

Compact x-ray systems for multi-contrast x-ray microtomography

Carlos Navarrete-León

Research Fellow in X-ray Microscopy
Francis Crick Institute / University College London



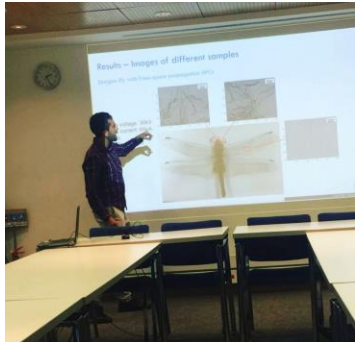
Nikon-UCL Prosperity Partnership
on Next-Generation X-Ray Imaging



Engineering and
Physical Sciences
Research Council



Career path



Pregrado - Física (2015-2019)

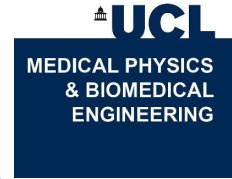
Asistente de Investigación
Grupo de Altas Energías
(2019-2020)

 Universidad de los Andes | Grupo de Investigación Altas Energías

PhD in X-ray Imaging
Advanced X-ray Imaging Group
(2020-2024)



Research Fellow in X-ray Microscopy and Microtomography (2024-)

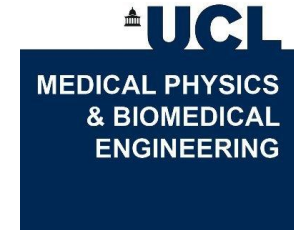


Advanced X-ray Imaging Group



Research topics:

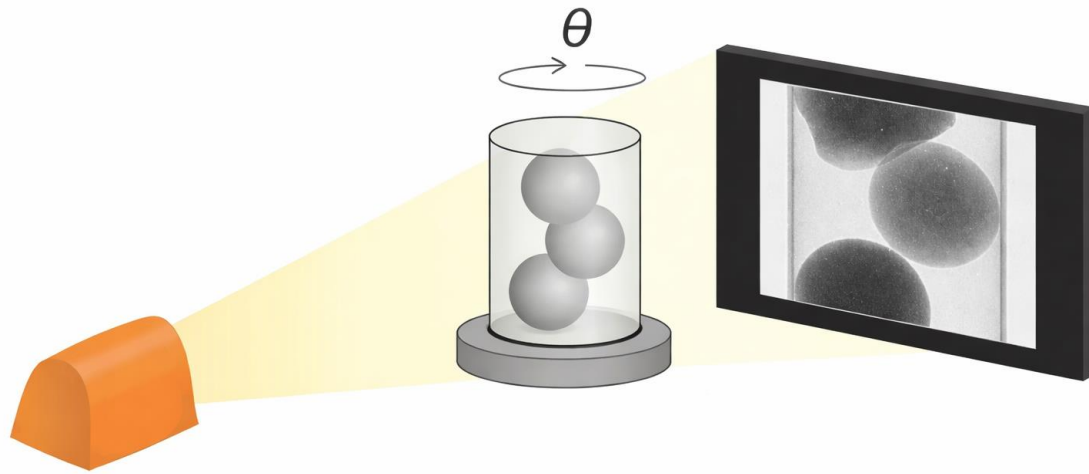
- X-ray phase-imaging
- X-ray microscopy and CT
- New x-ray sources and detectors
- Spectral x-ray imaging
- Applications: biomedicine, security, engineering.
- IP generation



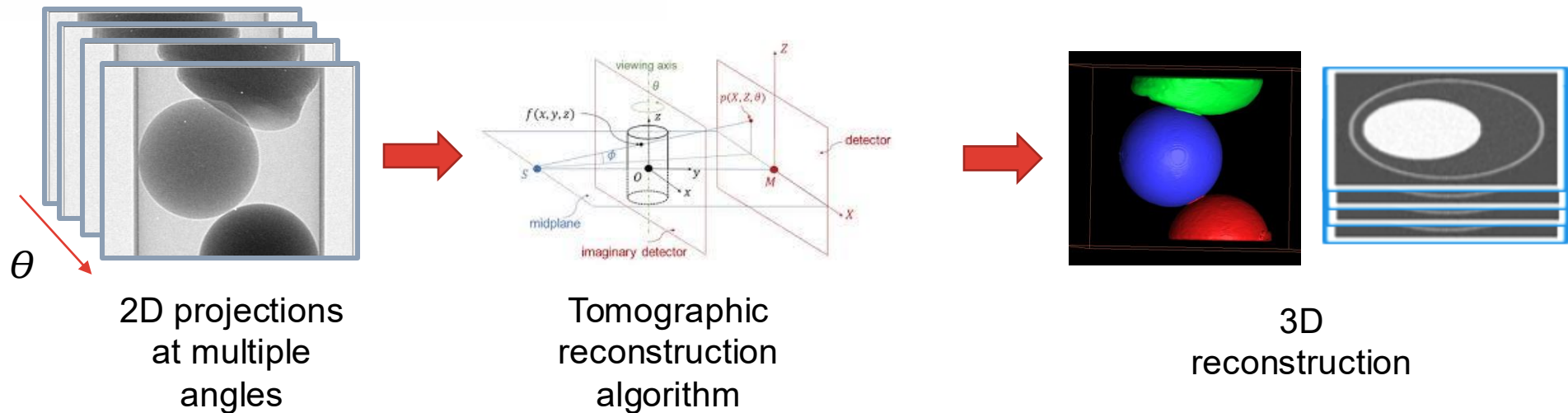
<https://www.ucl.ac.uk/medical-physics-biomedical-engineering/research/research-groups/advanced-x-ray-imaging-group-axim>

X-ray micro-CT

In tomography, three-dimensional images are reconstructed from a series of two-dimensional X-ray projections acquired while rotating the sample



Beer-Lambert law:
$$-\ln \frac{I}{I_0} = \int \mu dz$$



Limitations of X-ray micro-CT

Poor contrast between materials with similar attenuation

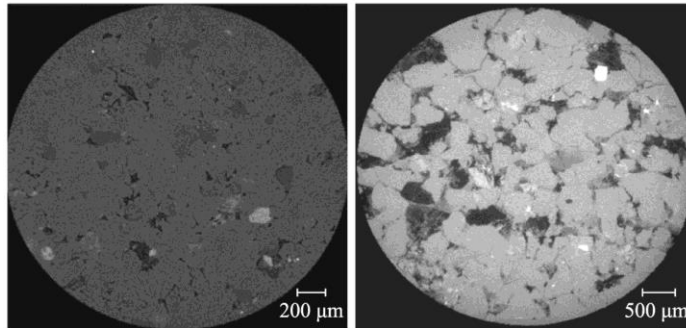


Roque-Torres, G.D. Micro-CT in Medicine and Engineering (2025)

Biology

Soft tissue imaging

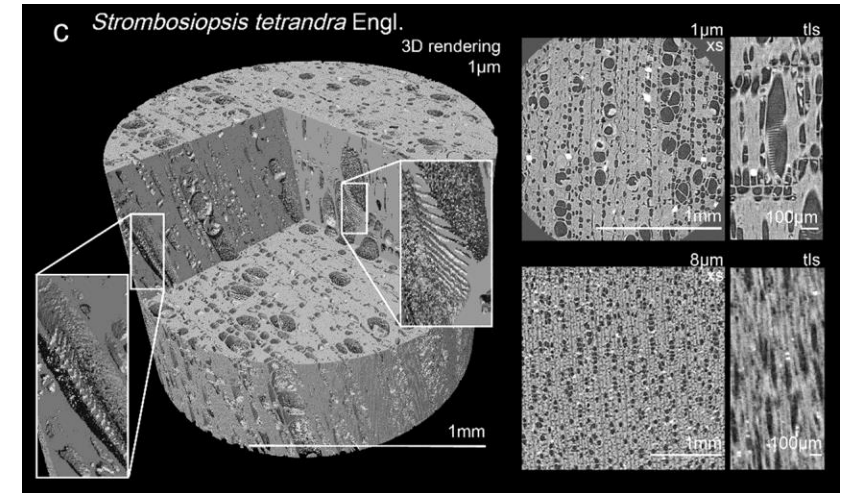
Information is limited by the resolution of the system (1-10 μm)



Briolet et al, *Geochimica et Cosmochimica Acta* 397 (2025)

Earth sciences

Mineral phases in rocks



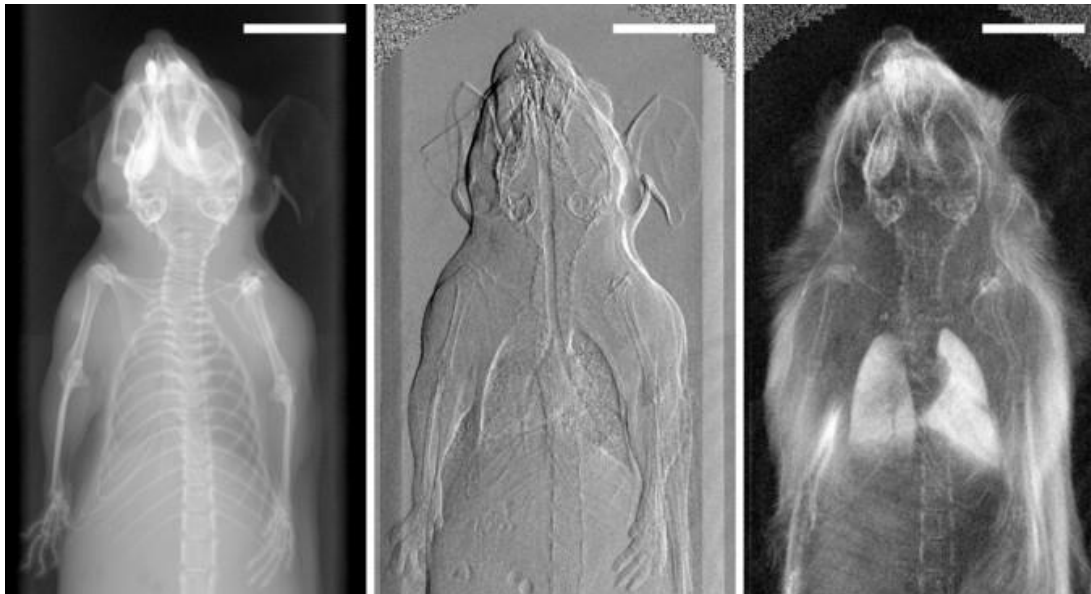
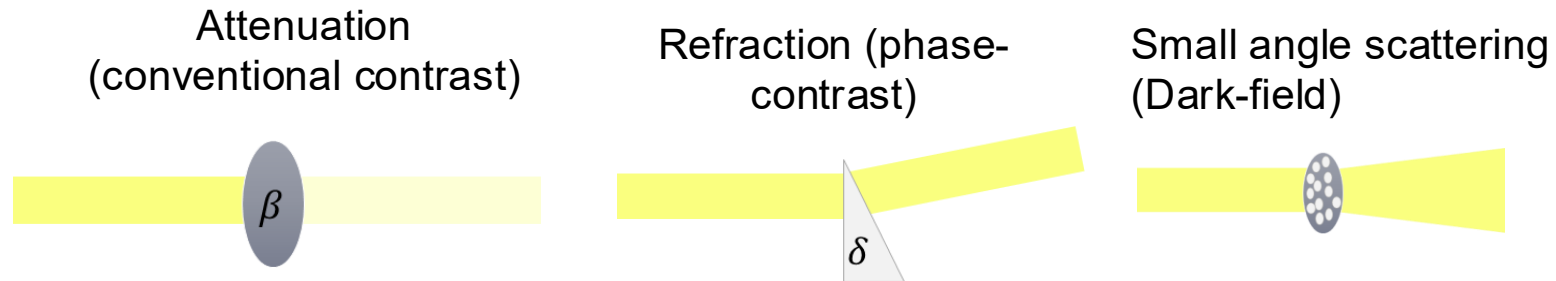
Direicks et al. *Plant Methods* 20, 98 (2024).

Plant science

Microstructure in woods

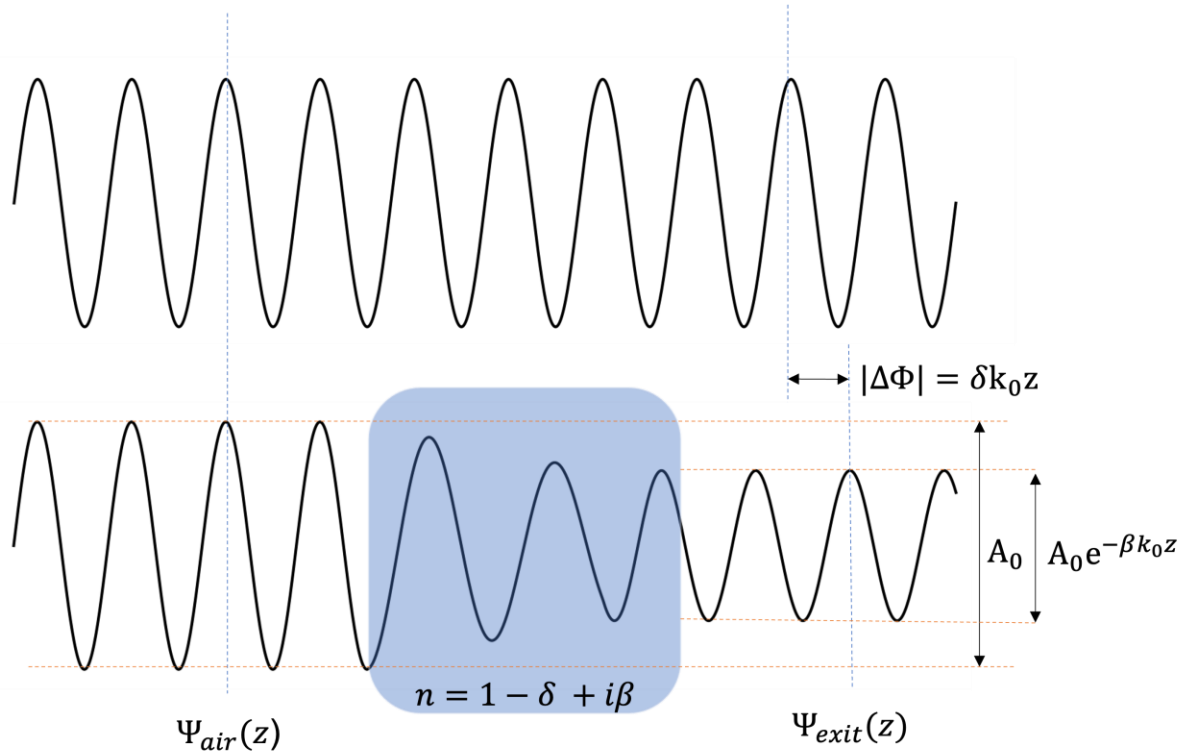
Multi-contrast x-ray imaging

Besides attenuation, X-rays also refract and scatter as they pass through a sample.



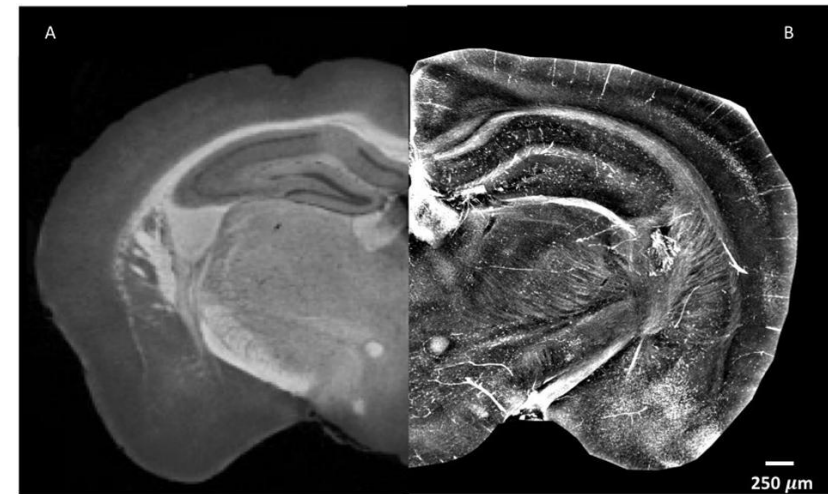
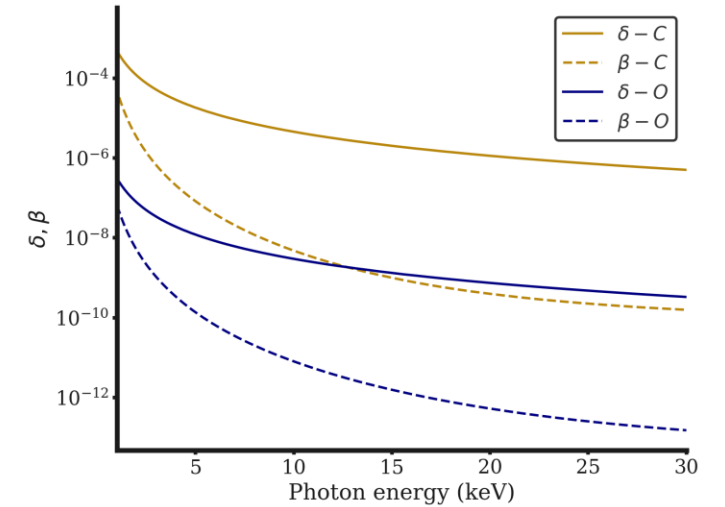
Bech et al. Sci Rep 3, 3209 (2013)

Phase-contrast imaging



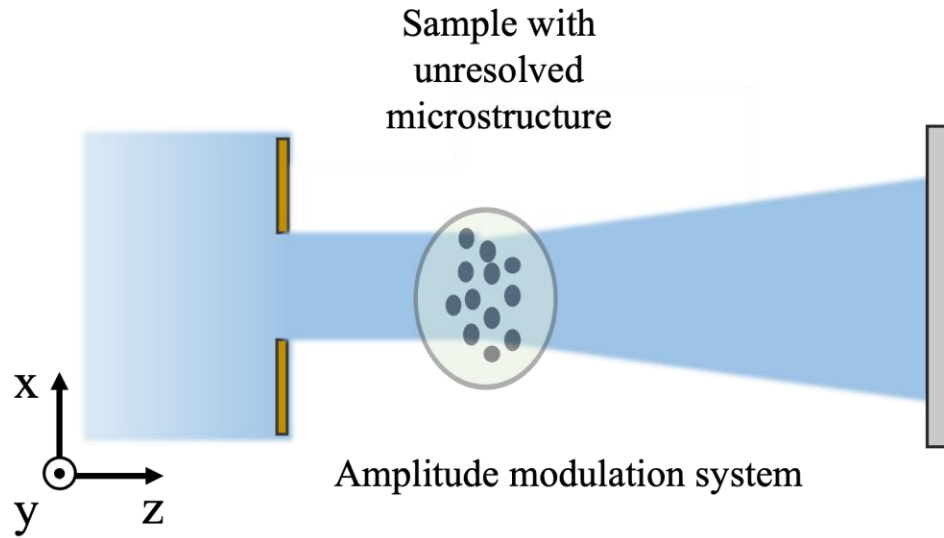
$$\psi_{air}(z) = A_0 e^{i(k_0 z - \omega t)}$$

$$\psi_{exit}(z) = A_0 e^{-\beta k_0 z} e^{i[(1-\delta)k_0 z - \omega t]}$$



Palemo et al (2020). Frontiers in Neuroscience, 14

Dark field imaging



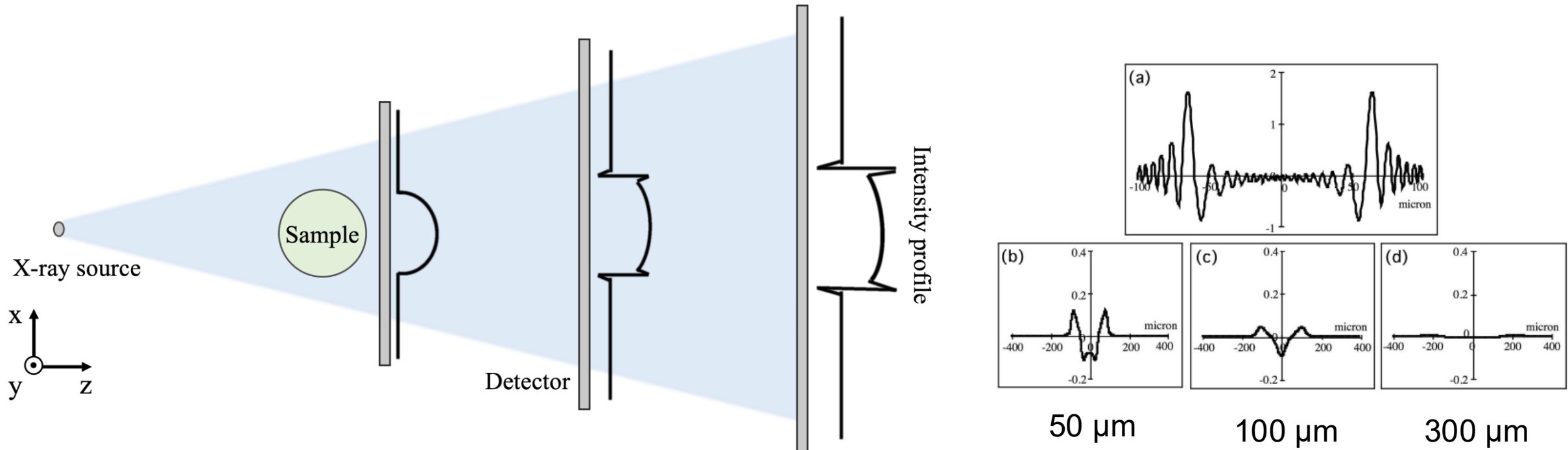
- The dark field signal arises from unresolved phase shifts and scattering from subpixel structures.
- The signal depends on the density of the scatterers, their spacing, orientation, and shape.
- Examples are micro-particles, pores, bubbles, fibres, and cracks.



Attenuation

Dark-field

Why is it hard to retrieve these signals in a lab?

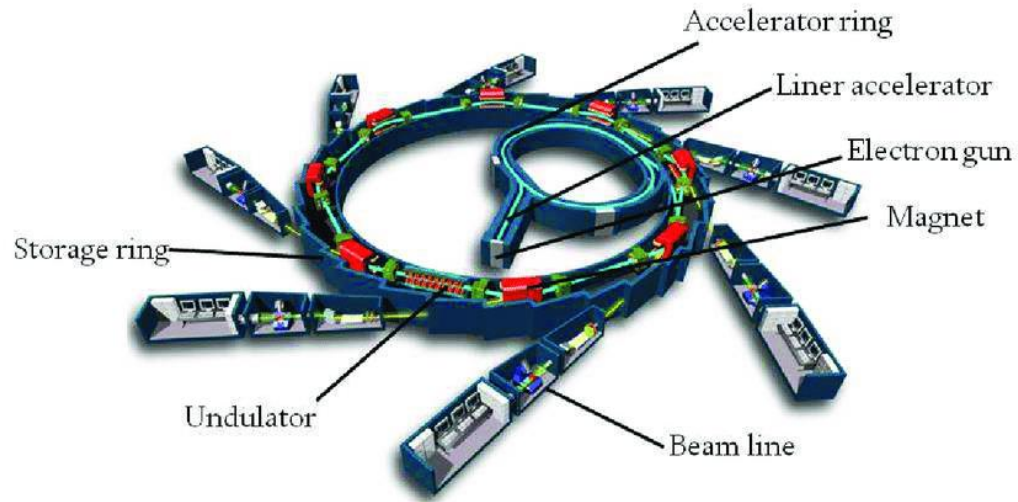


Olivo & Castelli (2014). Riv. Nuovo Cimento. Vol. 37, No. 9

The source and the detector response functions often blur out the signal

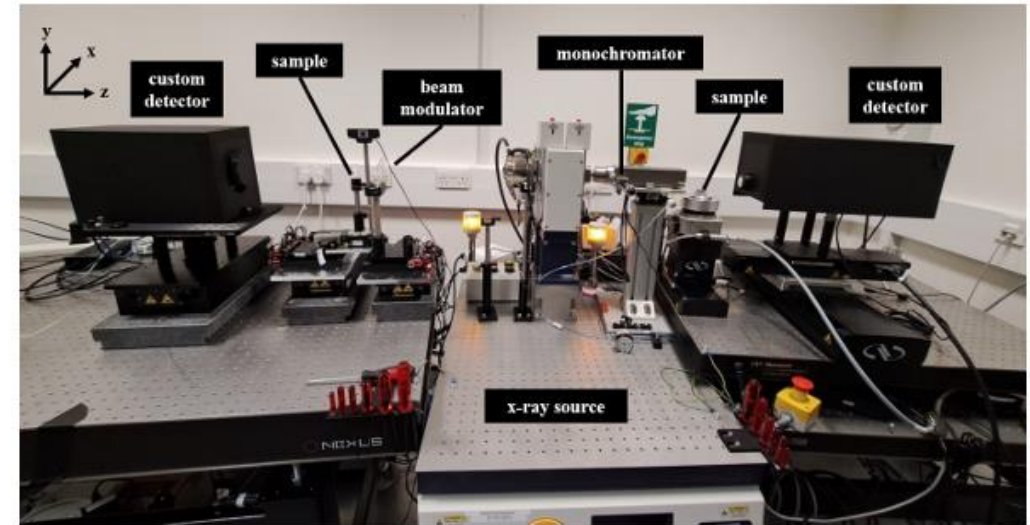
From Synchrotrons to Laboratory Systems

Synchrotrons



- Monochromatic x-rays.
- Highly coherent source, high flux.
- Plenty of propagation distance.
- But limited access and beamtime.

Lab-based bench top systems

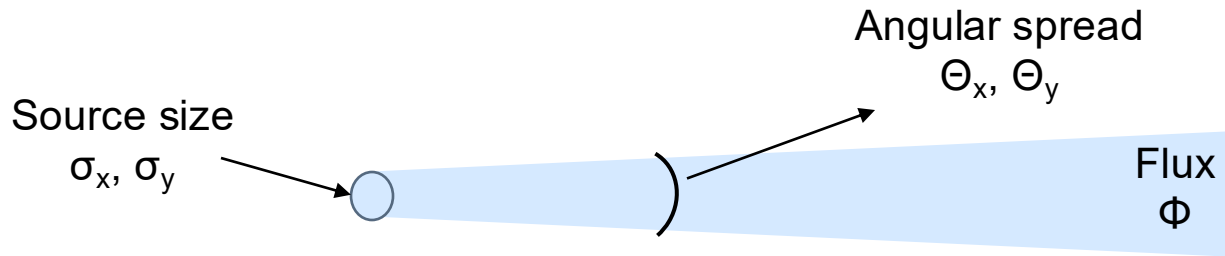


- Polychromatic radiation.
- Low-coherence sources, lower X-ray flux.
- Compact set-ups.
- Challenges in terms of system design, signal retrieval, and noise.

X-ray instrumentation

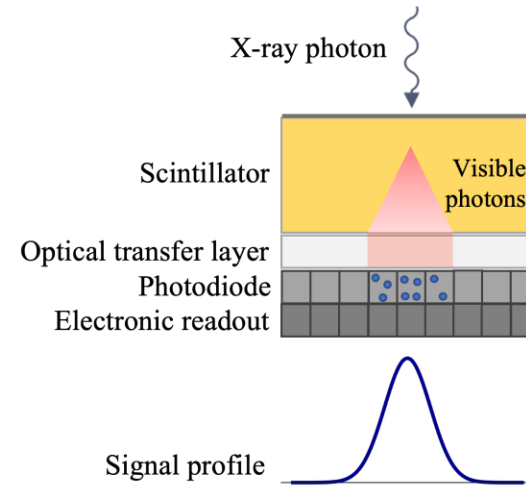
Source and coherence

Brilliance:
$$B(E) = \frac{\Phi(E)}{4\pi^2 \sigma_x \sigma_y \Theta_x \Theta_y}$$

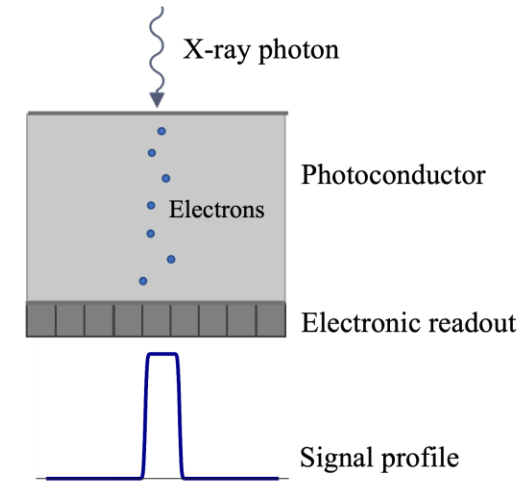


Detectors

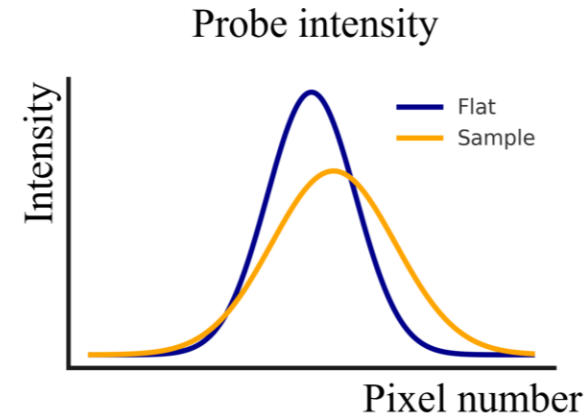
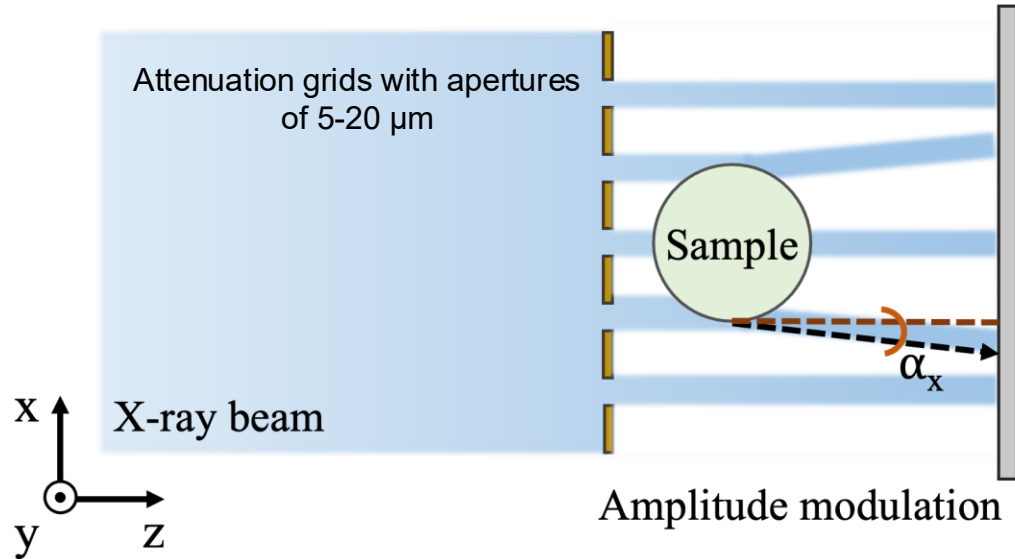
Indirect conversion



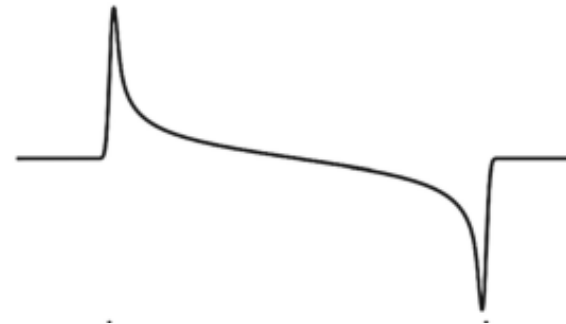
Direct conversion



Amplitude modulation methods

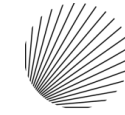


$$\alpha_{x,y} = \tan^{-1} \left(\frac{\Delta_{x,y}}{z_{od}} \right)$$

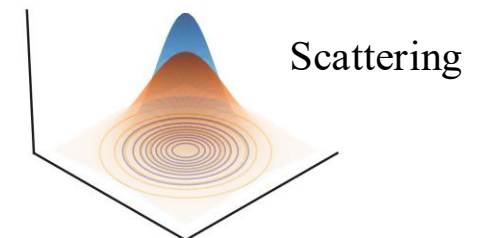
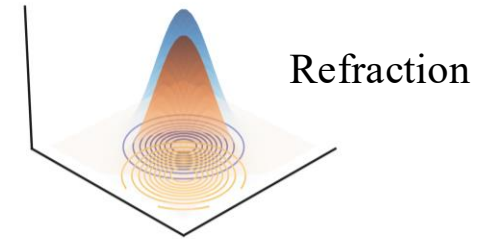
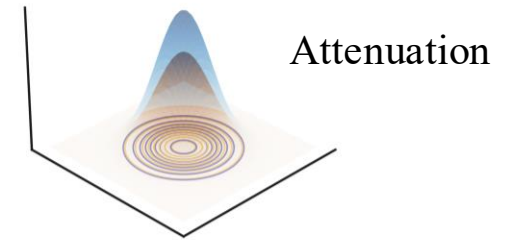
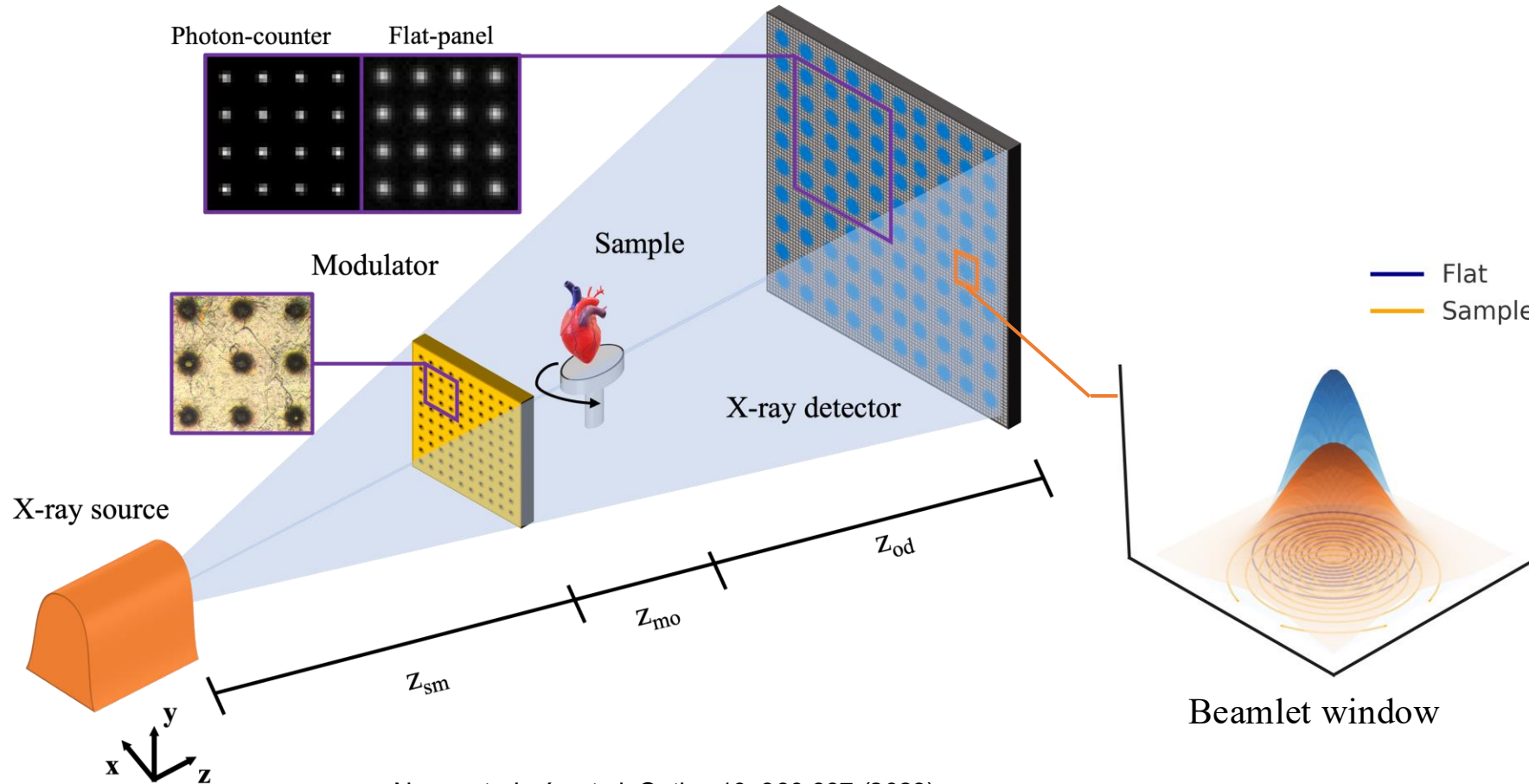


$$\alpha_x(x, y) = \frac{1}{k} \Delta \Phi_x(x, y)$$

Two-directional beam-tracking



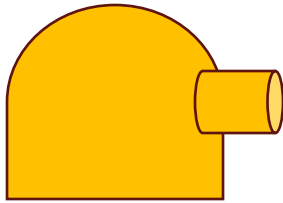
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Navarrete-León et al. *Optica* 10, 880-887 (2023)

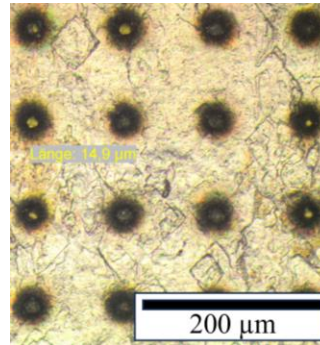
System's technical requirements

X-ray source



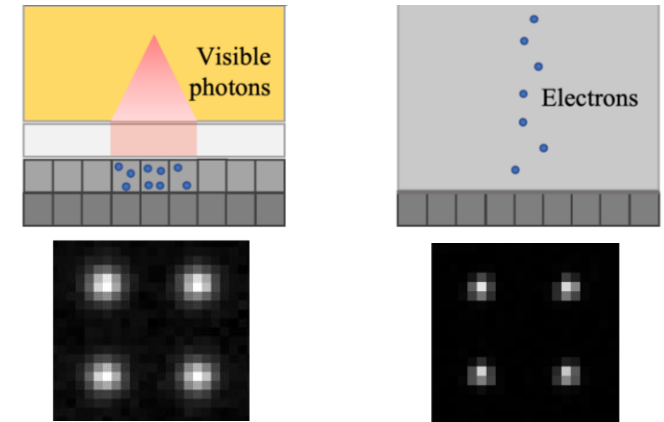
- ✓ Low-power (10 W).
- ✓ Microfocus (10 μm).
- ✓ Sealed (no cooling).
- ✓ Low cost (£20k).

Intensity modulator



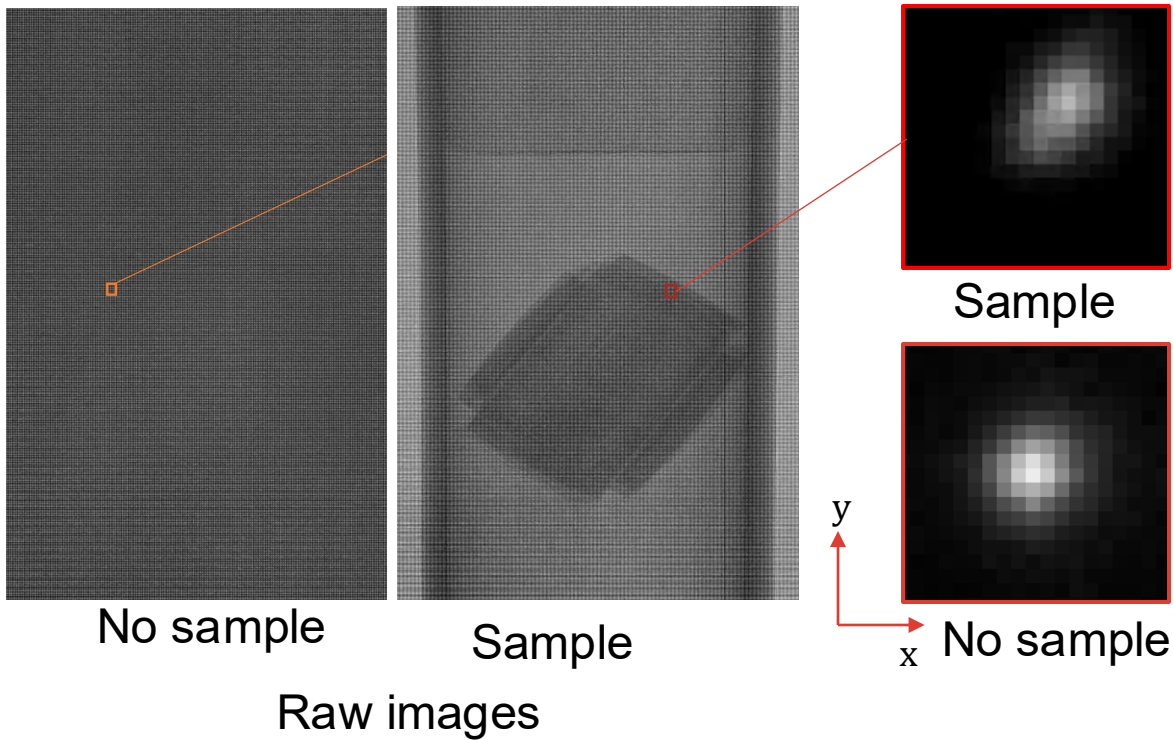
- ✓ Aperture size of 15 μm .
- ✓ Periods of 50 and 100 μm .
- ✓ Made from Tungsten foil.
- ✓ Fabricated through laser ablation.
- ✓ No chemical etching / wet lab required.
- ✓ Position accuracy of 1-5 μm .

X-ray detectors



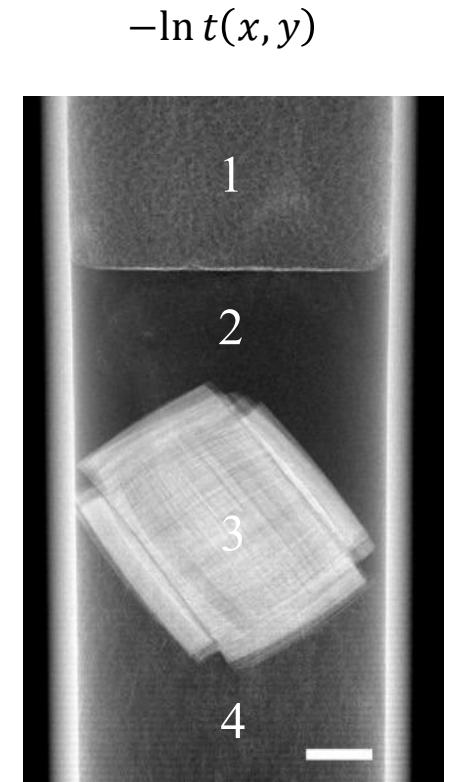
- ✓ Pixel size of 50-62 μm .
- ✓ Photon-counting: high sensitivity, FOV: 1.4x1.4 cm^2 – 3x3 cm^2 .
- ✓ Indirect flat panel: bigger FOV - 10x10 cm^2 .

Attenuation measurement



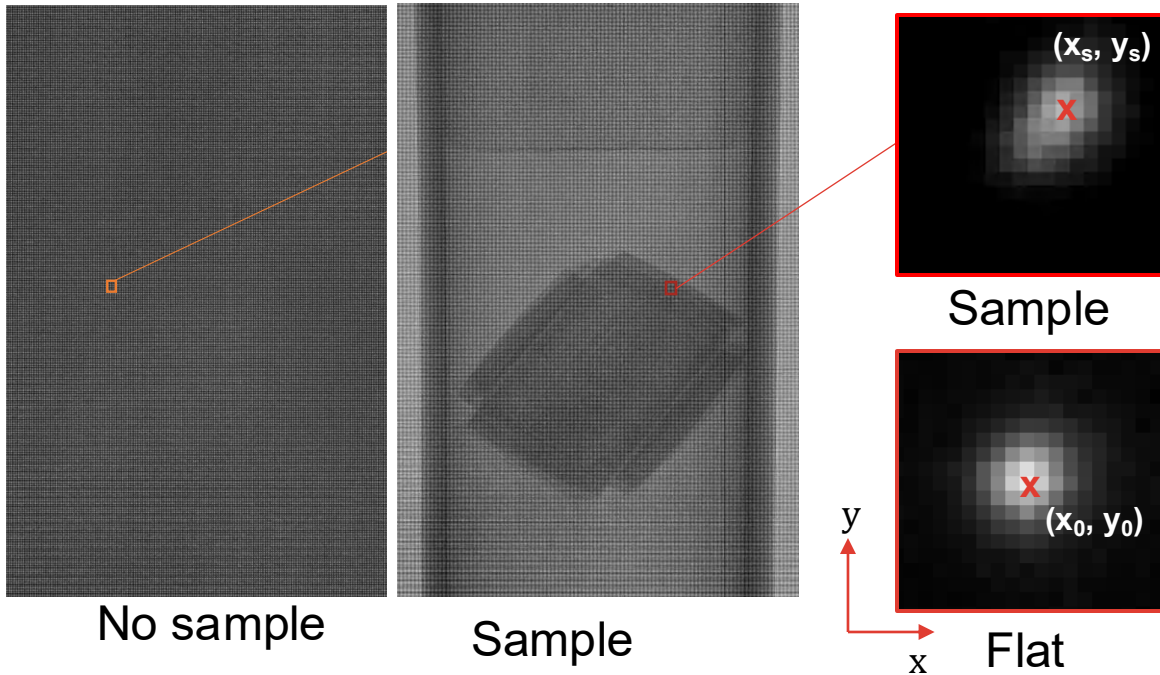
Transmission / Attenuation

$$-\ln t(x, y) = -\ln \frac{\sum I_s(x, y)}{\sum I_0(x, y)}$$



1: Plastic scaffold, 2: polystyrene foam, 3: fibre-reinforced composite, 4: polystyrene foam

Refraction and phase measurement

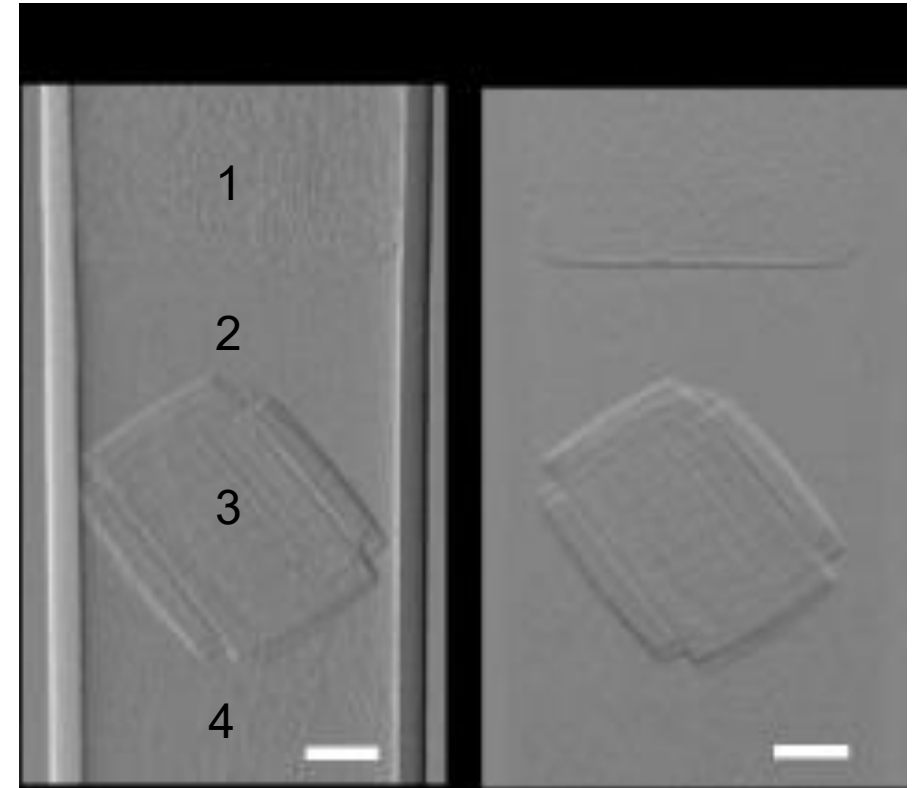


Raw images

Refraction

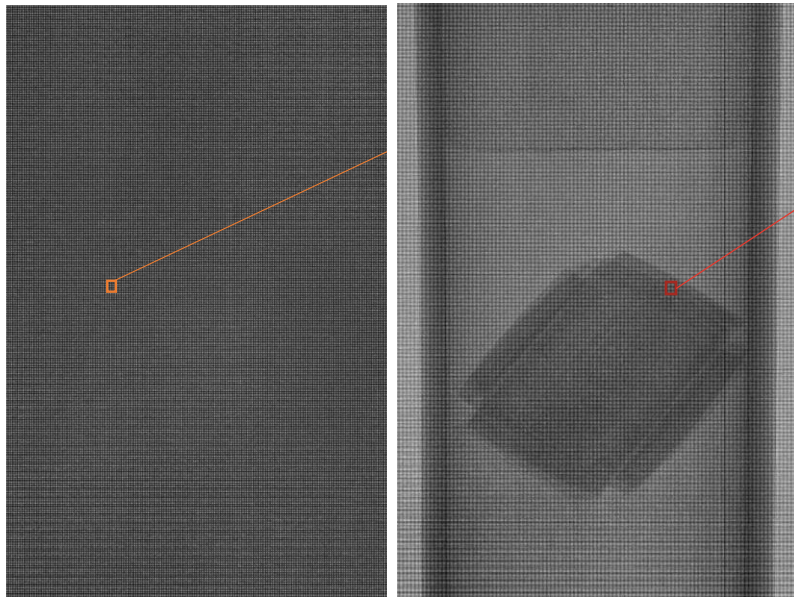
$$\Delta_x(x, y) = x_s - x_0$$

$$\Delta_y(x, y) = y_s - y_0$$



1: Plastic scaffold, 2: polystyrene foam, 3: fibre-reinforced composite, 4: polystyrene foam

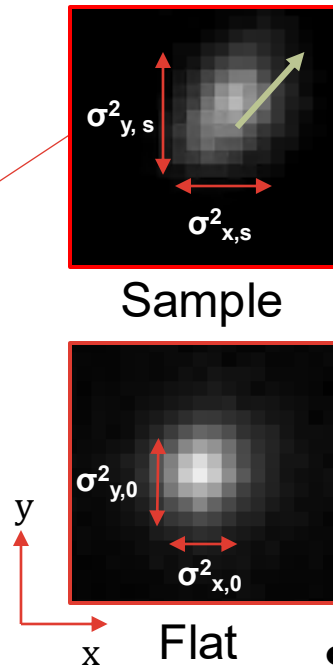
Scattering measurement



No sample

Sample

Raw images



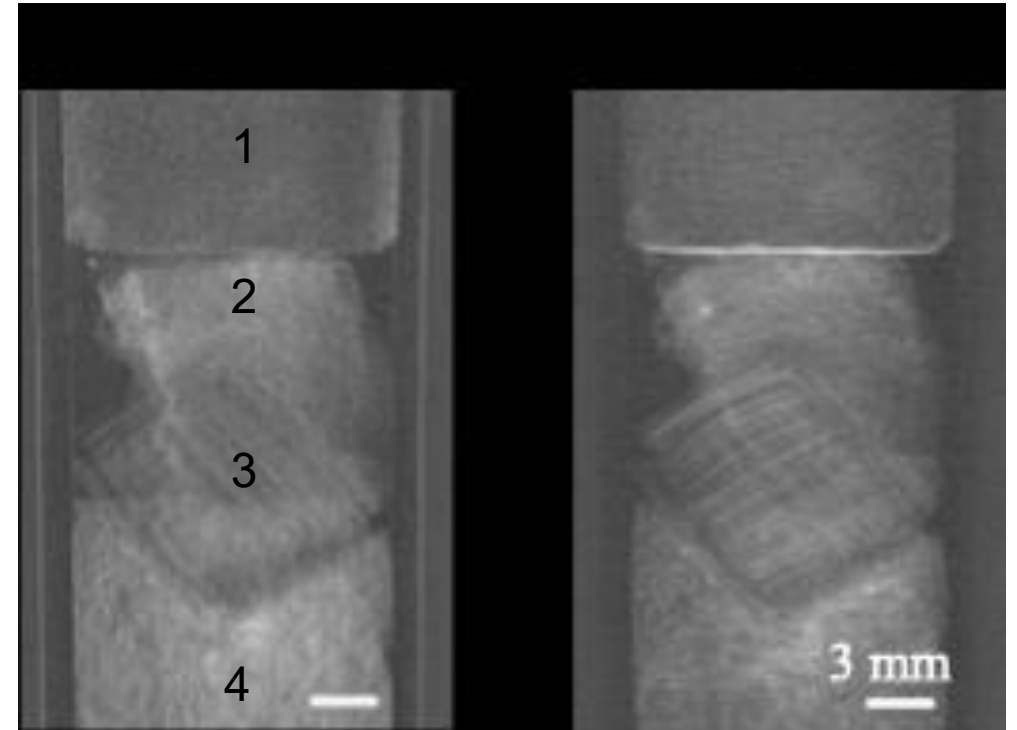
Sample

Flat

Scattering

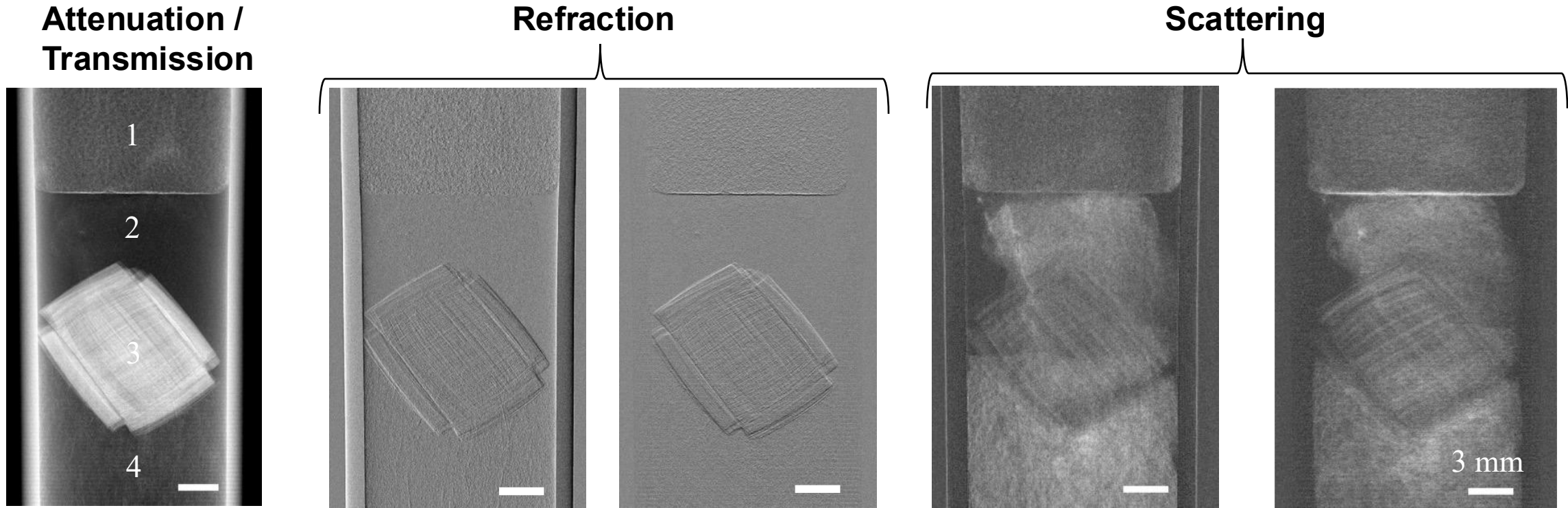
$$\Delta\sigma_x^2(x, y) = \sigma_{x,s}^2 - \sigma_{x,0}^2$$

$$\Delta\sigma_y^2(x, y) = \sigma_{y,s}^2 - \sigma_{y,0}^2$$



1: Plastic scaffold, 2: polystyrene foam, 3: fibre-reinforced composite, 4: polystyrene foam

Complementary contrast channels

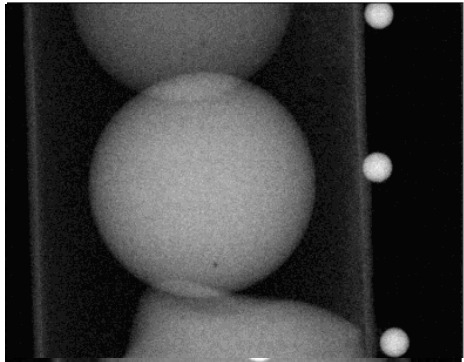


1: Plastic scaffold, 2: polystyrene foam, 3: fibre-reinforced composite, 4: polystyrene foam

Quantitative phase μ -CT

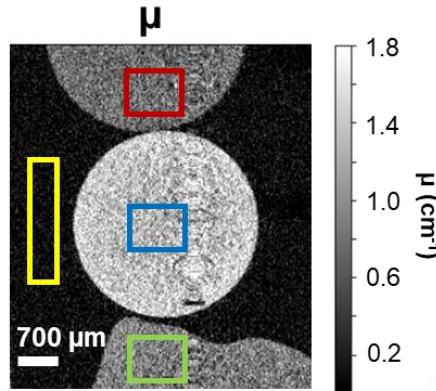
Projections

$$-\ln(I/I_0)$$



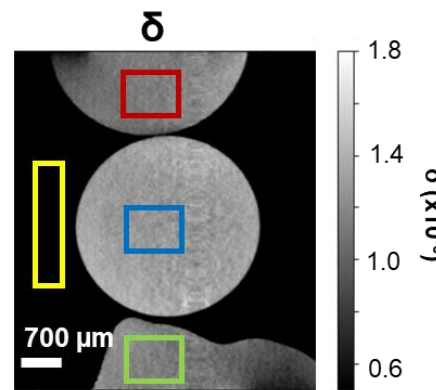
$$-\ln t(x, y) = \int_0^z \mu(x, y, z) dz$$

CT reconstructions



Filtered back-projection (FDK)

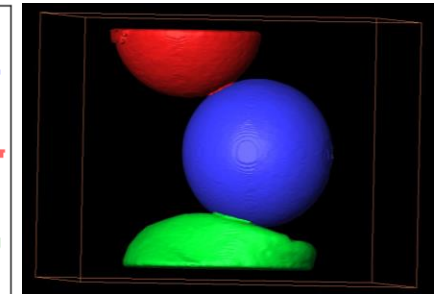
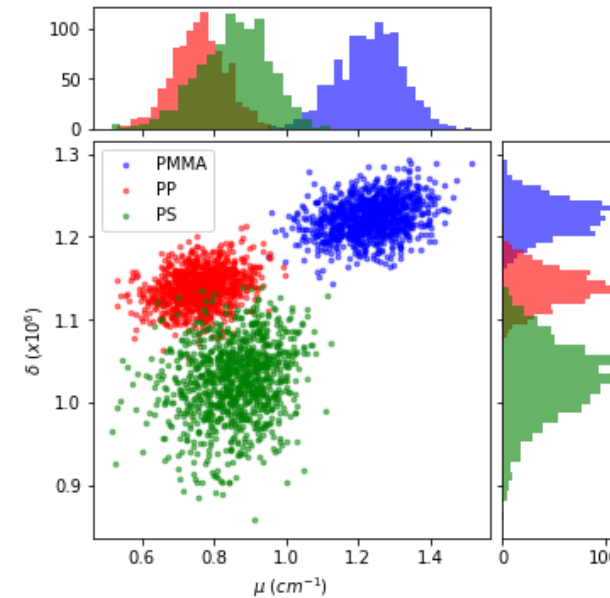
$$-\Delta|\Phi(x, y)| = \int_0^z \delta(x, y, z) dz$$



CNR comparison

Material	CNR of μ	CNR of δ
PP	4.1	31.6
PMMA	7.1	34.0
PS	4.7	28.4

Improved material discrimination



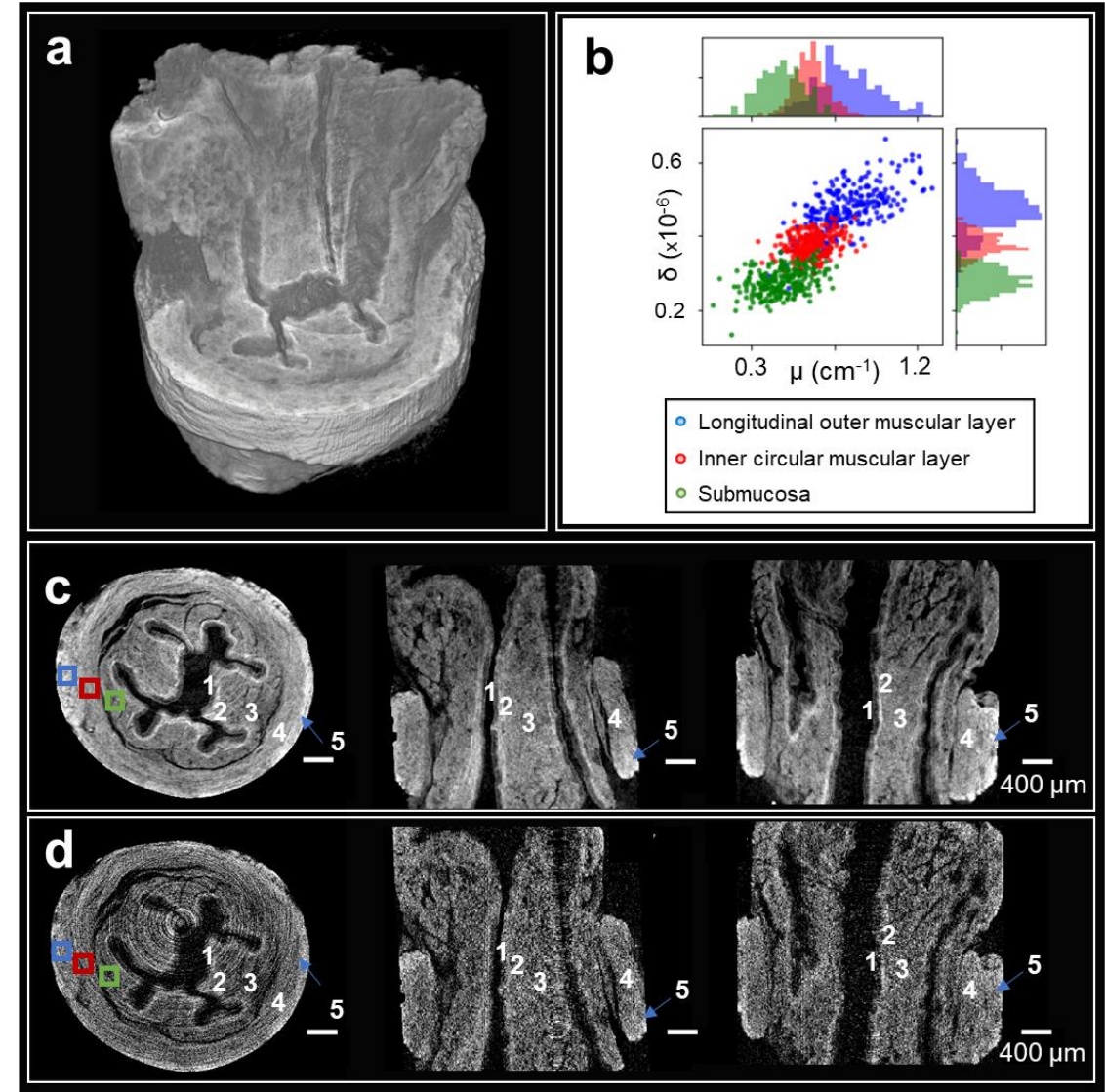
More information for image segmentation.

Ex-vivo imaging of unstained soft tissue

Sample is a piglet derived oesophagus prepared through paraformaldehyde (PFA) fixation followed by critical point drying with CO₂.

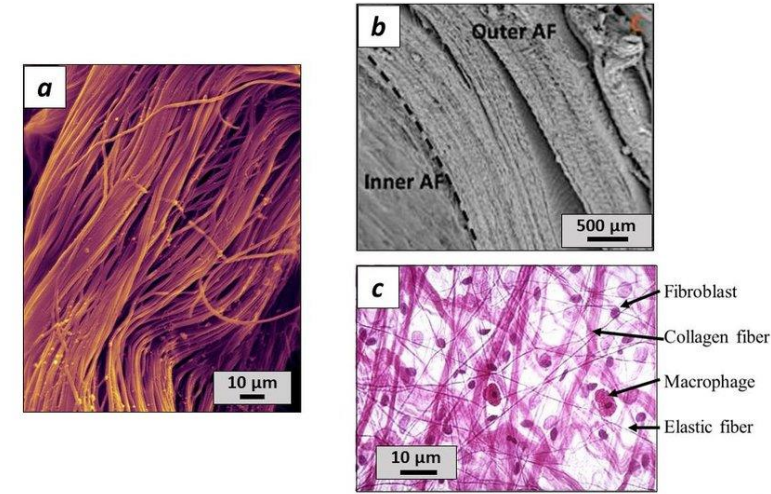
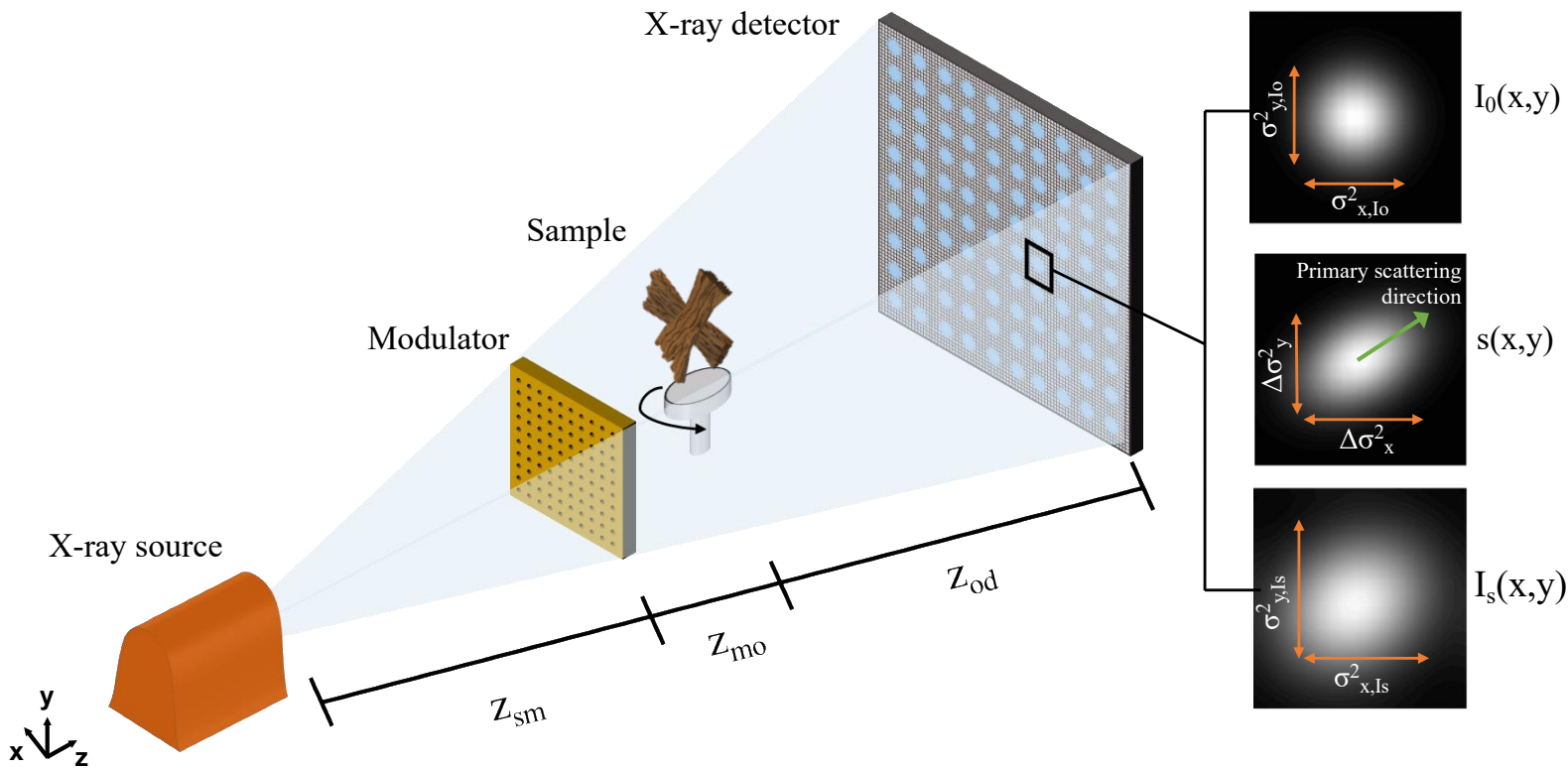
Scan parameters:

- 900 projections x (8x8 sampling steps) x 1s = 16h
- Resolution: 15µm.
- FOV: 2x2 mm.



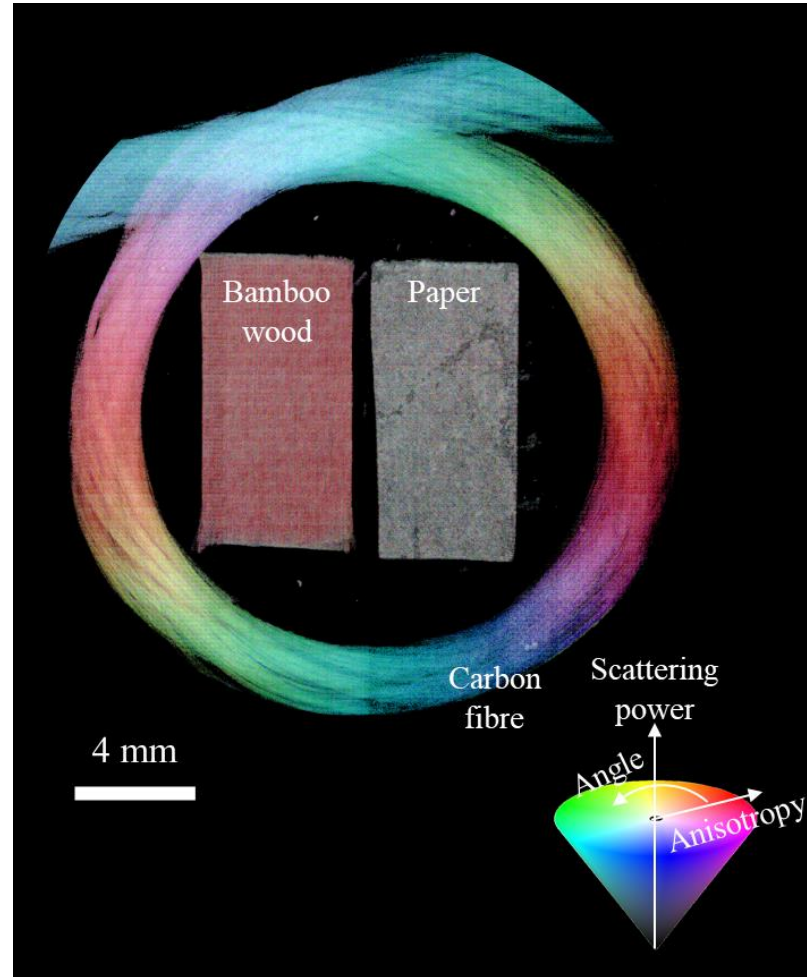
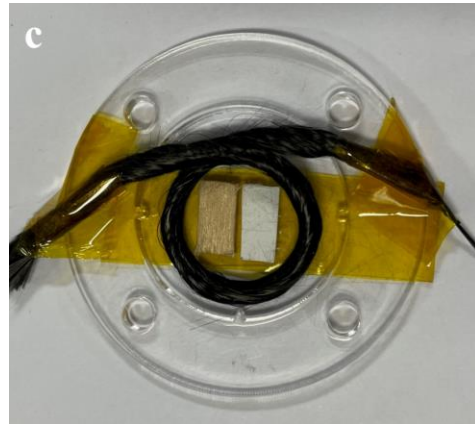
Navarrete-León et al. Optica 10, 880-887 (2023)

Directional dark-field imaging

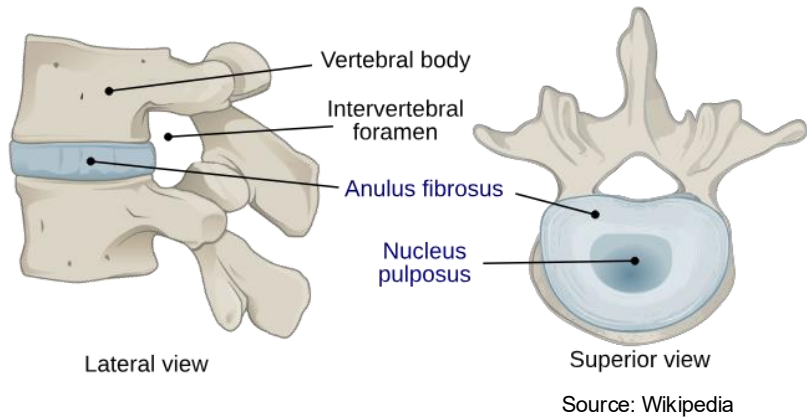


Firbous structures in nature

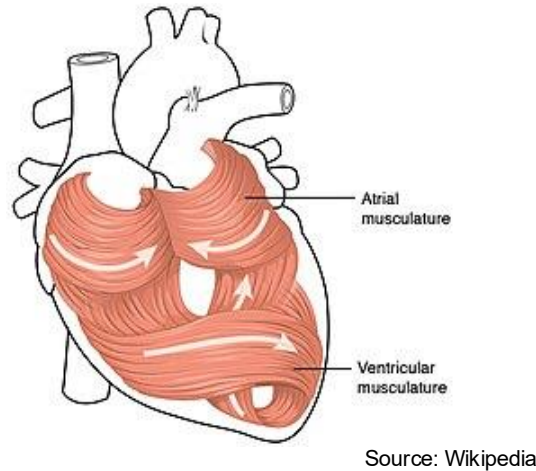
Directional scattering in a known phantom



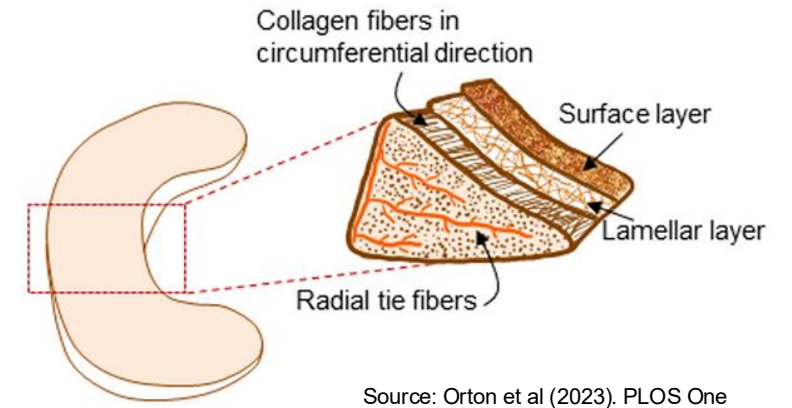
Fibre-structured tissues



**Bovine intervertebral disc
(Radio)**



**Mouse heart
(Tomo)**

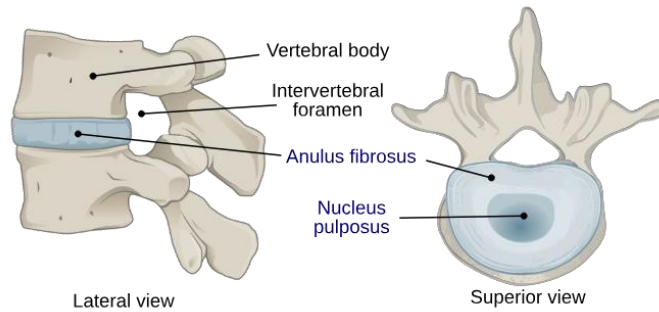


**Porcine meniscus
(Tomo)**

Samples were dehydrated in ethanol and dried through Critical Point Drying / HMDS.
Collaboration with Alvaro and Alissa Parmenter.



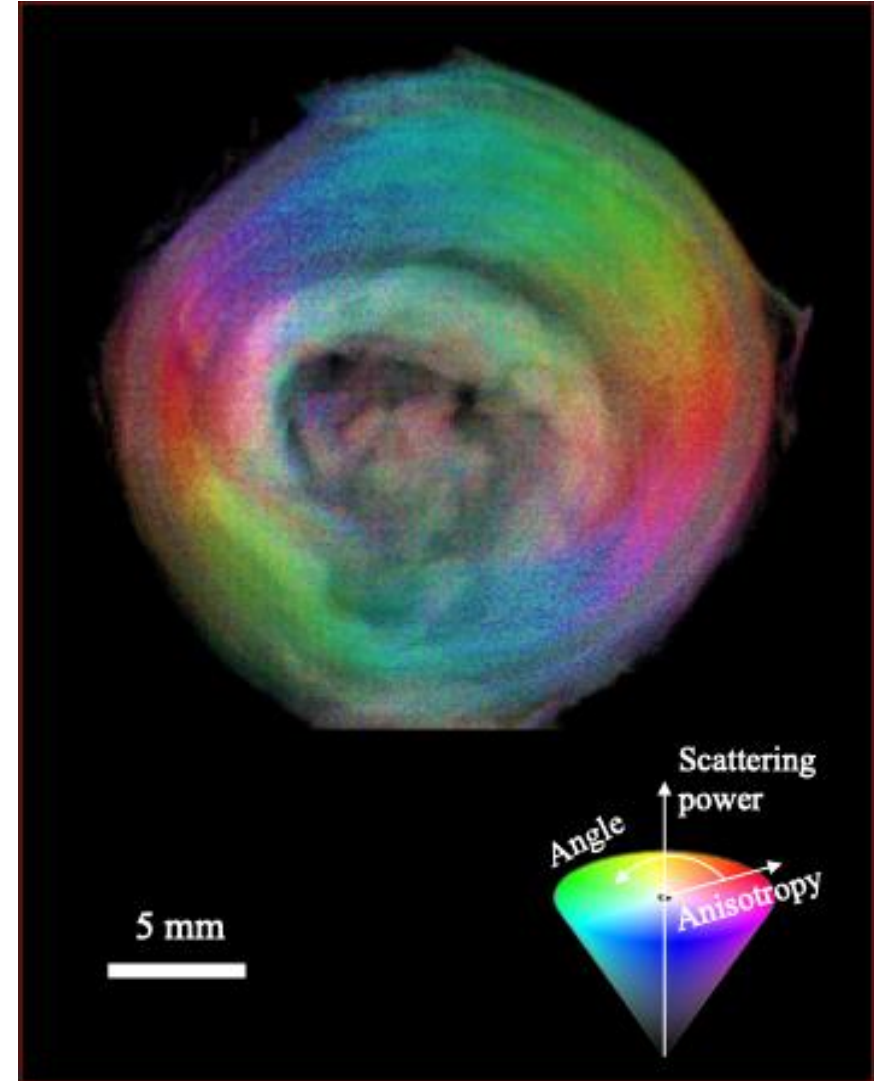
Bovine intervertebral disc



Source: Wikipedia

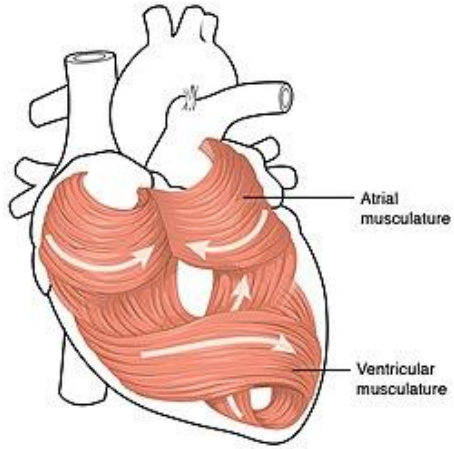
Scan parameters:

- Scan time: 2 min
- Voxel size: $15 \times 15 \times 15 \mu\text{m}^3$.
- FOV: $3 \times 3 \text{ cm}^2$.



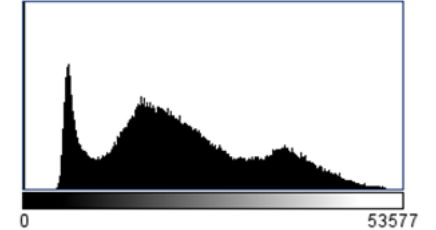
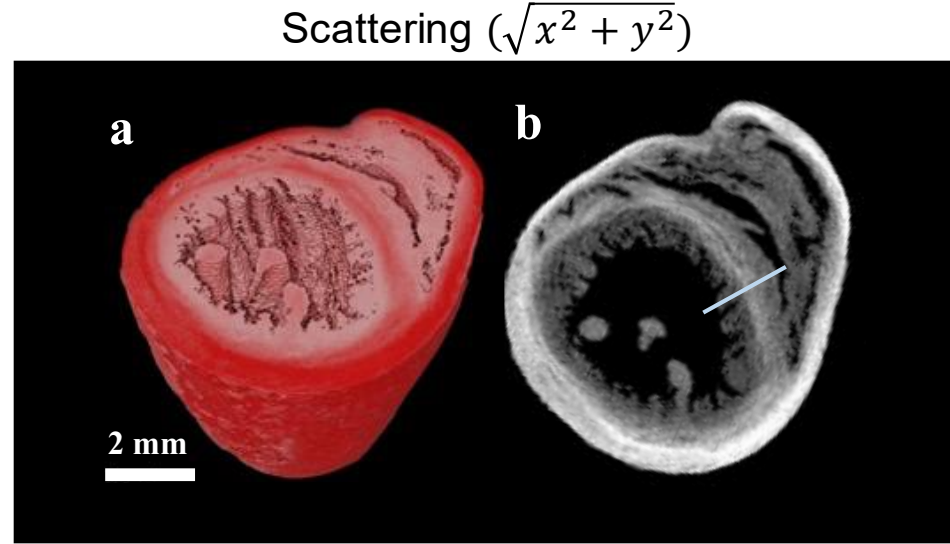
Directional dark-field

Mouse heart

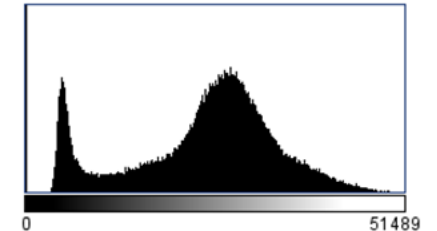
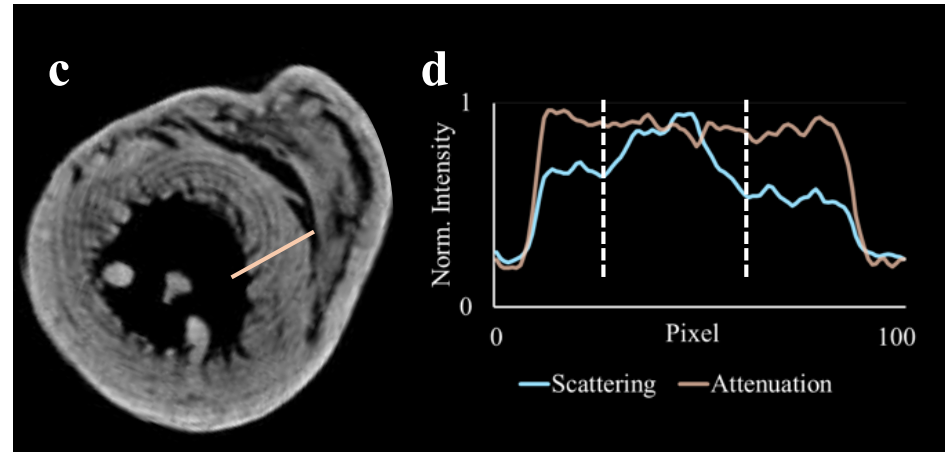


Scan parameters:

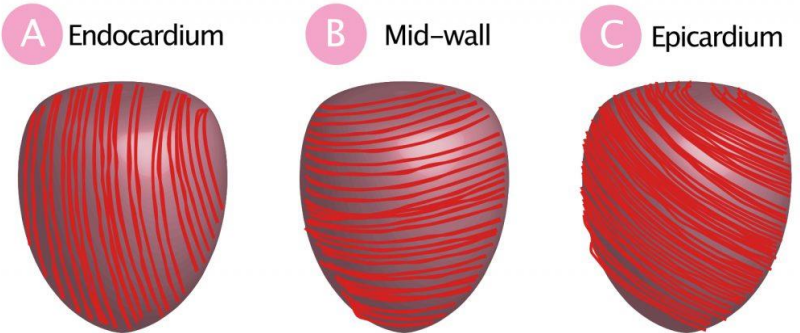
- Scan time: 18h
- Voxel size: 30x30x30 μm^3 .
- FOV: 3x3 cm^2 .



Attenuation

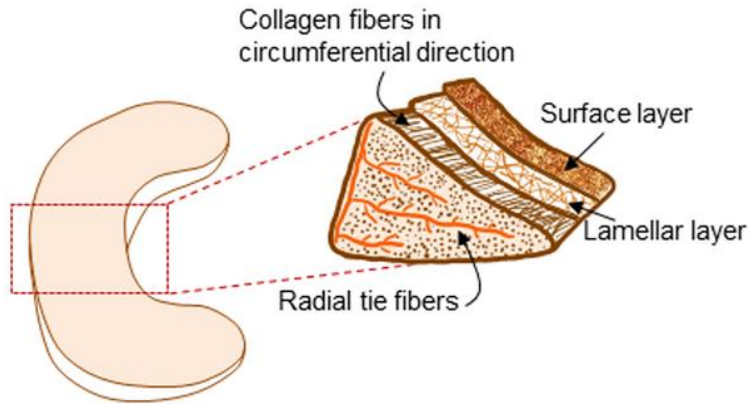


Orientation of myocardial fibers



Source:
Myocardial mechanics: Structure and function of myocardial fibers.
ECGWaves

Porcine meniscus

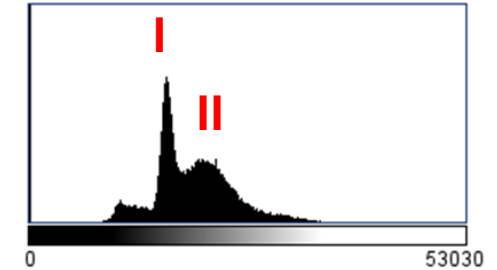
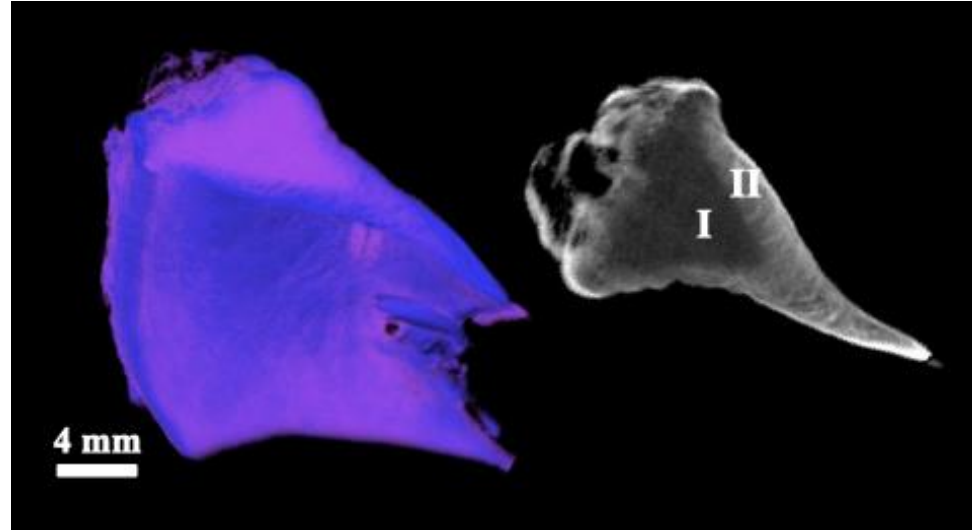


Source: Orton et al (2023). PLOS One

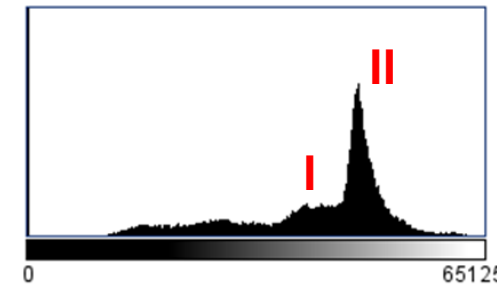
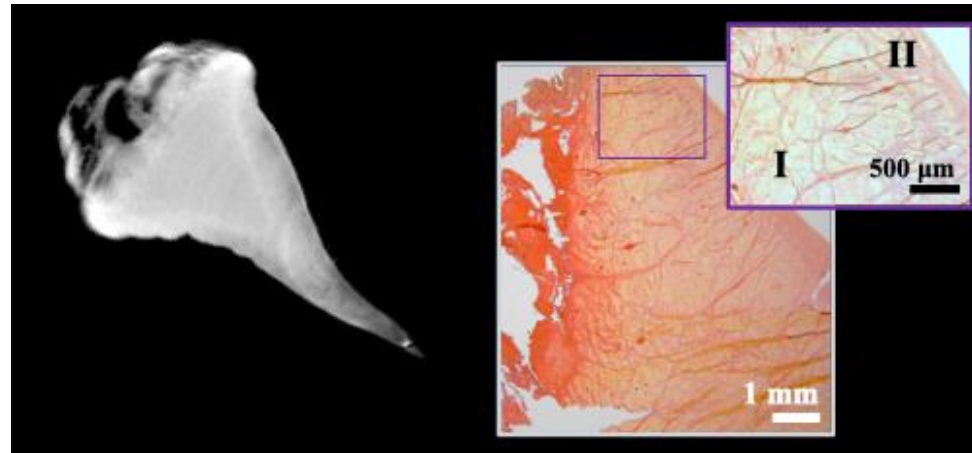
Scan parameters:

- Scan time: 18h
- Voxel size: 30x30x30 μm^3 .
- FOV: 3x3 cm^2 .

Scattering ($\sqrt{x^2 + y^2}$)



Attenuation



Conclusions

- X-ray microCT relies on attenuation contrast
- Phase- and dark-field contrast offer complementary information
- Beam-tracking allows for compact multi-contrast tomography
- Dark-field enables volumetric mapping of fibre structure in soft tissues
- These techniques offer novel applications in biomedicine and material characterisation

Future directions

- Compact setups: Sources, modulators, detectors
- Fast acquisition: sub-sampling, cycloidal, deep-learning reconstructions.
- Applications: biomedicine, material characterization, geology.
- Phase and dark field retrieval.
- Spectral and multicontrast imaging.
- Many channels... deep learning segmentation.
- Collaboration, collaboration, collaboration.

¡Gracias!

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LinkedIn: carlosfnavarrete



Nikon-UCL Prosperity Partnership
on Next-Generation X-Ray Imaging



Engineering and
Physical Sciences
Research Council



Funding in the UK

British Council Women in STEM Scholarships

<https://www.britishcouncil.org/study-work-abroad/in-uk/scholarship-women-stem>

Who can apply for a Chevening Scholarship?

<https://www.chevening.org/scholarships/who-can-apply/>



**UK Research
and Innovation**

<https://www.ukri.org/what-we-offer/developing-people-and-skills/find-studentships-and-doctoral-training/>

UCL's Research Excellence Scholarship (UCL-RES) is our new prestigious scholarship which aims to attract outstanding scholars to undertake doctoral research at UCL.

<https://www.ucl.ac.uk/scholarships/research-excellence-scholarship>

X-ray imaging groups

- **Any synchrotron facility:** Diamod Light Source (Oxford, UK), ESRF (Grenoble, France), Soleil (Saint-Aublin, France), Alba (Barcelona, Spain), Desy (Hamburg, Germany), Paul Scherrer Institute (Villigen, Switzerland).
- Advanced X-ray Imaging Group (**UCL, London, UK**).
- Munich Institute of Biomedical Engineering (**TUM, Munich, Germany**).
- Imec Vision Lab (**U of Antwerp, Belgium**).
- Biomedical and X-ray Physics Group (**KTH, Stockholm, Sweden**)
- Medical Radiation Physics Group (**U of Lund, Sweden**)
- Institute for X-ray Physics (**U of Gottingen, Germany**).
- Pepi Lab (**Univeristy of Trieste, Italy**)