Australian Government

ANSTO

Introduction to **Neutron imaging**

Floriana Salvemini

Science. Ingenuity. Sustainability.

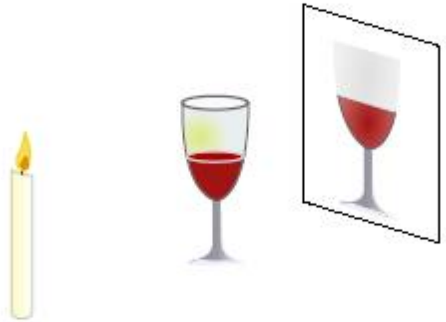
Outline

- Introduction to the method
- How image is formed
- Computed tomography
- Instrument components
- Case studies

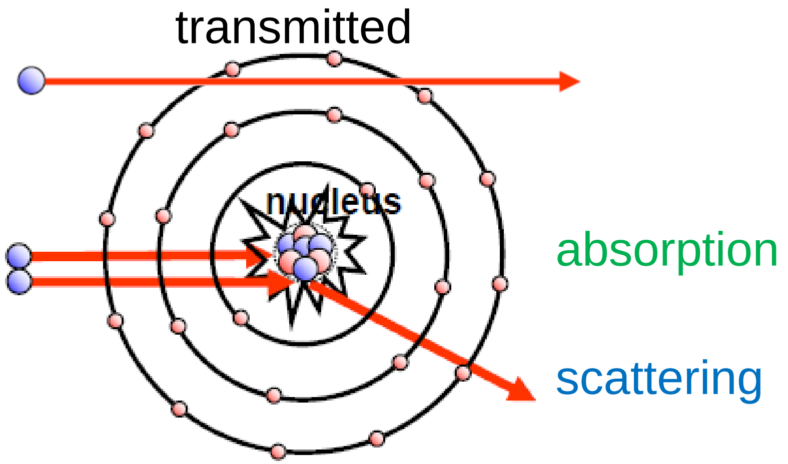
What is imaging?

We have a solid item to investigate

1. Take a first look of the outside
2. Use a transmission image
3. Cut the item in pieces ... virtually



Interaction with matter



Neutron imaging techniques

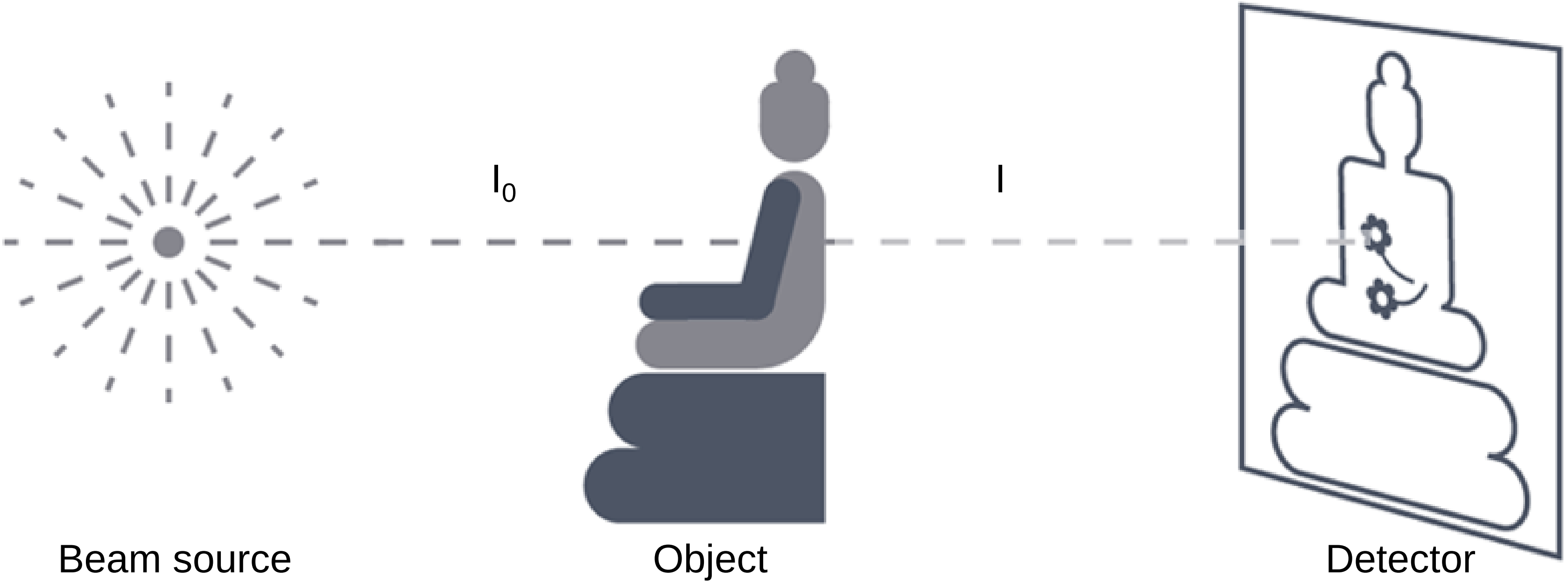
Radiography
Tomography
Real-time imaging
Stroboscopic imaging

Resonance capture analysis

Energy-selective imaging
Grating interferometry

https://www.psi.ch/niag/what-is-neutron-imaging

Transmission Image



Beer-Lambert law

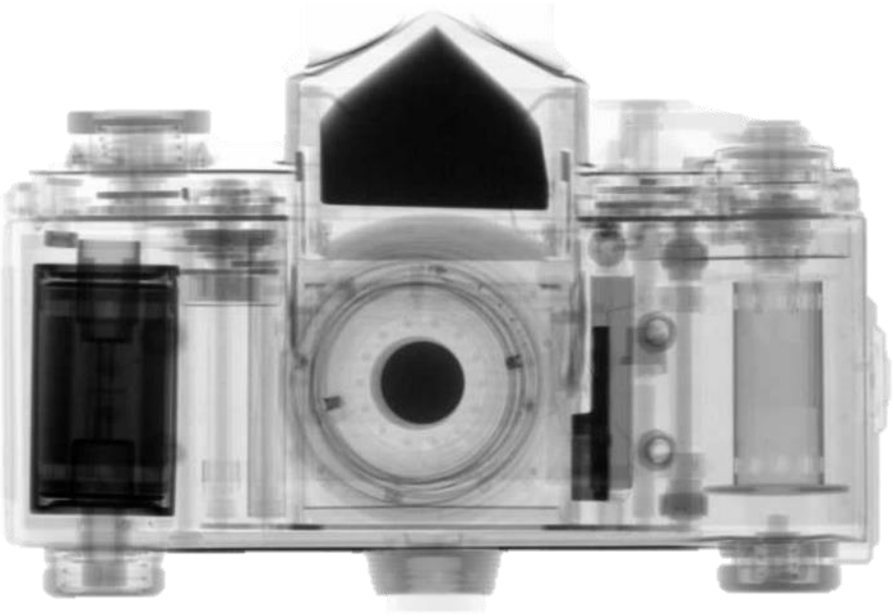
$$I(\lambda) = I_0(\lambda)e^{-\sum_i(\mu(\lambda)d)_i}$$

$I(\lambda)$ - transmitted intensity of a monochromatic beam
$I_0(\lambda)$ - incident intensity
d – path length
$\mu(\lambda)$ – total linear attenuation coefficient

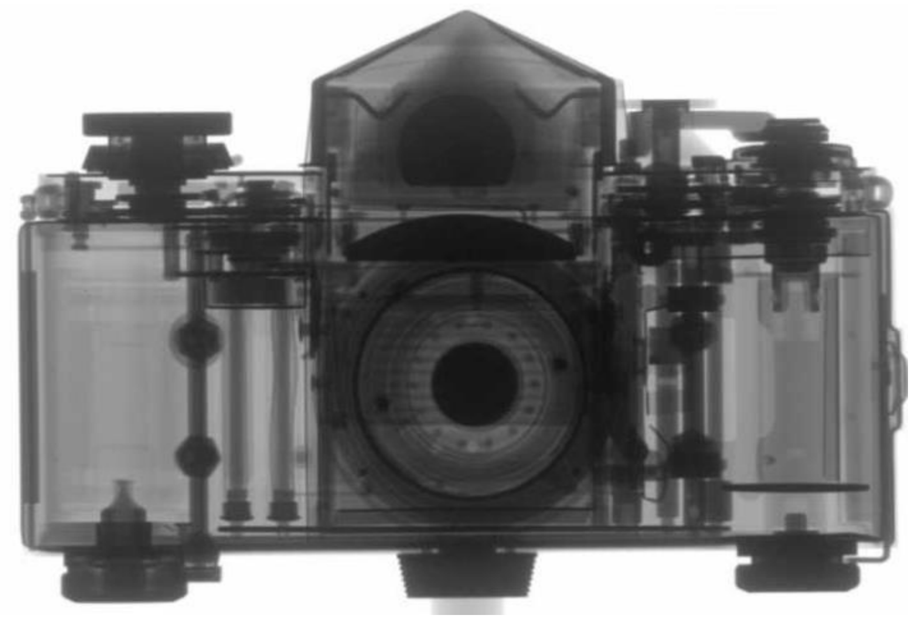
$$\mu(\lambda) = \sigma_t(\lambda)\frac{\rho N_A}{M}$$

$\sigma_t(\lambda)$- total cross-section
ρ - density
N_A - Avogadro's number
M – atomic mass

Neutrons vs X-ray

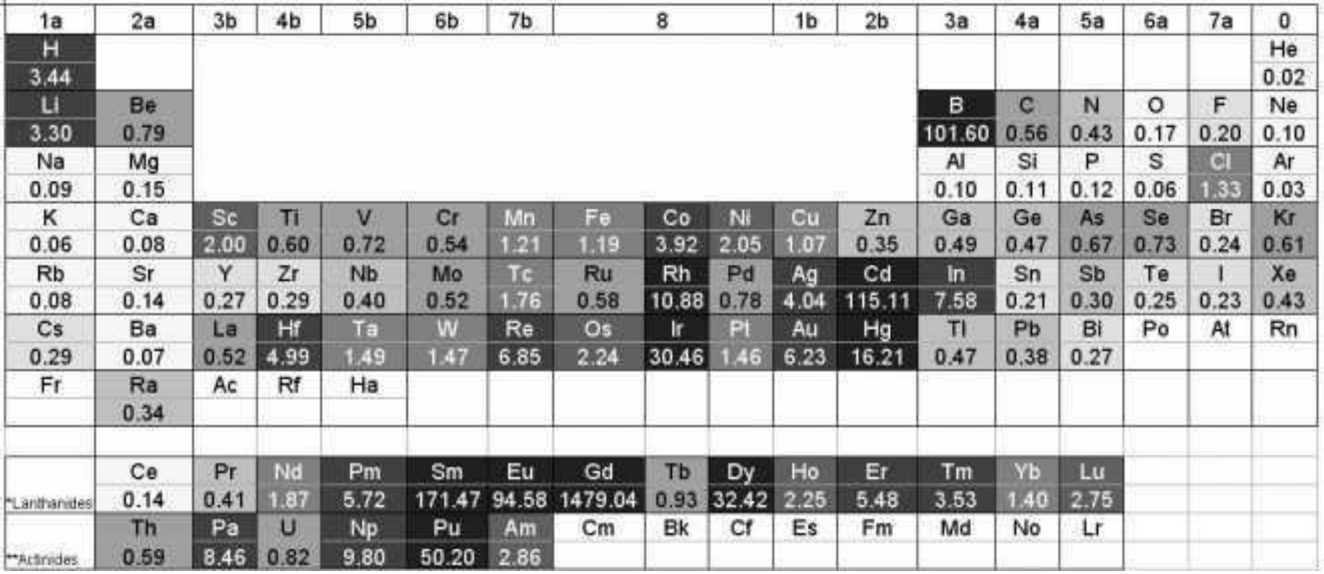


Neutrons



X-ray

Neutrons



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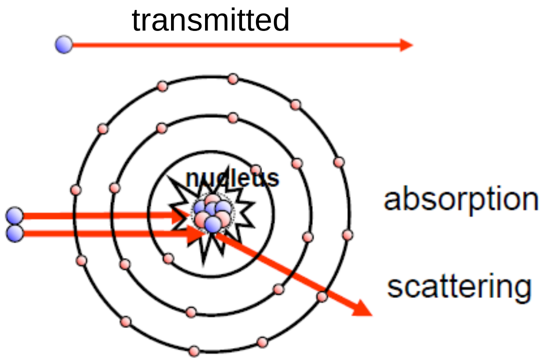
H 3.44																	He 0.02
Li 3.30	Be 0.79											B 101.60	C 0.56	N 0.43	O 0.17	F 0.20	Ne 0.10
Na 0.09	Mg 0.15											Al 0.10	Si 0.11	P 0.12	S 0.06	Cl 1.33	Ar 0.03
K 0.06	Ca 0.08	Sc 2.00	Ti 0.60	V 0.72	Cr 0.54	Mn 1.21	Fe 1.19	Co 3.92	Ni 2.05	Cu 1.07	Zn 0.35	Ga 0.49	Ge 0.47	As 0.67	Se 0.73	Br 0.24	Kr 0.61
Rb 0.08	Sr 0.14	Y 0.27	Zr 0.29	Nb 0.40	Mo 0.52	Tc 1.76	Ru 0.58	Rh 10.88	Pd 0.78	Ag 4.04	Cd 115.11	In 7.58	Sn 0.21	Sb 0.30	Te 0.25	I 0.23	Xe 0.43
Cs 0.29	Ba 0.07	La 0.52	Hf 4.99	Ta 1.49	W 1.47	Re 6.85	Os 2.24	Ir 30.46	Pt 1.46	Au 6.23	Hg 16.21	Tl 0.47	Pb 0.38	Bi 0.27	Po	At	Rn
Fr	Ra 0.34	Ac	Rf	Ha													
*Lanthanides	Ce 0.14	Pr 0.41	Nd 1.87	Pm 5.72	Sm 171.47	Eu 94.58	Gd 1479.04	Tb 0.93	Dy 32.42	Ho 2.25	Er 5.48	Tm 3.53	Yb 1.40	Lu 2.75			
**Actinides	Th 0.59	Pa 8.46	U 0.82	Np 9.80	Pu 50.20	Am 2.86	Cm	Bk	Cf	Es	Fm	Md	No	Lr			



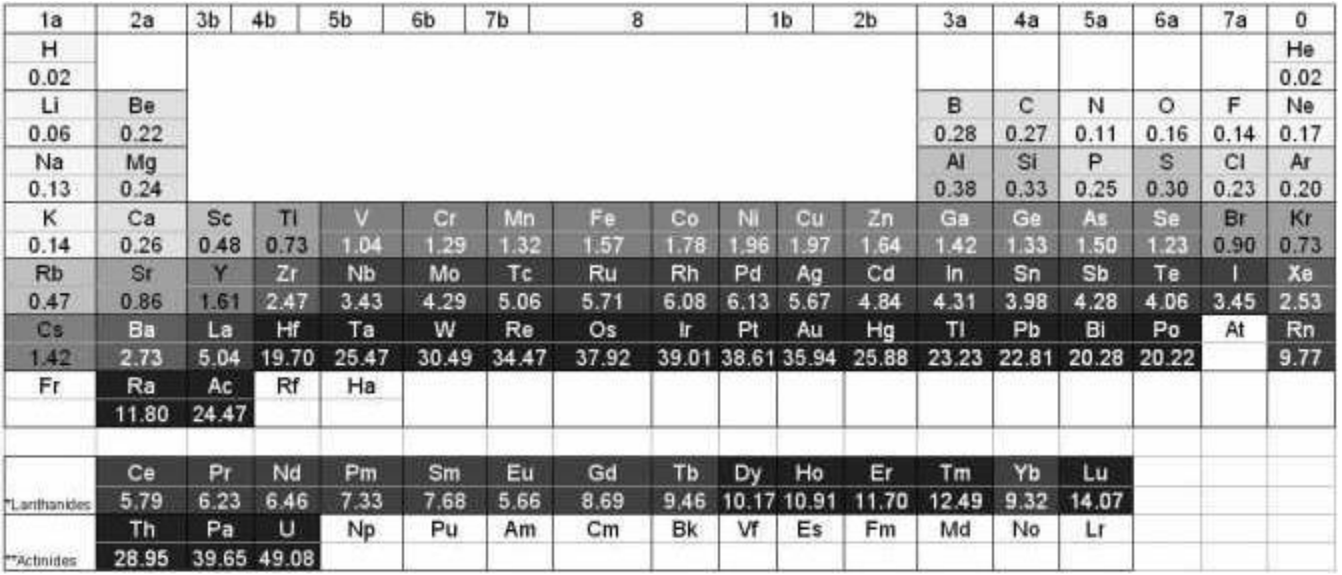
Pros

- High penetration power
- High sensitivity to H
- Non-invasive method

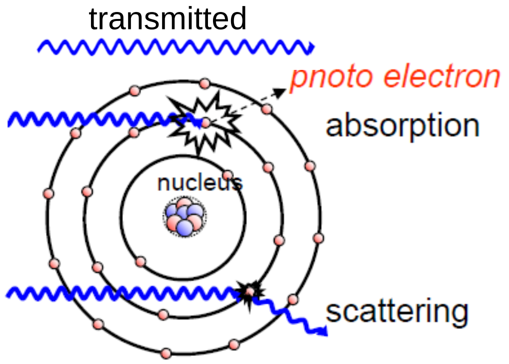
Cons

- Acquisition time
- Resolution
- Post-experiment radioactivity

X-ray



1a	2a	3b	4b	5b	6b	7b	8			1b	2b	3a	4a	5a	6a	7a	0
H 0.02																	He 0.02
Li 0.06	Be 0.22											B 0.28	C 0.27	N 0.11	O 0.16	F 0.14	Ne 0.17
Na 0.13	Mg 0.24											Al 0.38	Si 0.33	P 0.25	S 0.30	Cl 0.23	Ar 0.20
K 0.14	Ca 0.26	Sc 0.48	Ti 0.73	V 1.04	Cr 1.29	Mn 1.32	Fe 1.57	Co 1.78	Ni 1.96	Cu 1.97	Zn 1.64	Ga 1.42	Ge 1.33	As 1.50	Se 1.23	Br 0.90	Kr 0.73
Rb 0.47	Sr 0.86	Y 1.61	Zr 2.47	Nb 3.43	Mo 4.29	Tc 5.06	Ru 5.71	Rh 6.08	Pd 6.13	Ag 5.67	Cd 4.84	In 4.31	Sn 3.98	Sb 4.28	Te 4.06	I 3.45	Xe 2.53
Cs 1.42	Ba 2.73	La 5.04	Hf 19.70	Ta 25.47	W 30.49	Re 34.47	Os 37.92	Ir 39.01	Pt 38.61	Au 35.94	Hg 25.88	Tl 23.23	Pb 22.81	Bi 20.28	Po 20.22	At	Rn 9.77
Fr	Ra 11.80	Ac 24.47	Rf	Ha													
*Lanthanides	Ce 5.79	Pr 6.23	Nd 6.46	Pm 7.33	Sm 7.68	Eu 5.66	Gd 8.69	Tb 9.46	Dy 10.17	Ho 10.91	Er 11.70	Tm 12.49	Yb 9.32	Lu 14.07			
**Actinides	Th 28.95	Pa 39.65	U 49.08	Np	Pu	Am	Cm	Bk	Vf	Es	Fm	Md	No	Lr			



Pros

- Fast acquisition
- High resolution
- No after-radiation

Cons

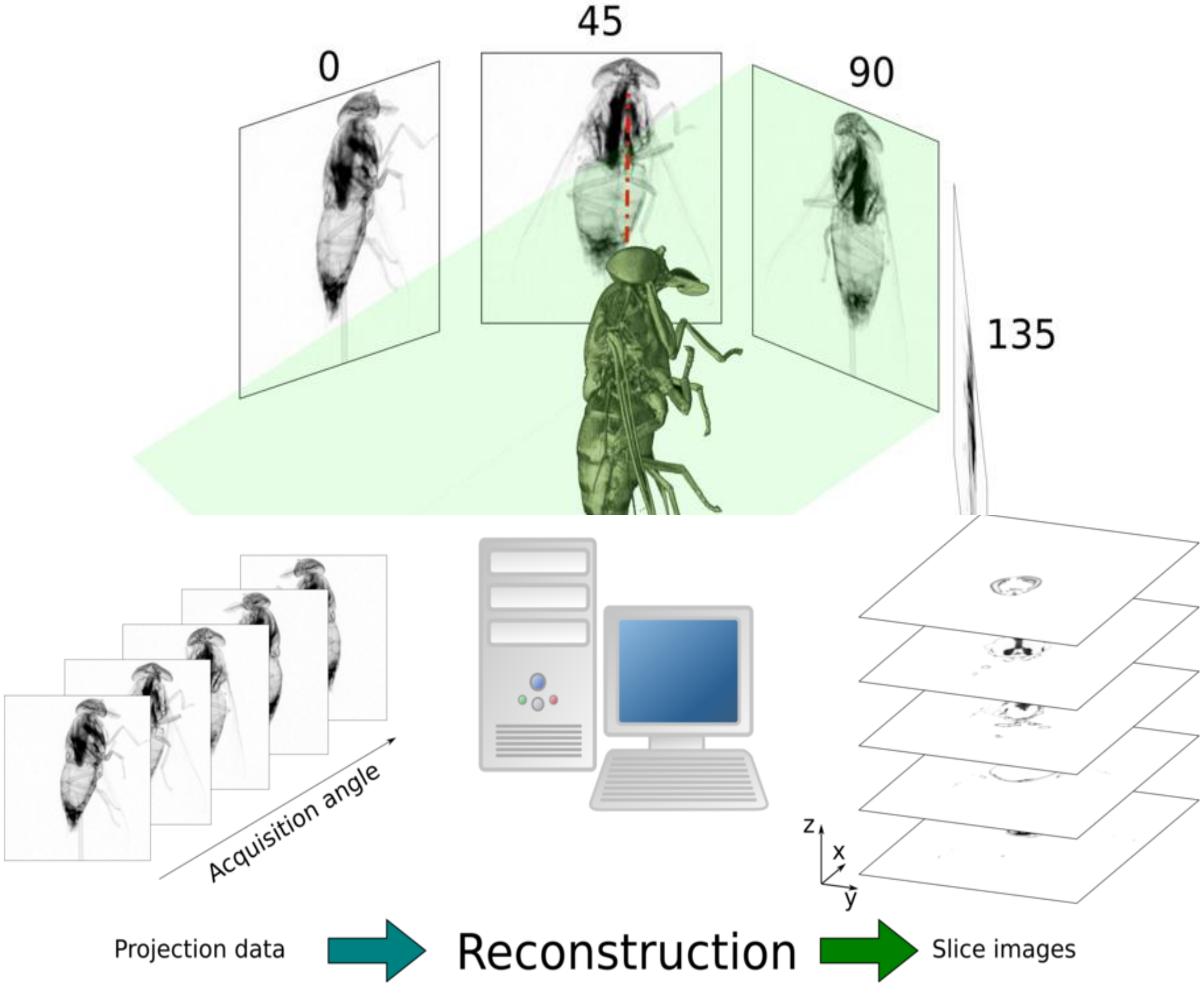
- High Z materials
- Lower material differentiation

Computed Tomography

Credit: https://www.psi.ch/media/x-ray-and-neutron-imaging-for-palaeontologists-and-archaeologists

https://www.psi.ch/niag/what-is-neutron-imaging

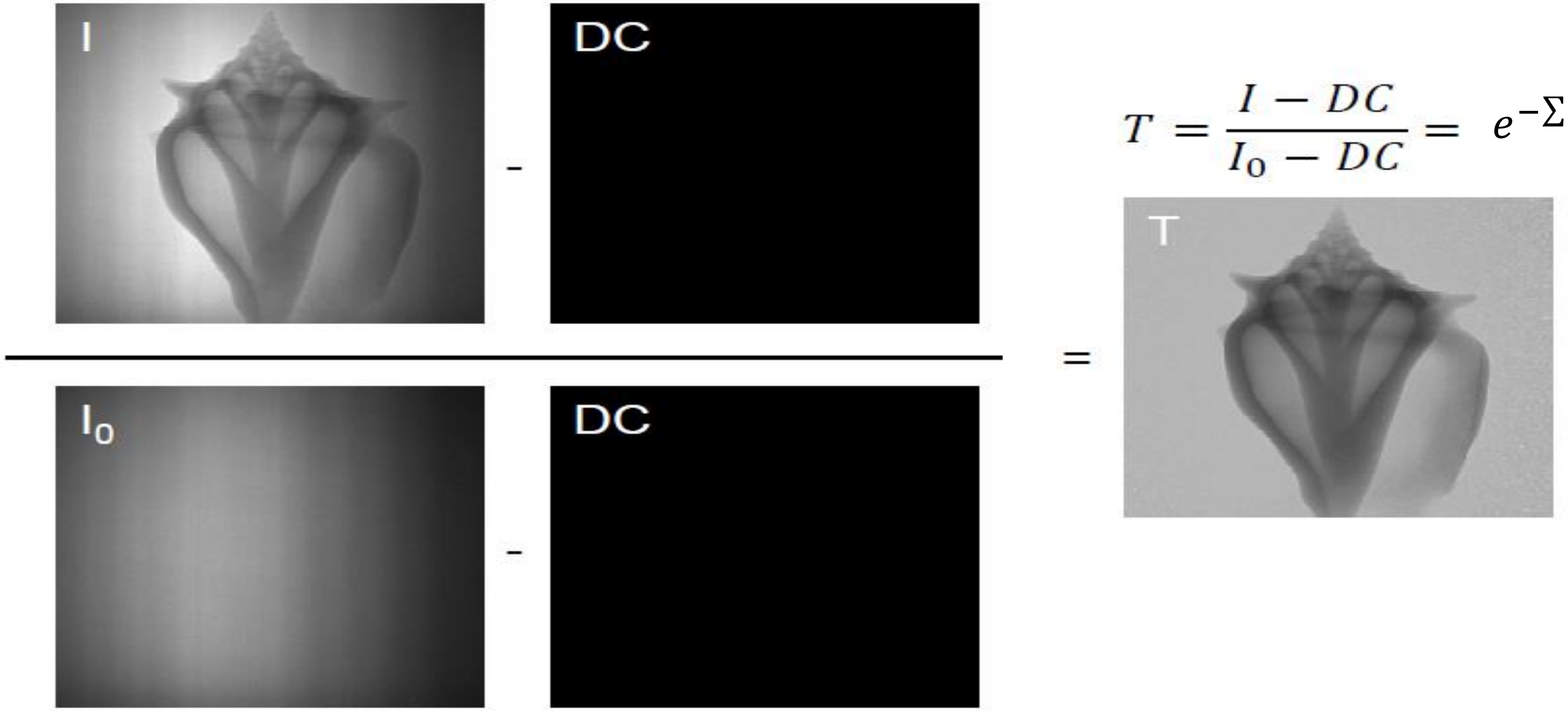
Computed Tomography



Computing a transmission Image

Beer-Lambert law for each pixel of the 2D detector

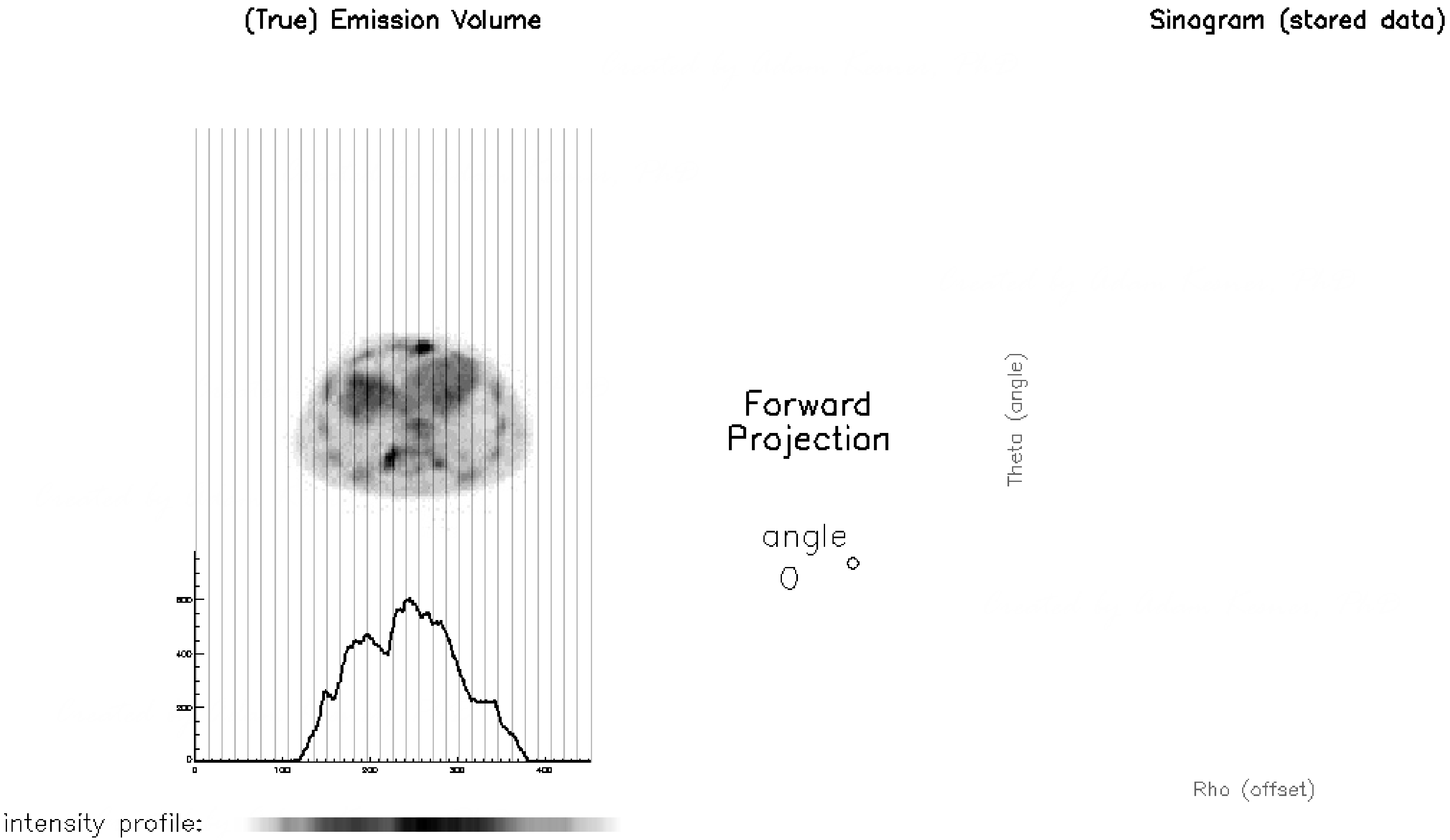
$$T = \frac{I - DC}{I_0 - DC} = e^{-\sum_i (\mu(\lambda) d)_i}$$



Eliminate incident beam intensity variation (I_0) and camera intensity offset (DC) to get transmission image (T)

Hymanhealth.iaea.org
M. Strobl, et al., Journal of Physics D Applied Physics · 2009

Image reconstruction: The Radon Transform and the sinogram



Approximations:

- Parallel and monoenergetic beam
- Interactions outside the sample and scattered neutrons are not taken into account.

The Radon transform of the one-dimensional projections Pθ (t) of single slices at angles θ can be formulated as

$$P_\theta(t) = -\ln \frac{I_\theta(t)}{I_0(t)} = \int_{\mathrm{ray}(\theta,t)} \mu(x, y)\cdot \mathrm{d}s$$

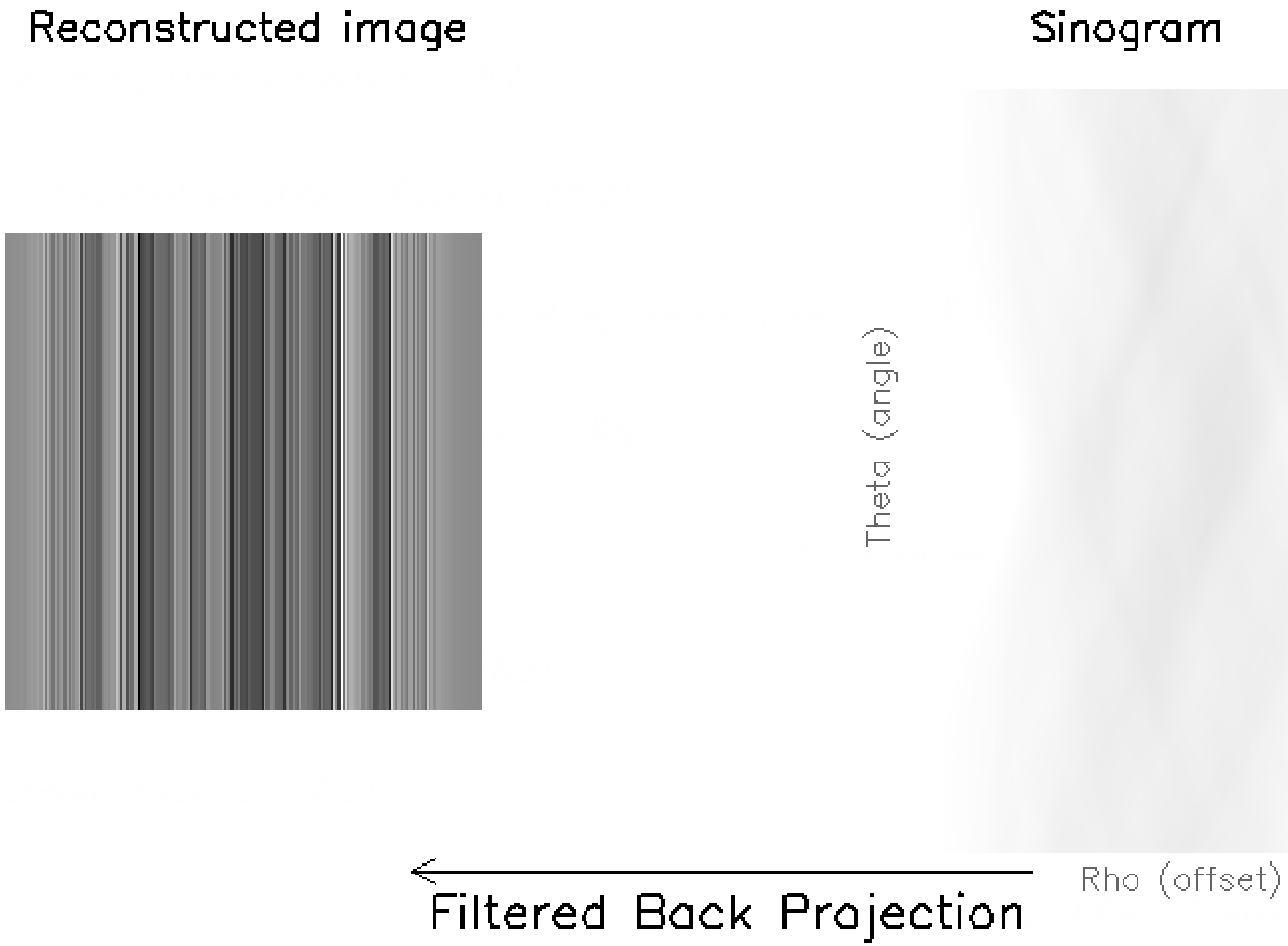
$$= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \delta_D(x\ \cos\theta + y\sin\theta - t)$$

$$\times\ \mu(x, y)\cdot \mathrm{d}x\,\mathrm{d}y,$$

where t = x cos θ + y sin θ and is perpendicular to the rotation axis.

Hymanhealth.iaea.org
M. Strobl, et al., Journal of Physics D Applied Physics · 2009

Filtered-back projection Radon transform



The **Fourier slice theorem** states that the one-dimensional Fourier transform Pθ (ω) of the projections Pθ (t) of the two-dimensional function μ(x, y) is equal to the two-dimensional Fourier transform S(u, v) of the slice μ(x, y). Consequently, an infinite number of projections will fill the whole Fourier space and enable a perfect reconstruction of μ(x, y) by the back transformation

$$\begin{aligned}\mu(x, y) &= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} S(u, v)\cdot \mathrm{e}^{2\pi \mathrm{i}(ux+vy)}\cdot \mathrm{d}u\,\mathrm{d}v\\ &= \int_{0}^{\pi}\int_{0}^{\infty}\left(\int_{-\infty}^{\infty} P_\theta(t)\cdot \mathrm{e}^{-2\pi \mathrm{i}\omega t}\cdot \mathrm{d}t\right)\\ &\quad\times \mathrm{e}^{2\pi \mathrm{i}(x\cos\theta+y\sin\theta)}\cdot|\omega|\cdot \mathrm{d}\omega\,\mathrm{d}\theta,\end{aligned}$$

where |ω| results from the transformation into polar coordinates (u, v).

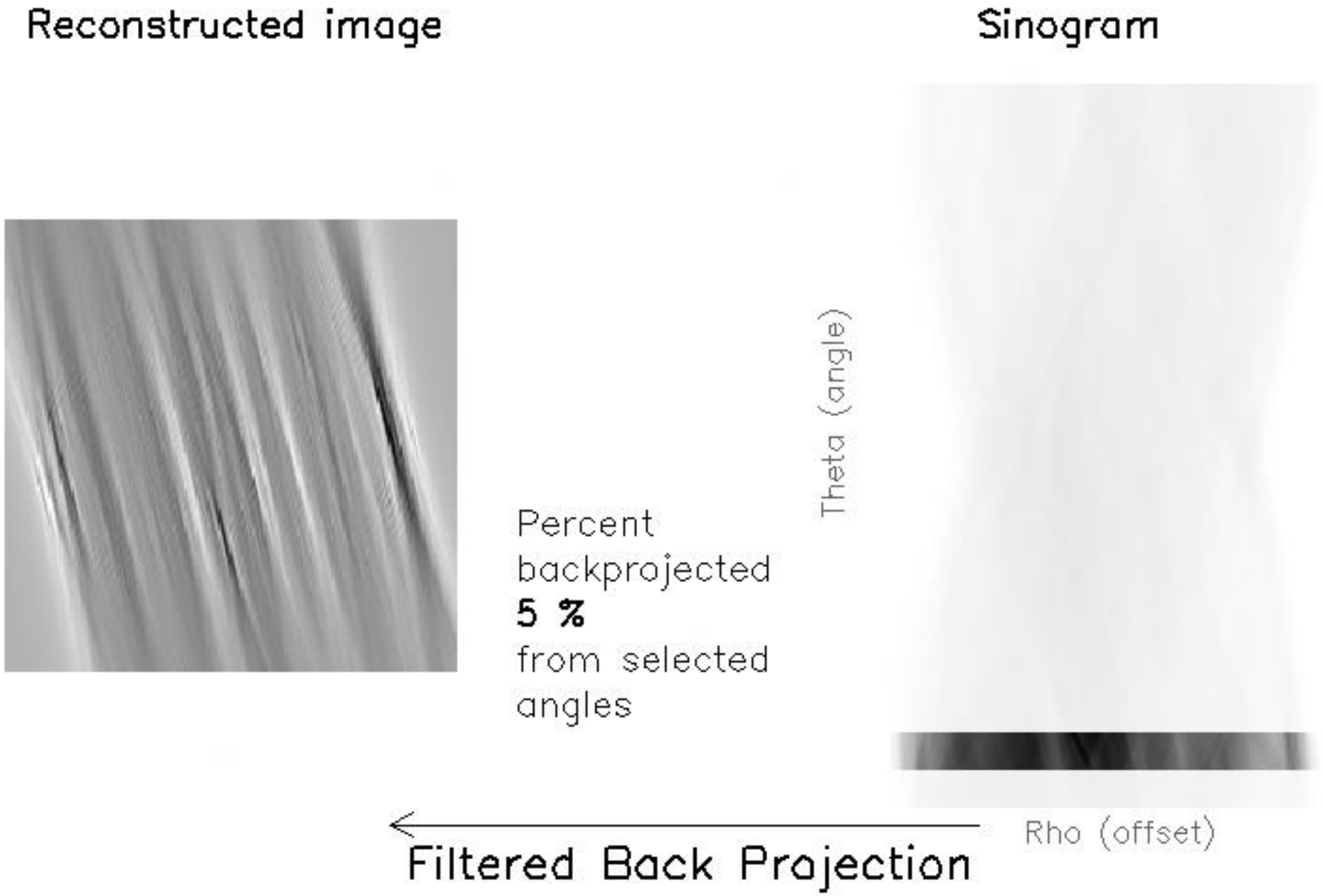
$$Q_\theta(t) = \int_{0}^{\infty} P_\theta(\omega)\cdot \mathrm{e}^{2\pi \mathrm{i}(x\cos\theta+y\sin\theta)}|\omega|\cdot \mathrm{d}\omega$$

This function is called a filtered projection where |ω| can be considered to be a ramp filter.

Hymanhealth.iaea.org
M. Strobl, et al., Journal of Physics D Applied Physics · 2009

How many projections are needed?

The number of projections is determined by the **Nyquist–Shannon sampling theorem**

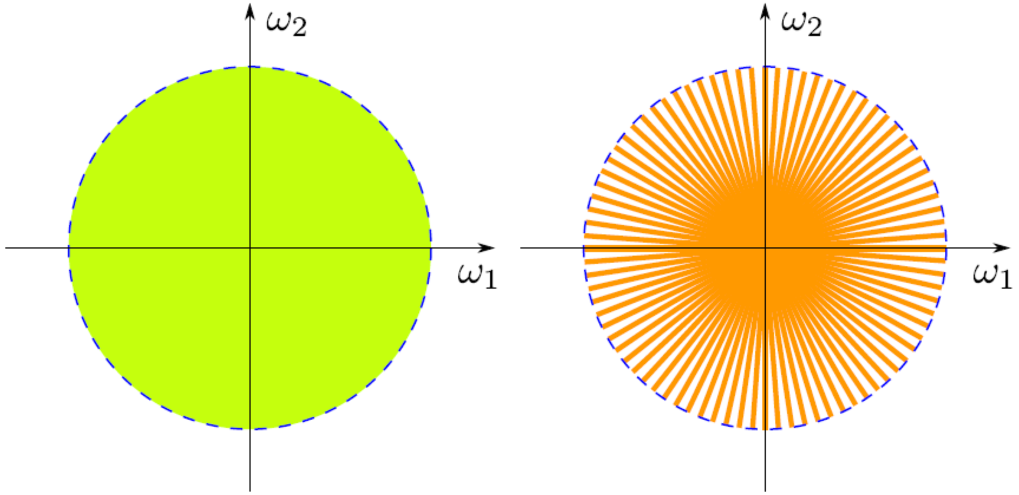


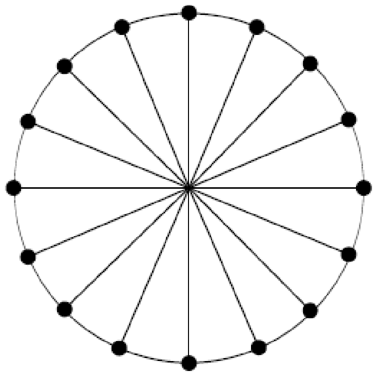
$$N = \frac{\pi}{2} M$$

N= number of projections
M=Number of pixels in the direction perpendicular to the axis of rotation

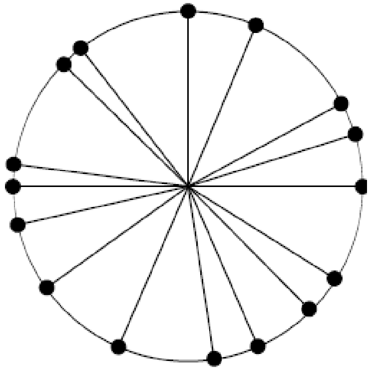
When the analytical solution has problem

The unit circle in the Fourier domain must be filled

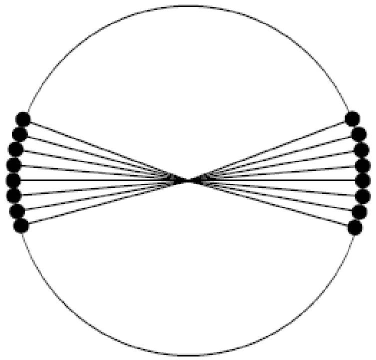




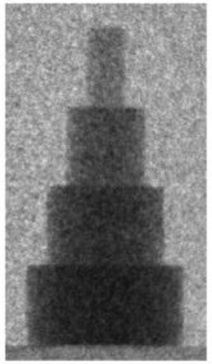
Few projections



Irregularly distributed



Limited view



Low SNR

Iterative methods

Pros

Spare, irregular, sampled projection data

Physical model can be included

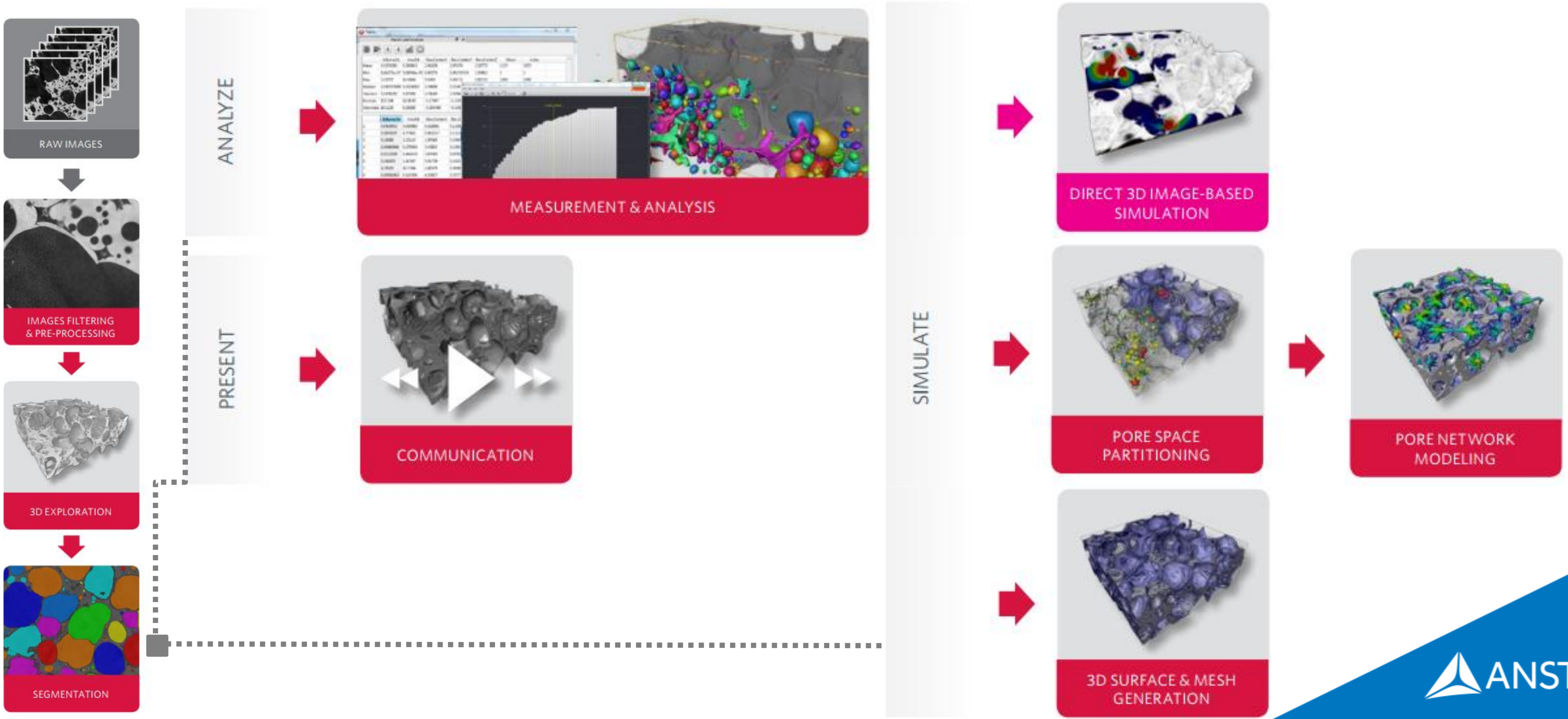
Cons

Require *a piori* knowledge for best performance

Time consuming

https://www.fei.com/WorkArea/DownloadAsset.aspx?id=25769803898

Image processing



RAW IMAGES

IMAGES FILTERING
& PRE-PROCESSING

3D EXPLORATION

SEGMENTATION

ANALYZE

MEASUREMENT & ANALYSIS

PRESENT

COMMUNICATION

SIMULATE

DIRECT 3D IMAGE-BASED
SIMULATION

PORE SPACE
PARTITIONING

PORE NETWORK
MODELING

3D SURFACE & MESH
GENERATION

Software for data reconstruction and analysis

Preliminary data treatment and filtering

ImageJ
FIJI
MATLAB – Image processing toolbox
ImageMagick

Tomographic reconstruction

Octopus
X-tract
MATLAB – Image processing toolbox
Exploring free-software i.e. *MuhRec, iMARS, CTAS*

Visualization and analysis

VG Studio MAX
Drishti
AVIZO (FEI)
Slicer3D
ParaView

Instrument components

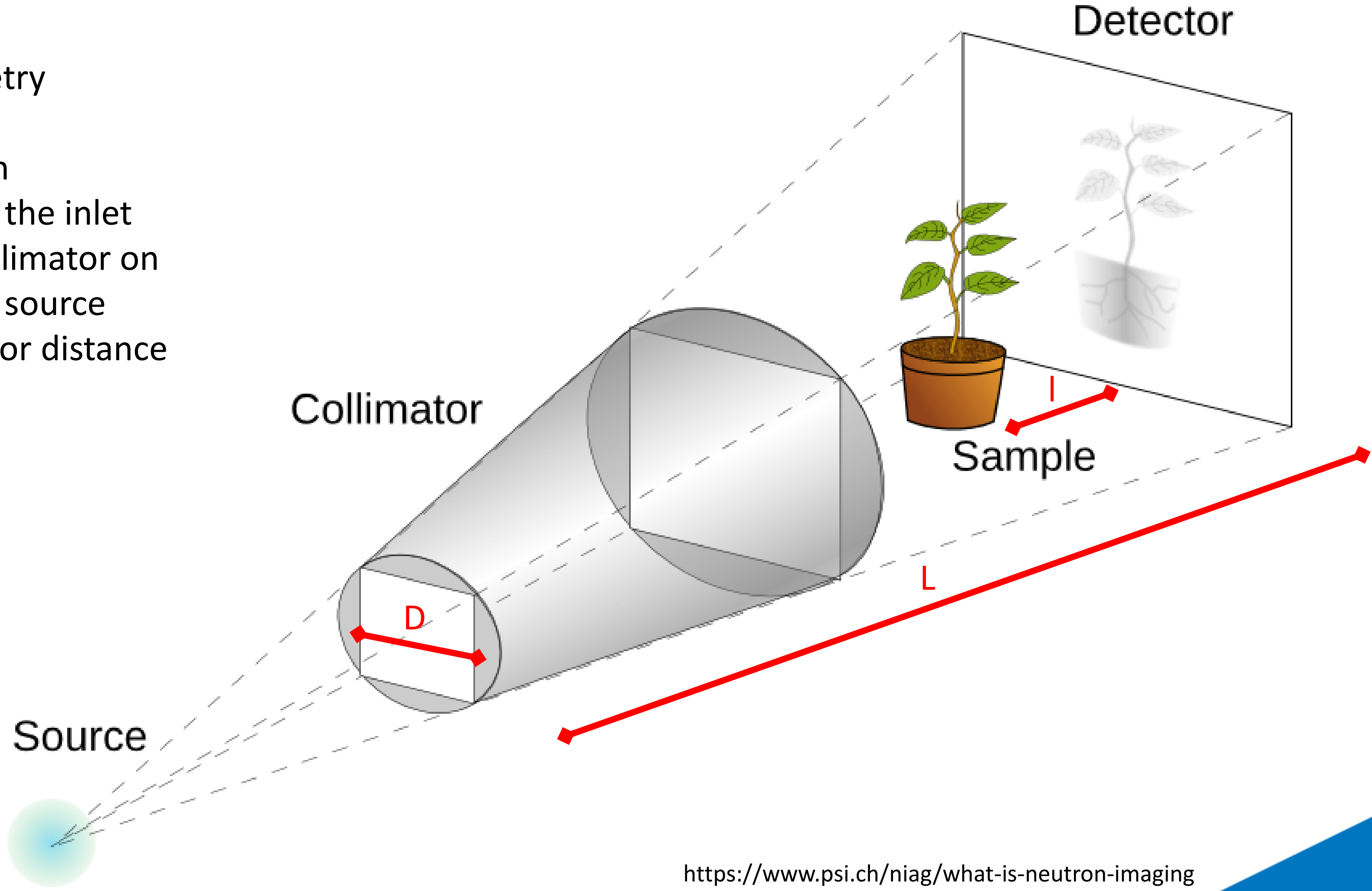
Collimation geometry

L/D

L: collimator length

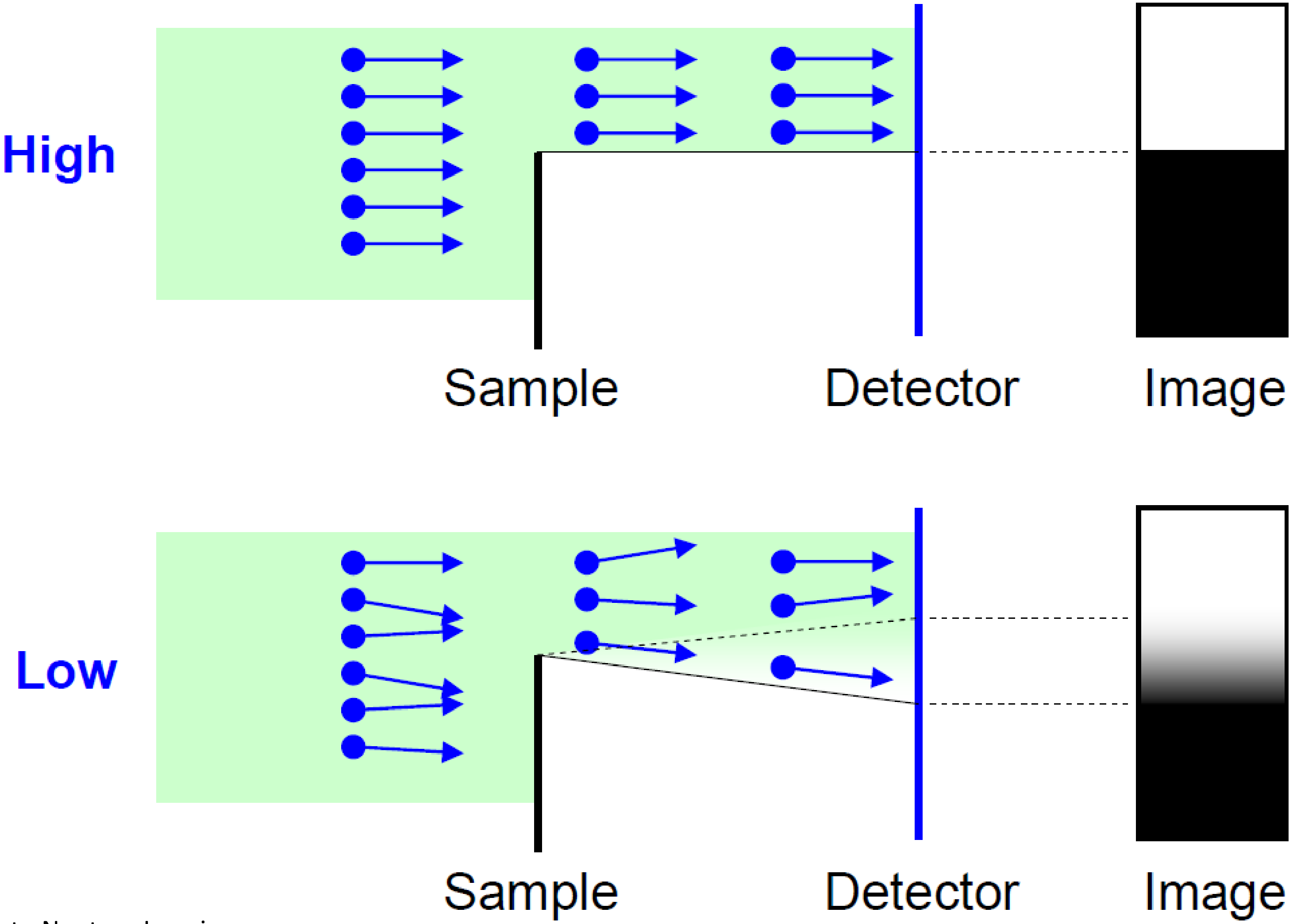
D: the diameter of the inlet aperture of the collimator on the side facing the source

l: sample to detector distance



https://www.psi.ch/niag/what-is-neutron-imaging

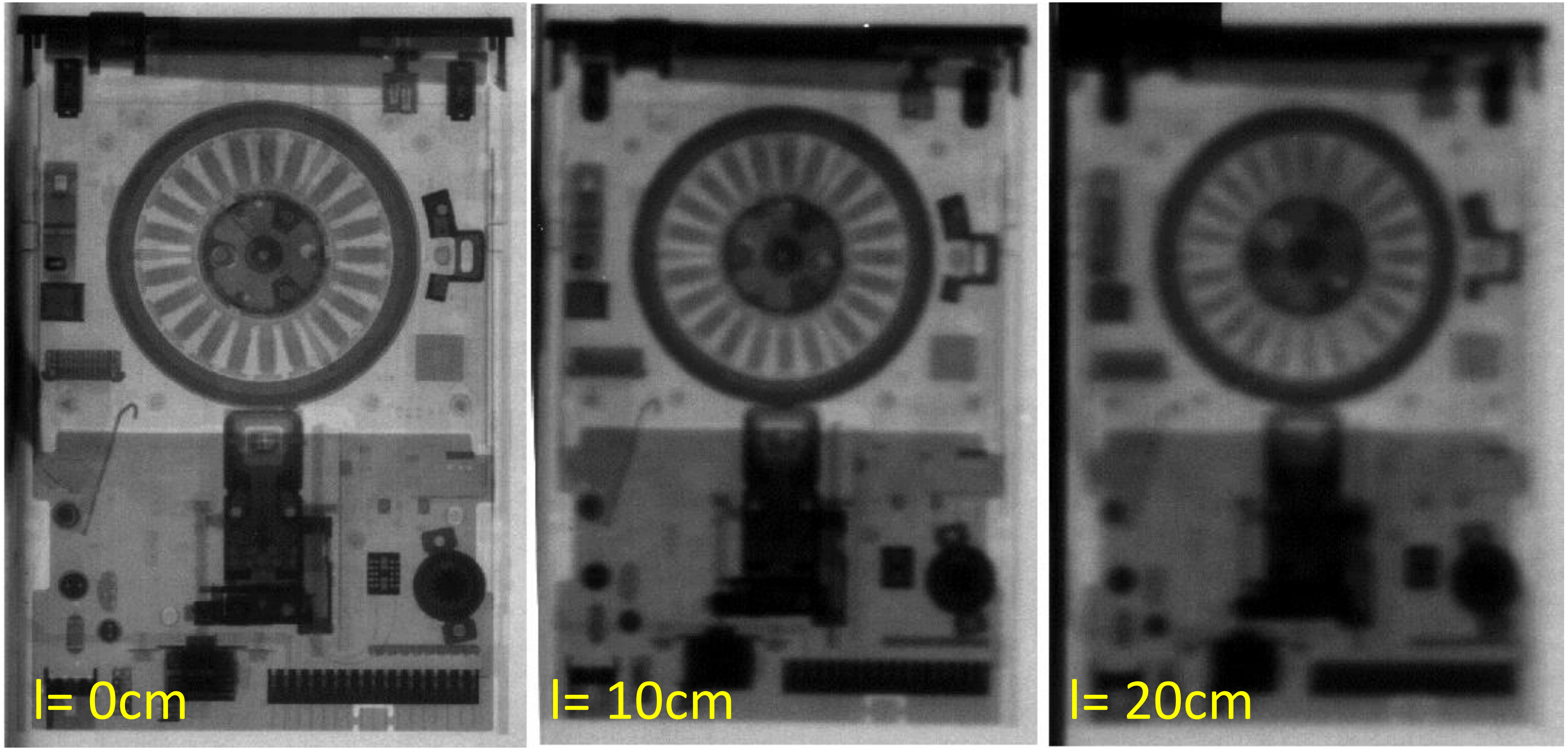
Effect of L/D on resolution



Pierre Boillat – PSI - Introduction to Neutron Imaging

Effect of *l* on resolution

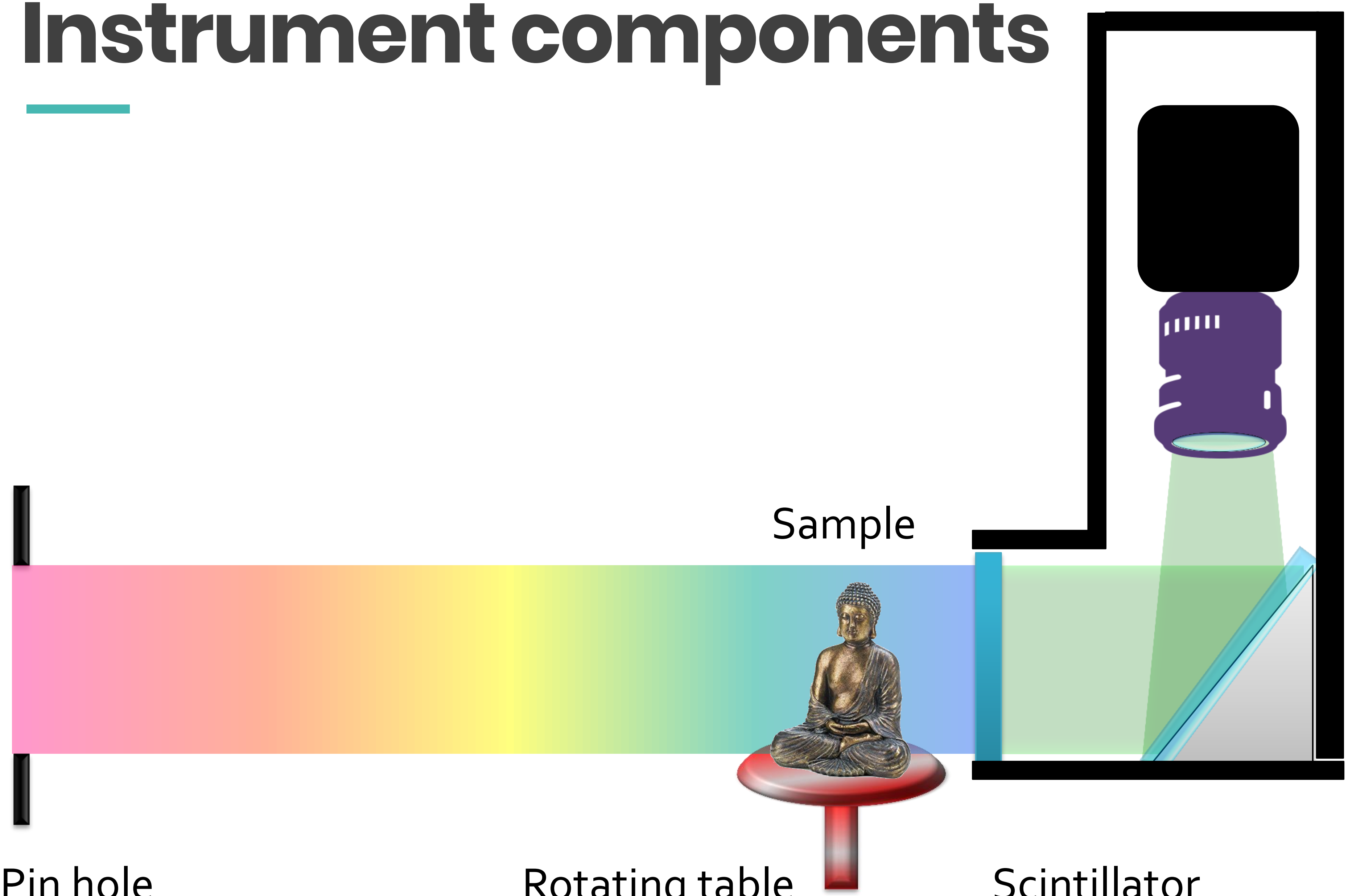
L/*D*=71



The measurements are performed at FRM-I, TU-München by B. Schillinger

Source: 32nd Berlin School on Neutron Scattering, March 8-16, 2012

Instrument components



Light-tight box

Detector

Lens

Sample

Mirror

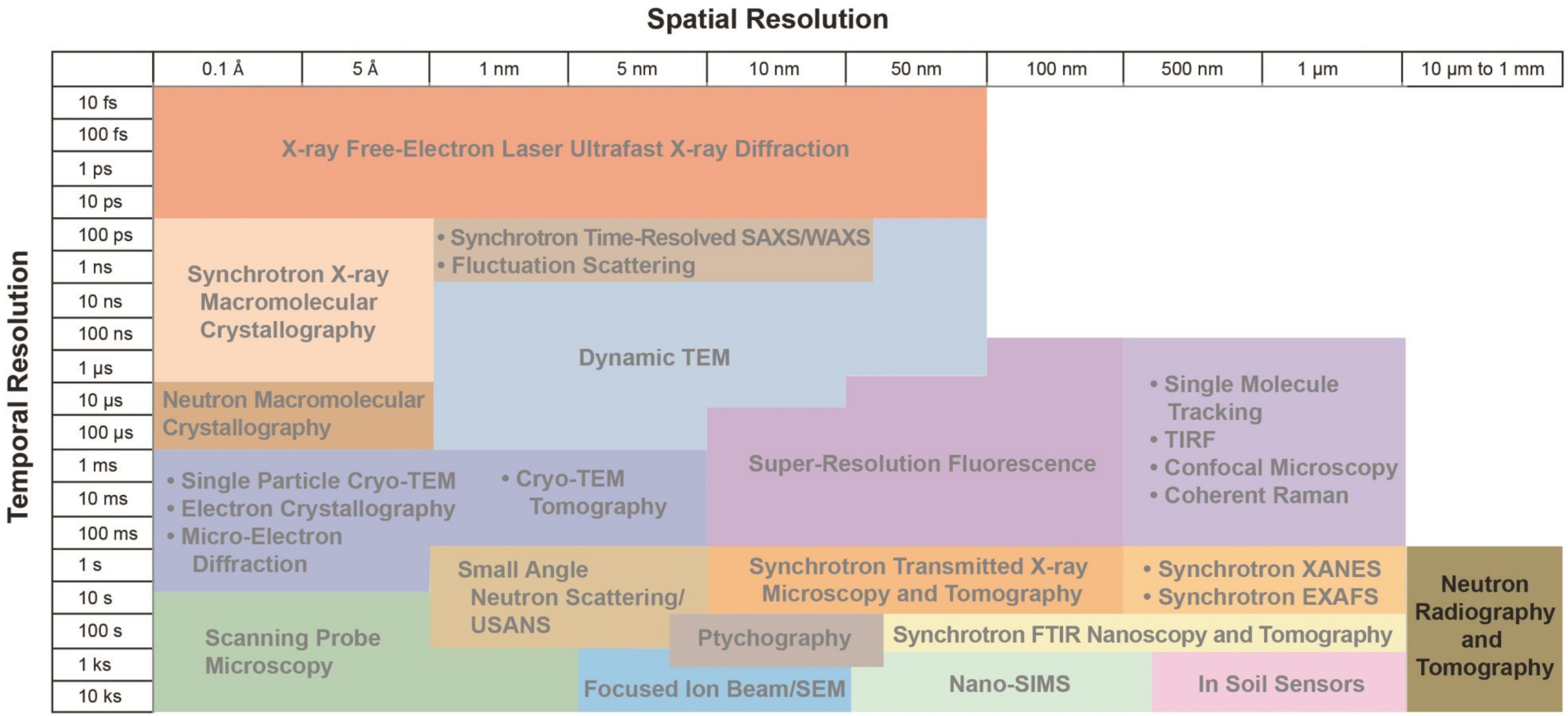
Pin hole

Rotating table

Scintillator

ANSTO

Spatial and Temporal Resolutions of Imaging Technologies



Spatial Resolution

0.1 Å | 5 Å | 1 nm | 5 nm | 10 nm | 50 nm | 100 nm | 500 nm | 1 µm | 10 µm to 1 mm

Temporal Resolution

10 fs | 100 fs | 1 ps | 10 ps | 100 ps | 1 ns | 10 ns | 100 ns | 1 µs | 10 µs | 100 µs | 1 ms | 10 ms | 100 ms | 1 s | 10 s | 100 s | 1 ks | 10 ks

X-ray Free-Electron Laser Ultrafast X-ray Diffraction

Synchrotron X-ray Macromolecular Crystallography

- Synchrotron Time-Resolved SAXS/WAXS
- Fluctuation Scattering

Dynamic TEM

Neutron Macromolecular Crystallography

- Single Molecule Tracking
- TIRF
- Confocal Microscopy
- Coherent Raman

Super-Resolution Fluorescence

- Single Particle Cryo-TEM
- Electron Crystallography
- Micro-Electron Diffraction

- Cryo-TEM Tomography

Small Angle Neutron Scattering/ USANS

Synchrotron Transmitted X-ray Microscopy and Tomography

- Synchrotron XANES
- Synchrotron EXAFS

Neutron Radiography and Tomography

Scanning Probe Microscopy

Ptychography

Synchrotron FTIR Nanoscopy and Tomography

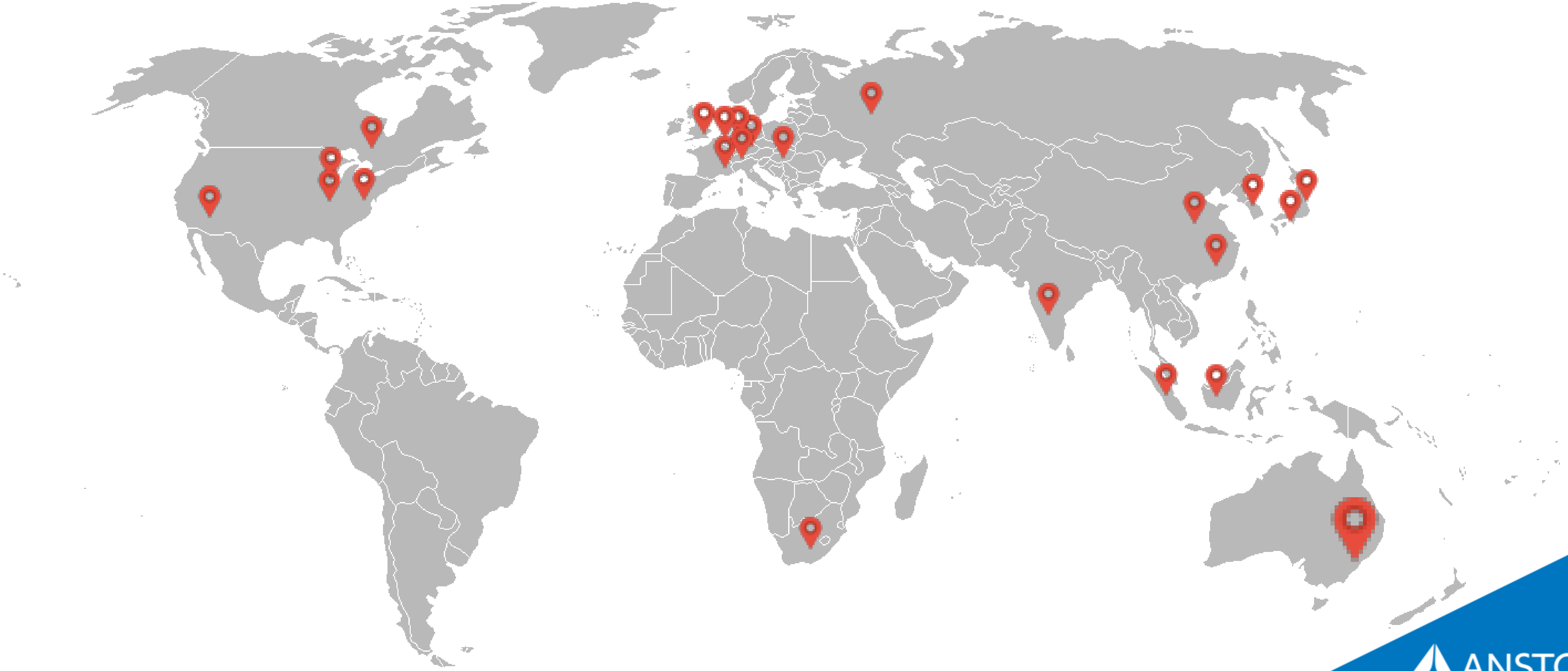
Focused Ion Beam/SEM

Nano-SIMS

In Soil Sensors

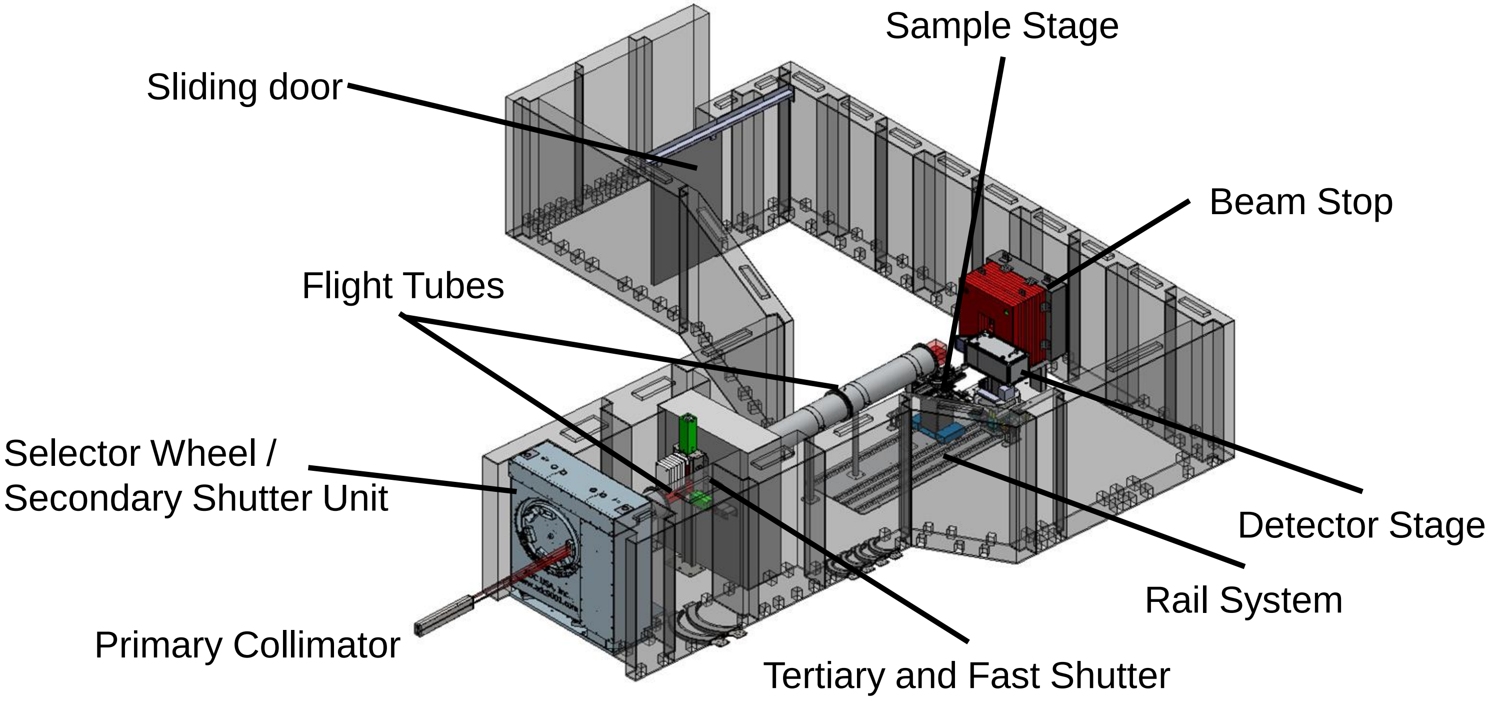
Image source: BER Structural Biology and Imaging Resources at Synchrotron and Neutron Facilities

Neutron Imaging beamline in the world



The neutron imaging beamline DINGO

DINGO specs

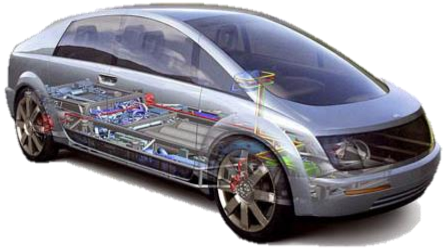


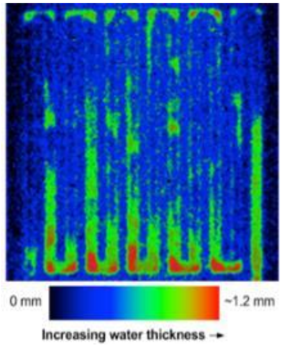
Technical details

- Ikon-l CCD, NEO CMOS camera
- Two Zeiss macro lens (50mm and 100mm)
- Three beam sizes 200 x 200, 100 x 100 and 50 x 50 mm^2
- Pixel size 10 – 100 µm
- 25fps fast imaging under development

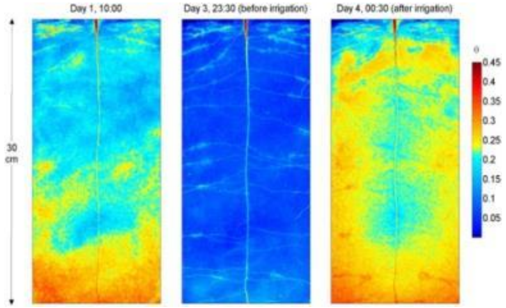
Applications overview

Energy

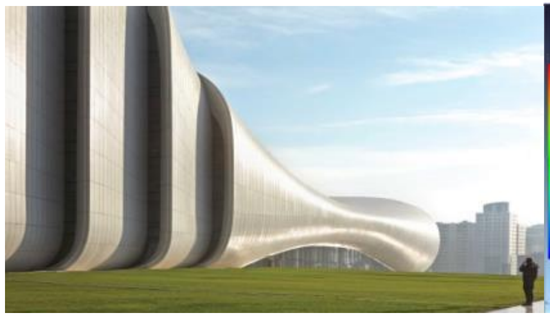


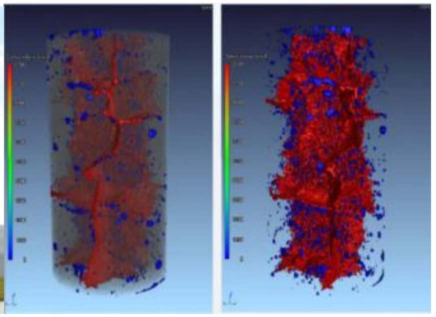


Agriculture & Food

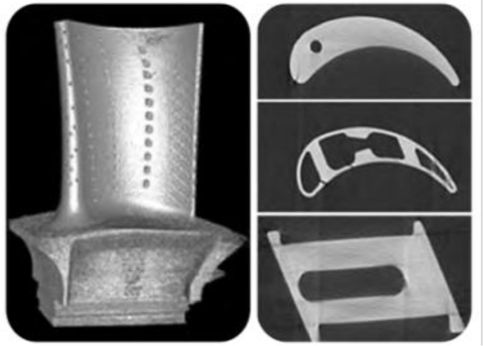


Civil engineering

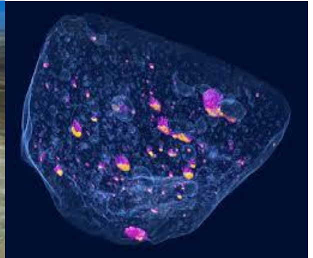




Industrial manufacturing

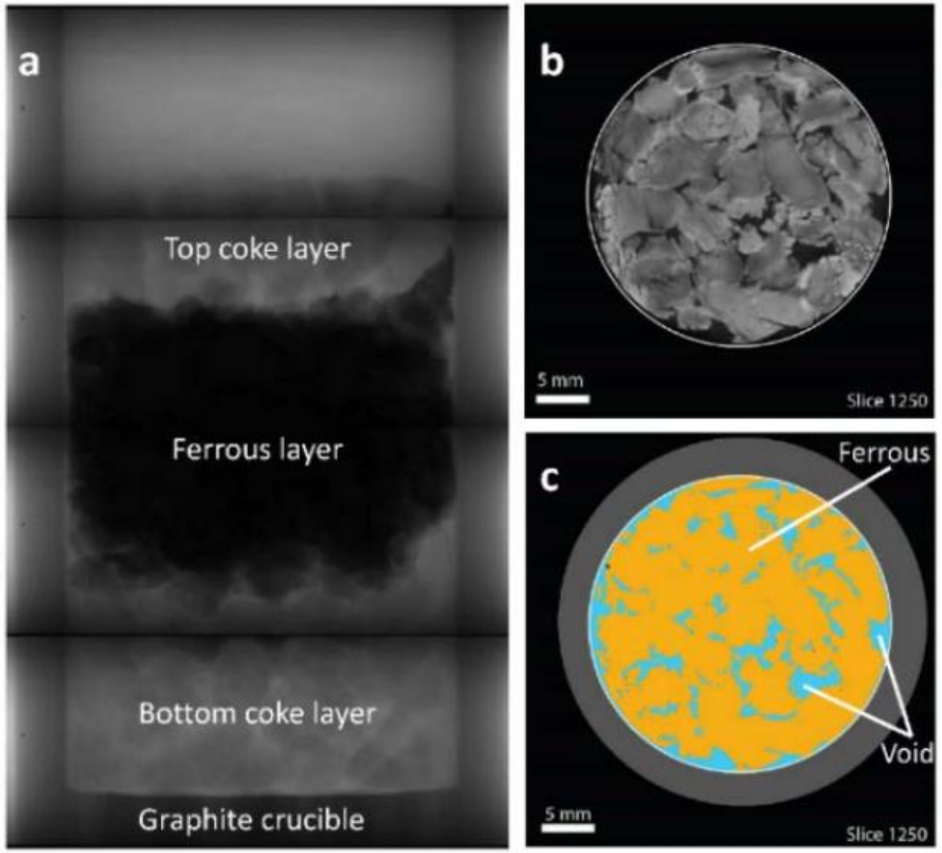


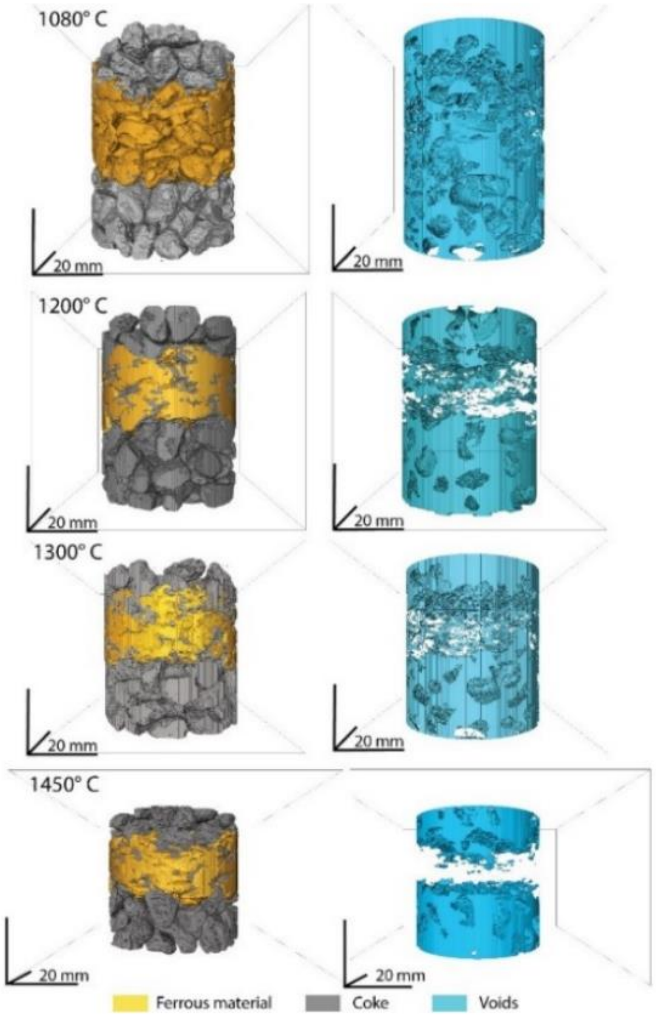
Earth & Planetary Science

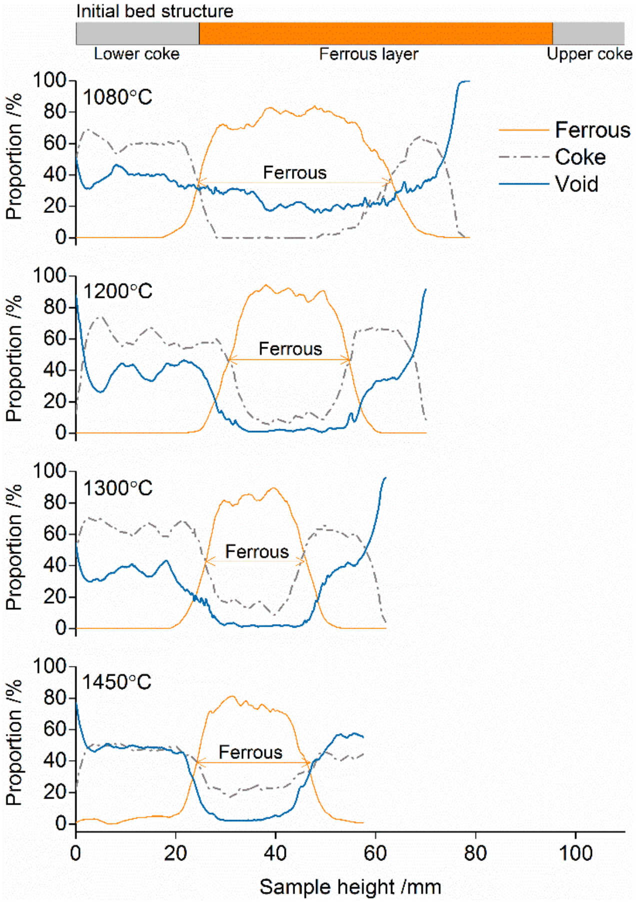


Biology and Medicine

Novel Measurement of Bed Voidage in Softening and Melting under Load Test

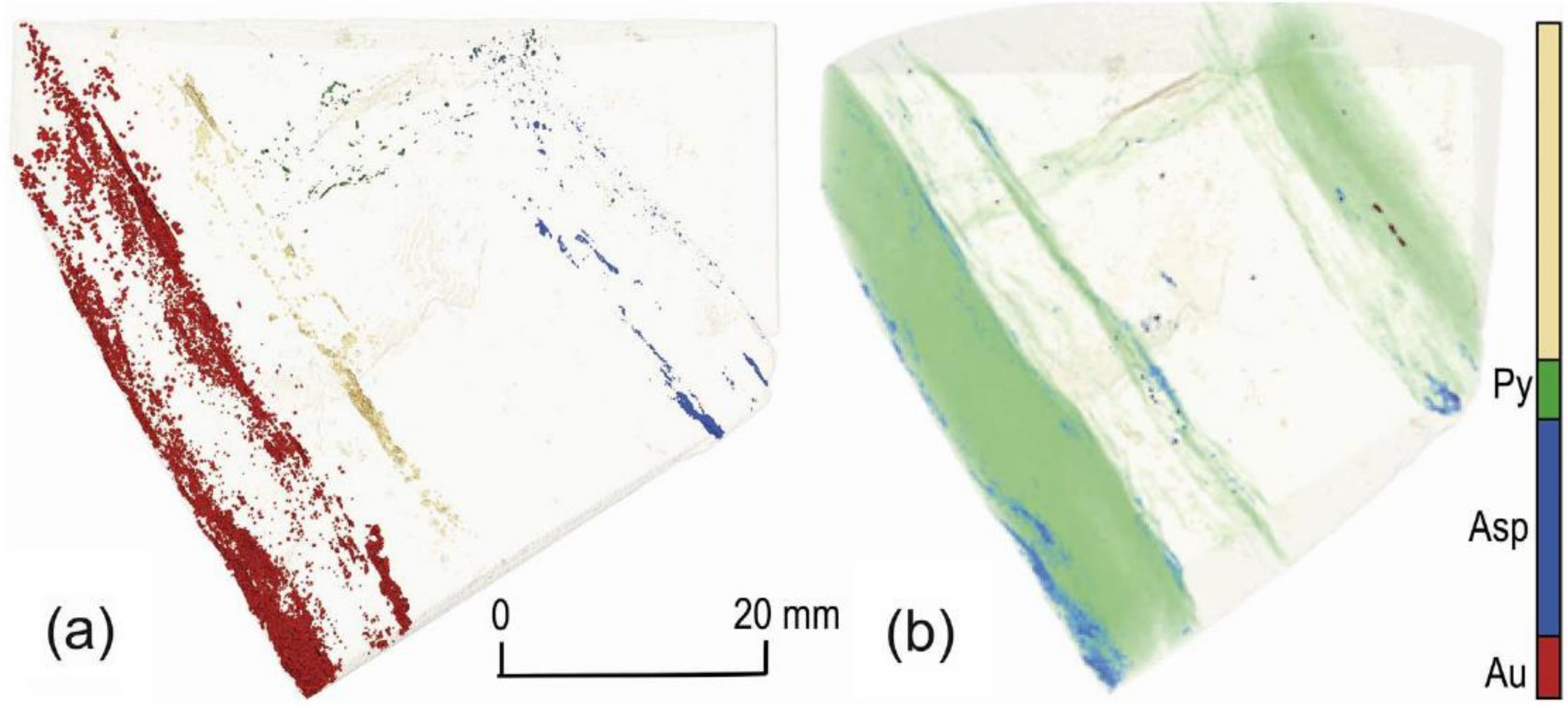






Xinliang Liu, et al., ISIJINT, 2018, 257

Costerfield antimony-gold deposit, southeast Australia: Coupling between brittle deformation and dissolution-precipitation reactions in the Melbourne Zone



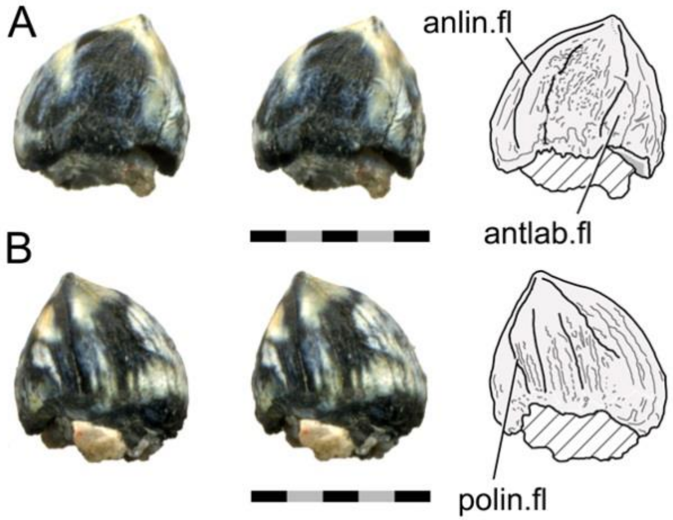
Phase	Composition	Σ [cm^{-1}] at 1.08 Å	Colour code
stibnite	Sb_2S_3	0.14	🟨
galena	PbS	0.19	🟨
antimony	Sb	0.23	🟨
sphalerite	$(Zn,Fe)S$	0.26	🟨
quartz	SiO_2	0.28	🟨
pyrite	FeS_2	0.40	🟩
muscovite	$KAl_2(Si_3Al)O_{10}(OH,F)_2$	0.82	🟦
biotite	$K(Mg,Fe{+}{+})_3[AlSi_3O_{10}(OH,F)_2$	0.85	🟦
arsenopyrite	$FeAsS$	0.95	🟦
gold	Au	3.95	🟥

attenuation coefficient Σ [cm^{-1}]

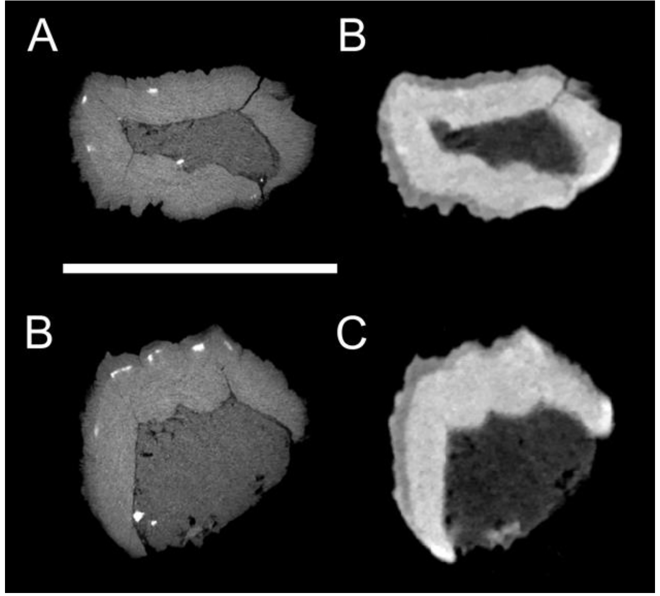
C. J.L. Wilson, D. H. Moore, V. Luzin, F. Salvemini, Ore Geology Reviews 91 (2017) 741–764.

Neutron scanning reveals unexpected complexity in the enamel thickness of an herbivorous Jurassic reptile

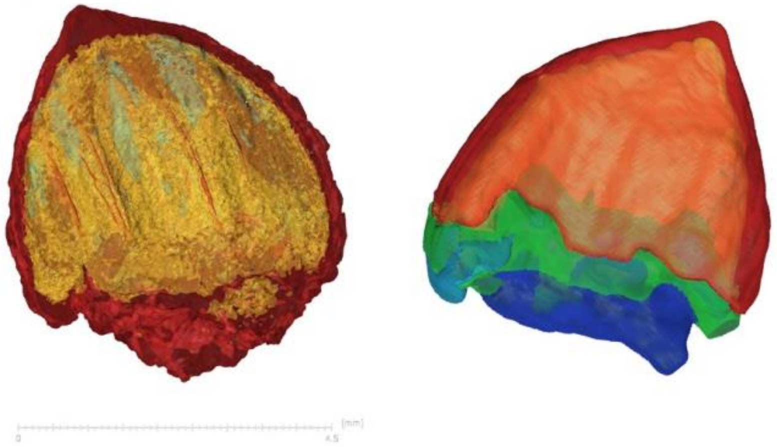
Eilenodon (Rhynchocephalia)
Jurassic Morrison formation
North America



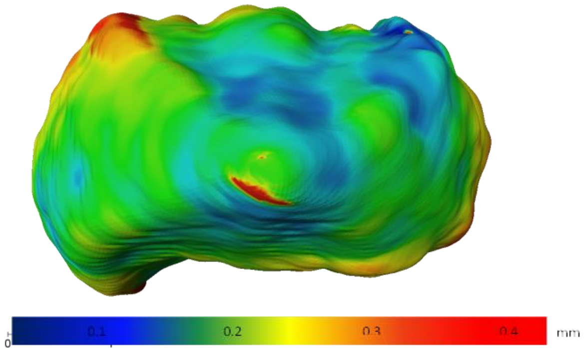
X-ray Neutron

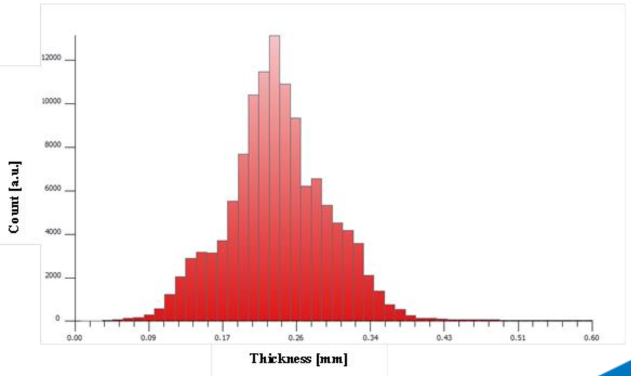


X-ray Neutron



Neutron 3D map of enamel thickness





Marc E. H. Jones, et al., 2018, J. R. Soc. Interface 15: 20180039

Final remarks

Neutron Imaging techniques as a tool to investigate matters

Technical advantages

- From micro- to macro- scale
- Bulk measurements
- Experiment can be designed

Materials

- Metals
- Ceramics
- Fossils
- Organic materials
- …..

Typical Investigations

- Documentation
- Identification of defects and inclusion
- Structural and Morphological bulk analysis
- Characterization of manufacturing technology
- Quality control

…..

Outcome

- Statistical analysis
- Spatial map
- 3-D rendering and visual inspection
- Surface and mesh generation
- Modelling and simulation
- …..

Non-invasive and non-destructive analyses

Thank you

ANSTO