Welcome to CIVIL-510
“Quantitative Imaging for Civil Engineers”

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Lecture Ten: 2021-11-18

Today's plan

A full-time lecture: **"Full" 3D with volume imaging** – the basic principles of x-ray tomography:

- How to generate x-rays

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This lecture is here to prepare next week's practical session with Gary on the x-ray machine

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- A bit of x-ray physics

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- Appreciation of which problems can be tackled with radiography/tomography

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- Appreciation of which problems can be tackled with radiography/tomography
- Understanding of key technical details

What are x-rays?

X-rays are high-energy electro-magnetic radiation

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Lower energy you are:

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Discovery of x-rays – a glowing sheet...

X-ray detection

Measuring x-ray radiation

One keyword: **scintillation**, the property of a material that *phosphoresces* when excited by ionising radiation.

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If phosphorescence is in the visible light range, we can use usual cameras, etc. Typical setups:

mirror+camera	flat panel

X-ray detection 2

Important note: *direct* x-ray detectors are coming soon (CdTe technology, see medipix, pixirad, direct conversion, dectris).

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“Photon counting” detectors, “x-ray colour” detectors

Making x-rays – basic physics

- Story of the discovery of x-rays, first Nobel prize in Physics

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- How to make x-rays with electrons interaction with matter/fields:

flying electrons	atomic electrons

Making x-rays – main devices

electron gun & target	magnetic field

X-ray interaction with matter

We have an x-ray generator, and an x-ray source, let's do some experiments!

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Let's measure x-ray transmission through an object, what do we expect?

X-ray interaction with matter

Beer Lambert law: *Transmission* through a sample (with attenuation reducing intensity of the beam by absorption):

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

X-ray interaction with matter

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

It's by far not the only x-ray-material (see phase contrast, diffraction...) interaction but it's what we'll use.

Integral of an attenuation field

Think of the physical process:

$$I = I_0 e^{-\int_0^l \mu(x) dx}$$

A practical example

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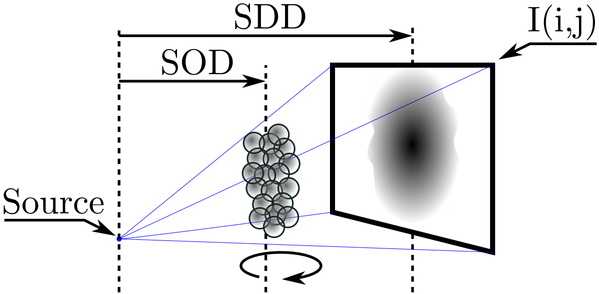
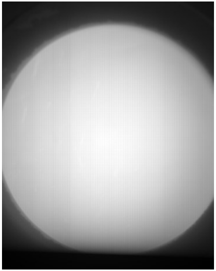


A real (toy) example

I_0	I	$\frac{I}{I_0}$	$-ln(\frac{I}{I_0})$
			
0-65535	0-65535	0.0-1.0	

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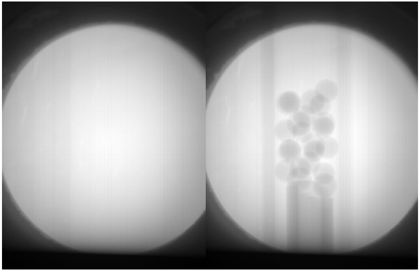

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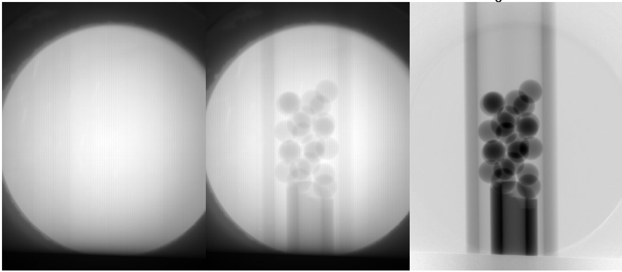

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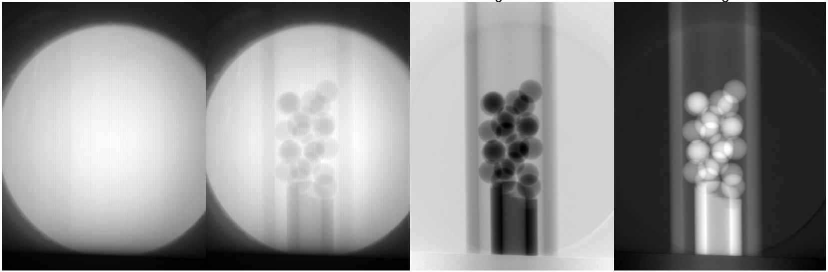

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Radiography by itself

...is already quite useful. Uses? Limitations?

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Ideal amount of transmission: 30%

Going for the 3D volume

The Radon transform (wikipedia): "In mathematics, the Radon transform is the integral transform which takes a function f defined on the plane to a function Rf defined on the (two-dimensional) space of lines in the plane, whose value at a particular line is equal to the line integral of the function over that line."

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Is that useful? Very. f in this case is $\mu(x, y)$ and Rf is a "sinogram"

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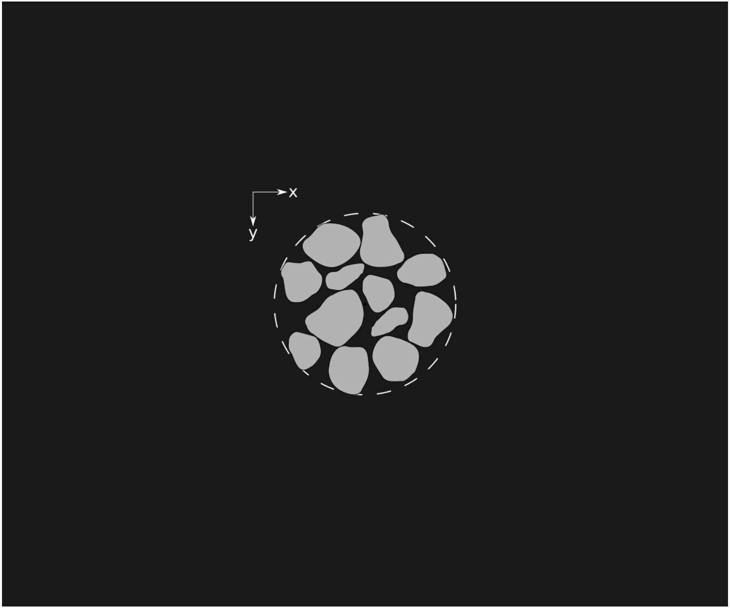
X-ray tomography in short:

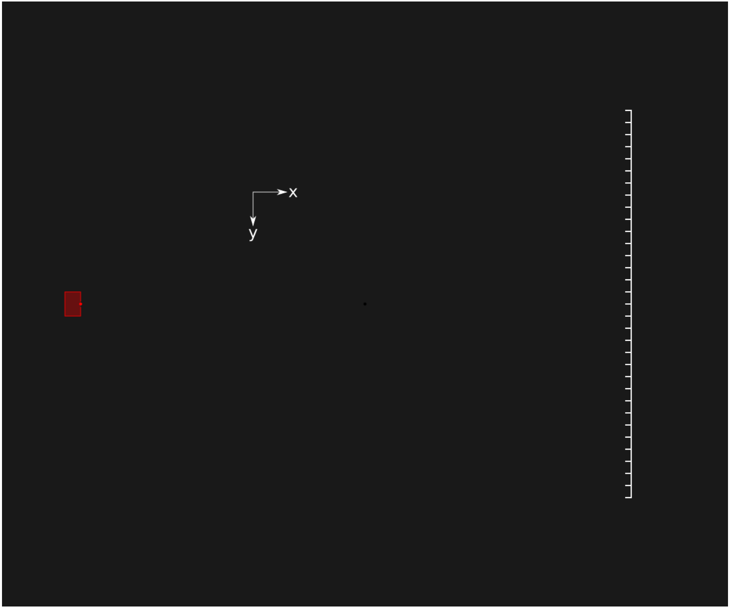
- We will measure many (but discrete) line integrals ("projections") of our object to put together Rf
- We'll try to compute the *inverse Radon transform* to get $\mu(x, y)$
- How many projections should we acquire?

Handwavy explanation of fourier slice theorem + FBP

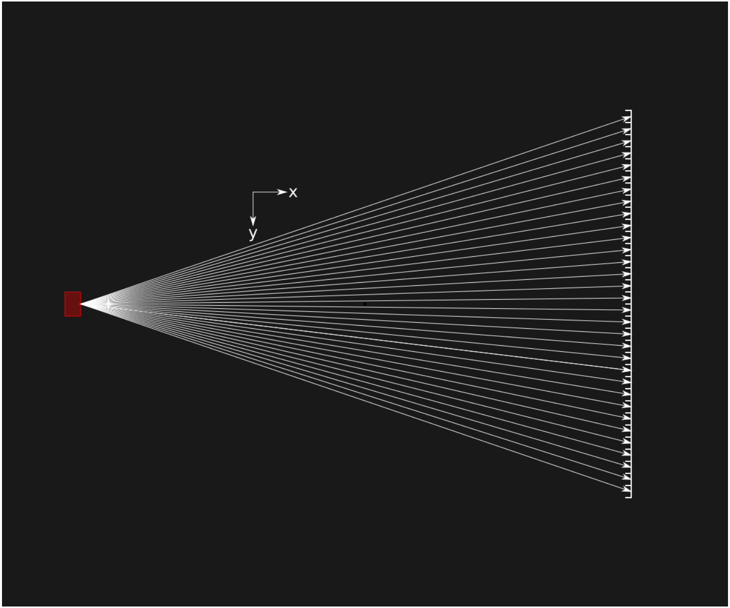
The field we want to measure – $\mu(x, y)$



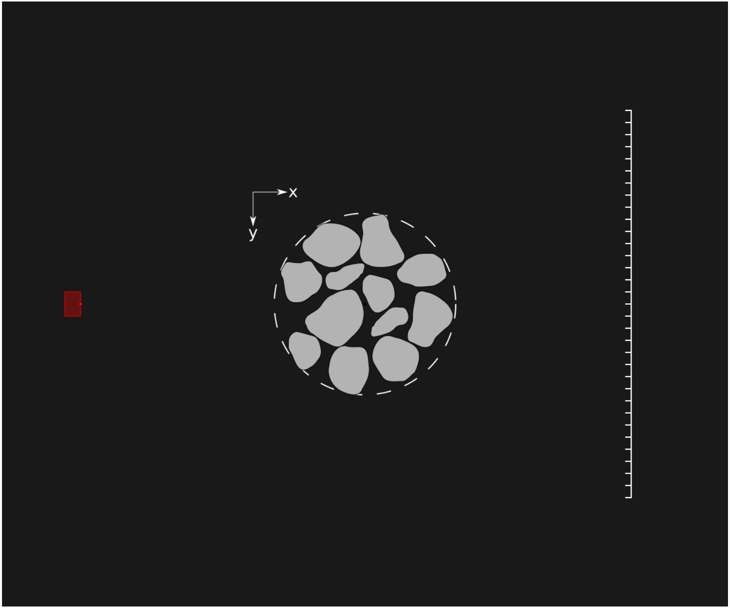
Source and detector system



Measure I_0



Let's measure the sample



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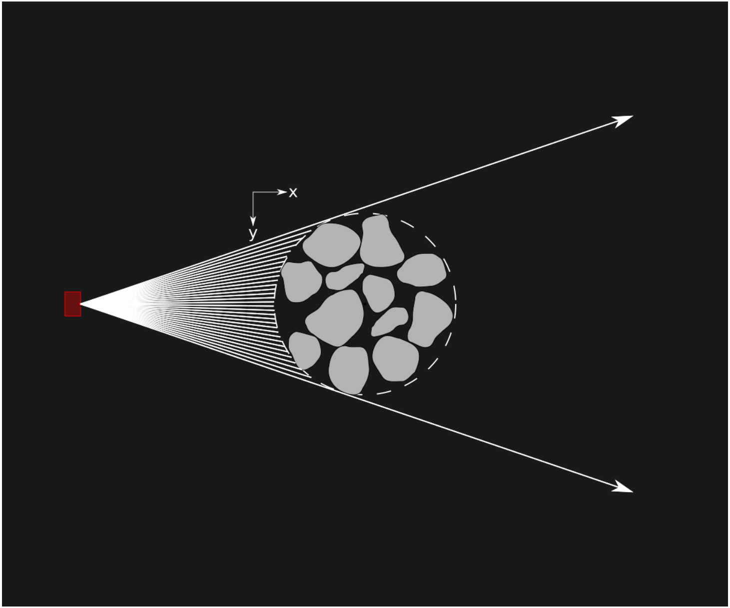
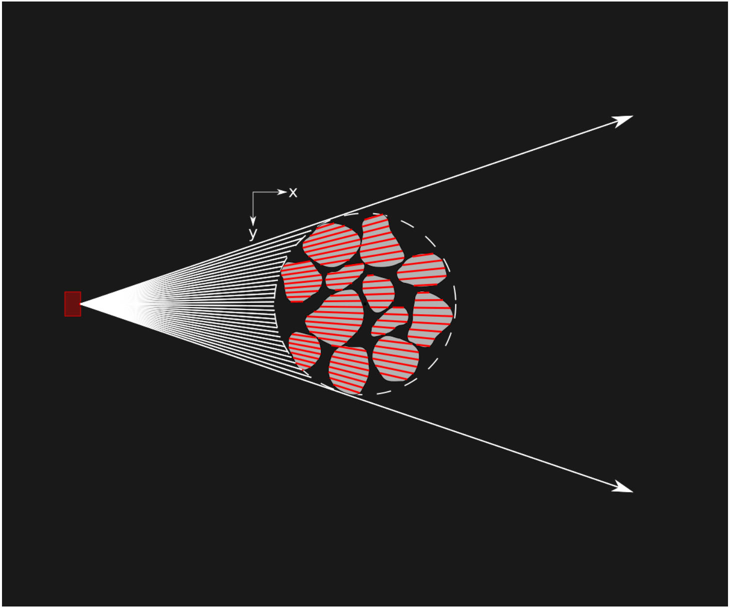
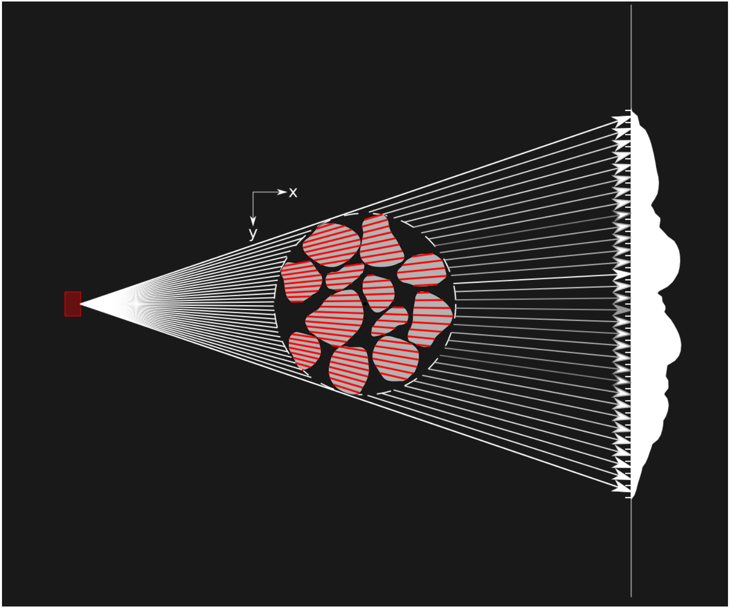


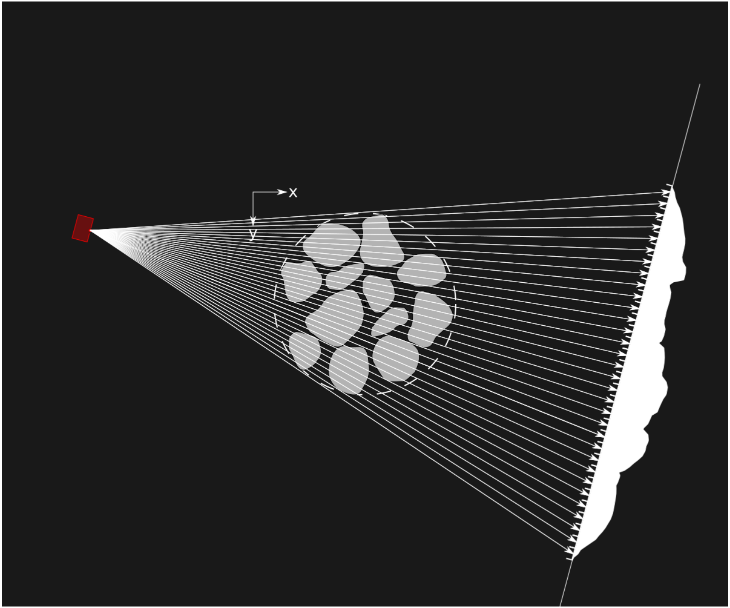
Let's measure the sample – x



Measure I – we have projected the field of $\mu(x, y)$



Project in another direction...



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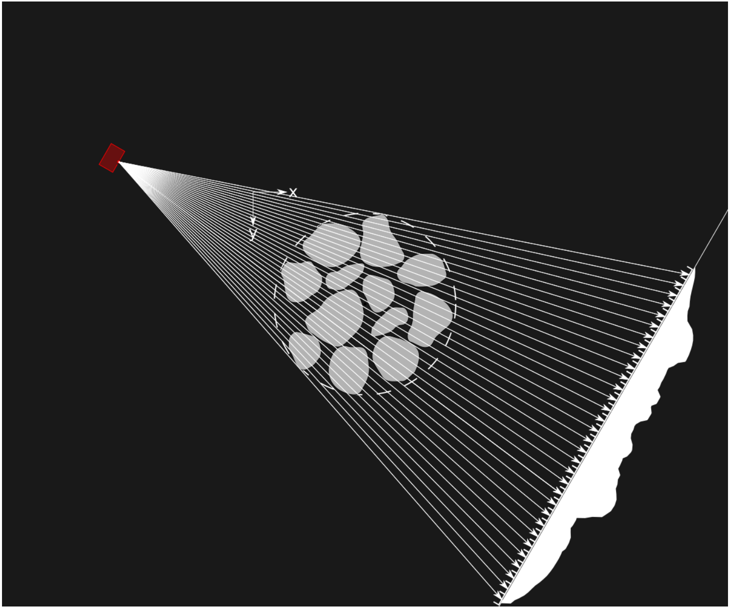

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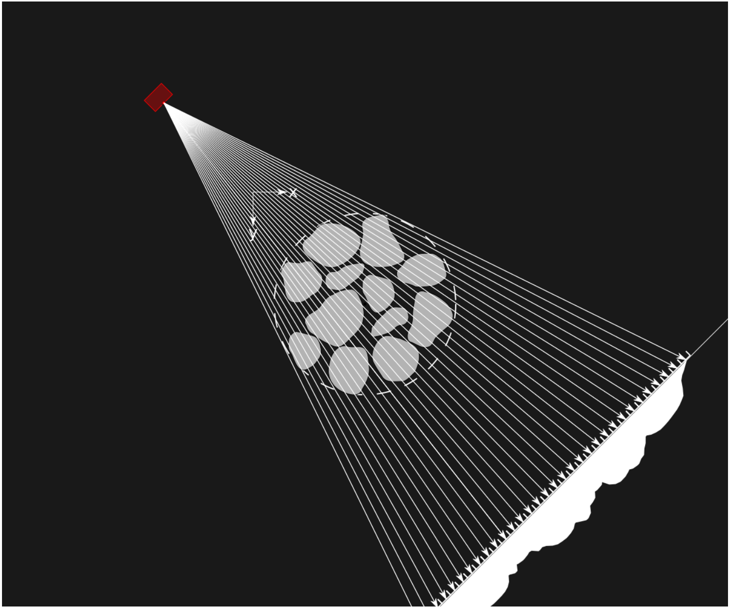

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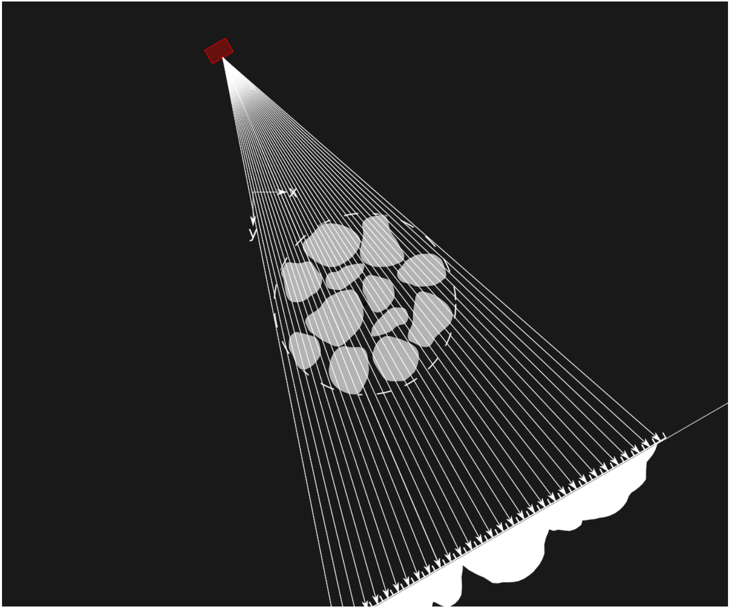

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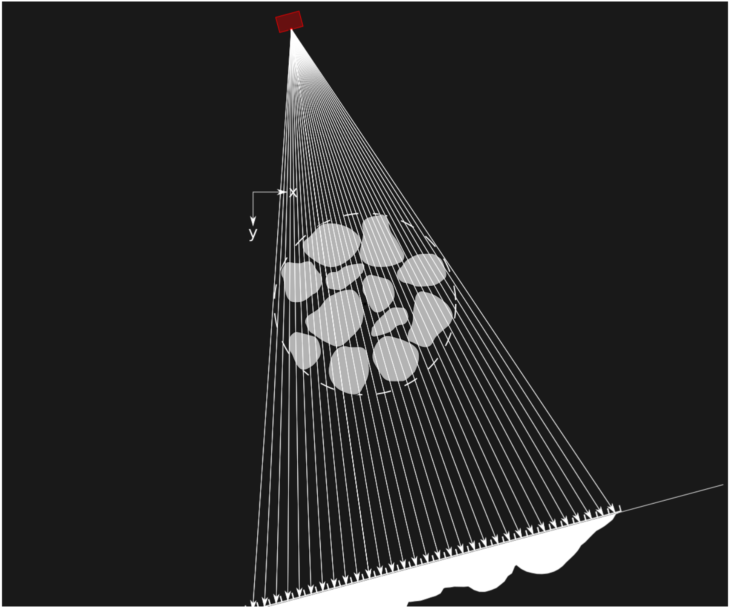

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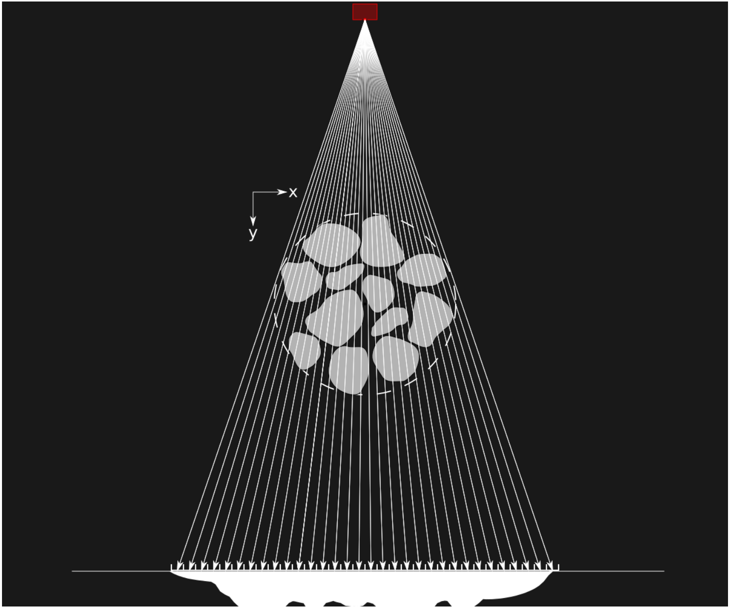
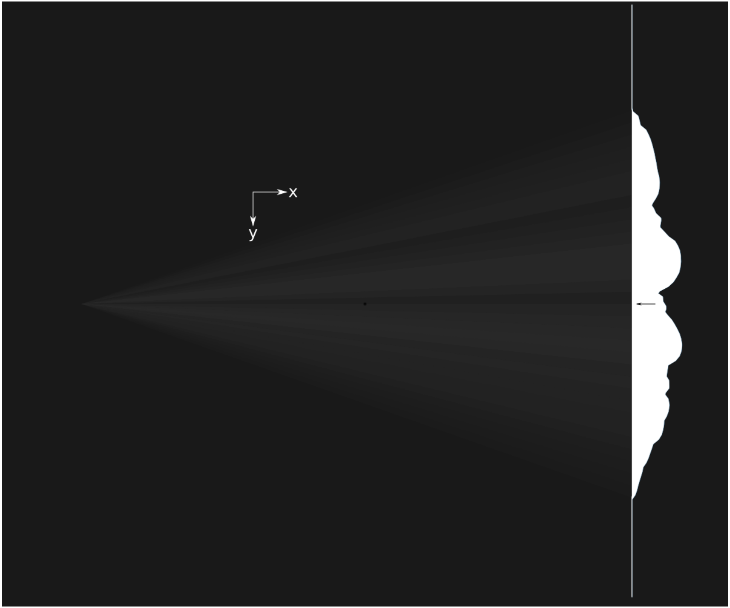


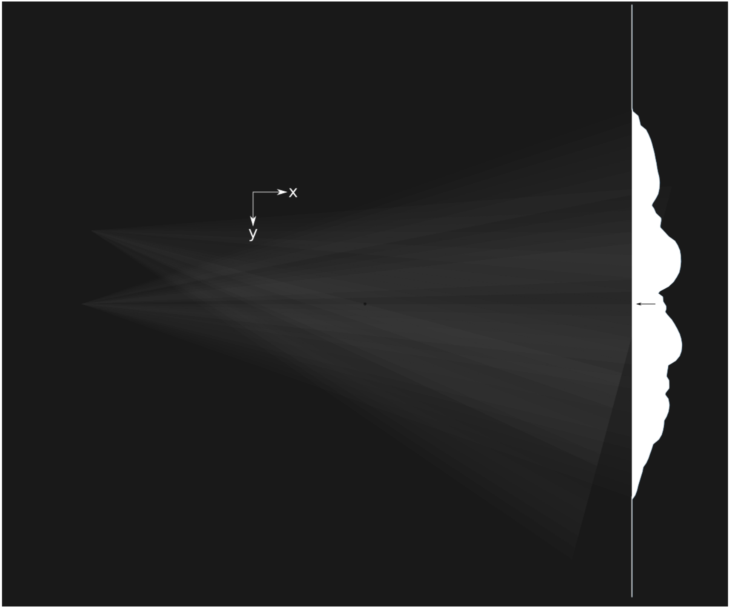
We have collected a load of projections of $\mu(x, y)$ as I

How do we go back to $\mu(x, y)$?

Backprojection



Backprojection



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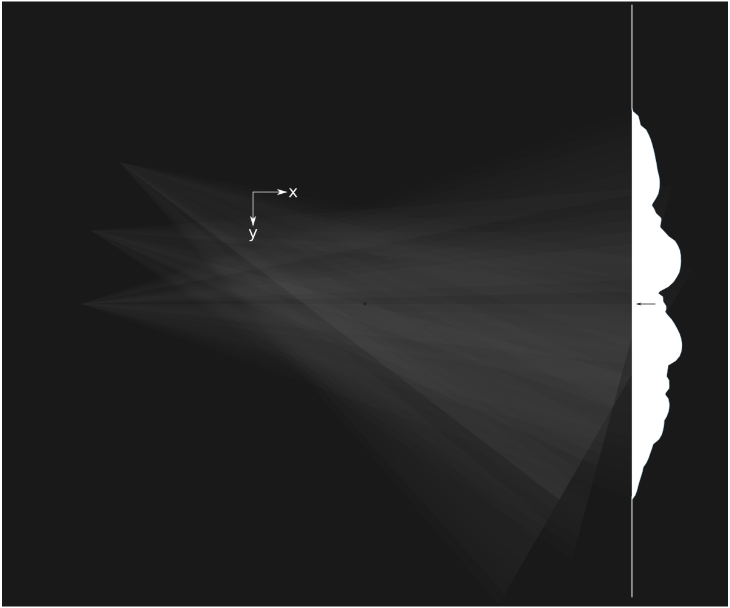

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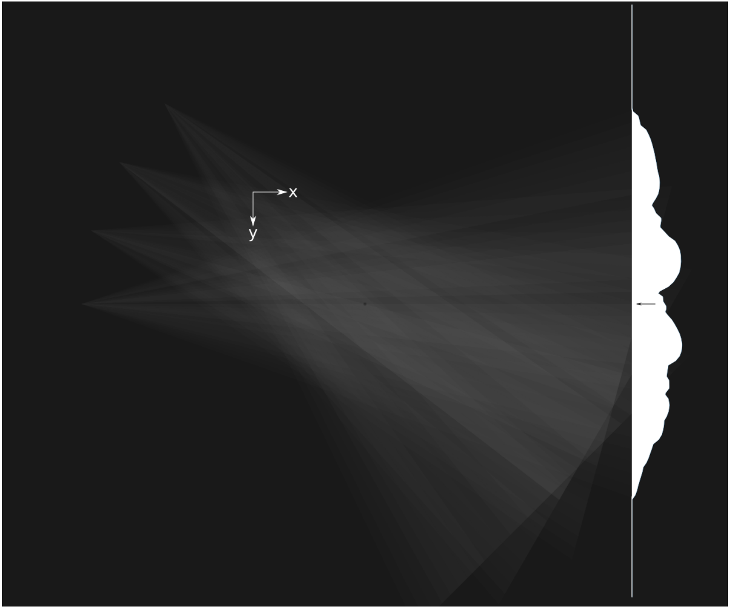

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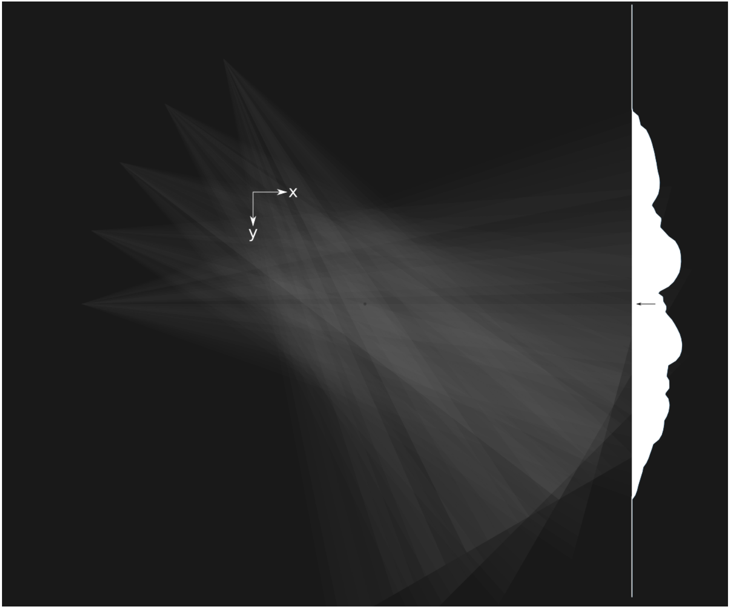

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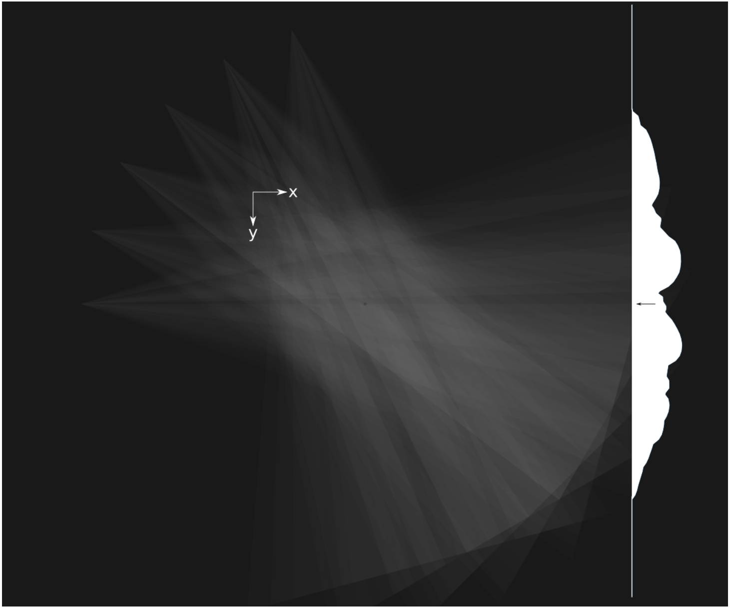

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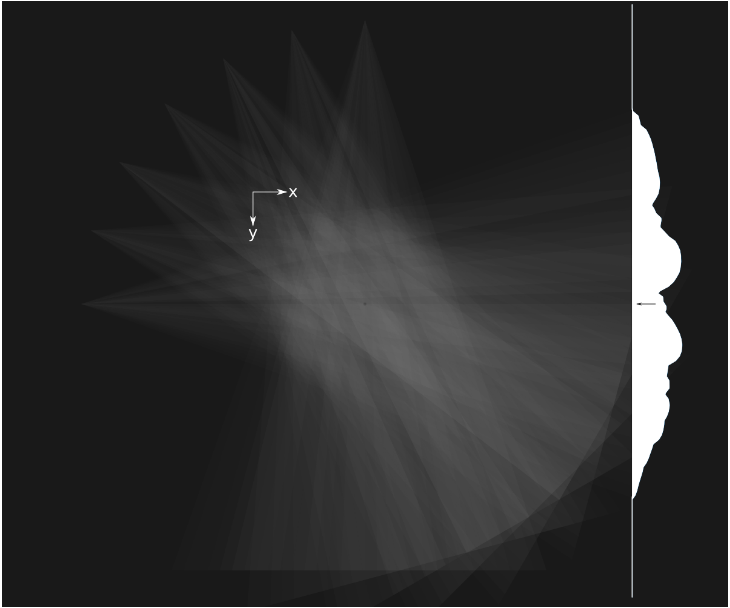
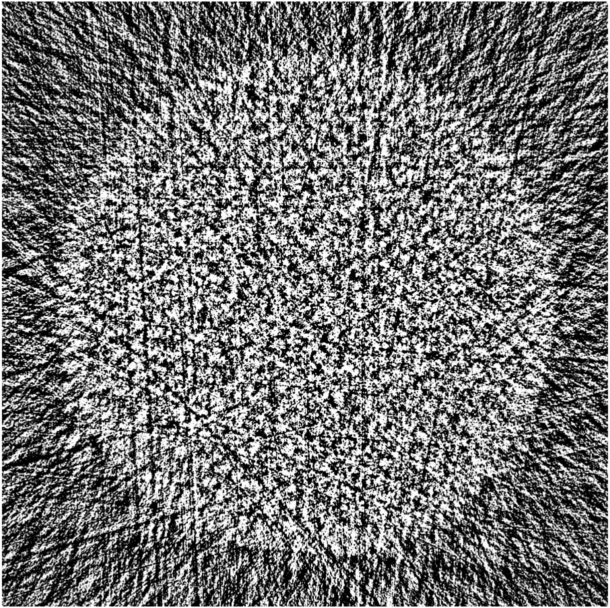
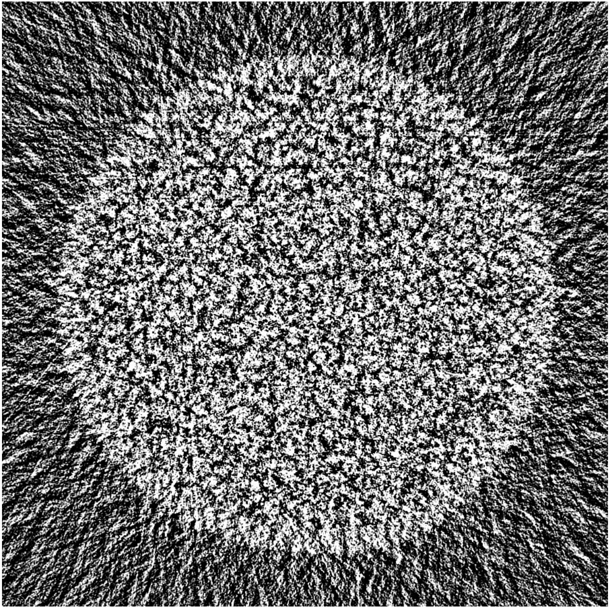


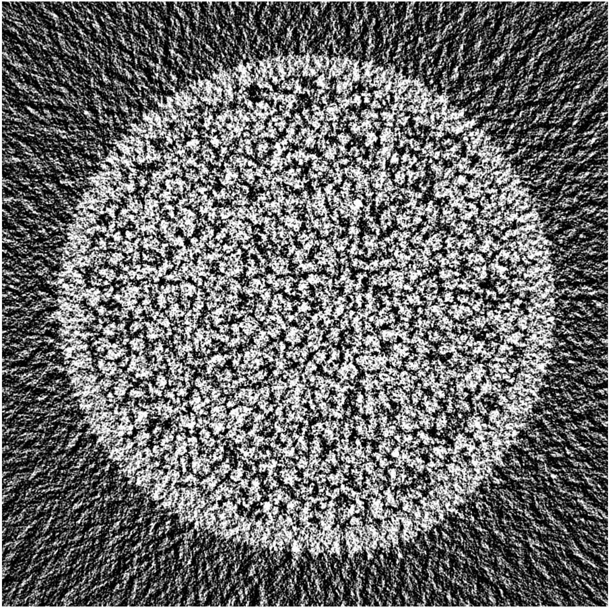
Example from M. Wiebicke 17



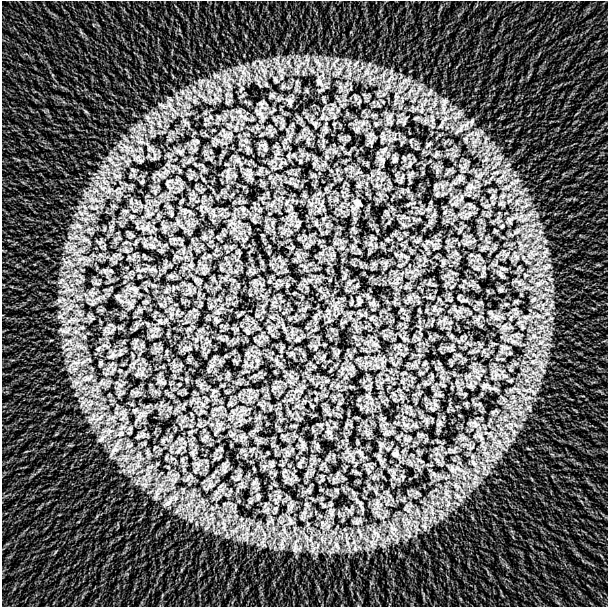
Example from M. Wiebicke 35



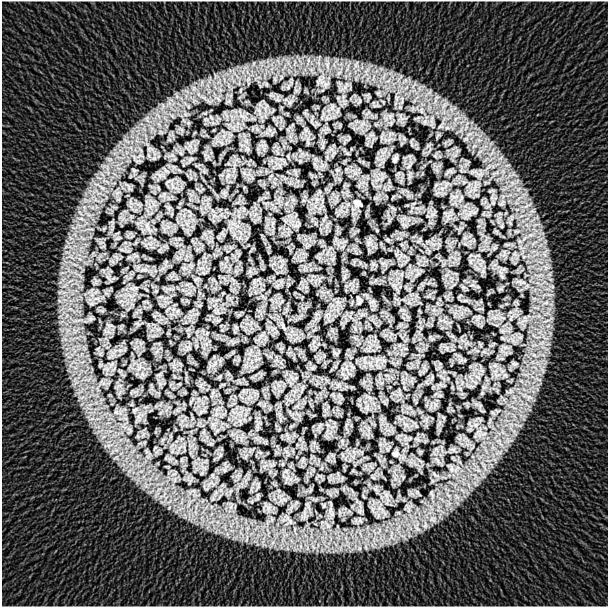
Example from M. Wiebicke 70



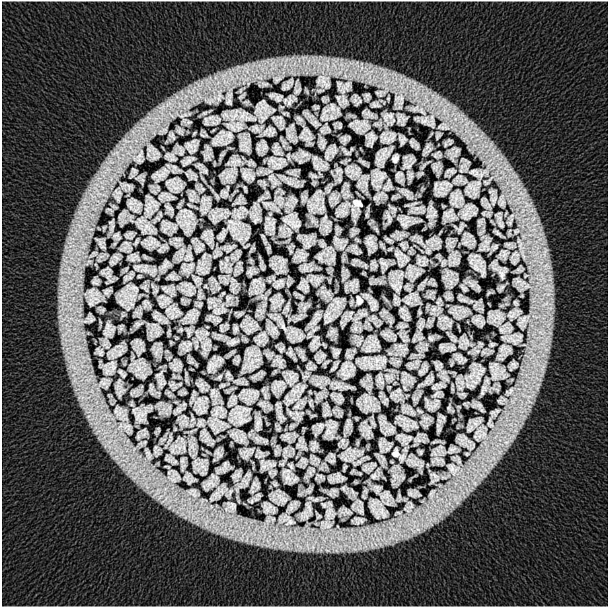
Example from M. Wiebicke 140



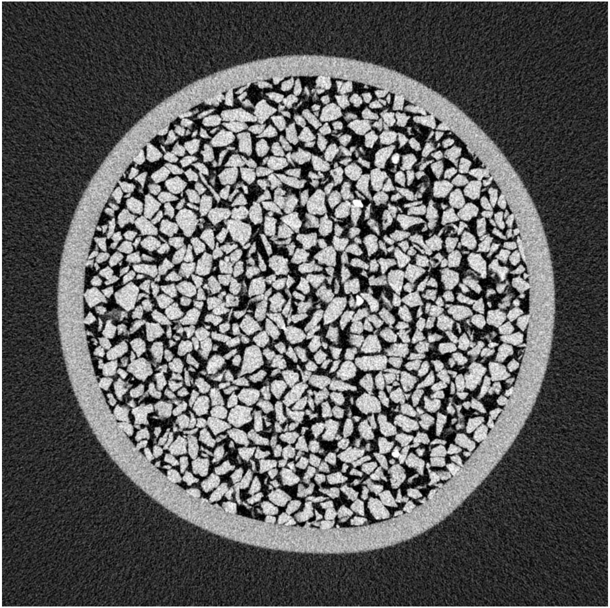
Example from M. Wiebicke 280



Example from M. Wiebicke 560



Example from M. Wiebicke 1120 – matrix of values



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- Signal-to-Noise ratio ($\frac{val(fg)}{STDev(bg)}$)

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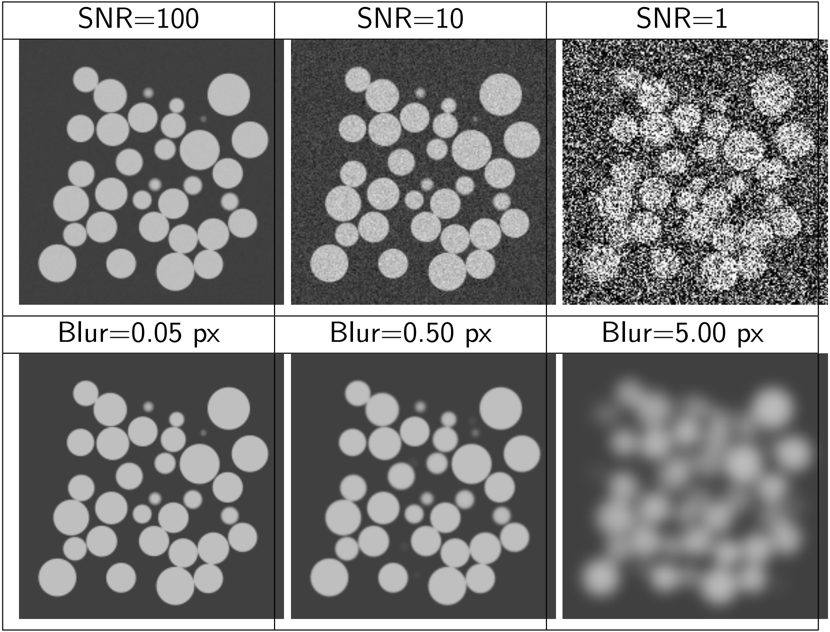
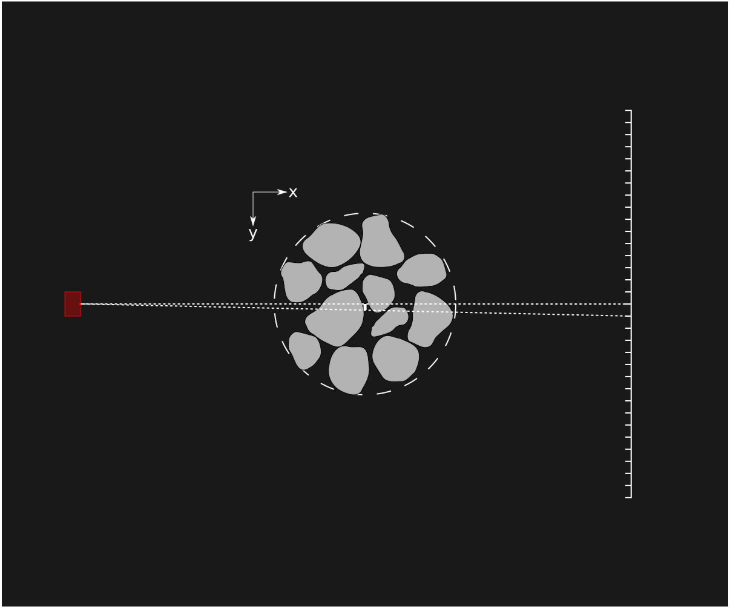
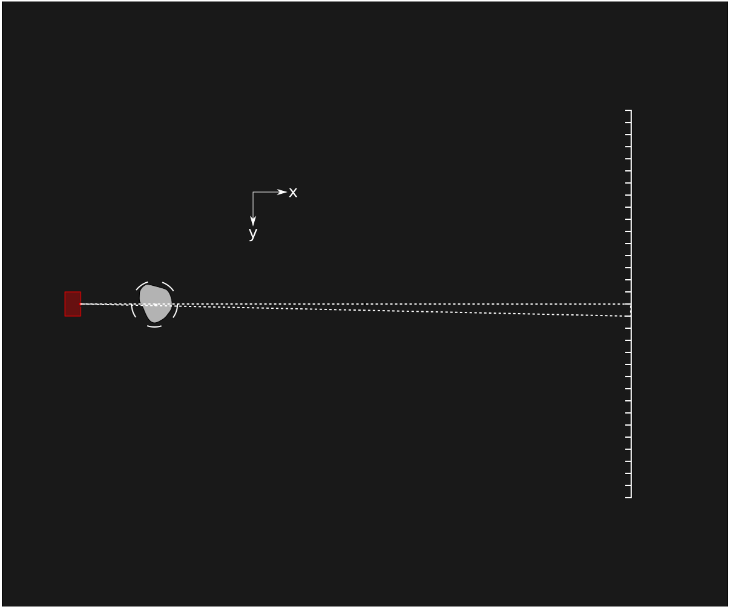
- Sharpness
- Tomography artefacts:
  - Beam hardening
  - Ring artefacts
  - Streaks...



A. Tengattini & E. Andò, *Kalisphera -- MST -- 2015*, Usual trade-off between field of view and pixel size



Usual trade-off between field of view and pixel size



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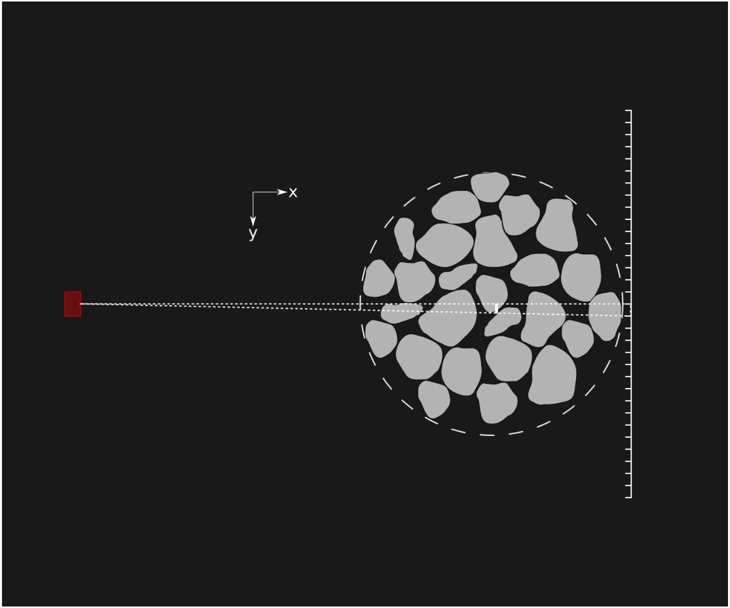
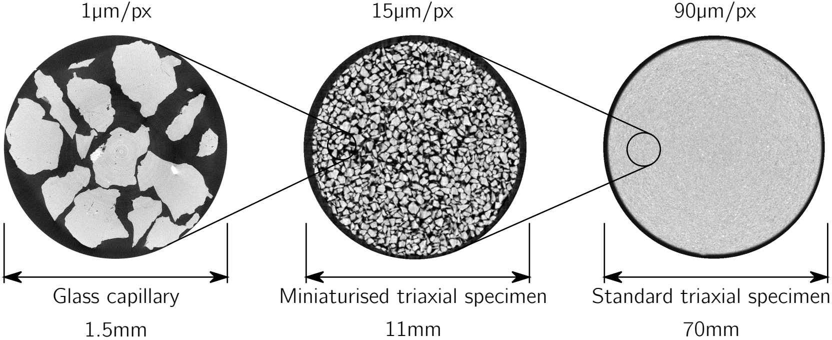
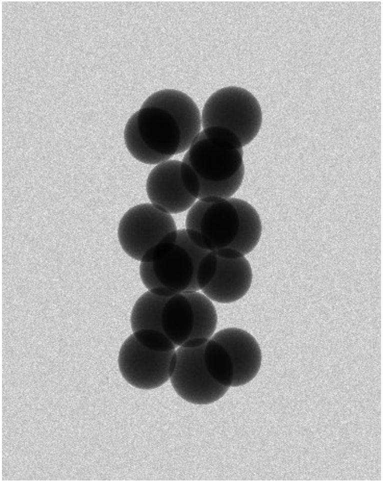


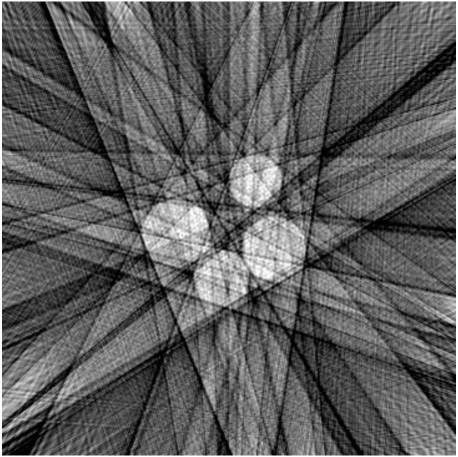
Hostun HN31 Sand (D_{50}=328μm)



Please note: the zoom-in illustrations are merely to relate the sizes, the scans shown are of different specimens r=1mm, $\frac{I}{I_0}$ with θ varying, note noise, overlaps:



What happens next typically, *backprojection* to get $\mu(x, y, z)$:
This is a horizontal slice as I add more θ:



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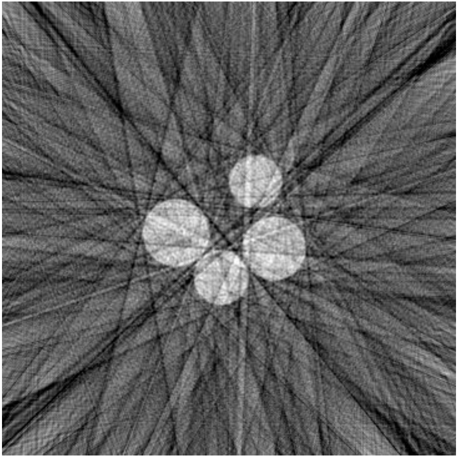

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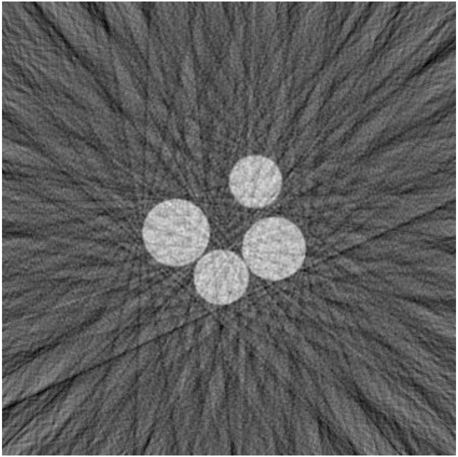

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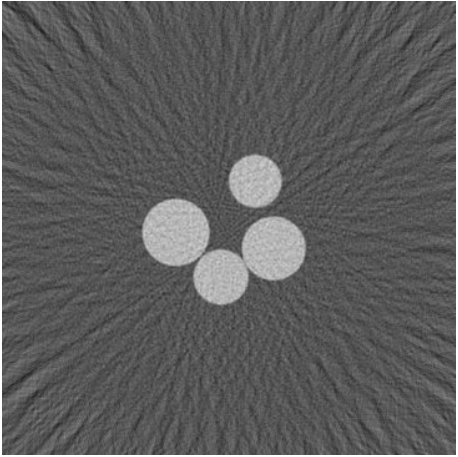

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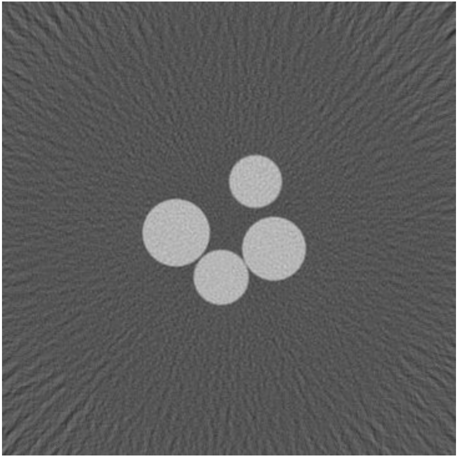

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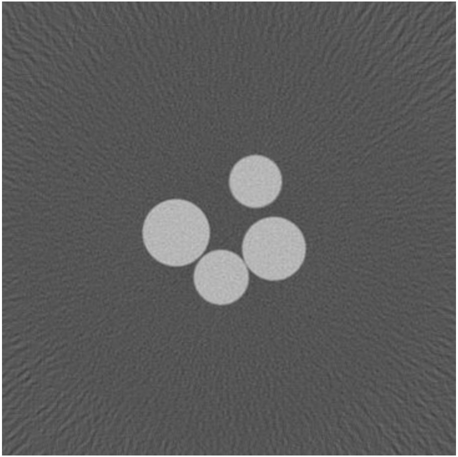

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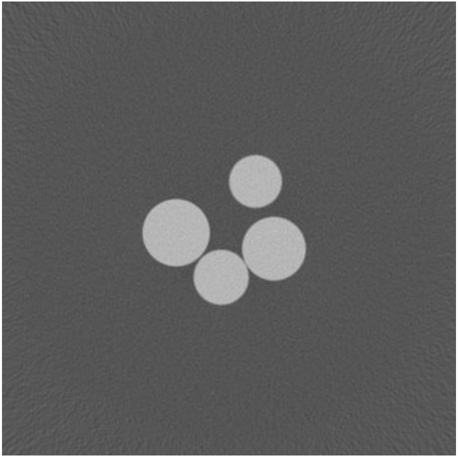

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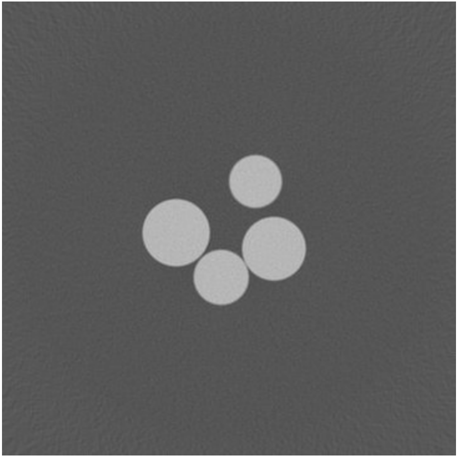
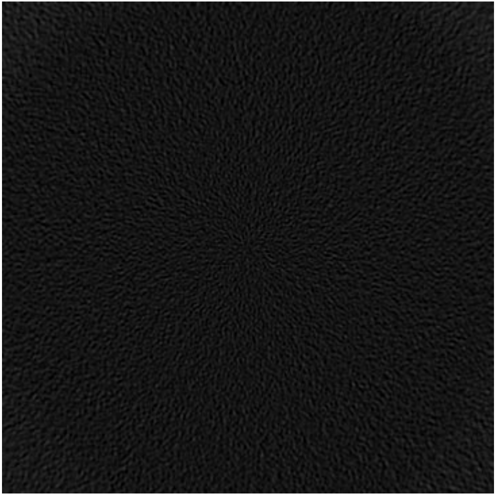


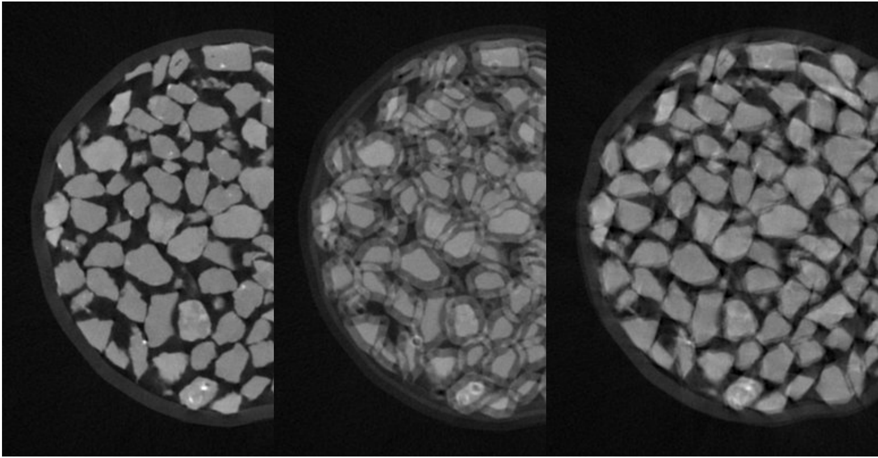
Result: 3D matrix of noisy $\mu(x, y, z)$, here we're moving through z



Practical aspects

Need to know the *centre of rotation*:

Good | Offset | Movement



Simplified x-ray scanner

Main control variables

Some metrological aspects

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Main tradeoffs

For a fixed volume and a fixed object:

Time (im/sec) *vs* Spatial Resolution (mm) *vs* Noise (SNR)

This is a nice model, reality a little more messy

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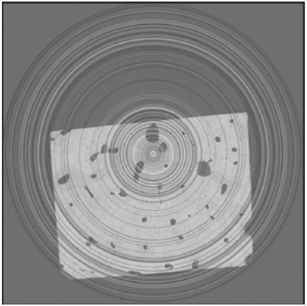
we can draw here

Some typical artefacts

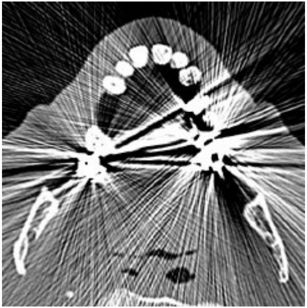
Rings



https://hal.archives-ouvertes.fr/

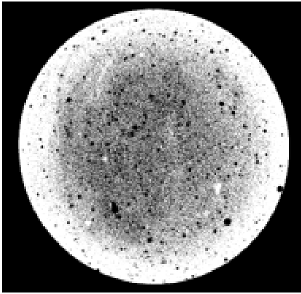
hal-01998216

Streaks



https://doi.org/10.1109/23.856534

Beam hardening



Mukunoki (2001)

Surprising things that work

- Local tomography
- Non-uniform angles (Laminography)

Summary

- Scintillation for detection
- X-rays made by electrons
- Beer lambert law
- We measure discrete Radon transform of the object
- We try to reconstruct the object by inverse radon (FBP), more fancy things available
- Resulting measurement typically with weird units
- Tradeoffs

Key tips

- Number of projections – Number of pixels
- Think in terms of tradeoff
- Set the energy well for your problem
- Don't trust the CT value too much
- Keep samples cylindrical
- Limitations in size (big and small)
- Limitations in contrast
- Dose limitations

Some cool examples

Freestyle examples (remember a 4D image)

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Freestyle examples (remember a 4D image)

Note: visualising and understanding 3D volumes is not easy!