


X-ray synchrotron microtomography helps to reveal the past: Principles

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European Synchrotron Radiation Facility history

- Opened in 1994
- 21 partners nations
- 43 beamlines
- More than 6000 scientific users as employees or visiting scientists
- 3rd generation synchrotron
- 6GeV and up to 200mA



@ESRF

Not the only ring of power over the world !!!



@Veqter

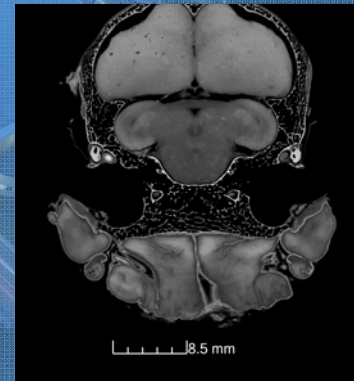
X-rays as a visualization tool

Discovered by Wilhelm Röntgen

Electromagnetic wave of high energy and short wavelength

Can penetrate many kind of materials

Energy between 0.1KeV and 100KeV

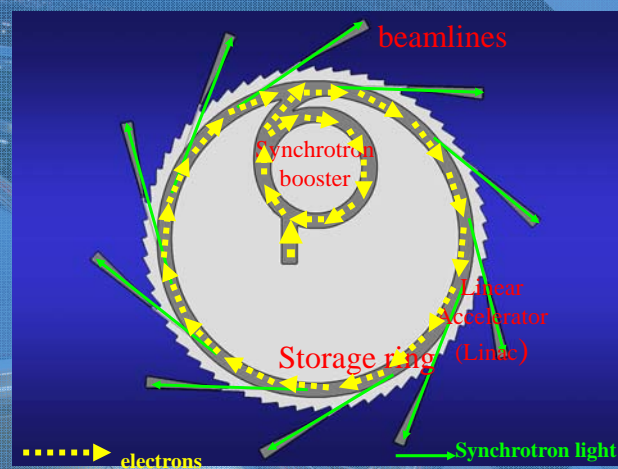


Principles of synchrotron radiation Discovery of synchrotron radiation (1st generation)

Synchrotron radiation is a polarized radiation emitted by a charged particle spinning in a magnetic field

In case of electrons, they are deviated by magnetic device,
Loss of energy as synchrotron light
First considered as parasitic noise

Dedicated sources and increasing power in 2nd generation



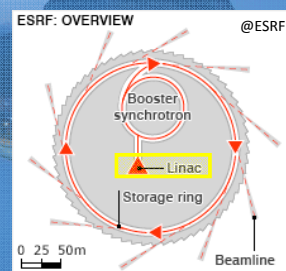
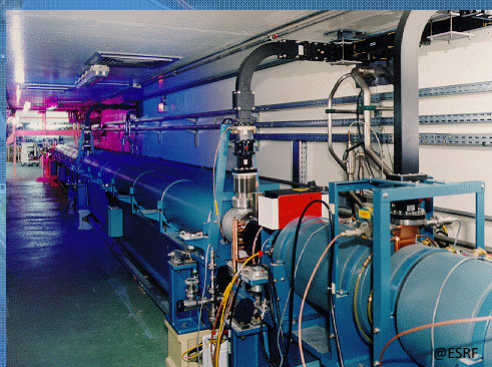
@From Tafforeau

3rd generation synchrotron organization General structure



3rd generation synchrotron organization LINAC

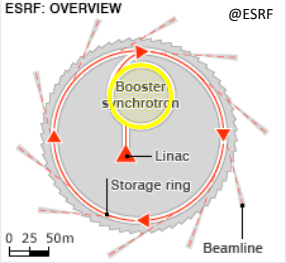
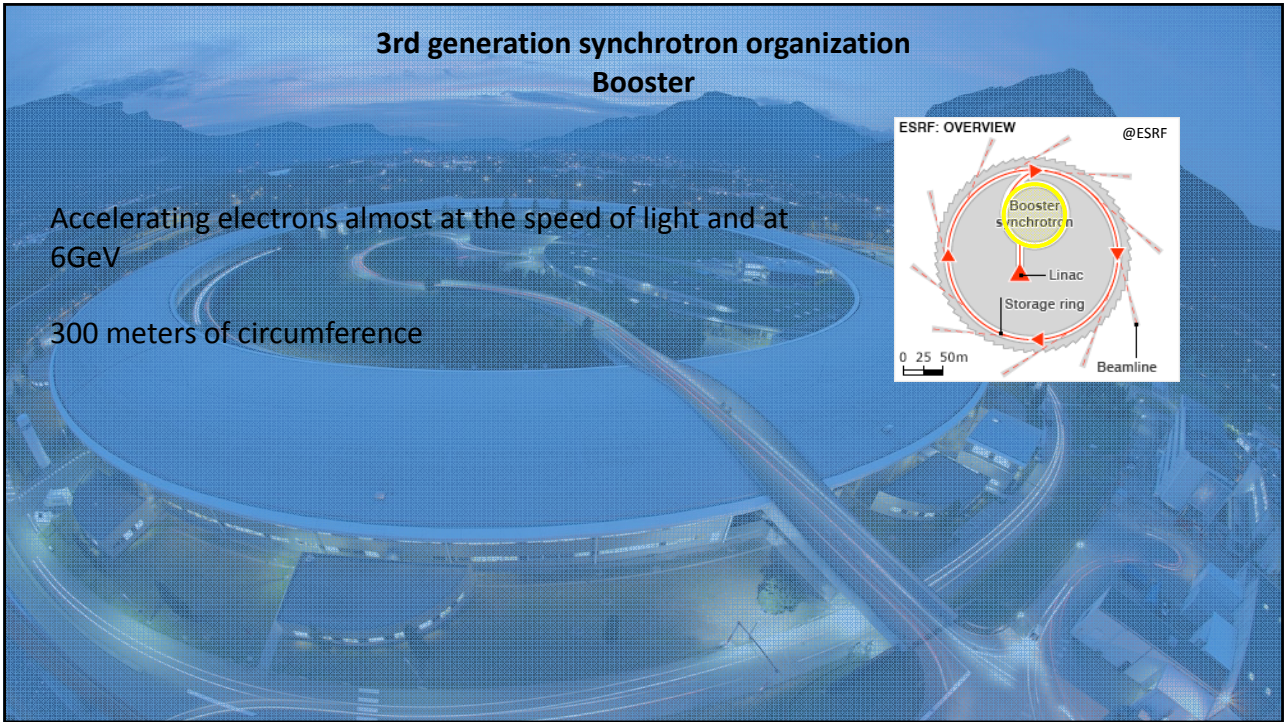
LINear ACcelerator
100KeV triode gun



Release bunches of electrons at 200MeV

3rd generation synchrotron organization Booster

Accelerating electrons almost at the speed of light and at 6GeV
300 meters of circumference

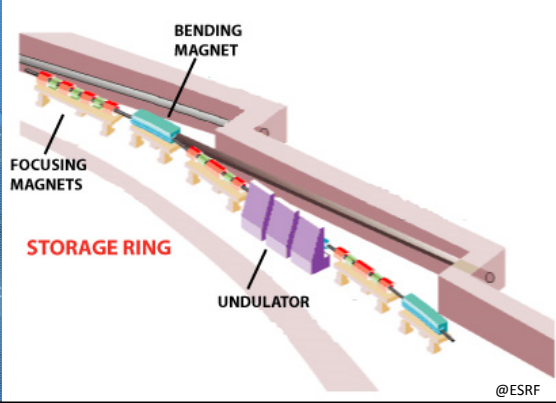
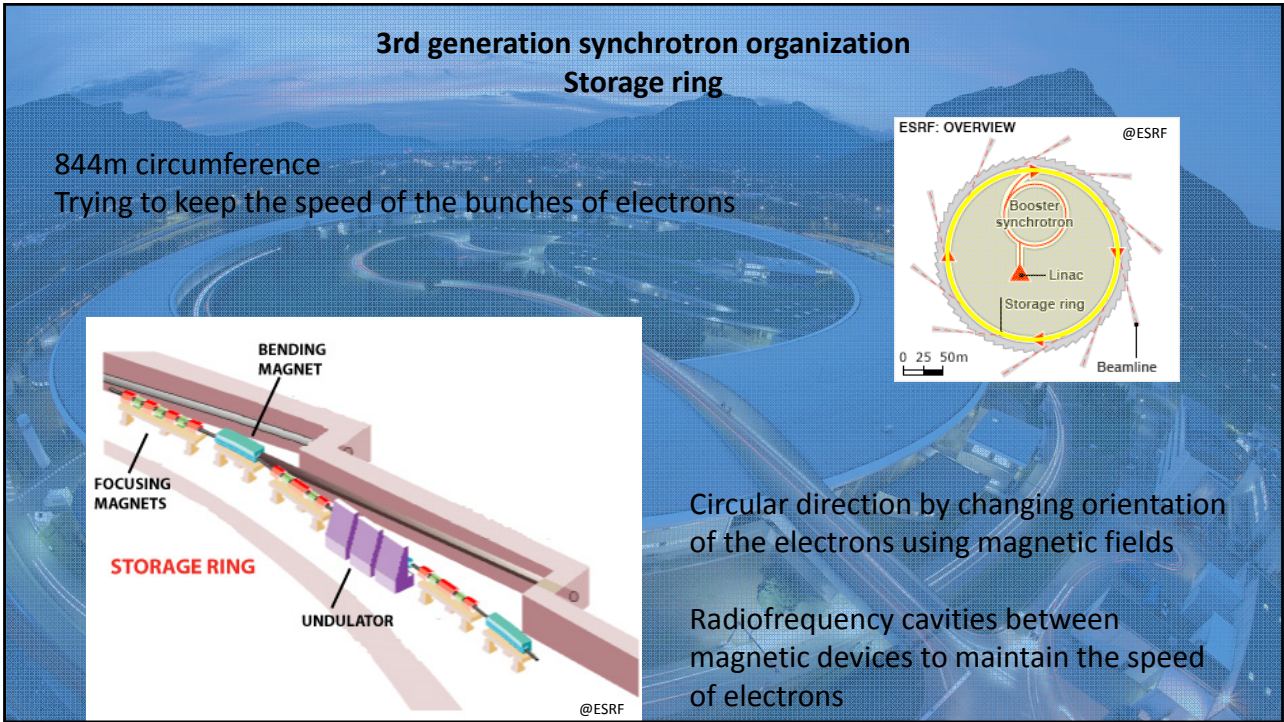


ESRF: OVERVIEW @ESRF

The diagram shows a circular layout with a central 'Booster synchrotron' (yellow circle), a 'Linac' (red triangle), a 'Storage ring' (red circle), and a 'Beamline' (red arrows pointing outwards). A scale bar indicates 0, 25, and 50 meters.

3rd generation synchrotron organization Storage ring

844m circumference
Trying to keep the speed of the bunches of electrons



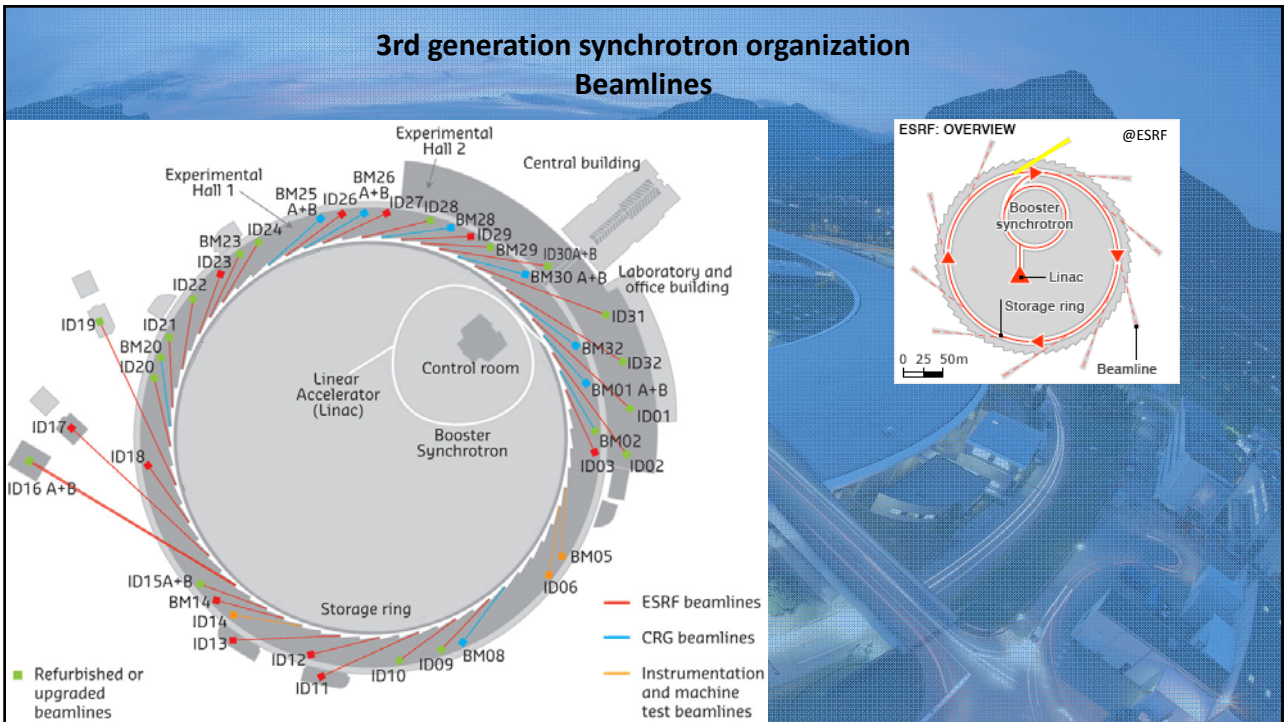
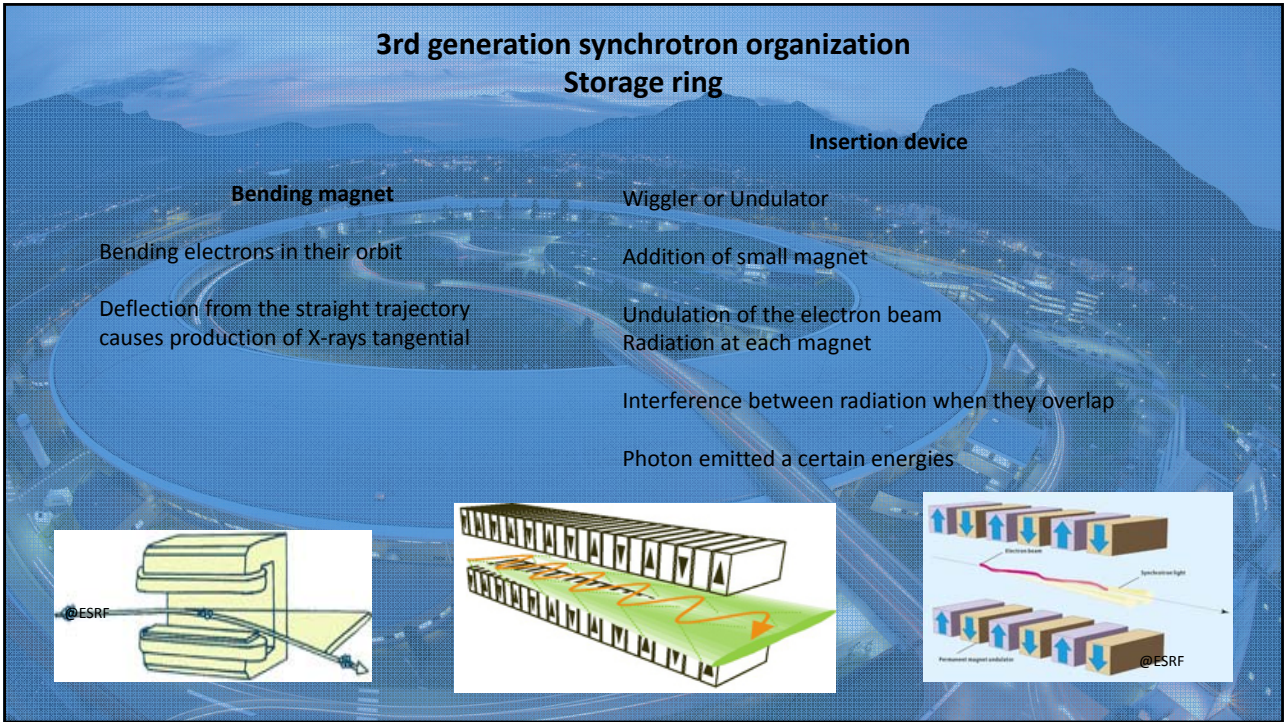
BENDING MAGNET
FOCUSING MAGNETS
STORAGE RING
UNDULATOR

ESRF: OVERVIEW @ESRF

The diagram shows a circular layout with a central 'Booster synchrotron' (yellow circle), a 'Linac' (red triangle), a 'Storage ring' (red circle), and a 'Beamline' (red arrows pointing outwards). A scale bar indicates 0, 25, and 50 meters.

Circular direction by changing orientation of the electrons using magnetic fields

Radiofrequency cavities between magnetic devices to maintain the speed of electrons



3rd generation synchrotron organization Beamlines

Beam passing through devices on the optical hutch (filters, monochromators,...)
To have the required energy and flux of the beam

Sample, detectors and cameras on the experimental hutch

Labels in diagram: Station de travail, Cabine d'expérience, Cabine optique, Ligne de lumière, Accélérateur, Linac, Booster, Anneau de stockage, Lignes de lumière, Lumière synchrotron.

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ESRF: OVERVIEW @ESRF

Labels in schematic: Booster synchrotron, Linac, Storage ring, Beamline.

Scale: 0 25 50m

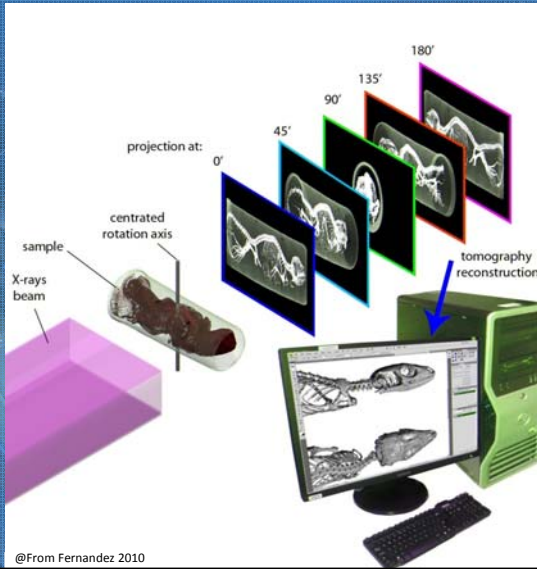
Large range of possible uses of a synchrotron

Diffraction contrast tomography	Laminography	Tomography Radiography
Phase contrast imaging	X-ray diffraction	Coherent diffraction imaging
Small angle X-ray scattering	Magnetic optical Kerr effect	Diffraction anomalous fine structure
X-ray photon correlation spectroscopy	X-ray reflectivity	X-ray fluorescence
Powder diffraction	X-ray dichroism	X-ray detected magnetic resonance

Tomography Definition

Computerized reconstruction of cross-sectional slices within a bulky object, based on 2D radiographs collected during rotational movement

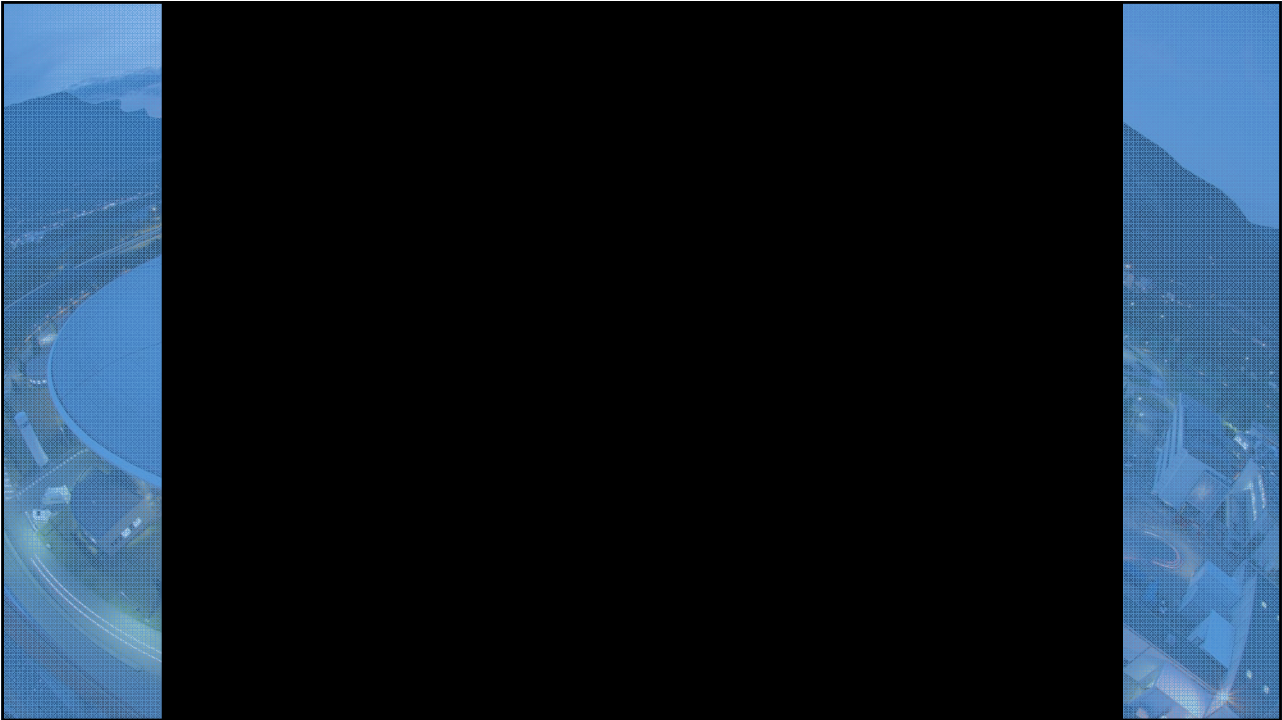
Advantage of accessing non-directly visible information without destroying the specimen



@From Fernandez 2010



@From Tafforeau



Tomography Methods

Absorption based CT

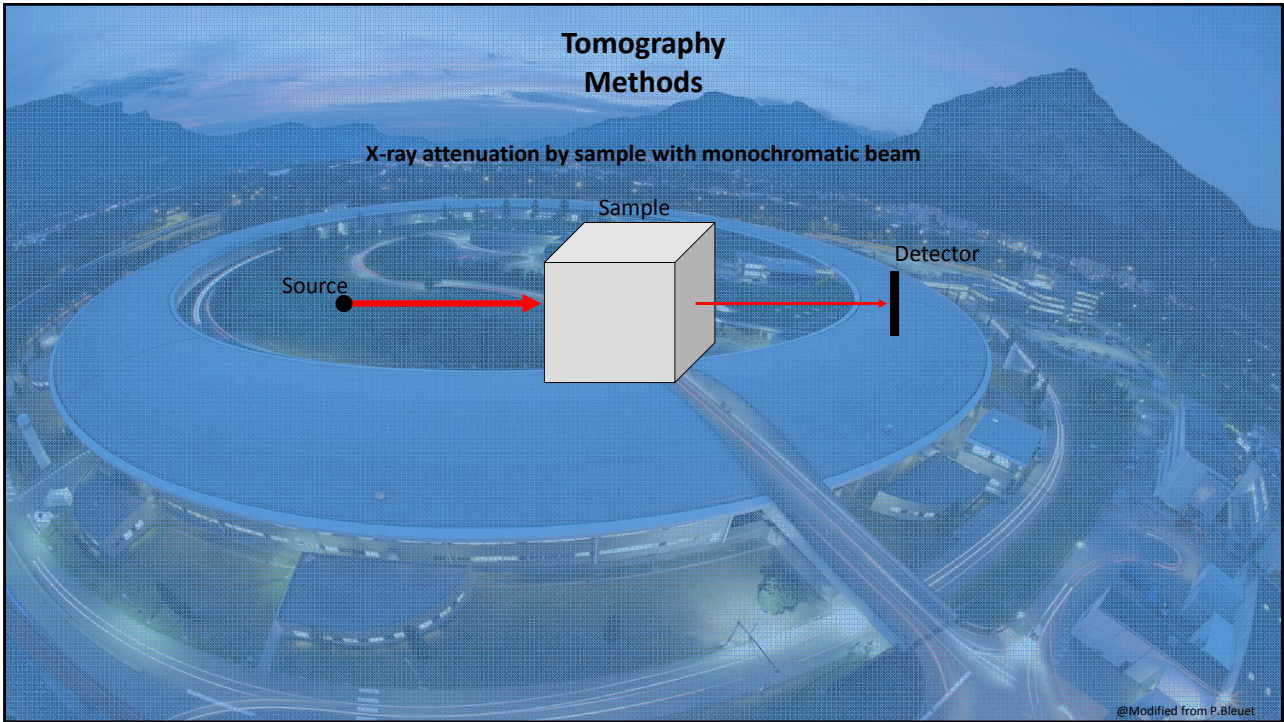
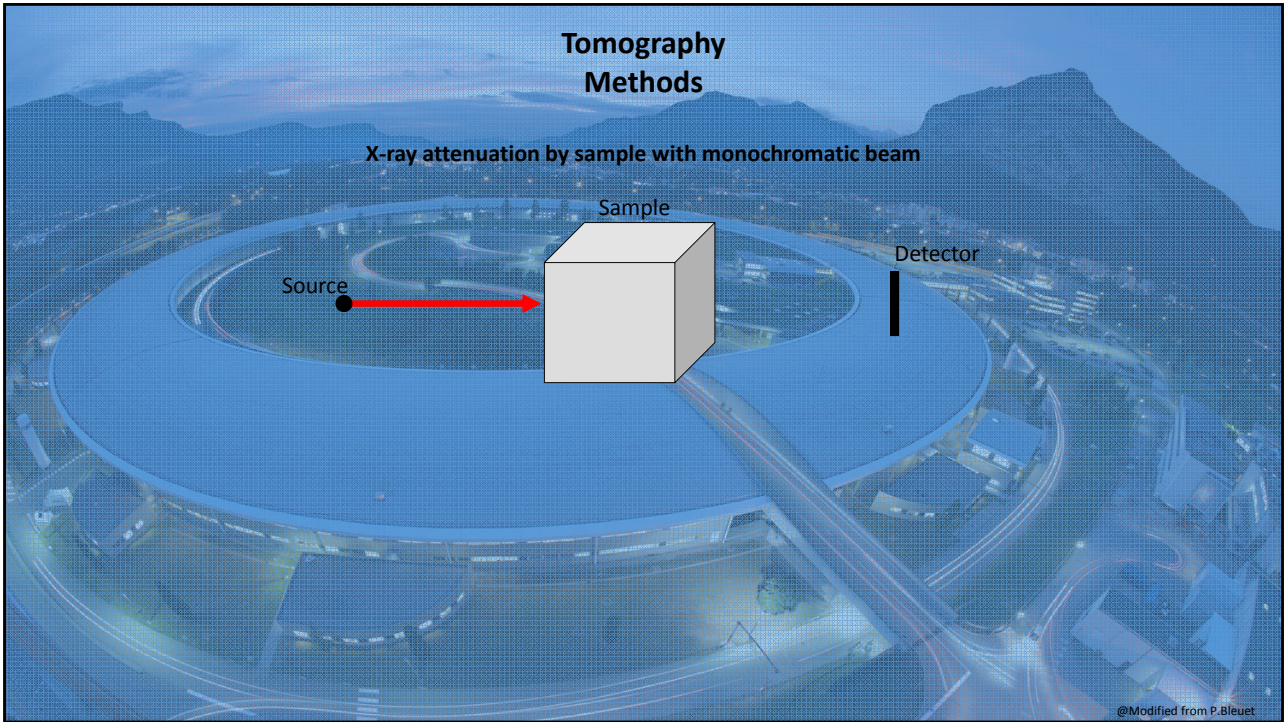
The diagram illustrates the components of an absorption-based CT scanner. A yellow beam of radiation enters from the right, passing through a 'white beam' source and a 'double Si 111 monochromator'. The beam then passes through a 'scintillator' and a 'rotation stage' where a 'sample' is positioned. The beam is reflected by a 'mirror' and passes through an 'eye-piece' and a 'magnification lens' to reach a 'CCD chipset'. An 'FReLoN camera' is positioned above the sample to capture the beam's path.

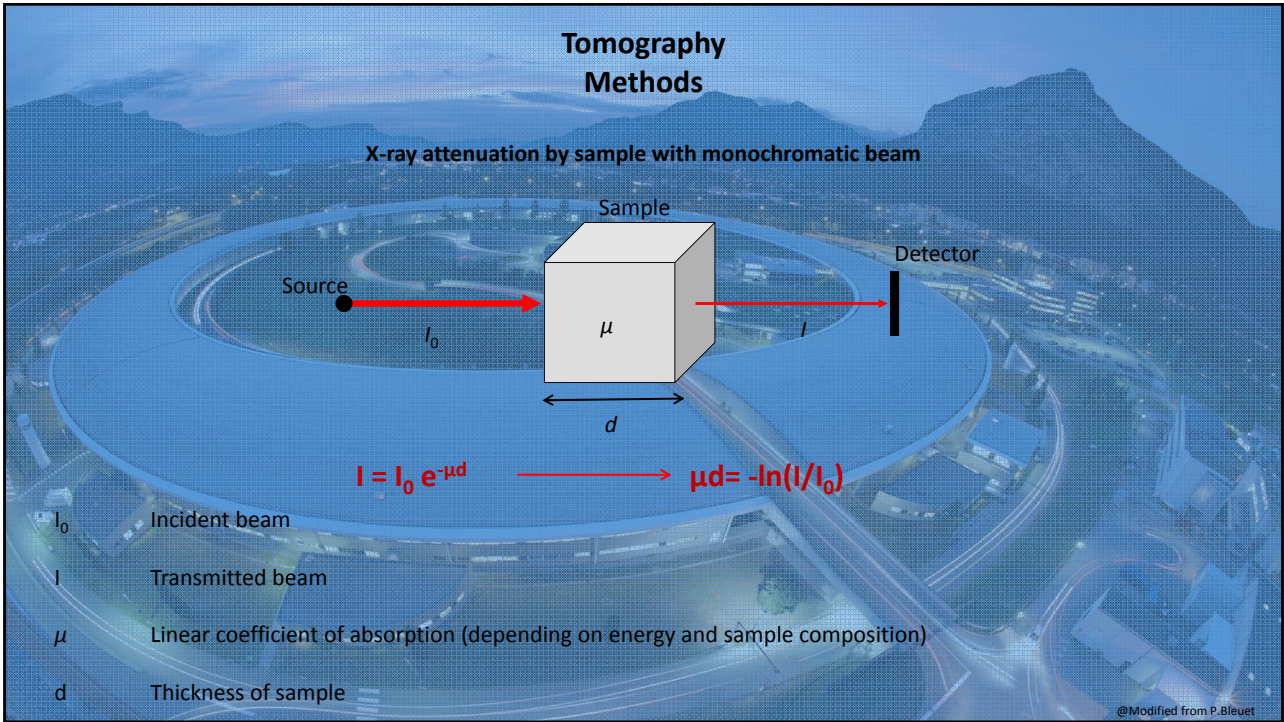
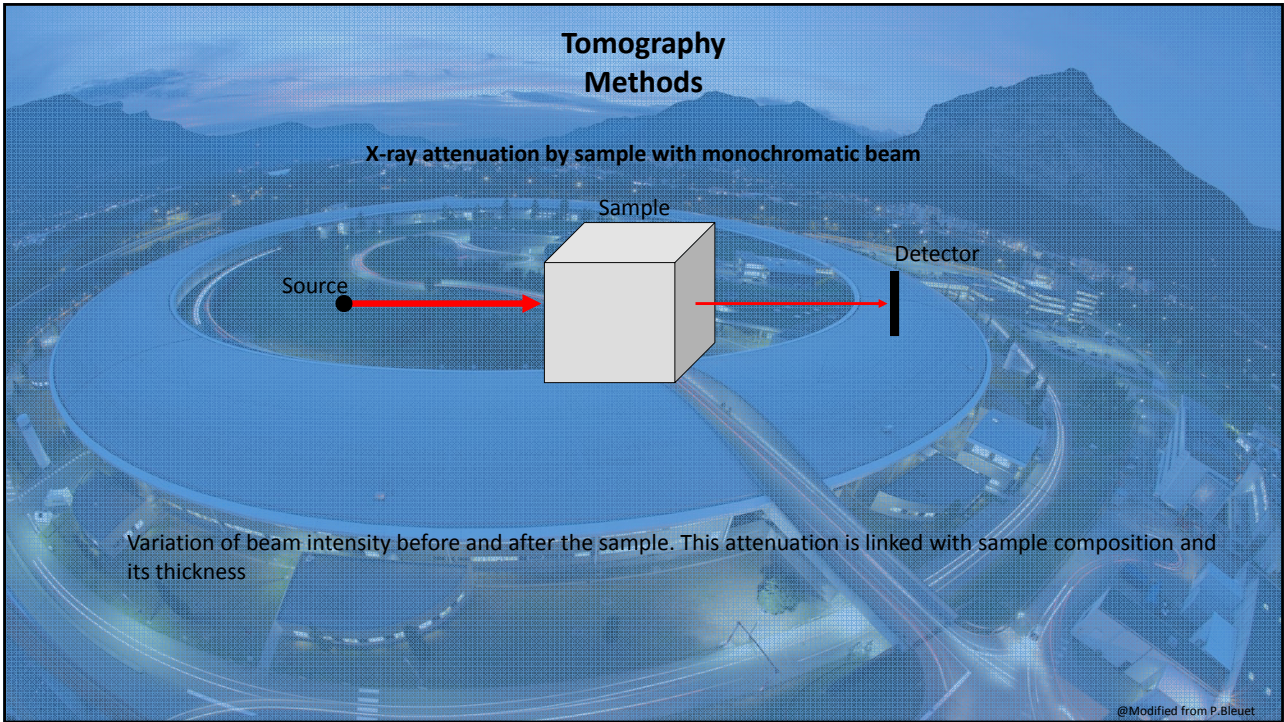
Differential absorbance properties of different material within the sample

Two dimensional projections combined in three dimensional reconstruction

Scintillators absorbs energy of a particle and emits (scintillate the absorbed energy in visible light)

@From Fernandez





Tomography Methods

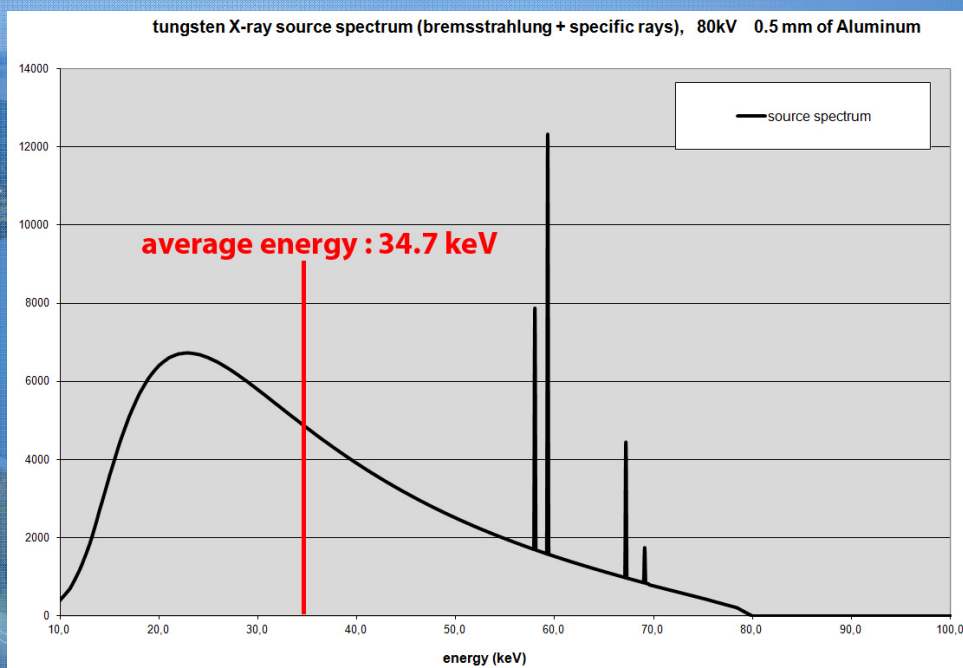
Beam hardening and monochromaticity

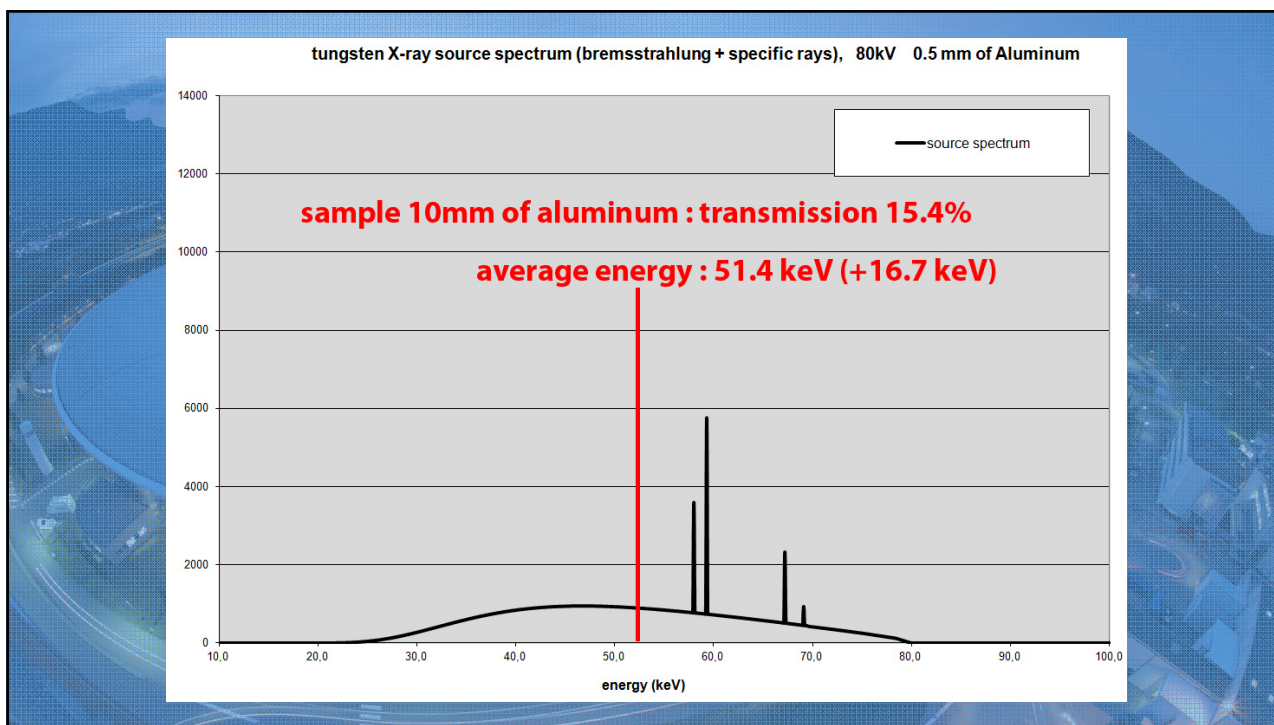
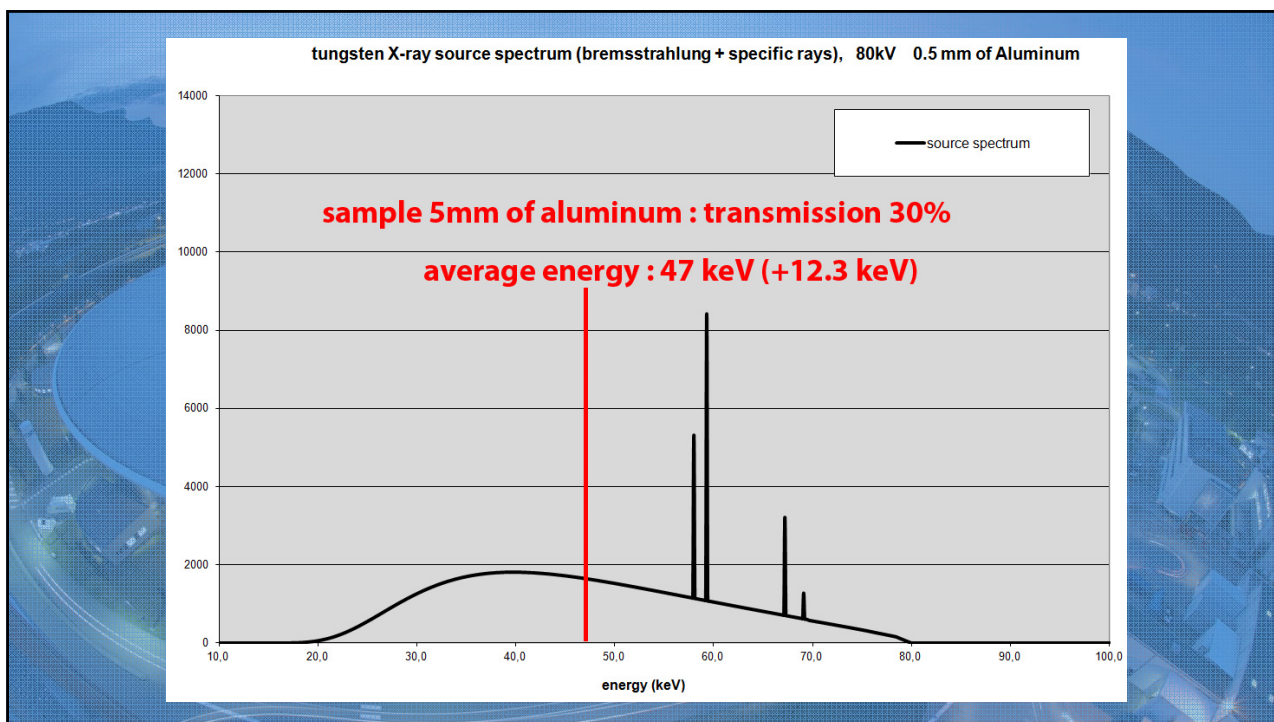
Tomography and microtomography using conventional X-ray sources suffer from beam hardening as a direct consequence of using polychromatic sources

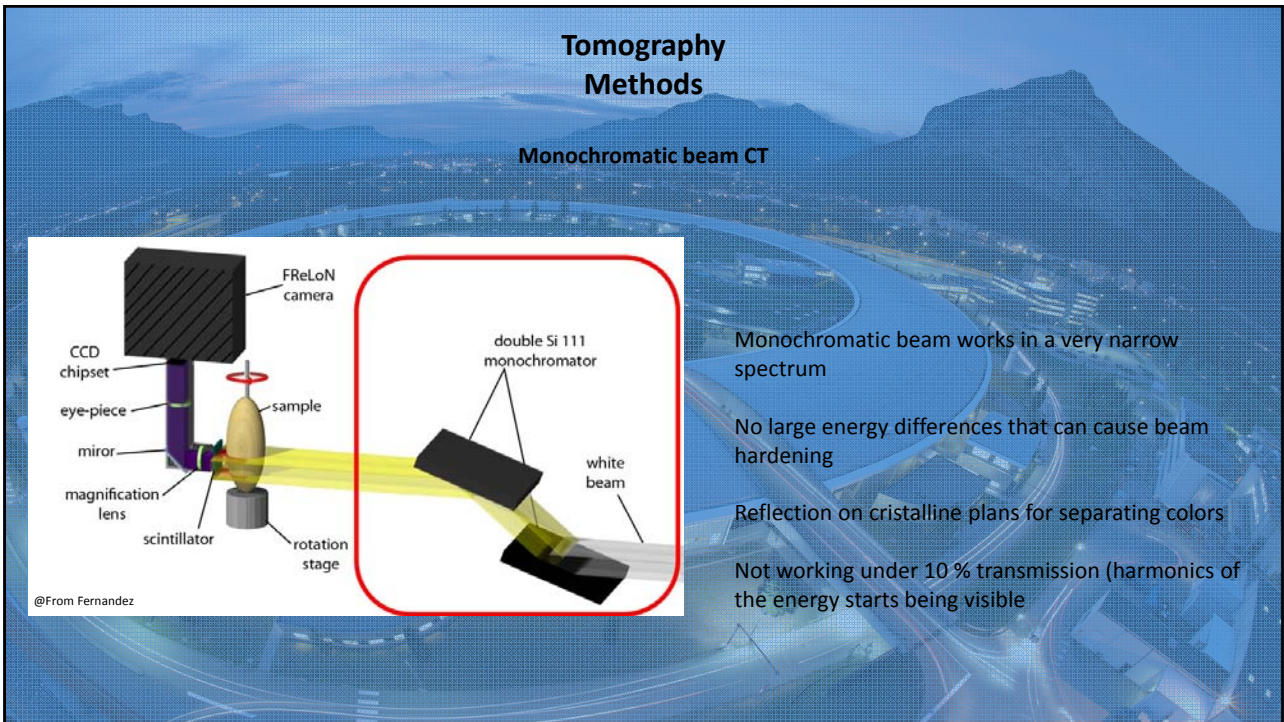
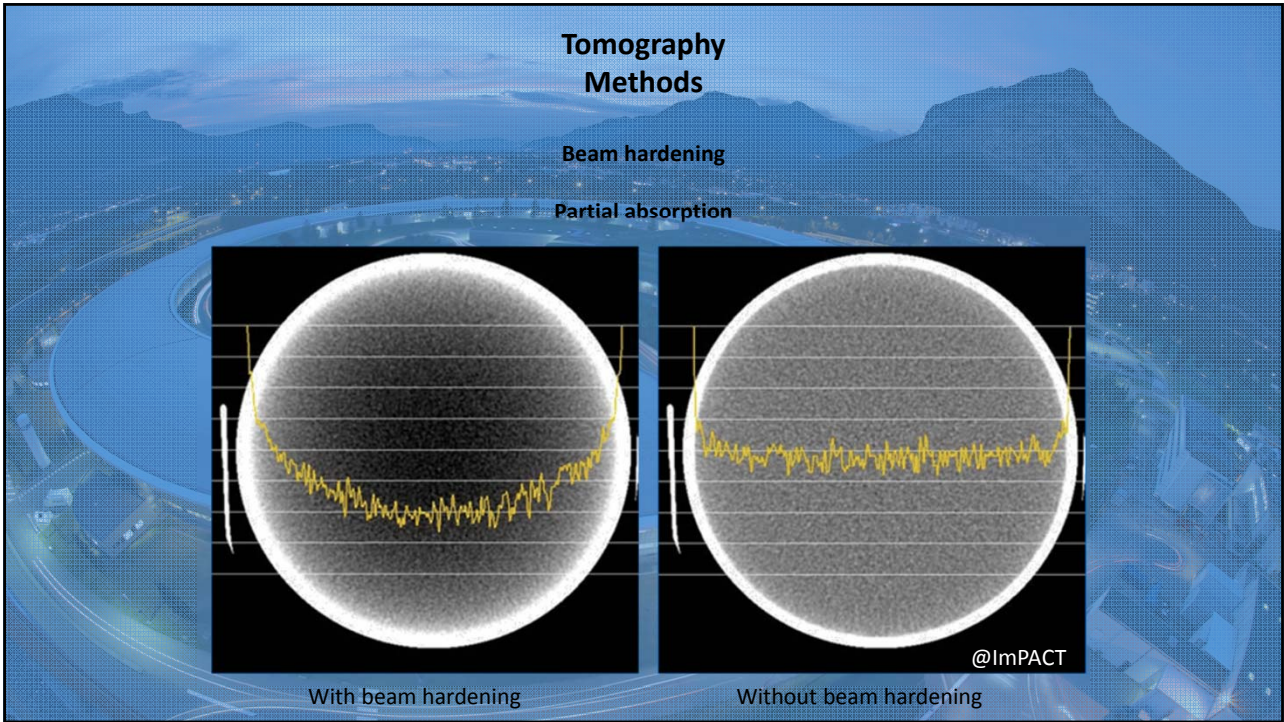
Beam hardening=differential absorption of the X-ray spectrum by the sample, with the lowest energies being more absorbed than the higher. The transmitted beam is therefore harder (contains more higher energies) than the incoming beam

This introduces misleading density data on the reconstructed slices with brightening of the sample borders and poor contrast within dense structures

Using a synchrotron allows to use monochromatic beam which remove origins of beam hardening effect



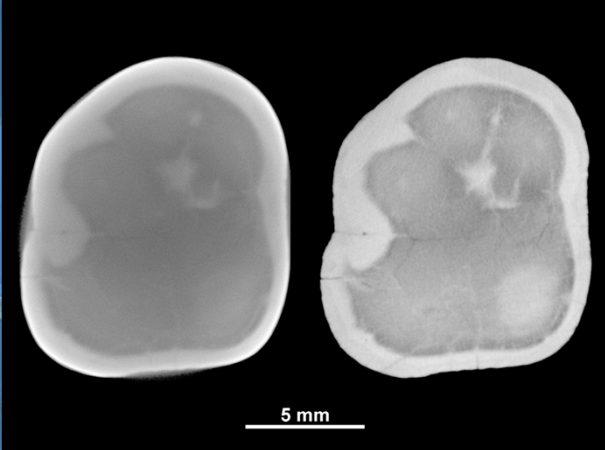




Tomography Methods

Monochromatic beam CT

Conventional X-ray CT slice



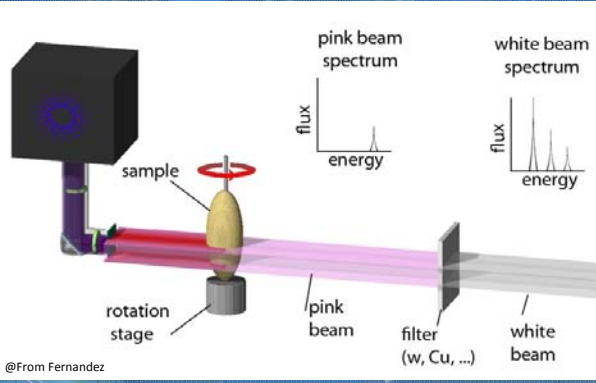
5 mm

ID 19 beamline, monochromatic beam, no beam hardening

Korapithecus molar (fossil primate)

Tomography Methods

Filtered white beam CT



sample

rotation stage

pink beam

filter (w, Cu, ...)

white beam

pink beam spectrum

white beam spectrum

flux

energy

flux

energy

Filtration of the white beam at the highest and lowest wavelength → Pink beam

Can counteract beam hardening but not as efficiently as monochromatic beam

Only with an undulator

@From Fernandez

Tomography Methods

Propagation phase contrast CT

Interference based on differences in phase caused by differences of density with variations of composition

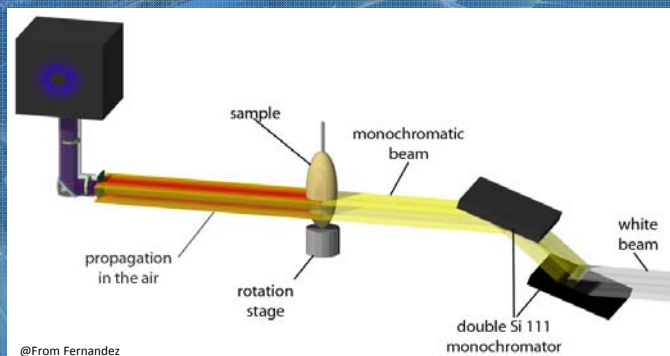
Phase shift (change in relative position of the electromagnetic waves) and attenuation (decrease of the amplitude)

« Differential refraction » at the media fringes can highlight internal structures in the sample

Increase of propagation distance reveal finer phase shifts until a limit at which phase fringes start to be less clear

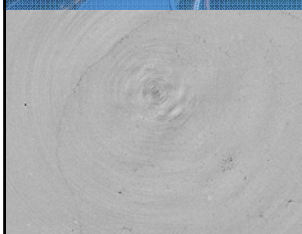
Optimal distance between the sample and the detector depending on resolution and energy

Holotomography uses many distance of propagation



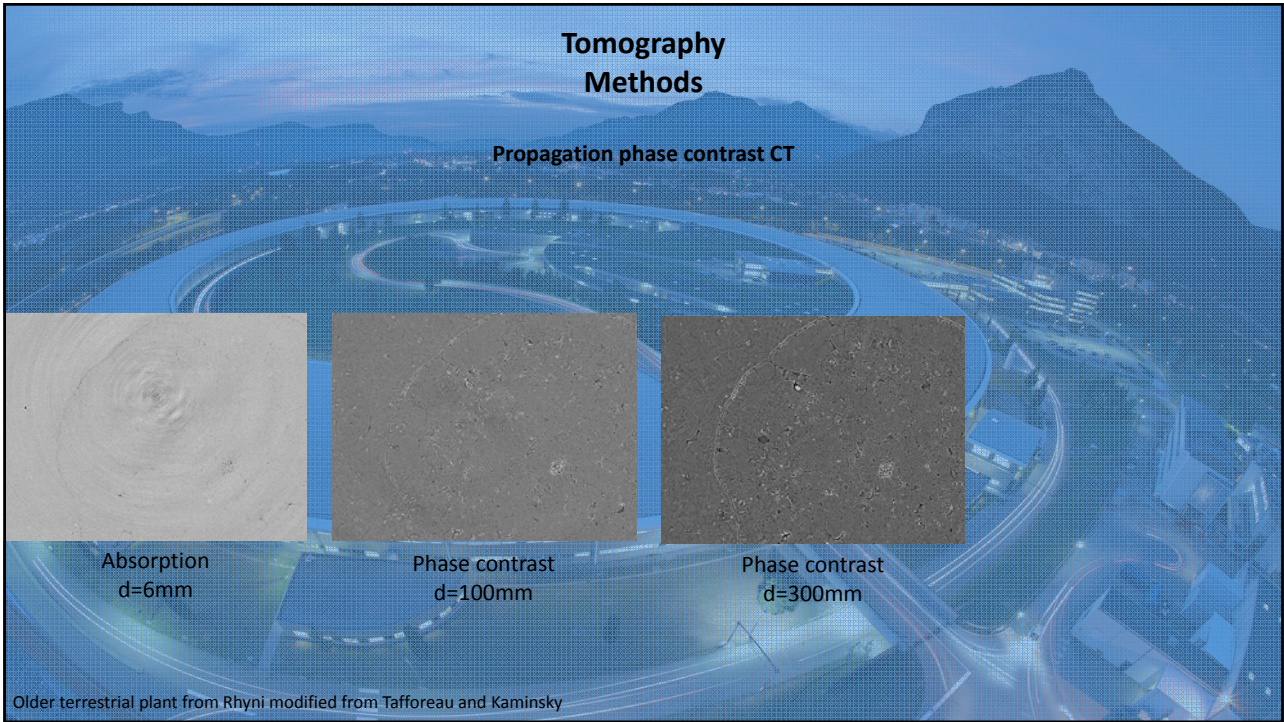
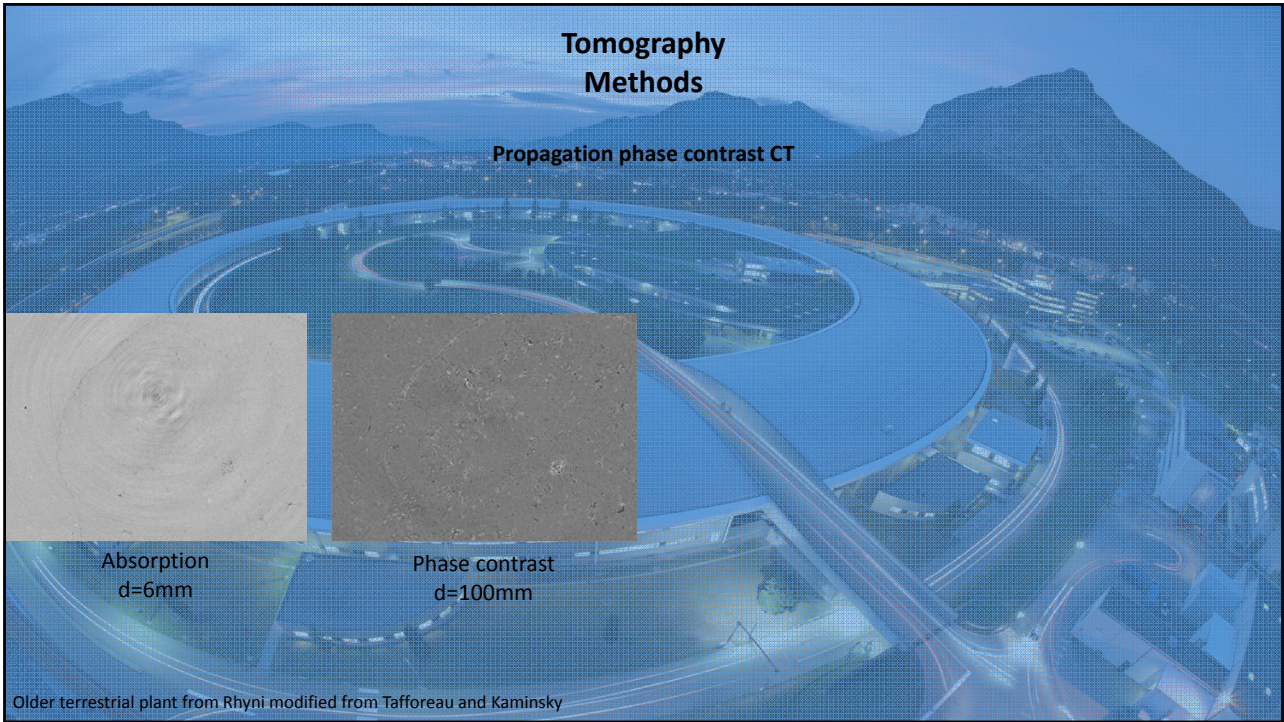
Tomography Methods

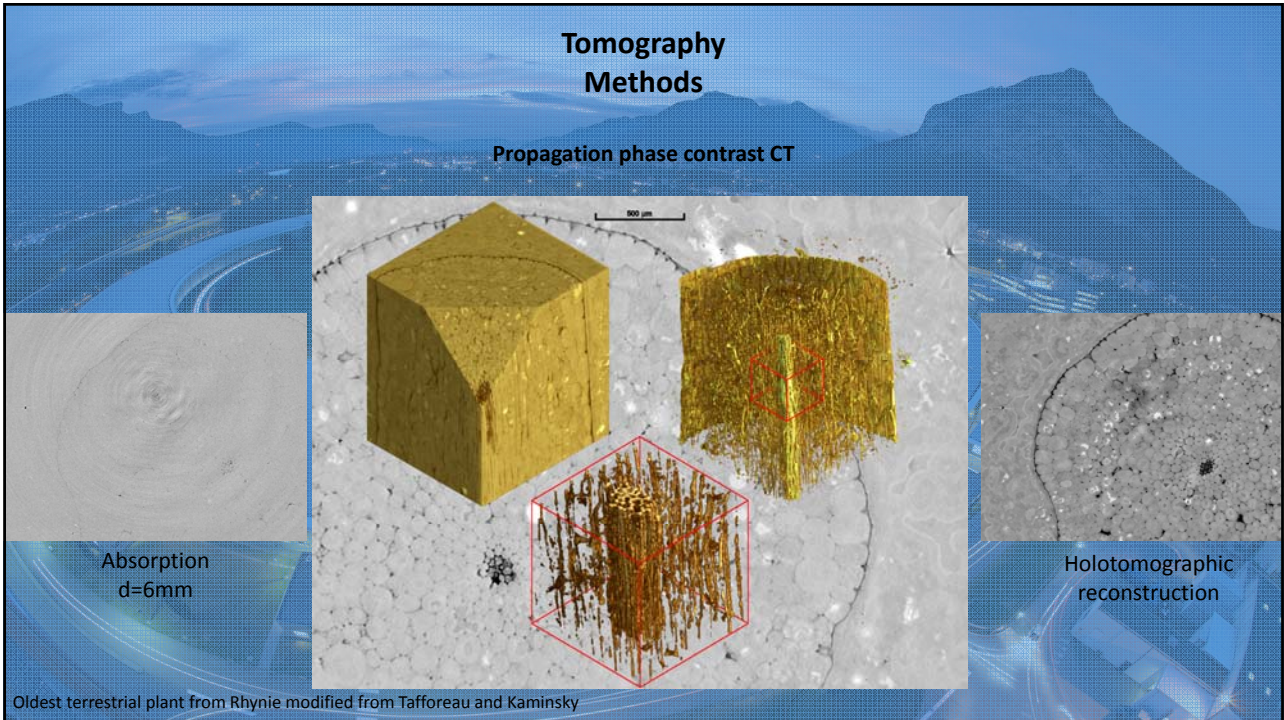
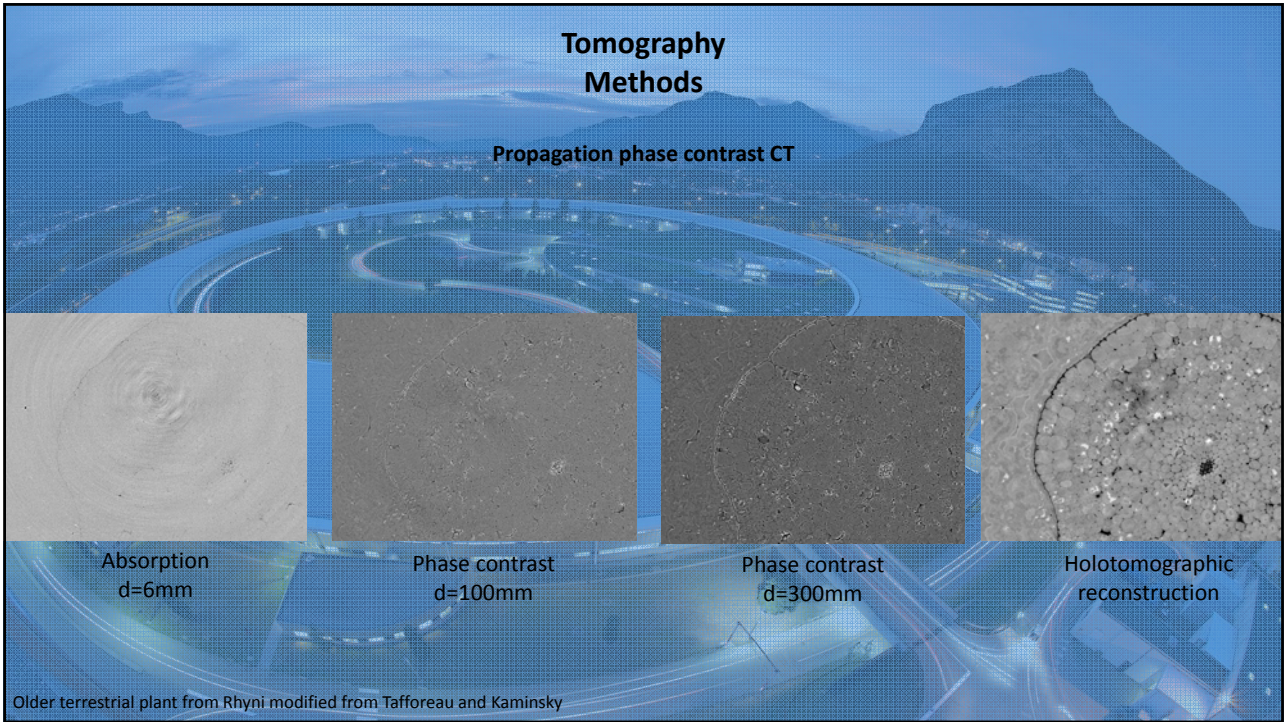
Propagation phase contrast CT

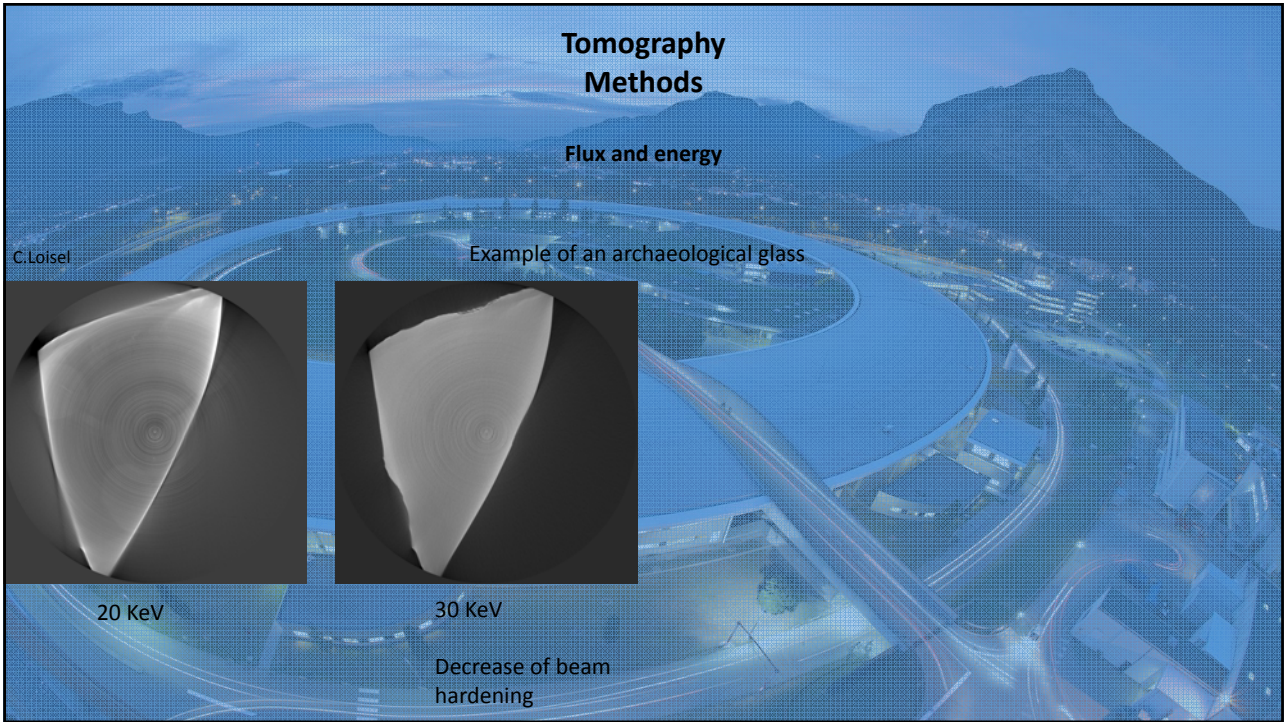
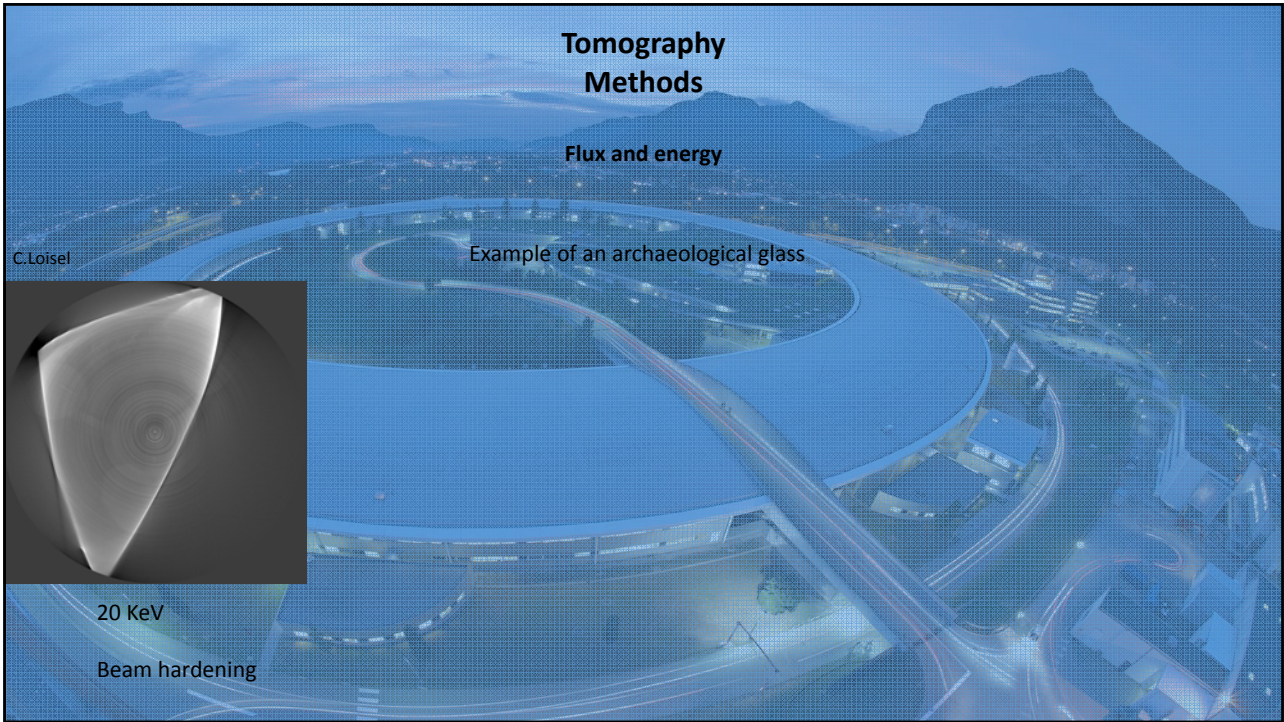


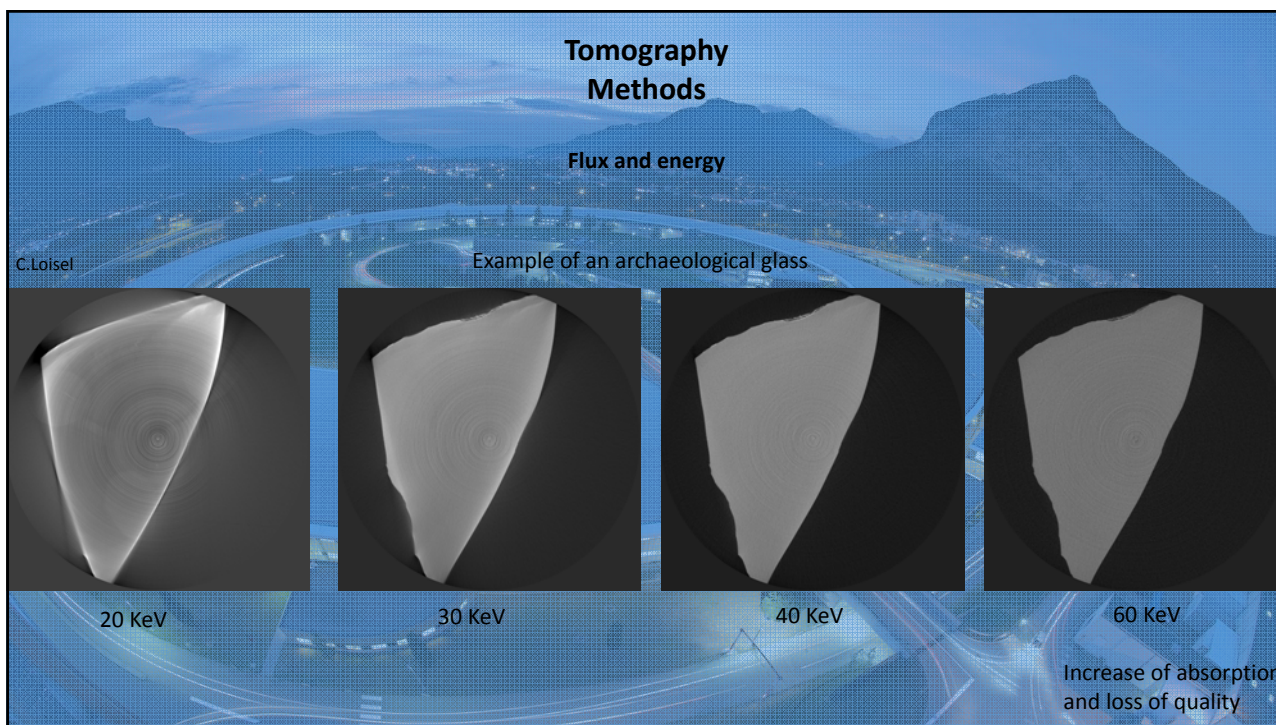
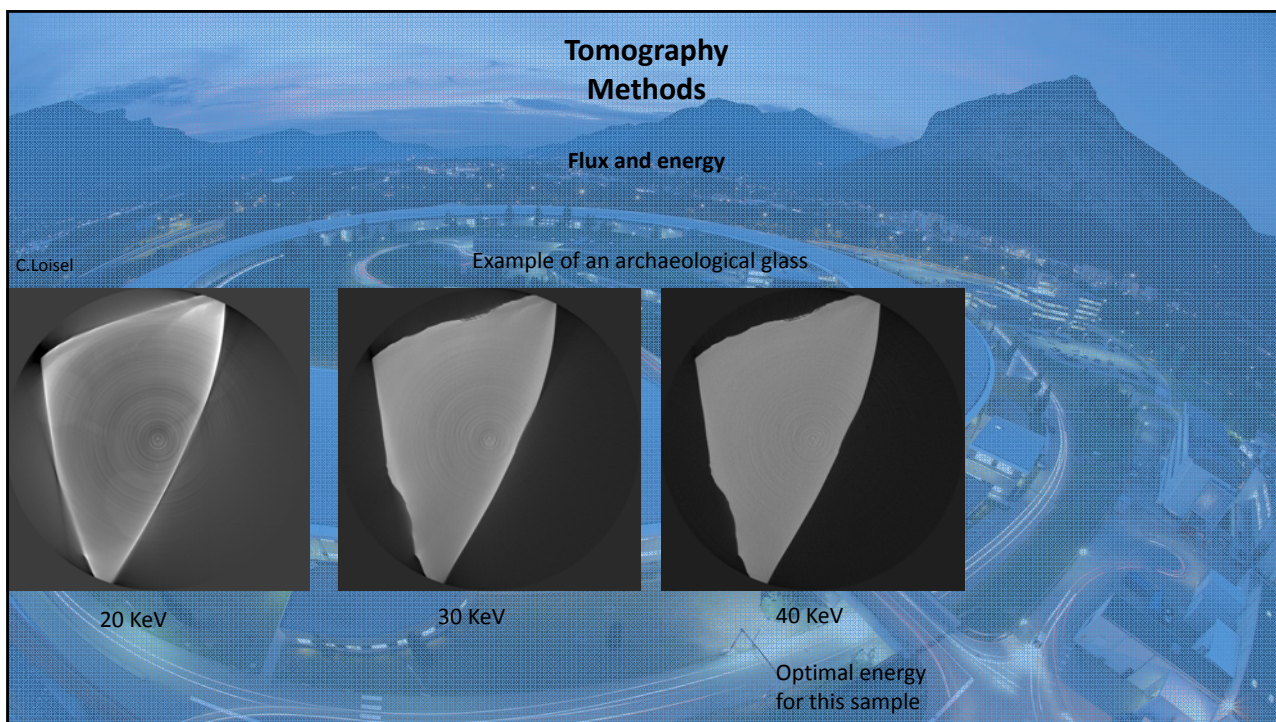
Absorption
d=6mm

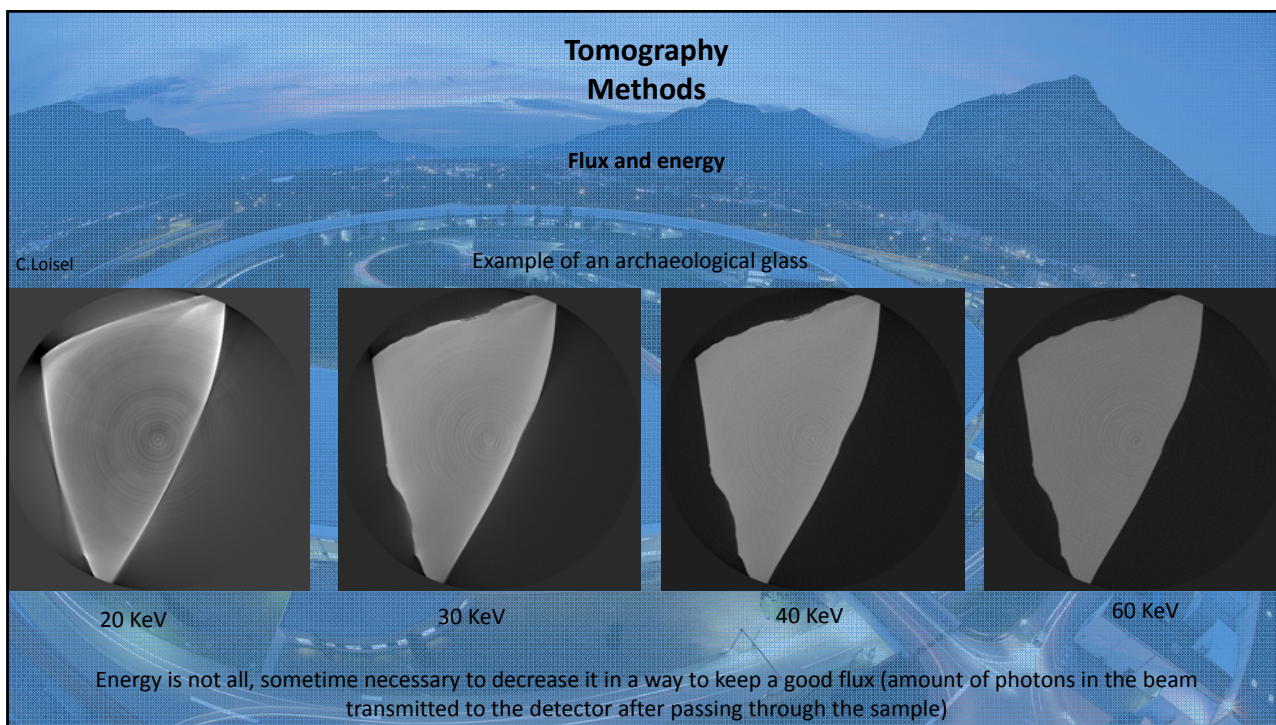
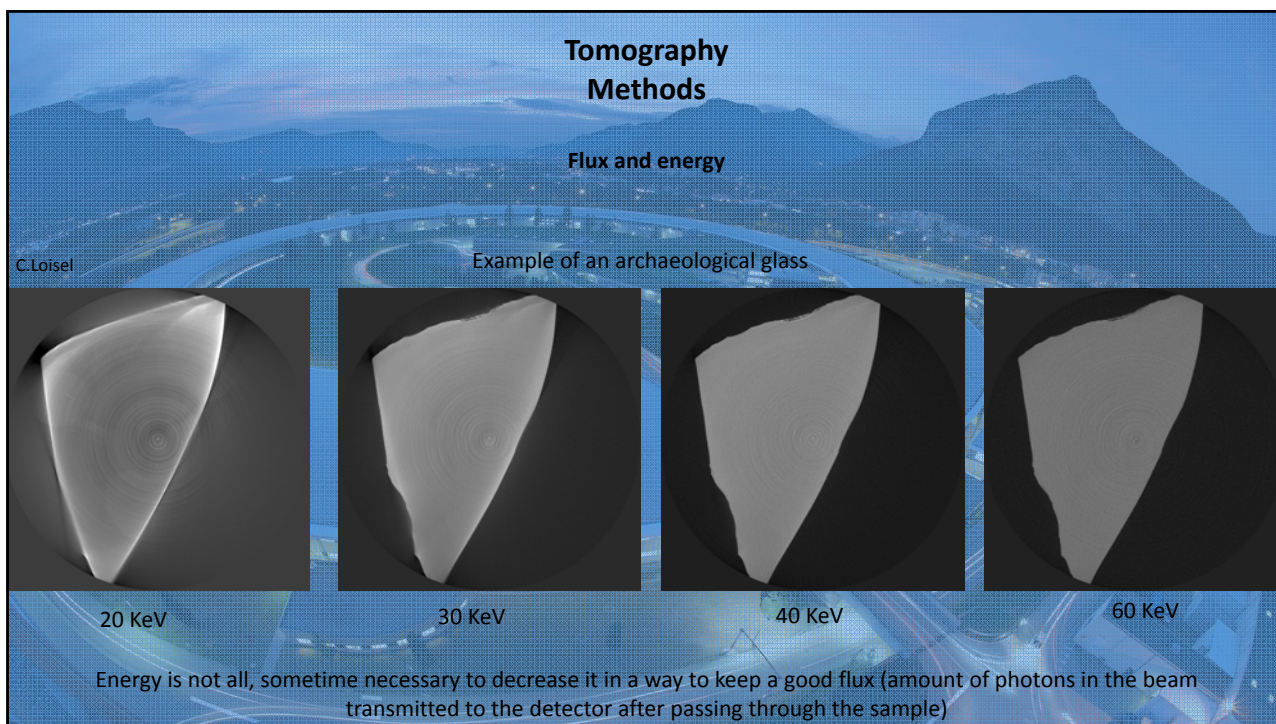
Older terrestrial plant from Rhyni modified from Tafforeau and Kaminsky

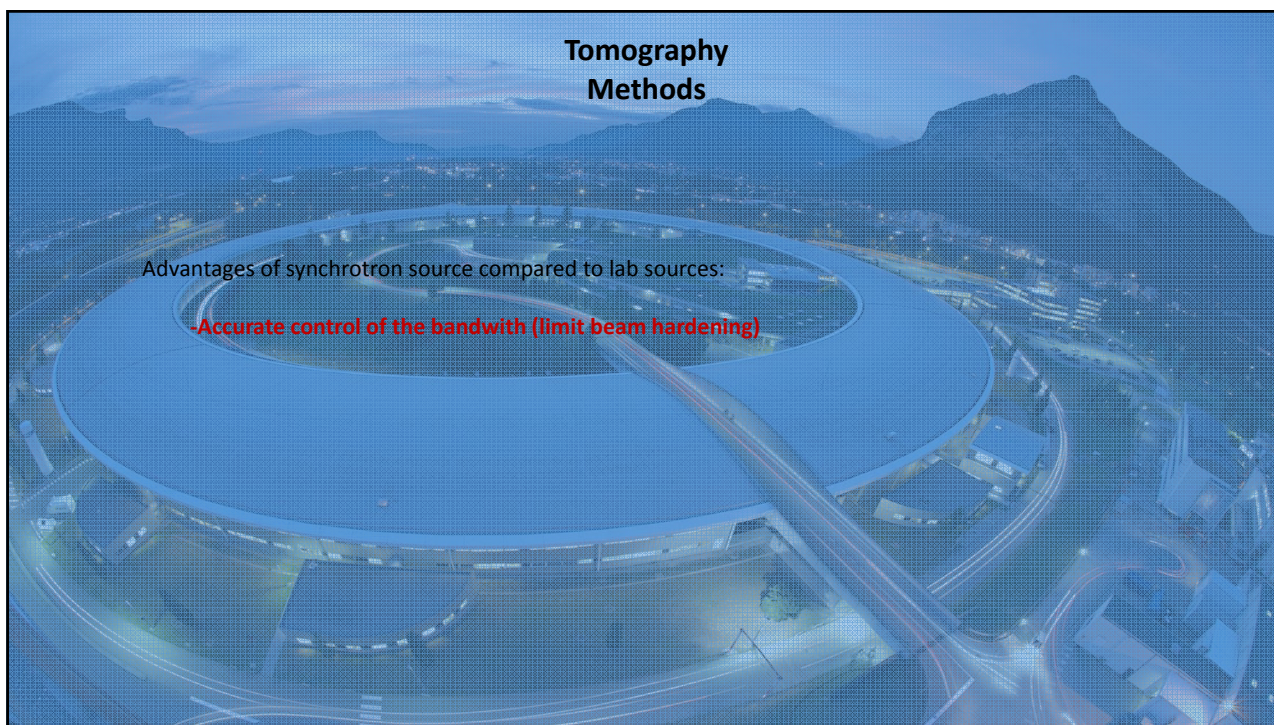
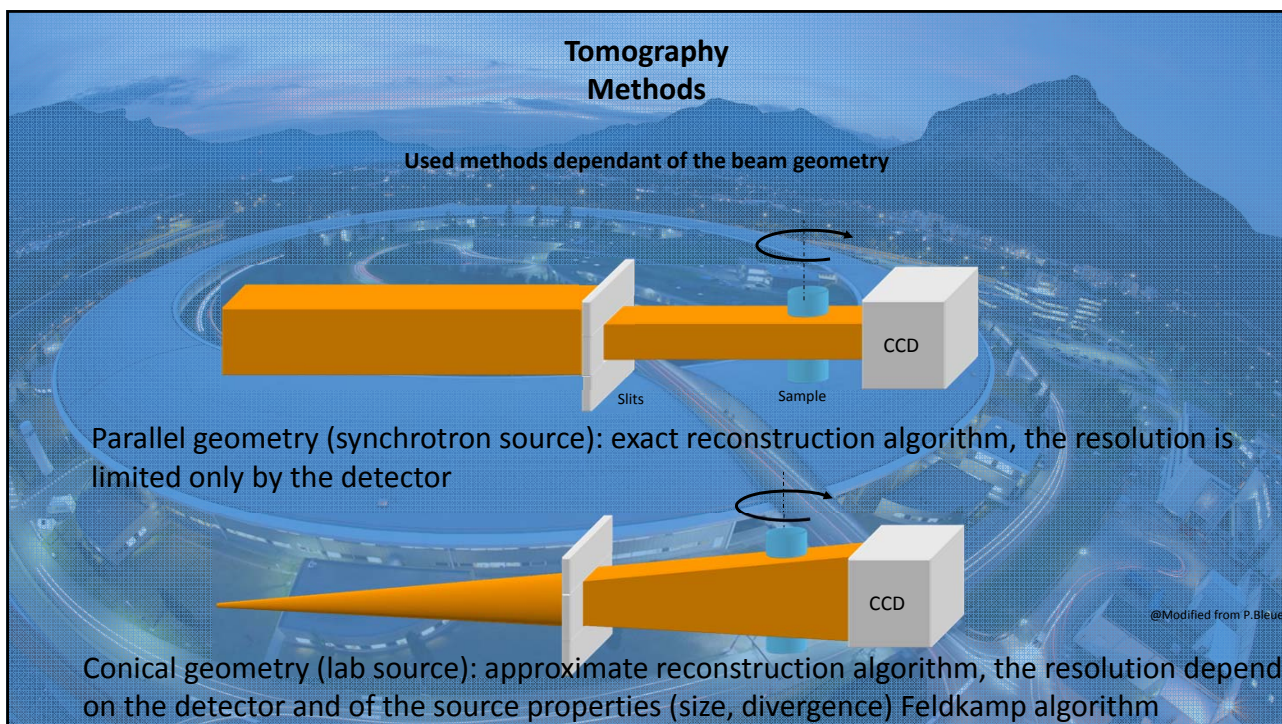


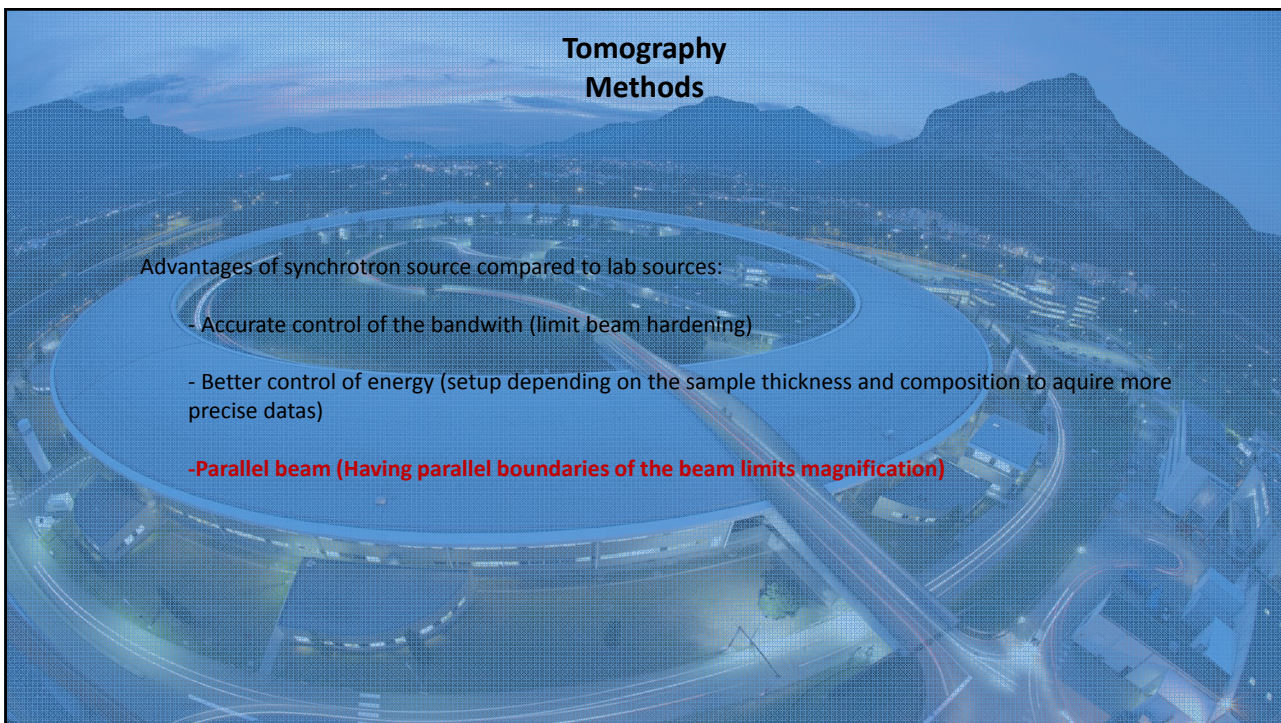
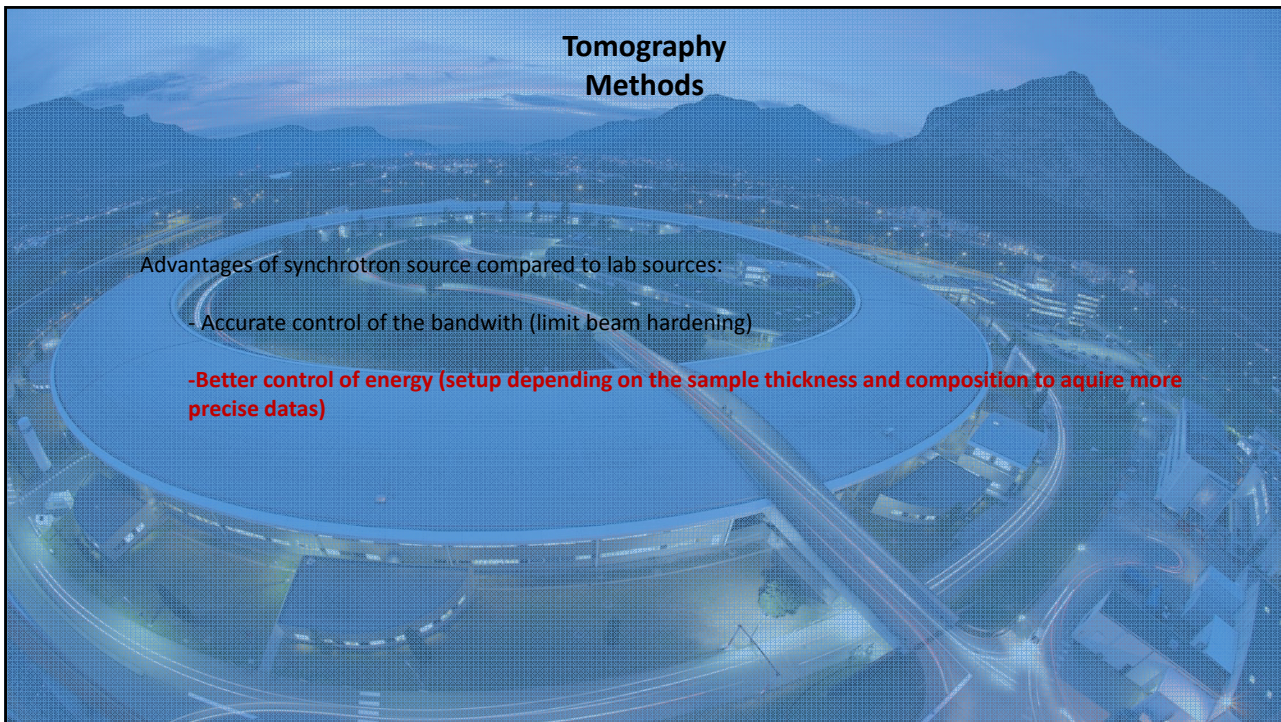


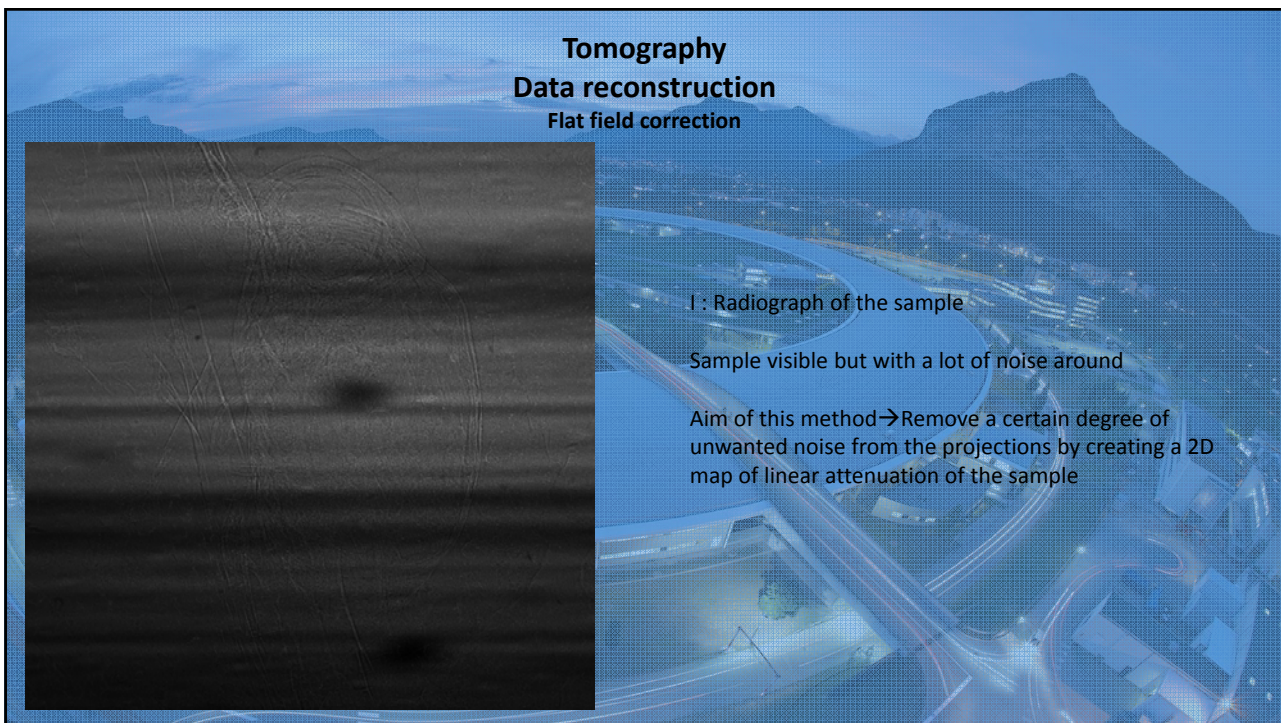
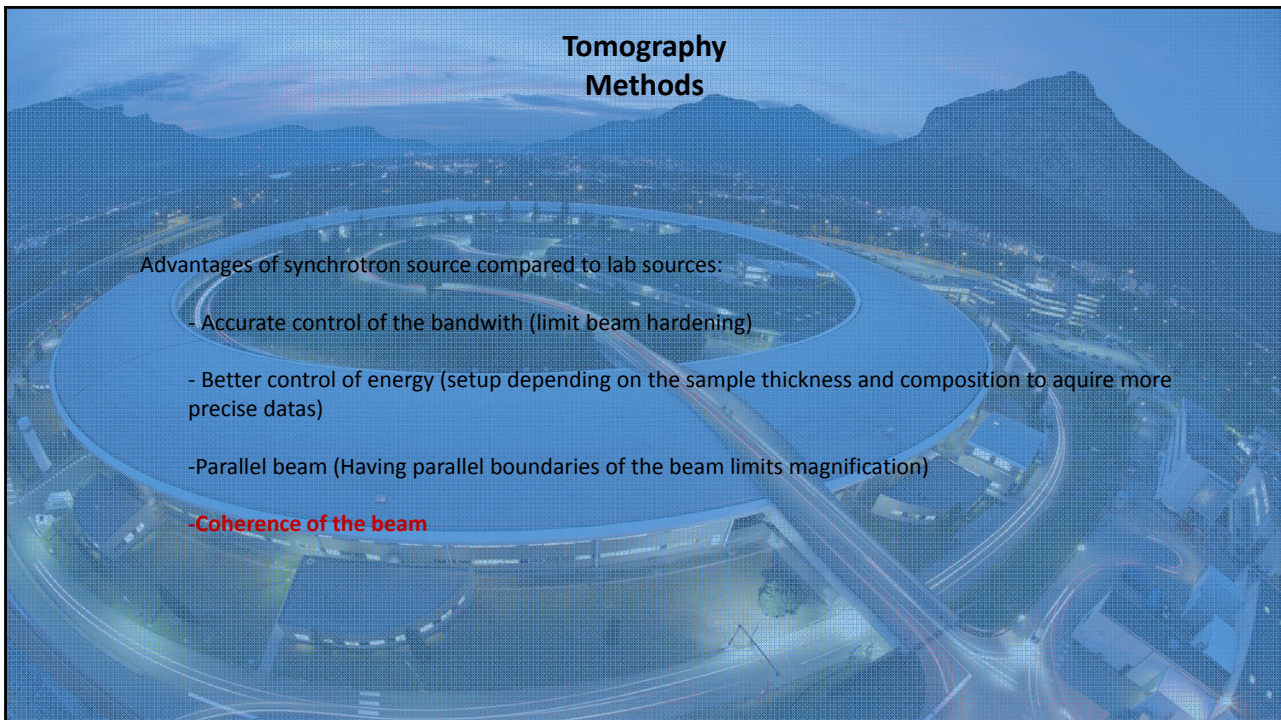


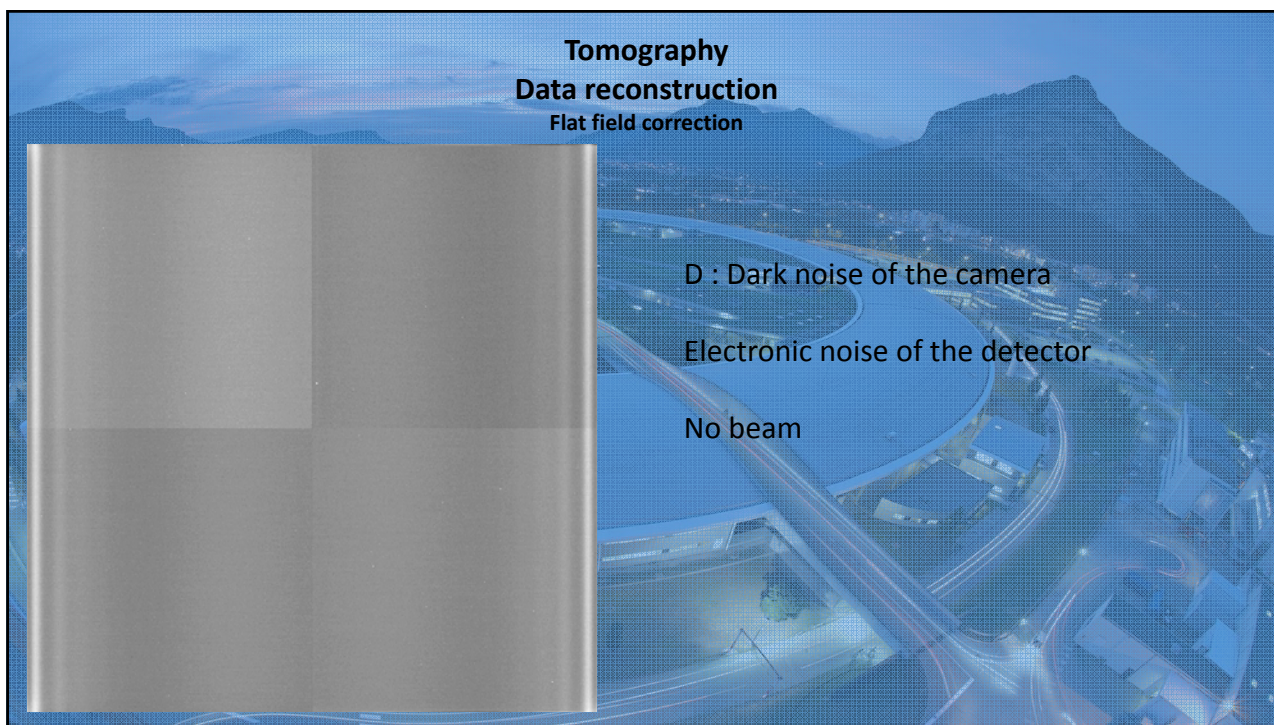
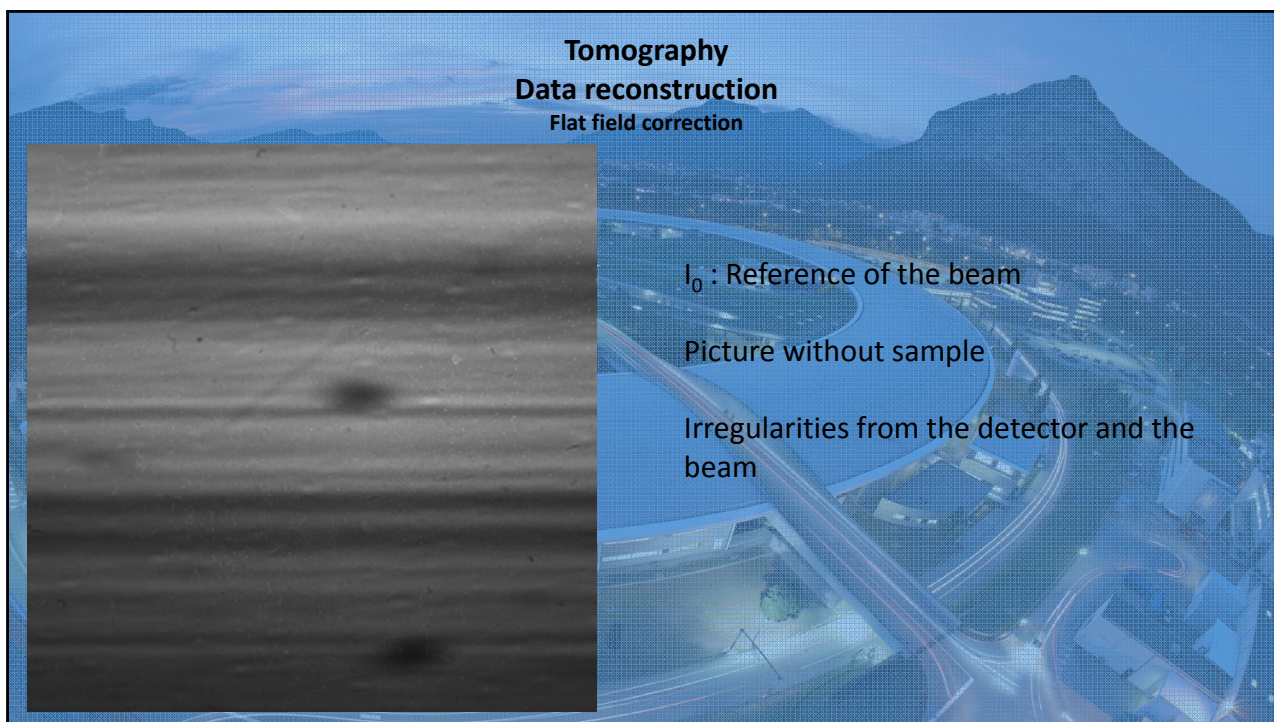


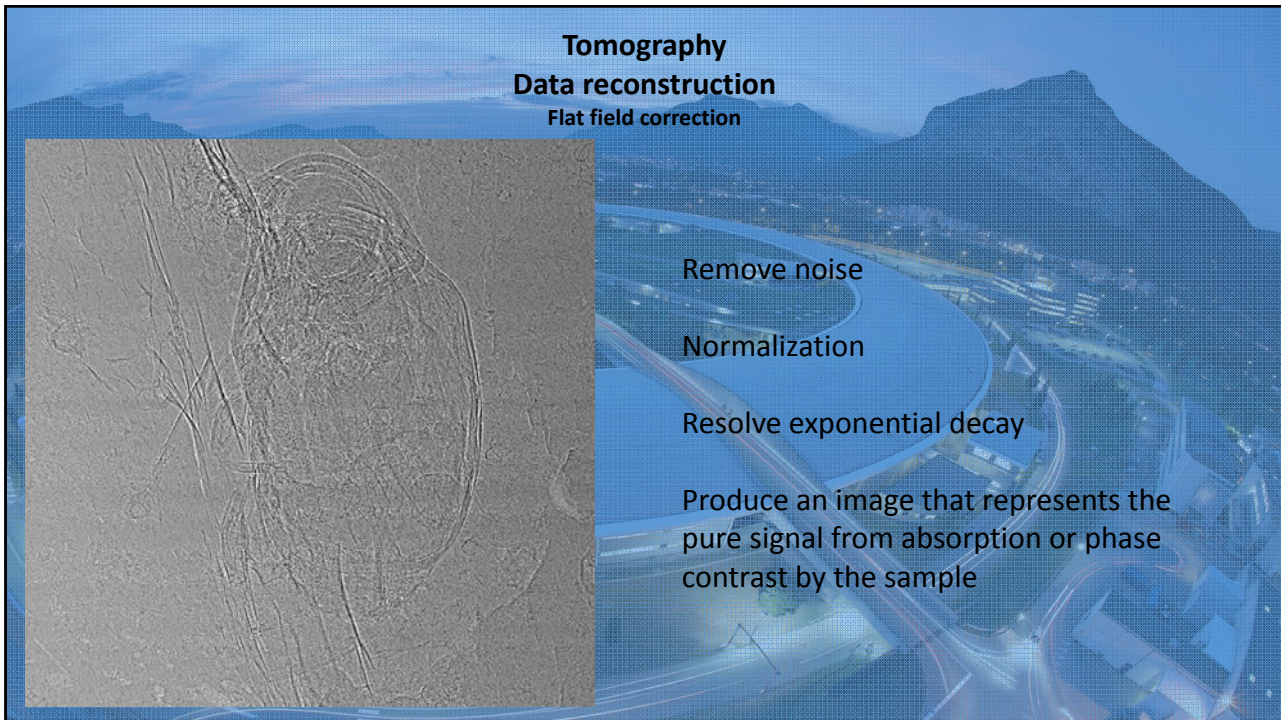
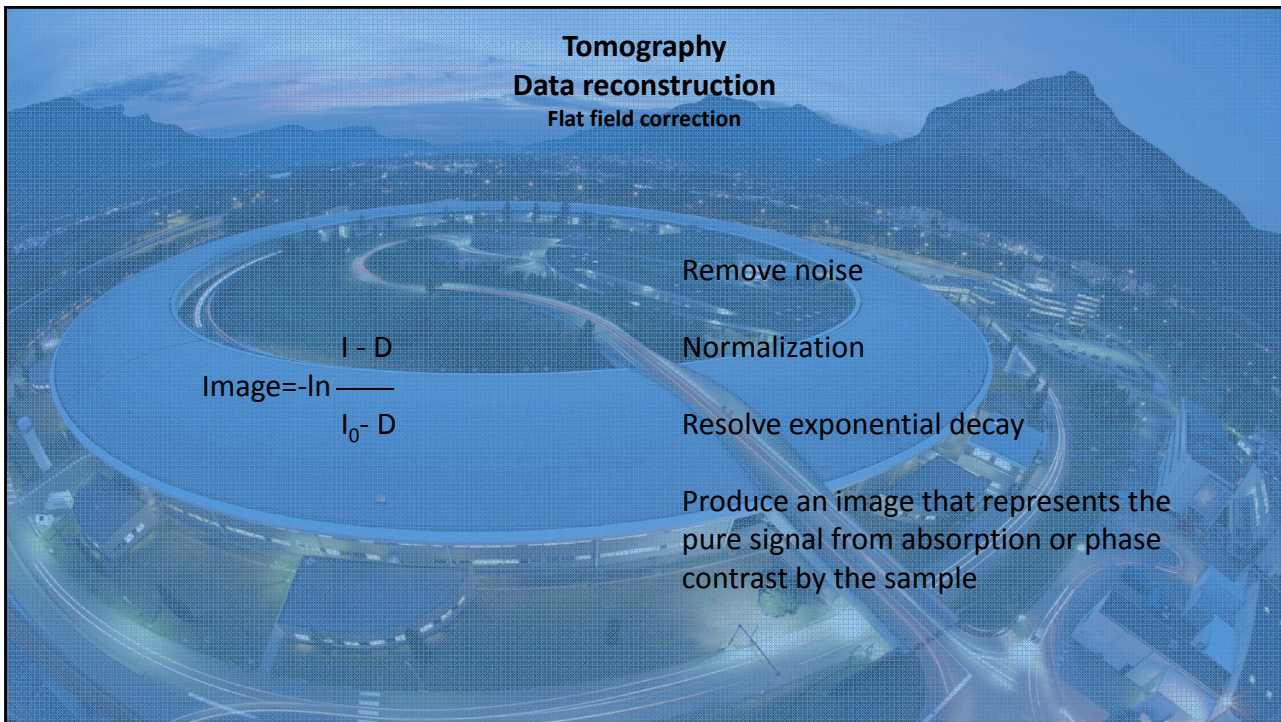


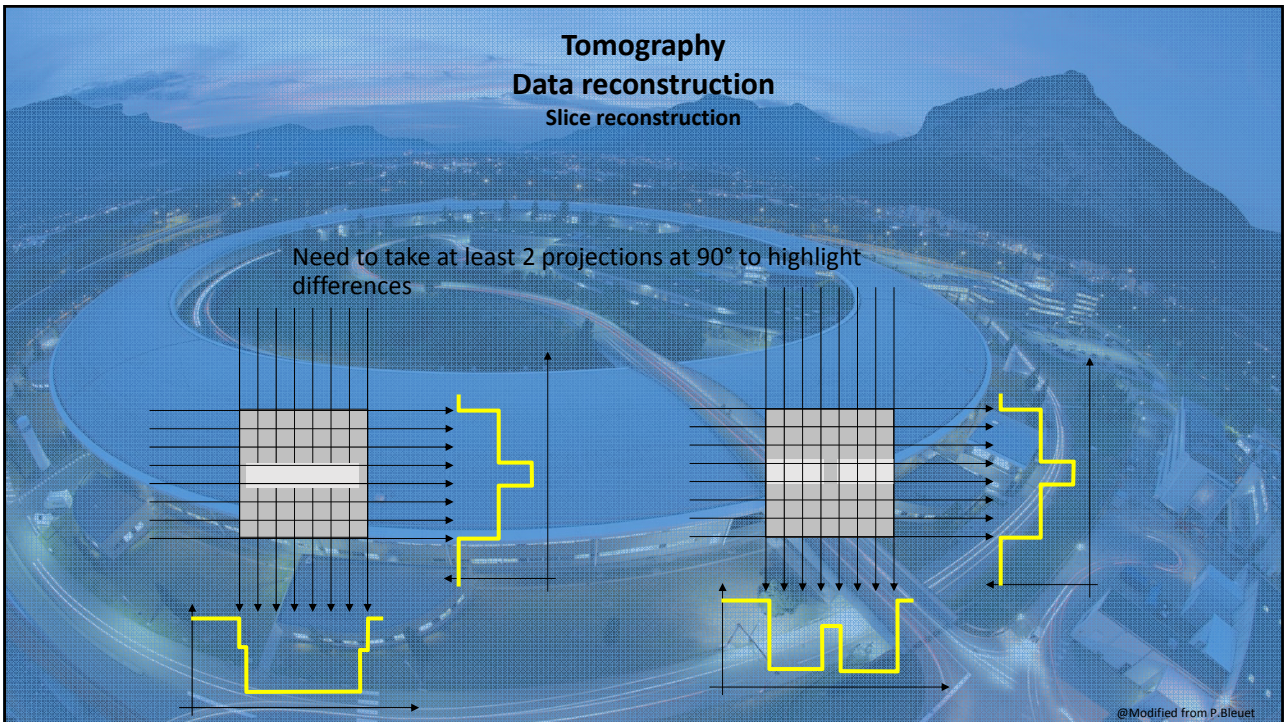
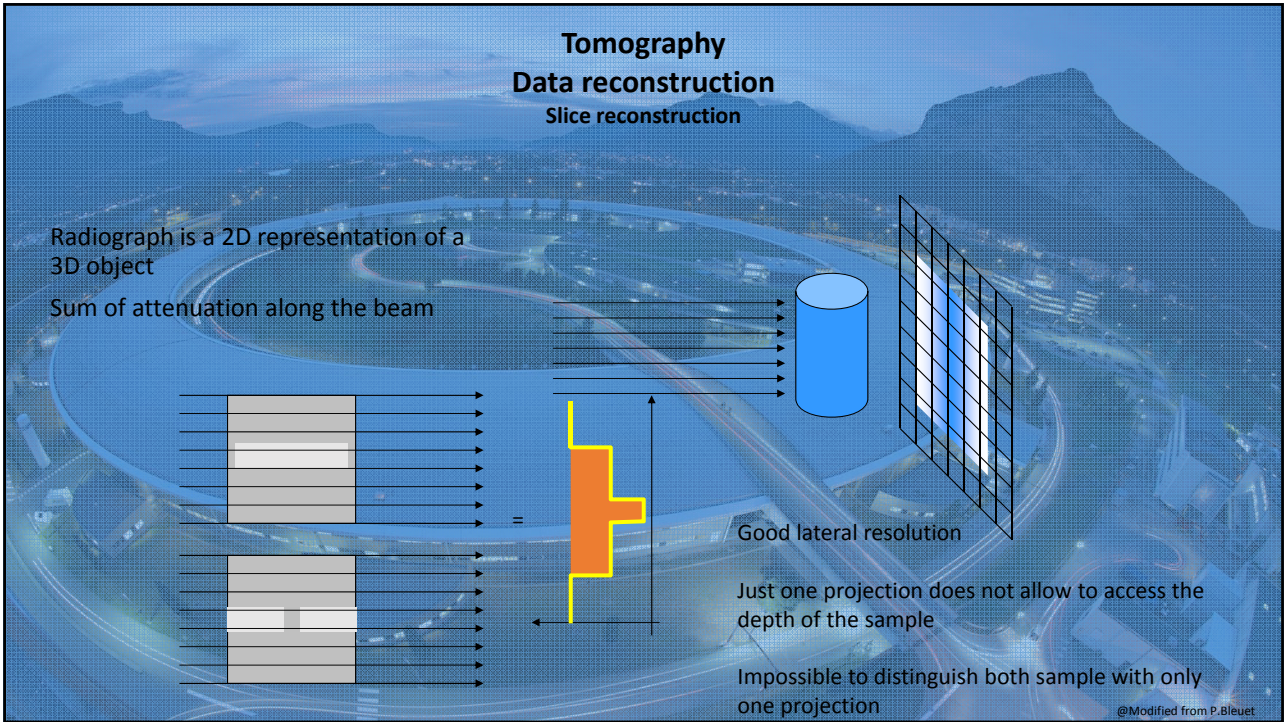


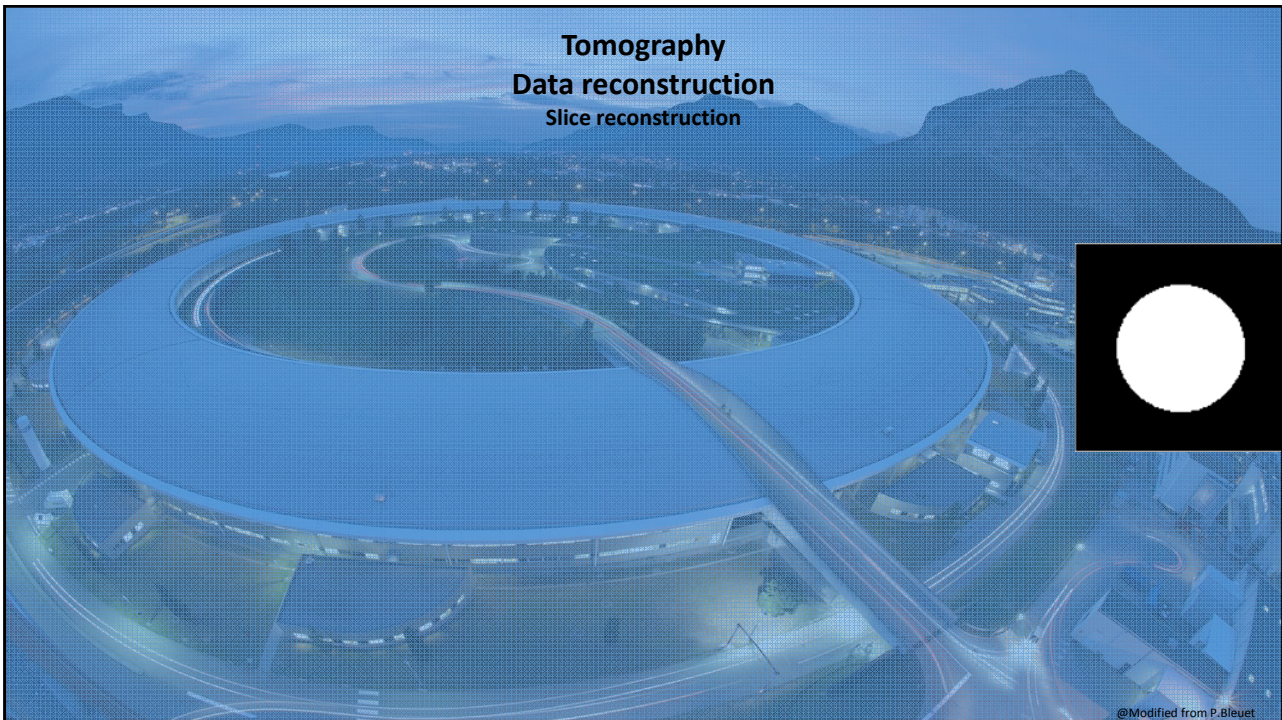
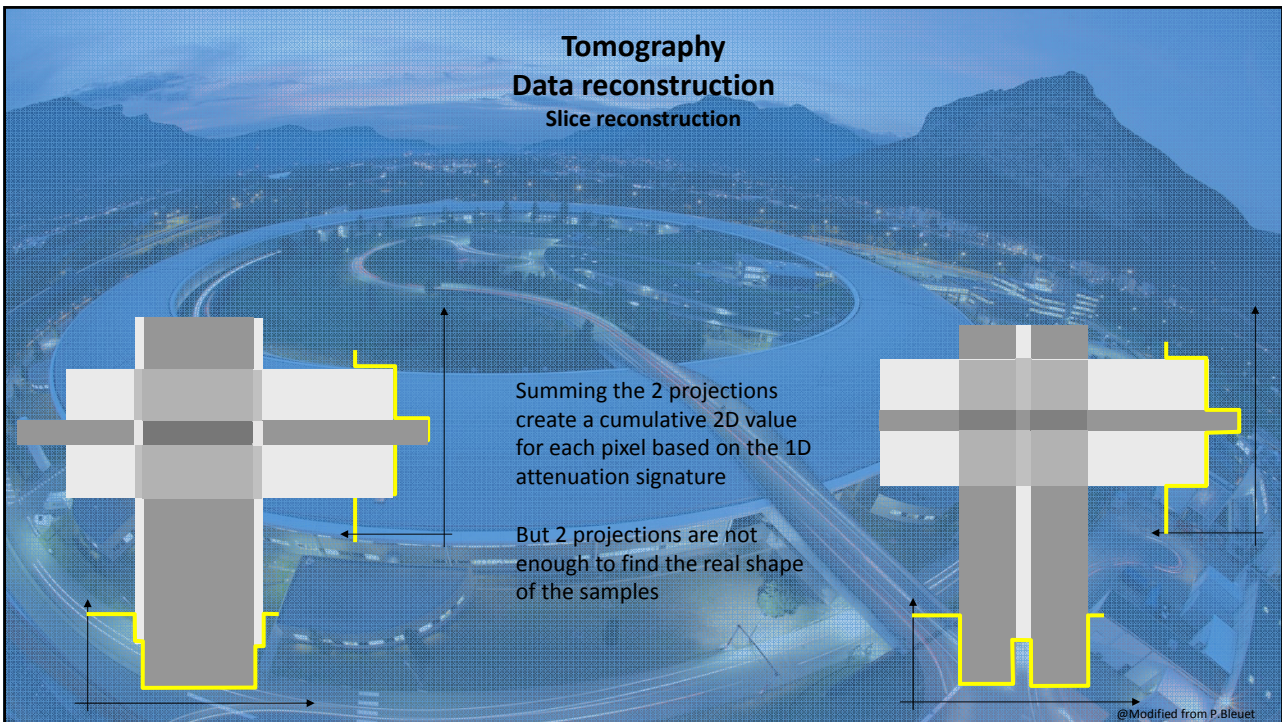


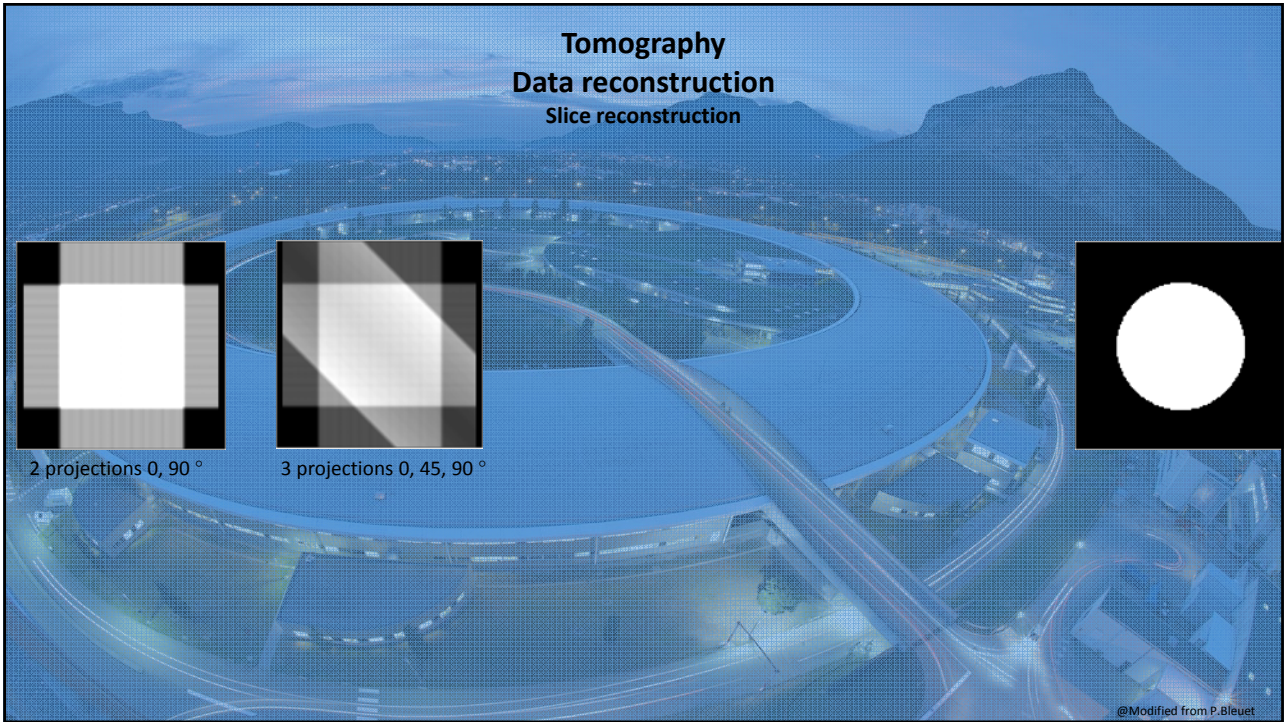
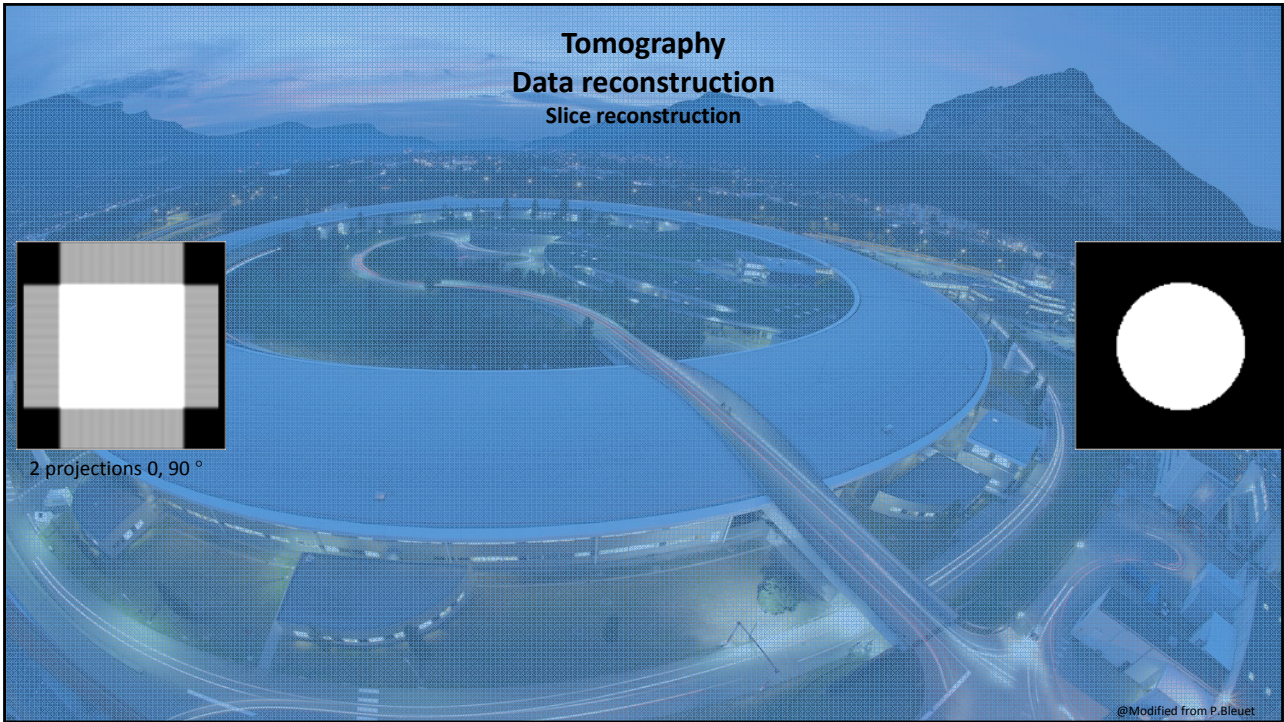


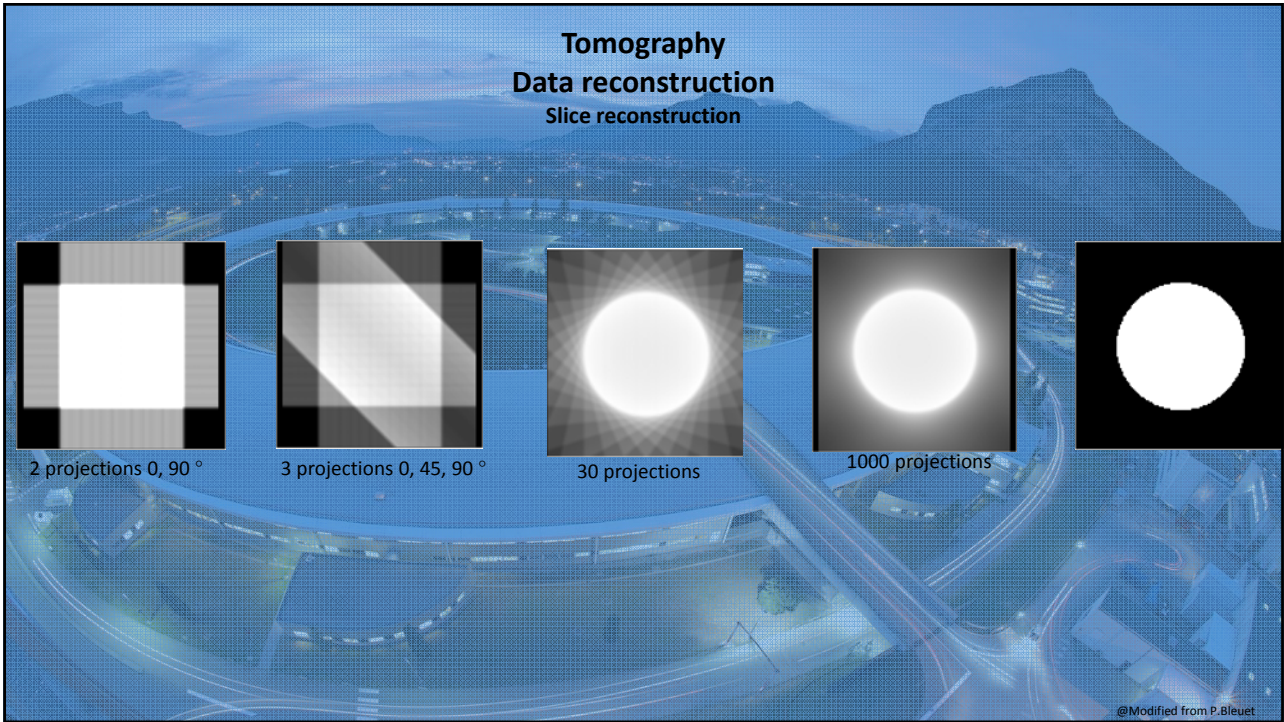
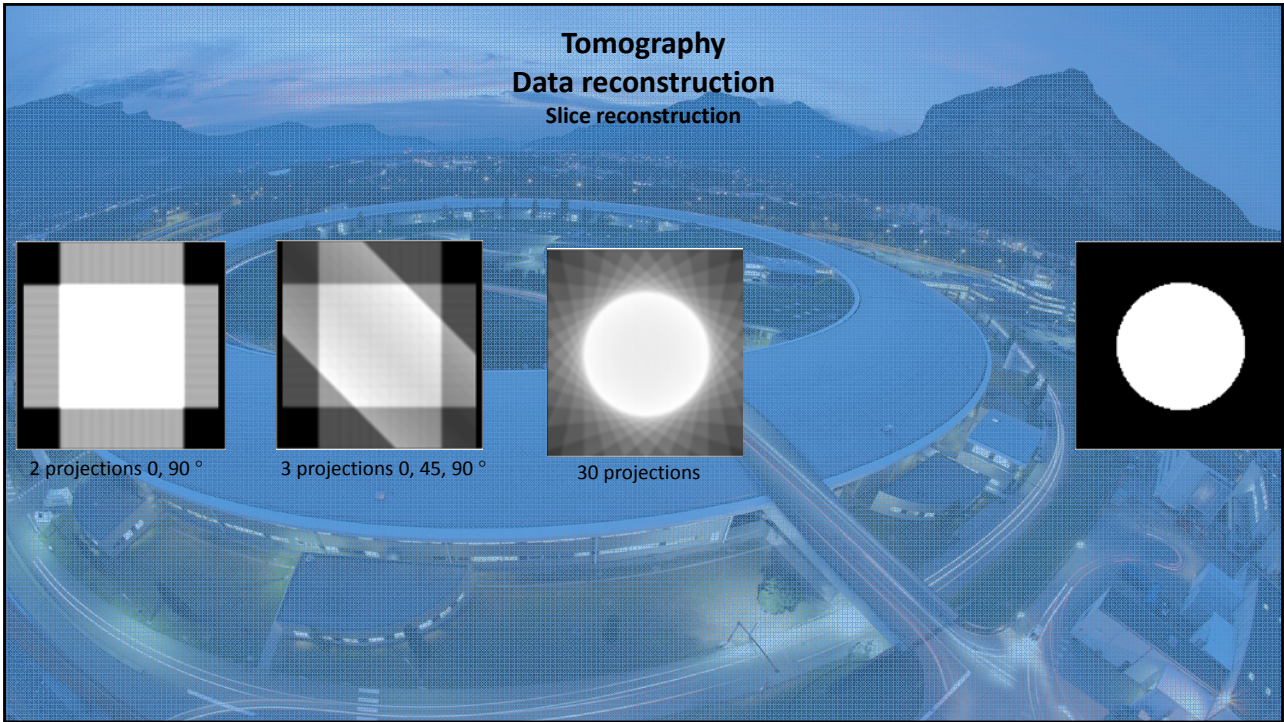


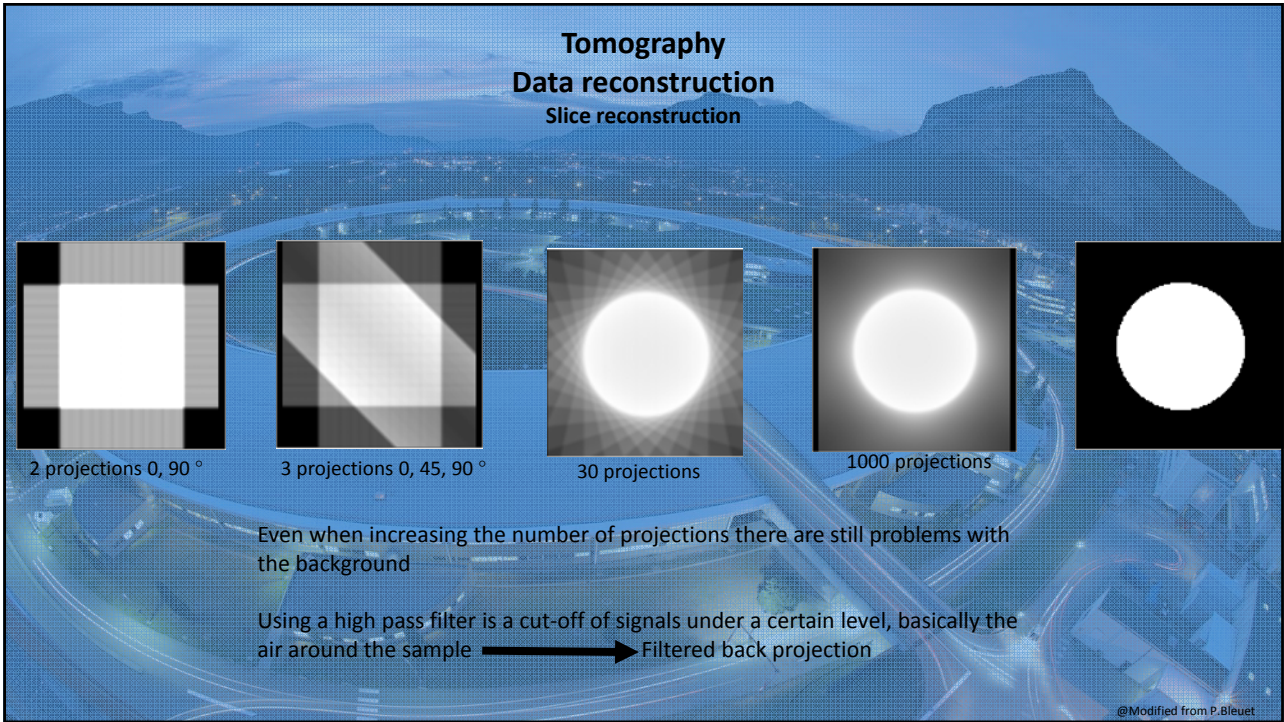
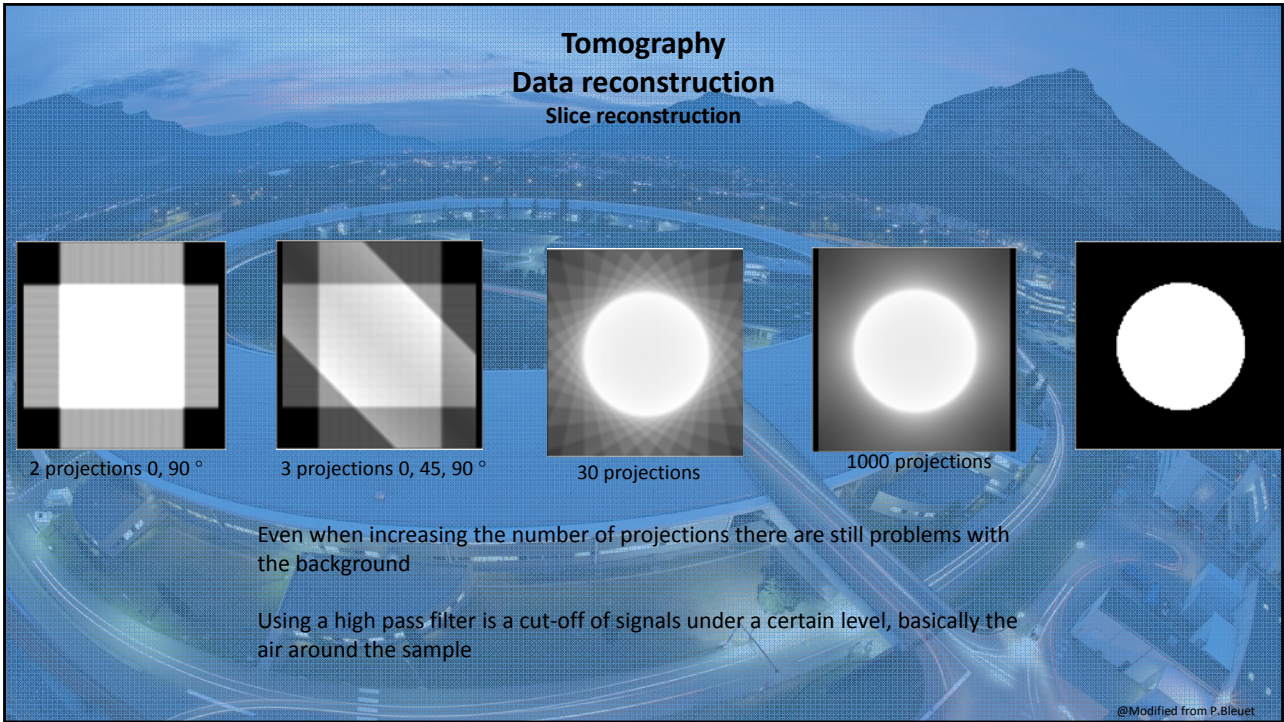


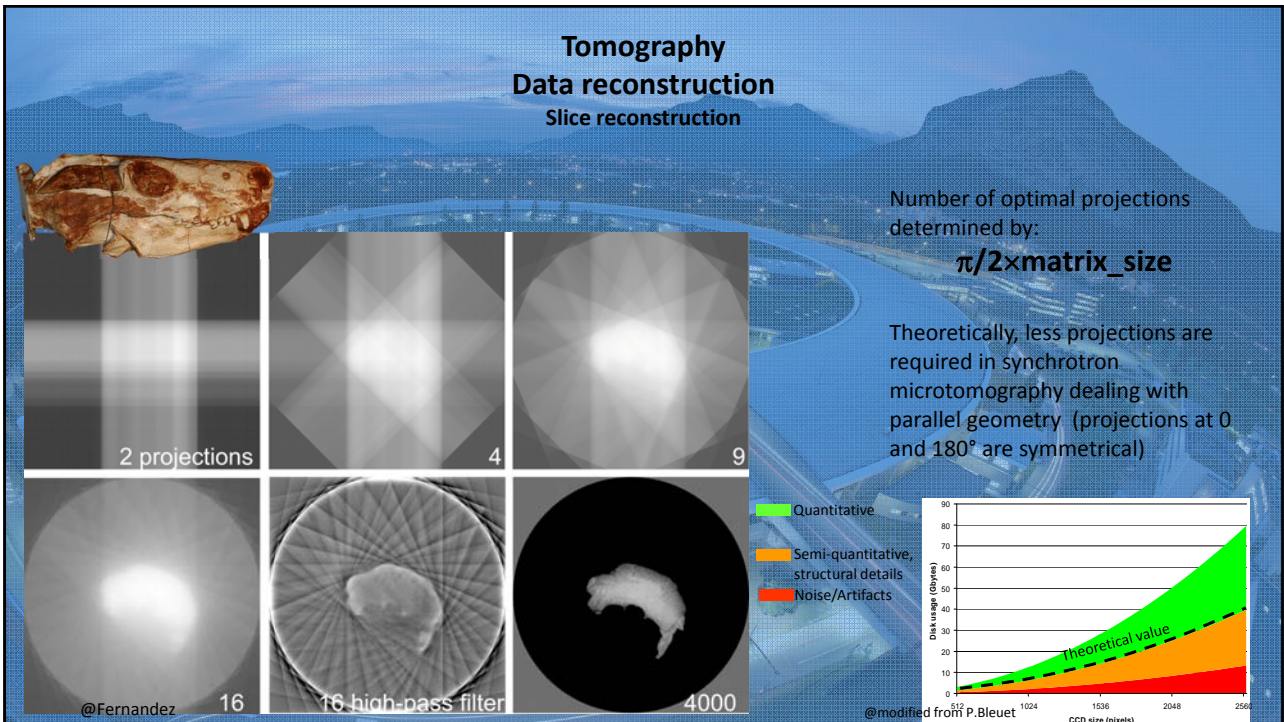
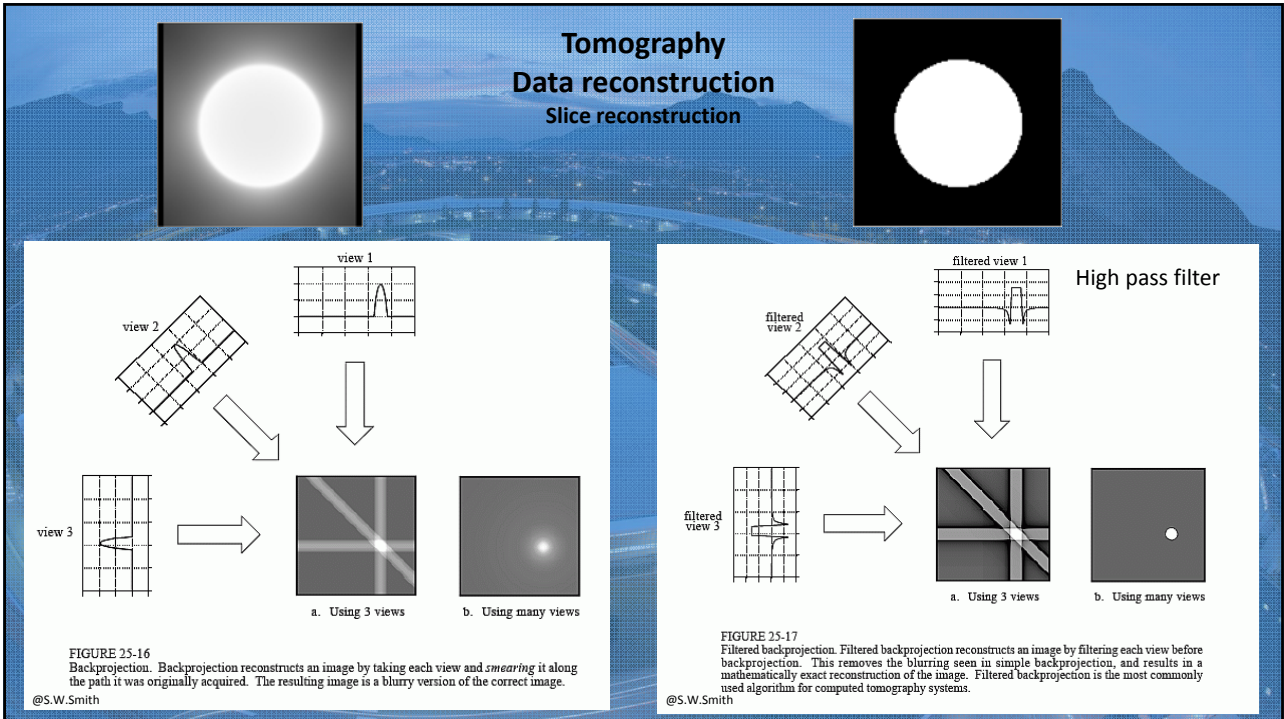


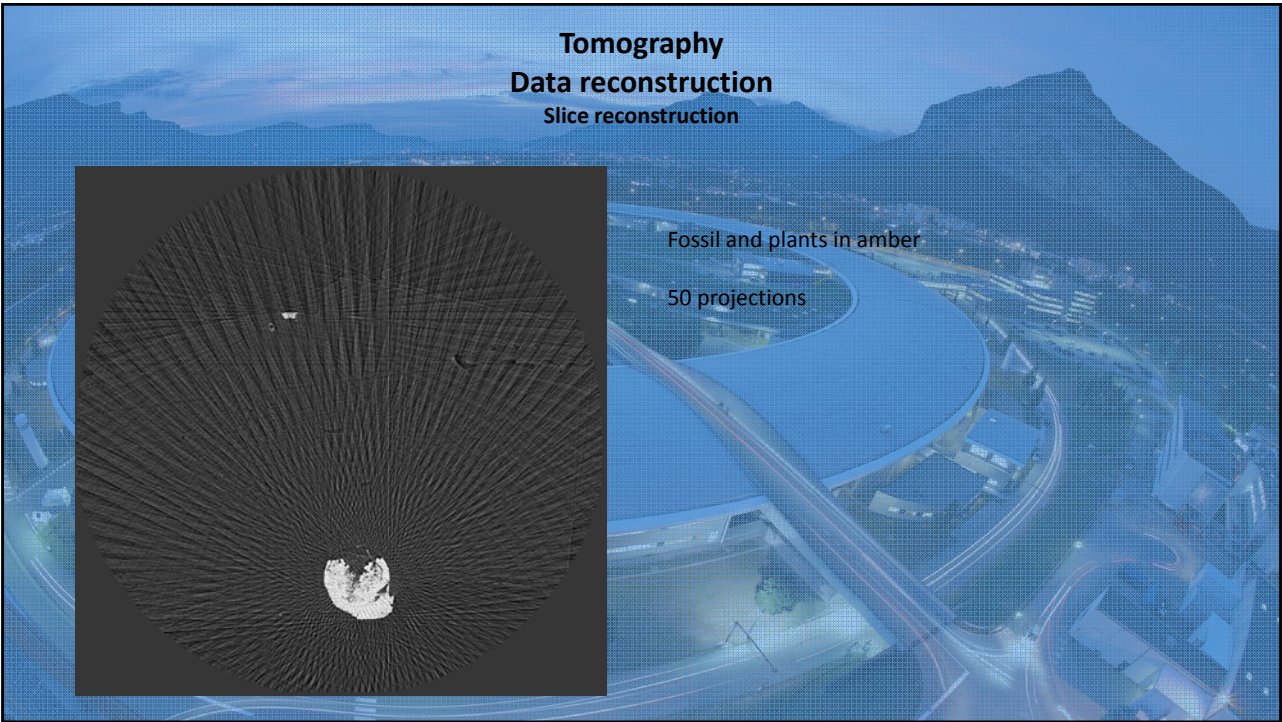
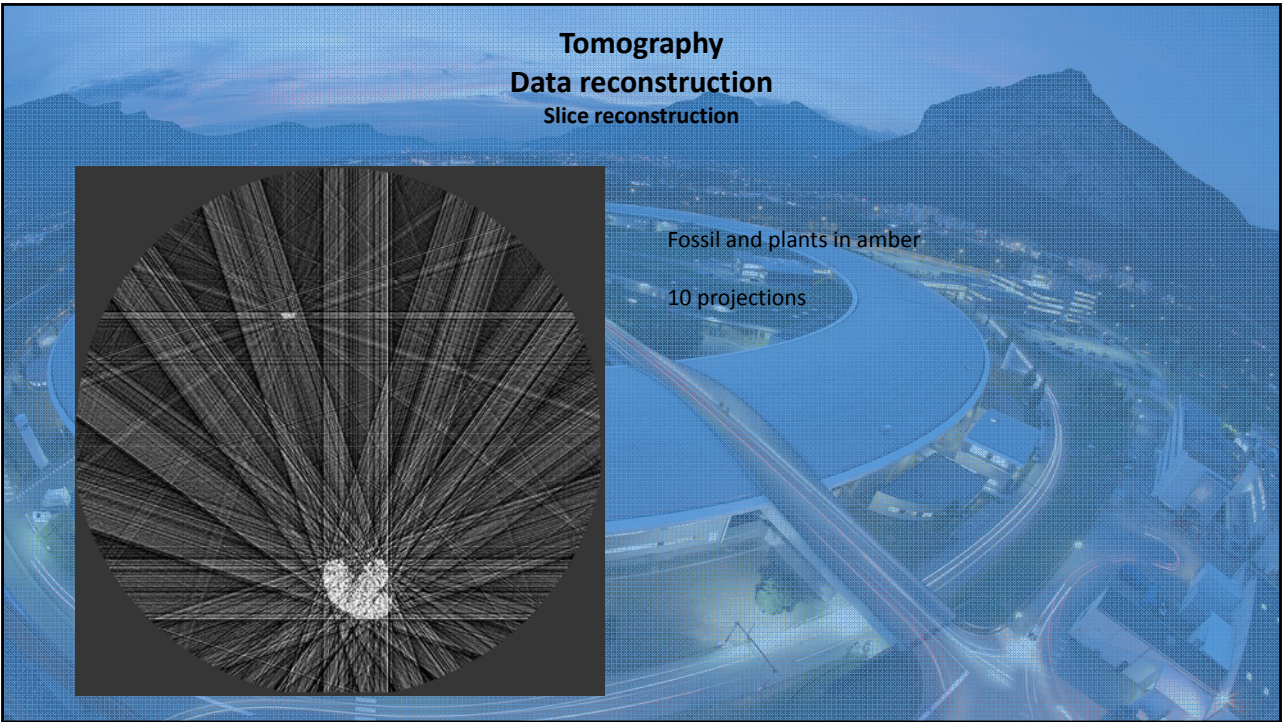


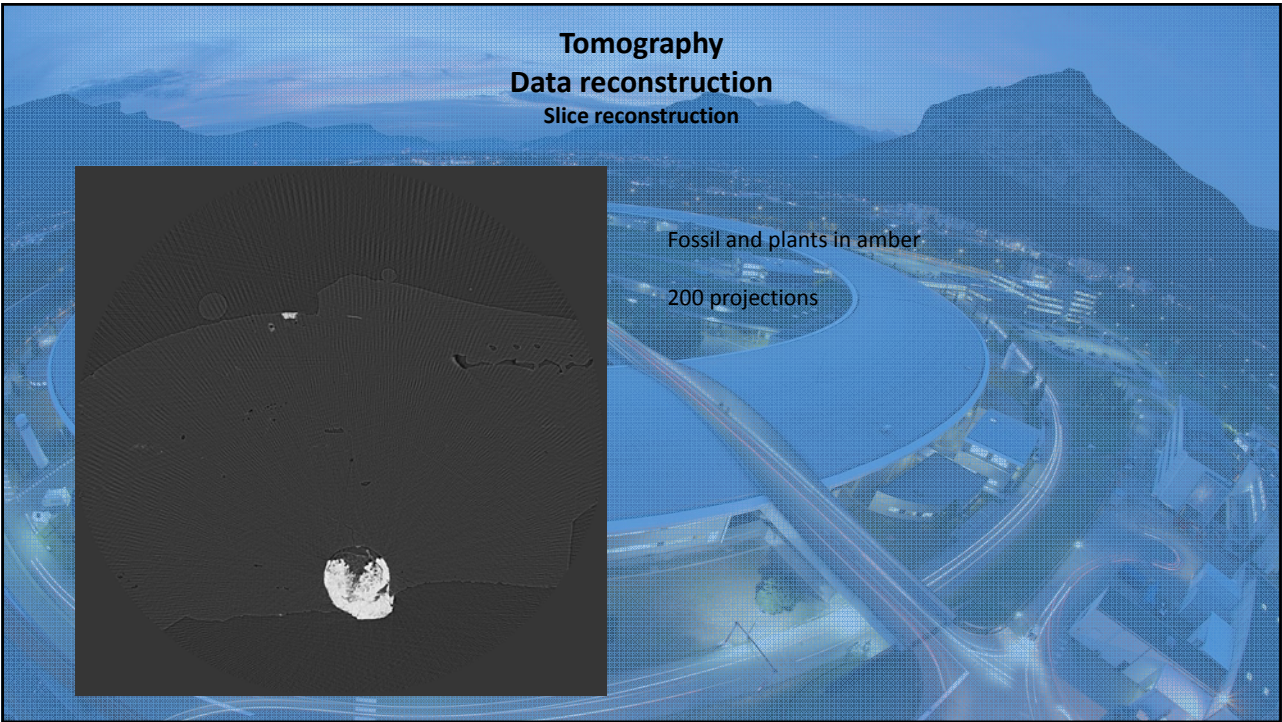
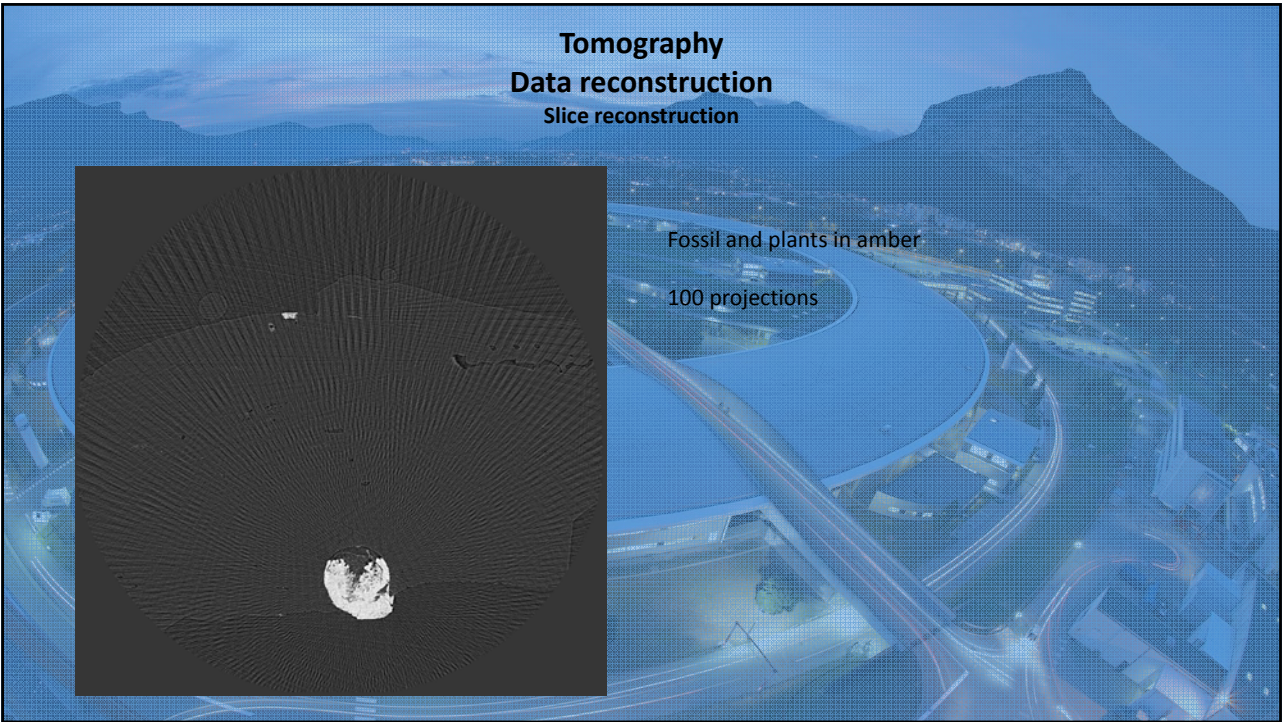


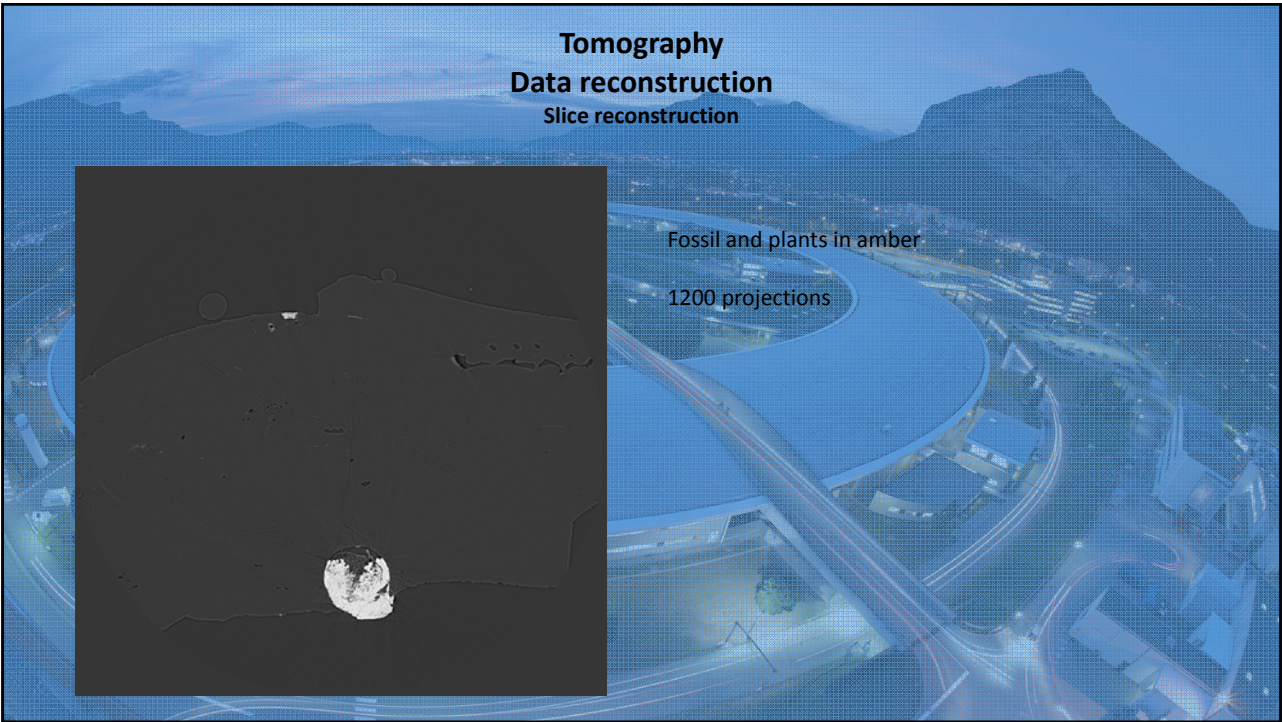
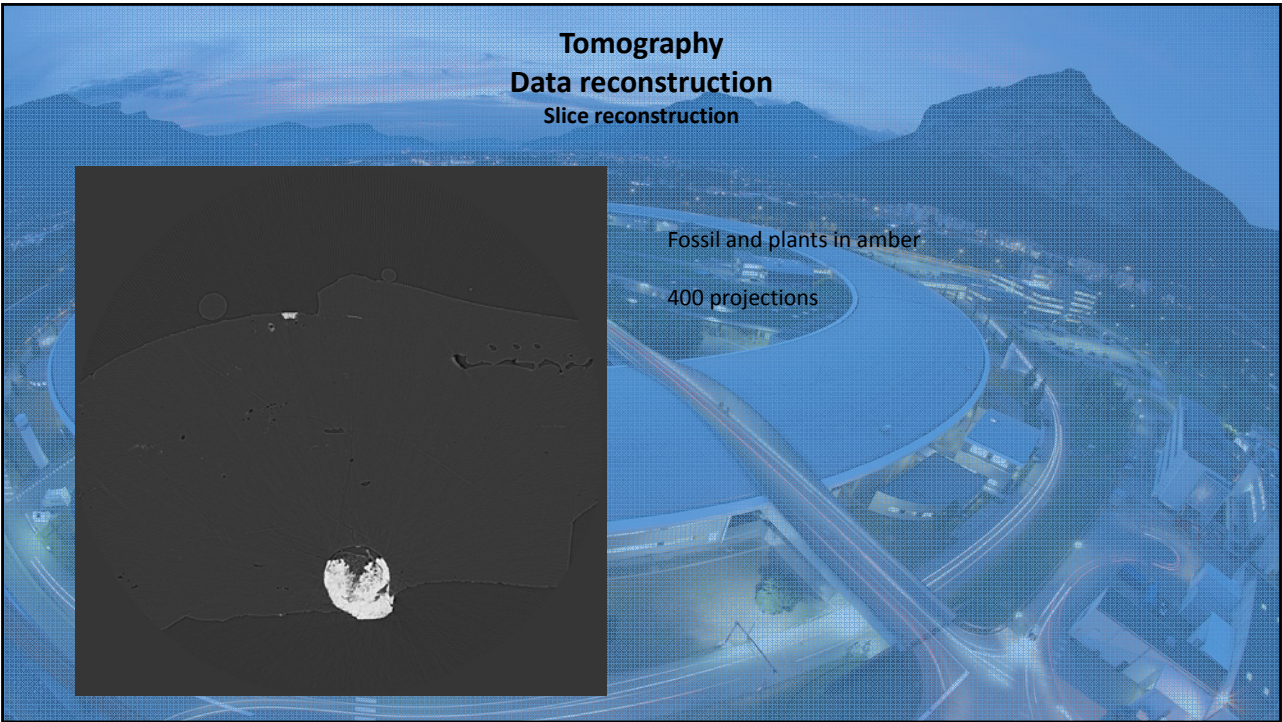


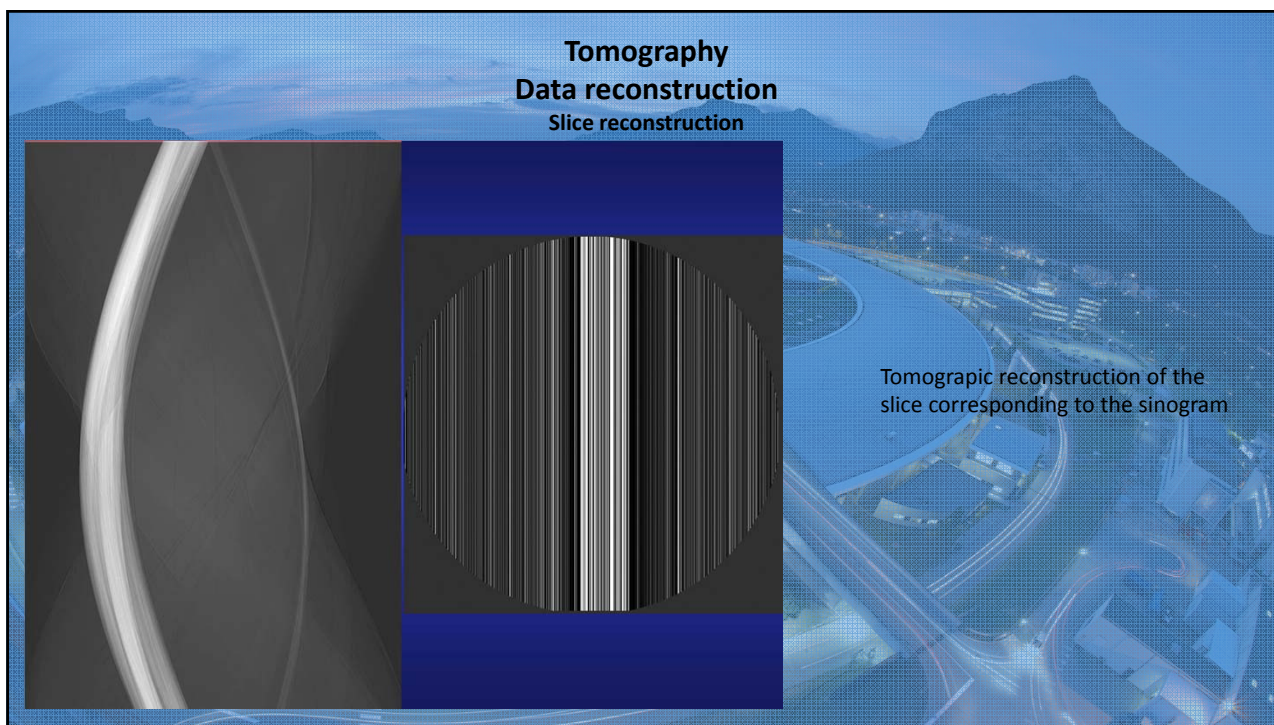
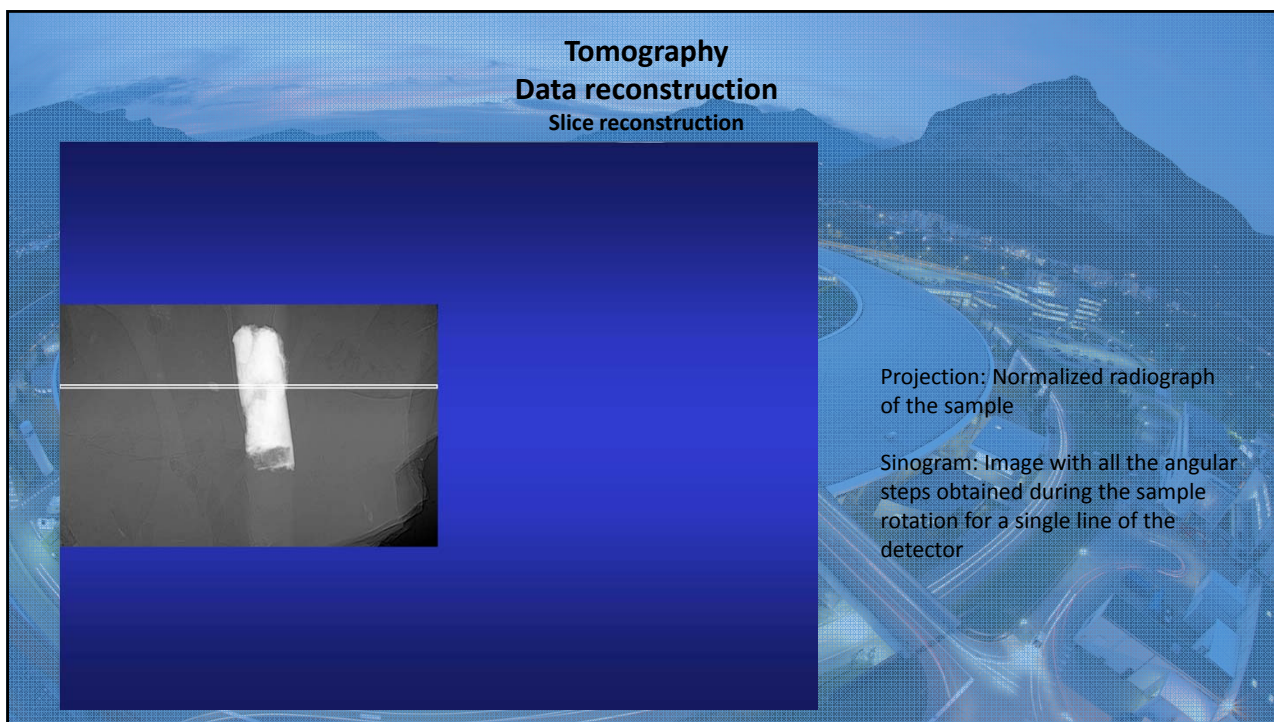


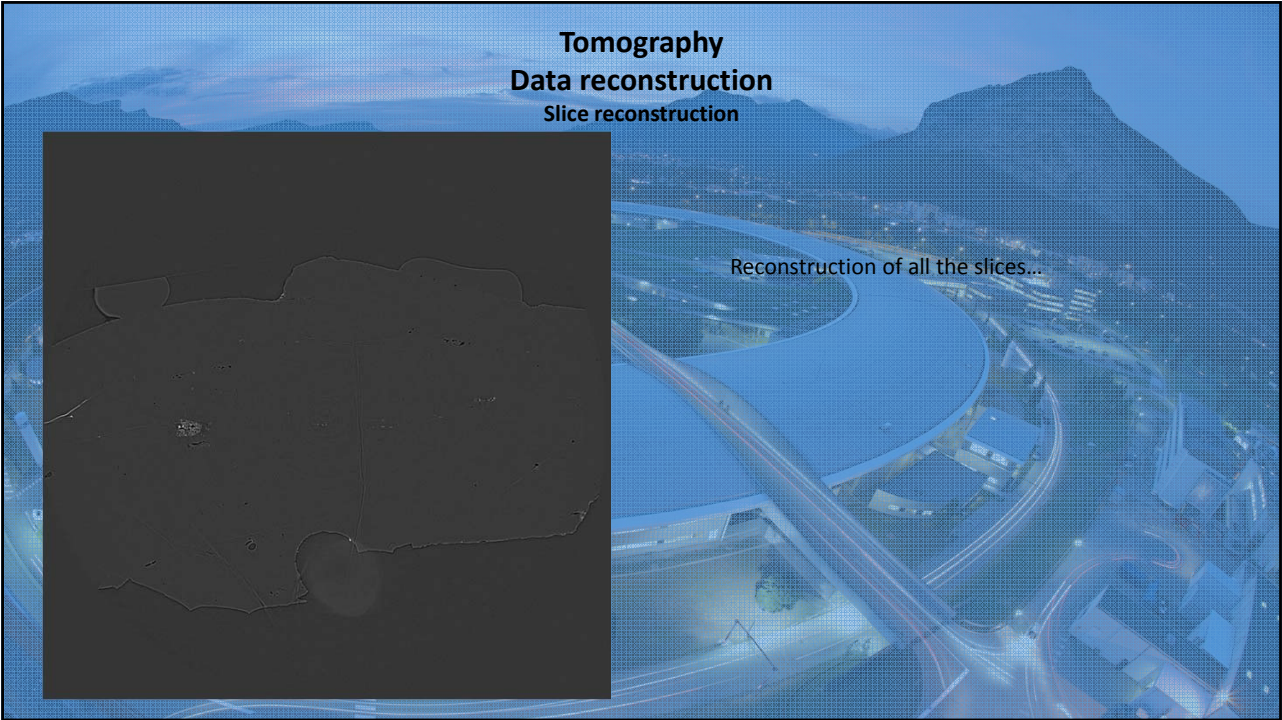












Non destructive method for the sample itself but what about its structure ?



Australopithecus sediba: 1.97 My
Imaged at the ESRF in 2009
Carlson, ..., Tafforeau, ... *Science*, 2011

Old fossils:

No risk for X-ray imaging



Homo neanderthalensis: 36 Ky

Recent fossils:

Risk of aDNA degradation

