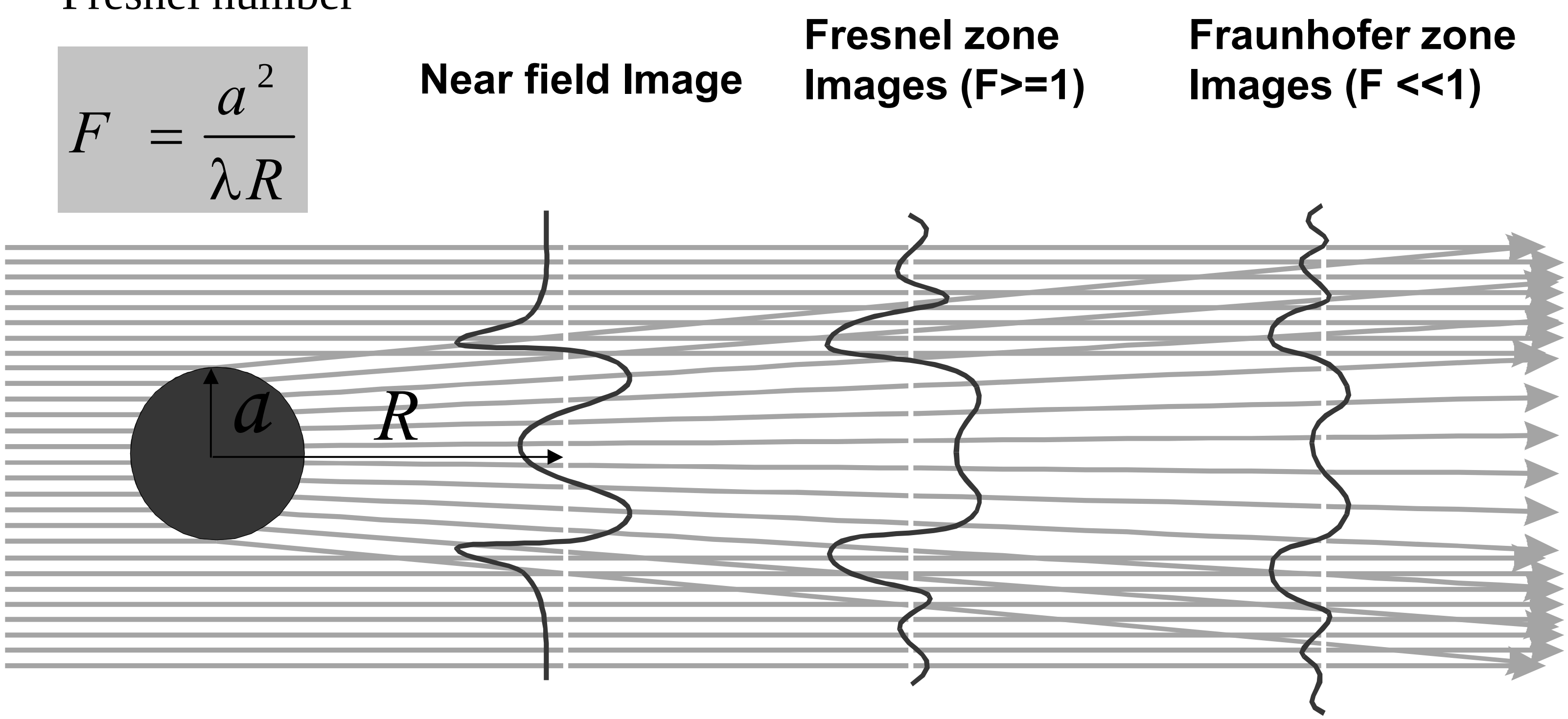
Absorption

Phase

Phase contrast imaging

Fresnel number

$$F = \frac{a^2}{\lambda R}$$



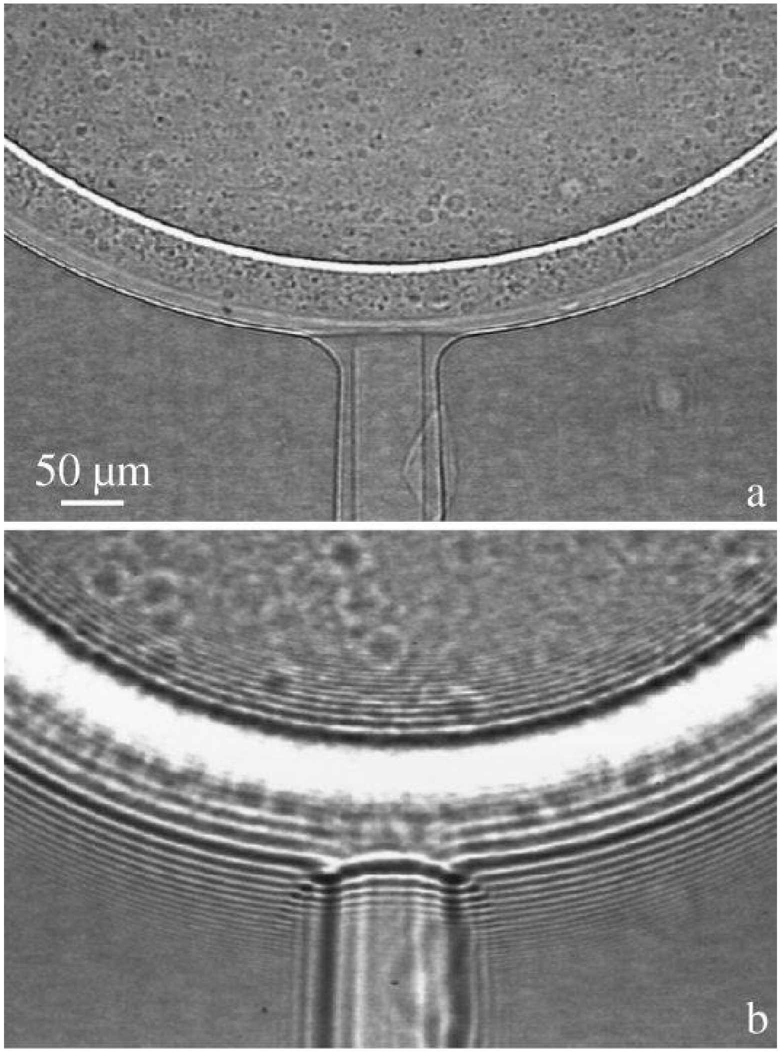
$$T_c = \frac{\lambda}{2\alpha} \qquad L_c = \frac{\lambda^2}{\Delta\lambda}$$

T_c =Transverse coherence length

L_c=Longitudinal coherence length

ə= wavelength, Ŭ=source divergence

Phase contrast imaging in x-rays



Two images of a hollow sphere consisting of two different polymer layers. In image a), recorded at a sample-detector distance of 19 cm and representative of the edge-detection regime, the borders are revealed by white-black contrast.

In image b), recorded at a distance of 3 metres and representative of the holographic regime, many interference fringes are observed

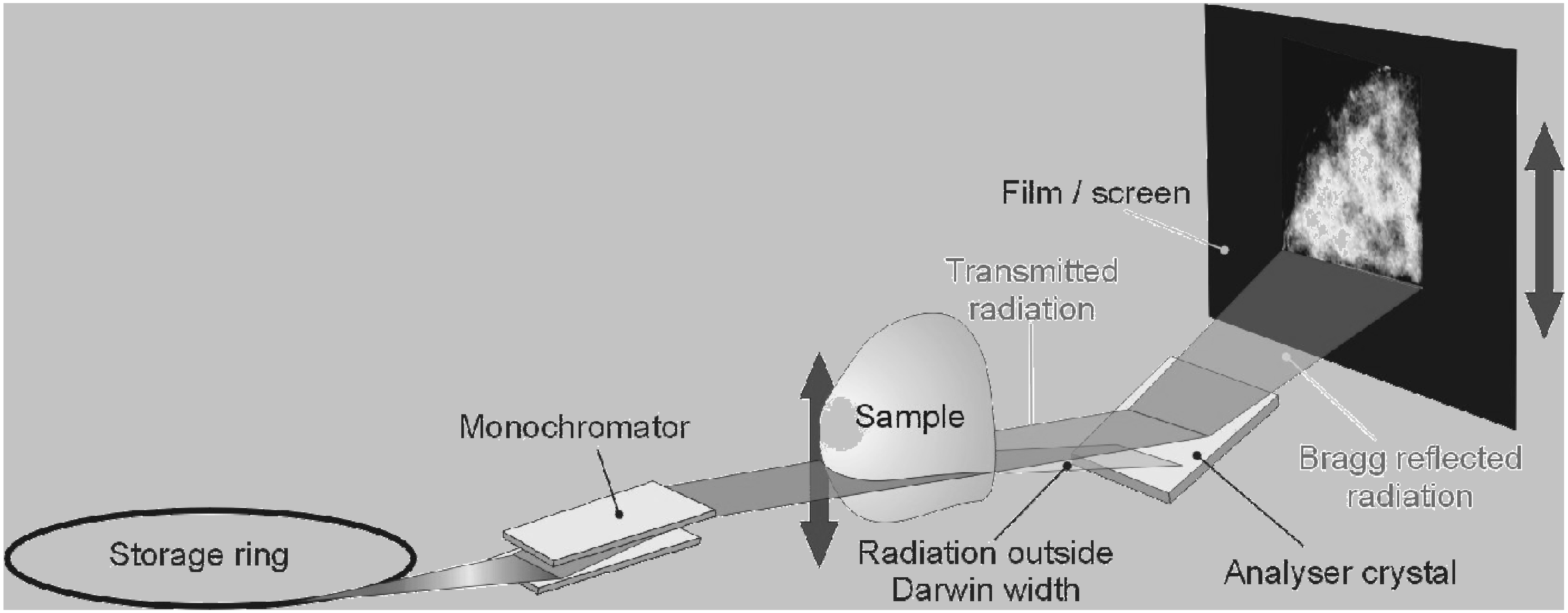
Courtesy ESRF ID19

Phase contrast imaging techniques

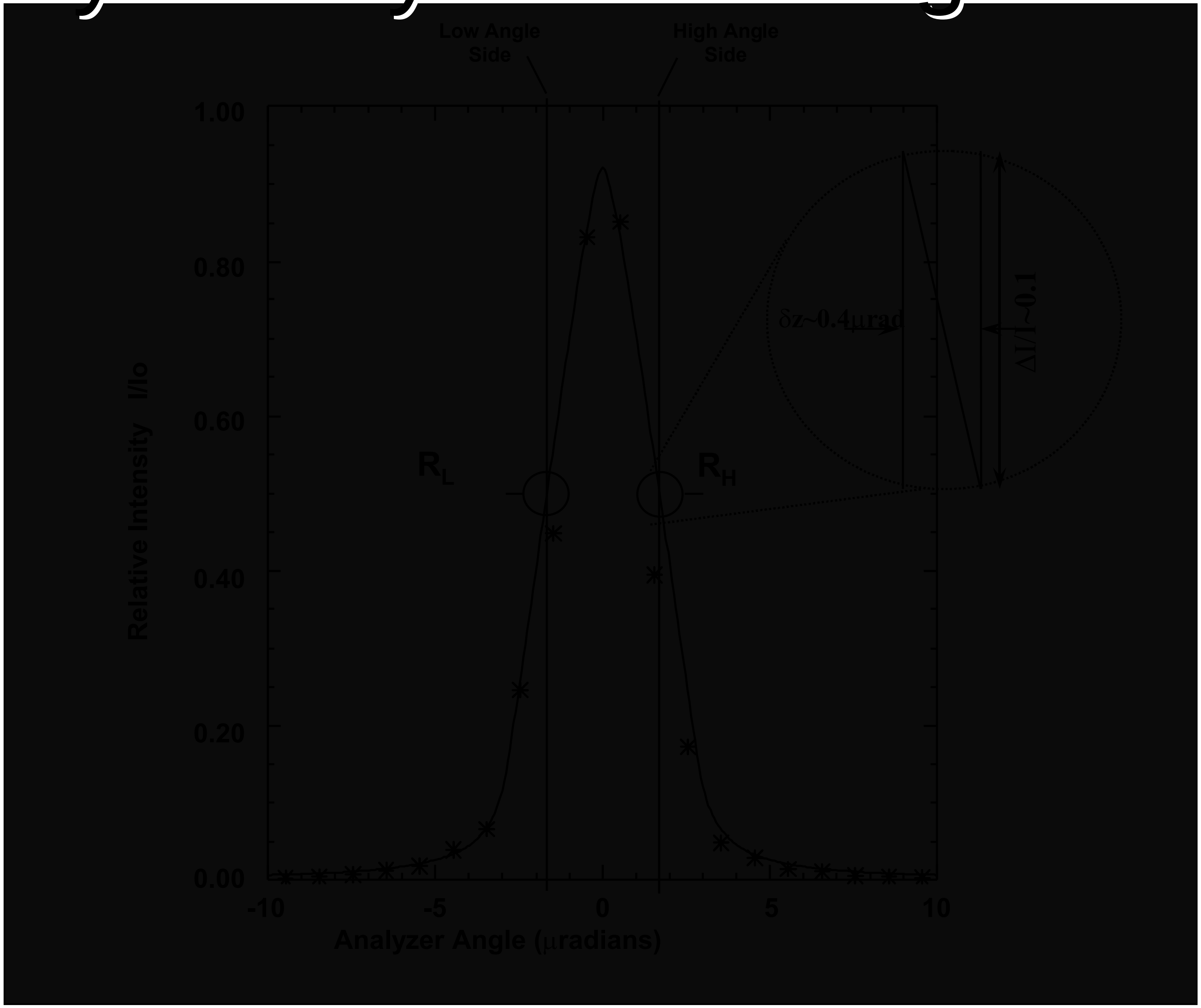
So far:

- Interferometry ï Phase directly
- Analyser based imaging ï Gradient of the phase (differential $\nabla\phi$)
- Propagation based imaging ï Laplacian of the phase (second order differential $\nabla^2\phi$).

Analyser Based Imaging (ABI)

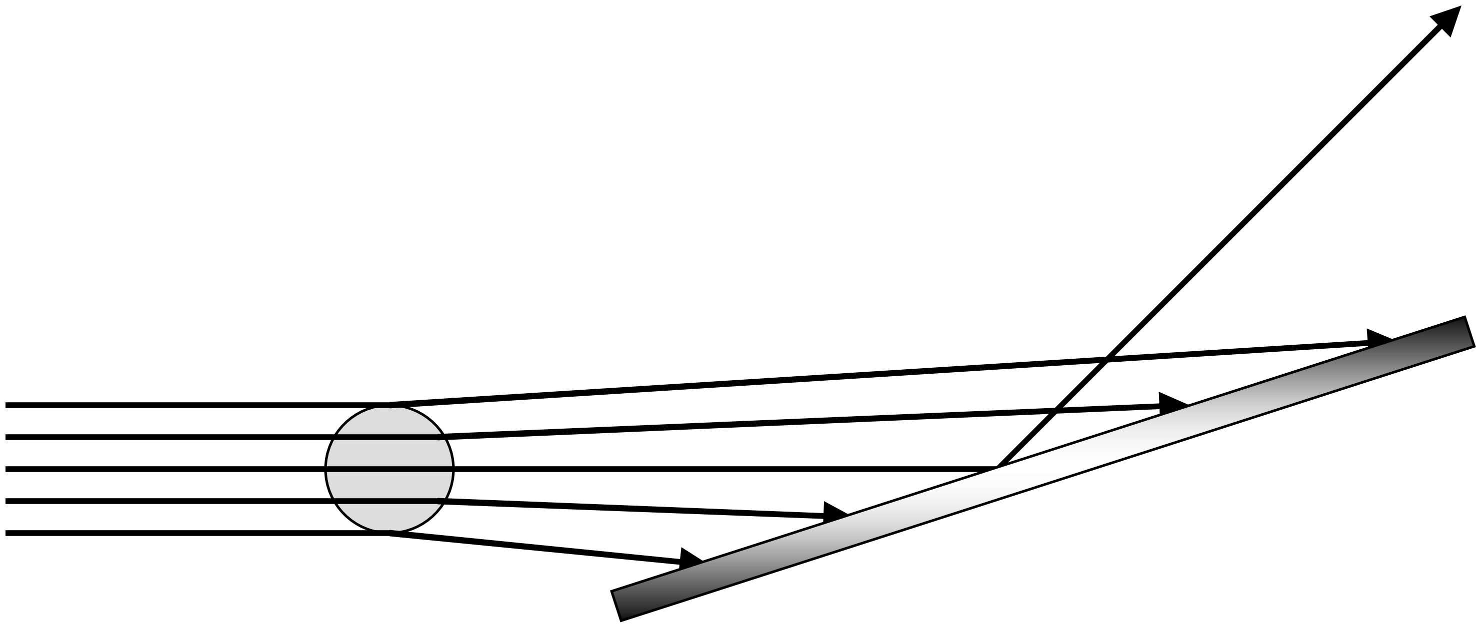


Analyser Crystal Rocking Curve

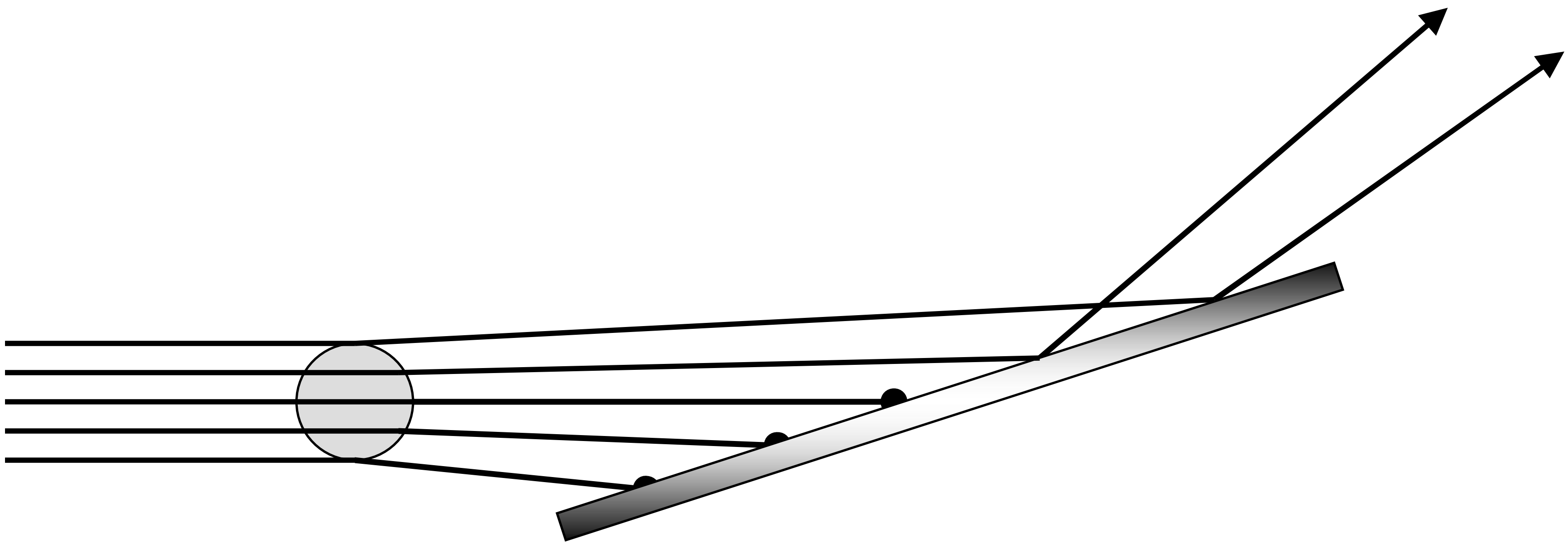


Beamline Camera

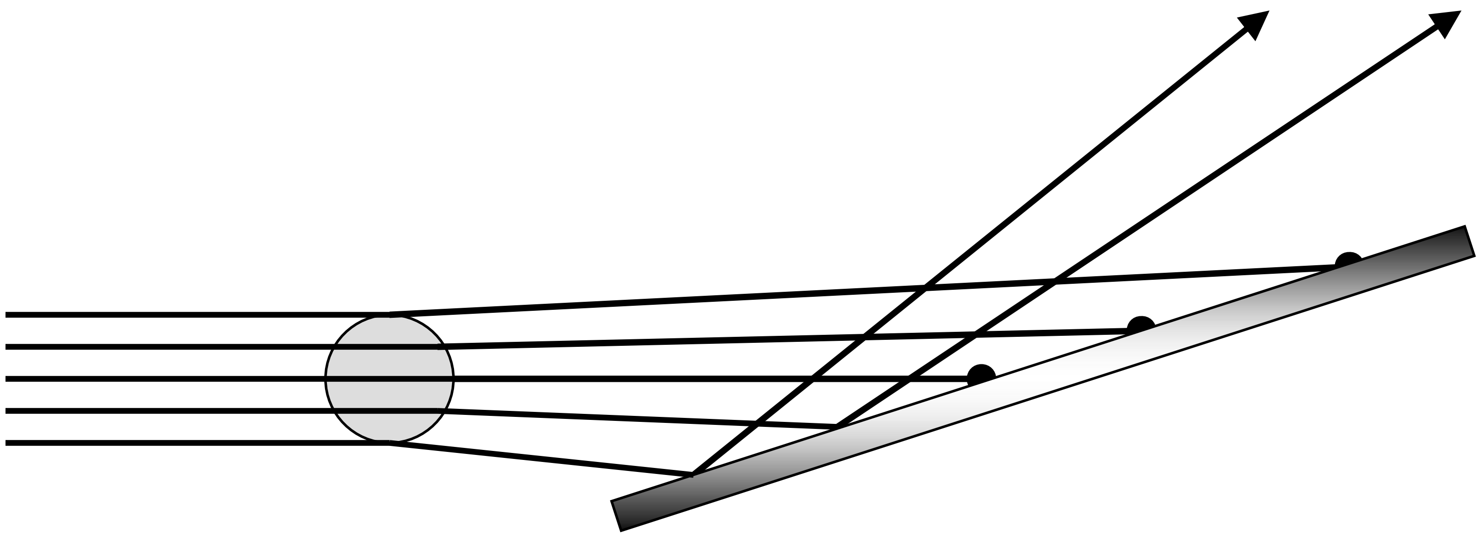
Peak of Rocking Curve



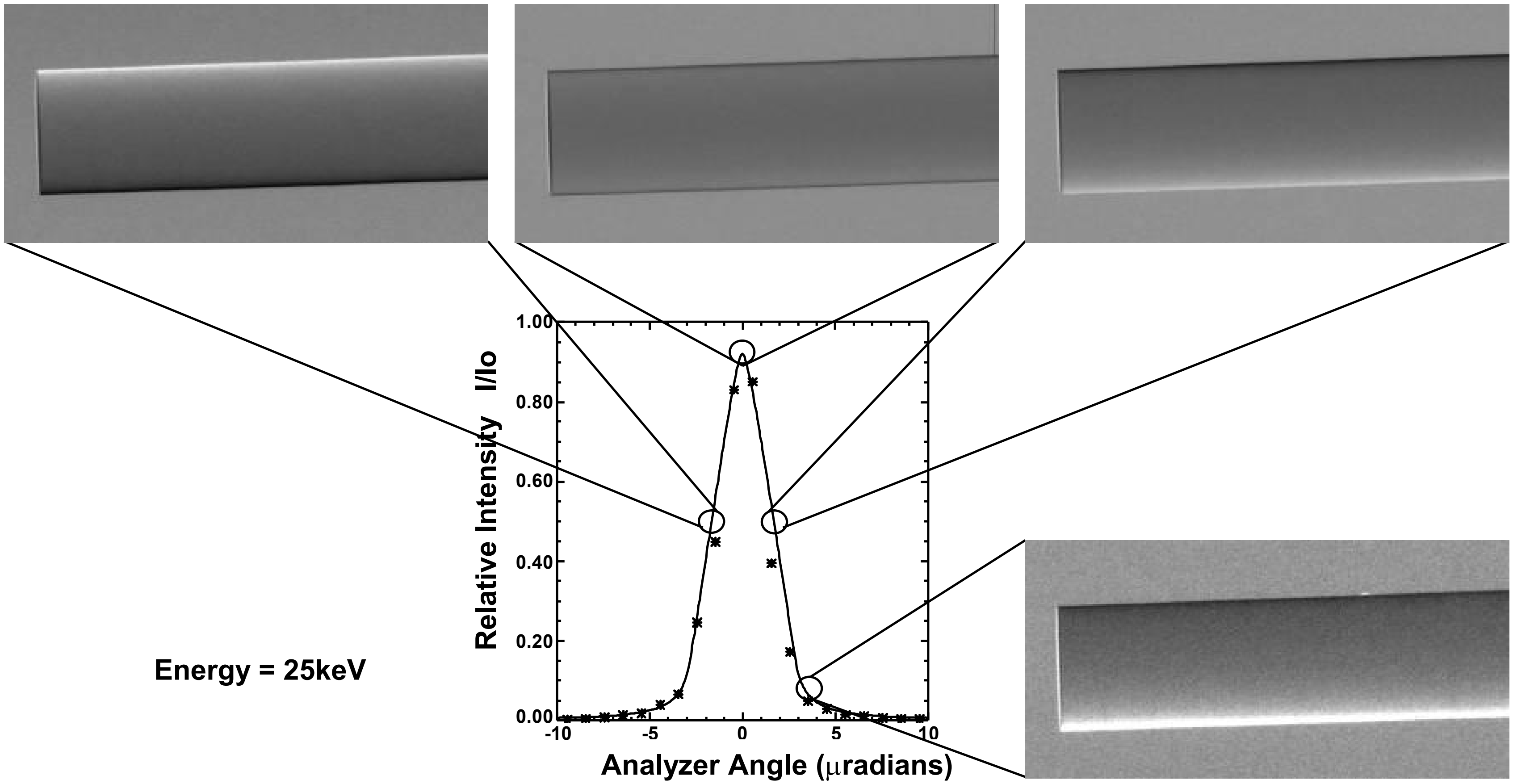
+ve Side of Rocking Curve



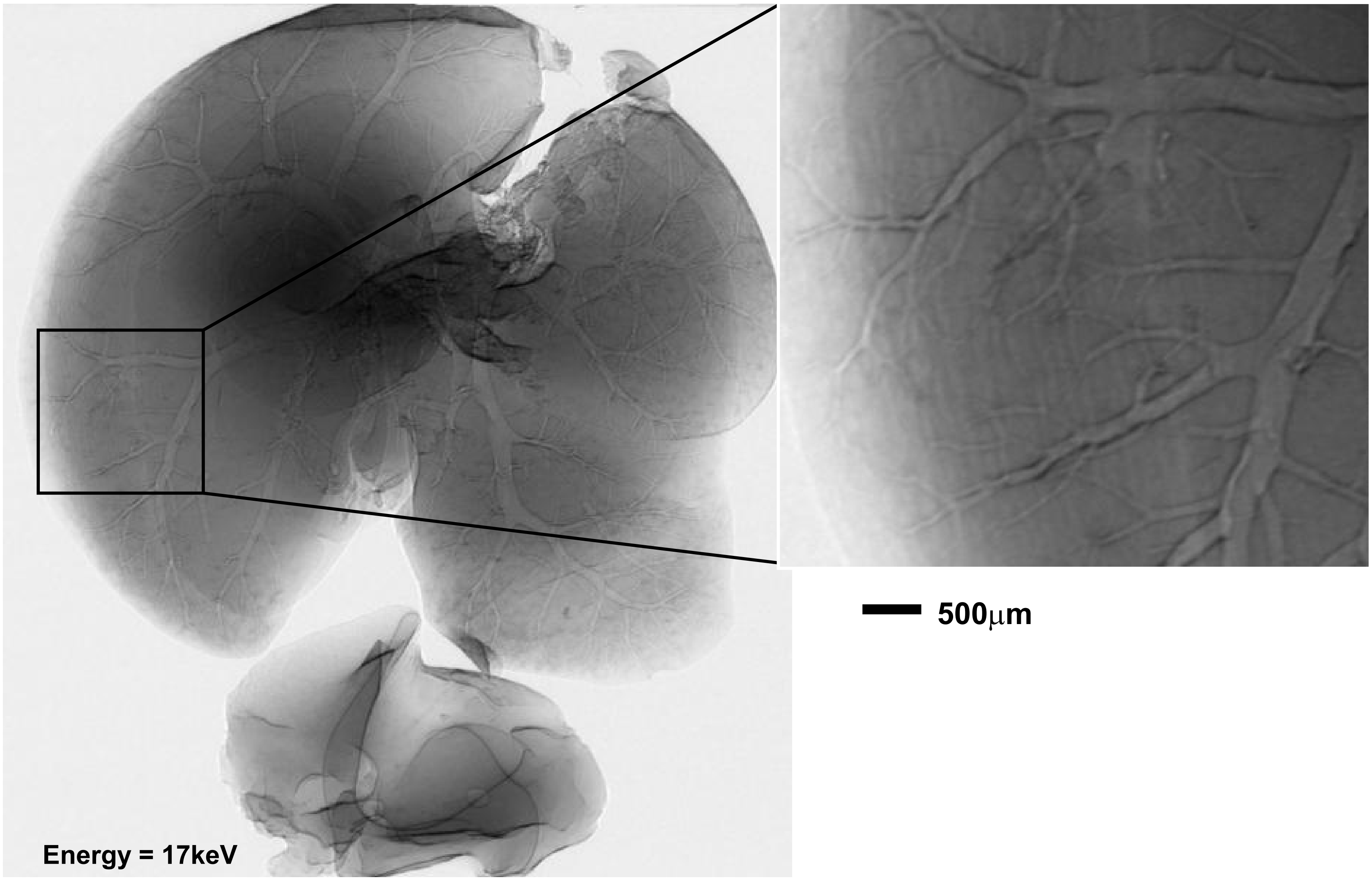
-ve Side of Rocking Curve



Diffraction Enhanced Imaging (DEI)



Mouse Liver Peak



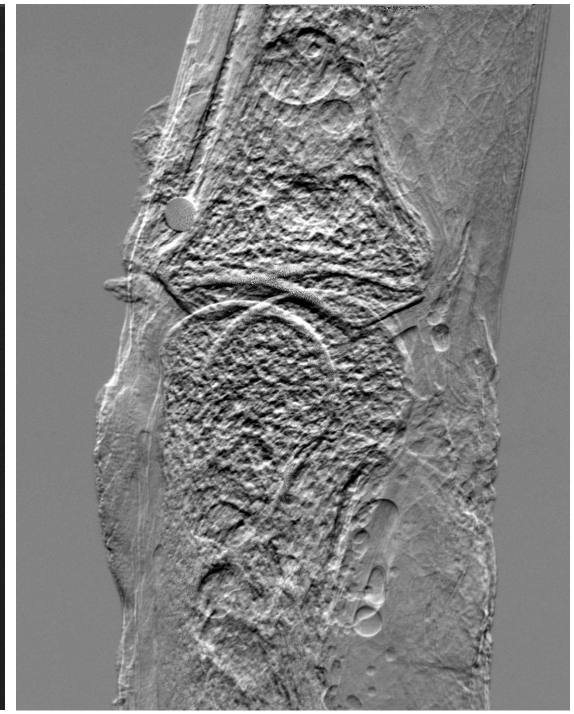
Mouse Liver Refraction

Human Finger

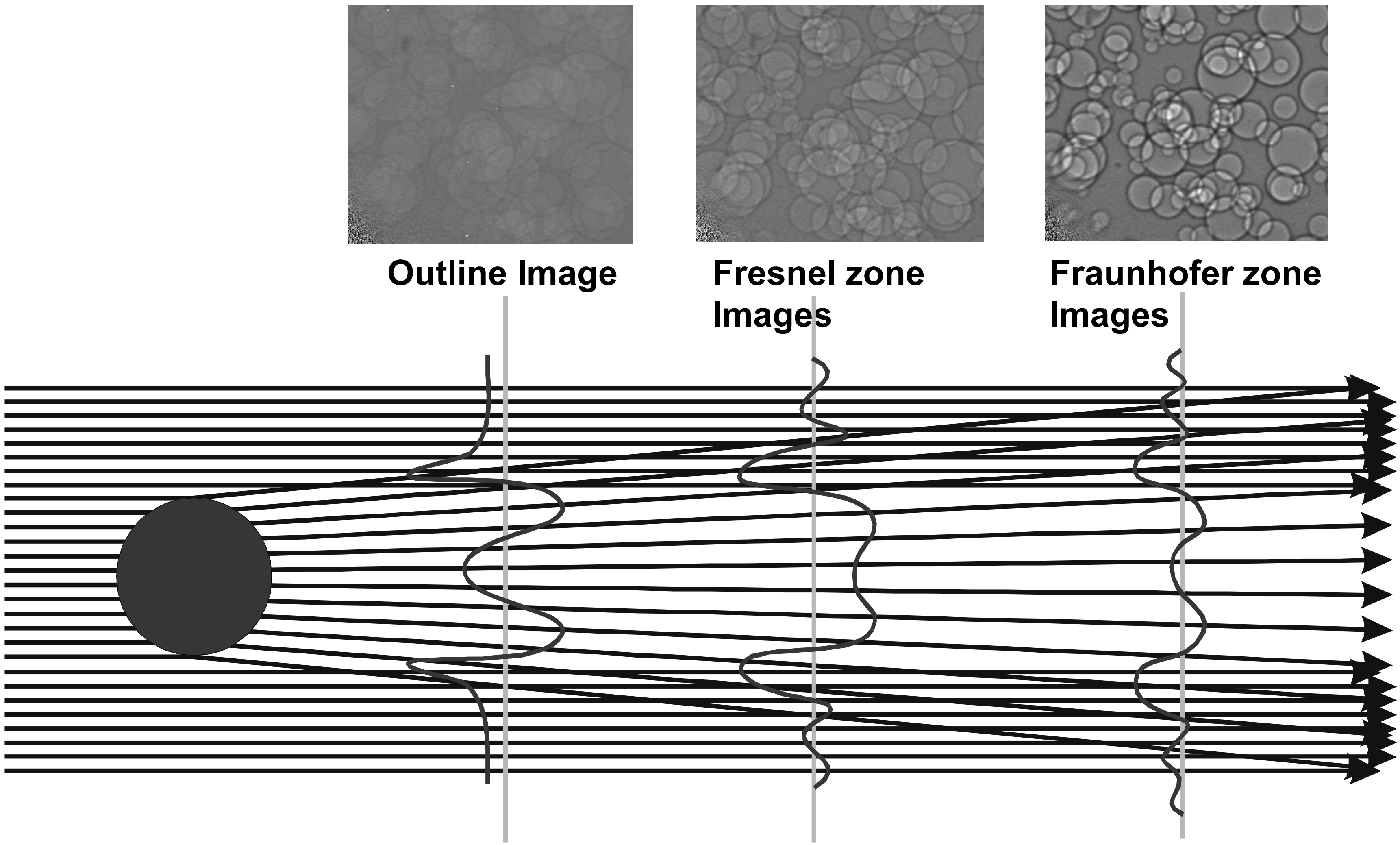
Conventional

Peak of Analyser

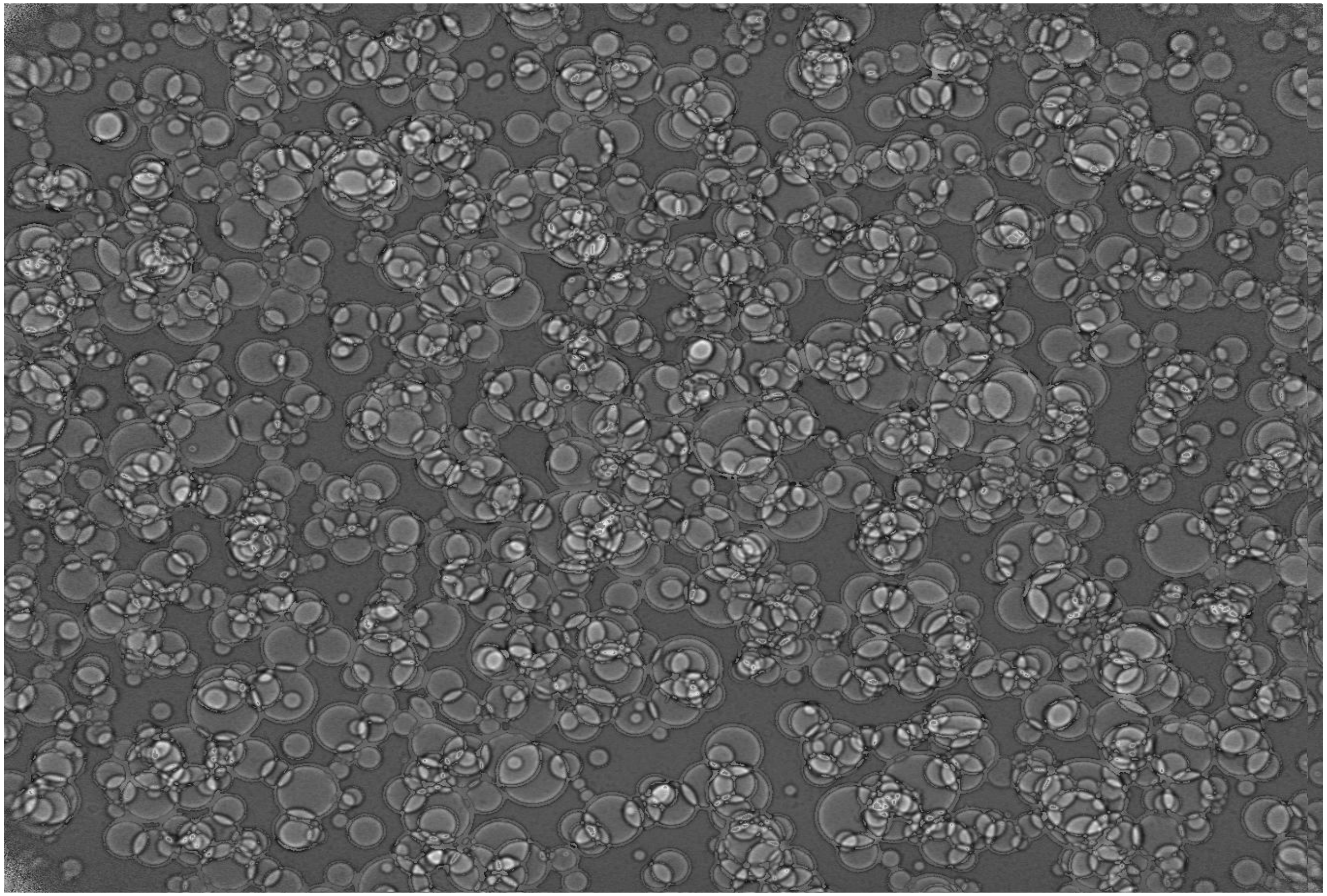
Refraction



Propagation Based Phase Contrast Imaging (PBI)

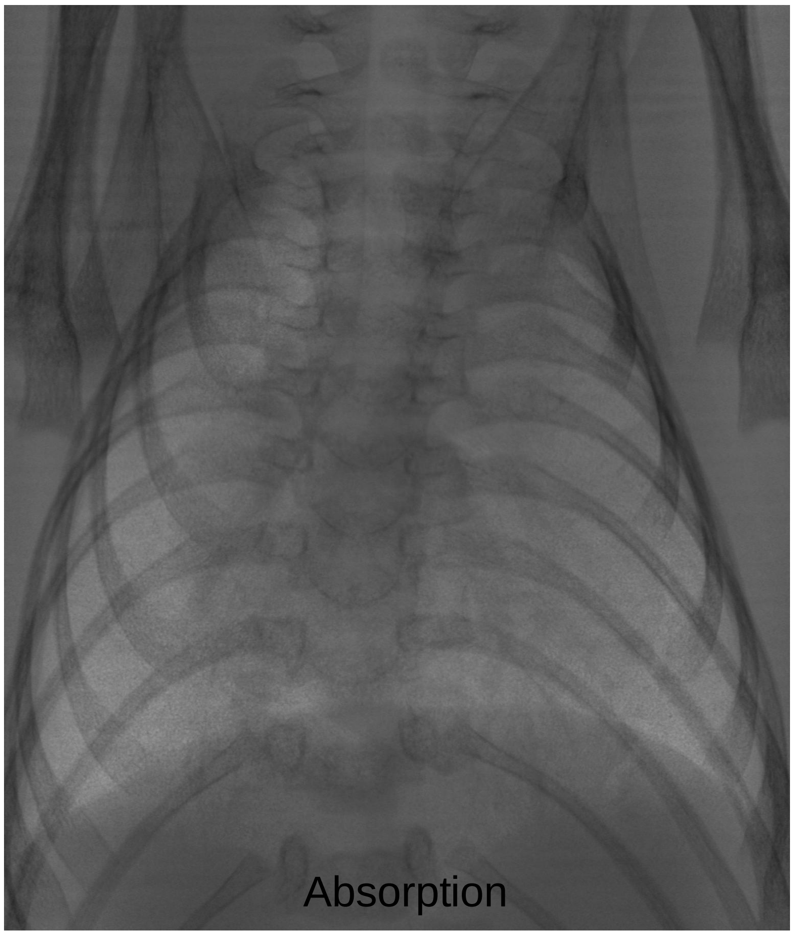


Propagation Based Imaging (PBI)

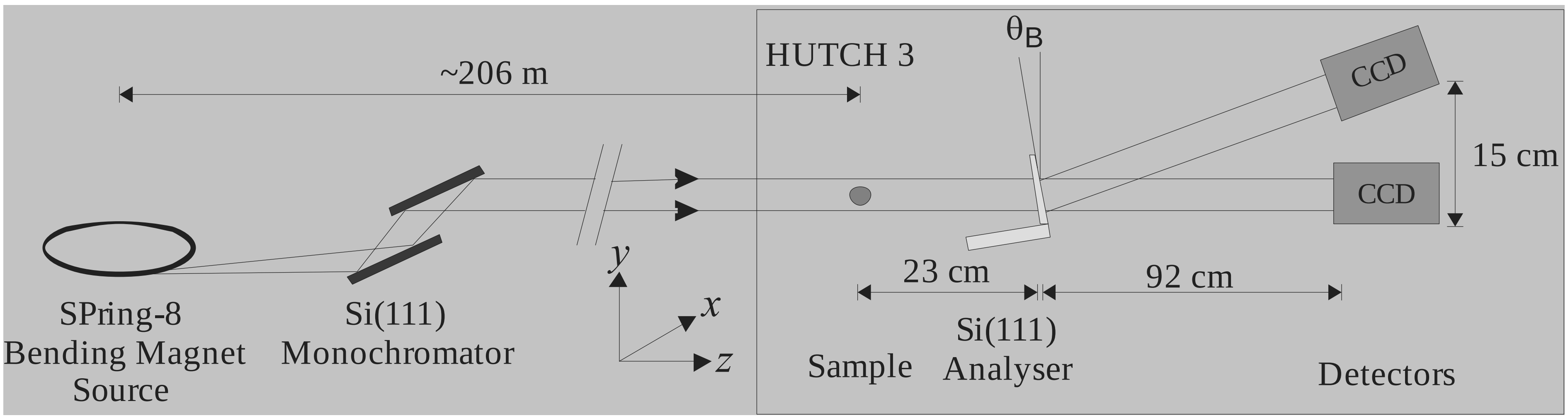


147cm

Why do PBI of the lung?



Imaging Setup

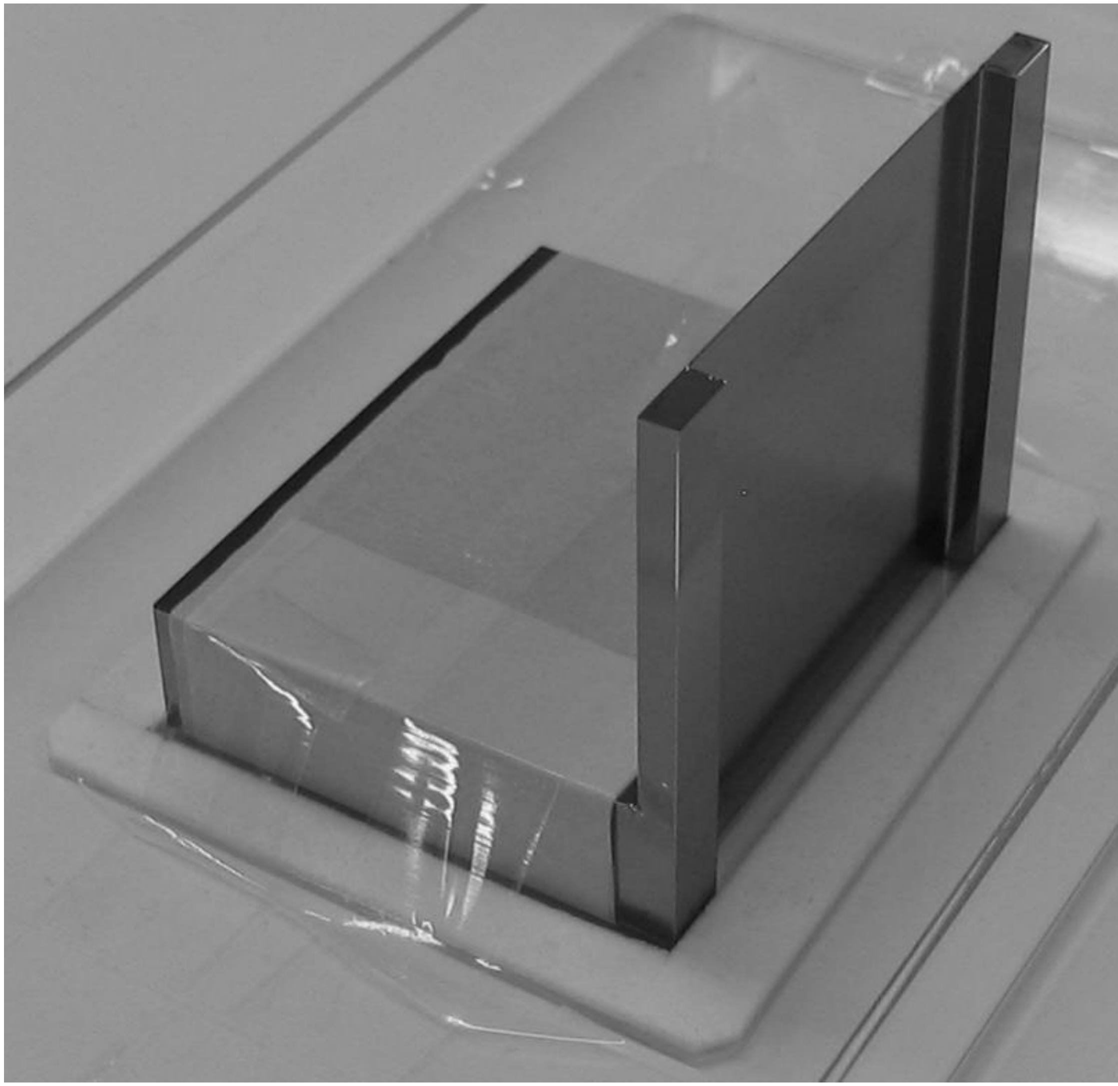


Beamline 20B2, Spring-8, Japan.

25 keV beam of highly coherent radiation.

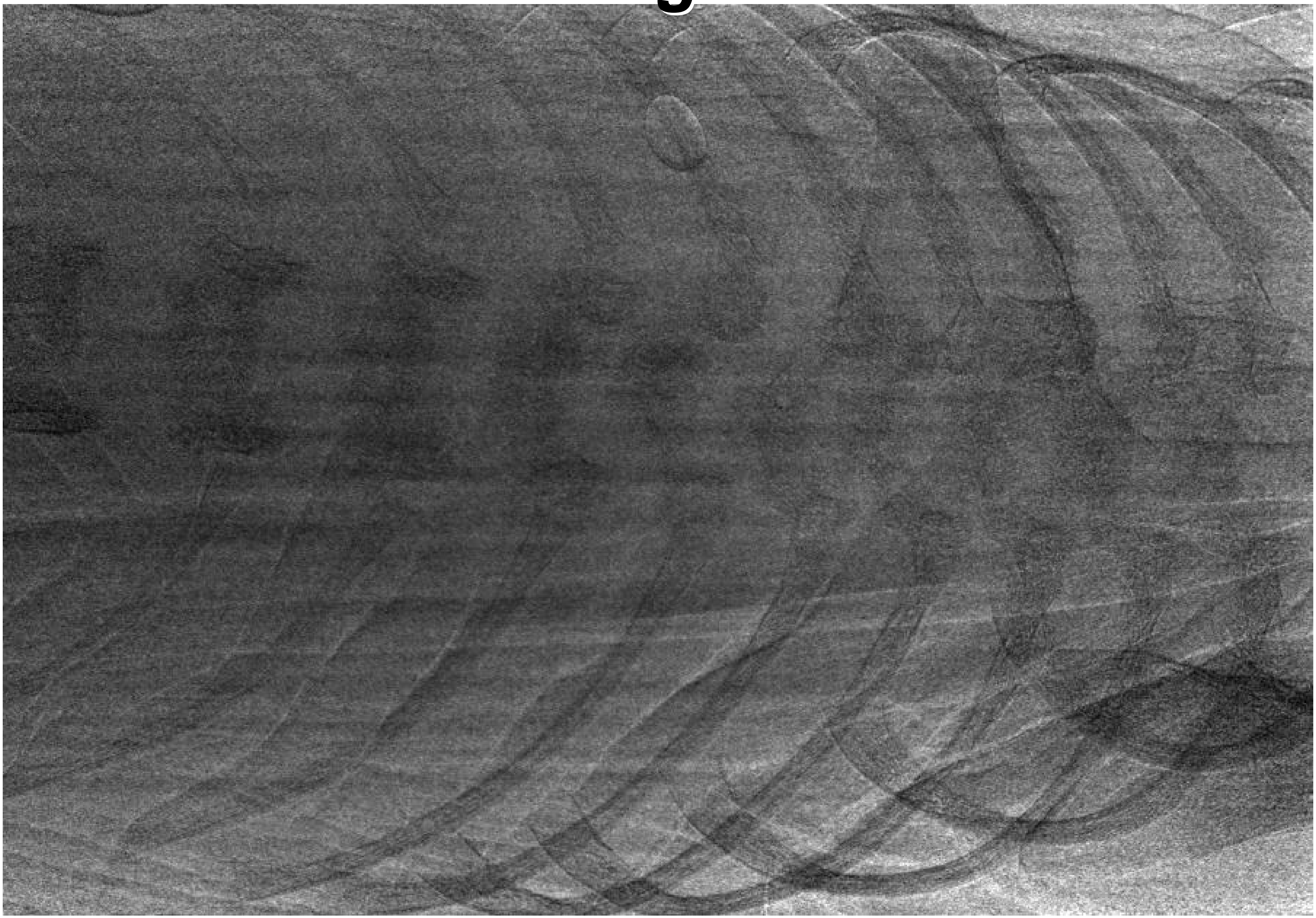
Courtesy Dr. Marcus Kitchen, Monash University

Laue analyser crystal

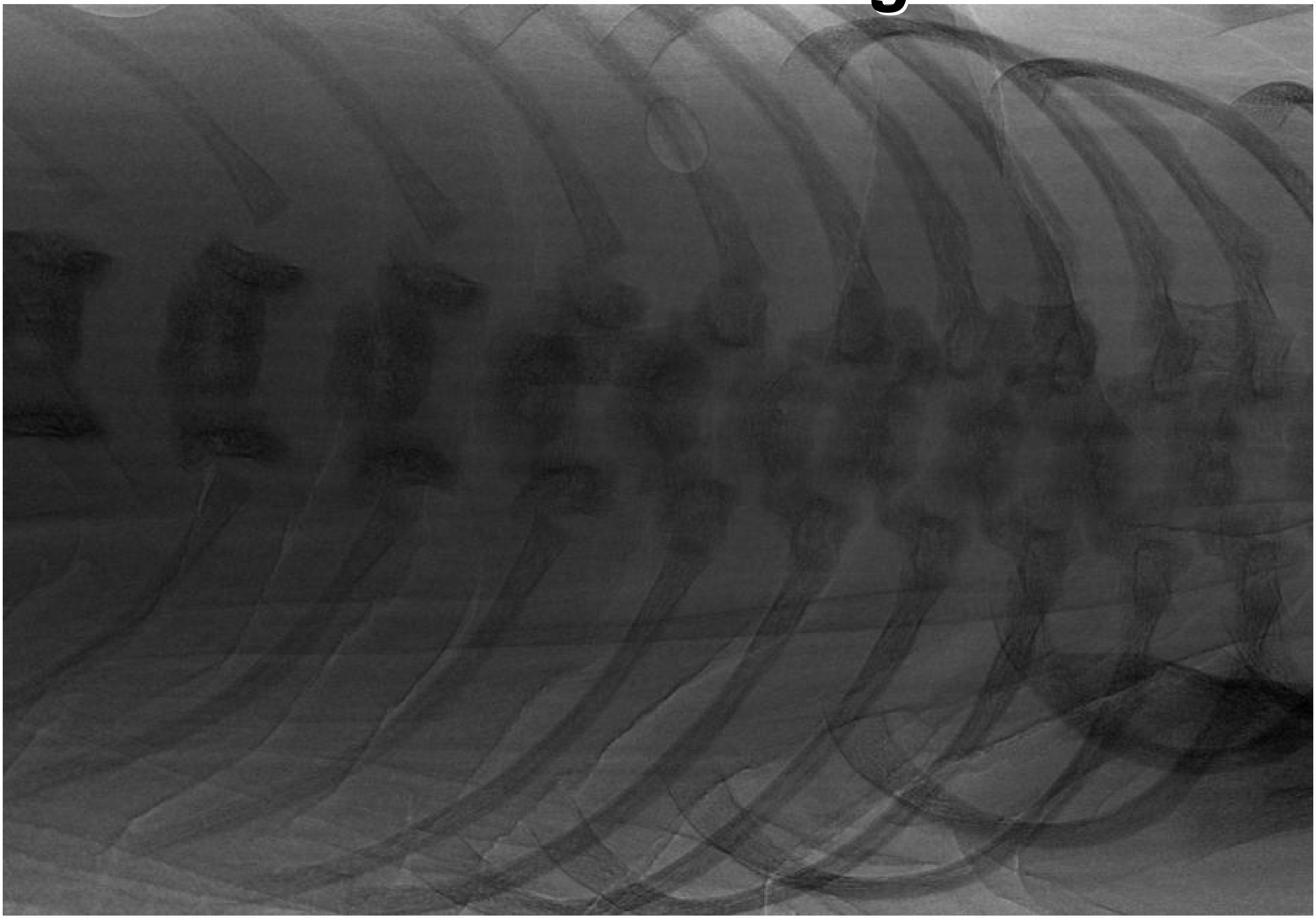


100 μm thick Si(1,-1,0) surface-cut designed for 25 keV X-ray beam.

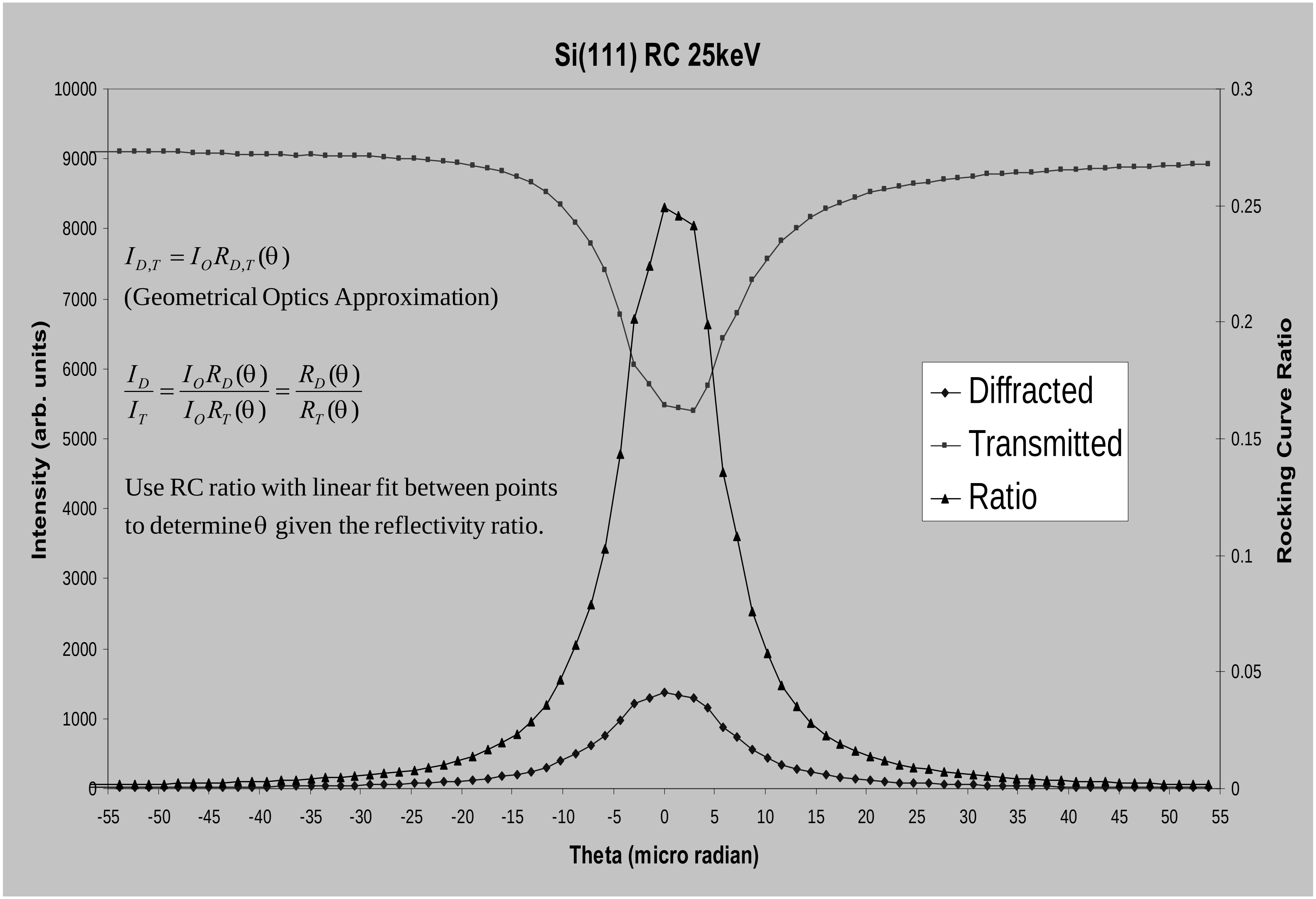
Diffracted Image - Corrected



Transmitted Image

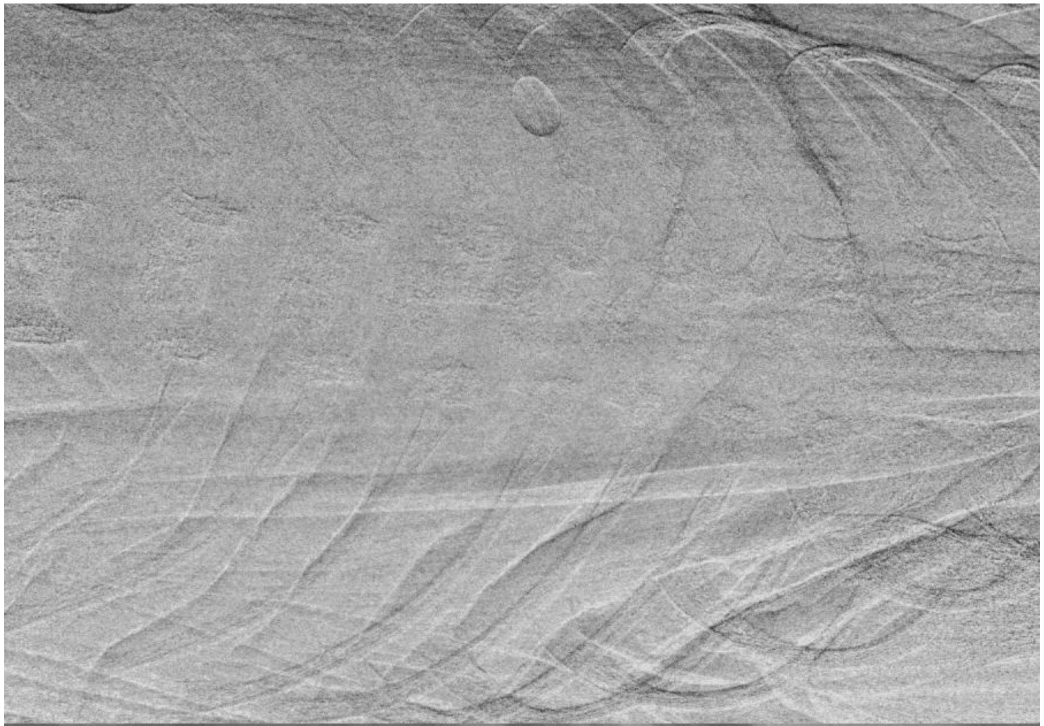


Rocking Curves and their Ratio

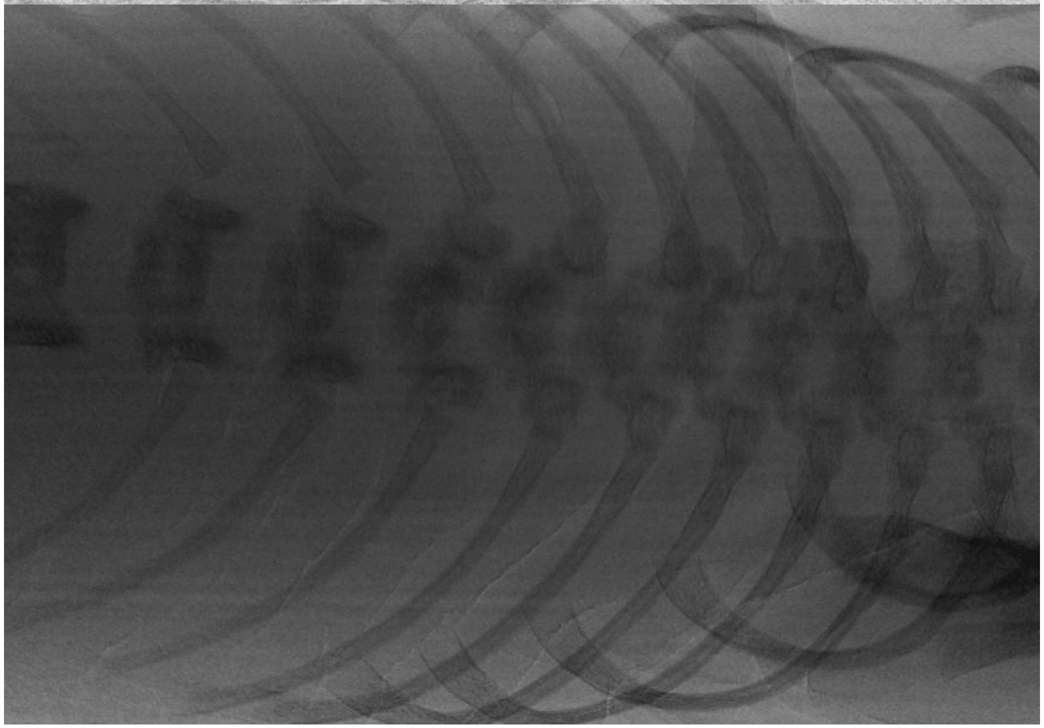


Exp=0.3 s, Int=2 s, 20 fps

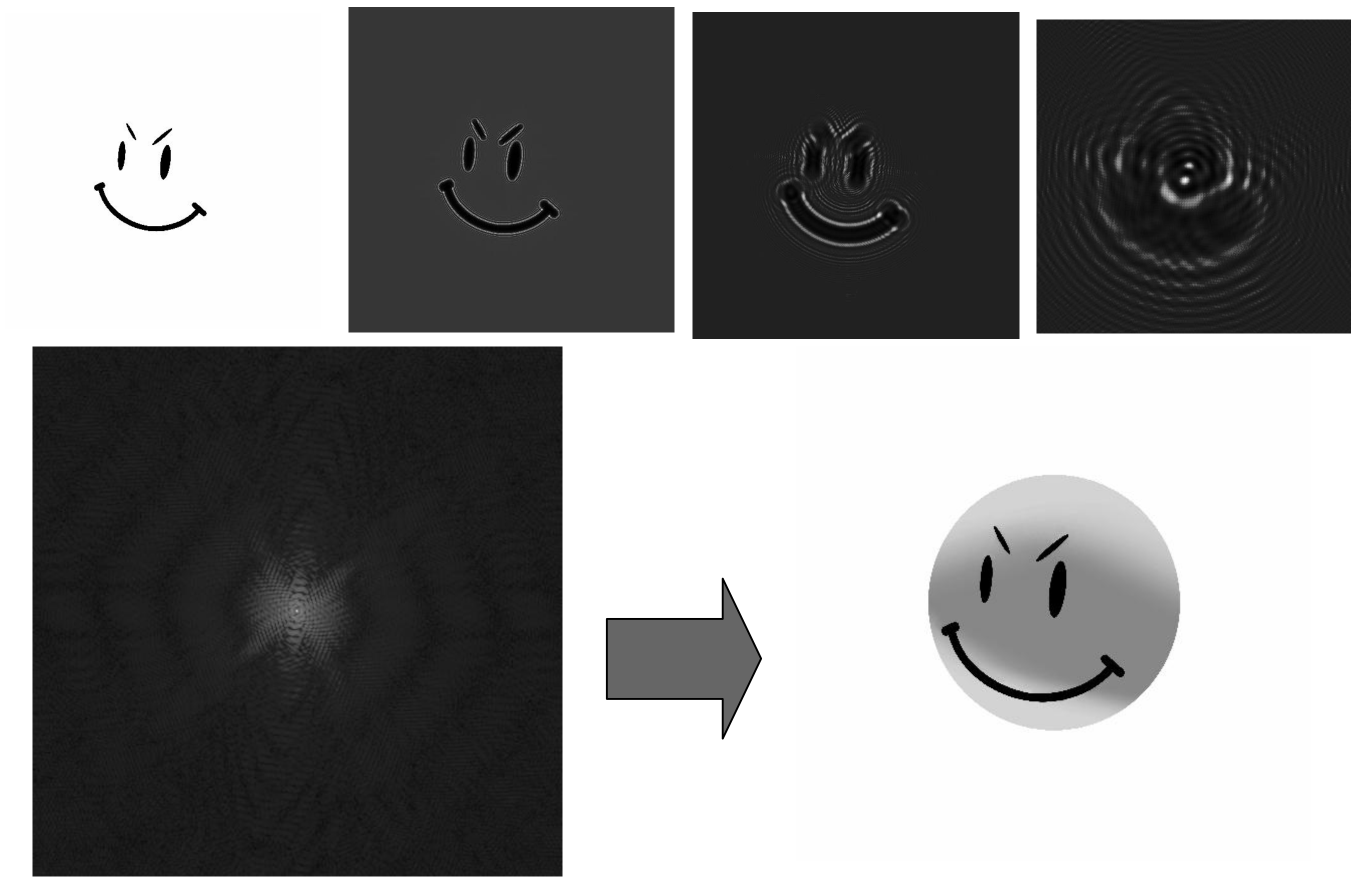
Refraction Angle Image



Apparent Absorption Image



Coherent X-ray Diffractive Imaging



See for example the work by J. Miao, K. Nugent et al

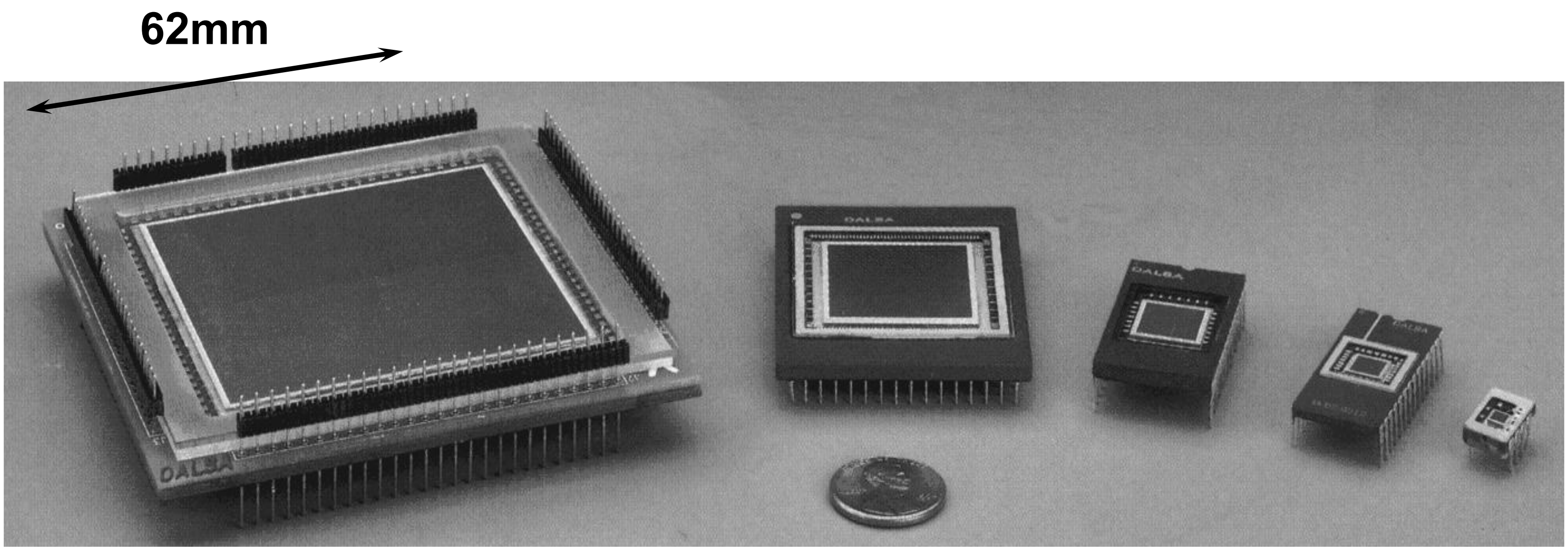
Detectors for SR Imaging

- Electronic imaging detectors
  - ï Direct conversion ï photons go straight to electrons.
  - ï Indirect conversion ï photons converted to other photons before converting to electrons.

Detectors for SR Imaging

- Analogue detectors
  - ï Films
  - ï Film-screen systems
  - ï Nuclear emulsions

CCDs



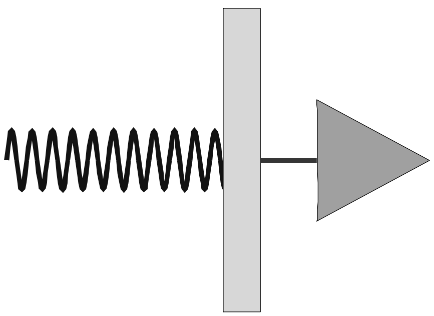
Although sizes > 50mm are available, the read speed is slow to preserve low noise and cte (line capacitance becomes very high)

Shutter required

CCD detectors

Direct detection

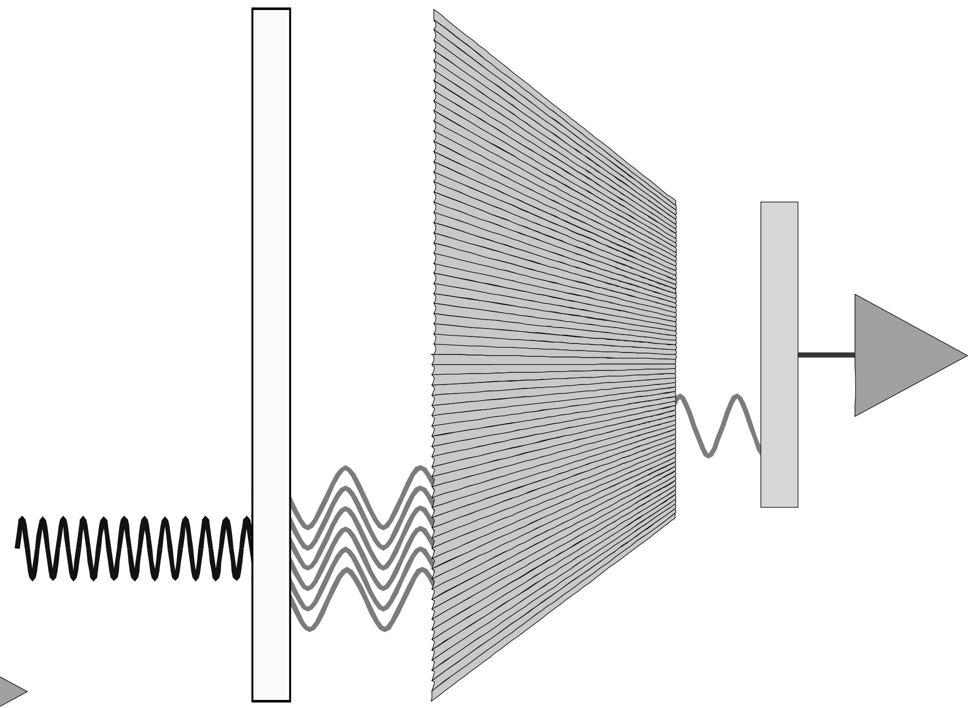
Gain ~ 2000e^- / 8keV x-ray



Phosphor coupled with reducing optics to CCD

Phosphor gain >> 1

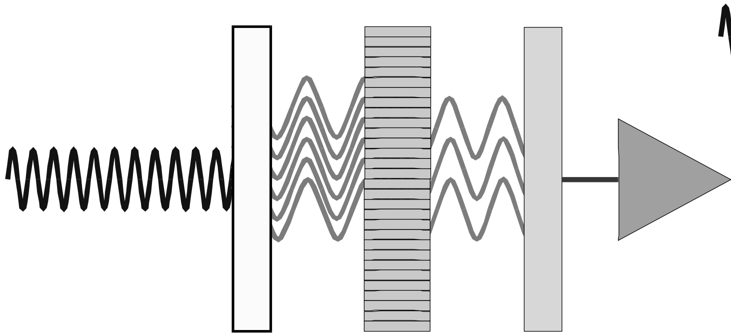
Optics Gain << 1



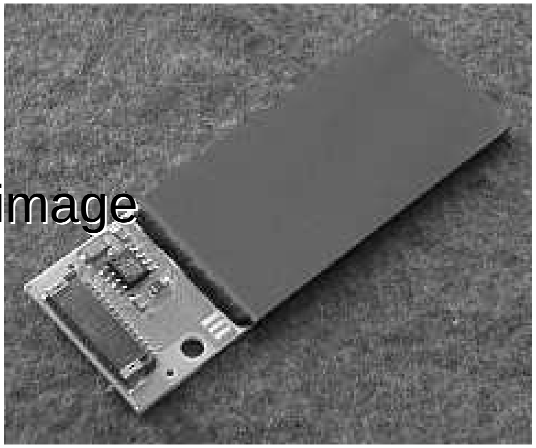
Phosphor coupled 1:1 to CCD

Phosphor gain >> 1

Optics Gain < 1



CMOS Imagers



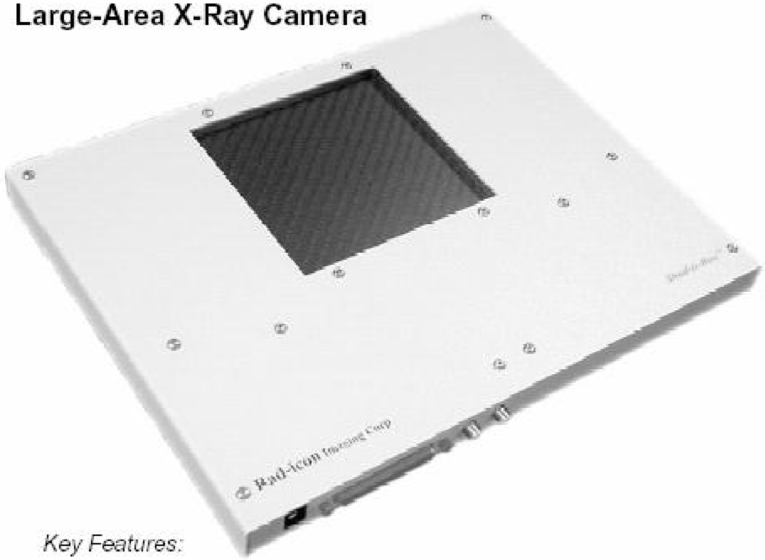
- Based on standard manufacturing technology
  - Electronics integrated onto same chip as image sensor
  - Gd_2O_2S - Kodak Lanex® Fine
- Rad Eye 1 from Radicon
  - 1024x512 48 micron pixels
  - 24.6 x 49.2 mm^2 active area
  - MTF good to 10 lp/mm
  - Tileable on 3 sides
  - Dark current ~4000e$^-$/s = 10 x CCD room temp
  - 10000:1 dynamic range
  - 4.5 frames/s
- Cheap

CMOS Imagers

Preliminary Data Sheet

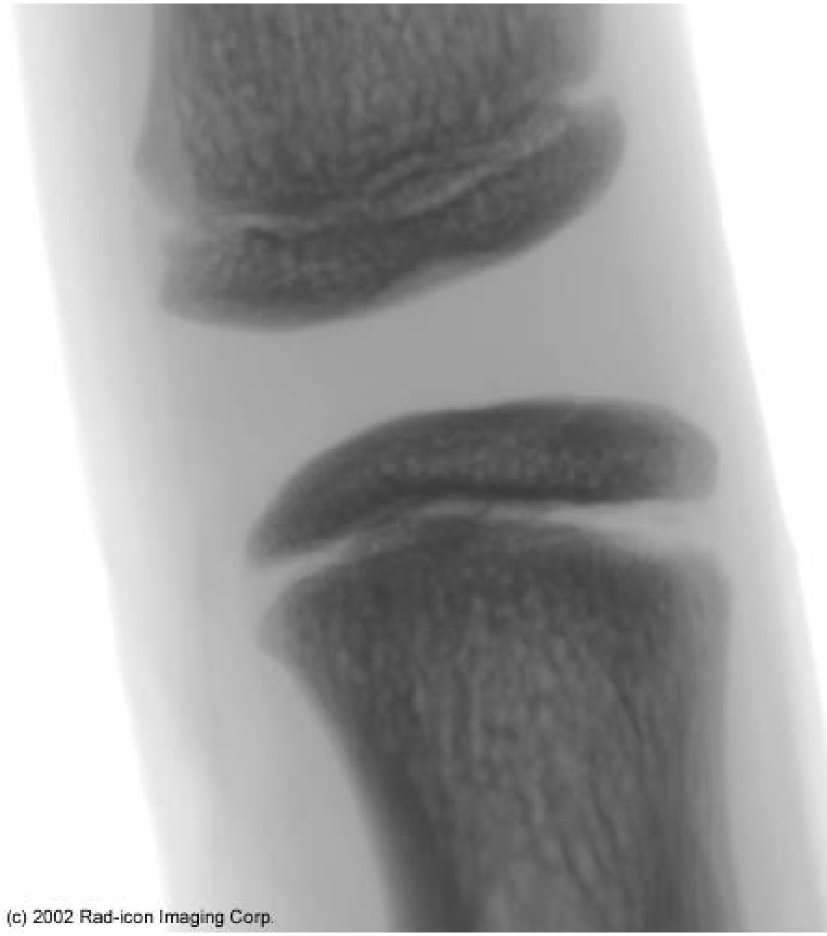
Shad-o-Box™ 4K

Large-Area X-Ray Camera



Key Features:

- Large active area of 10 x 10 cm
- 10 lp/mm (48 μm) resolution
- Over four million pixels
- 12-bit digital video output
- Thin, flat-panel form factor
- LVDS frame grabber interface with real-time video up to 2.7 fps
- Ready-to-run software and drivers



10 cm by 10 cm, 50 micron pixels

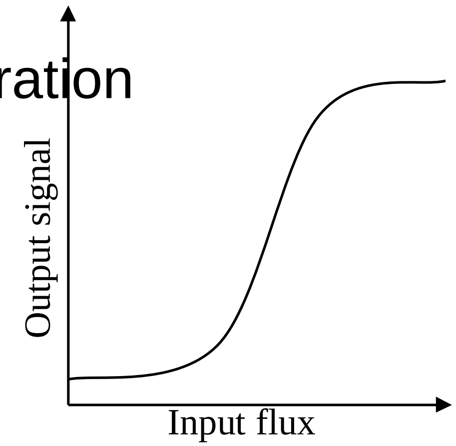
Rad-icon Imaging Corp
3193 Belick Street, Unit 1, Santa Clara, CA 95054

Detector Categories

Integrating

Measures deposited energy at end of integration period

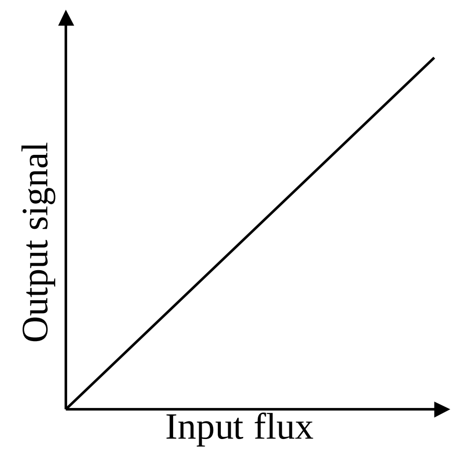
- ☑High input flux capability
- ☒Read noise dominates at low signal (ñfog levelò)
- ☒Dead time between frames
- ☒2×15 keV photons = 1×30keV photon
- Almost all medical imaging detectors



Photon Counting

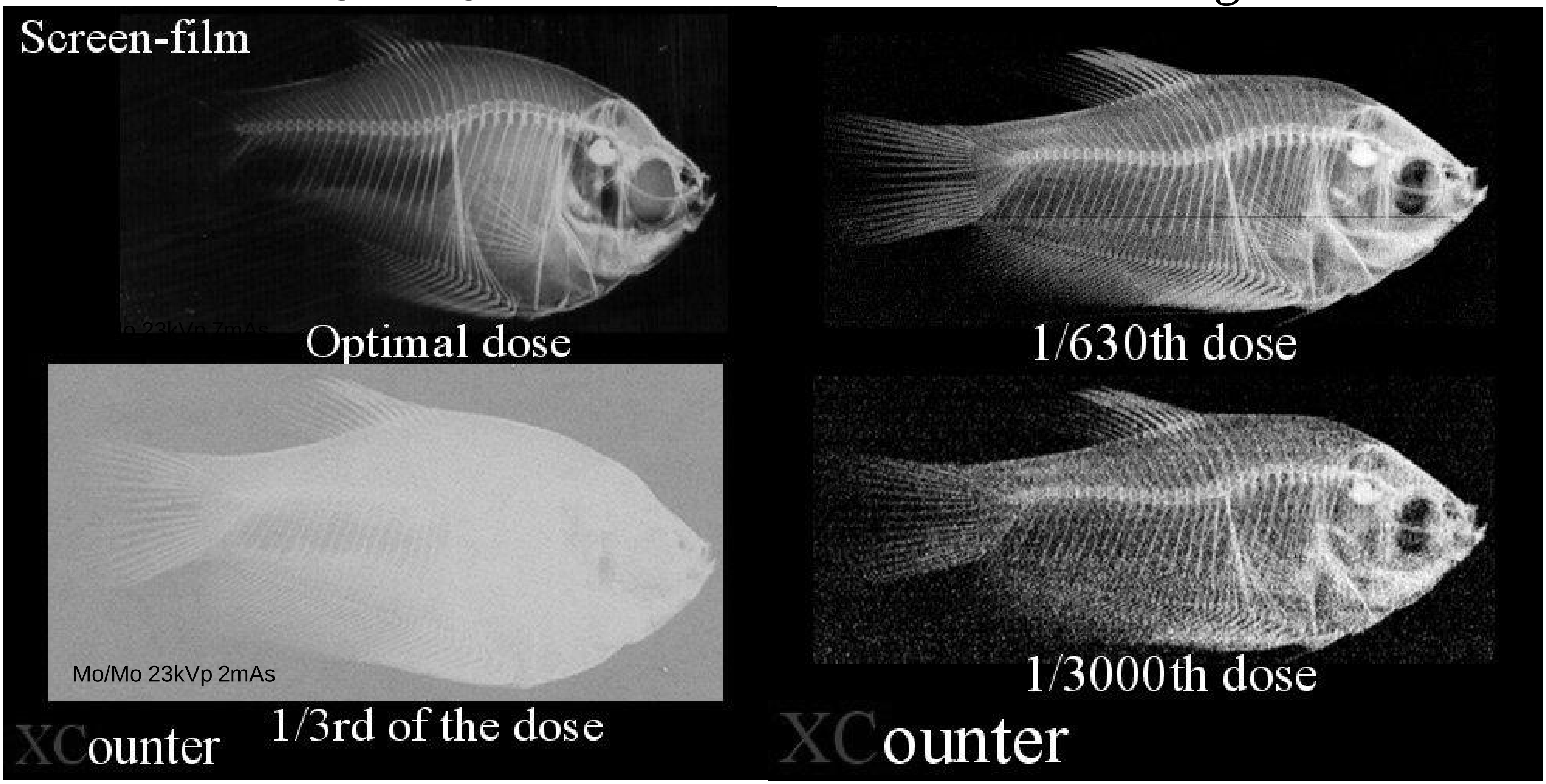
Detects every photon as it arrives

- ☑Quantum limited
- ☑No dead time between frames
- ☑Measures position and energy
- ☒Limited input flux capability
- Proportional counters, Scintillation counters



Integrating versus Counting

Integrating | Counting



Bottom image 0-10 phts/pix

Courtesy XCounter AB, Sweden

The End

'Why,' said the Dodo, 'the best way to explain it is to do it.'

Lewis Carroll