SESAME's UPGRADING NETWORK FOR
SCIENTIFIC USER TRAINING AND OUTREACH INTO THE NEXT ERA

X-ray radiography and tomography for cultural heritage

Alberto Bravin
[1]University of Milano-Bicocca
[2]University of Calabria, Italy
[3]INFN-Milano-Bicocca
[4]CNR-Nanotec, Italy

alberto.bravin@unimib.it

On-line Training meeting 16-4-2025

Outline

- Brief review of the radiation-matter interactions

- The image formation in radiography

- The key elements of the imaging setup: source & detection systems

- Imaging methods: absorption, dual energy, phase contrast

- From 2D to 3D: computed tomography

X-ray sources

X-ray sources

Synchrotron radiation

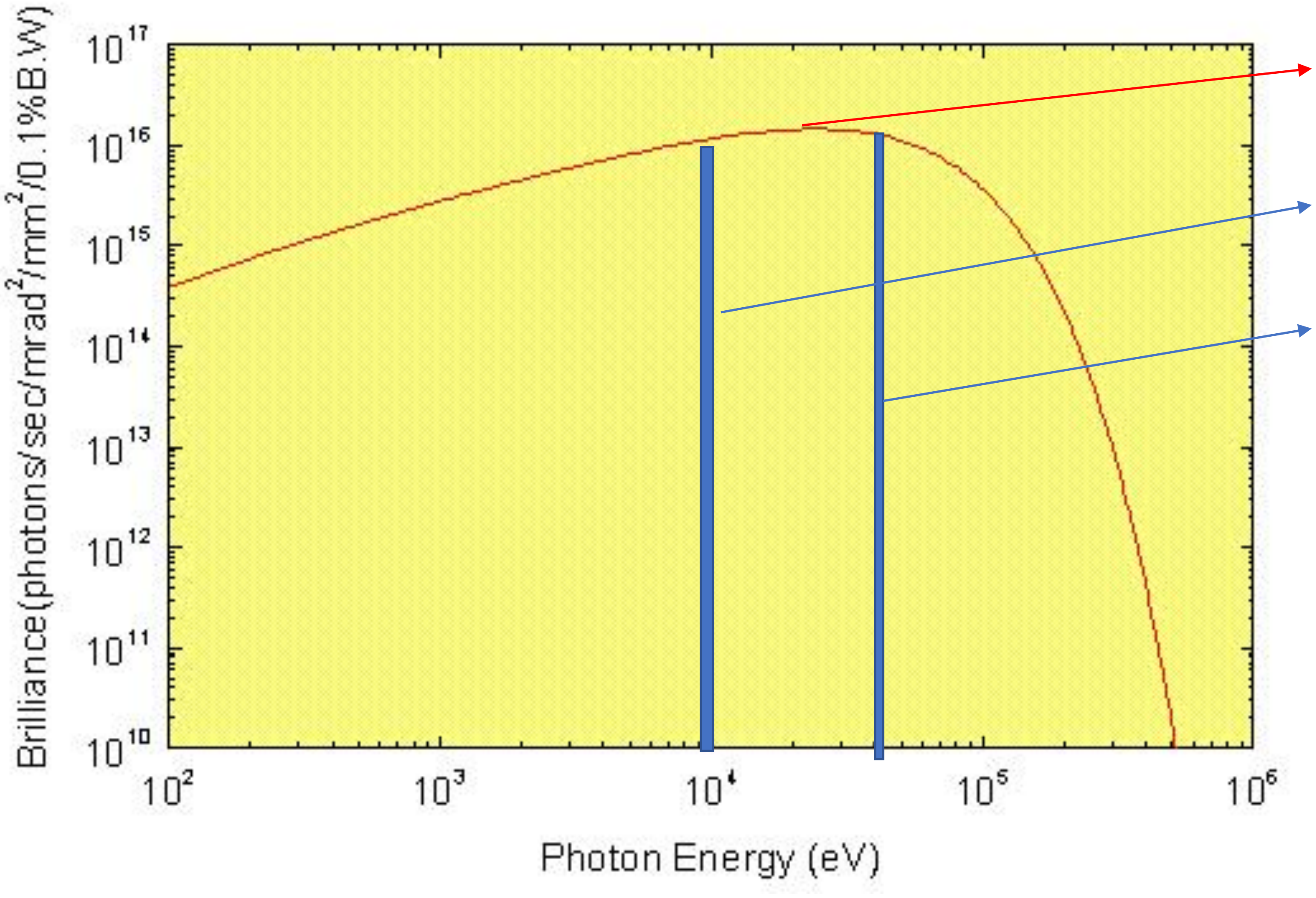
Electrons are accelerated in rings up to several GeV.
If electrons are compelled to move out of their orbit by deflecting magnets or "*wigglers*", "bending magnets", or "undulators" they emit an X-ray radiation named "synchrotron light".

From the beam of photons, monochromator crystals can select photons of well defined energy (usually from 5 to 100 keV).

The beam is very intense, which is orders of magnitude higher than that produced by X-ray tubes. This high flux allows for rapid data acquisition at very high spatial resolutions, resulting

Monochromatization permits an easier quantification of the elements in X-ray imaging and avoids image artefacts.

SR bending magnet and wiggler spectrum

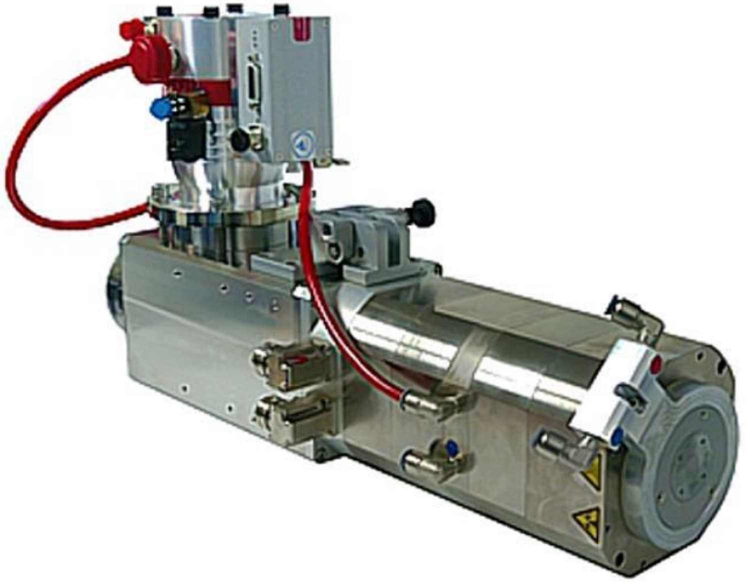


Fully available spectrum

Beam monochromatized by a crystal: very narrow bandwidth

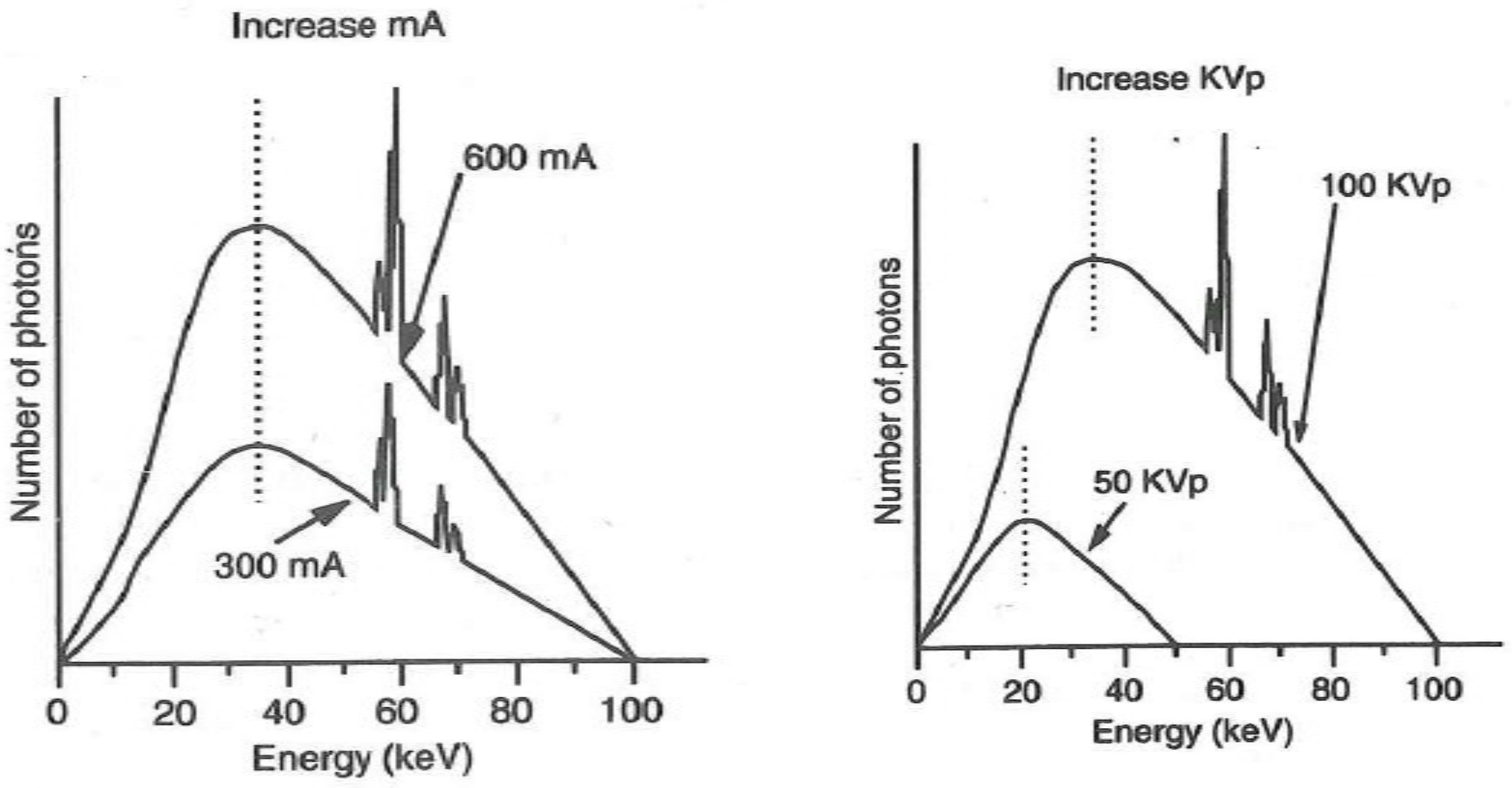
Microfocus and nanofocus

- Limited flux
- For having high spatial resolution and avoiding the “penumbra effect”, X-ray tubes must have a small focal spot.
- The tubes having a focal spot of the order of few microns (< 1 micron) are named microfocus (nanofocus)
- They can operate only at low current level (few µA)
- Operation voltage (X-ray energies) are around 5-30 kV (keV)



Morigi et al. Appl Phys A (2010) 100: 653–661

Conventional X-ray tubes: effect of varying I and kV_p



Conventional X-ray tubes cannot produce monochromatic radiation

Huda, Slone, Rev. Radiologic Physics IIEd.

Comparative summary of X-ray sources

Characteristic / Source	Synchrotron radiation sources (BM, wiggler, undulator)	Conventional X-ray tubes / linacs
Energy range	Up to 100 keV	5-250 keV
X-ray Intensity	maximum	5-10 orders of magnitude less
Longitudinal coherence (Monochromatization)	By crystals (BM, W), or 5-10% (U)	Broad spectrum
Spatial coherence (small source size + sample far)	Best possible (10-20 micron large source at 30-150 m)	5-30 micron source at 0.5 m
Availability	>50 sources, high competition	Laboratory

How is it an X-ray imaging setup made?

- A **radiation source**
- An equipment for moving (radiography-2D) or rotating (tomography 3D) the object or the source-detector system in order to acquire the digital radiographies at different angles, necessary to do the tomographic reconstruction
- A **detector** for digital images collection
- A computer for managing image acquisition
- A computer for image processing and rendering

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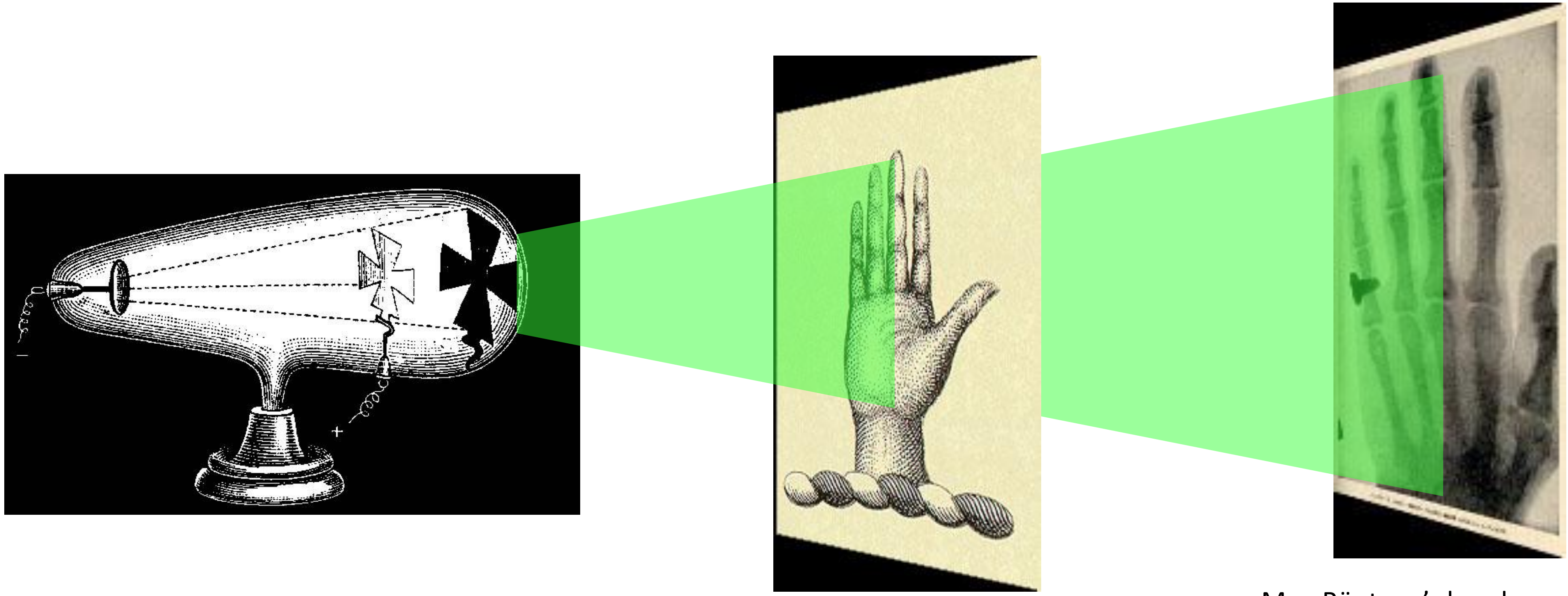
X-rays and Radiology

“X-rays are a non-destructive method for looking inside an object”

reveals INHOMOGENEITIES and SINGULARITIES in the sample

through the **interaction** of the used probe (i.e. X-rays) with the object



Mrs. Röntgen’s hand

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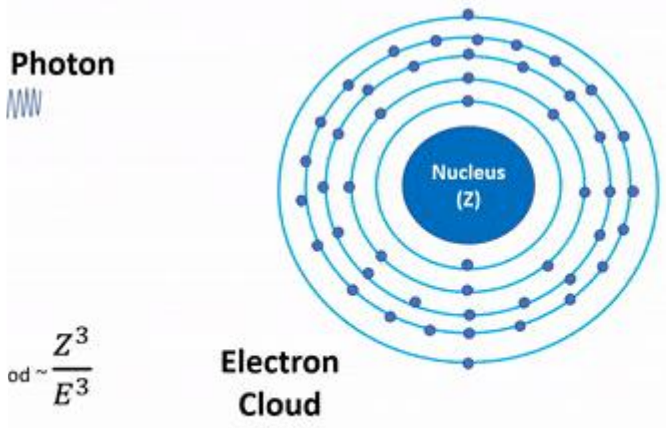
The interaction of X-rays with the sample

Short summary of X-ray interactions with matter

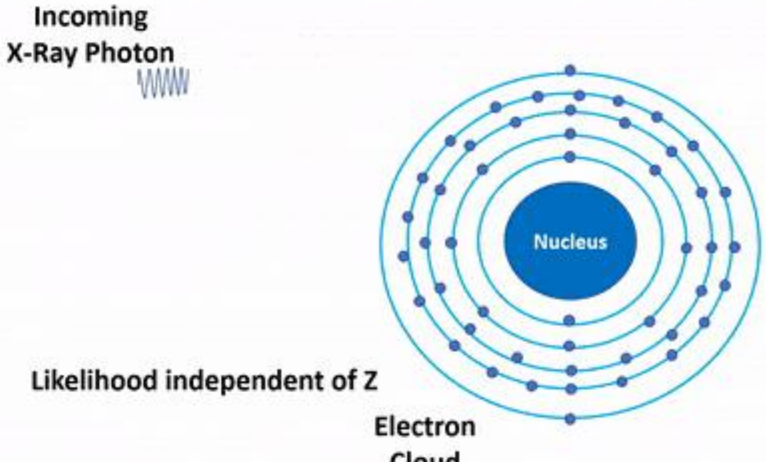
Photoelectric effect



The **photoelectric effect is the dominant contributor to the generation of signal in an x-ray image.**

The **x-ray is coming in and will be stopped and deposit its energy locally**. A lower energy photon is emitted (fluorescence photon) together with an electron.

Compton scattering

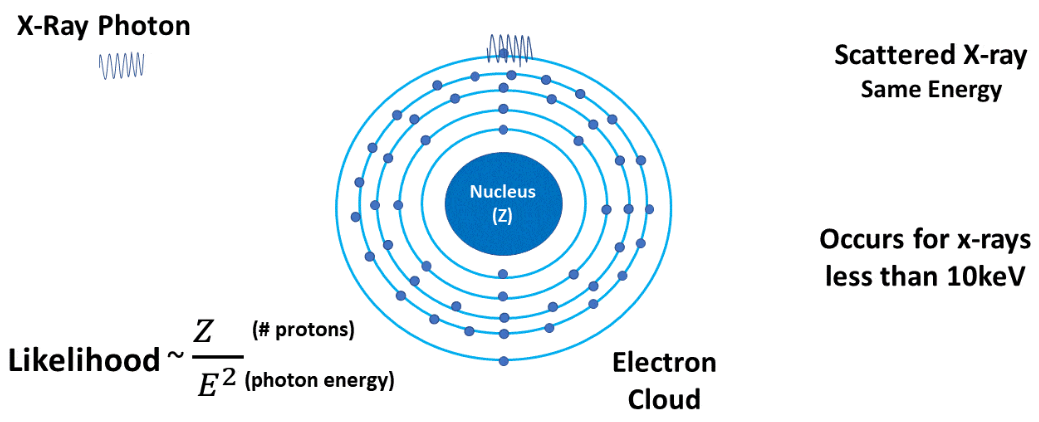


Compton Scattering is the second dominant effect in x-ray imaging.

The x-ray photon interacts with an electron in the outer shell. A lower energy photon is emitted and an electron.

https://howradiologyworks.com/x-ray-interactions/

Coherent (Rayleigh) scattering



In the range E=1-100 keV **the probability of this event is significant only at energies below 10 keV**.

Coherent happens when an X-ray photon interacts with electron cloud and goes out. The X-ray is scattered after this interaction but it has the same energy as it leaves.

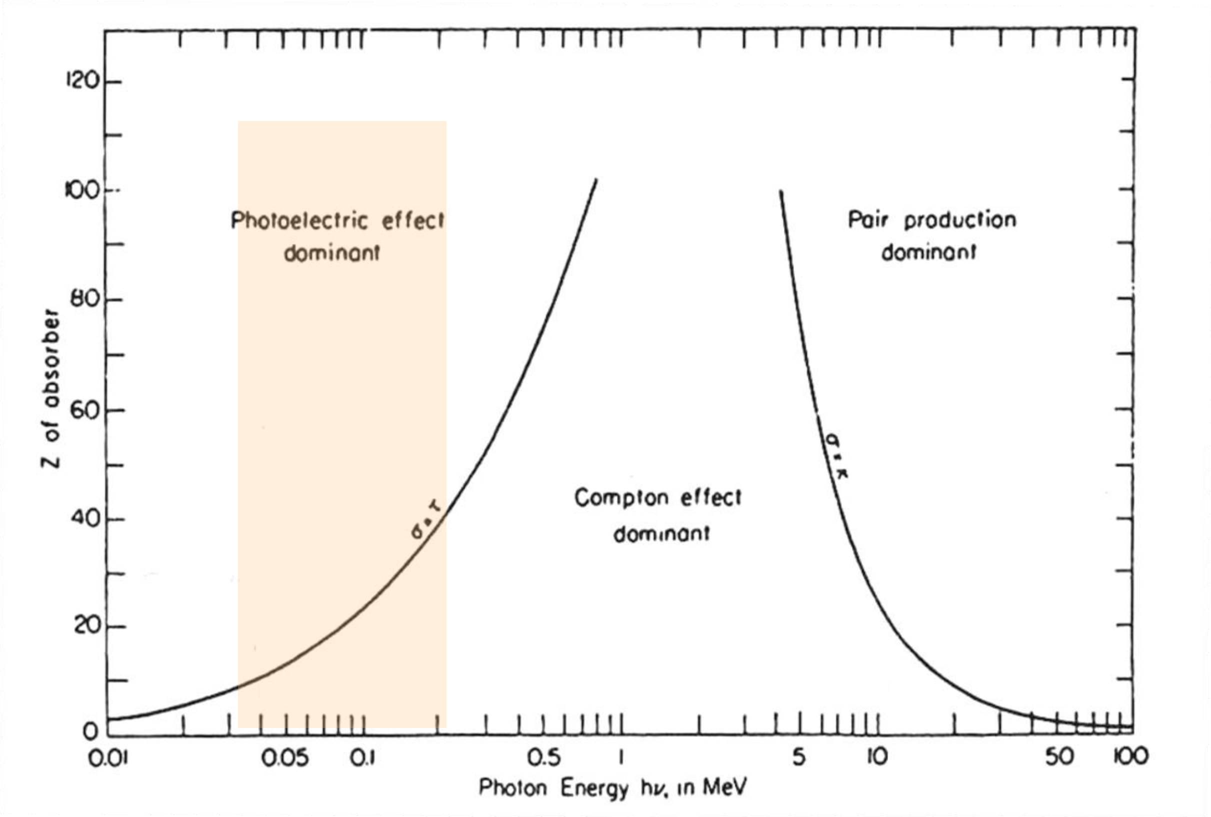
Couple production

It occurs **only for X-ray energies > 1.022 MeV**

Not relevant for SR imaging.

Relative contribution of the 3 major interactions

Z: Z of the atom, or Z effective for a compound



There are free large zones.

1) At low photon energy, AND low/medium/high Z target, photolectric effect prevails.

2) Compton prevails at low photon energies only for very low Z materials; or it prevails at larger energies, for Low/medium Z values.

3) Pair production prevails at energies $\geq$ 20 MeV

Summary of main X-ray-matter interactions in the energy range 10-100 keV

	Input	**Output**	**Energy/Dose deposition**	**How impacts images**	**Z dependence**	**Energy dependence**
Photoelectric	X-ray	- Electrons - Fluorescence radiation	YES: - Electrons - Fluorescence	Main image contrast source	Z^3 - Z^5	$1/E^3$
Compton scattering	X-ray	- X-ray at lower energy and different direction - Electron	YES: - Electron + secondary photon	The emitted X-ray contributes to image noise	Z	$1/E^2$
Coherent scattering	X-ray	X-ray of same energy at different direction	NO	The emitted X-ray contributes to image noise	Z - Z^2	$1/E^2$

How can I know what will happen to the X-rays incoming on my sample?

The interactions are probabilistic, NOT deterministic. So we can only determine the likelihood that one of these event occurs in a given sample thickness.

When passing through the sample, the same X-ray can undergo a **sequence of interactions** before exiting the sample: first Compton, then the emitted X-ray can undergo Coherent and finally disappear by photoelectric effect

The total probabilility of interaction of X-rays with the material is the sum of the probabilities of the 3 events in the sample. This is defined by the **total linear attenuation coefficient**.

$$\mu = \sum_i \mu_i = \tau + \sigma_{\mathrm{R}} + \sigma_{\mathrm{c}} + \kappa$$

τ = cross section photoelectric

σ_C = cross section for Compton

σ_R = cross section for Rayleigh

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Where do I find the linear attenuation coefficients for the materials in the public (official) databases ?

They report the **mass attenuation coefficient**, $\frac{\mu}{\rho}$ instead of the linear attenuation coefficient: μ

Atom characteristics are the same for water and ice, only density changes

Most useful databases

Attenuation coefficients:

https://www.nist.gov/pml/x-ray-mass-attenuation-coefficients

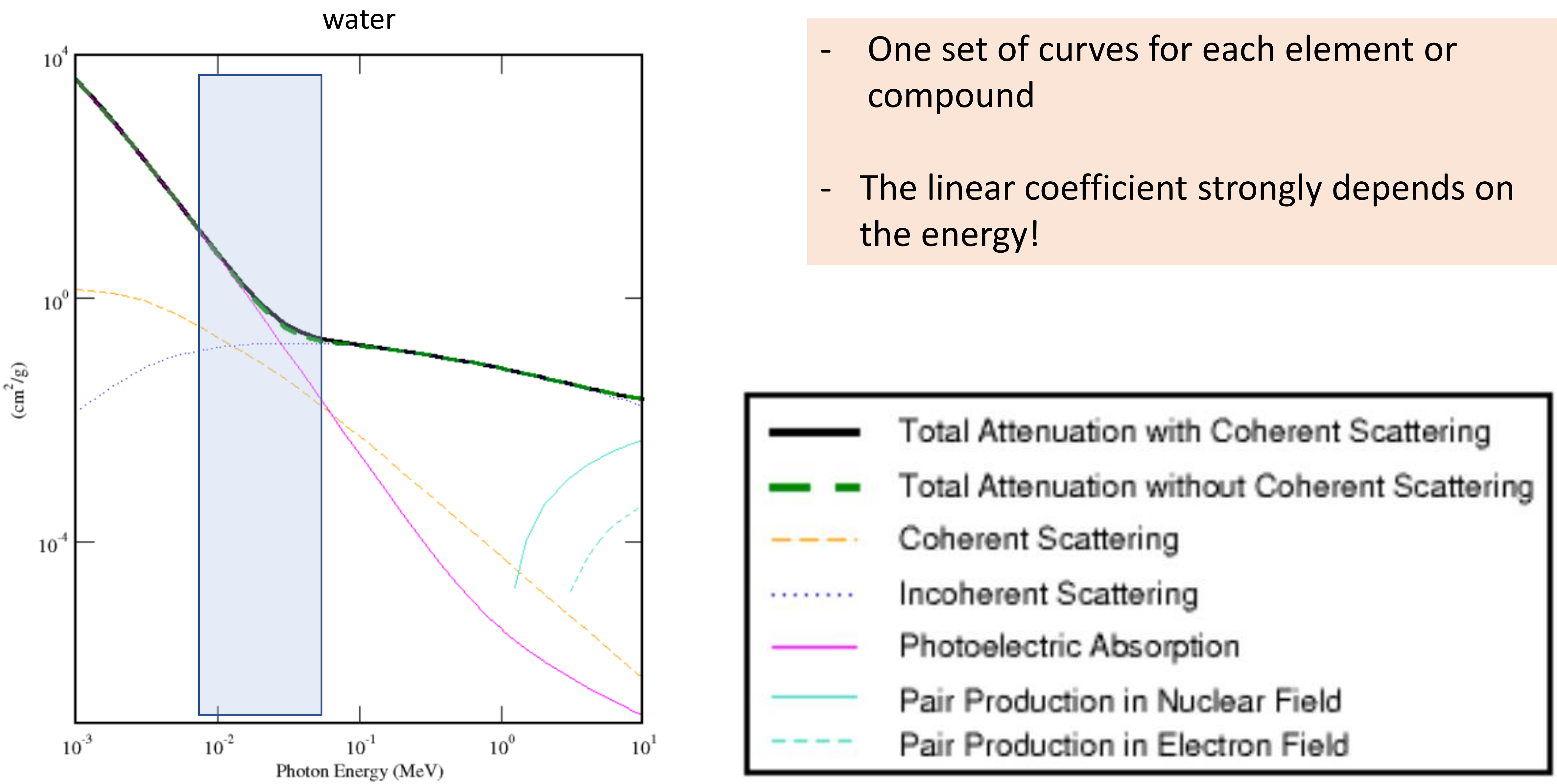
The other interactions:

https://physics.nist.gov/PhysRefData/Xcom/html/xcom1.html

Excitations, binding energies etc:

http://xdb.lbl.gov/

Energy-dependence of the mass absorption coefficient



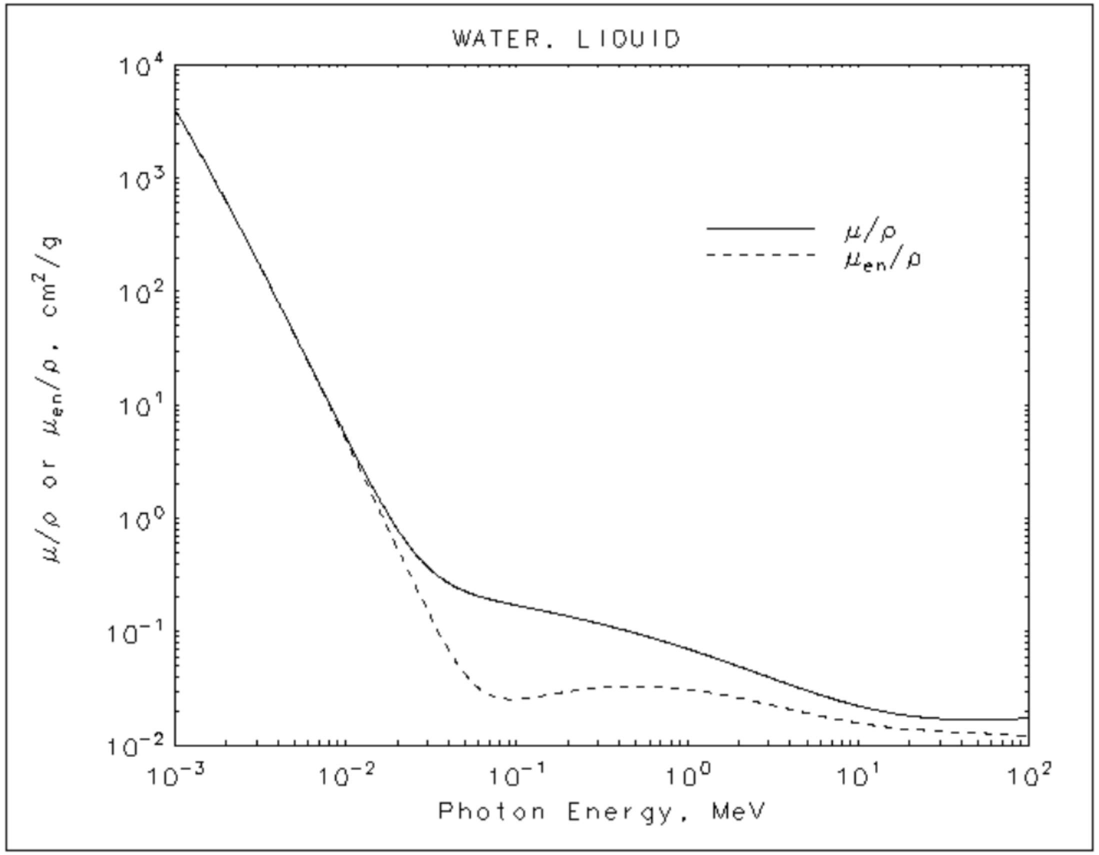
- One set of curves for each element or compound
- The linear coefficient strongly depends on the energy!

Database NIST

ICRU Report 44

https://physics.nist.gov/PhysRefData/XrayMassCoef/tab4.html

https://physics.nist.gov/PhysRefData/XrayMassCoef/ComTab/water.html



Water, Liquid
HTML table format

Energy (MeV)	μ/ρ (cm^2/g)	μ_{en}/ρ (cm^2/g)
1.00000E-03	4.078E+03	4.065E+03
1.50000E-03	1.376E+03	1.372E+03
2.00000E-03	6.173E+02	6.152E+02
3.00000E-03	1.929E+02	1.917E+02
4.00000E-03	8.278E+01	8.191E+01
5.00000E-03	4.258E+01	4.188E+01
6.00000E-03	2.464E+01	2.405E+01
8.00000E-03	1.037E+01	9.915E+00
1.00000E-02	5.329E+00	4.944E+00
1.50000E-02	1.673E+00	1.374E+00
2.00000E-02	8.096E-01	5.503E-01
3.00000E-02	3.756E-01	1.557E-01
4.00000E-02	2.683E-01	6.947E-02
5.00000E-02	2.269E-01	4.223E-02
6.00000E-02	2.059E-01	3.190E-02
8.00000E-02	1.837E-01	2.597E-02
1.00000E-01	1.707E-01	2.546E-02
1.50000E-01	1.505E-01	2.764E-02
2.00000E-01	1.370E-01	2.967E-02
3.00000E-01	1.186E-01	3.192E-02
4.00000E-01	1.061E-01	3.279E-02
5.00000E-01	9.687E-02	3.299E-02
6.00000E-01	8.956E-02	3.284E-02
8.00000E-01	7.865E-02	3.206E-02
1.00000E+00	7.072E-02	3.103E-02
1.25000E+00	6.323E-02	2.965E-02
1.50000E+00	5.754E-02	2.833E-02
2.00000E+00	4.942E-02	2.608E-02
3.00000E+00	3.969E-02	2.281E-02
4.00000E+00	3.403E-02	2.066E-02
5.00000E+00	3.031E-02	1.915E-02
6.00000E+00	2.770E-02	1.806E-02
8.00000E+00	2.429E-02	1.658E-02
1.00000E+01	2.219E-02	1.566E-02
1.50000E+01	1.941E-02	1.441E-02
2.00000E+01	1.813E-02	1.382E-02

Water, Liquid
ASCII format

Energy (MeV)	μ/ρ (cm^2/g)	μ_{en}/ρ (cm^2/g)
1.00000E-03	4.078E+03	4.065E+03
1.50000E-03	1.376E+03	1.372E+03
2.00000E-03	6.173E+02	6.152E+02
3.00000E-03	1.929E+02	1.917E+02
4.00000E-03	8.278E+01	8.191E+01
5.00000E-03	4.258E+01	4.188E+01
6.00000E-03	2.464E+01	2.405E+01
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4.00000E-02	2.683E-01	6.947E-02
5.00000E-02	2.269E-01	4.223E-02
6.00000E-02	2.059E-01	3.190E-02
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1.00000E-01	1.707E-01	2.546E-02
1.50000E-01	1.505E-01	2.764E-02
2.00000E-01	1.370E-01	2.967E-02
3.00000E-01	1.186E-01	3.192E-02
4.00000E-01	1.061E-01	3.279E-02
5.00000E-01	9.687E-02	3.299E-02
6.00000E-01	8.956E-02	3.284E-02
8.00000E-01	7.865E-02	3.206E-02
1.00000E+00	7.072E-02	3.103E-02
1.25000E+00	6.323E-02	2.965E-02
1.50000E+00	5.754E-02	2.833E-02
2.00000E+00	4.942E-02	2.608E-02
3.00000E+00	3.969E-02	2.281E-02
4.00000E+00	3.403E-02	2.066E-02
5.00000E+00	3.031E-02	1.915E-02
6.00000E+00	2.770E-02	1.806E-02
8.00000E+00	2.429E-02	1.658E-02
1.00000E+01	2.219E-02	1.566E-02
1.50000E+01	1.941E-02	1.441E-02
2.00000E+01	1.813E-02	1.382E-02

The image formation in radiography

How many photons will I have after the sample reaching the detector?

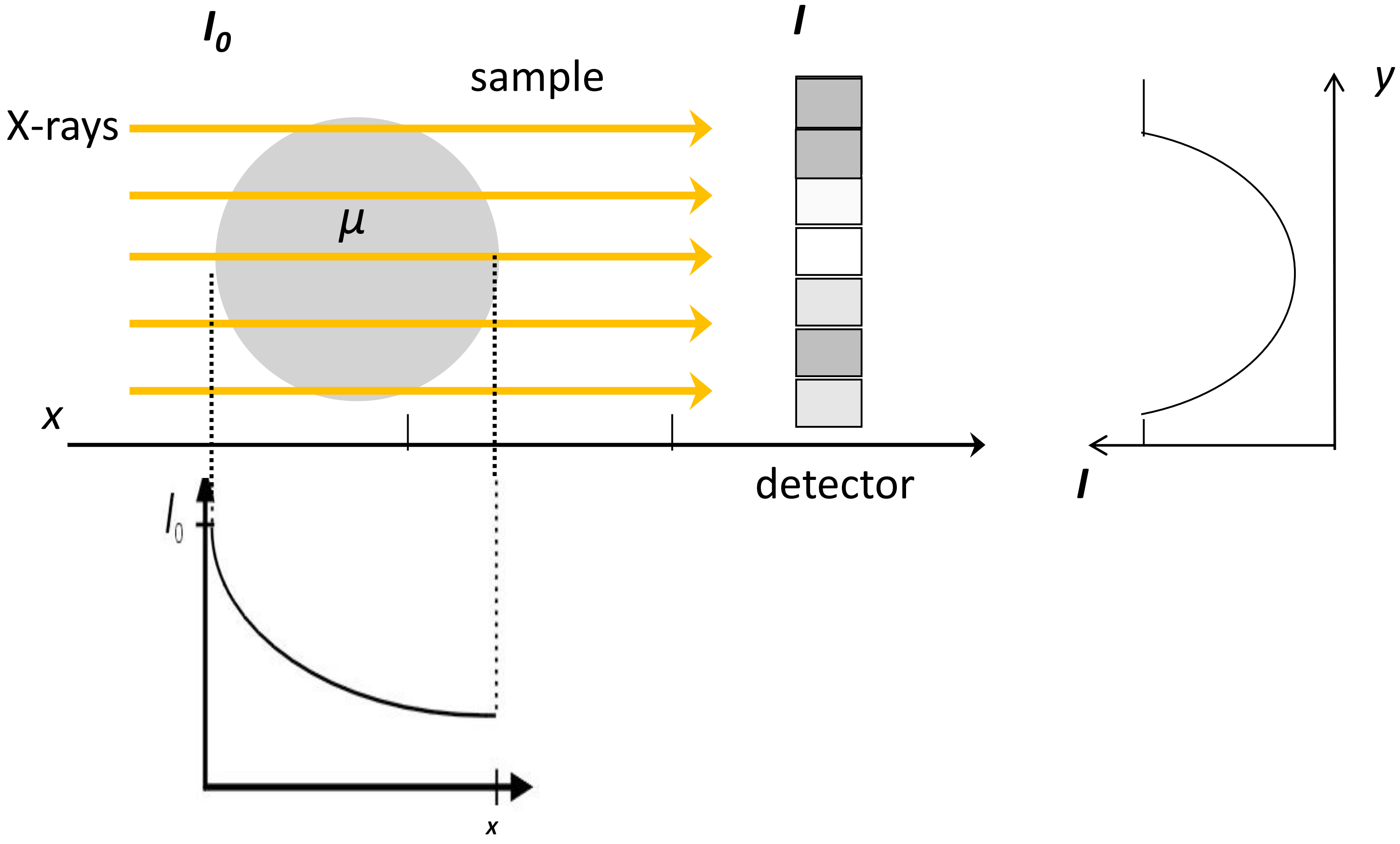
Let's consider the case of monoenergetic X-rays:

- **INTENSITY downstream the sample:**

$$I = I_0 \exp(-\mu x)$$

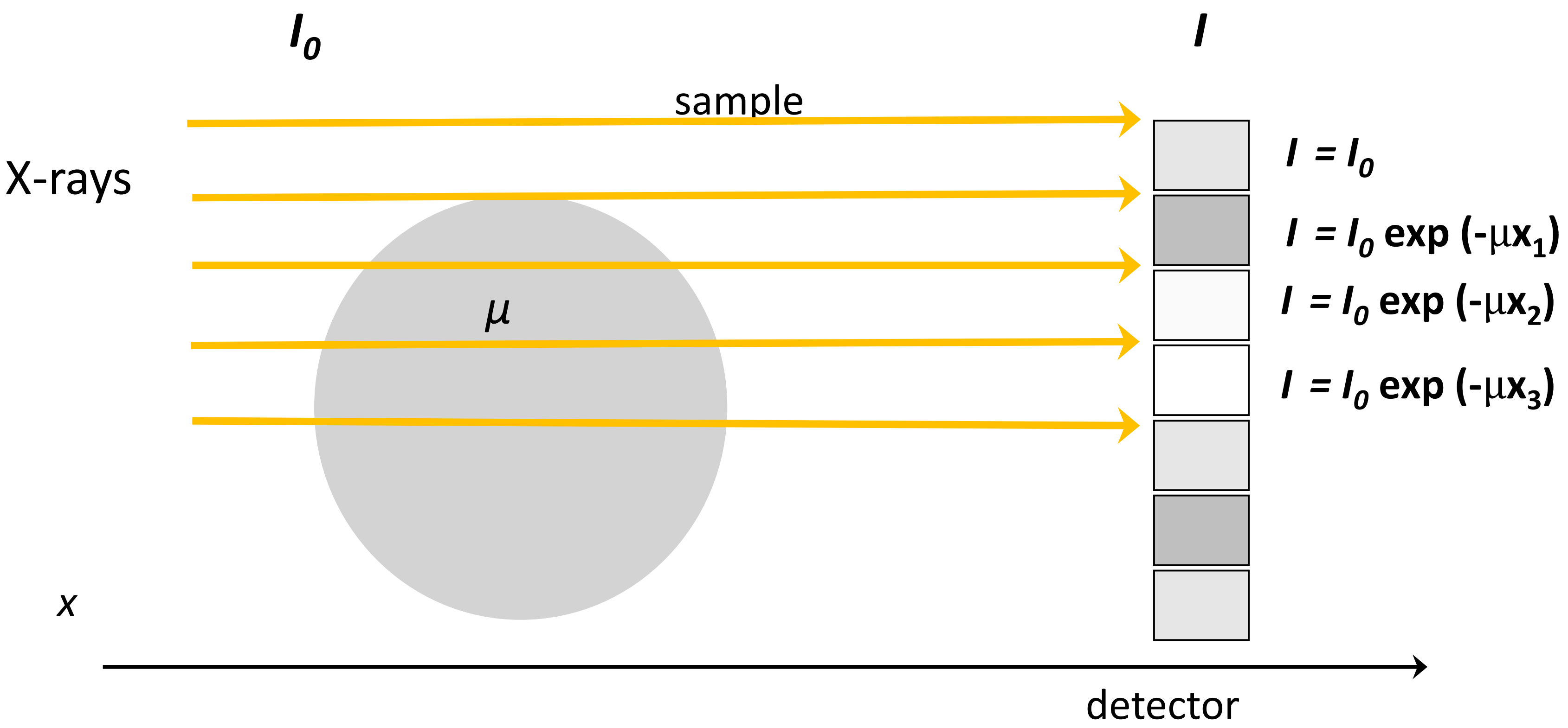
$$I = I_0 \exp\left(-\frac{\mu}{\rho} \rho\, x\right)$$

The Lambert-Beer's law



μ = total X-ray attenuation coefficient
for a given material and at the given energy

A radiography: a map of the transmission of the X-rays through the sample



To each value on the detector is assigned a gray scale:

From **0 to 1023** if the detector has 10 bits
From **0 to 16383** if the detector has 14 bits
From **0 to 65535** if the detector has 16 bits

A radiography: a map of the transmission of the X-rays through the sample

Let's suppose that the X-ray detector has 16 bits (0-65535)

If I send > 65535 photons to the detector, then the image will be **saturated**

Warning!

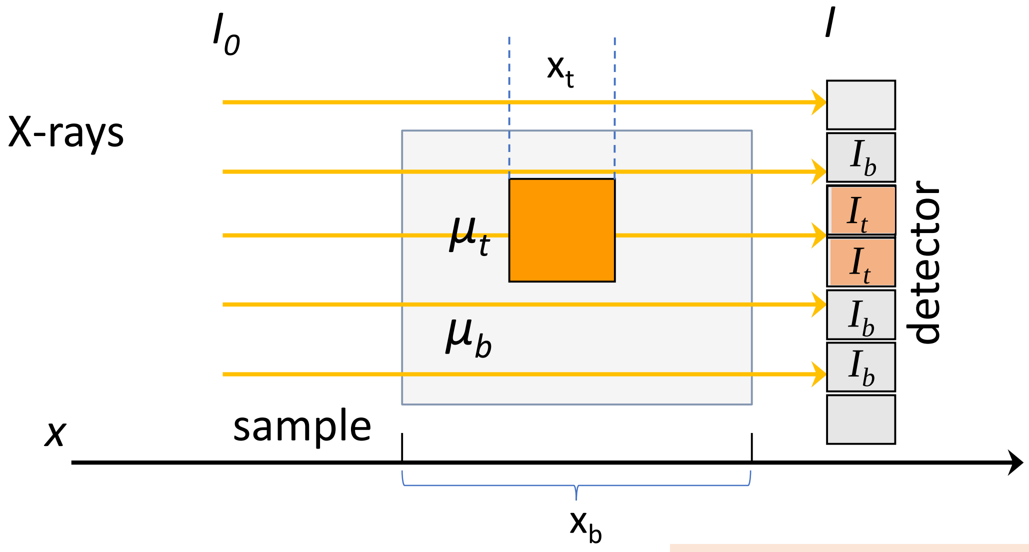
Most of the detector have an **unrealiable behaviour** (non-linear response) **already before saturation**. It is therefore important to know (ask) which is the maximum number of X-rays that the detector can convert linearly in gray-scale

Image contrast (ideal case)

μ = X-rays attenuation coefficient for a given material

b: background

t: tumour



- **INTENSITY on the detector:**

$$I_b = I_0 \exp(-\mu_b x_b)$$ *Lambert-Beer's law*

(monoenergetic case)

$$I_t = I_0 \exp(-\mu_b (x_b - x_t)) \exp(-\mu_t x_t)$$

CONTRAST: $C = \frac{I_b - I_t}{I_b} =$ #

Image contrast is the difference in between the intensity values in different parts of the image that enables to distinguish different tissue types

$$= \frac{I_0 \exp(-\mu_b x_b) - I_0 \exp\left(-\mu_b (x_b - x_t)\right) \exp(-\mu_t x_t)}{I_0 \exp(-\mu_b x_b)} = 1 - \exp\left(-x_t(\mu_t - \mu_b)\right) = 1 - \exp(-x_t \Delta\mu)$$

C increases exponentially with either x (thickness) and Δμ

this is one of the definitions of contrast present in the literature

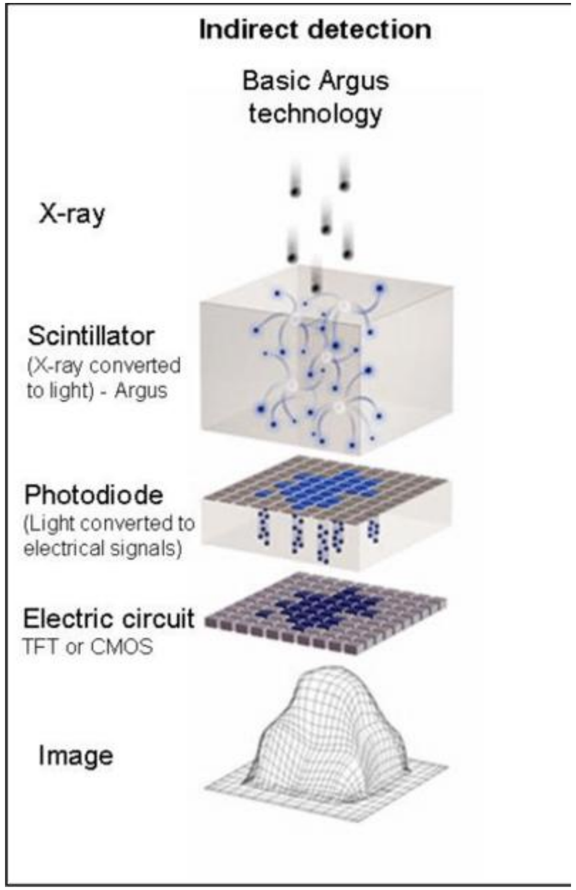
Detectors: indirect (X-ray) conversion

- X-rays are transformed into visible light by an X-ray **scintillator**.

- The visible light is then transmitted to a **photodiode** (flat panels) or a **CCD detector** or a **CMOS detector**, both very similar to those used in phone cameras or video cameras.

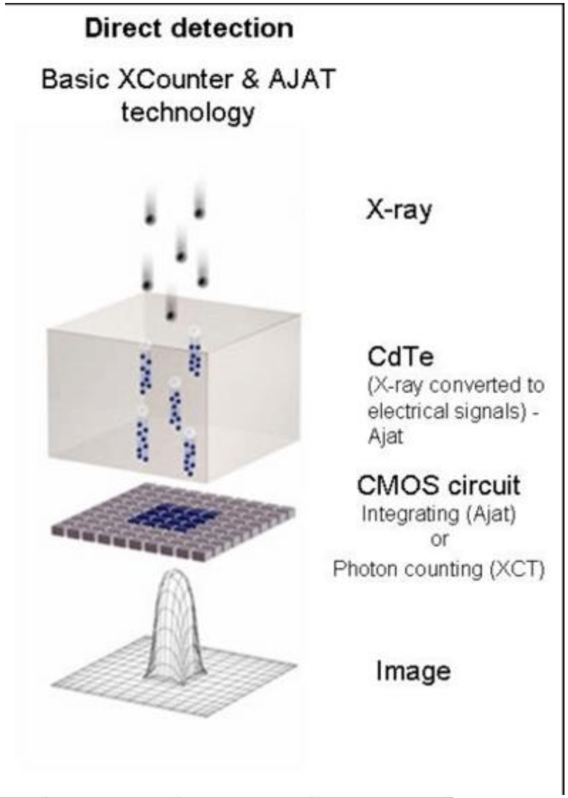
- The photodiodes, CCDs and CMOS transform the visible light signal in electron/holes in the semiconductors, which are polarized; this signal is finally **transformed into a voltage difference** or current and finally **digitalized** in bits.

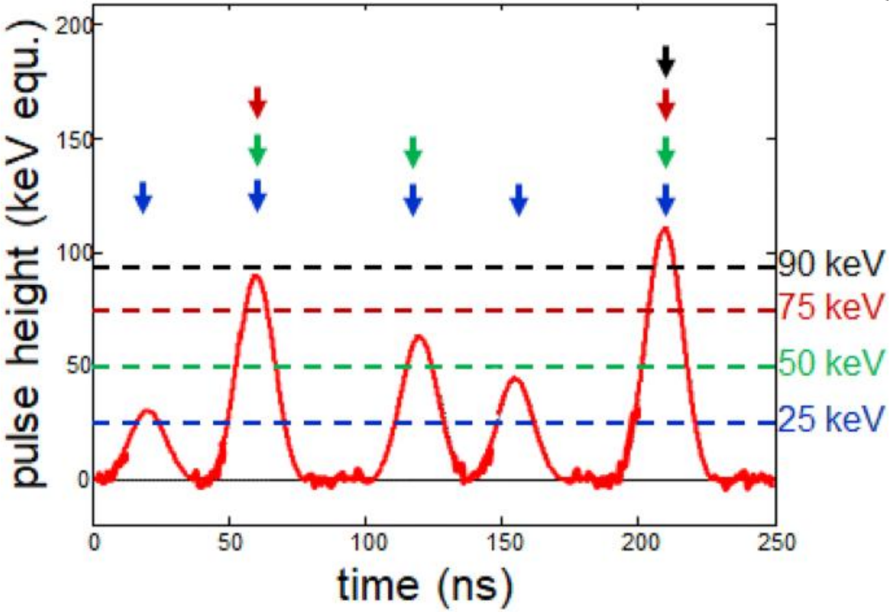
- Scintillators can be **structured** (they channel light) for higher resolution imaging, or **unstructured (**for higher efficient dose imaging)



Detectors: direct (X-ray) conversion

- **Each photon that hits the detector element generates an electrical pulse**
- **The pulse height is proportional to the energy deposited by the photon.**
- The electronics system of the detector counts the number of pulses with heights that exceed the preset threshold level.
- **Substantial reduction of image noise** (virtually zero electronic noise)
- **Increase of the spatial resolution** (except at the borders between two pixels, all signal is recorded in a single pixel).
- Allows to **reduce the radiation dose**



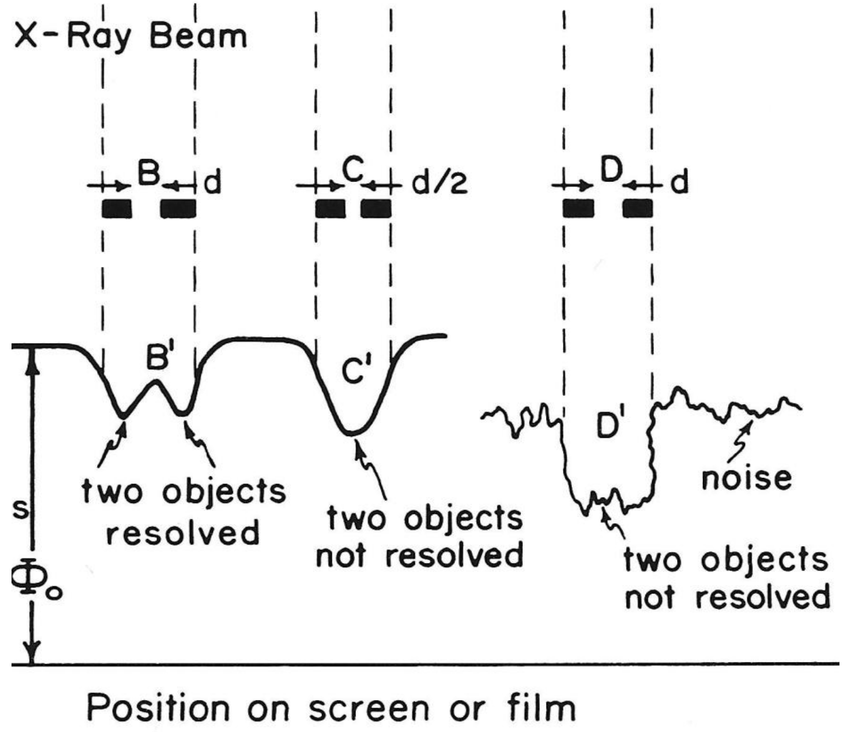


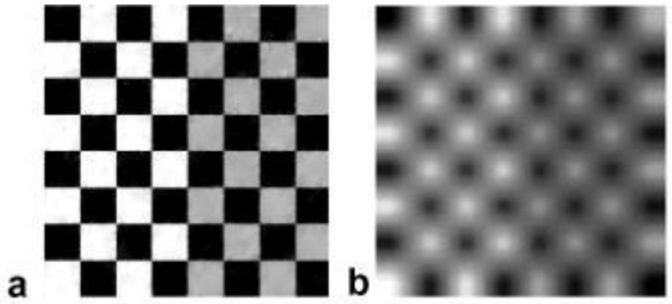
https://pubs.rsna.org/doi/full/10.1148/radiol.2018172656

The spatial resolution of the detection system

Spatial resolution

Is the ability of an imaging system to resolve two adjacent high-contrast objects as discrete entities





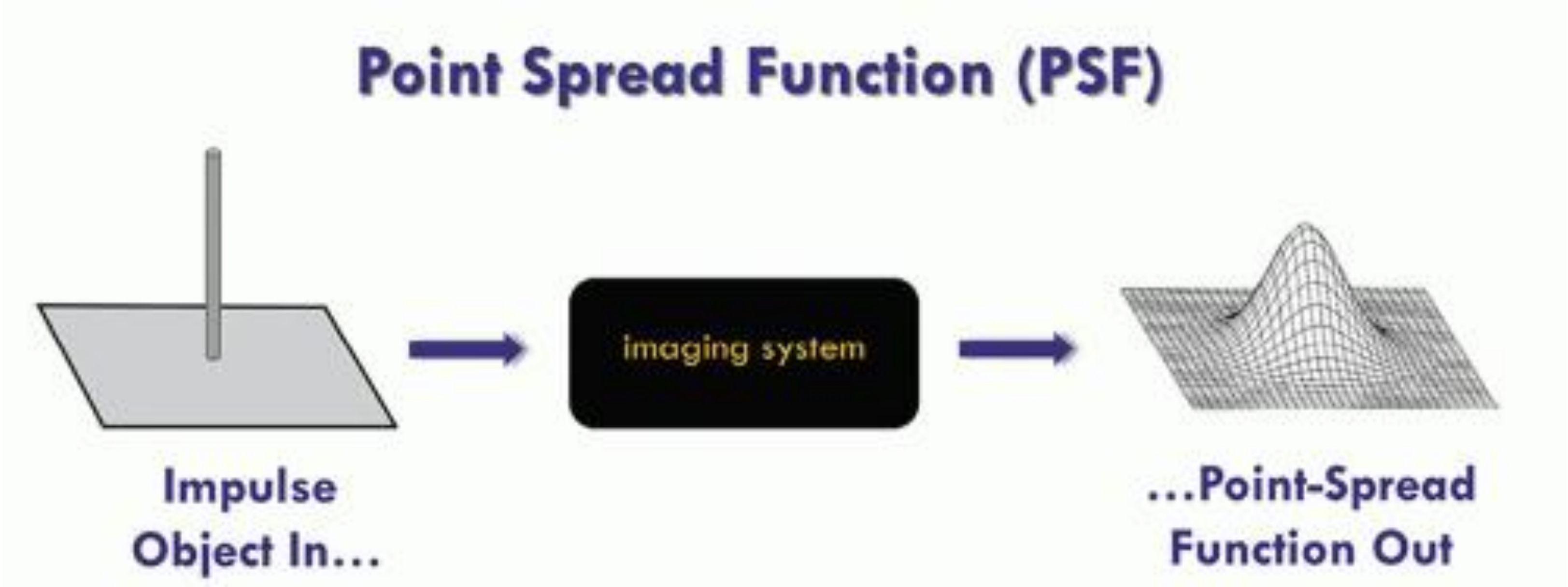
no blurred   blurred

- Spatial resolution can be described also in terms of ***BLUR***

Physics of Radiology, Johns, Cunningham
Saadi, Microprocessors and Microsystems Volume 37, Issue 1, 52–64

- An ideal infinitely thin signal («one ray of light») from an object is spread over more than one pixel due to the transfer function of the optical system. This transfer function is called **Point Spread Function** (PSF).

- When a real sample is imaged, the optical system spreads out the signal, in the same way as the system does for an infinitely thin sample.



https://radiologykey.com/image-quality-3/

- **The narrower the PSF is, the better the detector system reproduces the reality (higher spatial resolution)**

The PSF along a given direction is called **Line Spread Function (LSF)**

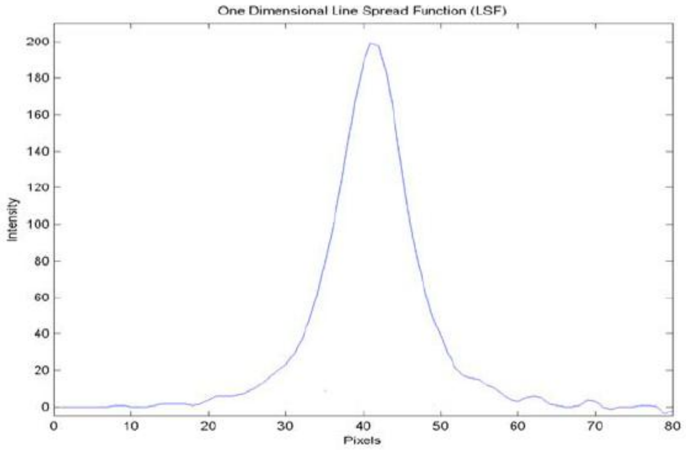
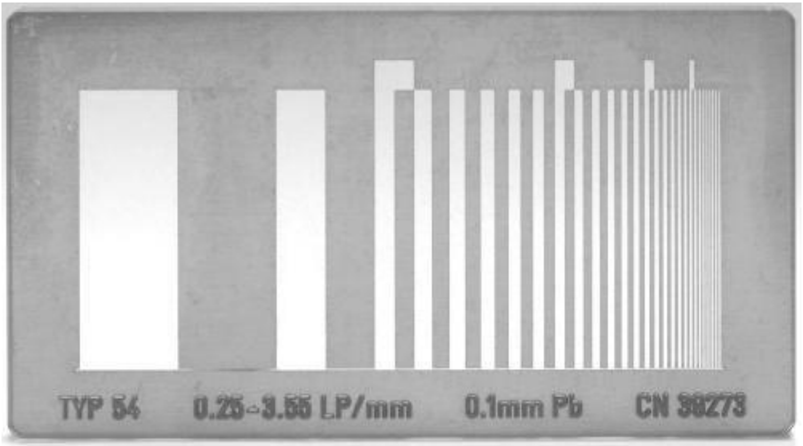


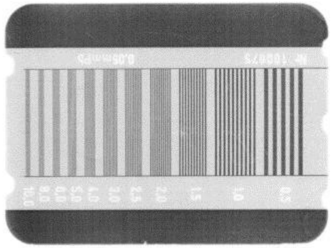
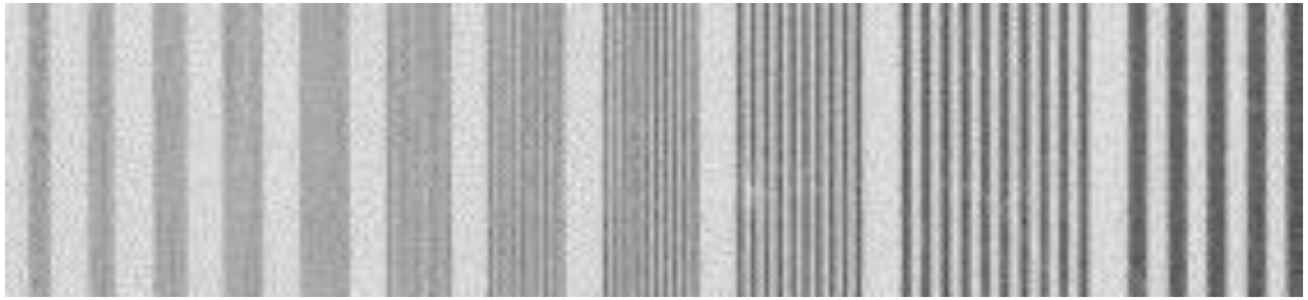
Image from: DOI: 10.1117/12.602124

How to measure the spatial resolution of an imaging system?

To measure the two LSFs, we can use a set of lines, of different spacing, typically made of lead.



How to measure the spatial resolution of an imaging system?

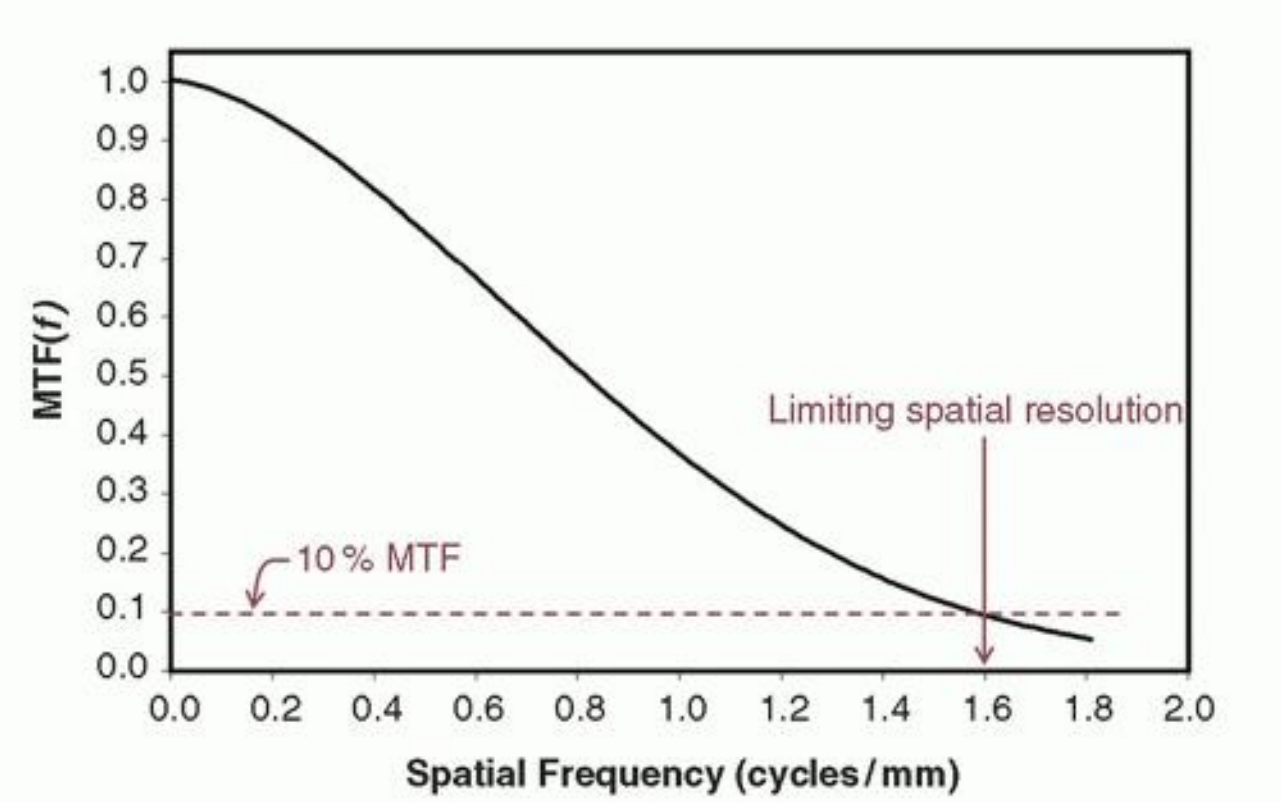
$S($  $) =$ 

- Resolution units is **line pairs per millimeter (lp/mm)**

1 line = 1 opaque line + 1 radiolucent space

1 lp/mm = 0.5 mm lead bars separated by 0.5 mm of radiolucent material
2 lp/mm = 0.25 mm lead bars separated by 0.25 mm of radiolucent material

The spatial resolution is represented by the Modulation Transfer Function



$$MTF = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

- The **limiting spatial resolution** is the max number of lp/mm that can be recorded by the imaging system
- Human eye → max 30 lp/mm on close inspection (0.5 lp/mm at 25 cm dist.)
- Film have high spatial resolution: ex. Mammography 15-20 lp/mm

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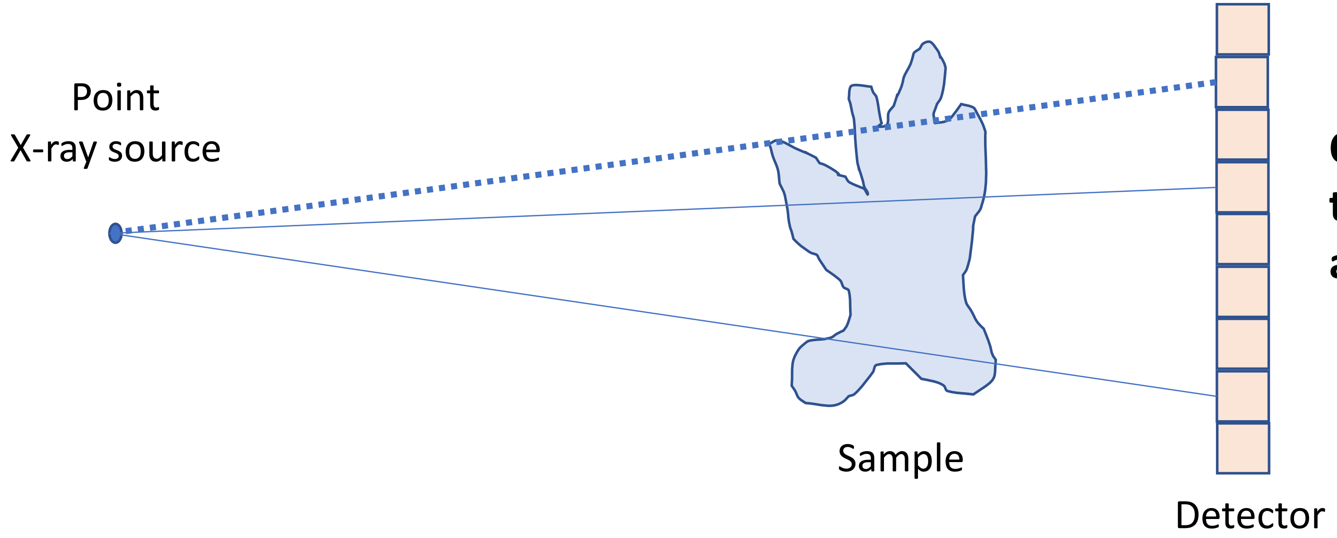
In practice:

- **For indirect conversion detectors**, the spatial resolution is about **2-2.5 times the pixel size**

- **For direct conversion detectors,** the spatial resolution is **close to the pixel size.**

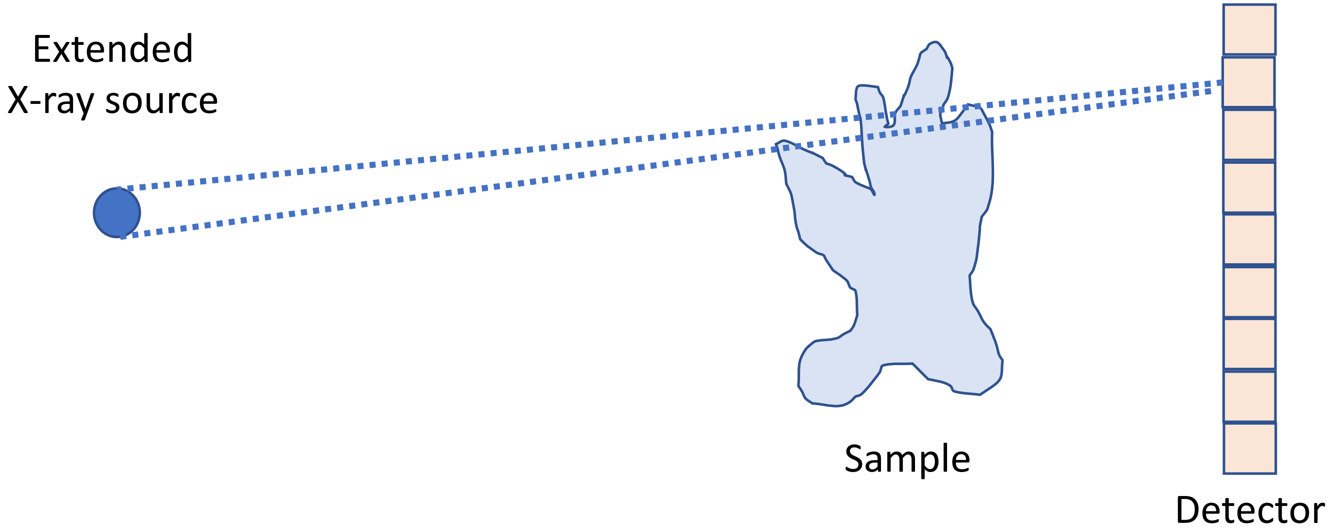
The importance of a small X-ray source size

Image blurring sources: case of an ideal source (no blurring)



One-to-one correspondence between the signal recorded in a given pixel and a section (slice) of the sample

Image blurring sources: extended source



The signal recorded in a given pixel corresponds to different zones of the samples -- >blurring of the image

Synchrotron radiation has **an extremely small X-ray source size**: 20-50 microns x 20-50 microns
Placed a dozen of meters far away from the sample

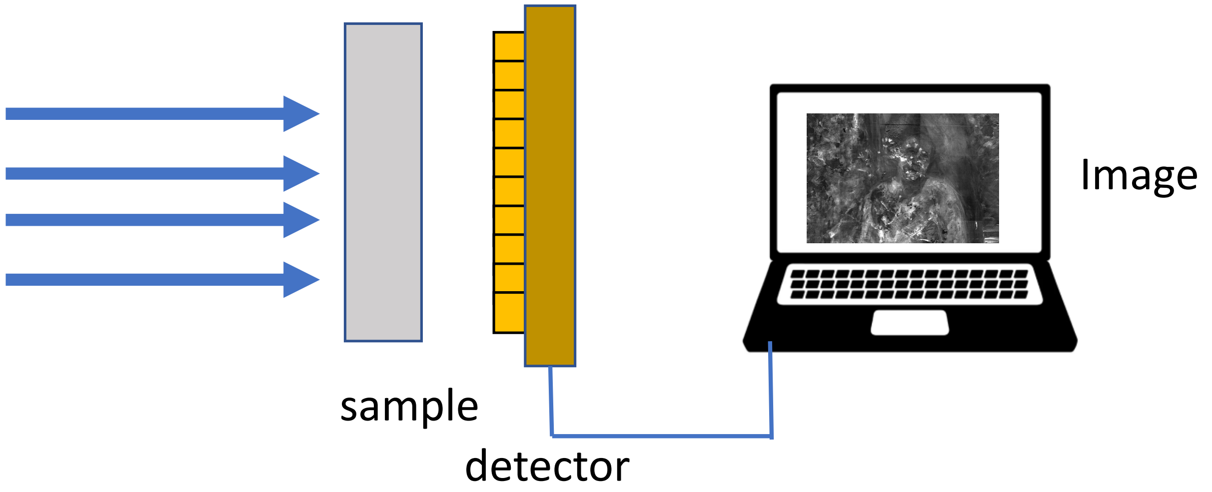
Conventional X-ray tubes have an X-ray source sizes similar or much larger : 20-400 microns x 20-40 microns **placed at 1-50 cm from the sample**

Synchrotron radiation determines much reduced blurring (due to the X-ray source) than a conventional source.

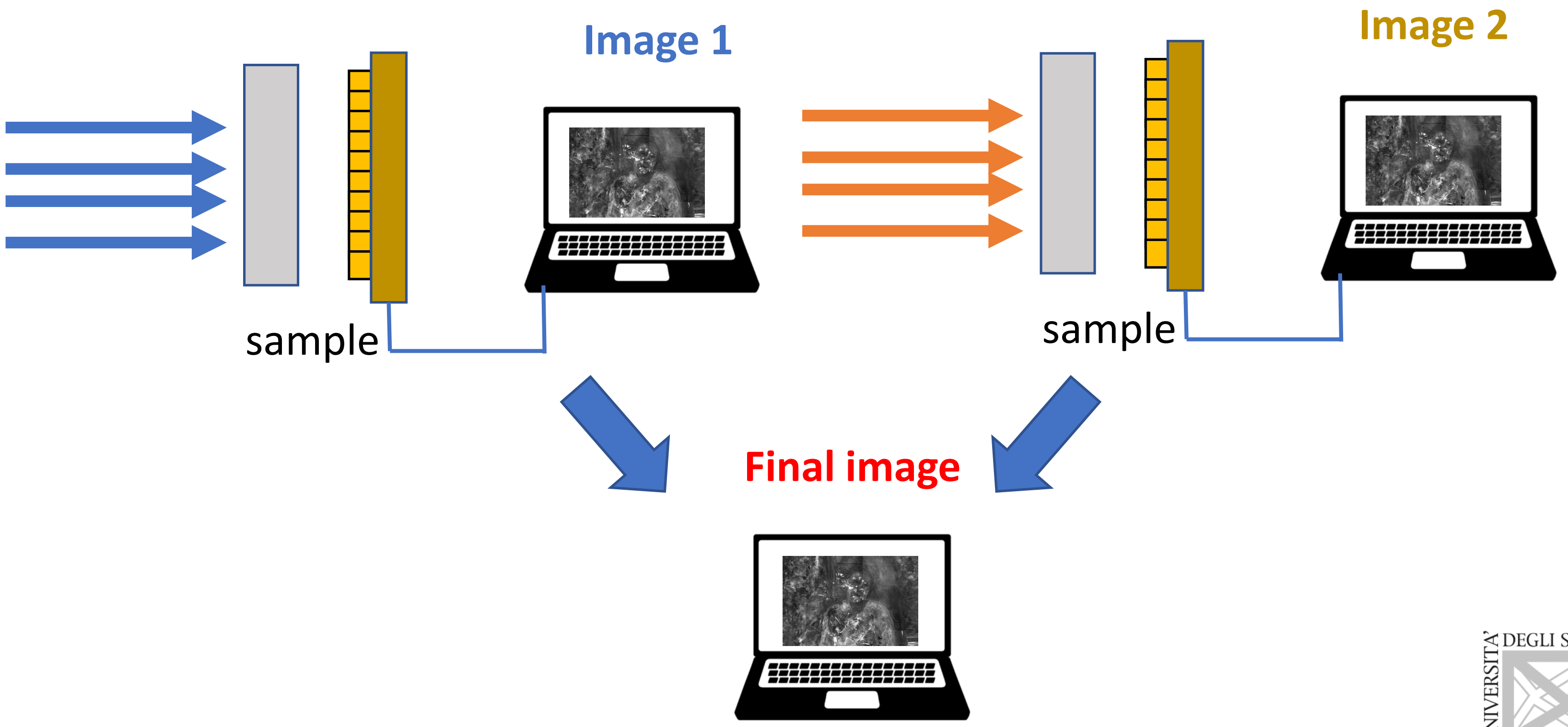
This is said that SR has much higher spatial coherence

X-ray imaging modalities

X-ray absorption



Dual energy imaging



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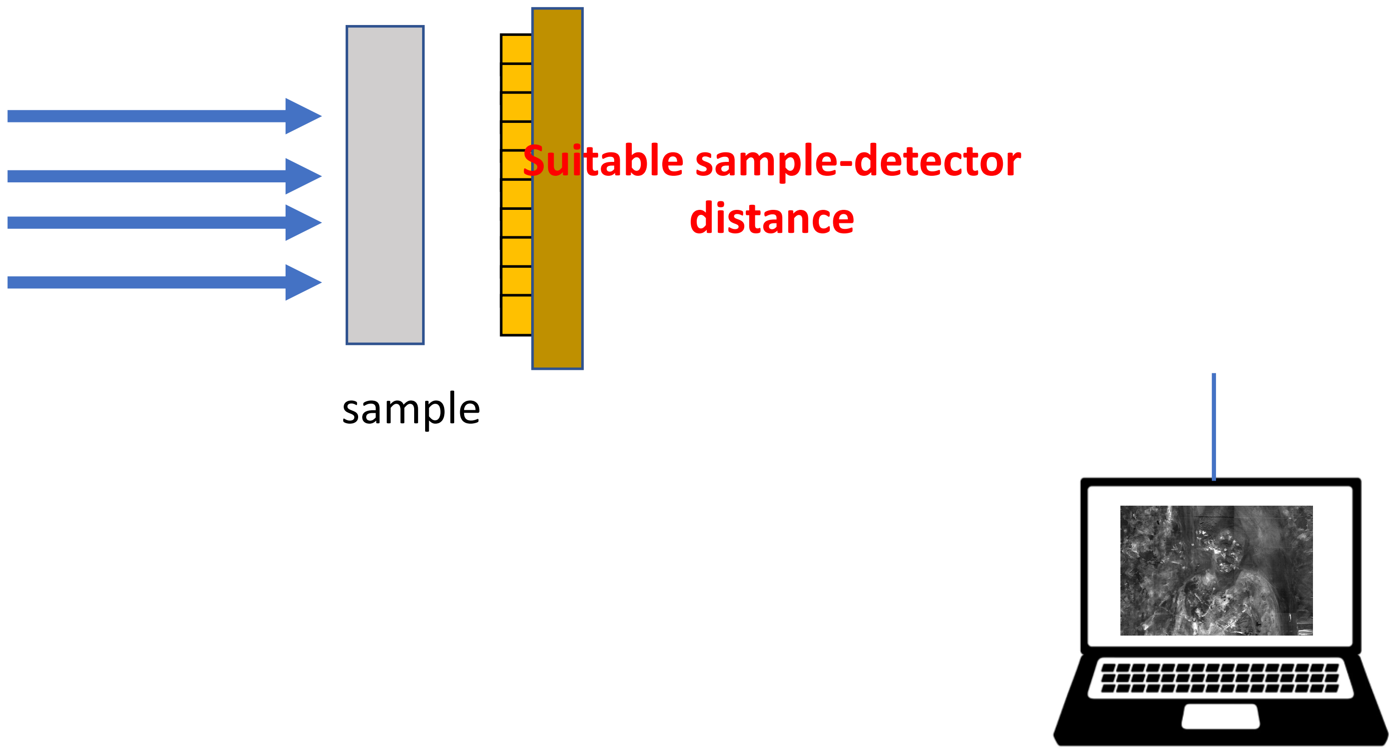
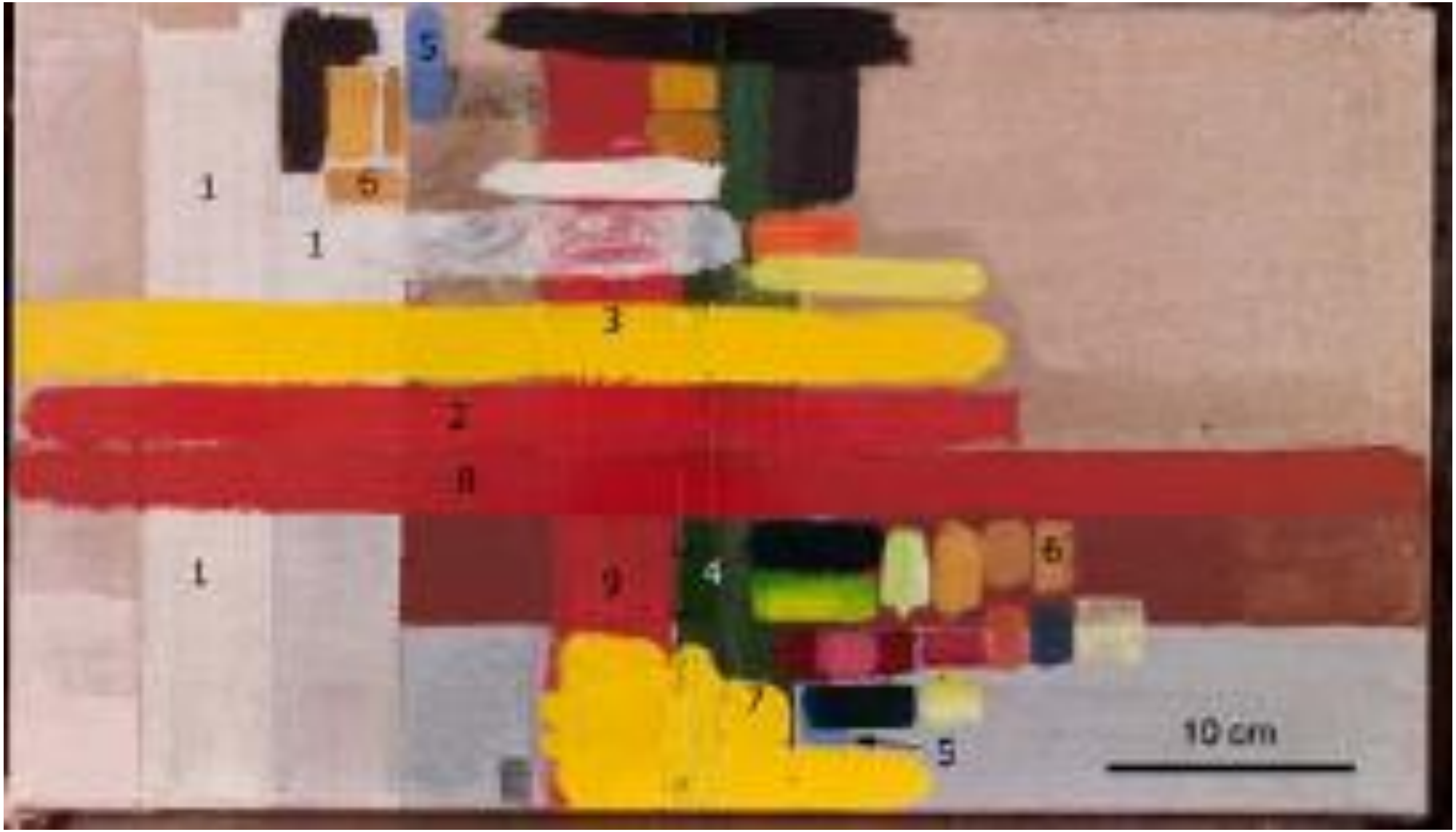
Phase contrast imaging

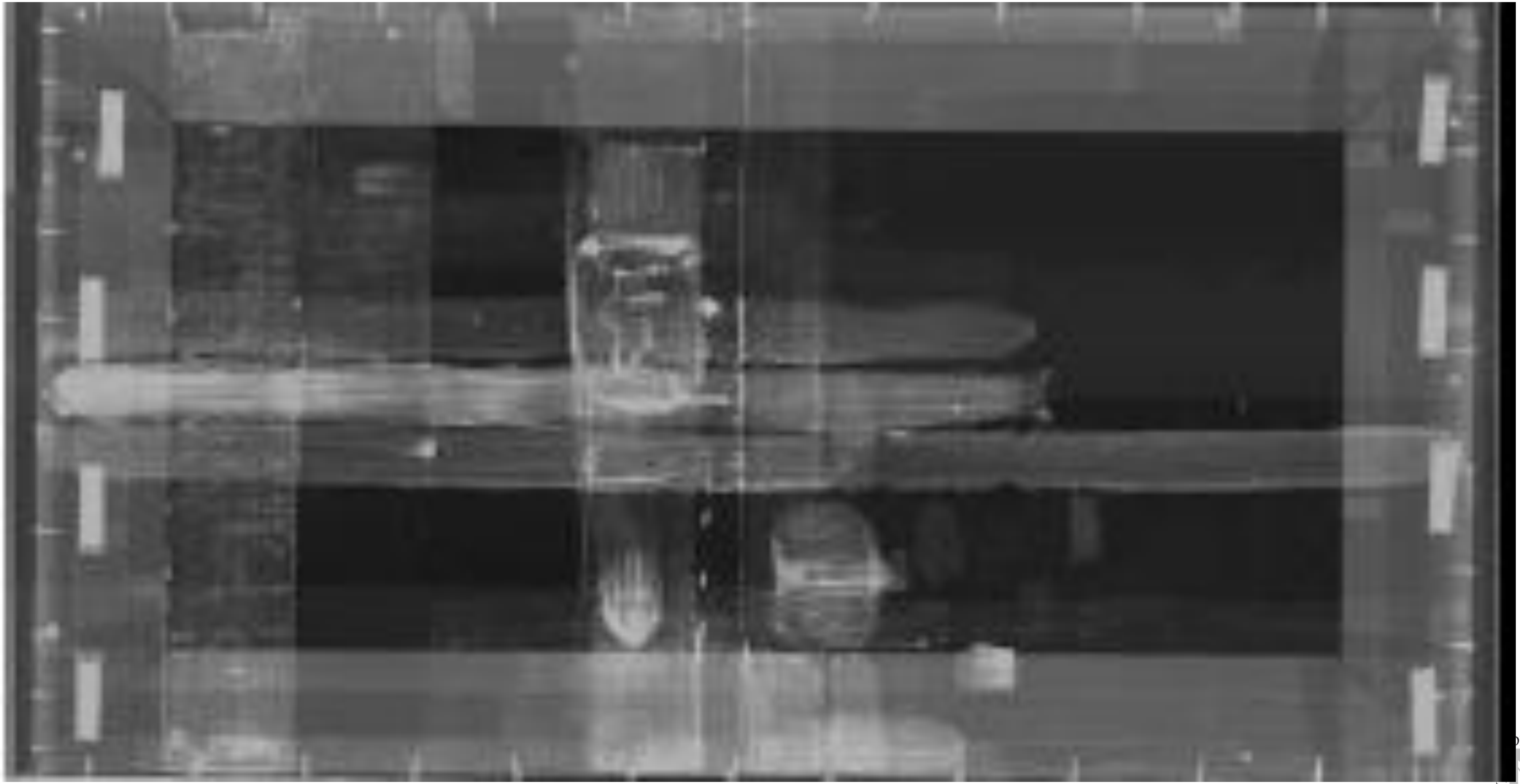


X-ray absorption

Visible light image



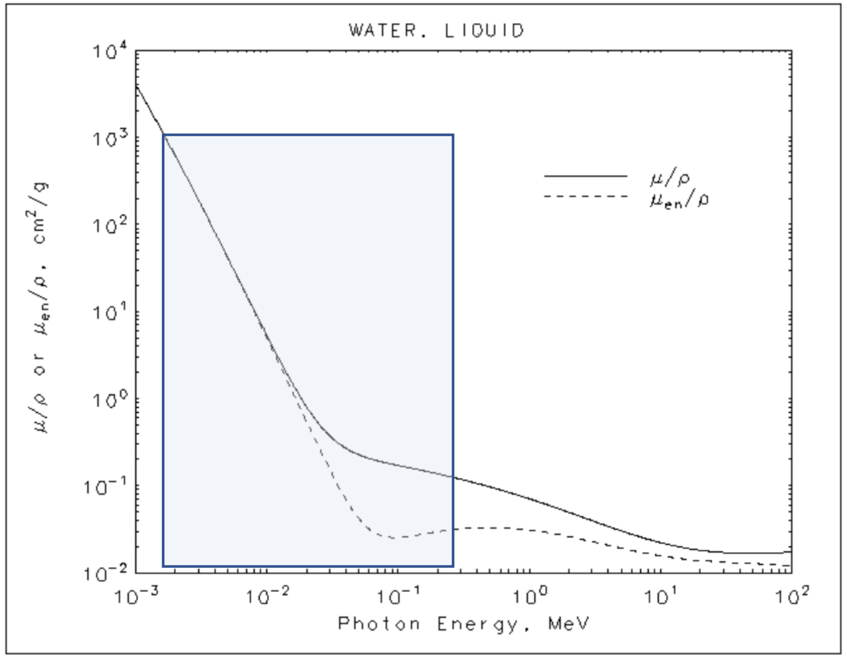
SR radiograph 50 keV

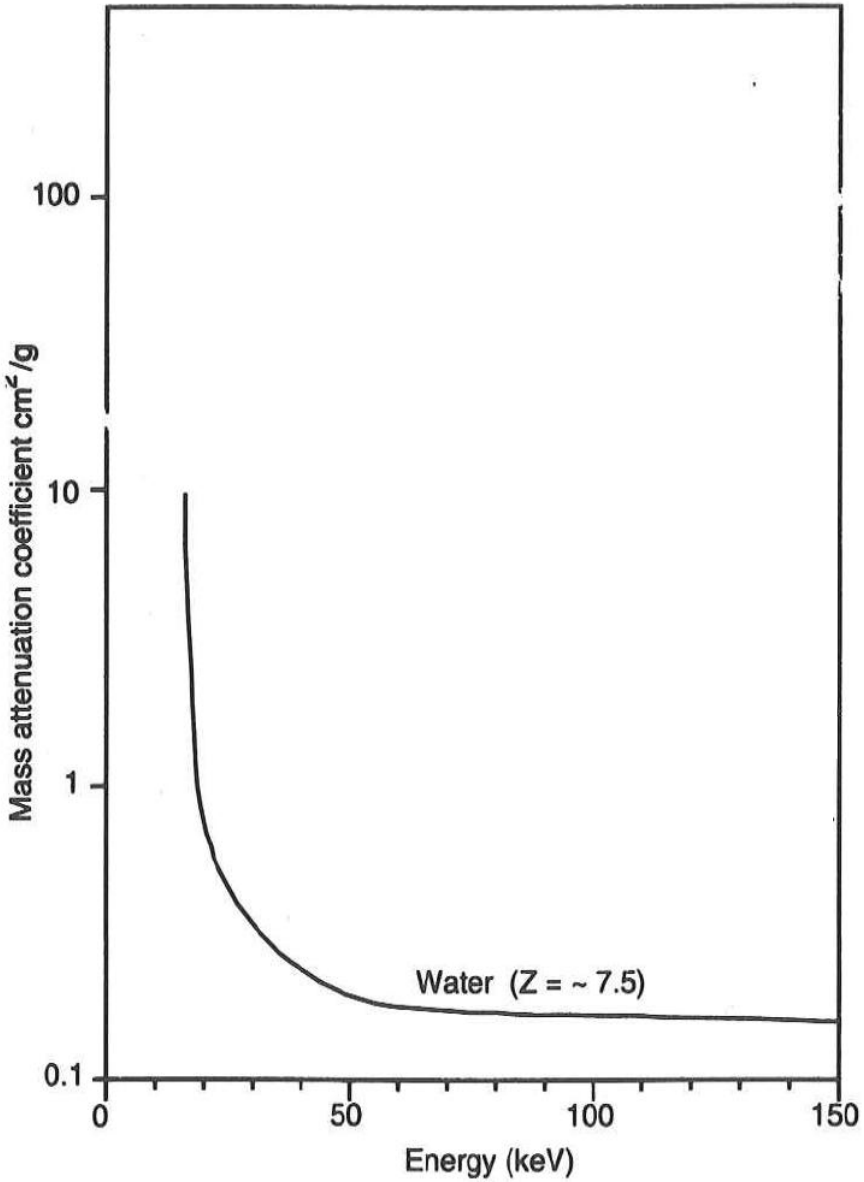


K. Krug et al. Appl. Phys. A 83, 247–251 (2006)

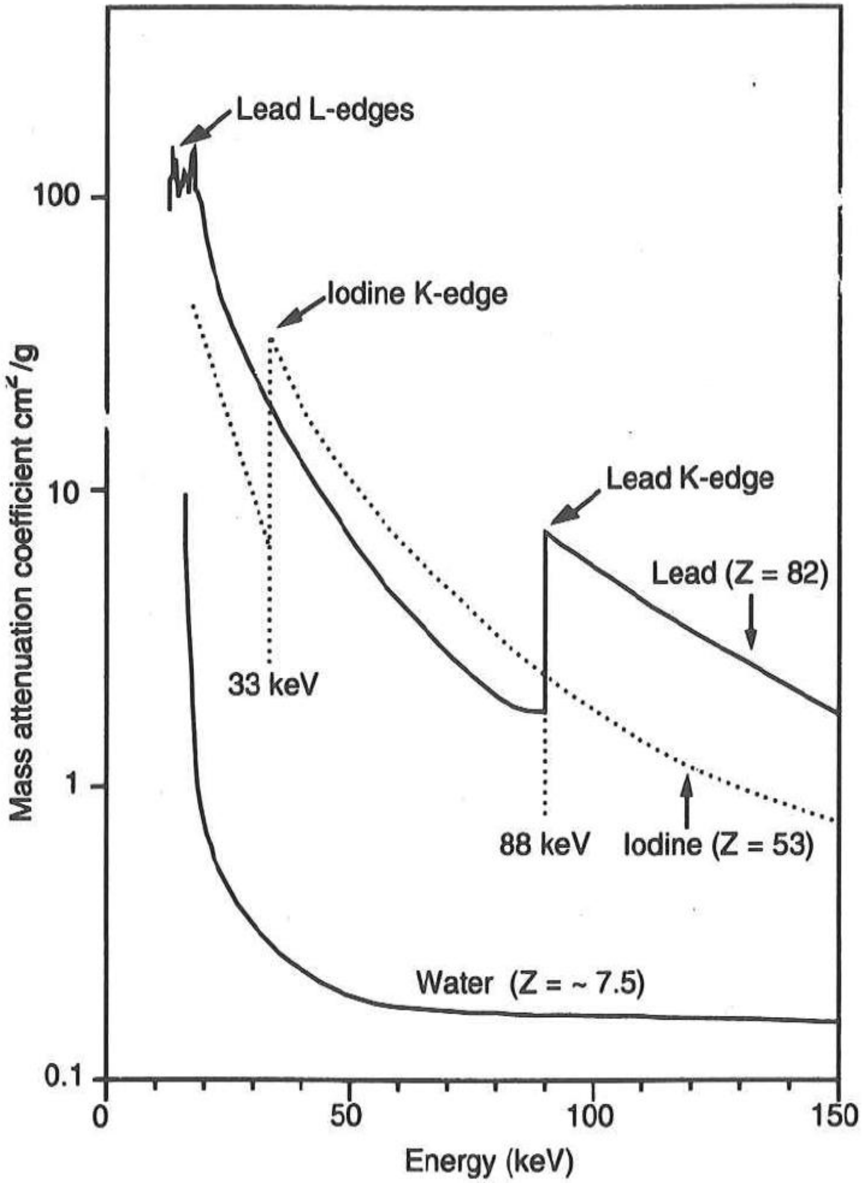
Dual energy imaging

Let's analyse again the linear attenuation coefficient vs energy for water





Specific shell absorption energies

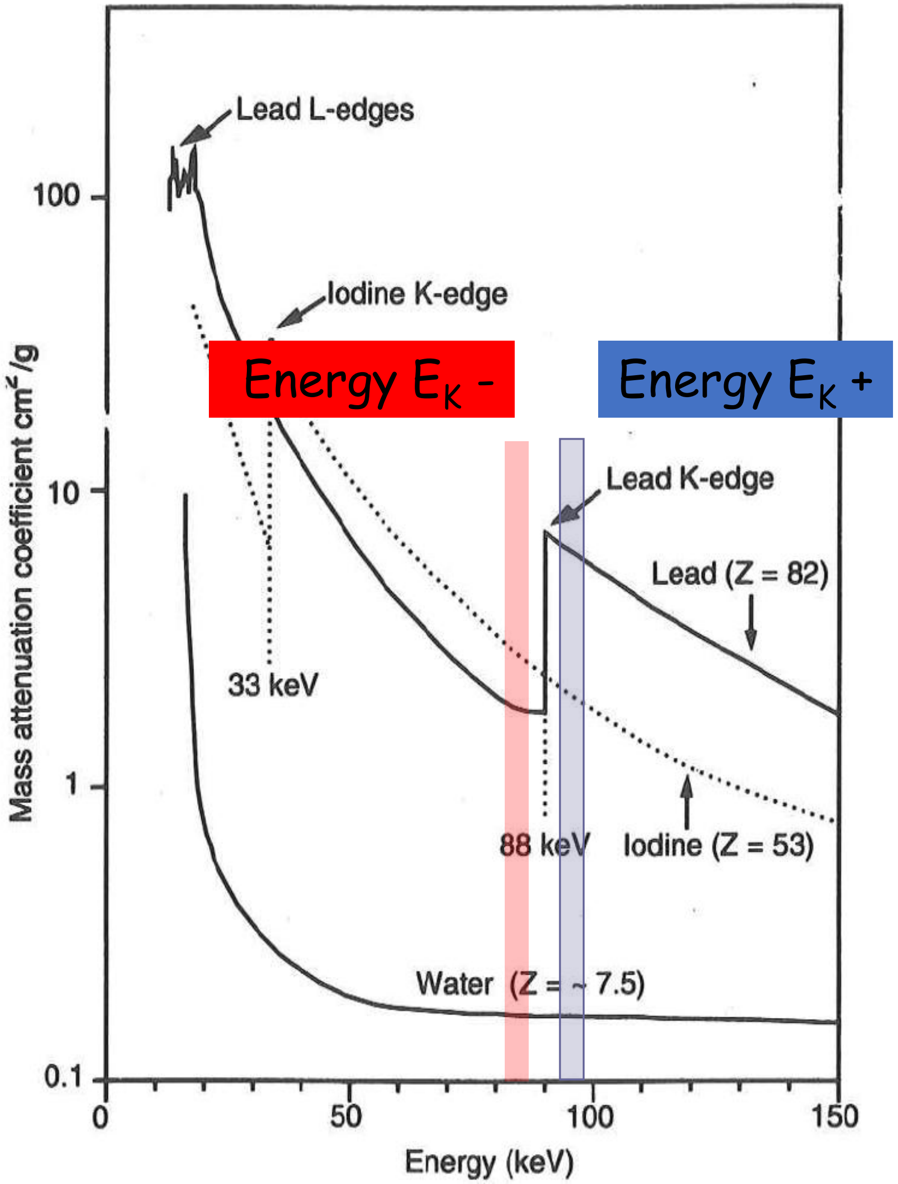


The behaviour of the mass attenuation coefficient, exponentially decreasing, is interrupted by an abrupt jump in cross section:

it corresponds to the **opening of the photoelectric interaction of the X-rays with electron in the K, L, M, N … shells. This effect is called K-edge (L-edge, etc).**

There is **no couple of elements in the periodic table that have K-edges at the same energy**! In a small energetic interval (ex: 200 eV) any other element will have an almost constant attenuation coefficient

Dual energy imaging



Map of Lead:

Image (E-) – Image (E+)

(with some weighting coefficients)

K- and L-edge absorption energies for selected elements

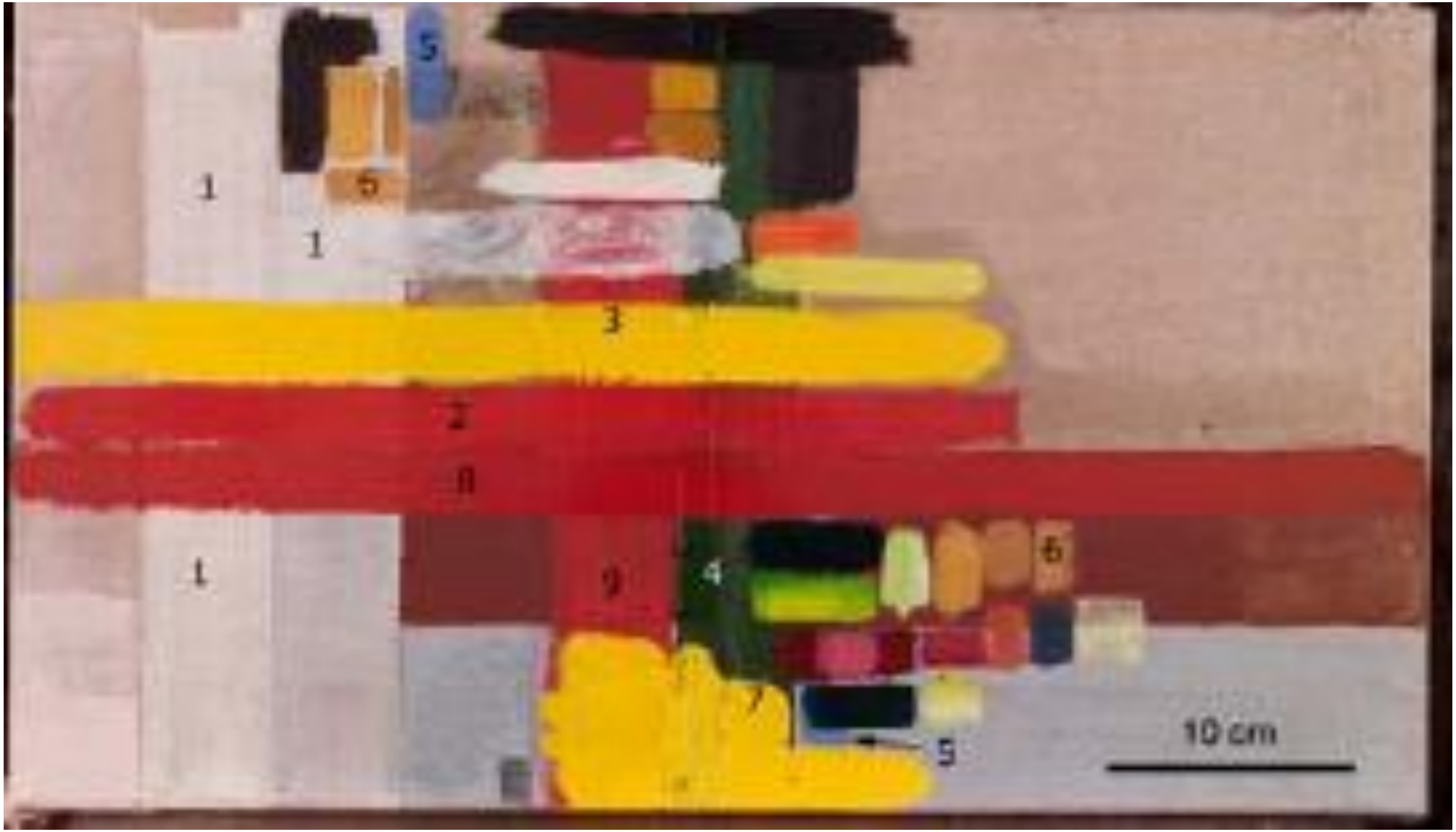
Element	K 1s
26 Fe	7112
27 Co	7709
28 Ni	8333
29 Cu	8979
30 Zn	9659
31 Ga	10367
32 Ge	11103
33 As	11867
34 Se	12658
35 Br	13474
36 Kr	14326
37 Rb	15200
38 Sr	16105
39 Y	17038
40 Zr	17998
41 Nb	18986
42 Mo	20000
43 Tc	21044
44 Ru	22117
45 Rh	23220
46 Pd	24350
47 Ag	25514

Element	K 1s	L_1 2s
48 Cd	26711	
49 In	27940	
50 Sn	29200	
51 Sb	30491	
52 Te	31814	
53 I	33169	
54 Xe	34561	
55 Cs	35985	
56 Ba	37441	
57 La	38925	
58 Ce	40443	
59 Pr	41991	
60 Nd	43569	7126
61 Pm	45184	7428
62 Sm	46834	7737
63 Eu	48519	8052
64 Gd	50239	8376
65 Tb	51996	8708
66 Dy	53789	9046
67 Ho	55618	9394
68 Er	57486	9751
69 Tm	59390	10116
70 Yb	61332	10486

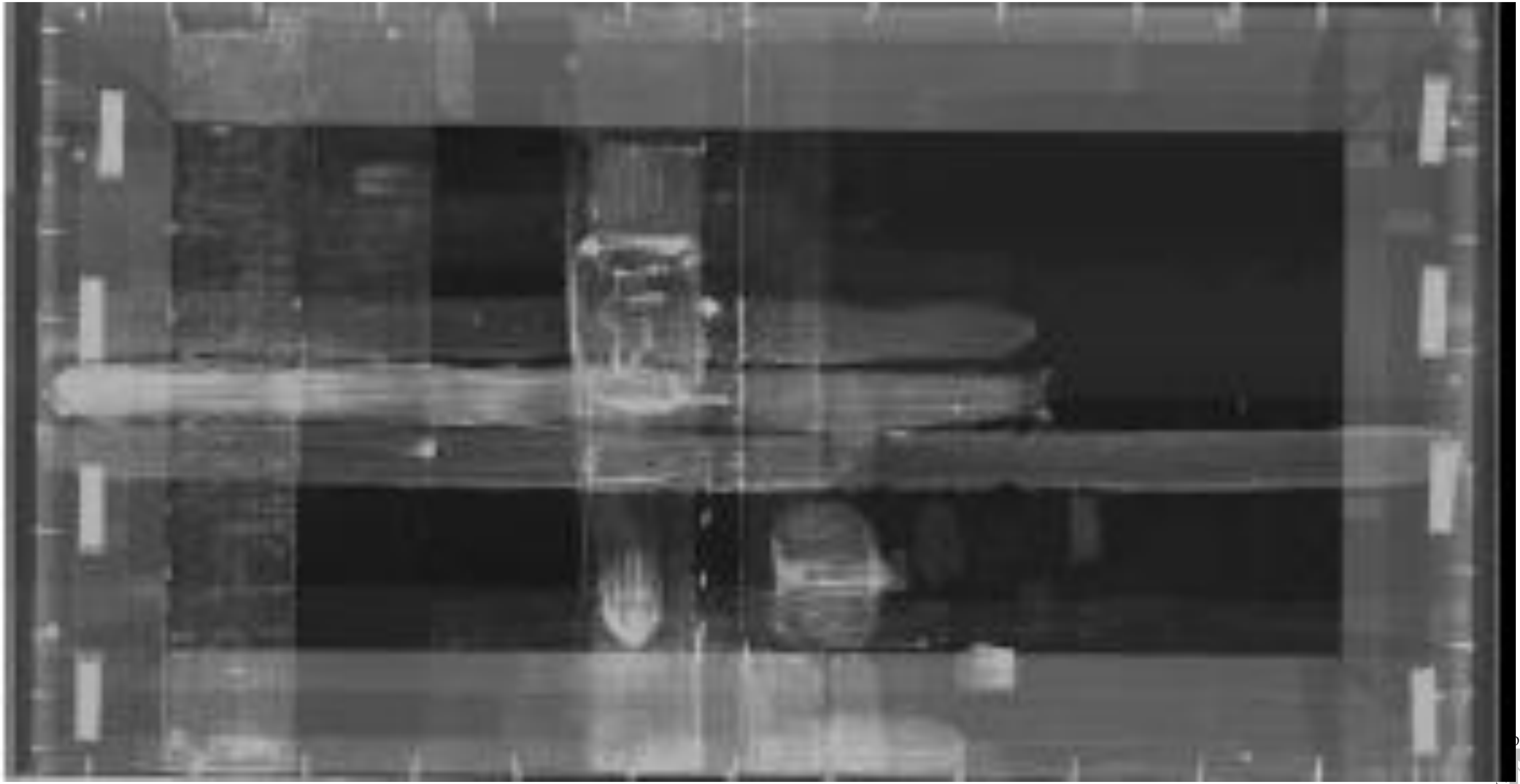
Element	K 1s	L_1 2s	L_2 $2p_{1/2}$	L_3 $2p_{3/2}$
71 Lu	63314	10870	10349	9244
72 Hf	65351	11271	10739	9561
73 Ta	67416	11682	11136	9881
74 W	69525	12100	11544	10207
75 Re	71676	12527	11959	10535
76 Os	73871	12968	12385	10871
77 Ir	76111	13419	12824	11215
78 Pt	78395	13880	13273	11564
79 Au	80725	14353	13734	11919
80 Hg	83102	14839	14209	12284
81 Tl	85530	15347	14698	12658
82 Pb	88005	15861	15200	13035
83 Bi	90524	16388	15711	13419

“Electron binding energies in eV”, X-ray data booklet, http://xdb.lbl.gov/

Visible light image



SR radiograph 50 keV; no energy subtraction



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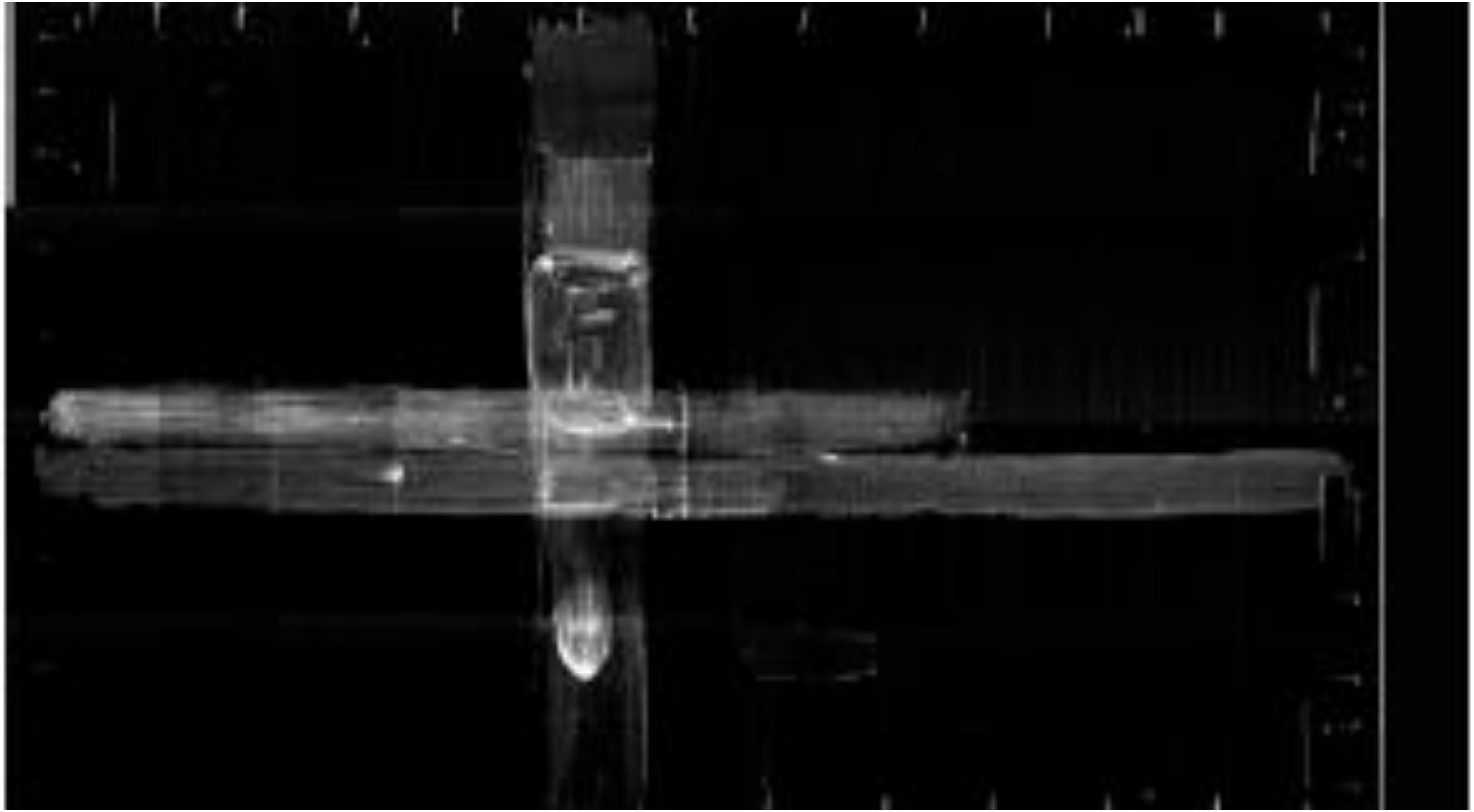
Barium map image



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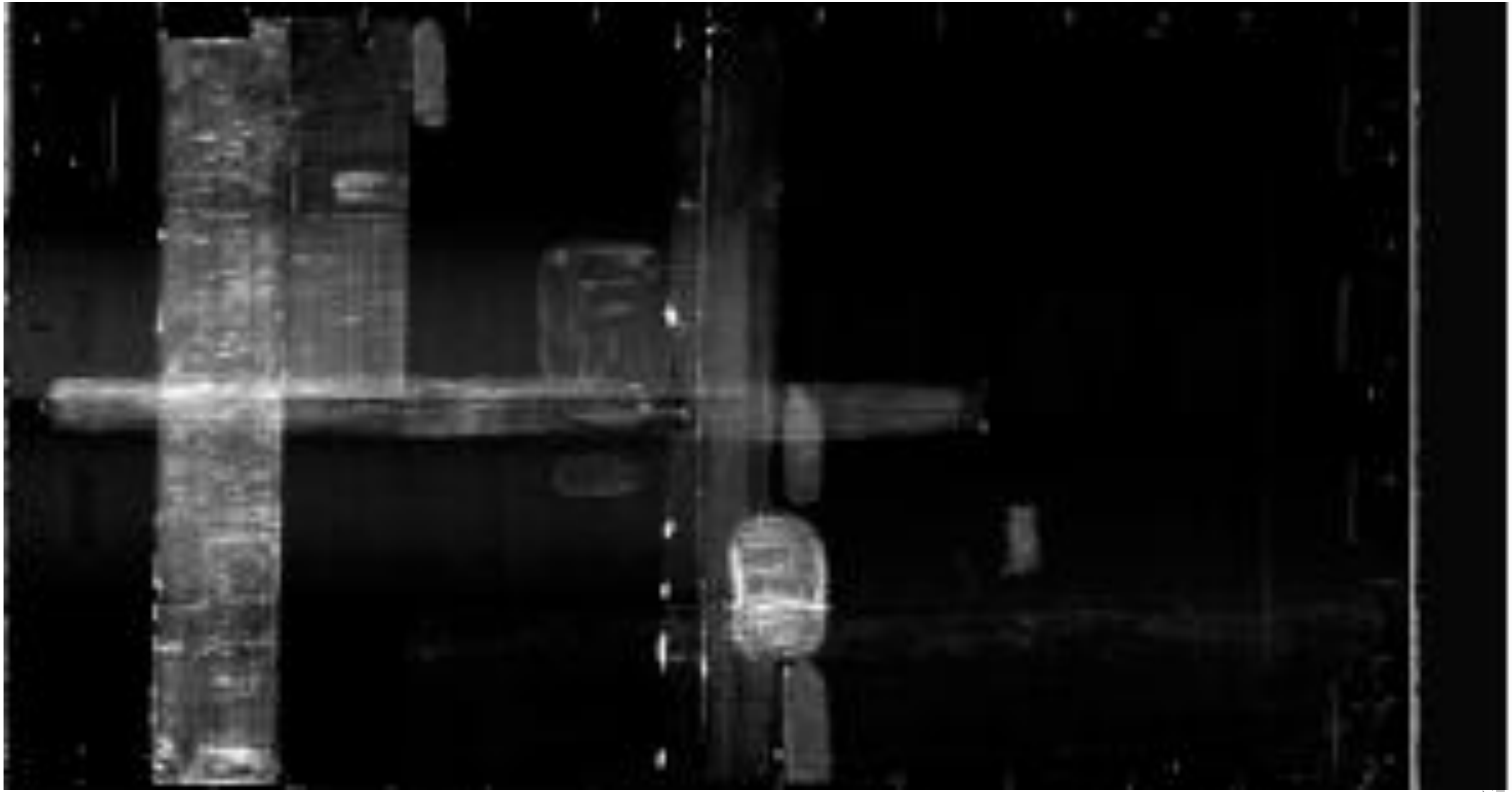
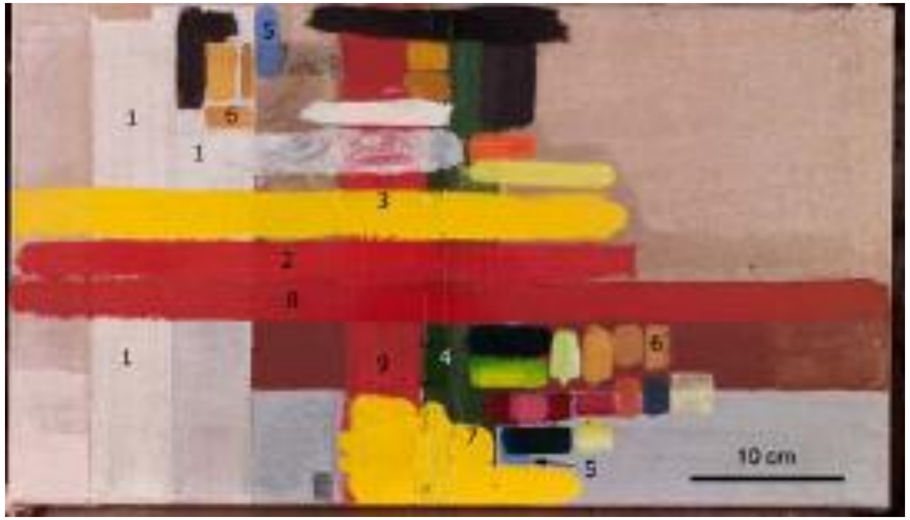
Lead image

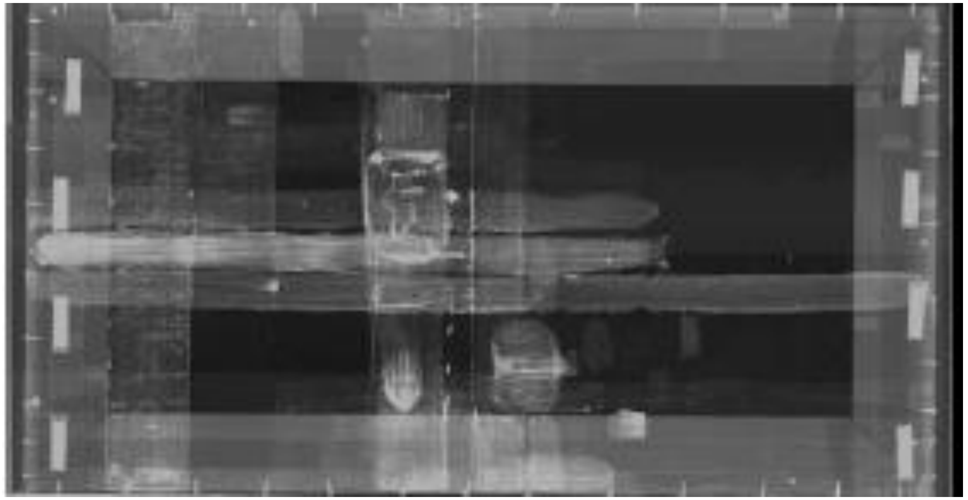


K. Krug et al. Appl. Phys. A 83, 247–251 (2006)

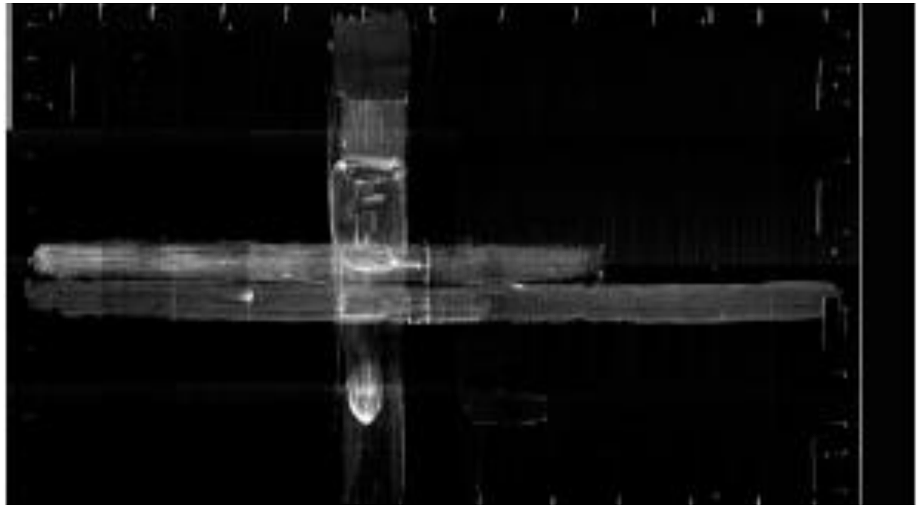
Visible light image



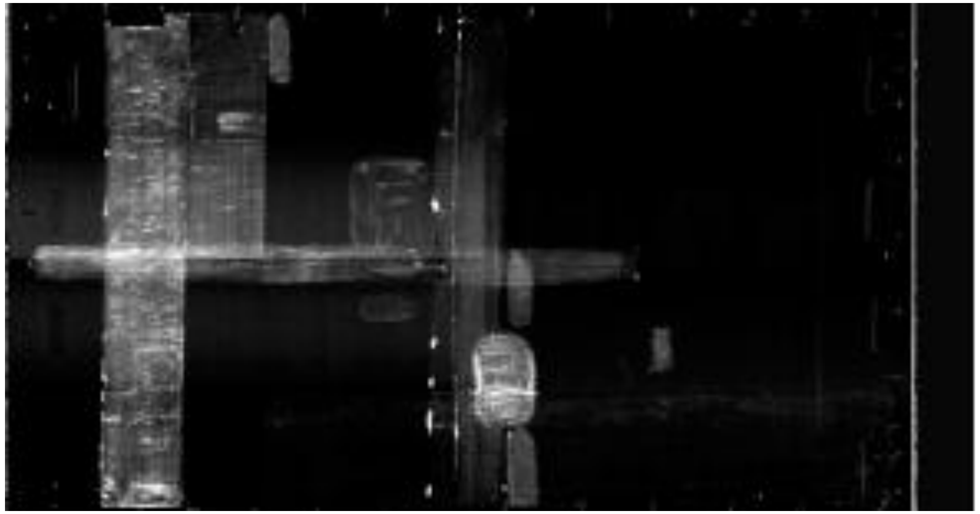
SR radiograph 50 keV; no energy subtraction



Barium image



Lead image



Perfect separation of colors; quantitative information of the local concentration is obtained

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Optical image

Lead image

Phase contrast imaging

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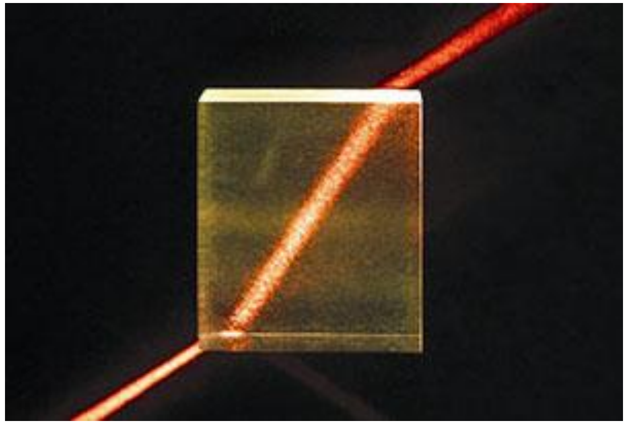
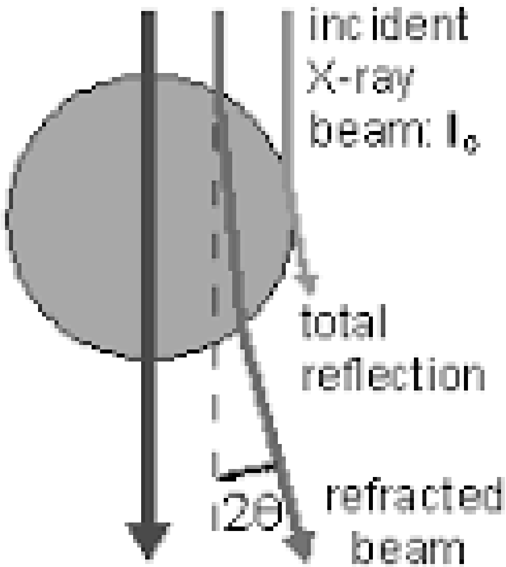


Refraction of visible light: it occurs when light (electromagnetic radiation
moves from one material to another one.

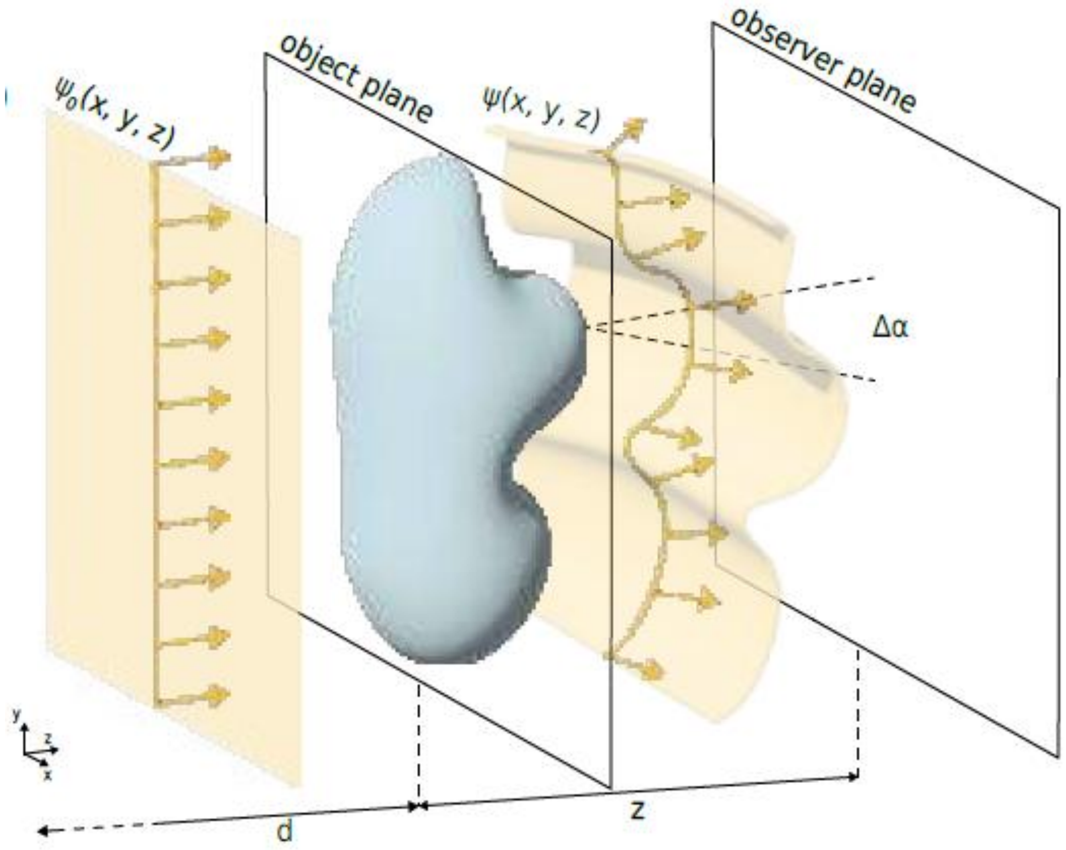
The refracted ray moves away **several degrees** with respect to the incoming ray



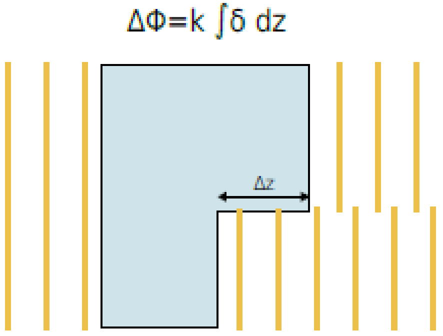
Refraction of X-rays : 10^{-5} degrees

Very difficult to detect

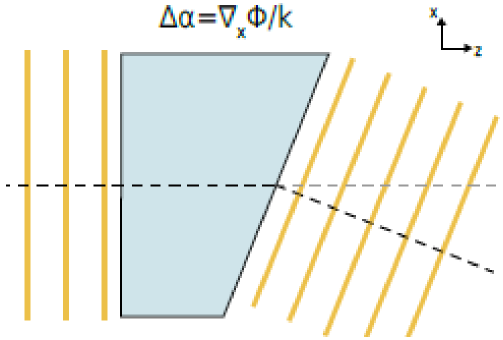
Images from http://www.bigshotcamera.com/learn/imaging-lens/refraction



A difference in phase is caused by a change in object thickness z.



Phase gradients are proportional to the refraction angle from sample interfaces.



Absorption image

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Phase contrast image

From 2D to 3D: computed tomography

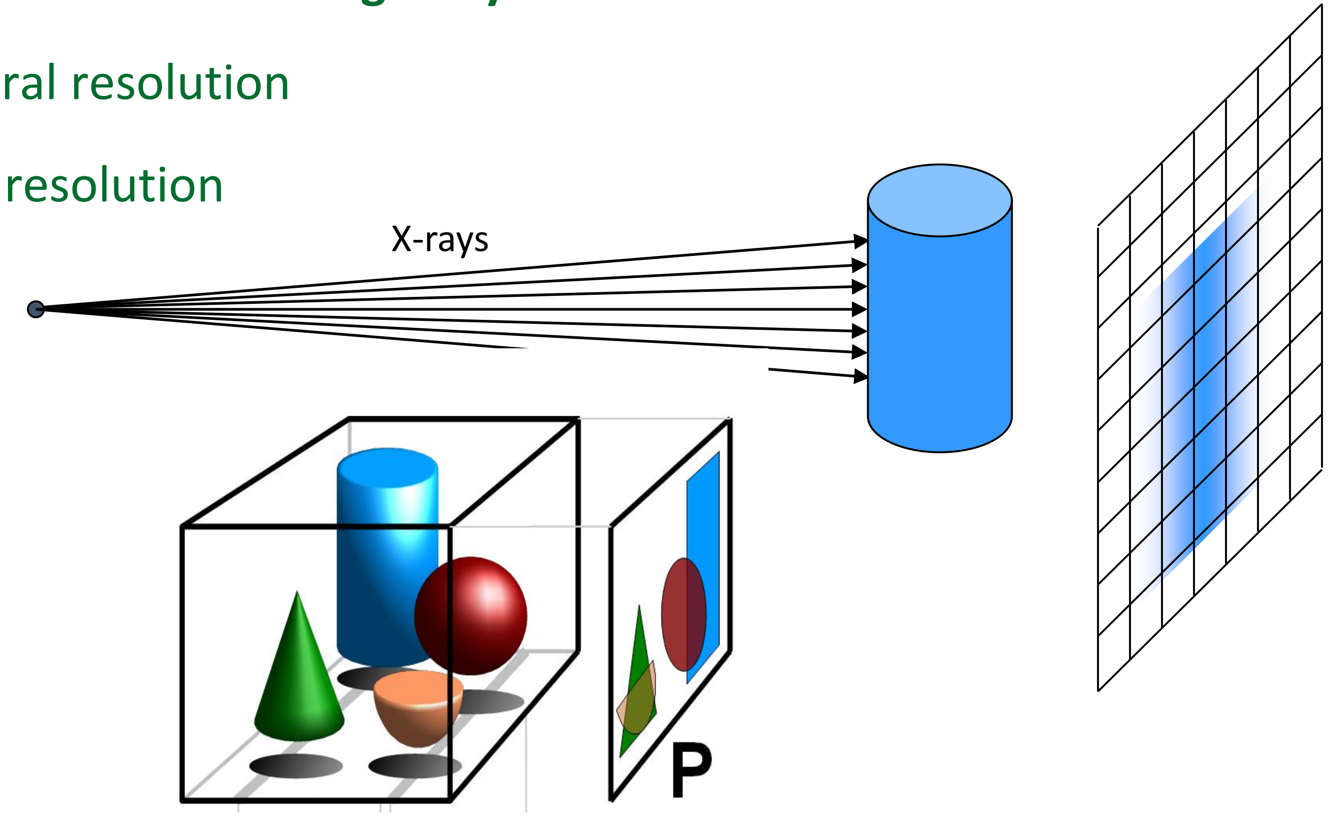
2D imaging (Radiography) vs 3D (Computed Tomography)

- **2D Radiography**

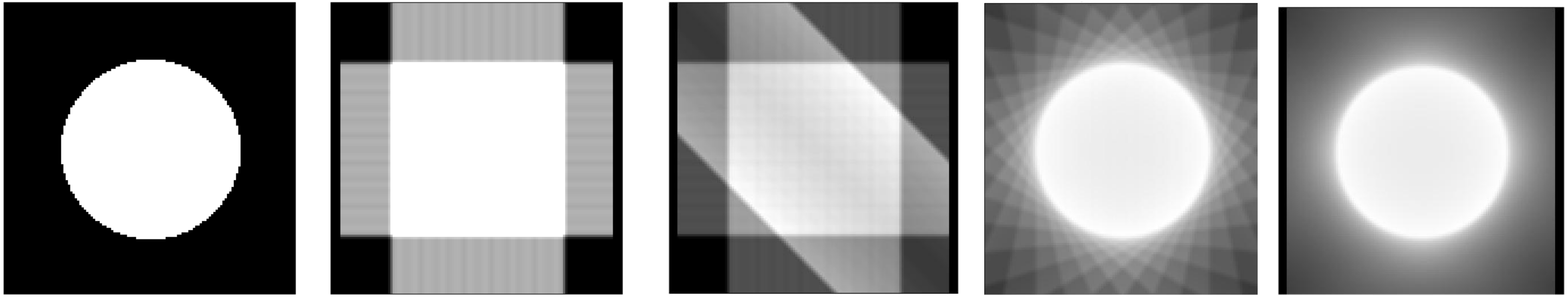
Sum of the attenuation along a ray

→Good lateral resolution

→No depth resolution



Let's image a cylinder with an increasing number of projections



Original sample | **2** projections 0, 90 ° | **3** projections 0, 45, 90 ° | **30** projections | **1000** projections

The background is still a problem

-- > Use of a high-pass filter to suppress it

How many radiographs (projections) do I need?

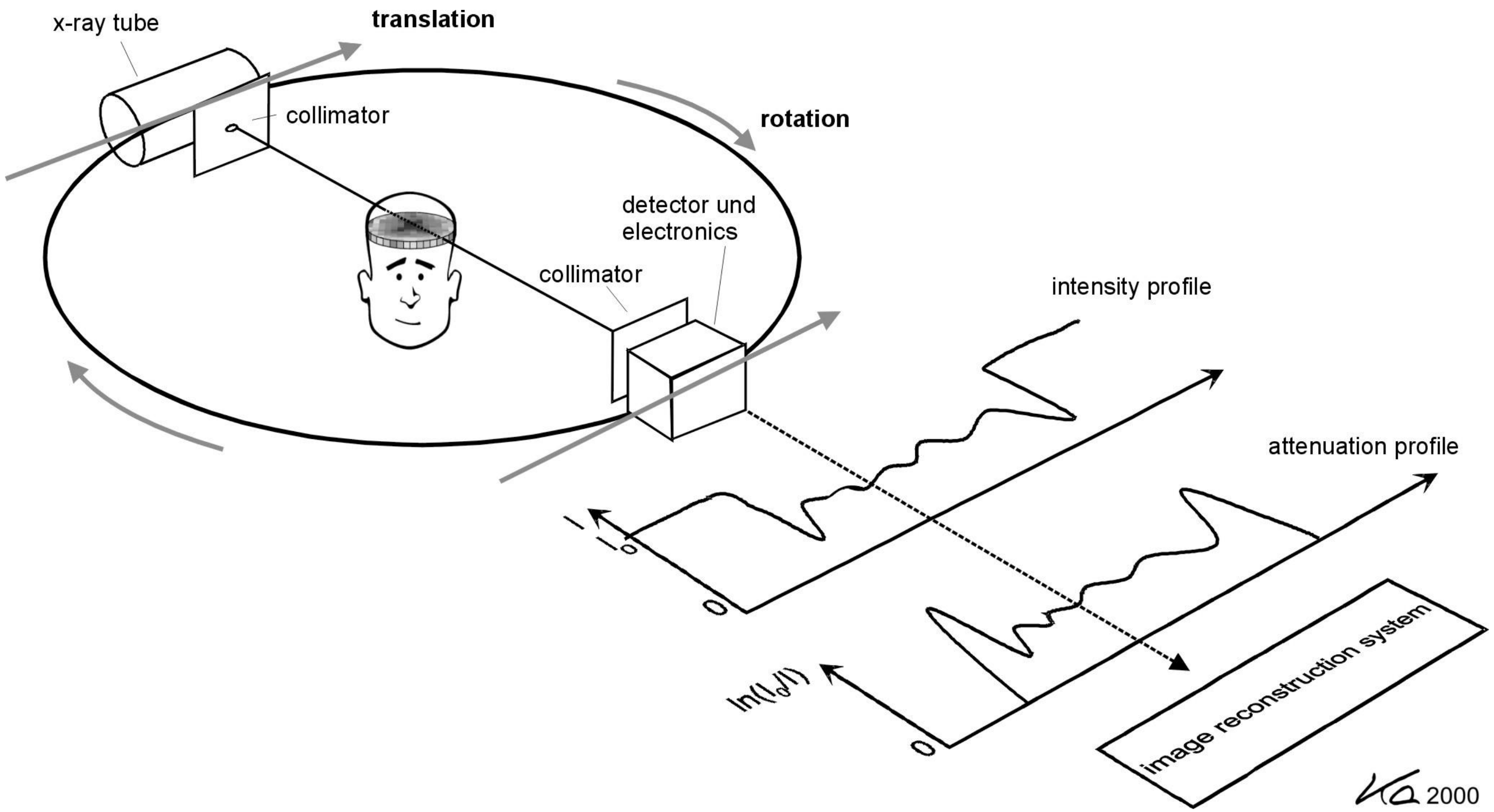
Nb_proj= $\left(\frac{\pi}{2}\right)$* (Number of pixels covered by sample)

Historical implementation of CT: pencil beam case

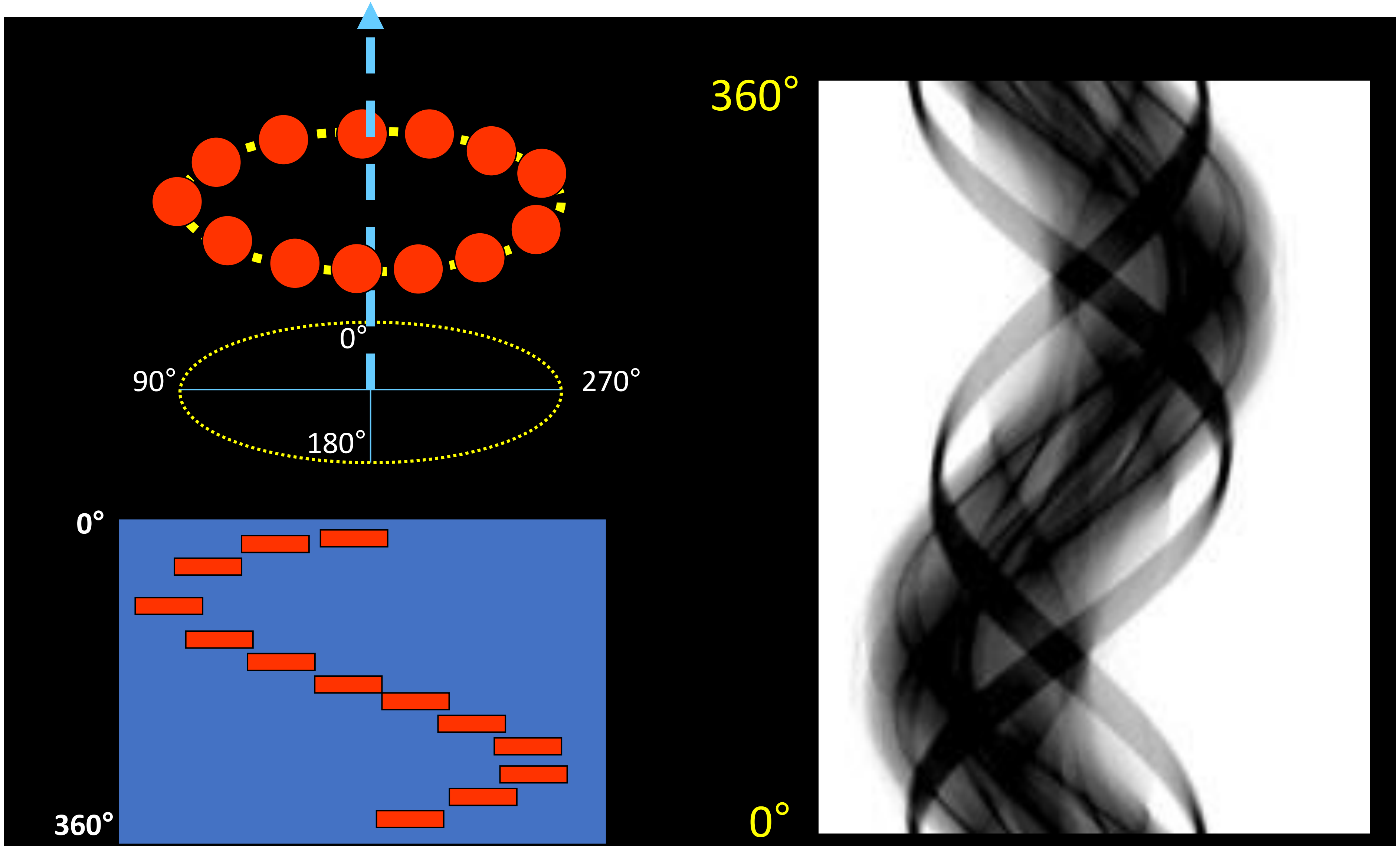
Double movement:

- translation of the source and detector to cover the organ at a fixed angle
- Repetition of the same procedure over 180°

First clinical implementation: step rotation=1°, 160 data points per projection



Computed tomography: image acquisition



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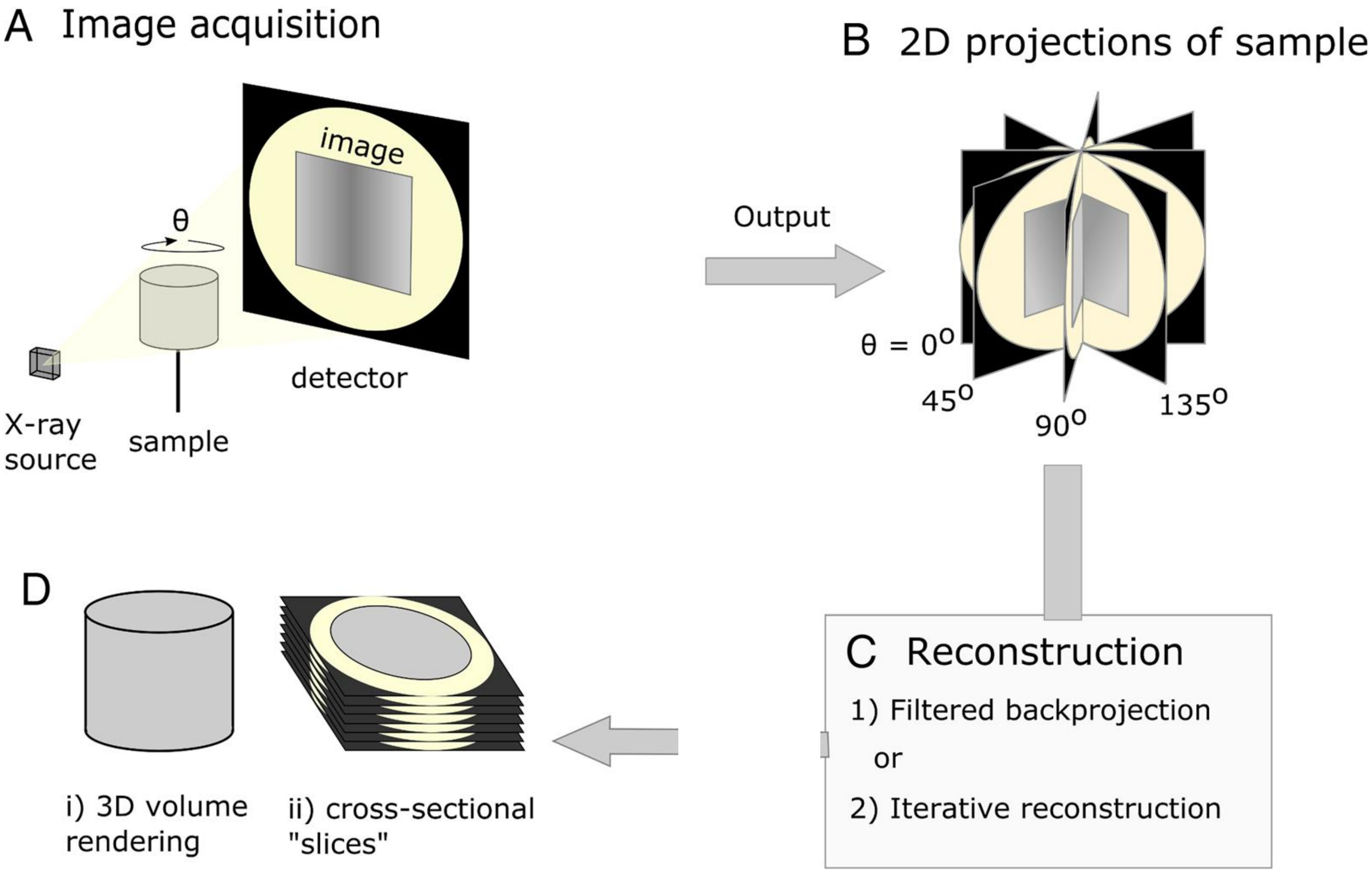
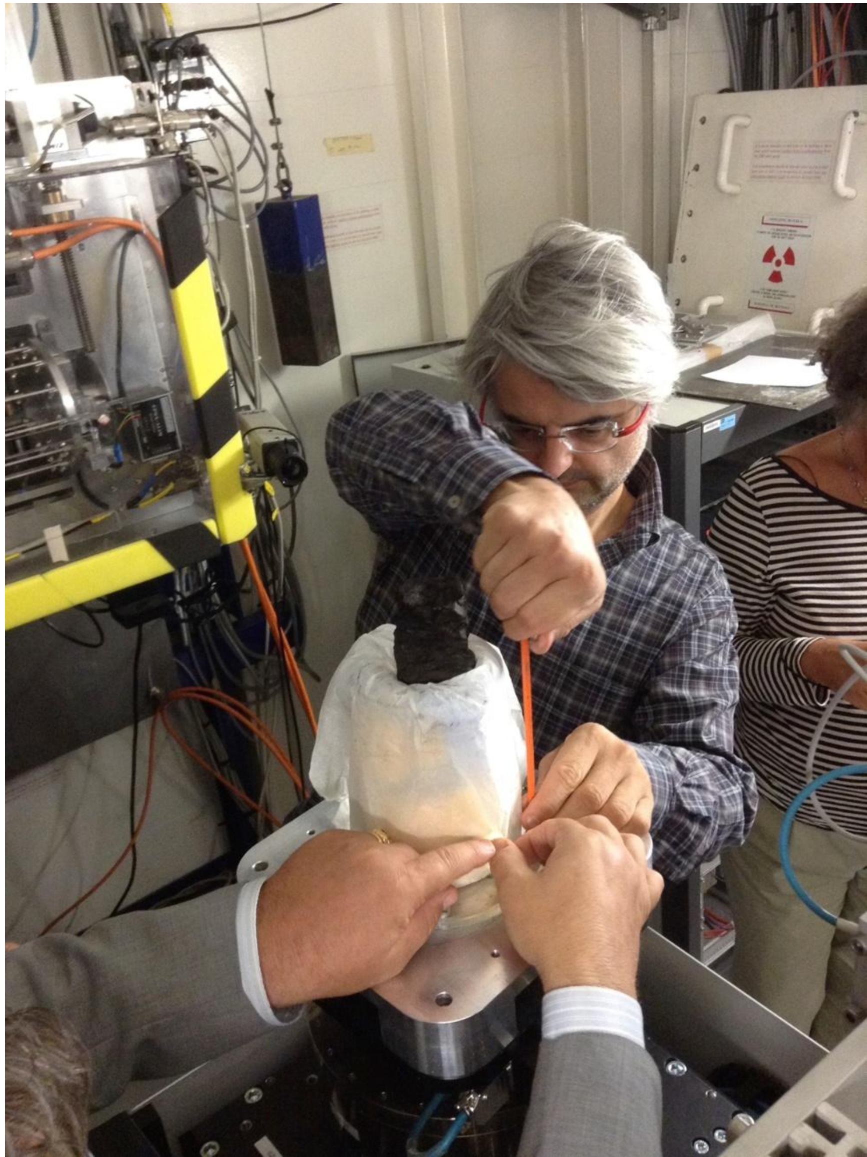
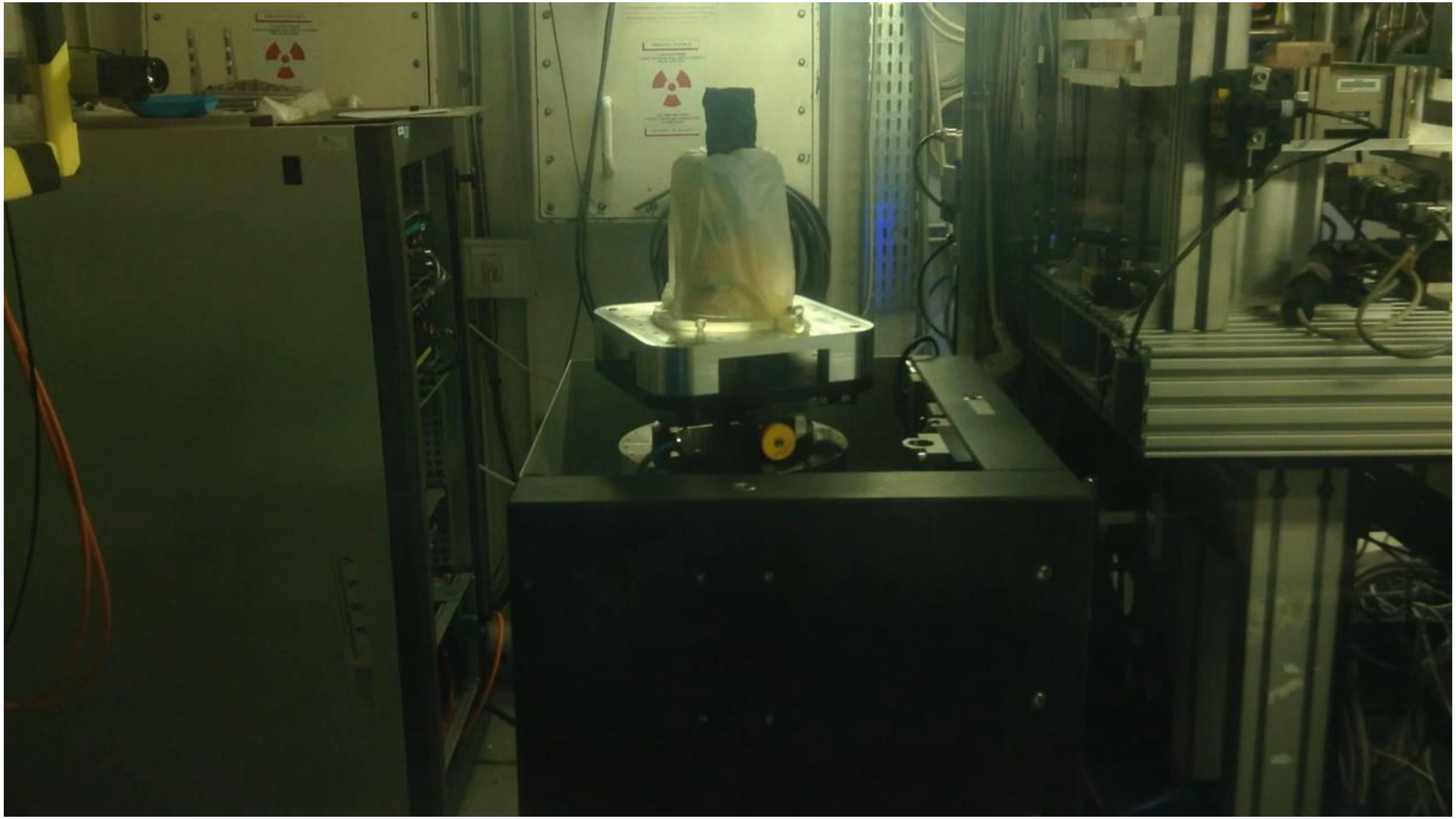
Computed tomography: the pipeline from acquisition to visualization

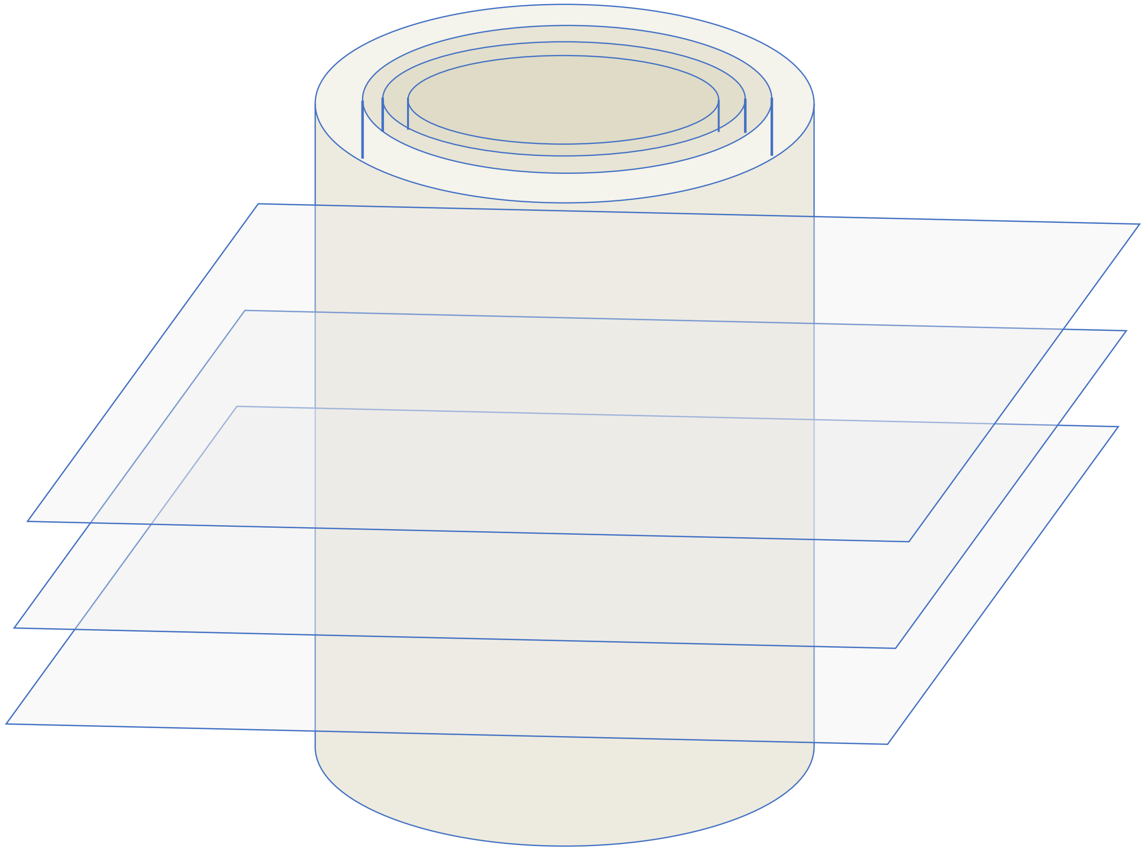


Images from DOI: doi.org/10.1017/S0031182017002074

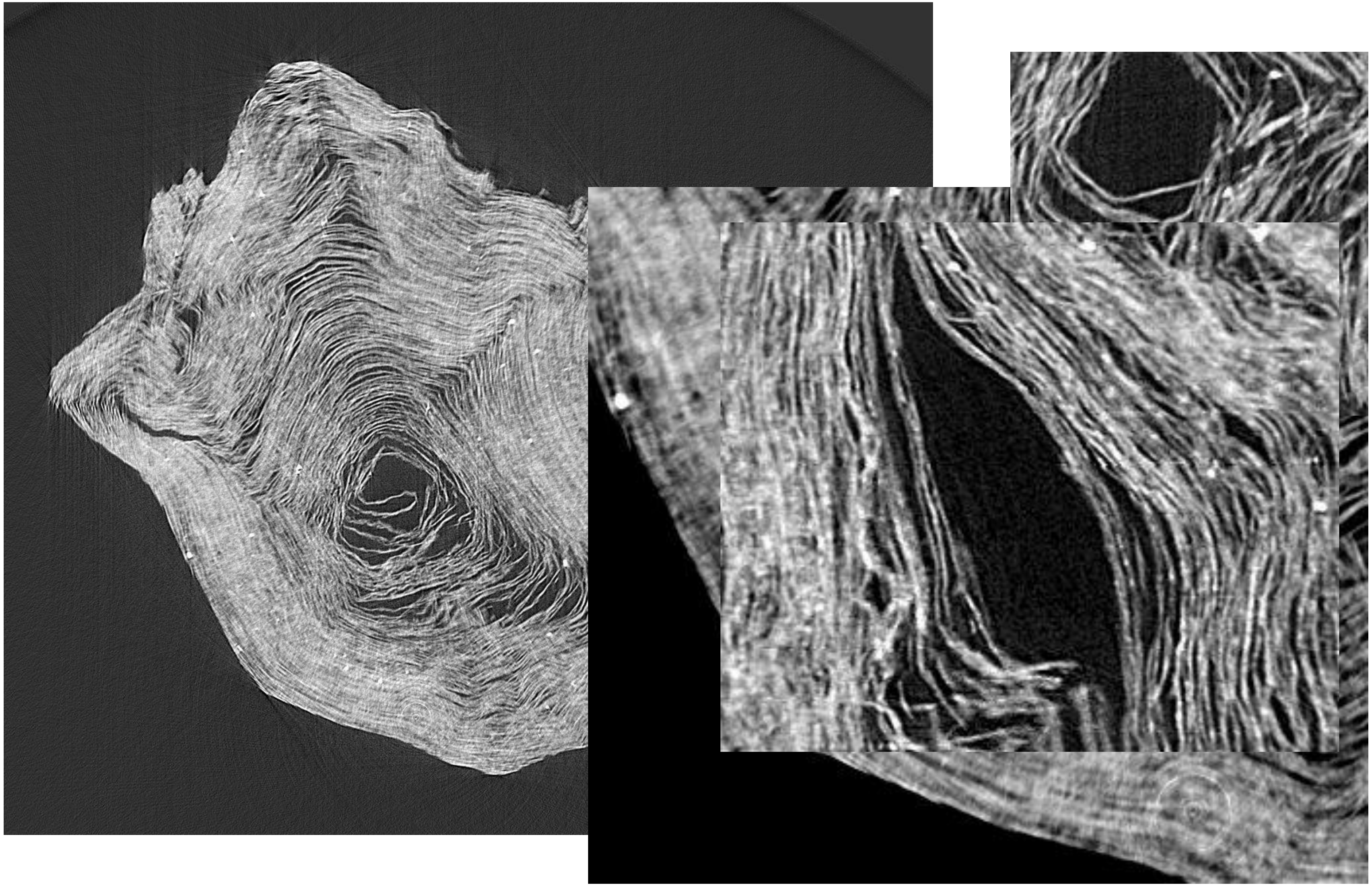
ESRF-ID 17 Medical Beamline



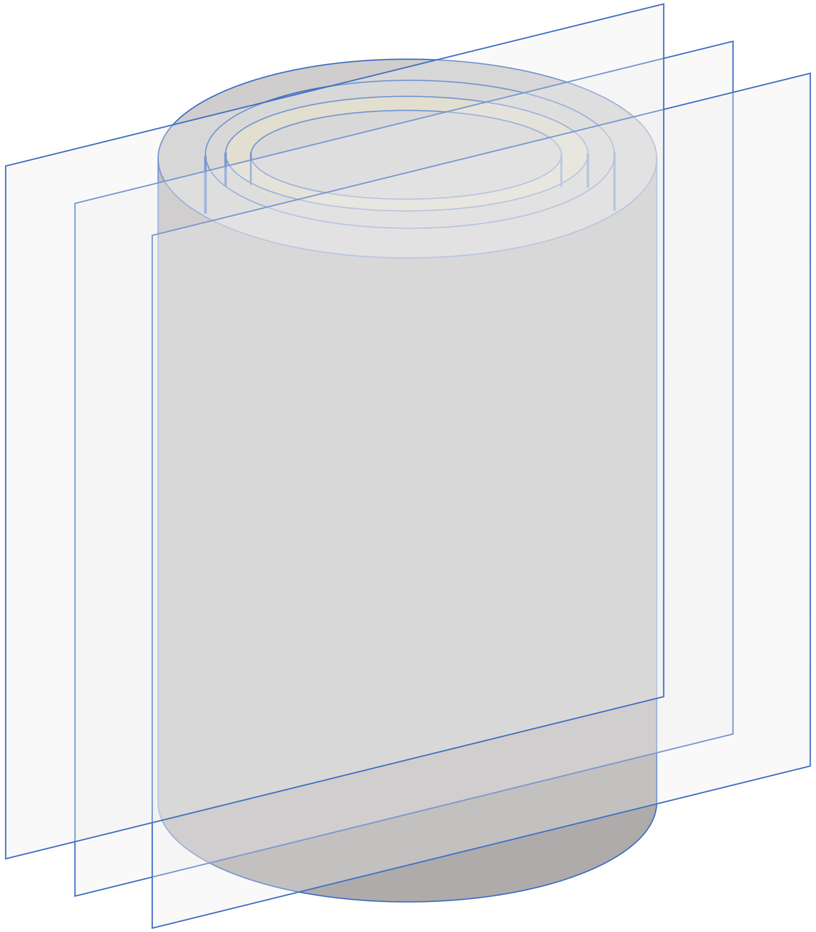


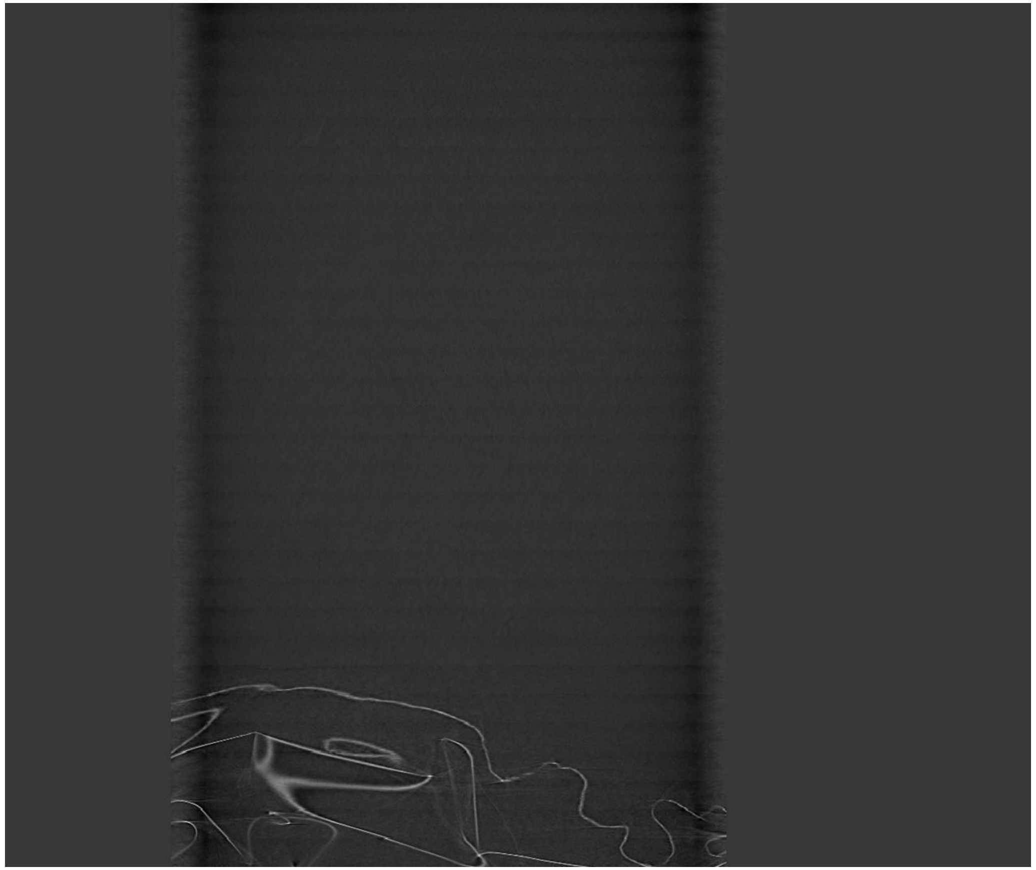


Pherc 495



Virtual slicing to study the internal structure





PHerc 495

Summary - Conclusions

SR emitted by a bending magnet or a wiggler permits to select the most suitable energy for analysing a given sample, thanks to **monochromators**.

Different imaging techniques can be applied, including: **radiography based on differential X-ray absoption, Dual energy imaging, phase contrast imaging**

Absorption imaging produces a map of the tranmission of the X-rays

Dual energy imaging permits to produce image maps of an individual element by performing 2 images At energies just above and below the characteristic «K-edge» of the specific element, an to subtract The background

Phase contrast imaging allows to enhance the borders of details/objects, improving their visibility

Computed tomography allows to visualize the samples in 3D