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# The art of bookbinding: uncovering the secrets of old masters with non-invasive 3D imaging

- the case of the prayer book of Mary, Queen of Scots -

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# Outline

- Science case and goal of the project
- Methodology of choice
- Measurements:
  - Micro-CT
  - C-14 dating
  - Pigments and inks analysis
- Summary and outlook

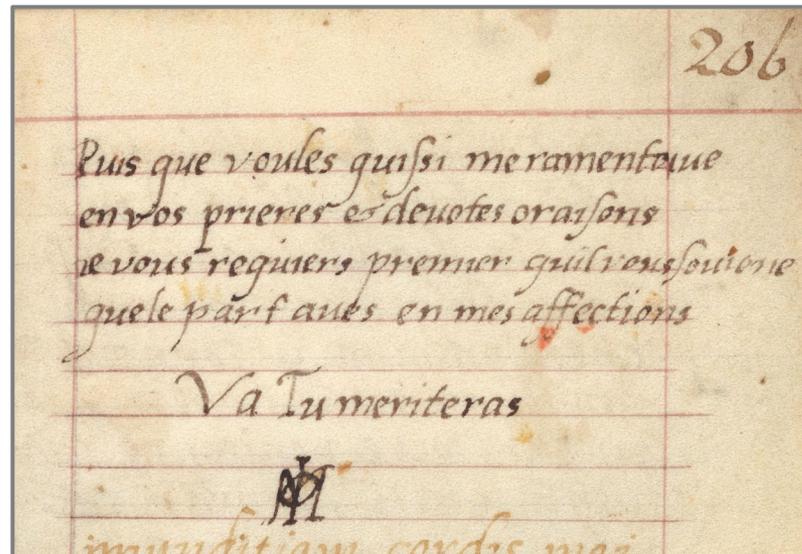
# Study case

- Manuscript on vellum, black and red ink, illuminations and several incipit letters highlighted:
  - Rare example of prayer book with prayers in the female form
  - made in 1535-1540 for Louise de Bourbon-Vendome, Abbess of Fontevraud



# Study case

- Manuscript on vellum, black and red ink, illuminations and several incipit letters highlighted:
  - Rare example of prayer book with prayers in the female form
  - made in 1535-1540 for Louise de Bourbon-Vendome, Abbess of Fontevraud
  - 1558-1561 donated to her grand-niece, Mary Stuart



# Study case: Mary Stuart's prayer book

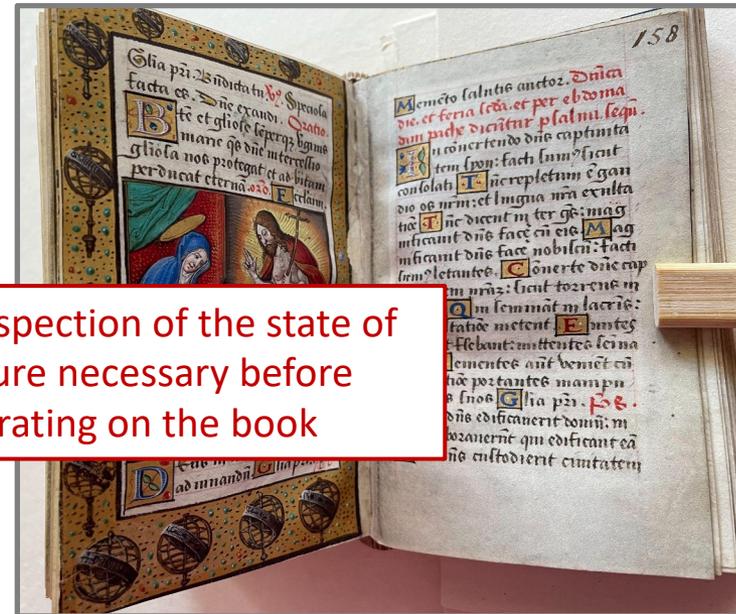
- Rebound in the late 18<sup>th</sup>/early 19<sup>th</sup> century
  - several changes introduced in the book structure
  - book could no longer be opened to more than ~30°



# Study case: Mary Stuart's prayer book



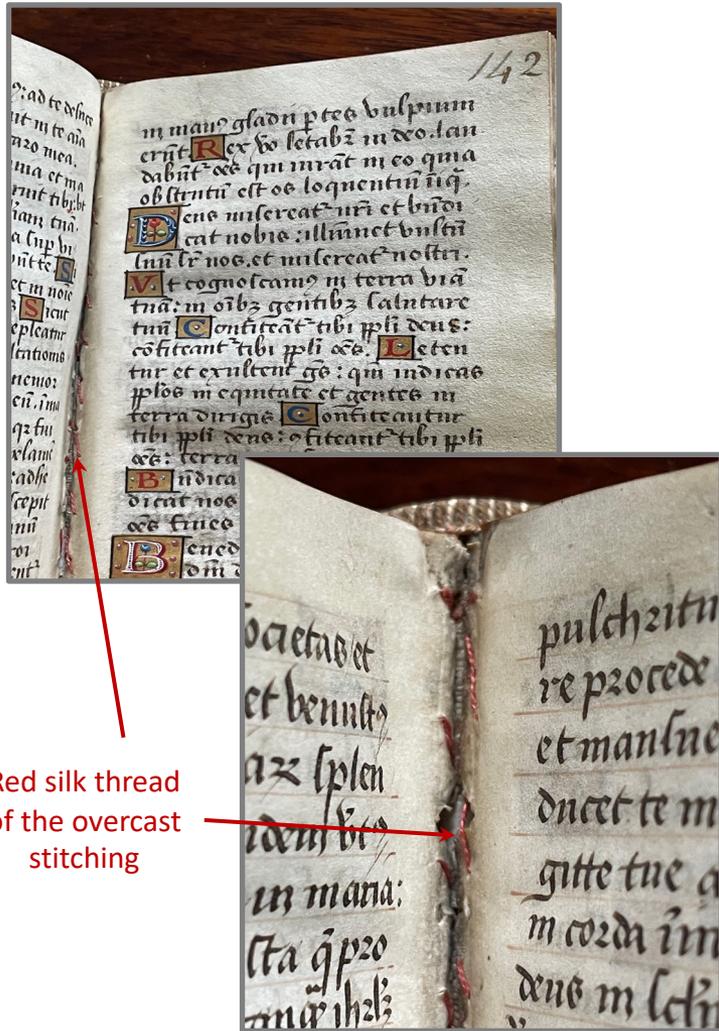
- Rebound in the late 18<sup>th</sup>/early 19<sup>th</sup> century
  - several changes introduced in the book structure
  - book could no longer be opened to more than ~30



⇒ non-invasive inspection of the state of the spine structure necessary before physically operating on the book



# Motivations



Non-invasive inspection of the condition of the book binding:

1. Visual assessment of the book:

- estimate the structure and the sewing
- overcast sewing was too tight to estimate the condition/status of the spine

--> crucial information for planning the conservation work is missing!

2. Non-invasive scientific analysis to verify the information assessed visually to

- gain deeper insight into the structure of the book spine
- understand the binding structure and its history

*Ultimate goal:*

*provide guidance for the conservation work*

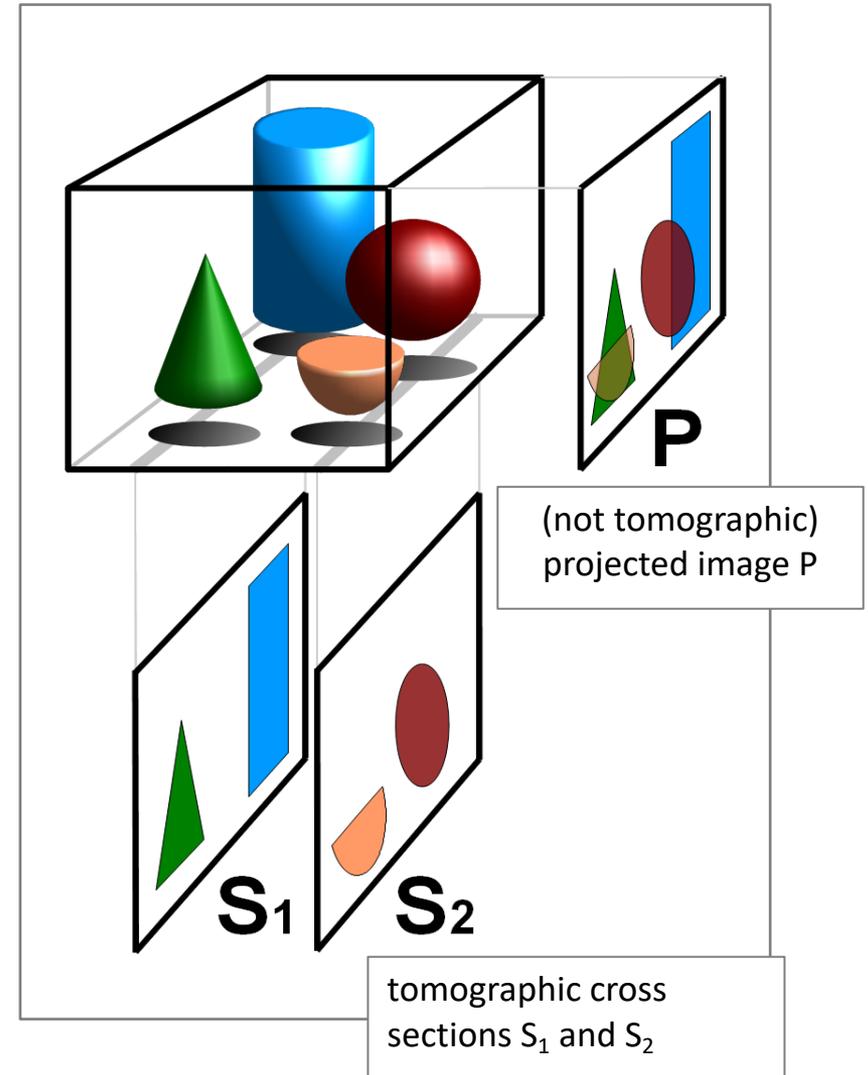
# Computed tomography: principles

- Etymology:

Greek *Tomo* (=slice) + *graphein* (=write or record)

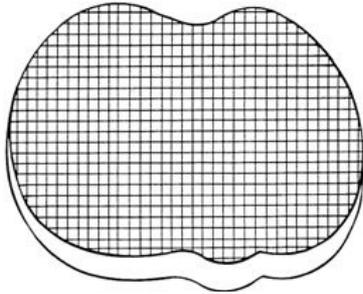
- Radiographic technique that selects a level in the object & blurs out structures below and above that plane

⇒ clear image of the selected layer

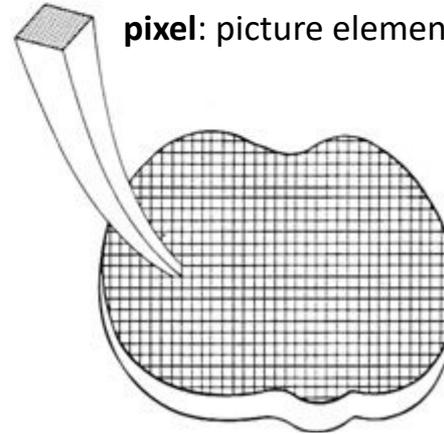


# Computed tomography: principles

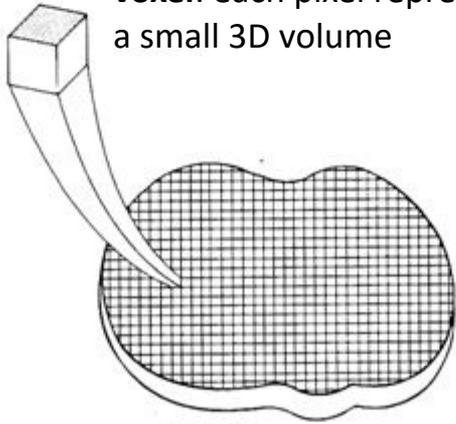
CT image: **matrix** of numbers



**pixel**: picture element



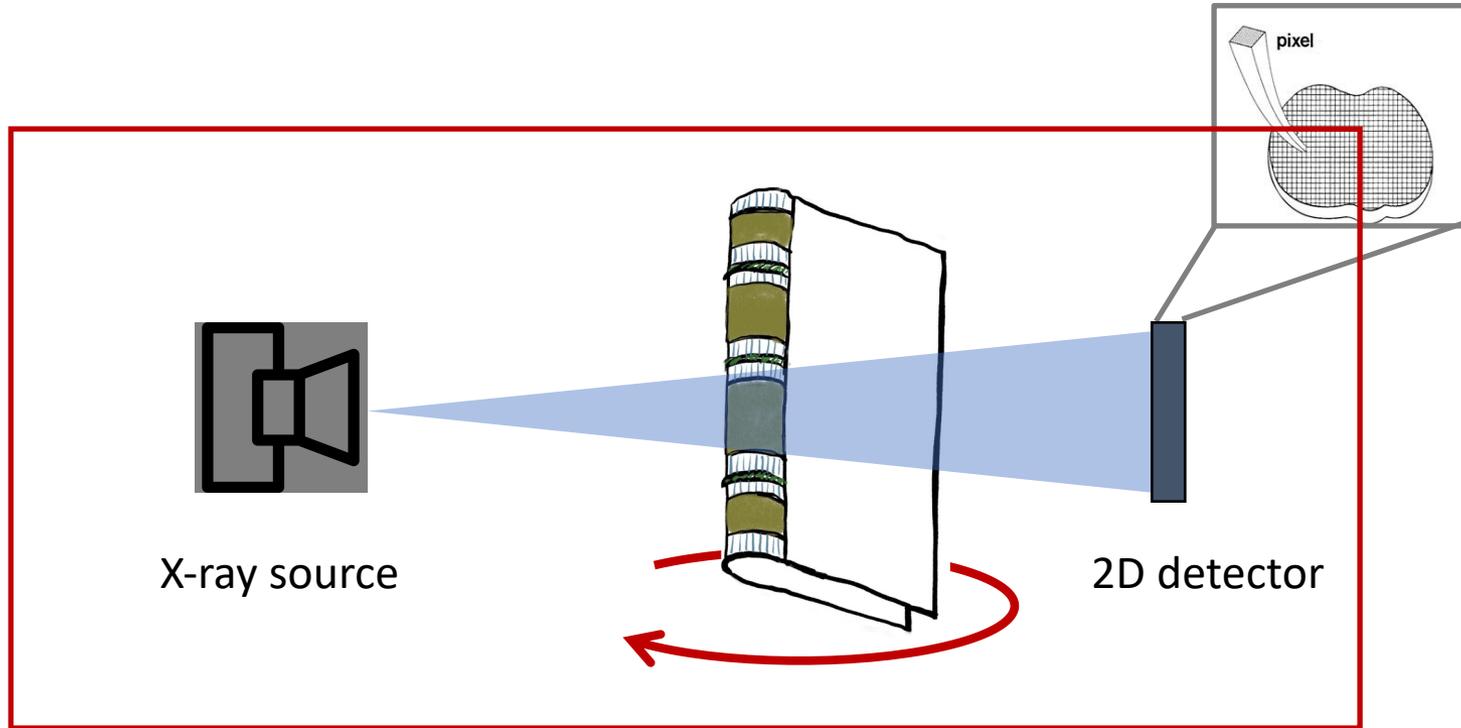
**voxel**: each pixel represents a small 3D volume



2D array of pixels in the CT image correspond to the same number of 3D voxels

# Computed tomography: principles

- ▶ Signal intensity in each pixel mirrors the material's chemical composition and the thickness of the material the X-rays went through



# Computed tomography: principles

- ▶ Q: What is measured?

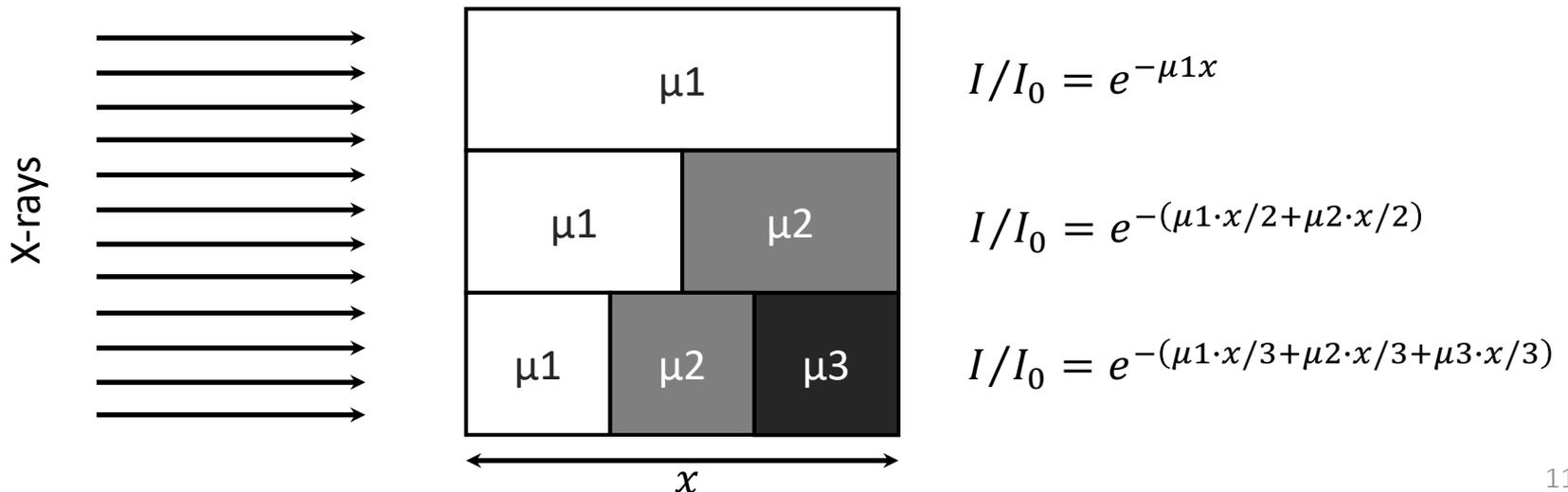
A: X-ray intensity (absorption) for each pixel

$$\frac{I}{I_0} = e^{-\mu x}$$

Chemical composition & X-ray energy

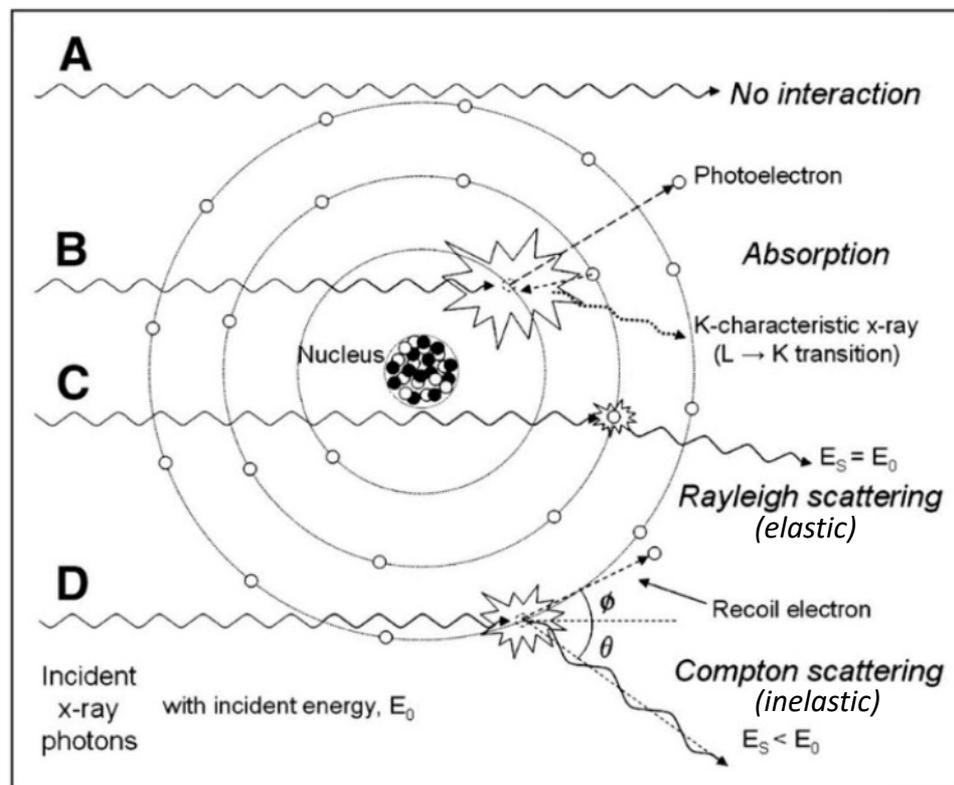
Thickness of the material

- ▶ If more materials are present, the signal's absorption is given by the cumulative effect of interaction with each material



# Computed tomography: principles

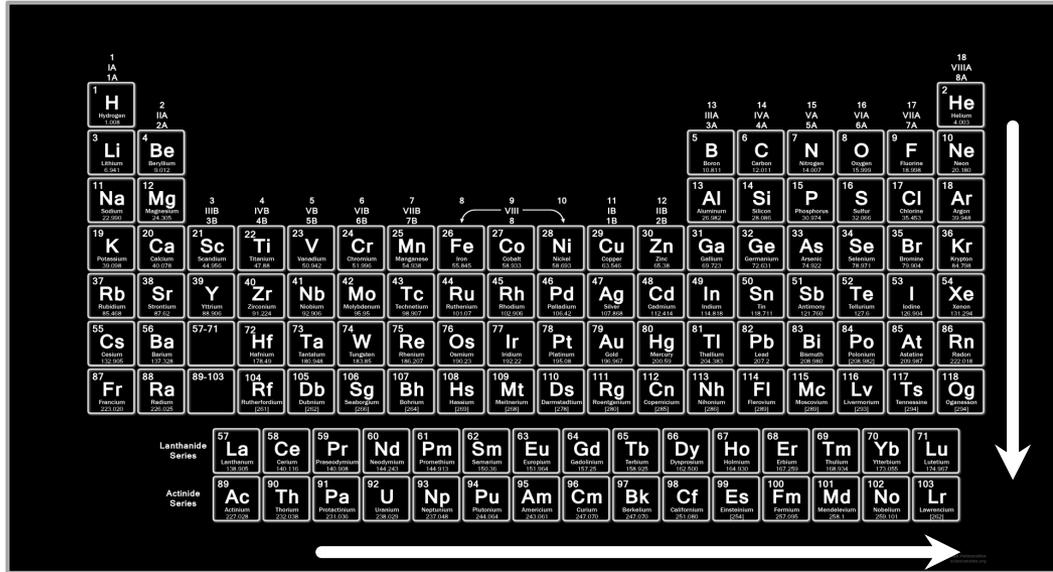
- ▶ Each pixel on the CT image shows the average x-ray attenuation properties of the material in the corresponding voxel:



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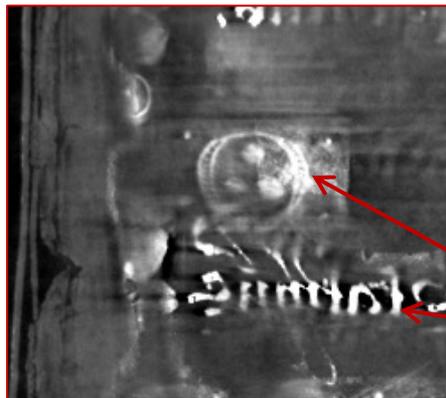
# Computed tomography: principles

- attenuation depends on the density & atomic number (Z) of the materials and on the energy of the X-rays

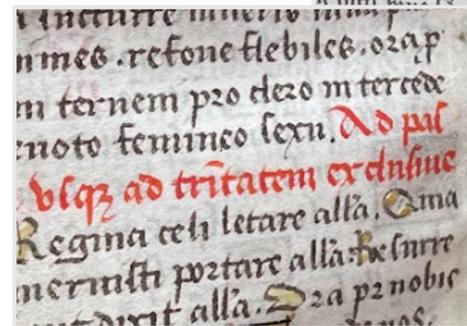


A periodic table of elements with arrows pointing to the right and down, indicating the direction of increasing atomic number and density.

1 IA H Hydrogen 1.008	2 IIA He Helium 4.003											18 VIIIA Ar Argon 39.948																							
3 Li Lithium 6.941	4 Be Beryllium 9.012											19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 52.00	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.69	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.63	33 As Arsenic 74.922	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80						
11 Na Sodium 22.990	12 Mg Magnesium 24.305											37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium 98.906	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.905	46 Pd Palladium 106.36	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.757	52 Te Tellurium 127.6	53 I Iodine 126.905	54 Xe Xenon 131.29						
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 52.00	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.69	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.63	33 As Arsenic 74.922	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80	37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium 98.906	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.905	46 Pd Palladium 106.36	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.757	52 Te Tellurium 127.6	53 I Iodine 126.905	54 Xe Xenon 131.29
55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71 Lanthanide Series	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.222	78 Pt Platinum 195.084	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium 209	85 At Astatine 210	86 Rn Radon 222	87 Fr Francium 223	88 Ra Radium 226	89-103 Actinide Series	104 Rf Rutherfordium 261	105 Db Dubnium 262	106 Sg Seaborgium 266	107 Bh Bohrium 264	108 Hs Hassium 269	109 Mt Meitnerium 268	110 Ds Darmstadtium 271	111 Rg Roentgenium 272	112 Cn Copernicium 285	113 Nh Nihonium 284	114 Fl Flerovium 289	115 Mc Moscovium 288	116 Lv Livermorium 293	117 Ts Tennessine 294	118 Og Oganesson 294



High-Z elements  
(Fe, Hg, Au, Pb, ...)



# Computed tomography: resolution

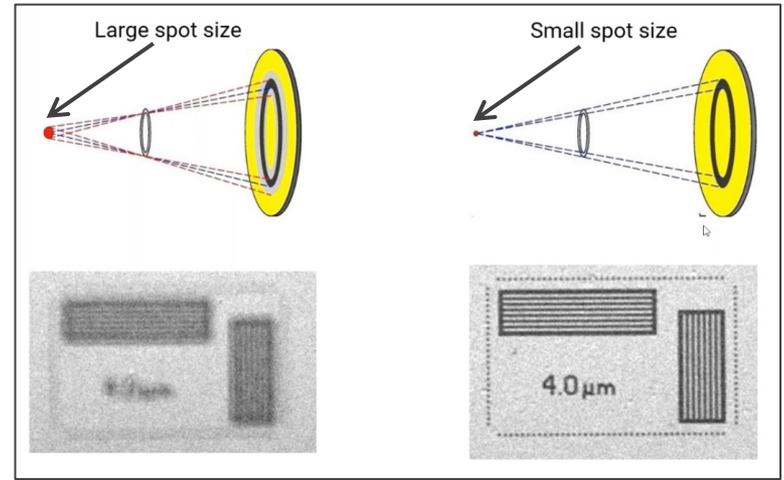
- **Resolution** = combination of different factors
- X-ray spot size (**S**) [focused X-ray spot from the source]
  - ⇒ *main limitation factor of the achievable resolution*
  - (if X-ray spot size becomes larger than the chosen voxel size, the spacial resolution becomes poorer)
- detector size and pixels (**d**)
- geometrical magnification (**M**)

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

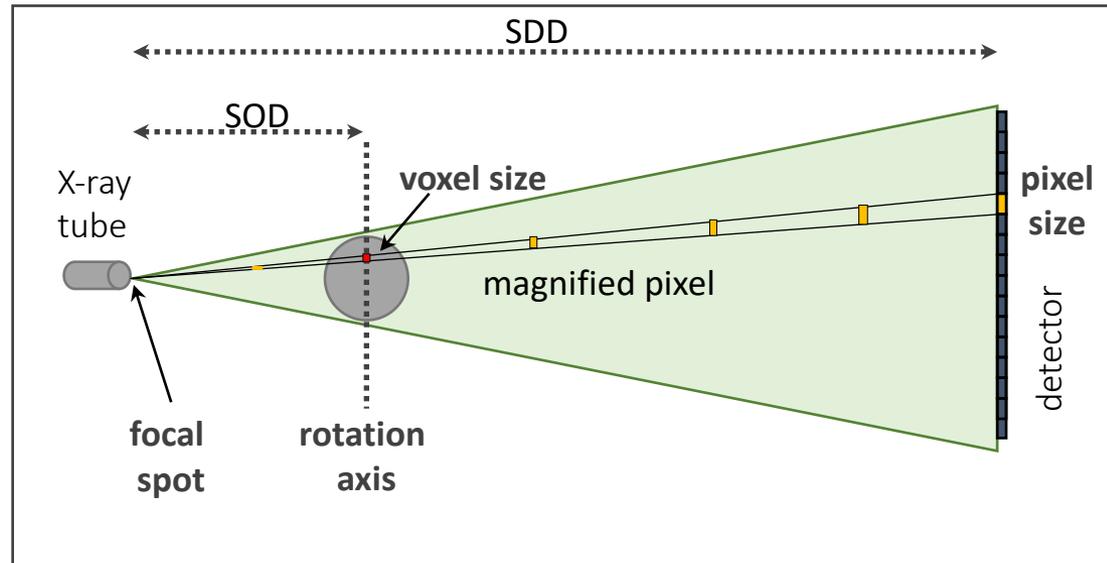
$$R = \frac{d}{M} + s \left(1 - \frac{1}{M}\right)$$

Sample positioned close to the source  
⇒ significant magnification

Sample positioned close to the detector  
⇒ minimal magnification

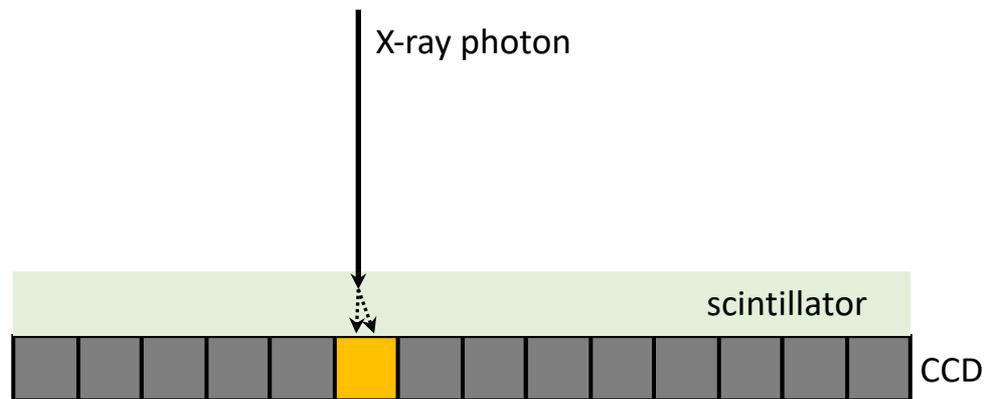


<https://info.tescan.com/micro-ct/insights/introduction-to-micro-ct>

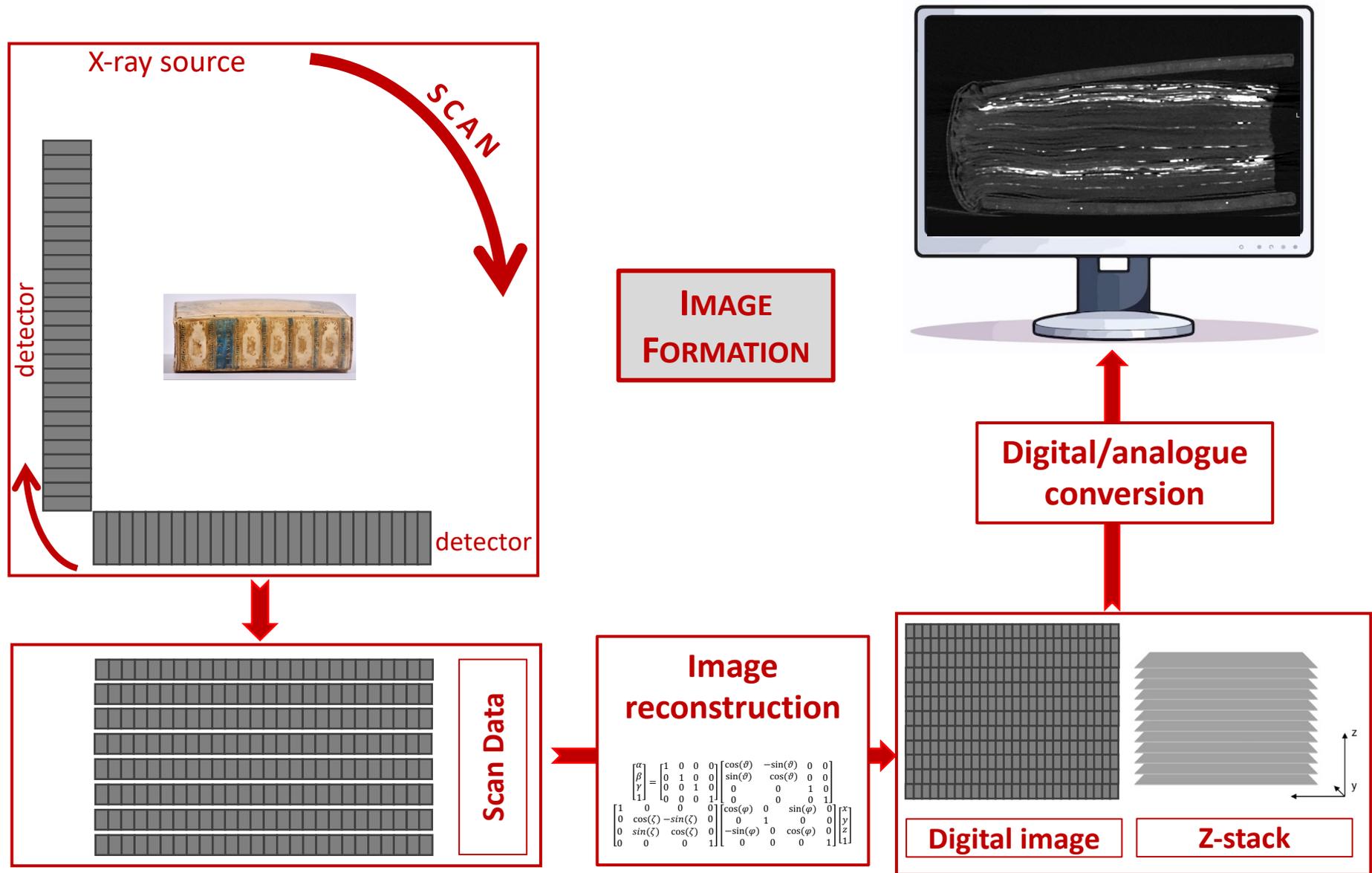


# Computed tomography: detection of X-rays

- Detector:
  - scintillating material transforms photons into visible light
  - light then strikes a photodiode, causing an electron flow within the diode matrix that is subsequently quantified.
- Compact micro-CT scanners
  - Use CCDs or small area CMOS image sensors (pixel pitch 5-10  $\mu\text{m}$ )



# Computed tomography: principles

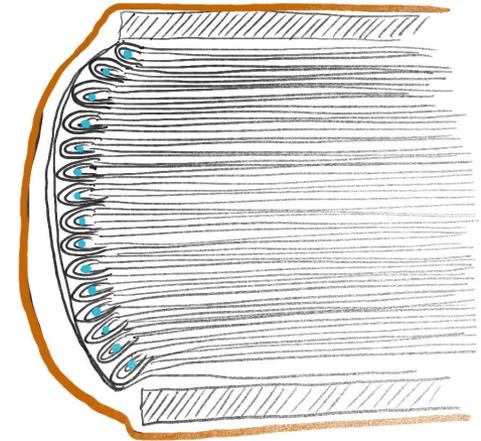
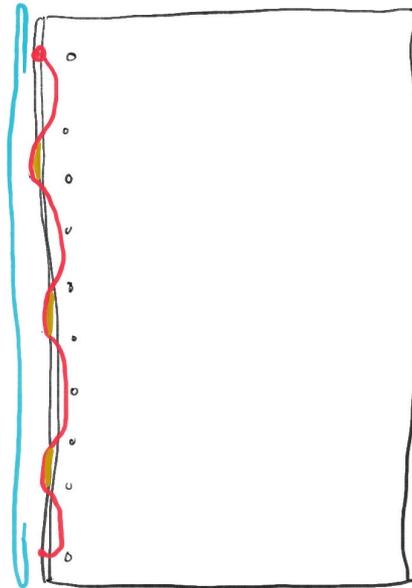
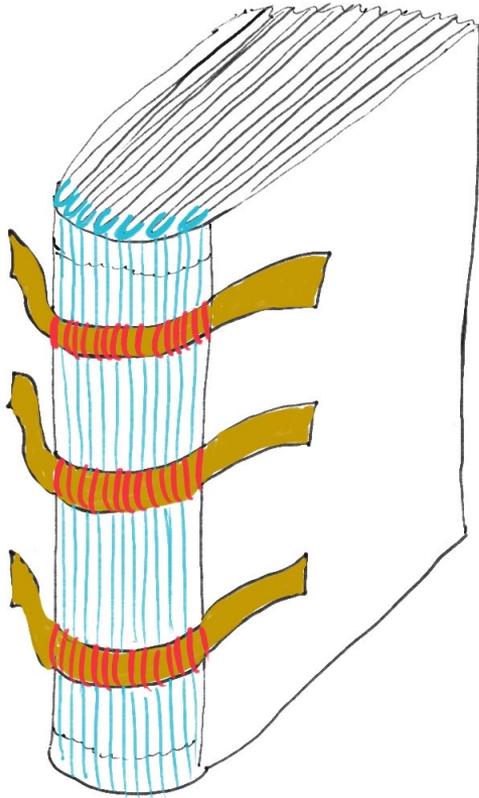


# Computed tomography: image reconstruction

- Computed tomography
  - reconstruct  $n$  dimension function (image)
  - it is a multi-dim inverse problem
  - uses *inverse Radon transform* to reconstruct the 3D image of an unknown object by using several 2D projections throughout the object (sinogram)
  - mathematical basis of the Radon transform and tomographic imaging were developed in 1917 by Johann Radon

# Simulations: mock-up sampler book

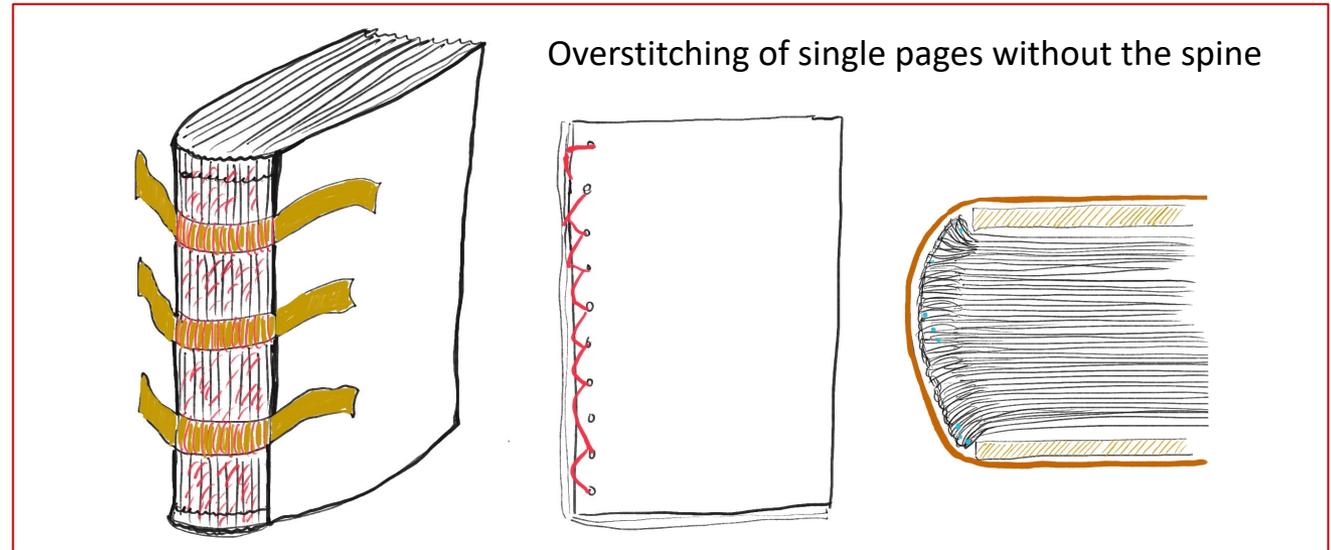
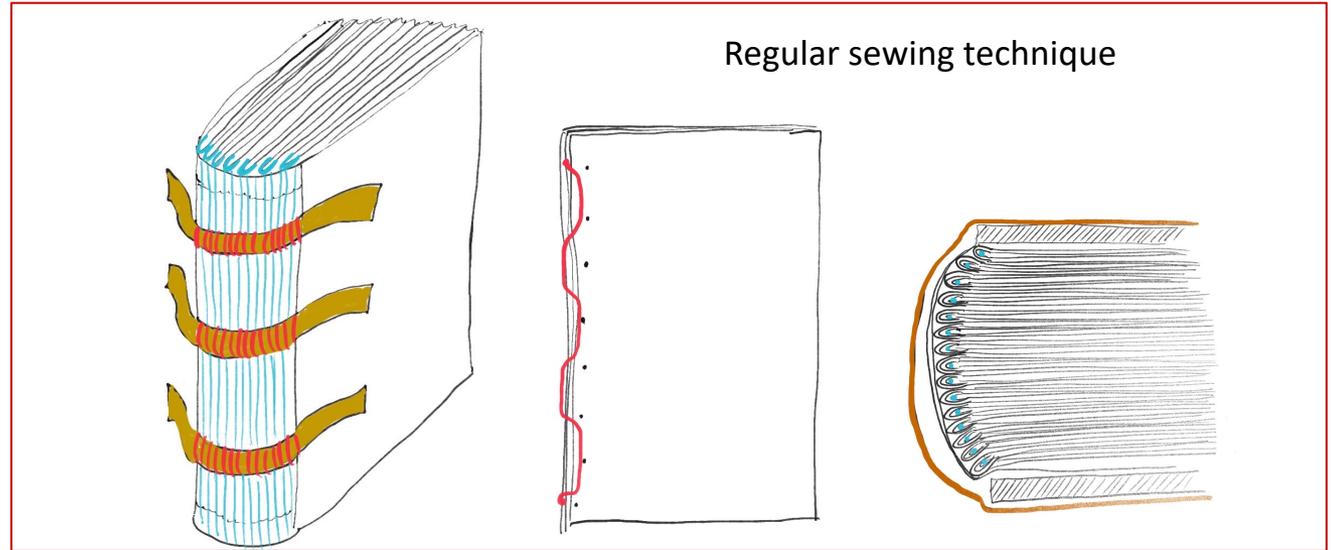
Expected structure of the bookbinding according to the knowledge of historical techniques and methods



# Simulations: mock-up sampler book

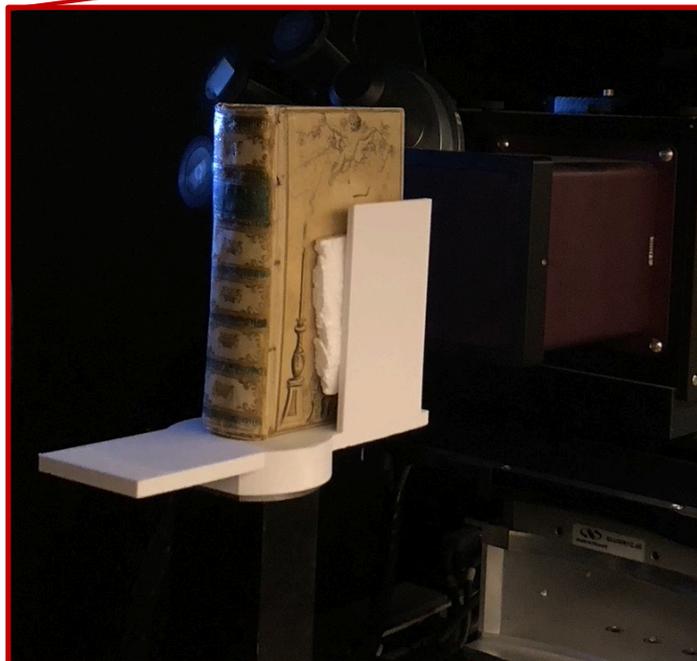
Sampler built in which various binding and stitching techniques are used

⇒ verify that different structures can be identified in micro-CT

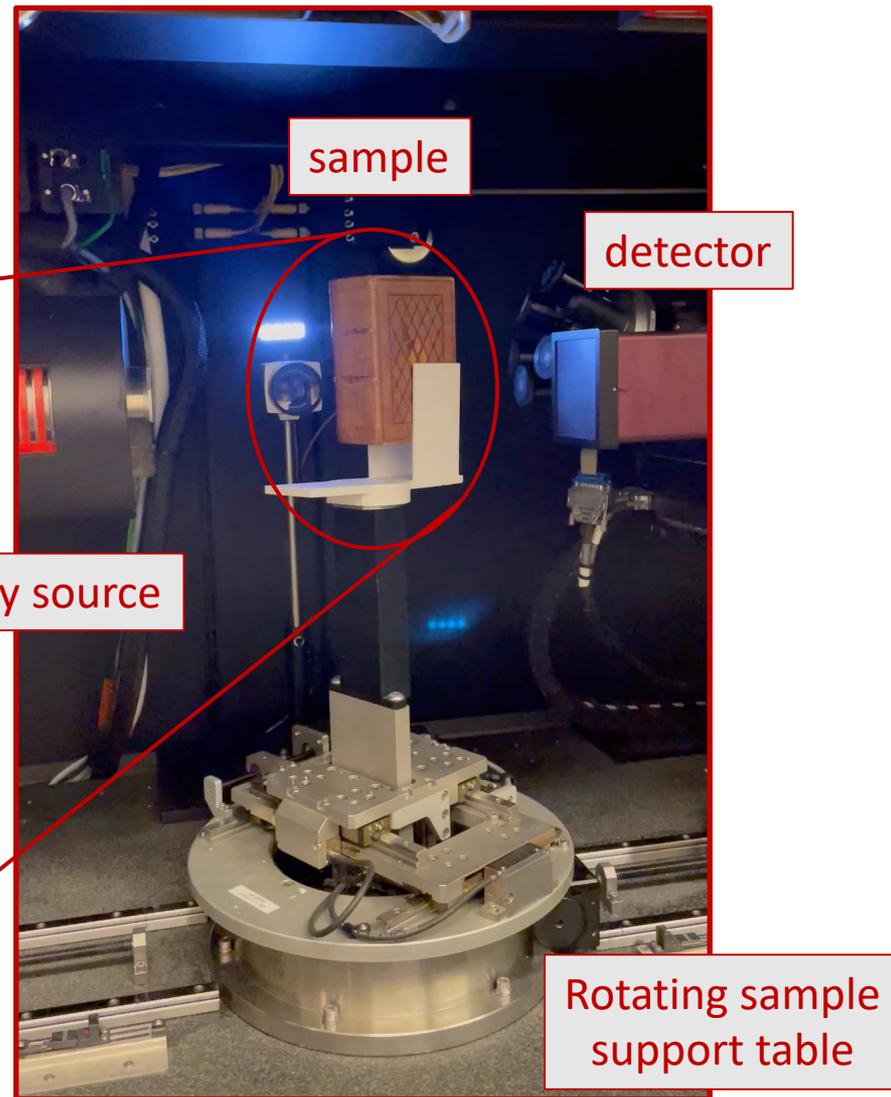


# micro-CT

HV: 100 kV  
P: 10 W  
I: 101  $\mu$ A  
Voxel: 45  $\mu$ m

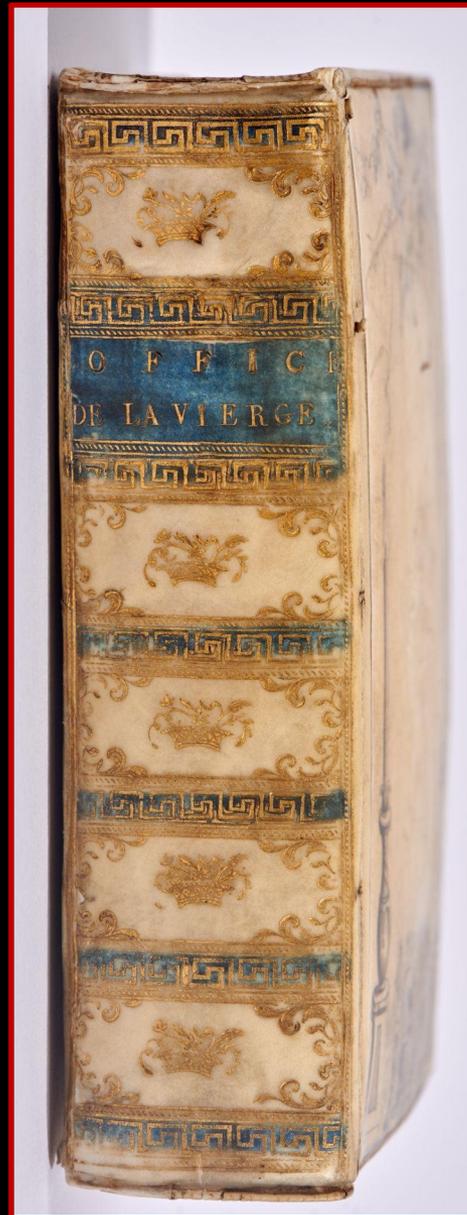
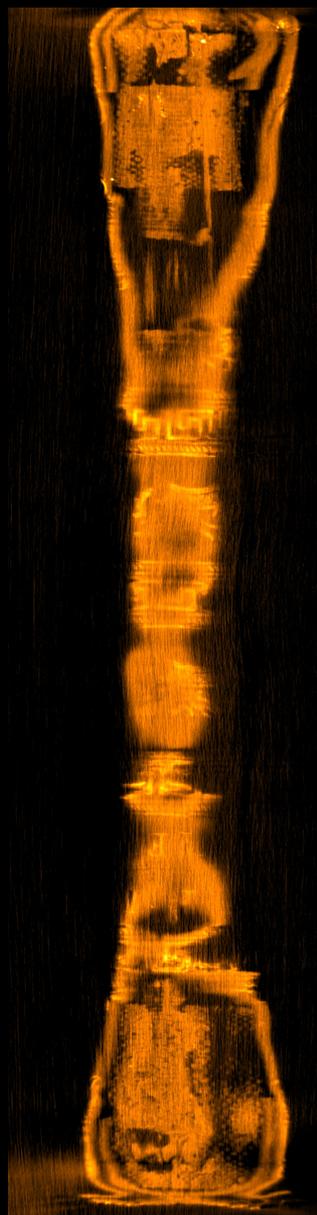


Micro XCT-400 xRadia scanner



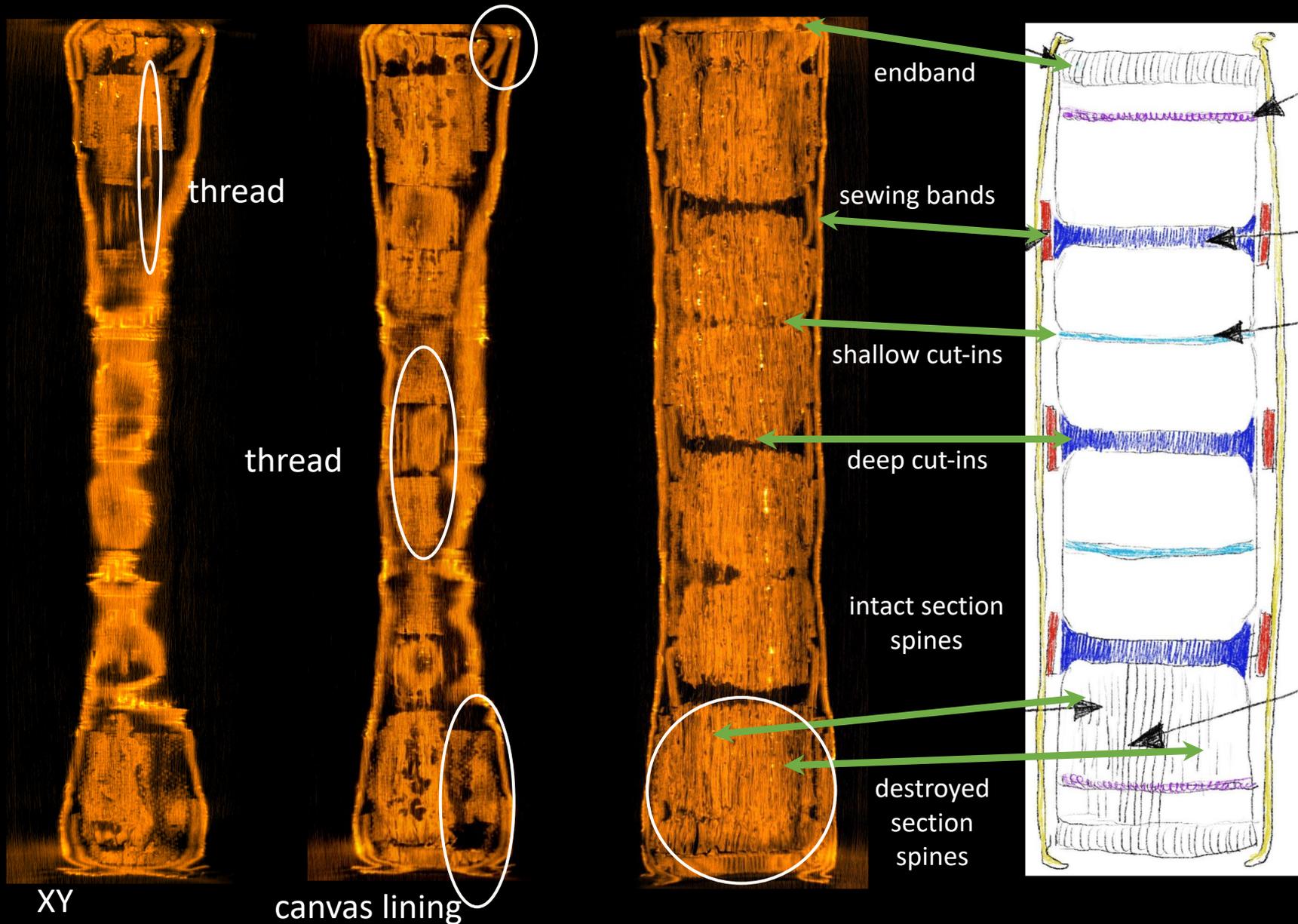
# Prayerbook: micro-CT before conservation

YZ projection



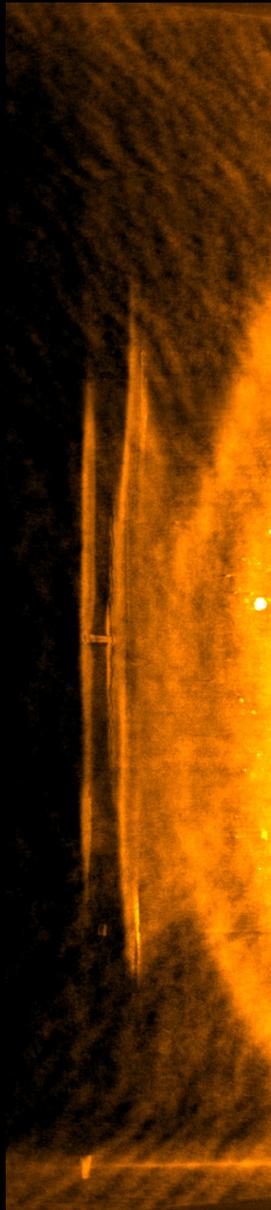
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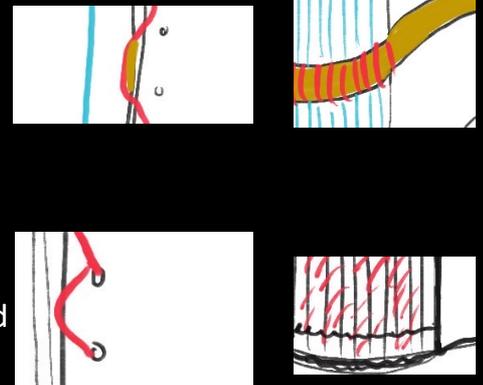
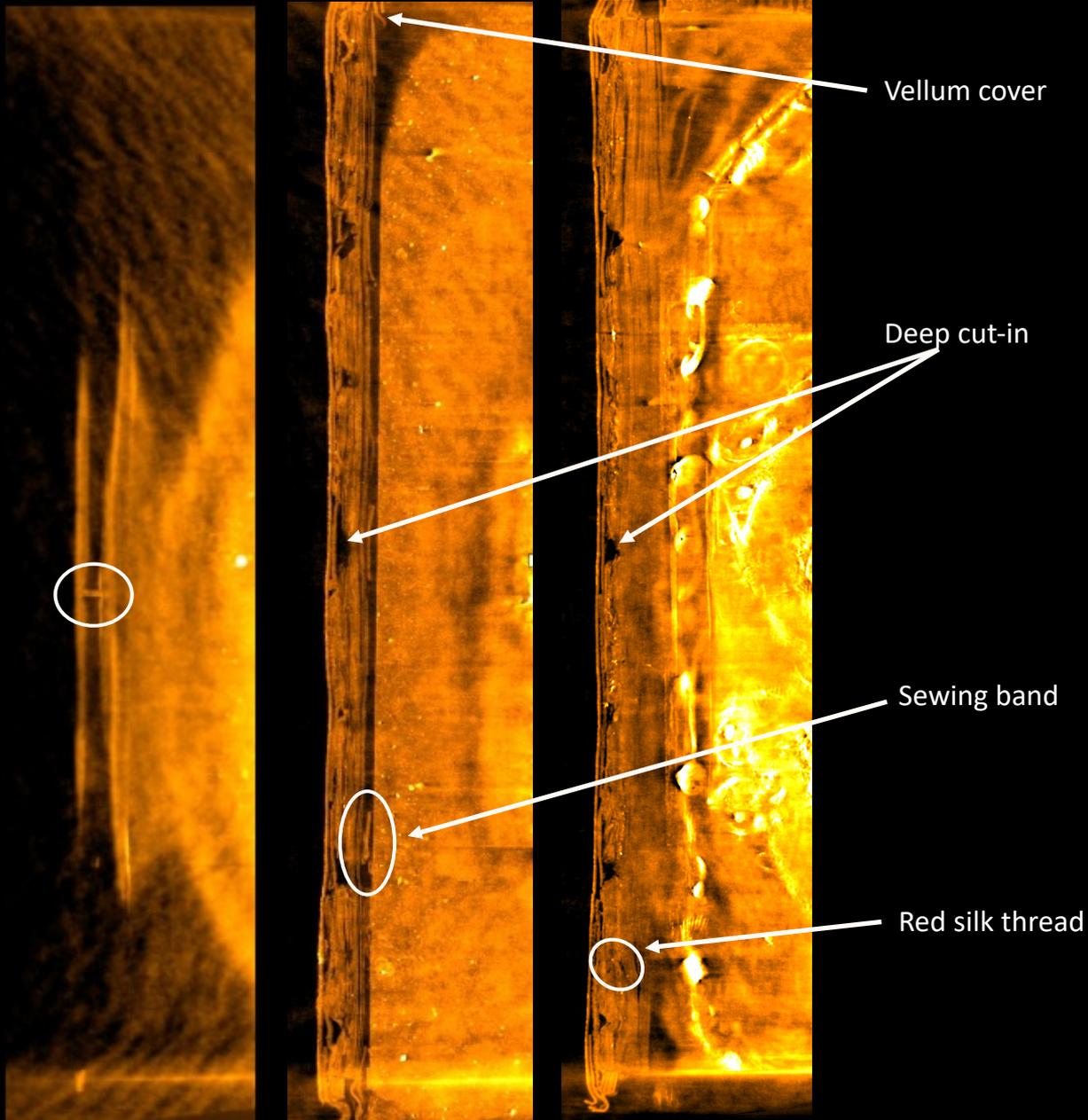
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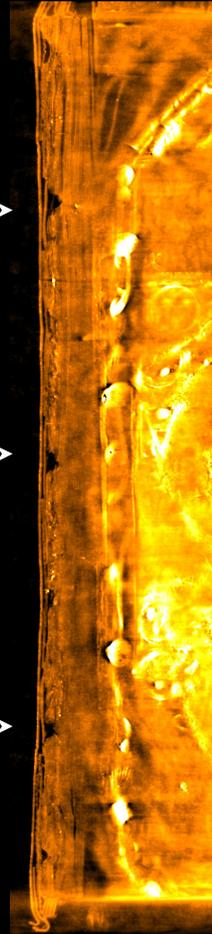
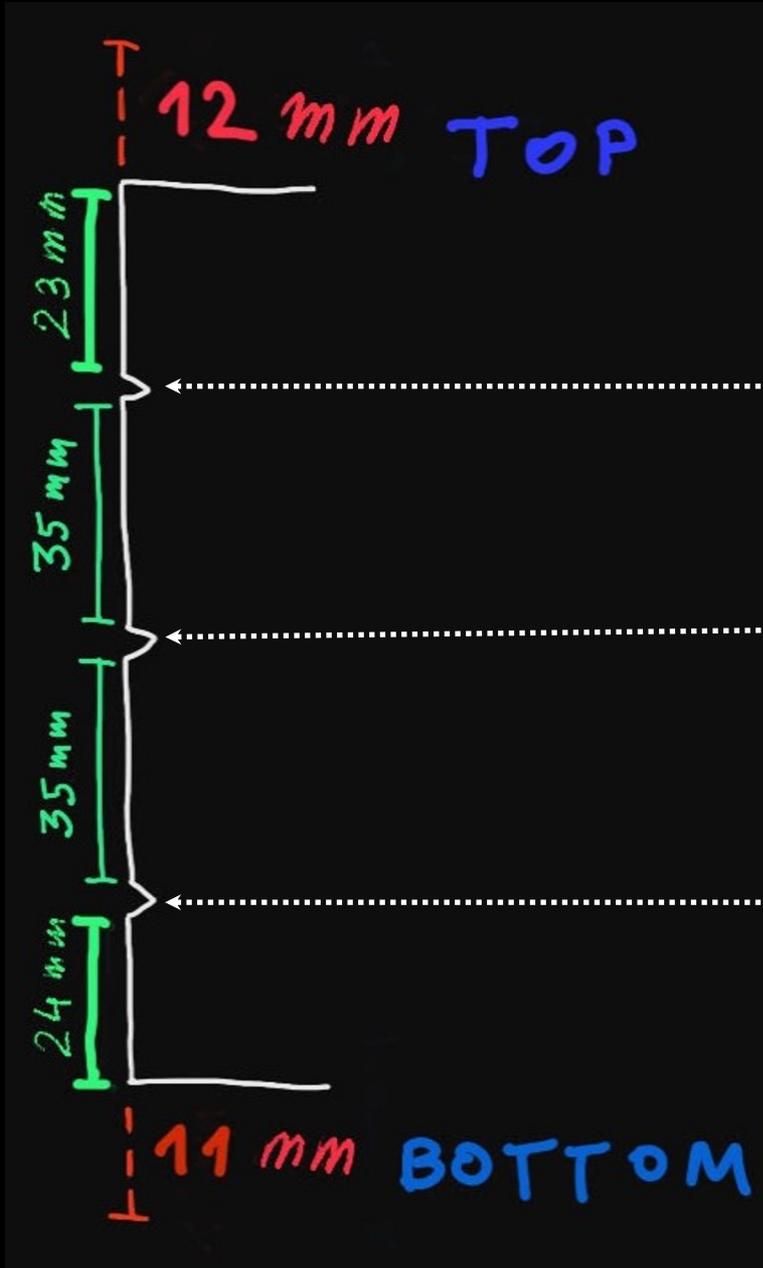
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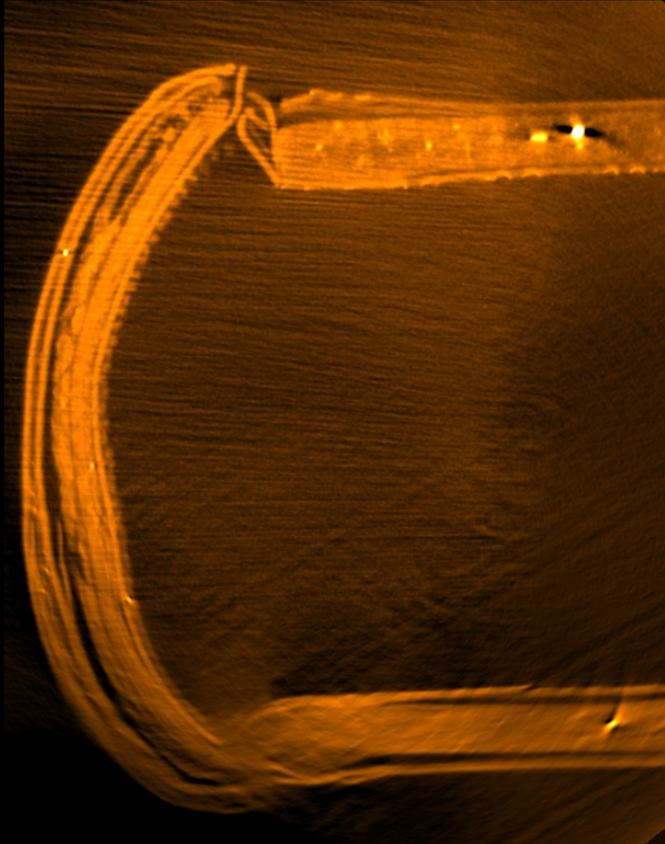
XZ projection



- Incision distance  
⇒ determined trimmed off top and bottom edges
- Side edge also likely trimmed
- Current size: 11.7 cm x 7 cm

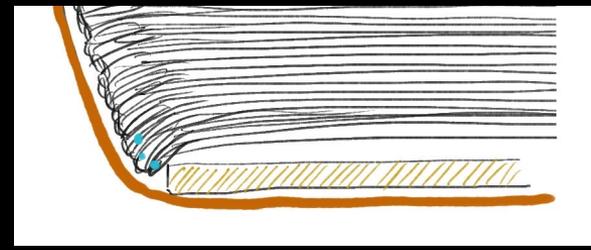
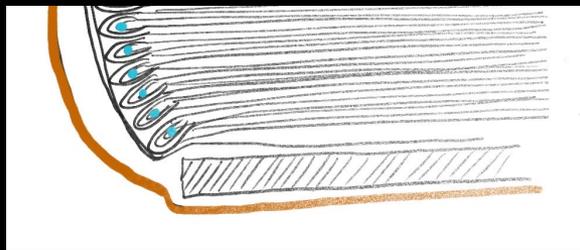
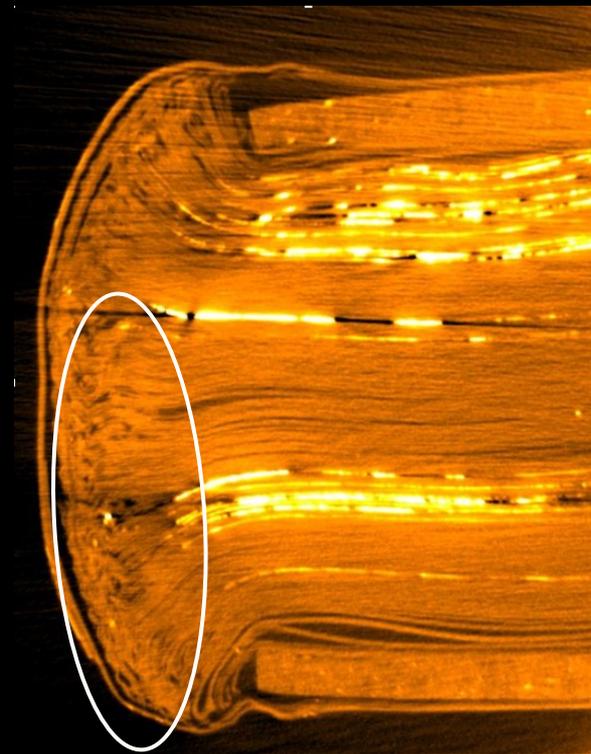
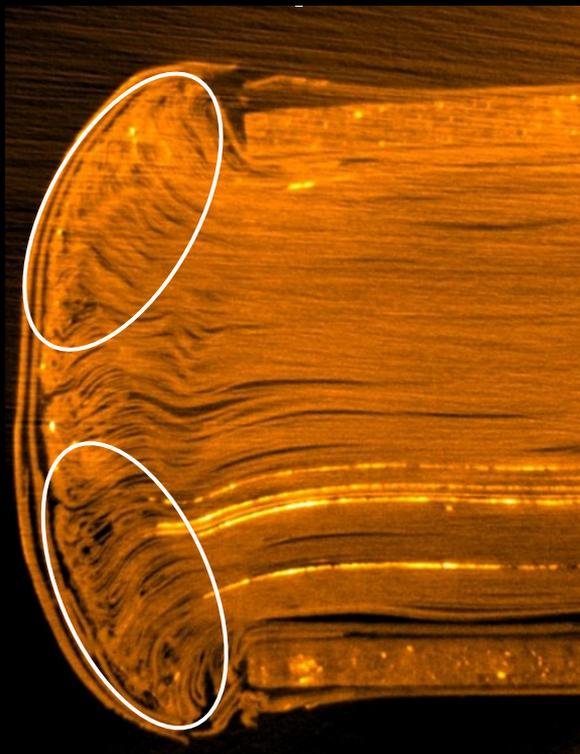
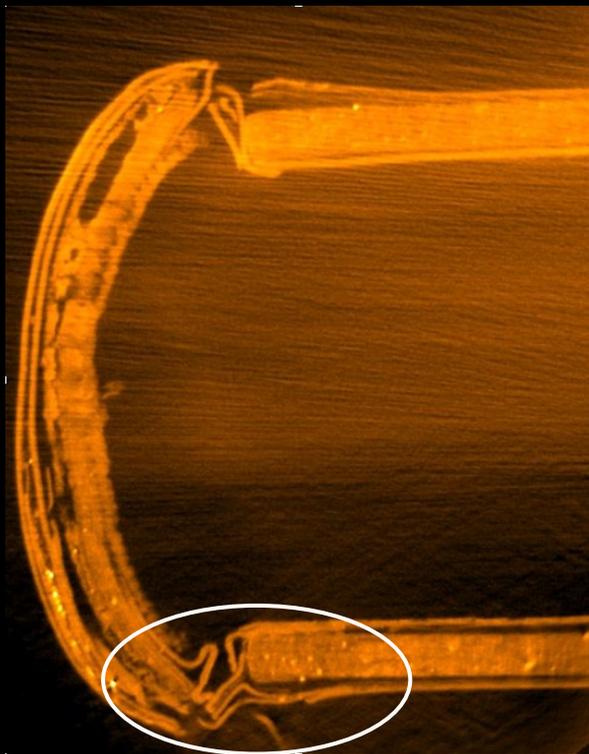
# Prayerbook: micro-CT before conservation

XY projection



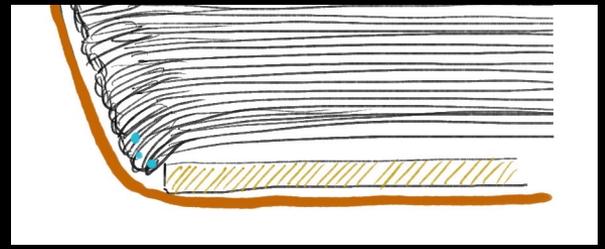
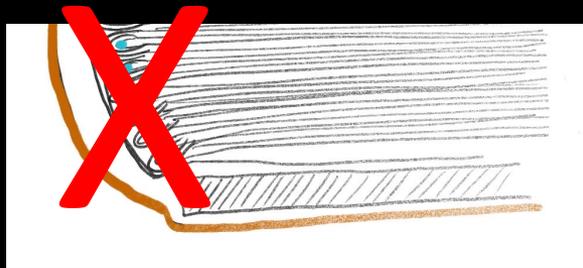
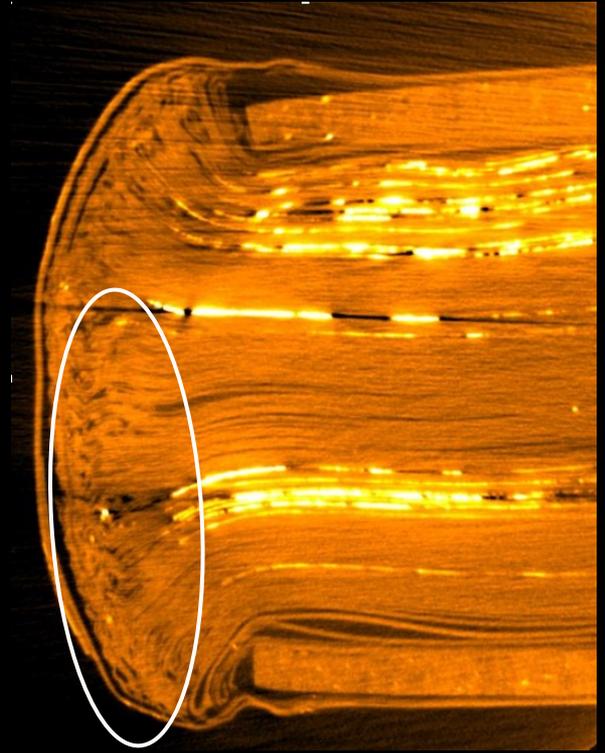
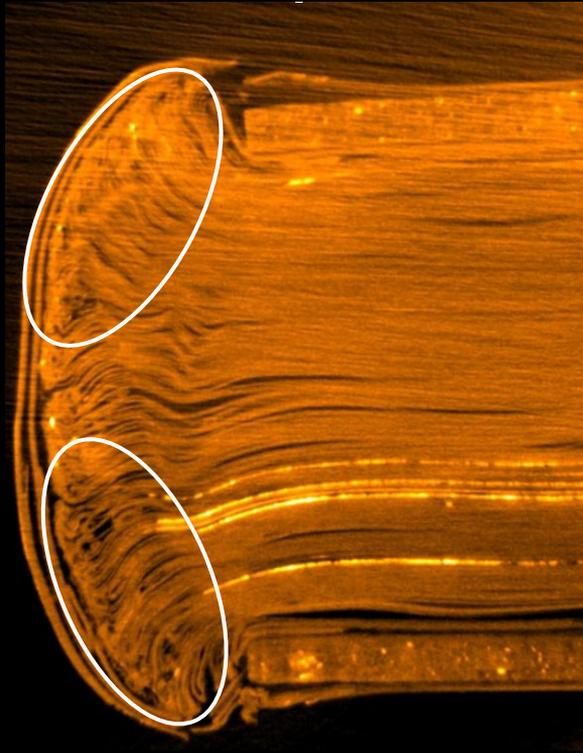
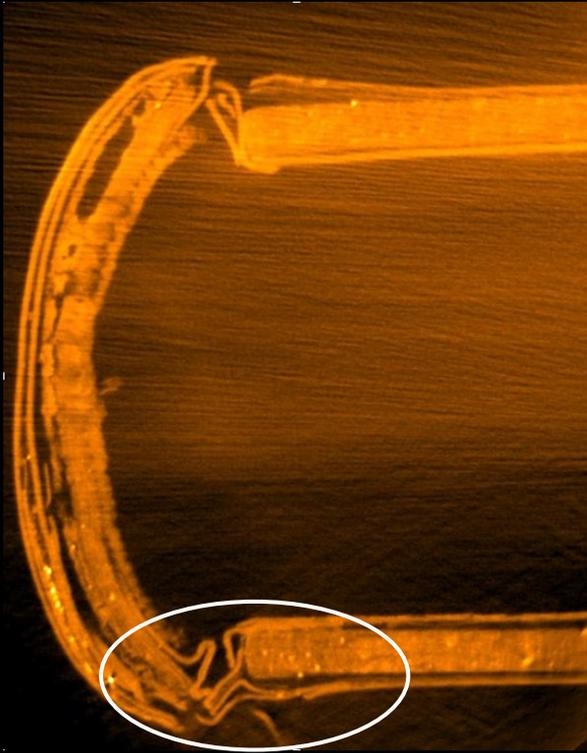
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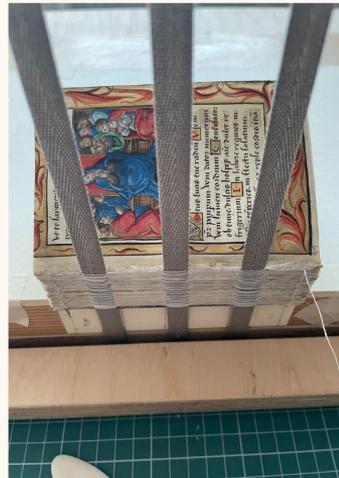
XY projection



# Prayerbook: micro-CT before conservation

XY projection



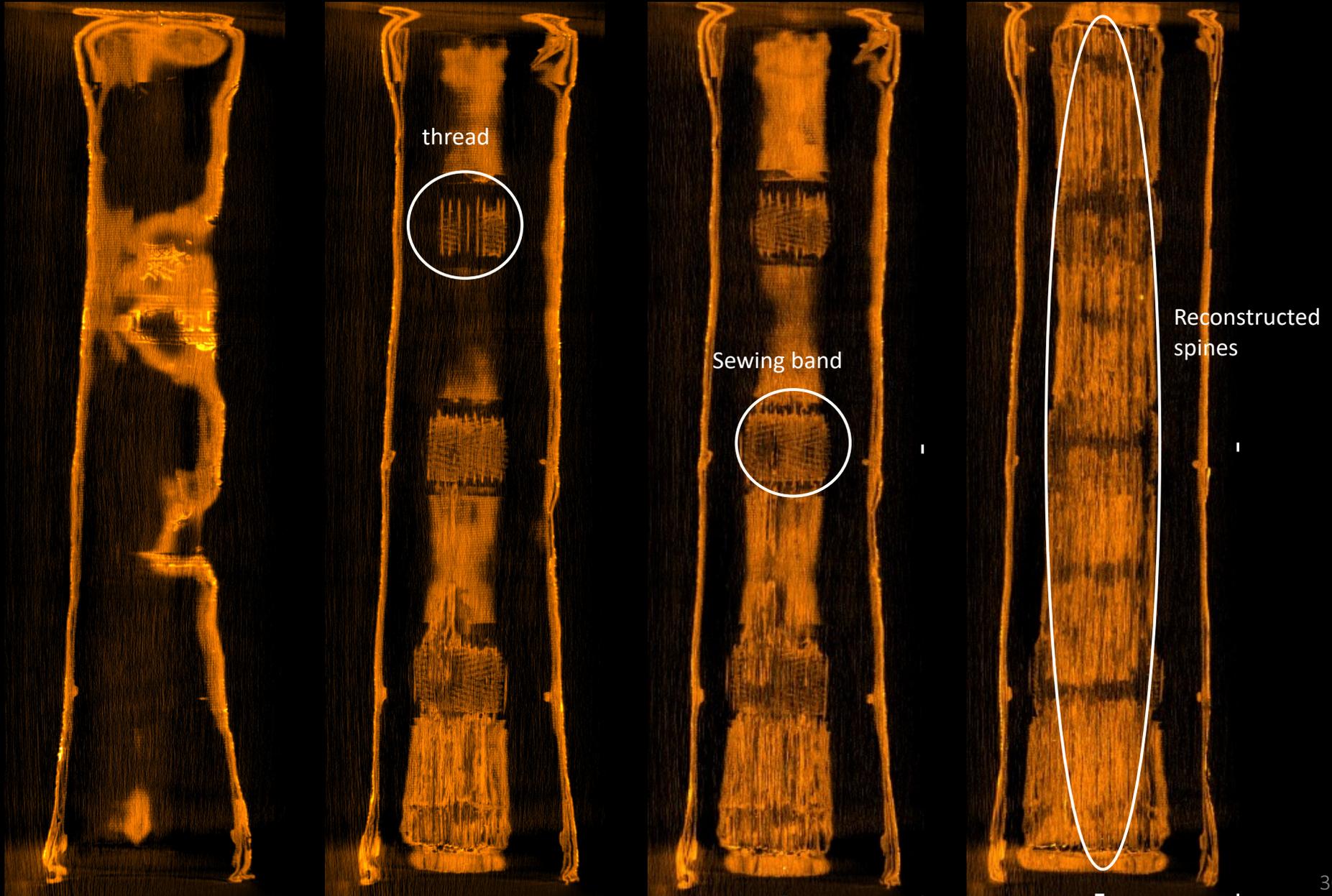


# Conservation and restoration



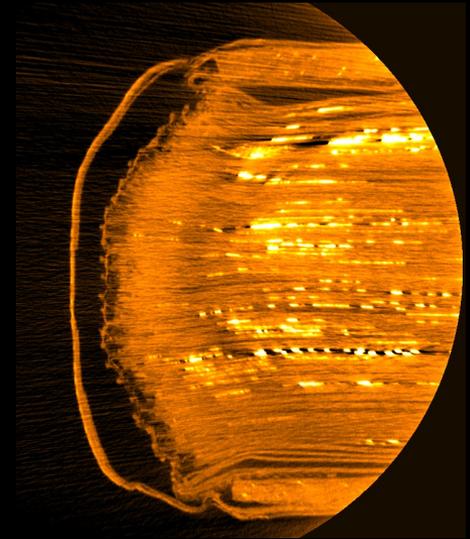
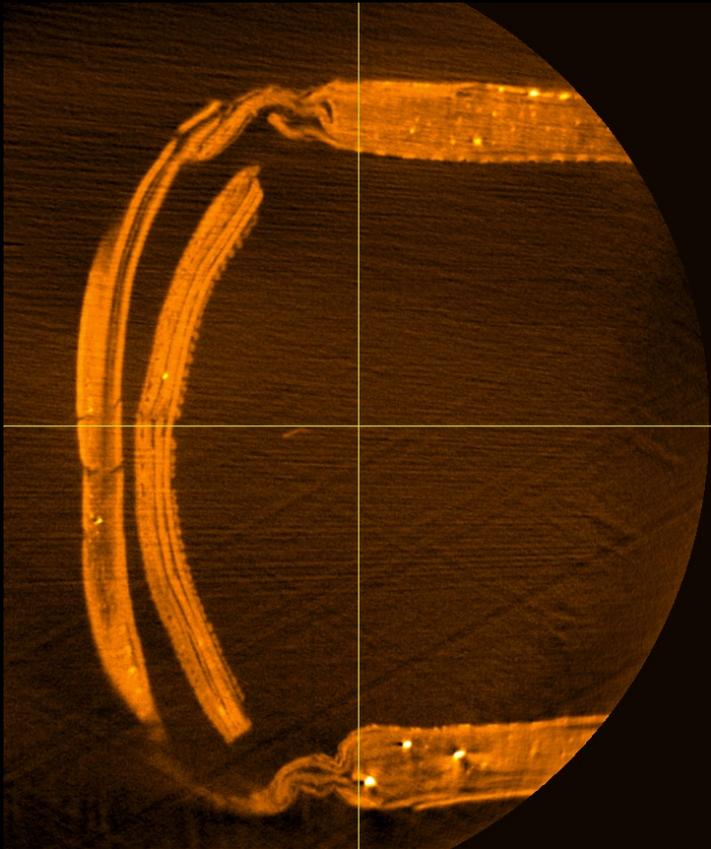
# Prayerbook: micro-CT after conservation

YZ projection

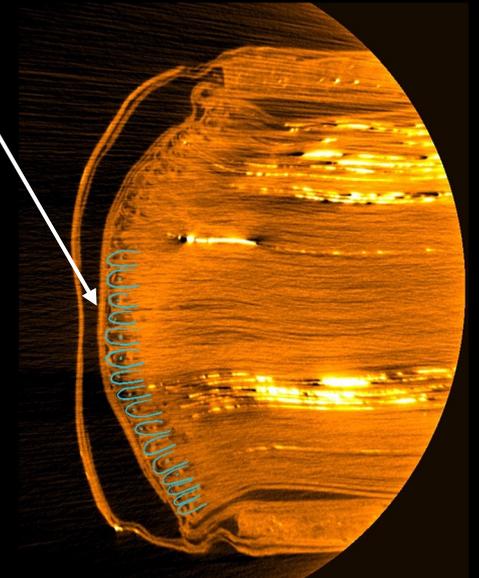
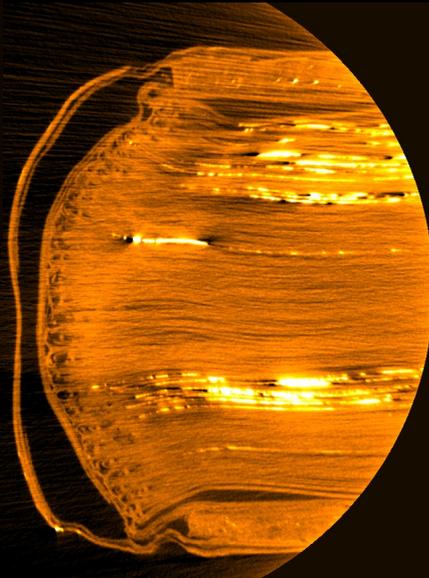


# Prayerbook: micro-CT after conservation

XY projection

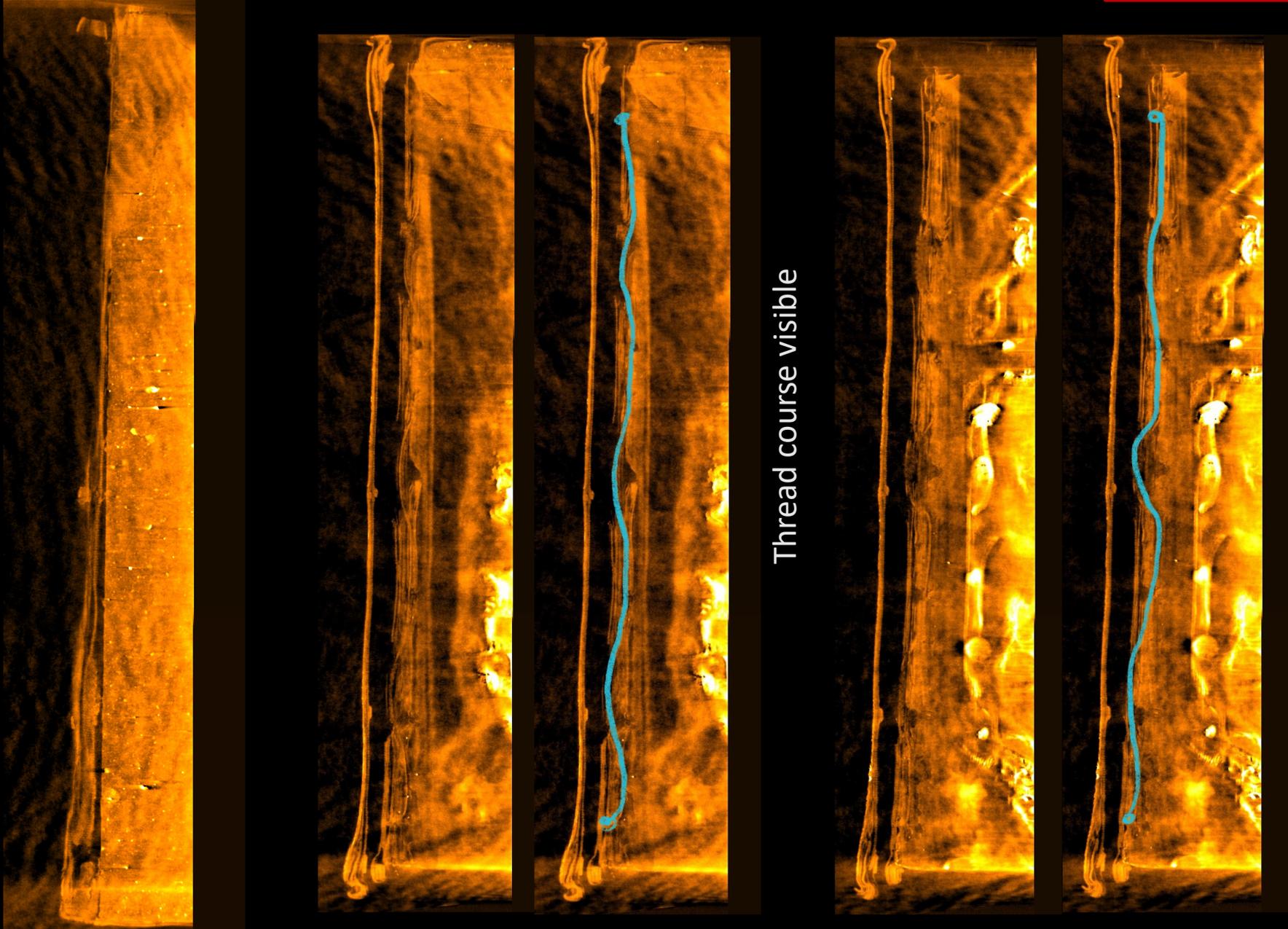


loops of the reconstructed spines  
(dot inside the loop is the thread of  
regular sewing)

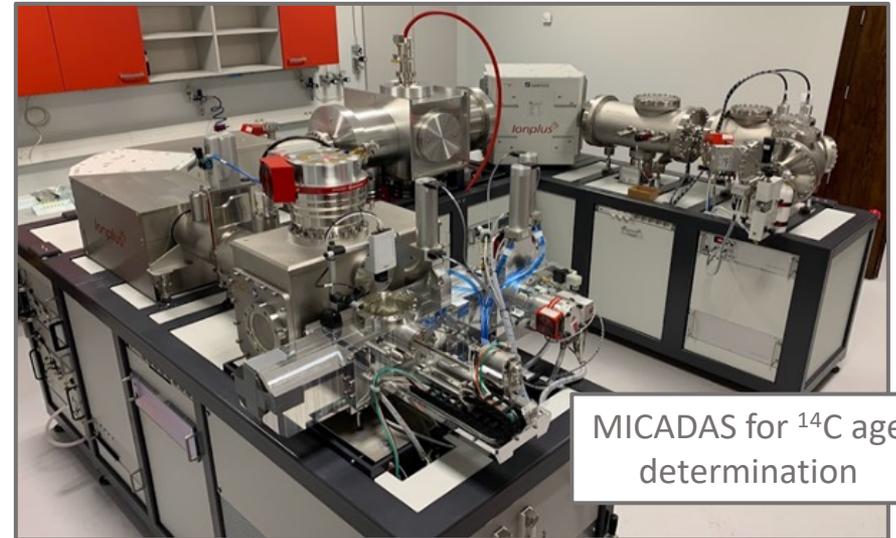


# Prayerbook: micro-CT before conservation

XZ projection



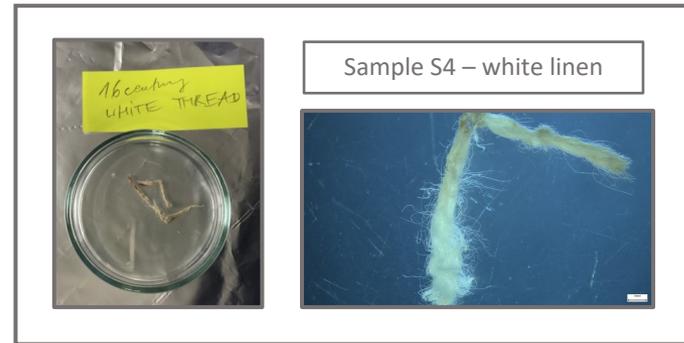
# Radiocarbon dating of the thread



**GLIWICE RADIOCARBON AND MASS SPECTROMETRY LABORATORY**

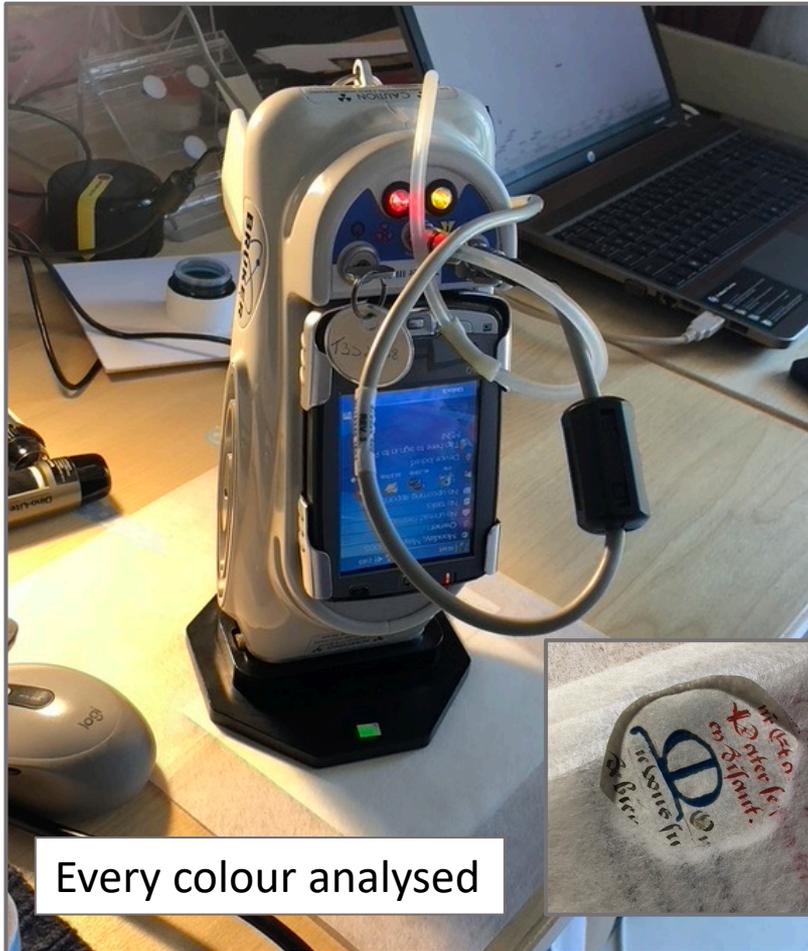
# Radiocarbon dating of the thread

4 samples of the thread used in the bindings could be analysed:



# XRF analysis: composition of pigments and inks

High-sensitivity for trace elements



Every colour analysed

Bruker Tracer-III-SD spectrometer

Mapping of the main components



Selected illuminations mapped

Bruker ELIO Spectrometer

# Summary and Outlook

- Micro-CT has proven to be an invaluable tool in diagnostic pre- and post-conservation of historical books, allowing to plan the course of the treatments and intervention in a fully non-destructive way
- C-14 dating of the sewing thread supports the conclusions on the history of the rebinding(s) of the book built during its restoration
- Non-destructive analysis conducted while the book was being restored (data under evaluation)
  - XRF (X-ray fluorescence spectroscopy) to study the composition of pigments, hues and inks as well as the vellum support
  - RTI (Reflectance Transformation Imaging) of the illuminations performed to study the painting technique
- Continuation is planned with the analysis of historical books of different period and geographical origin



Museum of King Jan III's Palace at Wilanów

Temporary exposition:  
*The Sobieskis and Stuarts – the Splendour and Spectre of the Crown*

October 25, 2025 – May 31, 2026

Thank you! to

Anna Kowalewska  
*Academia Copernicana, Toruń*

Jakub Jaroszewicz  
*Politechnika Warszawska, Warszawa*

Artur Bugaj, Aleksandra Towarek, Barbara Wagner, Barbara Żelazko  
*Uniwersytet Warszawski, Warszawa*

Natalia Piotrowska, Alicja Ustrzycka  
*Politechnika Śląska, Gliwice*

Mirosław Wachowiak  
*Uniwersytet Mikołaja Kopernika w Toruniu, Toruń*