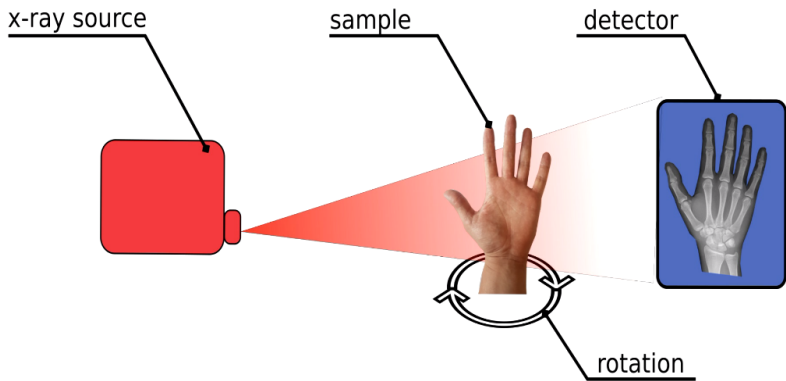
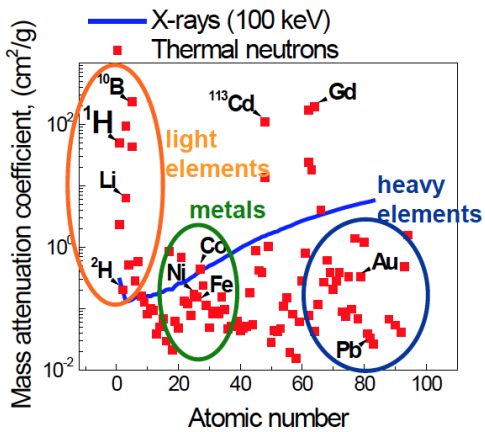
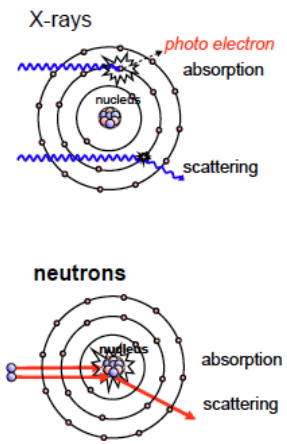


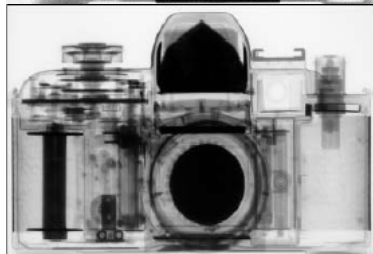
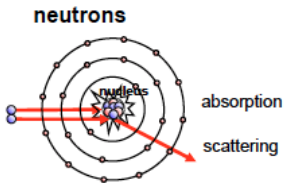
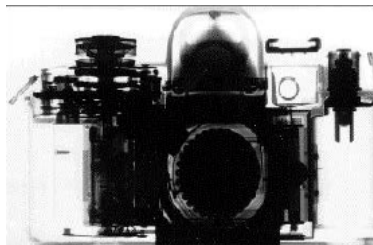
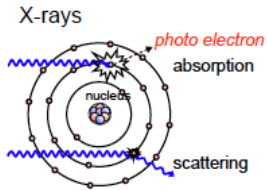
An introduction to Neutron and X-ray imaging

Alessandro Tengattini
tengattini@ill.fr

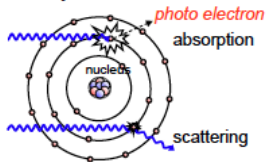
March 16, 2026
FASEM Doctoral School, Grenoble



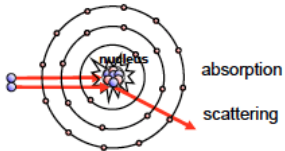




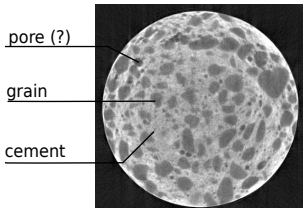
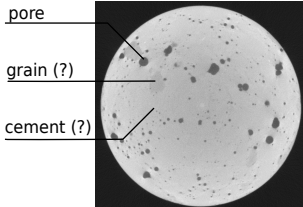
X-rays



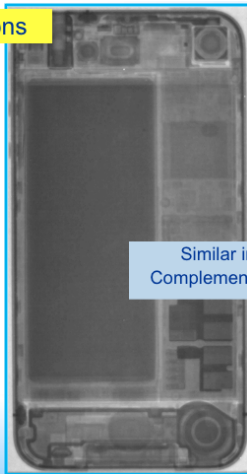
neutrons



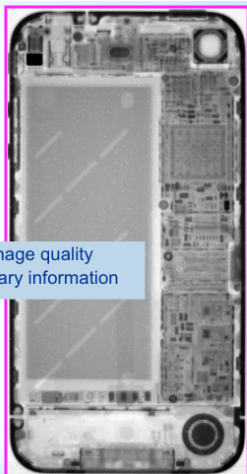
concrete



neutrons



Similar image quality
Complementary information

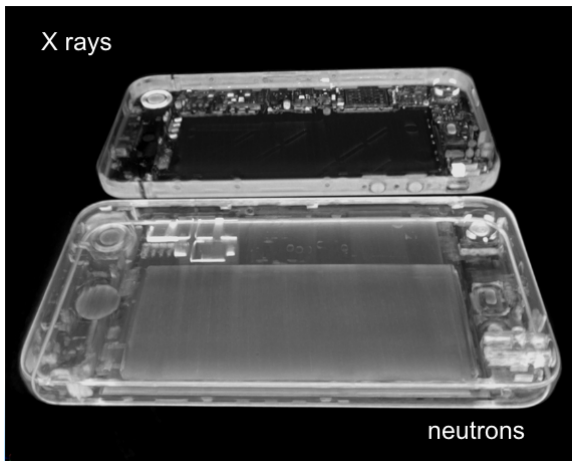


X rays

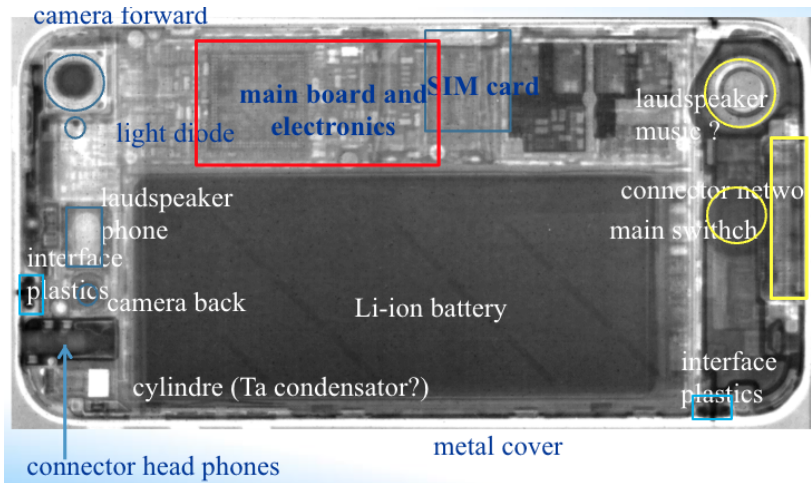
44

<https://elearning.iaea.org/m2/course/view.php?id=633>

X rays



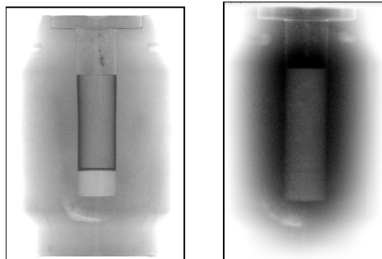
<https://elearning.iaea.org/m2/course/view.php?id=633>



<https://elearning.iaea.org/m2/course/view.php?id=633>

Advantages of neutrons:

- High penetration power, even through the thick cells used for high temperature/confinement

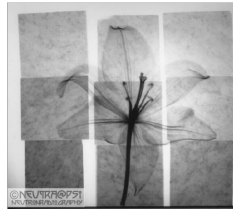
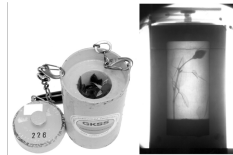


Lead container. The neutron image (left) 20 s exposure. Gamma radiography (right) 120 minutes of.

Images courtesy: Dr. Eberhard Lehmann (Paul-Scherrer-Institute, Switzerland)

Advantages of neutrons:

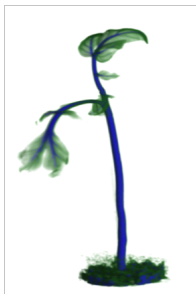
- High penetration power
- Hydrogen attenuates neutrons well so neutron imaging is good for detecting water



Plants visible both within lead container (top) and behind granite blocks (bottom)

Advantages of neutrons:

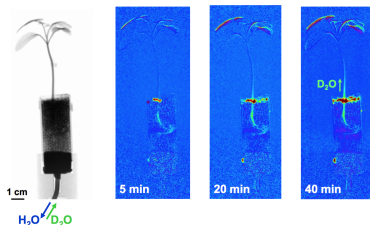
- High penetration power
- Hydrogen sensitive
- Low radiation damage



Plants and other living things can be imaged with limited damage

Advantages of neutrons:

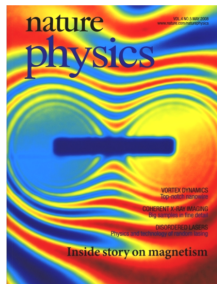
- High penetration power
- Hydrogen sensitive
- Low radiation damage
- Isotope sensitive



Deuterium and Water can be easily distinguished (H and D very similar chemically and mechanically, main difference being the extra neutron in the atom)

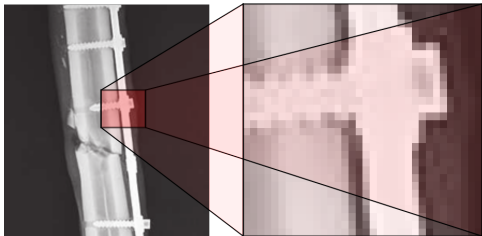
Advantages of neutrons:

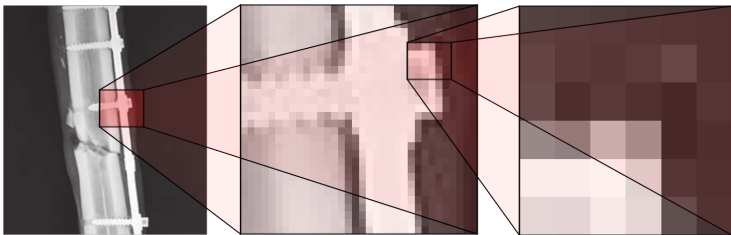
- High penetration power
- Hydrogen sensitive
- Low radiation damage
- Isotope sensitive
- Sensitive to magnetic moment (even though it does not carry charge)

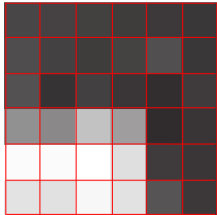
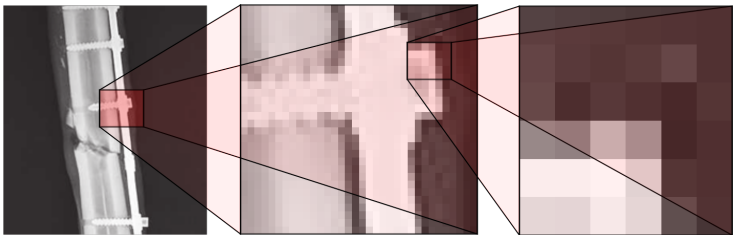


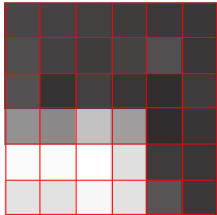
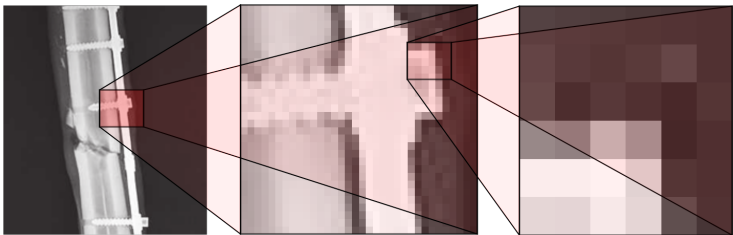
**N. Kardjilov, I. Manke, M. Strobl,
A. Hilger et al.
Nat. Phys. 4 (2008)**

Neutrons can be used to explore magnetic dipoles



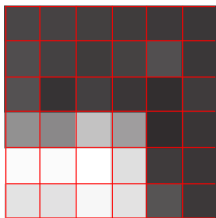
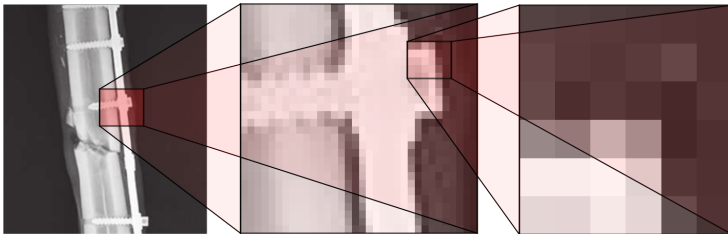






100	102	103	105	109	110
130	102	110	110	120	99
140	109	120	110	120	130
200	220	310	250	109	107
220	230	290	210	115	120
211	230	350	220	120	109

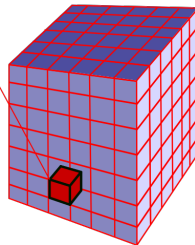
Attenuation
coefficient



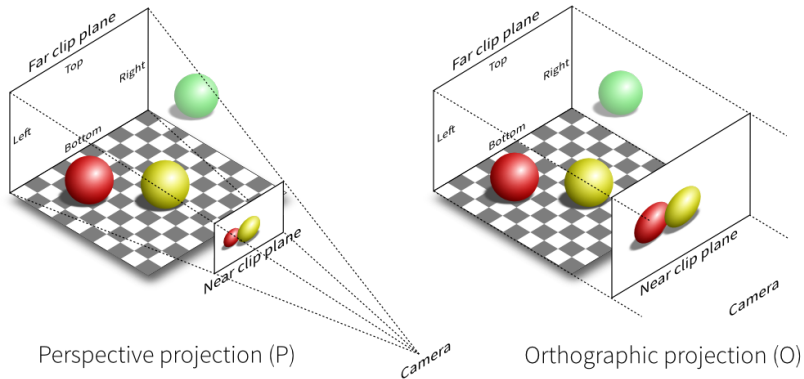
attenuation coefficient

100	102	103	105	109	110
130	102	110	110	120	99
140	109	120	110	120	130
200	220	310	250	109	107
220	230	290	210	115	120
211	230	350	220	120	109

and in 3D?



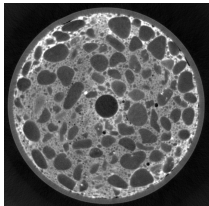
OK, but what about the “nice 3D images”?



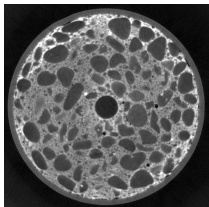
Perspective projection (P)

Orthographic projection (O)

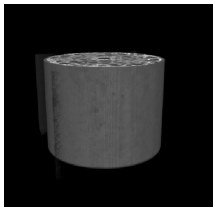
2D Slice



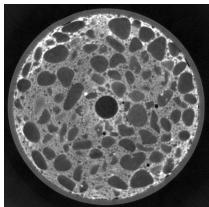
2D Slice



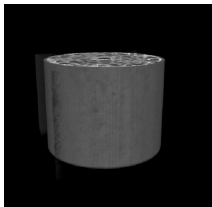
3D Rendering
(we just see the outer shell!)



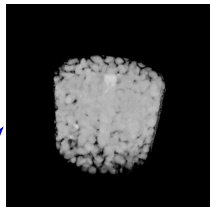
2D Slice



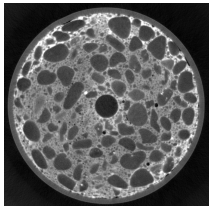
3D Rendering
(we just see the outer shell!)



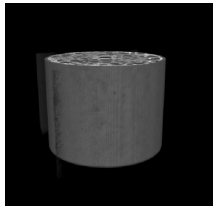
Change Transparency



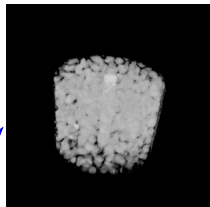
2D Slice



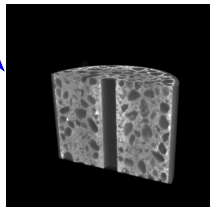
3D Rendering
(we just see the outer shell!)



Change Transparency



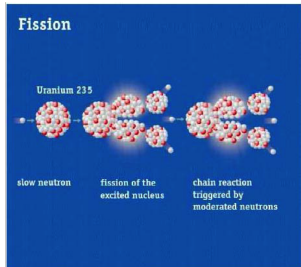
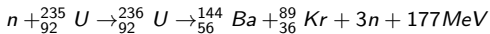
"Subsets"



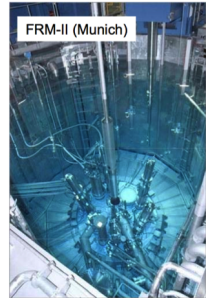
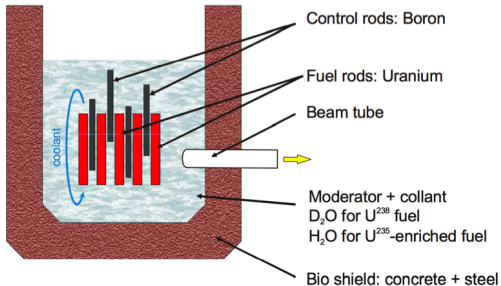
etc..

Fission

A continuous flux of neutrons is produced in the core of a conventional fission reactor. For neutron scattering purposes, research reactors with compact cores are used rather than the more abundant nuclear power plants.



Reactor sources: Nuclear fission



Neutron sources vs x-ray sources

	Brightness ($s^{-1}m^{-2}ster^{-1}$)	dE/E (%)	Divergence ($mrad^2$)	Flux ($s^{-1}m^{-2}$)
Neutrons	10^{15}	2	10×10	10^{11}
Rotating anode	10^{16}	3	0.5×10	5×10^{10}
Bending Magnet	10^{24}	0.01	0.1×5	5×10^{17}
Wiggler	10^{26}	0.01	0.1×1	10^{19}
Undulator (APS)	10^{33}	0.01	0.01×1	10^{24}

Main issue: **not as much flux!**

- Thermal flux in reactor core $\sim 10^{15} s^{-1} cm^{-2}$
- Monochromatic flux on sample $\sim 10^8 s^{-1} cm^{-2}$

Availability: **40 (neutron) vs 50'000 (x-ray)** (but only ~ 40 synchrotrons)

Velocity of Neutrons:

Whilst x-rays travel with the speed of light, neutrons have mass and so have a velocity that depends on their energy

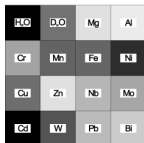
	Energy (meV)	Wavelength (\AA)	Velocity (m/s)
Ultracold	0.3	520	7.6
Cold	1	9.0446	437
	5	4.0449	978
Thermal	25	1.8089	2187
	50	1.2791	3093

Different velocities can be utilised to look at different wavelengths/energies as a function of time, so-called “time-of-flight” measurements

Thickness of materials: 1 cm

Neutrons

thermal neutrons (E = 25 meV)

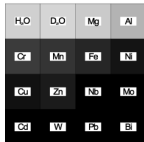


fast (fission) neutrons (E = 1.7 MeV)



X-rays and gamma-rays

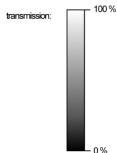
X-rays (E = 120 keV)



gamma-rays (E = 1.25 MeV)



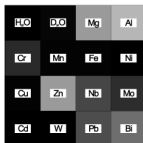
gamma-rays (E = 6 MeV)



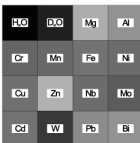
Thickness of materials: 4 cm

Neutrons

thermal neutrons (E = 25 meV)

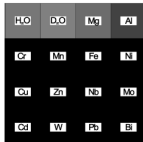


fast (fission) neutrons (E = 1.7 MeV)



X-rays and gamma-rays

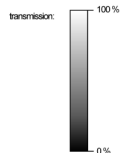
X-rays (E = 120 keV)



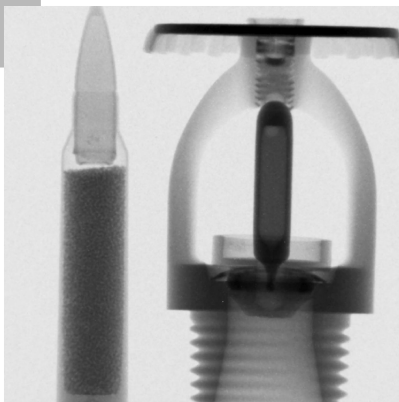
gamma-rays (E = 1.25 MeV)



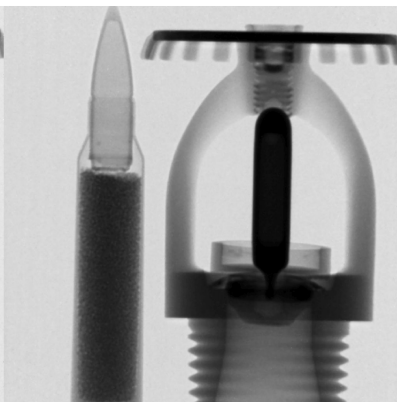
gamma-rays (E = 6 MeV)



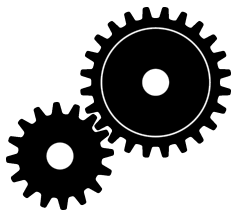
Thermal neutrons



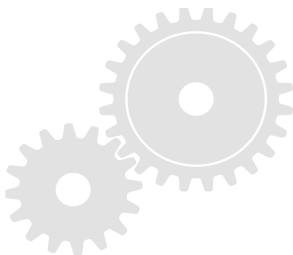
Cold neutrons



High Resolution
High Contrast



High Resolution
Low Contrast



Low Resolution
High Contrast



Low Resolution
Low Contrast

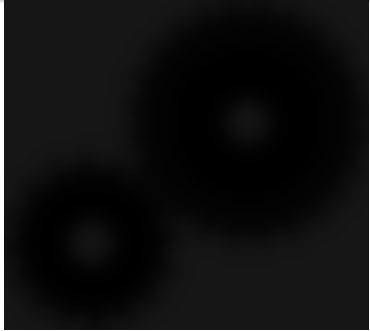


Resolution:

Detection system, collimation, field of view.. → see later

Contrast:

type of radiation (neutron vs x-rays, energy)



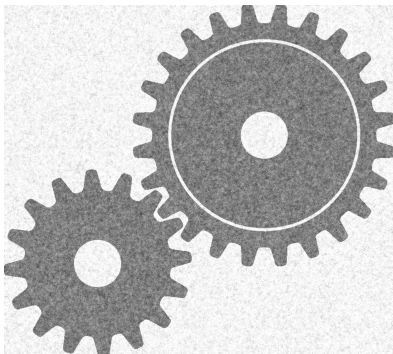
not enough penetration:
should have used higher energy



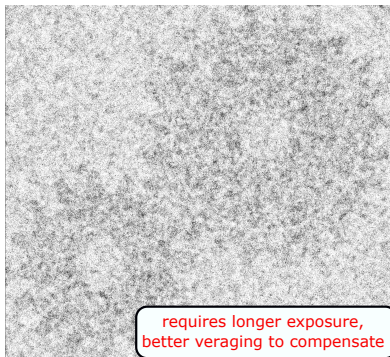
not enough contrast:
should have used lower energy

A quick note on noise and contrast

effect of noise on high contrast image



effect of noise on low contrast image



Neutrons exhibit particle and wave-like behaviours, like x-rays, so much of the theory of scattering can be considered to be the same. . .

. . . BUT the underlying interactions with matter are different...

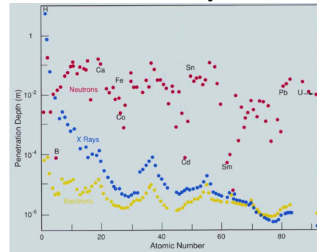
Interaction with matter

Neutrons: weak and comparable strength interactions with nuclei and magnetic fields

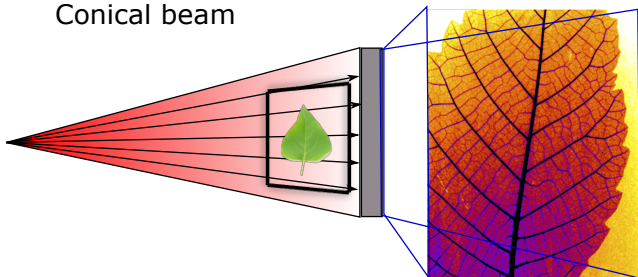
Electrons: very strong interaction with charge dominates

X-rays, light: strong interaction with charge, many orders of magnitude weaker with magnetic moments

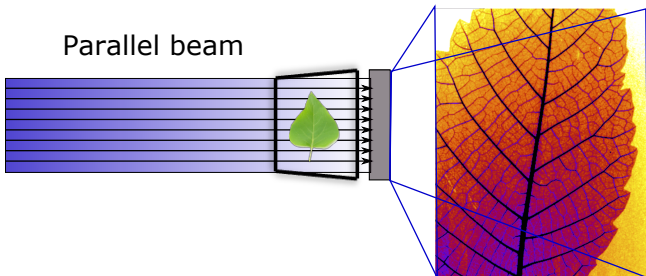
Penetration power of neutrons, electrons and x-ray



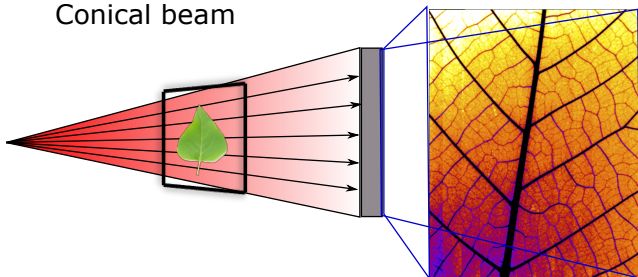
Conical beam



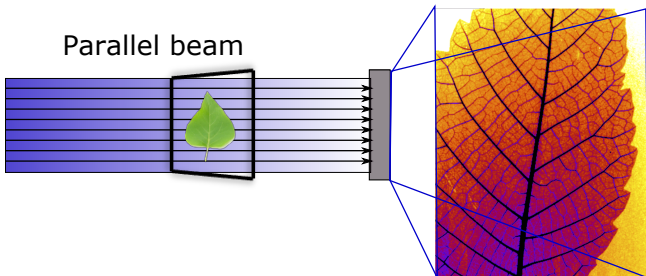
Parallel beam



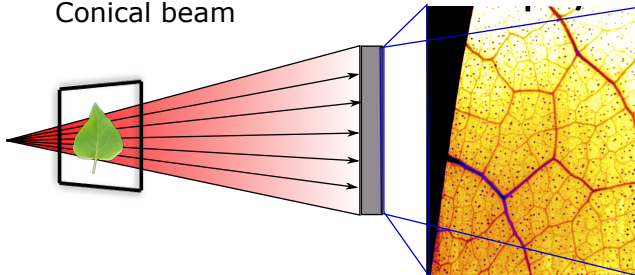
Conical beam



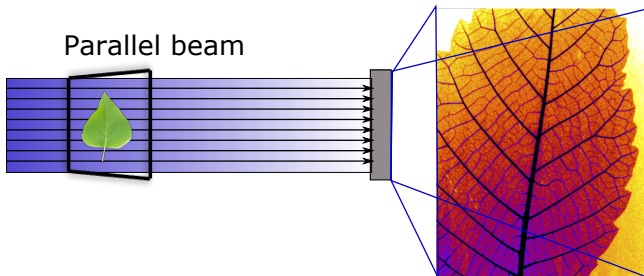
Parallel beam



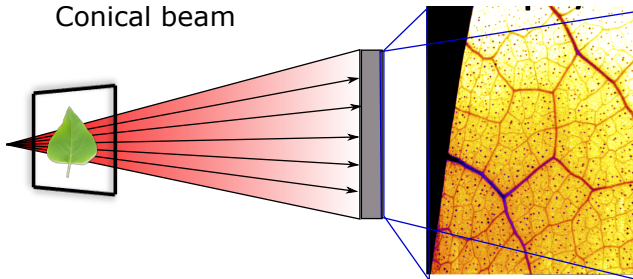
Conical beam



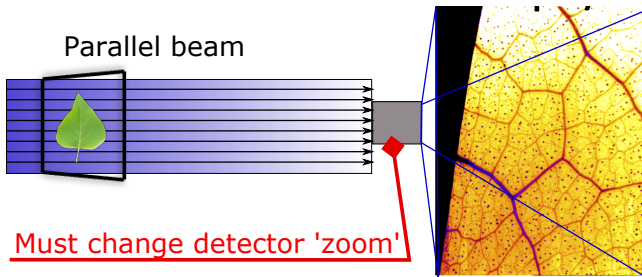
Parallel beam



Conical beam

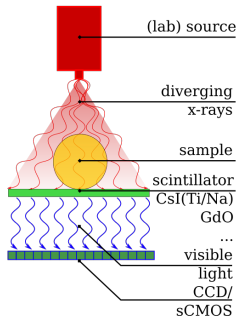


Parallel beam

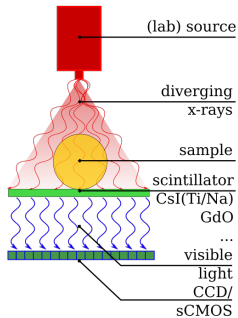


Must change detector 'zoom'

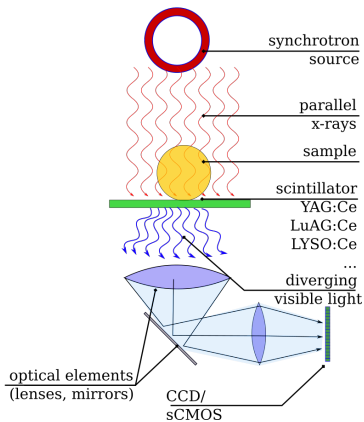
Lab scanner-type detector (flat panel)



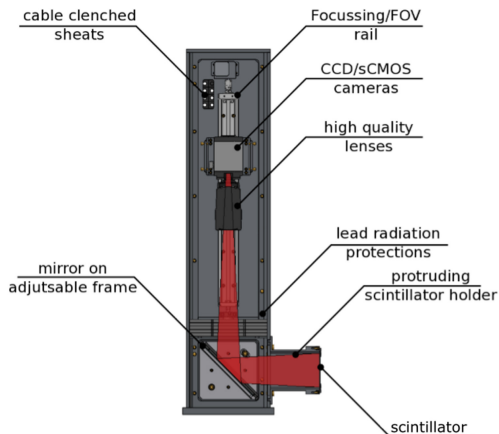
Lab scanner-type detector (flat panel)



Synchrotron-type detector(s)



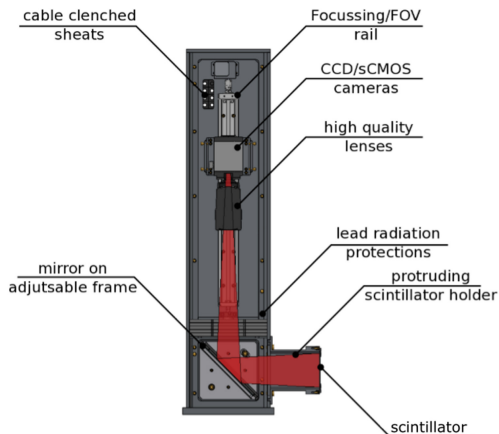
An example of a detector:



Its technical specification

- Maximum field of view: **300x300 mm**
- Resolution: from 160 microns at 160x160 down to **3 microns**
- Maximum speed of the camera: 100 Hz

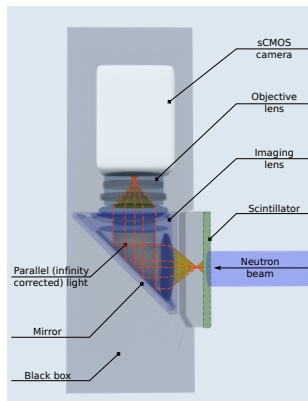
An example of a detector:



Optics:

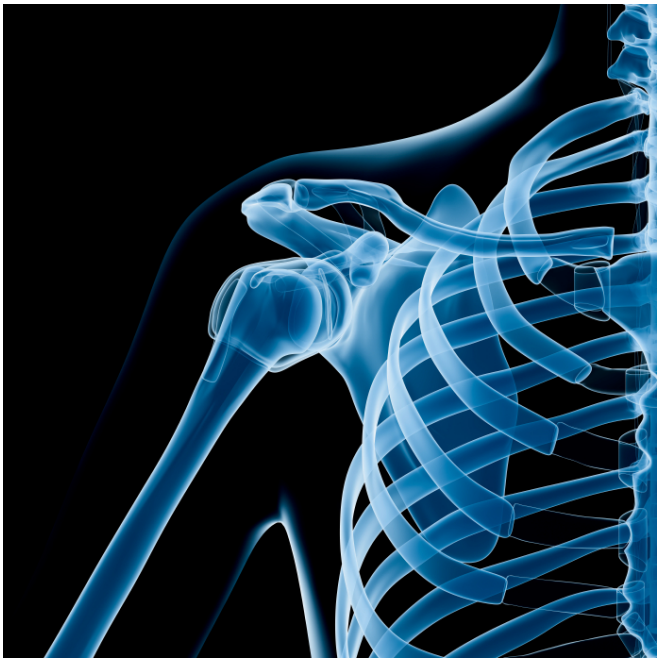
- Field of view = pixel size \times number of pixels
- pixel size: **in classical optics** = lens distance plus focal length of lens
- pixel size: infinity corrected optics = lens focal length ratio

An example of a detector:

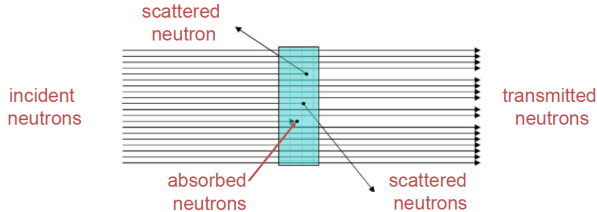


Optics:

- Field of view = pixel size \times number of pixels
- pixel size: in classical optics = lens distance plus focal length of lens
- pixel size: **infinity corrected optics** = lens focal length ratio



What is radiography



When

Neutrons (or x-rays) are incident on a sample they can be transmitted, scattered, or absorbed by the sample. In imaging, we measure transmitted beams to obtain information.

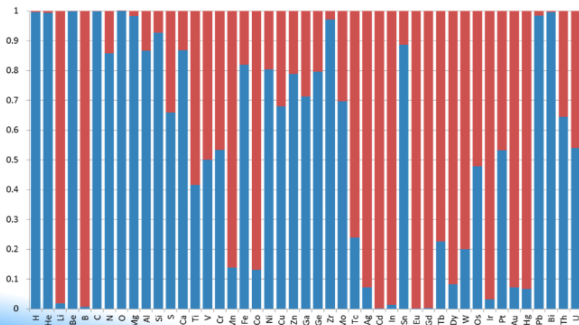
- σ_A is the absorption cross-section (barns/atom)
- σ_S is the scattering cross-section (barns/atom)
- $\sigma_T = \sigma_A + \sigma_S$ is the total cross-section (barns/atom)

Neutron interactions with matter (absorption vs. scattering)



Portion

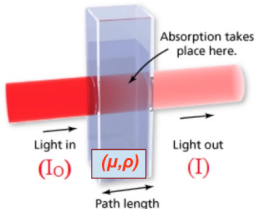
- Normalized absorption cross section
- Normalized scattering cross section



Material with increasing mass number

Attenuation Tomography: The Beer-Lambert Law

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



Where:

What we measure

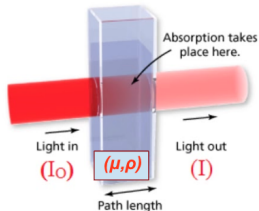
- I and I_0 x-ray fluxes in photons/second

What we deduce

- μ is the attenuation coefficient of the object
- ρ density
- x path length

Attenuation Tomography: The Beer-Lambert Law

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



Where:

What we measure

- I and I_0 x-ray fluxes in photons/second

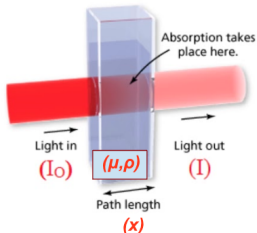
What we deduce

- μ is the attenuation coefficient of the object
- ρ density
- x path length

Wavelength dependent, tabulated for some elements at given wavelengths

Attenuation Tomography: The Beer-Lambert Law

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



Where:

What we measure

- I and I_0 x-ray fluxes in photons/second

What we deduce

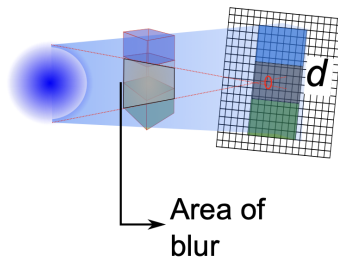
- μ is the attenuation coefficient of the object
- ρ density
- x path length

Wavelength dependent, tabulated for some elements at given wavelengths

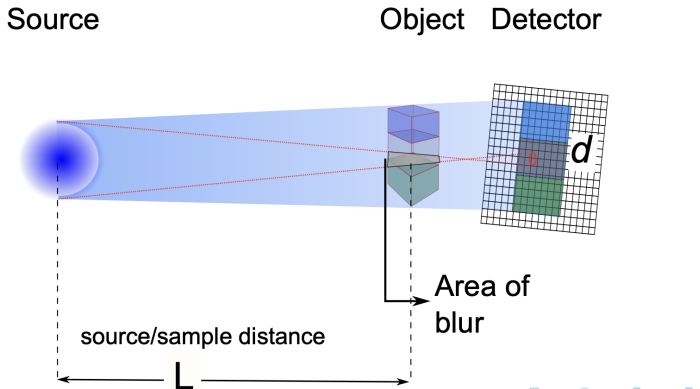
Also measured if tomography or occasionally known a priori

Collimation and penumbra

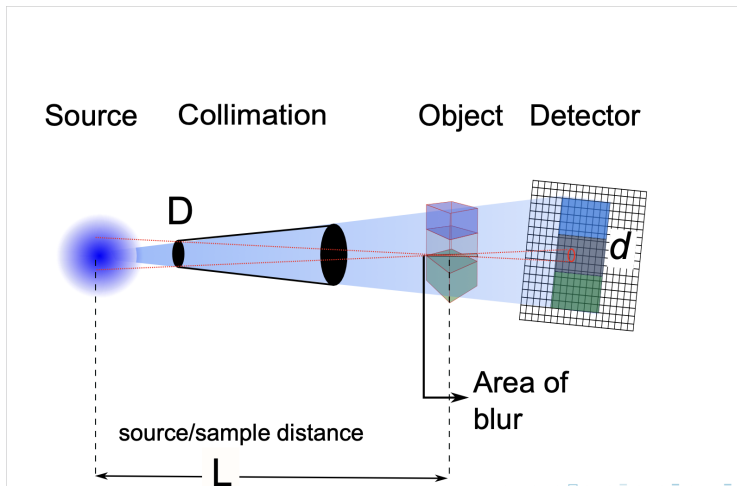
Source Object Detector



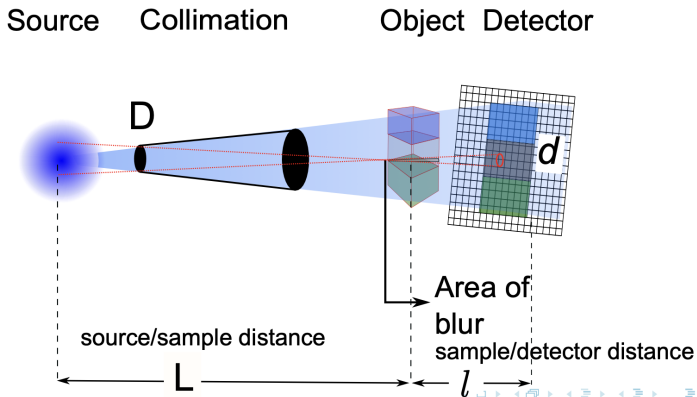
Collimation and penumbra



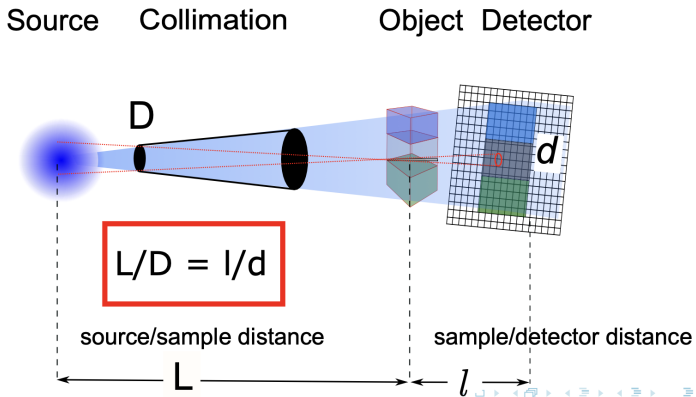
Collimation and penumbra



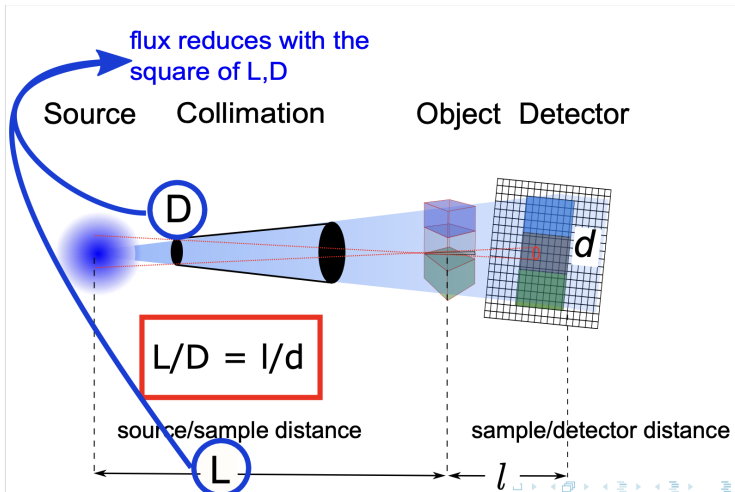
Collimation and penumbra



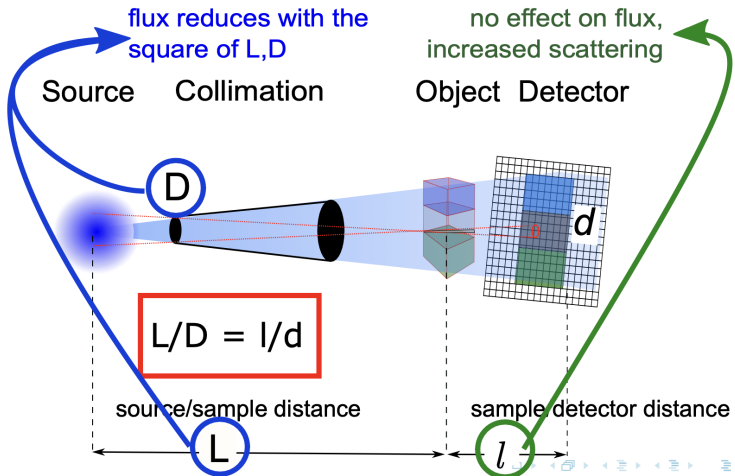
Collimation and penumbra




Collimation and penumbra

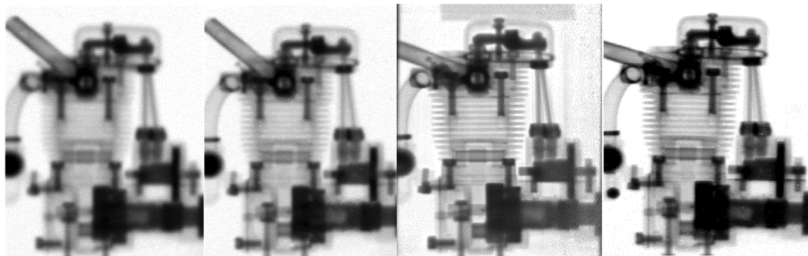


Collimation and penumbra



Effect of L/D and sample detector distance

increasing L/D 



$L/D=71$

$L/D=115$

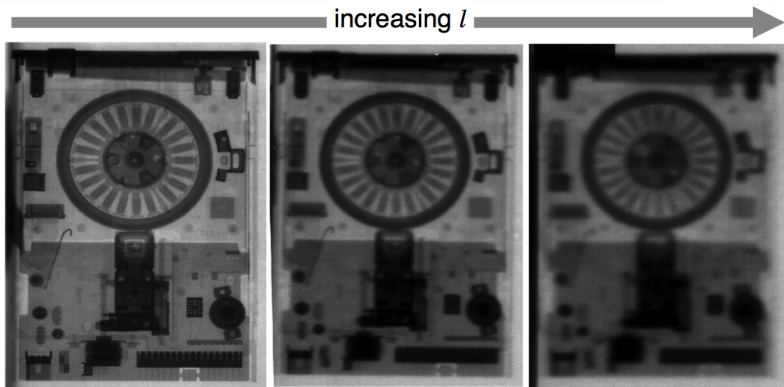
$L/D=320$

$L/D>500$

Neutron radiographs of a small engine

But: higher L/D implies lower flux and longer exposition time

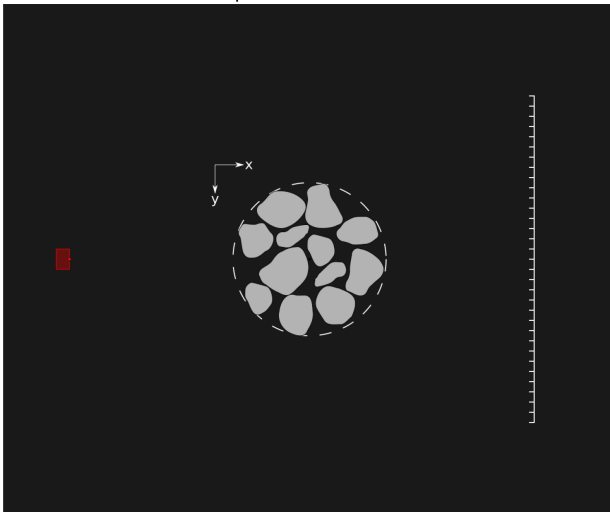
Effect of L/D and sample detector distance

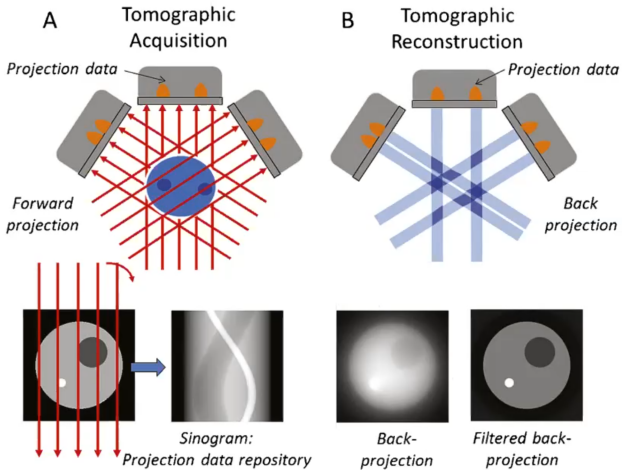


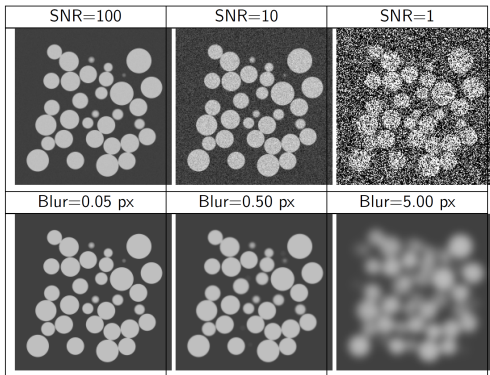
3,5" floppy drive images with $l = 0$ cm 10 cm and 20 cm distance, detection: film + Gd sandwich, cold neutron guide with $L/D=71$.

Collimation: essential concept in neutron imaging, sometimes overlooked in Laboratory X-ray Scanners (spot size) important but often easily achieved in synchrotron imaging (very high collimation of the source)

Let's measure the sample

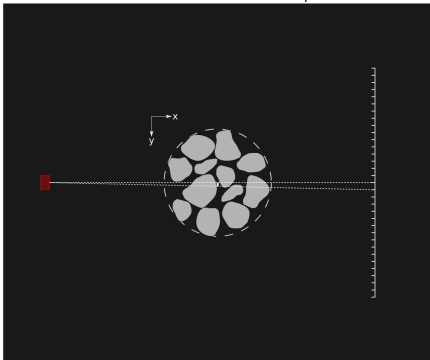




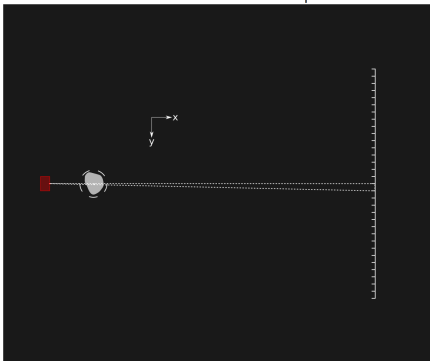


A. Tengattini & E. Andò, *Kaliosphera* -- MST -- 2015,

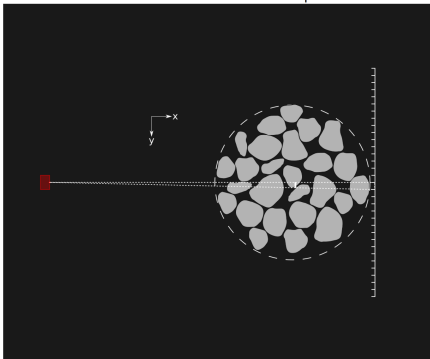
Usual trade-off between field of view and pixel size



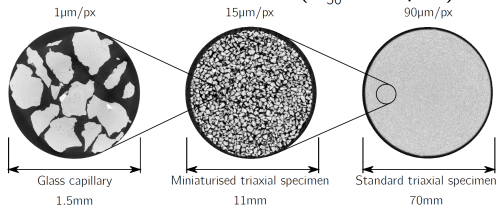
Usual trade-off between field of view and pixel size



Usual trade-off between field of view and pixel size



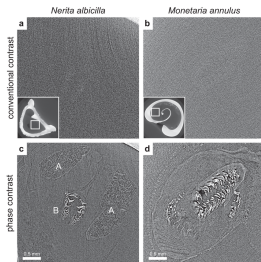
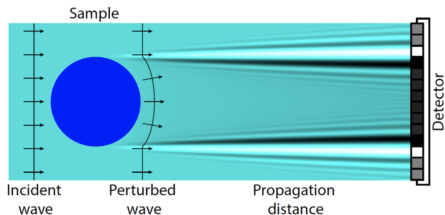
Hostun HN31 Sand ($D_{50}=328\mu\text{m}$)



Please note: the zoom-in illustrations are merely to relate the sizes, the scans shown are of different specimens

E. Andò & Viggiani, *On the ease of experimental access to deformation entities in granular assemblies*, RIG - 2018

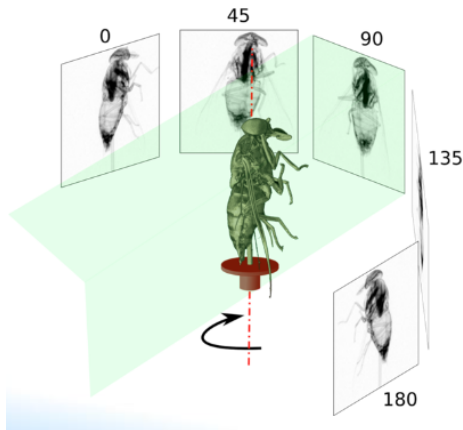
So far attenuation imaging, but there is also phase contrast imaging!



Häggmark *et al.*,

See upcoming presentations!

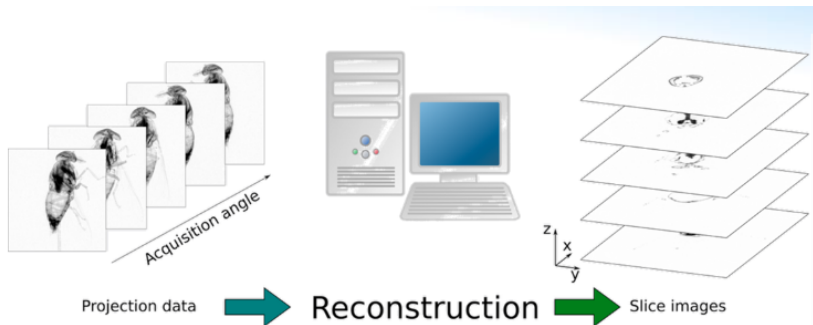
Summary



For neutron tomographic experiments, the sample is rotated around a vertical axis while transmission projections of an object are acquired by a position sensitive detector at different angles.

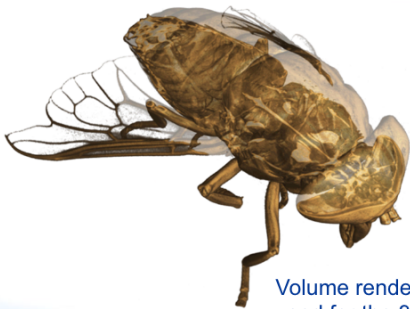
<https://elearning.iaea.org/m2/course/view.php?id=633>

Summary



The set of 2D angular projections is used for mathematical reconstruction of the 3D matrix of the attenuation coefficients.

<https://elearning.iaea.org/m2/course/view.php?id=633>



Volume rendering software can be used for the 3D visualization by assigning different colors for the different attenuation coefficients. ²¹

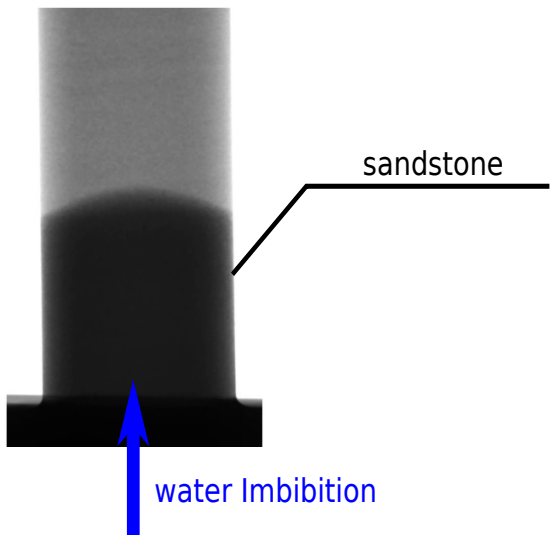
<https://www.osi.ch/en/niaa/neutron-tomography>

<https://elearning.iaea.org/m2/course/view.php?id=633>

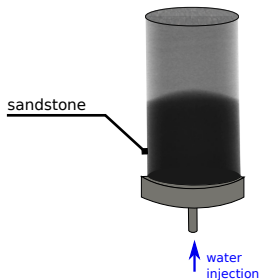
Elements playing in the resolution of an image:

- Field of view (“zoom”)/number of pixels (optics)
- Detector sharpness (Scintillator thickness, type, optics used, alignment...)
- Collimation ratio L/D , λ where applicable
- Signal to noise ratio/contrast, statistics
- For tomography: number of projections (sampling theorem)

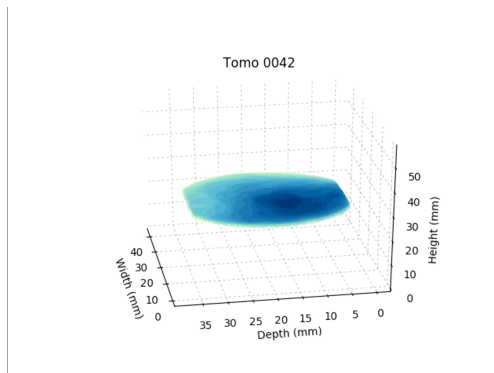




Fluid flow within an intact rock

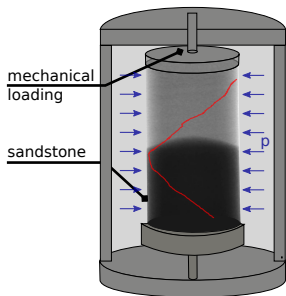


Quantification of front position, speed, permeability



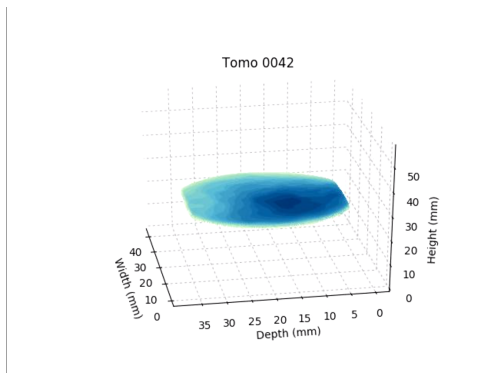
Tudisco, *et al.*, *Journal of Geophysical Research: Solid Earth* (2019)
Extegarai, *et al.*, submitted (2021)

Fluid flow within a damaged rock



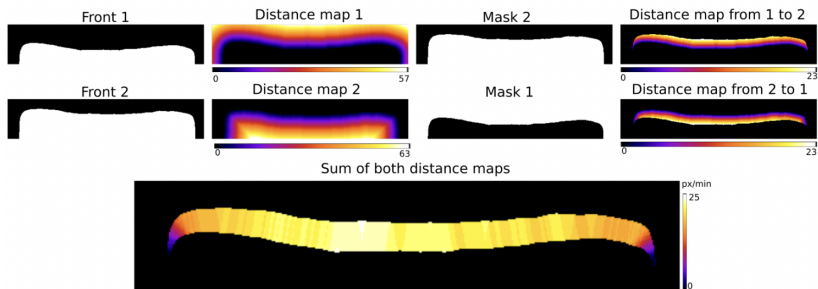
↑ water injection

Quantification of front position, speed, permeability



Tudisco, *et al.*, *Journal of Geophysical Research: Solid Earth* (2019)
Extegarai, *et al.*, submitted (2021)

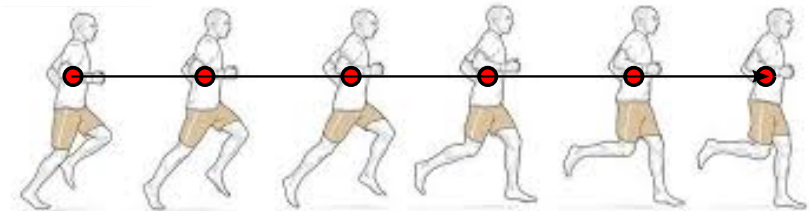
An example of “Bespoke analysis” – speed maps



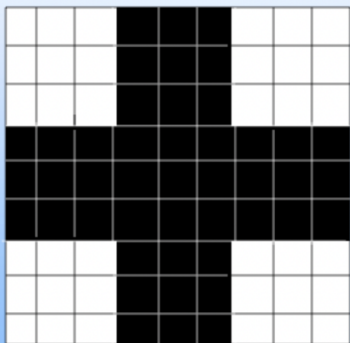
A “go-to keystone Tool” Digital Volume Correlation (e.g., SPAM)



A “go-to keystone Tool” Digital Volume Correlation (e.g., SPAM)

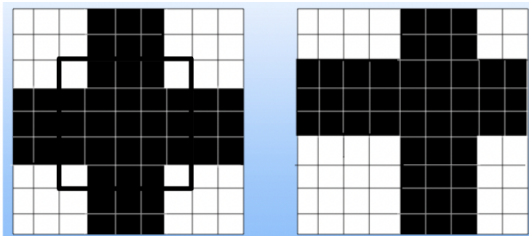


A “go-to keystone Tool” Digital Volume Correlation (e.g., SPAM)



```
100 100 100 0 0 0 100 100 100
100 100 100 0 0 0 100 100 100
100 100 100 0 0 0 100 100 100
0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0
100 100 100 0 0 0 100 100 100
100 100 100 0 0 0 100 100 100
100 100 100 0 0 0 100 100 100
```

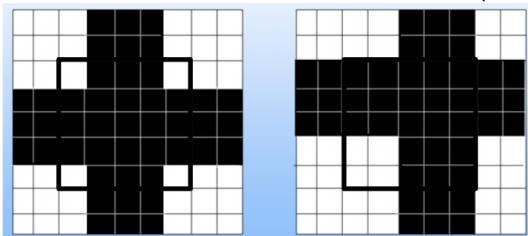
A “go-to keystone Tool” Digital Volume Correlation (e.g., SPAM)



100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100

100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100

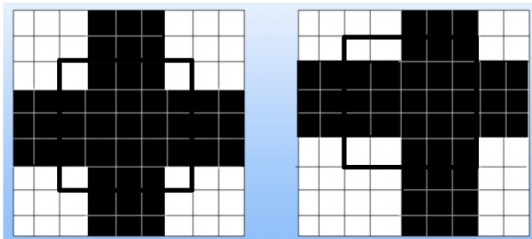
A “go-to keystone Tool” Digital Volume Correlation (e.g., SPAM)



100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100

100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100

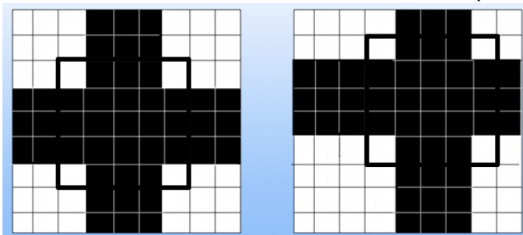
A “go-to keystone Tool” Digital Volume Correlation (e.g., SPAM)



100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100

100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100

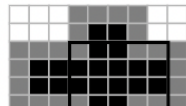
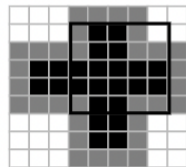
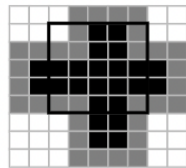
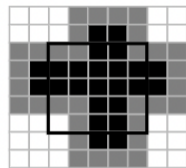
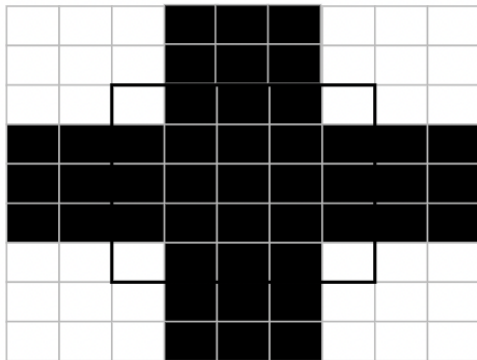
A “go-to keystone Tool” Digital Volume Correlation (e.g., SPAM)



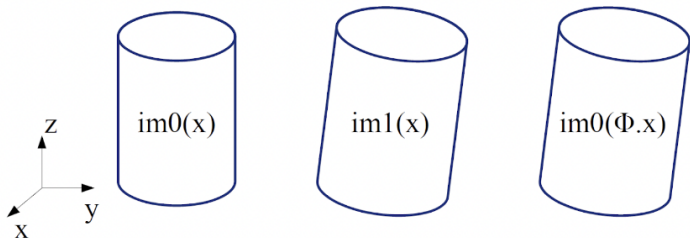
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100

100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100

Best correlation?



A “go-to keystone Tool” Digital Volume Correlation (e.g., SPAM)



Transformation Gradient Tensor
Displacement

$$im0(\Phi.x) = im1(x) \quad \Phi = \begin{bmatrix} F_{zz} & F_{zy} & F_{zx} & t_z \\ F_{yz} & F_{yy} & F_{yx} & t_y \\ F_{xz} & F_{xy} & F_{xx} & t_x \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

A “go-to keystone Tool” Digital Volume Correlation (e.g., SPAM)

Error function:

$$\tau(\Phi) = \frac{1}{2} \sum_{x \in ROI} (im0(x) - im1(\Phi x))^2$$

Minimisation problem:

$$\nabla \tau(\Phi) = 0$$

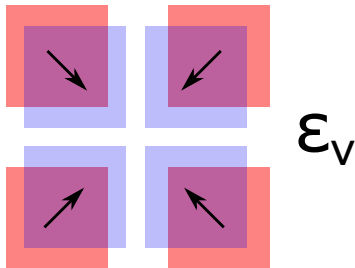
Newton's method:

$$\nabla \tau(\Phi^n) + \nabla^2 \tau(\Phi^n) : \delta \Phi^{n+1} = 0$$

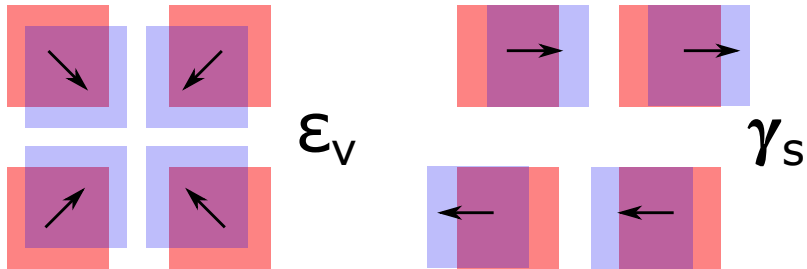
Implementation *:

$$\delta \Phi^{n+1} = (M^n)^{-1} A^n$$

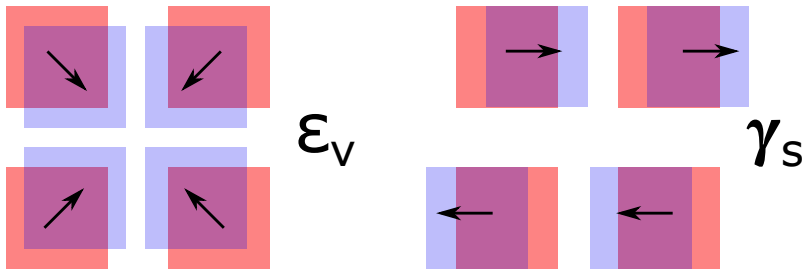
From displacement to strain



From displacement to strain



From displacement to strain



$$\begin{bmatrix} \epsilon_{xx} & \epsilon_{xy} & \epsilon_{xz} \\ \epsilon_{yx} & \epsilon_{yy} & \epsilon_{yz} \\ \epsilon_{zx} & \epsilon_{zy} & \epsilon_{zz} \end{bmatrix} = \begin{bmatrix} \frac{\partial u_x}{\partial x} & \frac{1}{2} \left(\frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x} \right) & \frac{1}{2} \left(\frac{\partial u_x}{\partial z} + \frac{\partial u_z}{\partial x} \right) \\ \frac{1}{2} \left(\frac{\partial u_y}{\partial x} + \frac{\partial u_x}{\partial y} \right) & \frac{\partial u_y}{\partial y} & \frac{1}{2} \left(\frac{\partial u_y}{\partial z} + \frac{\partial u_z}{\partial y} \right) \\ \frac{1}{2} \left(\frac{\partial u_z}{\partial x} + \frac{\partial u_x}{\partial z} \right) & \frac{1}{2} \left(\frac{\partial u_z}{\partial y} + \frac{\partial u_y}{\partial z} \right) & \frac{\partial u_z}{\partial z} \end{bmatrix}$$

A “go-to keystone Tool” Digital Volume Correlation (e.g., SPAM)

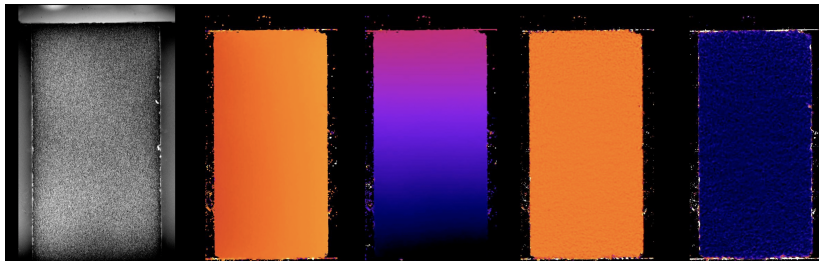
Original

X Displ.

Z Displ.

Shear Strain

Vol. Strain



A “go-to keystone Tool” Digital Volume Correlation (e.g., SPAM)

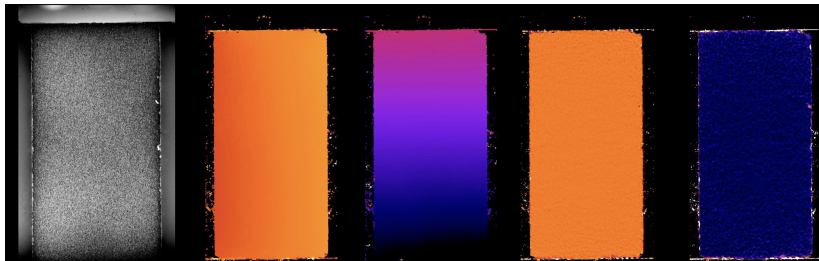
Original

X Displ.

Z Displ.

Shear Strain

Vol. Strain



A “go-to keystone Tool” Digital Volume Correlation (e.g., SPAM)

Original

X Displ.

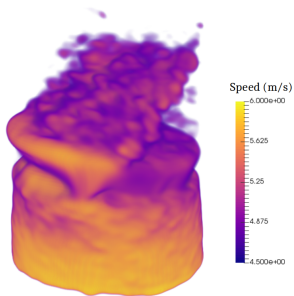
Z Displ.

Shear Strain Vol. Strain

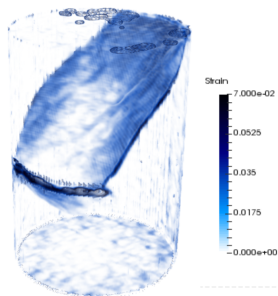


Quantification of incremental strain through Digital Volume correlation of the map of fluid Speed

3D SPEED FIELD



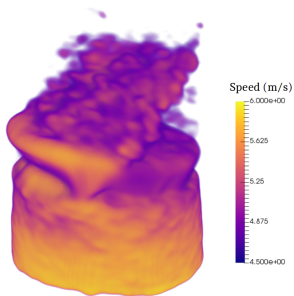
3D DEVIATORIC STRAIN FIELD



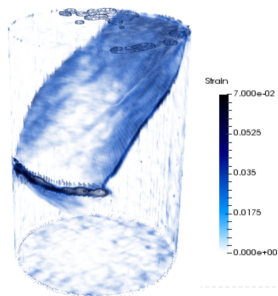
34

Quantification of incremental strain through Digital Volume correlation of the map of fluid Speed

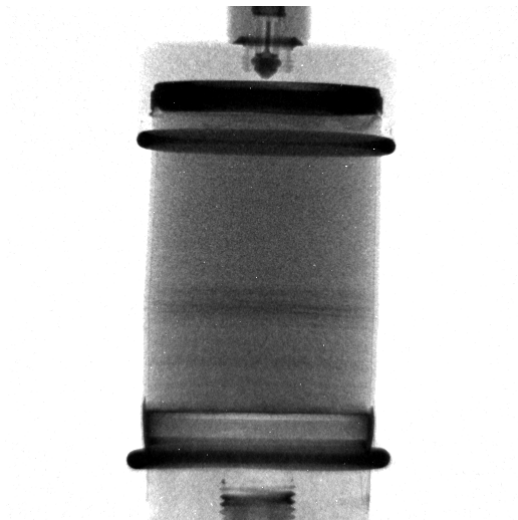
3D SPEED FIELD



3D DEVIATORIC STRAIN FIELD

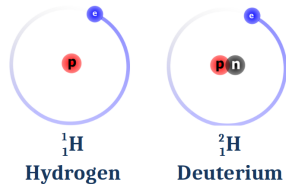
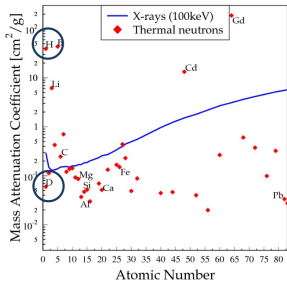


How about more complex geometries?

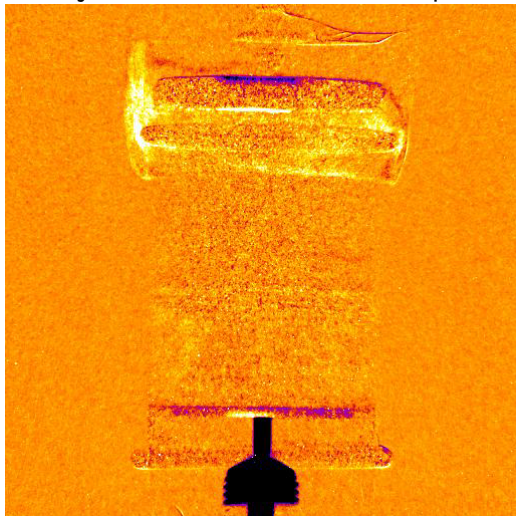


Lewis *et al.*, EGU (2017)
Lewis *et al.*, under redaction (2021)

Neutrons are isotope sensitive, “**normal water**” and **heavy water** have an order of magnitude difference in opacity
 Can be used to **track fluid in an already saturated sample**

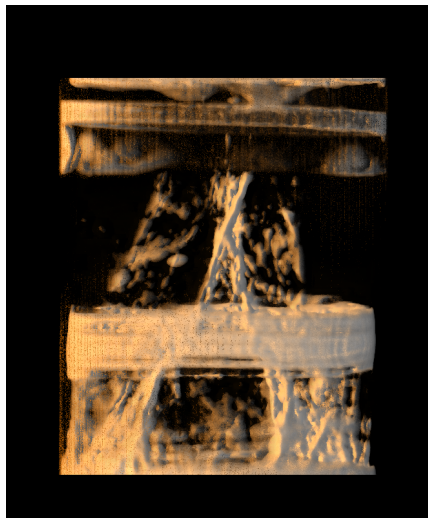


Injection in D2O-saturated sample

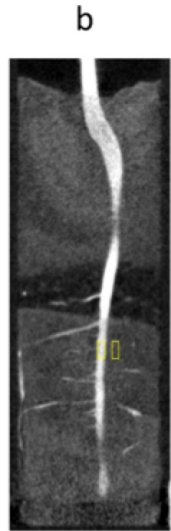
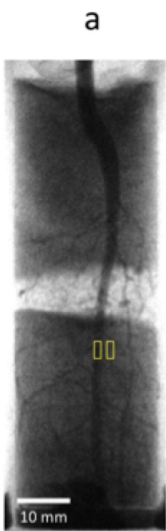


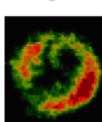
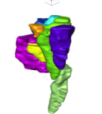
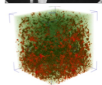
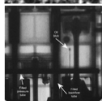
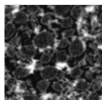
Lewis *et al.*, EGU (2017)
Lewis *et al.*, under redaction (2021)

and in 3D?



Lewis *et al.*, EGU (2017)
Lewis *et al.*, under redaction (2021)





- White beam attenuation imaging
- Fast and stroboscopic imaging
- Bragg edge diffraction imaging
- Structural and magnetic dark-field imaging
- Polarized neutron imaging
- X-ray plus neutron imaging

Key aspects of white beam imaging

Using all the beam intensity (all wavelengths)

- High flux

- Faster acquisition

- Big objects (good penetration in reasonable times)

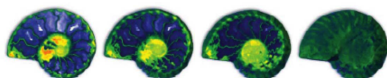
- Downside: Loose information relating to wavelength dependence of absorption
(like standard x-ray tomography)

Domain of application

- Biology and Agriculture
- Geology
- Archeology
- Paleontology
- Art History
- Material science and Engineering
- Industry
- etc.

For Reviews on neutron imaging

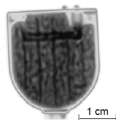
- M. Strobl et al., J. Phys. D (2009)
- N.Kardjilov..M.Strobl et al. Materials Today (2011)
- Tengattini A., et al. GEE (2021)



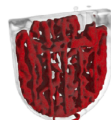
Example: LiI Battery

2D-radiography projection

3D-tomography reconstruction

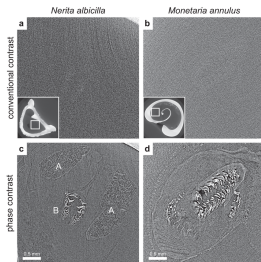
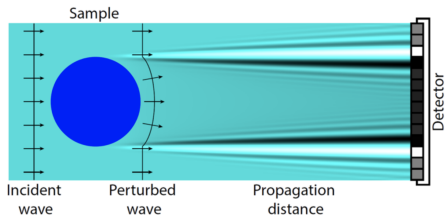


General view



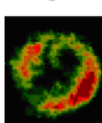
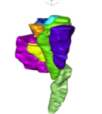
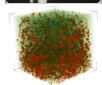
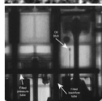
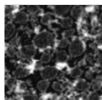
Lithium distribution

So far attenuation imaging, but there is also phase contrast imaging!



Häggmark *et al.*,

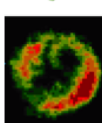
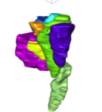
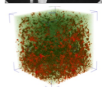
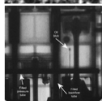
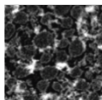
See upcoming presentations!



- White beam imaging
- Fast and stroboscopic imaging
- Bragg edge diffraction imaging
- Structural and magnetic dark-field imaging
- Polarized neutron imaging
- X-ray plus neutron imaging

Stroboscopic imaging fast process-synchronised imaging





- White beam imaging
- Fast and stroboscopic imaging
- Bragg edge diffraction imaging
- Structural and magnetic dark-field imaging
- Polarized neutron imaging
- X-ray plus neutron imaging

- Making use of the energy (wavelength) dependence of the attenuation
- Looking at the loss in transmission due to back-scattering

Bragg's Law:

$$n \lambda = 2 d \sin (\theta)$$

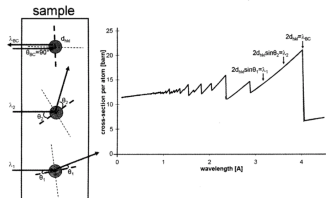
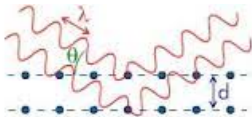
where

λ is the wavelength of the rays

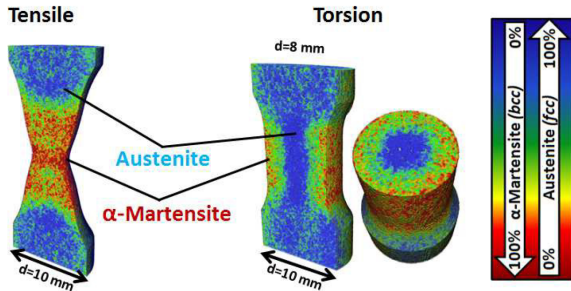
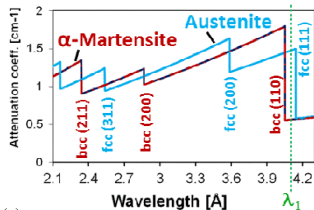
θ is the angle between the incident rays and the surface of the crystal

d is the spacing between layers of atoms

and constructive interference occurs when n is an integer (whole number)



How is it useful?

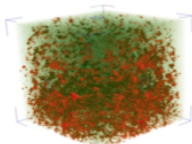


Worachek et al., 2015

Bragg edge diffraction imaging:

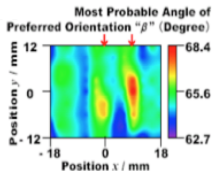
- Making use of the energy (wavelength) dependence of the attenuation
- Looking at the loss in transmission due to back-scattering

Chemical phase mapping

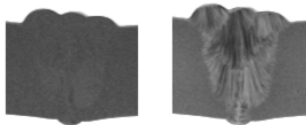
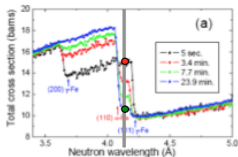


I. Manke, M. Strobl et al.

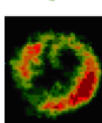
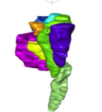
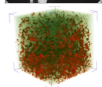
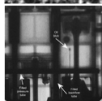
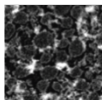
Microstructure and texture mapping



H. Sato et al. J. Phys 2010

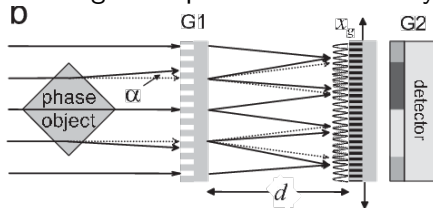


E. Lehmann, N. Kardjilov et al. NIMA 2009

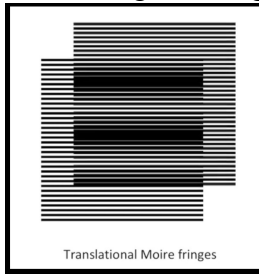


- White beam imaging
- Fast and stroboscopic imaging
- Bragg edge diffraction imaging
- Structural and magnetic dark-field imaging
- Polarized neutron imaging
- X-ray plus neutron imaging

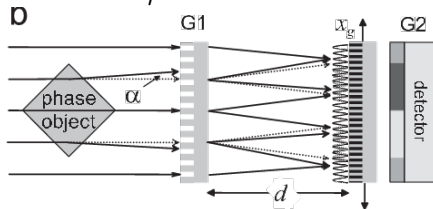
Working Principle of Interferometry



Moire Fringes Analogy



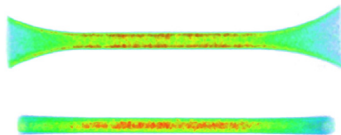
Selective laser melted (SLM) AM sample in stainless steel 316 Set for $1.93\mu\text{m}$



Concentration of $\sim 2\mu\text{m}$ pores in the sample



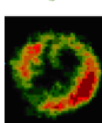
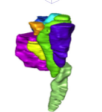
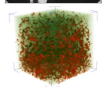
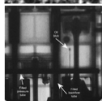
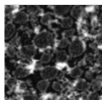
Fractured Sample



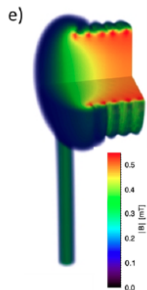
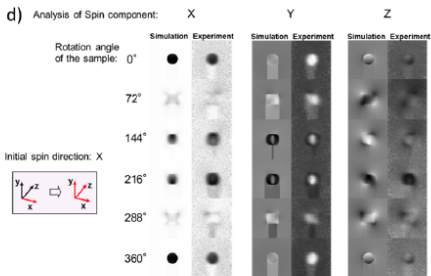
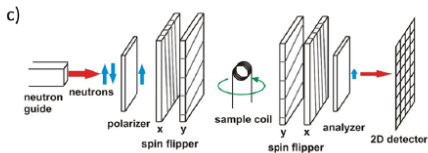
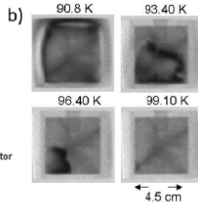
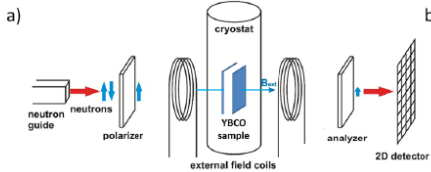
Stressed sample

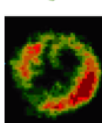
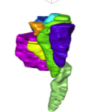
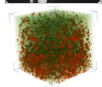
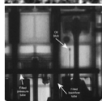
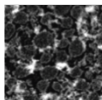
Brooks et al., 2017

Brooks et al., 2018



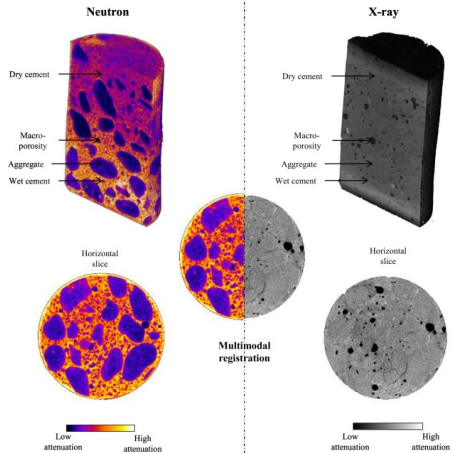
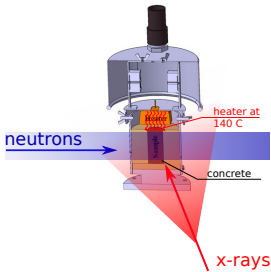
- White beam imaging
- Fast and stroboscopic imaging
- Bragg edge diffraction imaging
- Structural and magnetic dark-field imaging
- Polarized neutron imaging
- X-ray plus neutron imaging





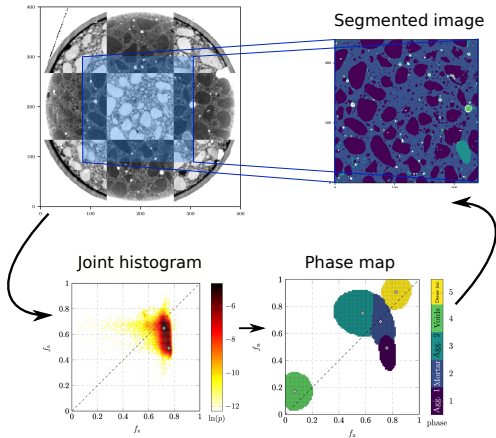
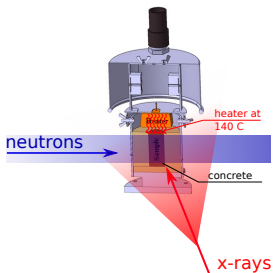
- White beam imaging
- Fast and stroboscopic imaging
- Bragg edge diffraction imaging
- Structural and magnetic dark-field imaging
- Polarized neutron imaging
- X-ray plus neutron imaging

Heating construction materials to high temperatures



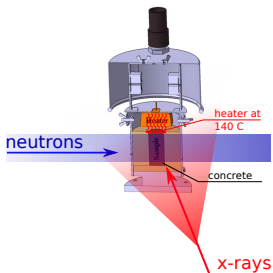
Tudisco *et Al.*, Measurement Science and Technology (2017)
Roubin *et Al.*, Cement and Concrete Composites (2019)
Sleiman, Cement and Concrete Research (2021)

Heating construction materials to high temperatures

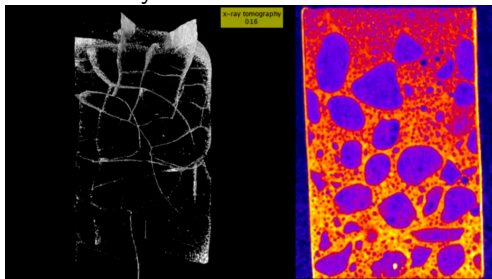


Tudisco *et Al.*, Measurement Science and Technology (2017)
 Roubin *et Al.*, Cement and Concrete Composites (2019)
 Sleiman, Cement and Concrete Research (2021)

Heating construction materials to high temperatures



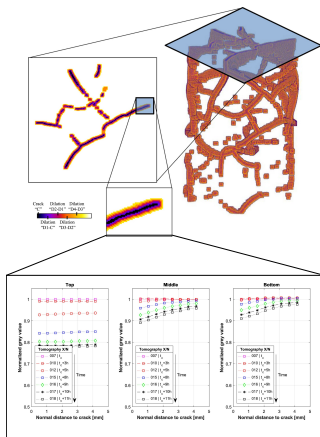
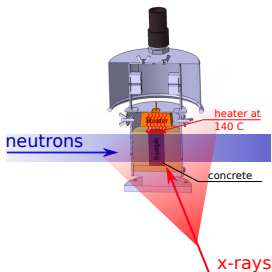
x-ray



neutrons

Tudisco *et Al.*, Measurement Science and Technology (2017)
Roubin *et Al.*, Cement and Concrete Composites (2019)
Sleiman, Cement and Concrete Research (2021)

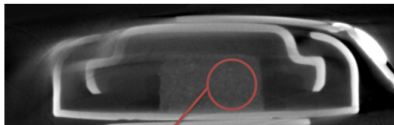
Heating construction materials to high temperatures



Tudisco *et Al.*, Measurement Science and Technology (2017)
 Roubin *et Al.*, Cement and Concrete Composites (2019)
 Sleiman, Cement and Concrete Research (2021)

Structure

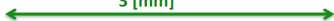
X-ray tomography at 10 μm pixel size
1 hour scan



Matrix

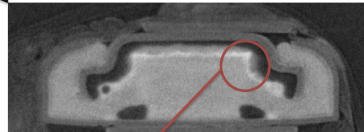


3 [mm]

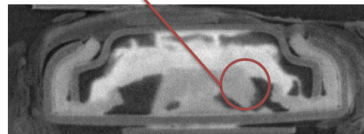


Electro-chemistry

Neutron tomography at 3.5 μm pixel size
2 hour scan



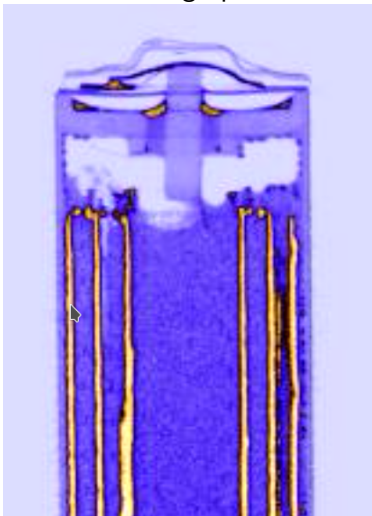
Electrolyte



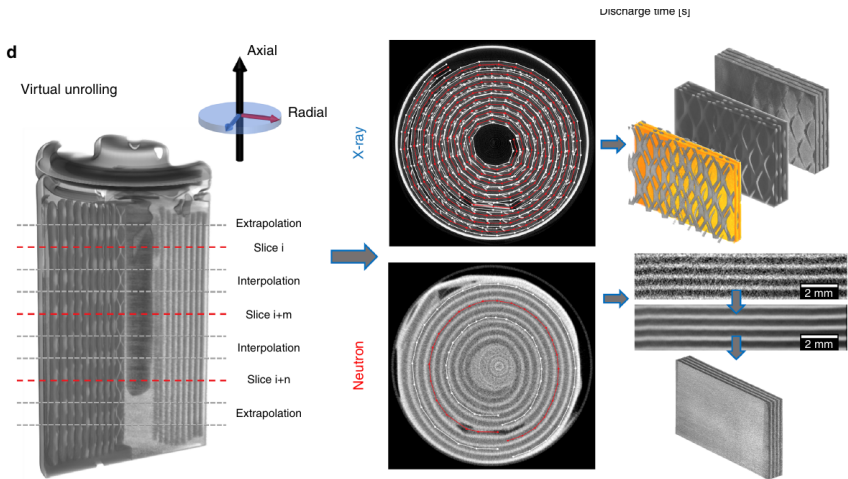
3 [mm]



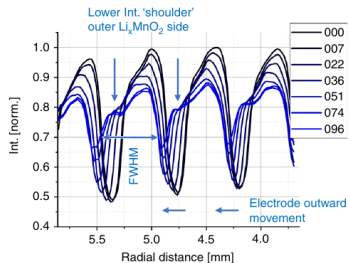
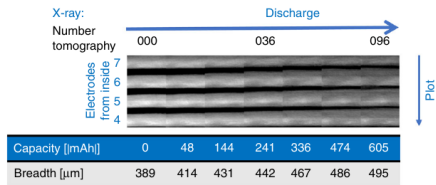
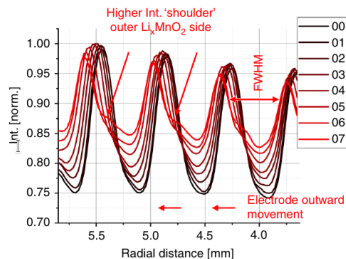
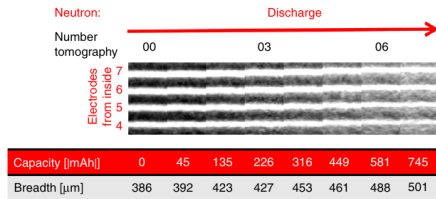
30 minute tomographies at 30um



Ziesche et Al. 2020 Nature Comm.
Ziesche et Al. 2020 J. Electrochem. Soc.

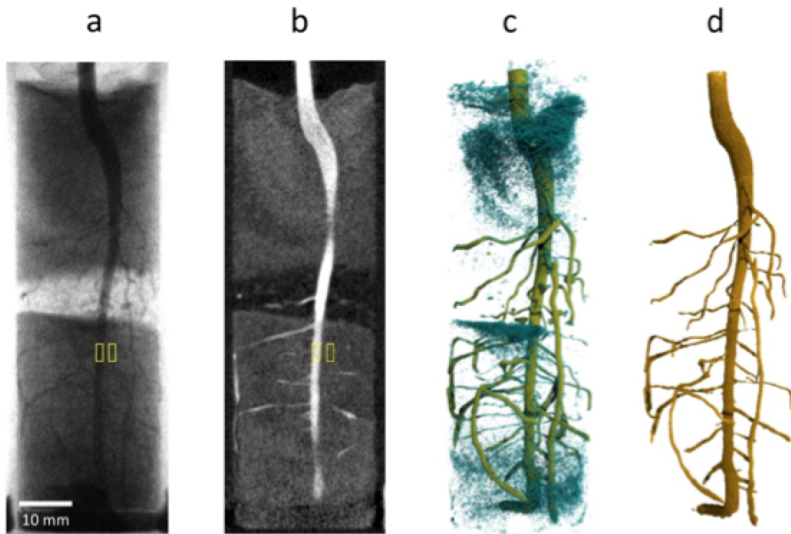


Ziesche et Al. 2020 Nature Comm.
Ziesche et Al. 2020 J. Electrochem. Soc.

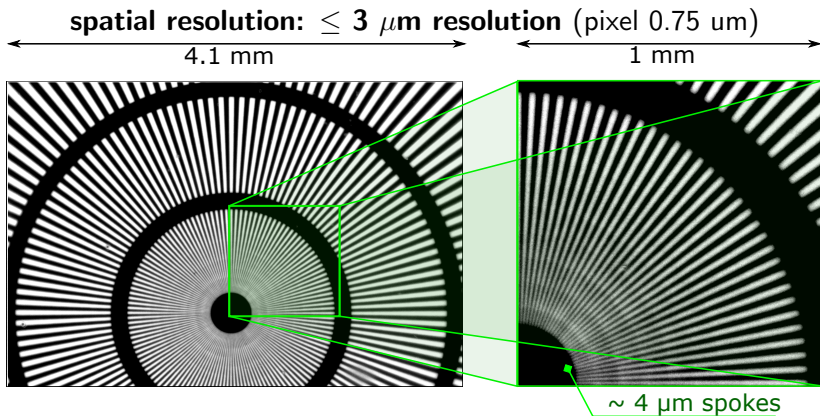
a**b**

Ziesche et Al. 2020 Nature Comm.
Ziesche et Al. 2020 J. Electrochem. Soc.

temporal resolution: 1.5s tomographies

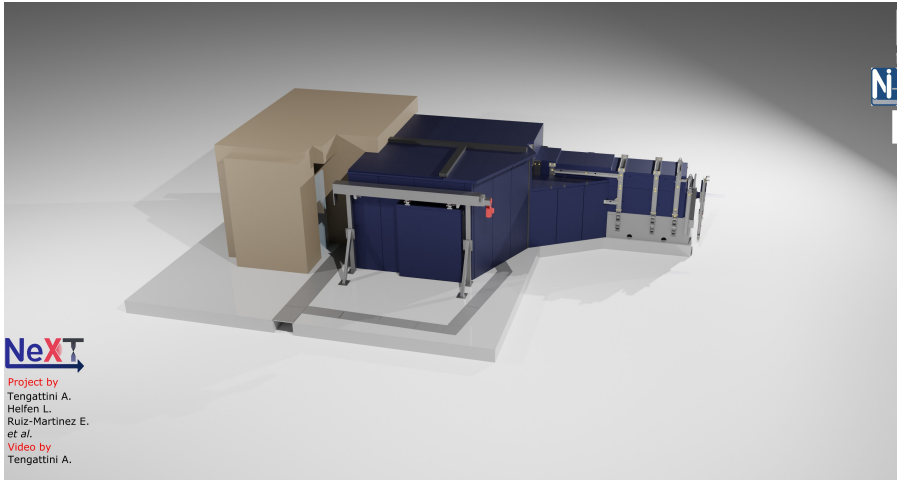


Totzke *et al.*, 2019 Optics Express



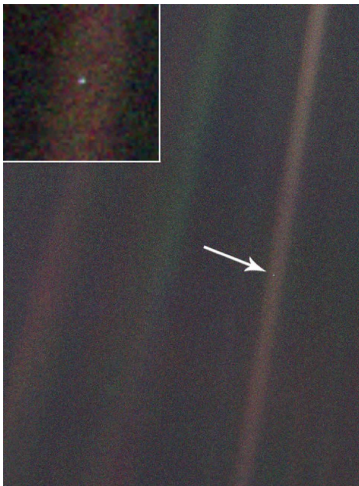
Tengattini, Kardjilov, Helfen *et al.*, 2021 Optics Express

NeXT 2.0



NeXT

Project by
Tengattini A.
Helfen L.
Ruiz-Martinez E.
et al.
Video by
Tengattini A.



The 'Pale Blue Dot'

Photograph of planet Earth taken on February 14, 1990, by Voyager 1.
Distance: 6 billion km

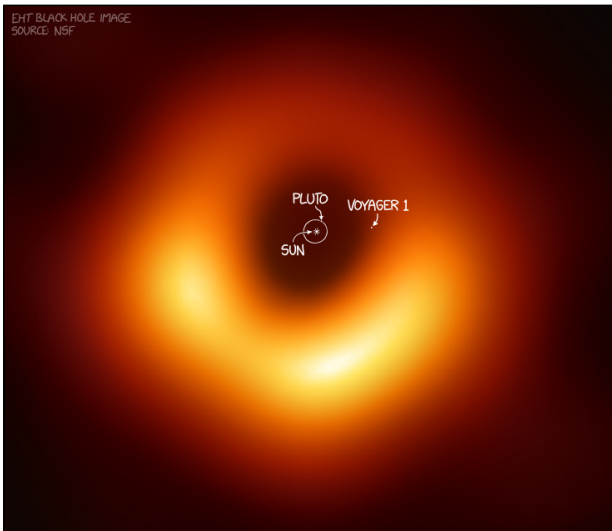
In the photograph, Earth's apparent size is less than a pixel.

Spatial resolution is not the only thing that is important. Uniqueness of contrast and information!

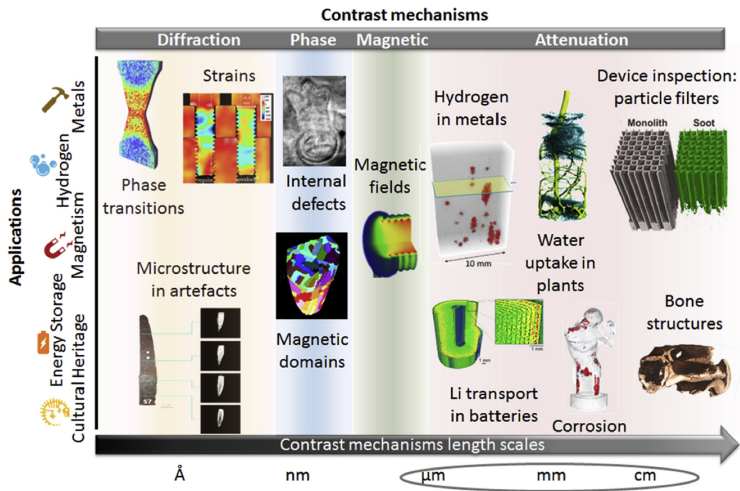
Moreover: Use the synergy of neutrons and x-rays (and other methods) to complement contrast and spatial resolution

Woracheck

SIZE COMPARISON:
THE M87 BLACK HOLE
AND
OUR SOLAR SYSTEM



Example of the range of applications for (Neutron) imaging



Kardjilov et Al 2018