Advanced X-ray imaging:
Spectral and Phase-contrast Techniques

Workshop on Particle Detectors for Interdisciplinary Applications
Dept. of Physics, University de los Andes, Bogota, Colombia (online)
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Universidad de los Andes | Facultad de Ciencias Departamento de Física 2024
Workshop on Particle Detectors for Interdisciplinary Applications. September 30 – October 2.

Financial interests and relationship

NOTHING TO DISCLOSE!

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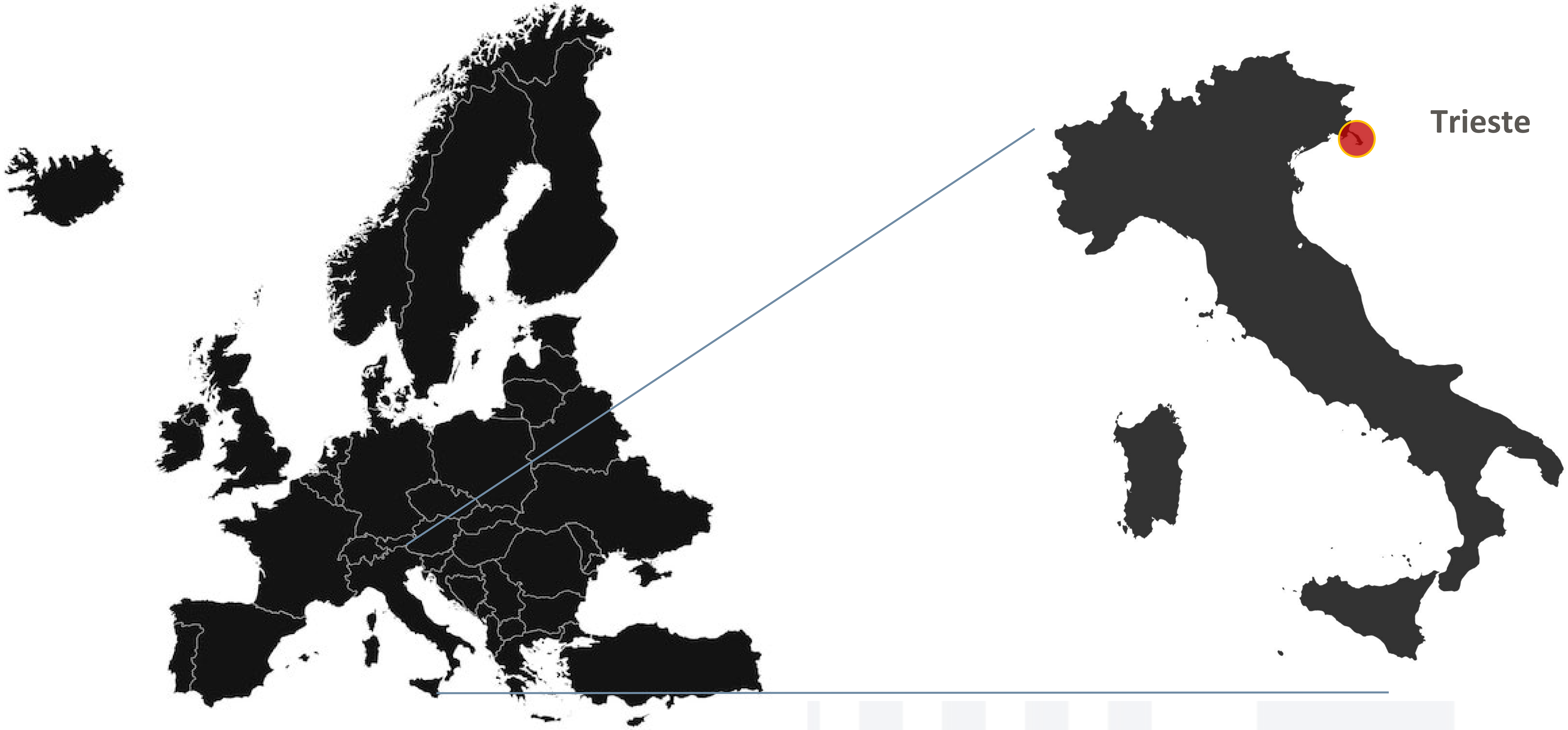
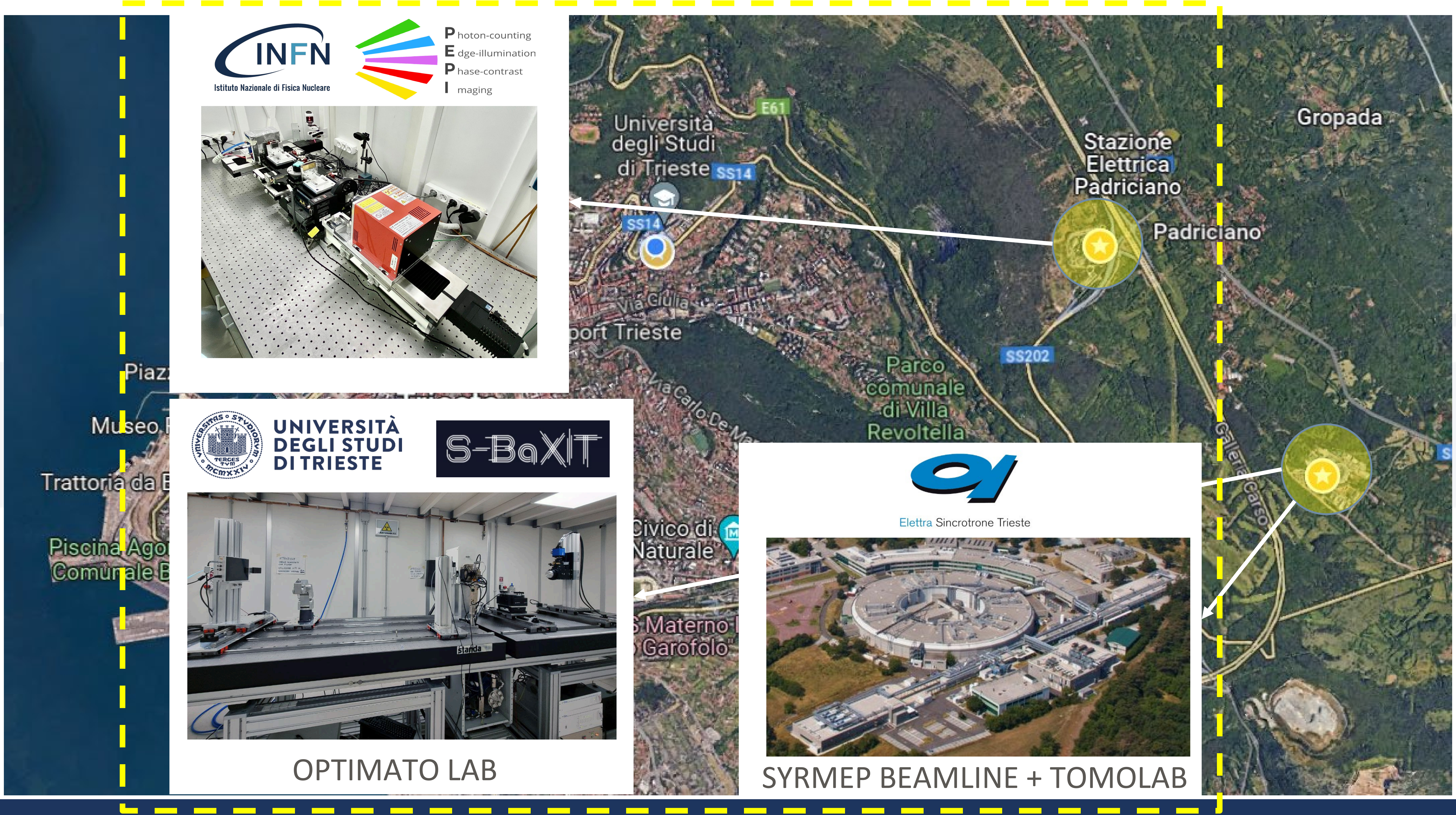
Finanziato dall'Unione europea
NextGenerationEU

TRIESTE X-RAY TOMOGRAPHY COLLABORATIVE



TRIESTE X-RAY TOMOGRAPHY COLLABORATIVE



OUTLINE

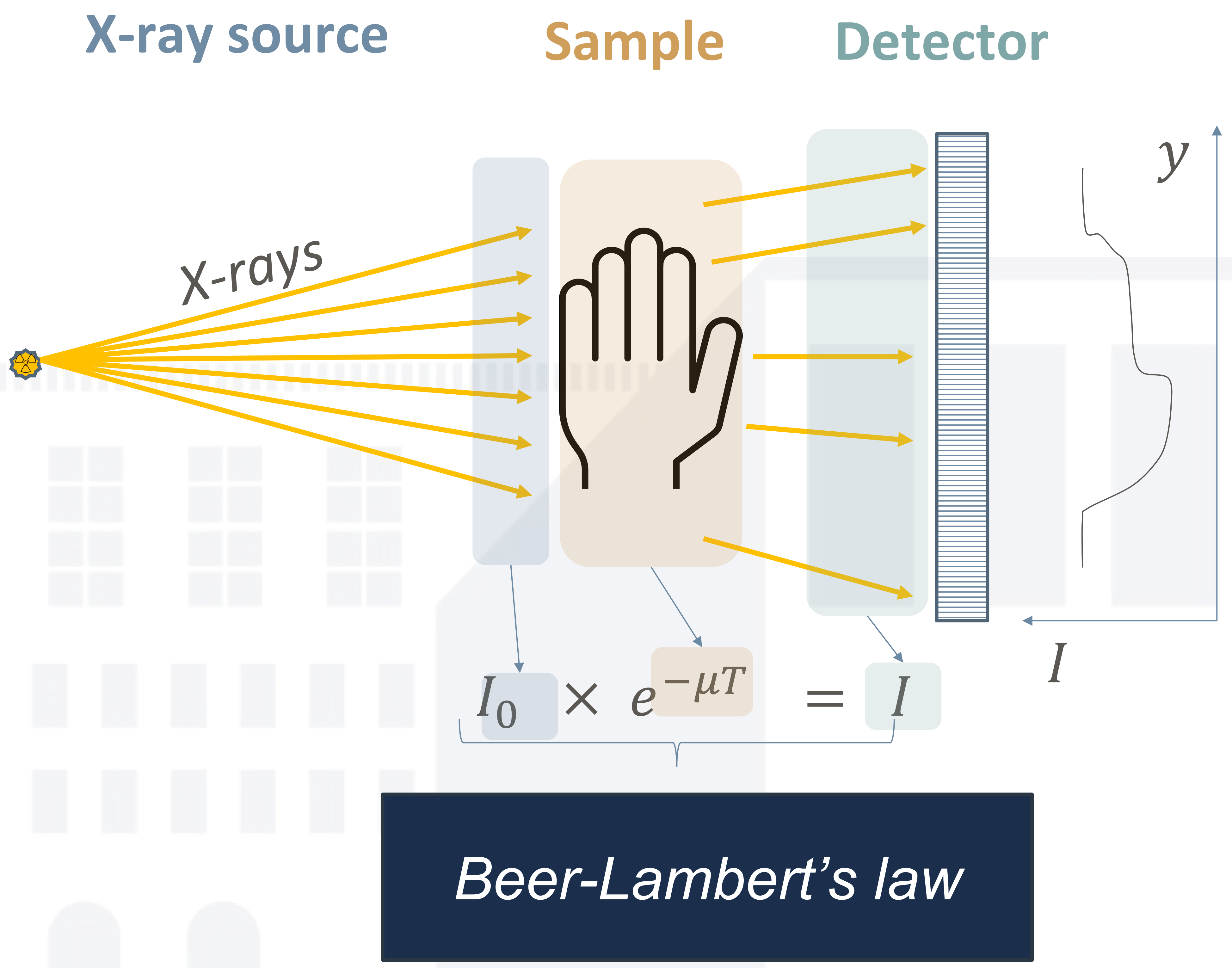
- **X-ray imaging fundamentals**
- Spectral imaging
- Phase-contrast imaging
- Spectral phase-contrast imaging

WHAT'S CONVENTIONAL X-RAY IMAGING?

The basics before getting advanced…

The key elements of conventional X-ray imaging are:

1. **X-ray source** (e.g., X-ray tube)
2. **Sample** to be investigated
3. **Detector** sensitive only to X-ray intensity

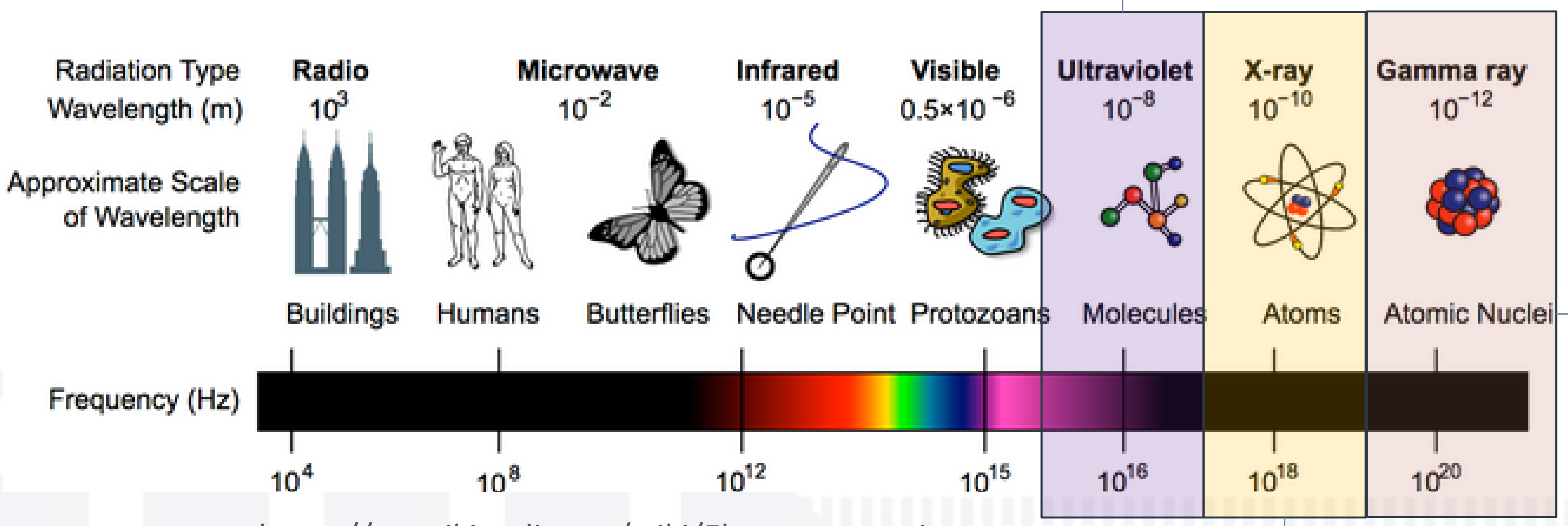


Sample's visibility depends on the (partial) attenuation of X-rays:

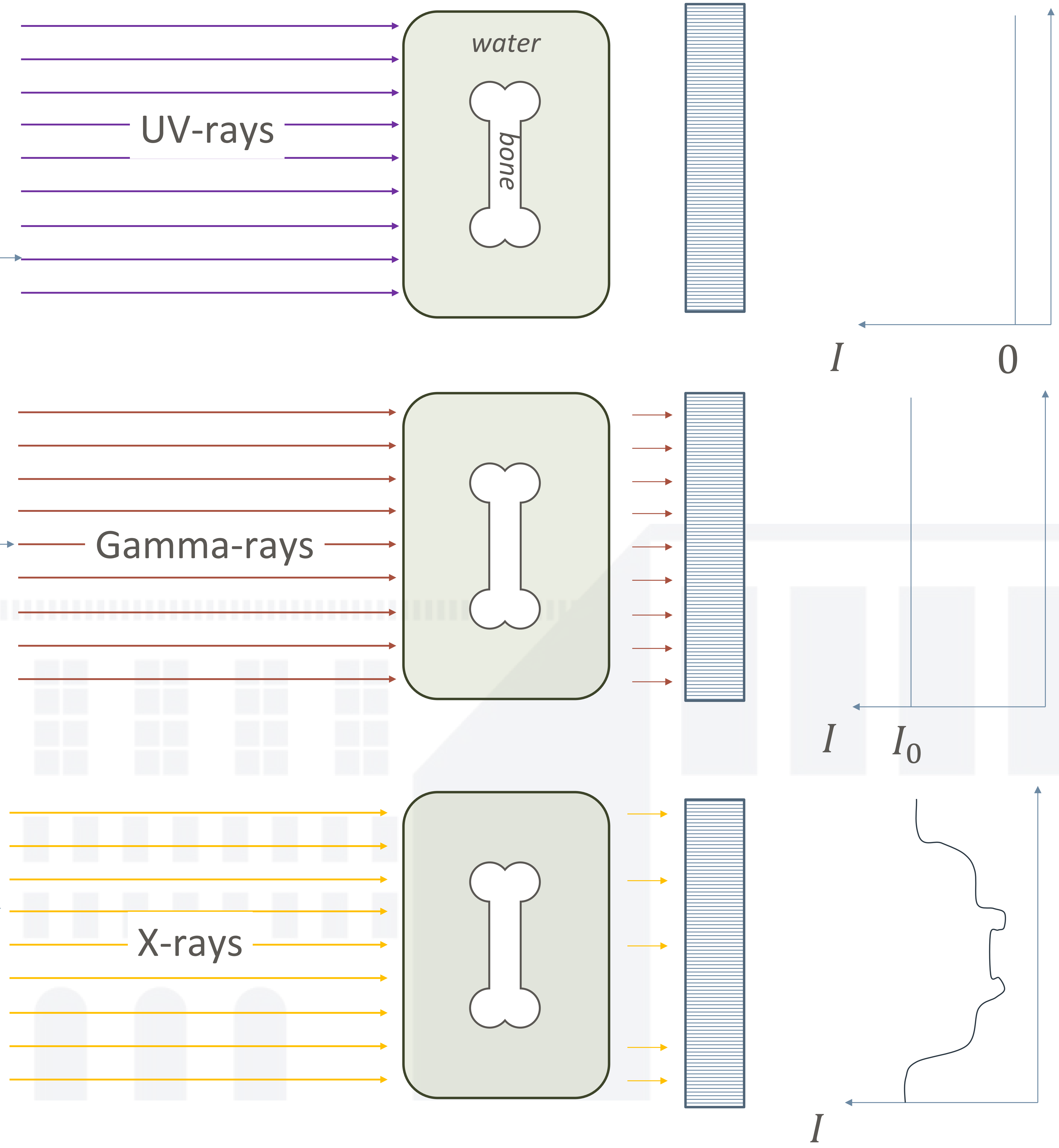
- Sample thickness (T)
- Linear attenuation coefficient of the sample (μ)

WHY X-RAYS?

The basics before getting advanced…



https://en.wikipedia.org/wiki/Electromagnetic_spectrum



Because:

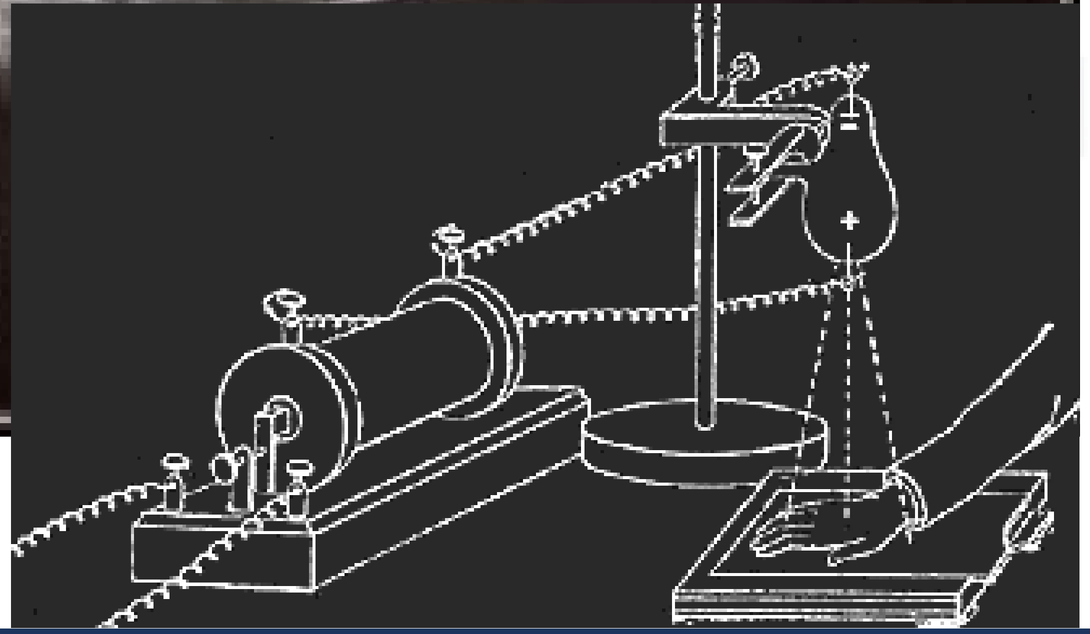
1. They have a **sufficiently weak interaction** with matter → <u>they can partly go through</u>

2. They have a **sufficiently strong interaction** with matter → <u>contrast</u> (i.e. attenuation difference) among transversed features <u>is formed</u> on the detector

130 YEARS OF PROGRESS…

First radiograph by
Wilhelm Conrad Roentgen
- Fall 1895,
- 1st Nobel Prize in Physics 1901

130 years later…



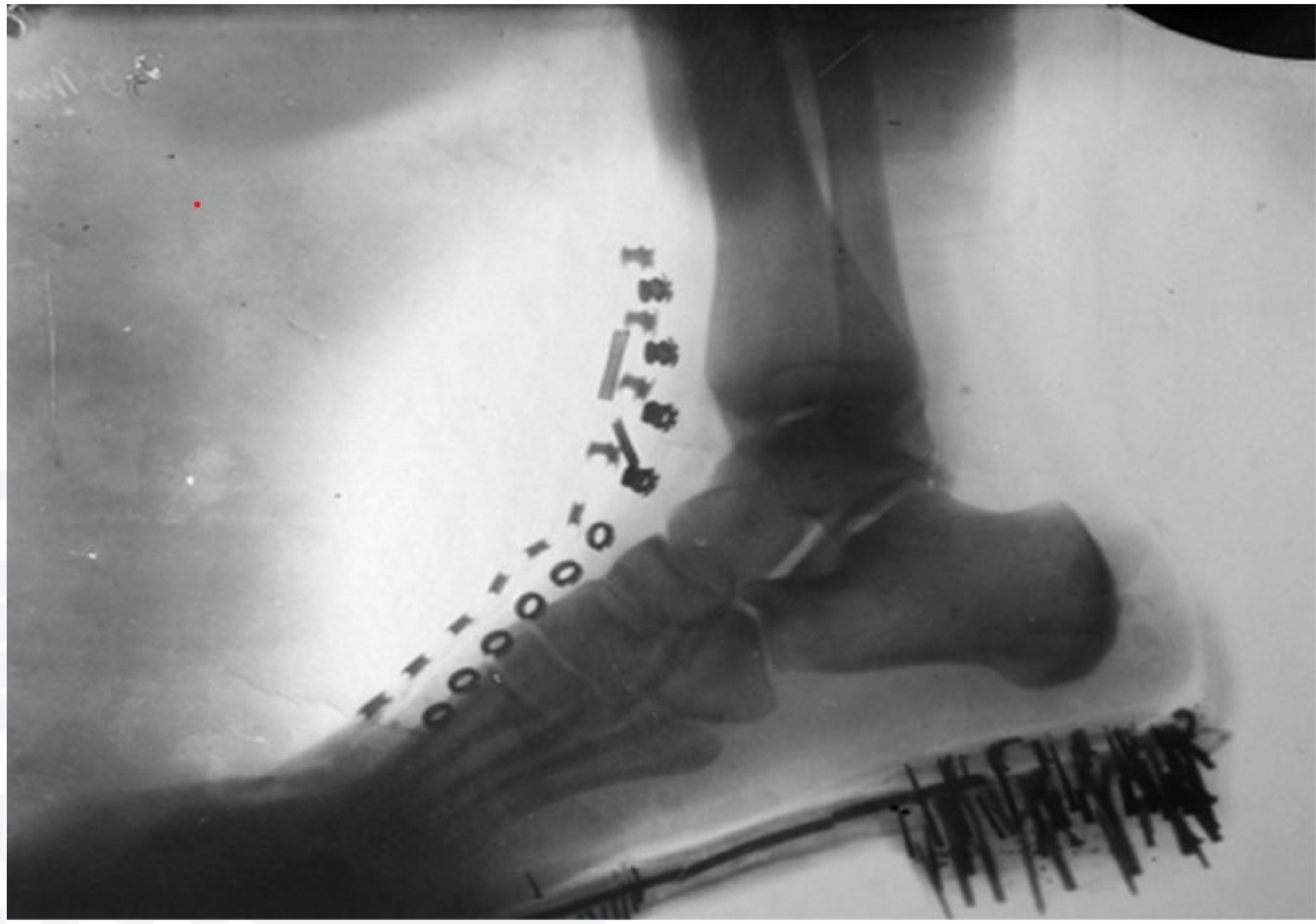
← First commercial device
spring 1896

Commercial devices →
nowadays

…CONSPIRACY THEORY DETOUR…

Wilhelm Conrad Roentgen
Fall 1895

1 year later…



Nikola Tesla
1896

Was Roentgen the first to discover X-rays?
Check this out
https://doiserbia.nb.rs/img/doi/0025-8105/2016/0025-81051610313V.pdf

ADVANCED X-RAY IMAGING

CONVENTIONAL IMAGING

1. **X-ray source –** conventional X-ray tube
2. **Detector** sensitive only to beam intensity
3. **Sample** to be investigated

ADVANCED IMAGING

1. **X-ray source with high coherence (spatial/temporal)** or **capable of producing different X-ray spectra at the same time**
2. **Detector sensitive to the energy spectrum of x-rays**
3. **Optical elements to condition the beam upstream and/or downstream of the sample**

ADVANCED X-RAY IMAGING

SPECTRAL imaging

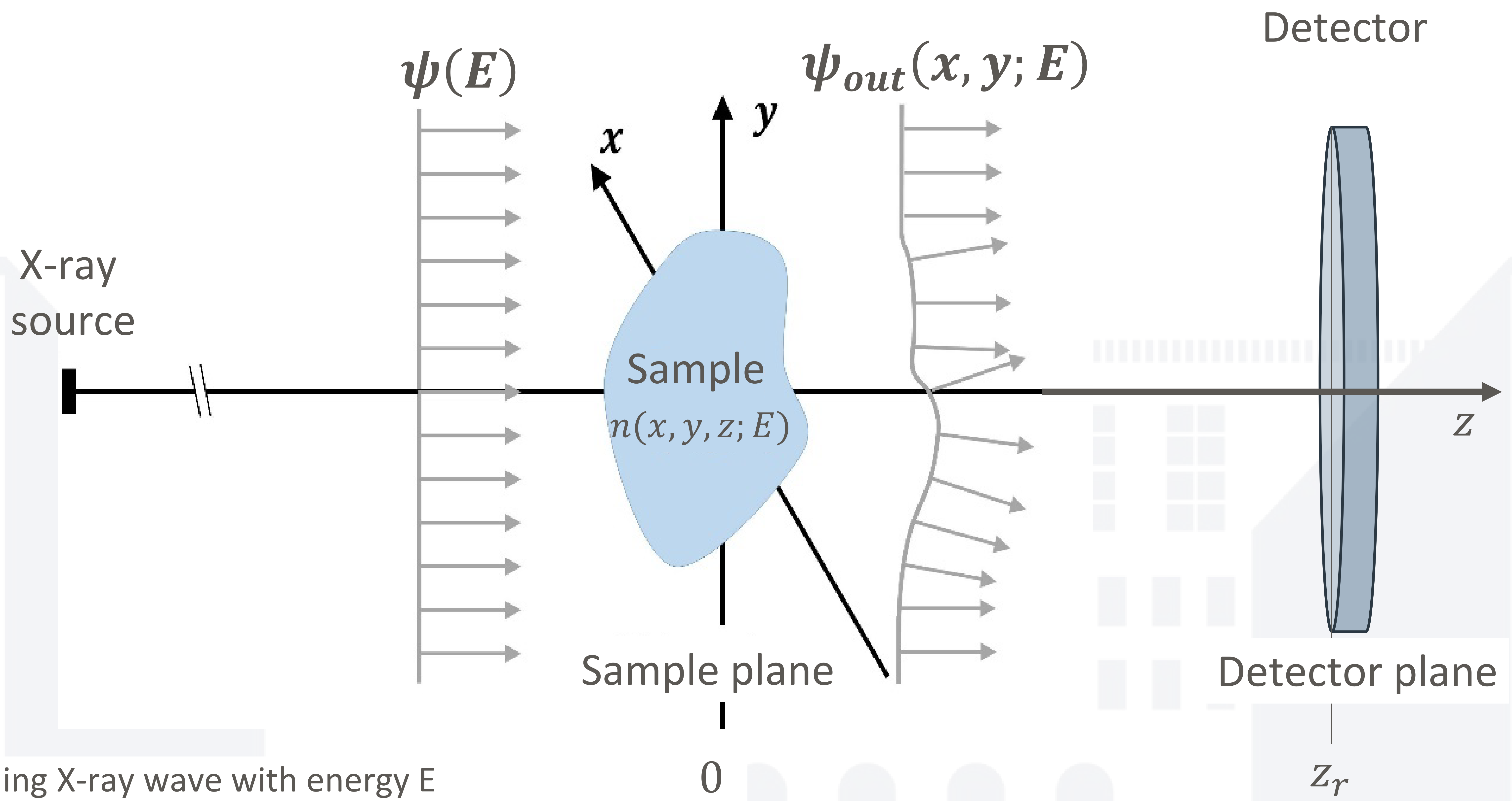
PHASE-CONTRAST imaging

ADVANCED IMAGING

1. X-ray source with high coherence (spatial/temporal) or capable of producing different X-ray spectra at the same time
2. Detector sensitive to the energy spectrum of x-rays
3. Optical elements to condition the beam upstream and/or downstream of the sample

X-RAY IMAGING IN WAVE FORMALISM

Just a few slides

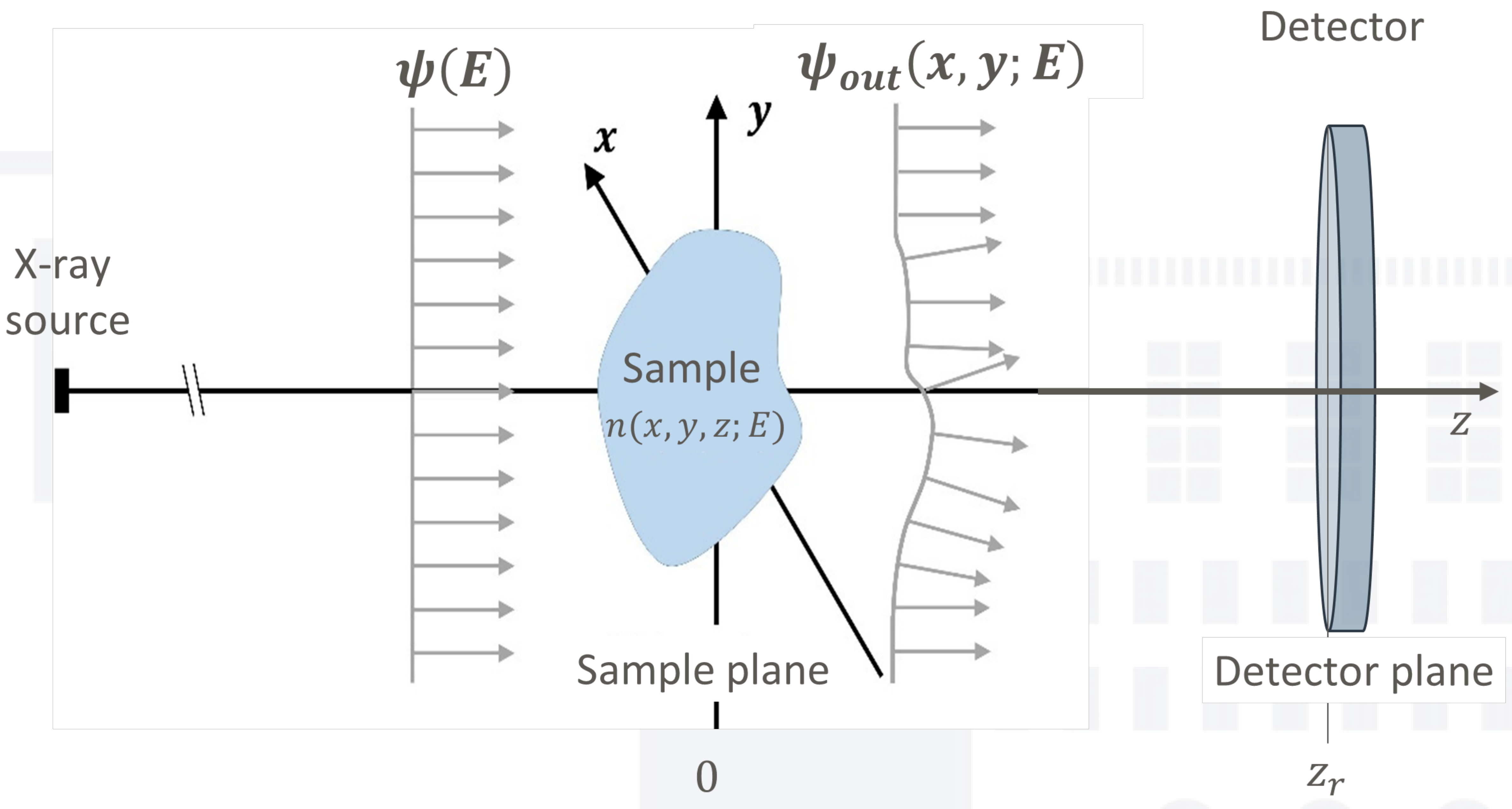


$\psi(E)$ = incoming X-ray wave with energy E
$\psi_{out}(x, y; E)$ = outgoing X-ray wave modulated by the sample
$n(x, y, z; E)$ = complex refractive index

Rigon, Luigi. "X-ray imaging with coherent sources." (2014): 193-216.

X-RAY IMAGING IN WAVE FORMALISM

Just a few slides



$\psi_{in}(E)$ = incoming plane wave at energy E
$\psi_{out}(x, y; E)$ = object-modulated wave at energy E
k = wave number

- In the wave model the interaction of X-rays with matter is described through the complex refractive index *n*

$$n(E) = 1 - \delta(E) + i\beta(E)$$

$$\beta(E) = \frac{\mu(E)}{2k}$$

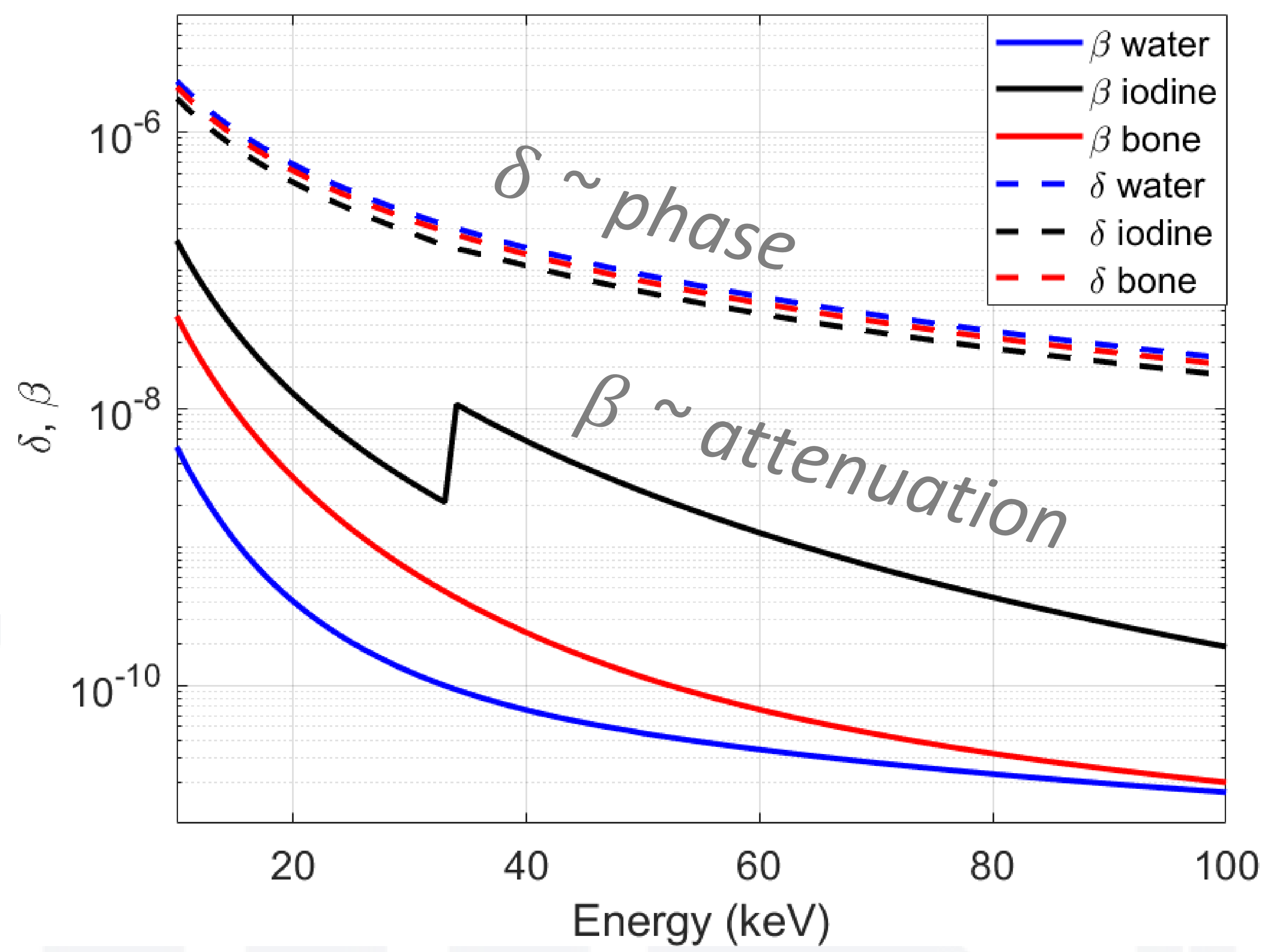
absorption coefficient

$$\psi_{out}(x, y; E) = \psi_{in}(E) e^{-k\int \beta(x,y,z;E)dz} e^{-ik\int \delta(x,y,z;E)dz}$$

Attenuation → Spectral imaging

Phase shift → Phase-contrast imaging

WHY SPECTRAL?

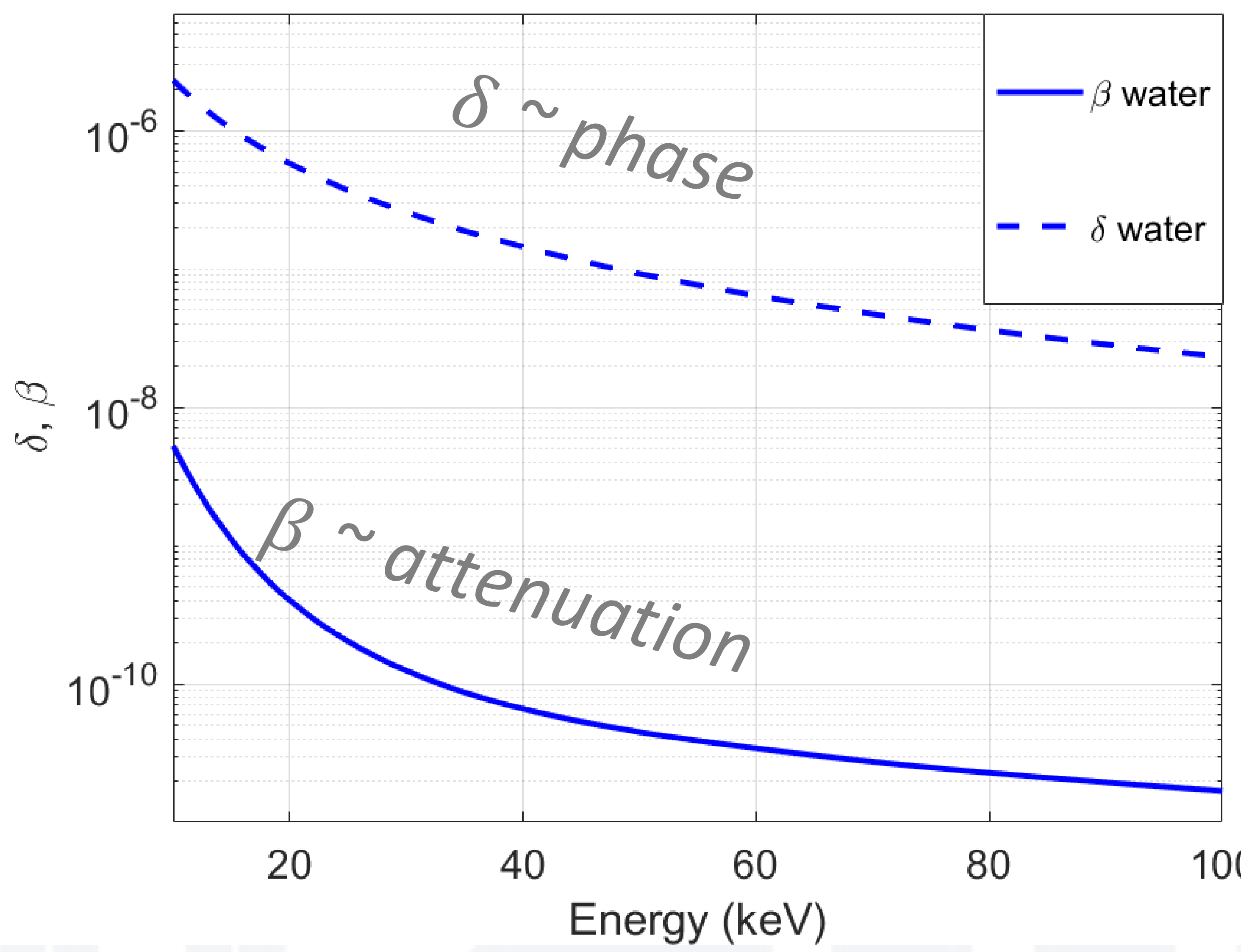


- *Energy dependence of the attenuation coefficient is sensitive to chemical composition (i.e., difference in atomic number Z)*

$$\mu(E) = \underbrace{\mu_{photoelectric}(E)}_{\propto \frac{Z^4}{E^{3.5}}} + \underbrace{\mu_{scattering}(E)}_{\propto Z} + \underbrace{\mu_{K_{edge}}(E)}_{\neq 0 \text{ at } K_{edge}}$$

to separate and quantify chemical elements!

WHY PHASE-CONTRAST?



- For light materials and energies in the range 10 – 100 keV phase effects are much larger than attenuation

$$\frac{\delta}{\beta} \sim 10^3$$

to increase visibility of light materials! (e.g. soft tissues)

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OUTLINE

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- **Spectral imaging**
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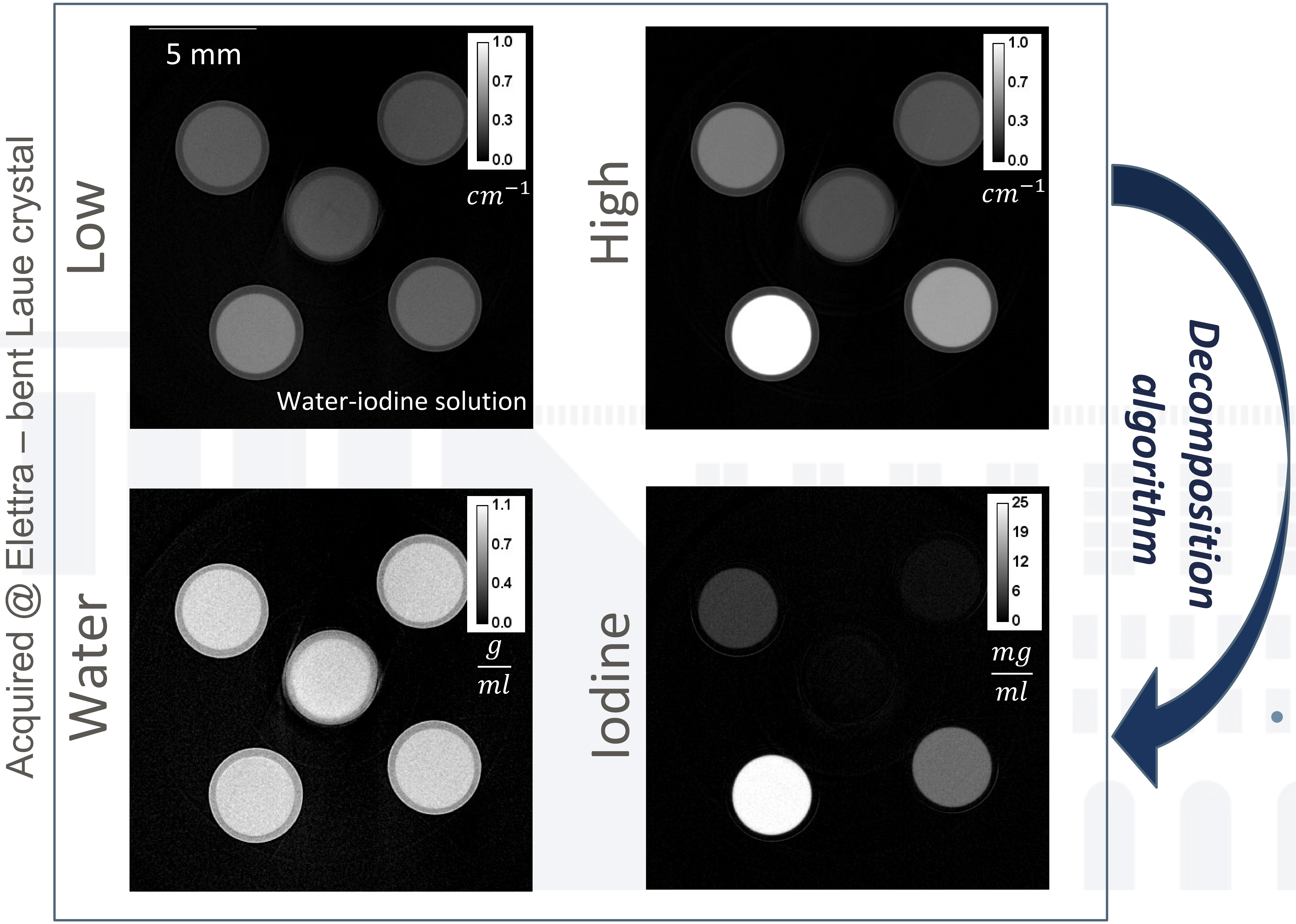
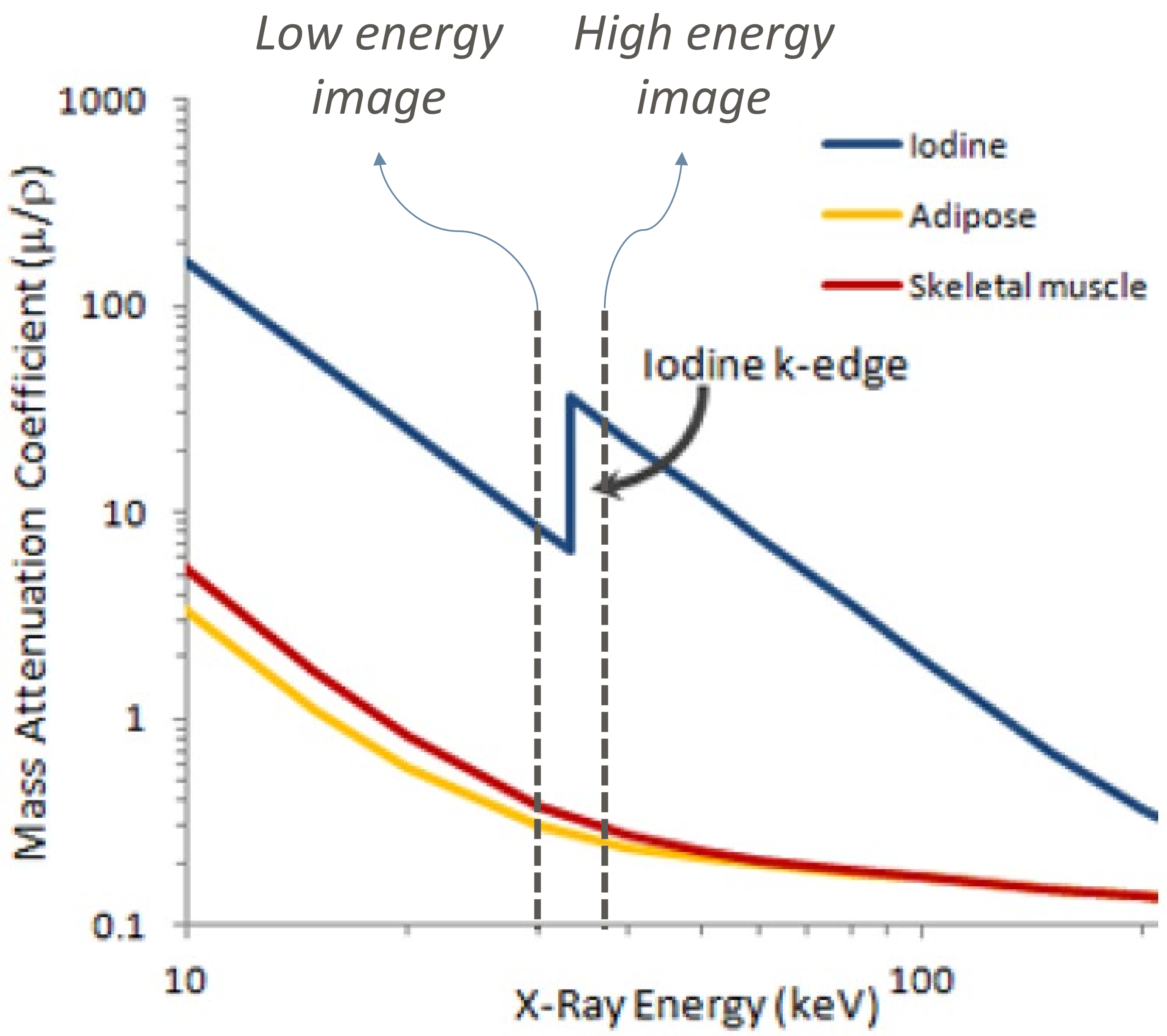
X-RAY SPECTRAL IMAGING

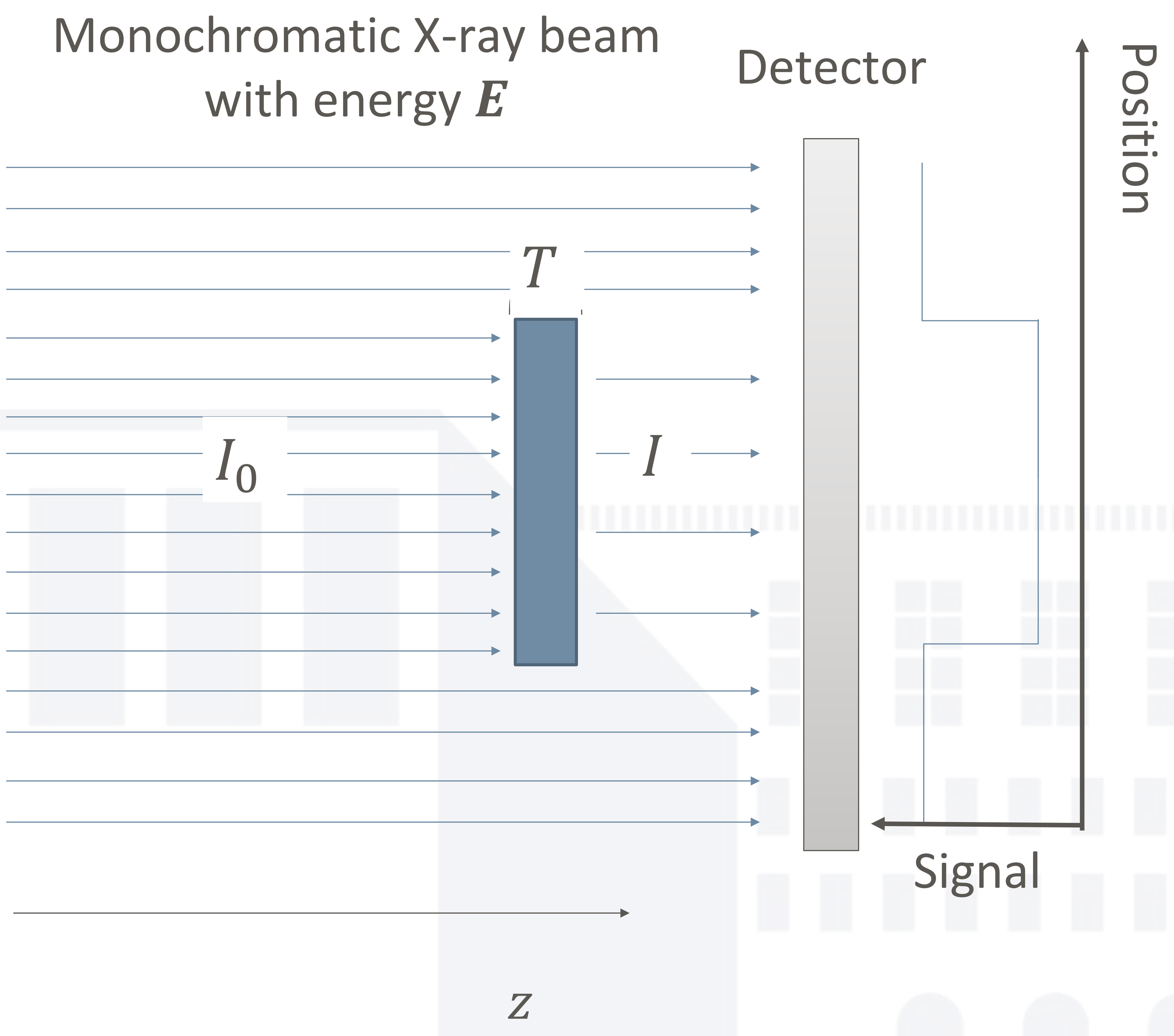


- Spectral imaging requires to probe the attenuation properties of the sample (at least) at 2 different energies



- Images acquired at different energies are processed through matrix inversion algorithms to **extract (quantitative) maps of elements** of interest

X-RAY SPECTRAL RADIOGRAPHY – BASICS (1)



Beer-Lambert law

$$I = I_0 e^{-\int \mu(E) dz}$$

For a homogenous object of thickness T

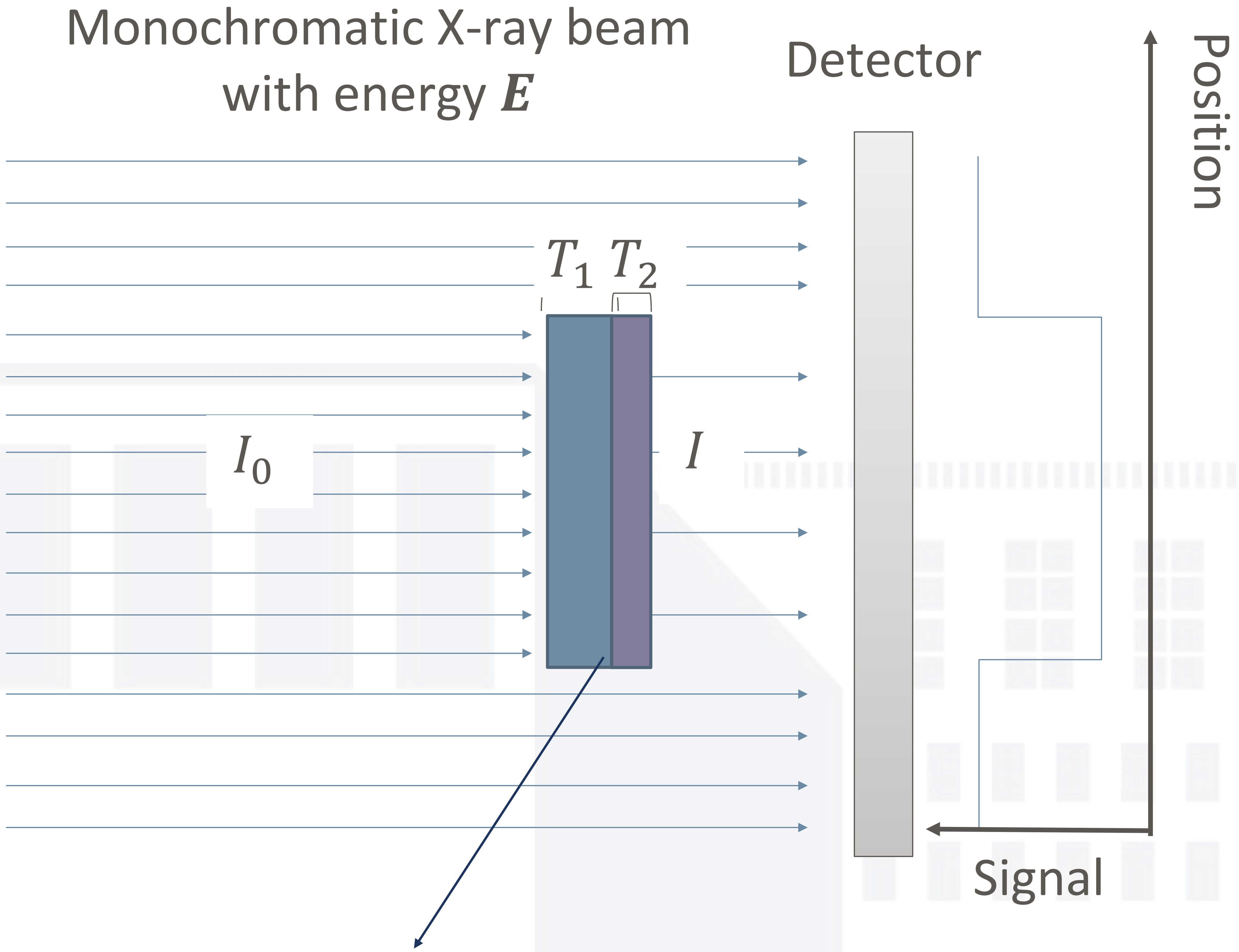
$$= I_0\, e^{-\mu(E)\, T}$$

$$I = I_0 e^{-\frac{\mu}{\rho}(E)\, \rho T}$$

$\boldsymbol{\frac{\mu}{\rho}(E)}$ → mass attenuation coefficient

independent on the physical state of the material/compound

X-RAY SPECTRAL RADIOGRAPHY – BASICS (2)



Note: the object can be also a mixture of the two materials

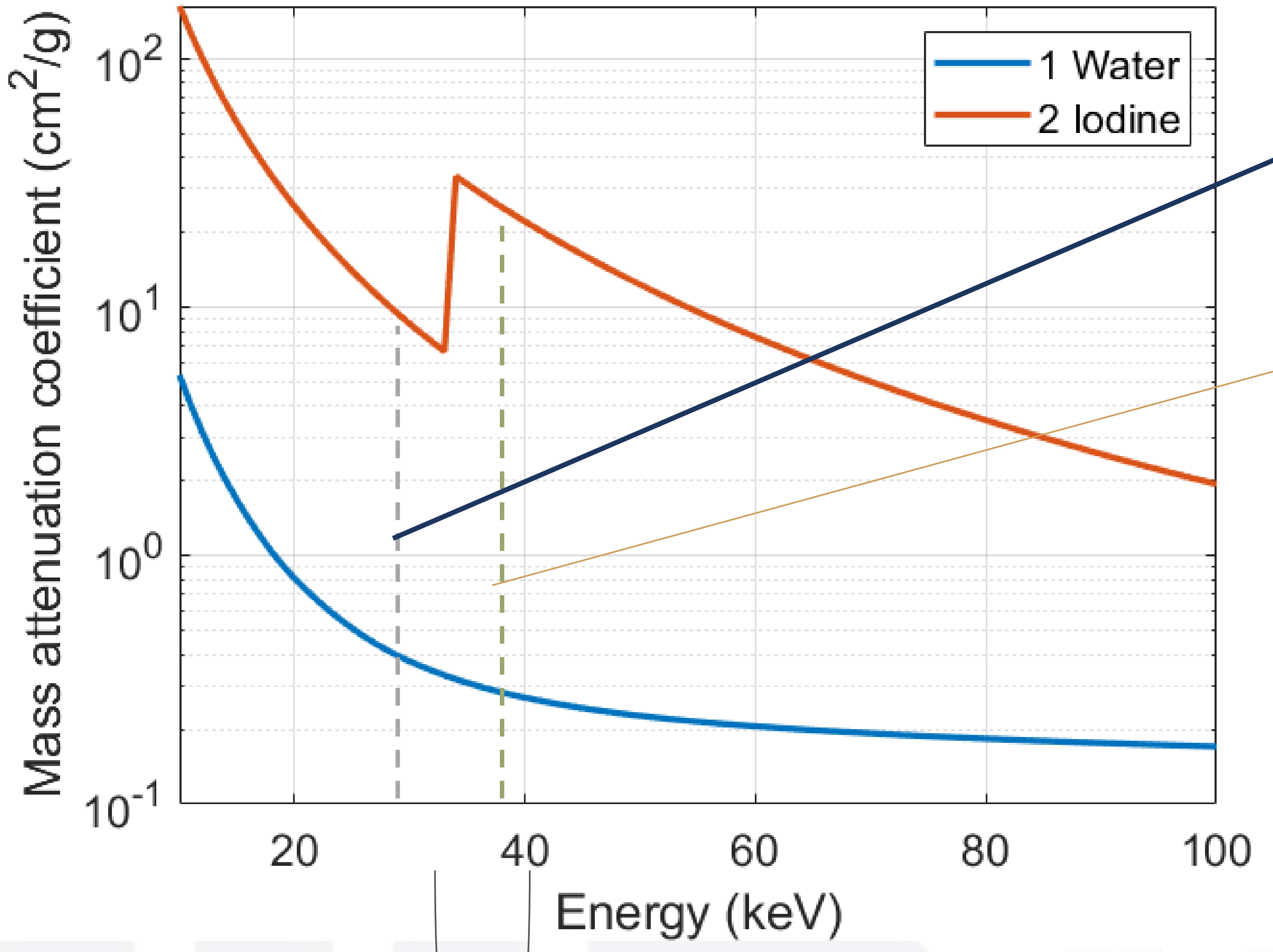
If we have 2 objects made of different materials…

$$I = I_0 e^{\left[-\frac{\mu}{\rho}(E)\big|_1 \rho_1 T_1 - \frac{\mu}{\rho}(E)\big|_2 \rho_2 T_2\right]}$$

$$P \equiv -\ln\left(\frac{I}{I_0}\right) = \left[\frac{\mu}{\rho}(E)\Big|_1 \rho_1 T_1 + \frac{\mu}{\rho}(E)\Big|_2 \rho_2 T_2\right]$$

From a single image I, one cannot uncouple/distinguish the 2 materials, i.e. **we cannot solve the equation for $\boldsymbol{\rho_1 T_1}$ and $\boldsymbol{\rho_2 T_2}$**

BASIS MATERIAL DECOMPOSITION



Two monochromatic energy channels (e.g., with synchrotron)

Low energy image $P^l = \left.\frac{\mu}{\rho}\right|_1^l \rho_1 T_1 + \left.\frac{\mu}{\rho}\right|_2^l \rho_2 T_2$

High energy image $P^h = \left.\frac{\mu}{\rho}\right|_1^h \rho_1 T_1 + \left.\frac{\mu}{\rho}\right|_2^h \rho_2 T_2$

In a matrix form:

$$\begin{pmatrix} P^l \\ P^h \end{pmatrix} = \begin{pmatrix} \left.\frac{\mu}{\rho}\right|_1^l & \left.\frac{\mu}{\rho}\right|_2^l \\ \left.\frac{\mu}{\rho}\right|_1^h & \left.\frac{\mu}{\rho}\right|_2^h \end{pmatrix} \begin{pmatrix} \rho_1 T_1 \\ \rho_2 T_2 \end{pmatrix}$$

Matrix inversion:

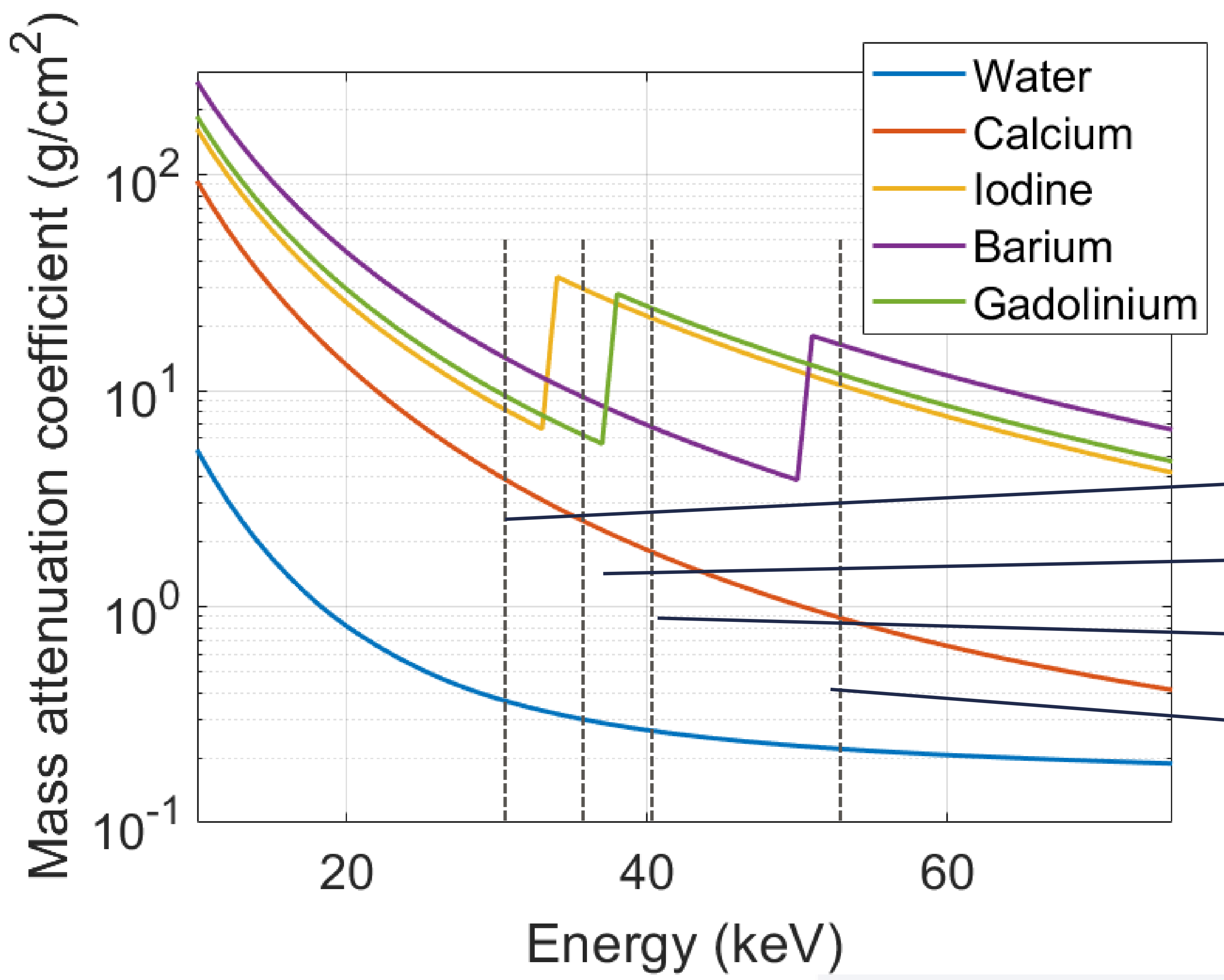
$$\begin{pmatrix} \rho_1 T_1 \\ \rho_2 T_2 \end{pmatrix} = \begin{pmatrix} \left.\frac{\mu}{\rho}\right|_1^l & \left.\frac{\mu}{\rho}\right|_2^l \\ \left.\frac{\mu}{\rho}\right|_1^h & \left.\frac{\mu}{\rho}\right|_2^h \end{pmatrix}^{-1} \begin{pmatrix} P^l \\ P^h \end{pmatrix}$$

References

- *Alvarez, R E; Macovski, A (1976). Energy-selective reconstructions in X-ray computerised tomography. Physics in Medicine and Biology, 21(5), 733–744.*
- Lehmann LA, Alvarez RE, Macovski A, Brody WR, Pelc NJ, Riederer SJ, Hall AL. Generalized image combinations in dual KVP digital radiography. Med Phys. 1981 Sep-Oct;8(5):659-67

MULTIPLE BASIS MATERIAL DECOMPOSITION

- The algorithm can be **extended to multiple energy channels** and **multiple** decomposition **materials**



n energy channels

$$\mu_1 = \frac{\mu}{\rho}\bigg|_1^1 \rho^1 + \cdots + \frac{\mu}{\rho}\bigg|_1^m \rho^m$$

$$\vdots \qquad \ddots \qquad \vdots$$

$$\mu_n = \frac{\mu}{\rho}\bigg|_n^1 \rho^1 + \cdots + \frac{\mu}{\rho}\bigg|_n^m \rho^m$$

$m(\leq n)$ materials

Decomposition matrix

$$\vec{\boldsymbol{\mu}} = \boldsymbol{A}\vec{\boldsymbol{\rho}}$$

$$\vec{\boldsymbol{\rho}} = \boldsymbol{A}^{-1}\vec{\boldsymbol{\mu}}$$

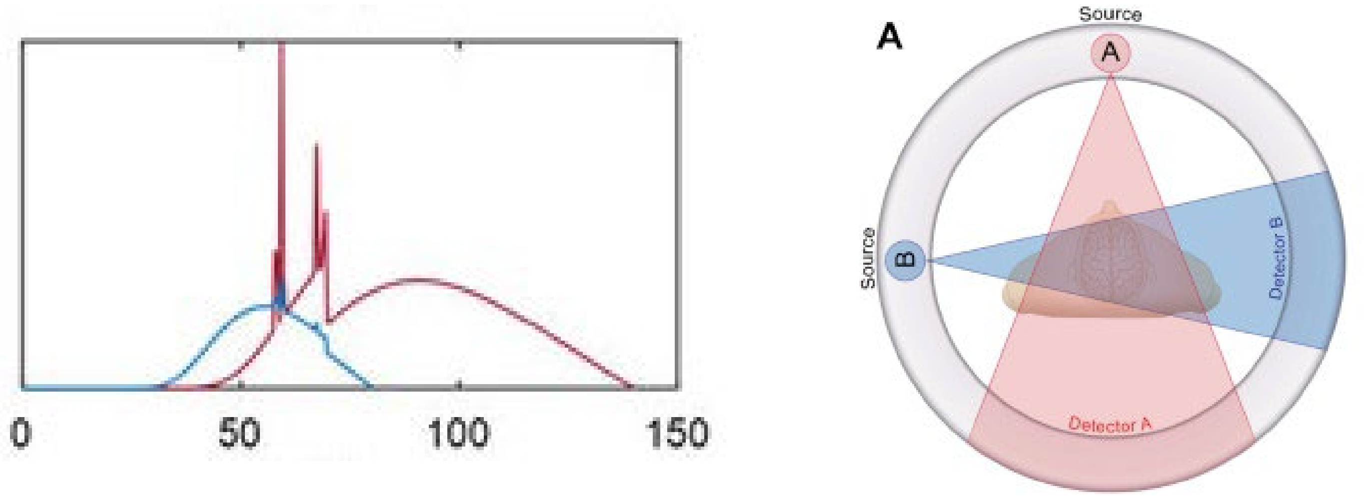
Inversion performed through least-squares

NOTE:
The choice of basis materials is crucial for the decomposition quality!
E.g., if materials are too similar the noise will be amplified

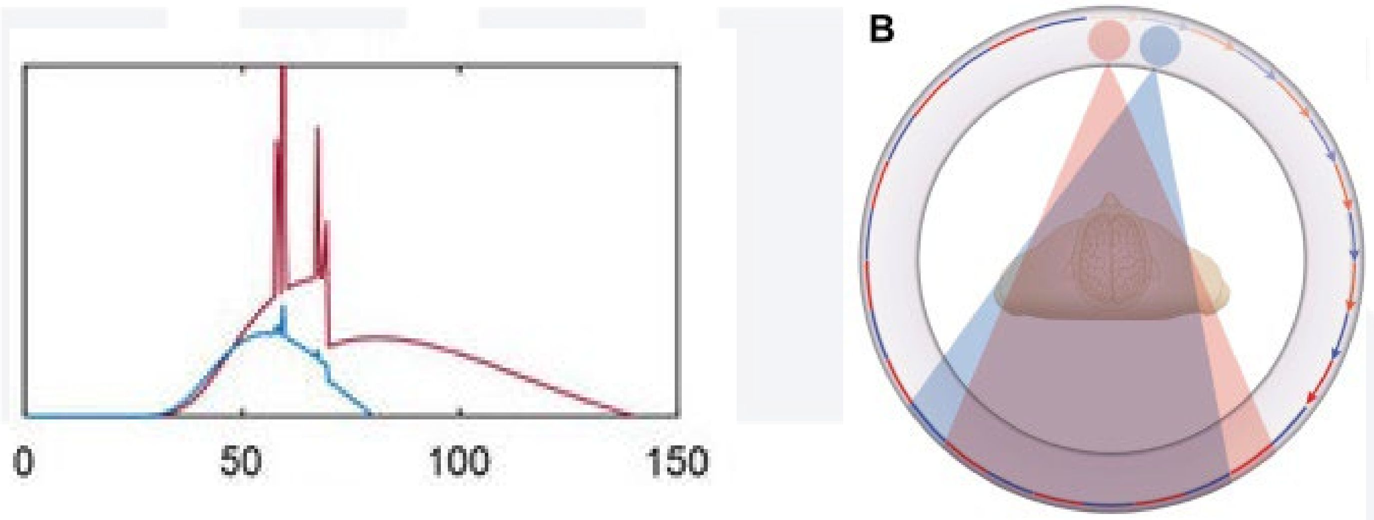
SPECTRAL IMAGING SYSTEMS

X-ray spectrum-based

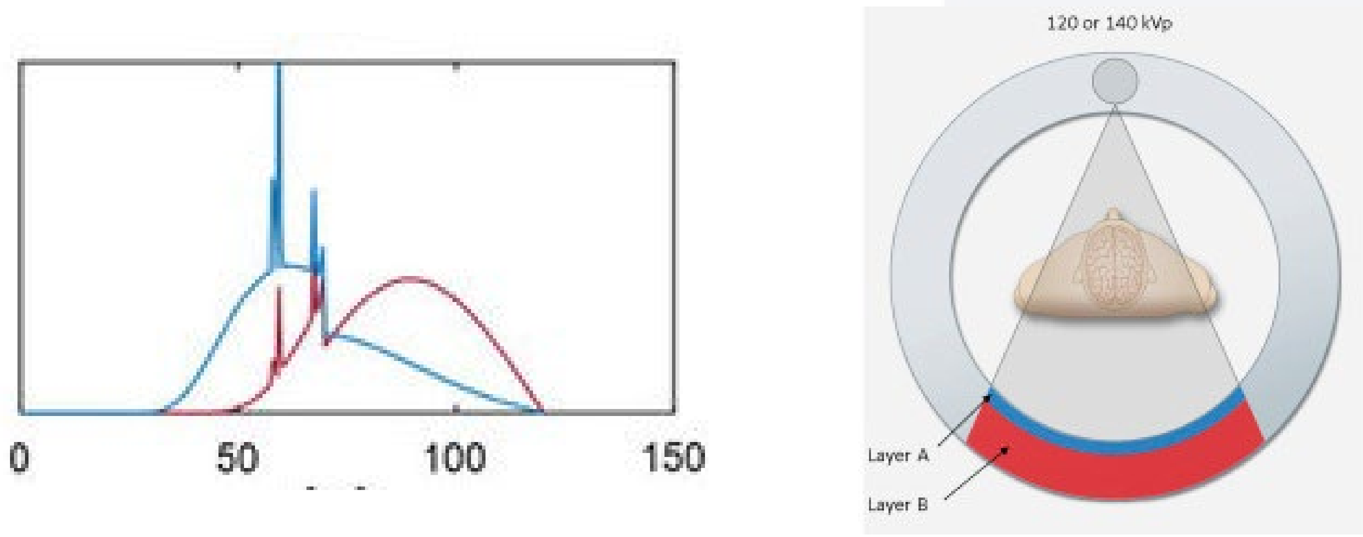
- 2 X-ray tubes with different voltages



- Voltage switching

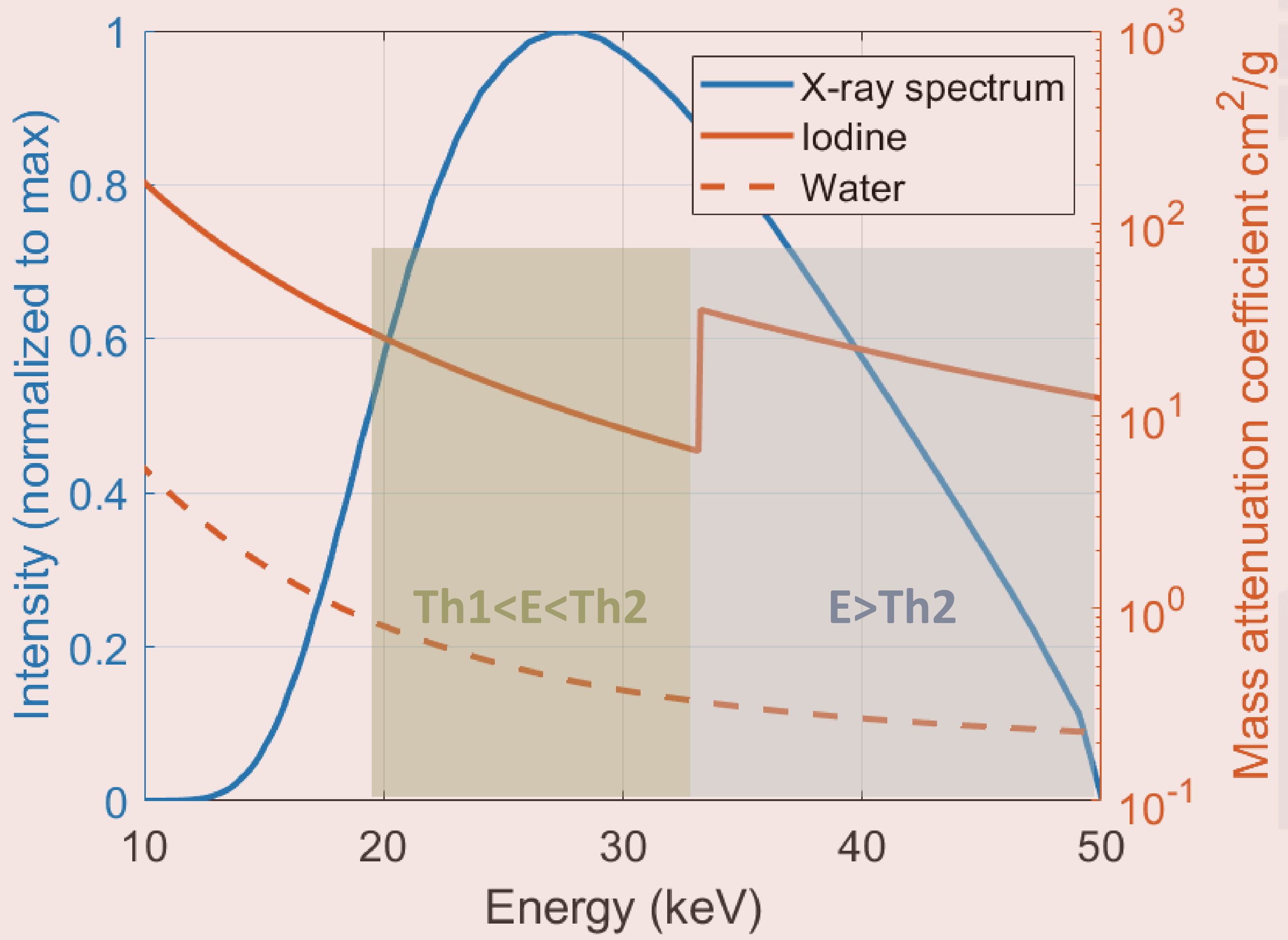


- Dual layer detectors



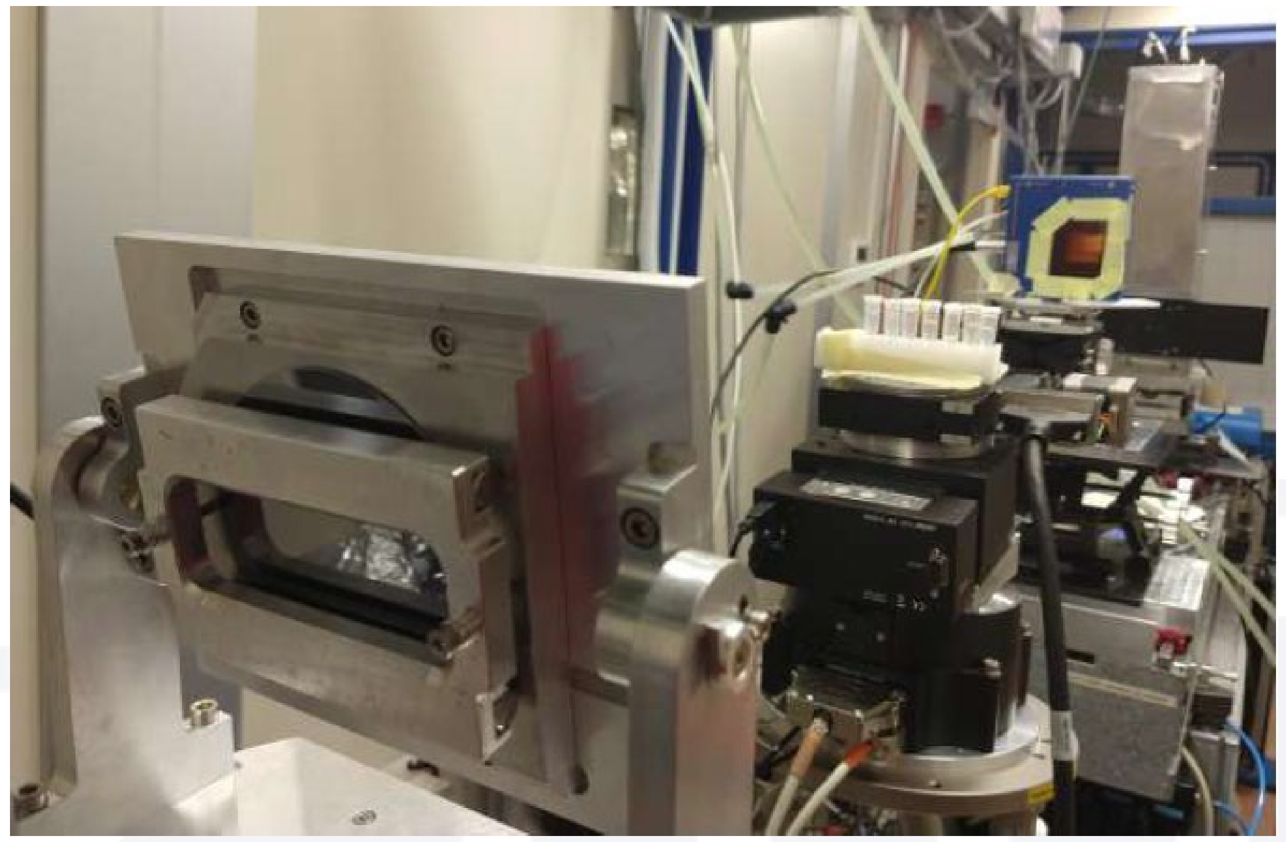
Detector-based

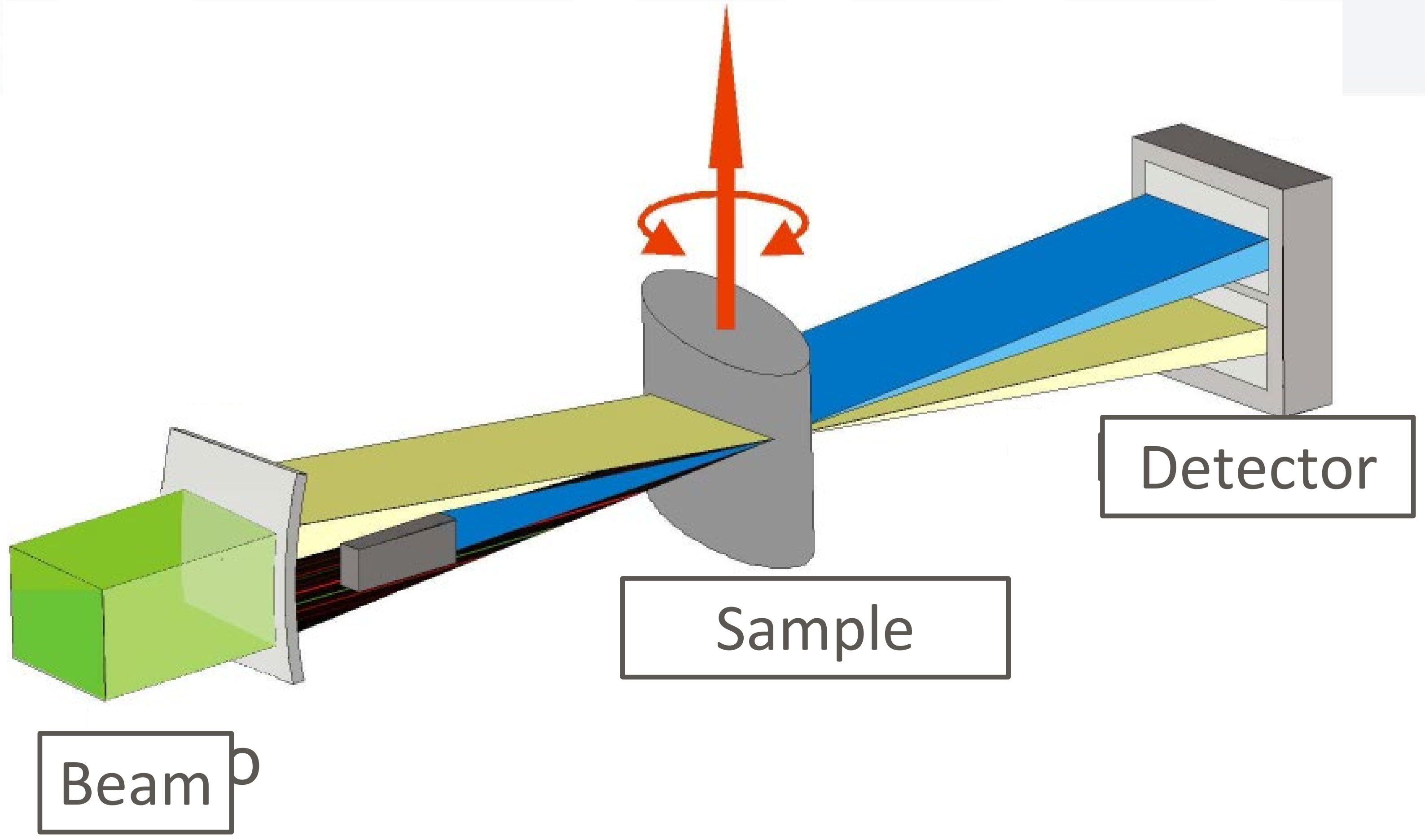
pixel-by-pixel energy discrimination



Crystal-based

energy dispersive systems based on bent crystals (@ synchrotrons)





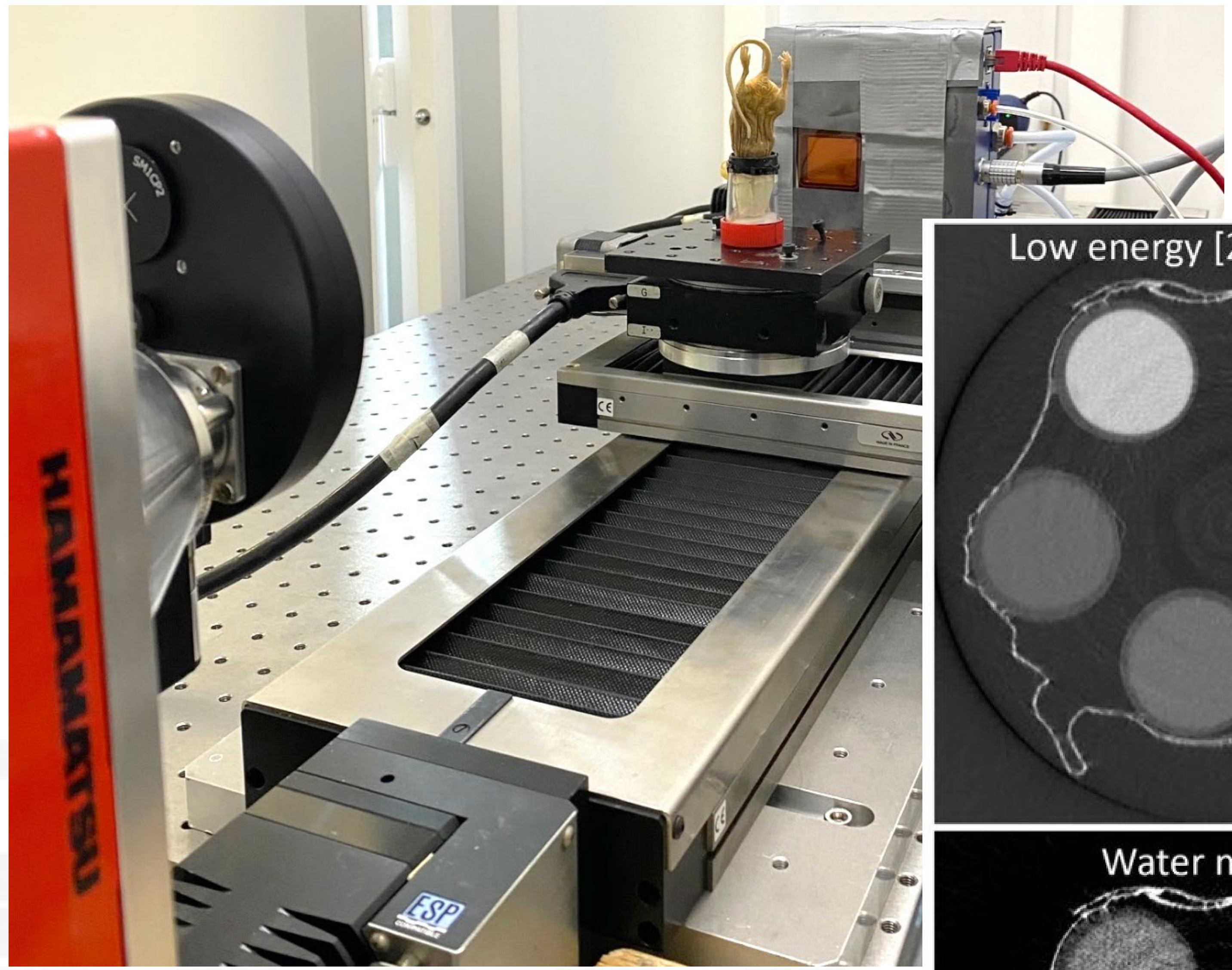
SPECTRAL DETECTORS

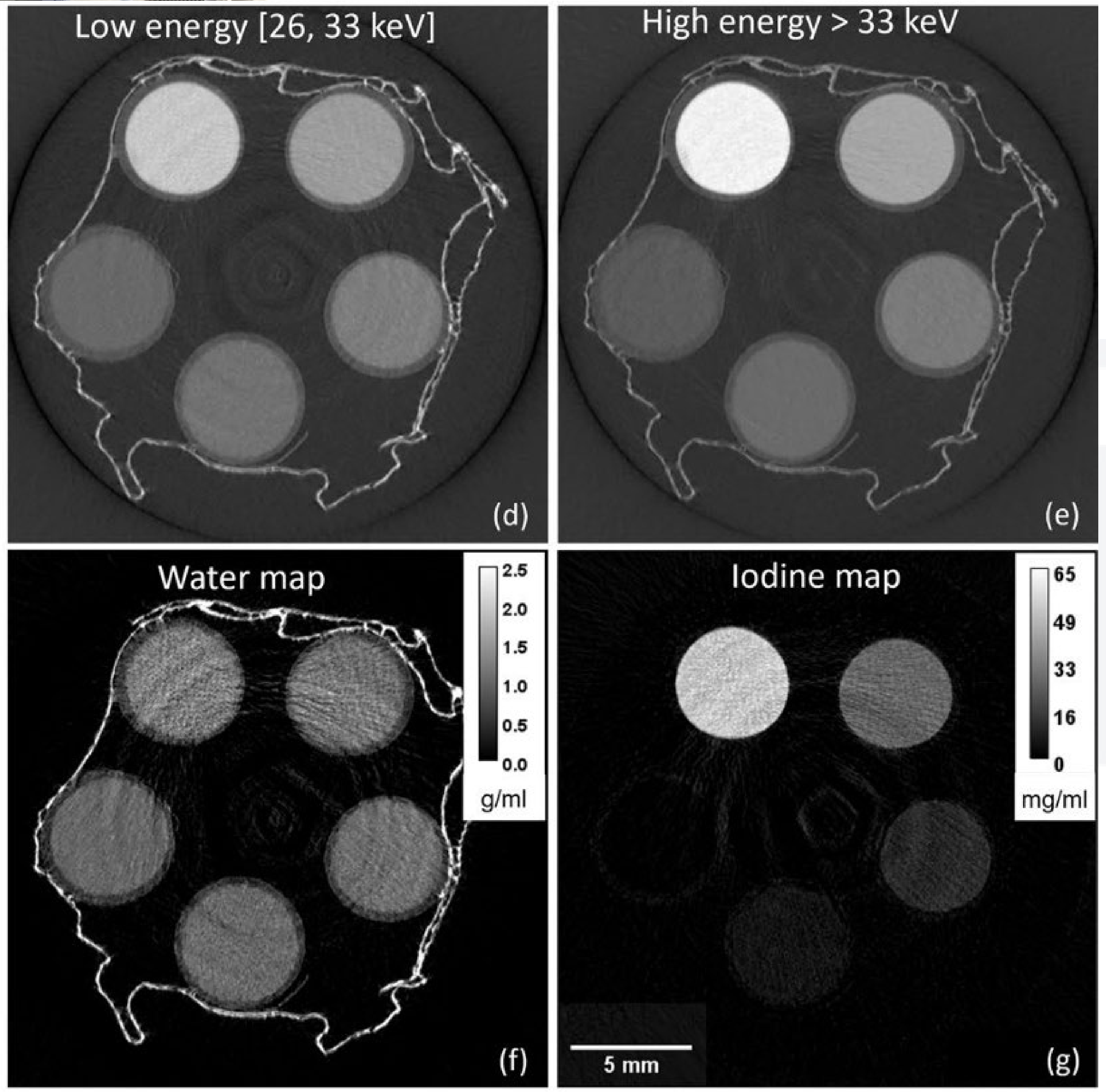
- Spectral detectors can acquire multiple **images** over **different energy channels in a single shot**
- **High-Z sensors** (CdTe, CZT, GaAs, …) are used for spectral imaging due to their high efficiency at high energies (>30 keV)

CHIP/PRODUCER	PIXEL SIZE (μm)	NUMBER OF THRESHOLDS
MEDIPIX3	55	2 (8 in 2x2 Binning)
PIXIRAD – PIXIEIII	62	2
DIRECT CONVERSION	100	2
DECTRIS - EIGER 2	75	2
TIMEPIX4	55	Full Spectrum, ~1.5 KeV resolution
…		

k-edge spectral tomography ⟷ *Funded by INFN*

F Brun, et al. *Phys. Med. & Biol.* 65.5 (2020): 055016.





Brombal, Luca, et al. *Sci. Rep.* 13.1 (2023): 4206

SPECTRAL DETECTORS: HOW DO WE MEASURE X-RAY ENERGY?

Energy measurement principle

- **Time-over-threshold**
  - Example: *Timepix*
- **Photon counting with multiple thresholds**
  - Example: *Medipix, Pixirad*
- **Charge integrating single photon sensitivity**
  - Example: *CITIUS by REIKEN*

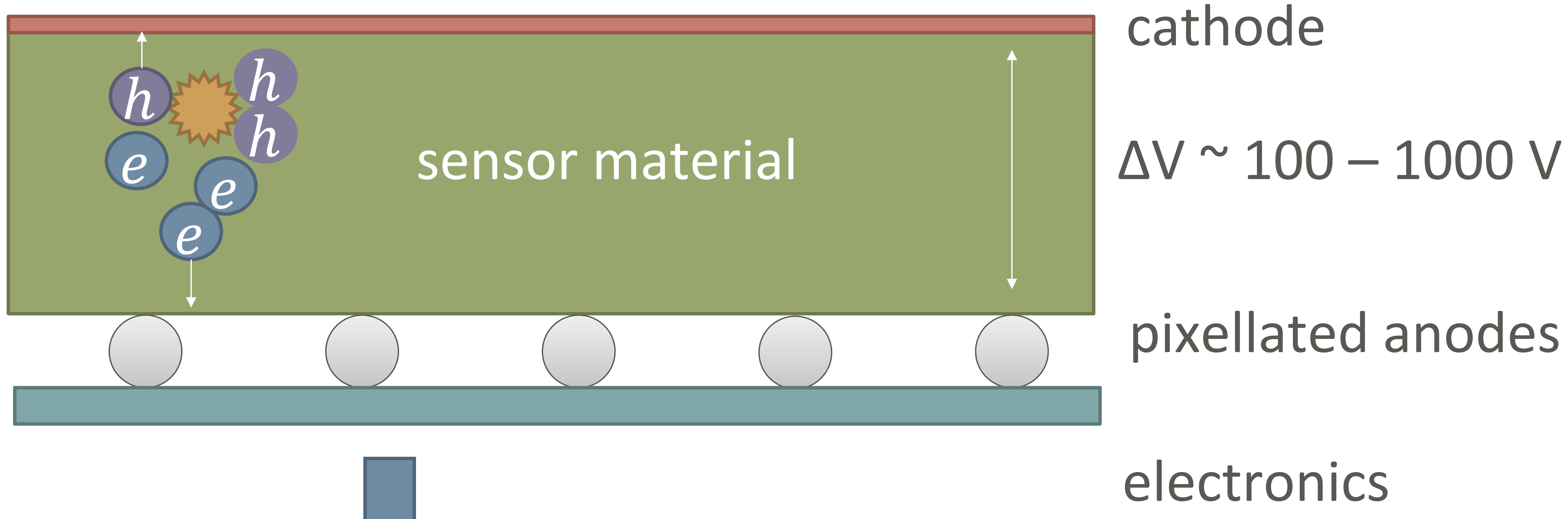
ENERGY MEASUREMENT VIA TIME-OVER-THRESHOLD (TOT)

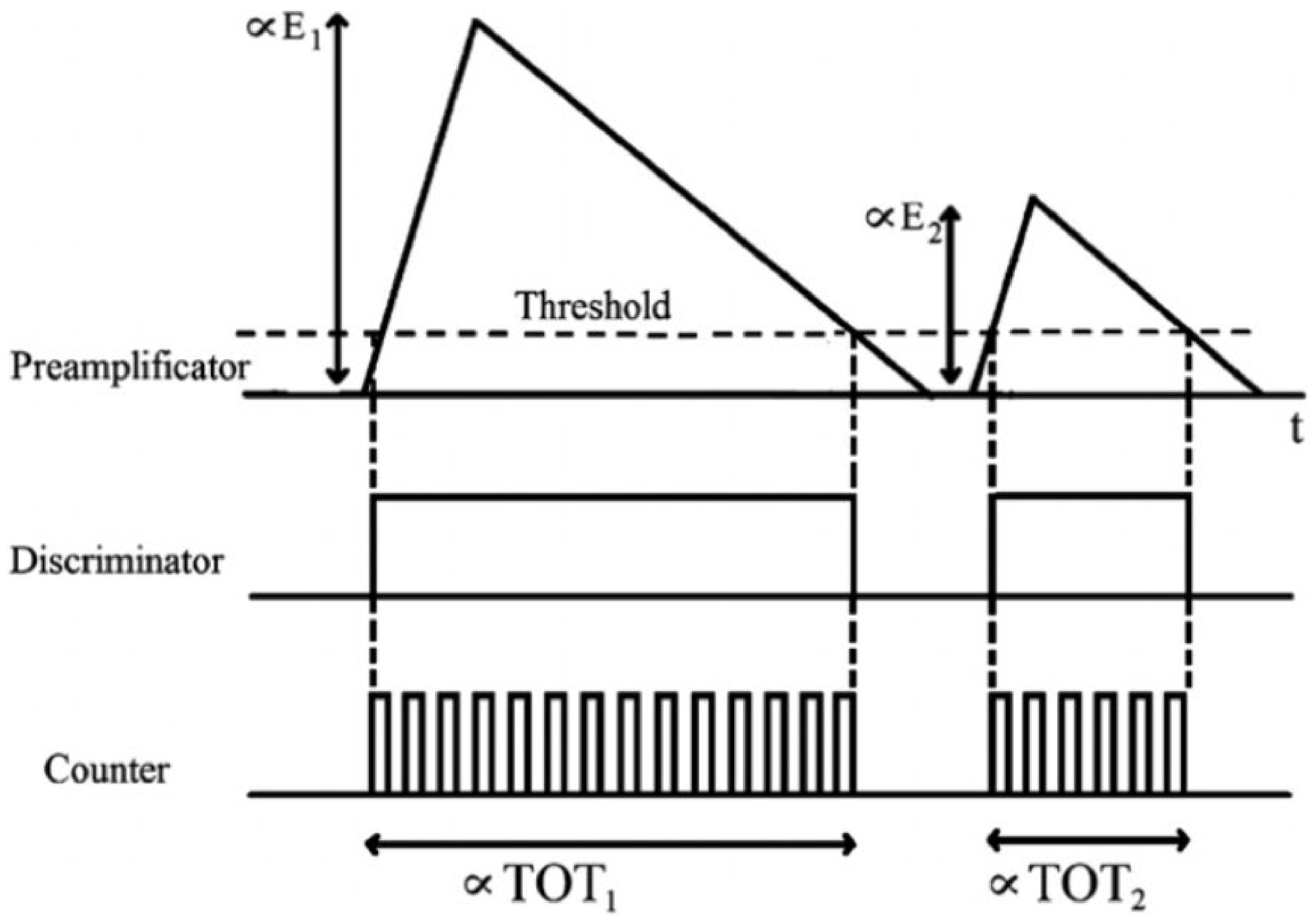
The signal amplitude and duration is proportional to the energy released in the sensor from the X-ray

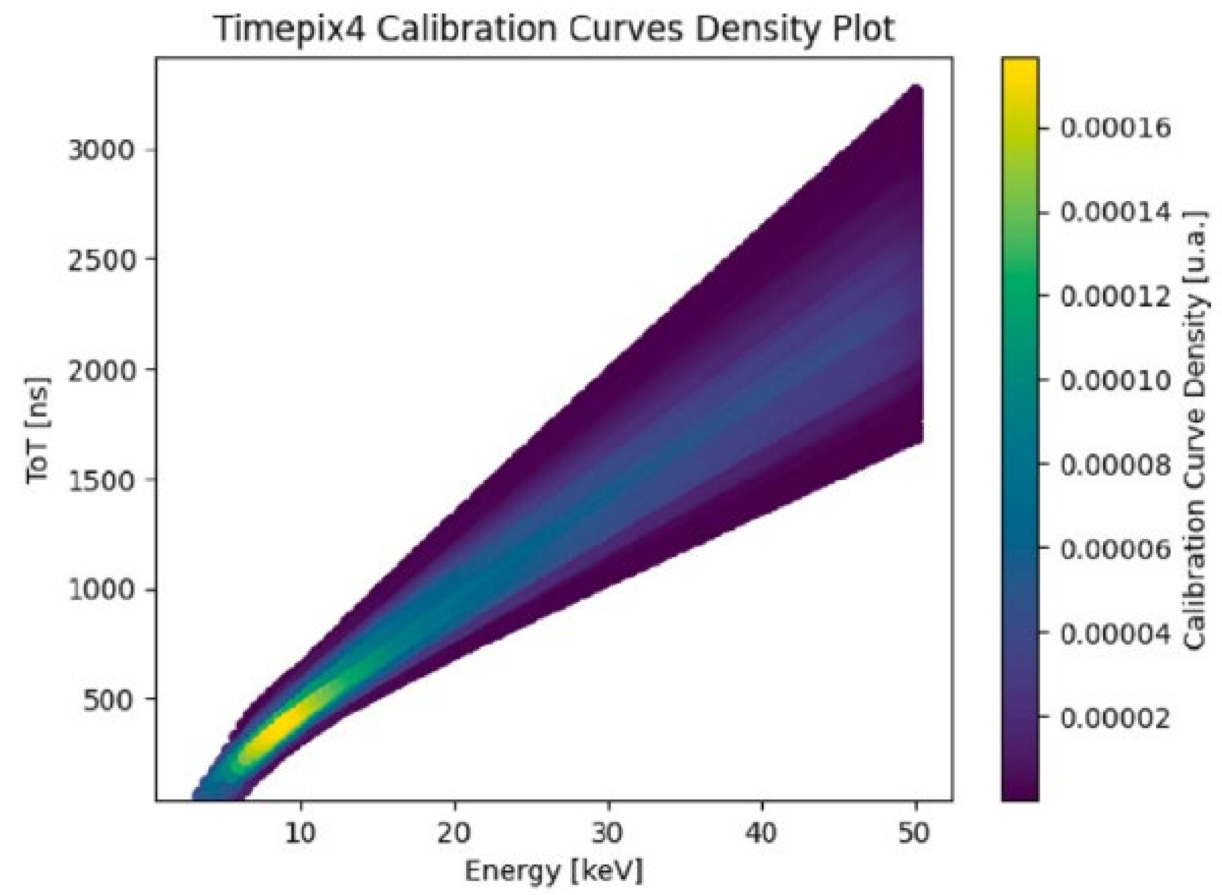
When the signal amplitude exceeds a threshold, a clock starts. It stops when the signal is below the threshold

The number of clock cycles is proportional to the amplitude i.e. the energy

For each event you have the full energy information (*hyperspectral performance*)







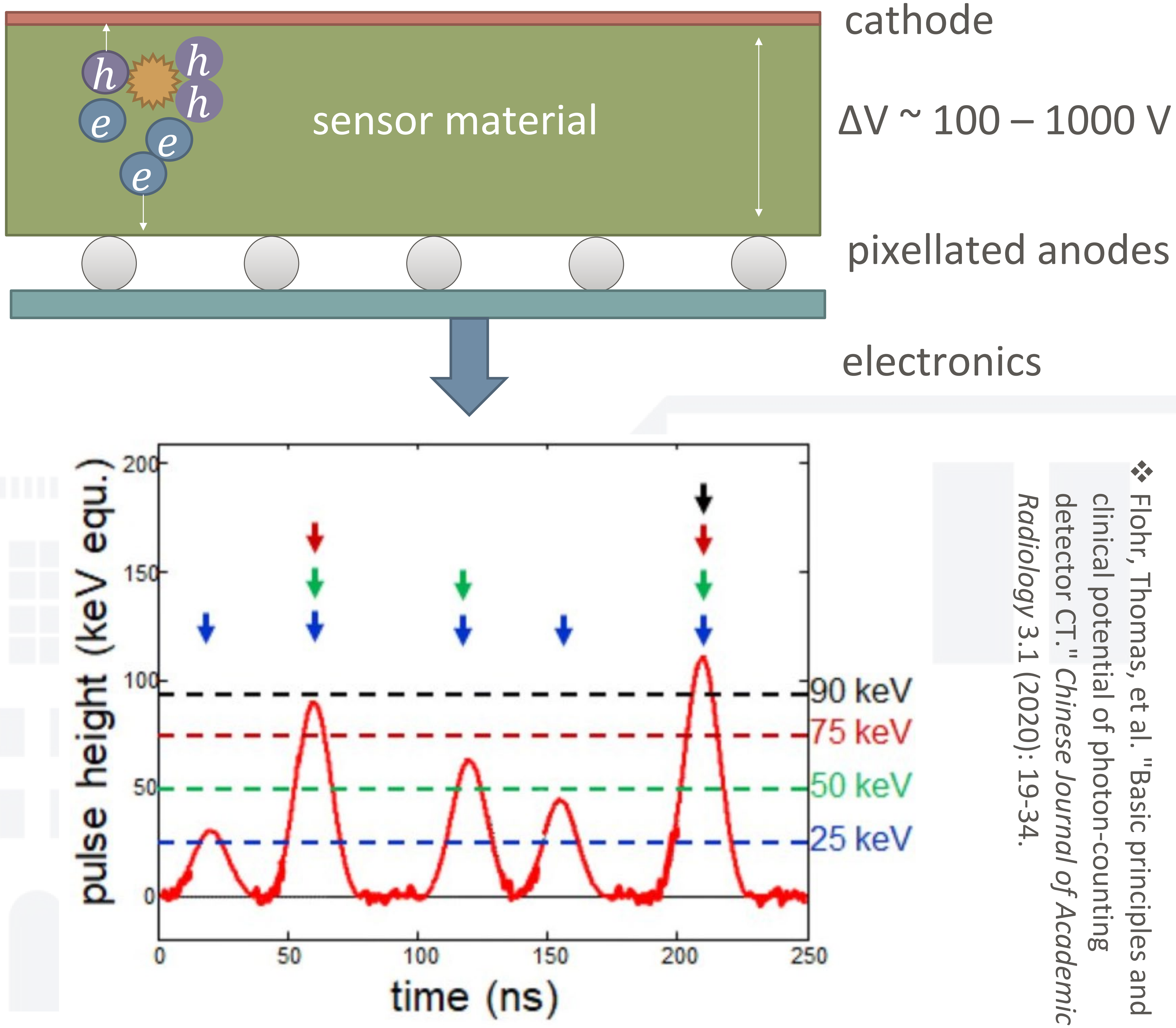
Delogu, P., et al. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 1068 (2024): 169716.

ENERGY MEASUREMENT VIA DISCRIMINATION (PHOTON-COUNTING)

The signal amplitude and duration is proportional to the energy released in the sensor from the X-ray

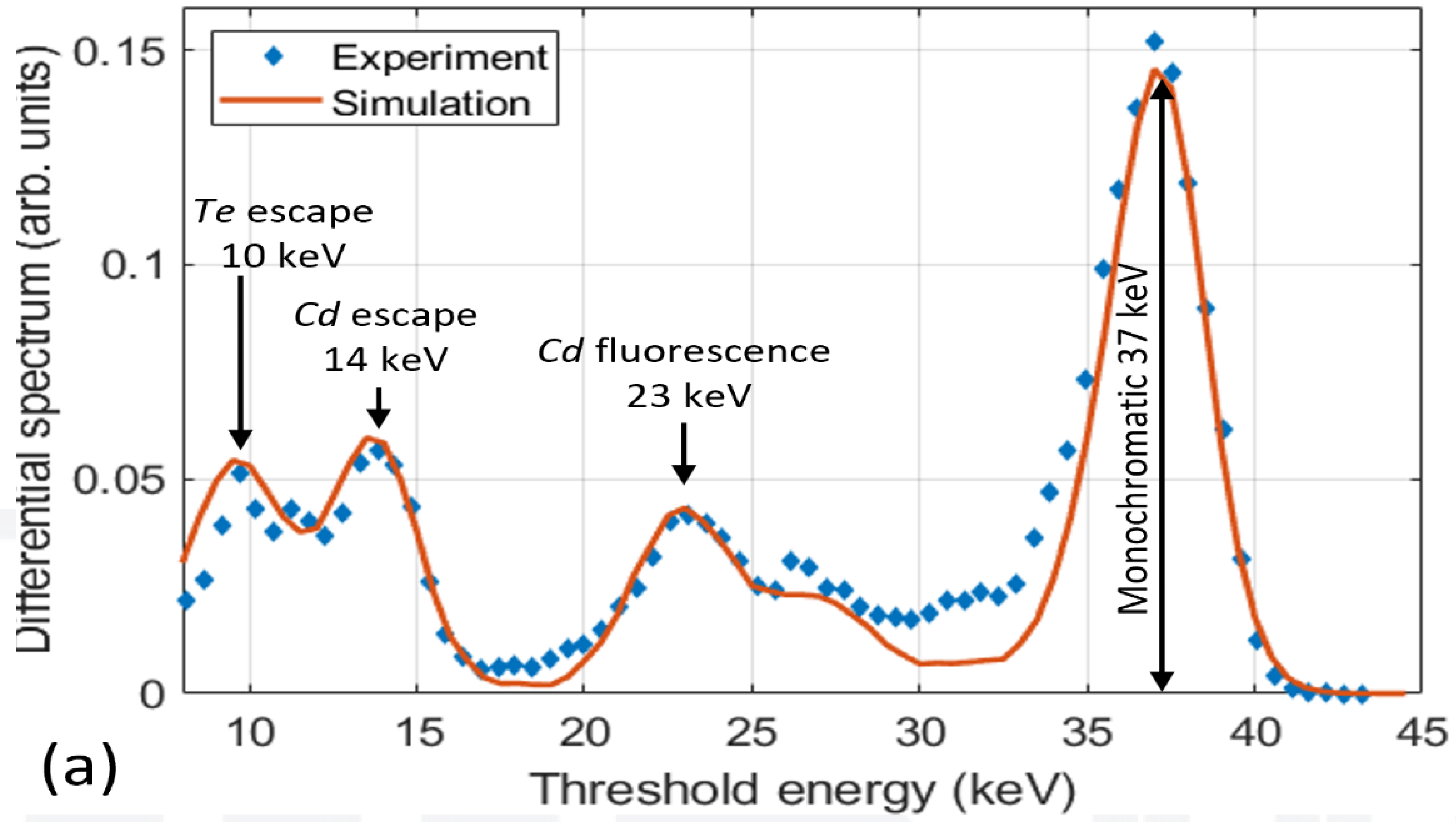
When the signal amplitude exceeds a programmable energy-calibrated threshold a counter is incremented (+1)

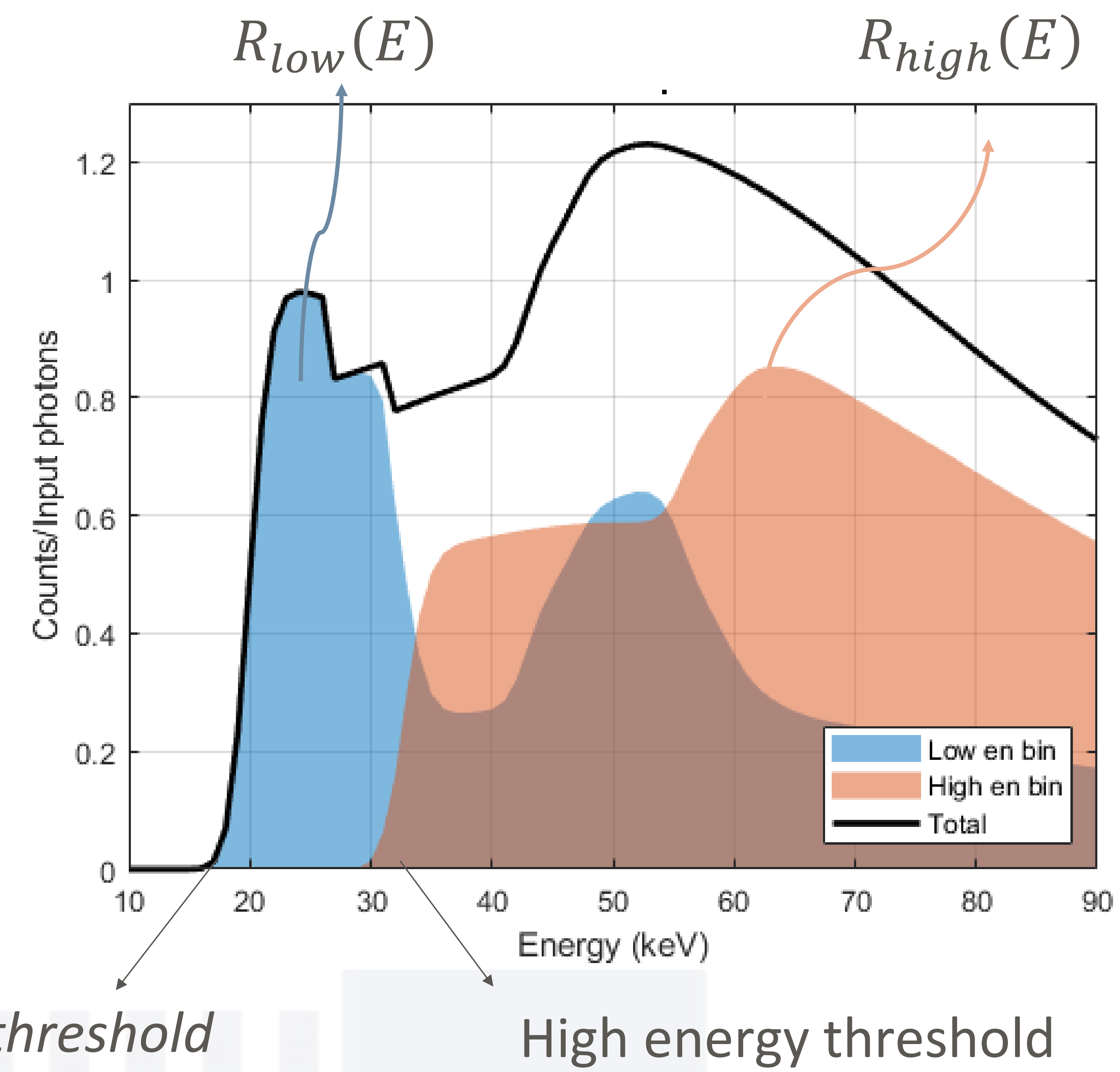
By having multiple thresholds per pixel multiple energy bins are acquired



❖ Flohr, Thomas, et al. "Basic principles and clinical potential of photon-counting detector CT." *Chinese Journal of Academic Radiology* 3.1 (2020): 19-34.

MODELLING DETECTOR’S ENERGY RESPONSE



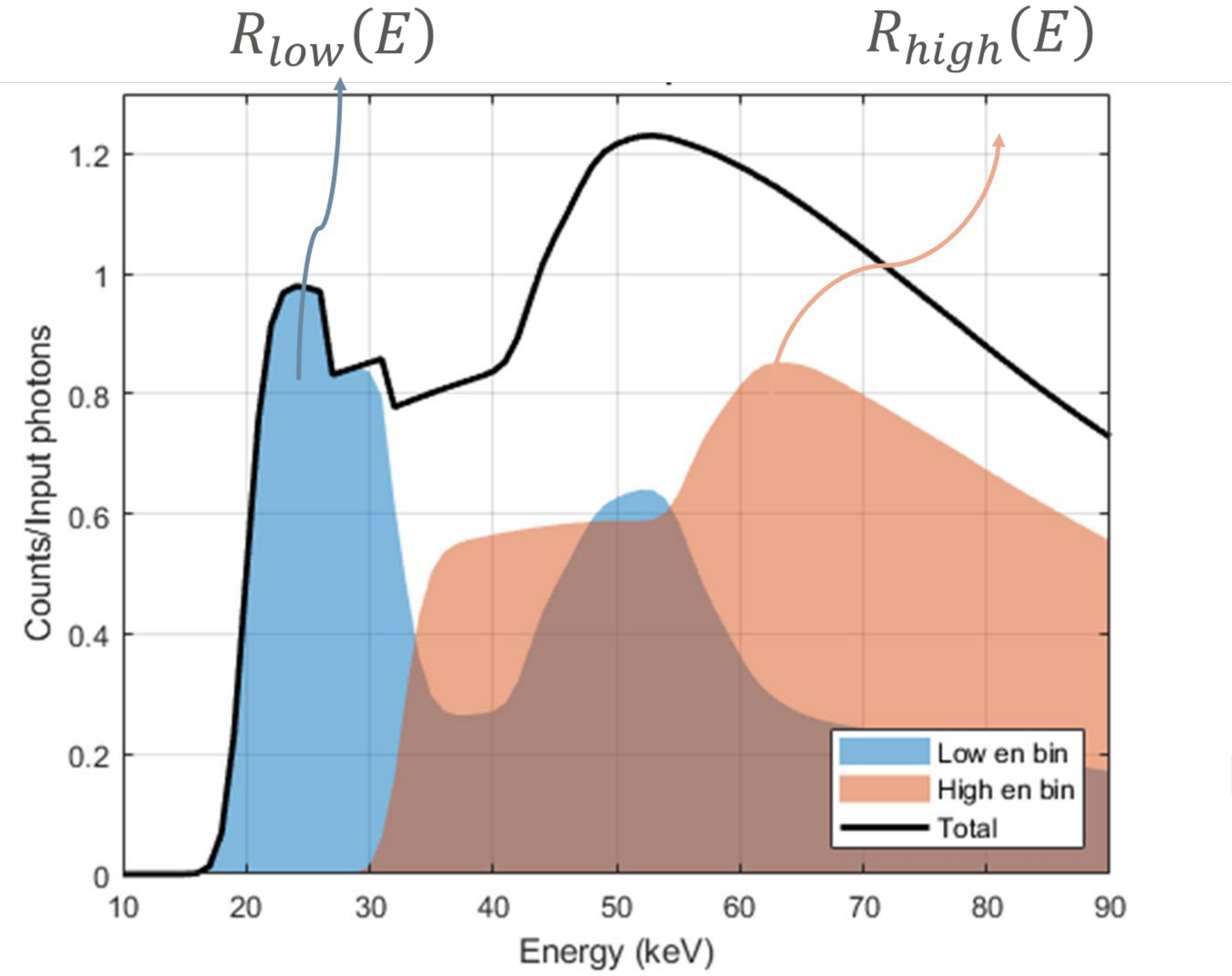


1. **Measure the energy response** of the detector to monochromatic radiation
2. **Model** its **energy response** at arbitrary energy levels

3. For given threshold setting, **compute the probability that a photon of energy *E* is counted in a given bin**

COMPUTING THE BASIS-DECOMPOSITION MATRIX

Detector response



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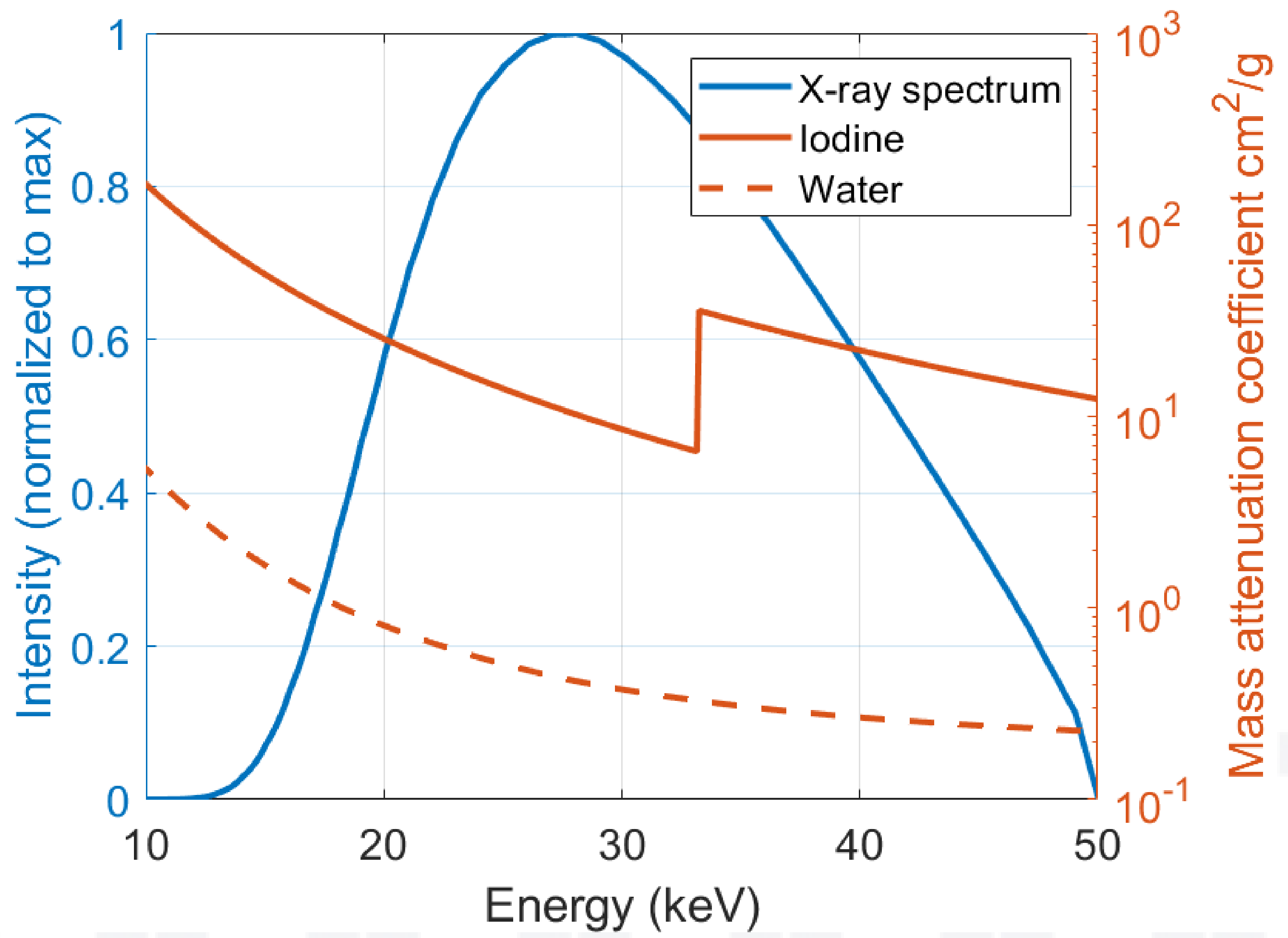
X-ray spectrum



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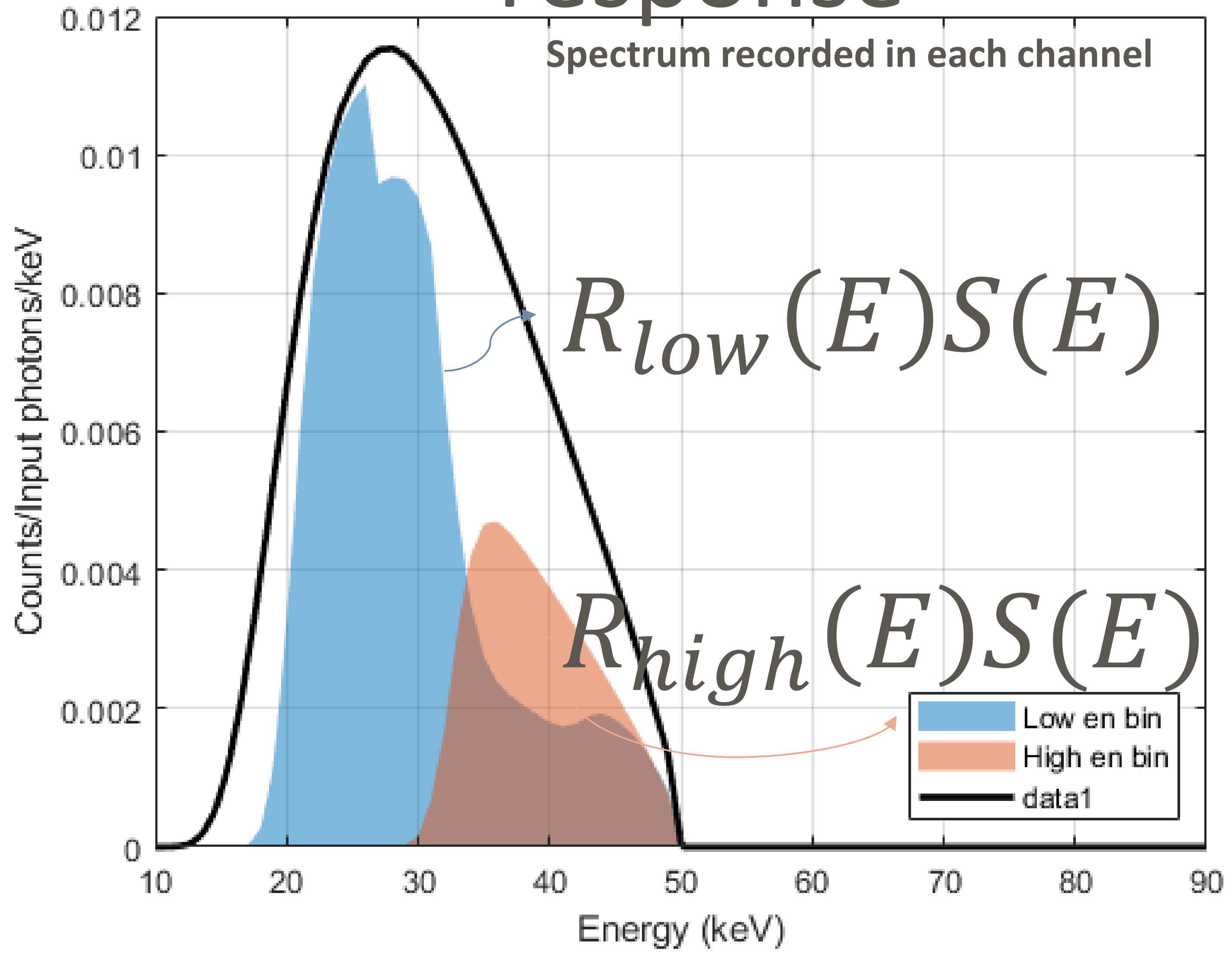
System's spectral response



- **Decomposition matrix** calculated as a **weighted sum of the mass attenuation coefficients**.
- The **weights** are given by the **system's spectral response**

$$\left\langle \frac{\mu^j}{\rho_i} \right\rangle = \frac{\int S(E)R_i(E)\mu/\rho_j(E)dE}{\int S(E)R_i(E)dE}$$

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1924 2024
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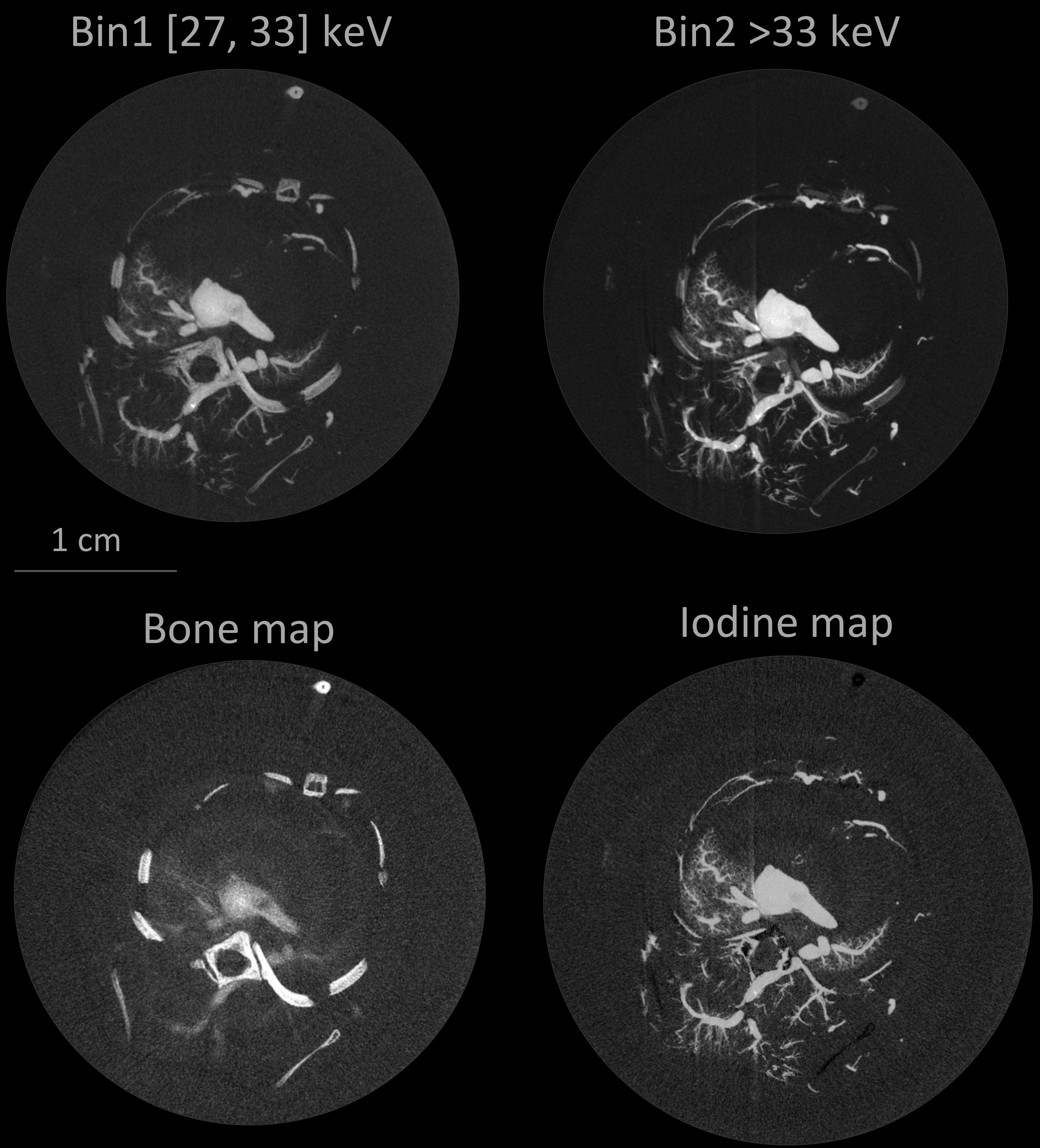
APPLICATIONS: CADIOVASCULAR IMAGING



Ex-vivo murine model perfused with µAngiofil®

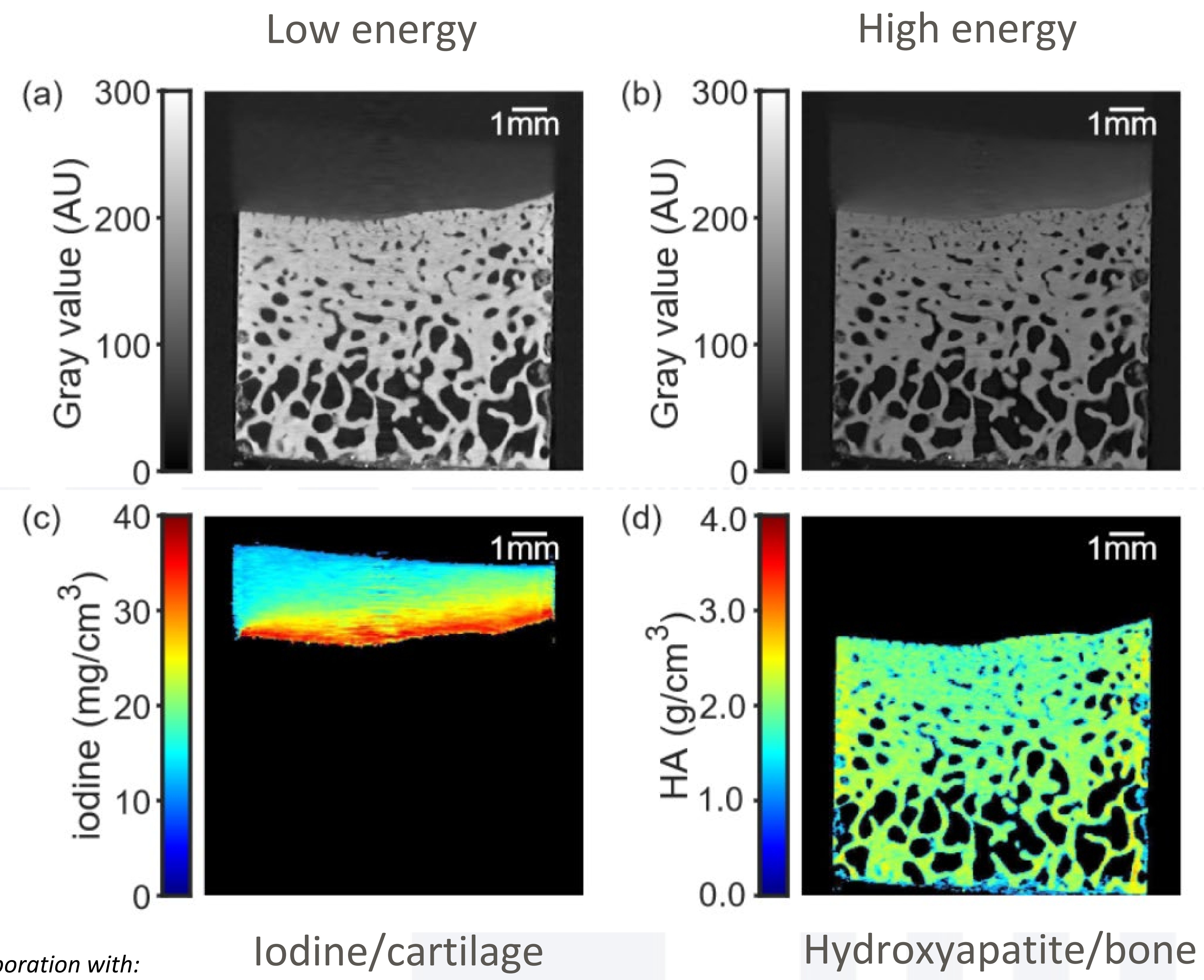
- 35 µm voxel size
- 790 x 790 x 2500 voxel x 2 energies
- 12 Gb dataset

Thanks to Paola Perion

In collaboration with HELMHOLTZ MUNICH

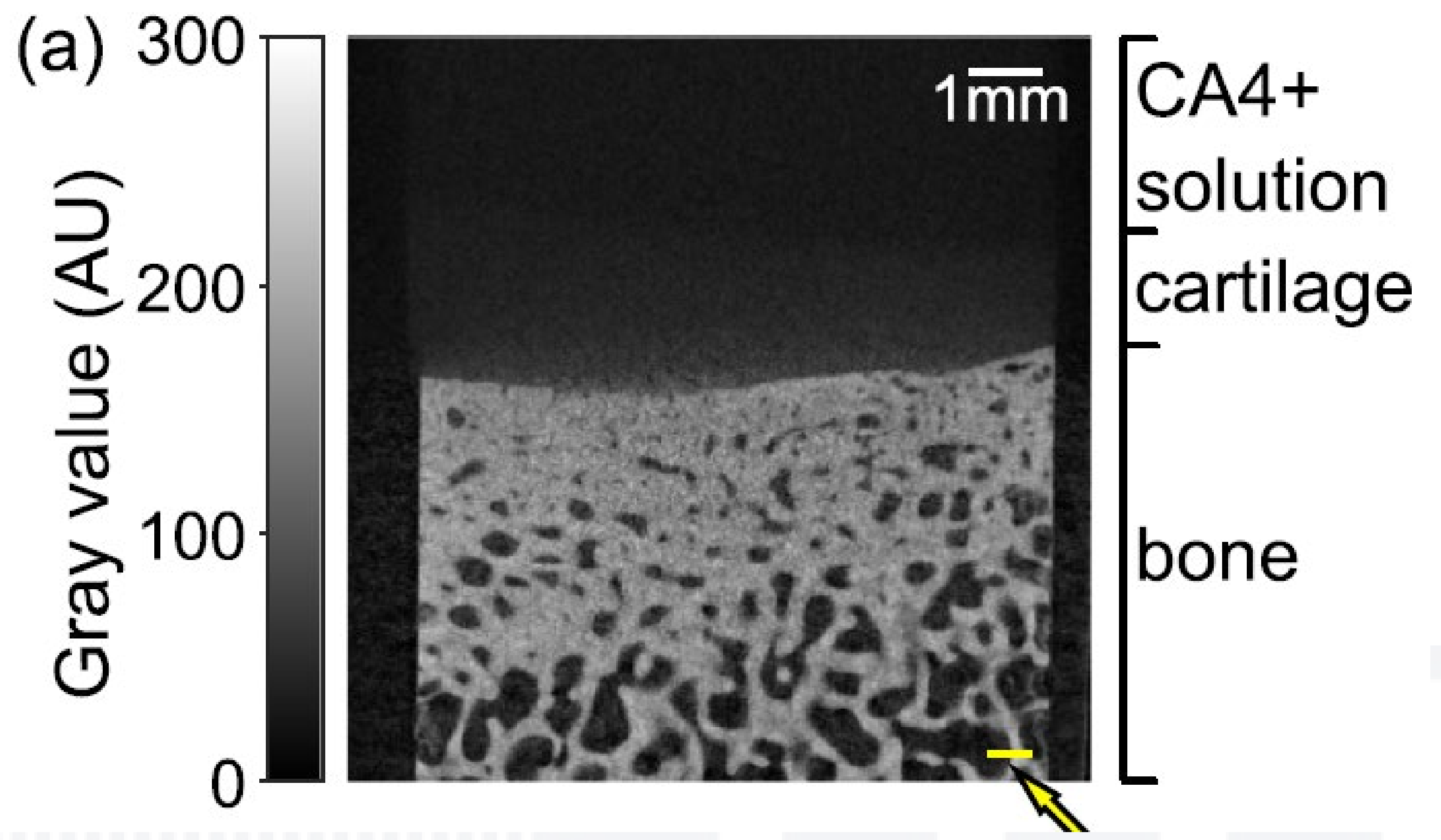
APPLICATION TO CA4+ LABELED OSTEOARTICULAR SAMPLES

voxel size 34 µm, scan time ~120 min



Spectral µCT

Conventional µCT



Bovine stifle joint sample labeled with a cationic iodinated contrast medium (CA4+)

Fantoni, Simone, et al. *The European Physical Journal Plus* 139.8 (2024): 1-10.

In collaboration with:

SERVIZIO SANITARIO REGIONALE
EMILIA - ROMAGNA
Istituto Ortopedico Rizzoli di Bologna
Istituto di Ricovero e Cura a Carattere Scientifico

UNIVERSITÀ DEGLI STUDI DI TRIESTE

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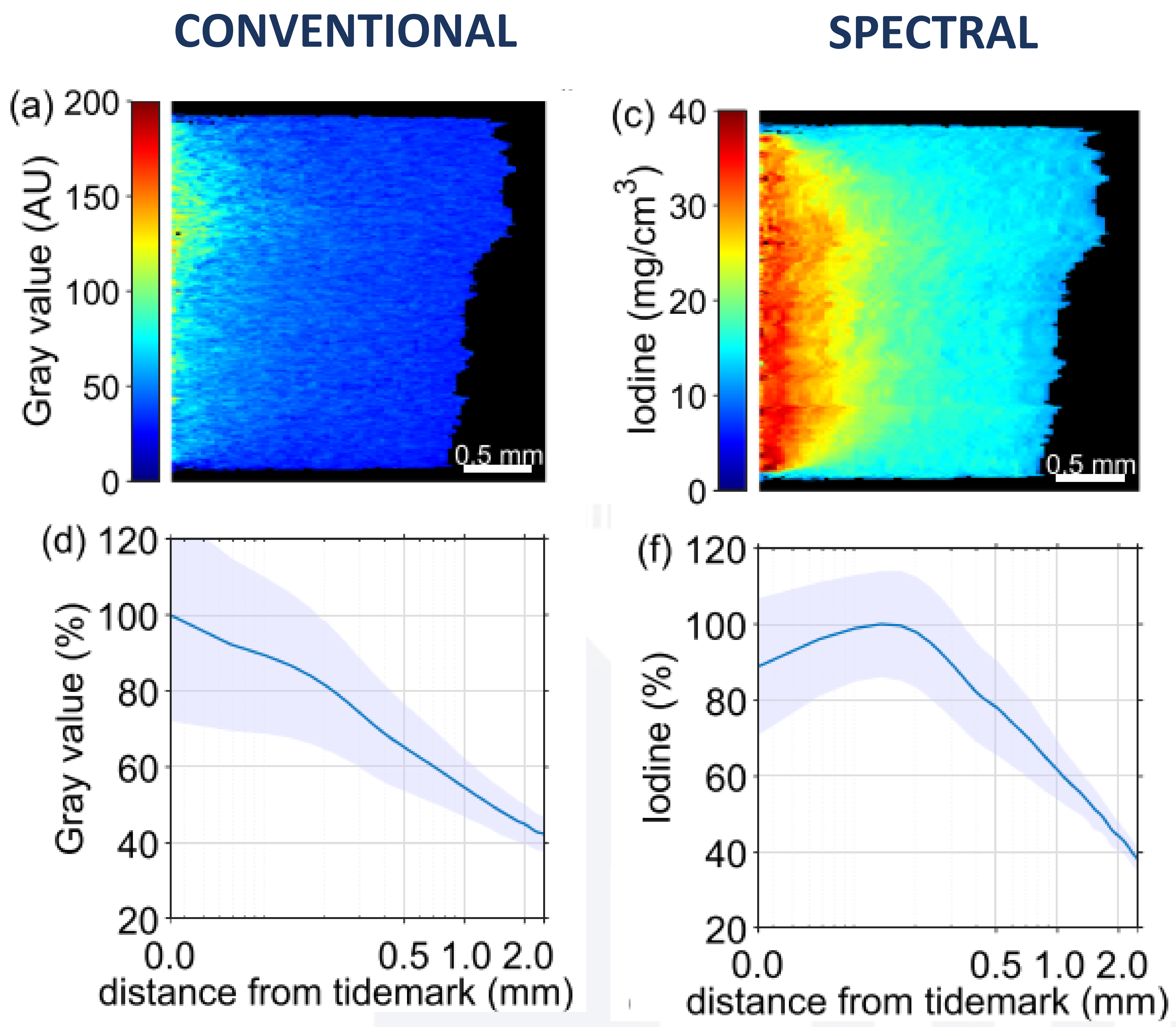

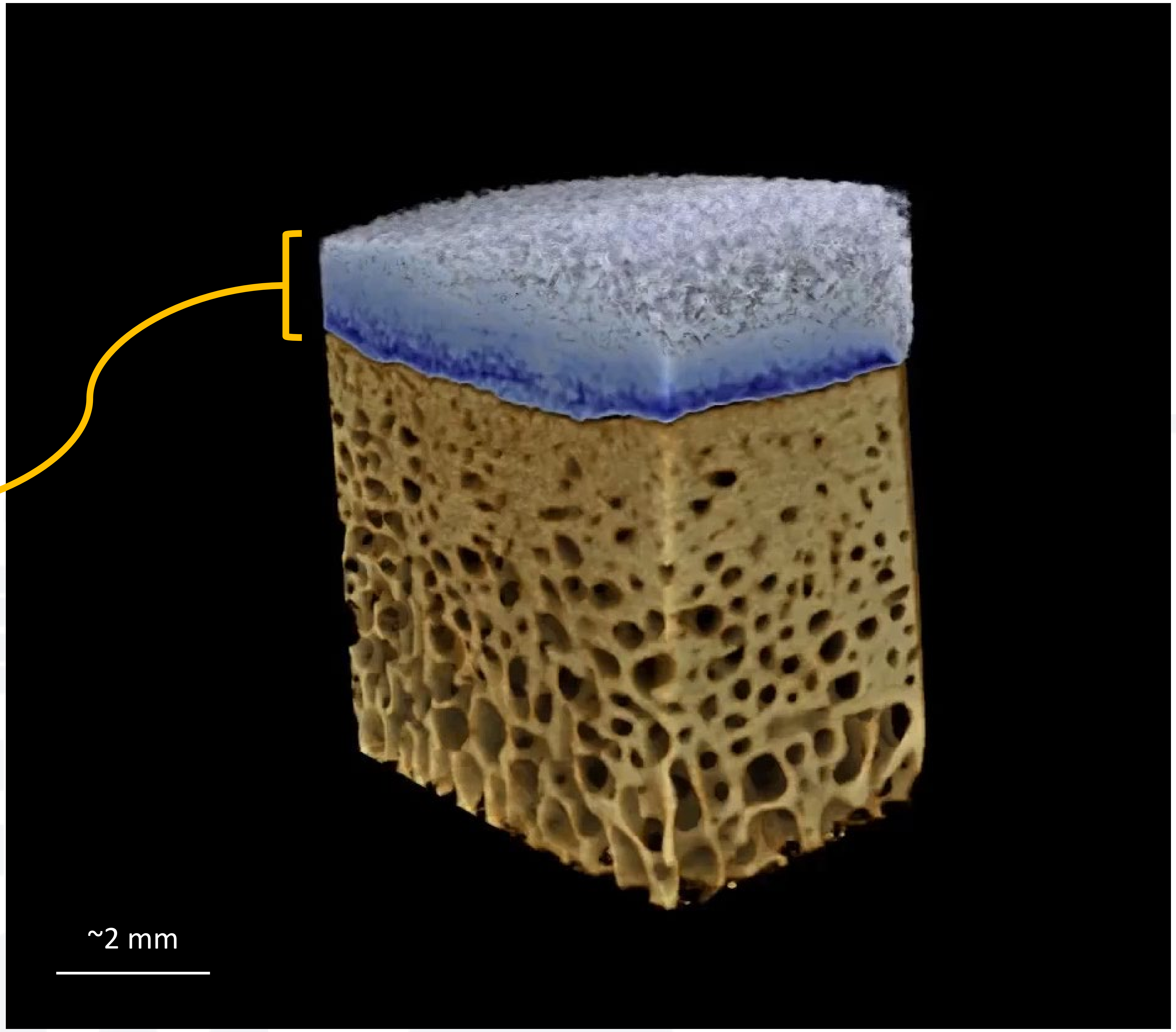

Fantoni et al. *"Quantitative spectral micro-CT of a CA4+ loaded osteochondral sample with a tabletop system"*. Accepted in EPJ plus (2024)

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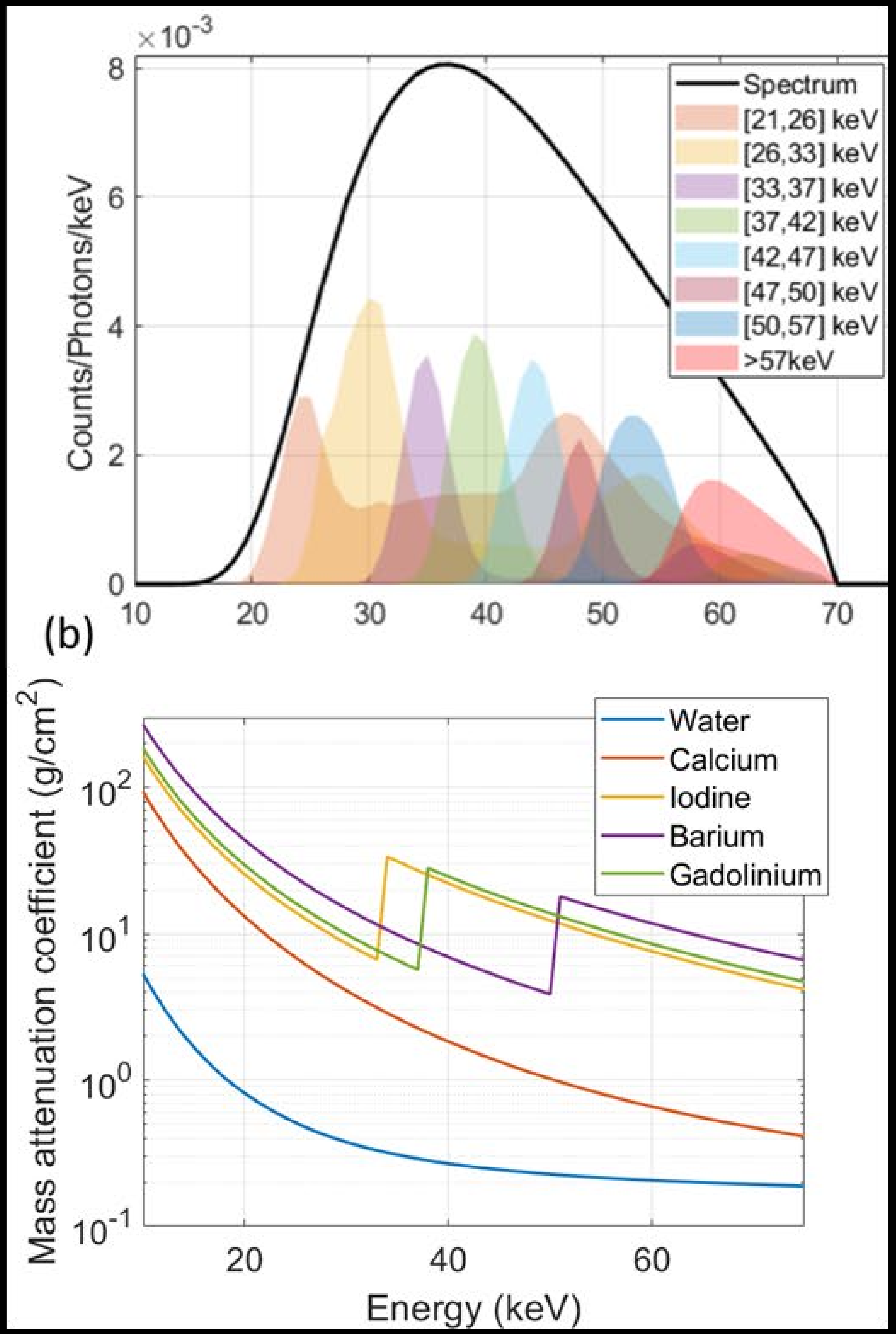
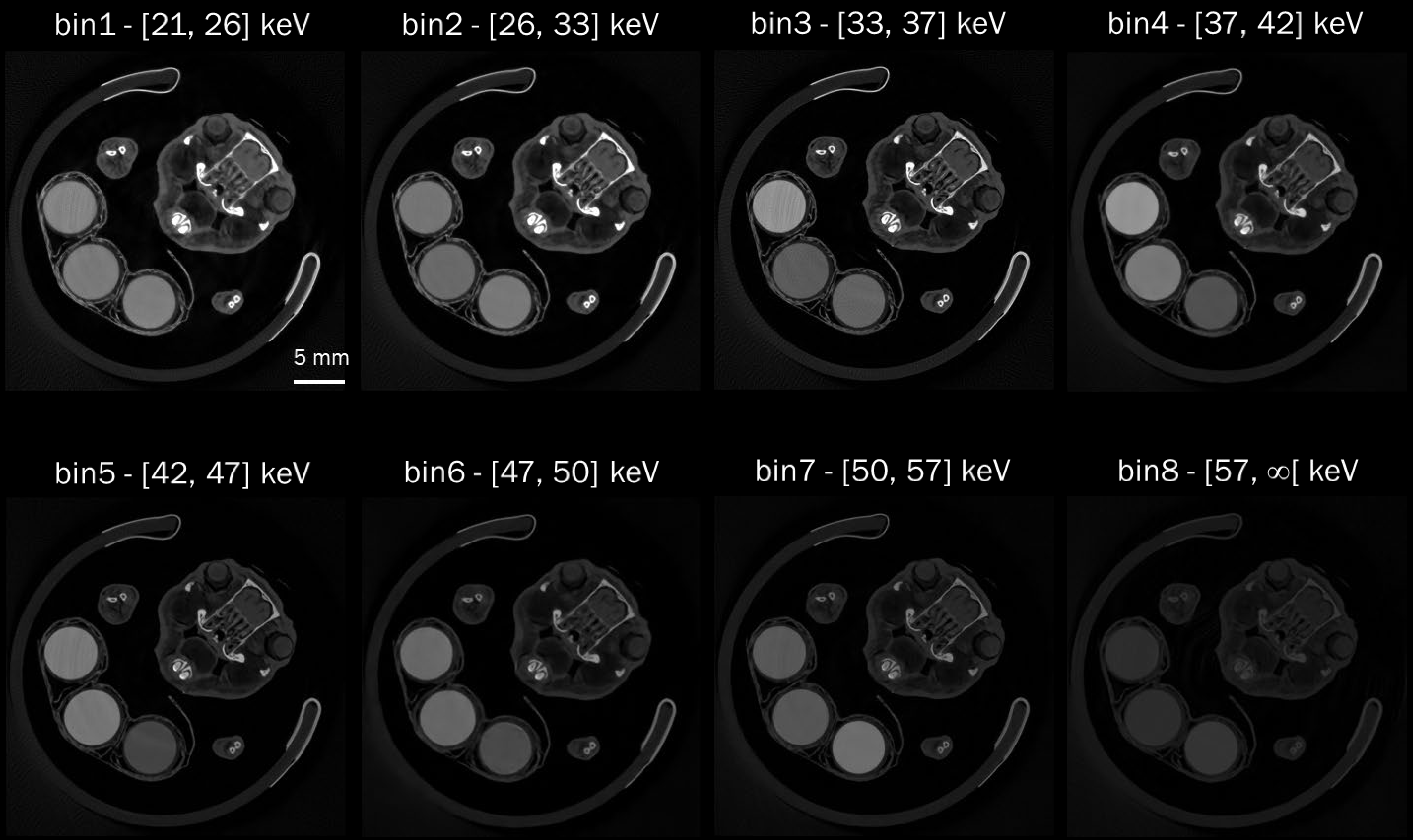
Istituto di Ricovero e Cura a Carattere Scientifico

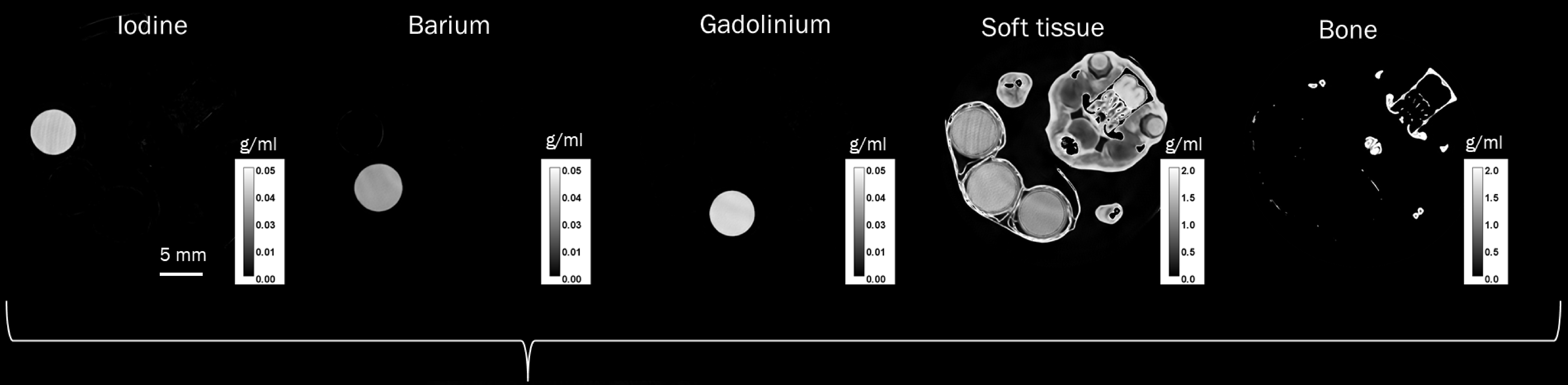
QUANTITATIVE MULTI-CONTRAST μCT

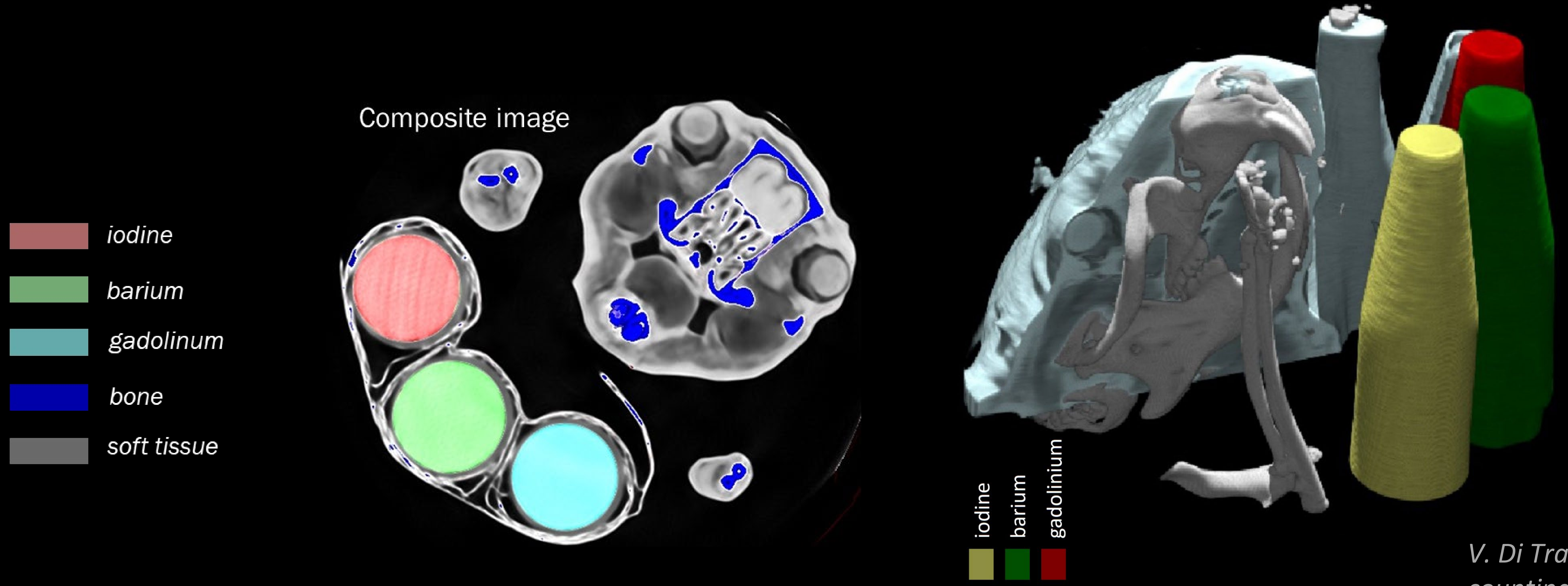




Di Trapani, V., L. Brombal, and F. Brun. "Multi-material spectral photon-counting micro-CT with minimum residual decomposition and self-supervised deep denoising." Optics Express 30.24 (2022): 42995-43011.

QUANTITATIVE MULTI-CONTRAST μCT

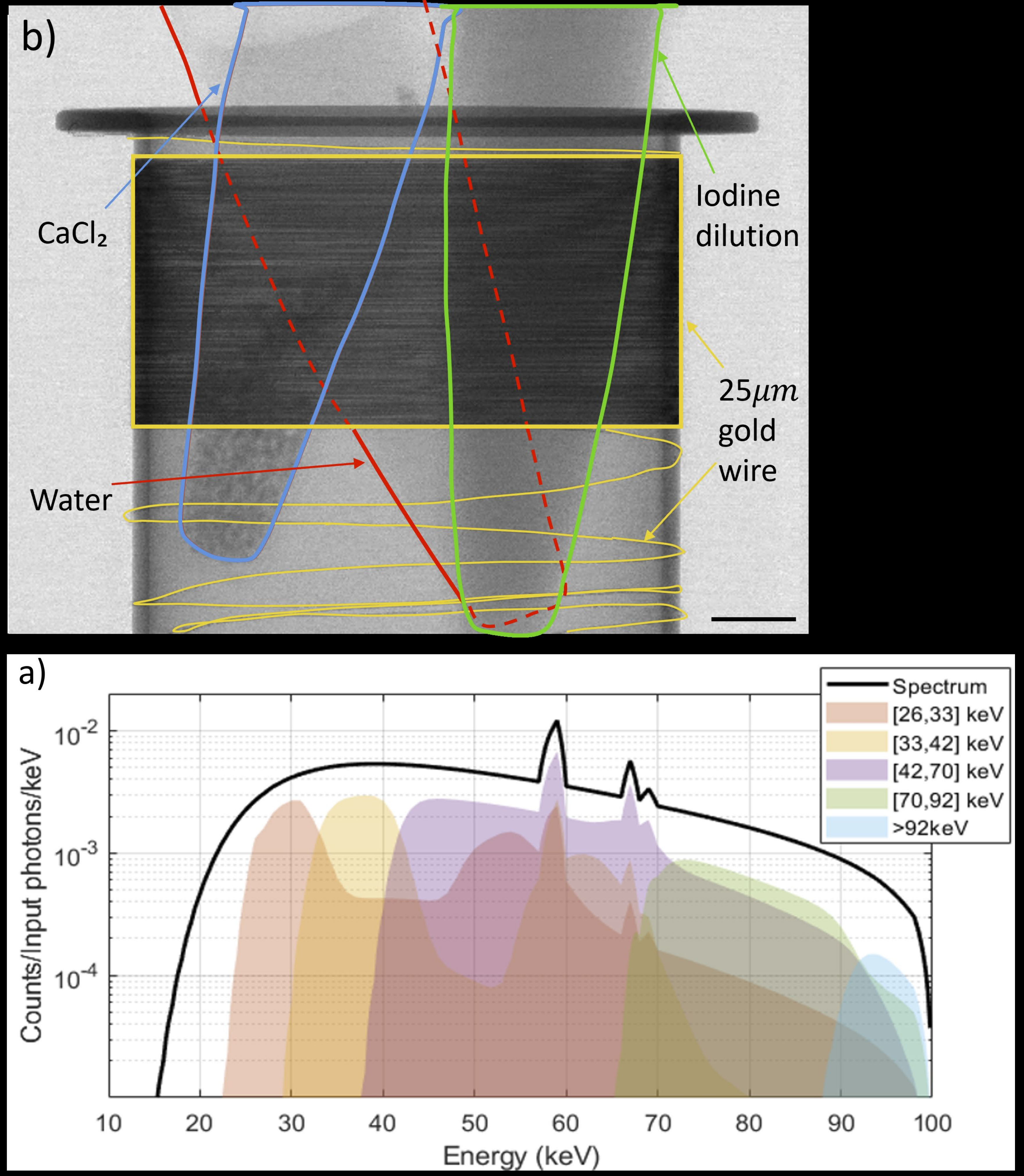


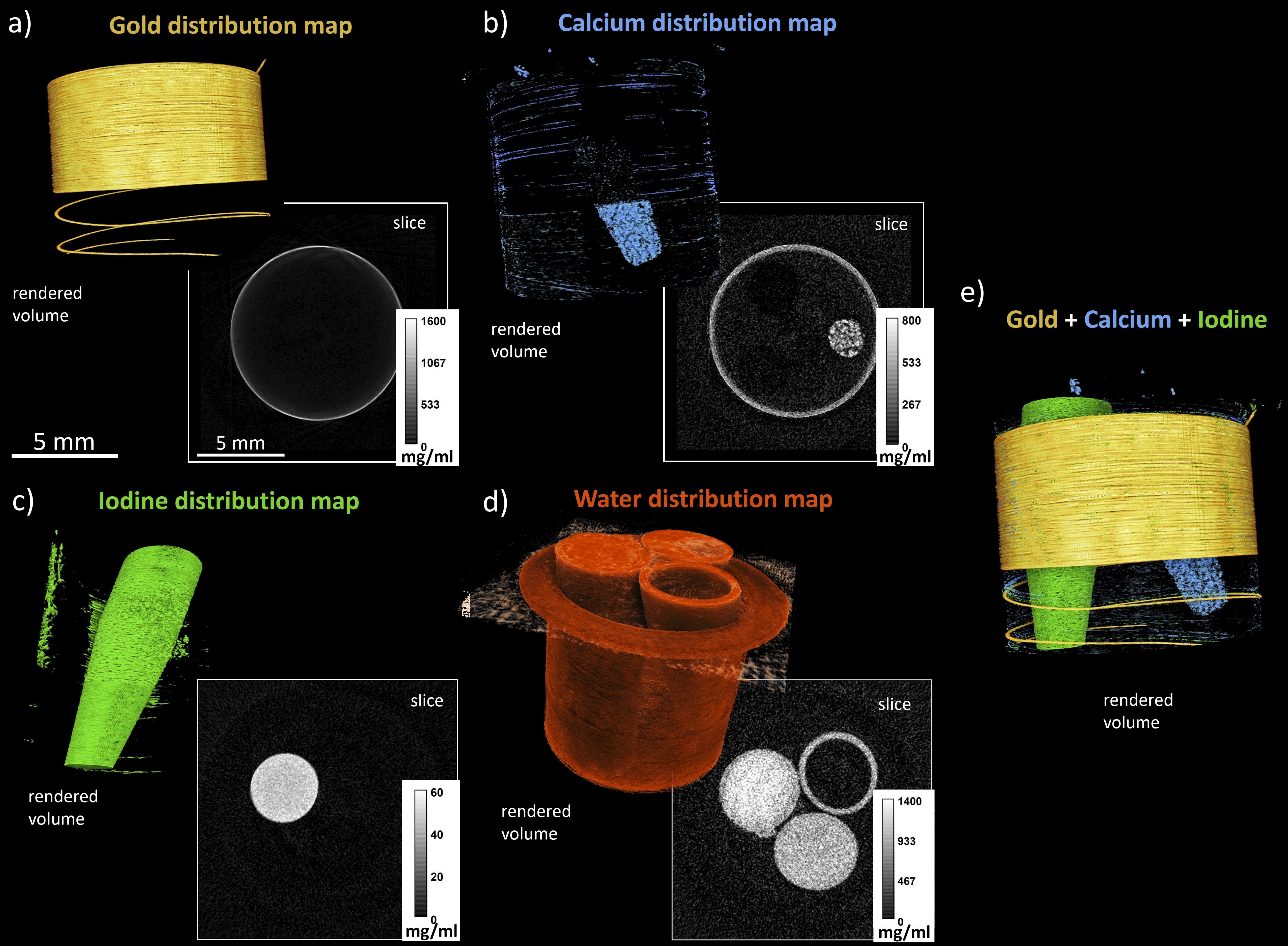


	Nominal [mg/ml]	Measured [mg/ml]
Iodine	40	37.6 ± 0.8
Barium	35	30.2 ± 0.5
Gadolinium	39	41.2 ± 0.4

V. Di Trapani, L. Brombal, and F. Brun. "Multi-material spectral photon-counting micro-CT with minimum residual decomposition and self-supervised deep denoising." Optics Express 30.24 (2022): 42995-43011.

APPLICATIONS: HIGH-ENERGY SPECTRAL IMAGING





Perion et al. "Spectral micro-CT for simultaneous gold and iodine detection, and multi-material identification", accepted on JINST (2024)

OUTLINE

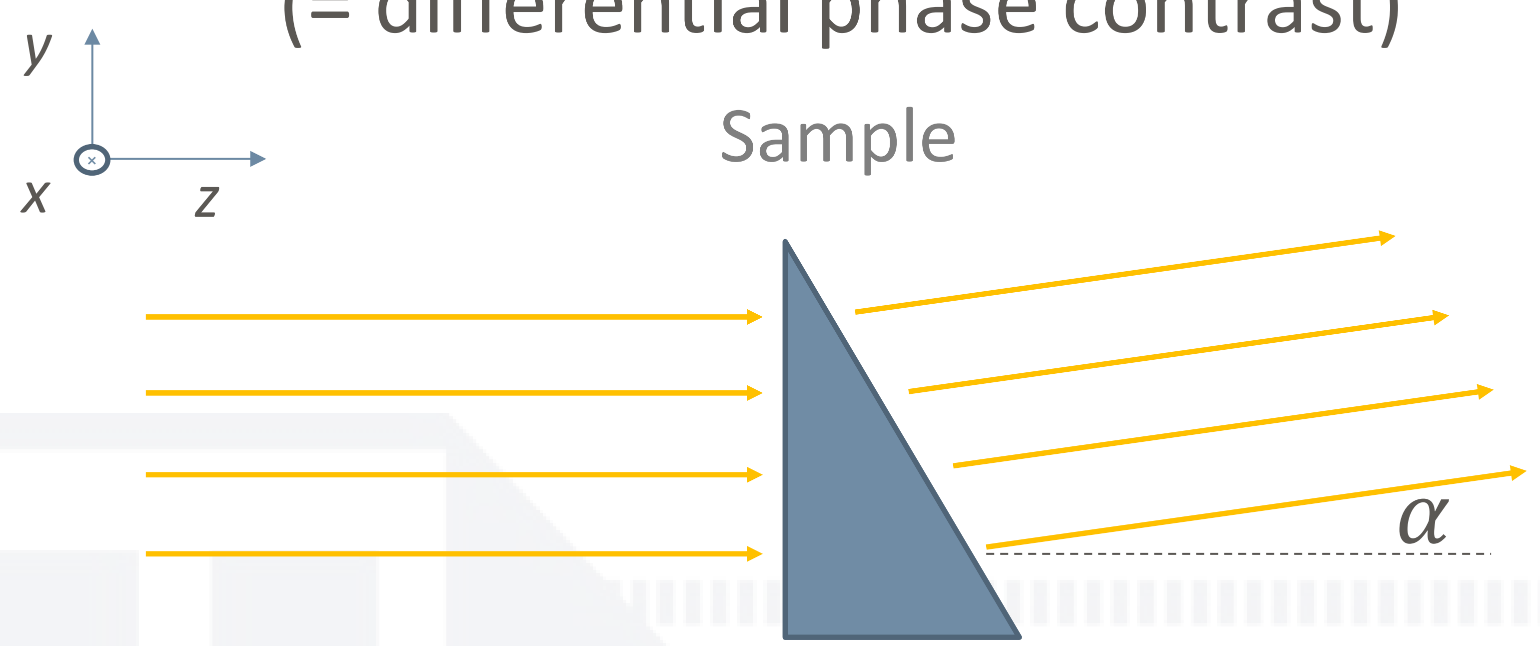
- X-ray imaging fundamentals
- Spectral imaging
- **Phase-contrast imaging**
- Spectral phase-contrast imaging

PHASE EFFECTS

A naïve interpretation

Refraction

(= differential phase contrast)

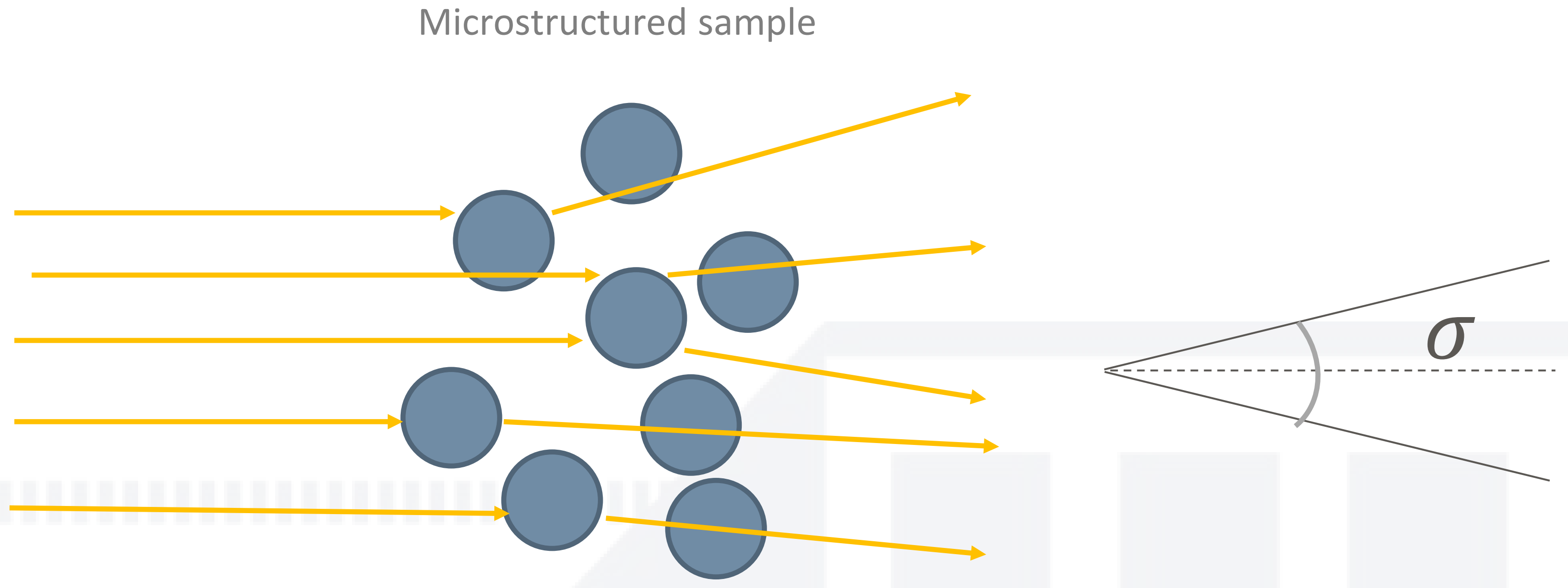


$$\alpha = -\nabla_{xy} \int \delta(x, y, z; E)dz$$

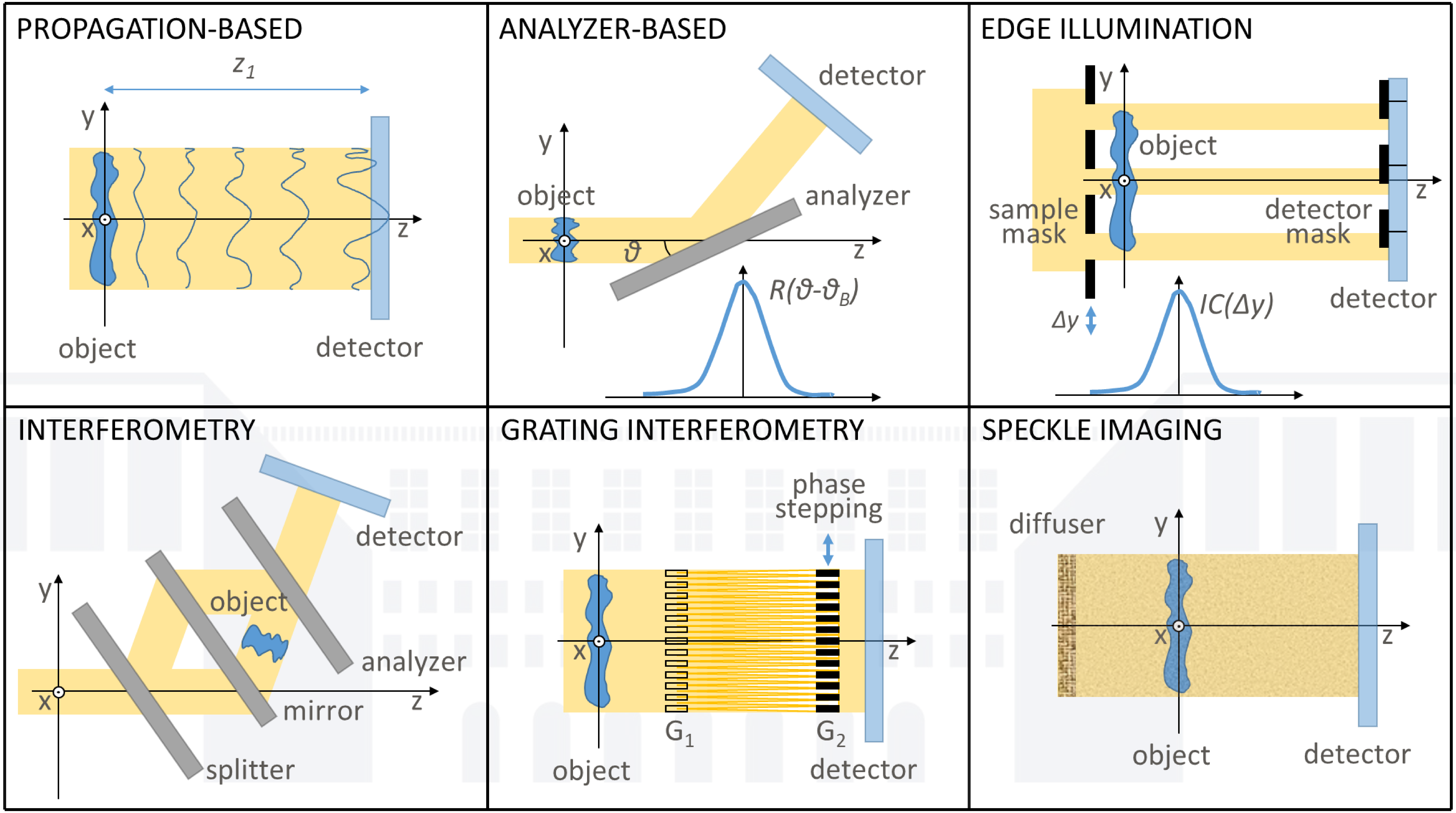
- Within the ray-optical approximation phase effects = *refraction*
- Refraction is proportional to the gradient of δ → strong at the edges
- Refraction angles range 1-100 µrad

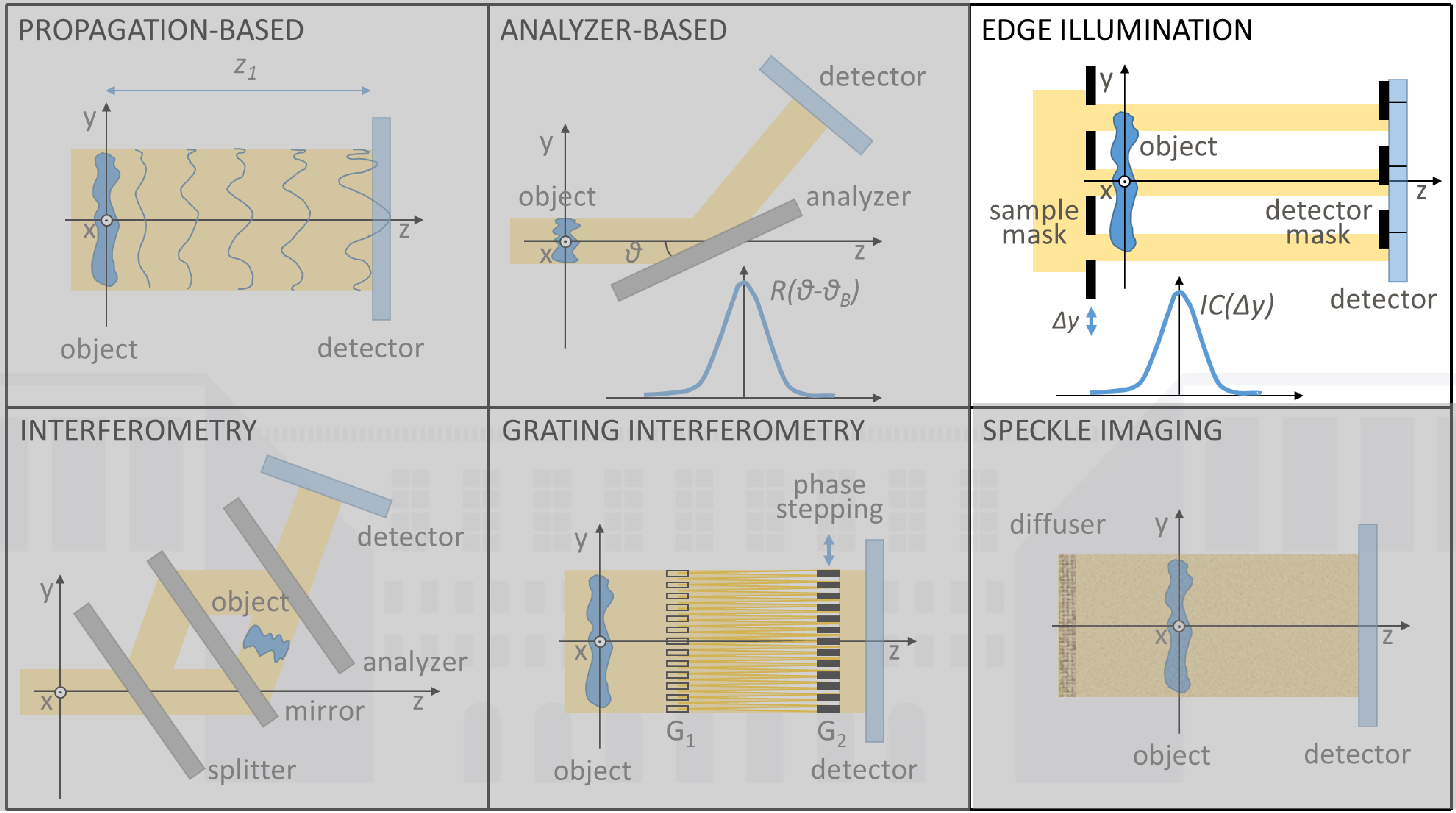
Ultra-small angle scattering

(= dark field)



- In microstructured samples multiple-refraction occurs, causing a diffusion of the beam in the range 1-100 µrad
- The "amount of diffusion", i.e. scattering signal, depends on sample's properties at a scale smaller than the system's spatial resolution


PROPAGATION-BASED
z1
y
x
z
object
detector
ANALYZER-BASED
detector
y
object
analyzer
x
ϑ
z
R(ϑ-ϑB)
EDGE ILLUMINATION
y
object
x
z
sample
mask
detector
mask
Δy
IC(Δy)
detector
INTERFEROMETRY
detector
y
object
analyzer
x
mirror
z
splitter
GRATING INTERFEROMETRY
phase
stepping
y
x
z
G1
G2
object
detector
SPECKLE IMAGING
diffuser
y
x
z
object
detector


PROPAGATION-BASED
z1
y
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z
object
detector
ANALYZER-BASED
detector
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object
analyzer
x
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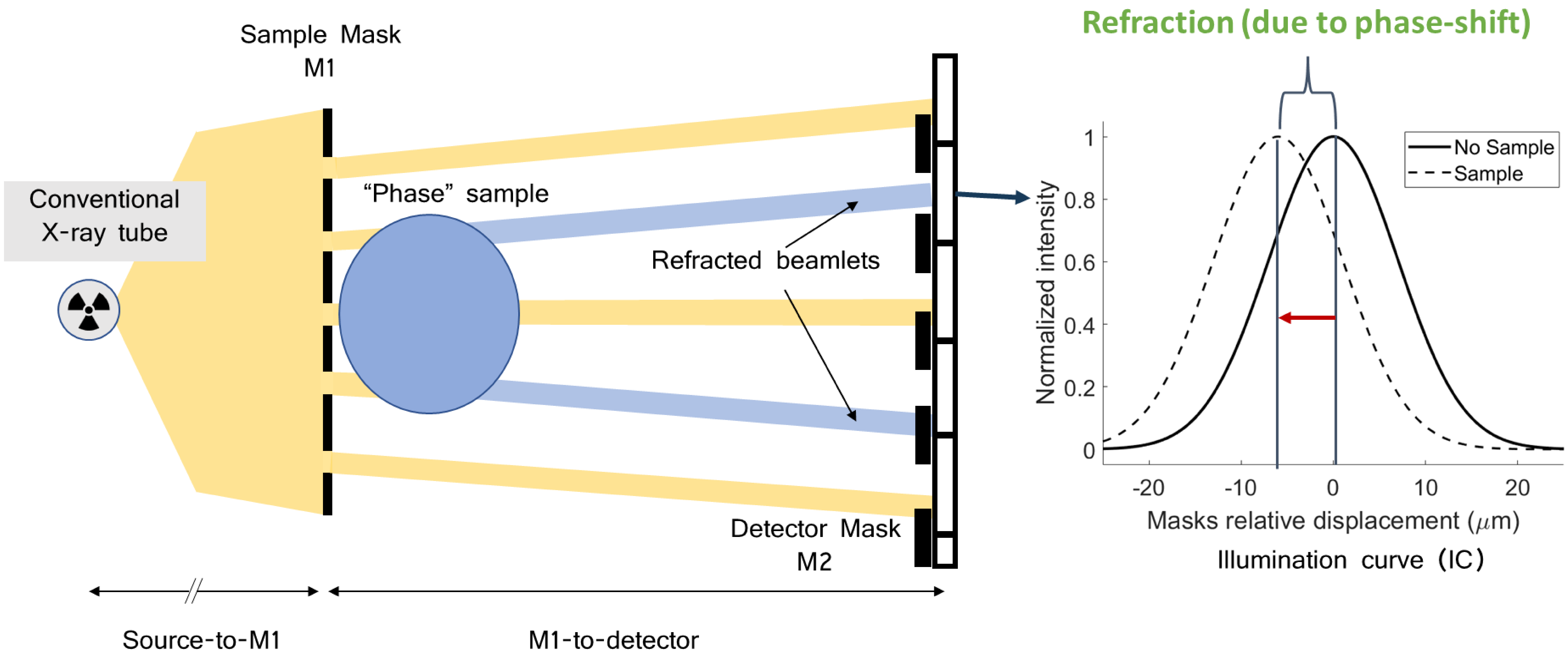
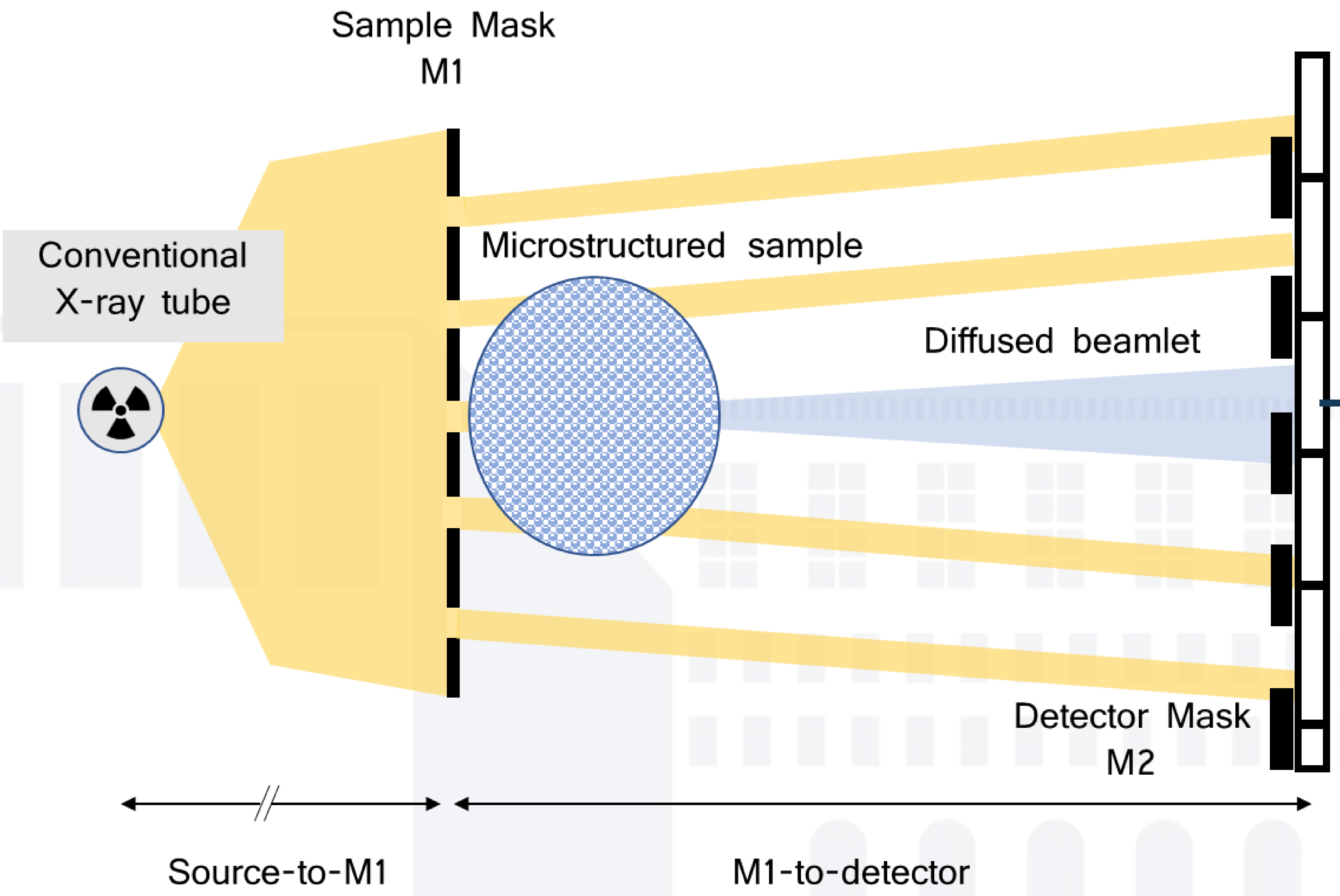
z
R(ϑ-ϑB)
EDGE ILLUMINATION
y
object
x
z
sample mask
detector mask
Δy
IC(Δy)
detector
INTERFEROMETRY
detector
y
object
analyzer
x
mirror
z
splitter
GRATING INTERFEROMETRY
phase stepping
y
x
z
G1
G2
object
detector
SPECKLE IMAGING
diffuser
y
x
z
object
detector

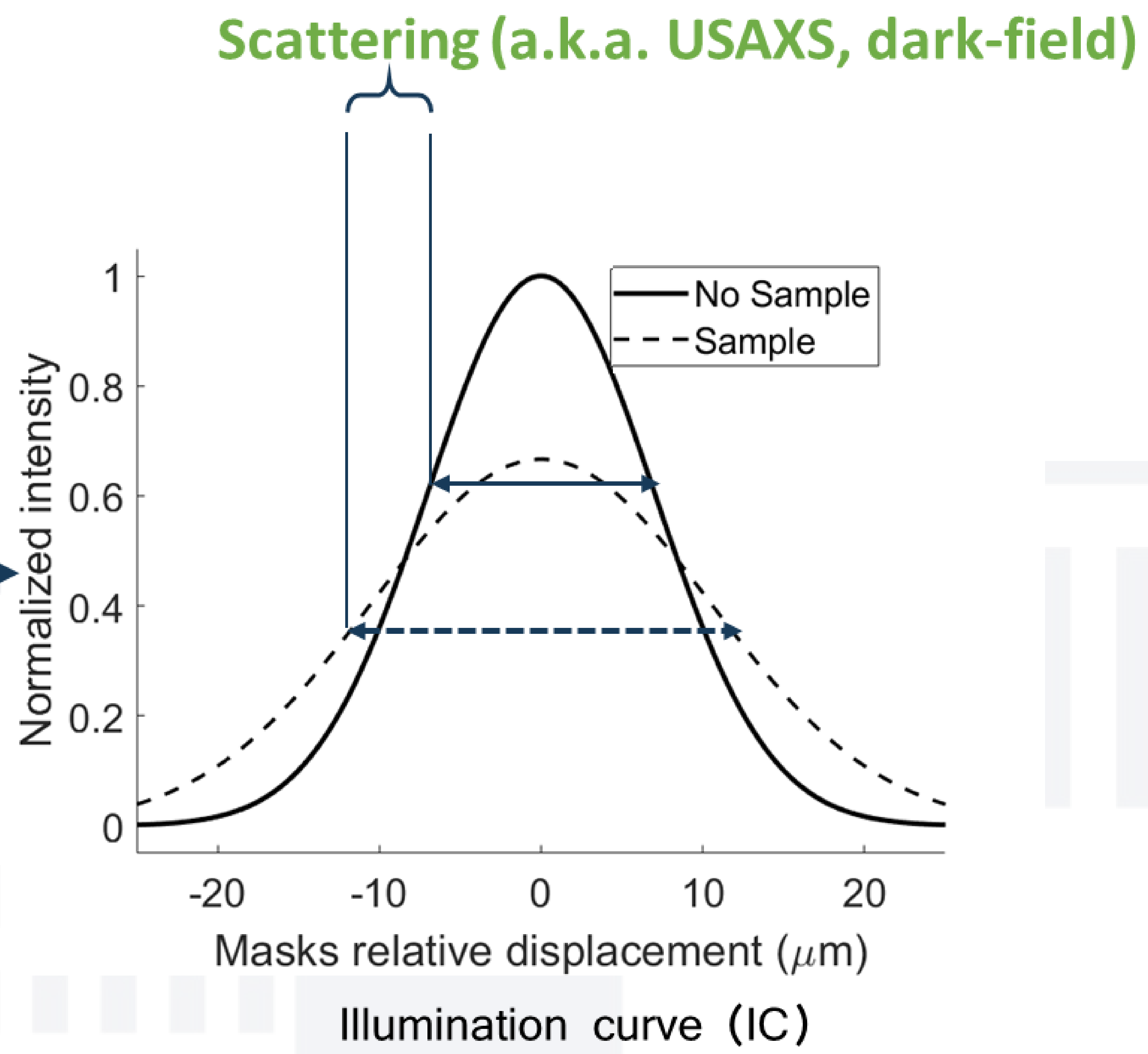
EDGE ILLUMINATION: HOW IT WORKS



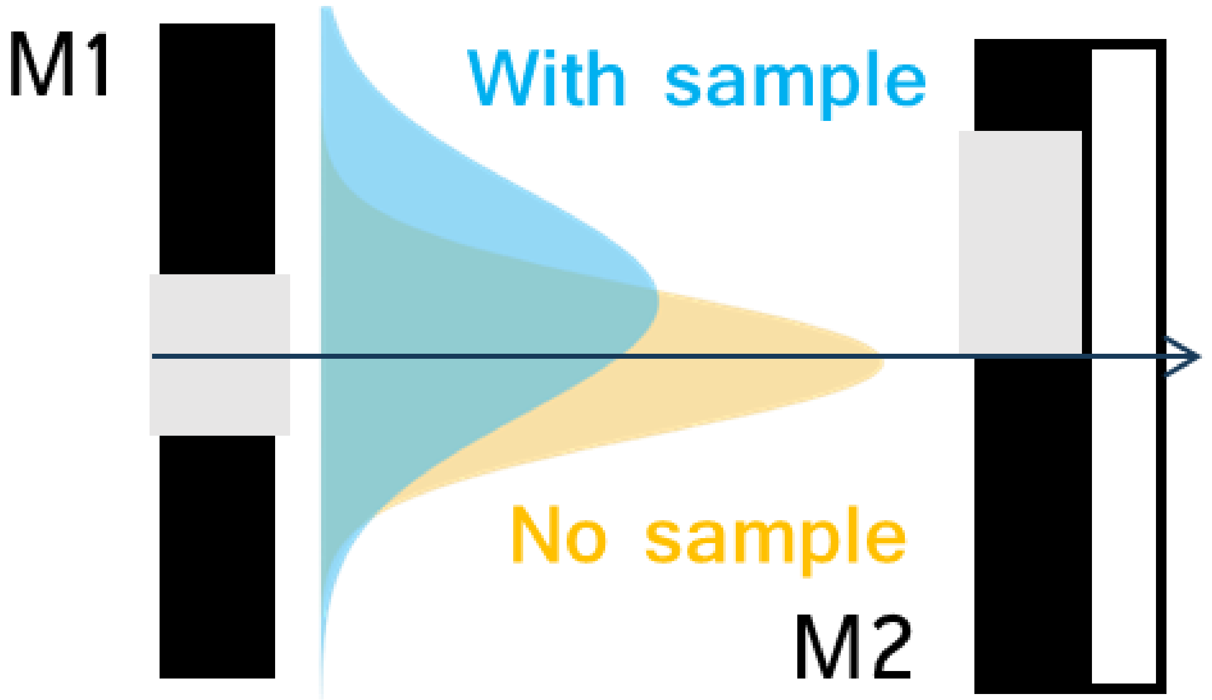
Olivo, Alessandro. "Edge-illumination x-ray phase-contrast imaging." *Journal of Physics: Condensed Matter* 33.36 (2021): 363002.

EDGE ILLUMINATION: HOW IT WORKS





EDGE ILUMINATION: SIGNAL RETRIEVAL



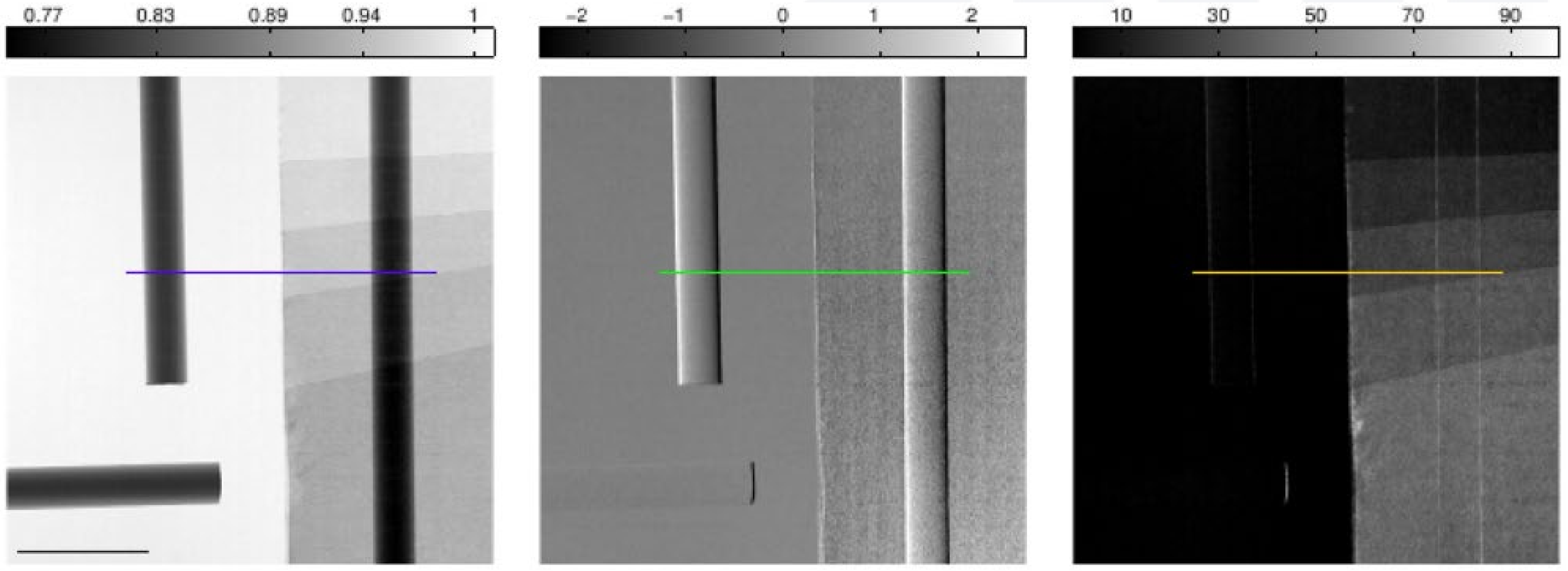
$$I(x) = (S * IL)(x - \Delta x)t$$

2/3 parametric images

- Attenuation $\mu \propto \beta$ → conventional X-ray imaging
- Refraction angle $\alpha \propto \nabla\delta$ → refraction/phase maps (via integration)
- Scattering σ → Dark-field or USAXS imaging

2/3 (or more) input images at different Positions on the IC

Phase Retrieval



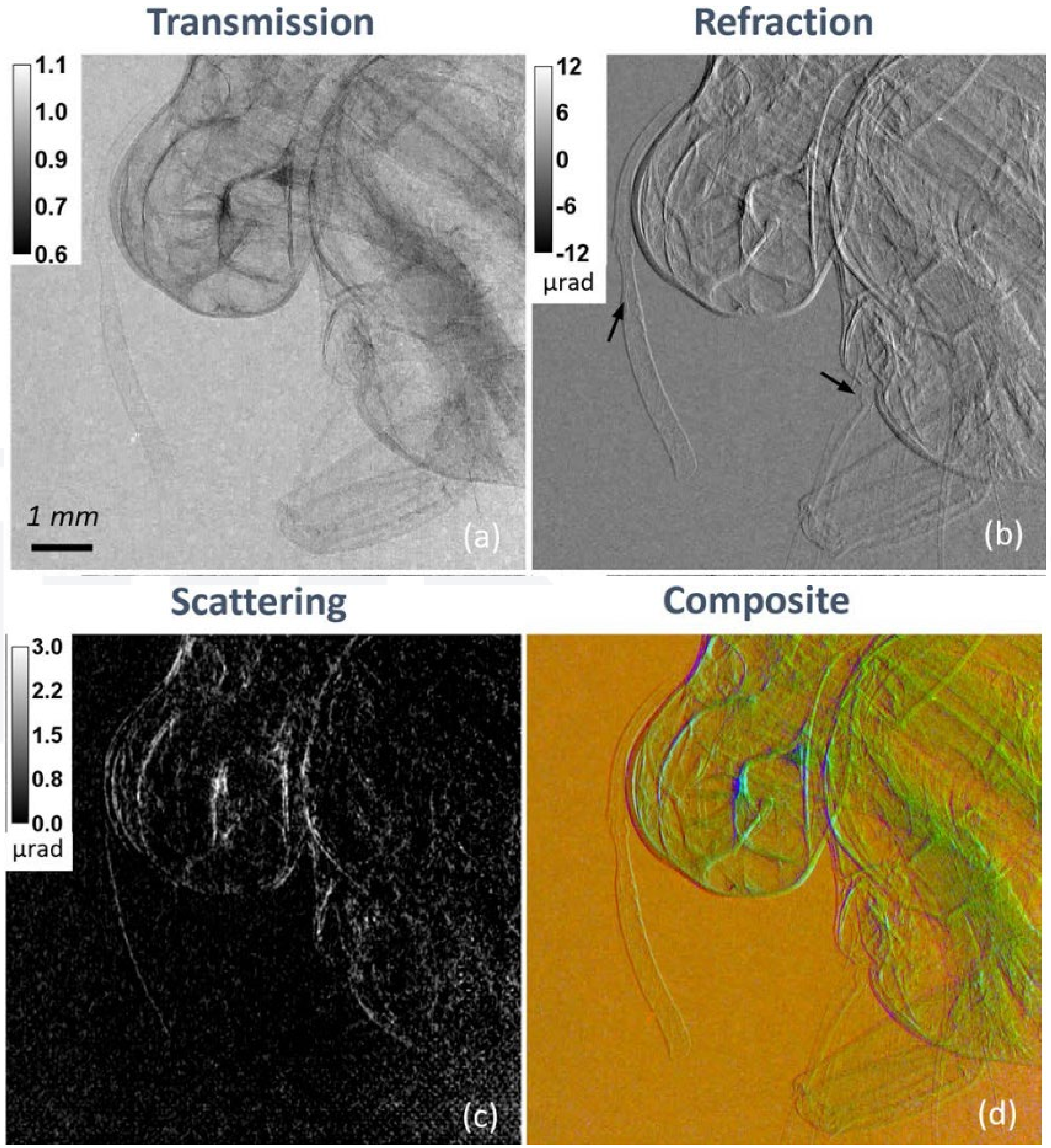
Transmission/attenuation | Refraction (µrad) | Scattering (µrad^2)

M. Endrizzi *et al.*, Appl. Phys. Lett. 104, 024106 (2014)

Both planar (2D) and tomography (3D)

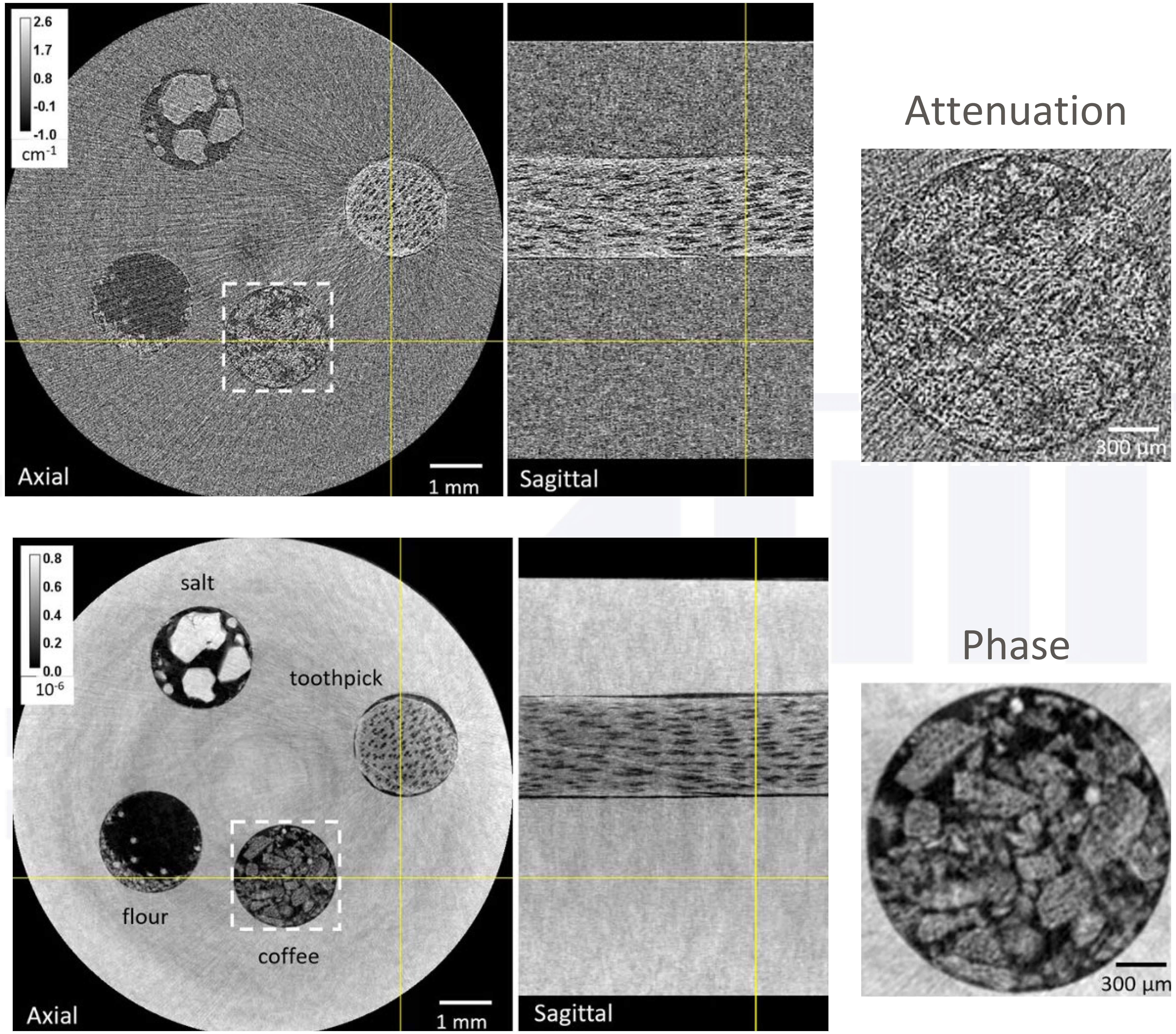
PHASE-CONTRAST CAPABILITIES

Phase contrast radiography



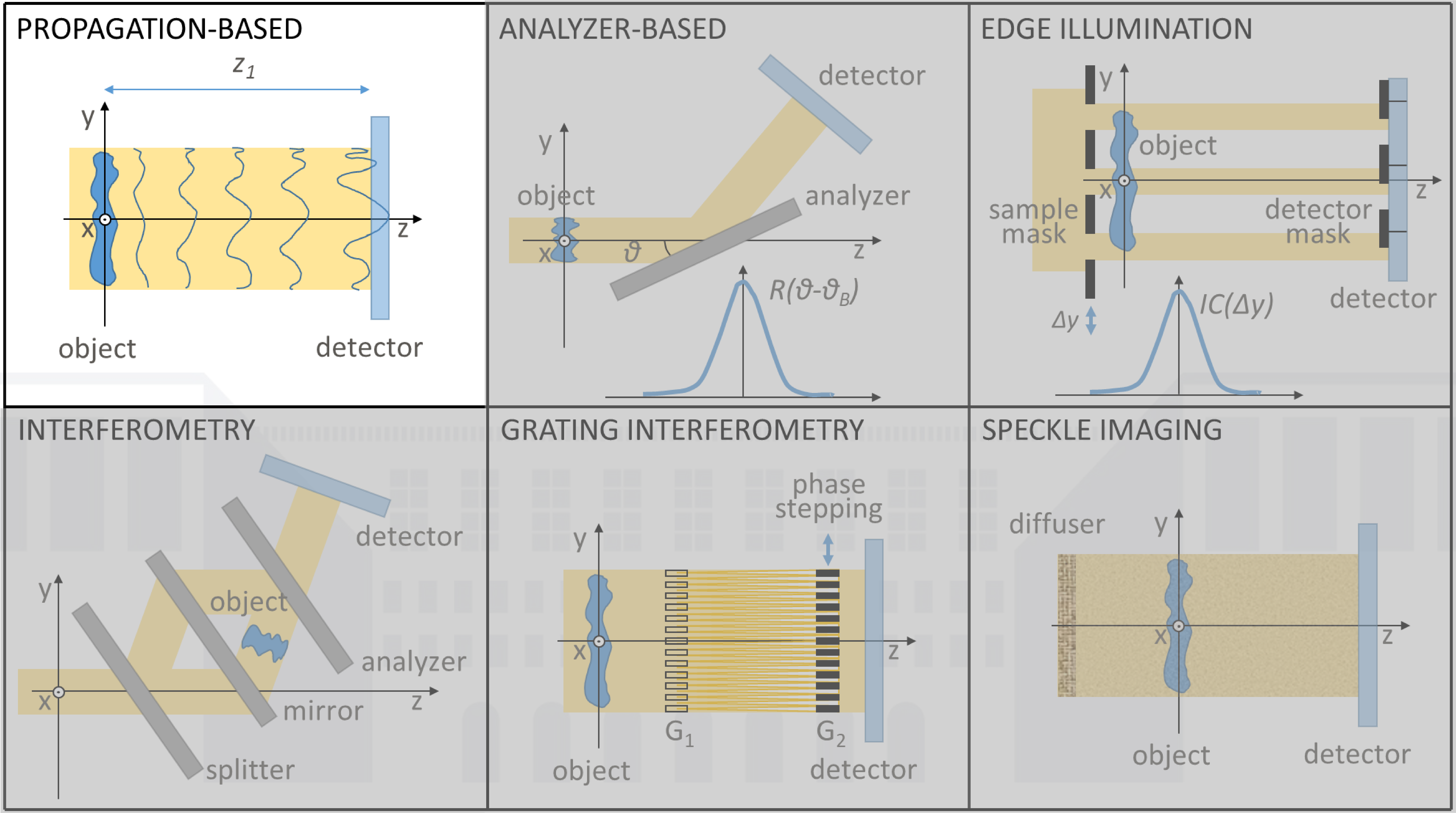
Phase contrast tomography

Brombal, Luca, et al. *Sci. Rep.* 13.1 (2023): 4206



EDGE ILLUMINATION PROS AND CONS

+	−
Compatible with low-coherence X-ray source	“Photon hungry” technique
Works with polychromatic spectra	Alignment of masks is critical
Flexible acquisition protocols (sensitivity vs speed, spatial resolution vs speed)	Masks are “relatively” expensive


PROPAGATION-BASED
z1
y
x
z
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detector
ANALYZER-BASED
detector
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EDGE ILLUMINATION
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sample mask
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Δy
IC(Δy)
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detector
y
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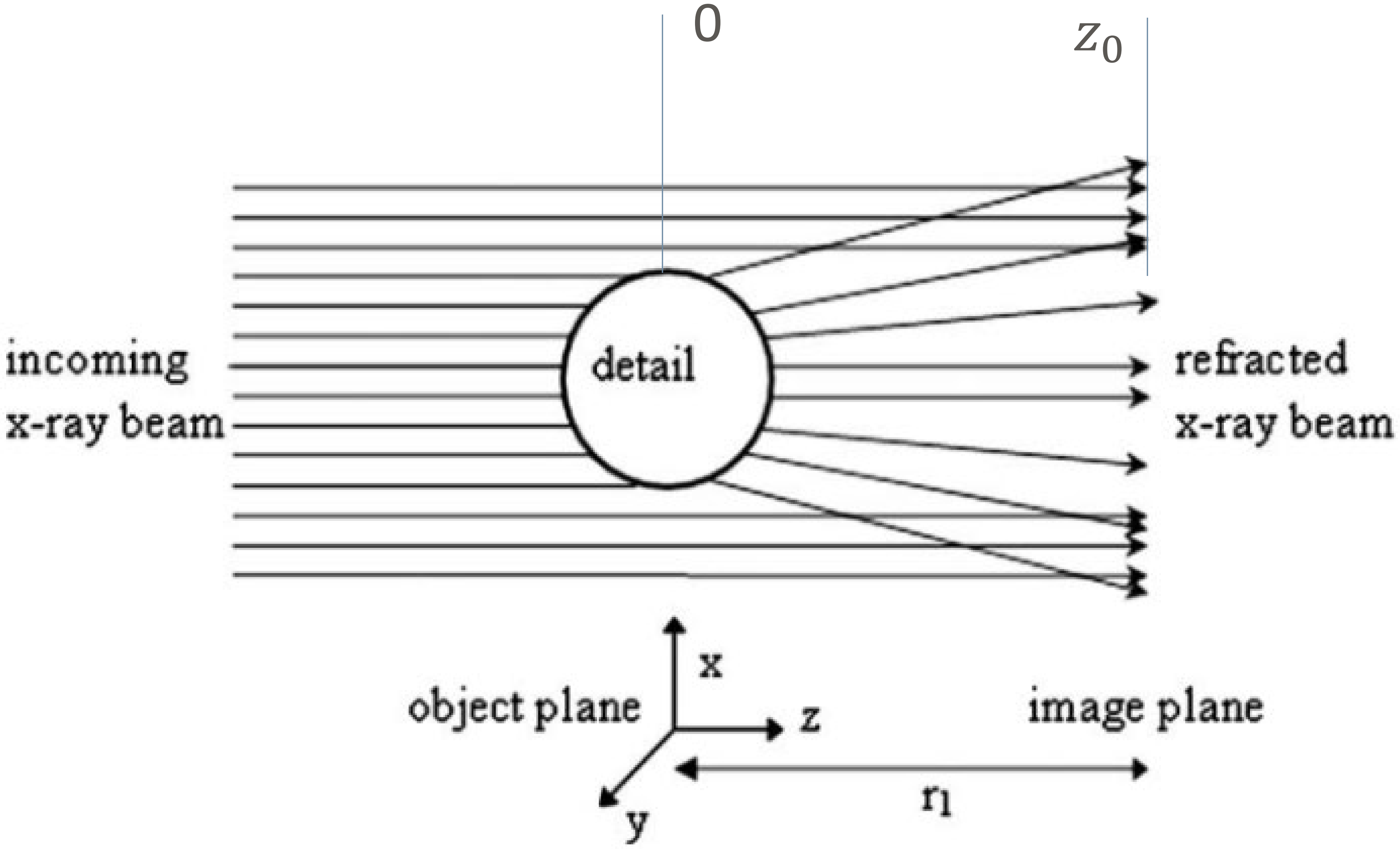
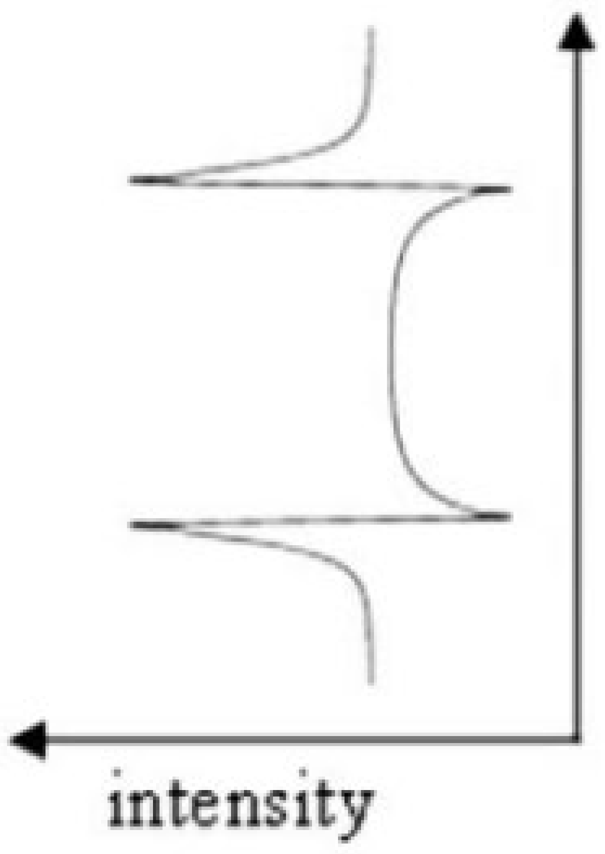
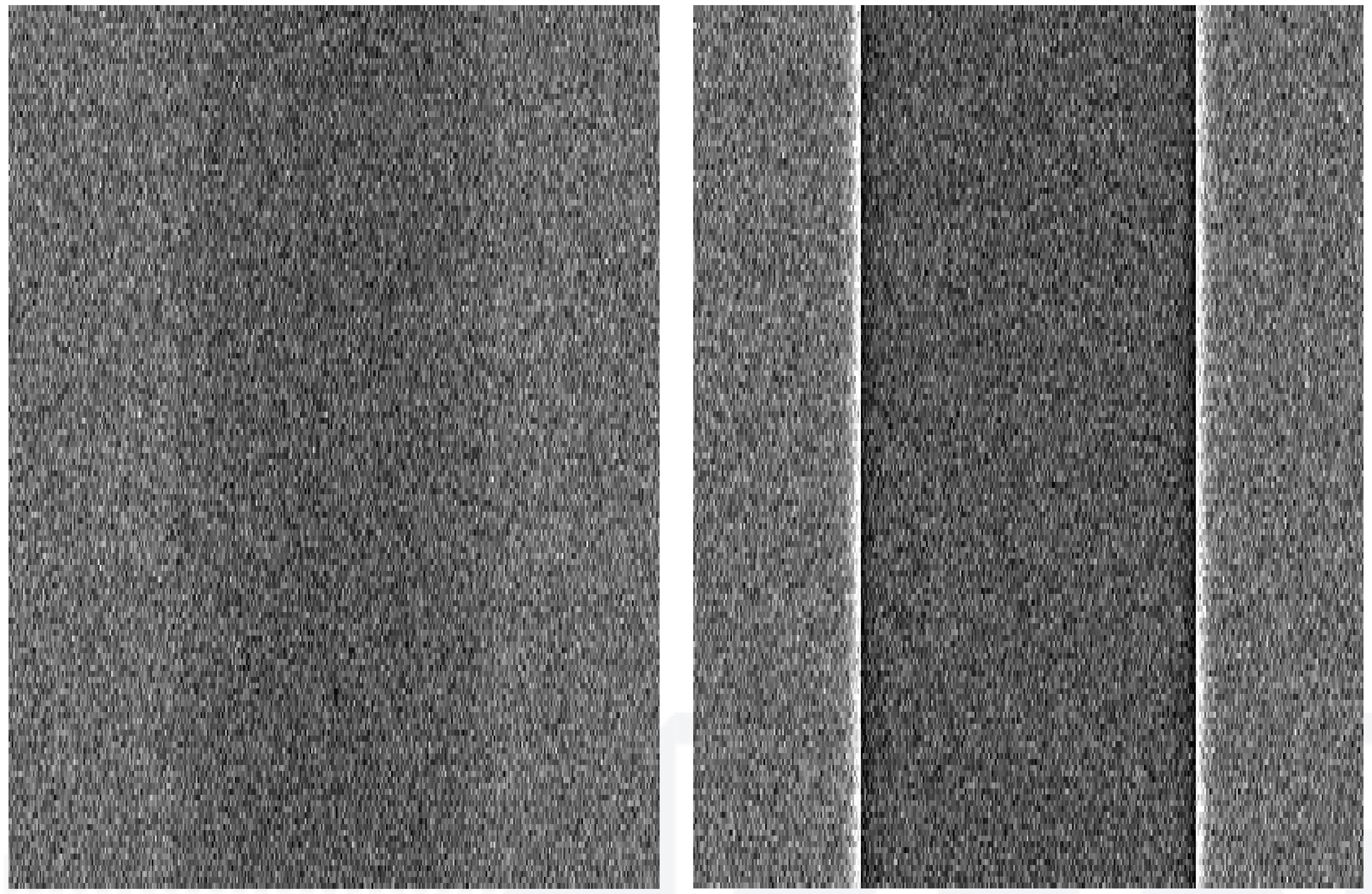
splitter
GRATING INTERFEROMETRY
phase stepping
y
x
z
G1
G2
object
detector
SPECKLE IMAGING
diffuser
y
x
z
object
detector

PROPAGATION-BASED IMAGING - PBI







$$\psi_{out}(x,y;E) = \psi_{in}(E)e^{-k\int \beta(x,y,z;E)\mathrm{d}z}\, e^{-ik\int \delta(x,y,z;E)dz}$$

$$\Phi(x,y;E) = -k\int \delta(x,y,z;E)dz$$ ⟵ **PHASE SHIFT**

Wilkins SW, et al. (1996) Nature 384: 335–338.

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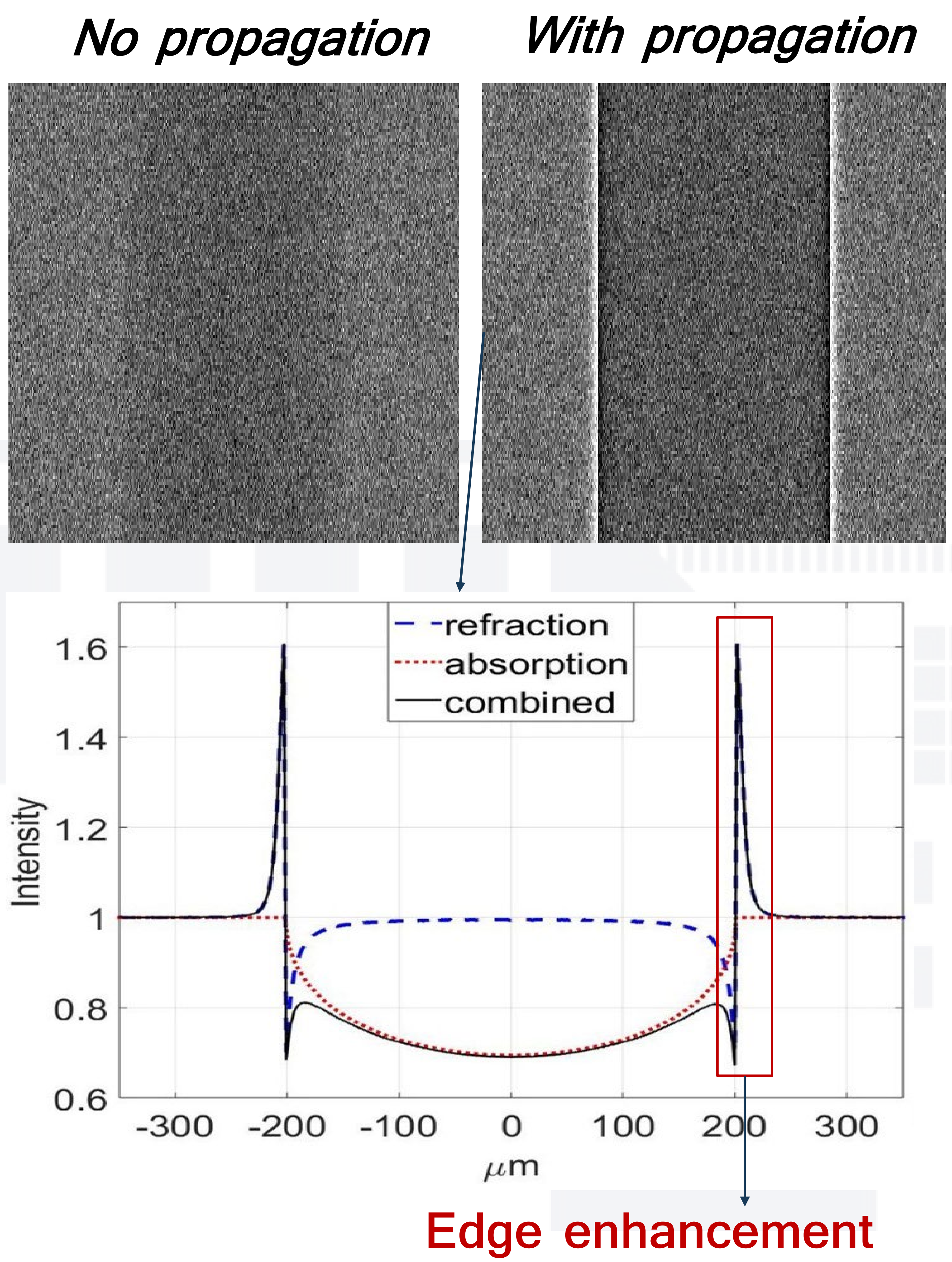
X-RAY INTENSITY PROPAGATION
(after some calculations…)



$$I(x,y;z=z_0) = I_0(x,y;z=0)\left(1-\frac{z_0}{k}\nabla^2\Phi(x,y)\right)$$

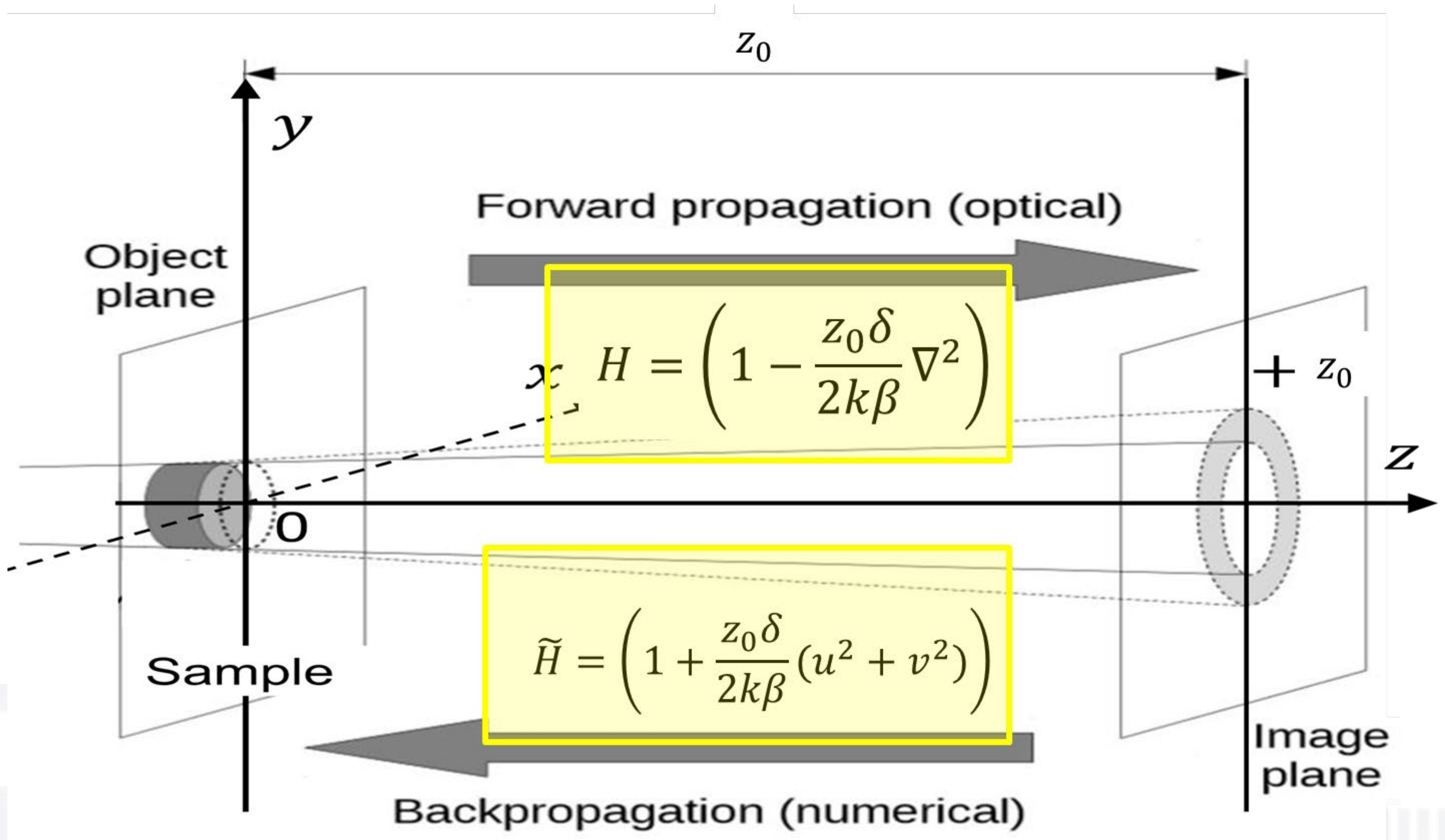
conventional attenuation image

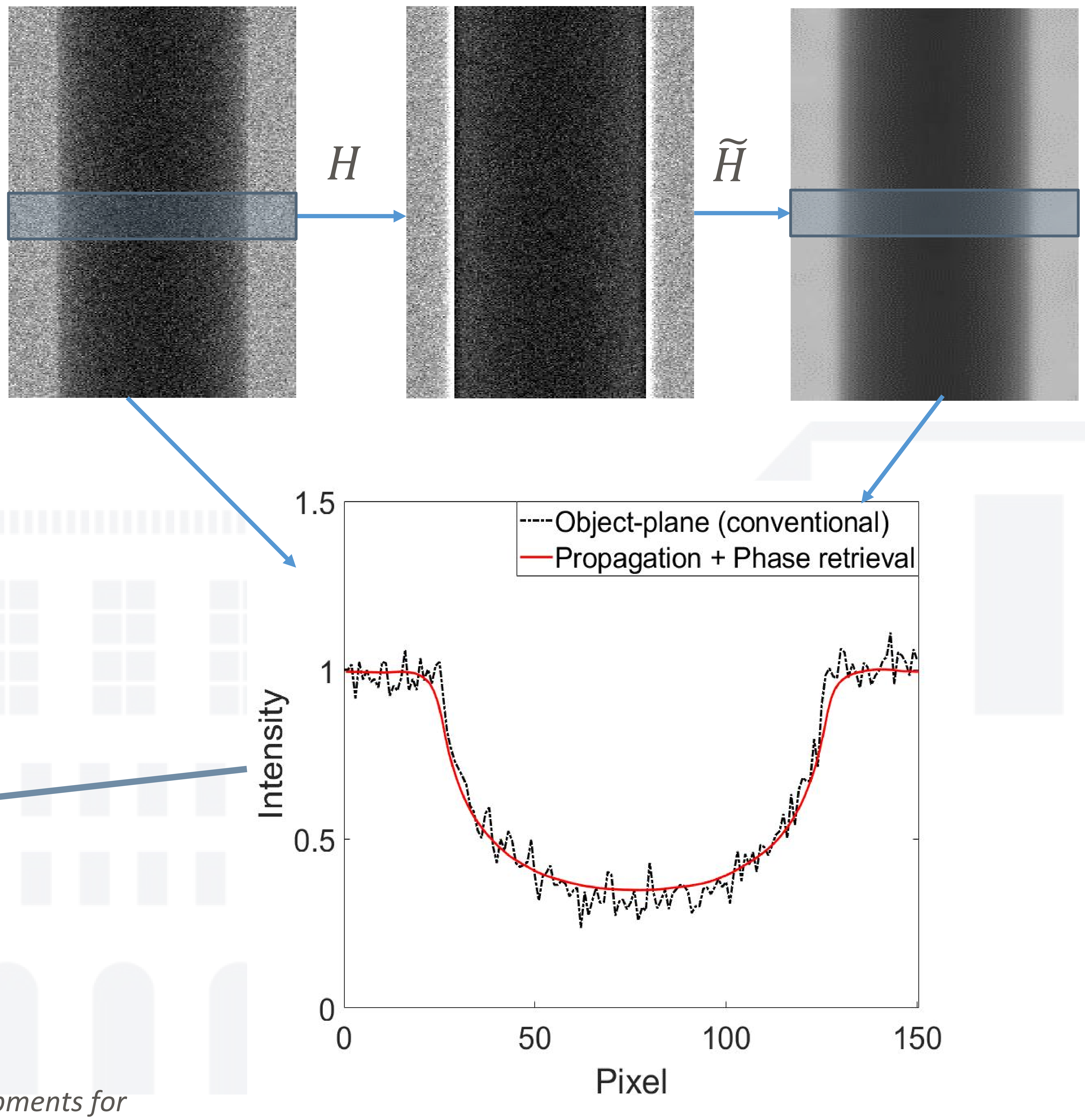
phase contrast term!

$\propto z_0$ (= propagation distance)

$\propto \nabla^2\Phi(x,y)$

PAGANIN'S PHASE-RETRIEVAL = "UNDOING PROPAGATION"





	Large area Contrast	Noise (σ)	SNR	Blur (resolution^{-1})
Propagation	=	=	=	↓
Phase retrieval	=	↓	↑	↑
Propagation + phase retrieval	=	↓	↑	=

❖*Gureyev et al., J. Opt. Soc. Am. A 34, 2251-2260 (2017)*

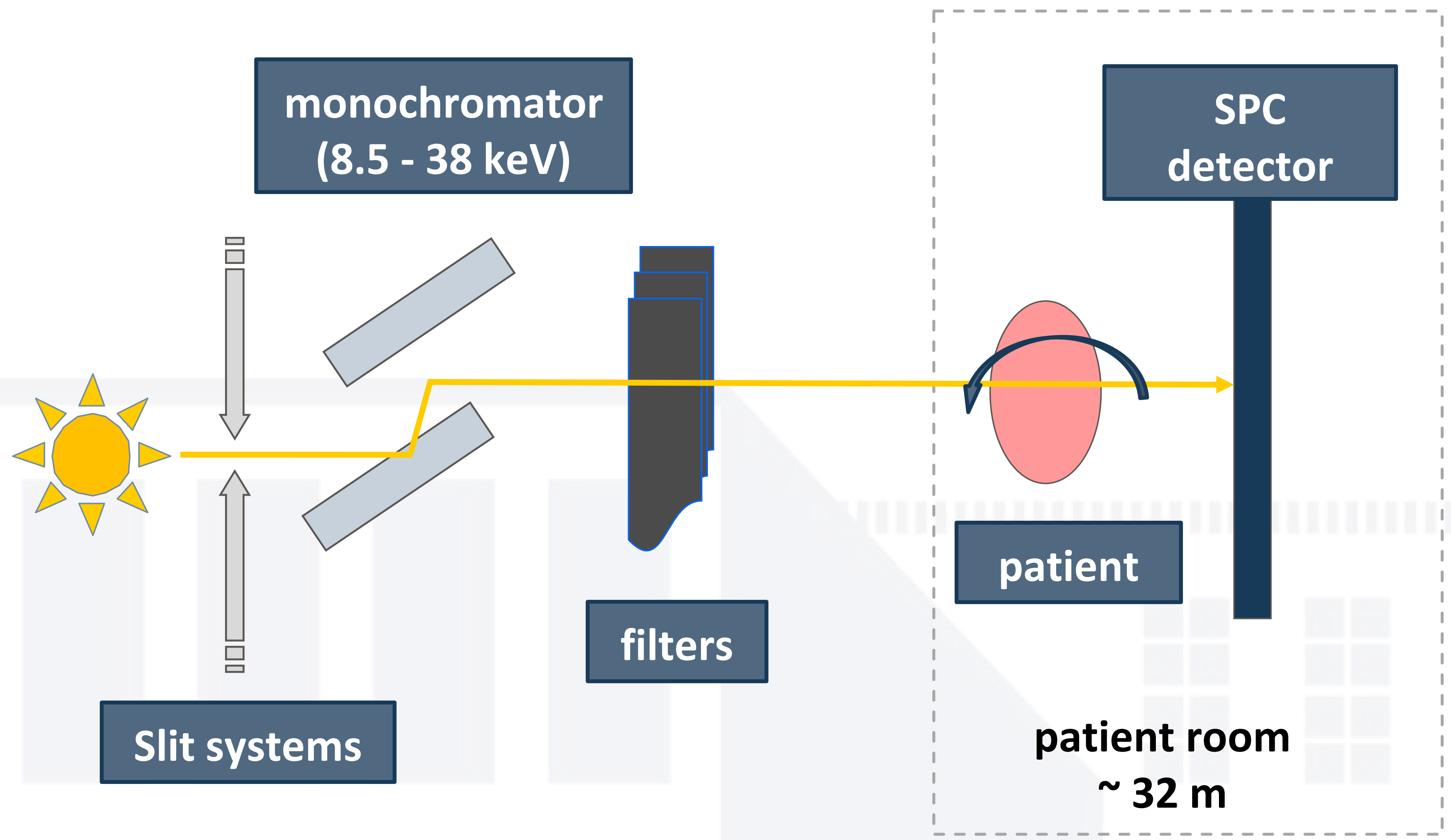
❖Brombal, Luca. *X-ray phase-contrast tomography: Underlying Physics and Developments for Breast Imaging*. Springer Nature, 2020.

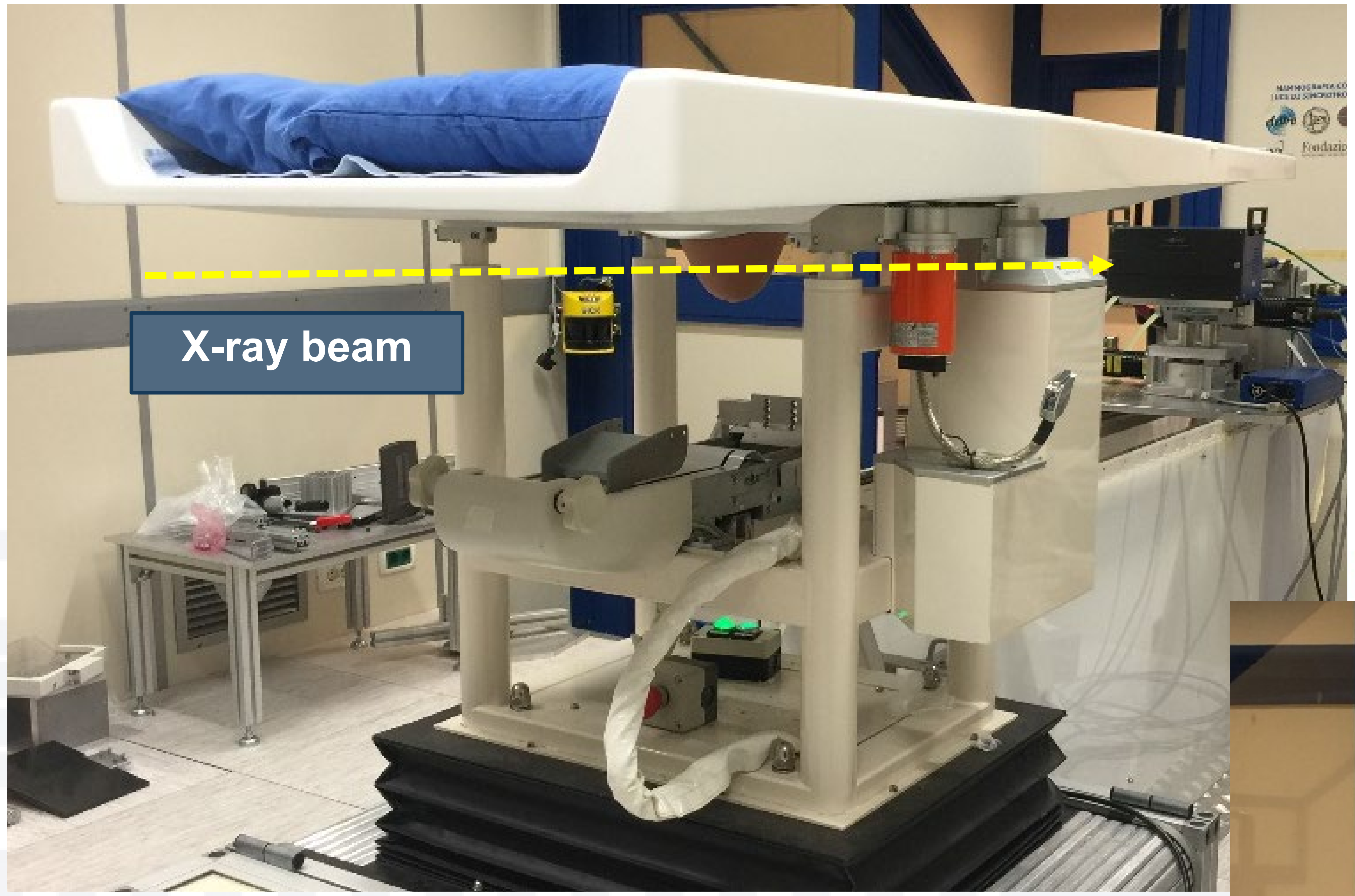
PROPAGATION-BASED PROS AND CONS

+	−
Easiest phase-contrast technique to implement	A high-coherence X-ray source is required (low power or synchrotron)
Widely used in research, robust data processing	It does not give access to different contrast channels separately (phase and attenuation are linked)

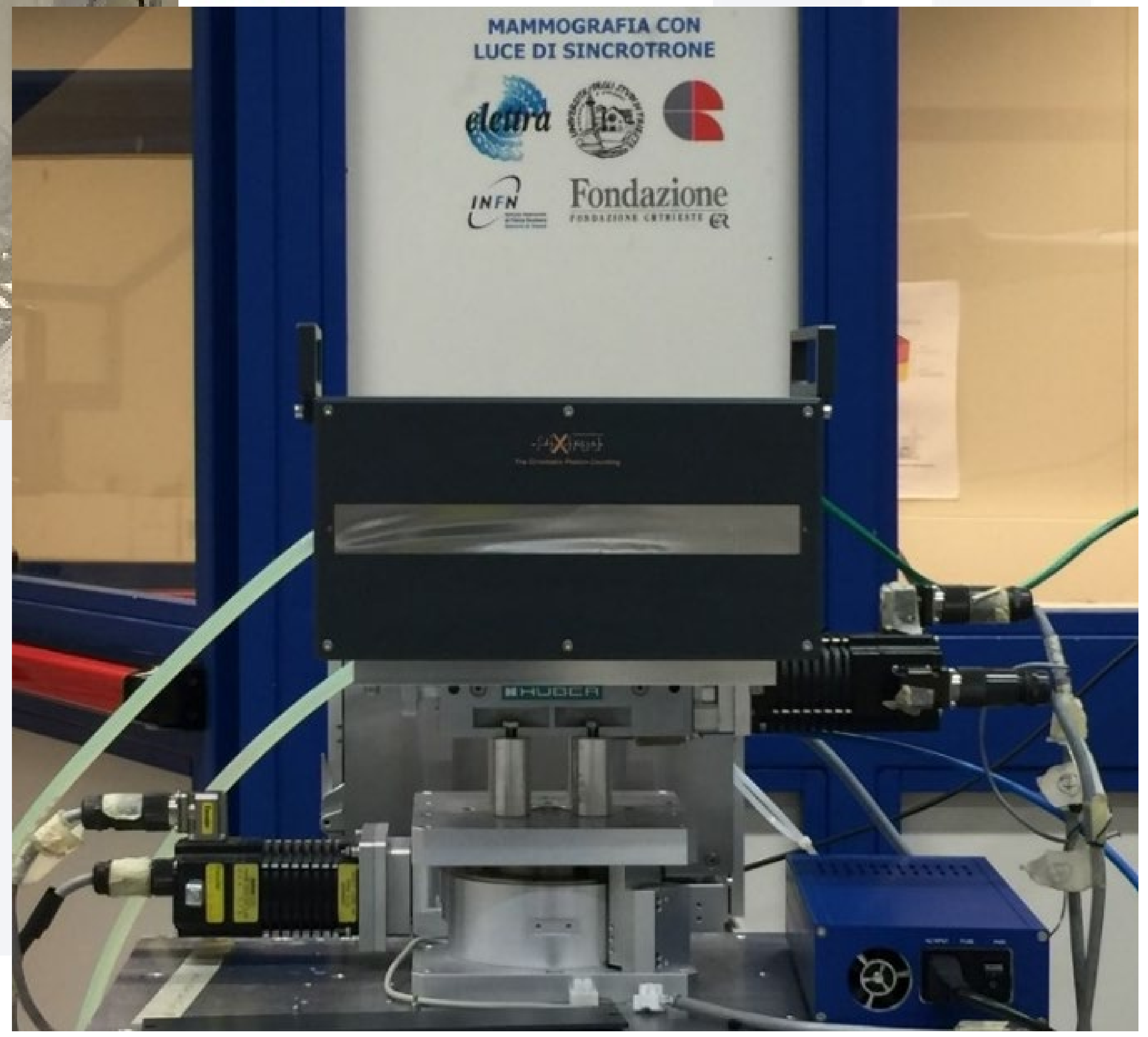
PROPAGATION-BASED BREAST CT @ SYNCHROTRON

SYRMEP Beamline @ Elettra synchrotron

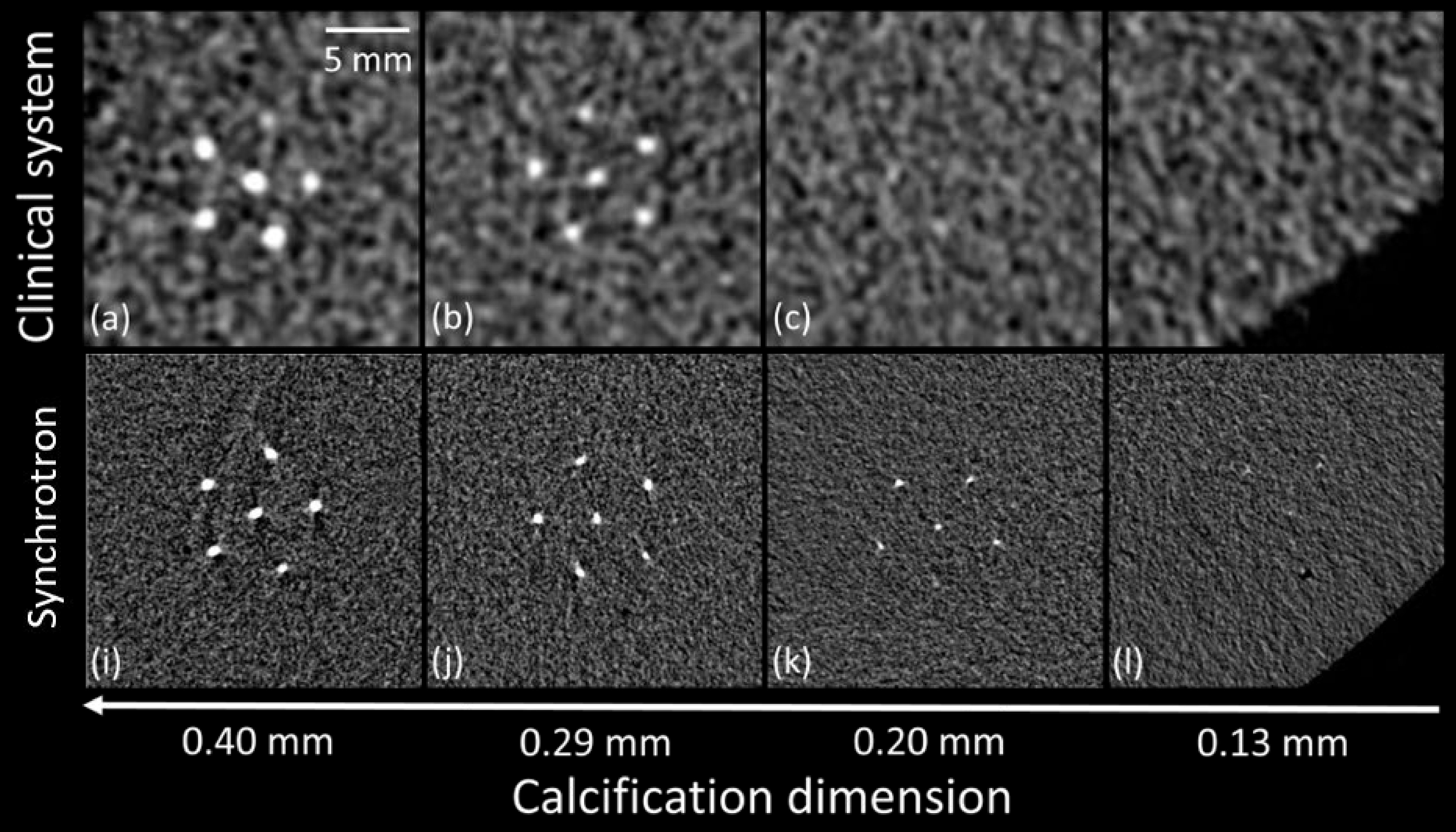




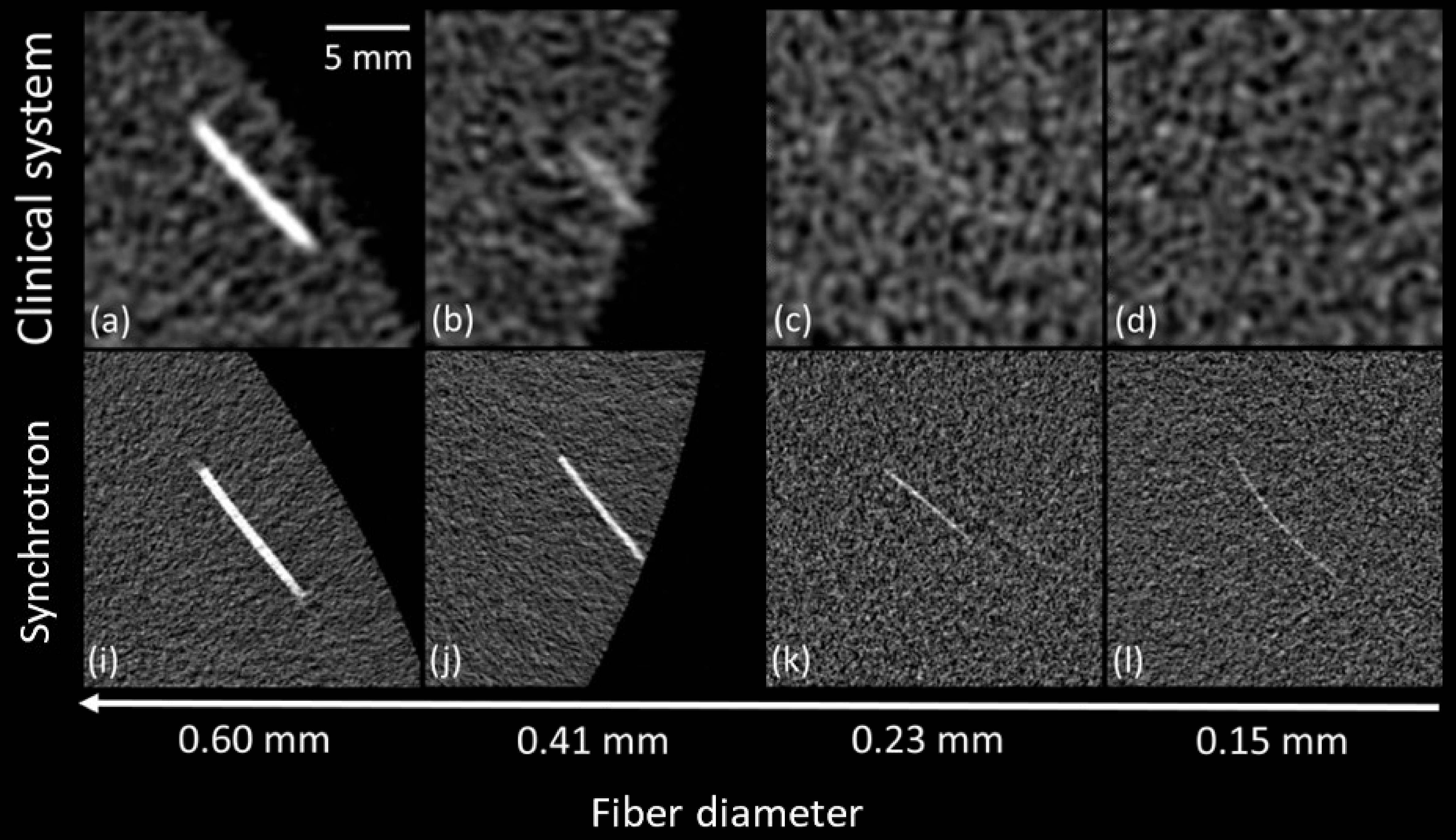
Elettra Sincrotrone Trieste



PBI APPLICATIONS: CLINICAL VS PBI BCT



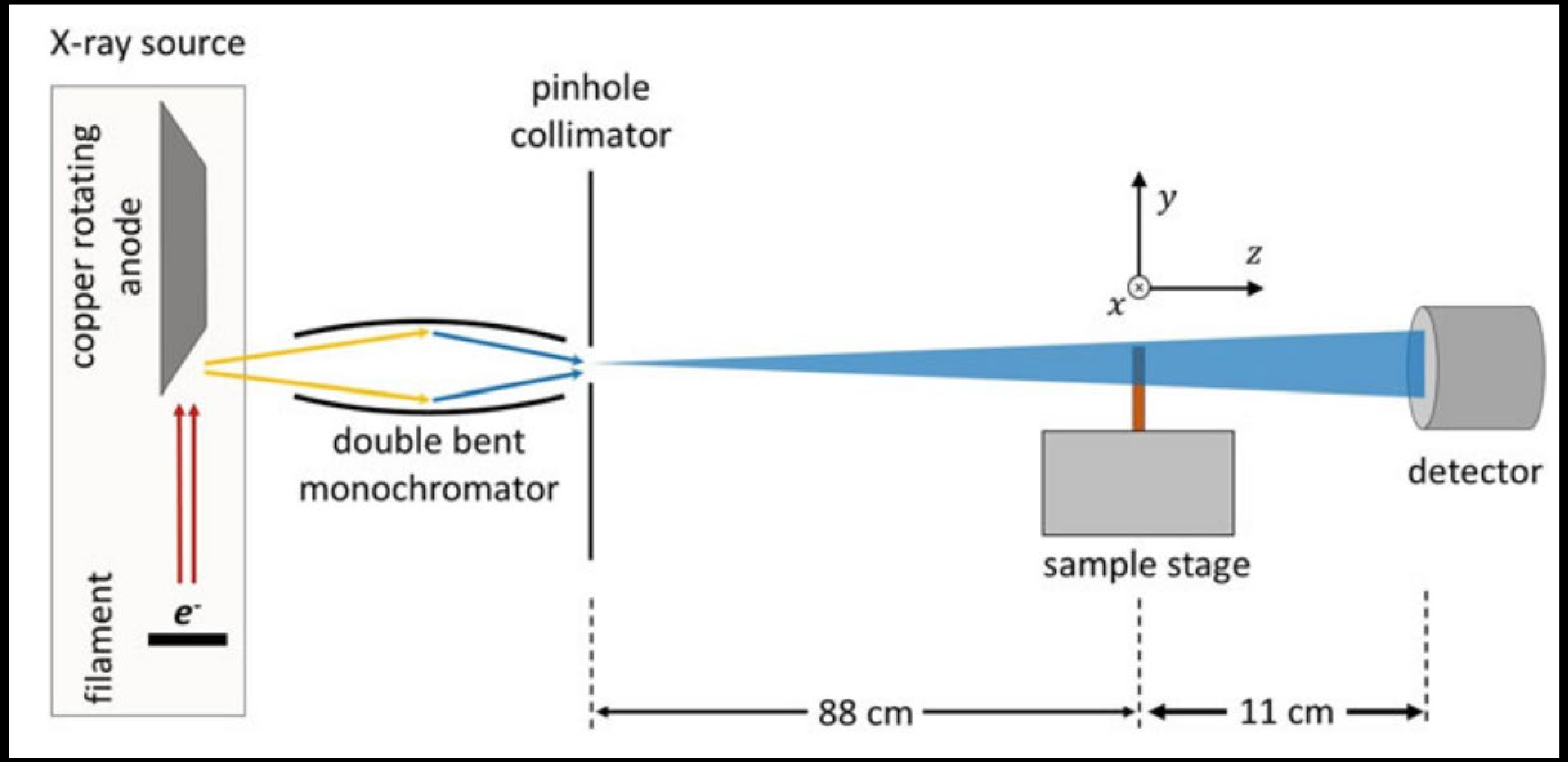
Clinically compatible radiation dose ~5 mGy



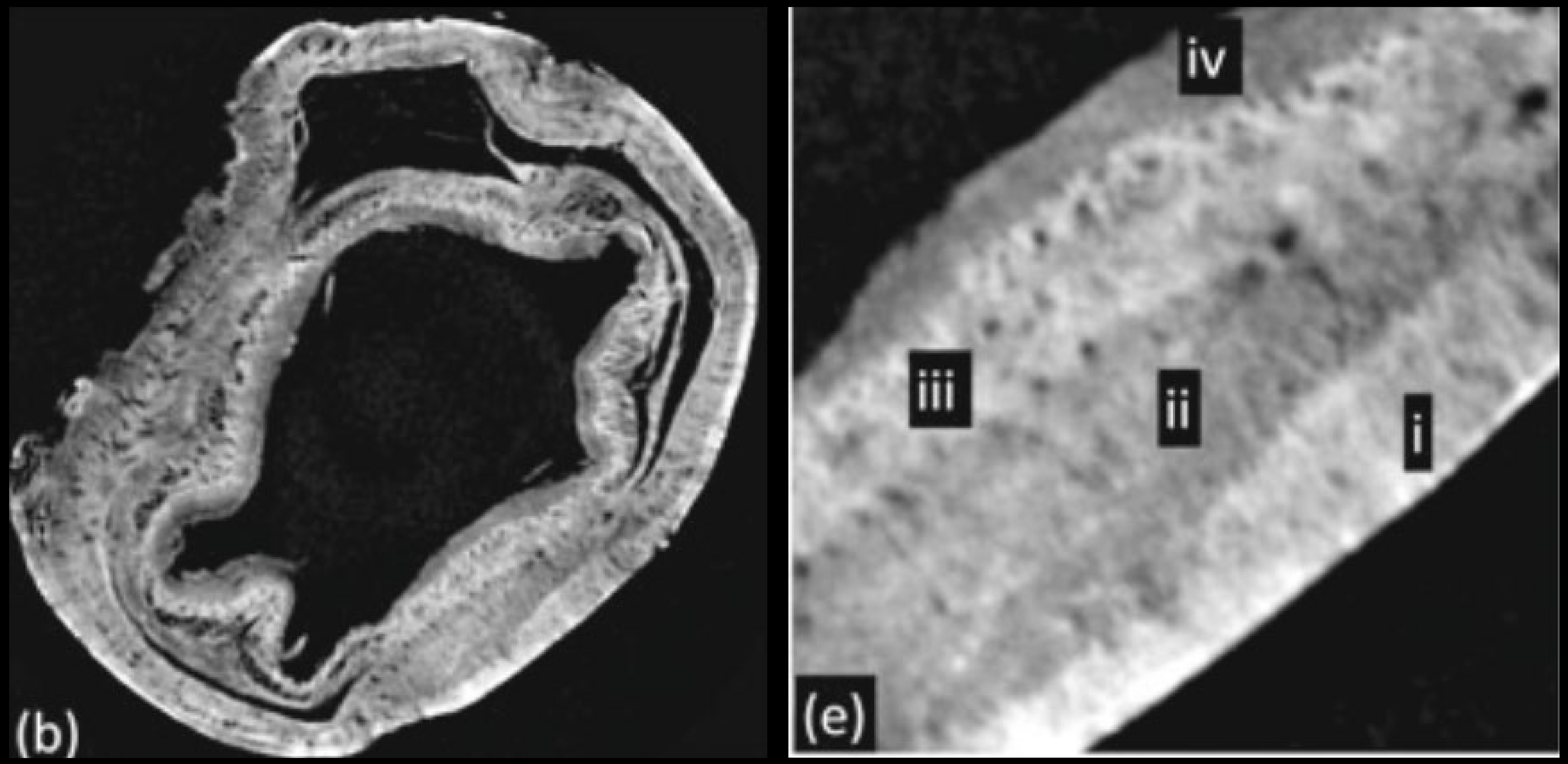
❖ *Brombal, Luca, et al. "Image quality comparison between a phase-contrast synchrotron radiation breast CT and a clinical breast CT: a phantom based study." Scientific reports 9.1 (2019): 1-12.*

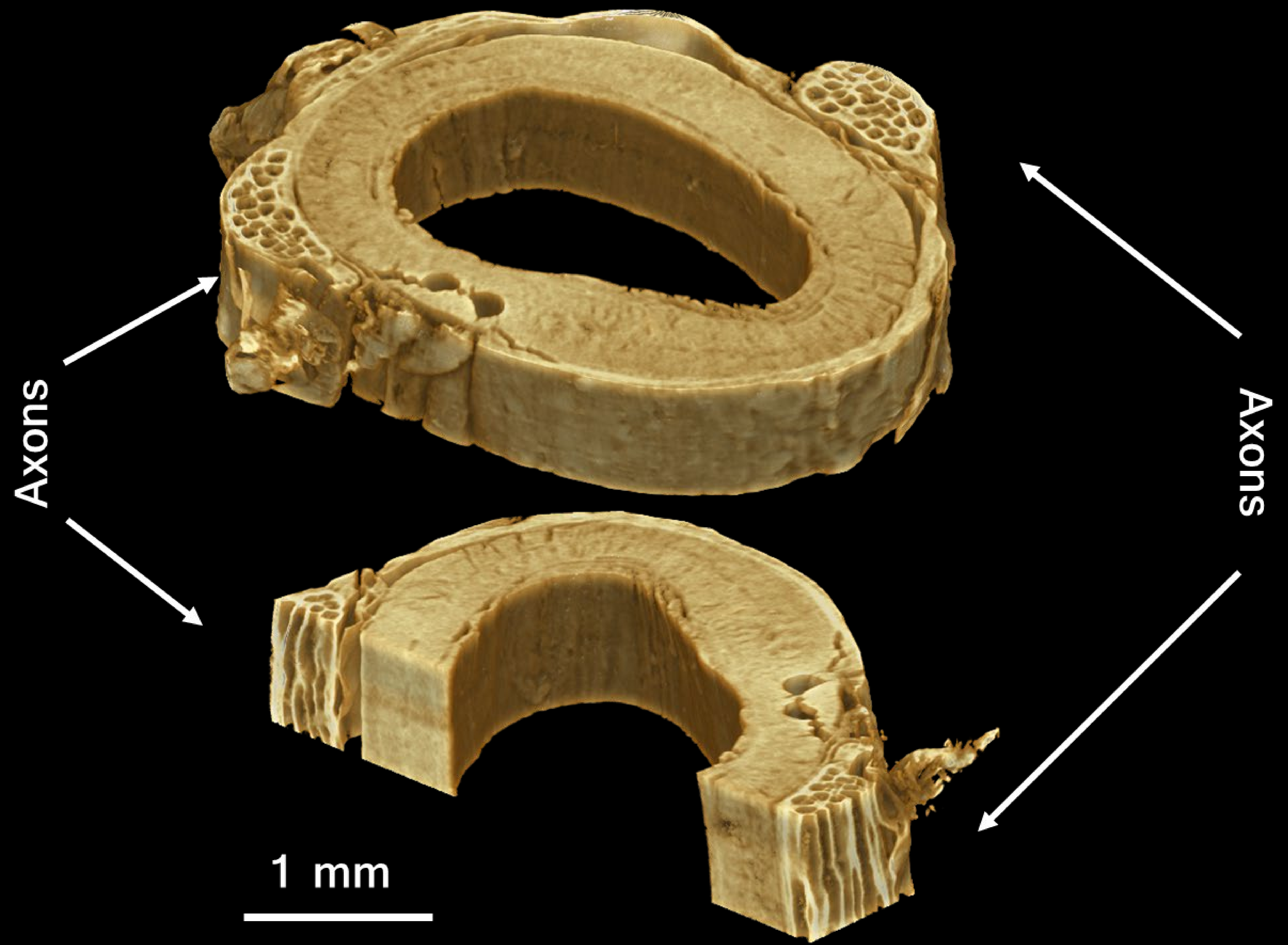
Radboudumc

PBI APPLICATIONS: VIRTUAL HISTOLOGY IN THE LAB



Piglet's esophagus





i) Adventitia
ii) Muscularis propria
iii) Sub-mucosa
iv) mucosa

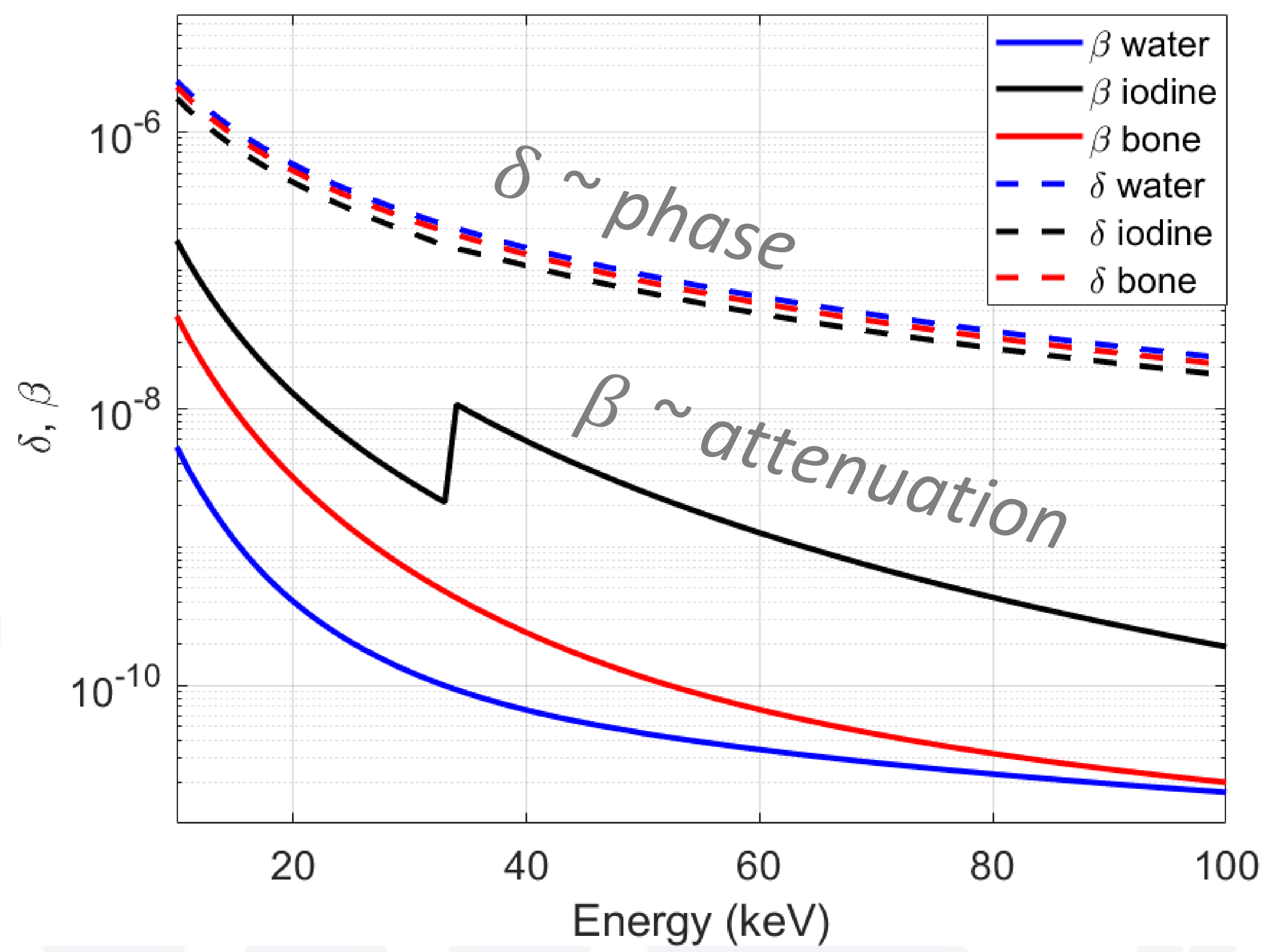
Brombal, L., et al. Physical Review Applied 11.3 (2019): 034004.

UCL

OUTLINE

- X-ray imaging fundamentals
- Spectral imaging
- Phase-contrast imaging
- **Spectral phase-contrast imaging**

WHY SPECTRAL?



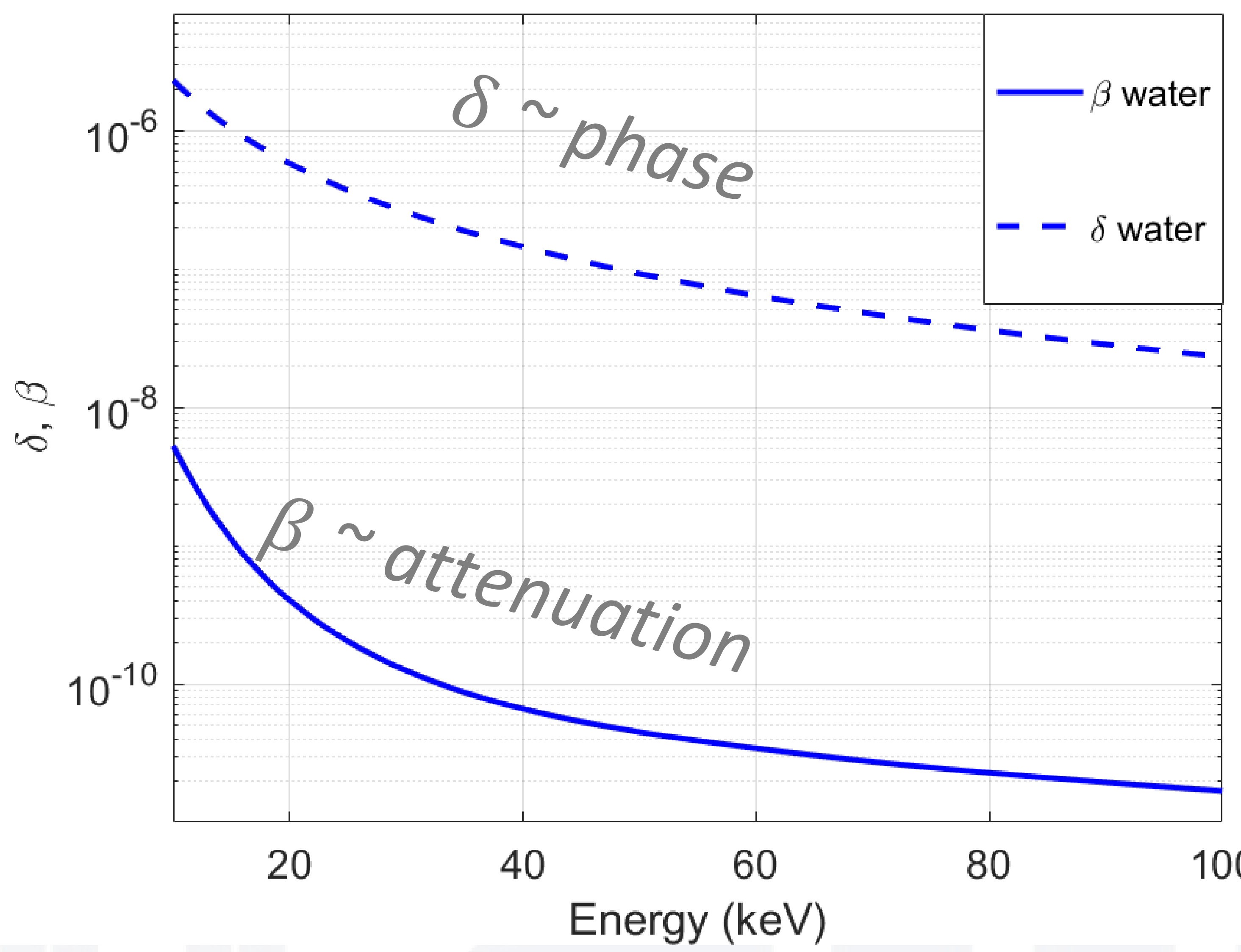
- *Energy dependence of the attenuation coefficient is sensitive to chemical composition (i.e., difference in atomic number Z)*

$$\mu(E) = \mu_{photoelectric}(E) + \mu_{scattering}(E) + \mu_{K_{edge}}(E)$$

$$\propto \frac{Z^4}{E^{3.5}} \qquad \propto Z \qquad \neq 0 \text{ at } K_{edge}$$

to separate and quantify chemical elements!

WHY PHASE-CONTRAST?



- For light materials and energies in the range 10 – 100 keV phase effects are much larger than attenuation

$$\frac{\delta}{\beta} \sim 10^3$$

to increase visibility of soft tissues!

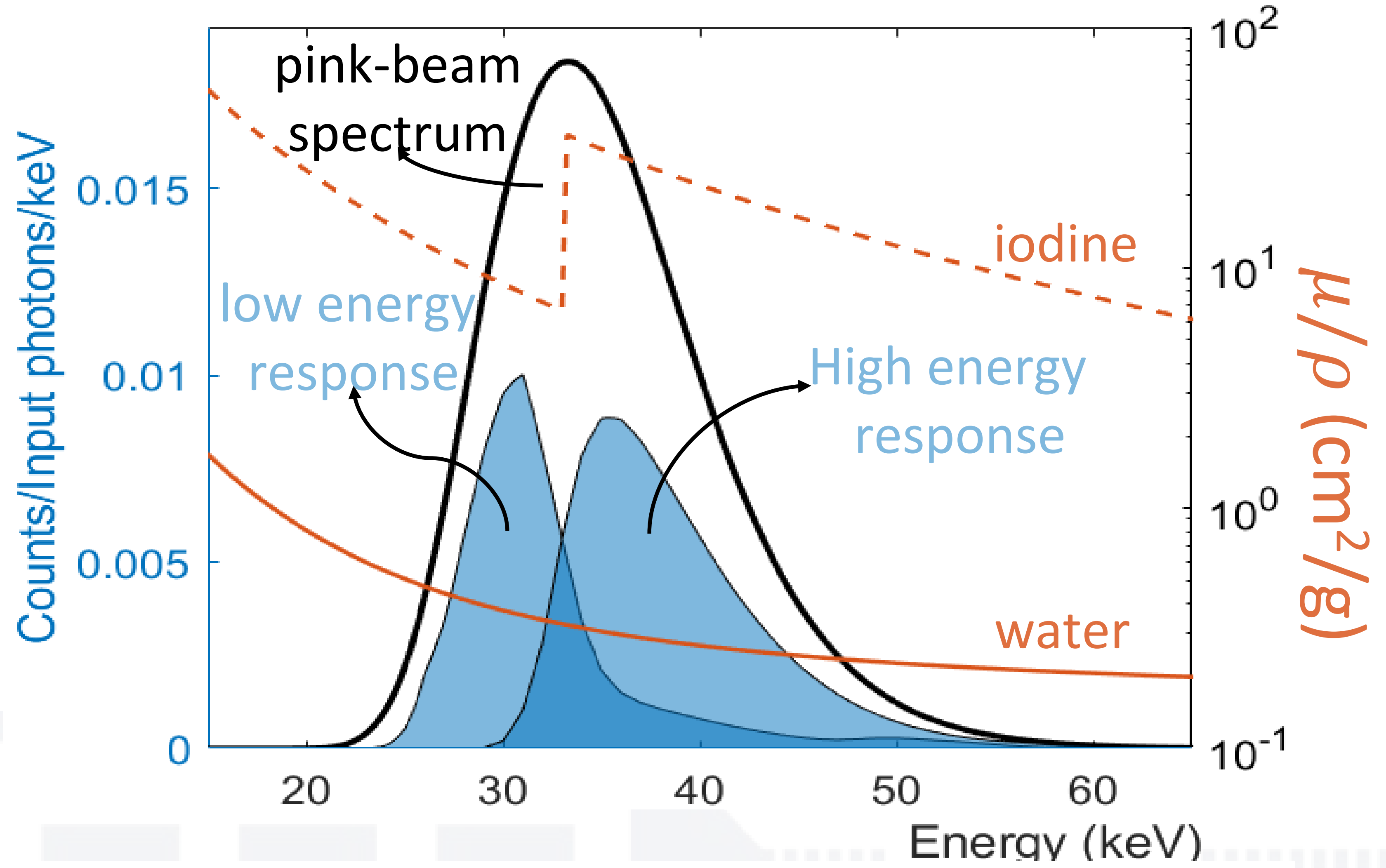
SPECTRAL IMAGING

PHASE-CONTRAST IMAGING

SPECTRAL PHASE-CONTRAST IMAGING

- ✓ BOTH SOFT TISSUE VISIBILITY AND MATERIAL QUANTIFICATION
- ✓ ROBUST METERIAL DECOMPOSITION THANKS TO THE LOW-NOISE PHASE-CHANNEL
- ✓ DECOMPOSITION OF 1 ADDITIONAL MATERIAL BY ADDING PHASE CHANNEL INTO DECOMPOSITION MATRIX

SPECTRAL PHASE-CONTRAST MATERIAL DECOMPOSITION

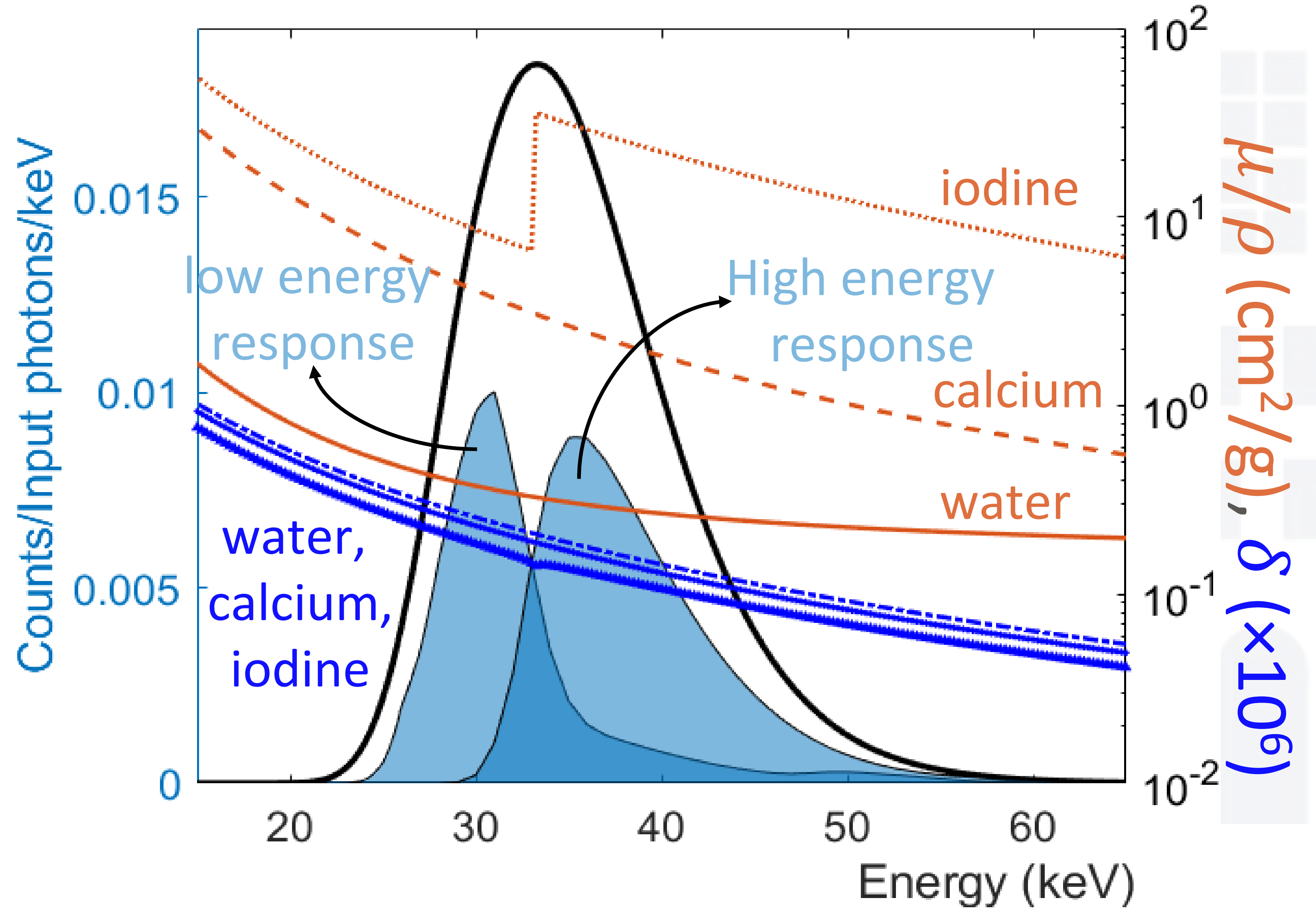


$$\mu_{low} = \left.\frac{\mu}{\rho}\right|_{low}^{water} \rho^{water} + \left.\frac{\mu}{\rho}\right|_{low}^{iodine} \rho^{iodine}$$

$$\mu_{high} = \left.\frac{\mu}{\rho}\right|_{high}^{water} \rho^{water} + \left.\frac{\mu}{\rho}\right|_{high}^{iodine} \rho^{iodine}$$

What if we want a third material?

Add the phase (δ) channel!



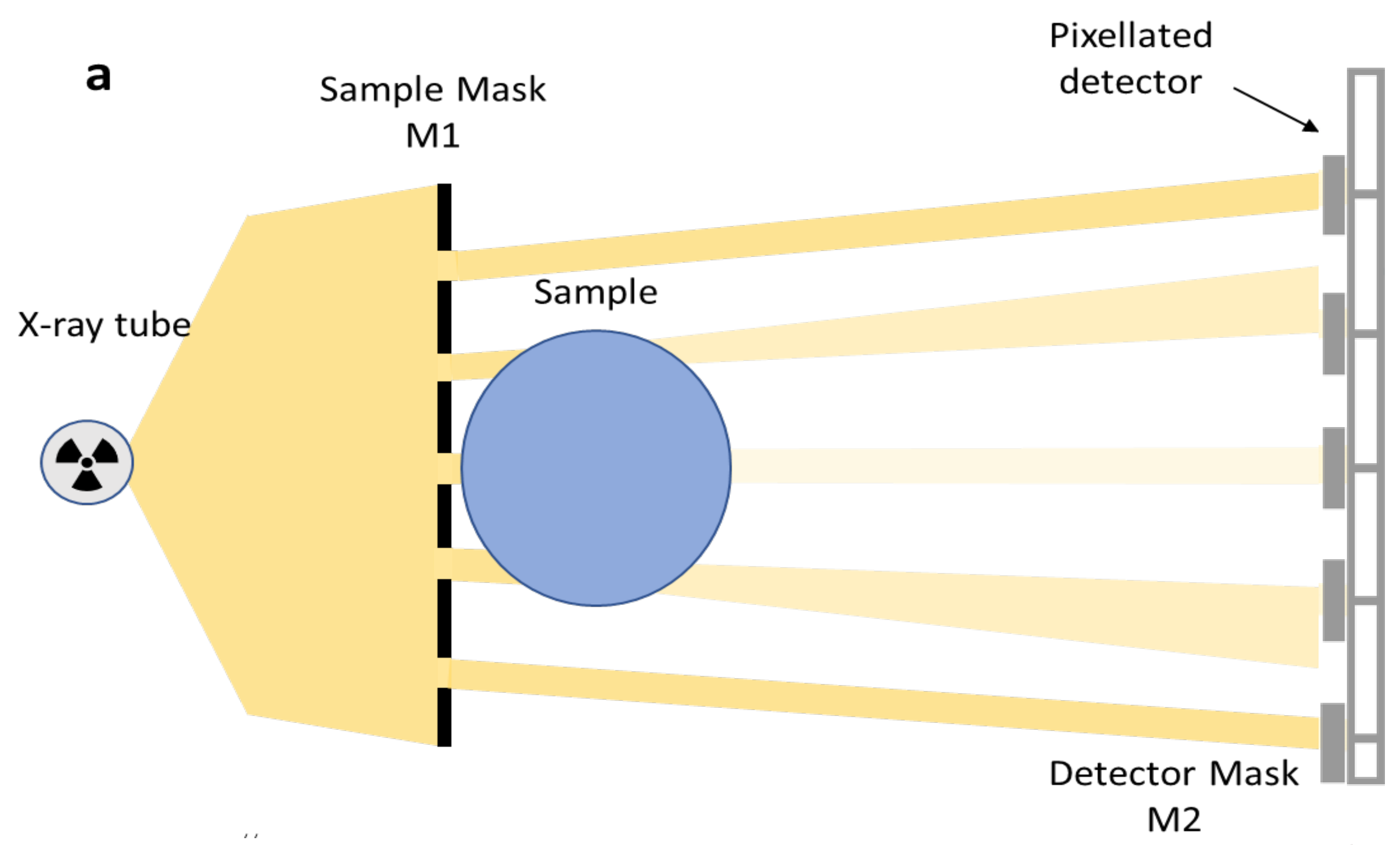
$$\mu_{low} = \left.\frac{\mu}{\rho}\right|_{low}^{water} \rho^{water} + \left.\frac{\mu}{\rho}\right|_{low}^{calcium} \rho^{calcium} + \left.\frac{\mu}{\rho}\right|_{low}^{iodine} \rho^{iodine}$$

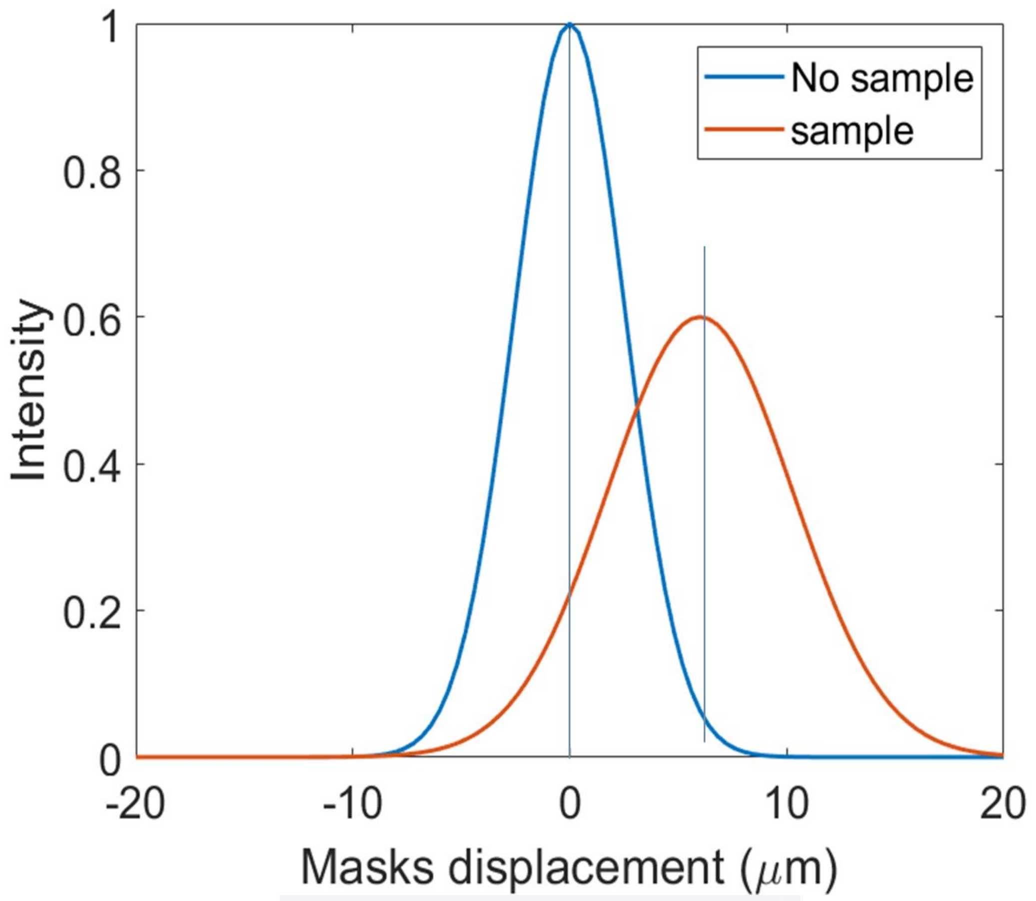
$$\mu_{high} = \left.\frac{\mu}{\rho}\right|_{high}^{water} \rho^{water} + \left.\frac{\mu}{\rho}\right|_{high}^{calcium} \rho^{calcium} + \left.\frac{\mu}{\rho}\right|_{high}^{iodine} \rho^{iodine}$$

$$\delta = \left.\frac{\delta}{\rho}\right|^{water} \rho^{water} + \left.\frac{\delta}{\rho}\right|^{calcium} \rho^{calcium} + \left.\frac{\delta}{\rho}\right|_{high}^{iodine} \rho^{iodine}$$

EDGE-ILLUMINATION SPECTRAL PHASE-CONTRAST CT @ ELETTRA

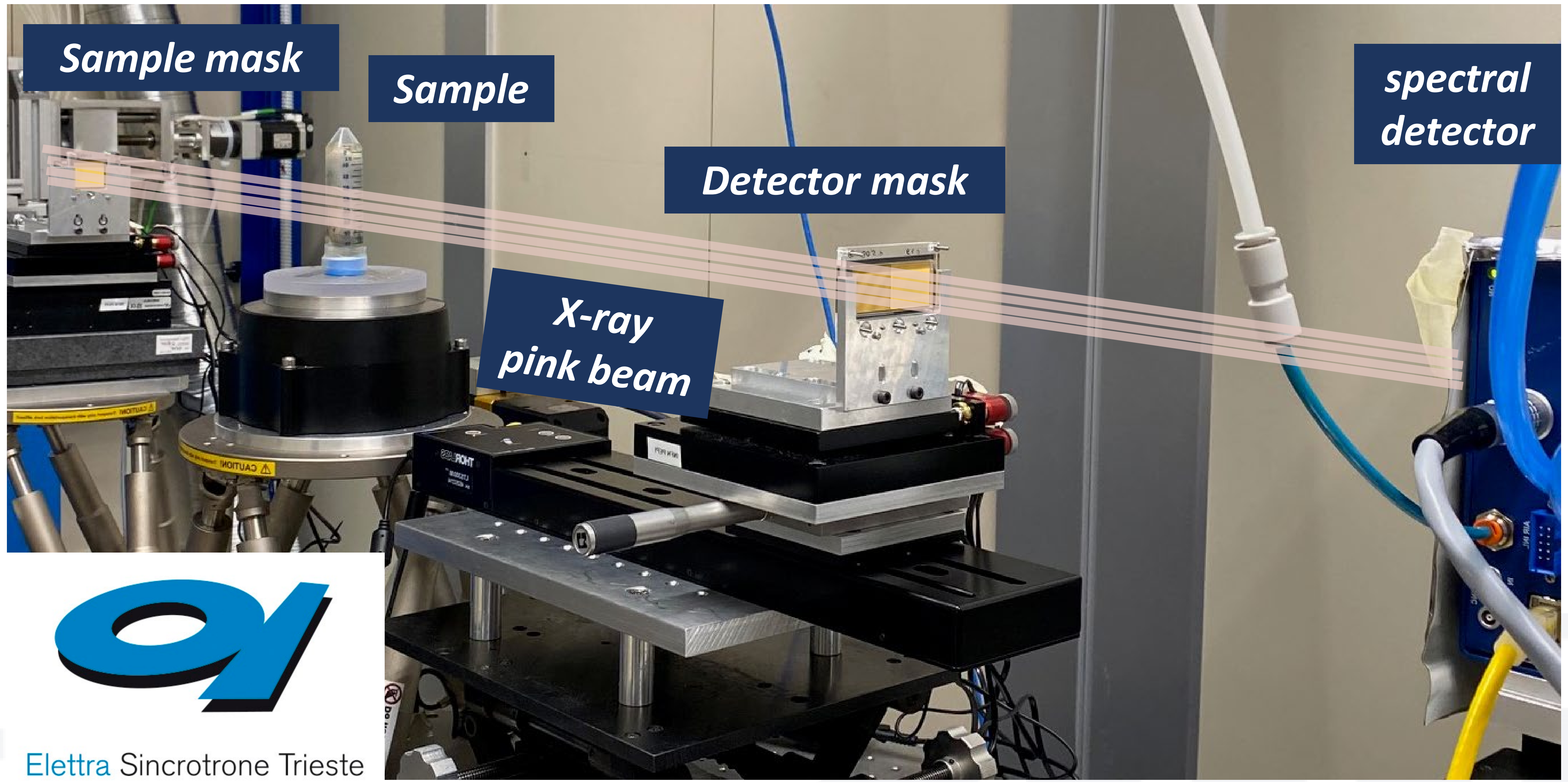
EI technique





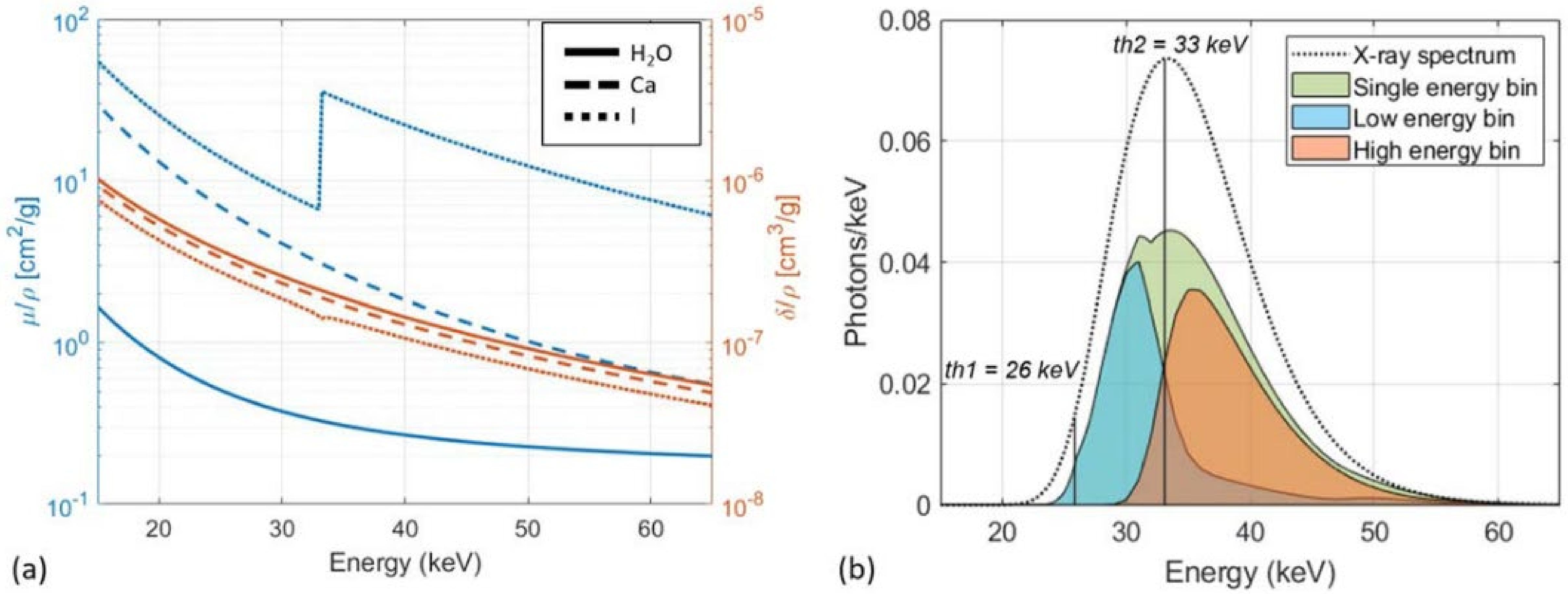
$$IC(x) \rightarrow T \times IC(x - \Delta x) * S$$

Setup



Elettra Sincrotrone Trieste

Spectrum



Brombal, Luca, et al. "Edge-illumination spectral phase-contrast tomography." *Physics in Medicine & Biology* 69.7 (2024): 075027.

In collaboration with:

UCL

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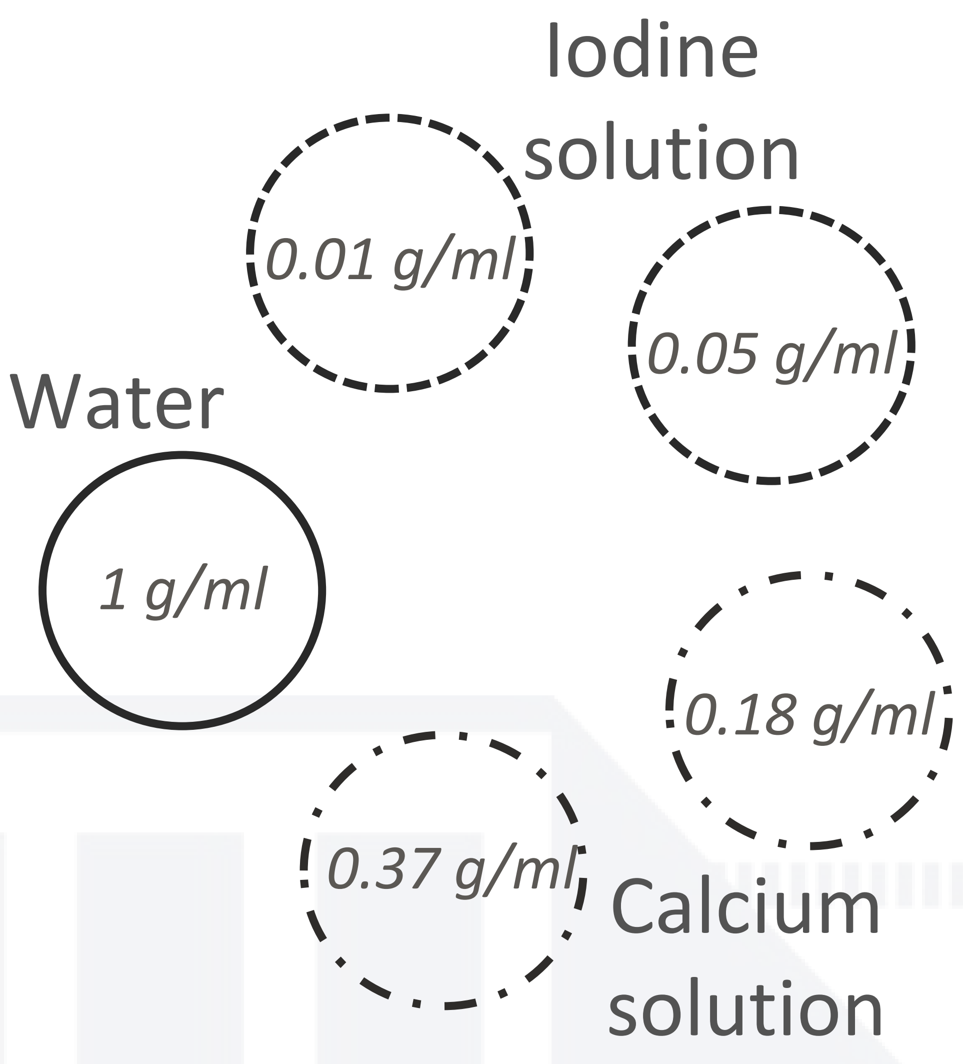
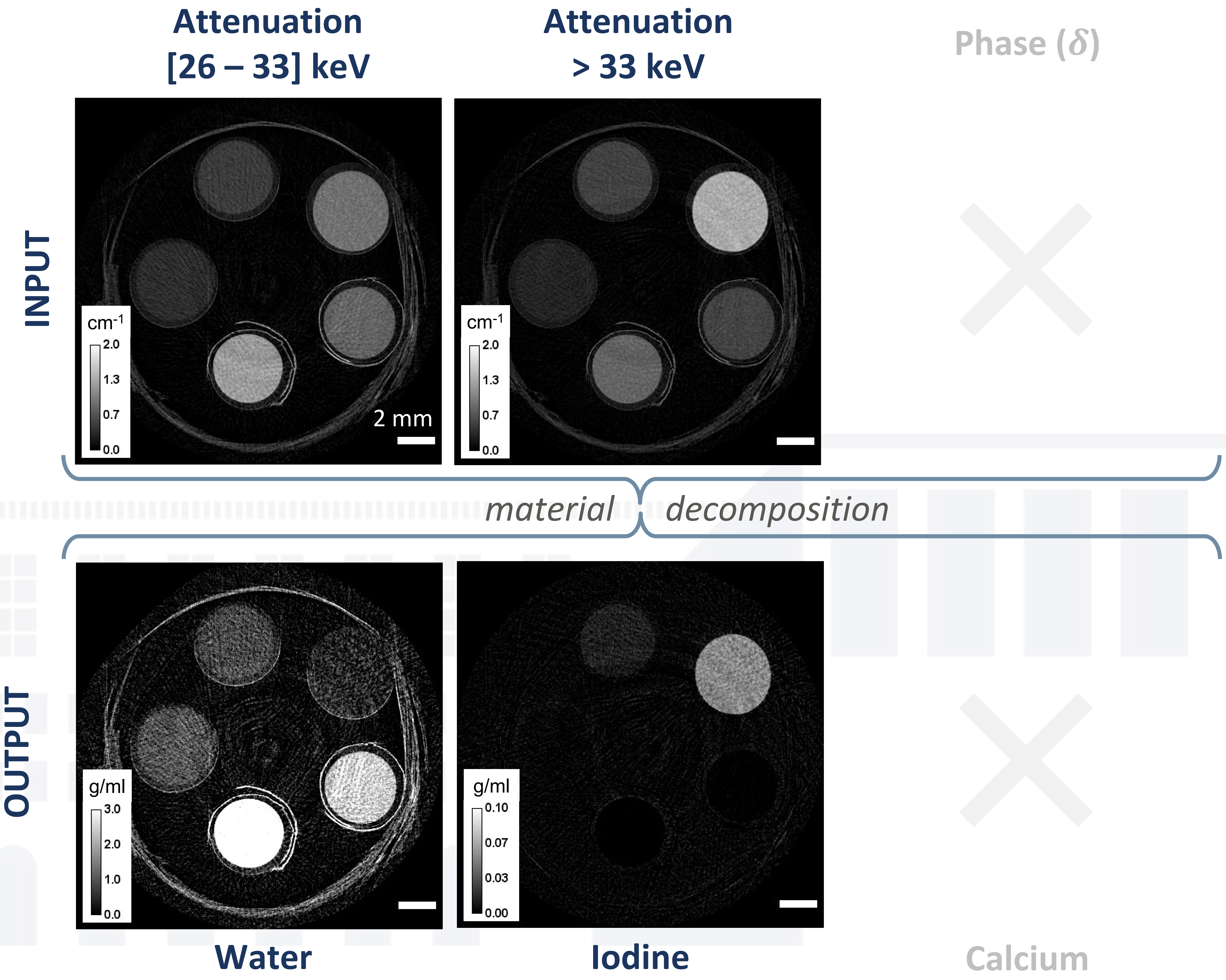
SPECTRAL





- ✓ **YES Iodine contrast medium quantification**
- × **NO calcium quantification**
- × **High noise in water image**
- × **Contamination of calcium in water image**

Brombal, Luca, et al. "Edge-illumination spectral phase-contrast tomography." *Physics in Medicine & Biology* 69.7 (2024): 075027.

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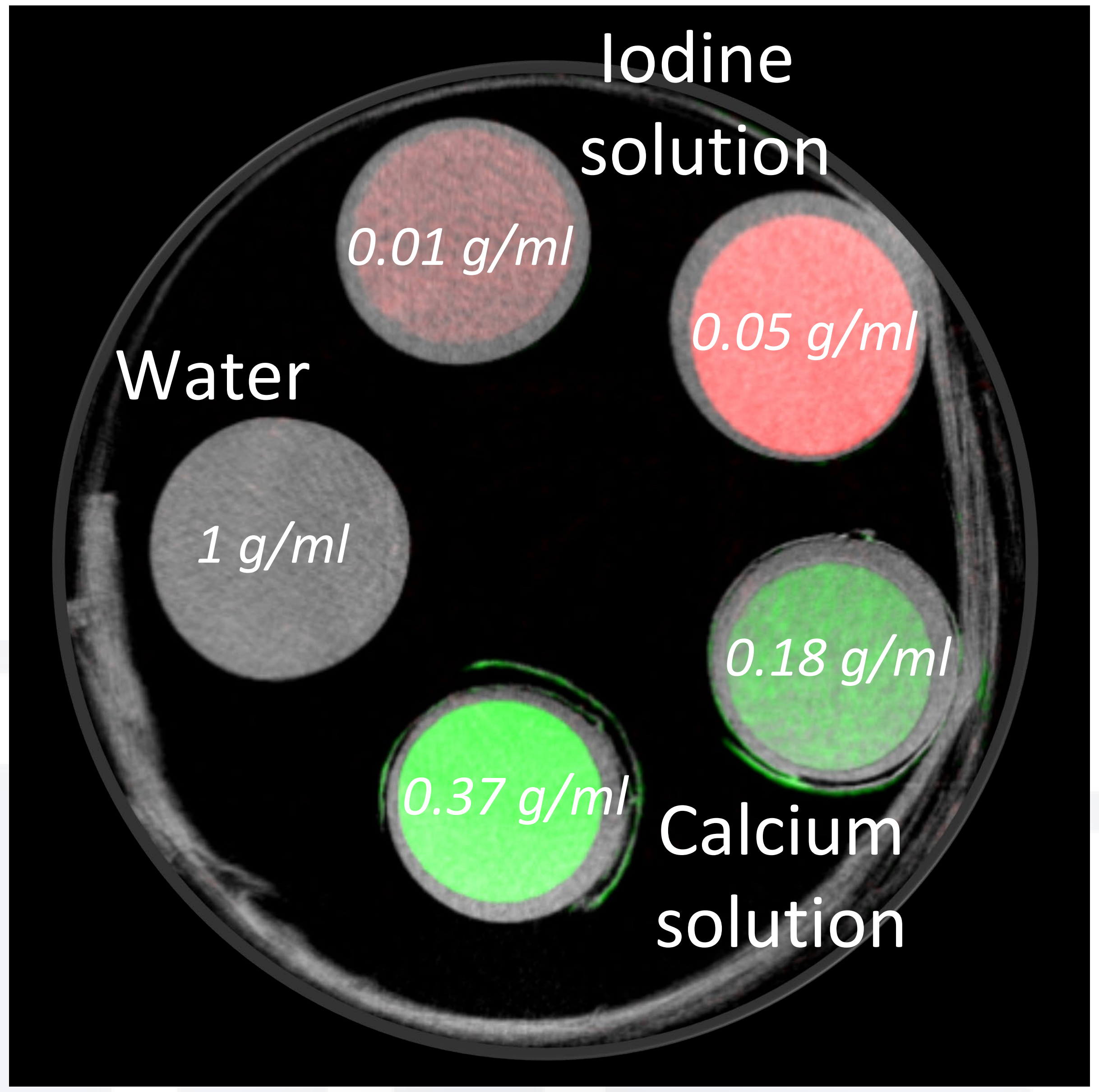
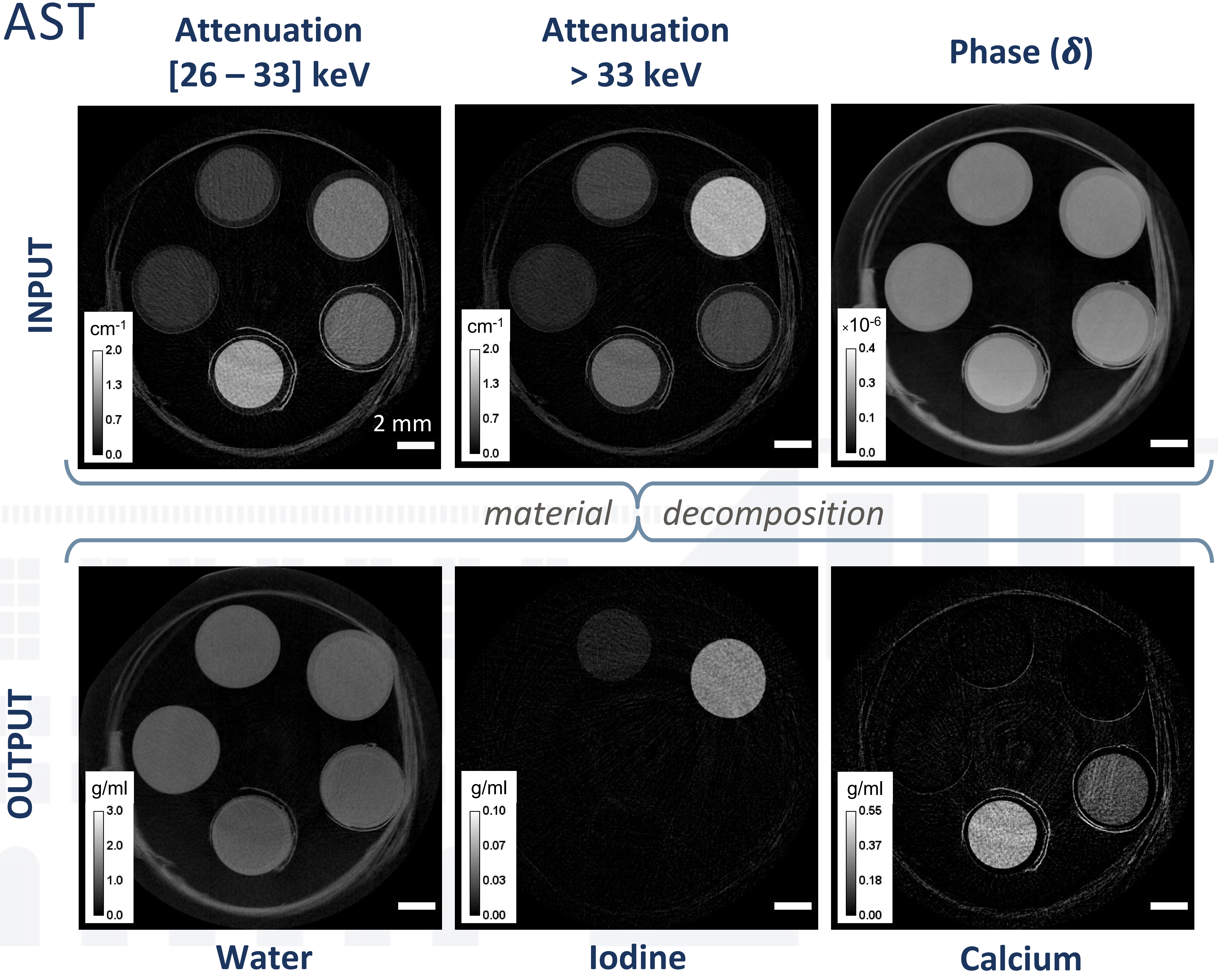
SPECTRAL + PHASE-CONTRAST



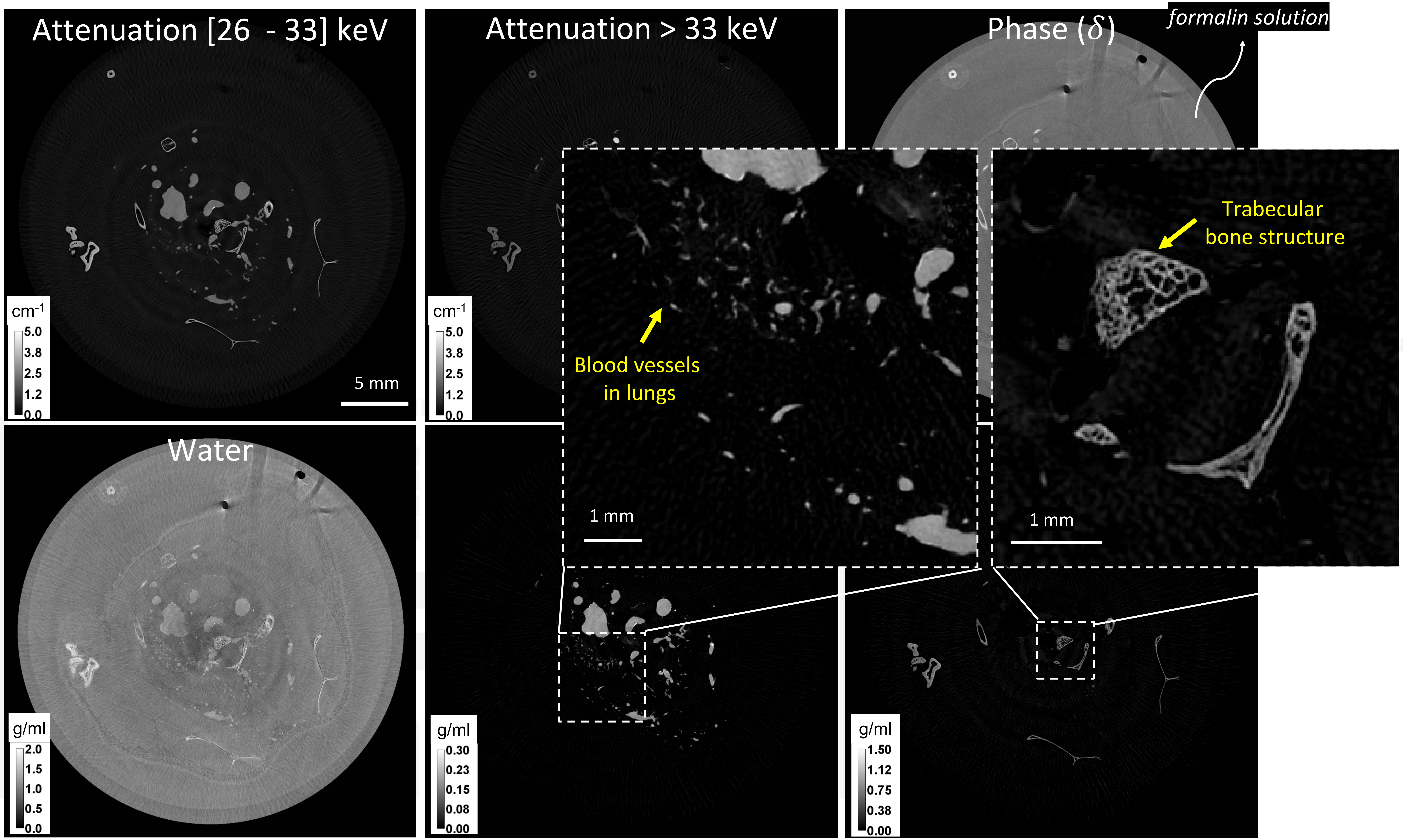


- ✓ **YES Iodine contrast medium quantification**
- ✓ **YES Calcium quantification**
- ✓ **Low noise in decomposed images**
- ✓ **NO contamination**

Brombal, Luca, et al. "Edge-illumination spectral phase-contrast tomography." *Physics in Medicine & Biology* 69.7 (2024): 075027.

SPECTRAL PHASE-CONTRAST: EX-VIVO MURINE MODEL

- Murine model (ex-vivo) in formalin
- Perfused (ex-vivo) with iodine-based contrast agent µAngiofil®
- In-plane pixel size 20 µm



In collaboration with:

HELMHOLTZ MUNICH

Brombal, Luca, et al. *Phys. Med. Bio.* 69.7 (2024): 075027.

…TAKE HOME…

- Detector-based spectral imaging already in clinics and in micro-CT laboratories
- Phase-contrast is widely used in pre-clinical and non-clinical studies. It is moving its first step into clinics
- The combination of the two techniques will become an option in the future and research is starting now

Finanziato dall'Unione europea
NextGenerationEU

THANK YOU!