Spectral and phase-contrast imaging: from crystal-based synchrotron setups to detector-based compact systems

28/06/2022

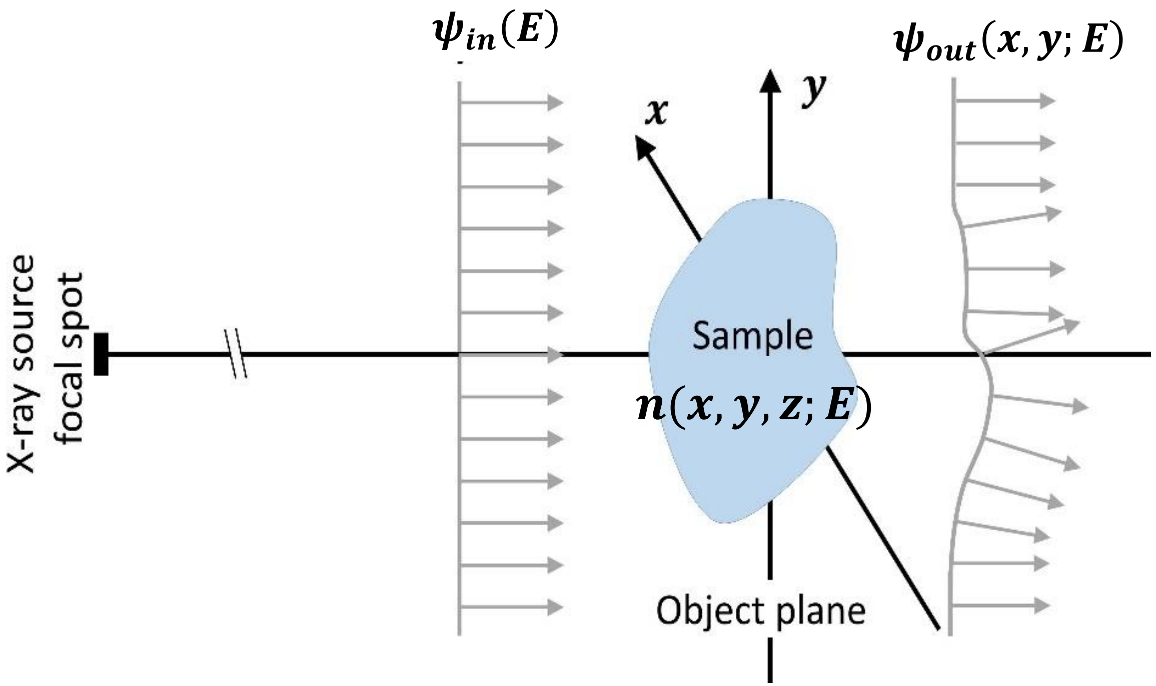
Luca Brombal – INFN Trieste

iWoRiD 2022 – Riva Del Garda (TN), Italy – 26-30 June 2022

OVERVIEW

- Principles
- X-ray spectral imaging
  - Crystal-based systems
  - Detector-based systems
- Phase-contrast imaging
  - Analyzer-based imaging @ synchrotron
  - Edge illumination in the lab
- PEPILab: a compact spectral and phase-contrast imaging tool

X-rays in matter



$\psi_{in}(E)$ = 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*

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

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

attenuation coefficient

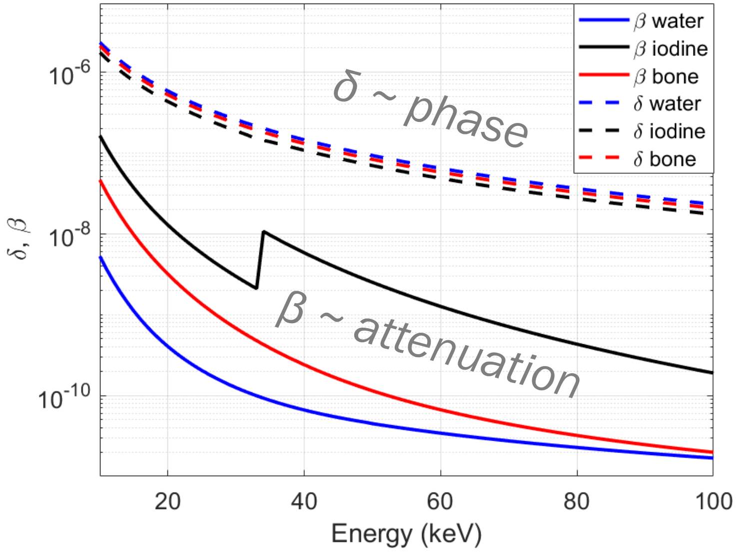
$$\psi_{out}(x, y; E) = \psi_{in}(E) e^{-k \int \beta(x,y,z;E)\mathrm{d}z} e^{-ik \int \delta(x,y,z;E)dz}$$

Attenuation → Spectral imaging

Phase shift → Phase-contrast imaging

X-rays in matter

Why spectral imaging?



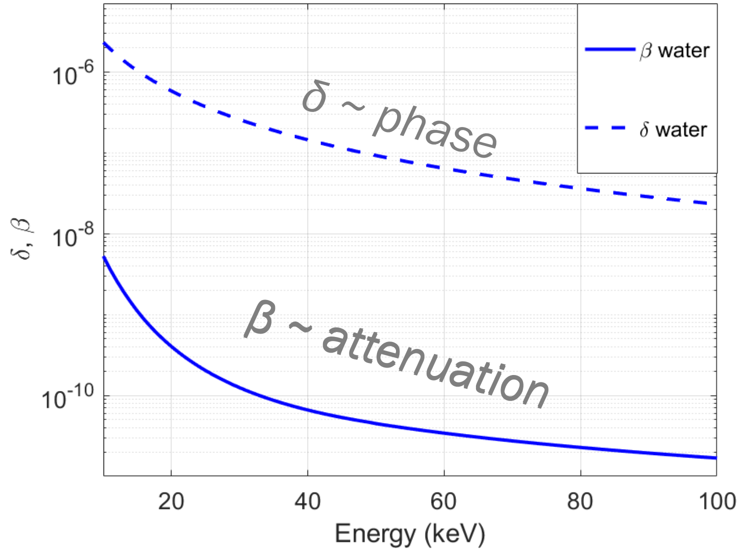
- *Energy dependence of the attenuation coefficient is sensitive to chemical composition (i.e., difference in atomic number Z)*

$$\beta(E) = \beta_{photoelectric}(E) + \beta_{scattering}(E) + \beta_{K_{edge}}(E)$$

$$\propto \frac{Z^4}{E^{4.5}} \qquad \propto \frac{Z}{E} \qquad \neq 0 \; at \; K_{edge} \; energies$$

to separate and quantify chemical elements!

Why phase-contrast imaging?



- For light materials (e.g. soft tissues) and energies of radiological interest (10 – 100 keV) phase effects are much larger than attenuation

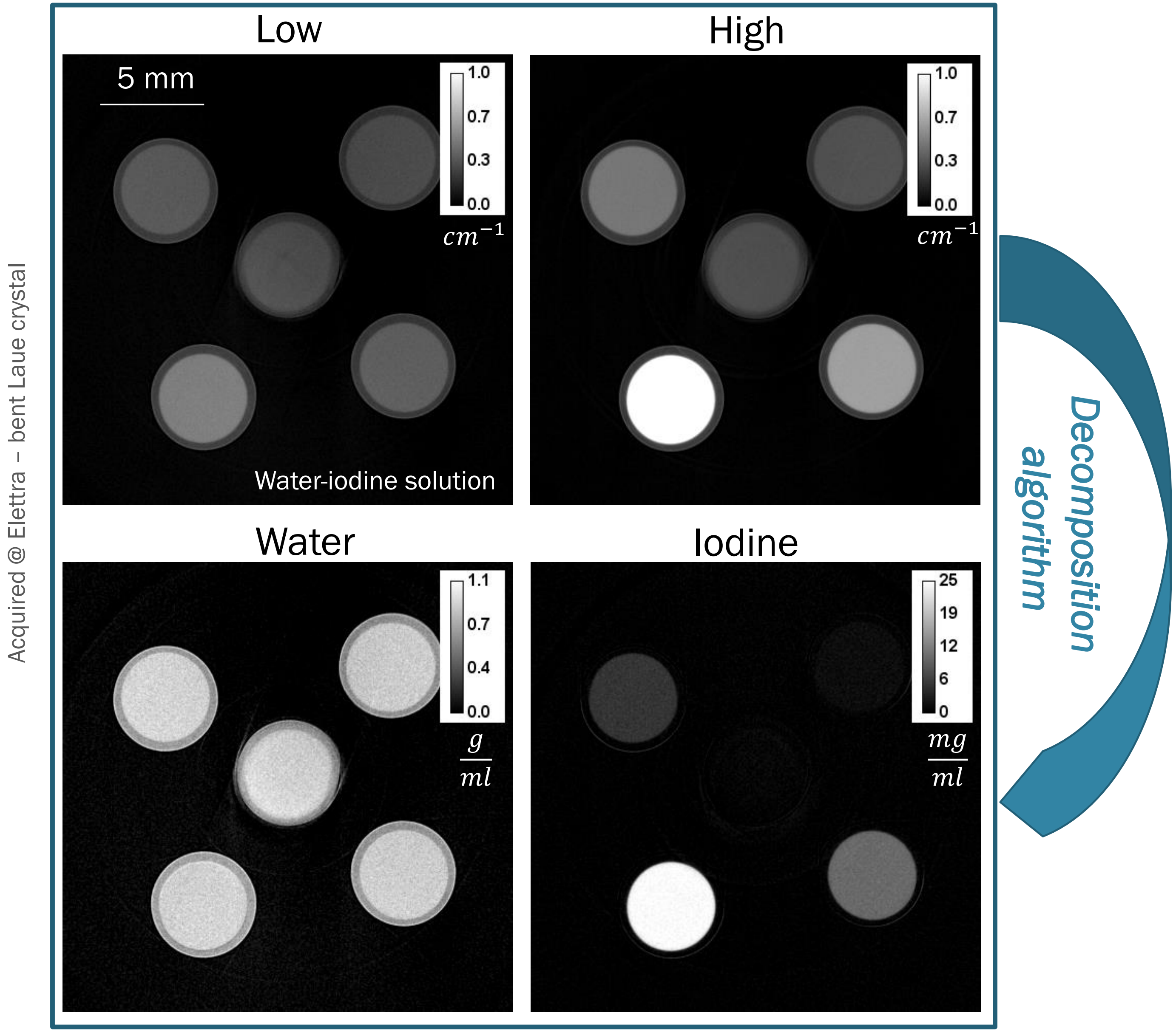
$$\frac{\delta}{\beta} \sim 10^3$$

to increase visibility of soft tissues!

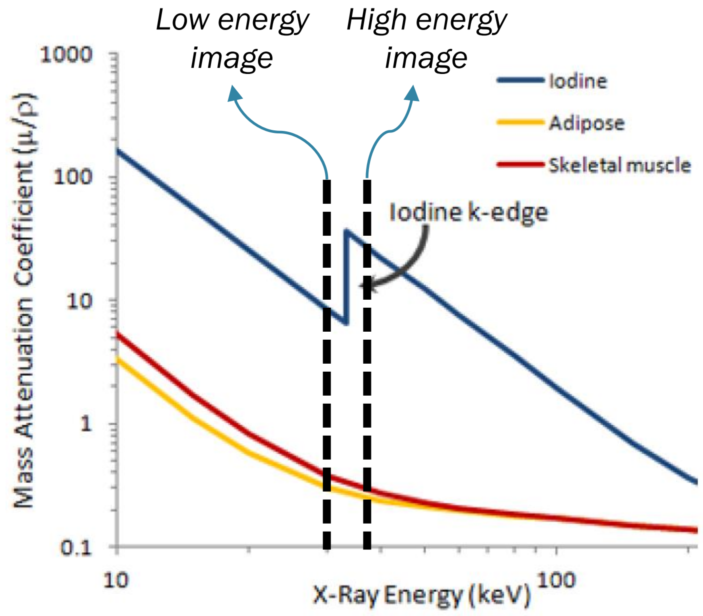
OVERVIEW

- Principles
- X-ray spectral imaging
  - Crystal-based systems
  - Detector-based systems
- Phase-contrast imaging
  - Analyzer-based imaging @ synchrotron
  - Edge illumination in the lab
- PEPILab: a compact spectral and phase-contrast imaging tool

X-ray spectral imaging

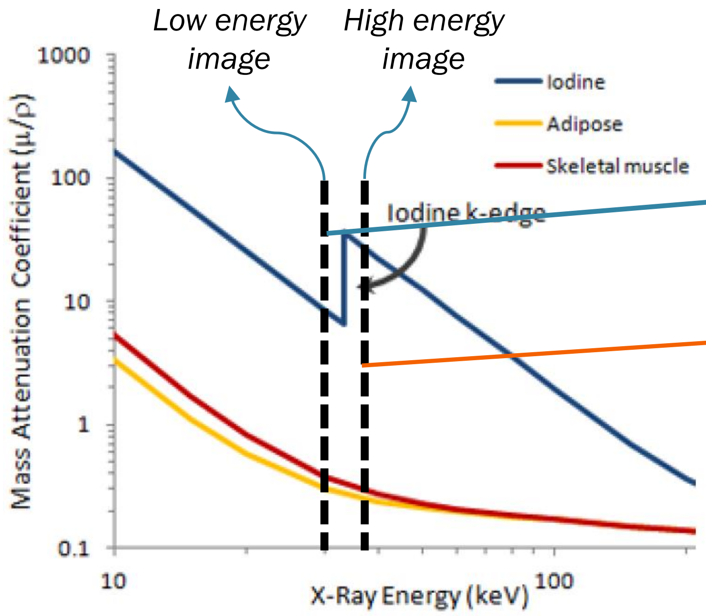


- Spectral imaging requires to probe the attenuation properties of the sample (at least) at 2 different energies



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

Basis material decomposition



- Attenuation images at each energy bin are written as a linear combination of basis materials mass attenuation coefficients

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

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

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

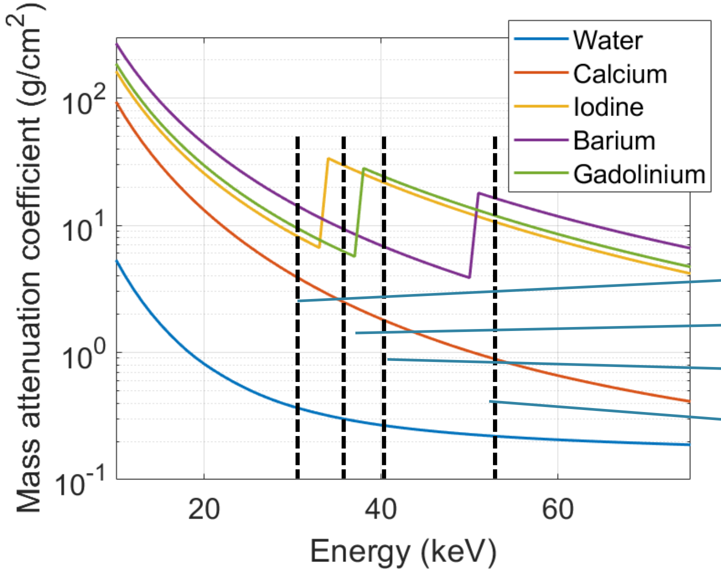
Decomposition matrix

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

Decomposed maps

- By inverting the linear system, density maps of basis materials are obtained

Multi-basis material decomposition



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

n energy channels

$$\begin{cases} \mu_1 = \frac{\mu}{\rho}\Big|_1^1 \rho^1 + \cdots + \frac{\mu}{\rho}\Big|_1^m \rho^m \\ \vdots \qquad \ddots \qquad \vdots \\ \mu_n = \frac{\mu}{\rho}\Big|_n^1 \rho^1 + \cdots + \frac{\mu}{\rho}\Big|_n^m \rho^m \end{cases}$$

$m(\leq n)$ materials

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

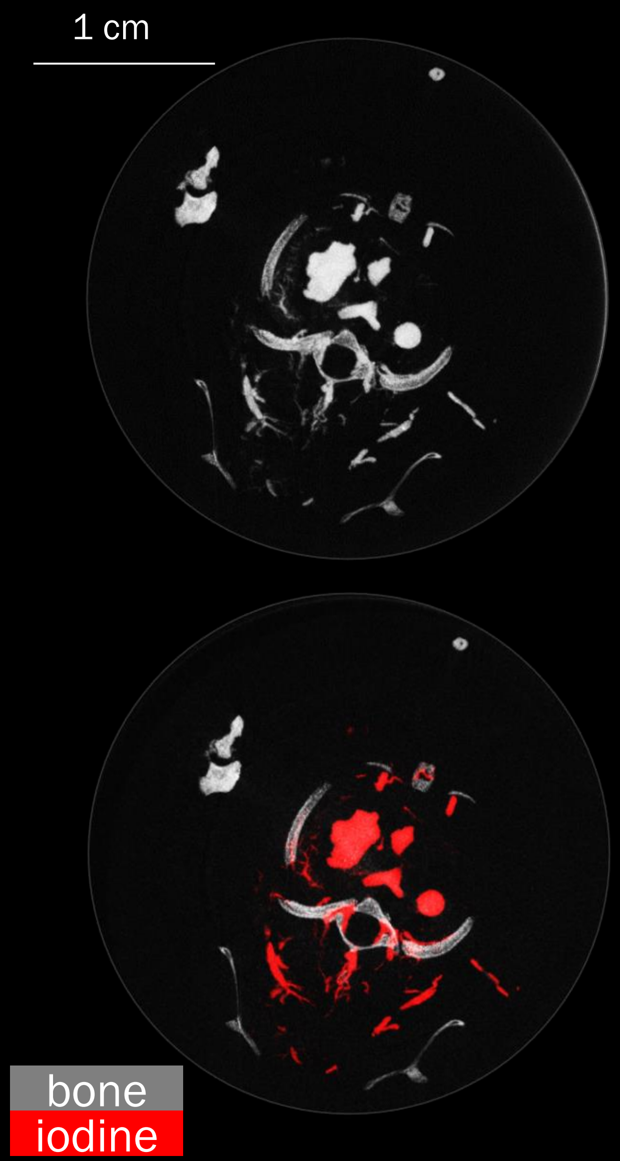
$$\vec{\rho} = A^{-1}\vec{\mu}$$

Inversion performed through least-squares

Applications: imaging with contrast medium

Acquired @ PEPI Lab INFN Trieste

IODINE (33 keV)

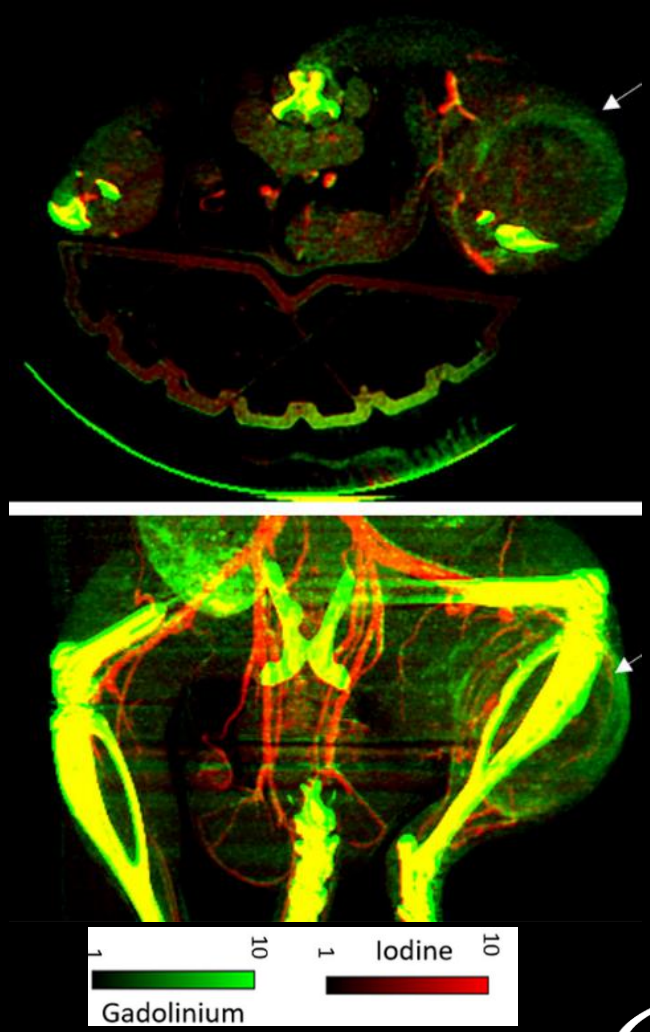


BARIUM (37 keV)

Panahifar, Arash, et al. *Physica Medica* 32.12 (2016): 1765-1770.

GADOLINIUM (50 keV)

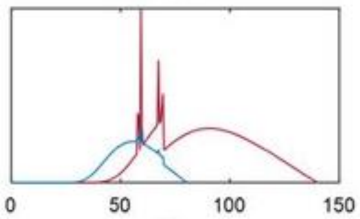
C T Badea et al 2019 *Phys. Med. Biol.* 64 065007

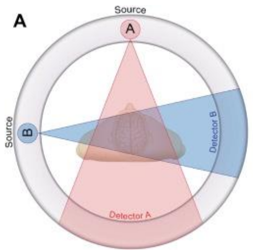


INFN

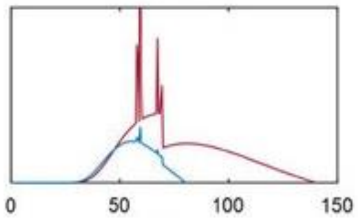
Spectral imaging systems

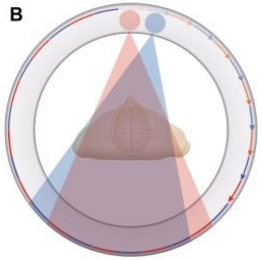
- **X-ray spectrum-based**
  - 2 X-ray tubes with different voltages



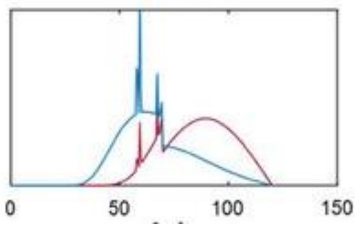


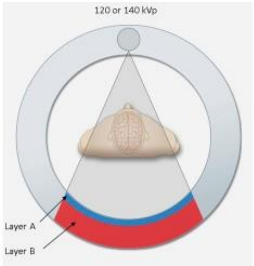
  - Voltage switching



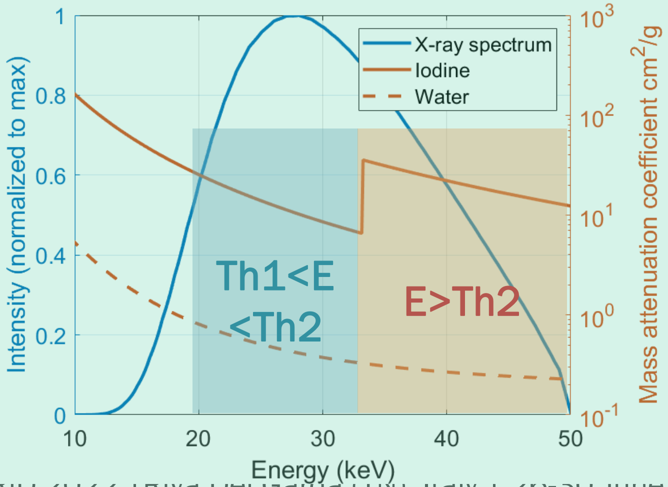


  - Dual layer detectors

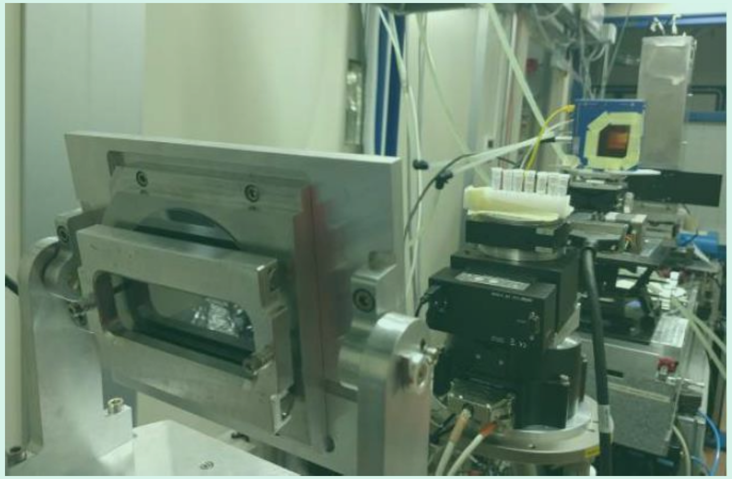


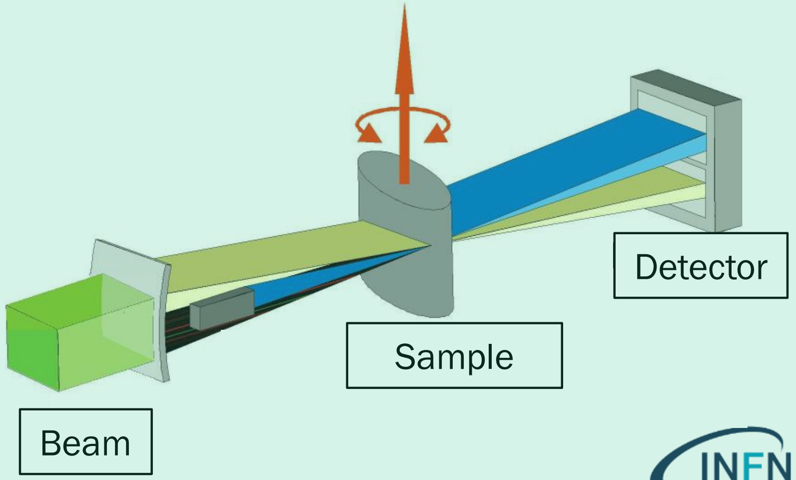


- **Detector-based**: energy discrimination on pixel-by-pixel basis



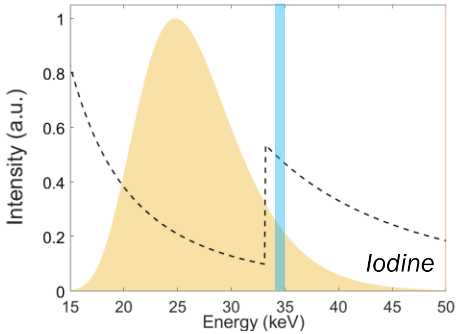
- **Crystal-based**: energy dispersive systems based on bent crystals (@ synchrotrons)

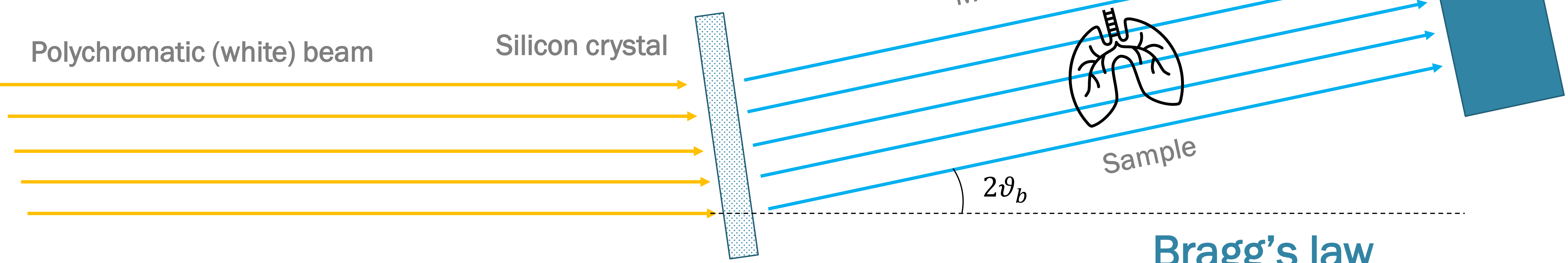




CRYSTAL-BASED SPECTRAL IMAGING

Laue diffraction



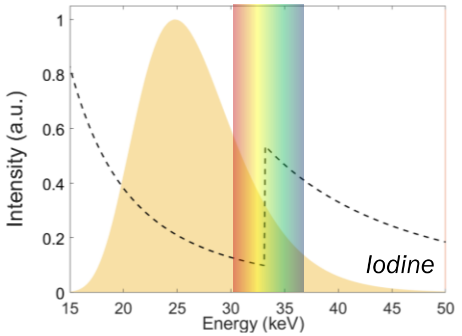


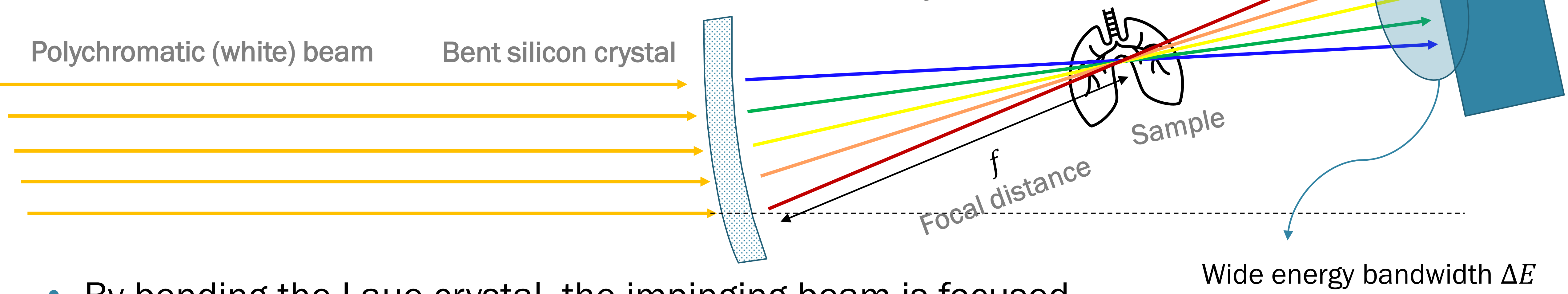
Bragg's law

$$E = \frac{hc}{2d\sin(\vartheta_b)}$$

ϑ_b = Bragg's angle
c = speed of light
h = Plank's constant
d = lattice spacing

Energy dispersive bent Laue diffraction



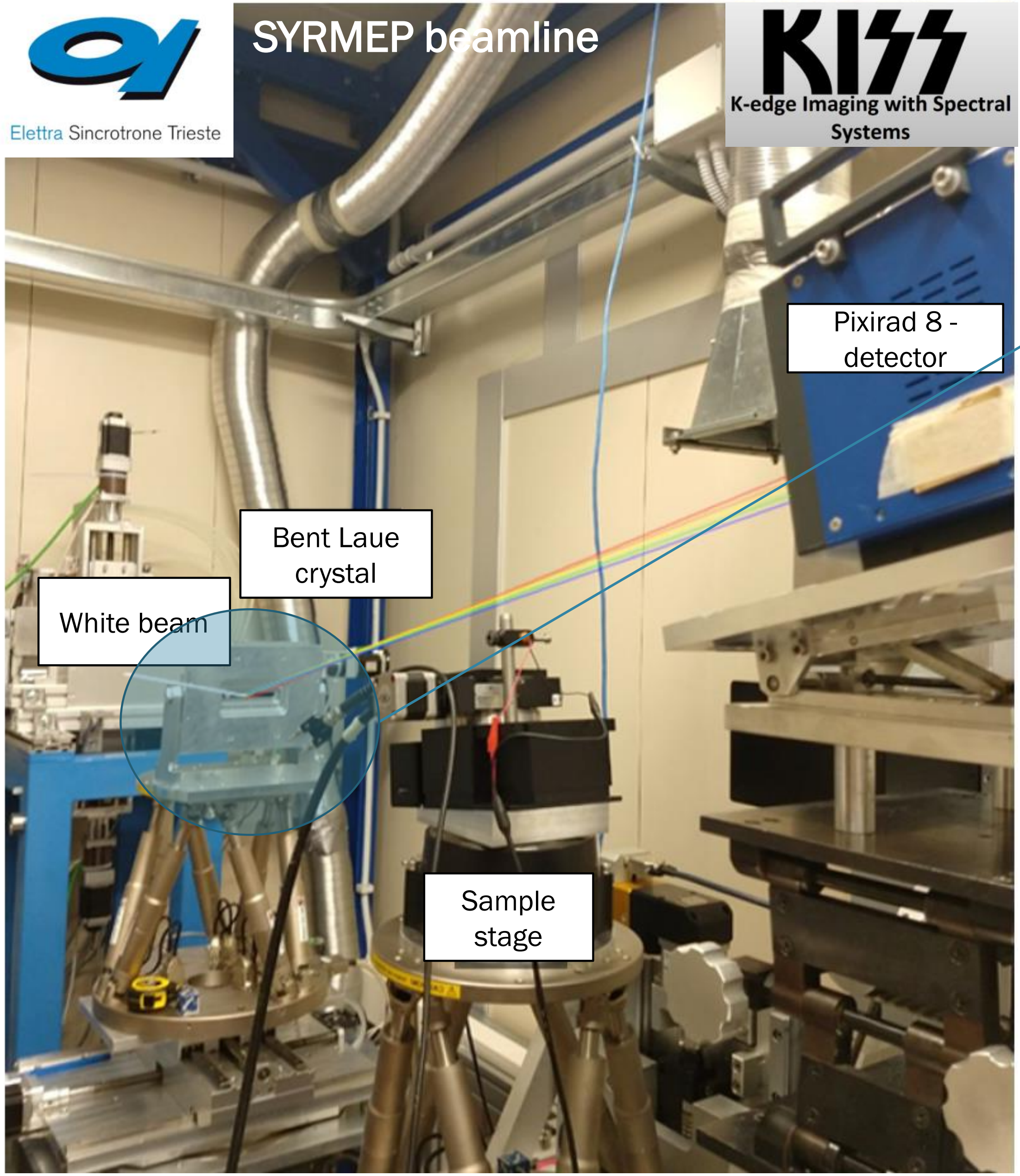


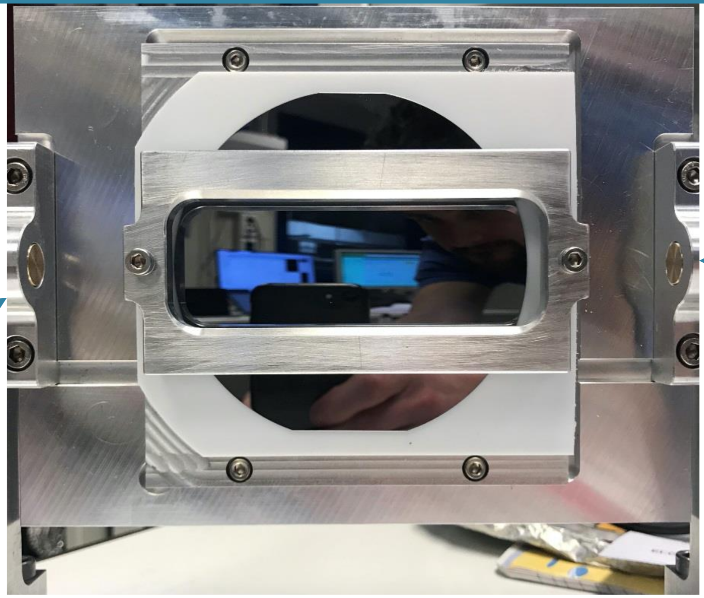
- By bending the Laue crystal, the impinging beam is focused
- Due to curvature Bragg's law is satisfied at different angles

The beam is **energetically dispersed in space!**

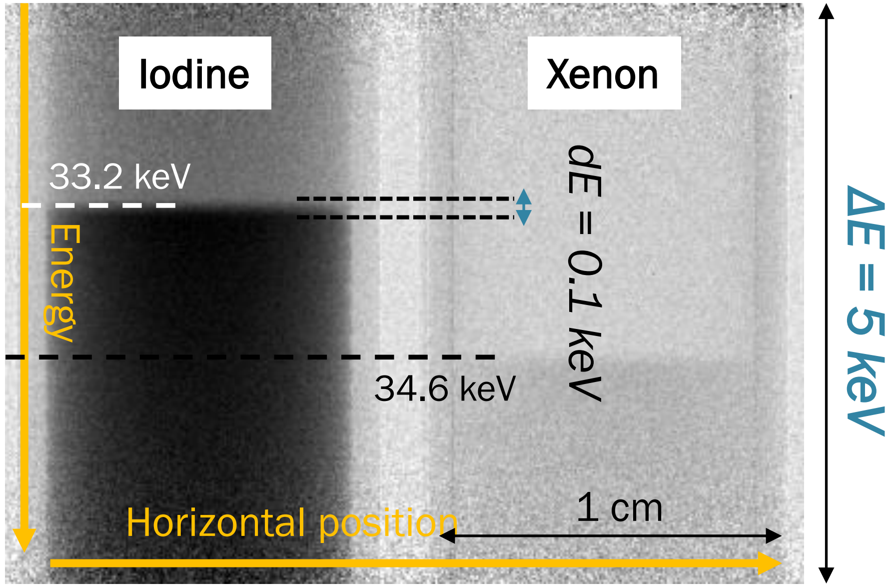
- $\boldsymbol{\Delta E \propto R}$
- $\boldsymbol{f \approx \frac{R}{2}}$
- $R = bending\ radius$

Spectral system @ SYRMEP beamline





Fixed radius frames
Radius = 0.5 m
Focus ~ 0.25 m

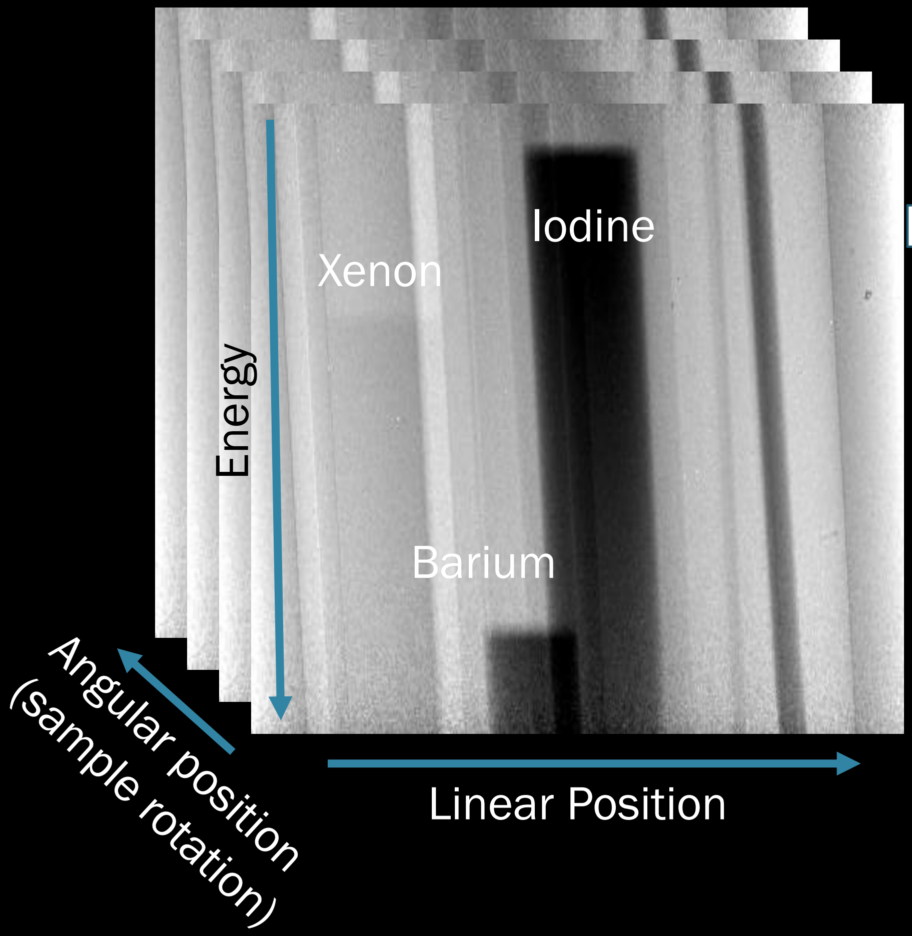


$$\frac{\Delta E}{dE} \approx 50$$

Largest bandwidth so far!

INFN

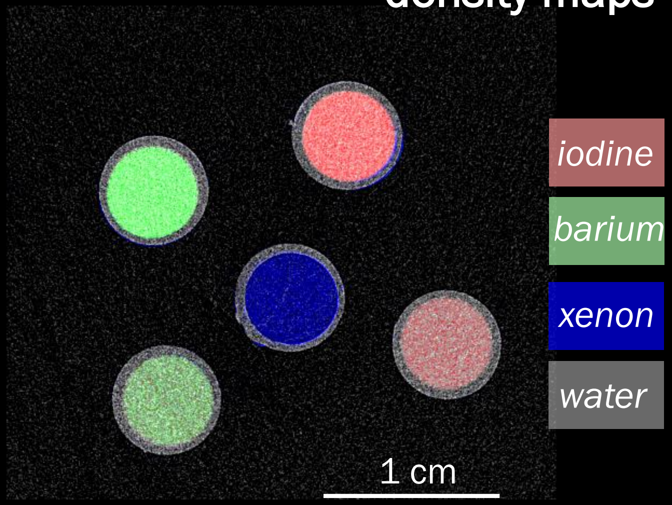
Tomographic multi-material imaging



Tomographic reconstruction

Multi-material decomposition

Multi-material density maps



Goal: simultaneous cardiovascular + respiratory + inflammatory imaging!

DETECTOR-BASED SPECTRAL IMAGING

Detectors in spectral imaging

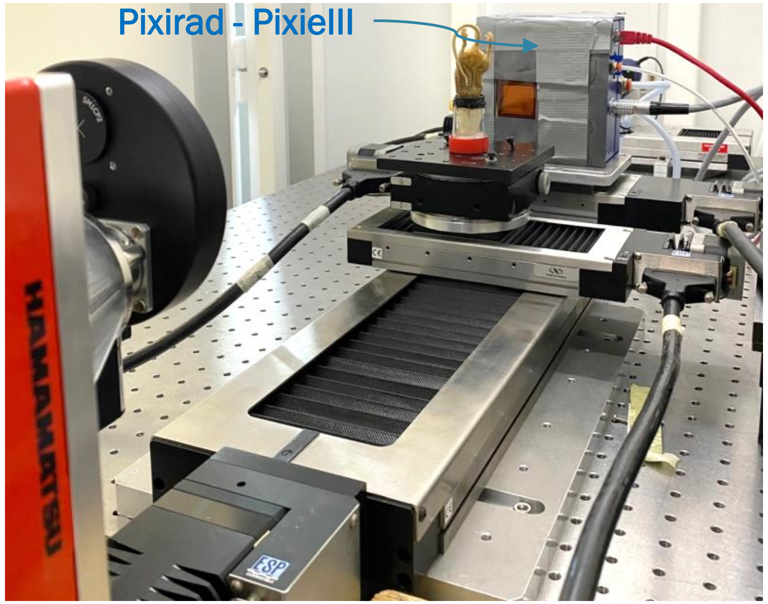
- Spectral detectors can acquire multiple **images** over **different energy channels in a single shot**
- **High-Z sensors** (CdTe, CZT, GaAs) are used for spectral imaging due to their high efficiency at high energies
- Modern small-pixel chips feature **charge sharing compensation mechanisms** (← crucial for spectral imaging applications!)

Funded by INFN

↕

k-edge spectral tomography

Spectral μCT setup @ INFN - Trieste



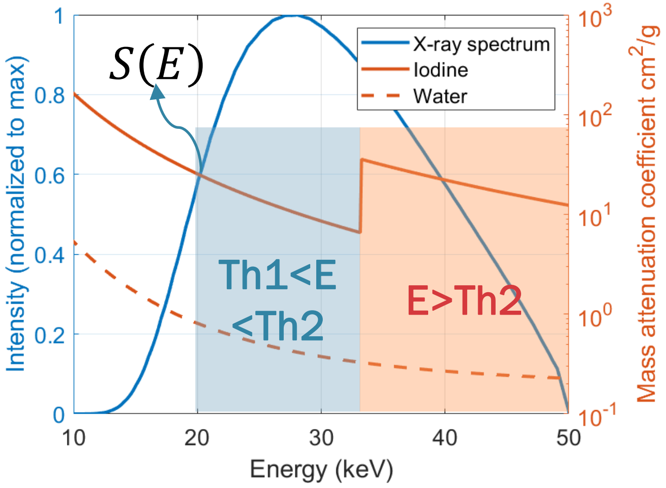
Chip/Producer	Pixel size (μm)	N.o Threshold
Medipix3	55	2 (8 in 2x2 binning)
Pixirad – PixieIII	62	2
Direct Conversion	100	2
Dectris - Eiger 2	75	2
…		

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

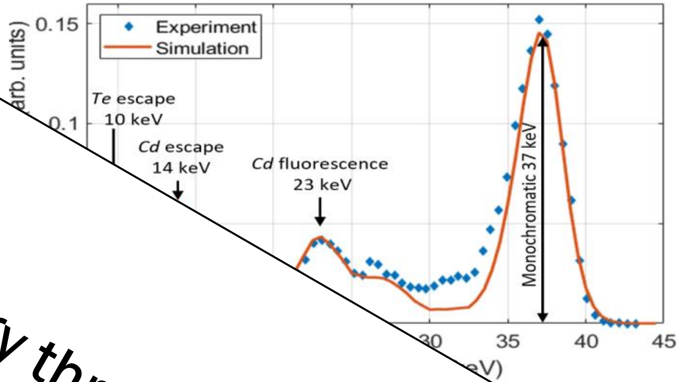
SYSTEM CHARACTERIZATION

Object composition

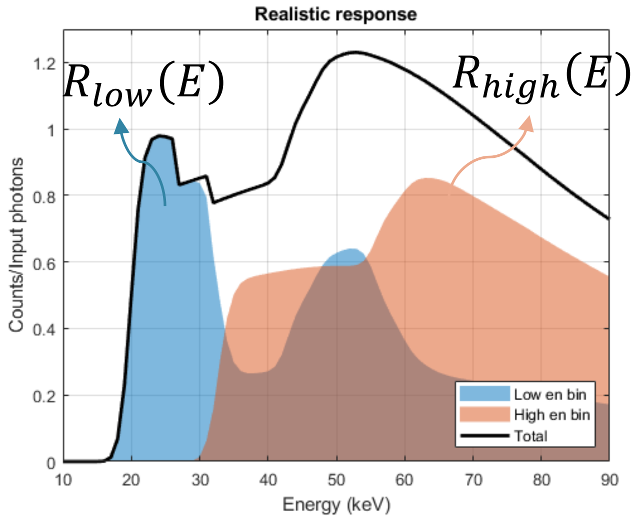
X-ray spectrum/ Threshold selection



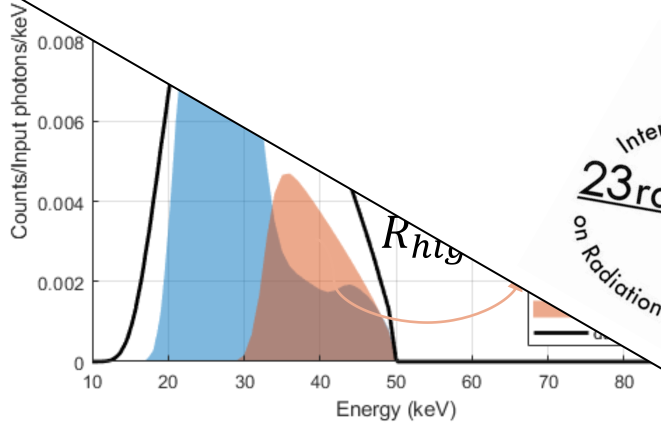
Input energy spectrum, threshold selection and attenuation coefficients



	ΔE/E
	± 2)%



Brombal, L., et al. JINST 17.01 (2022): C01043.
...pani, V., et al. NIM-A 955 (2020): 163220.



$$\frac{S(E)R_i(E)\mu/\rho_j(E)dE}{\int S(E)R_i(E)dE}$$

Material decomposition matrix

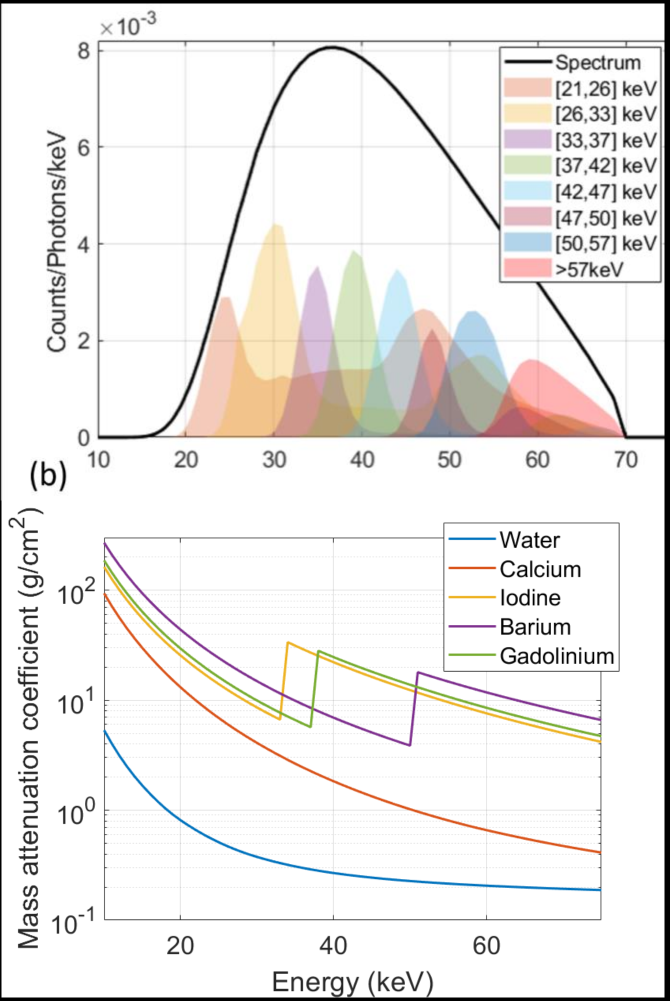
Poster

Optimization of energy threshold for fluorescence rejection in K-edge subtraction in synchrotron-based imaging with a spectral CdTe detector

Pasquale Delogu et al.

23rd iWoRiD International Workshop on Radiation Imaging Detectors

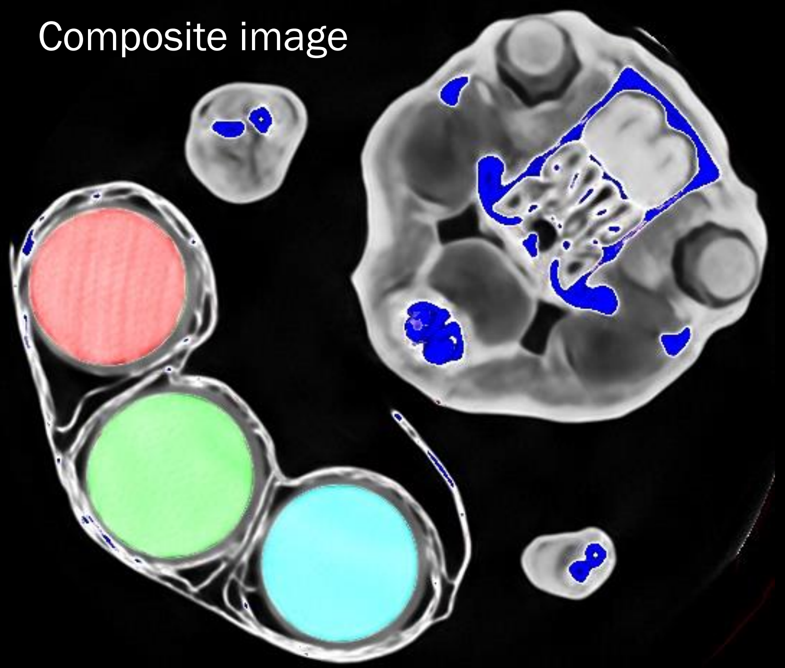
Quantitative multi-material μ-CT



Unpublished data – manuscript in preparation

Quantitative multi-material μ-CT

Composite image



iodine

barium

gadolinum

bone

soft tissue

Unpublished data – manuscript in preparation

Crystal vs Detector-based spectral imaging

	Crystal-based	Detector-based
Energy resolution	High (~100 eV)	Low (~3 keV)
Multi-material decomposition	Yes (nearby K-edges)	Yes (well separated K-edges)
Sensitivity	High – gold standard (<1 mg/ml)	Medium (function of detector/spectrum)
Setup complexity	High	Low
Scalability	Only in synchrotrons	Everywhere

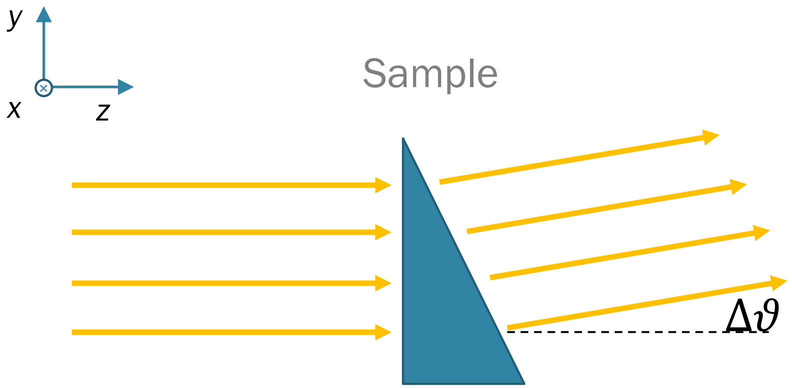
OVERVIEW

- Principles
- X-ray spectral imaging
  - Crystal-based systems
  - Detector-based systems
- Phase-contrast imaging
  - Analyzer-based imaging @ synchrotron
  - Edge illumination in the lab
- PEPILab: a compact spectral and phase-contrast imaging tool

Phase effects

Refraction

(= differential phase contrast)

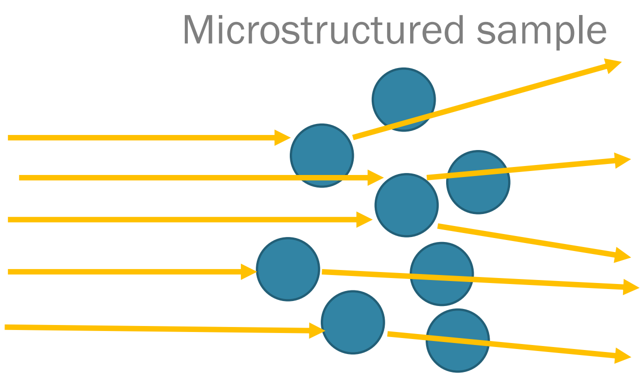


$$\Delta\vartheta = -\nabla_{xy} \int \delta(x,y,z;E)dz$$

- 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

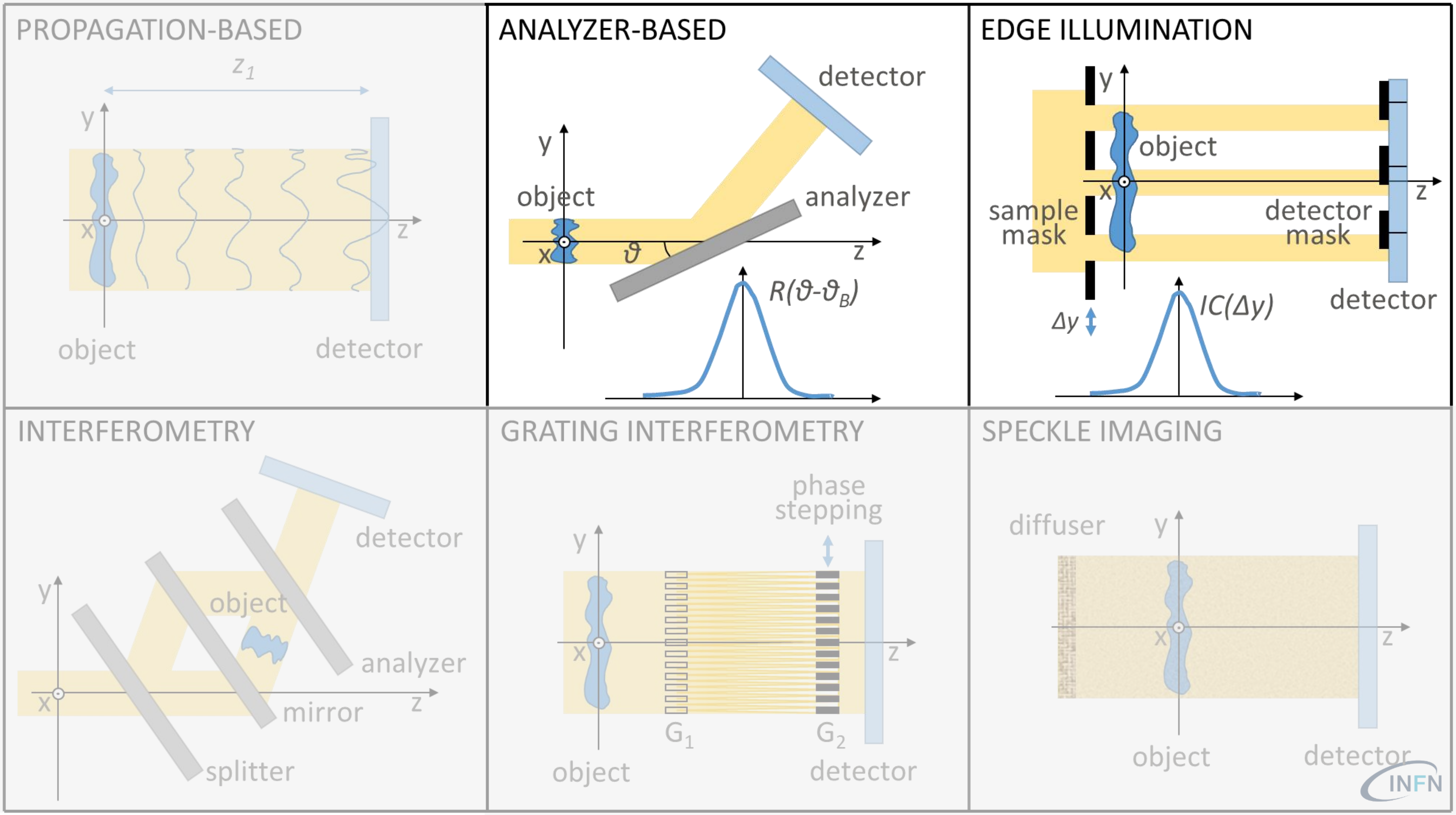
Ultra-small angle scattering

(= dark field)

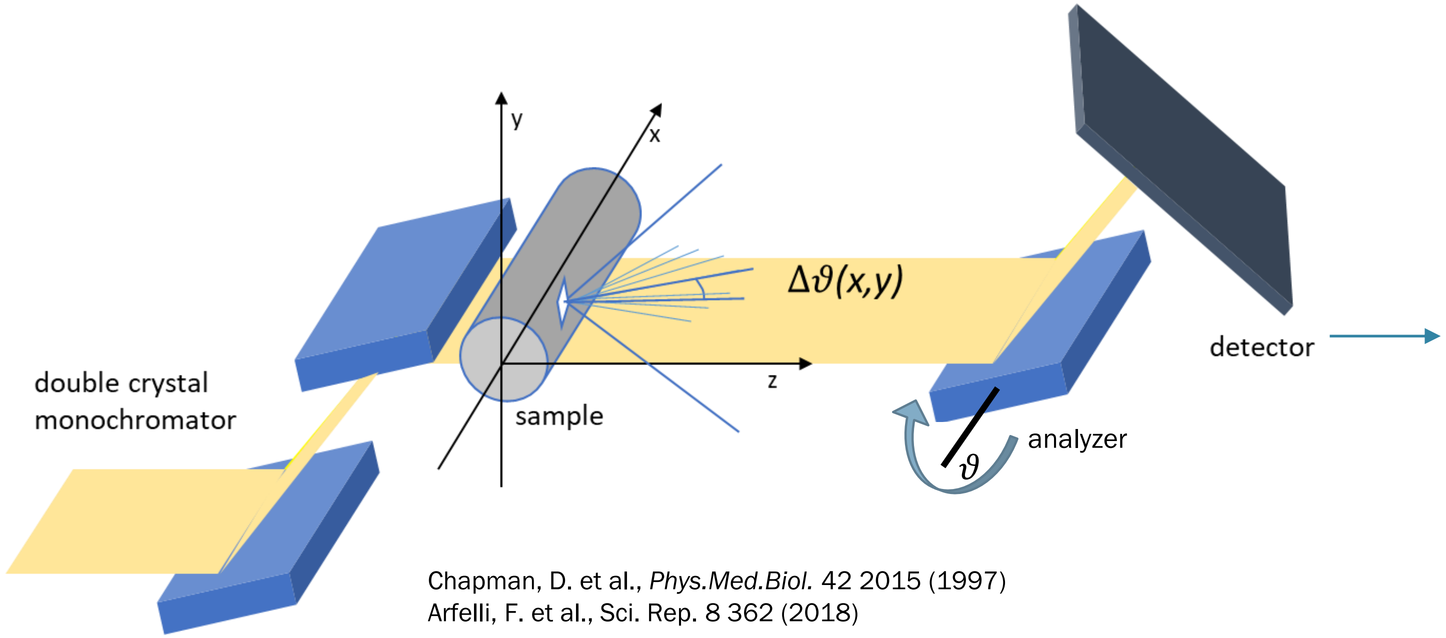


- In microstructured samples multiple-refraction occurs, causing a diffusion of the beam in the range 1-100 μrad
- The “amount of diffusion”, i.e. scattering signal, depends on sample’s properties at a scale smaller than the system’s spatial resolution

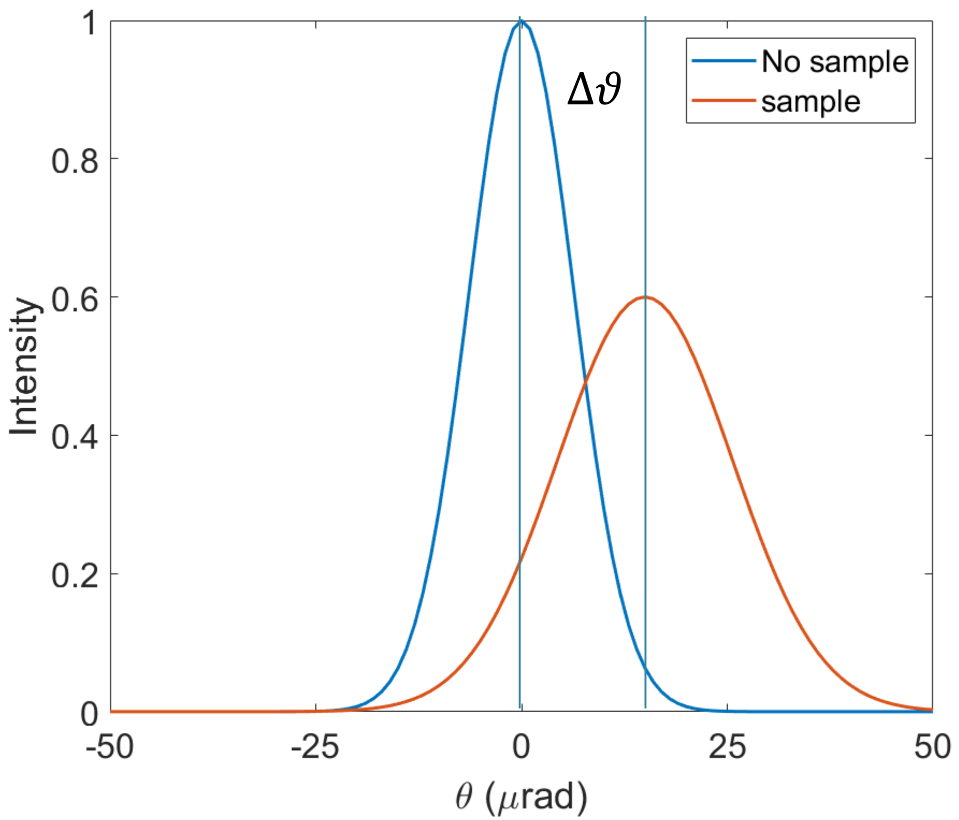
Phase-contrast imaging = to transform phase effects into detectable intensity modulations


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
detector
Δy
IC(Δy)
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
INFN

Analyzer-Based Imaging (ABI)



Chapman, D. et al., *Phys.Med.Biol.* 42 2015 (1997)
Arfelli, F. et al., Sci. Rep. 8 362 (2018)



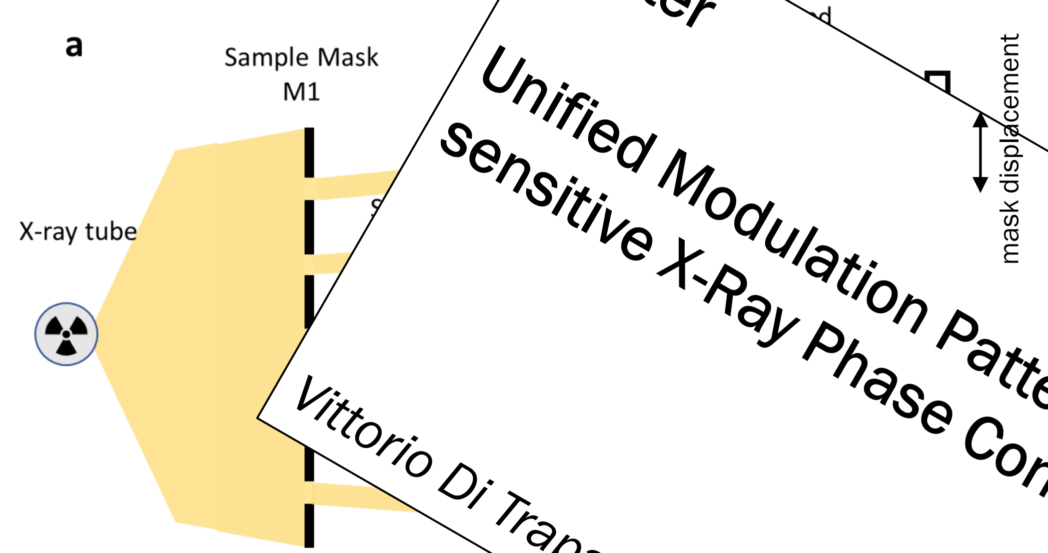
- An analyzer crystal is introduced downstream of the object to highlight refraction and scattering effects
- When perfectly aligned with the monochromator, the analyzer crystal diffracts the beam with 100% efficiency
- The diffracted intensity as a function of the misalignment ϑ defines the rocking curve $R(\vartheta)$

- The presence of the sample modifies the rocking curve

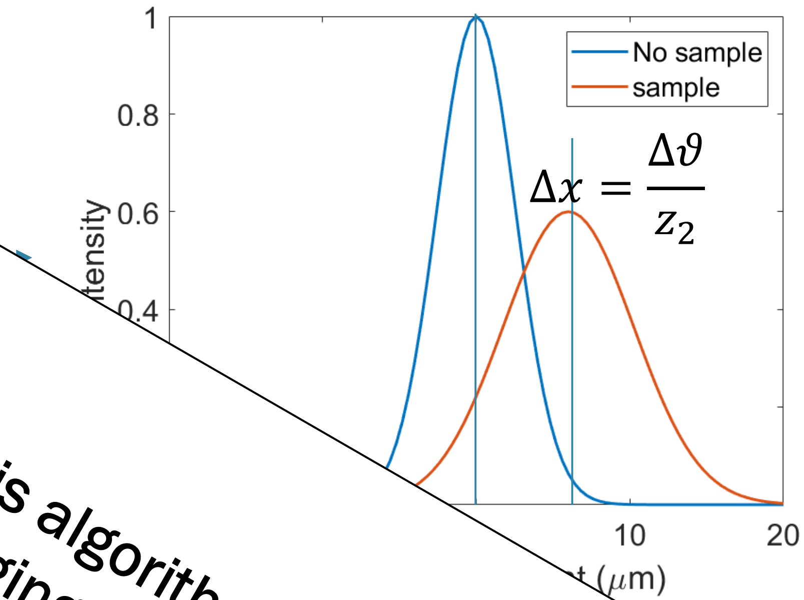
$$R(\vartheta) \rightarrow T \times R(\vartheta - \Delta\vartheta) * S$$

Transmission *Refraction* *Scattering*

Edge Illumination (EI)



M Endrizzi et al. *App. Phys. Letters* 104.2 (2014): 024106.



Poster

Unified Modulation Pattern Analysis algorithm (UMPA) for 1D sensitive X-Ray Phase Contrast Imaging techniques

Vittorio Di Trapani et al.

- In edge illumination (EI) the X-ray beam is str mutually independent beamlets by a structured absorbing mask
- The beamlets are analyzed by a second mask close to the detector or by the detector itself
- The detected intensity as a function of the misalignment between the two masks is the Illumination curve $IC(x)$

EI

Sample mask

Detector mask

Illumination curve

DEI & EI: pros and cons

DEI

Pros:
- High sensitivity (gold standard)
- Quantitativeness/monochromaticity

Cons:
- Complex setup
- Requires **laminar** beam
- Limited to synchrotron facilities

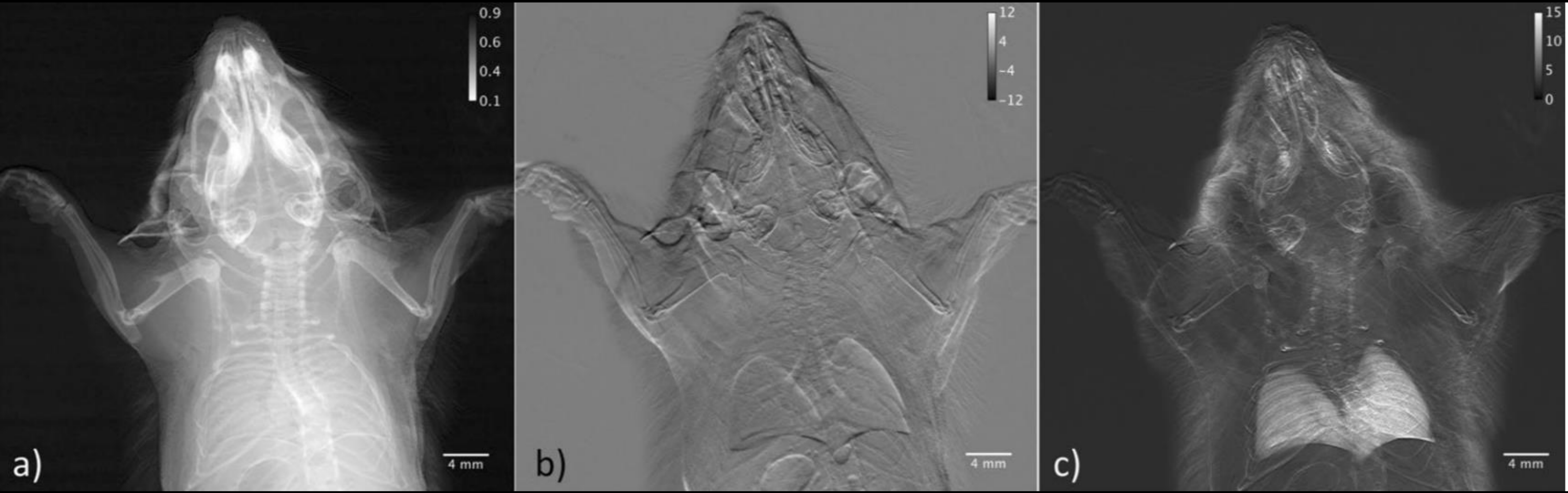
EI

Pros:
- Works with spatially incoherent sources
- Compact

Cons:
- Mask alignment is challenging
- “photon hungry”: most photons absorbed by the masks

DEI: Lung imaging

Transmission | Refraction/differential phase | Scattering/dark-field

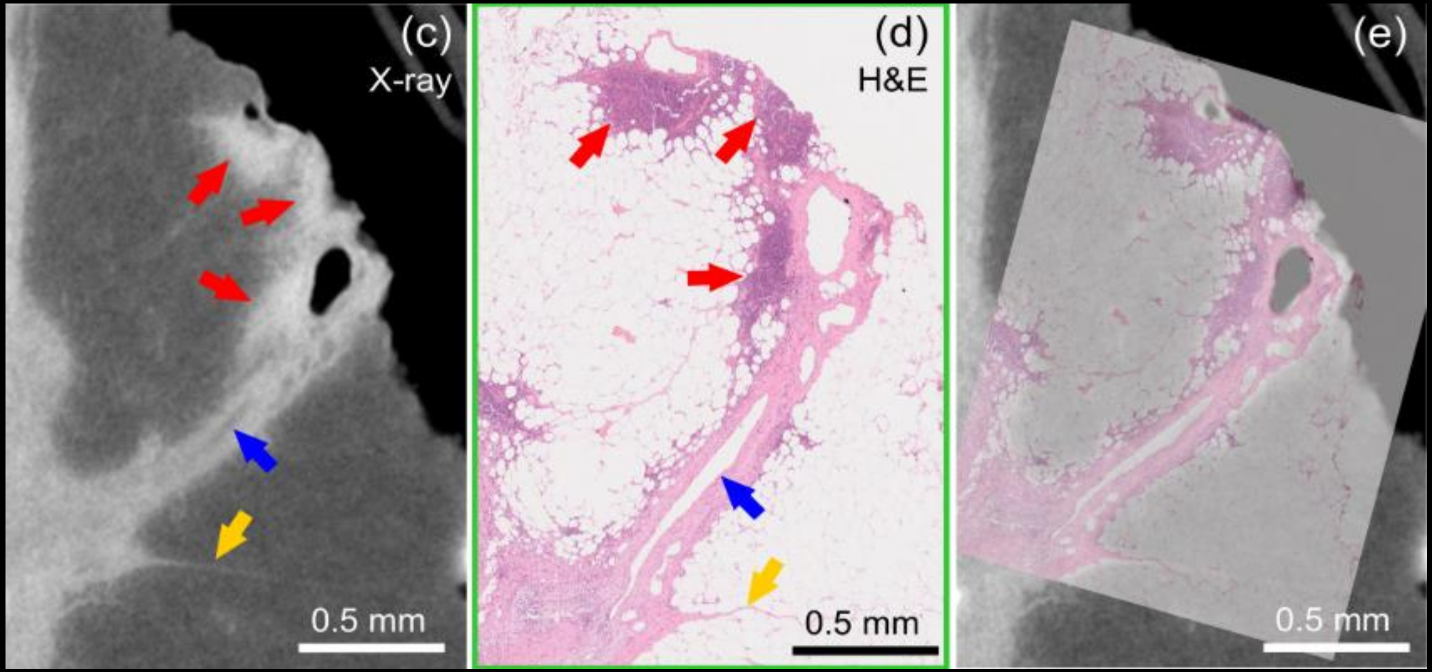


Menk, R. H., et al. "A novel approach to separate absorption, refraction and scattering in analyzer based lung imaging." *Journal of Instrumentation* 15.05 (2020): C05069.

INFN

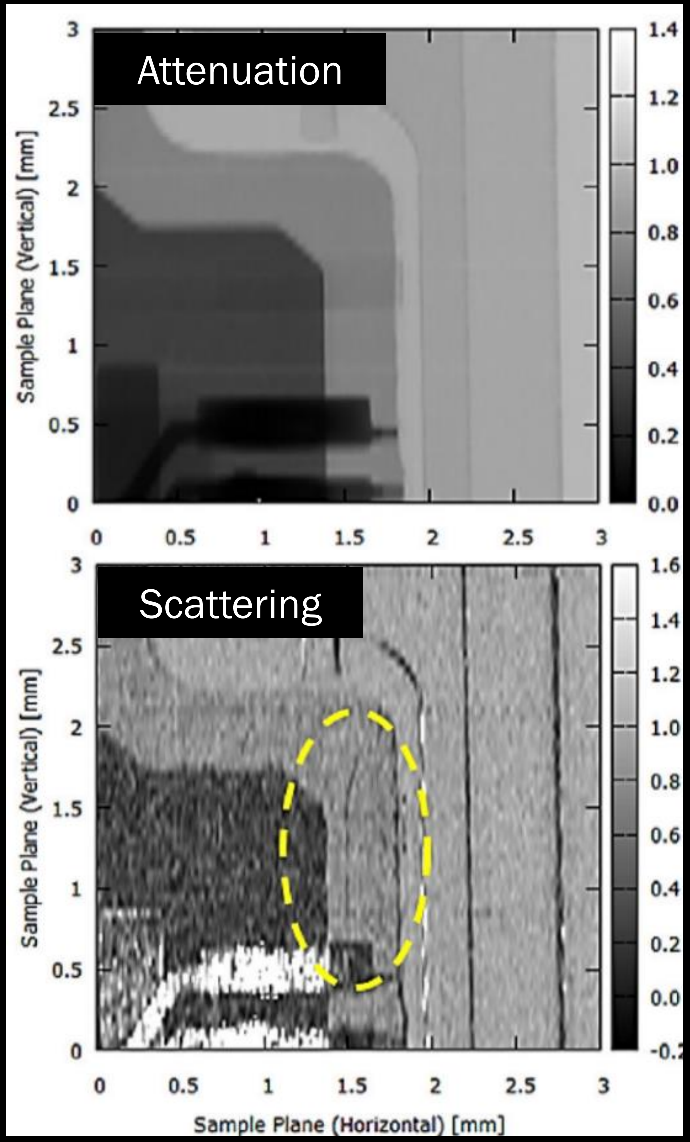
EI: soft tissue imaging and industrial inspection

Virtual histology



L Massimi et al. *IEEE TMI* 41.5 (2021): 1188-1195.

Material science/industrial inspection



Matsunaga *et al.*, J. Phys. D: Appl. Phys. 53 095401 (2020)

OVERVIEW

- Principles
- X-ray spectral imaging
  - Crystal-based systems
  - Detector-based systems
- Phase-contrast imaging
  - Analyzer-based imaging @ synchrotron
  - Edge illumination in the lab
- PEPILab: a compact spectral and phase-contrast imaging tool

Photon-counting Edge-illumination Phase-contrast Imaging

P hoton-counting
E dge-illumination
P hase-contrast
I maging

https://web.infn.it/PEPI/index.php

In collaboration with:

UNIVERSITÀ DEGLI STUDI DI TRIESTE

Elettra Sincrotrone Trieste

ICGEB

UCL

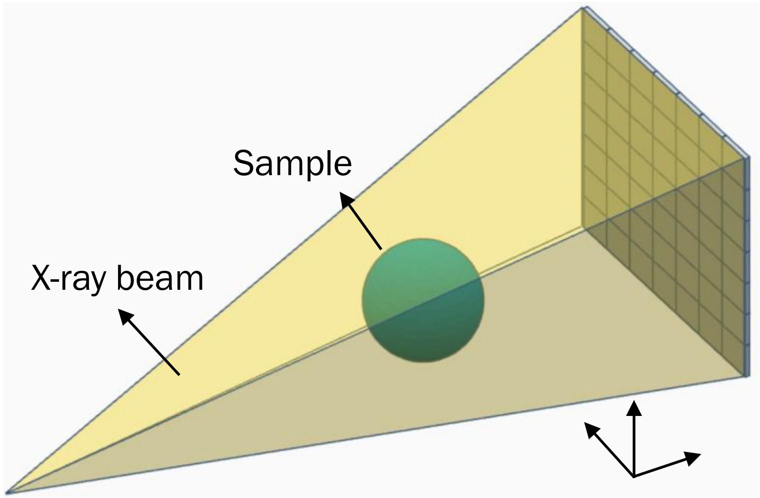
PEPI is a project funded by the *Young researchers grant* programme (2020/22260) – National Scientific Committee 5 – INFN

AIM: to develop a new laboratory phase-contrast imaging system based on a photon counting detector and the edge-illumination technique with 2 key features:

- *Flexibility: multiple imaging modalities (spectral/phase-contrast) on a broad energy range (from soft tissue to material science samples)*
- *Compactness: overall dimension < 1m*

Flexibility

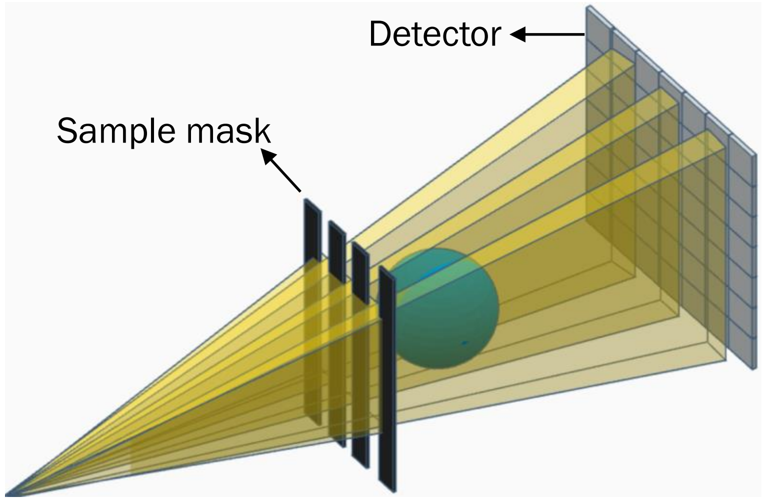
Spectral



Features

- Attenuation imaging
- Spectral imaging

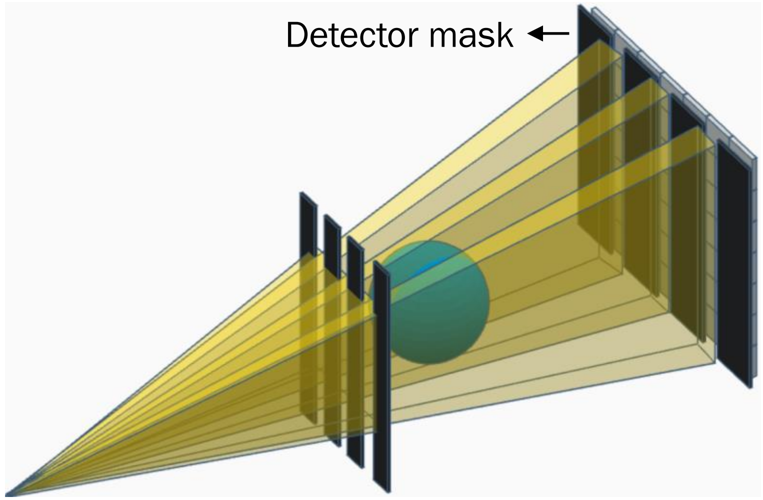
Single-Mask EI



Features

- Sensitivity to refraction (phase) and attenuation
- Single shot imaging
- Faster (2x or more) than double-mask

Double-Mask EI



Features

- Sensitivity to refraction (phase), scattering and attenuation
- High accuracy

Simulation and Design

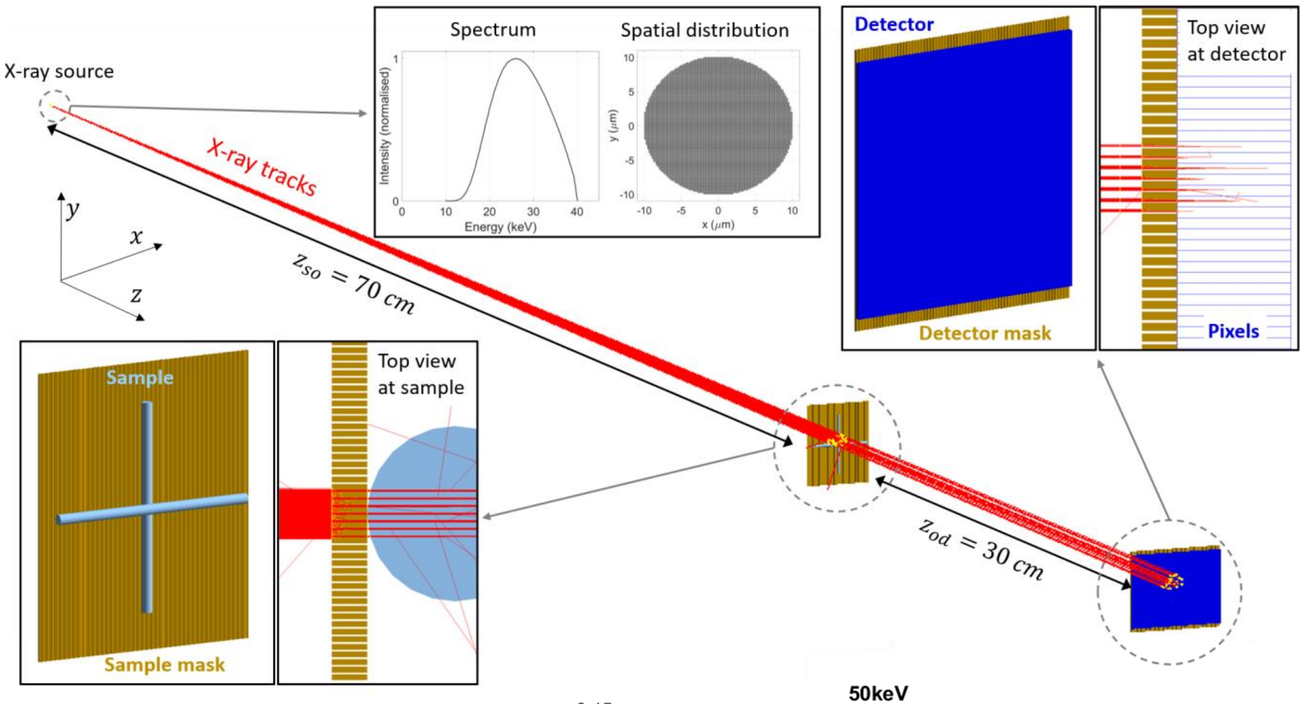
A Geant4 simulation platform accounting for the whole imaging chain including:

- X-ray refraction
- Detector's energy response
- Masks, material and geometry
- ...

The simulation was key in the choice of:

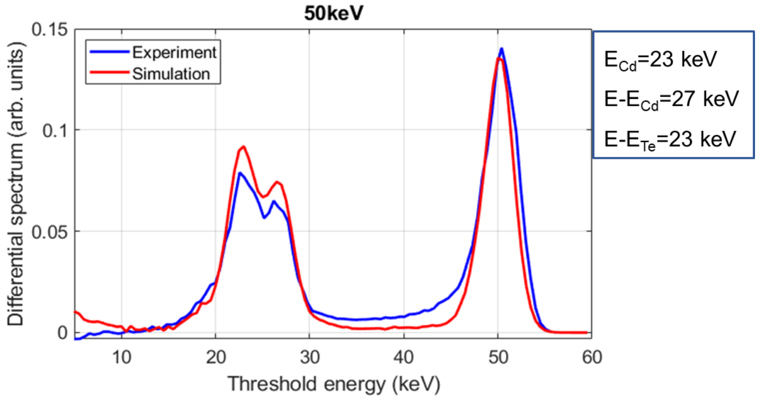
- X-ray source (Hamamatsu L10101 – 40 – 100 kV)
- Mask material/thickness (gold 250 μm)
- Geometry (magnification 2)
- ...

Open source:
https://web.infn.it/PEPI/index.php/it/#simulation



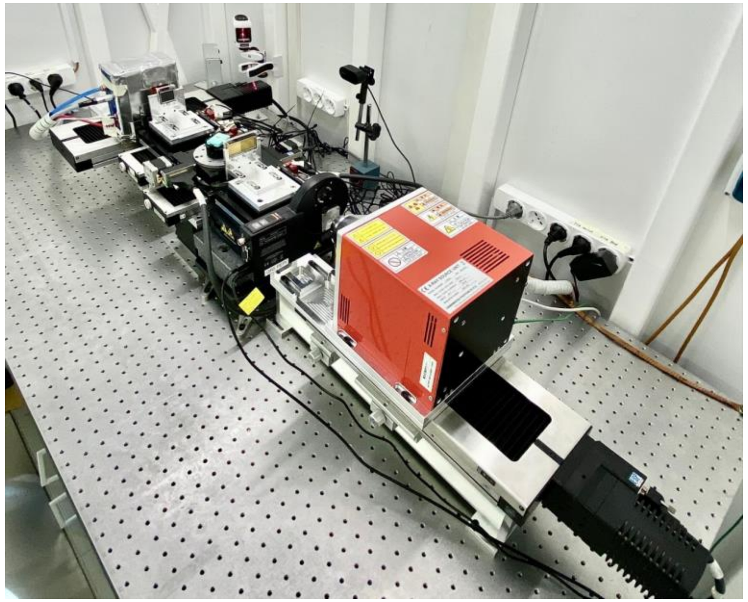
Brombal, L., et al. *Journal of Physics D* 55.4 (2021): 045102.

Brombal, L., et al. JINST 17.01 (2022): C01043.

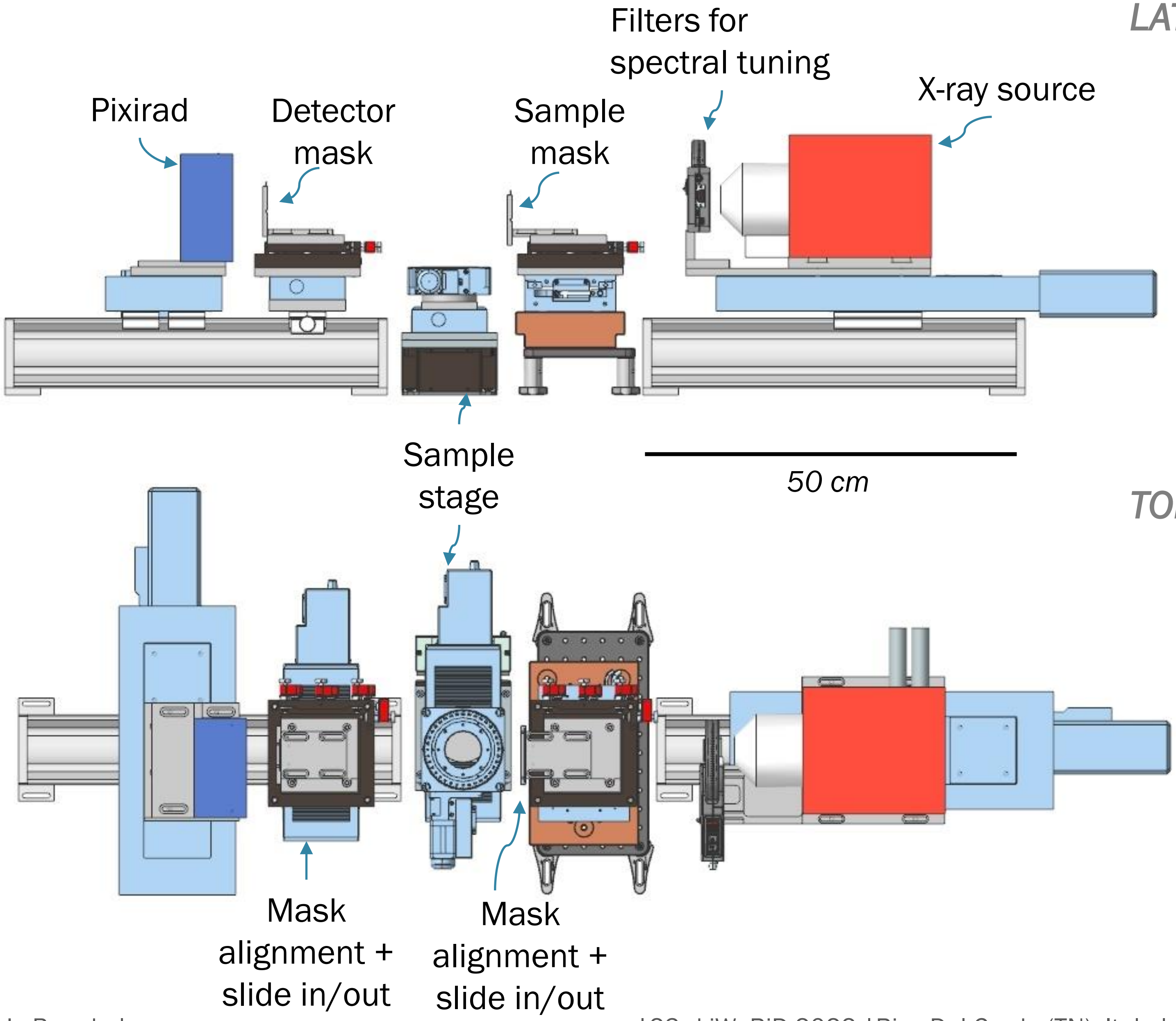


Realization

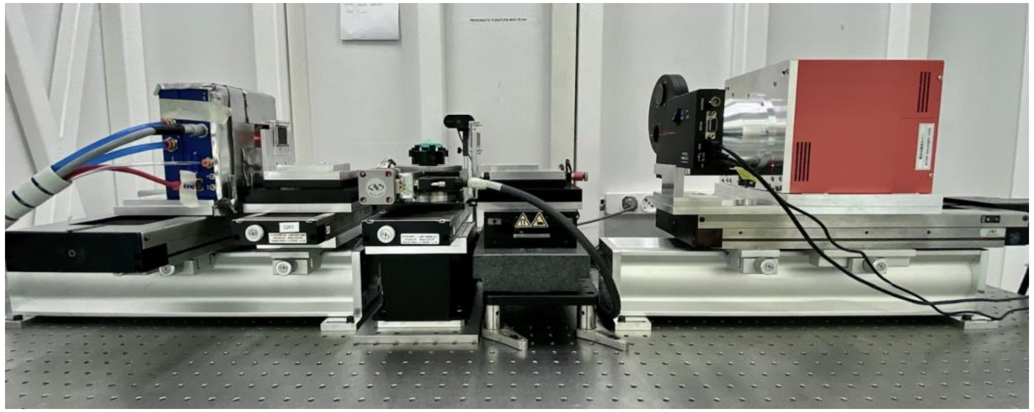
How it started…June 2021 → How it is…June 2022



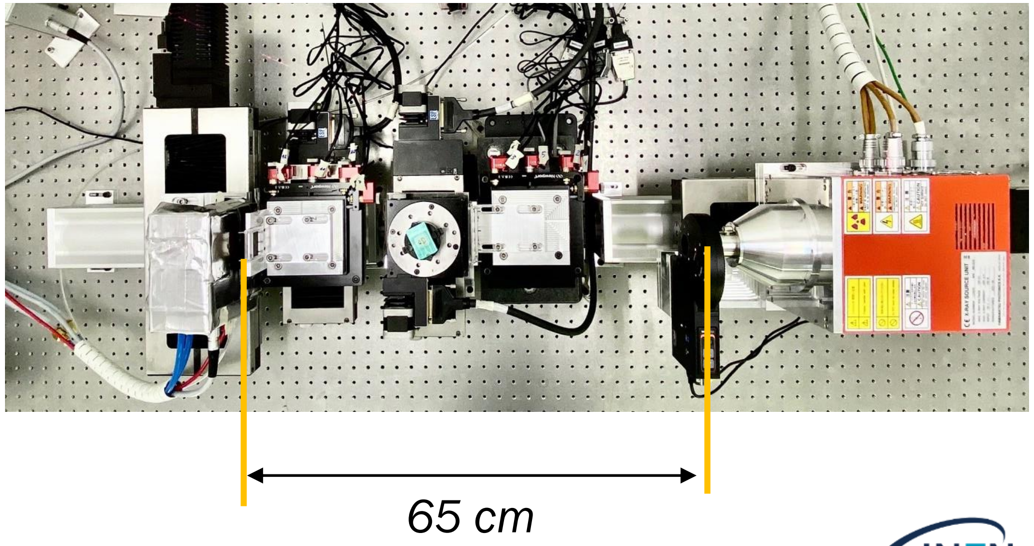
Setup



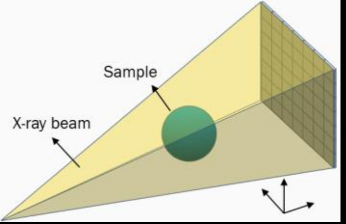
LATERAL VIEW



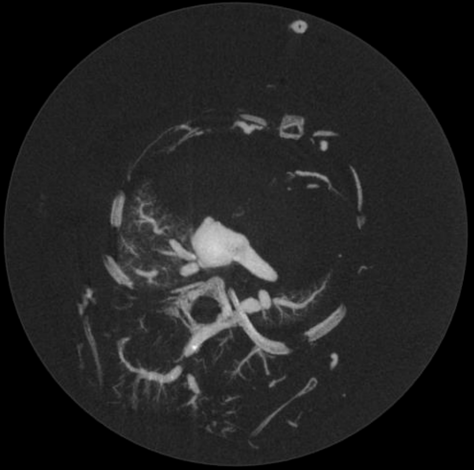
TOP VIEW



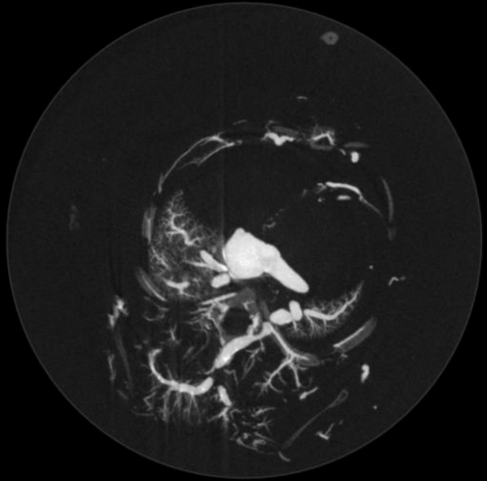
Spectral CT



Bin1 [27, 33] keV



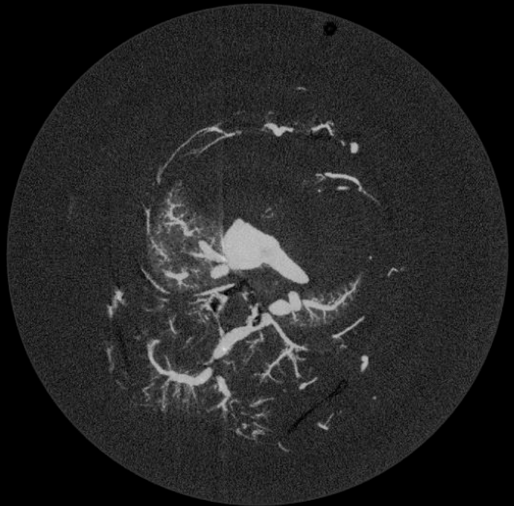
Bin2 >33 keV



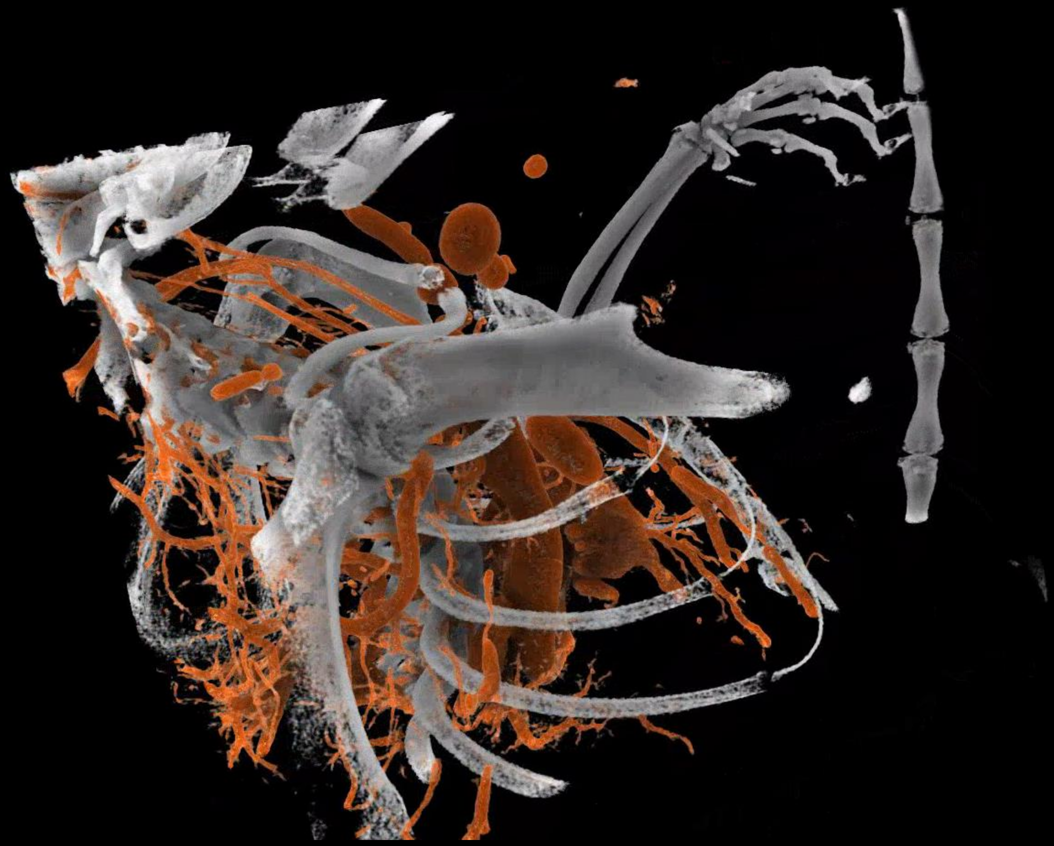
1 cm

Bone map

Iodine map



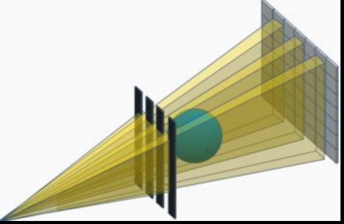
Ex-vivo murine model perfused with iodine-based contrast medium



Voxel size 38 µm

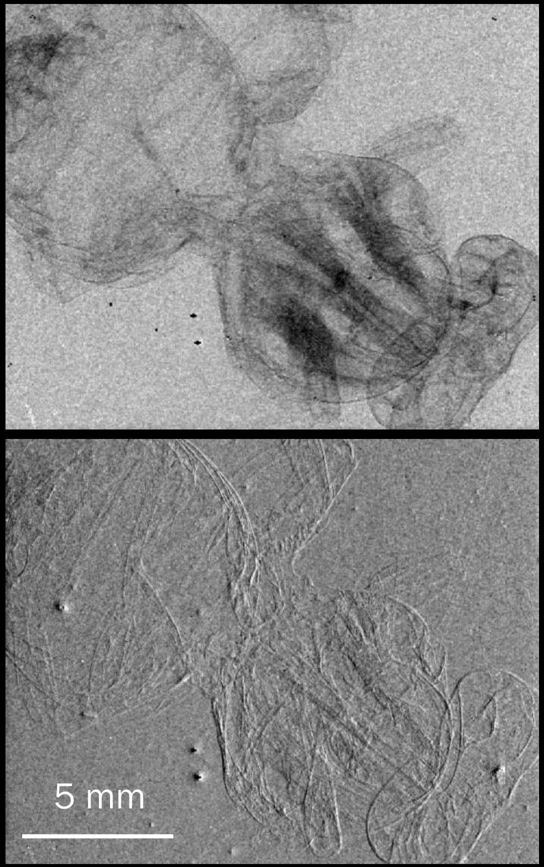
In collaboration with HELMHOLTZ MUNICH

INFN



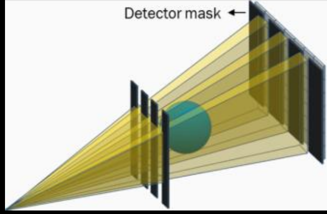
Single mask

Transmission

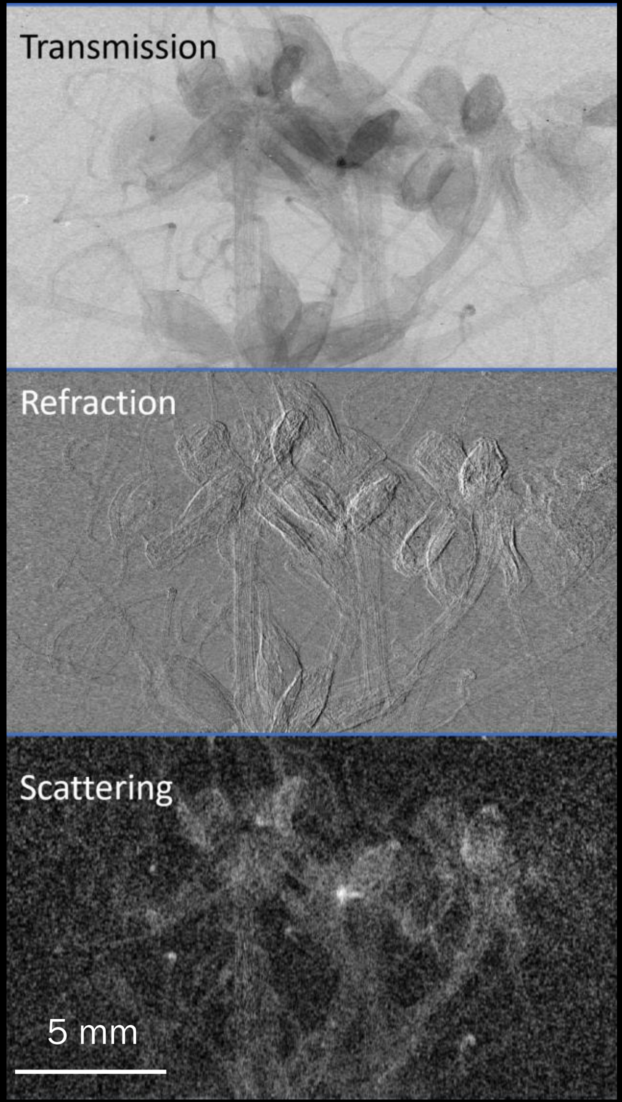


Refraction

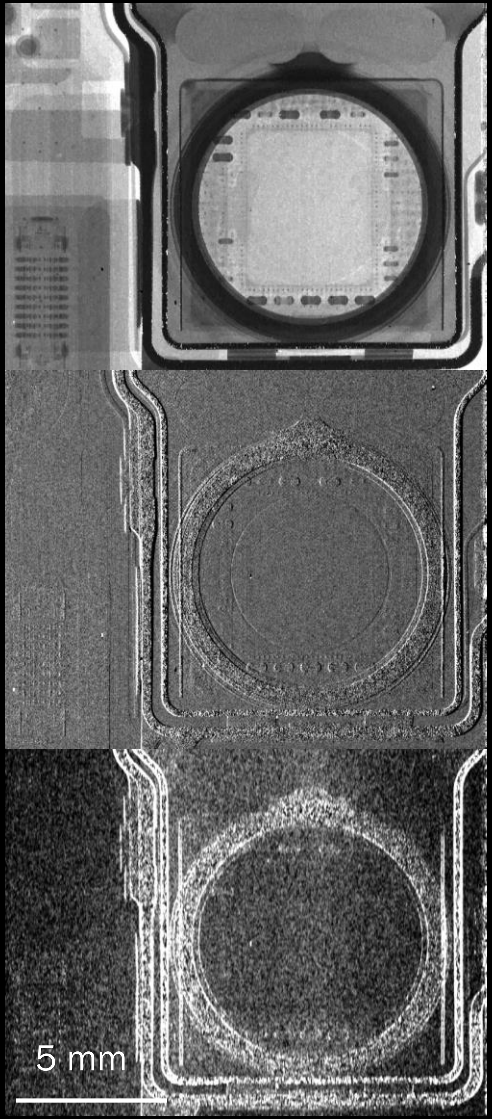
Double mask



Flower
low energy – 60 kVp



Smartphone camera
high energy – 100 kVp



Preliminary results

Next steps

- Spectral phase-contrast imaging
- Applications…
- Open to collaborations!

P hoton-counting
E dge-illumination
P hase-contrast
I maging

THANK YOU!

Acknowledgements

- Luigi Rigon (University of Trieste & INFN)
- Fulvia Arfelli (University of Trieste & INFN)
- Francesco Brun (University of Trieste & INFN)
- Ralf H. Menk (Elettra & INFN)
- Vittorio Di Trapani (University of Trieste)
- Paola Perion (University of Trieste)
- Sandro Donato (University of Calabria & INFN)
- Alessandro Olivo (University College London)
- Marco Endrizzi (University College London)
- …

UNIVERSITÀ DEGLI STUDI DI TRIESTE

Elettra Sincrotrone Trieste

ICGEB

UCL

INFN