



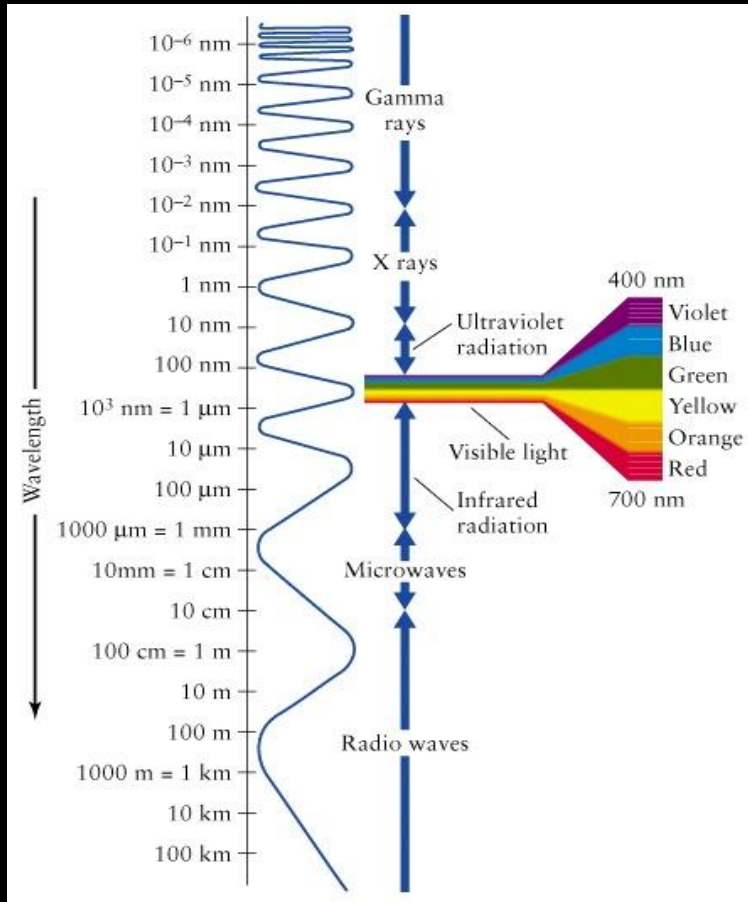
# *Possibilities and challenges of 3D high Resolution X-ray CT for plant structure investigation*

ir. Denis Van Loo

Denis.VanLoo@XRE.be



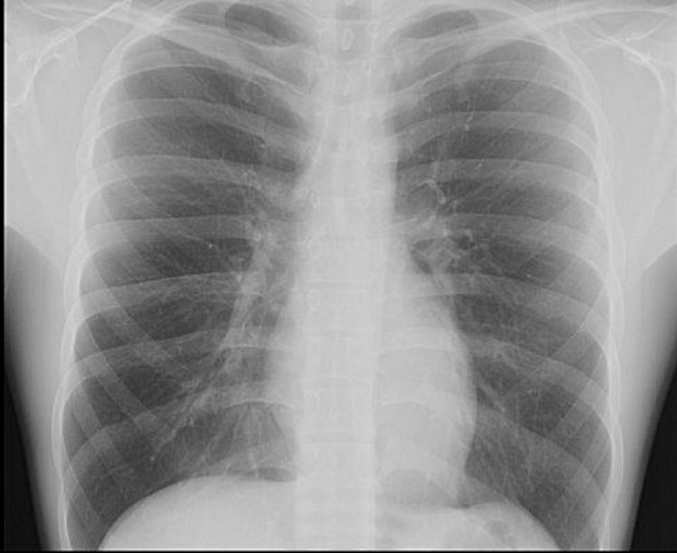
# X-Ray Imaging



Unlike visible light, X-rays can penetrate matter and is therefore suited for the internal and non-destructive inspection of objects

Wavelength 1 - 0.001 nm

# Medical applications



Chest X-ray



Broken bones



Dental imaging

# Other applications



R

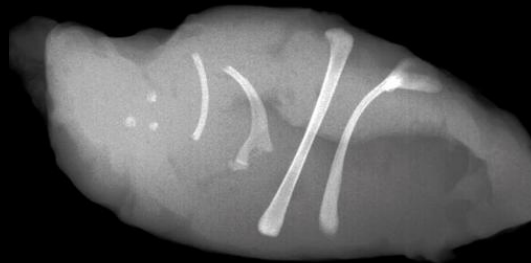


L

Weld inspection



Security

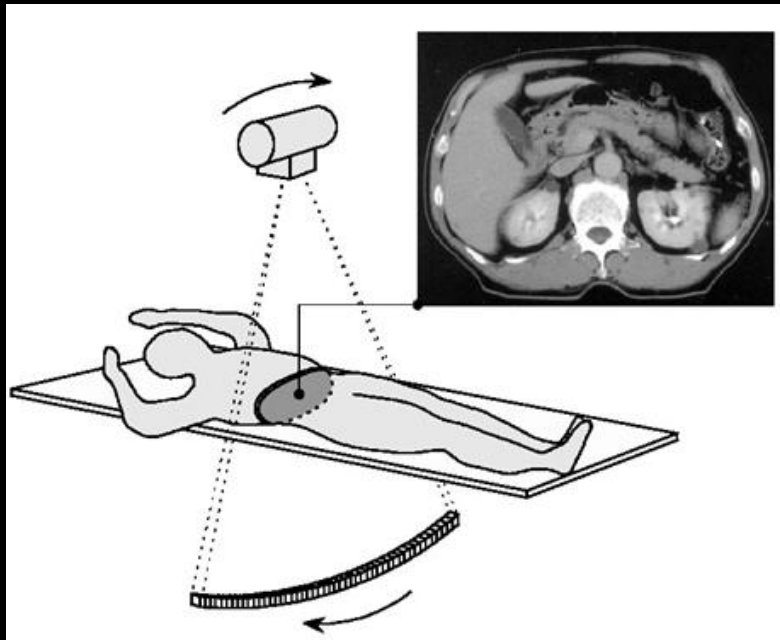


Food inspection

# CT or CAT in the hospital

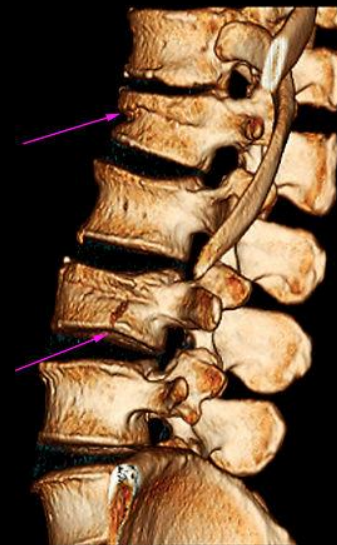
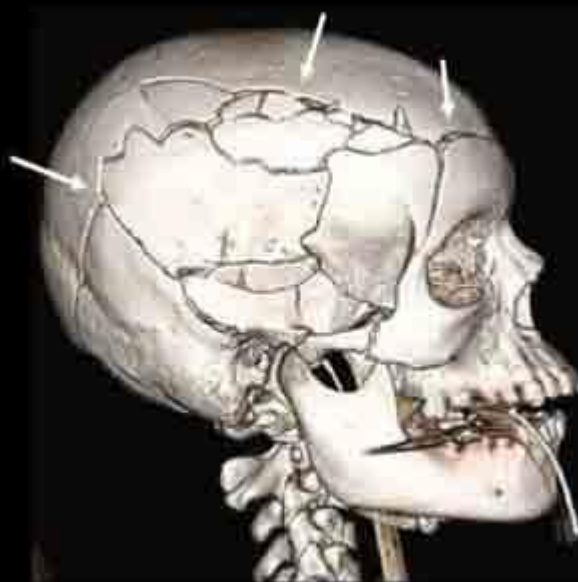
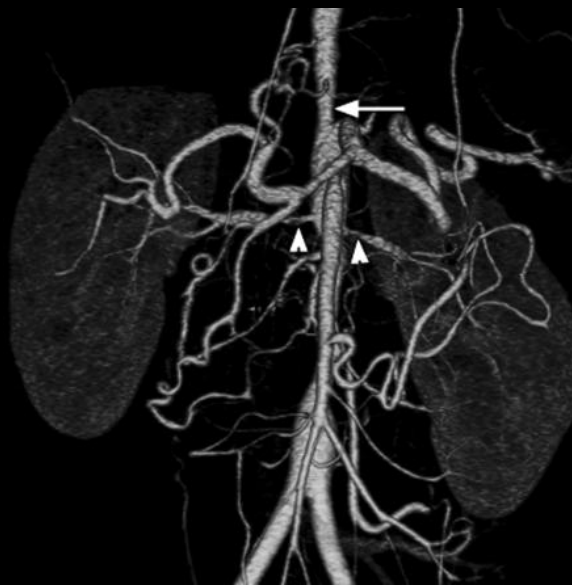








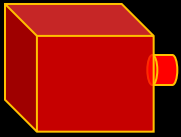
Aquilion



SCIENCEPHOTOLIBRARY

# 2D Imaging

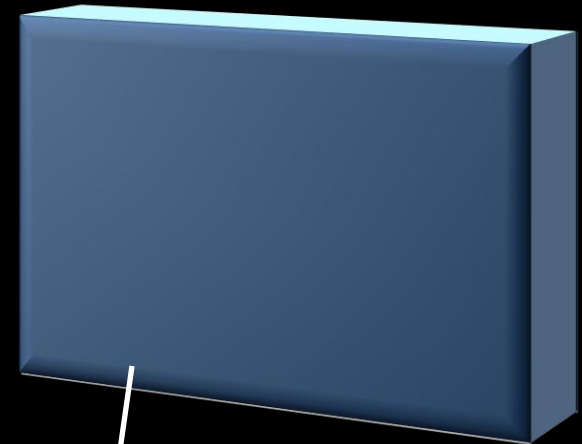
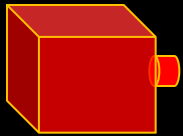
X-Ray source





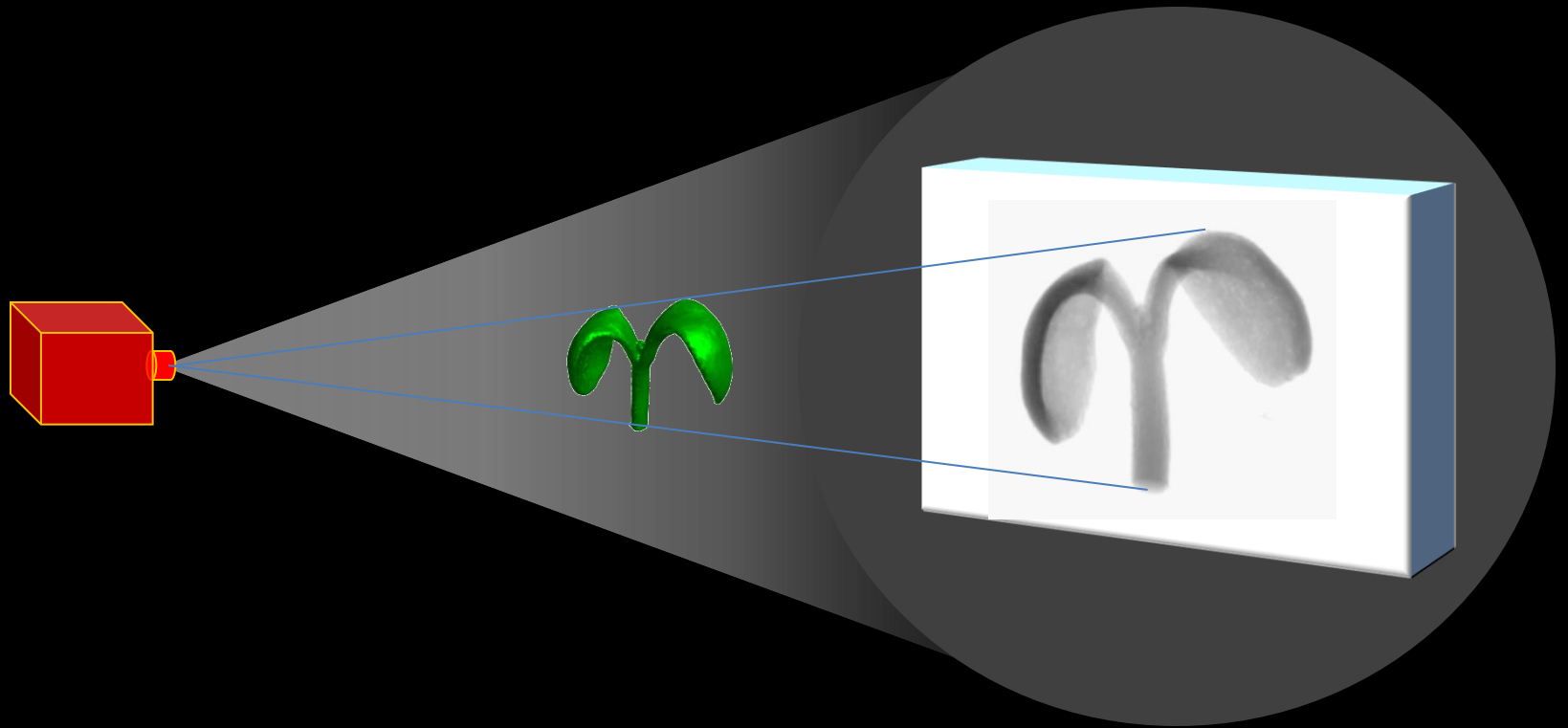
# 2D Imaging

X-Ray source



2D pixellated digital X-ray  
detector

# 2D Imaging

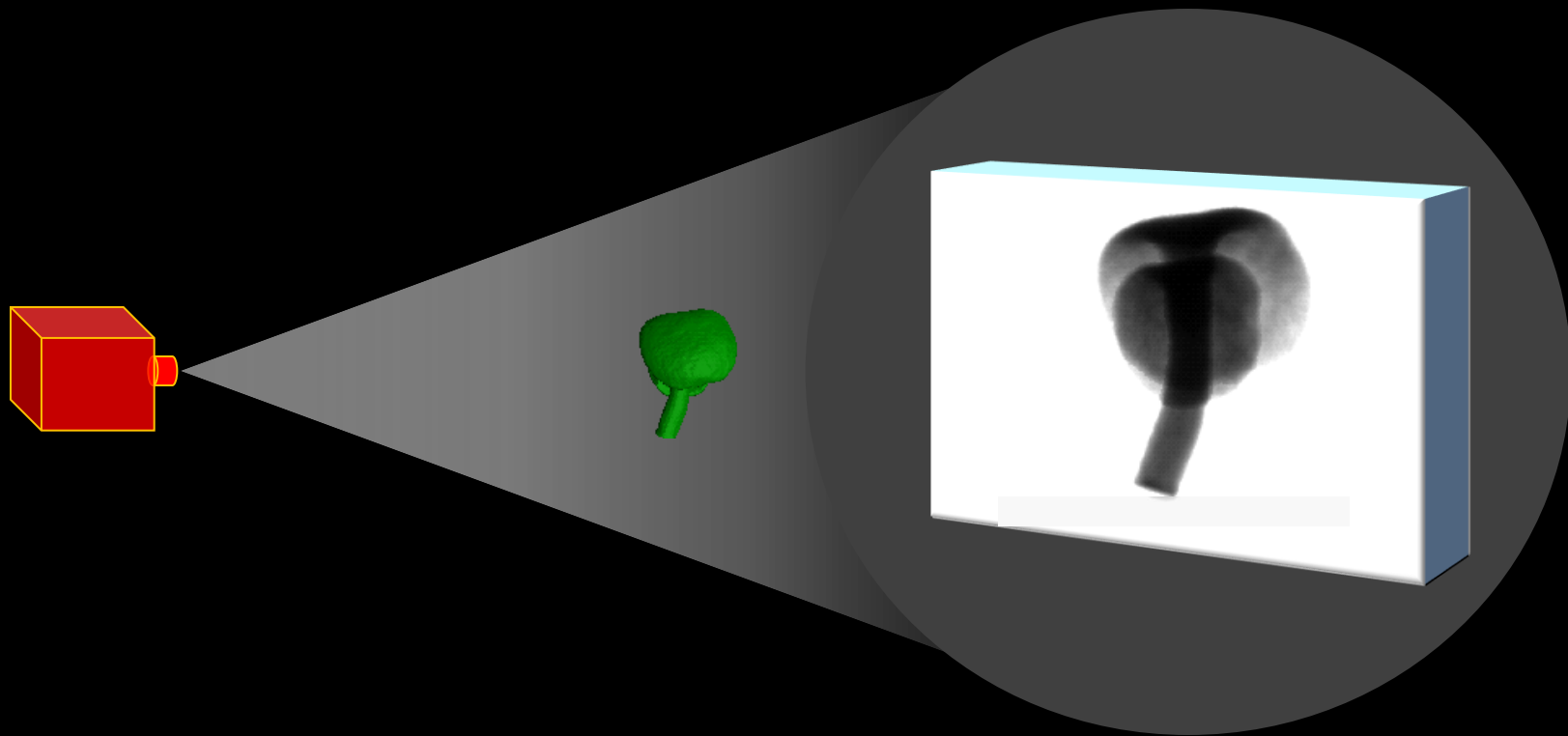


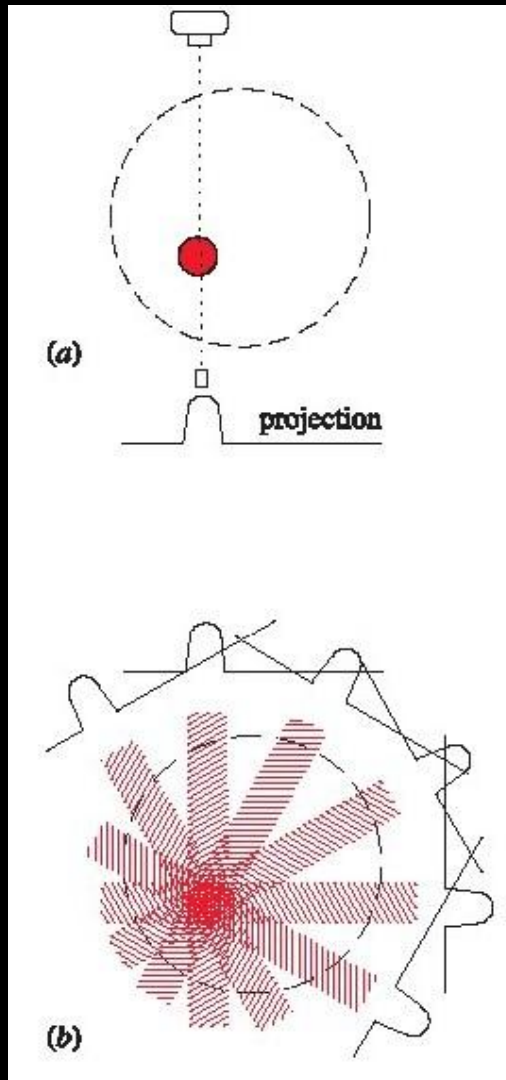
# Principle of X-ray Computed Tomography

Tomography is imaging using sections.

X-rays and computations are used to obtain cross-sections

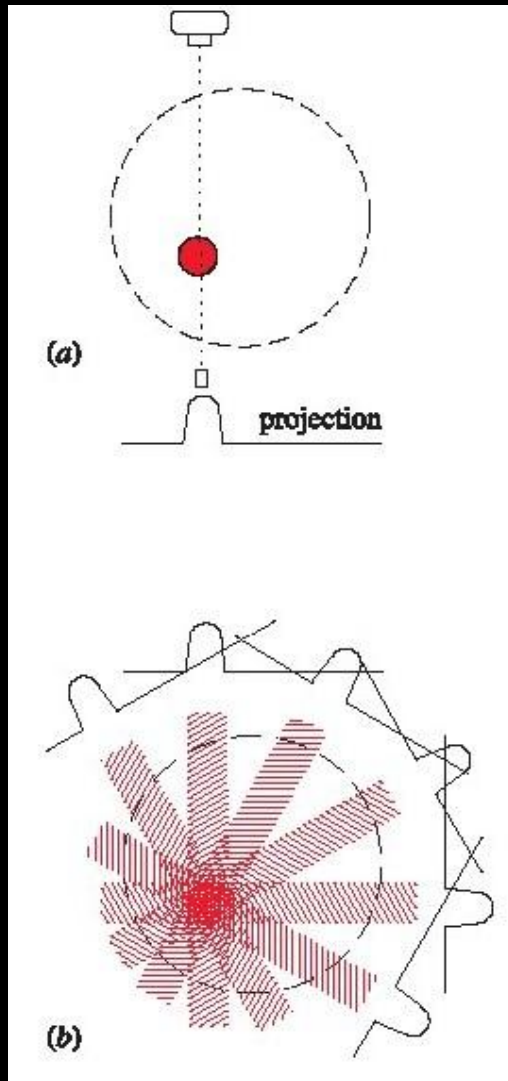
# 3D Imaging



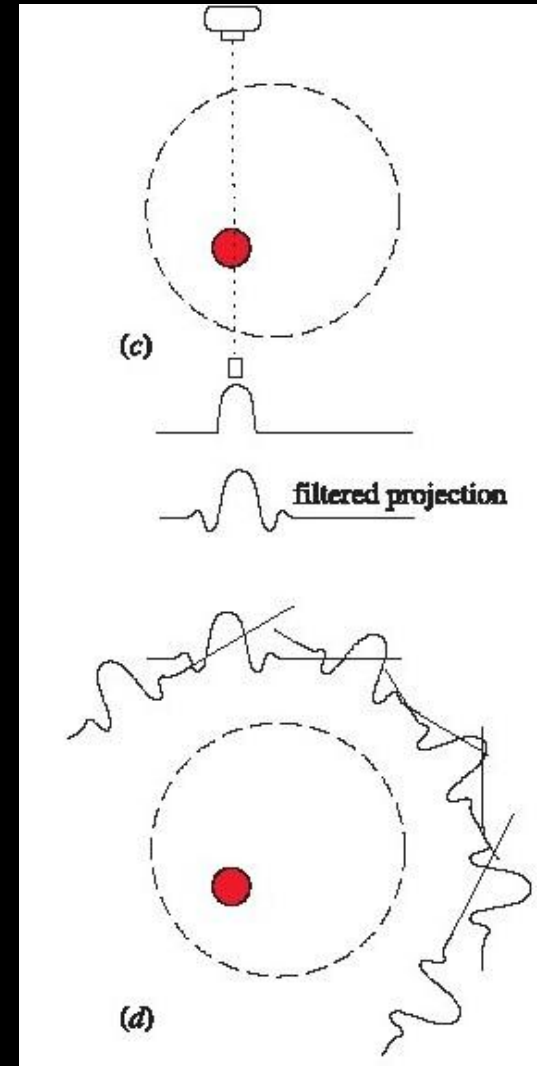


Back-projection



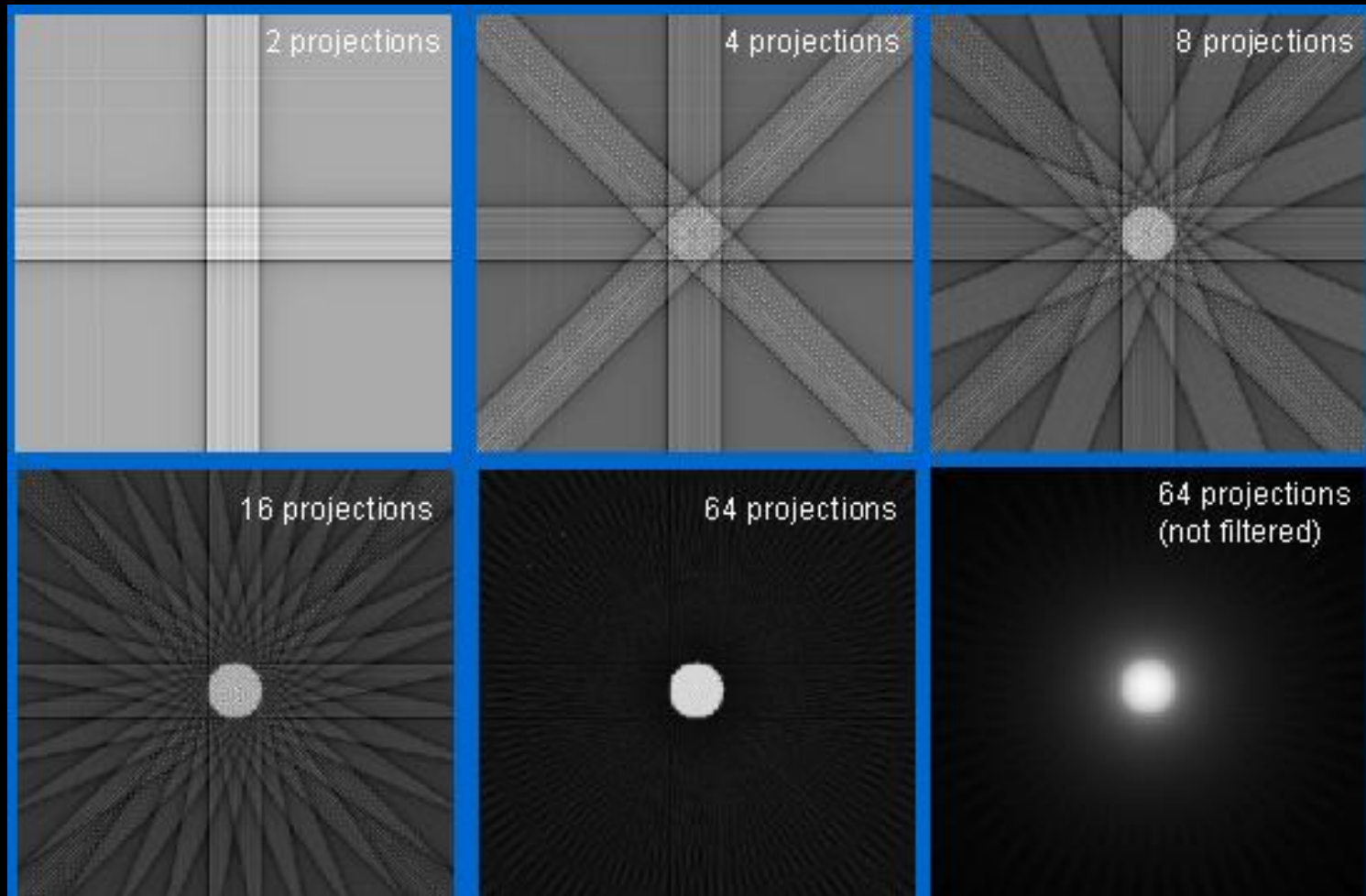


Back-projection

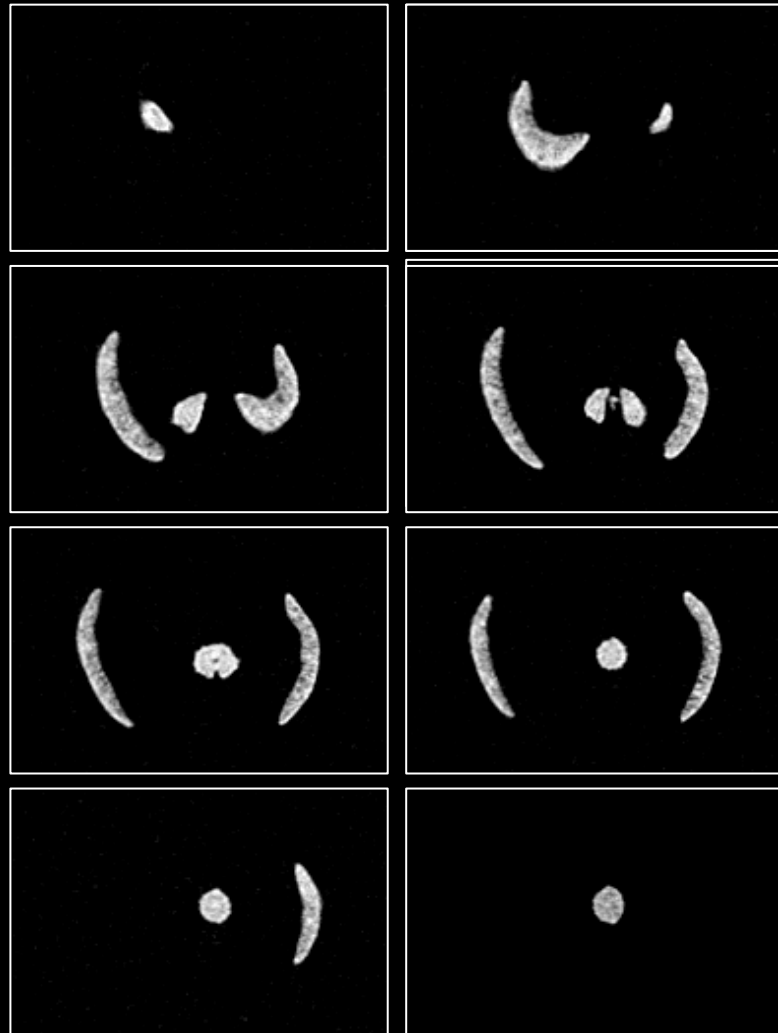
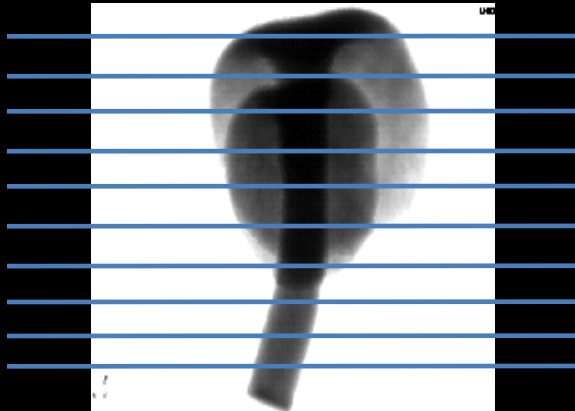


Filtered Back-projection

The more angles were recorded, the  
better the result



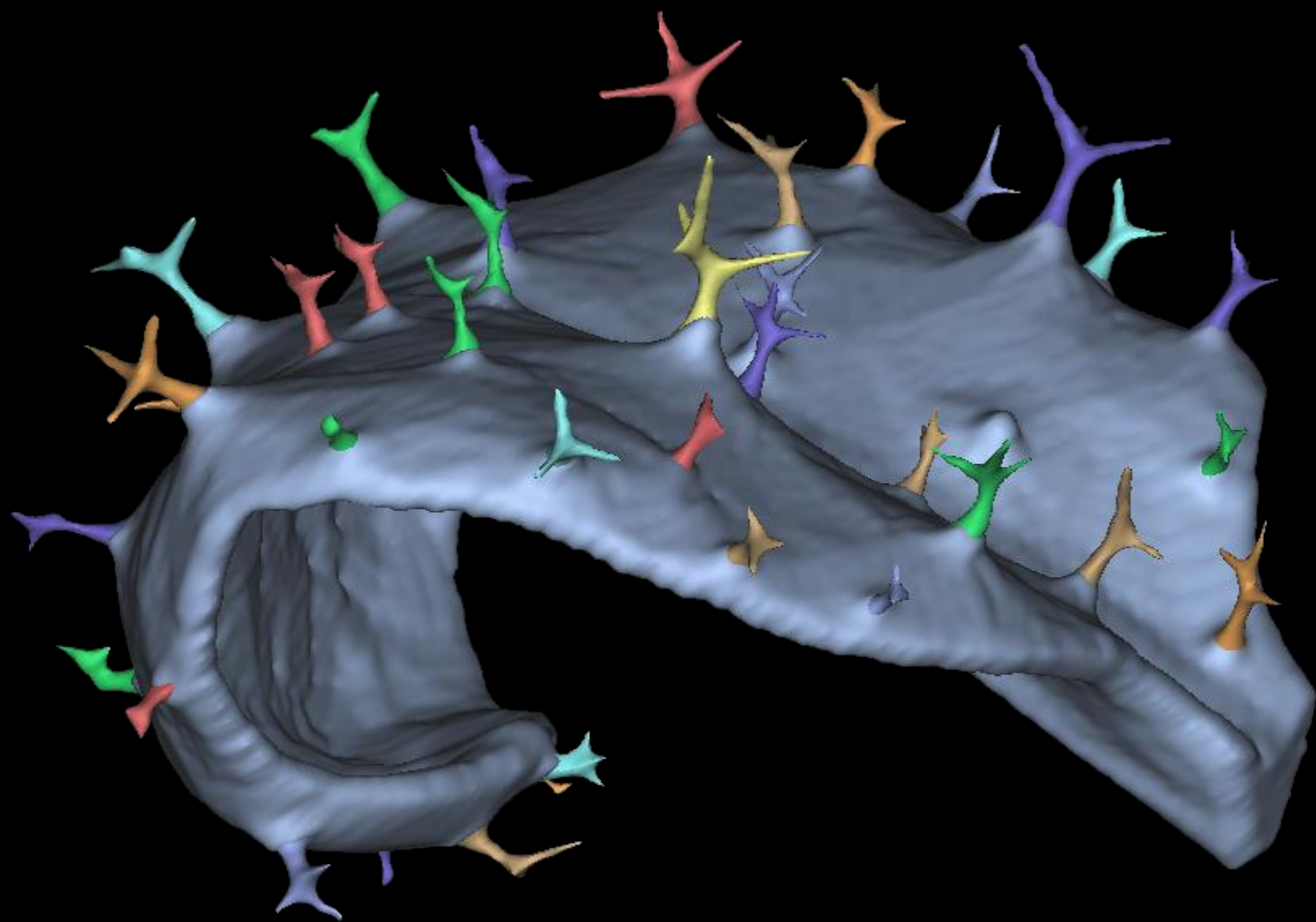
# Tomographic reconstruction

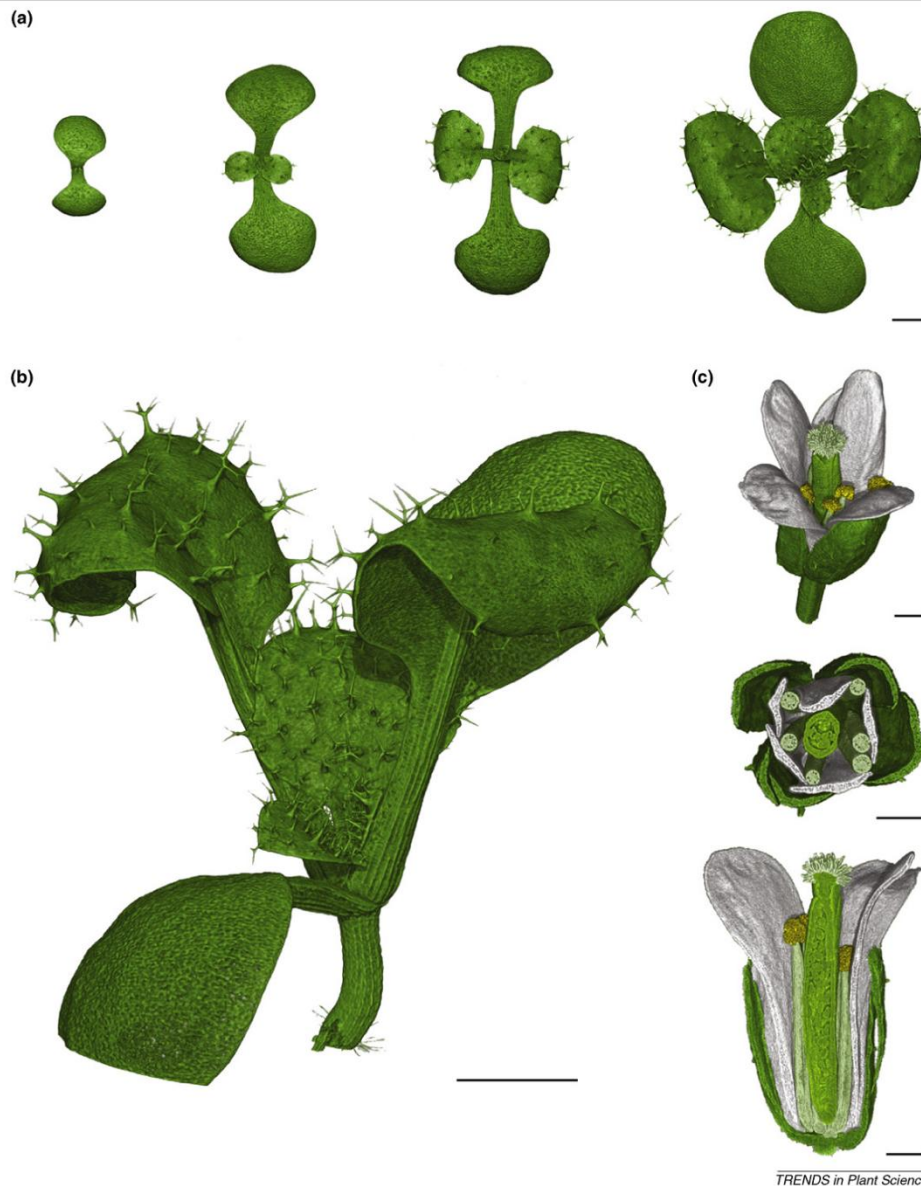




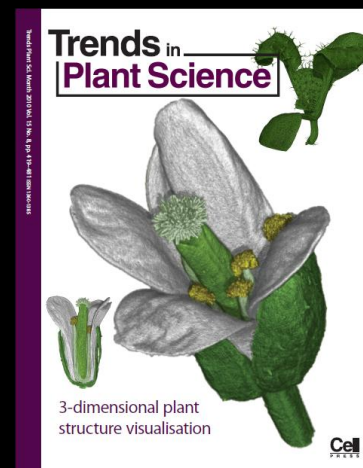
External morphology

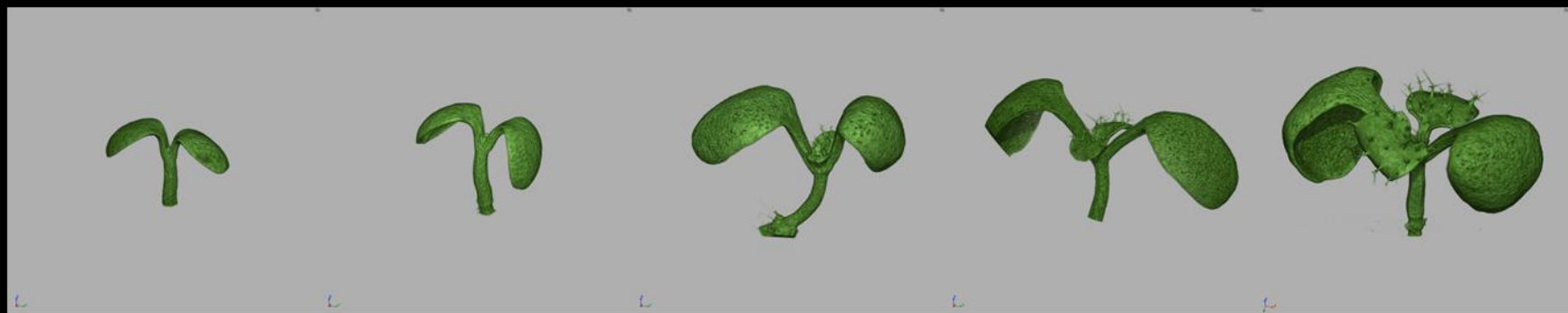
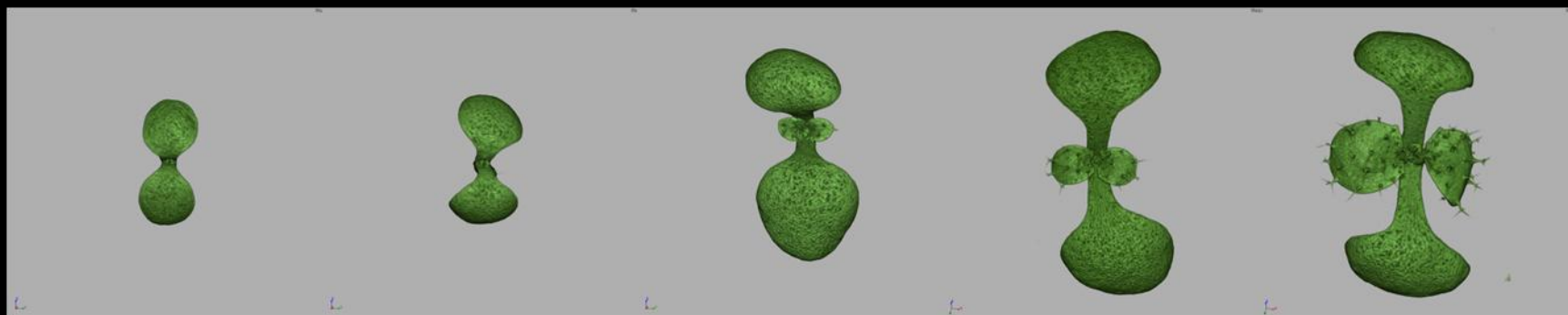


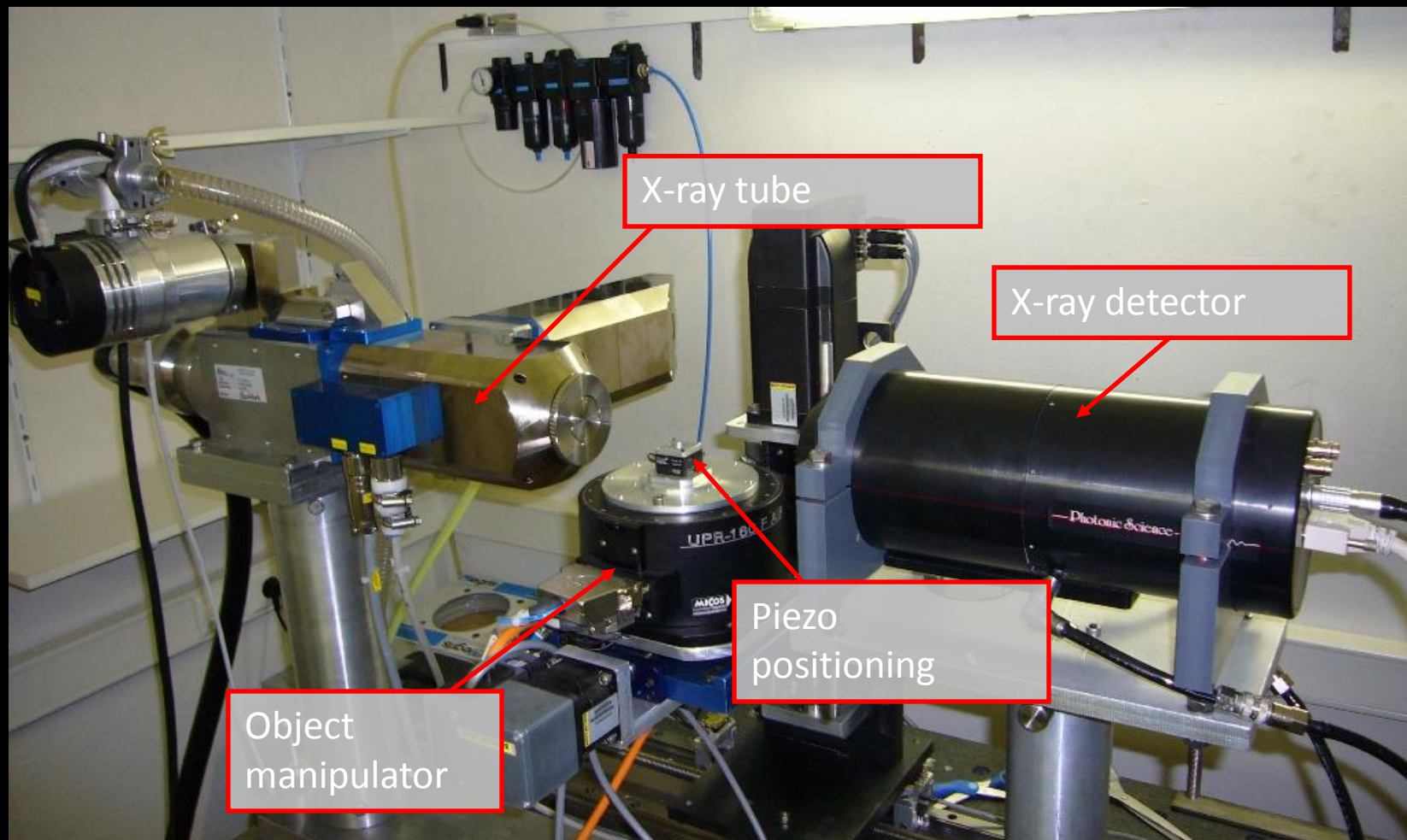




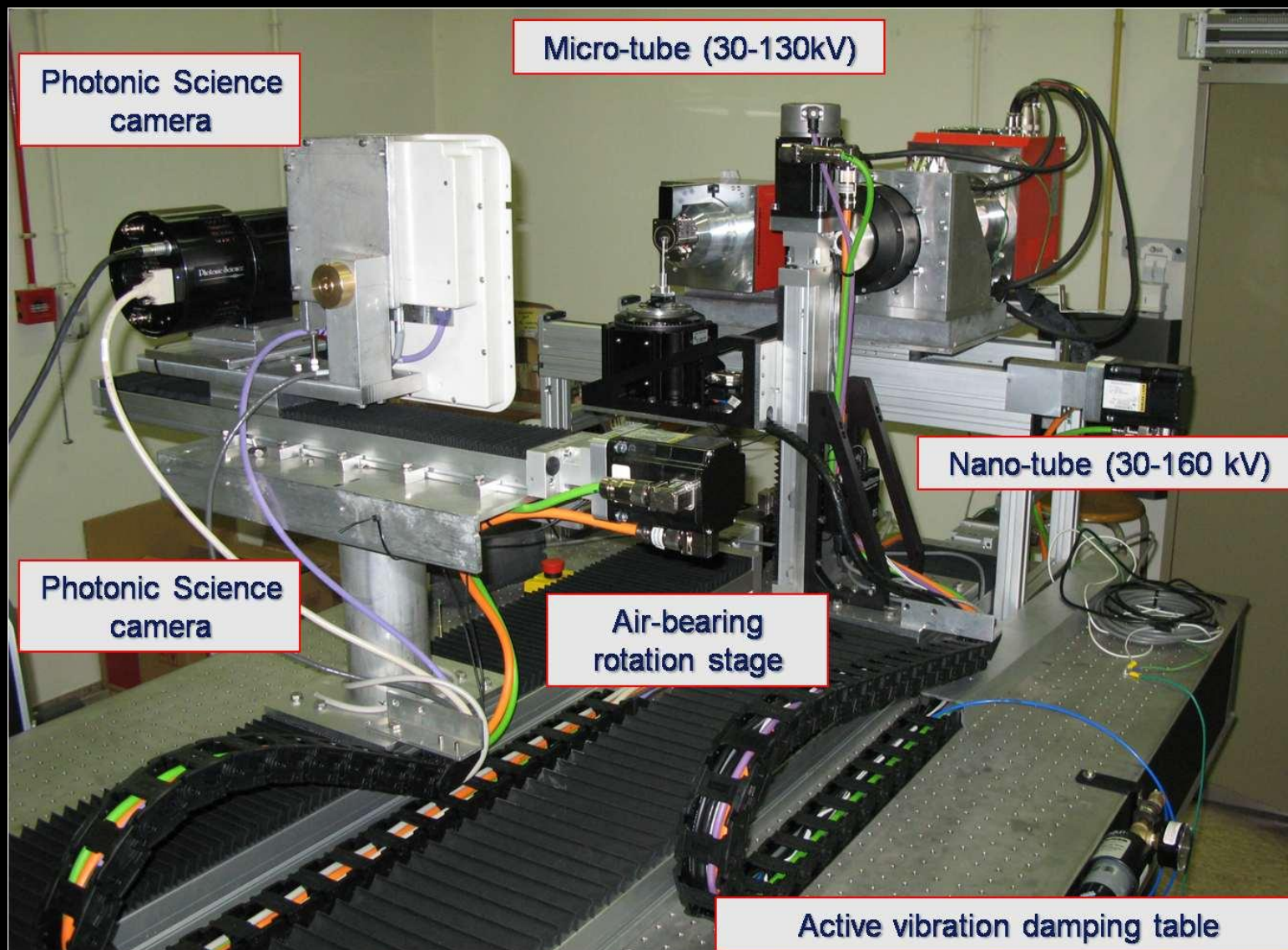
**Figure 1.** *In vivo* HRXCT scanning of an *Arabidopsis* Col-0 shoot and flower. (a) Top view of different 3-D-reconstructed *Arabidopsis* seedlings at 7, 9, 11, and 13 d after sowing (DAS). Voxel size = 13.8  $\mu\text{m}$ . Bar = 1 mm. (b) Side view of an *Arabidopsis* seedling at 13 DAS. Voxel size = 8.8  $\mu\text{m}$ . Scale bar = 1 mm. (c) 3-D reconstruction of an *Arabidopsis* flower (side view, horizontal section, vertical section). Voxel size = 5  $\mu\text{m}$ . Scale bar = 0.5 mm. Scanning periods < 20 min.











Micro-tube (30-130kV)

Photonic Science camera

Nano-tube (30-160 kV)

Photonic Science camera

Air-bearing rotation stage

Active vibration damping table



# Plant sciences



CT slice and 3D visualization of orchids Matt Box

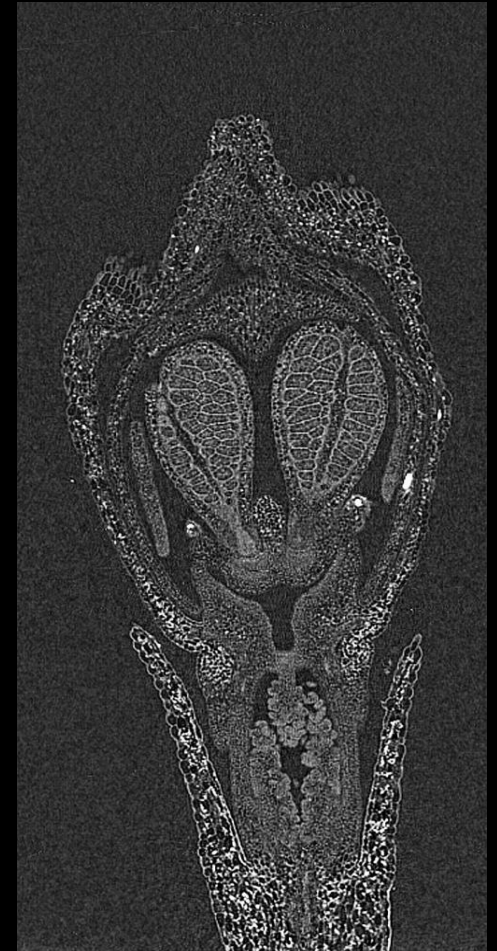
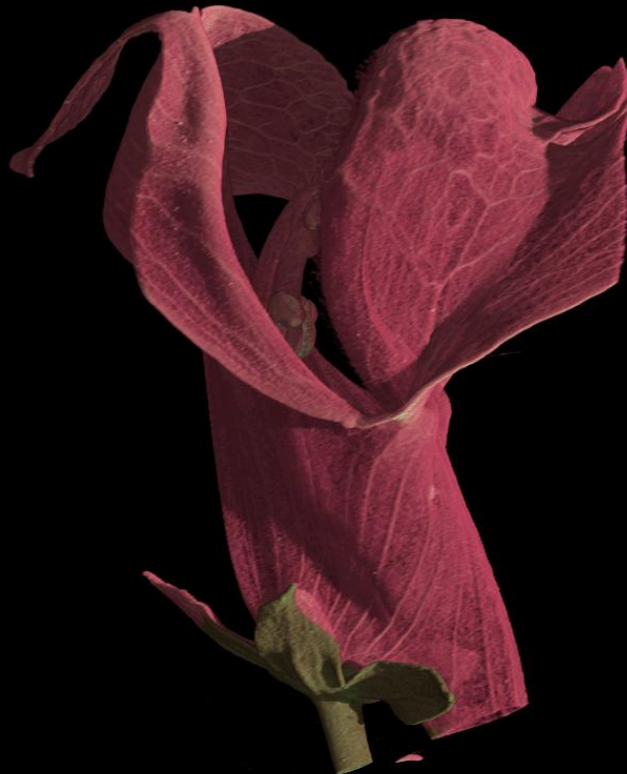


*Courtesy: University of Cambridge*

Internal morphology

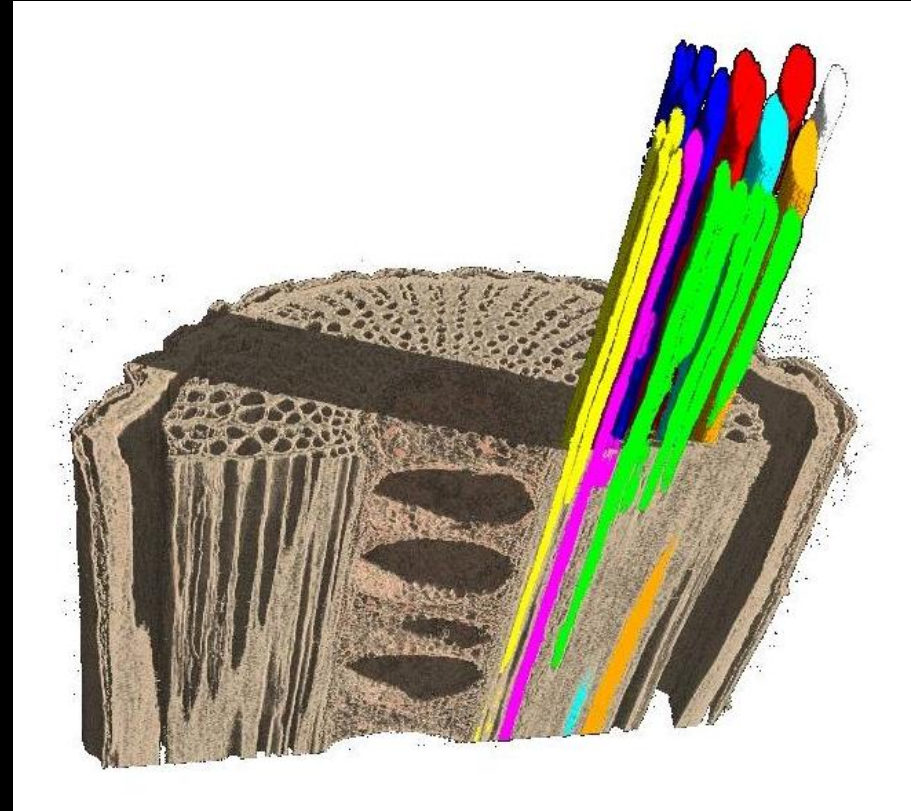
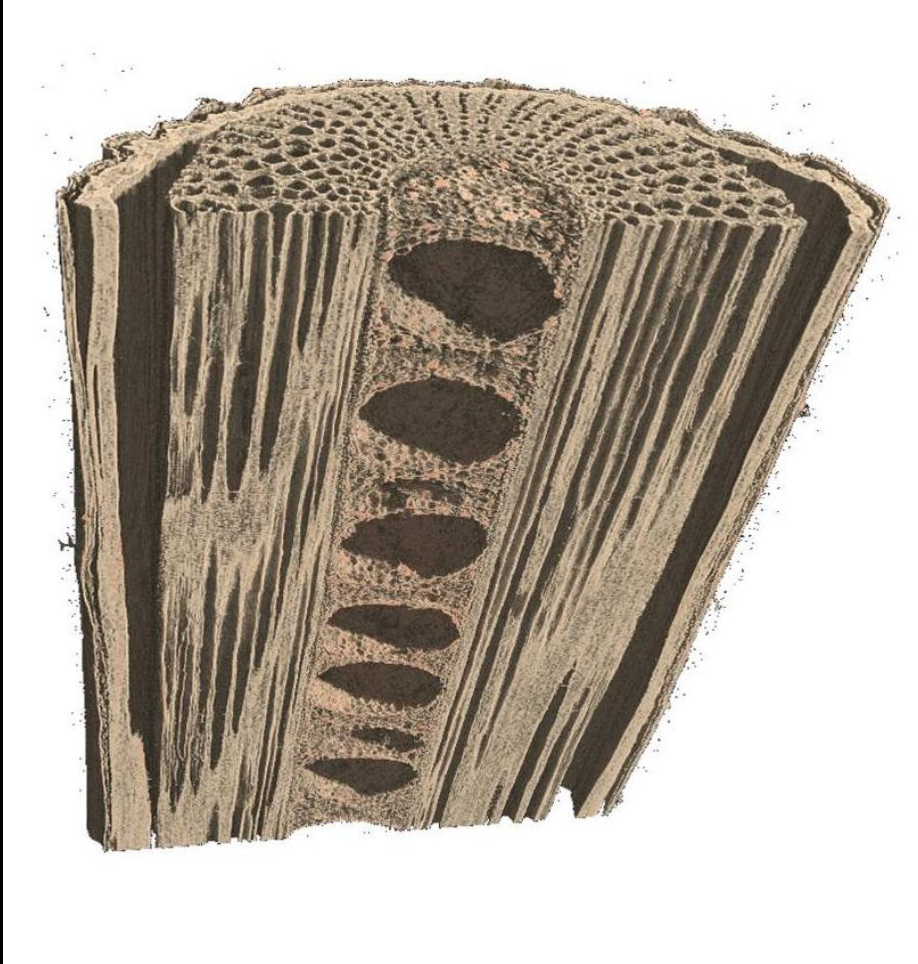
# Plant sciences

(c)



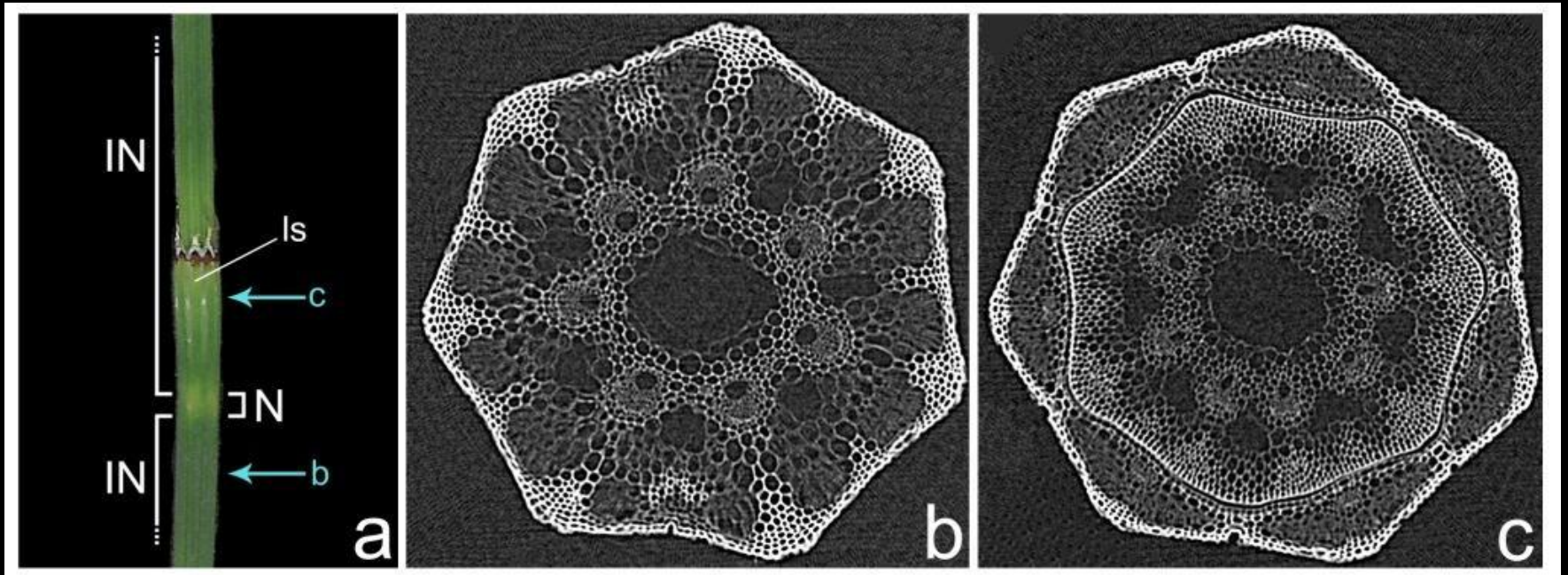


# Plant sciences



*Courtesy: Kew Gardens*

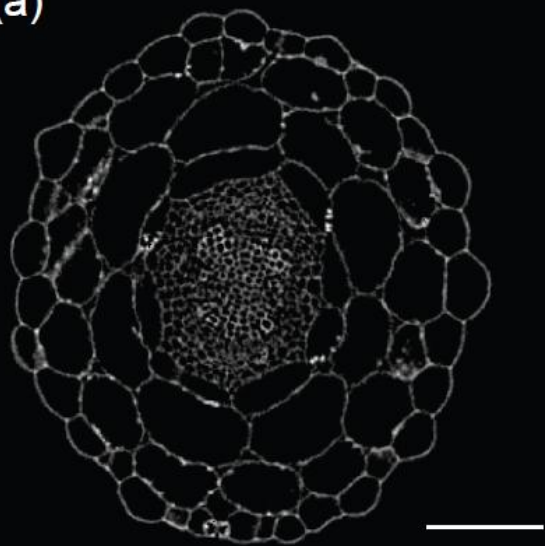
Analysis of wood pores



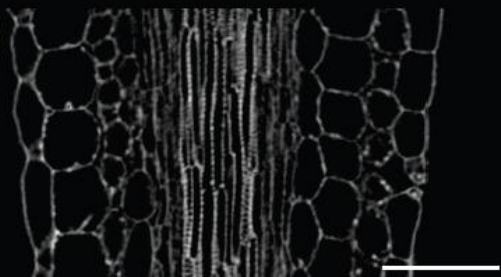
Equestum stem



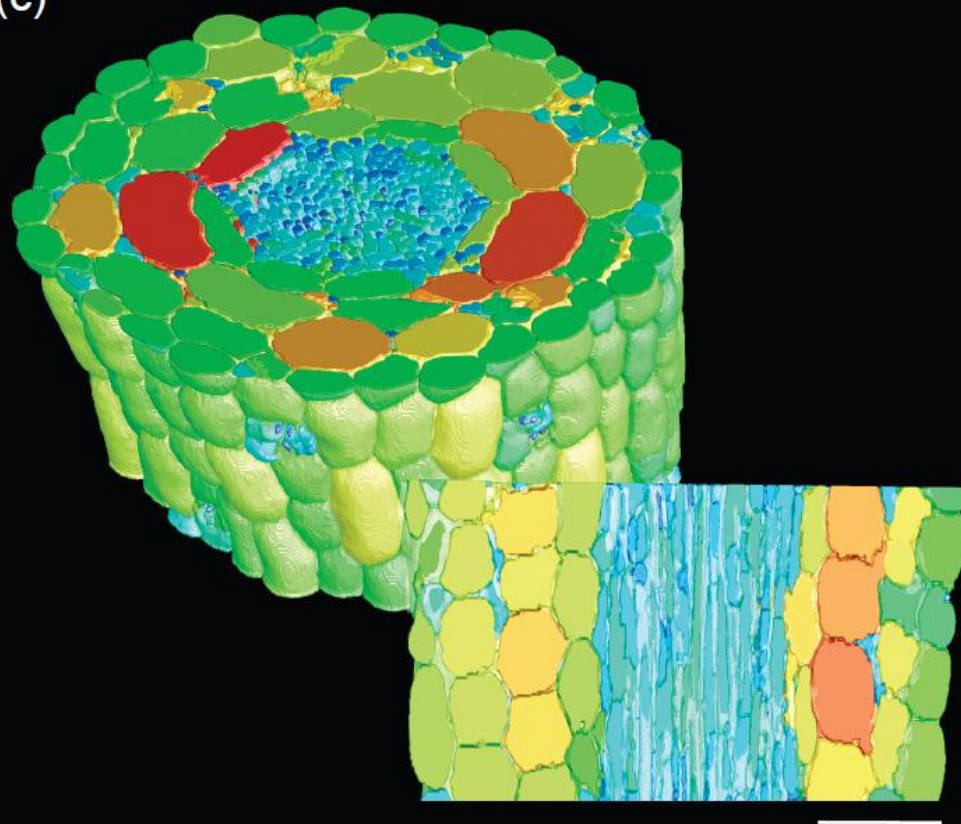
(a)

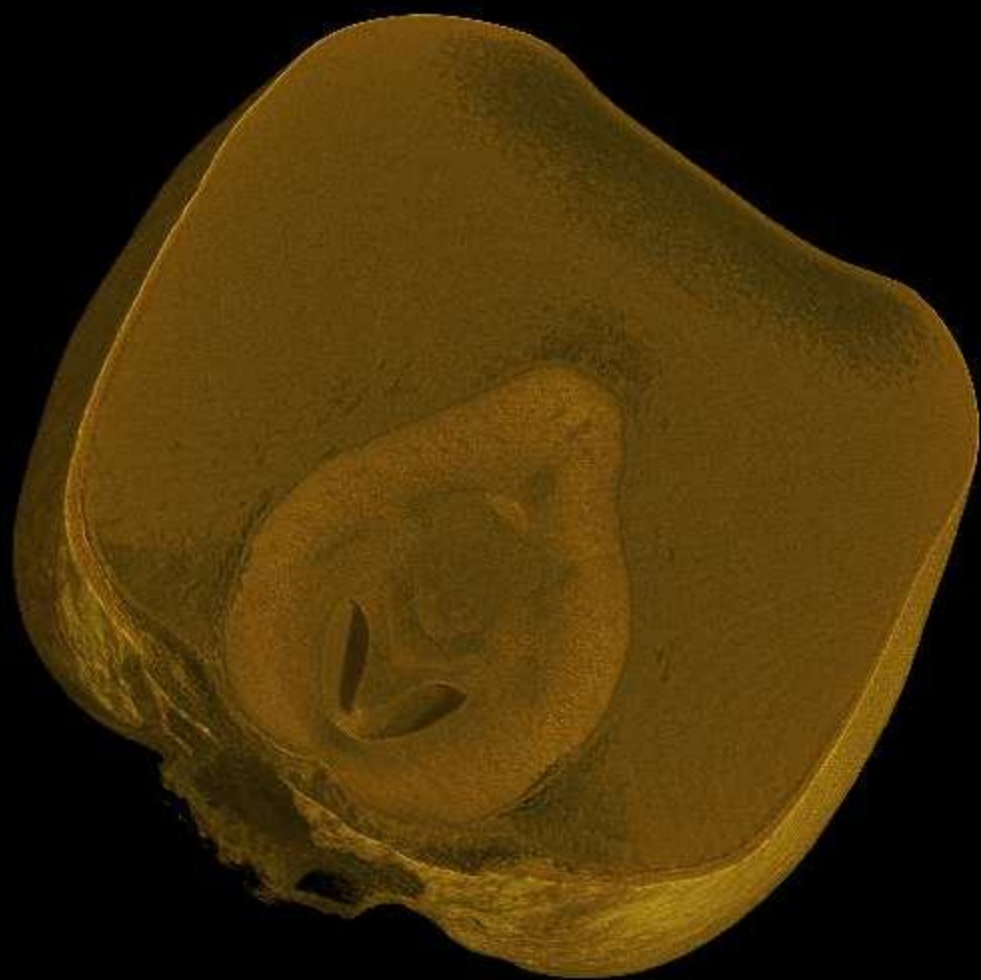


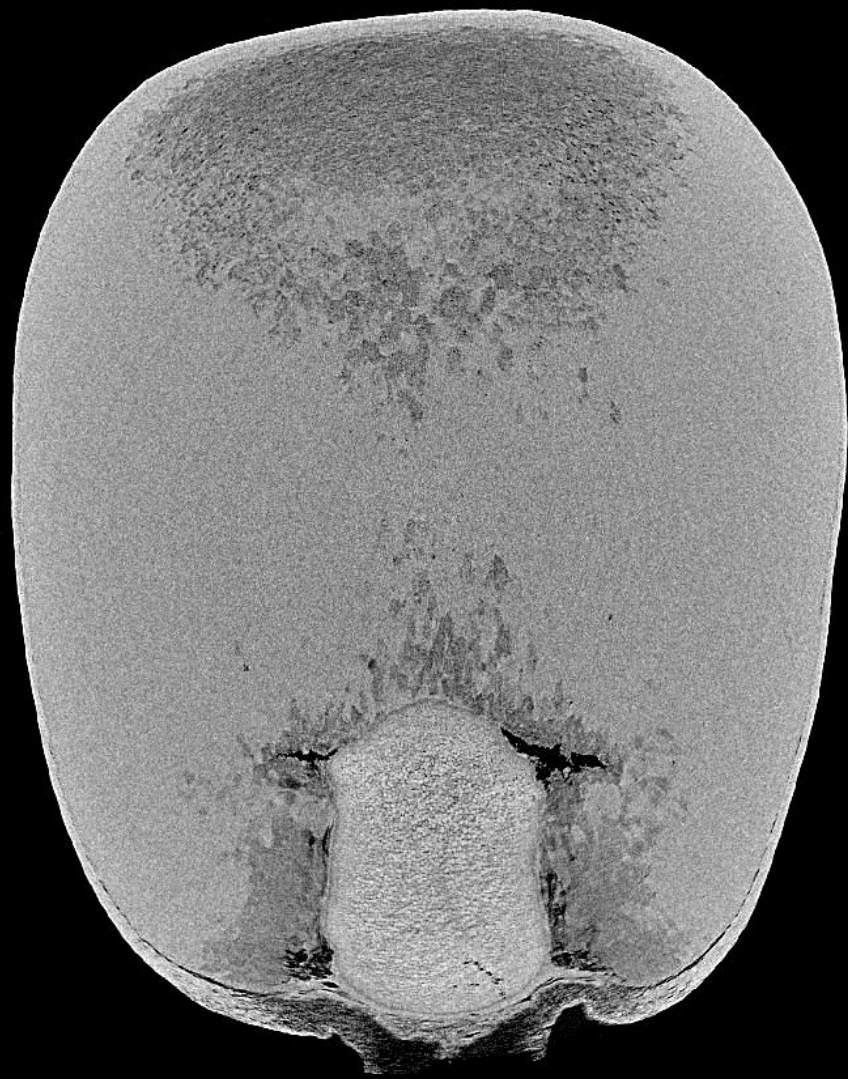
(b)

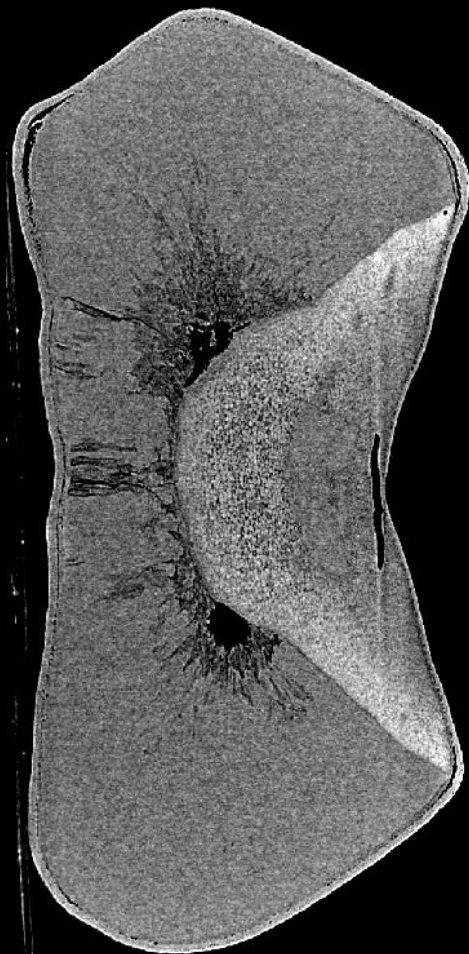
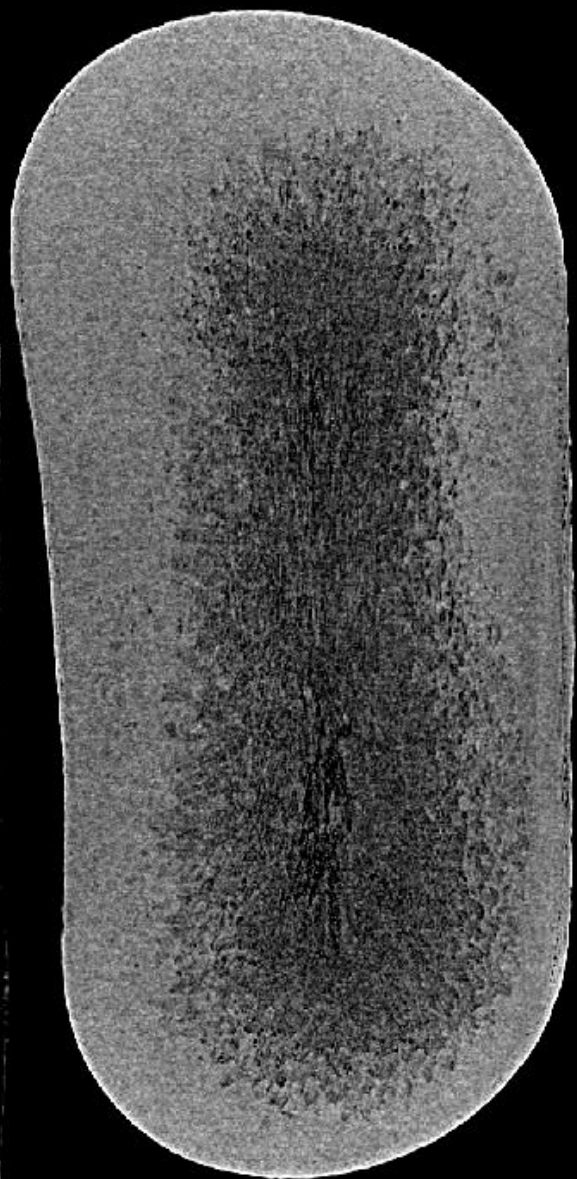


(c)



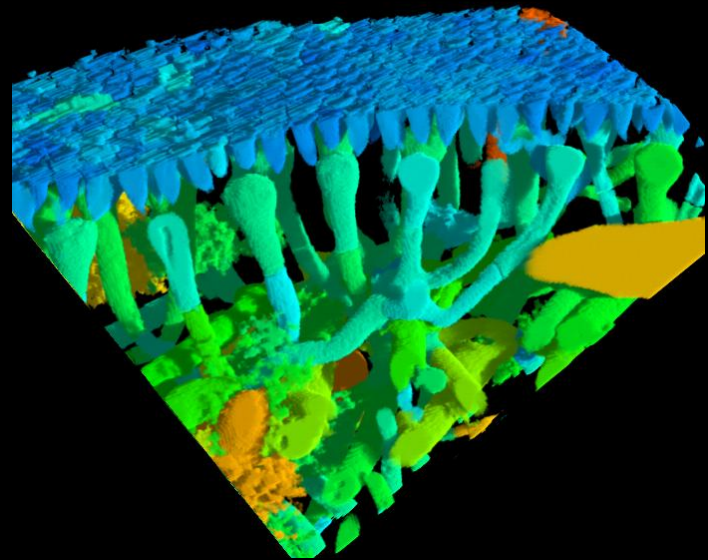
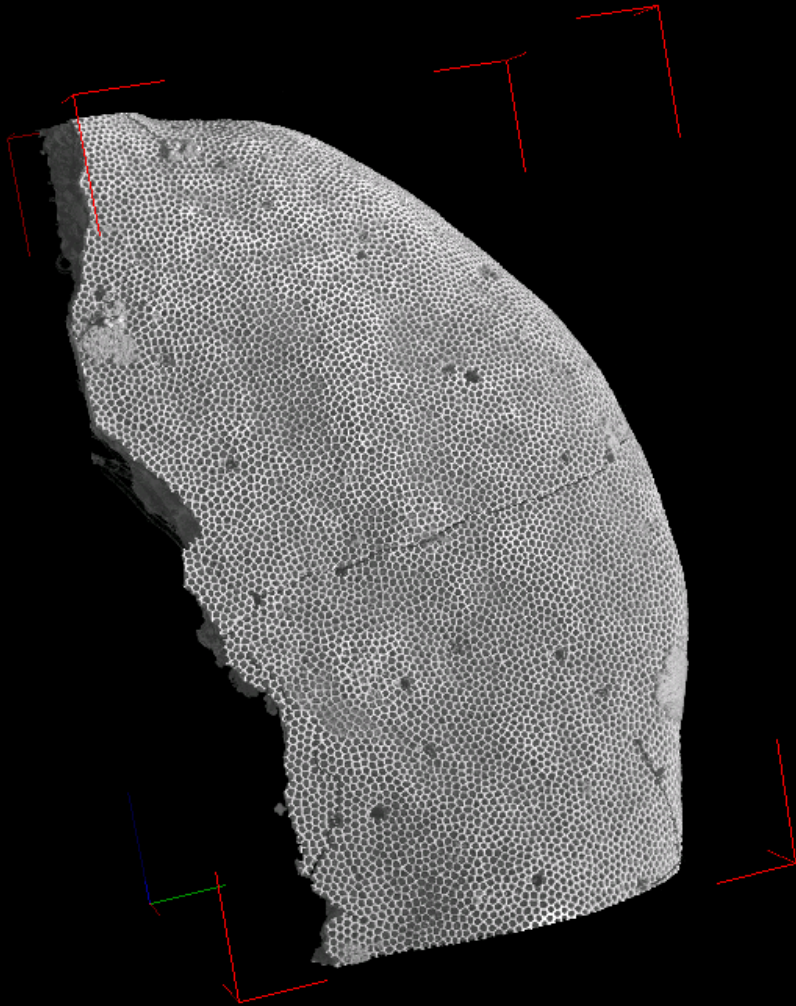








# Algae



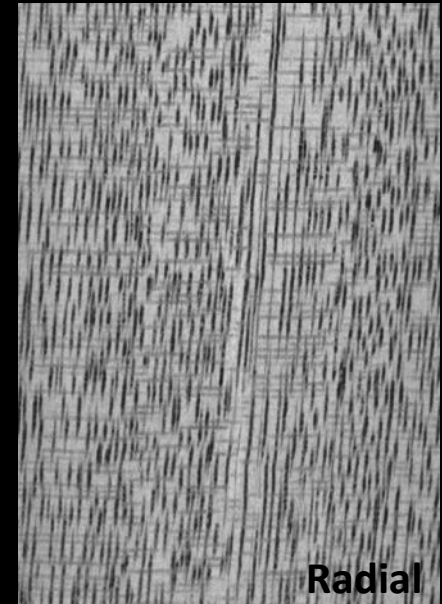
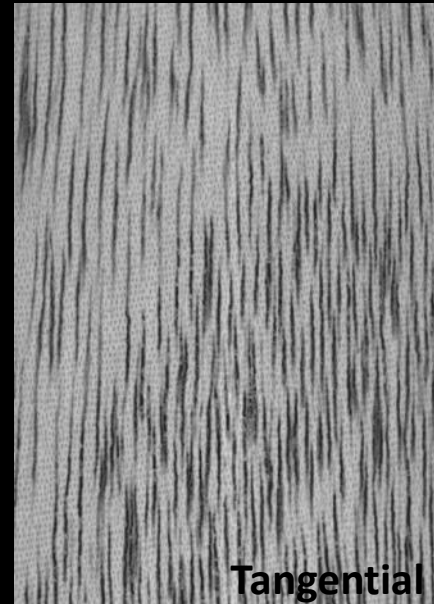
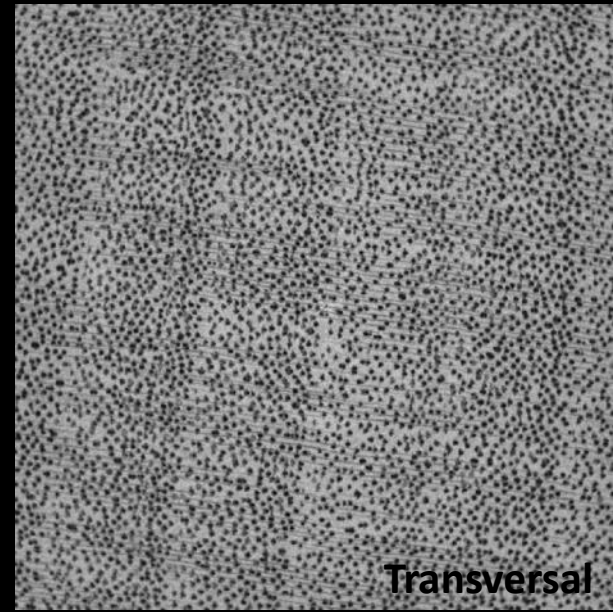
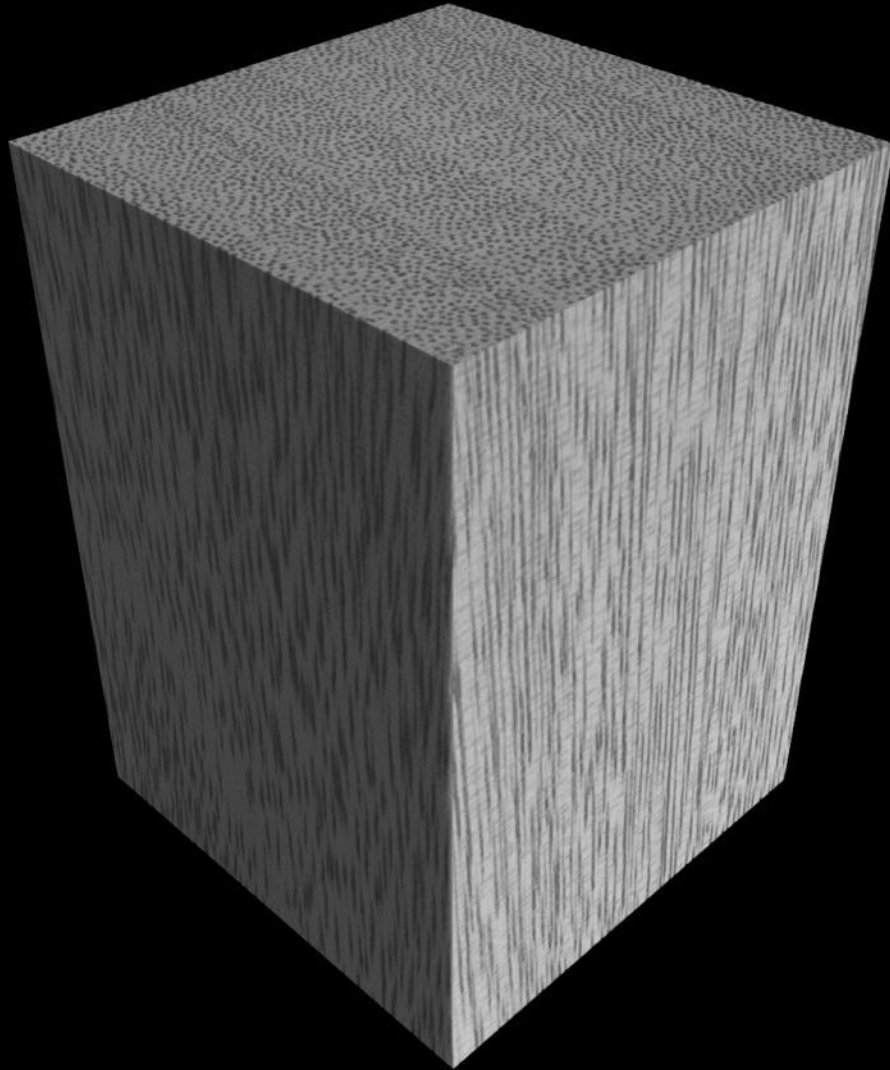
# Advantages

- Fylly 3D
- External and internal features
- Works with very complex structures
- Relatively fast
- Multiscale (from  $\mu\text{m}$  to m)

# Wood-technology

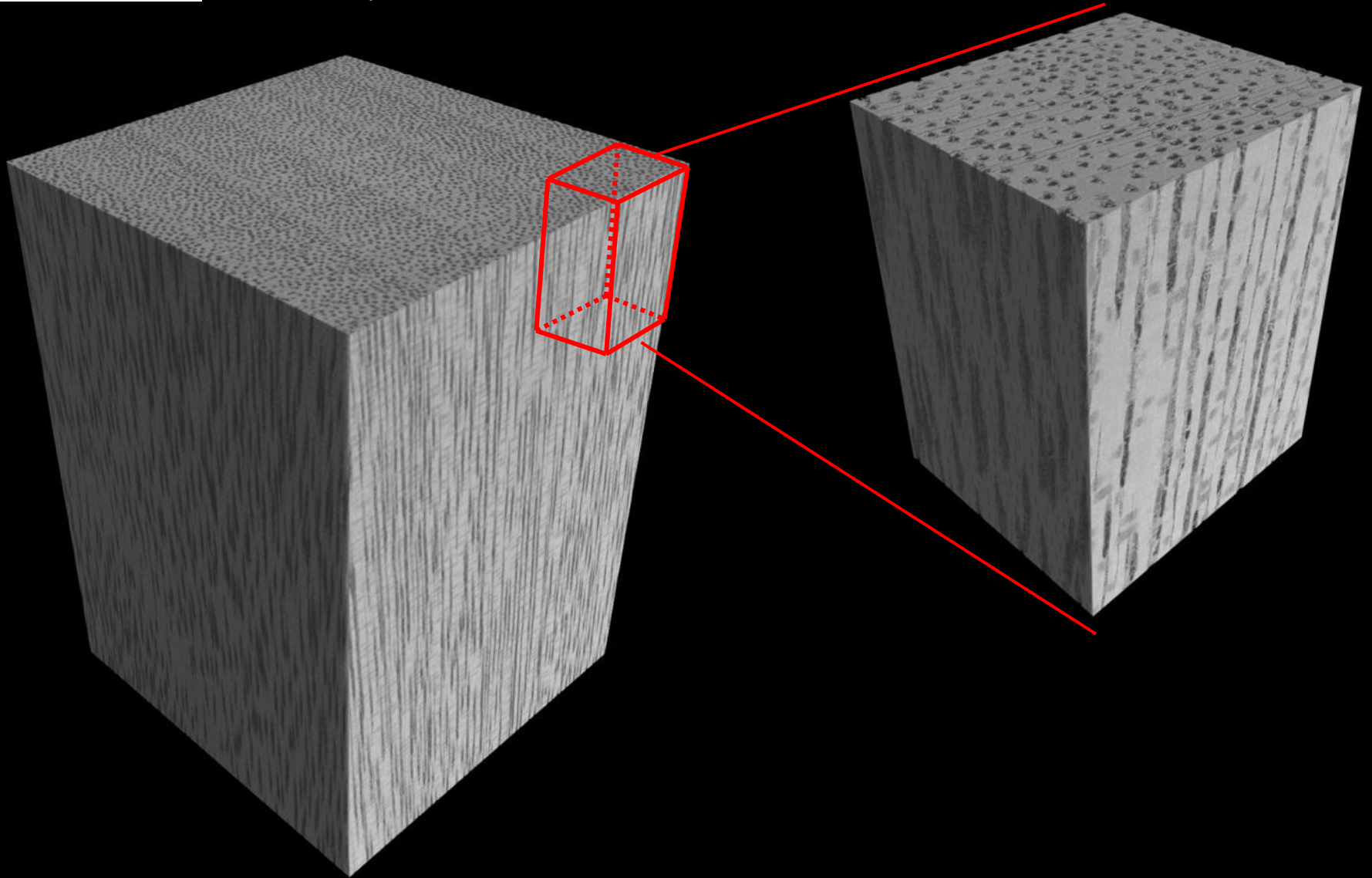


Macro – scan: 25 micron, cone-beam

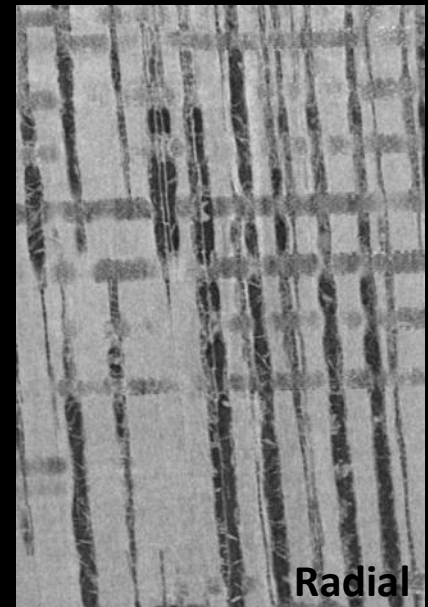
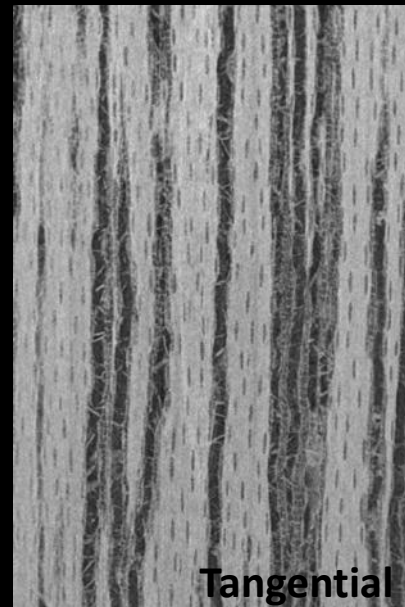
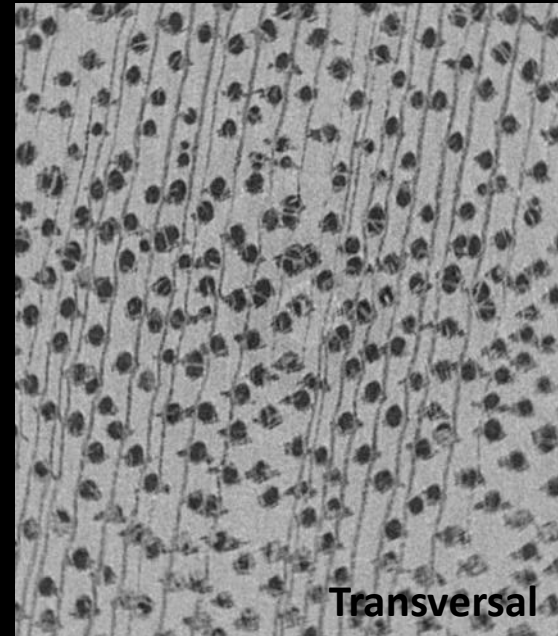
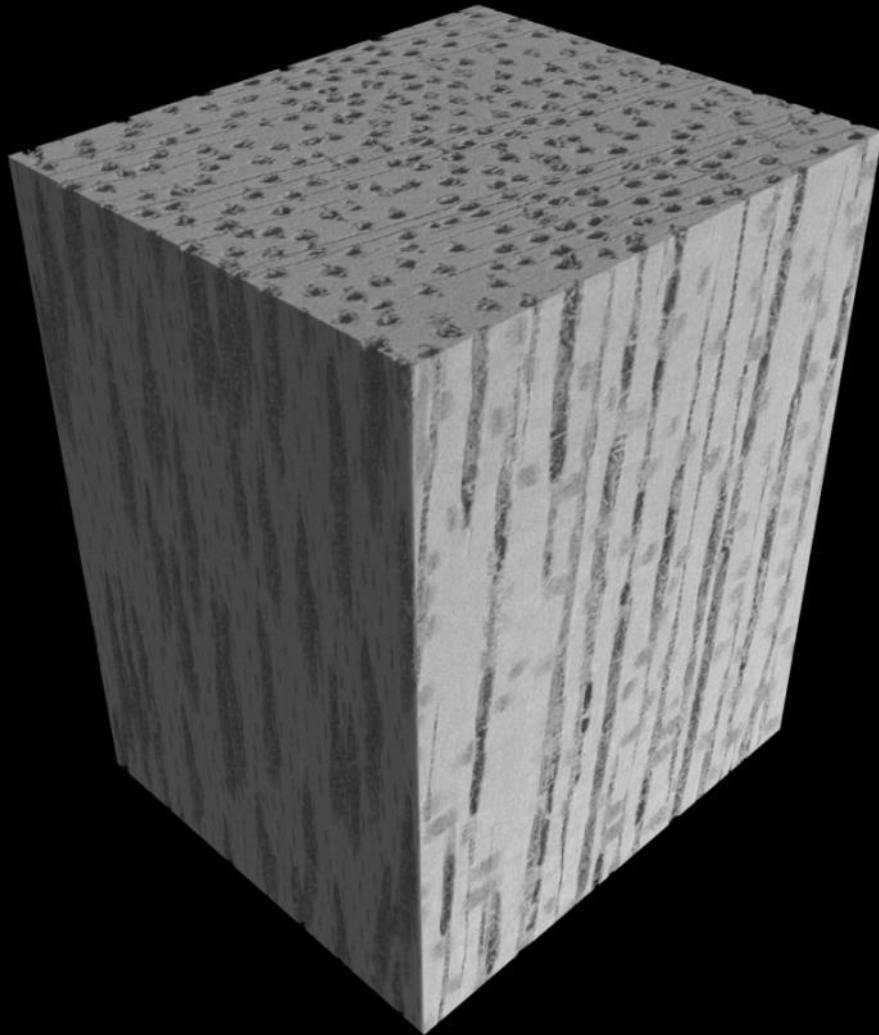




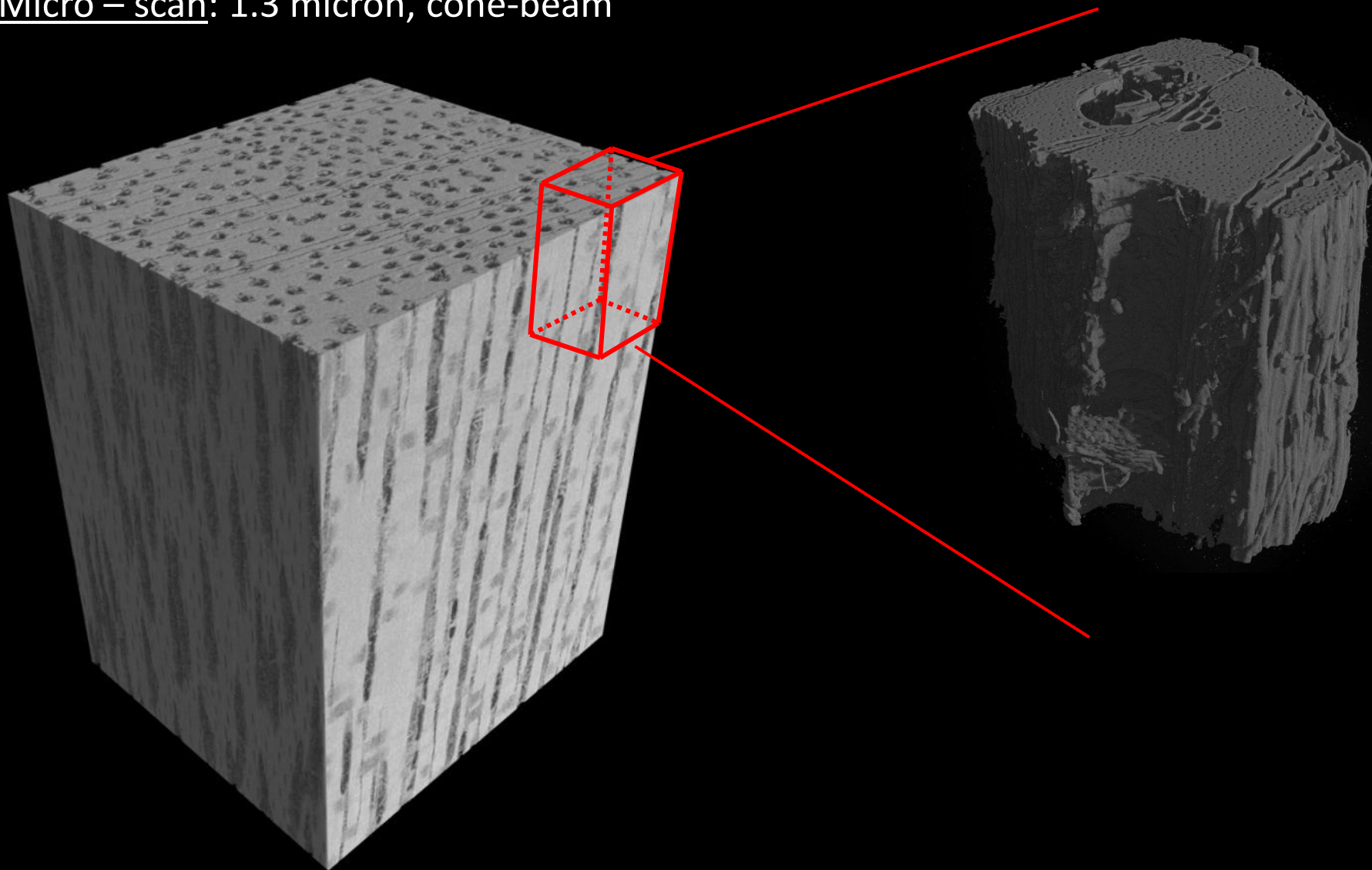
Micro – scan: 6 micron, cone-beam

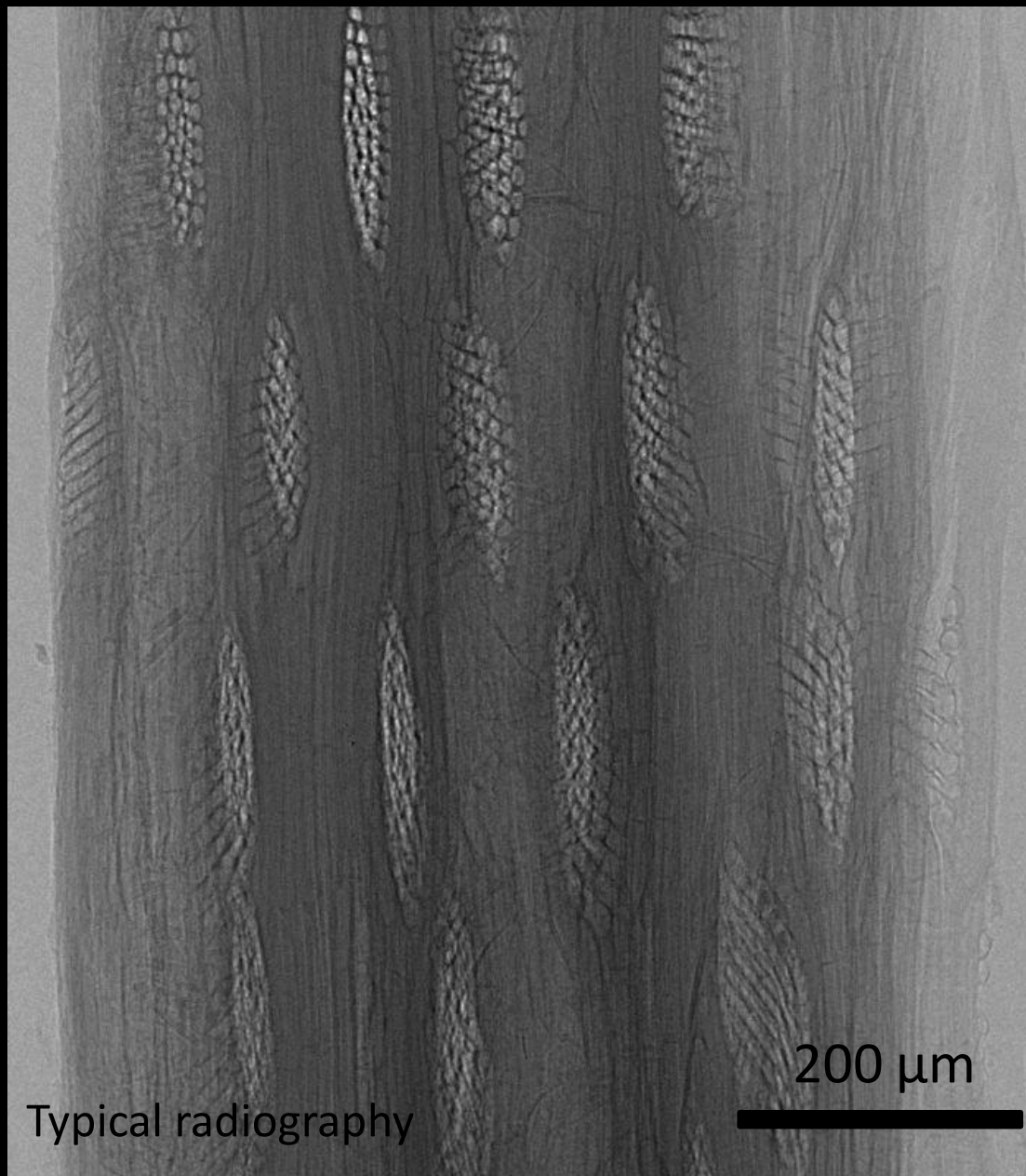


Micro – scan: 6 micron, cone-beam

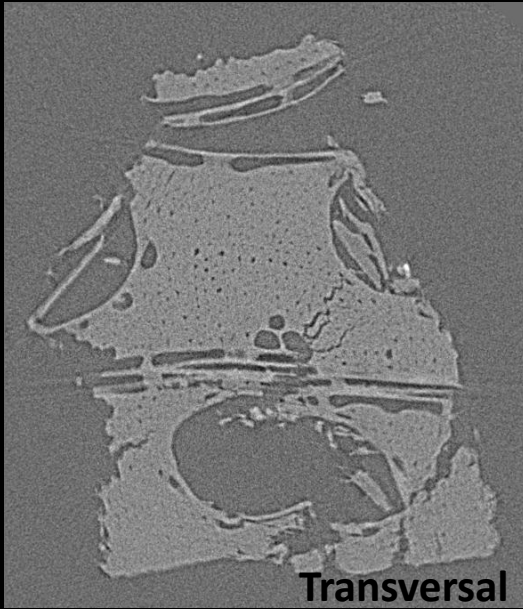


Micro – scan: 1.3 micron, cone-beam

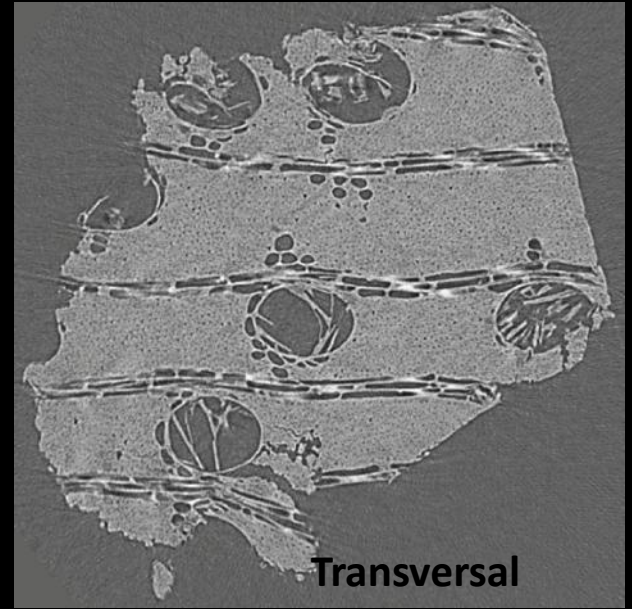




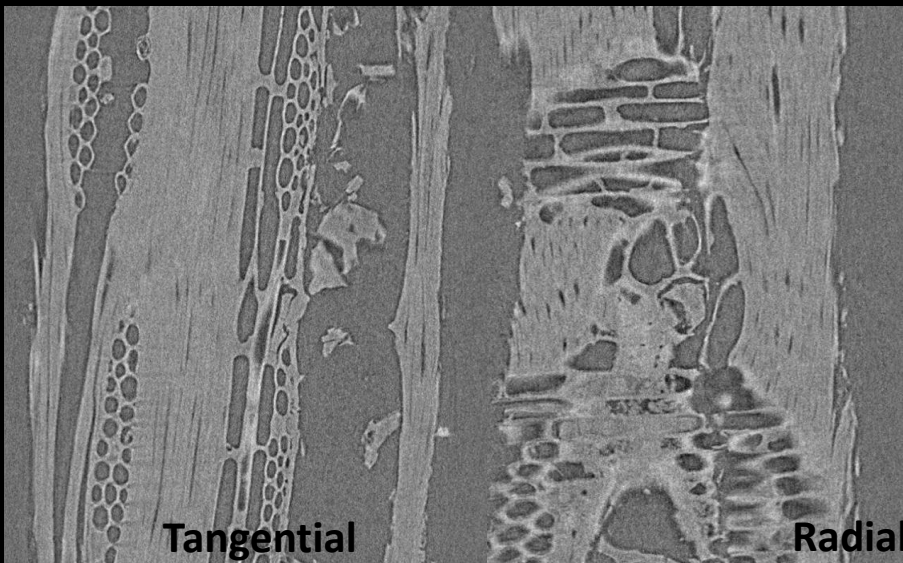




**Transversal**



**Transversal**



**Tangential**

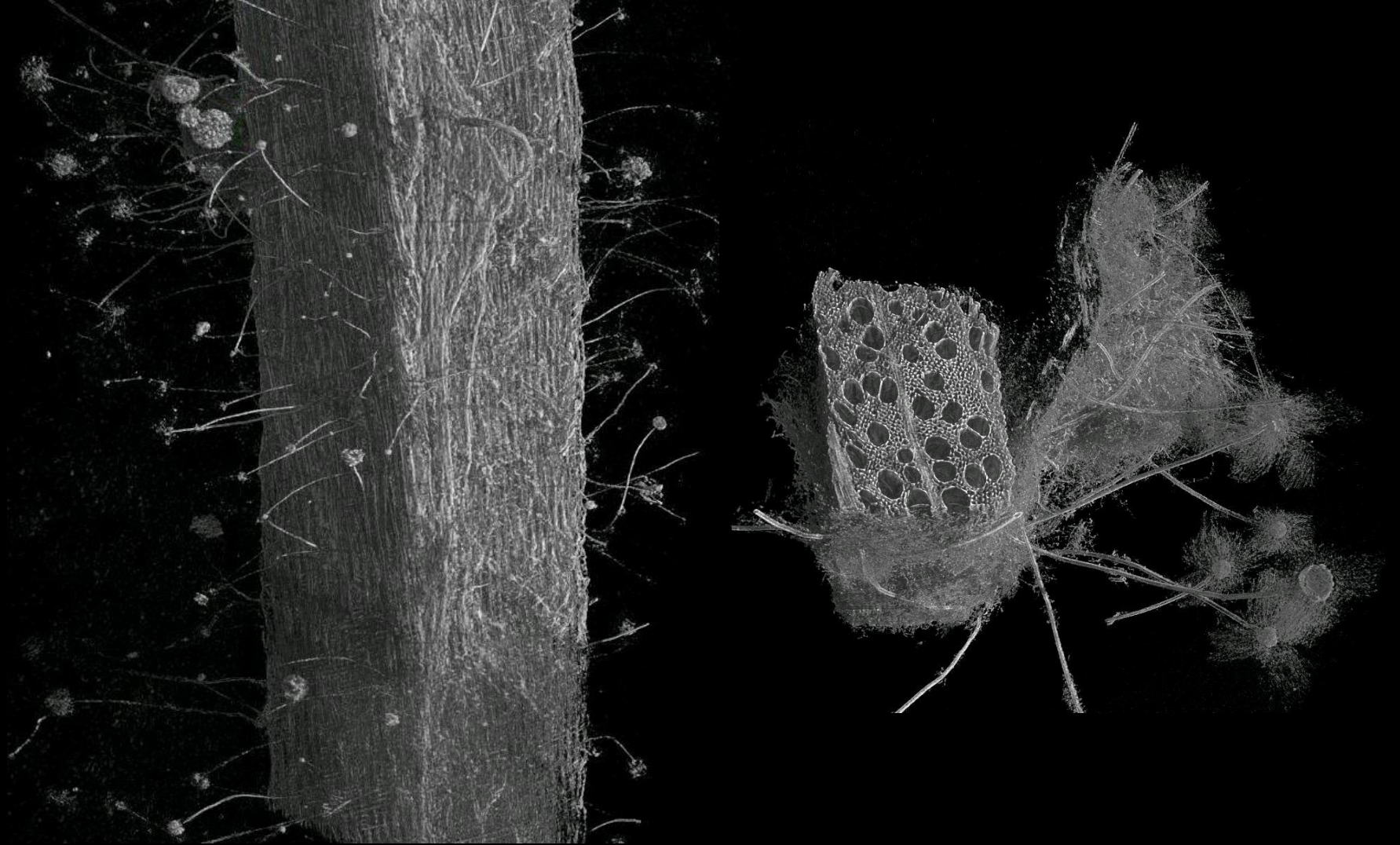
**Radial**



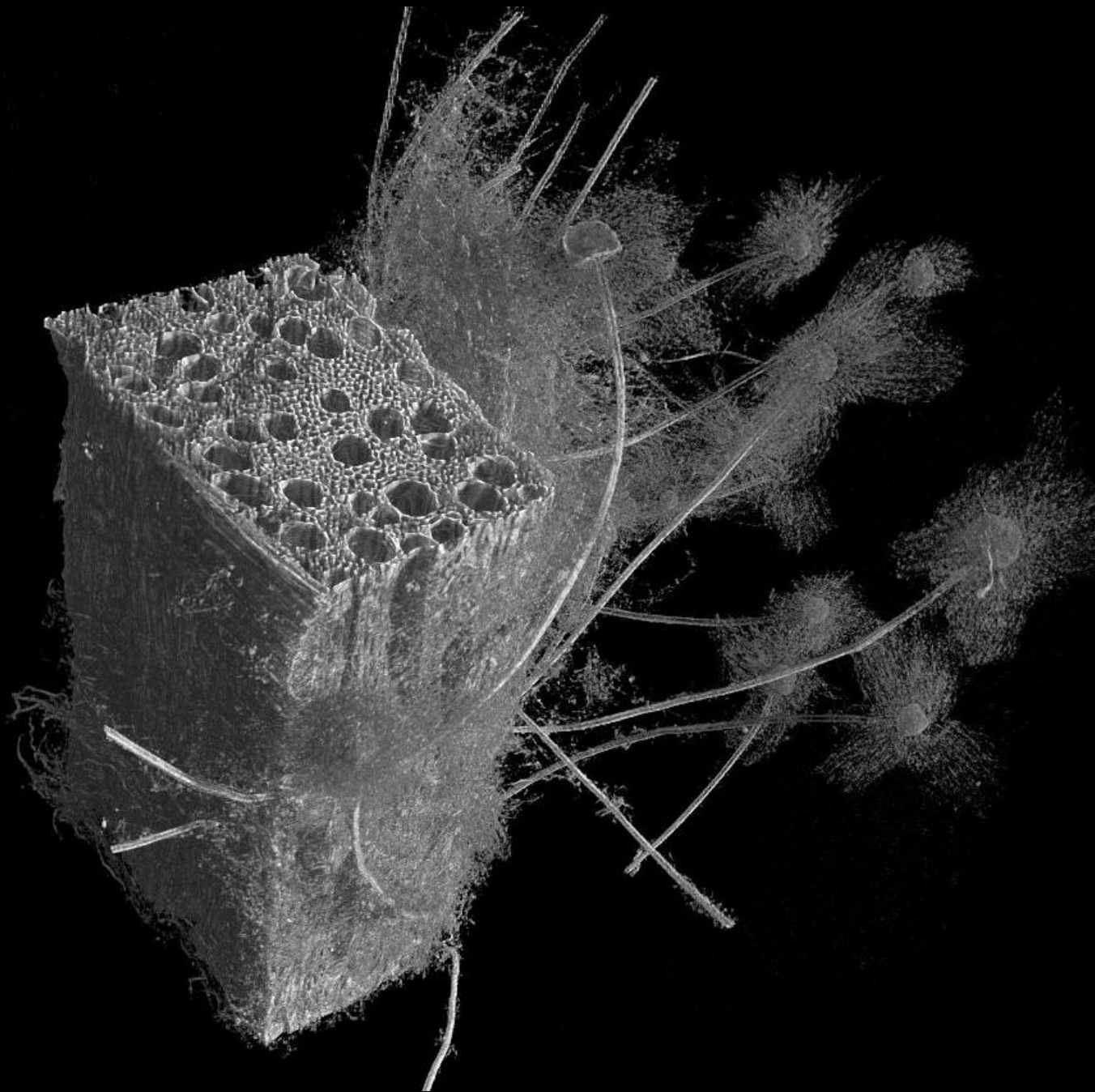
**Tangential**

**Radial**

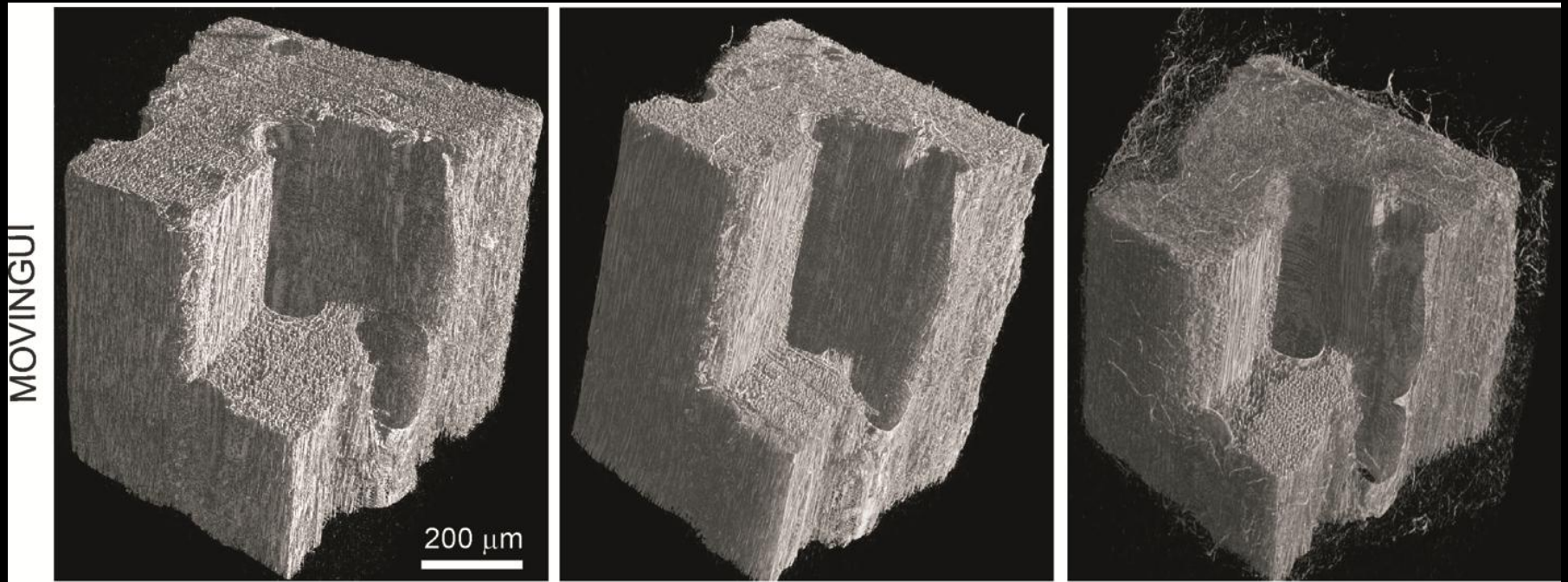
# Fungi in wood



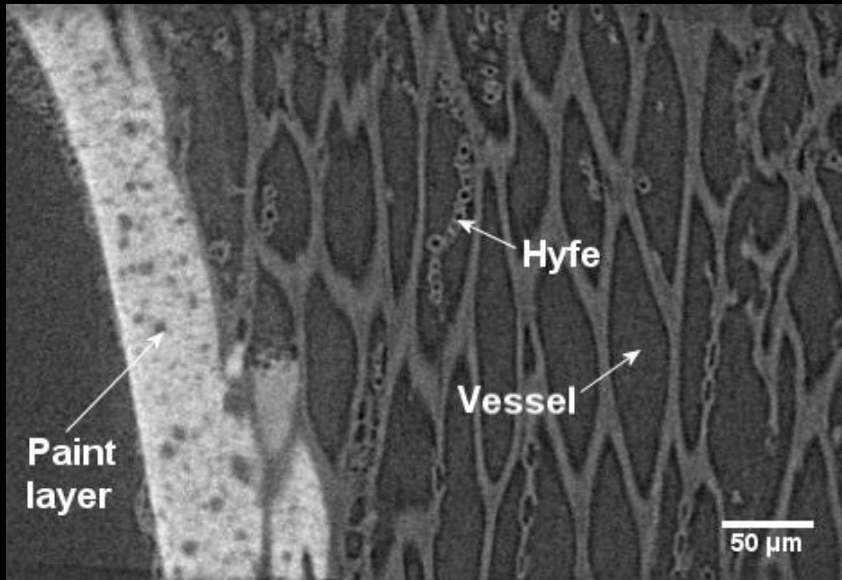


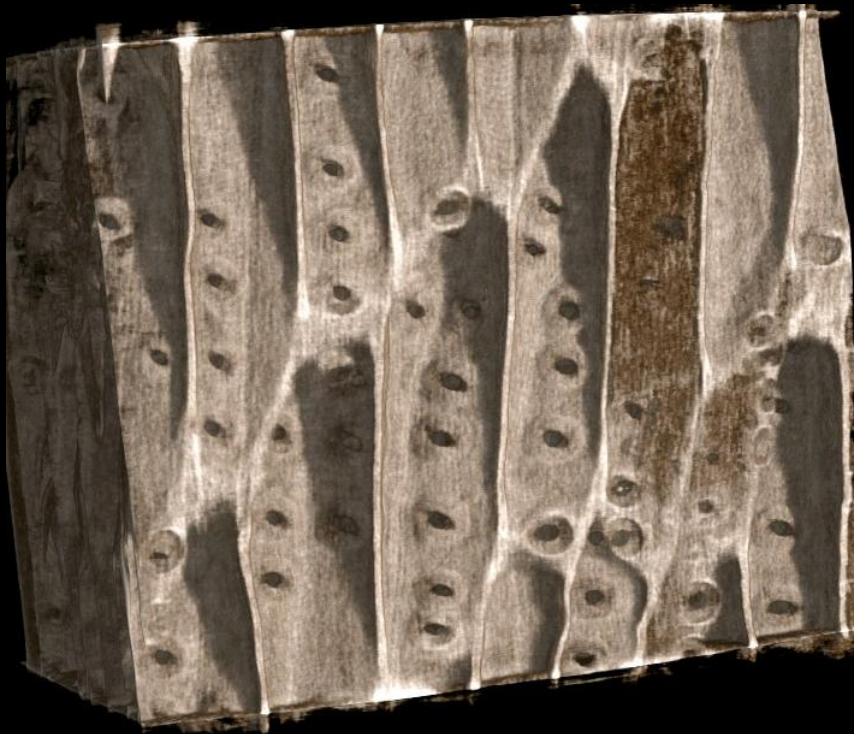


# Time-lapse fungal growth in wood

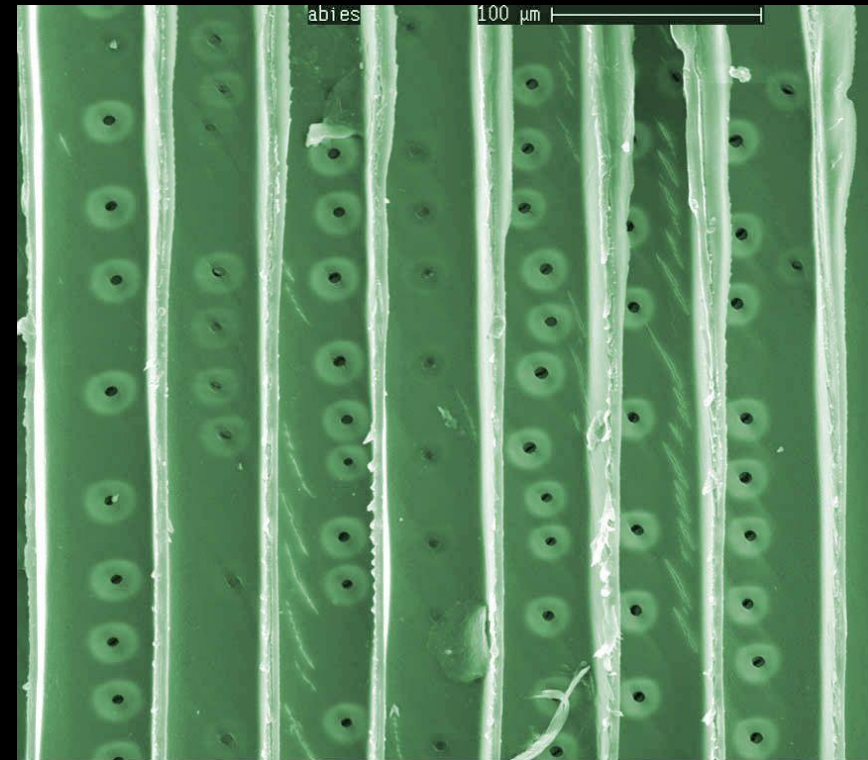








NanoCT scan of pine wood



SEM image of pine wood

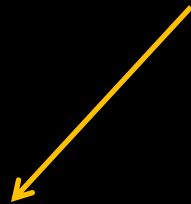
# Disadvantages

- Relatively expensive
- Computationally demanding
- Ionizing radiation:
  - Enclosure
  - Sample deterioration

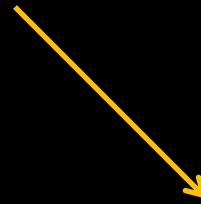
# Resolution challenge

Limited by a combination of several factors

$$R = \frac{d}{M} + s\left(1 - \frac{1}{M}\right)$$

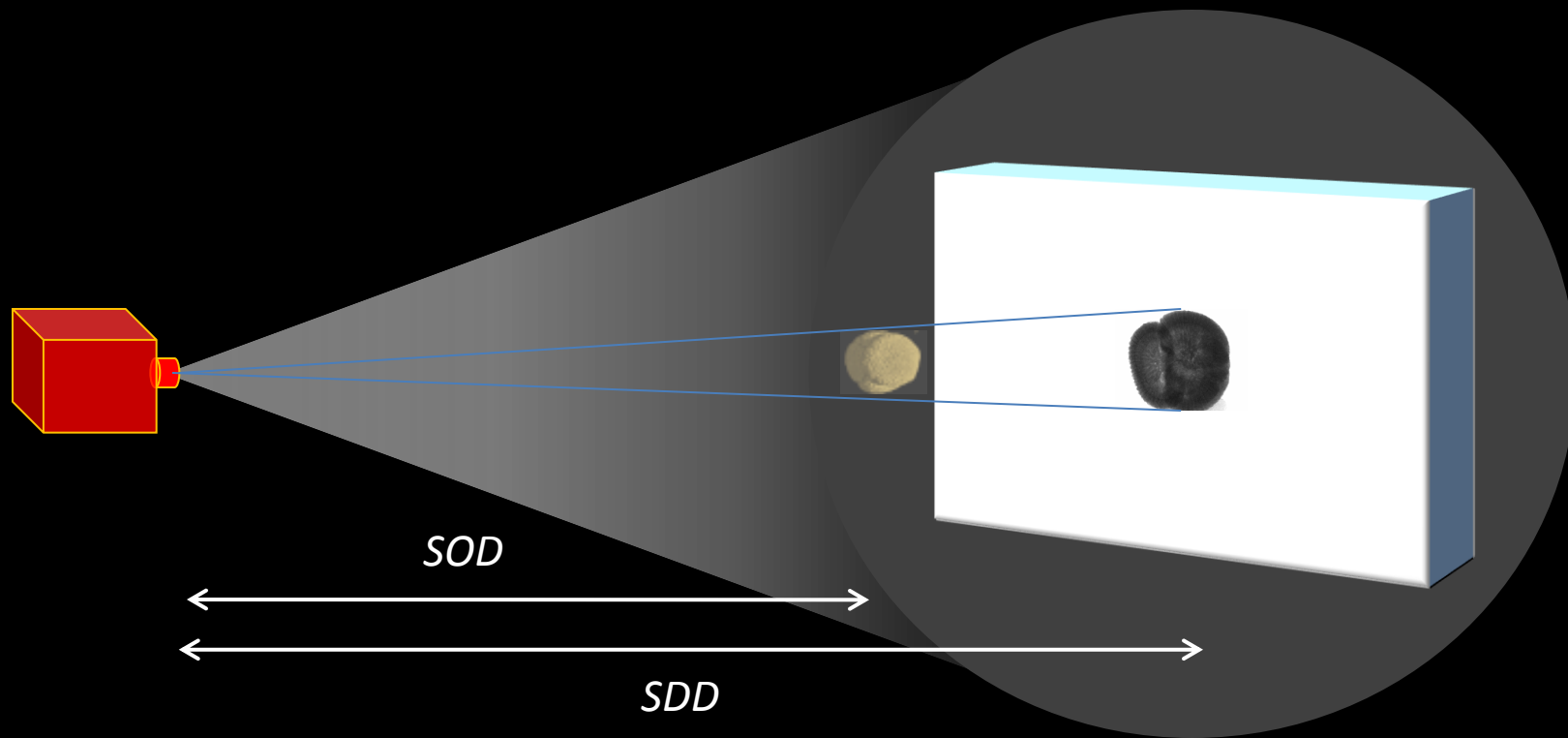


Resolution contribution due to  
detector pixel size  $d$

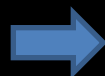


Resolution contribution due to  
X-ray spot size  $s$

$$R = \frac{d}{M} + s\left(1 - \frac{1}{M}\right)$$

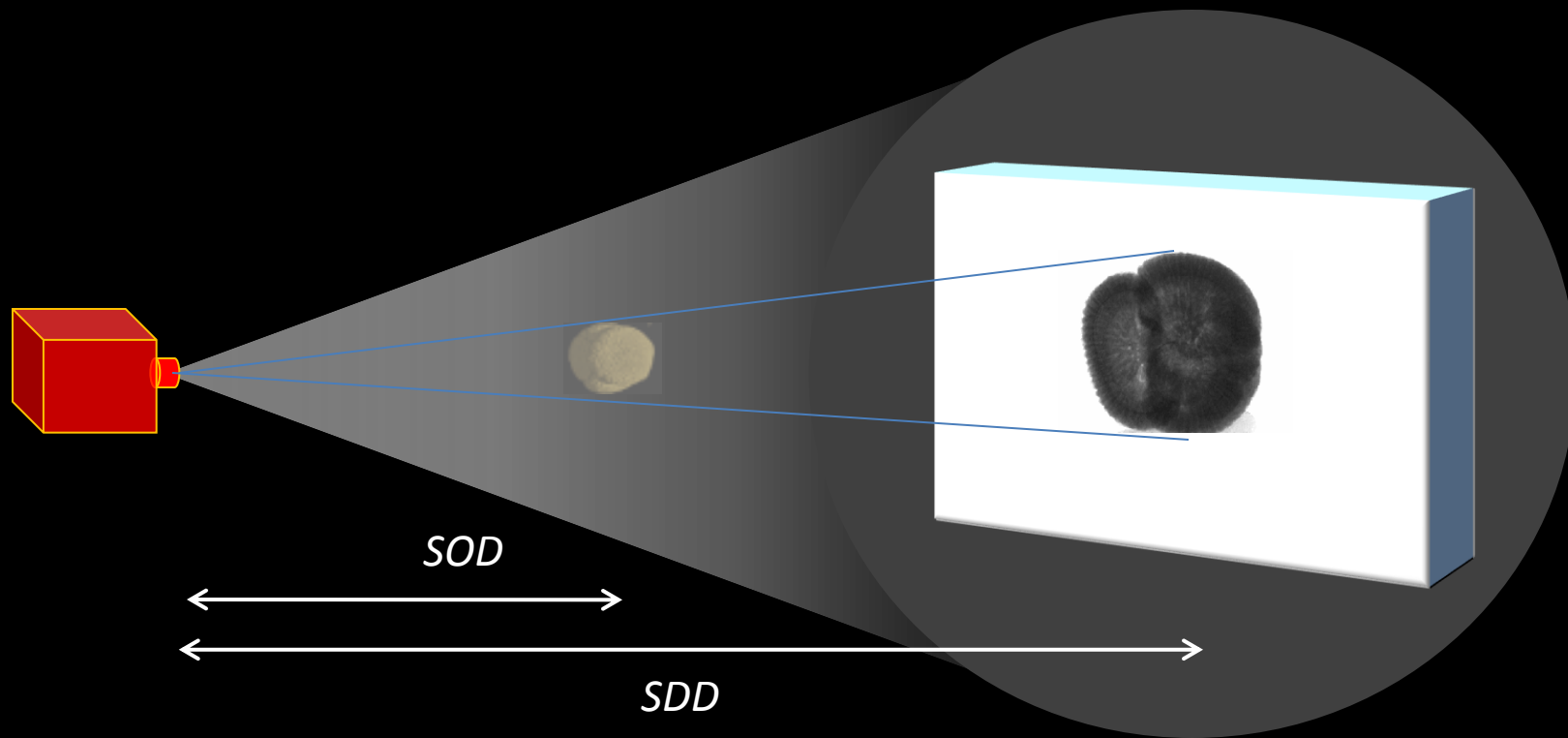


$$M = \frac{SDD}{SOD} \cong 1$$

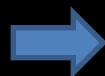


$$R \cong d$$

$$R = \frac{d}{M} + s\left(1 - \frac{1}{M}\right)$$



$$M = \frac{SDD}{SOD} \cong 2$$

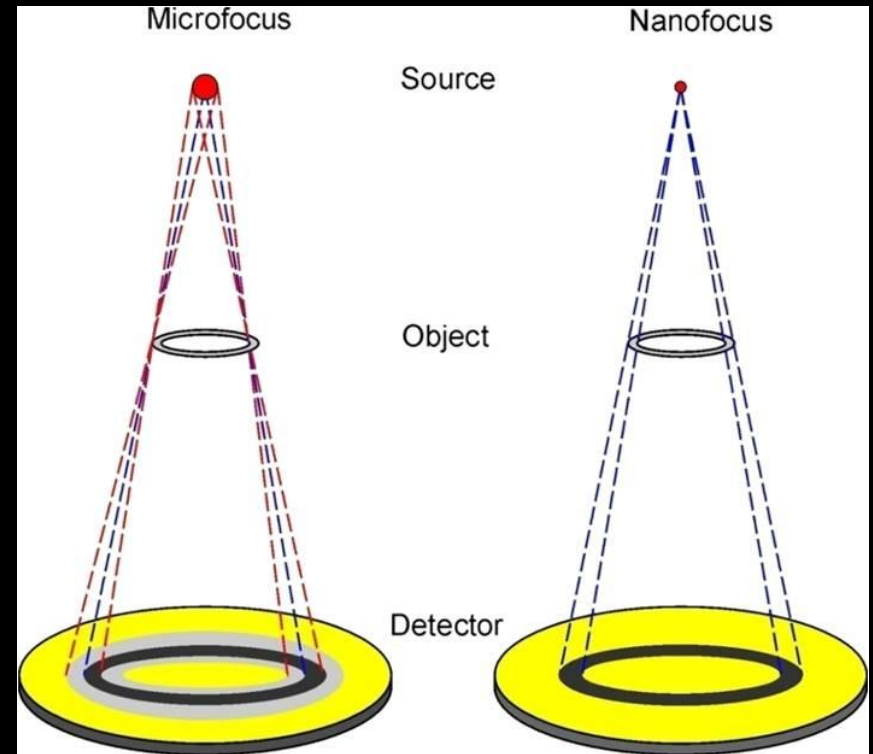


$$R = \frac{d}{2} + 0.5s$$

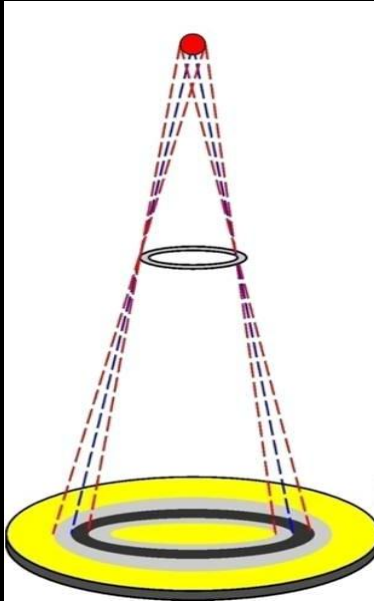


# Limited by X-ray spot size

Size of spot where X-rays are created limits achievable resolution



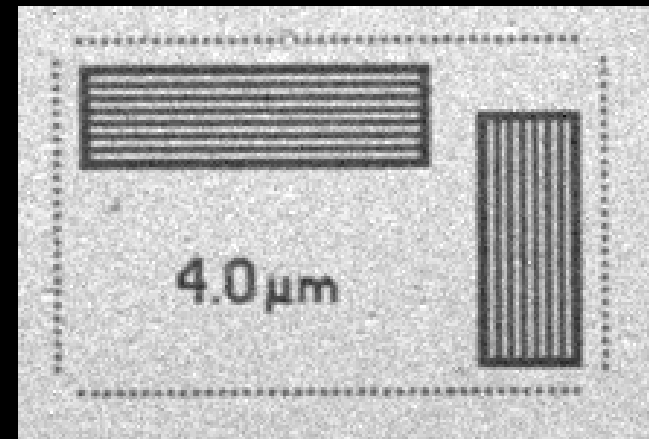
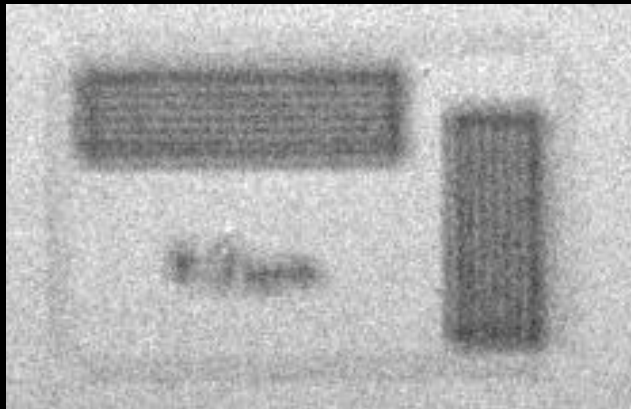
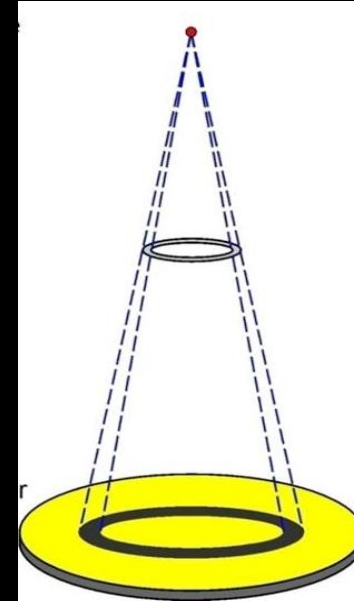
# Limited by X-ray spot size



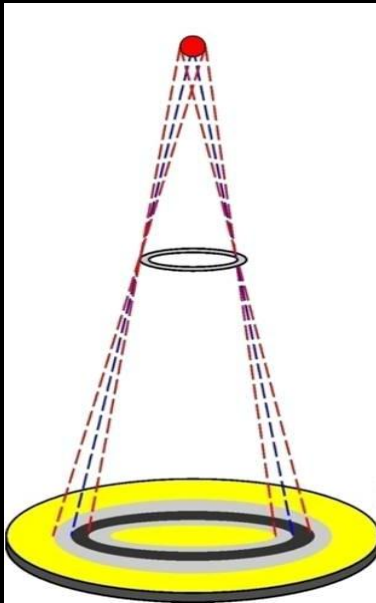
Source

Object

Detector



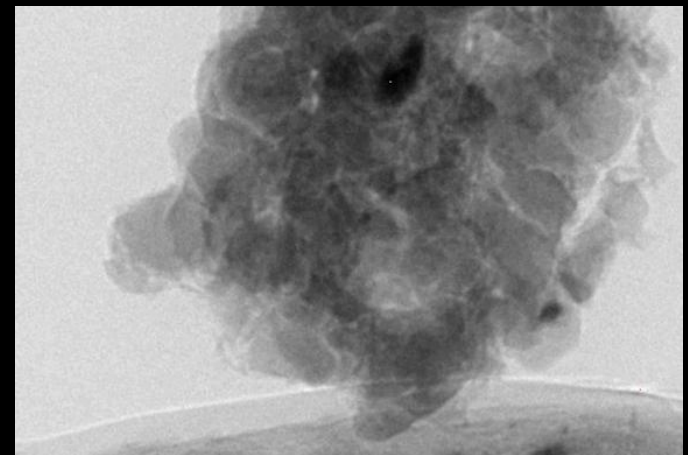
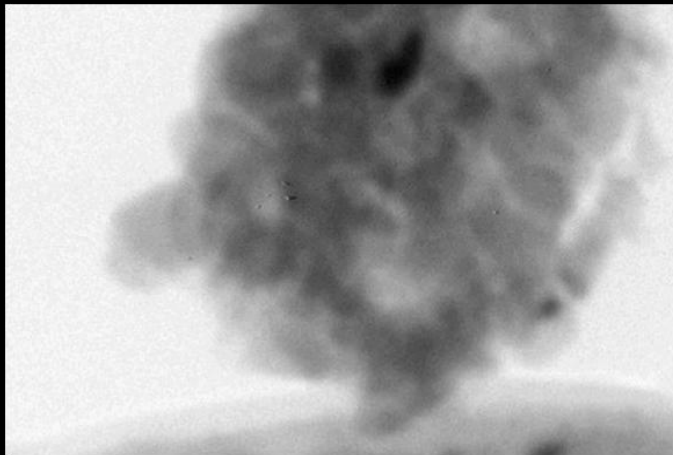
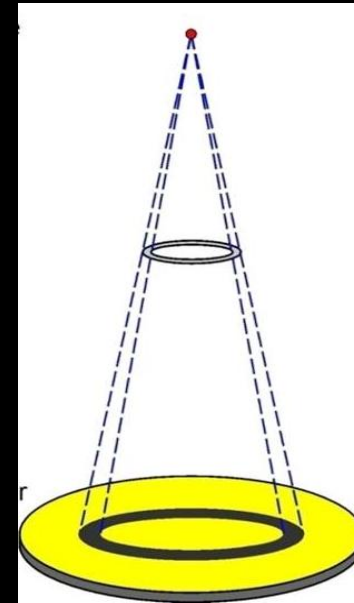
# Limited by X-ray spot size

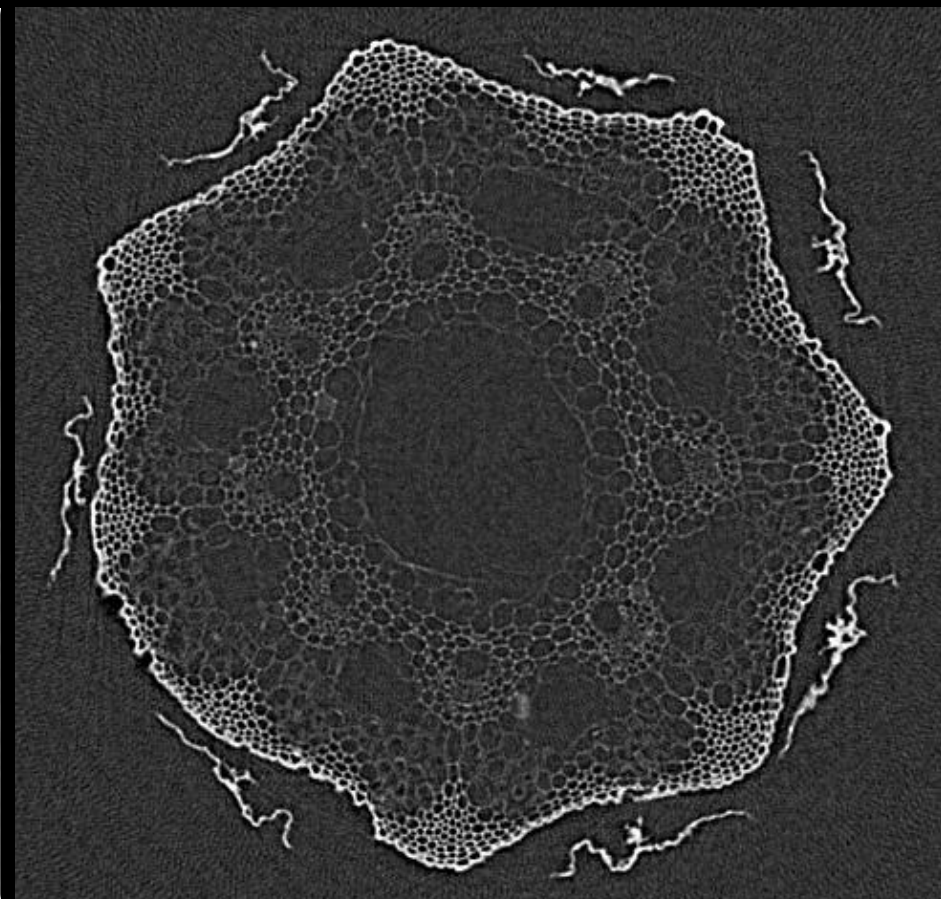
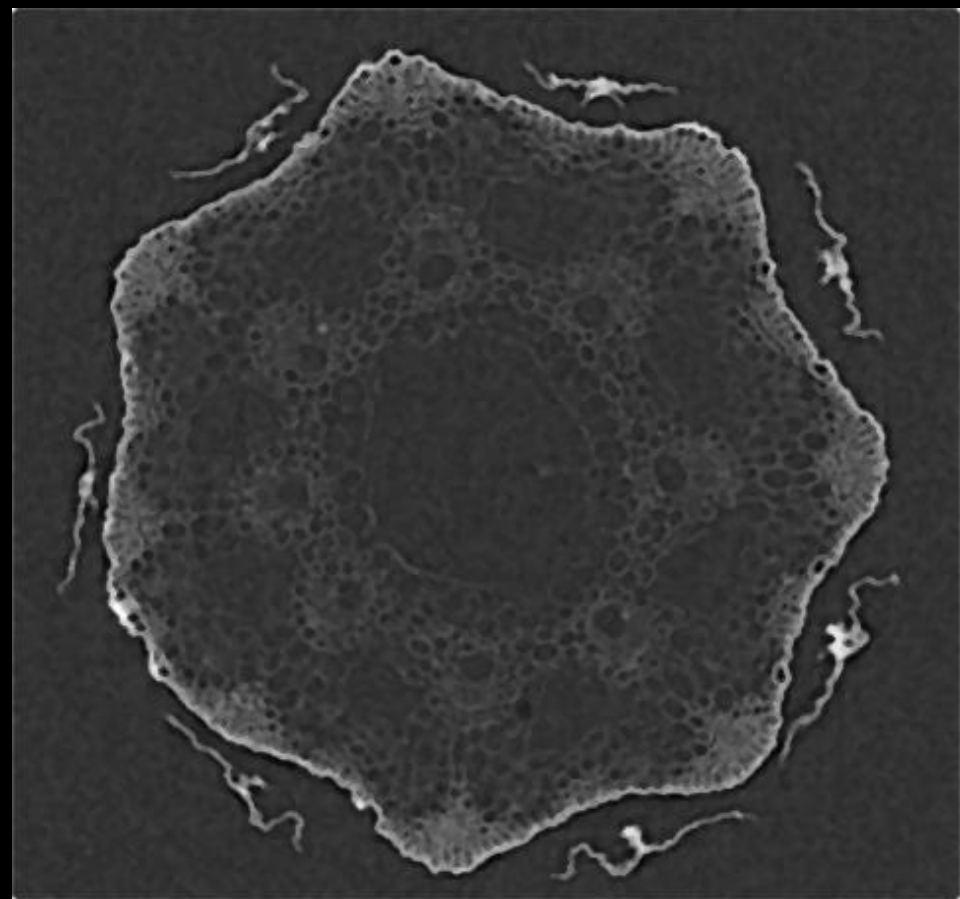
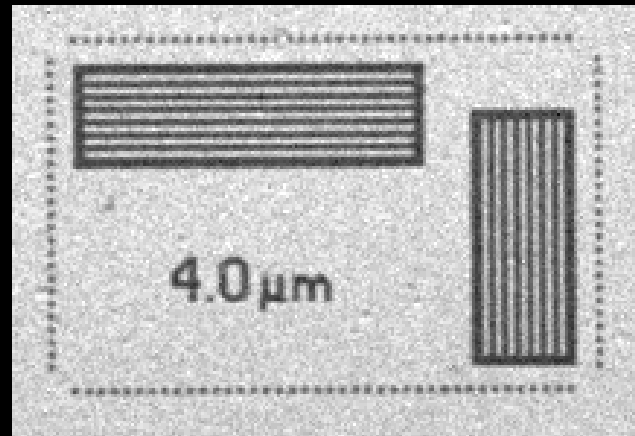
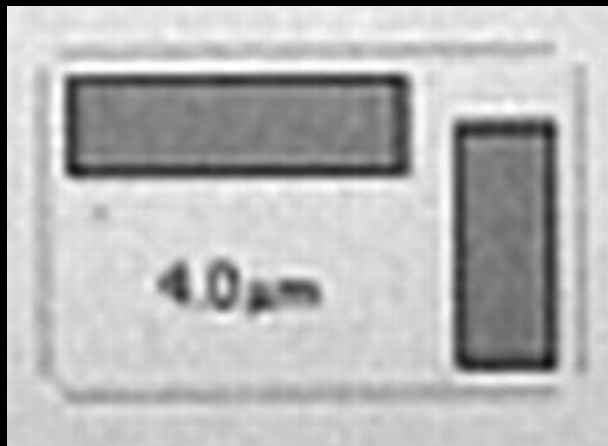


Source

Object

Detector





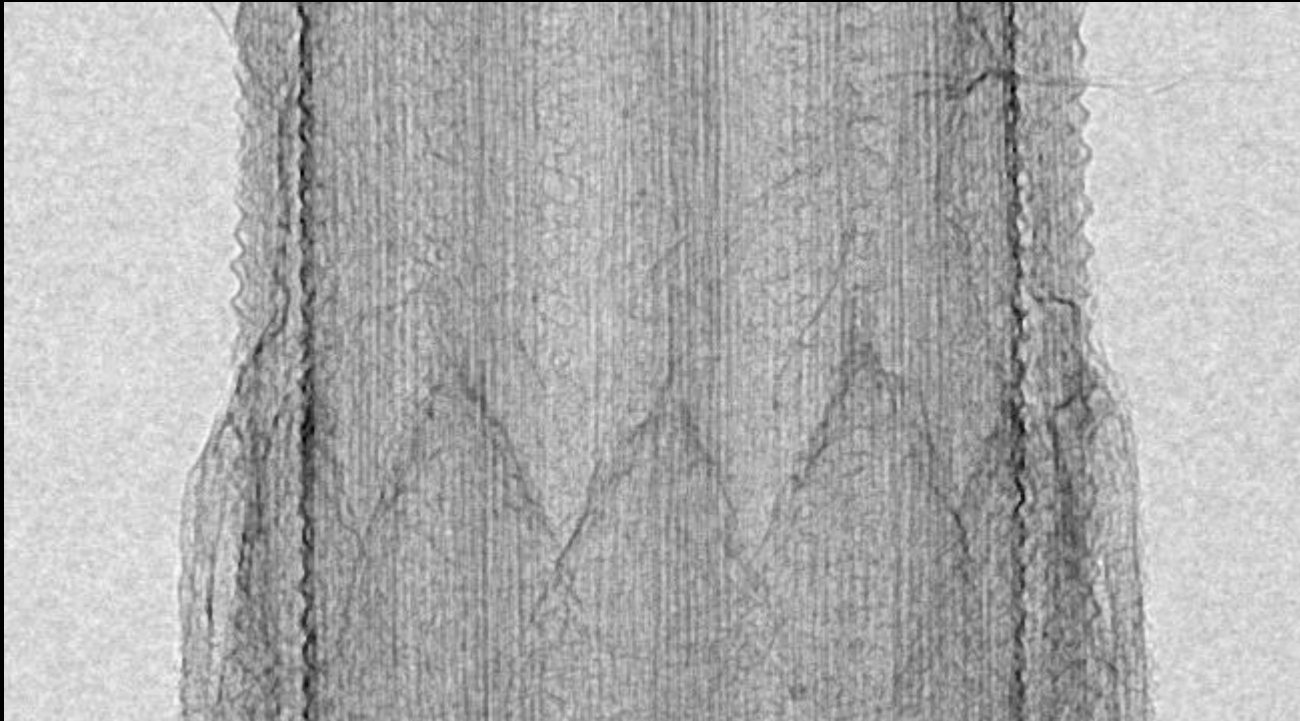
0.4



# System stability

- Spot stability
- Thermal expansion
- Wobble
- Angle accuracy
- Sample movement

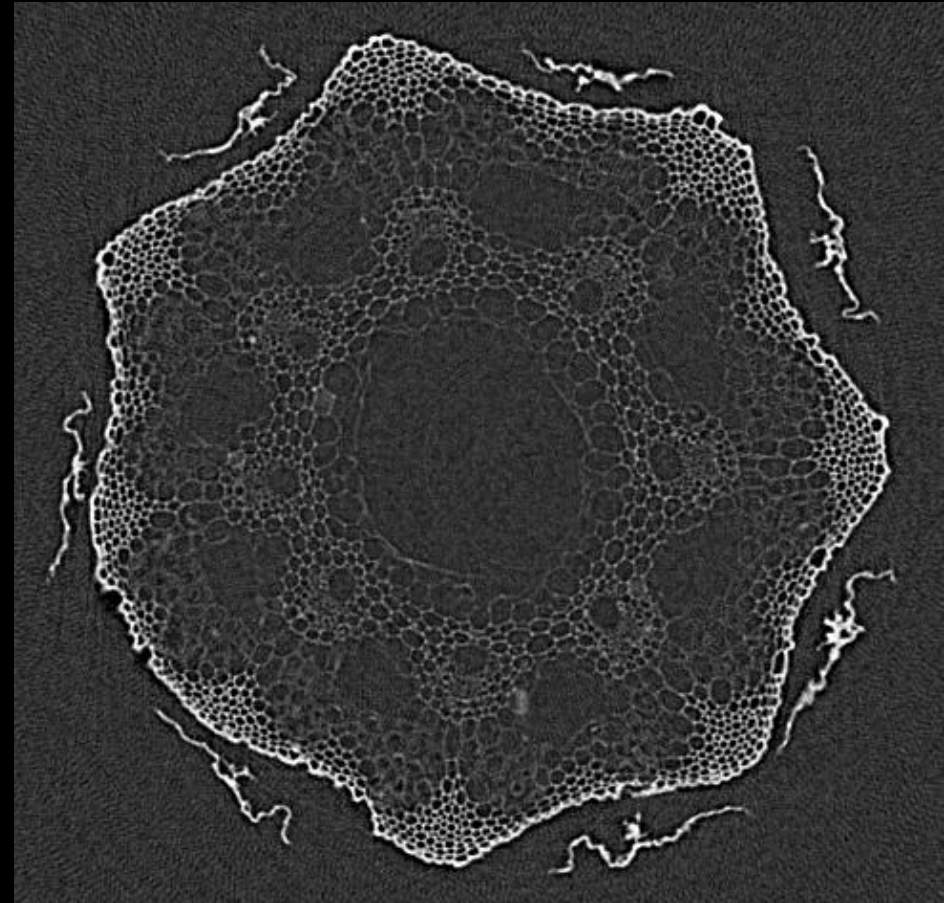
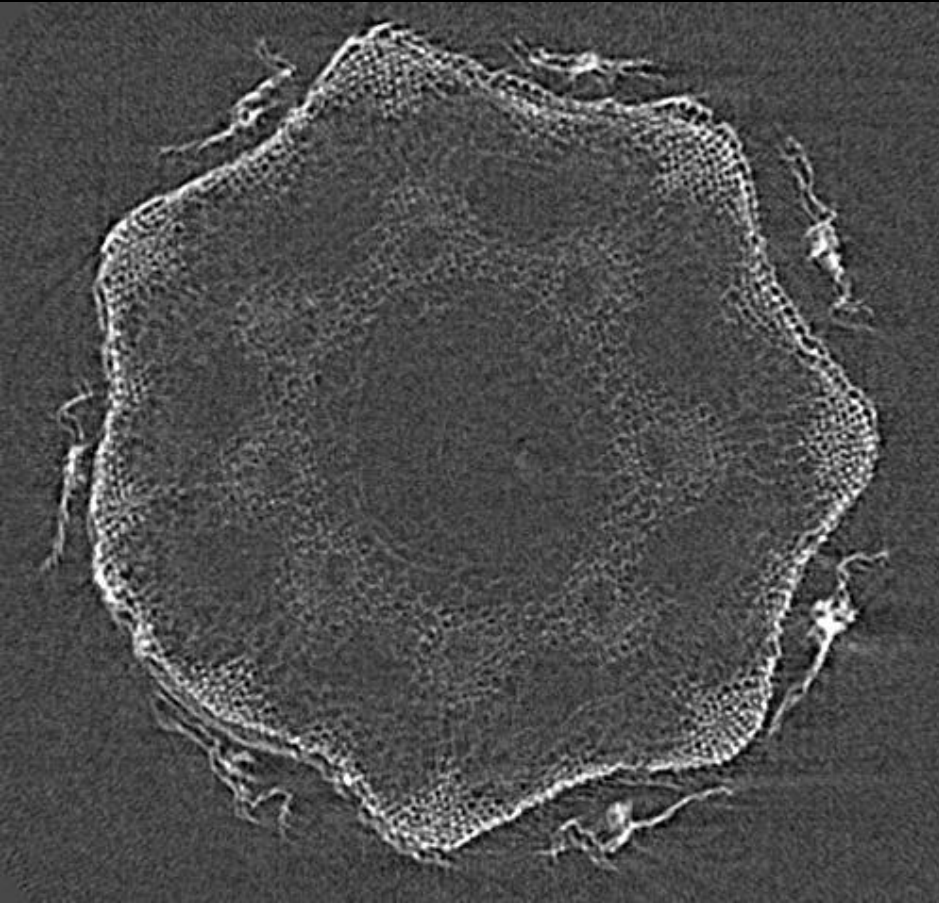
# System stability



# System stability

Non-stable

Stable



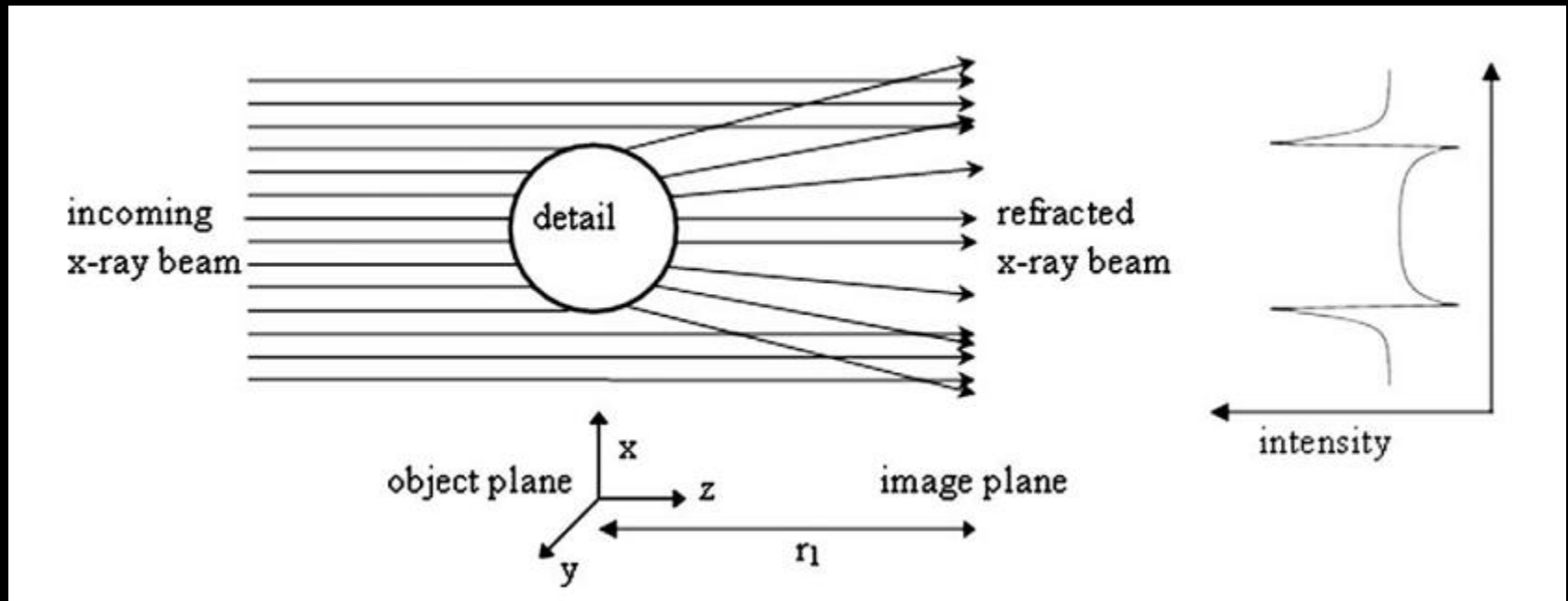
# Phase contrast

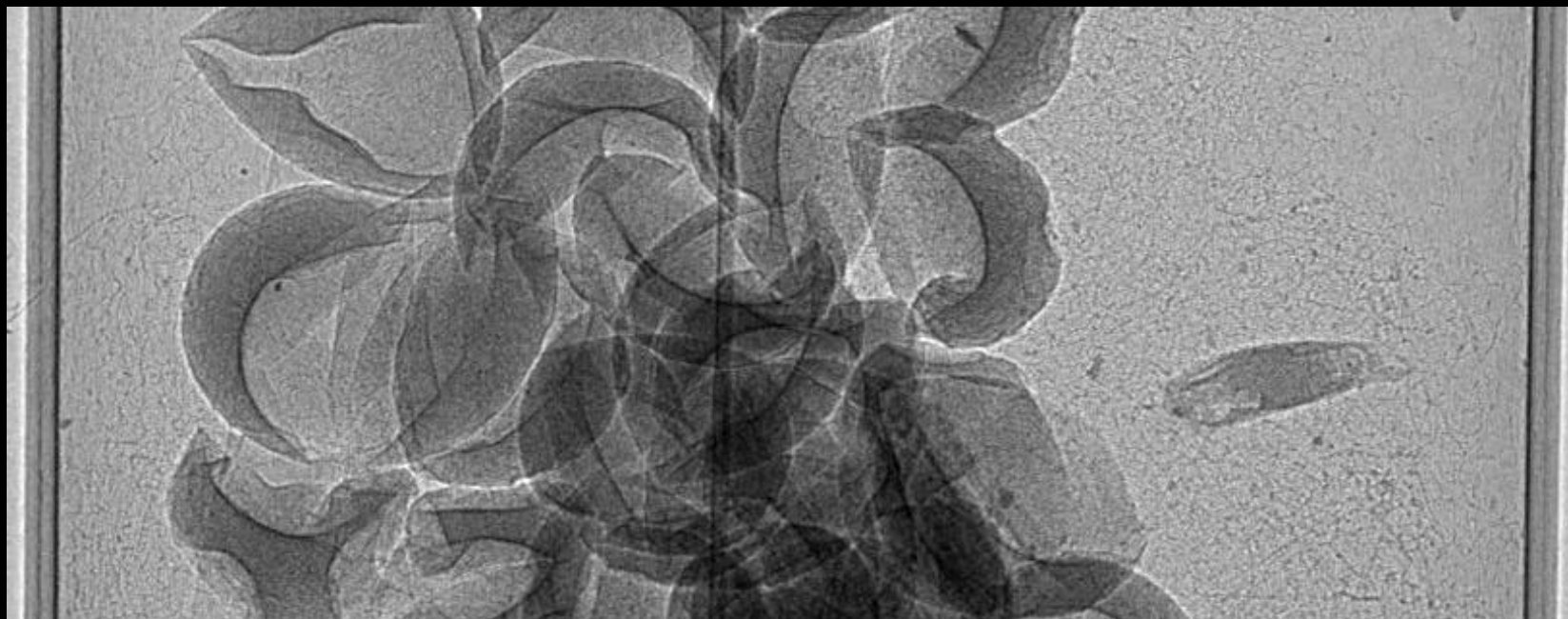
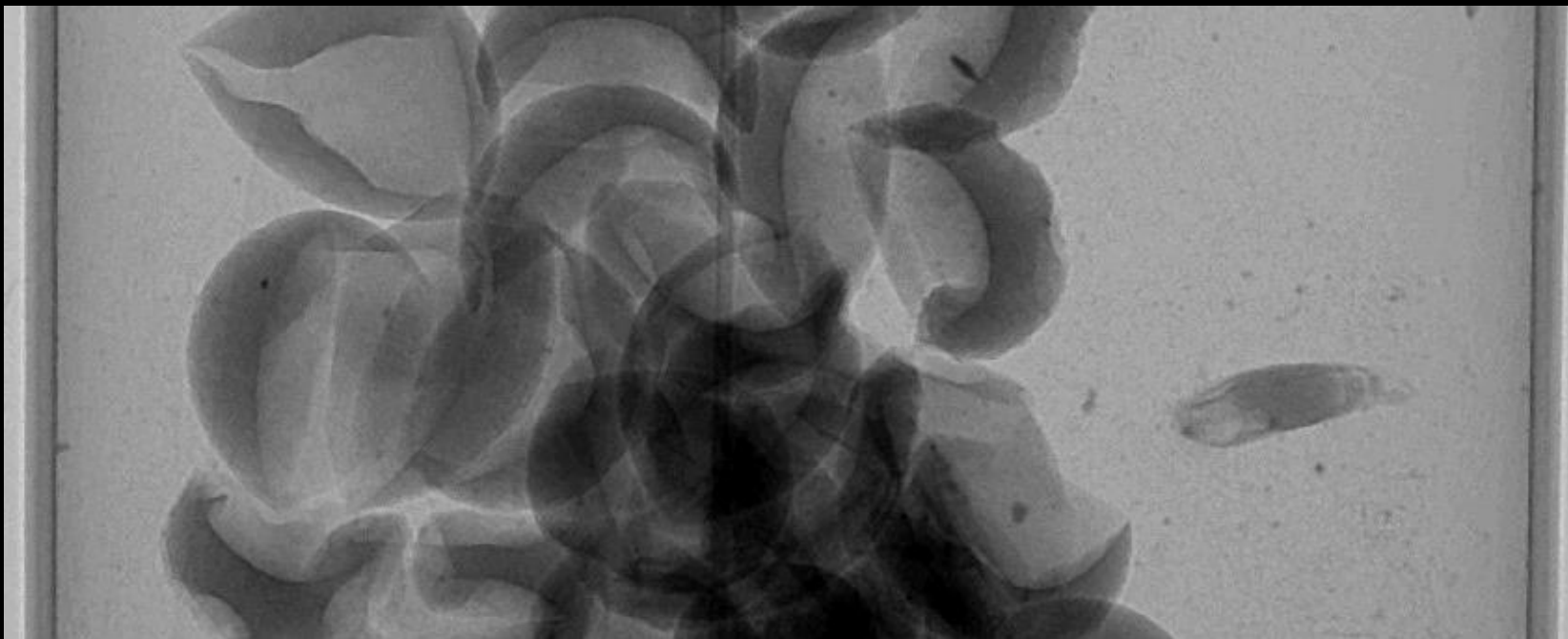
Refraction of X-rays when passing through object

→ Phase shift of the incoming X-ray beam

→ Phase contrast signal superimposed on absorption signal

→ Detected signal is combination of phase and absorption







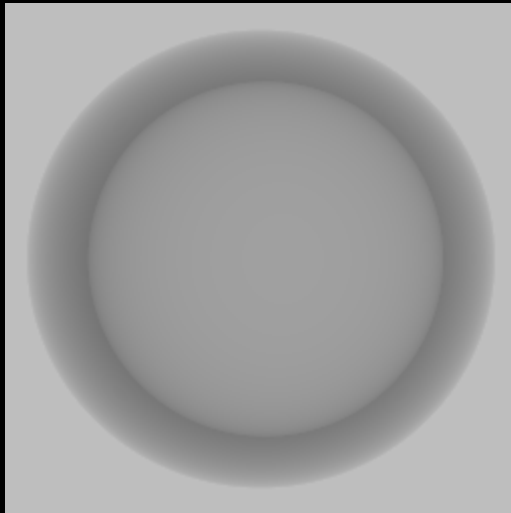
# Phase contrast

Refraction of X-rays when passing through object

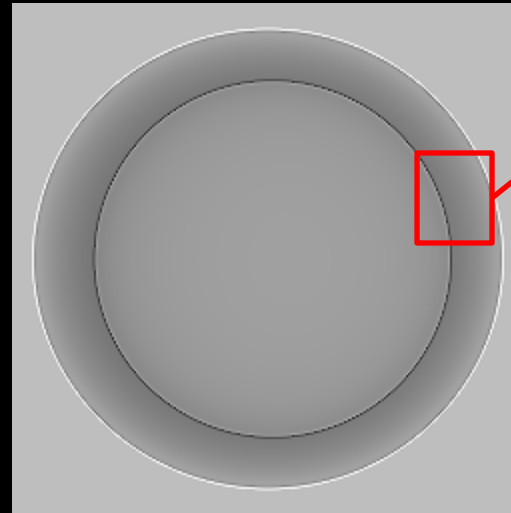
→ Phase shift of the incoming X-ray beam

→ Phase contrast signal superimposed on absorption signal

→ Detected signal is combination of phase and absorption



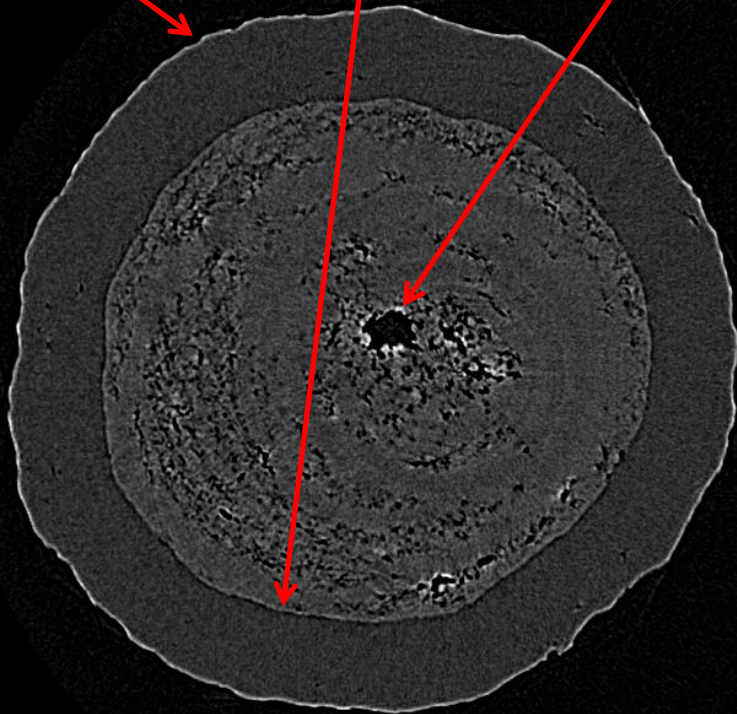
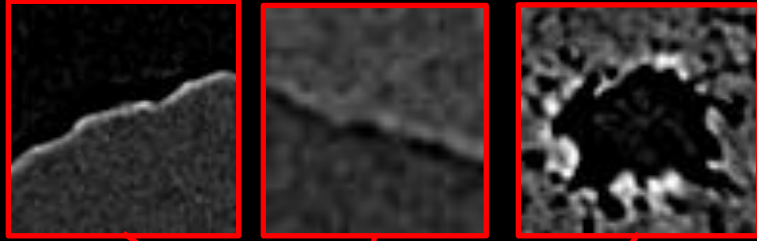
Hollow sphere  
Absorption



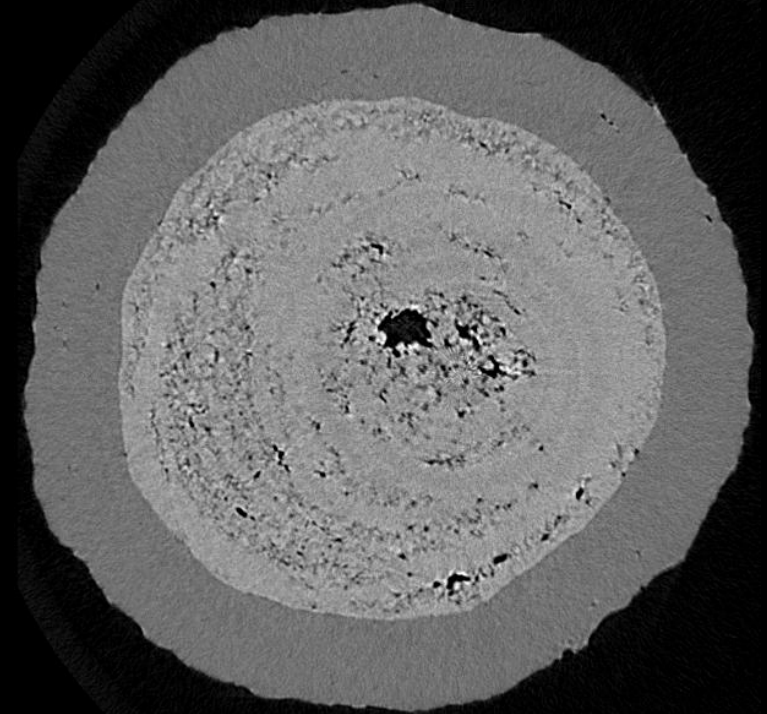
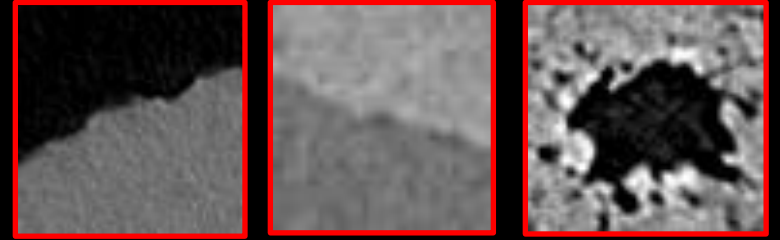
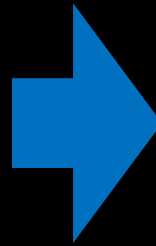
Hollow sphere  
Absorption and phase



# Phase contrast as an artifact

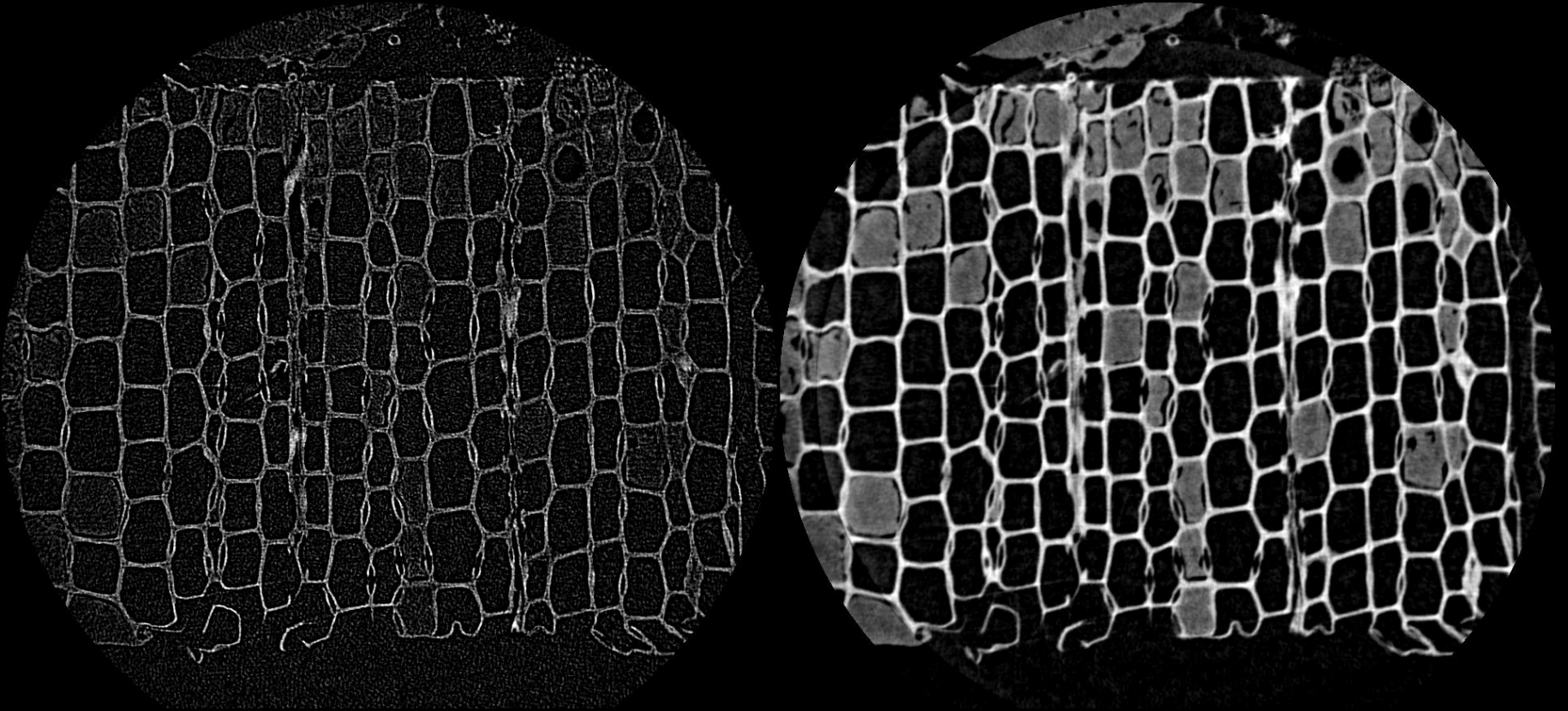


Normal reconstruction



BAC reconstruction

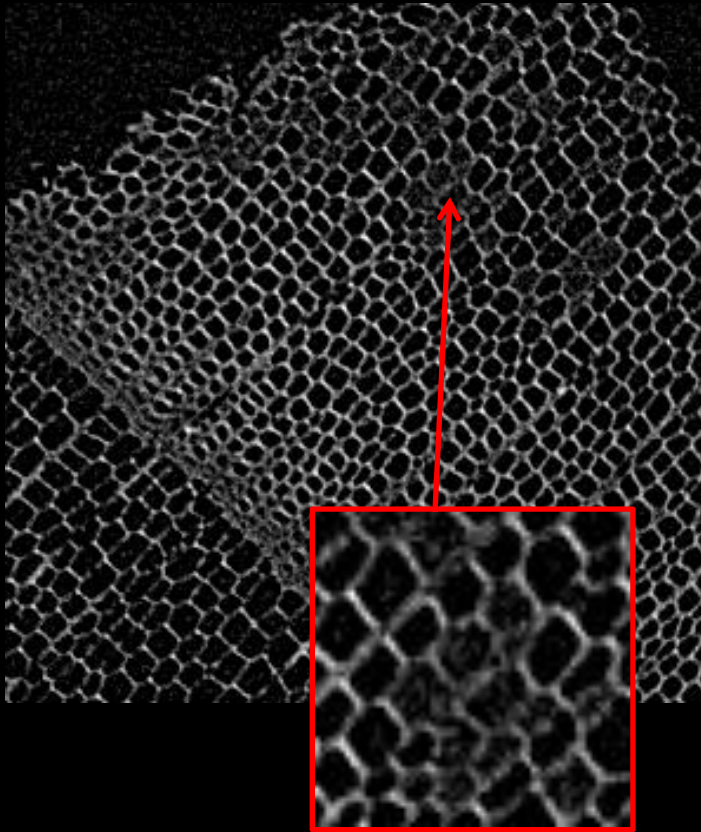
# Phase contrast for image improvement



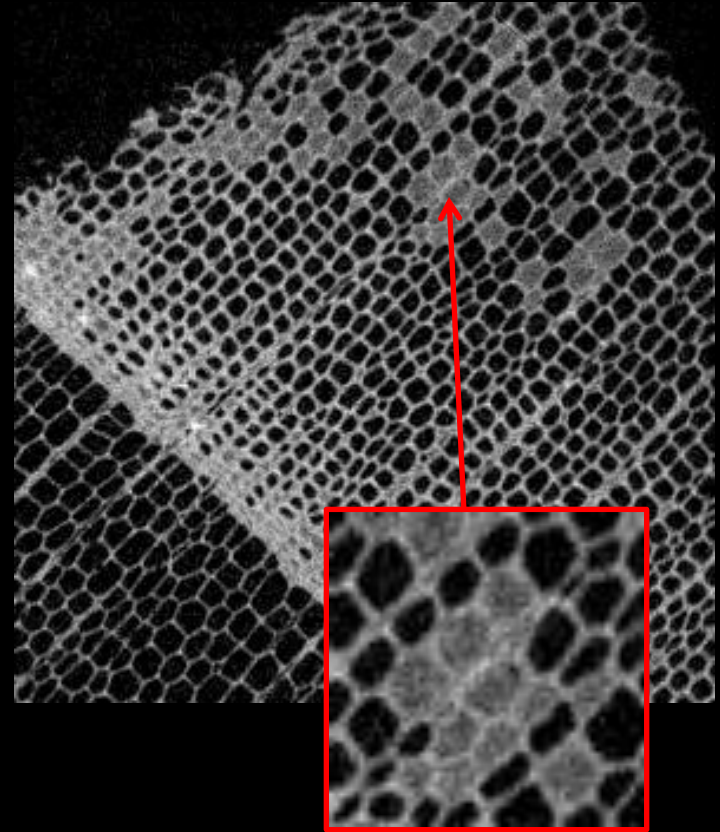
Phase corrected



# Phase contrast for image improvement



Normal reconstruction



BAC reconstruction

# With thanks to the UGCT-team!

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