Mechanics of granular materials

I. Experimental approach

Edward Andò

October 3, 2019

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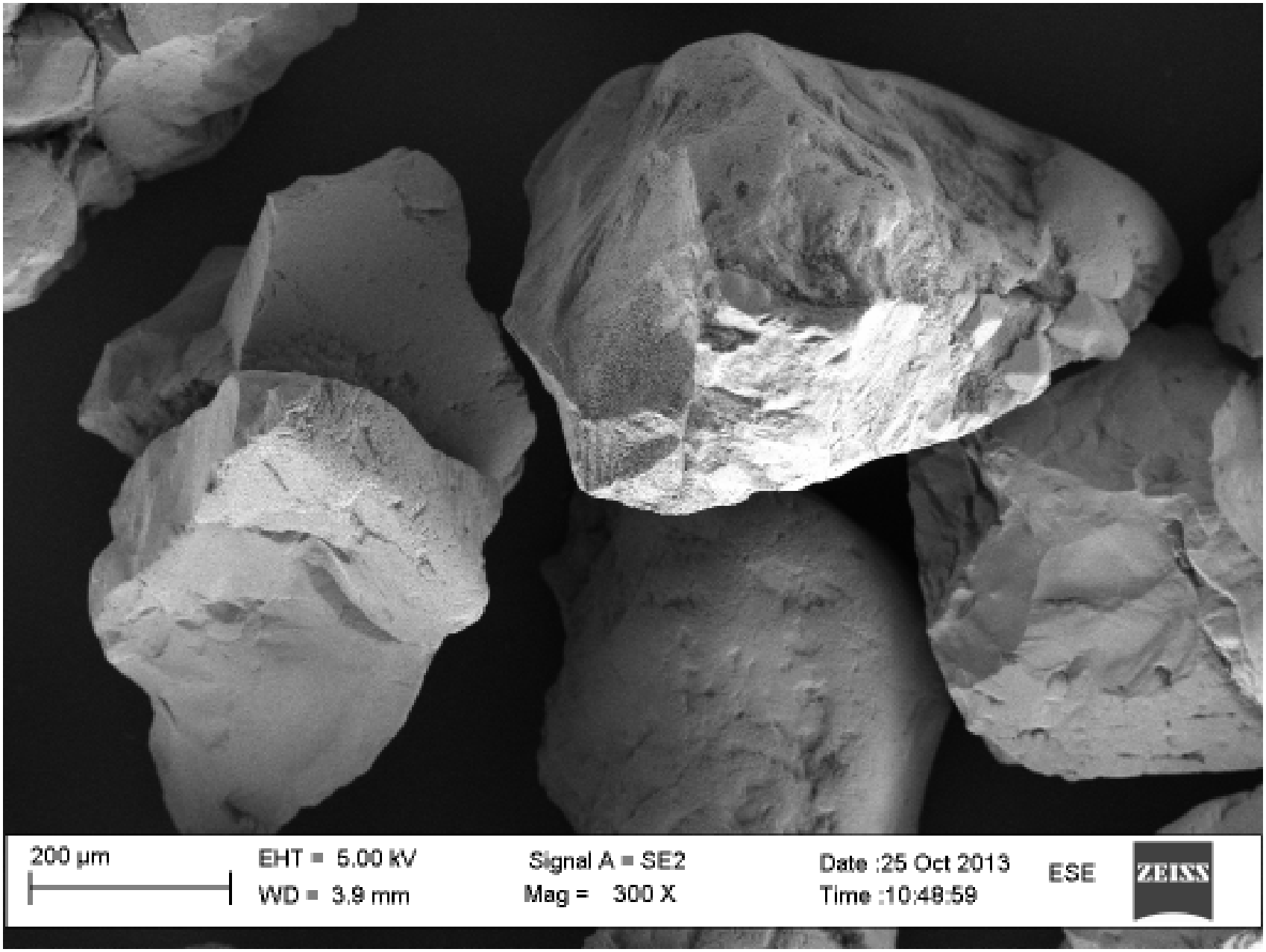
Let's walk back up the scales...

Grains, just grains



Courtesy A. Torabi

Grains, just grains

With separate particles we have to resort to geometry:

- Number of grains

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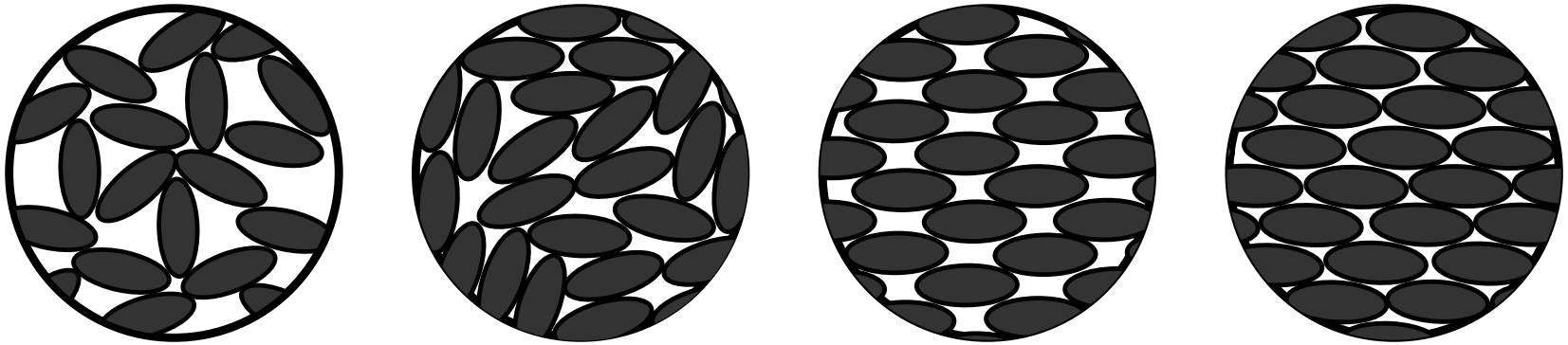
OK there's also the composition of grains.

An assembly of grains



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- Void ratio (e), Density (ρ), porosity (n), packing fraction (ϕ),

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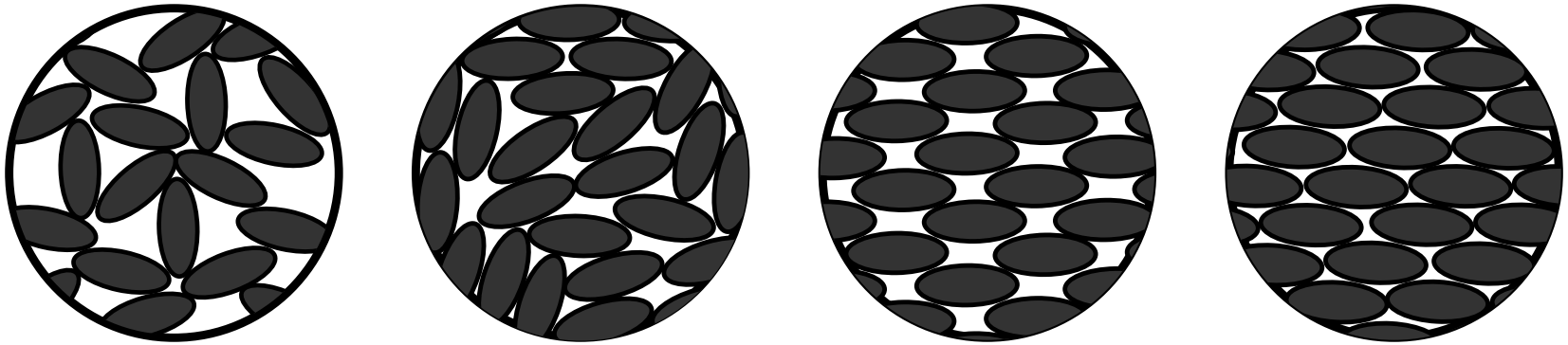

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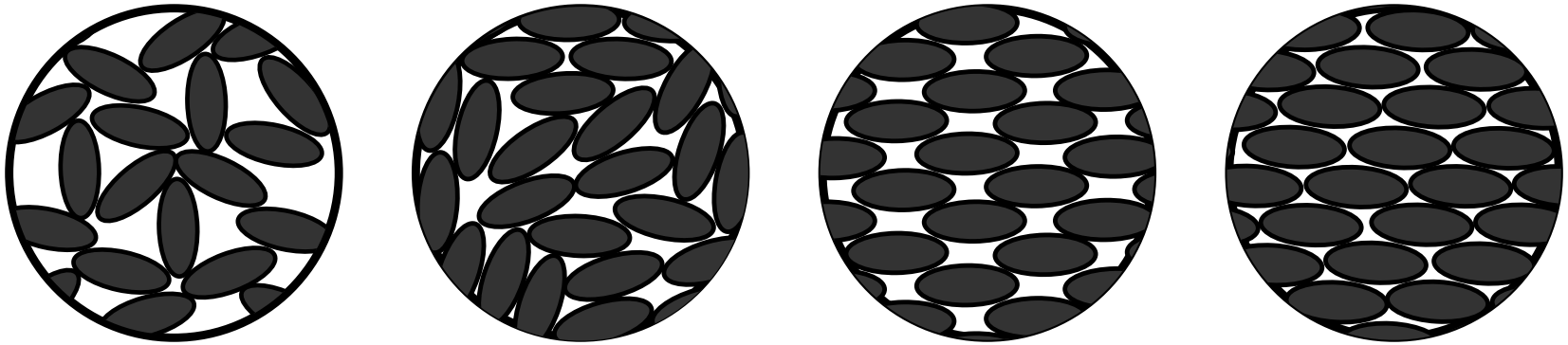

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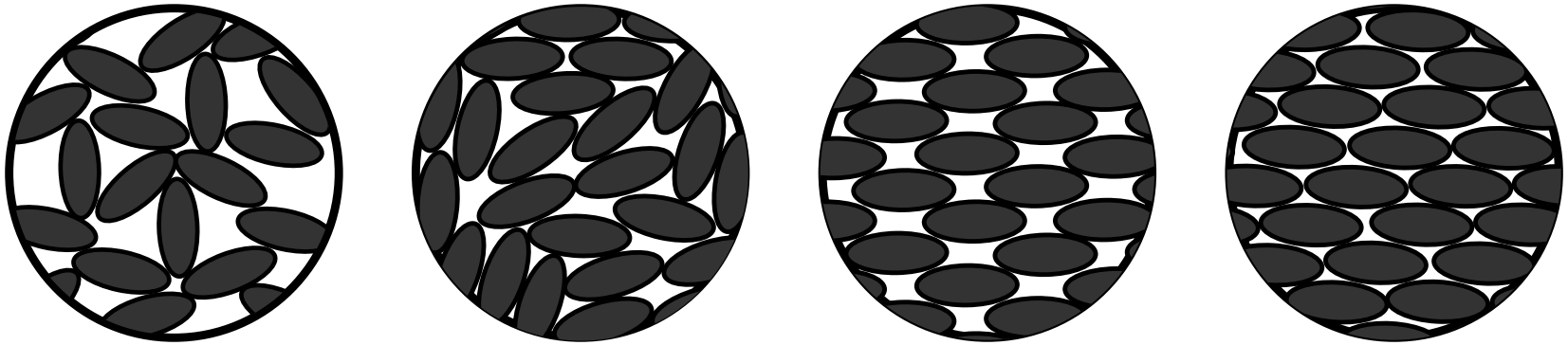

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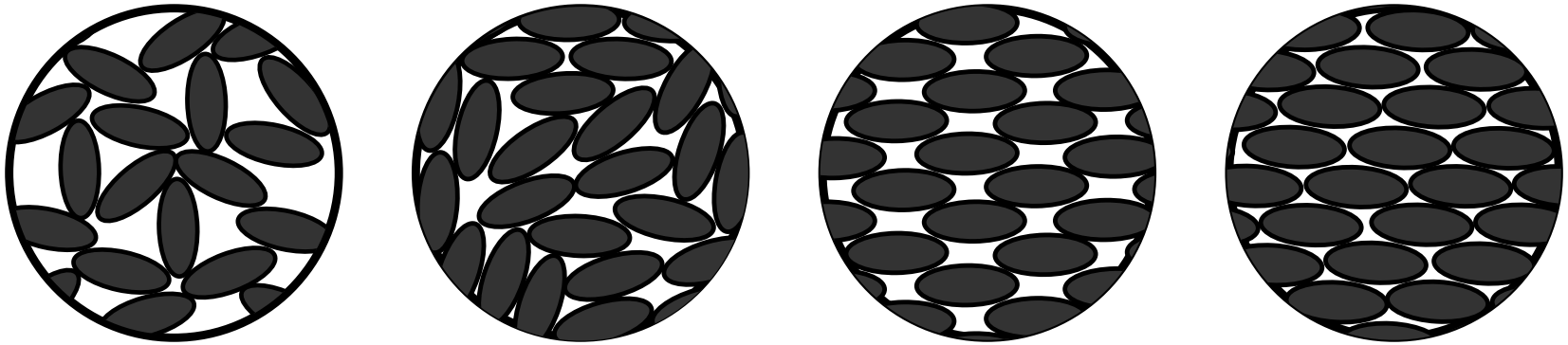

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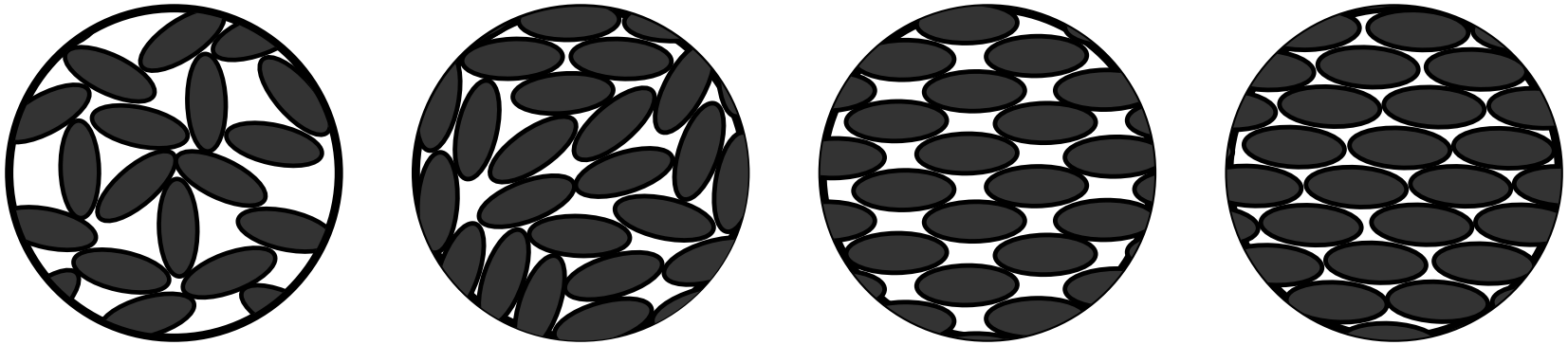

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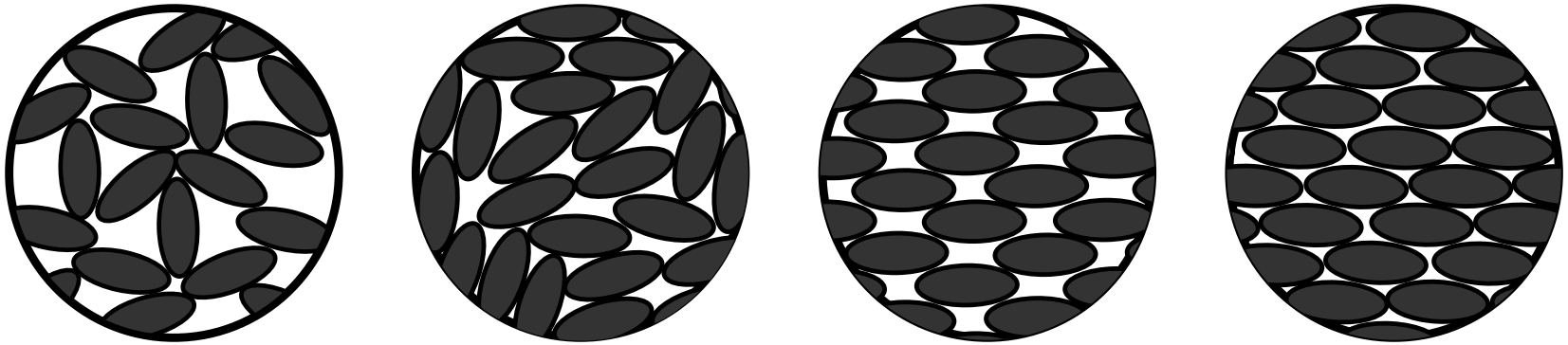

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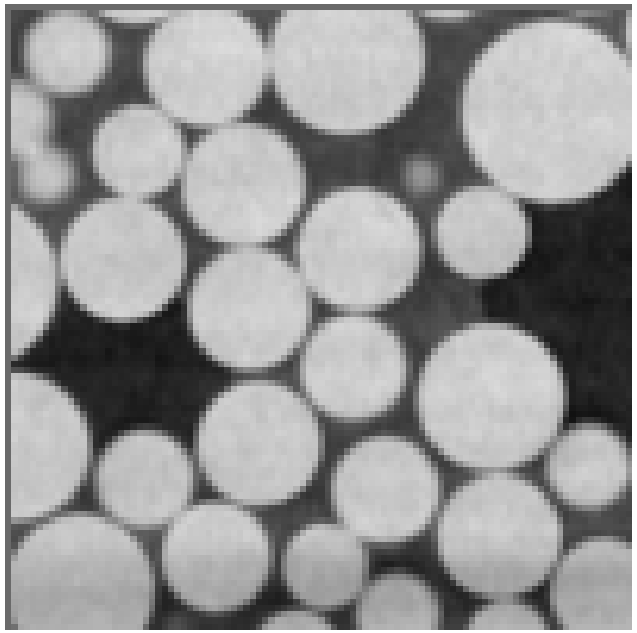

Experiment @ Laboratoire 3SR by M. Milatz

Don't forget the pores:

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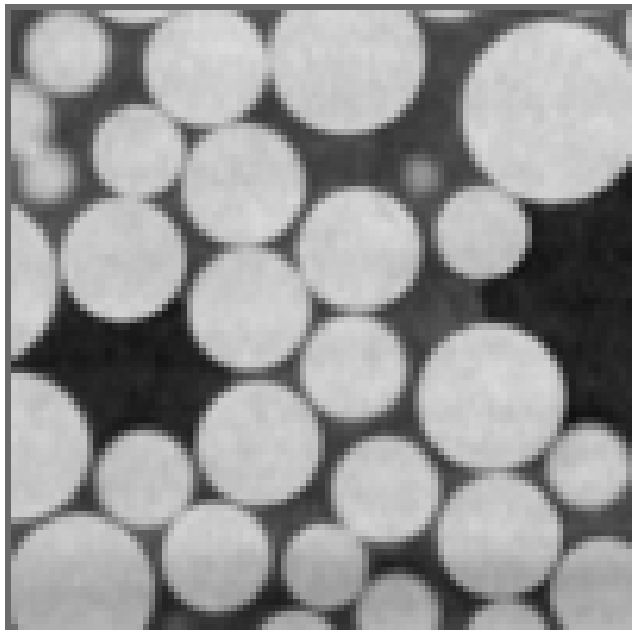

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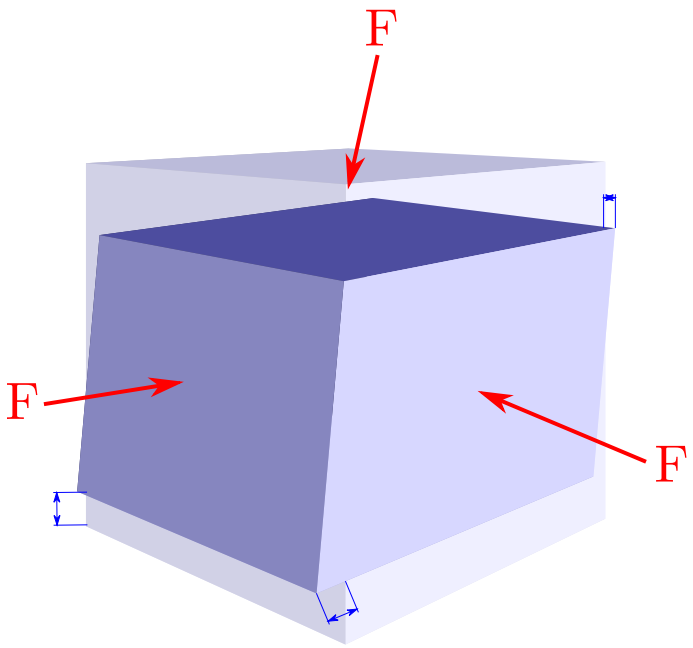
- Degree of saturation (S_r)

At some REV scale...



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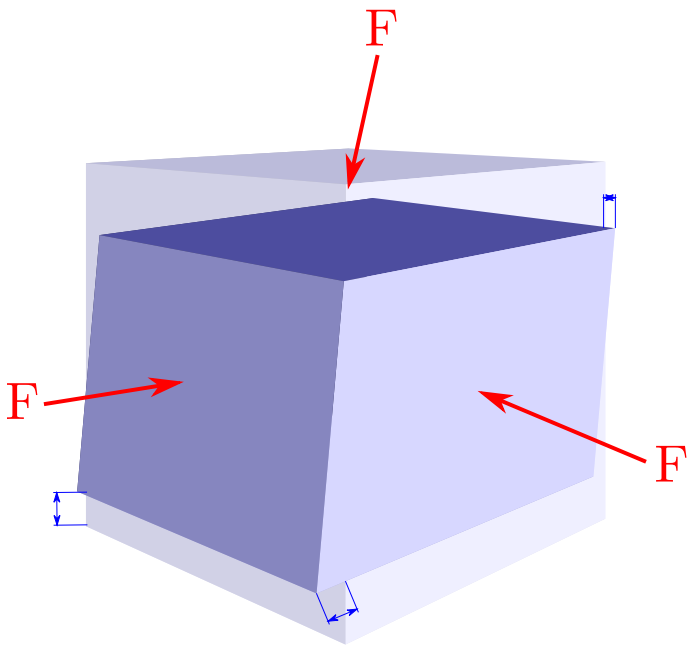

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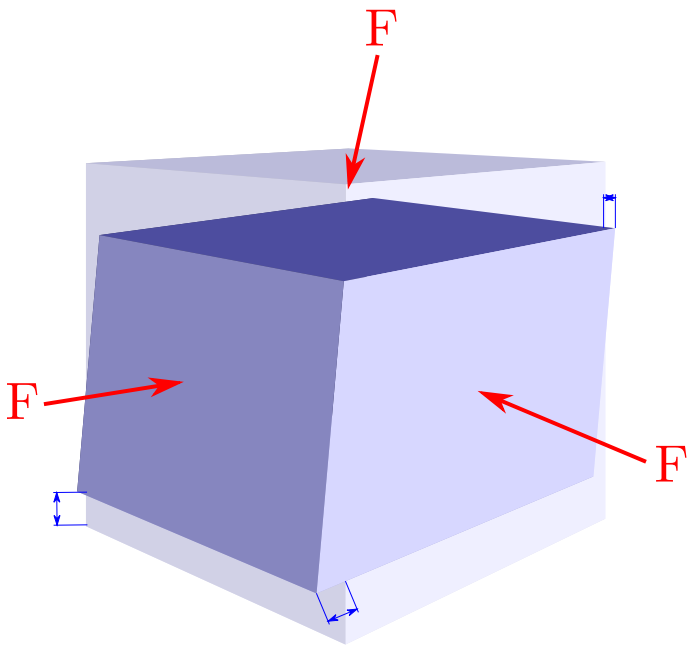

If representative, let's suppose that it's meaningful to define:

- Stresses (σ)
- Strains (ε)
- All assembly variables...?

Which one of these quantities are measurable?

All?

A question of hats

In geomechanics someone can wear three different hats:

The experimenter	The theoretician	The simulator

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Experimentalists are by far the most expensive...

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To be 100% sure about what is reported.

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Evaluating of uncertainty is key (otherwise how do we know what comes from heterogeneity?)... but first let's be practical a bit

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Let's measure a displacement...

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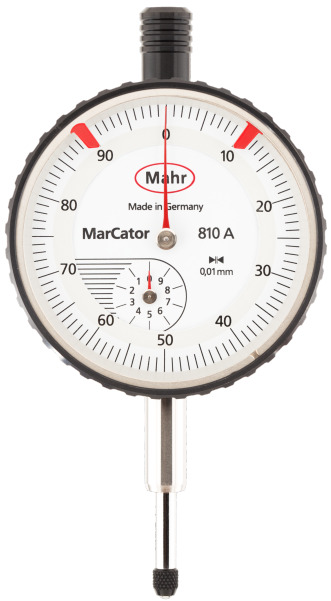
Example measurements of displacements

(mechanical) dial indicator	(electronic) LVDT
	

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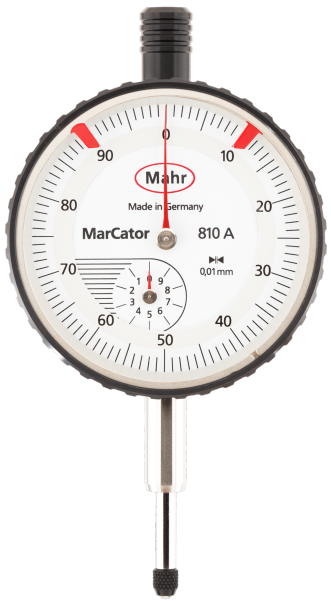	

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What could go wrong on the left?

Let's place the LVDT in context

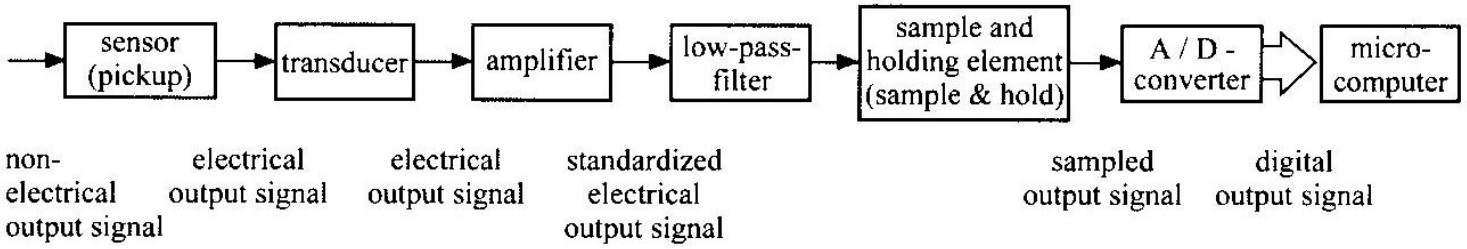

Figure 9.2. Measuring system

From Mechatronic Systems: Fundamentals

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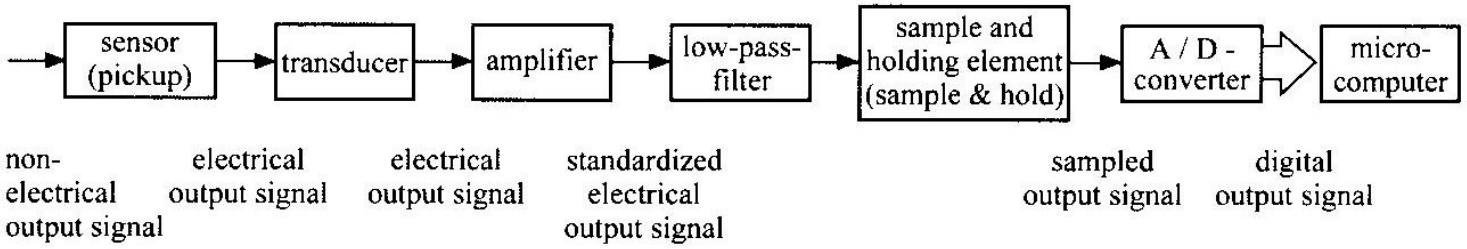

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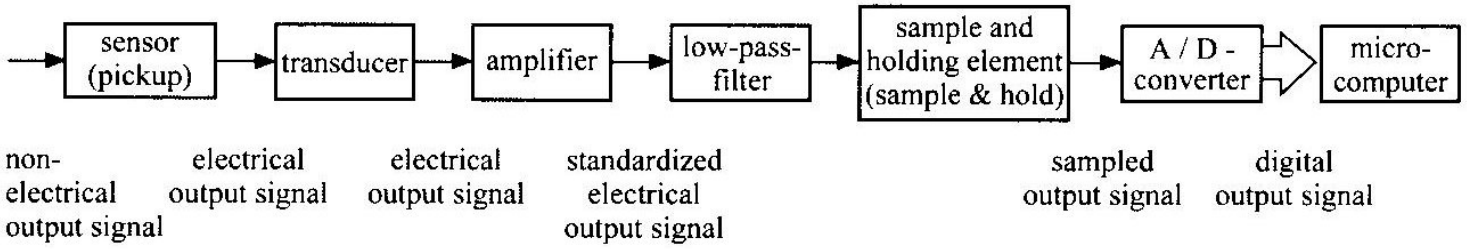

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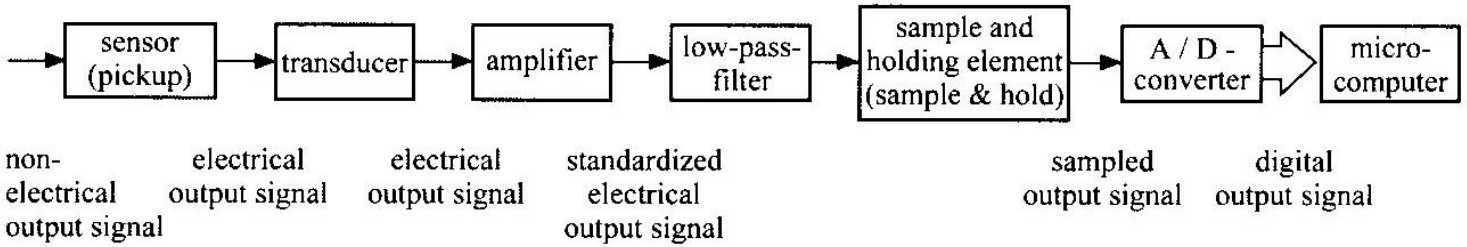

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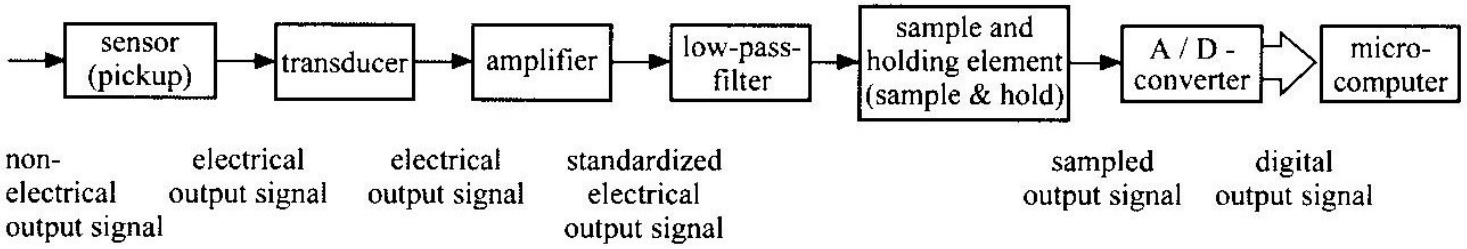

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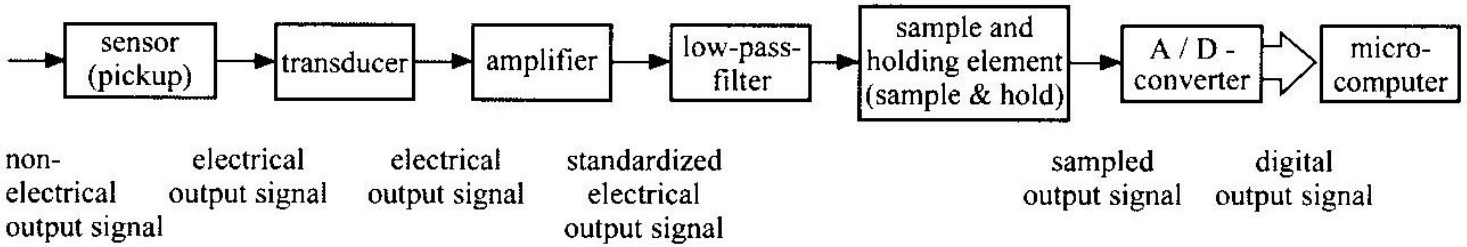

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- Discretisation into digital signal

DMW: Constant level of crudeness

Calibration

Dear future self, it's the middle of the night, but don't forget to tell students about Dynamic range and calibration (why do you need different LVDTs or load cells)?

How does a force meter work?

Any guesses?

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Gaussian noise is often a good initial model (but needs to be checked).

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- Electornic measurement systems have a million ways to be wrong, understand and characterise them!
- This means making a model of the system and the noise
- Buying an expensive system does not make a good experimenter (Beware the black box)

Usual quasistatic experimentation

You know these better than me...

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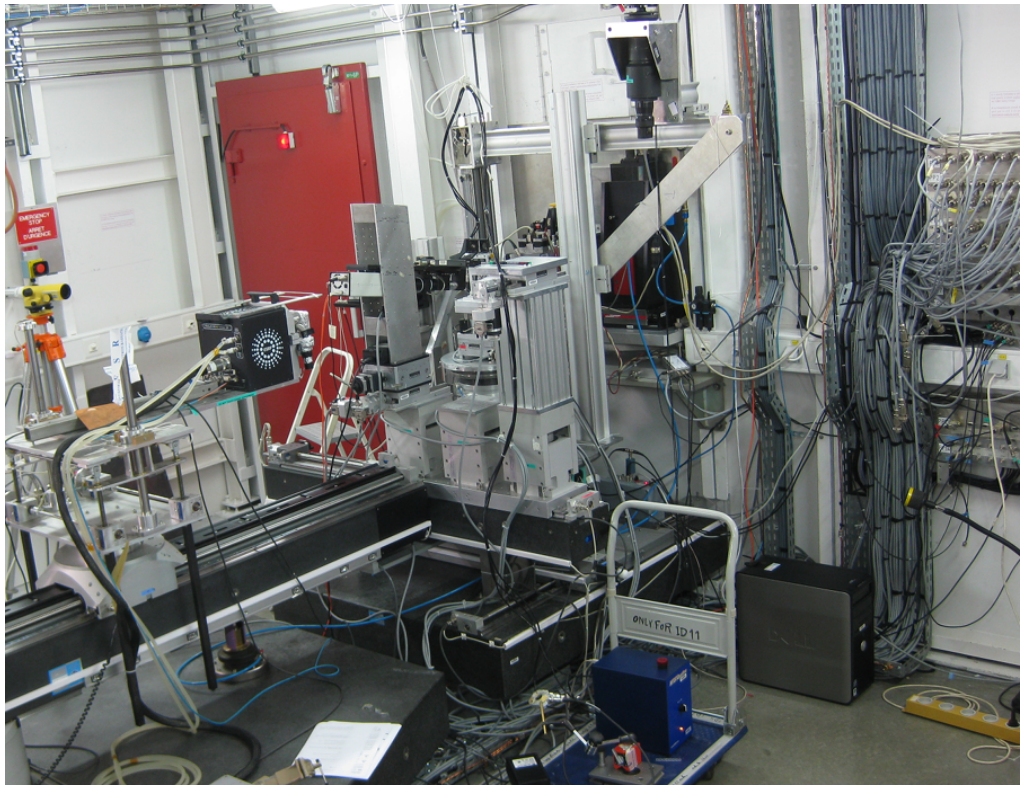
We don't have direct access to the grains, and so we're a bit stuck...

From displacement measurements...

To this...



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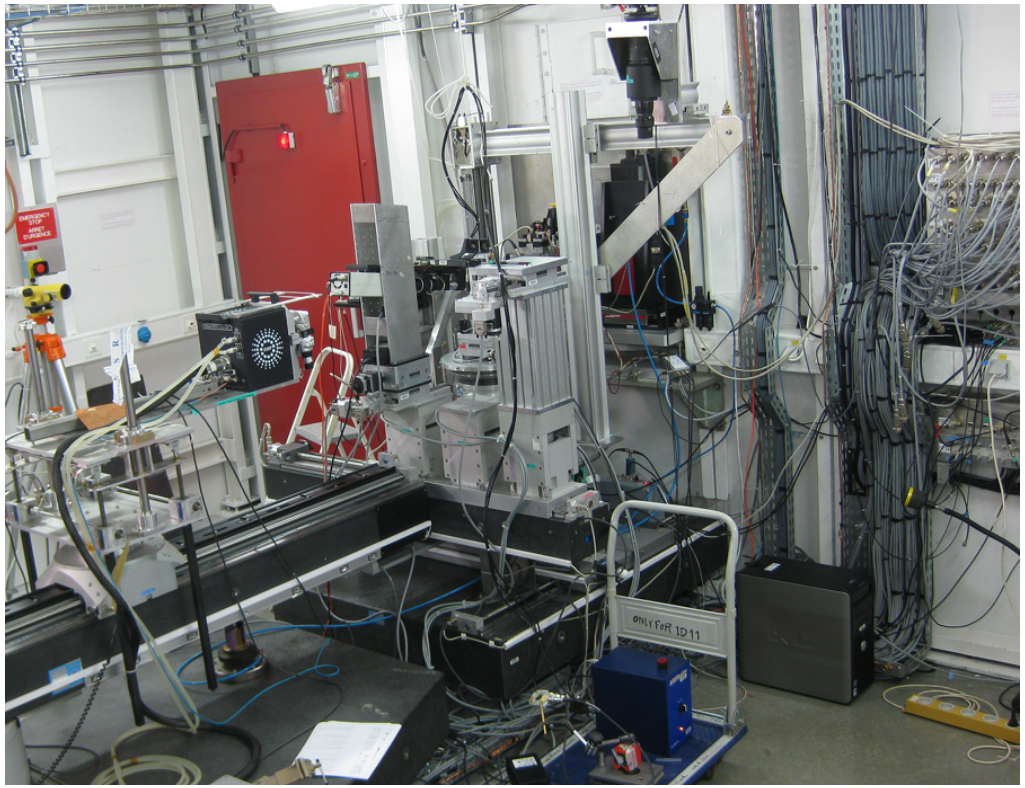

Why?? (And what is that thing?)

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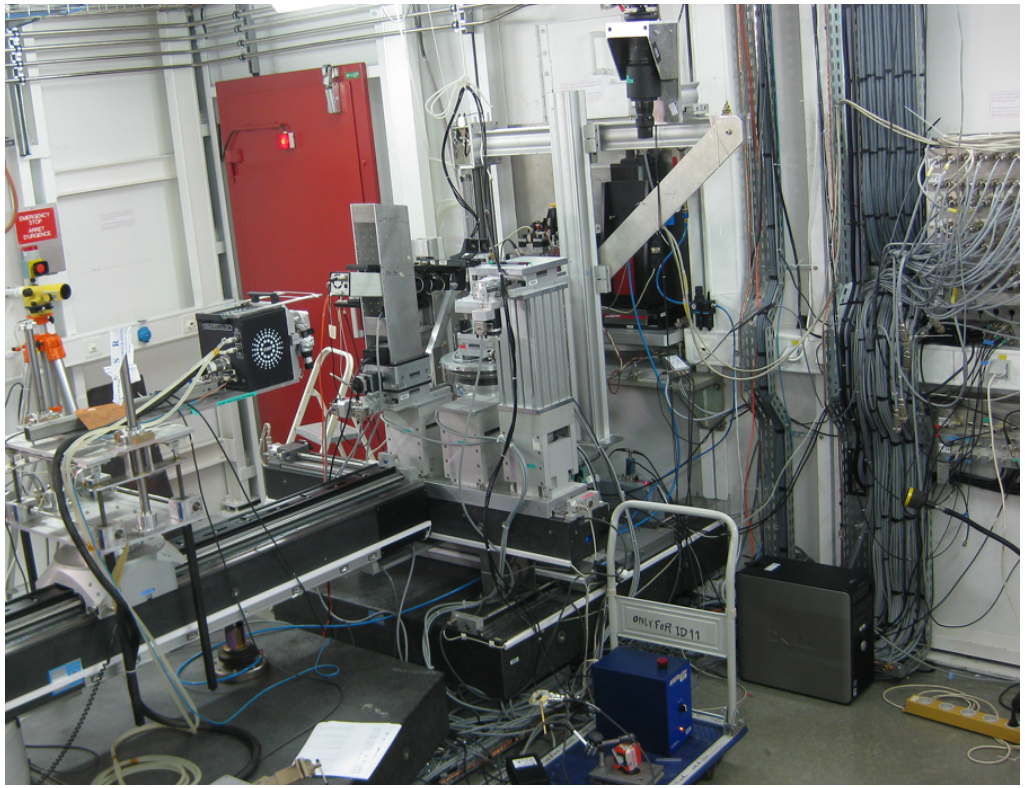

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Let's **look** at things.

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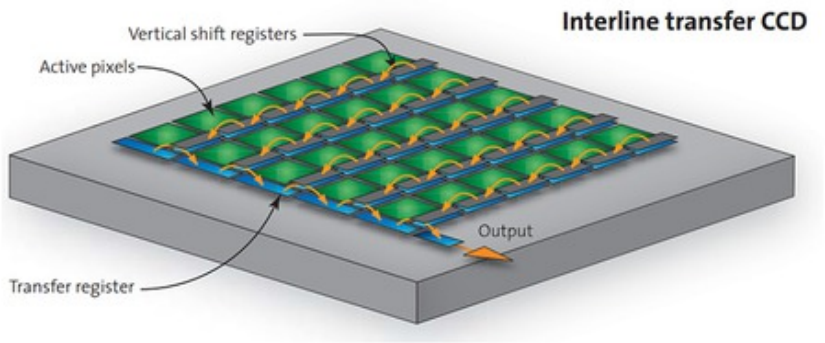

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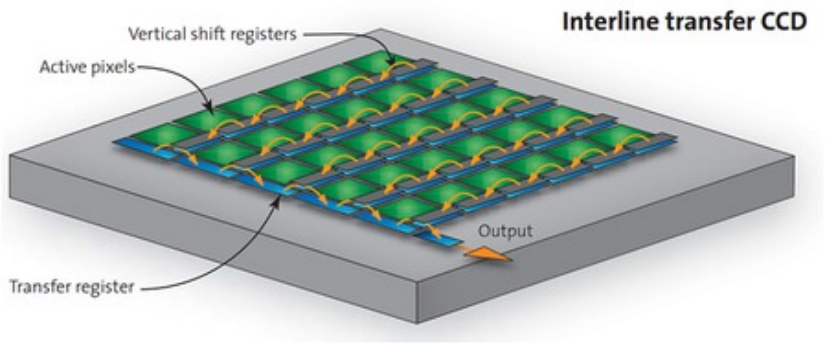

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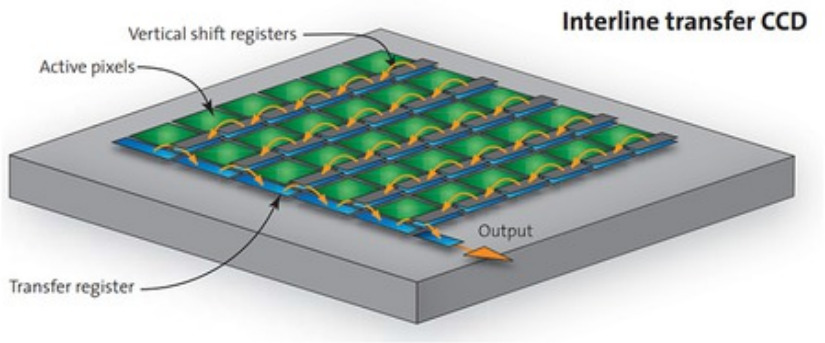

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Poisson noise (or "shot noise") can arise, which needs to be handled separately.

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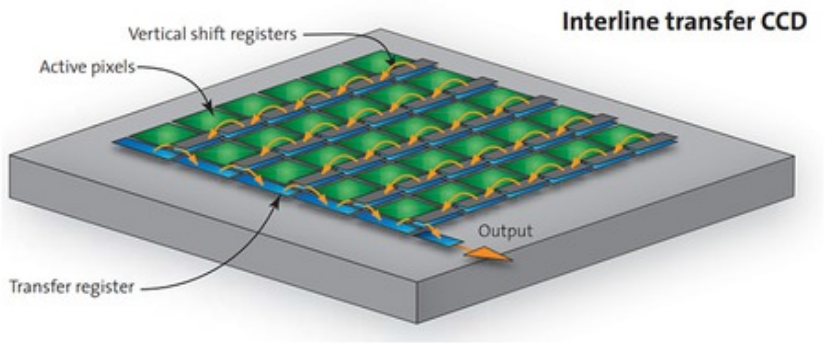


Imagine noisy photographs (high ISO) or trying to see in the dark.

Poisson noise (or "shot noise") can arise, which needs to be handled separately.

There can also be other noise from the readout electronic (as per LVDT)

Spot the difference

A

B

Spot the difference

A

B

Spot the difference

A

B

What is the difference between these two images?

Spot the difference

A

B

What is the difference between these two images? noise?

Spot the difference

A

B

What is the difference between these two images? noise?

Not exactly, there is some *blur*.

Spot the difference

A

B

What is the difference between these two images? noise?

Not exactly, there is some *blur*. Convolution with a kernel.

Spot the difference

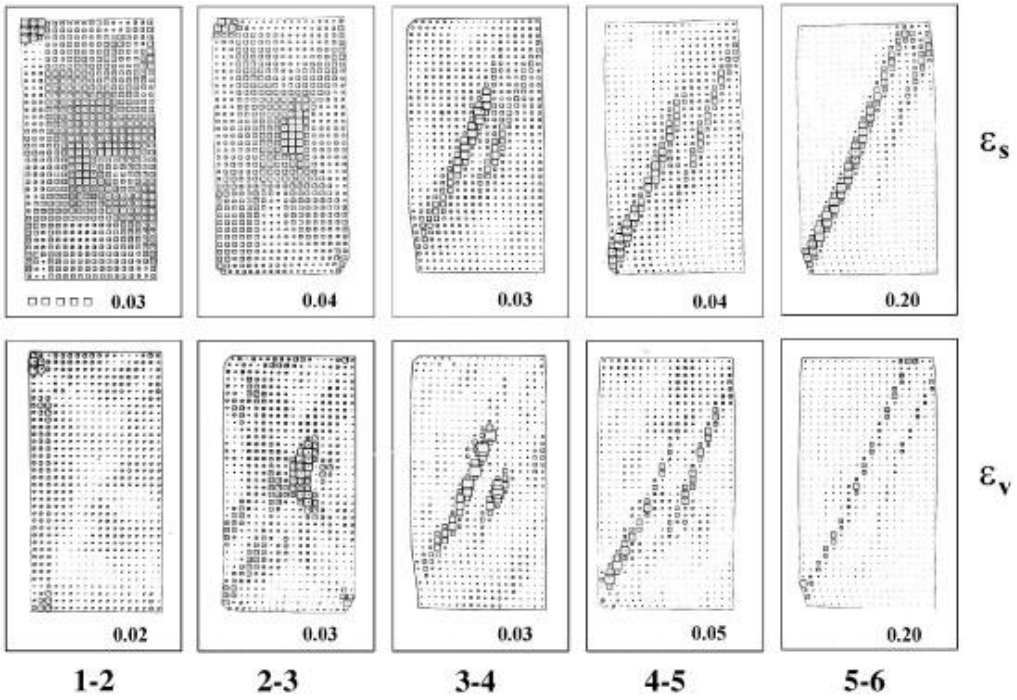
A

B

What is the difference between these two images? noise?

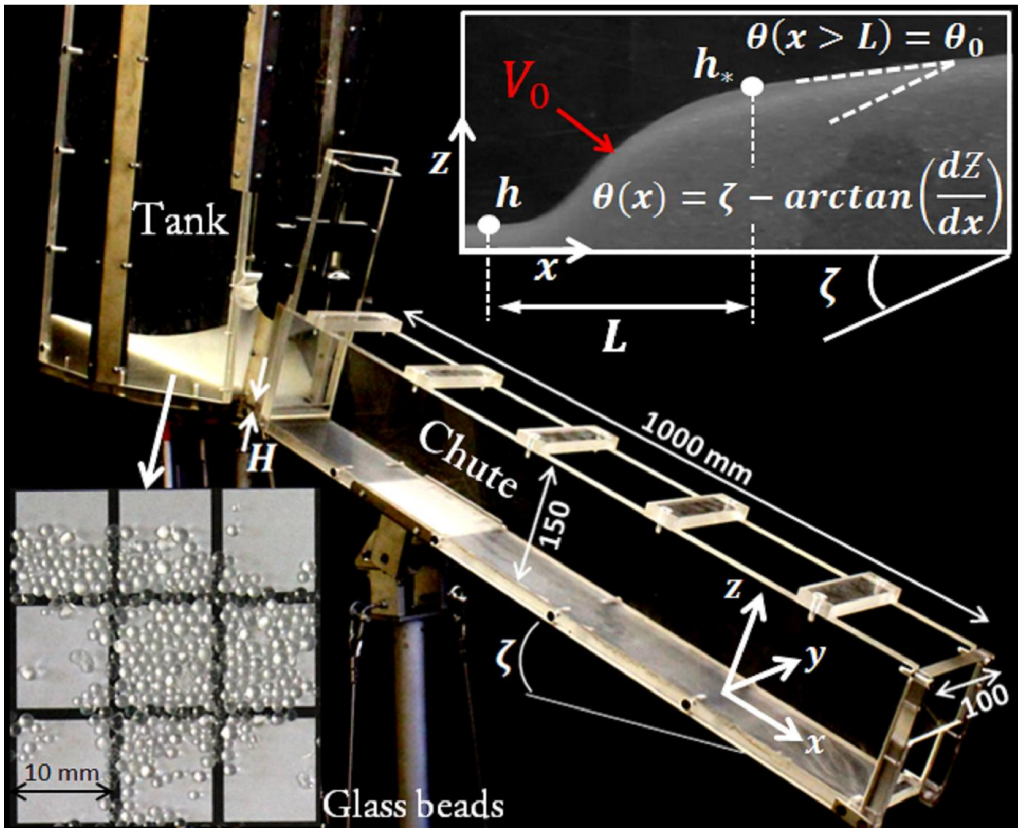
Not exactly, there is some *blur*. Convolution with a kernel. Local correlation (function) between values

Going fast



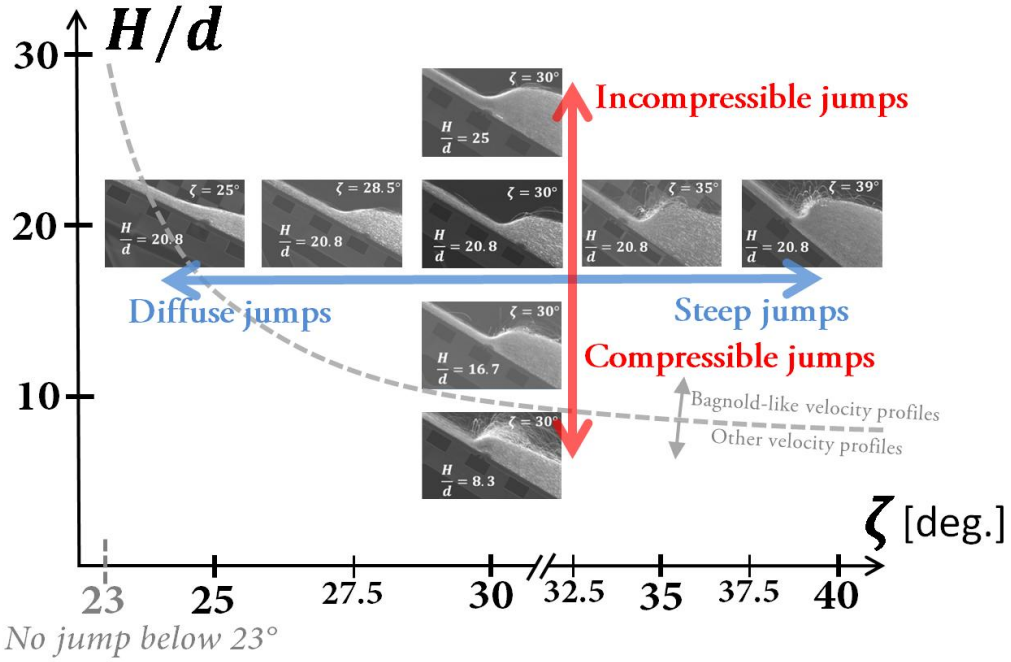
Desrues *et al.*, 2004

Going fast



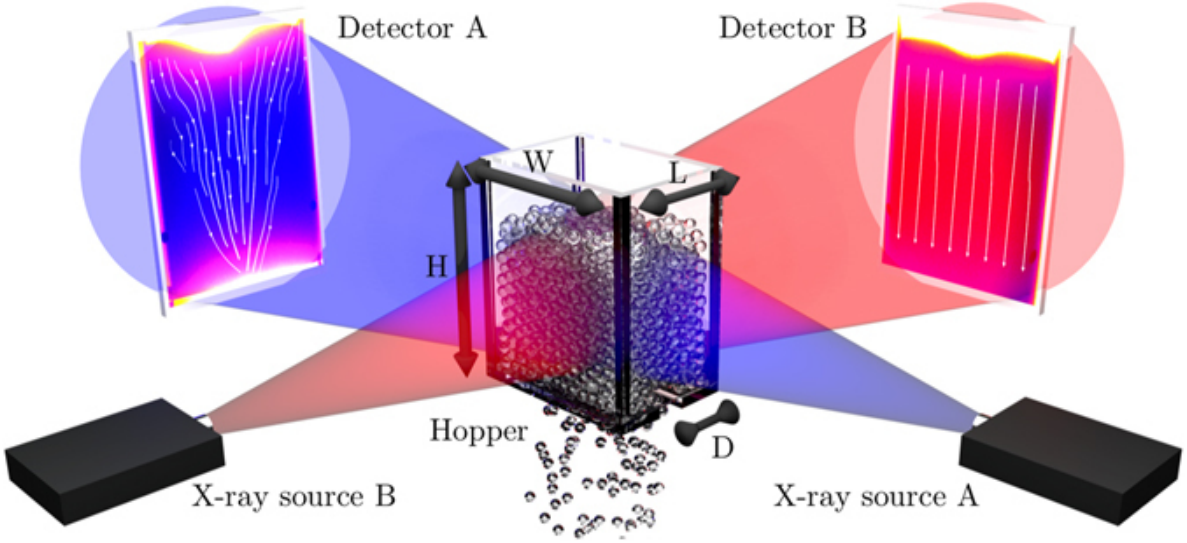
Faug *et al.*, 2015

Going fast



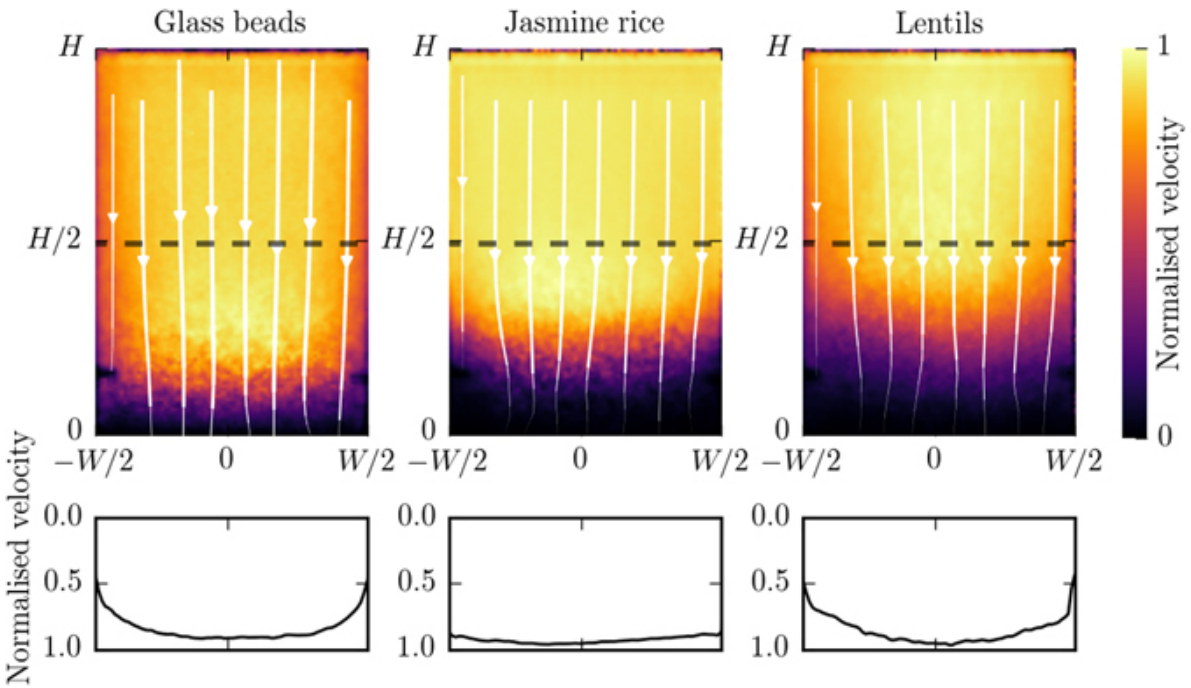
Faug *et al.*, 2015

Going fast and looking inside



Guillard *et al.* 2017

Going fast and looking inside



Guillard *et al.* 2017

Looking further inside - x-ray tomography

X-ray tomography is a 3D (*i.e.*, volumetric) measurement technique.

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Let's start with a physical model for x-ray interaction with matter. X-rays are penetrating radiation and are absorpbed by an object as follows:

$$I = I_0 e^{-\mu\rho x} \qquad \text{Beer-Lambert law} \tag{1}$$

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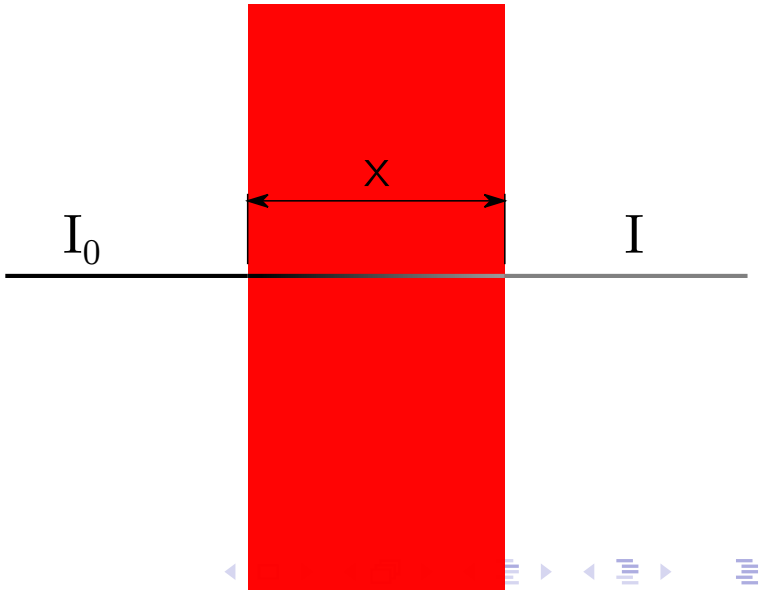
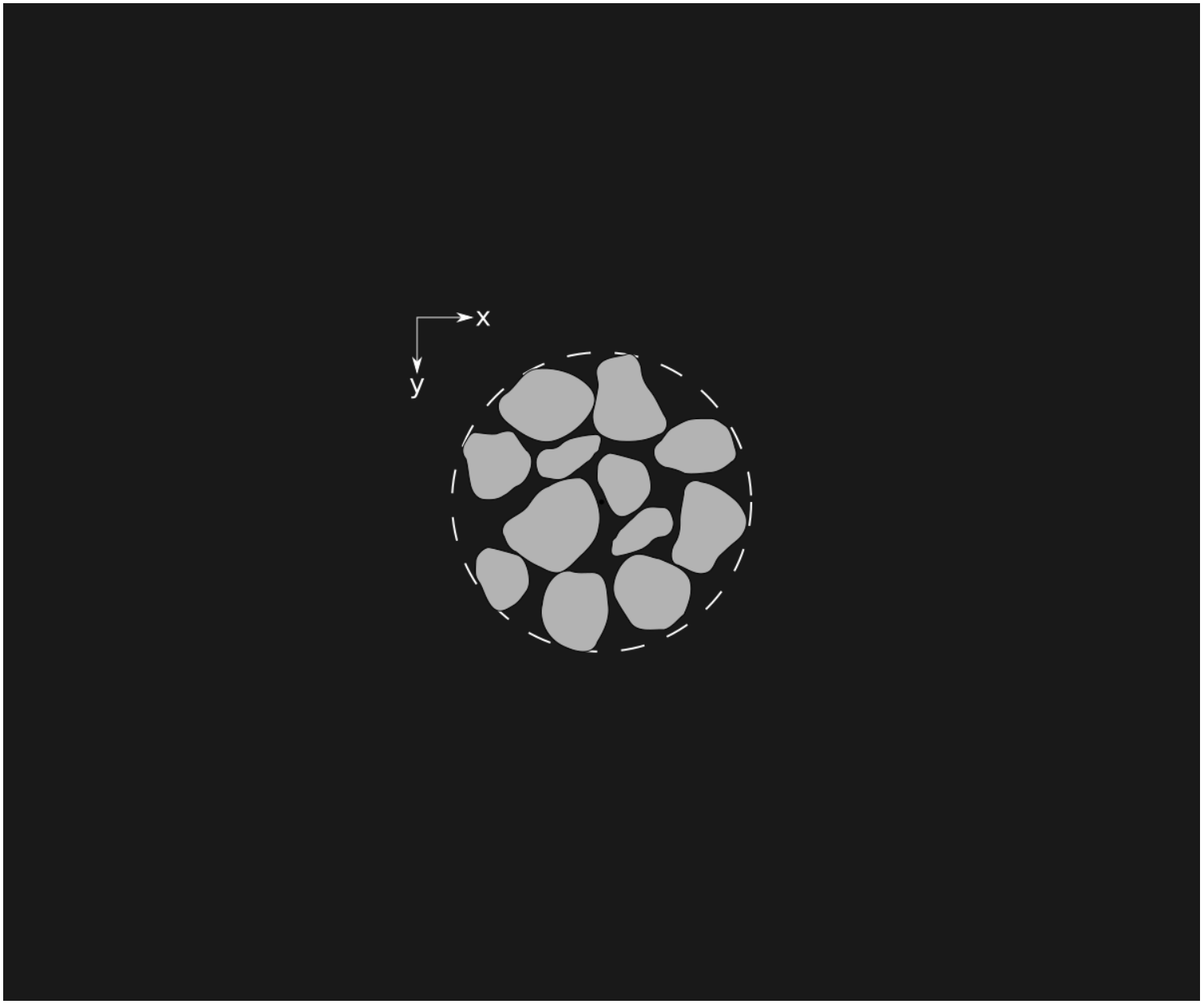
Where:

- I and I_0 are x-ray photon fluxes in ph/s
- μ is the attenuation coefficient of the object ($\approx \rho$)
- ρ is the density of the object
- x is the path length of the beam in the object

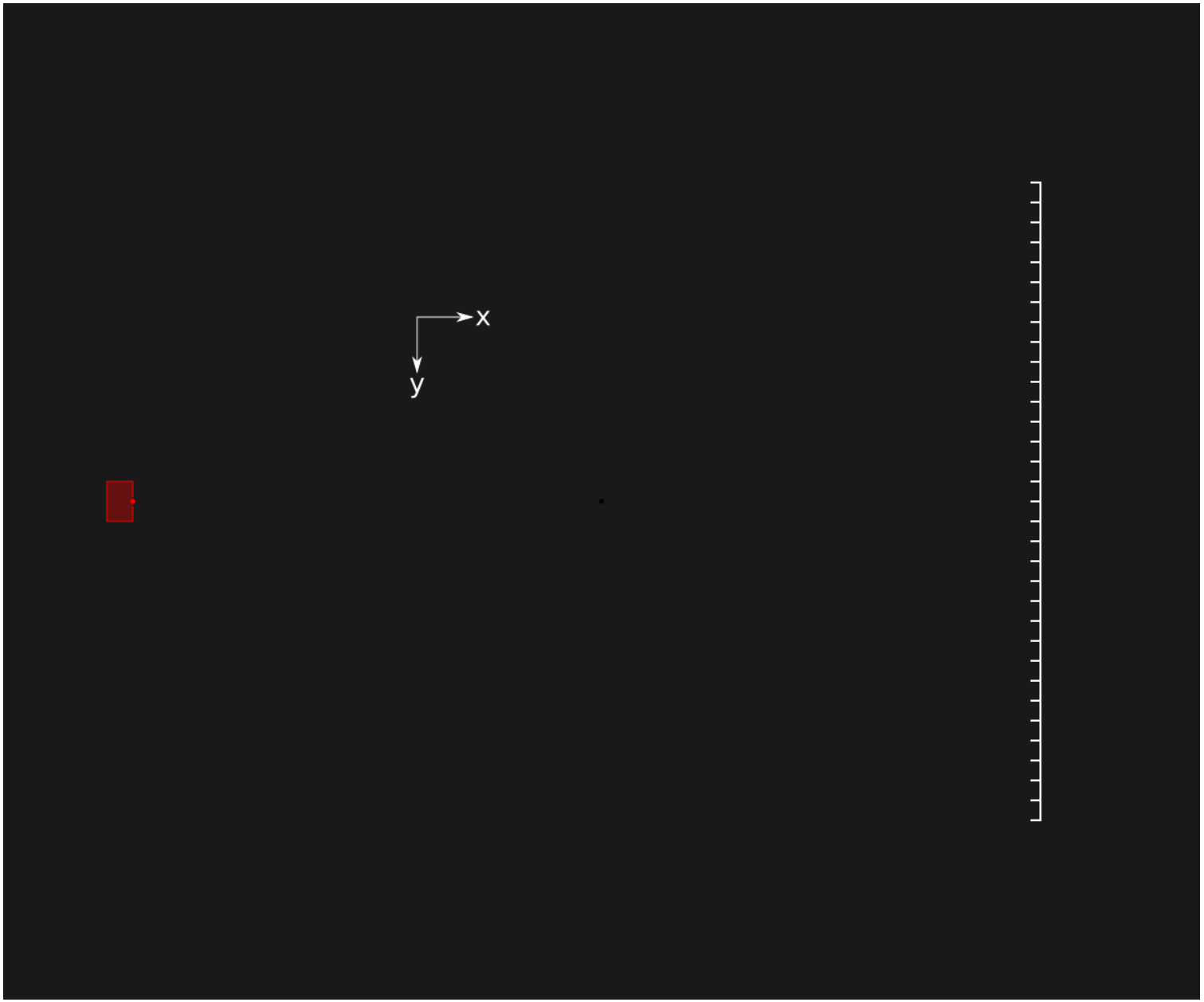


This is all that's used in regular x-ray tomography – let's put it to use!

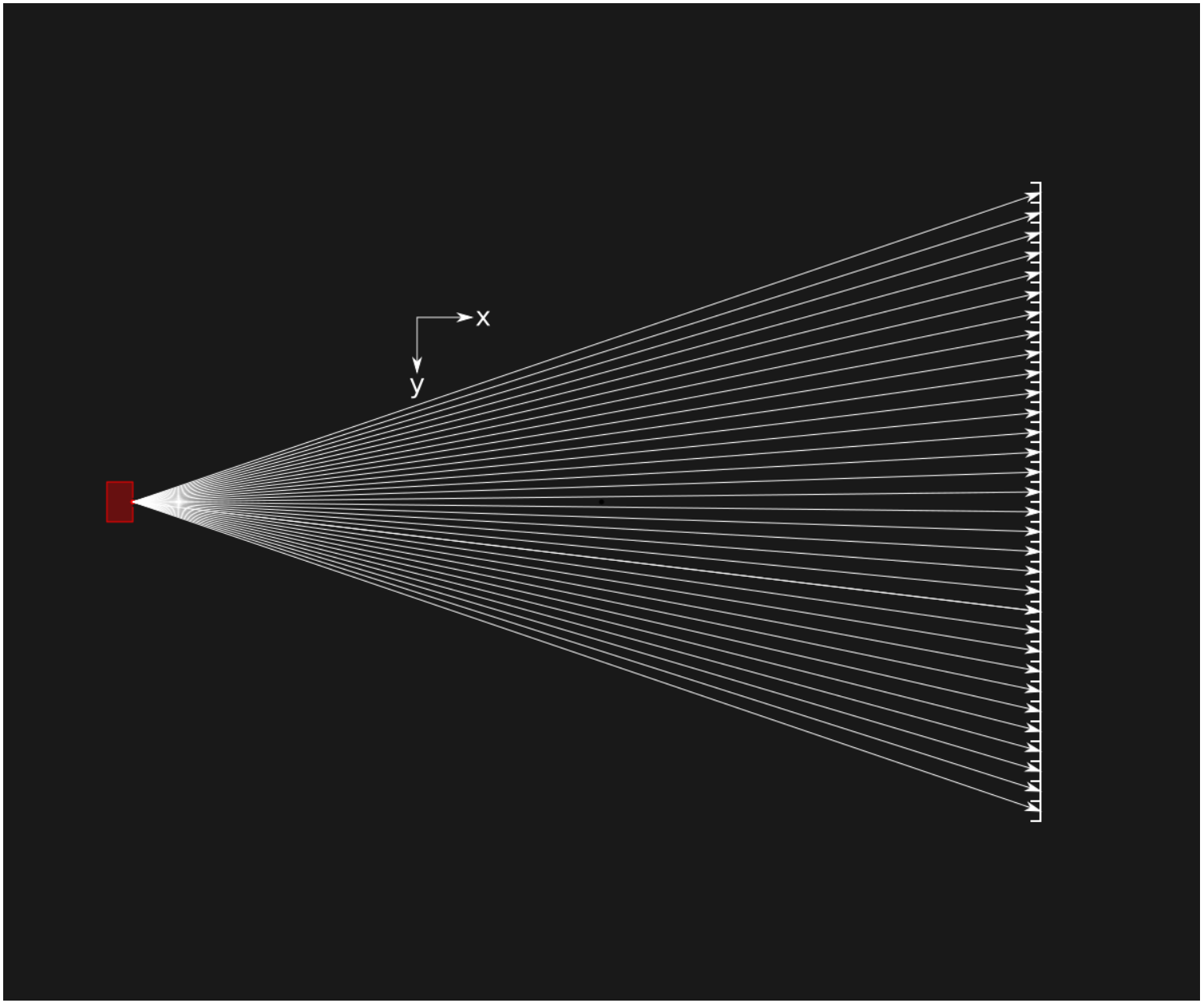
The field we want to measure – $\mu(x, y)$



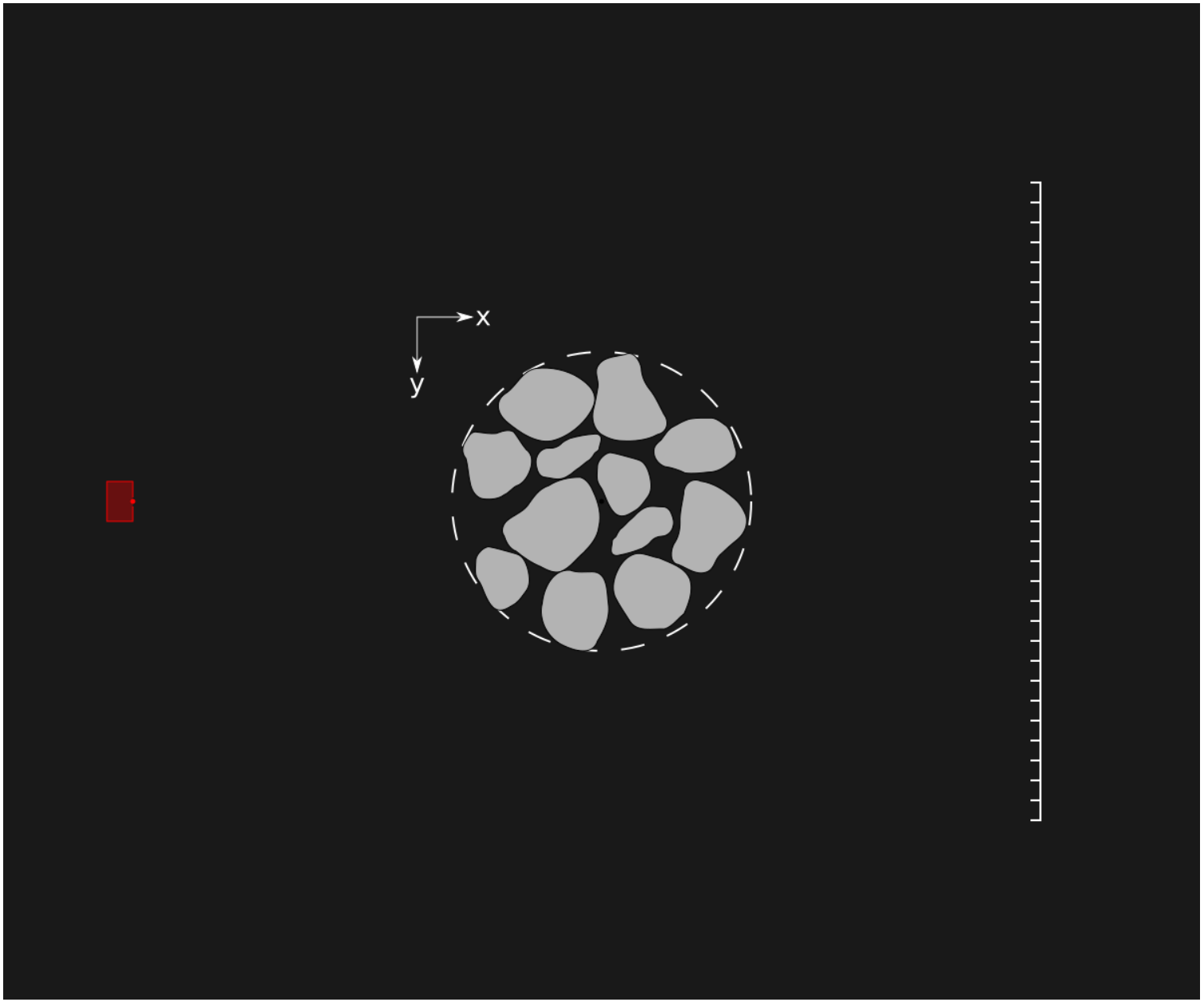
Source and detector system



Measure I_0



Let's measure the sample



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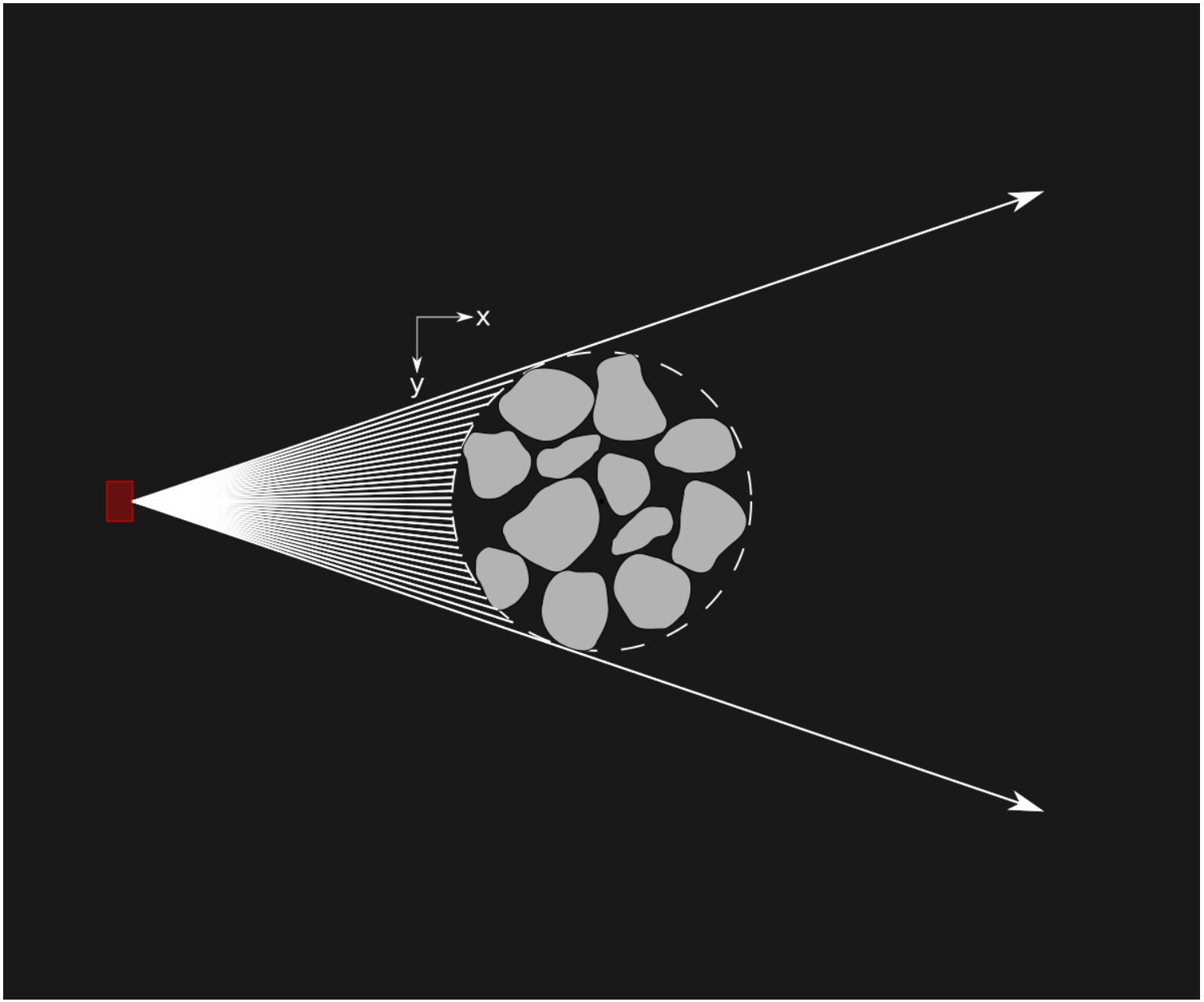
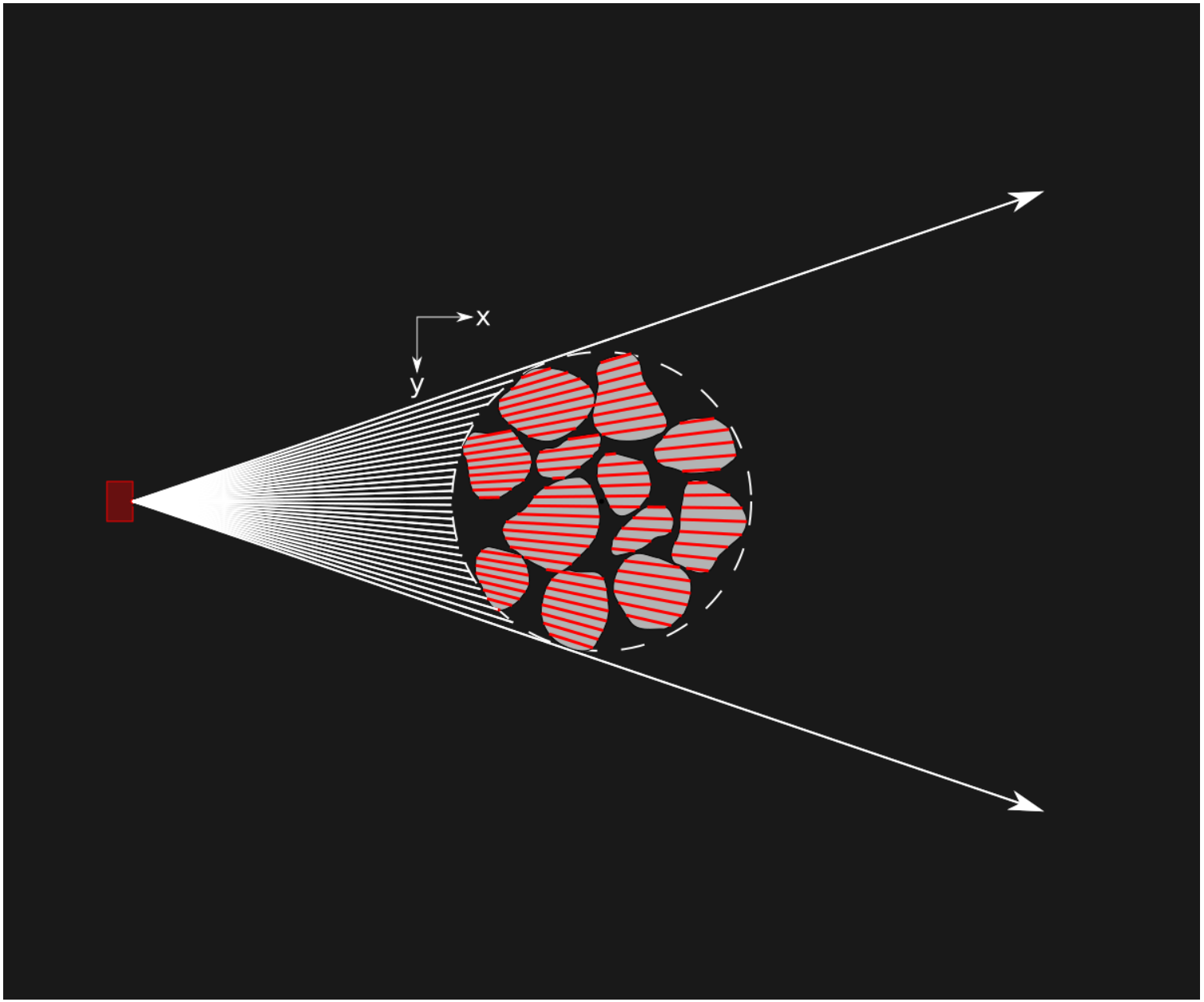
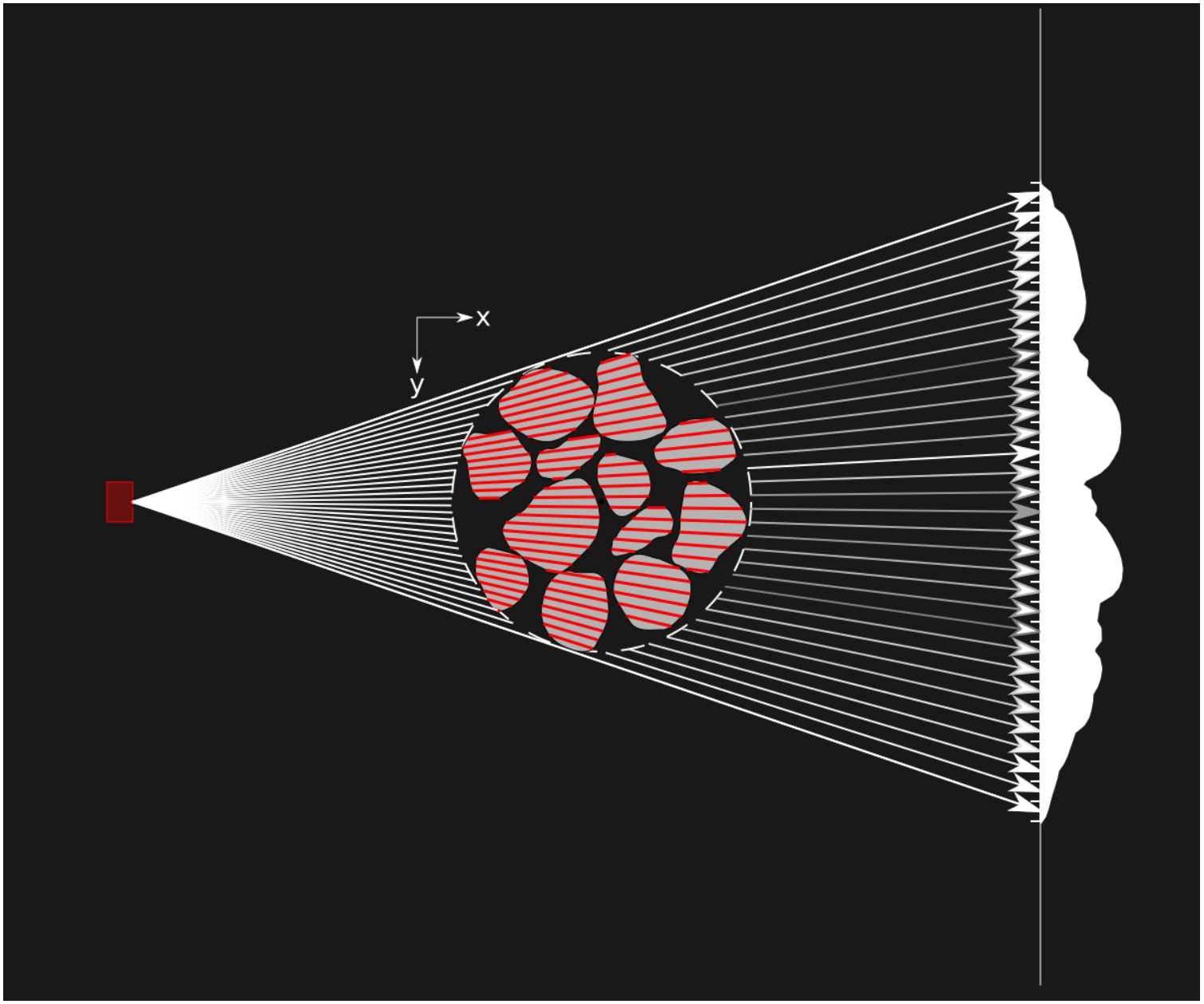


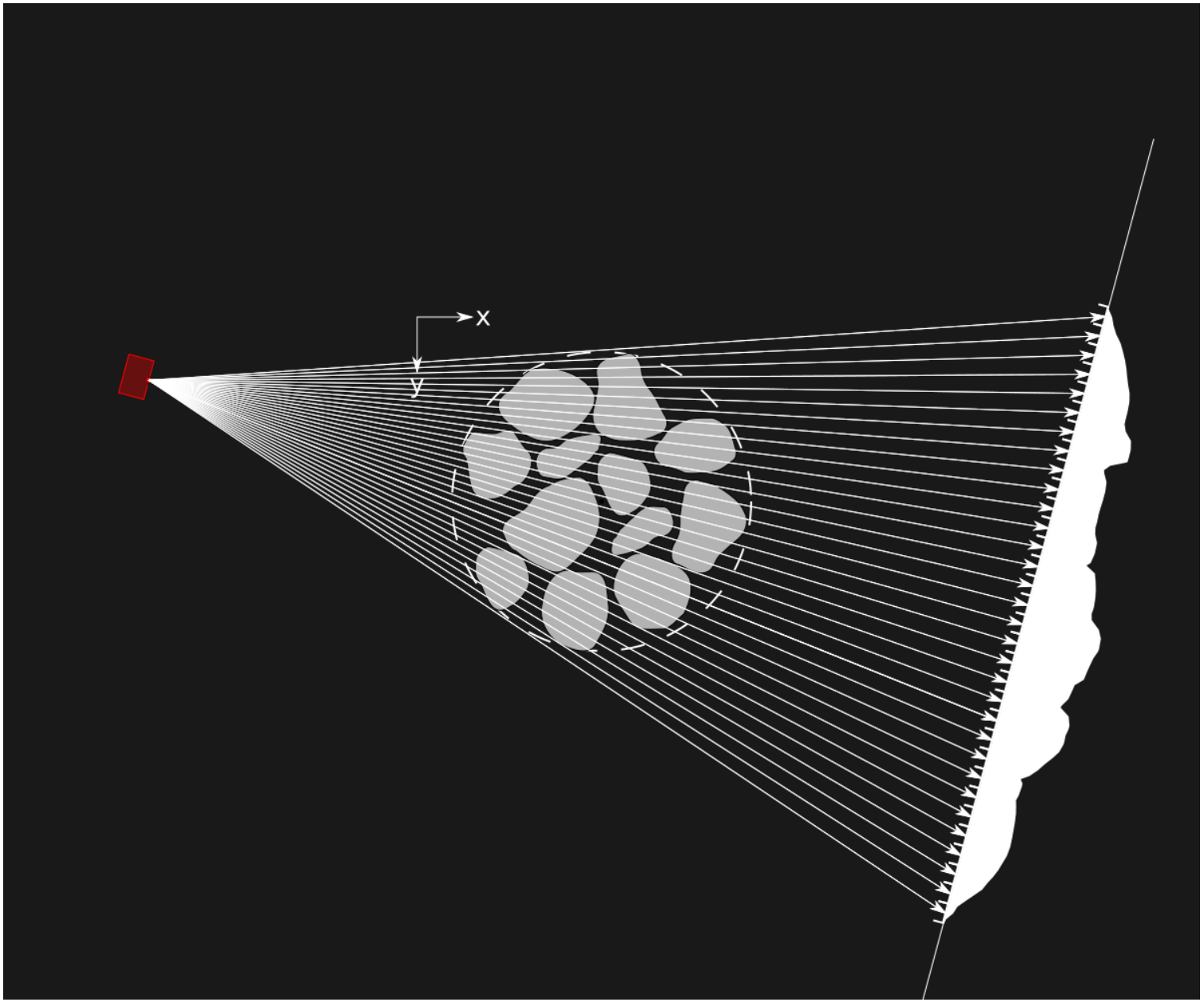
Let's measure the sample – x



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



Project in another direction...



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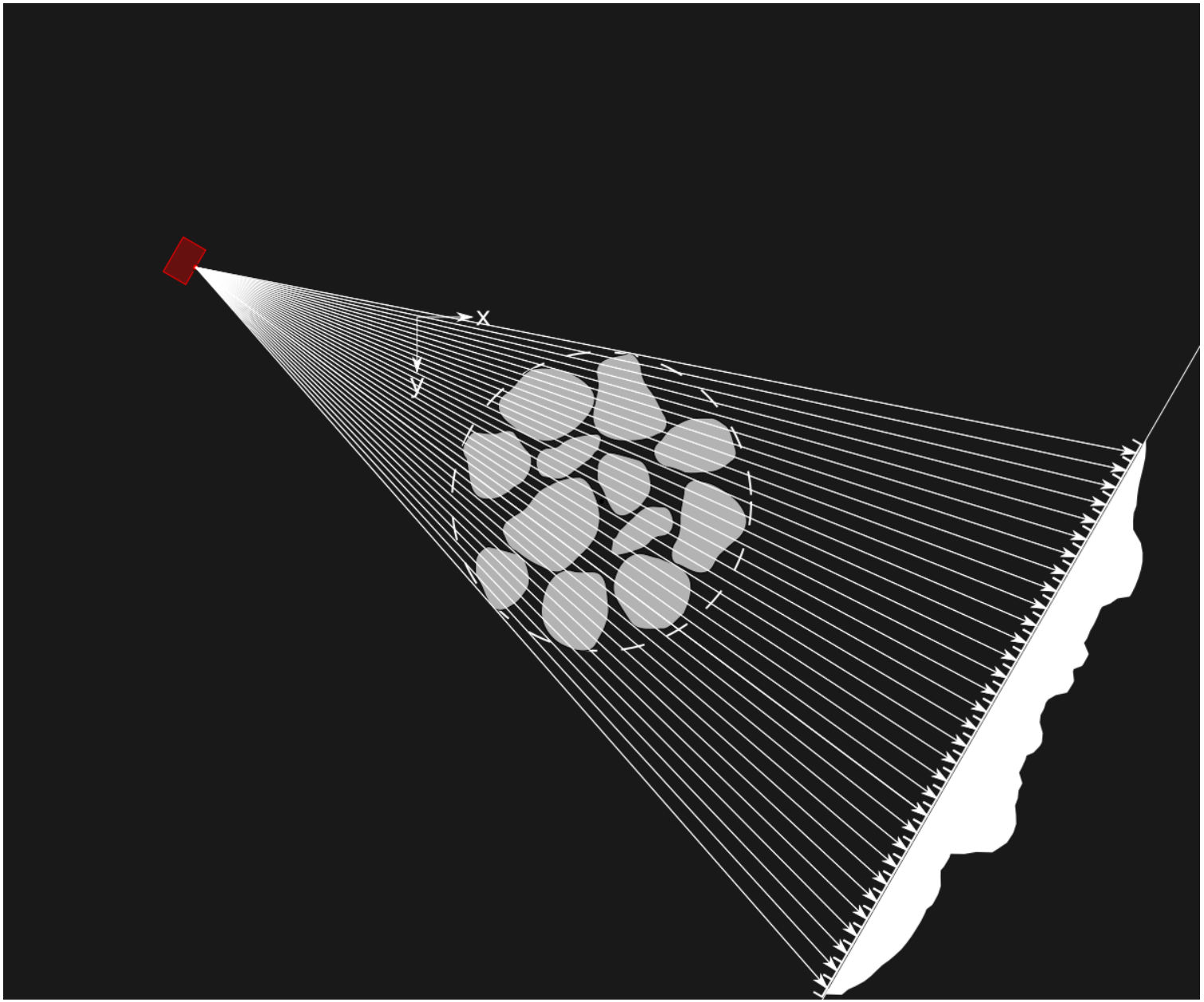

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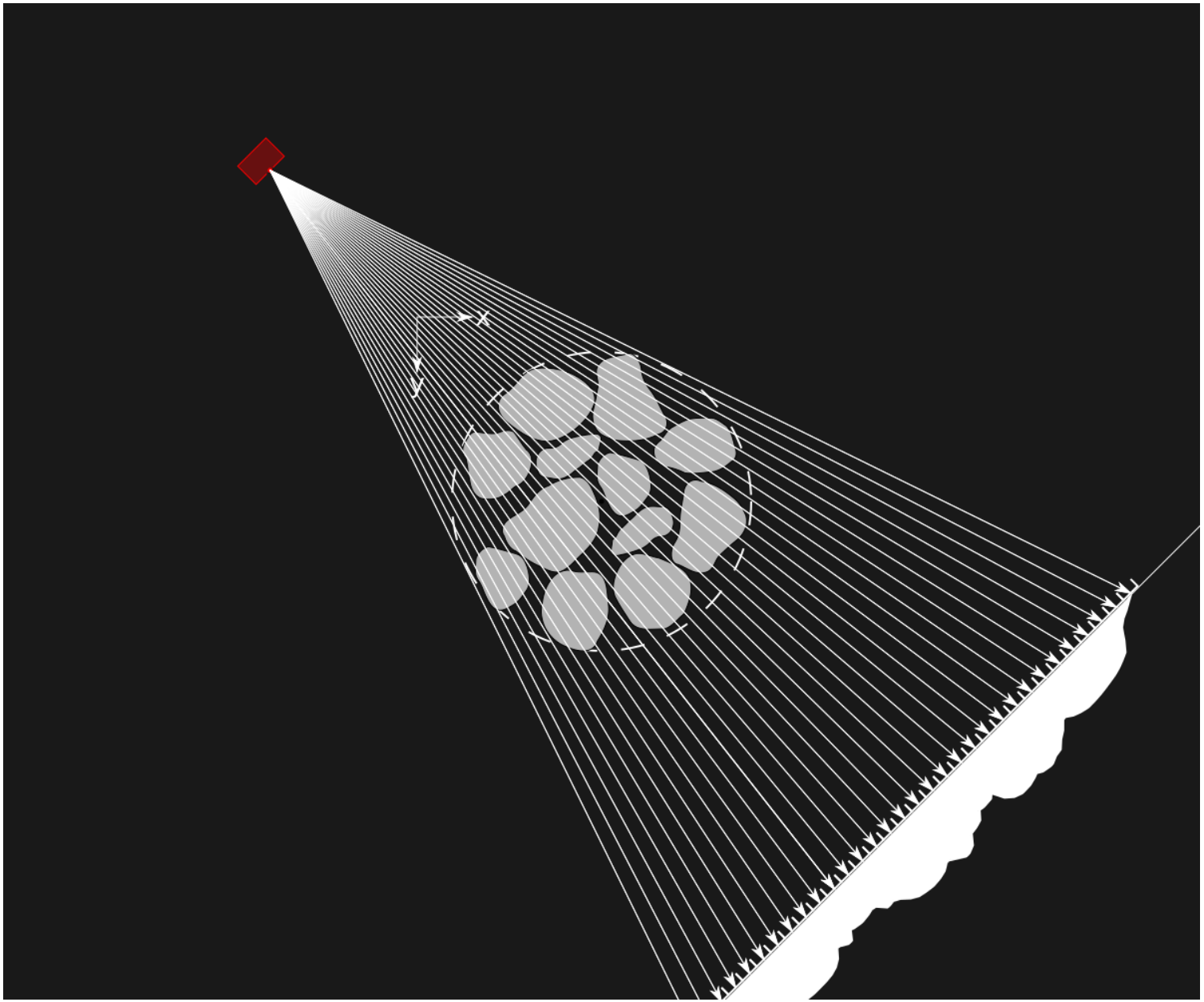

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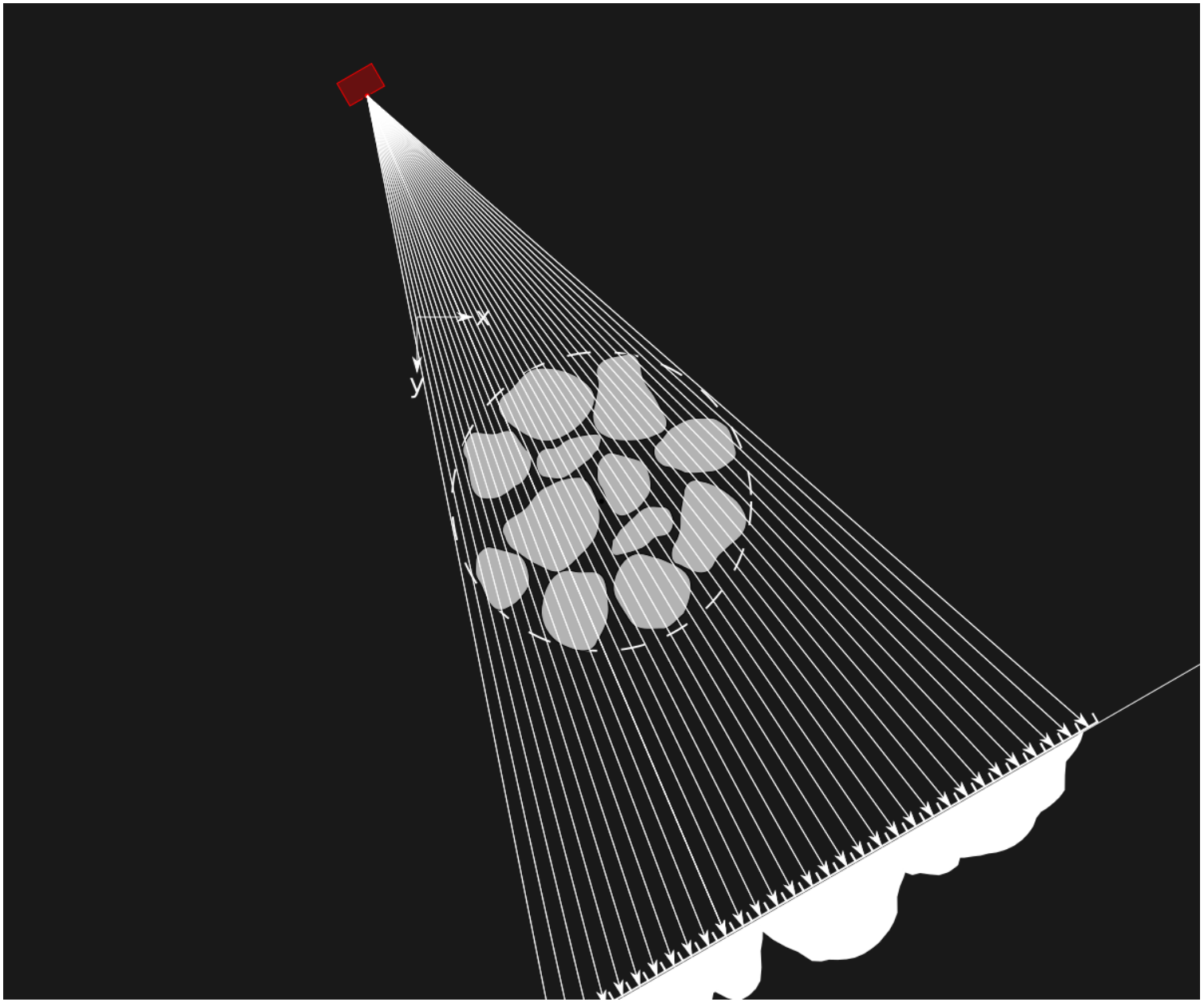

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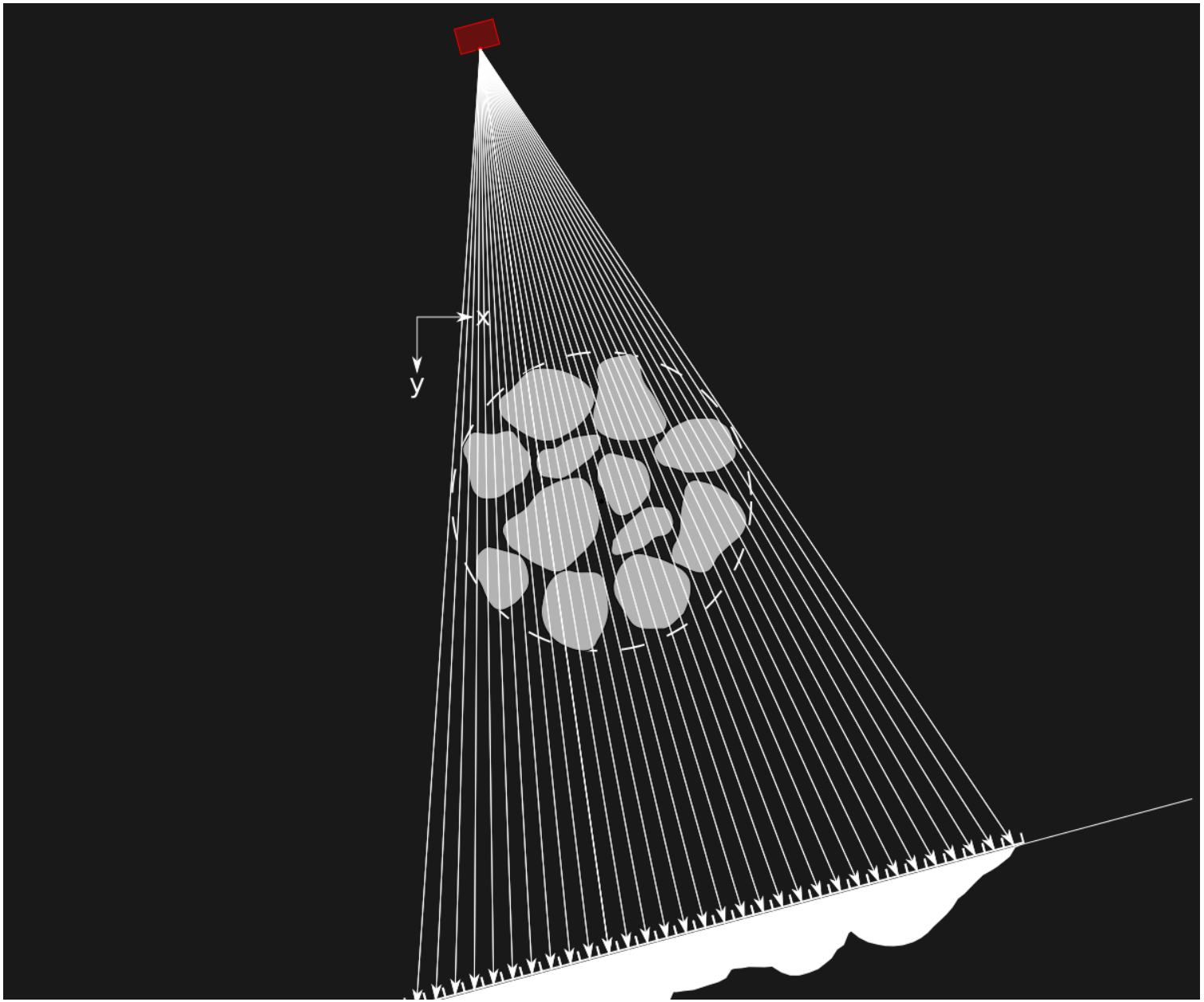
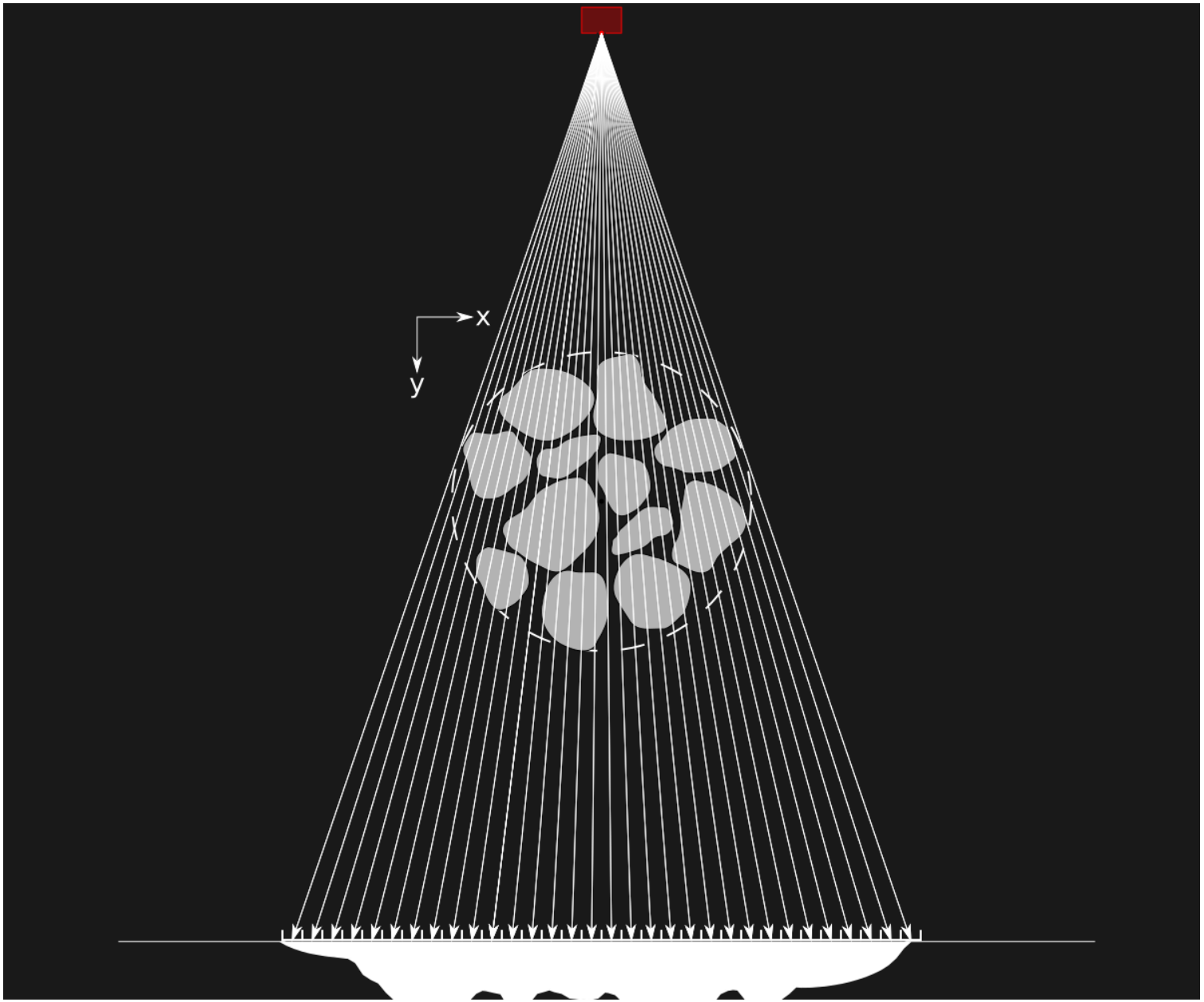


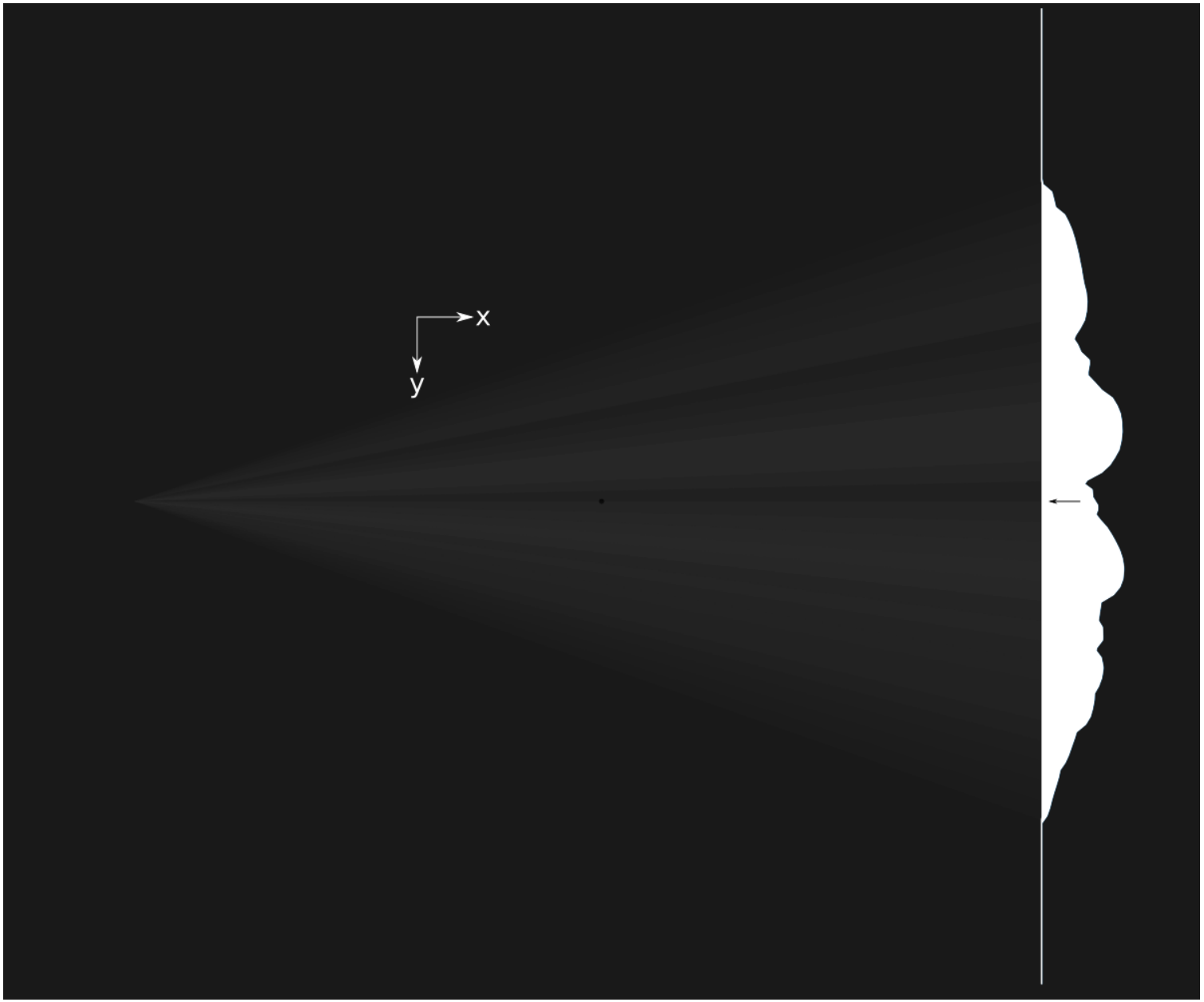
Project in another direction...



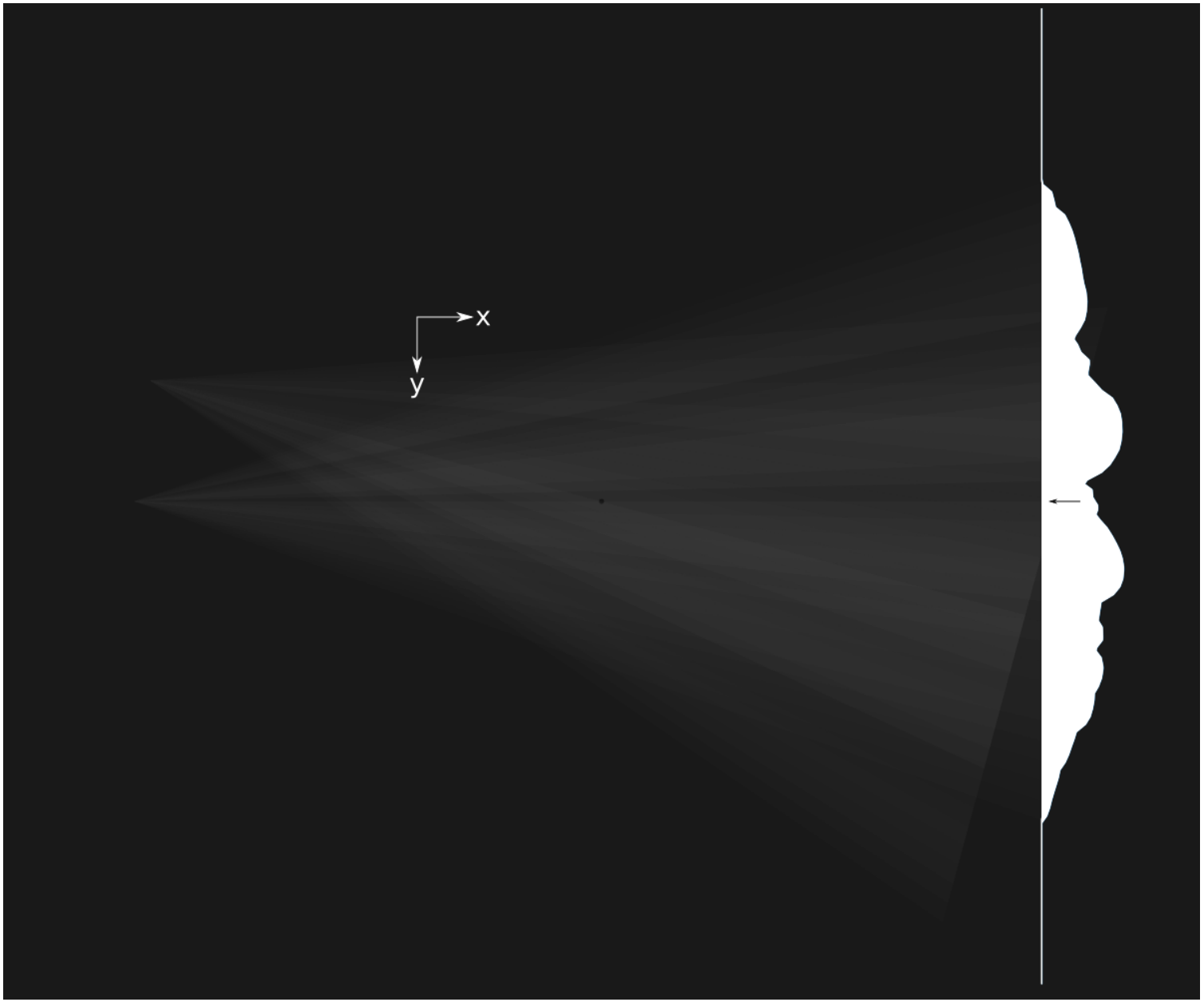
We have collected a load of projections of $\mu(x, y)$ as I

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

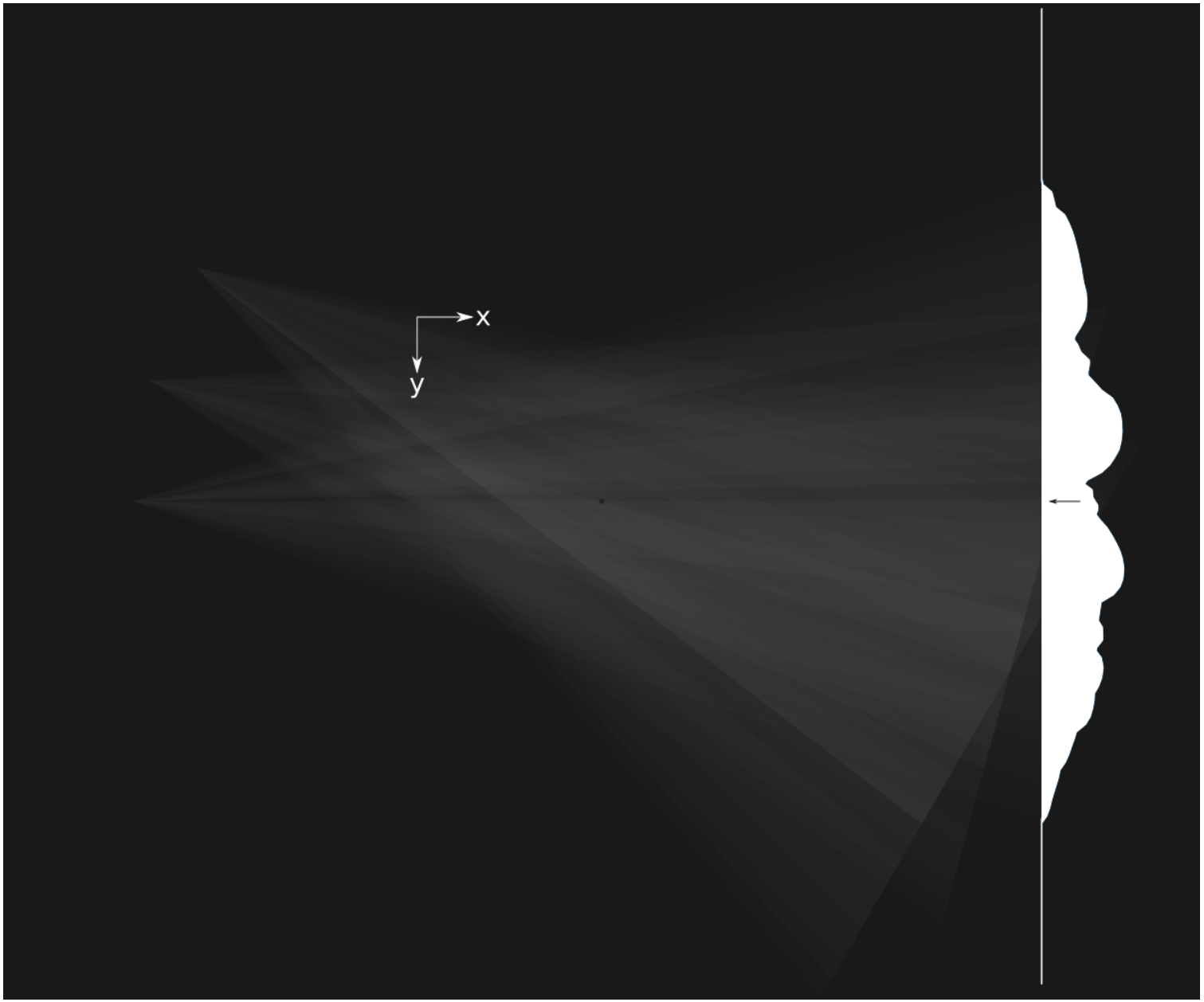
Backprojection



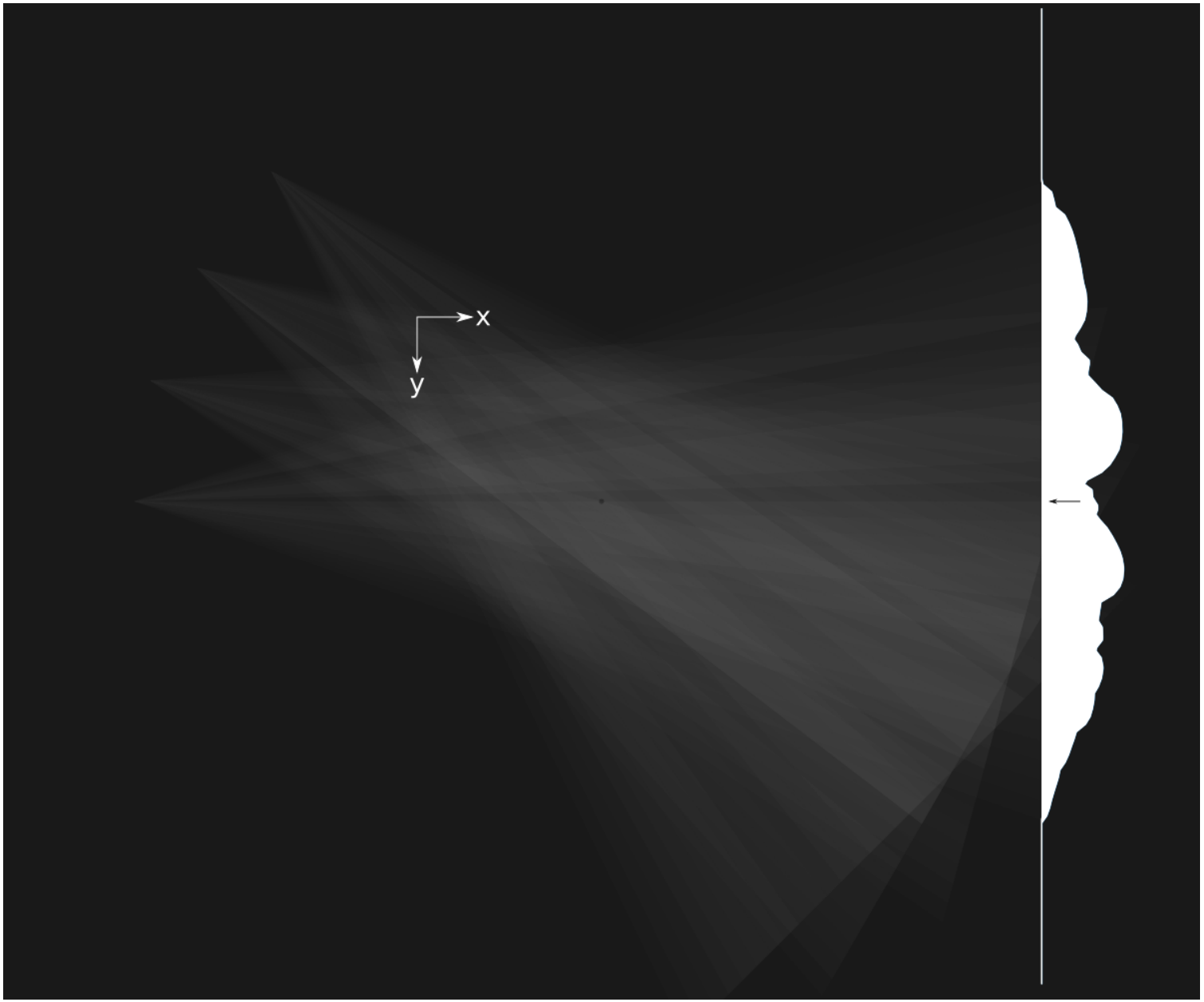
Backprojection



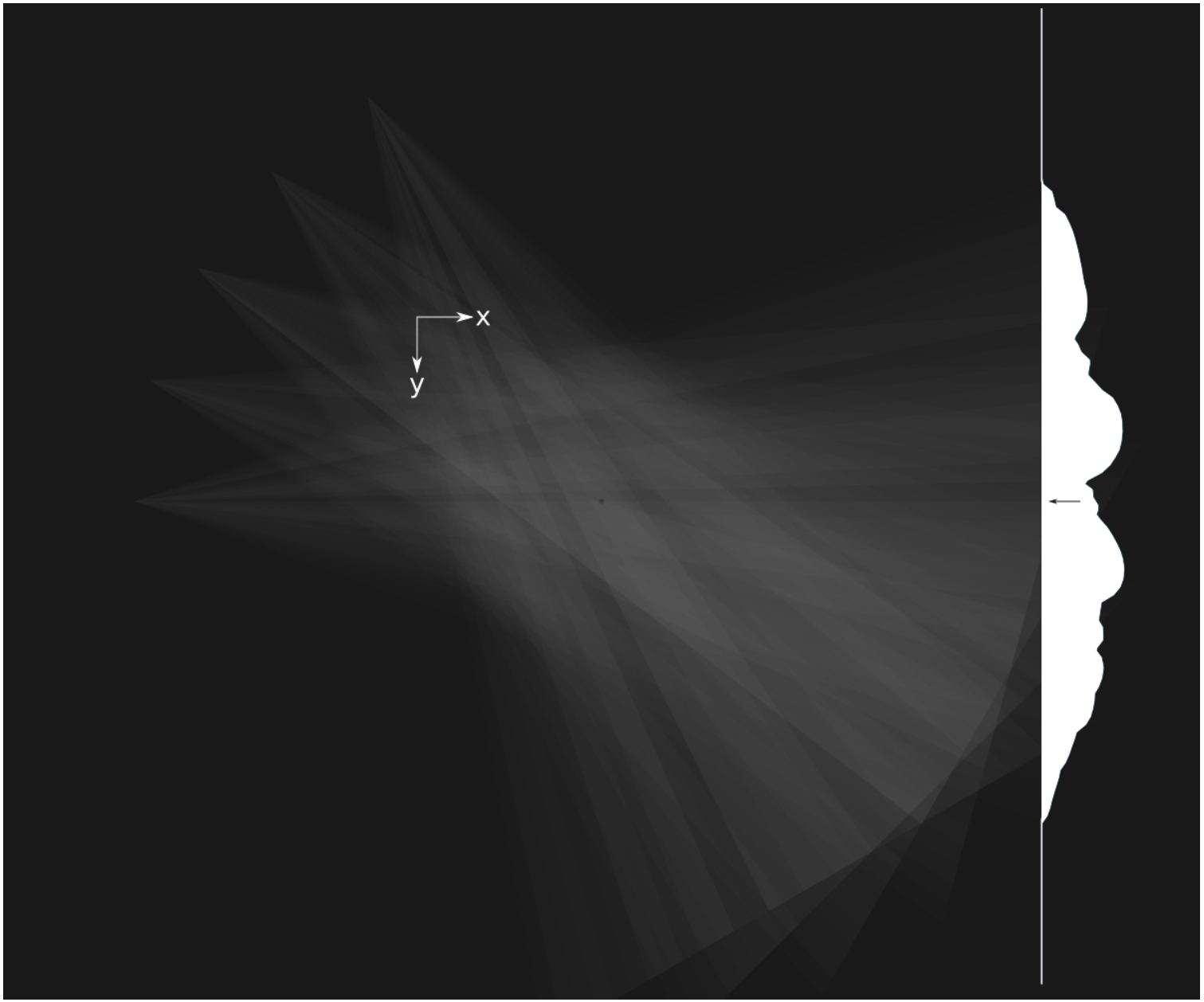
Backprojection



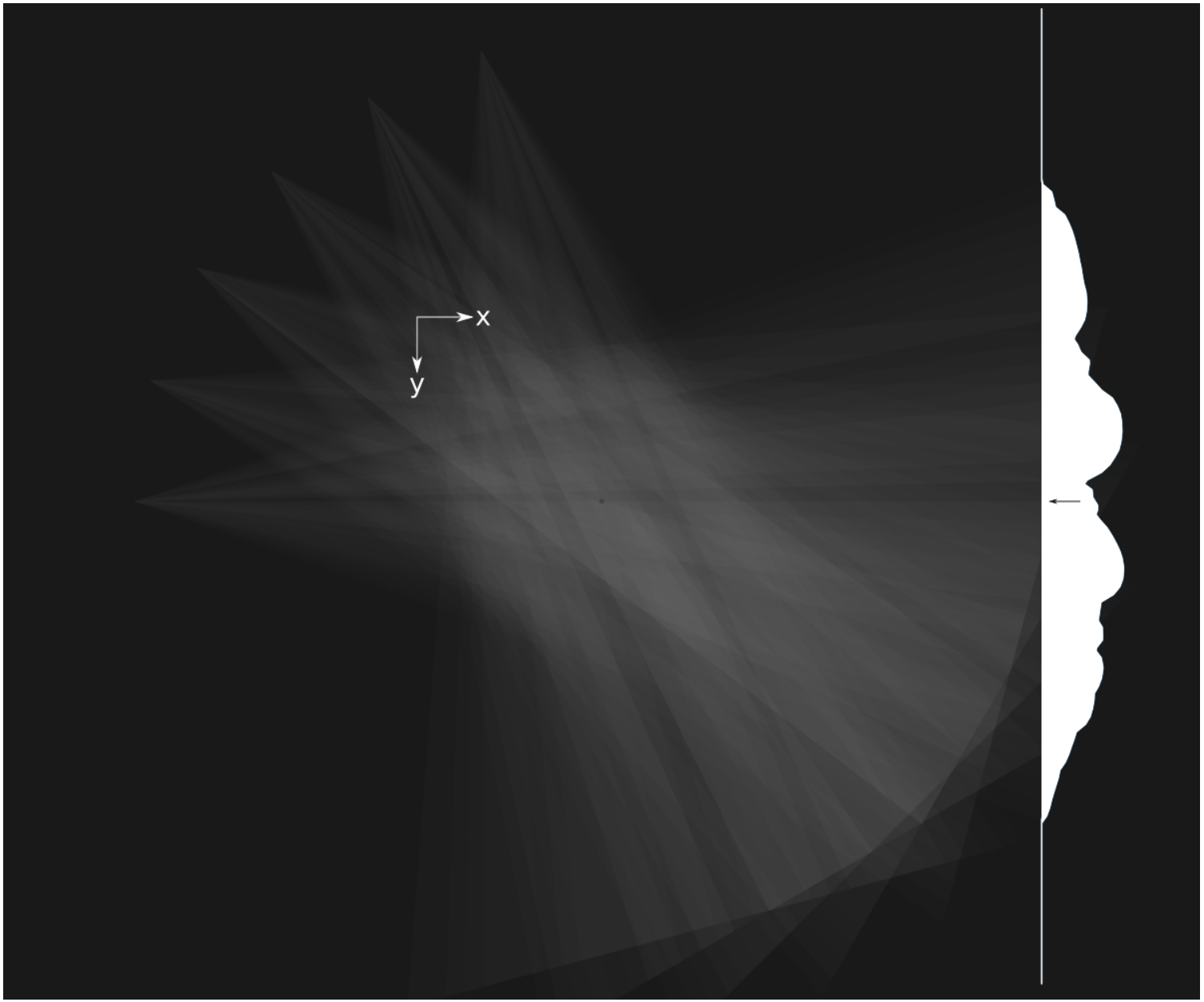
Backprojection



Backprojection



Backprojection



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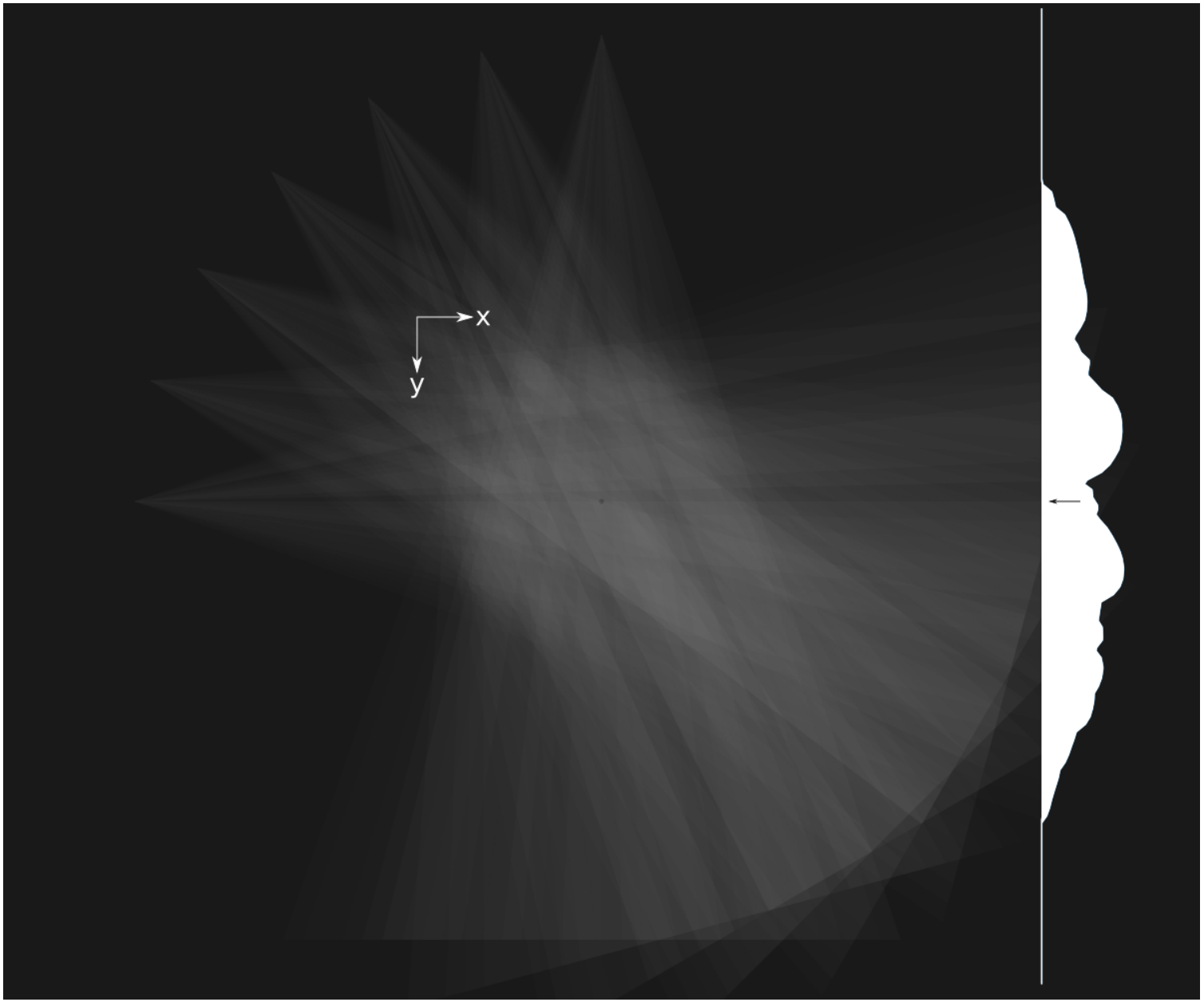
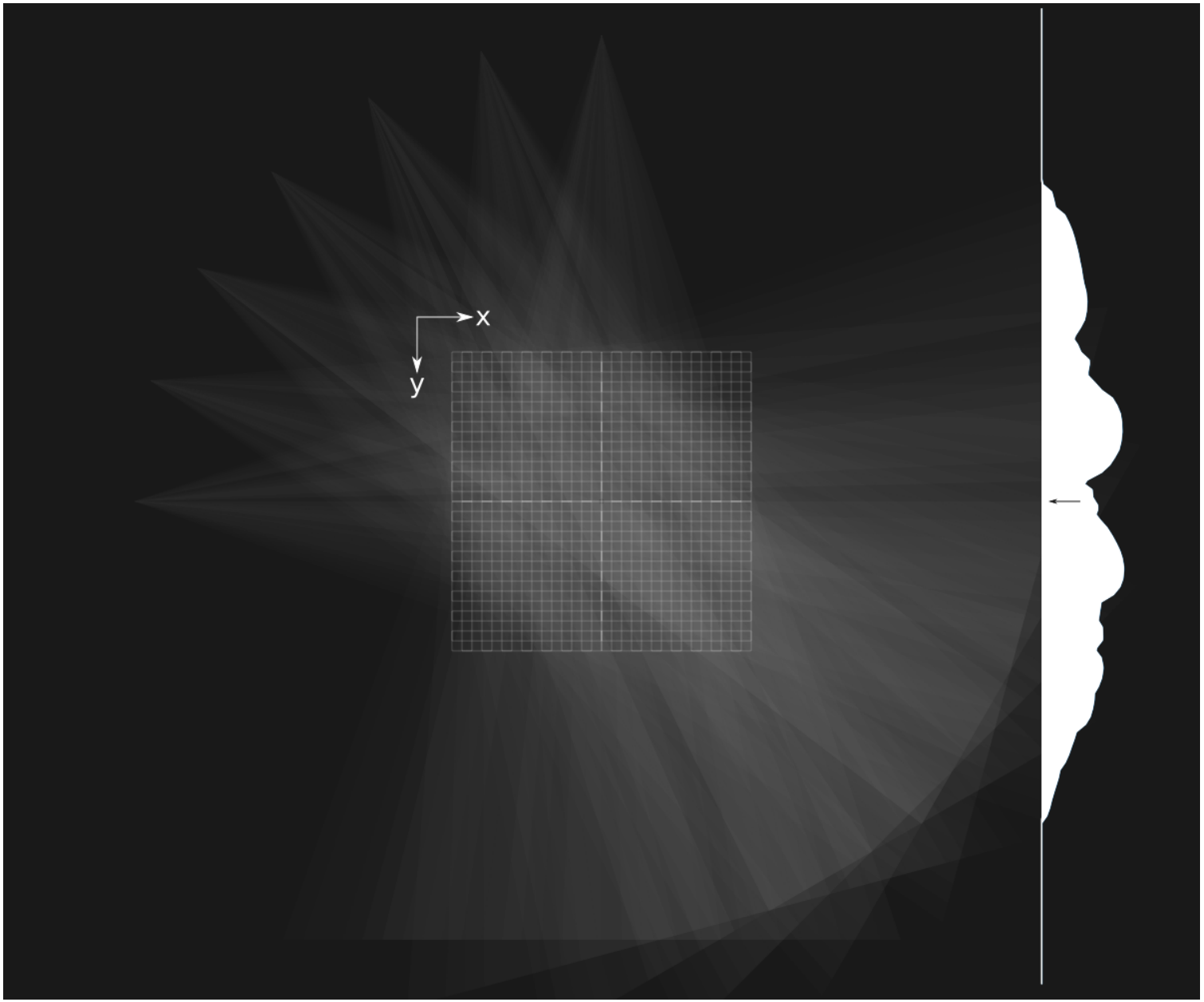
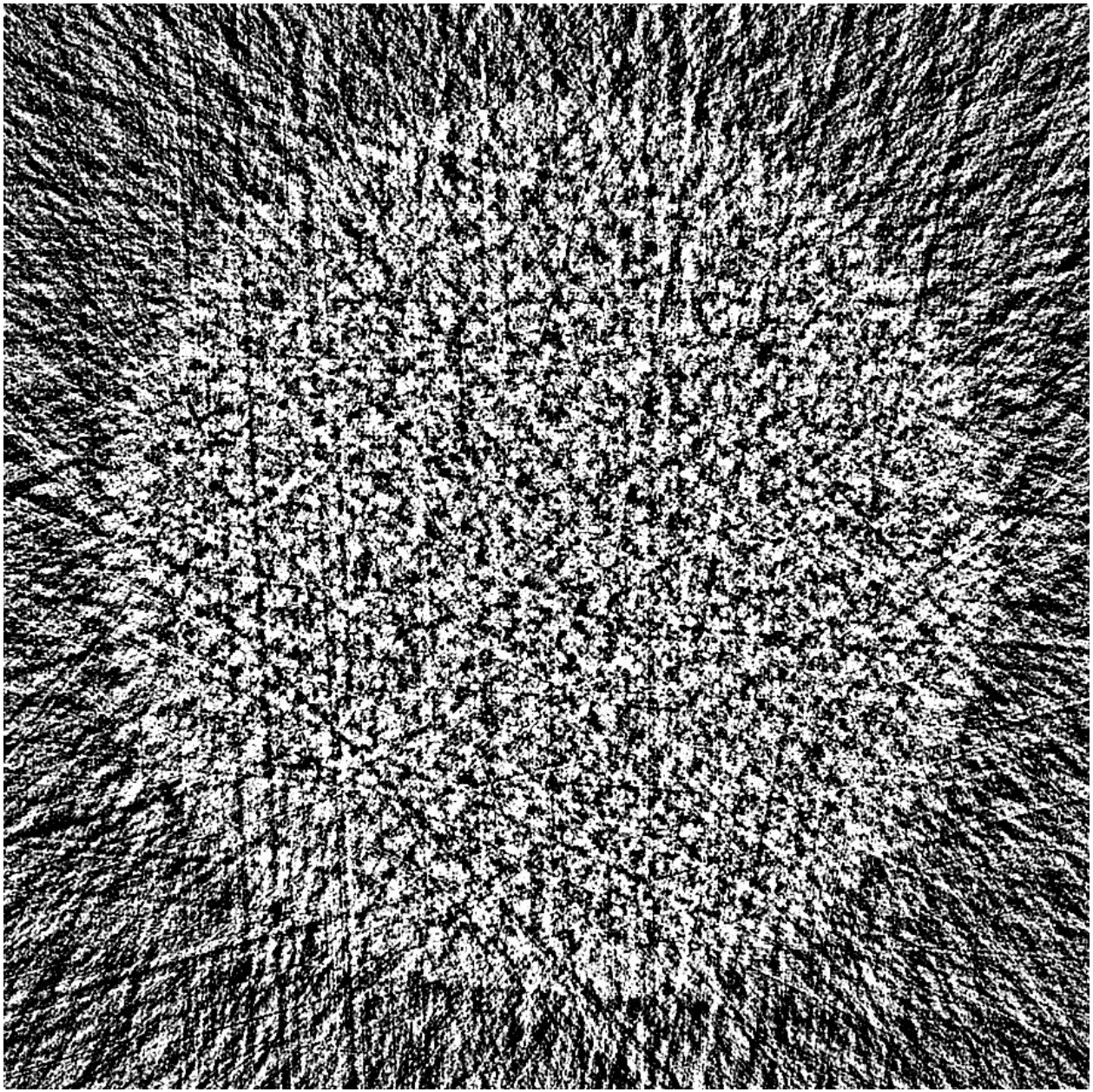


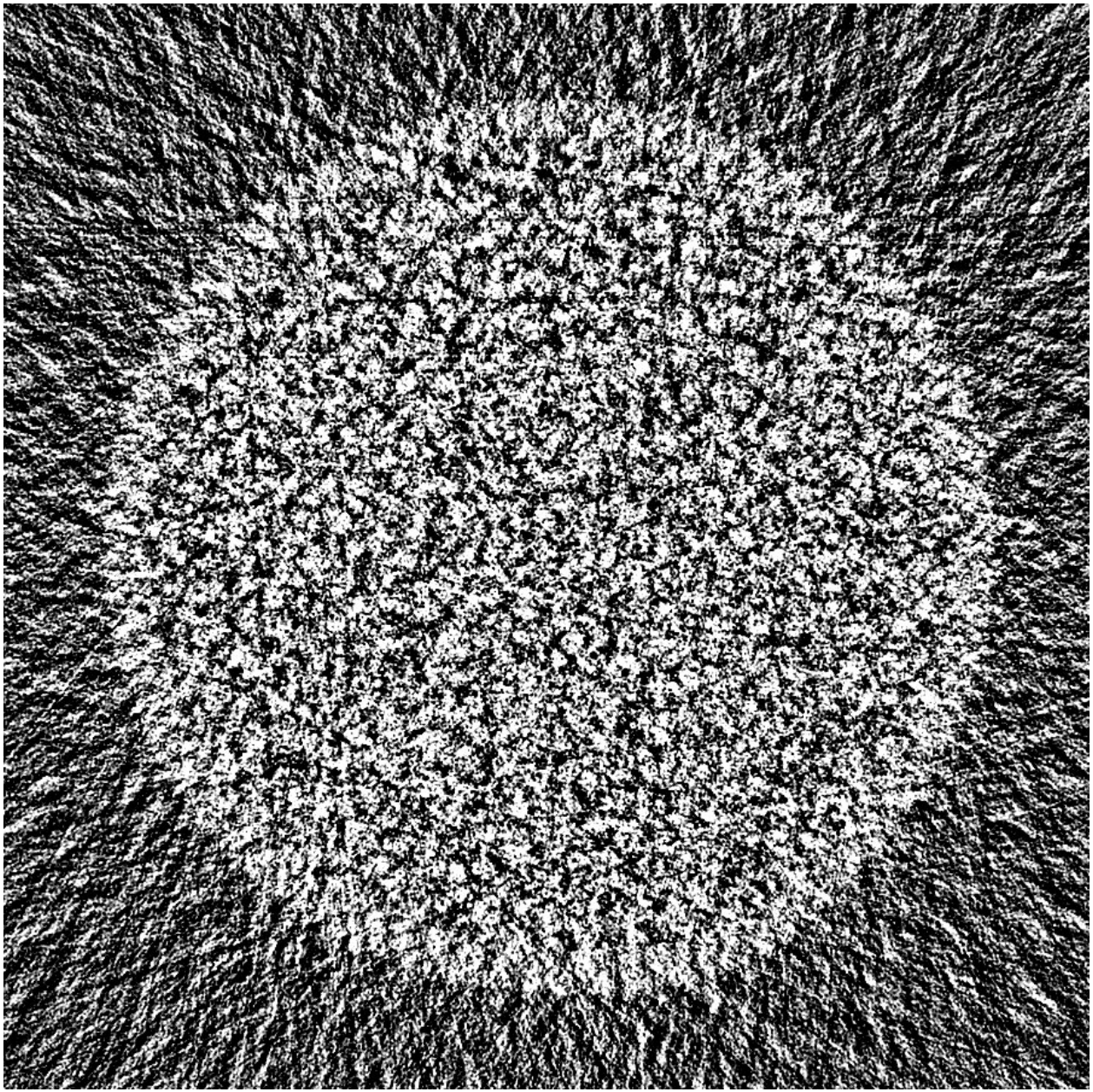
Backprojection



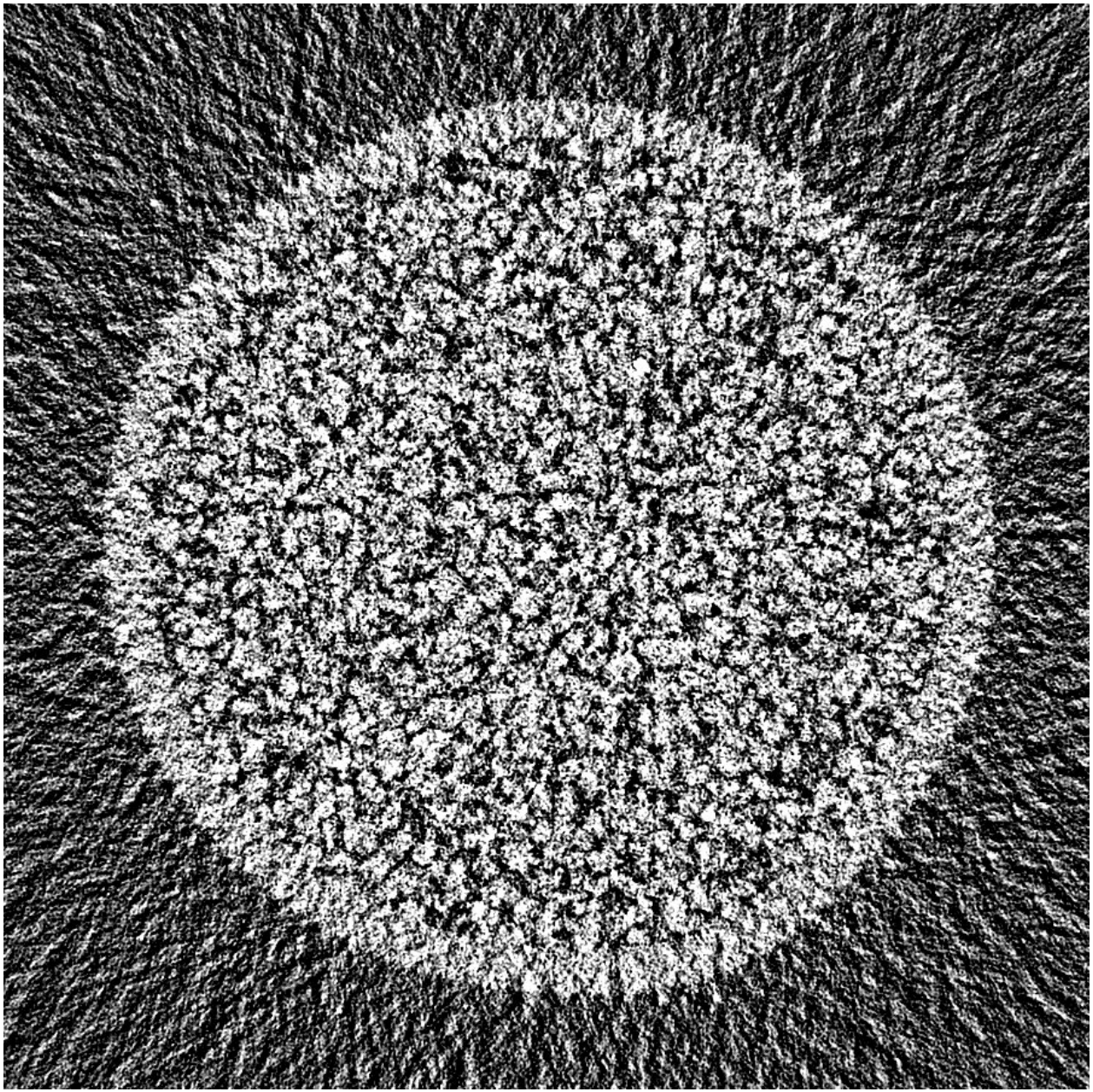
Example from M. Wiebicke 17



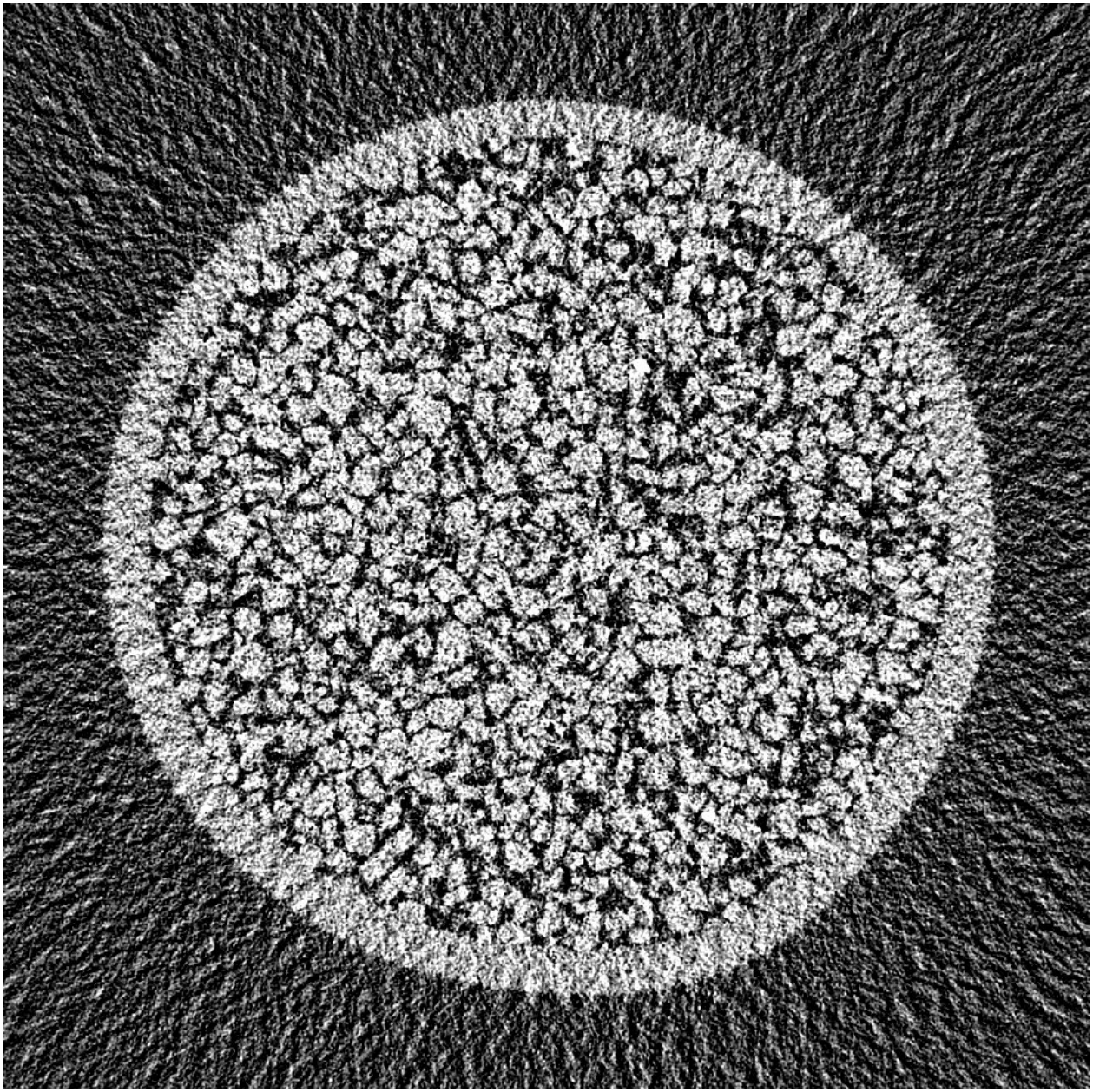
Example from M. Wiebicke 35



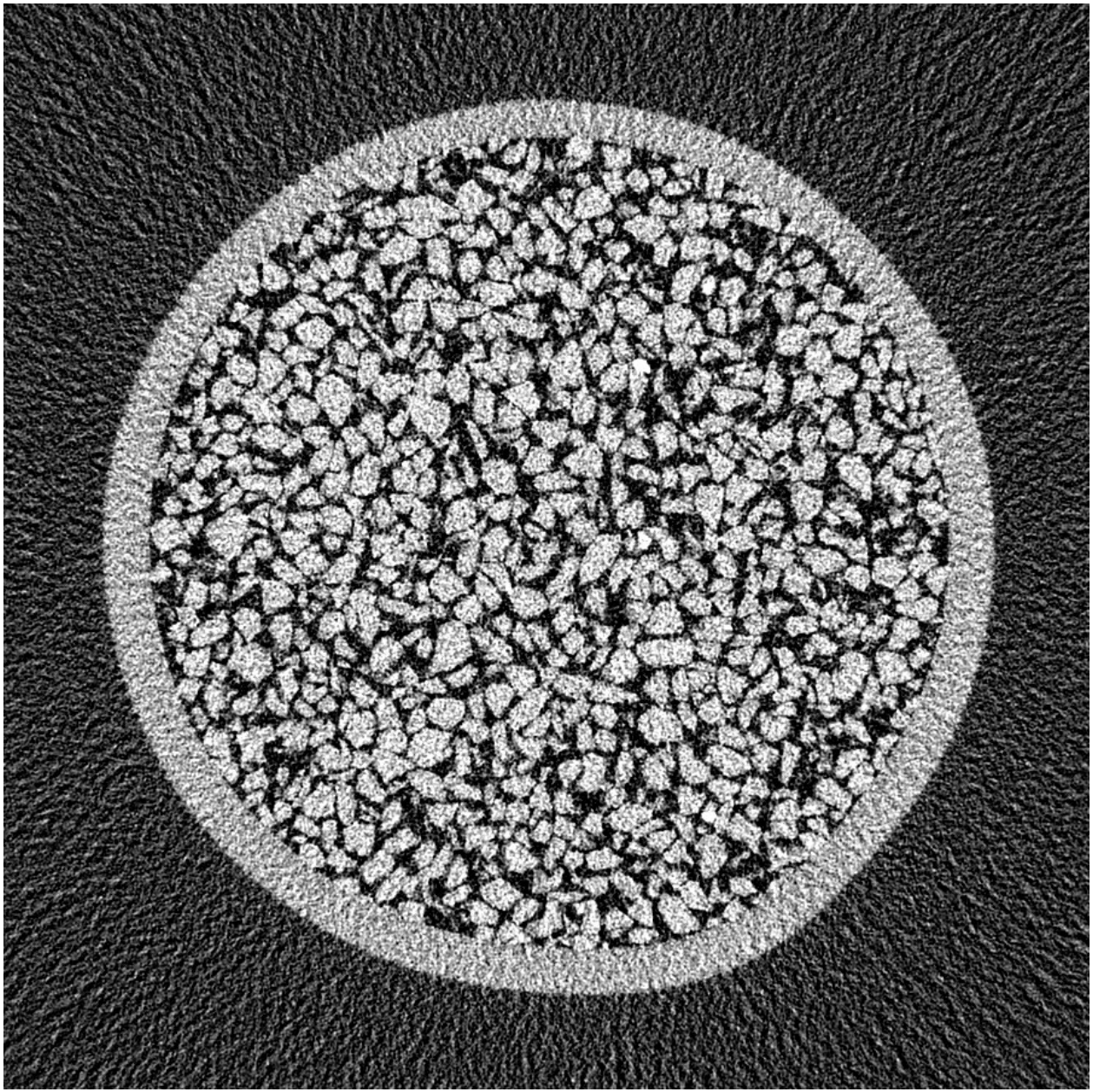
Example from M. Wiebicke 70



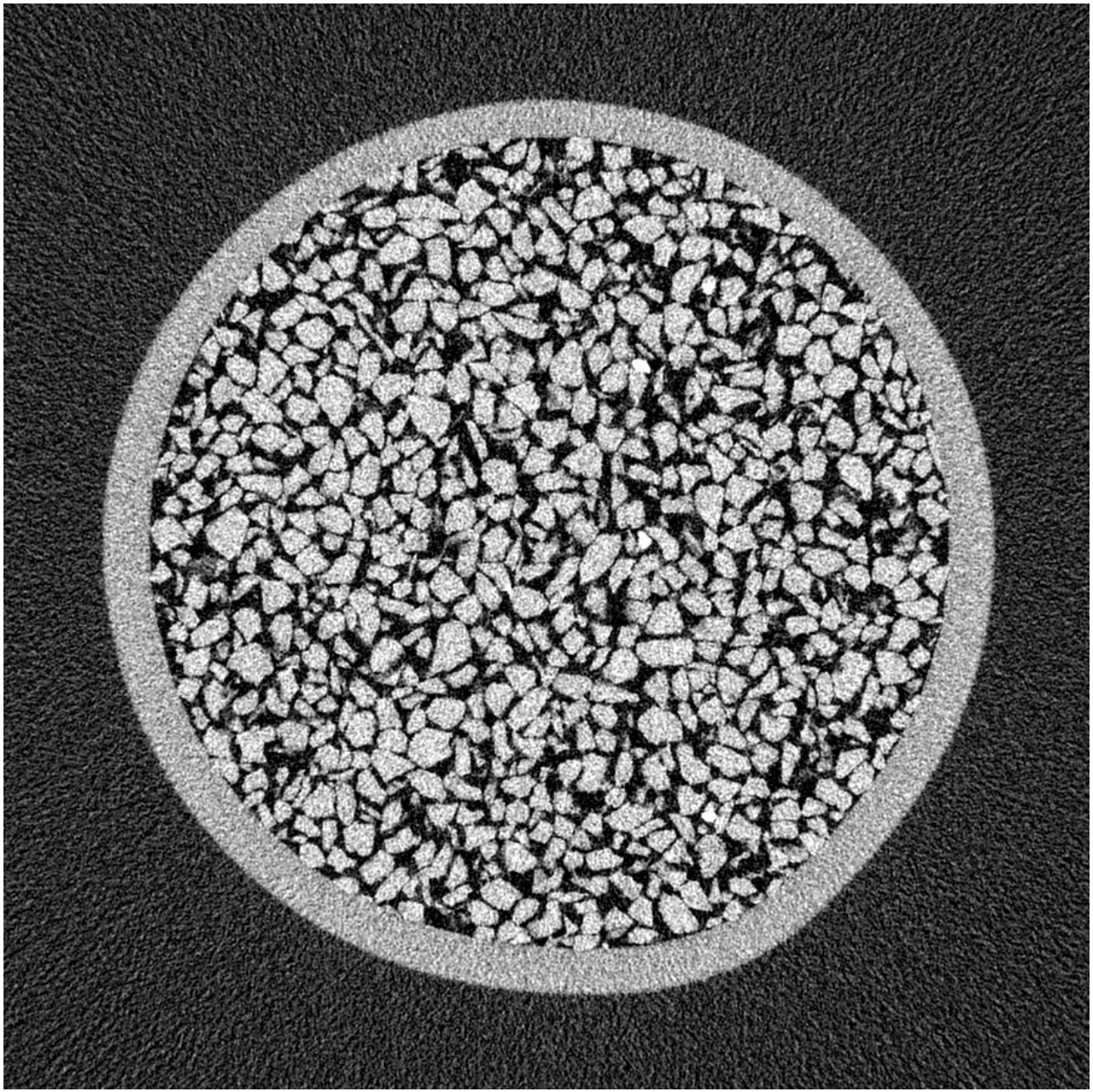
Example from M. Wiebicke 140



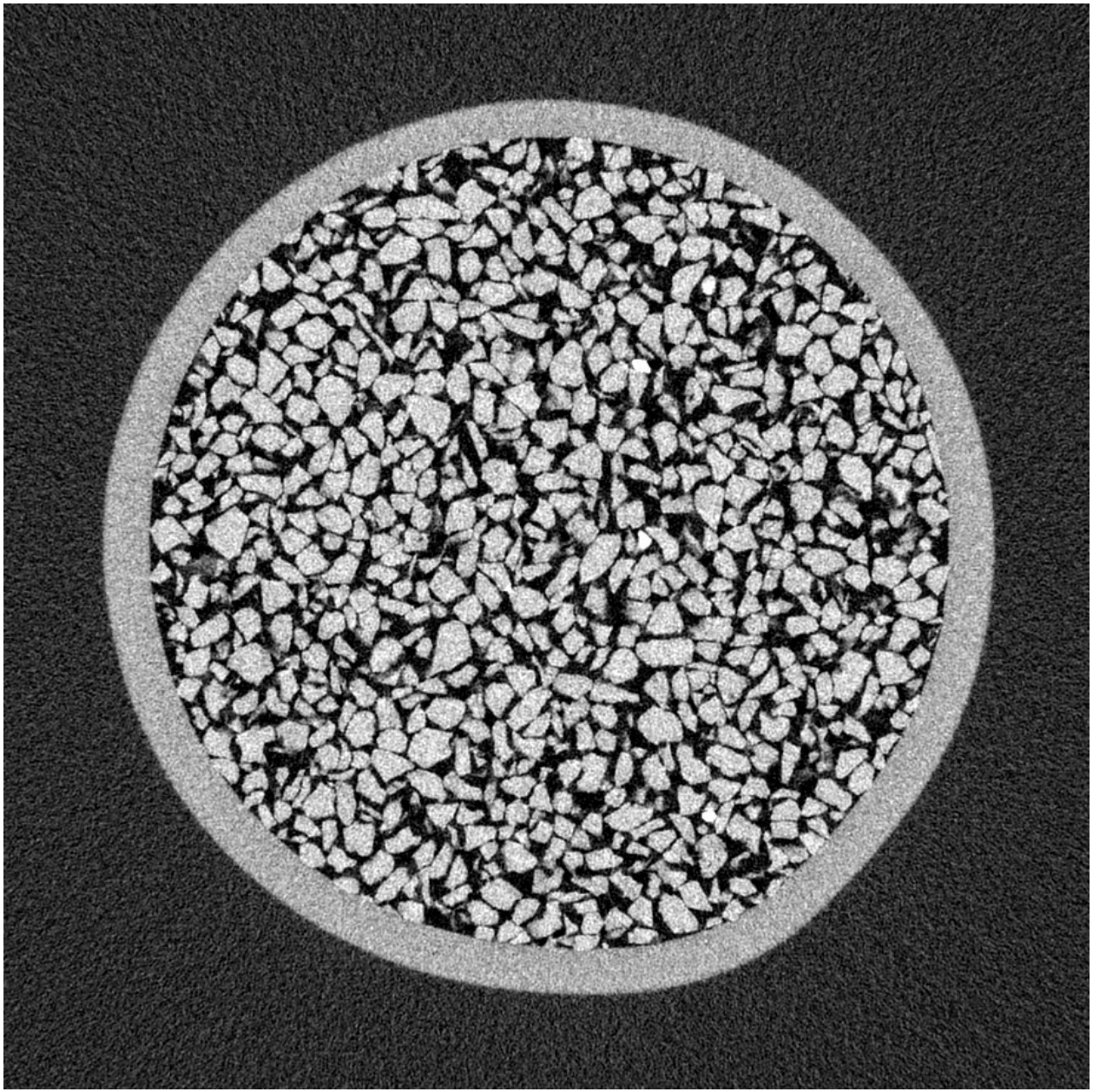
Example from M. Wiebicke 280



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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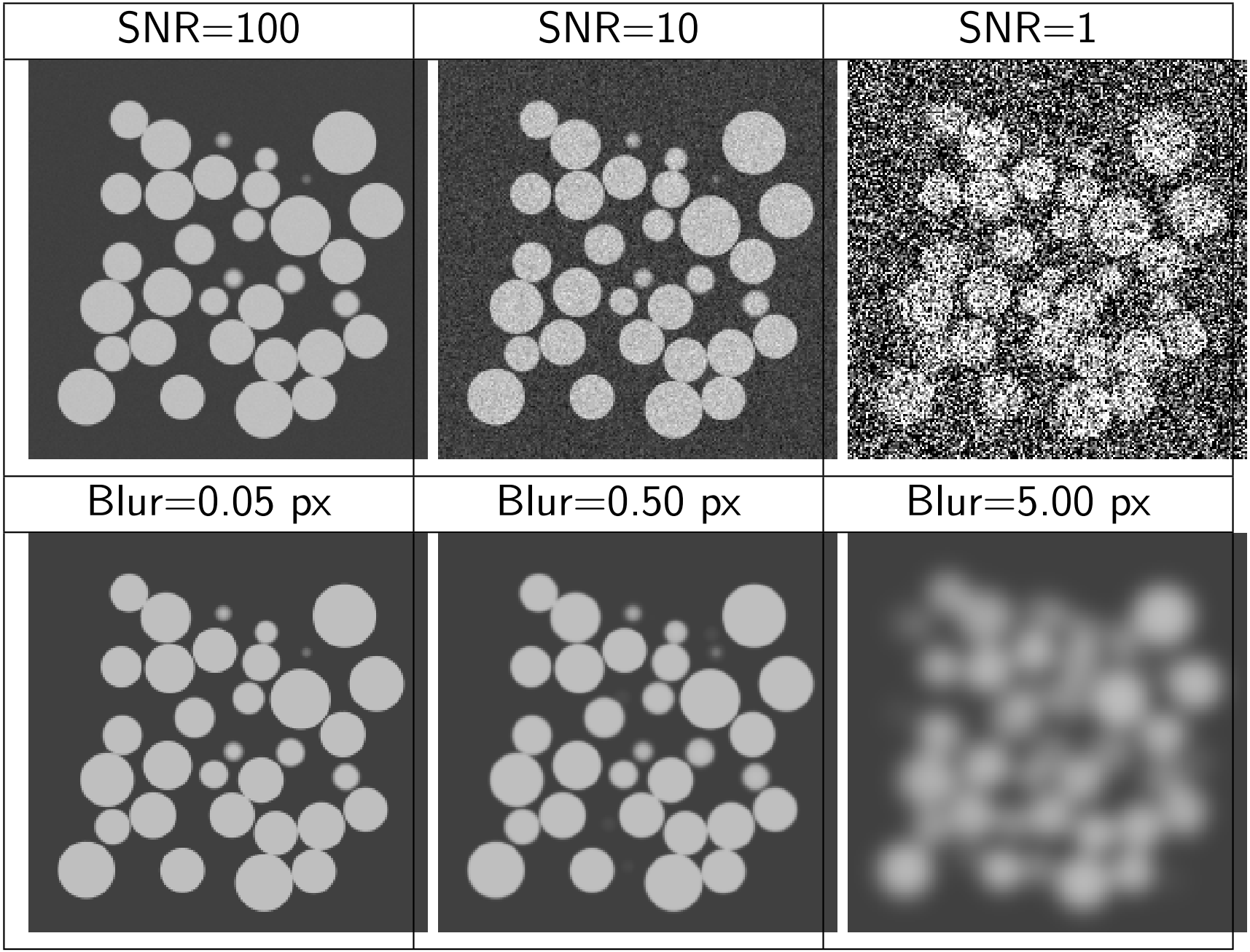
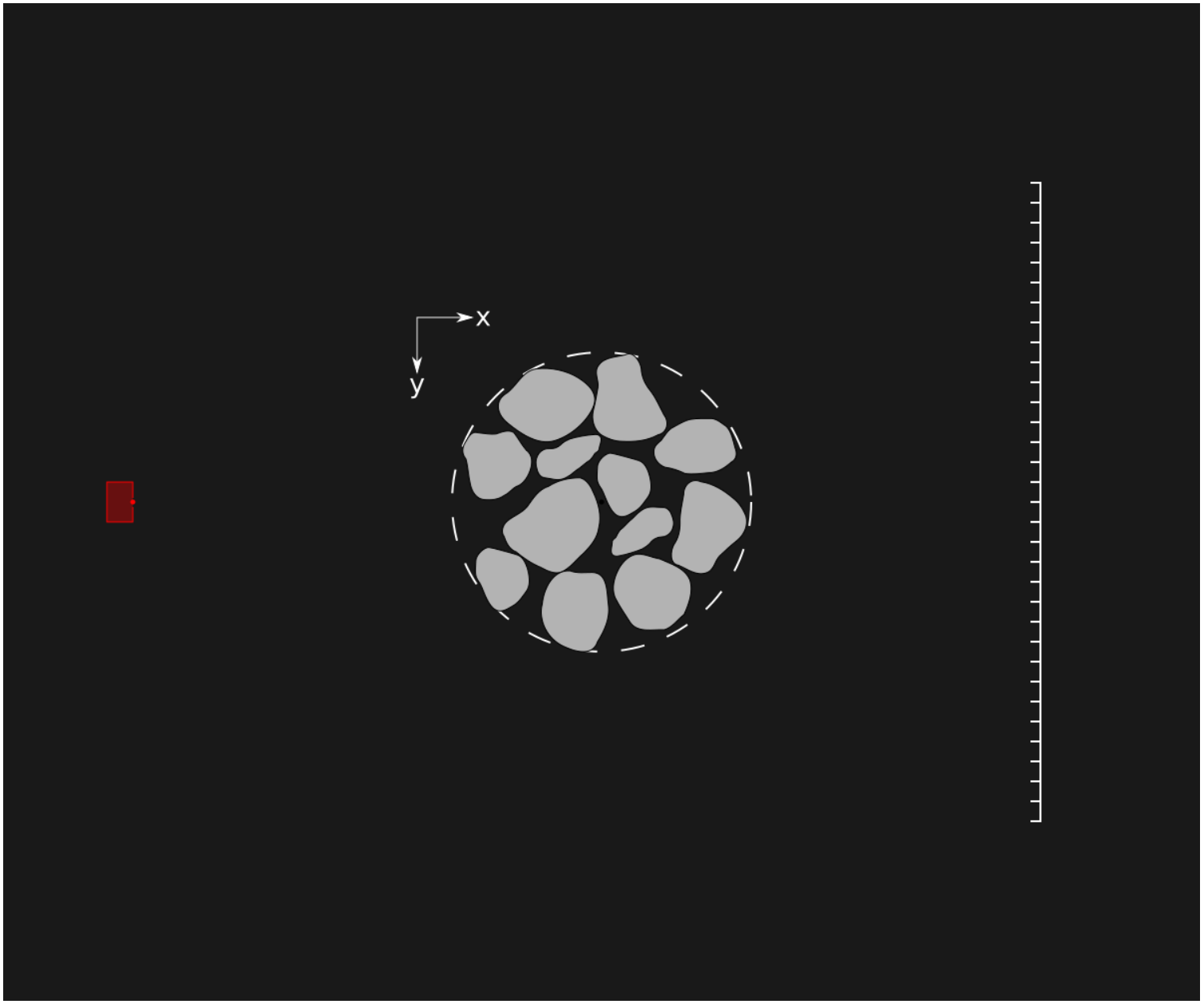
- Signal-to-Noise ratio ($\frac{val(fg)}{STDev(bg)}$)
- Sharpness, or the slippery and avoidable "spatial resolution"
- Acquisition/reconstruction related artefacts:
  - Beam hardening
  - Ring artefacts
  - Streaks...



A. Tengaittini & E. Andò, *Kalisphera: an analytical tool to reproduce the partial volume effect of spheres imaged in 3D*, MST - 2015

Usual trade-off between field of view and pixel size



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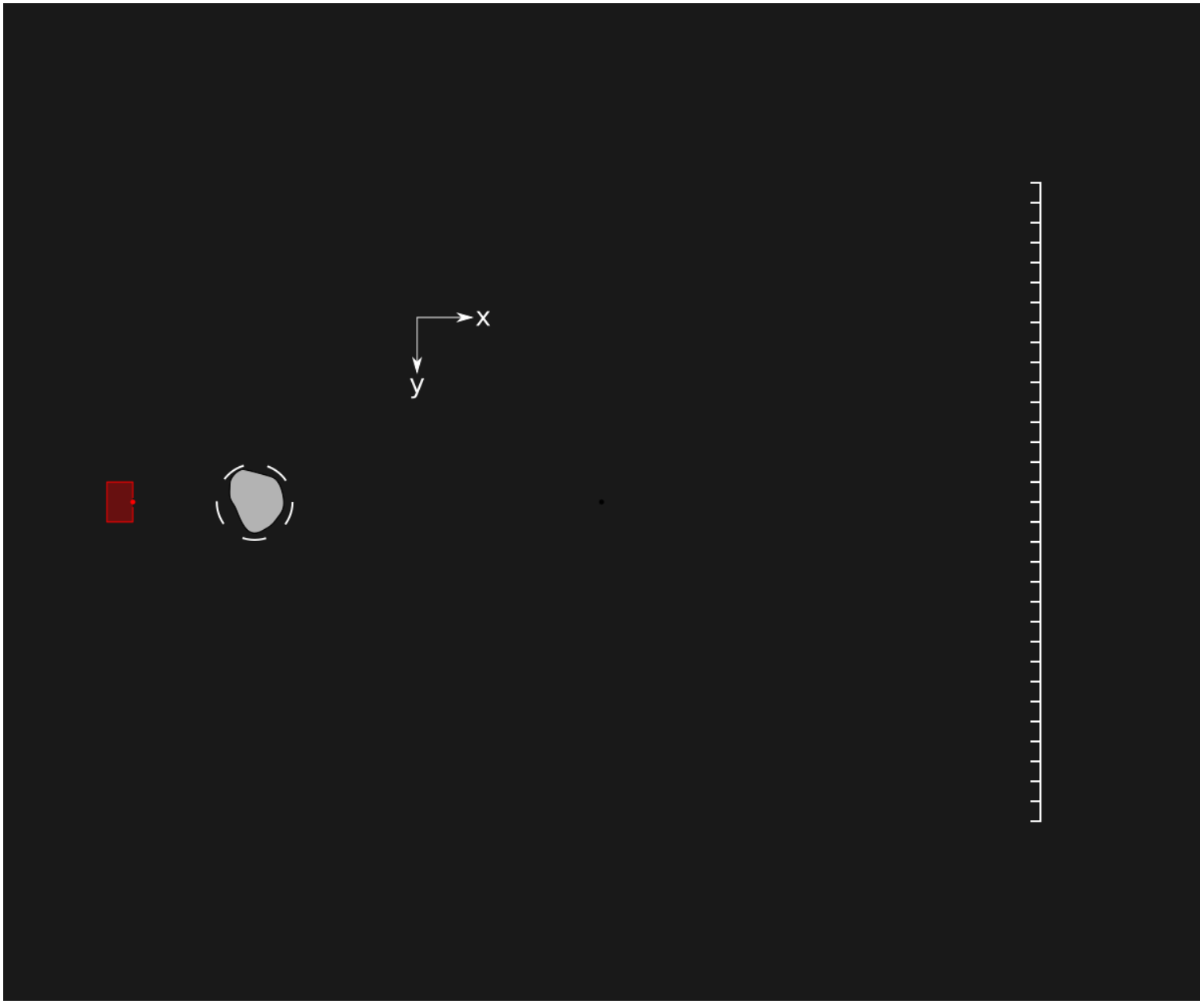

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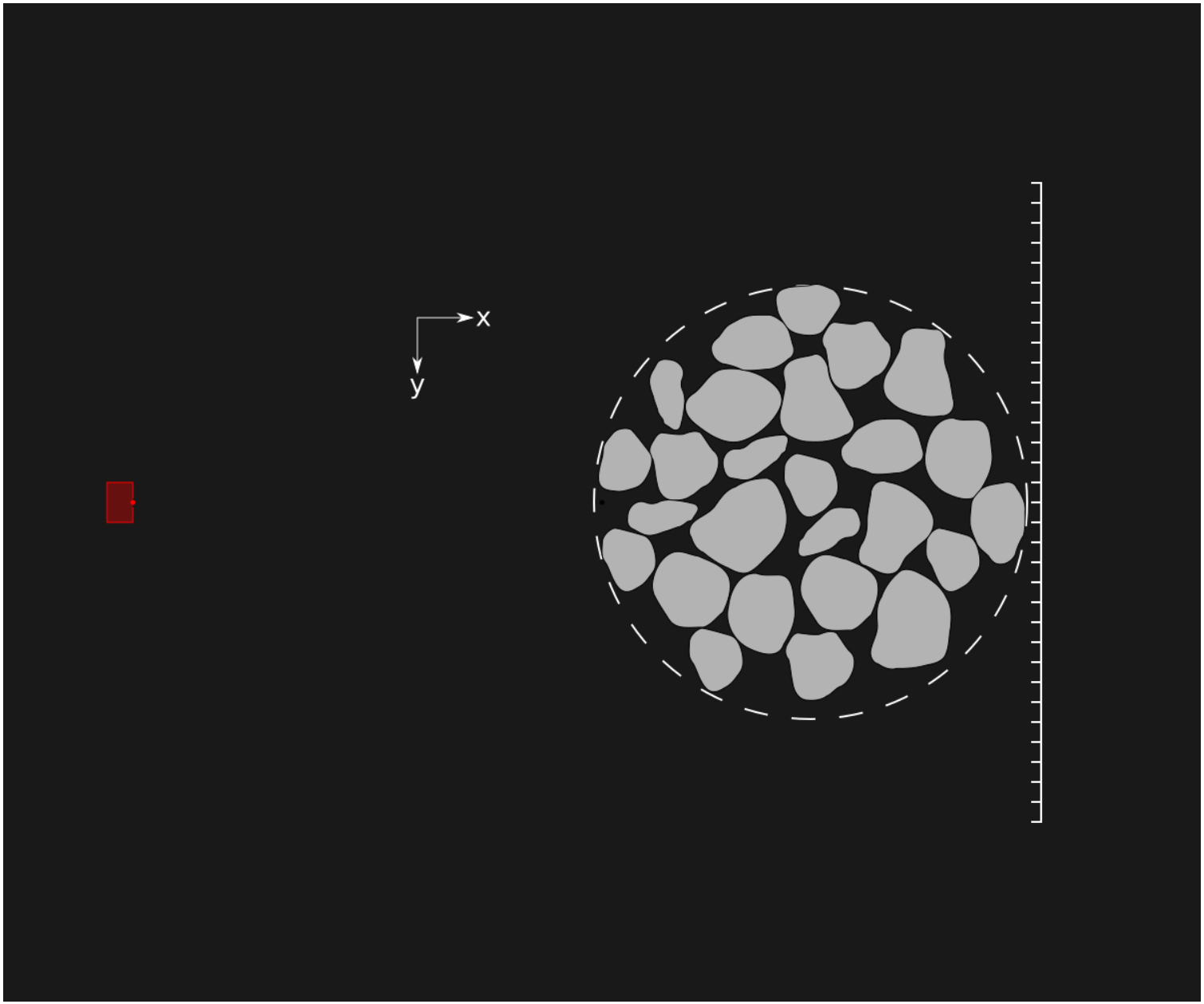
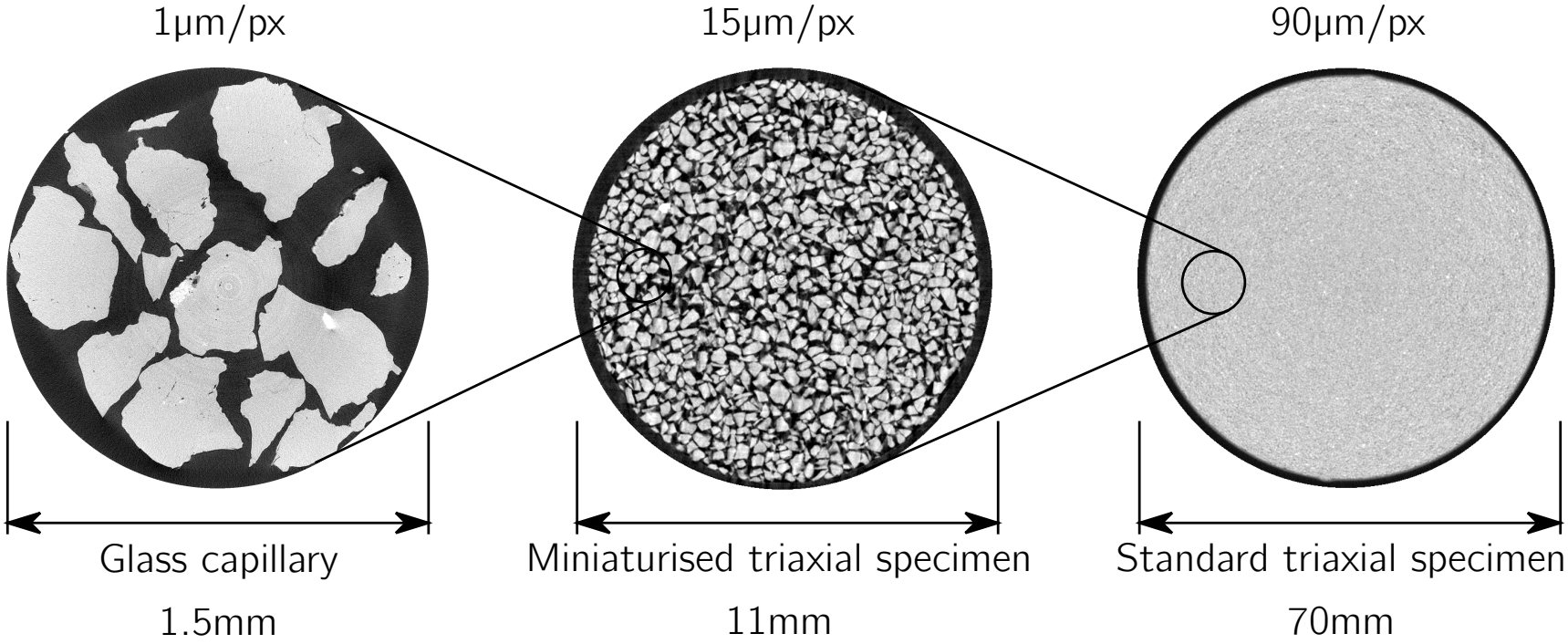


Hostun HN31 Sand (D_{50}=328µm)



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

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

Inherent three-way tradeoff:

- Signal to Noise Ratio related to $\sqrt{t}$

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- Signal to Noise Ratio related to $\sqrt{t}$
- Sharpness related to beam quality often $f(t)$
- Temporal resolution (seconds) (t)

To summarise this part

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a measurement of a 3D (OK only 2D so far...) x-ray attenuation field.

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It's roughly proportional to the density field.

As with all measurements there are errors that should be quantified (noise/blur),
and tradeoffs (field of view vs. pixel size & time *vs* quality)

Penetrating radiation not only can cross **a specimen**, but also **experimental equipment.**

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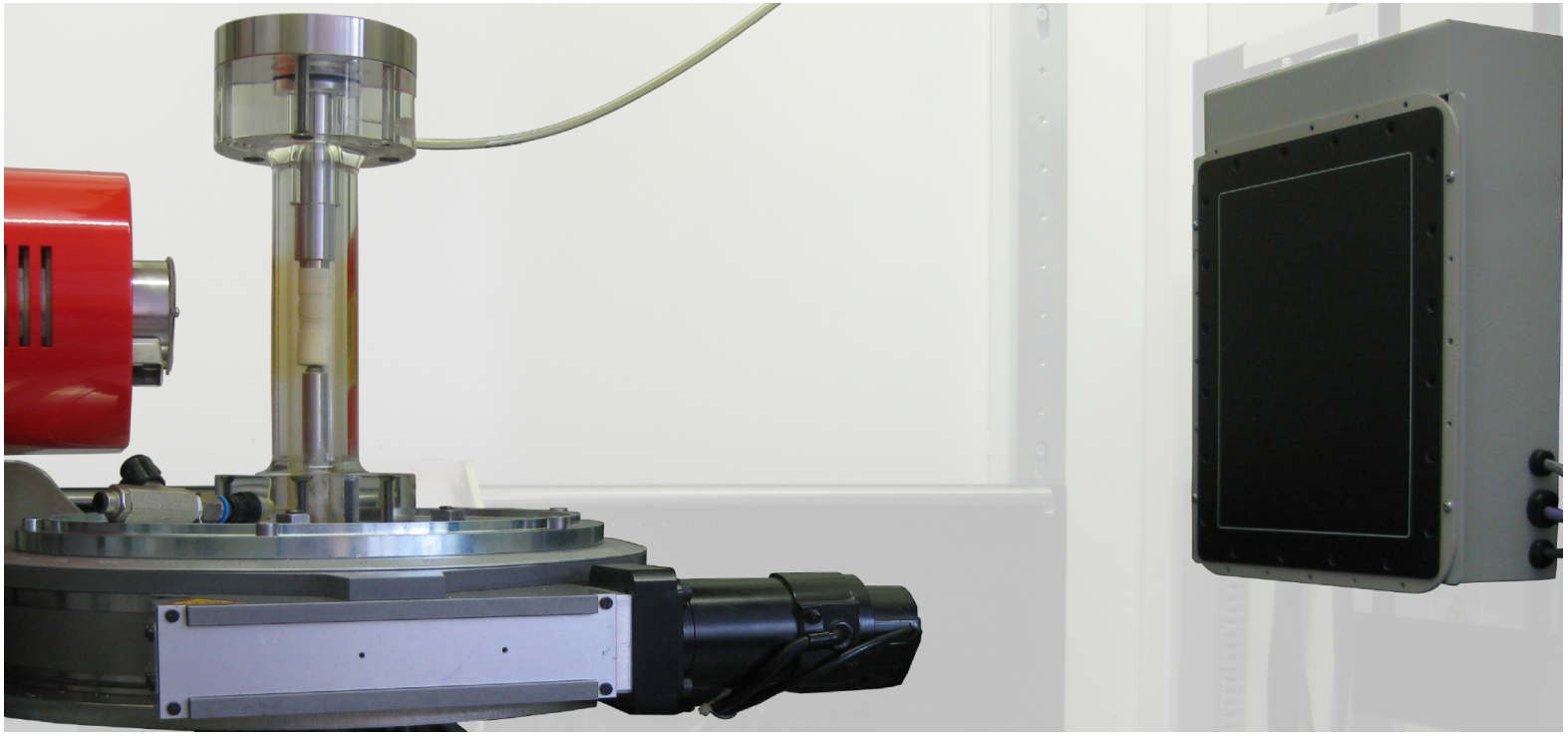
Let's dissect an example setup:



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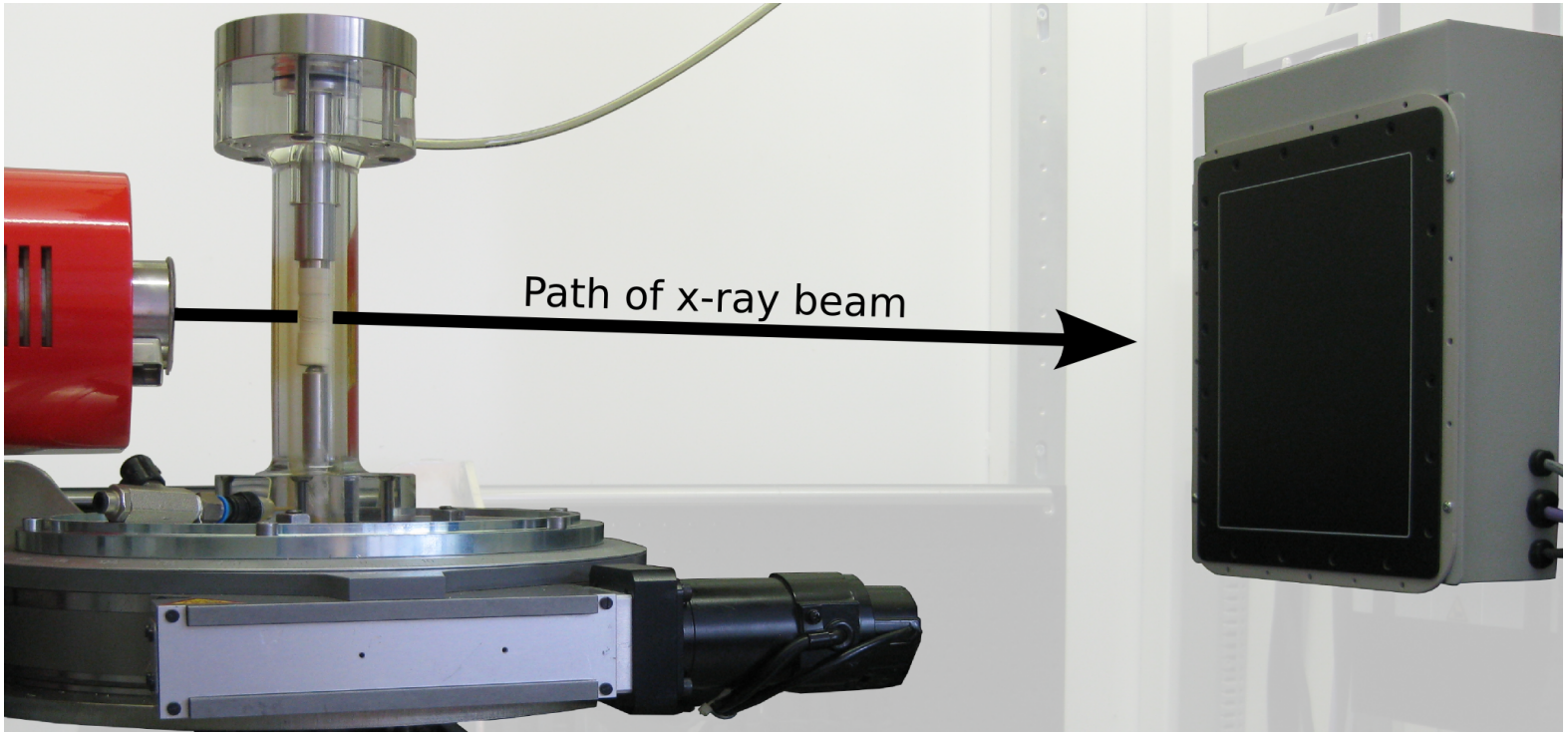

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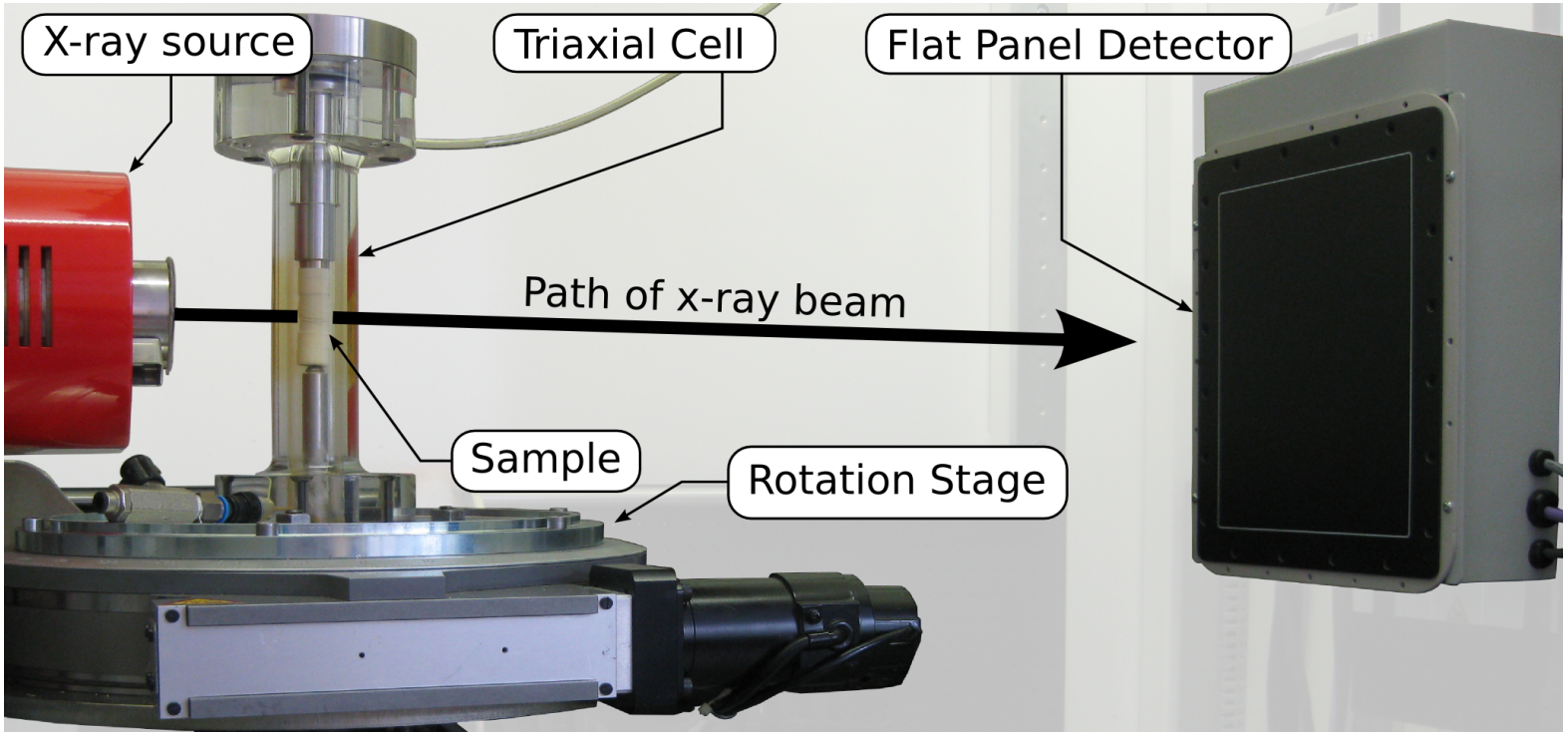

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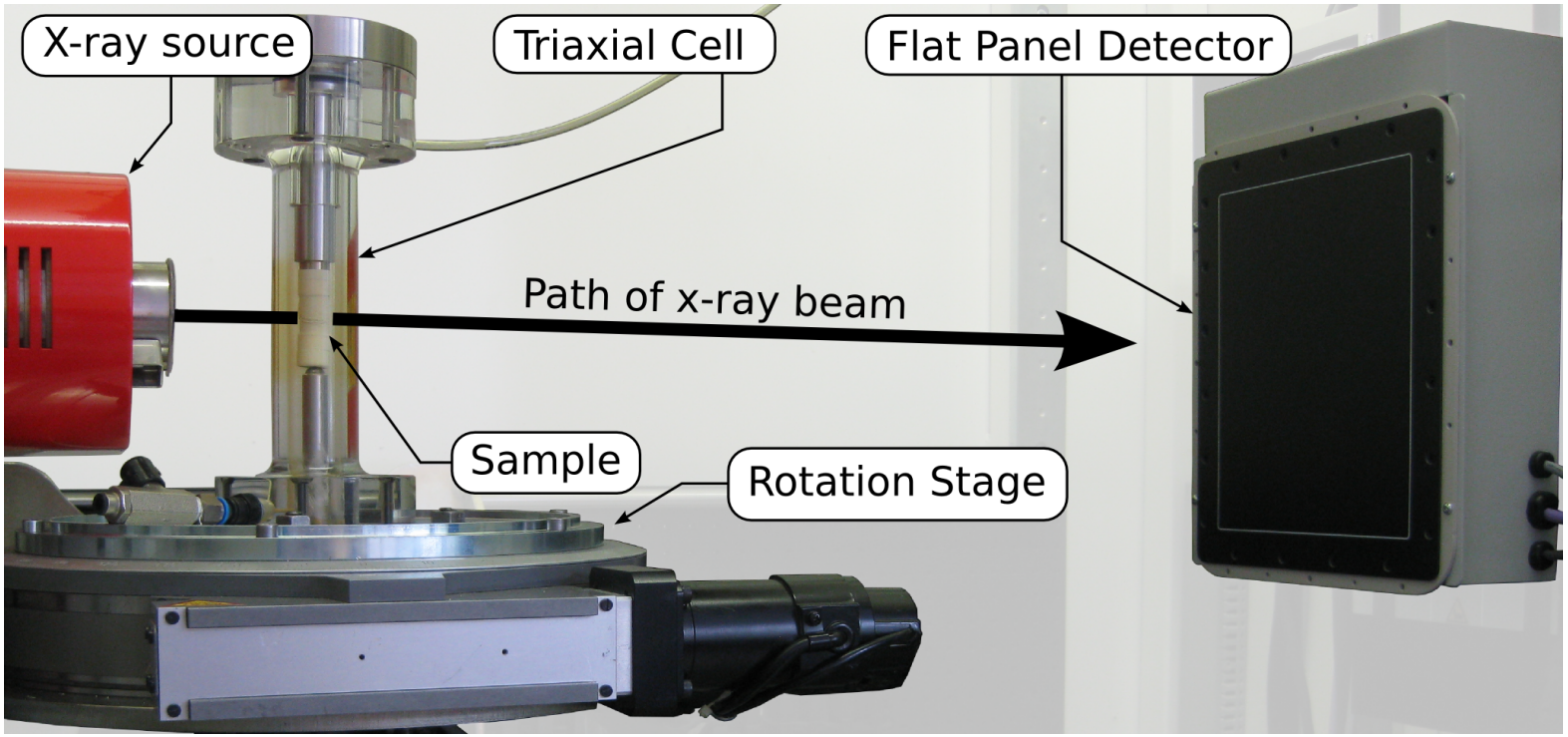
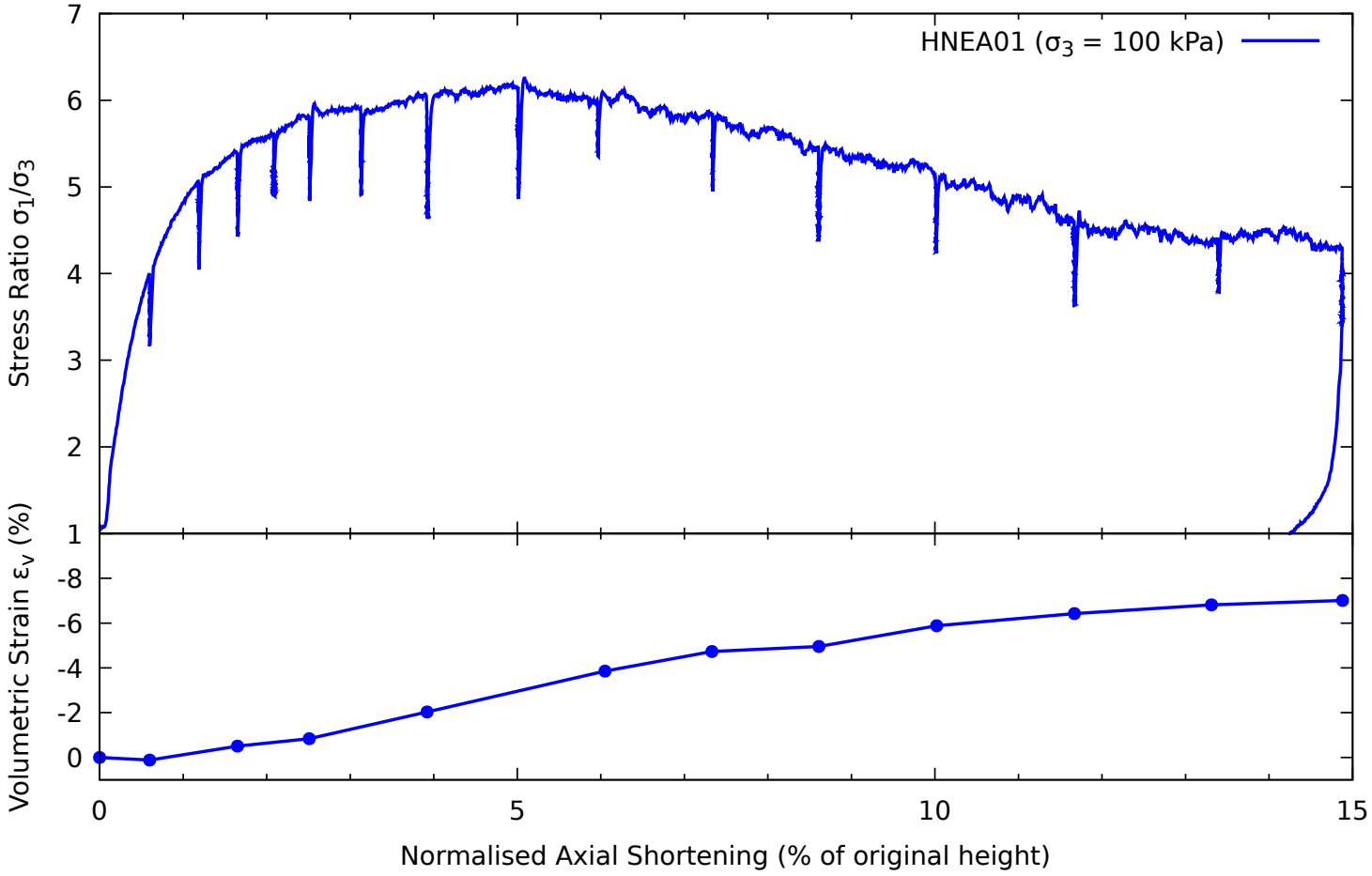


2D detector. Whole **experiment rotates**. High res.

Experimental Data collected during a triaxial test is the usual:



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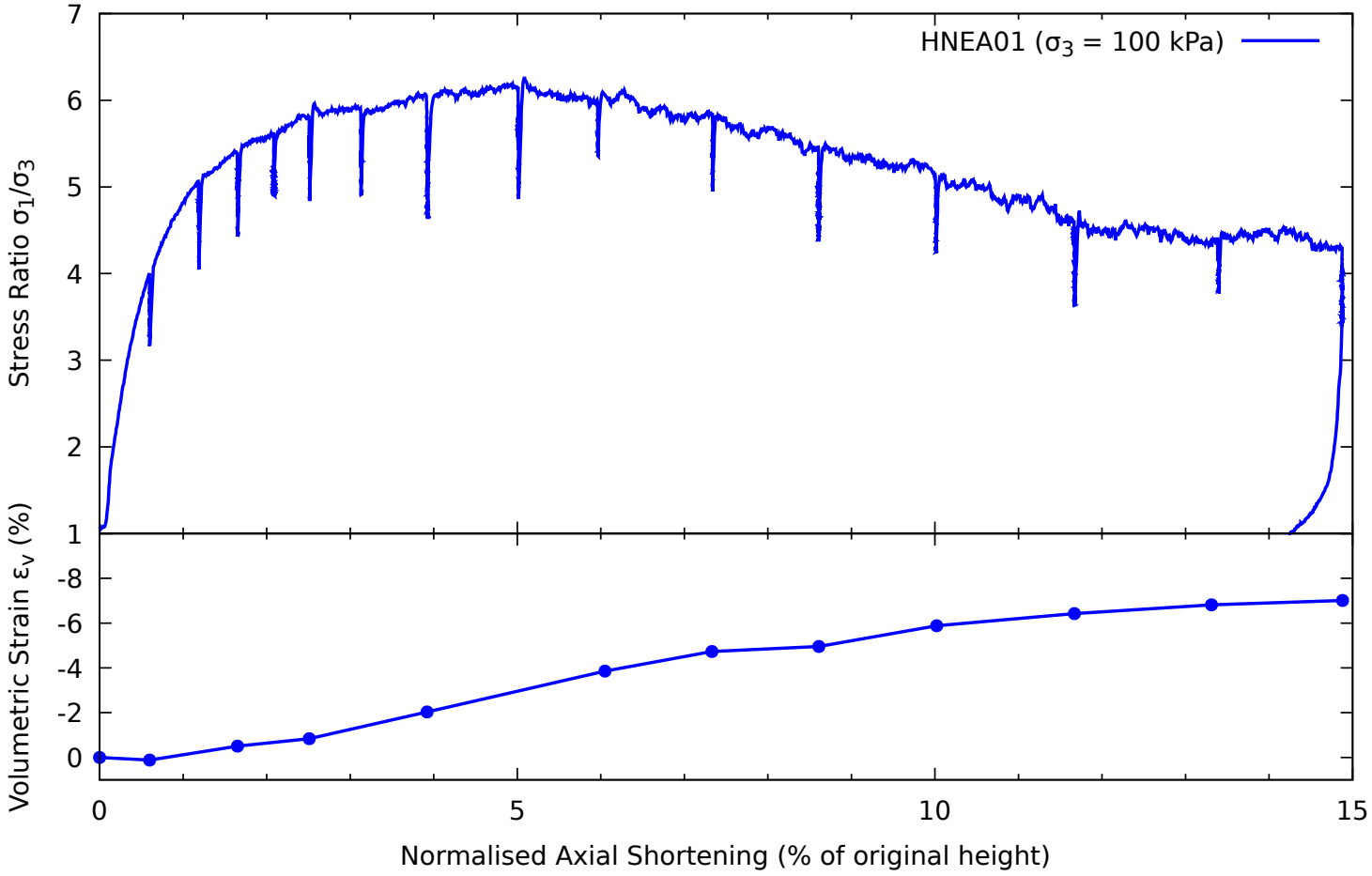
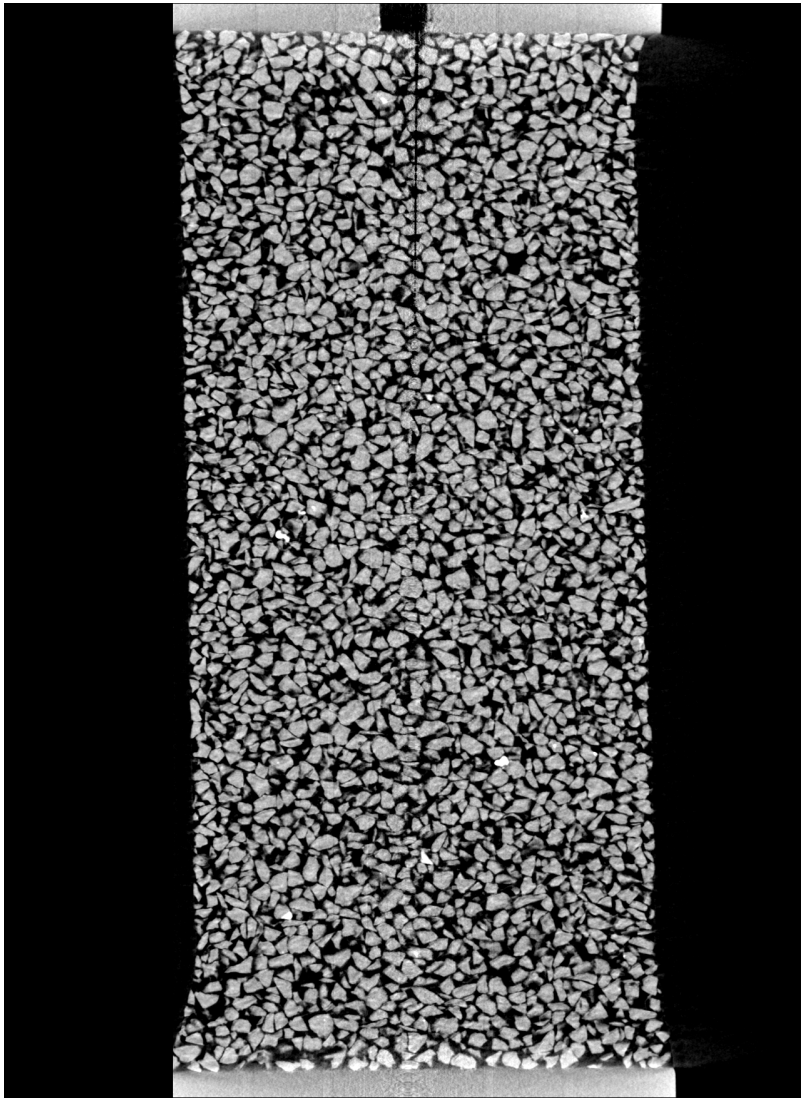


supplemented with...

Vertical slices through reconstructed volume (15 µm/px – $\phi = 11\,\mathrm{mm}$)



$\approx 1200 \times 1200 \times 1800$ **voxels**

E. Andò, *Experimental investigation of microstructural changes in deforming granular media using x-ray tomography*, PhD 2013

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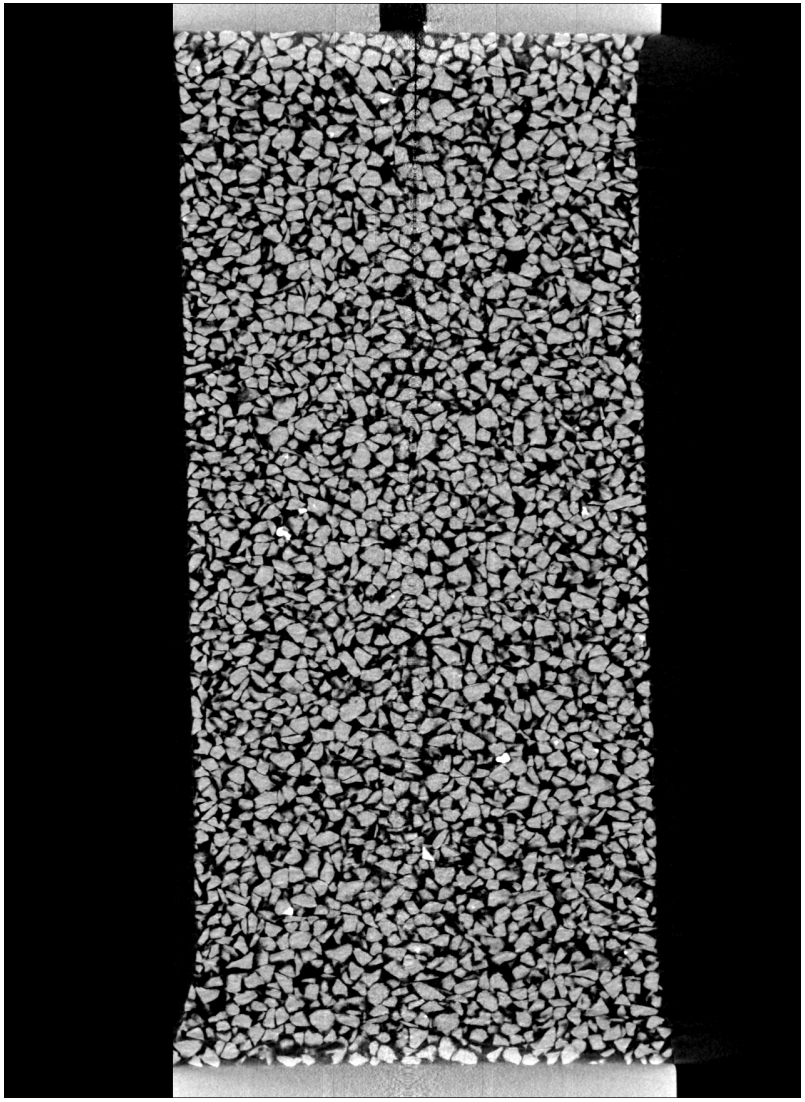

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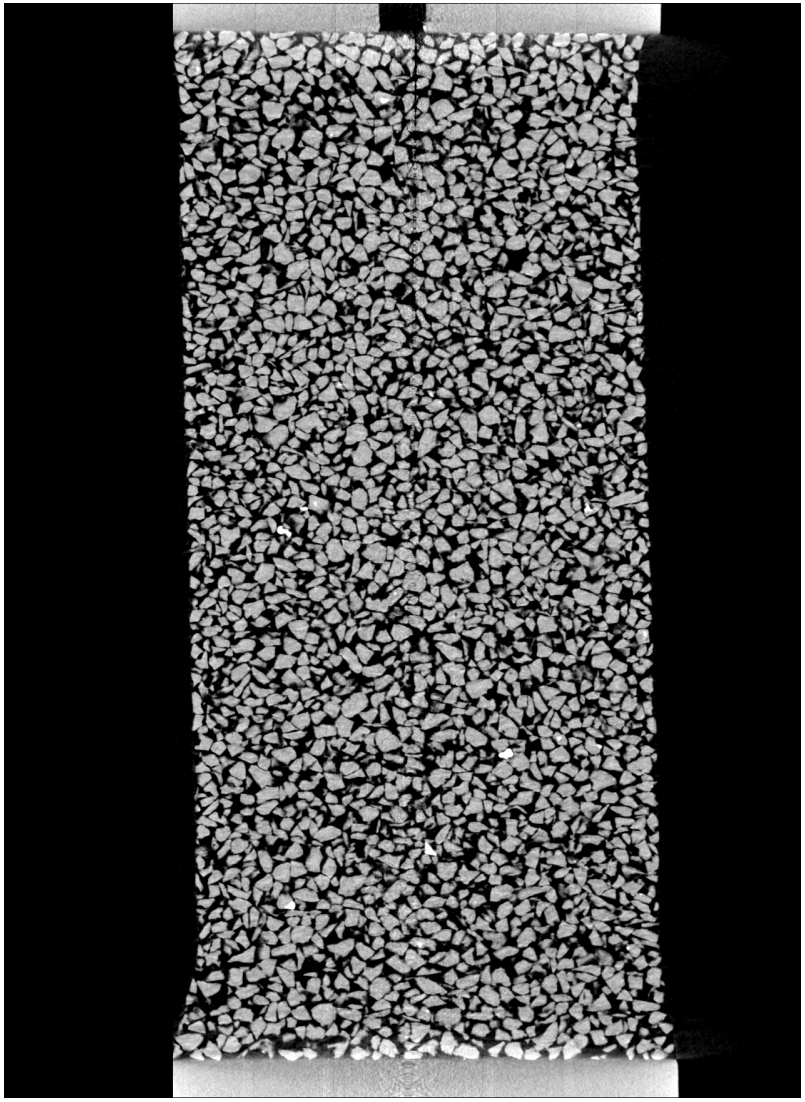

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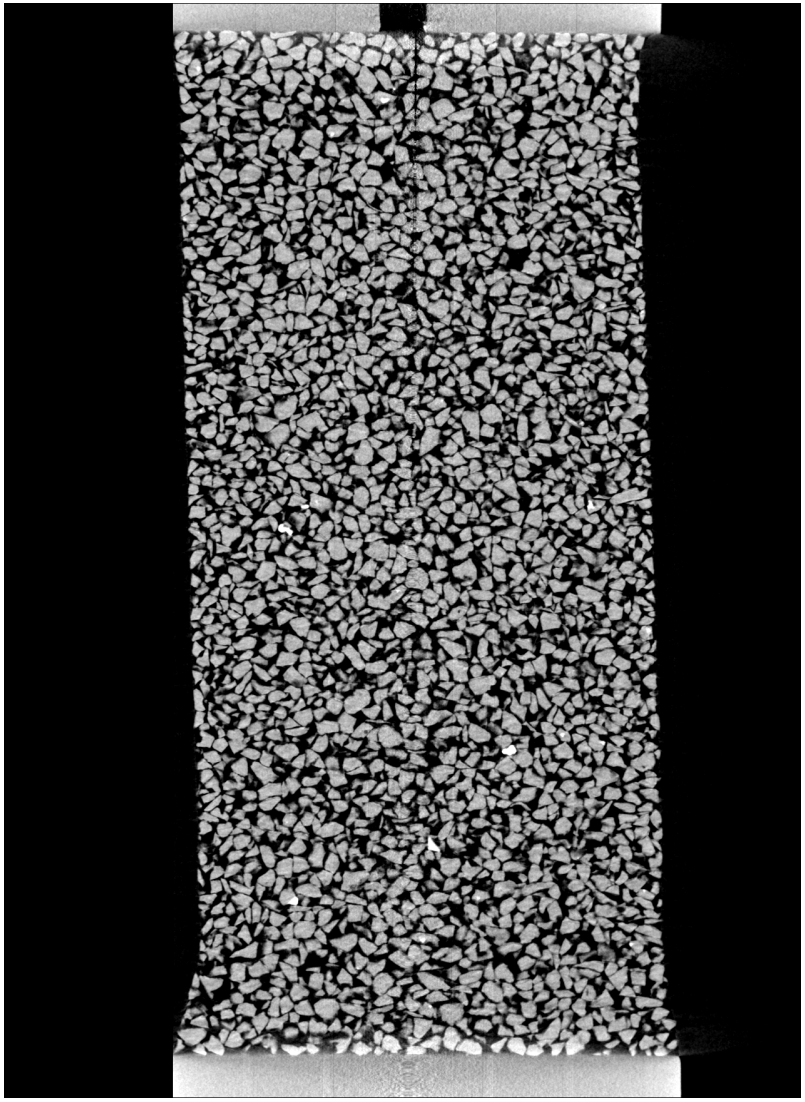
E. Andò, *Experimental investigation of microstructural changes in deforming granular media using x-ray tomography*, PhD 2013

Vertical slices through reconstructed volume (15 µm/px – $\phi = 11\,\mathrm{mm}$)



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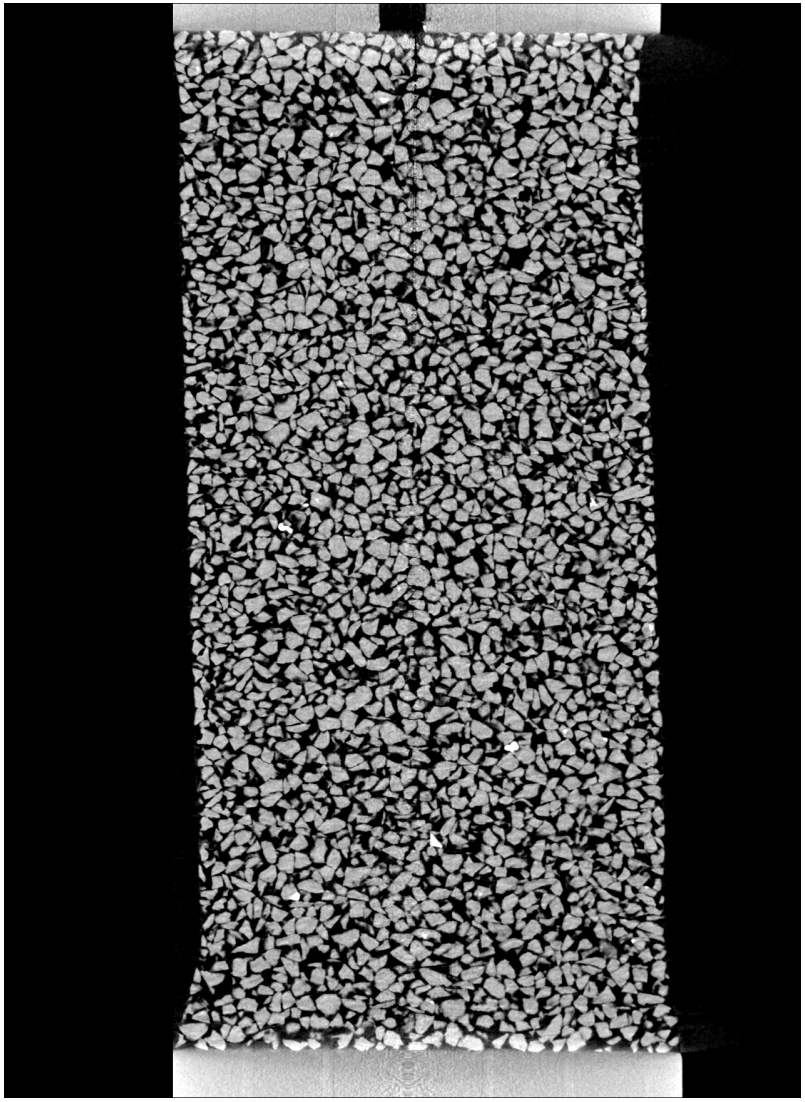

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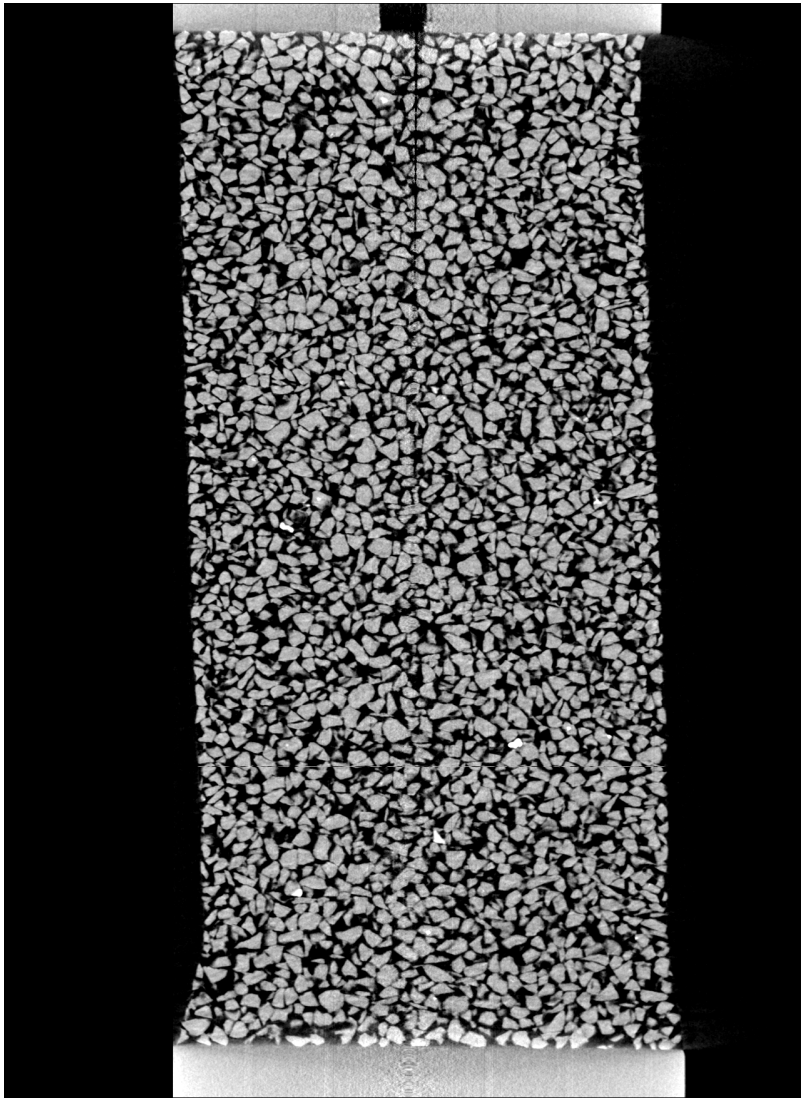

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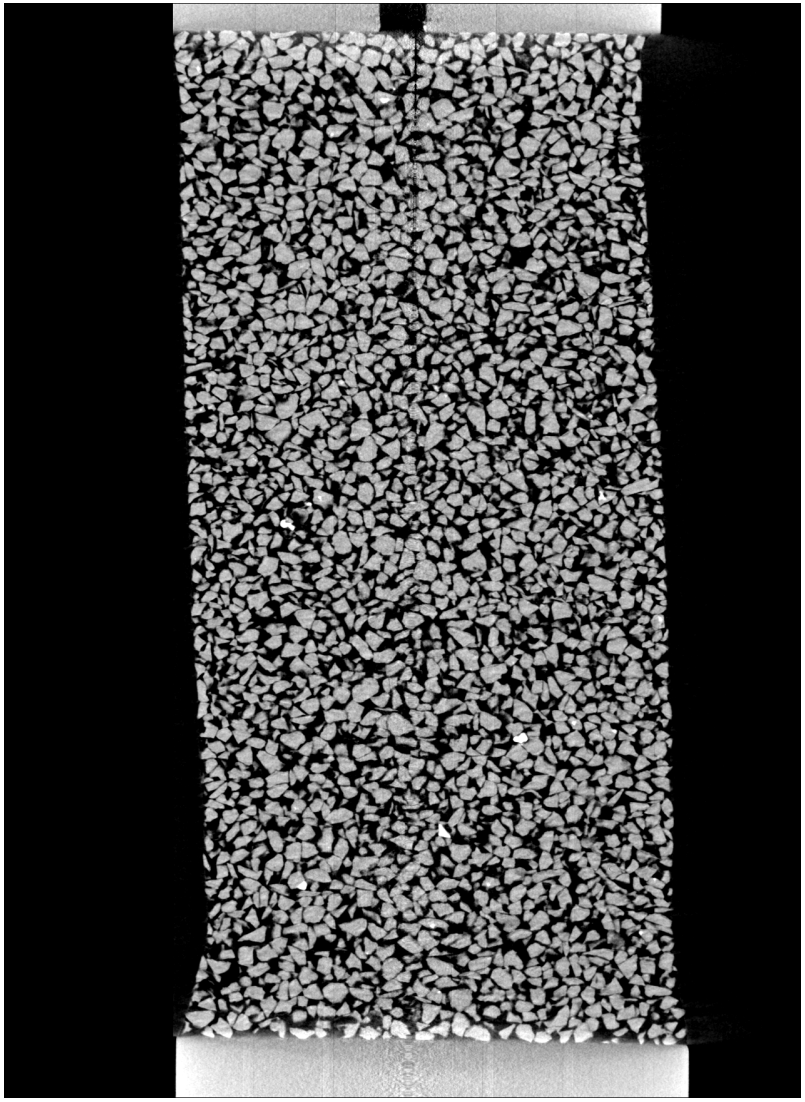

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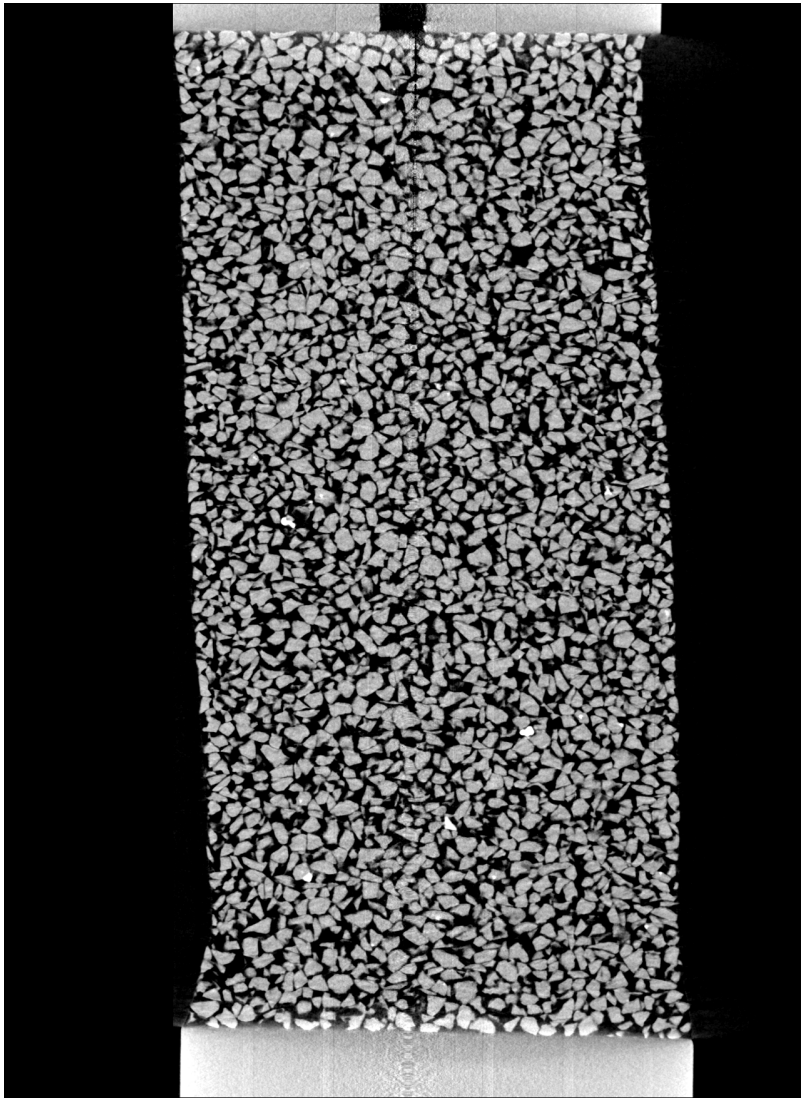

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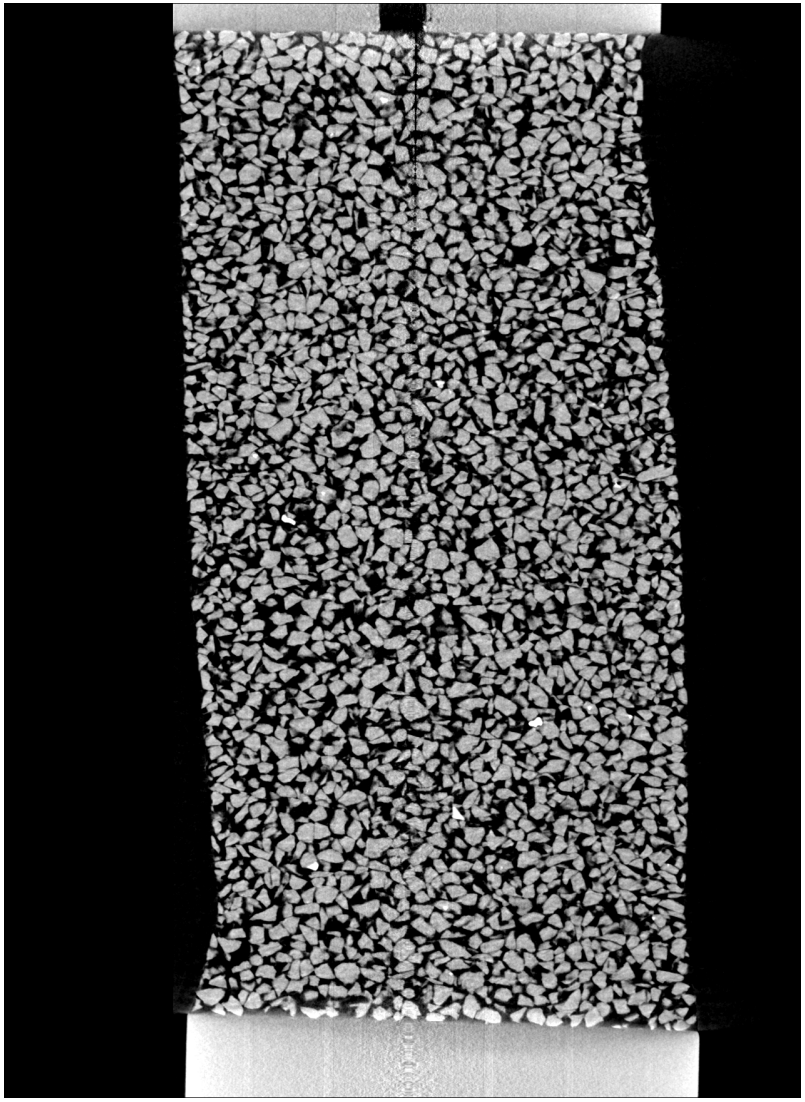

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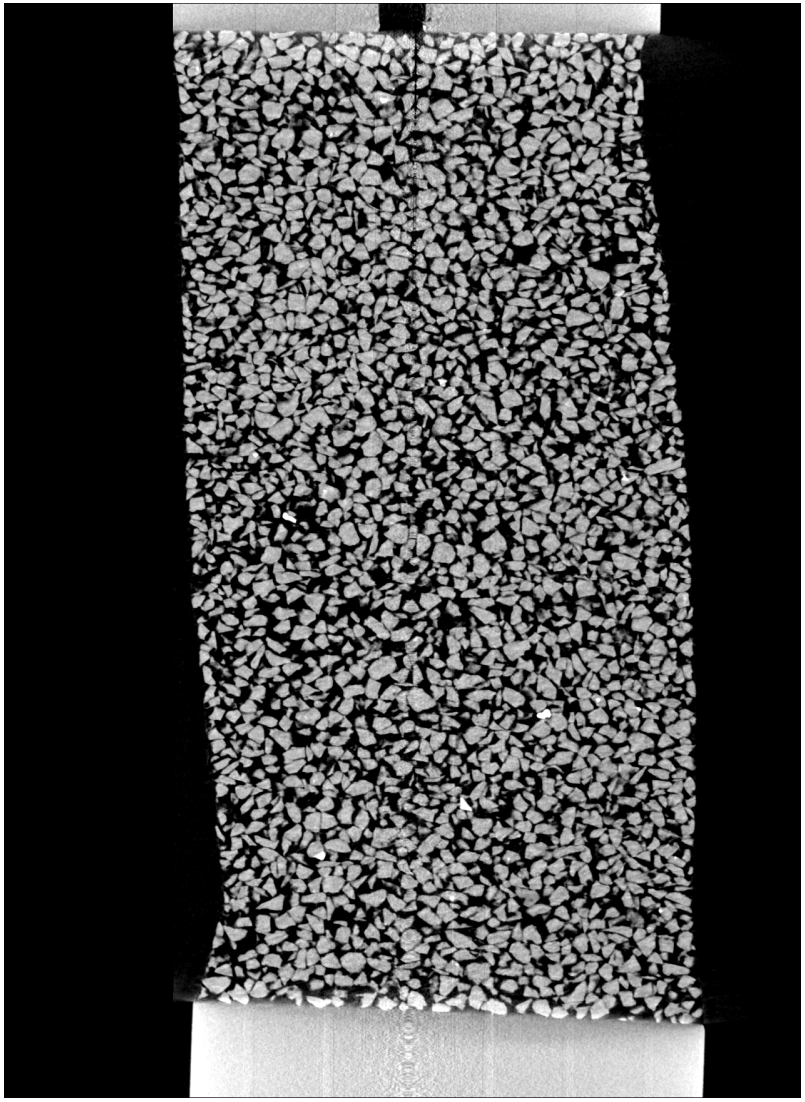

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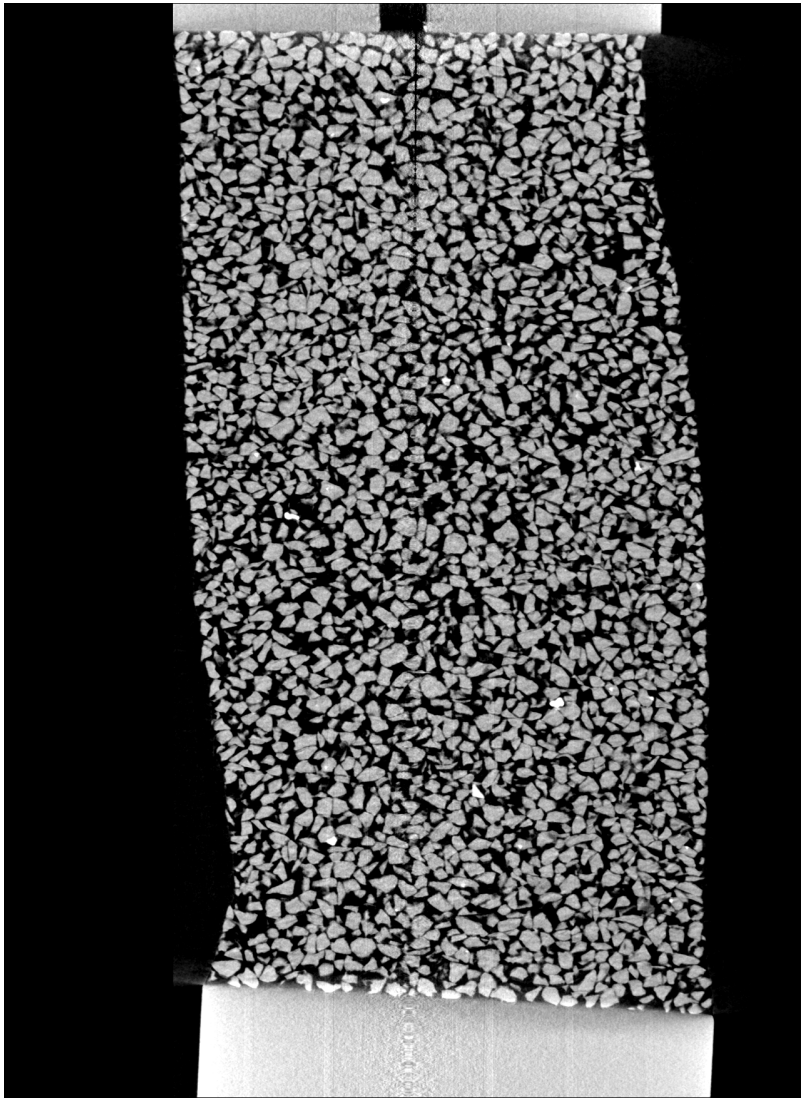

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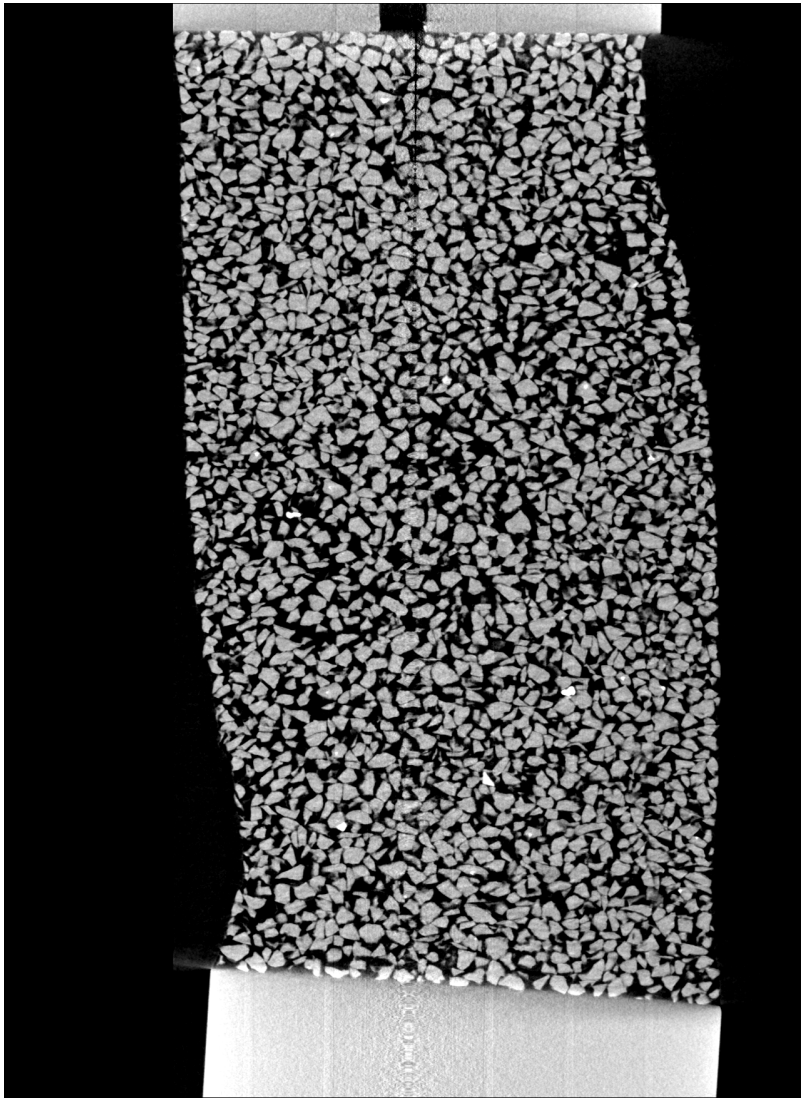

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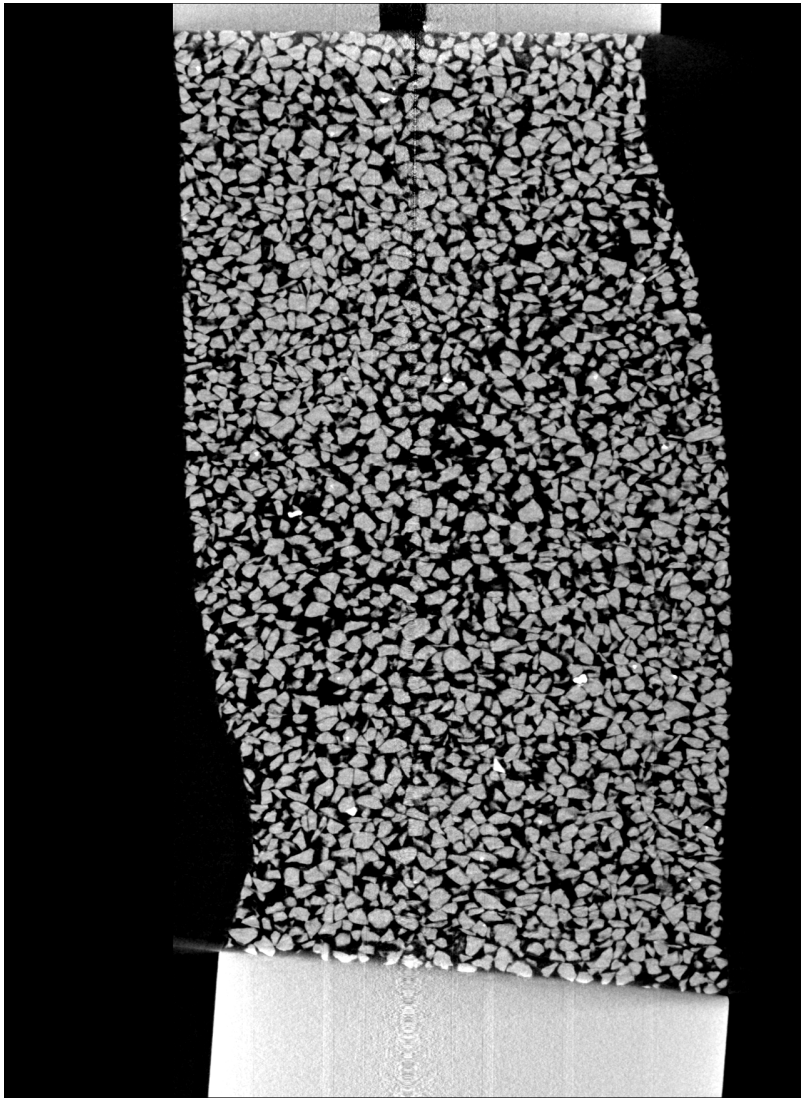

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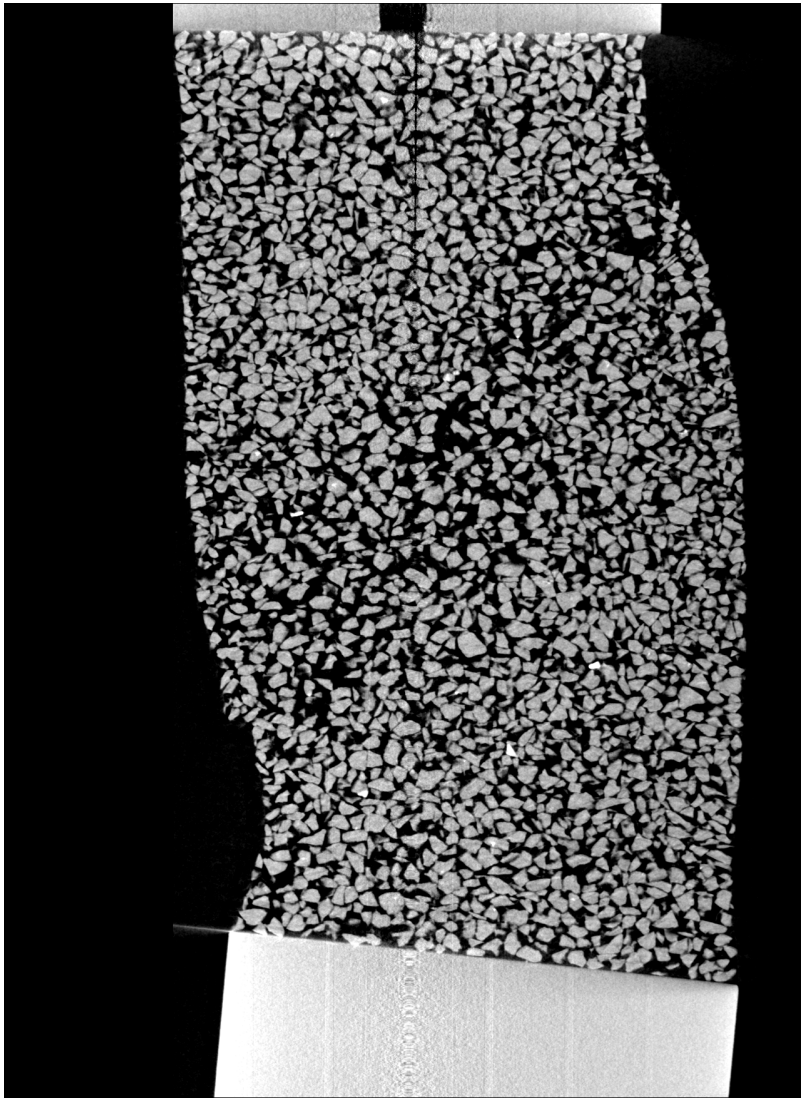

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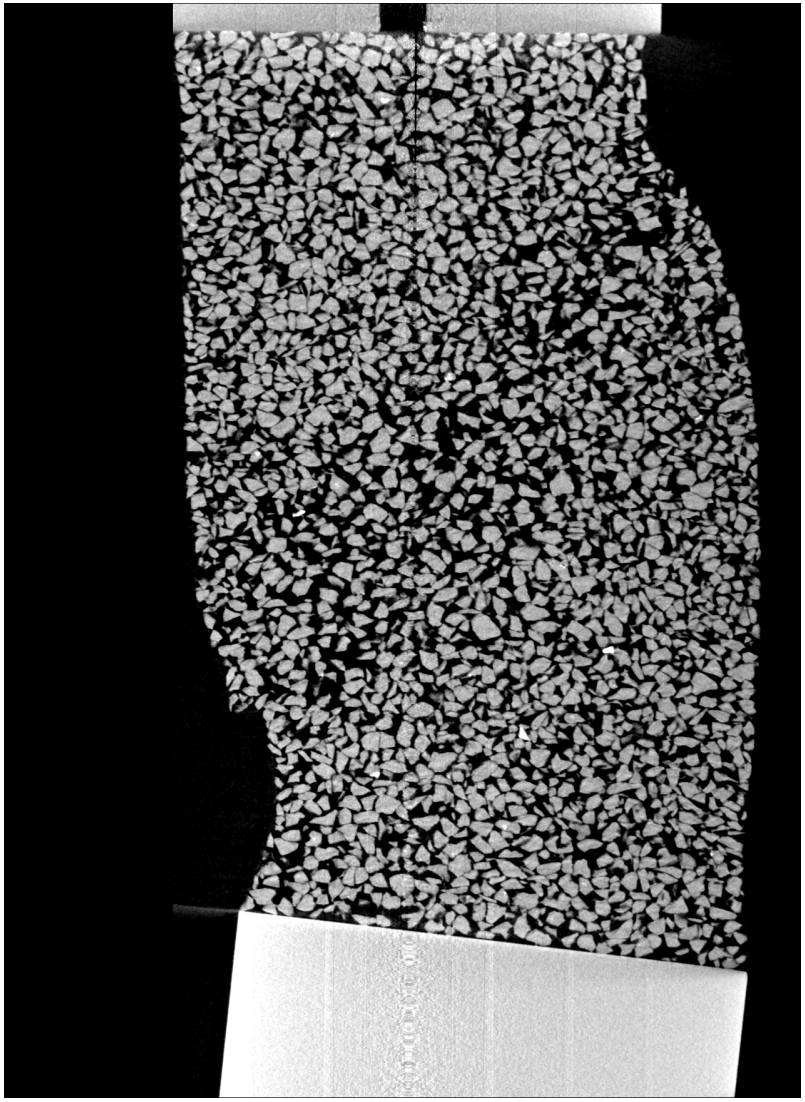

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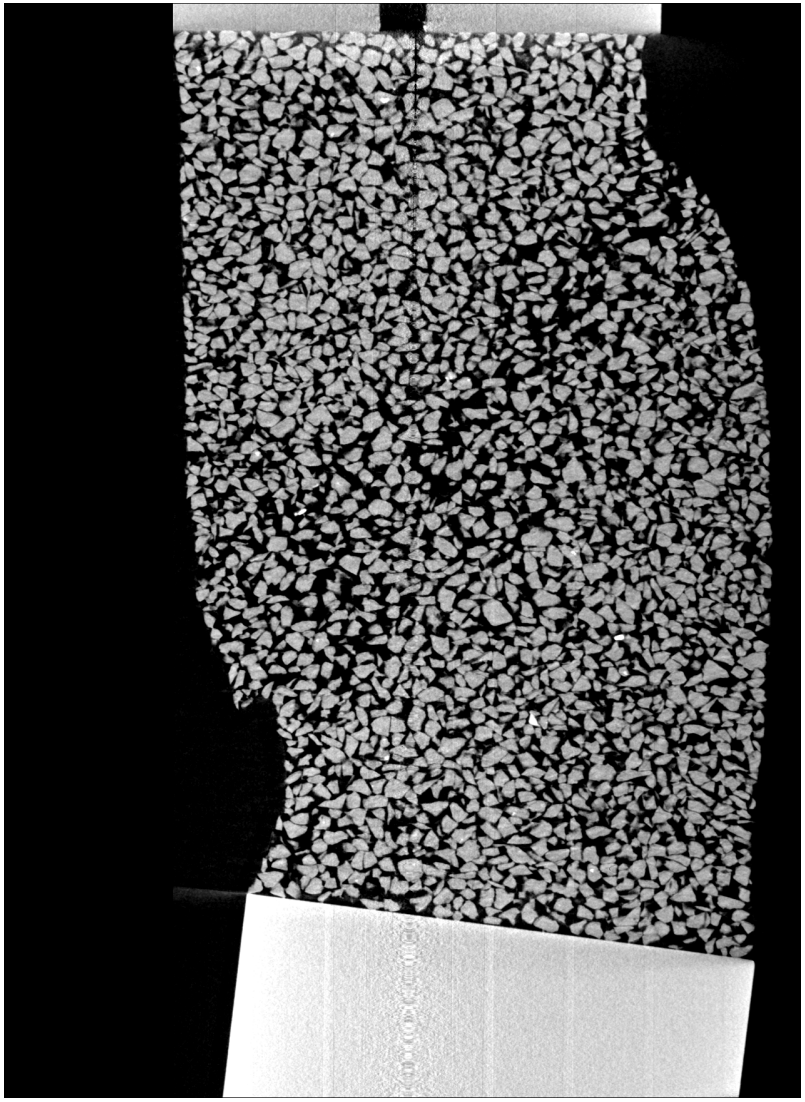

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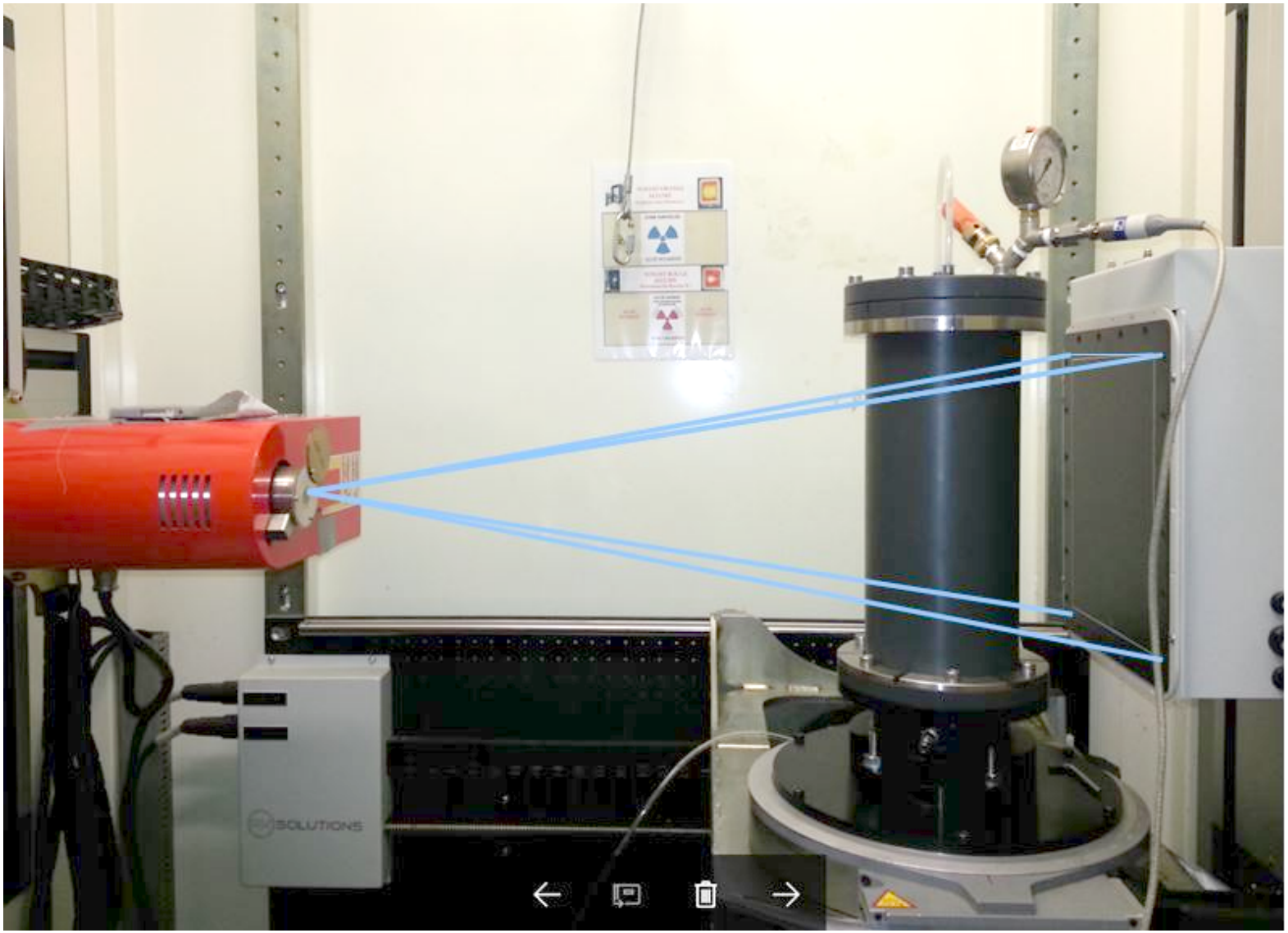
It's clear that there is a wealth of data. A triaxial test goes from a **few KB** to several **hundred GB**!

Another example, larger field of view (J. Desrues):



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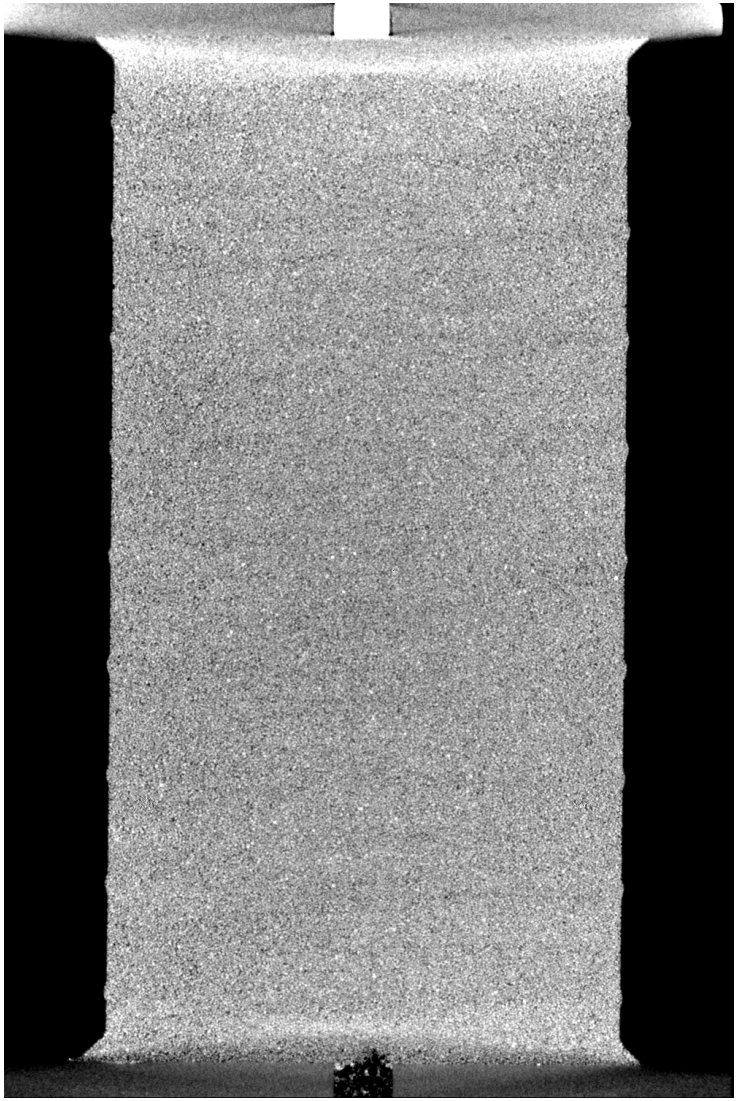

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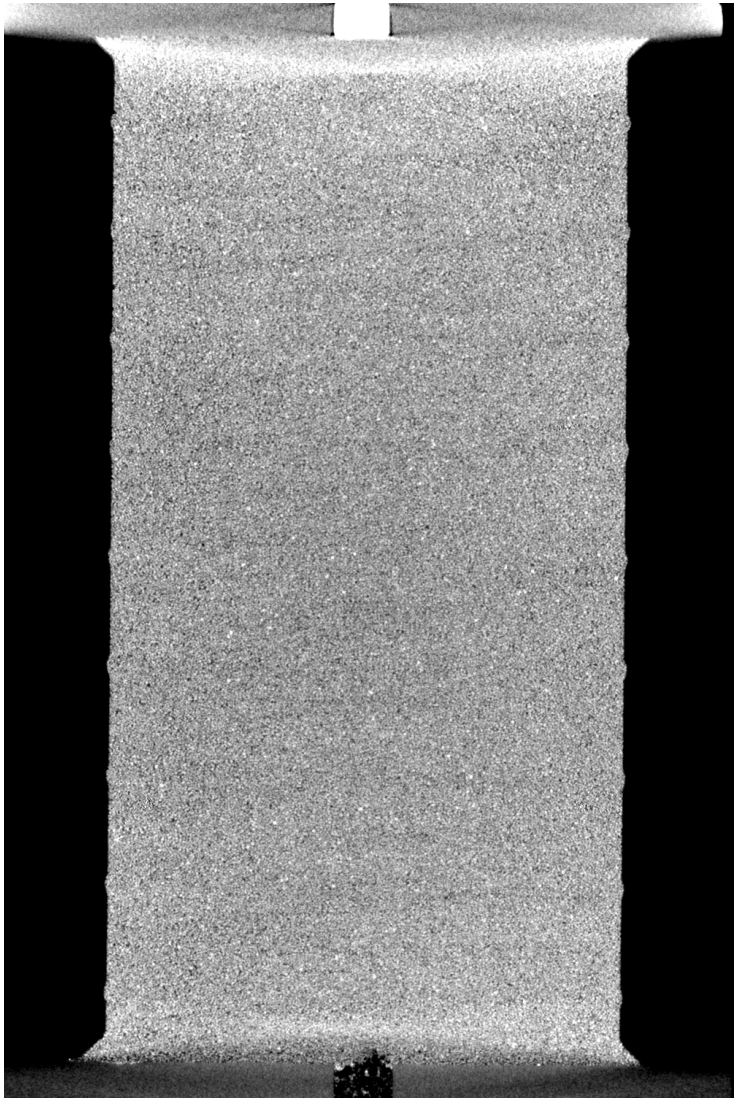

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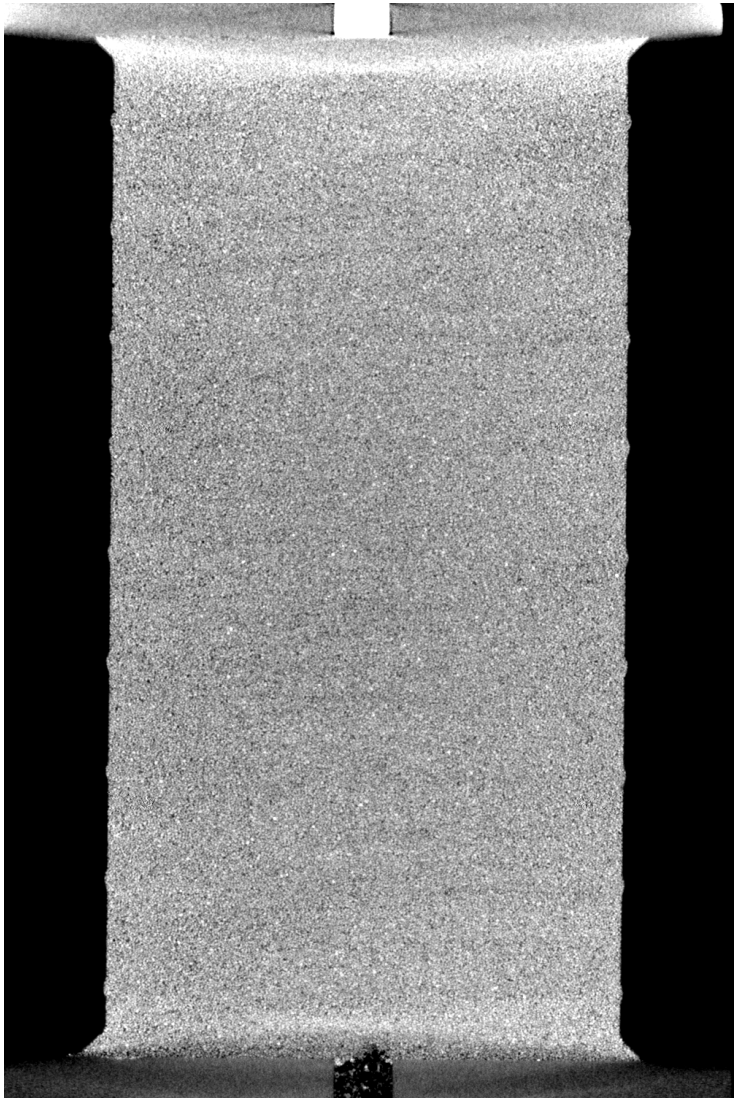

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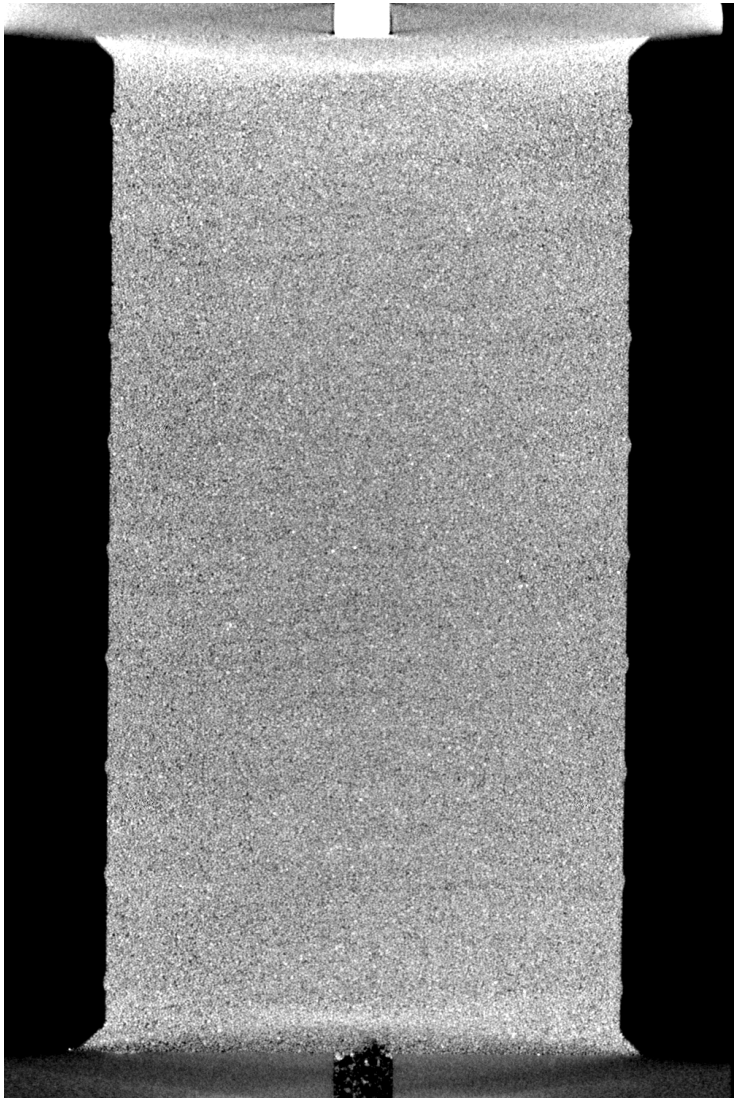

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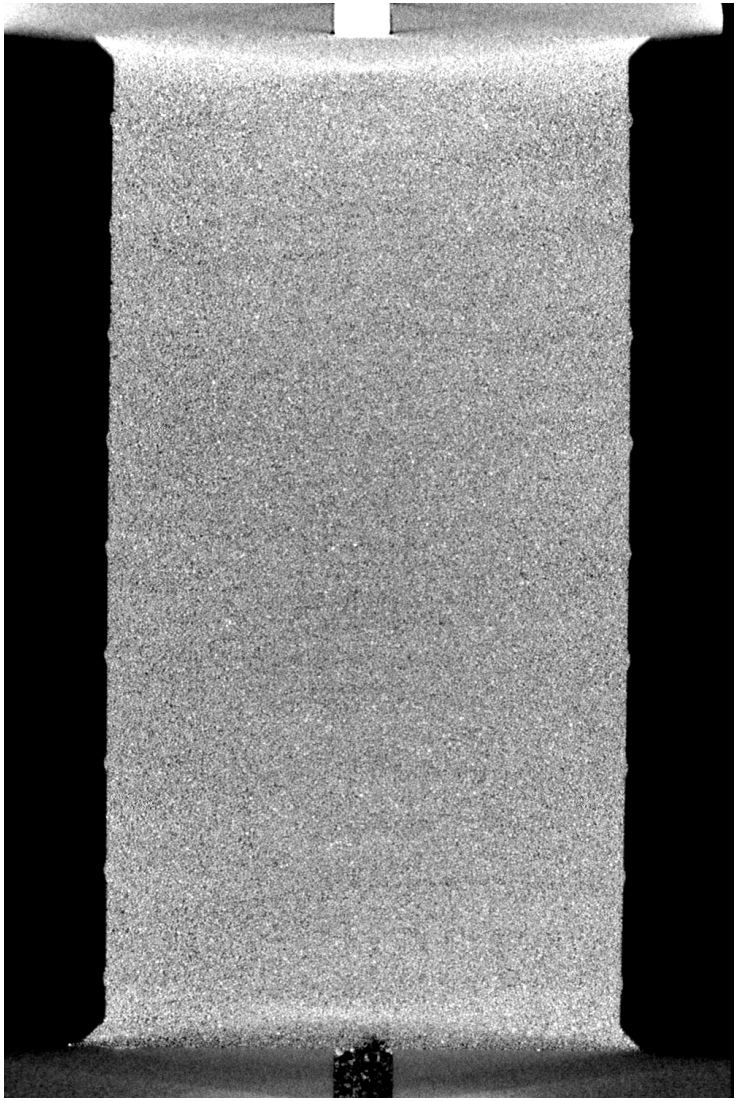

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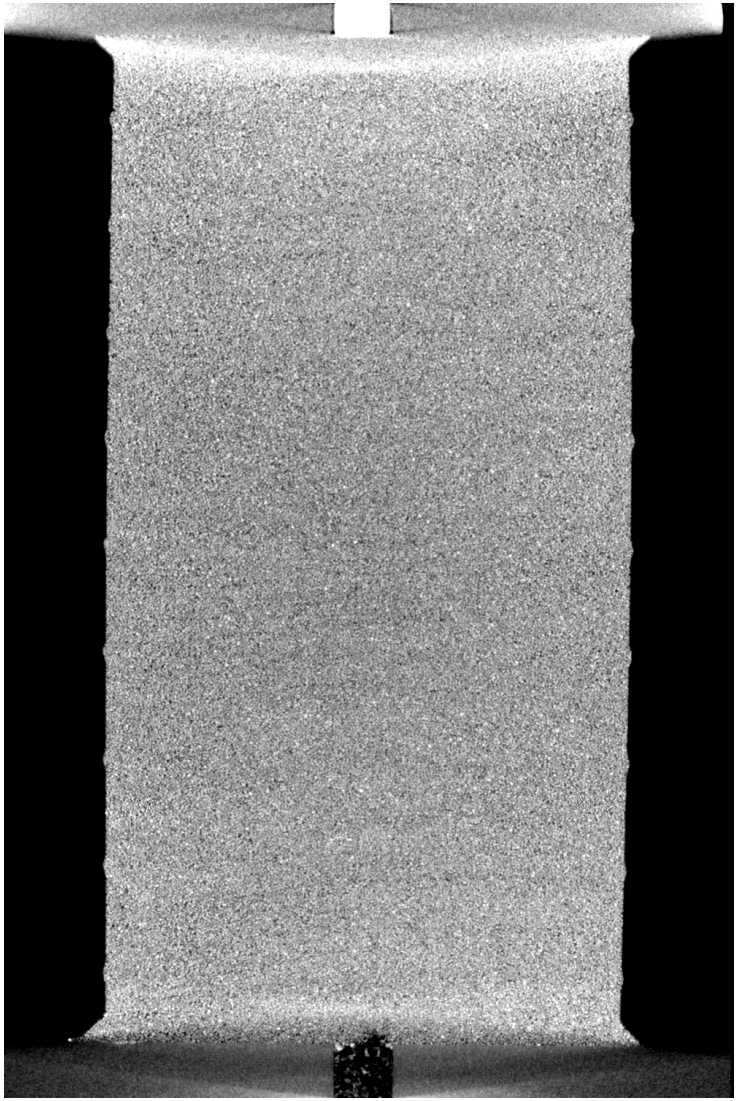

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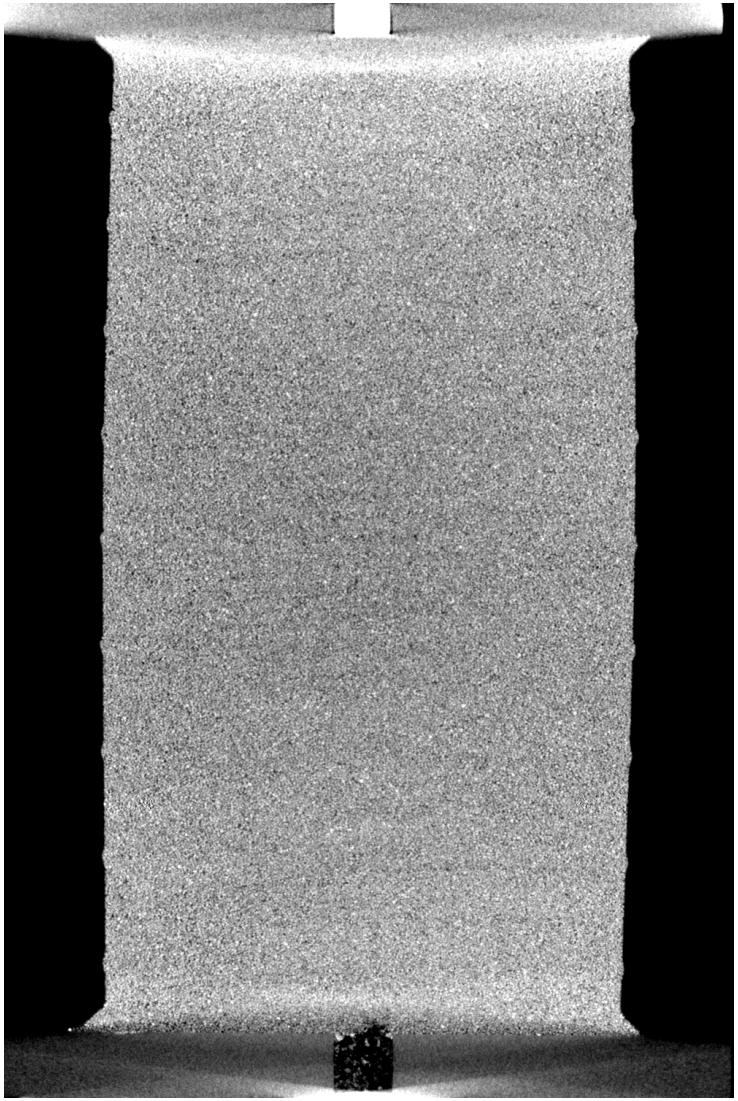

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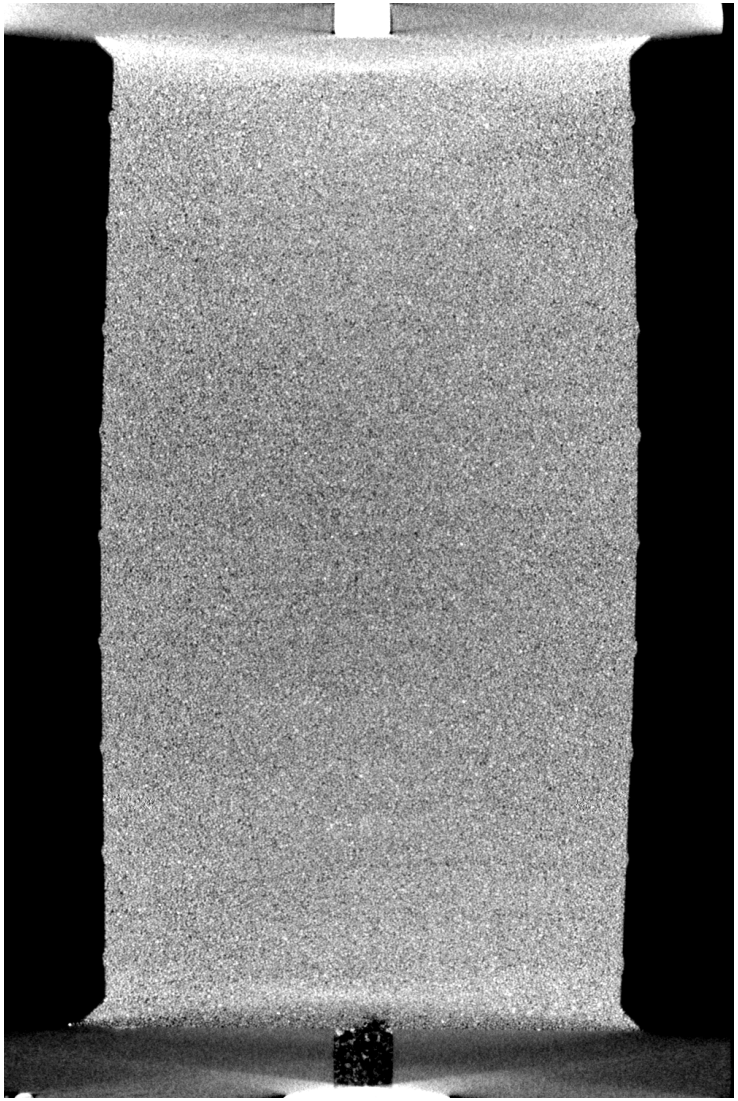

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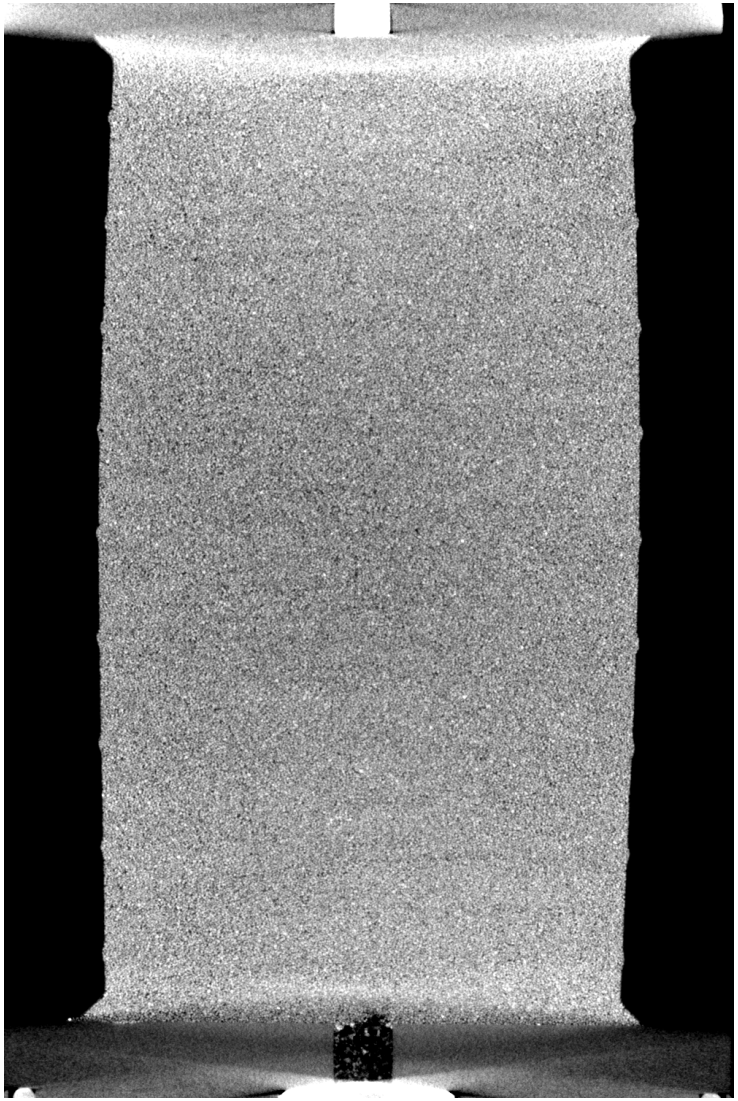

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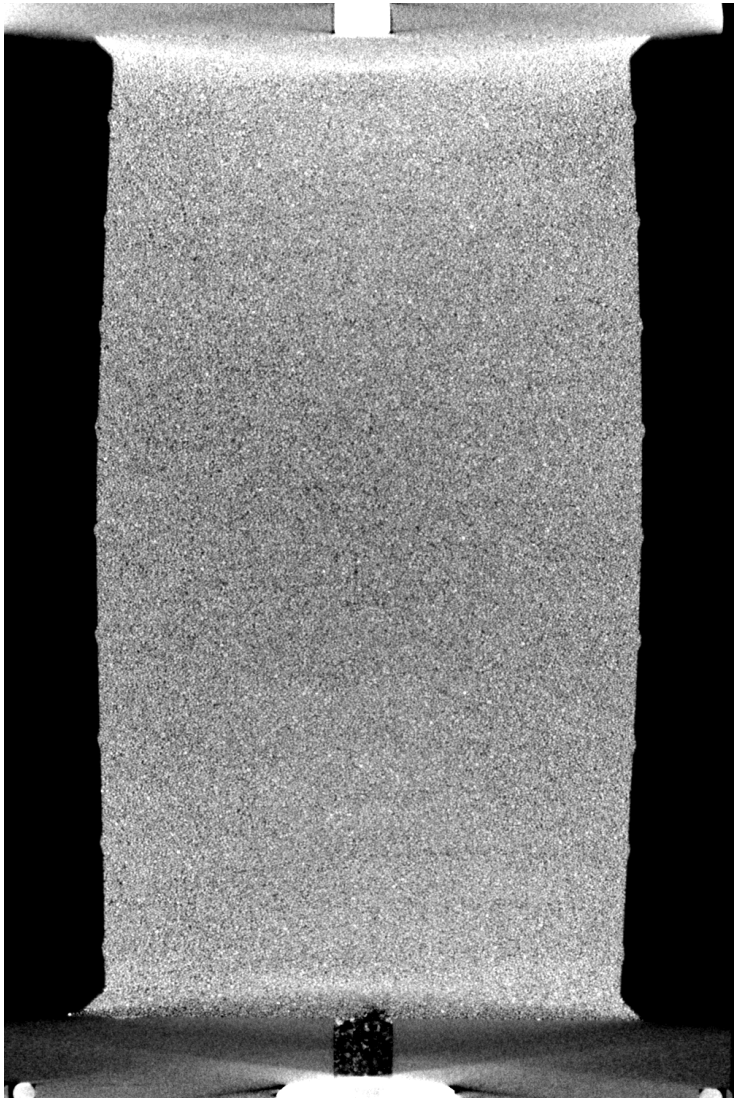

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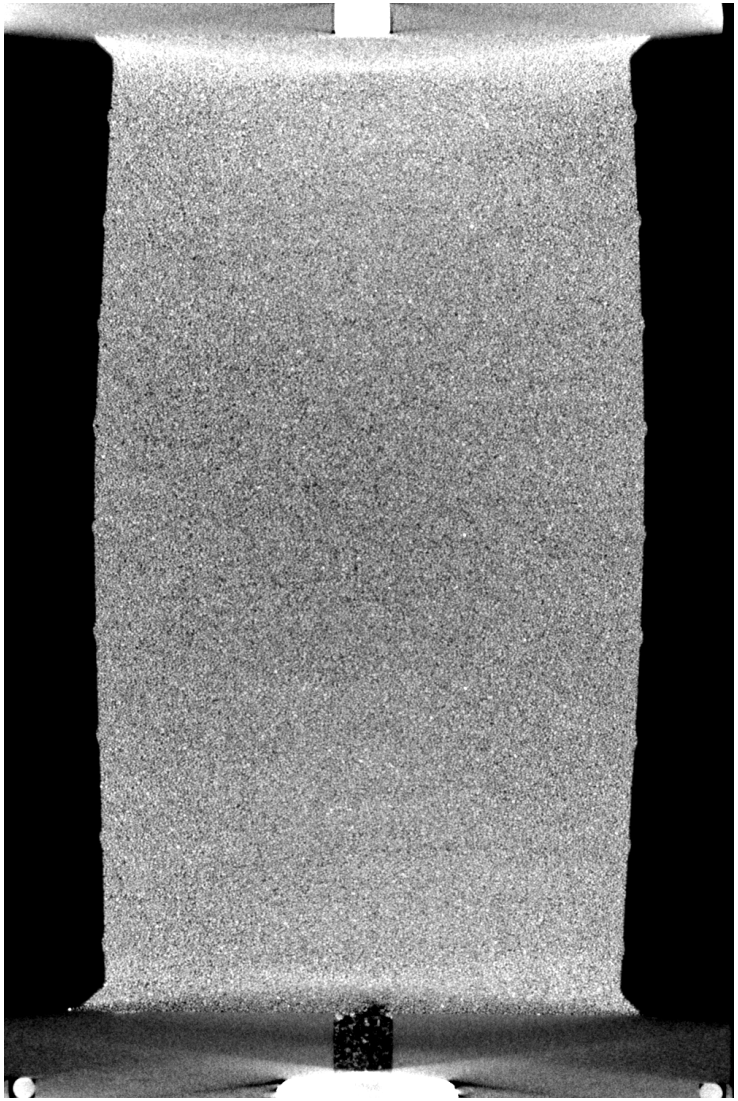

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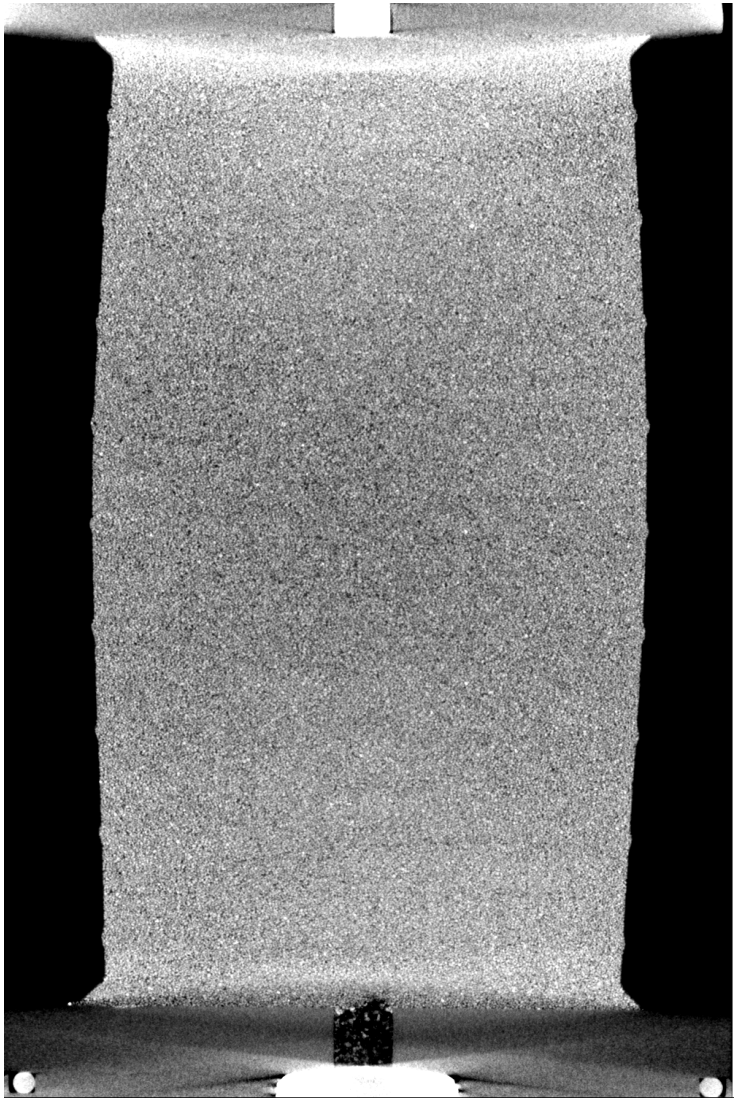

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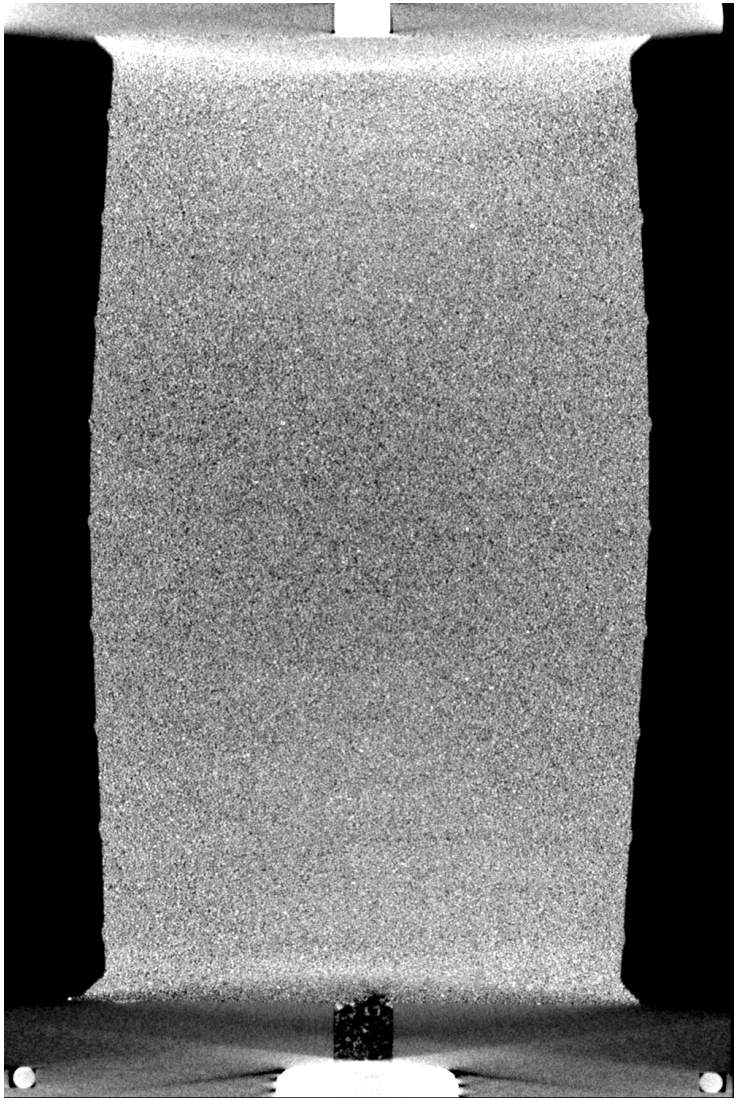

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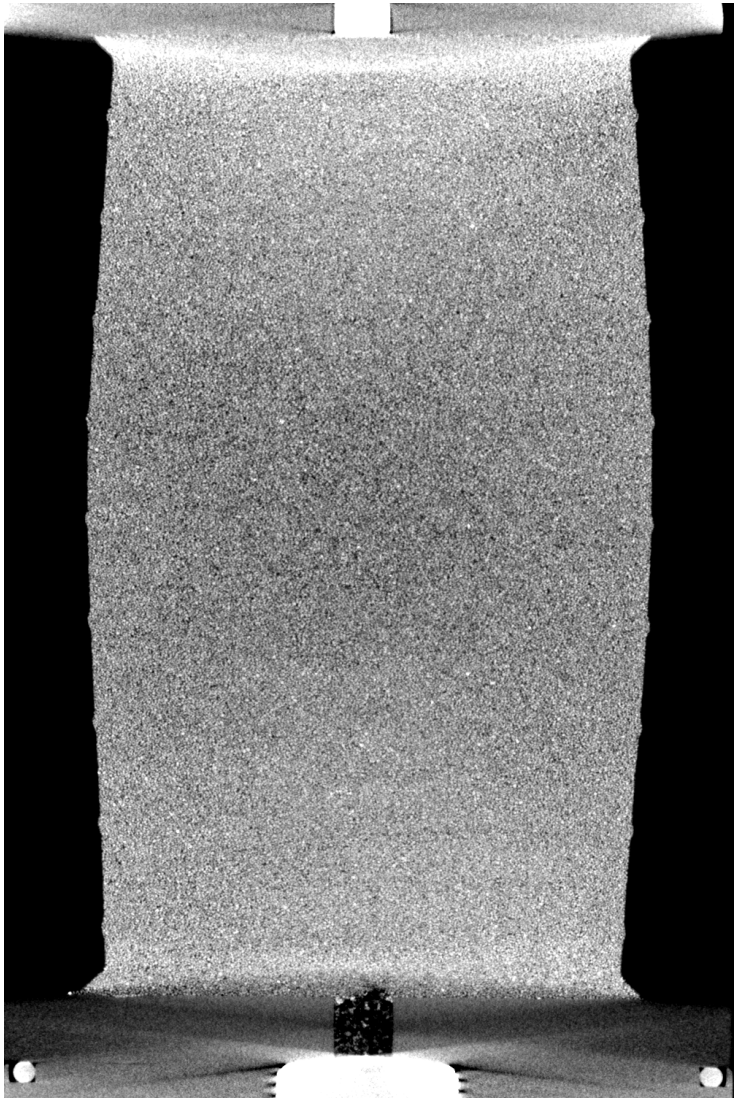

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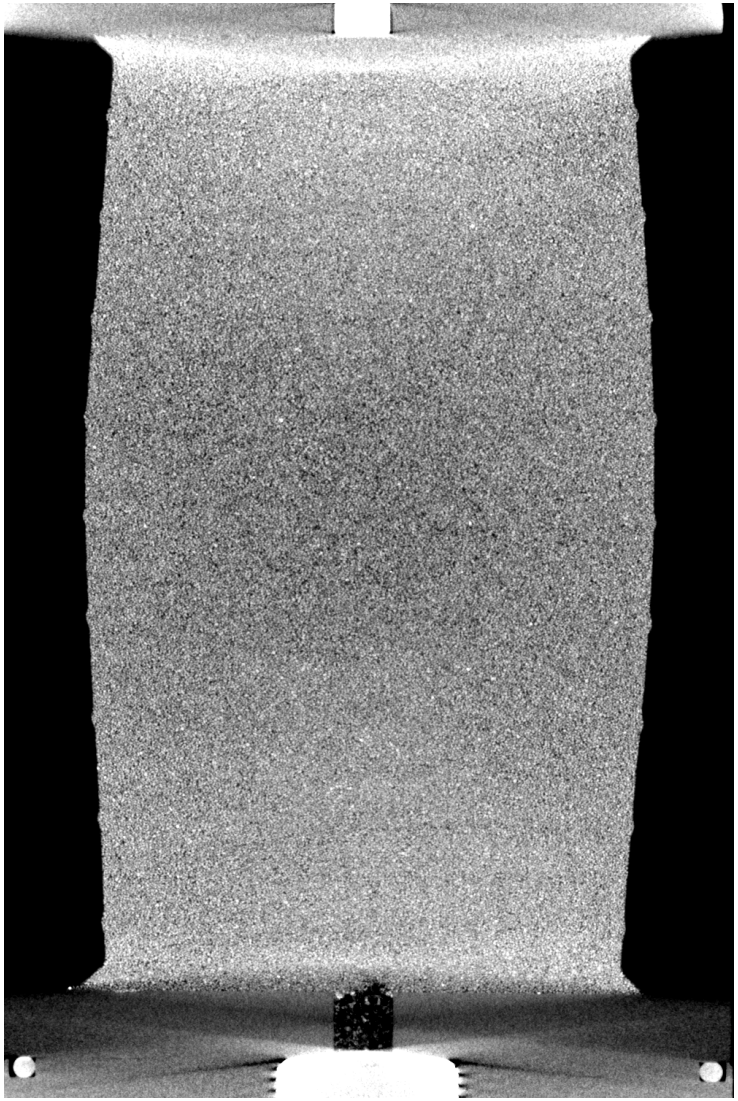

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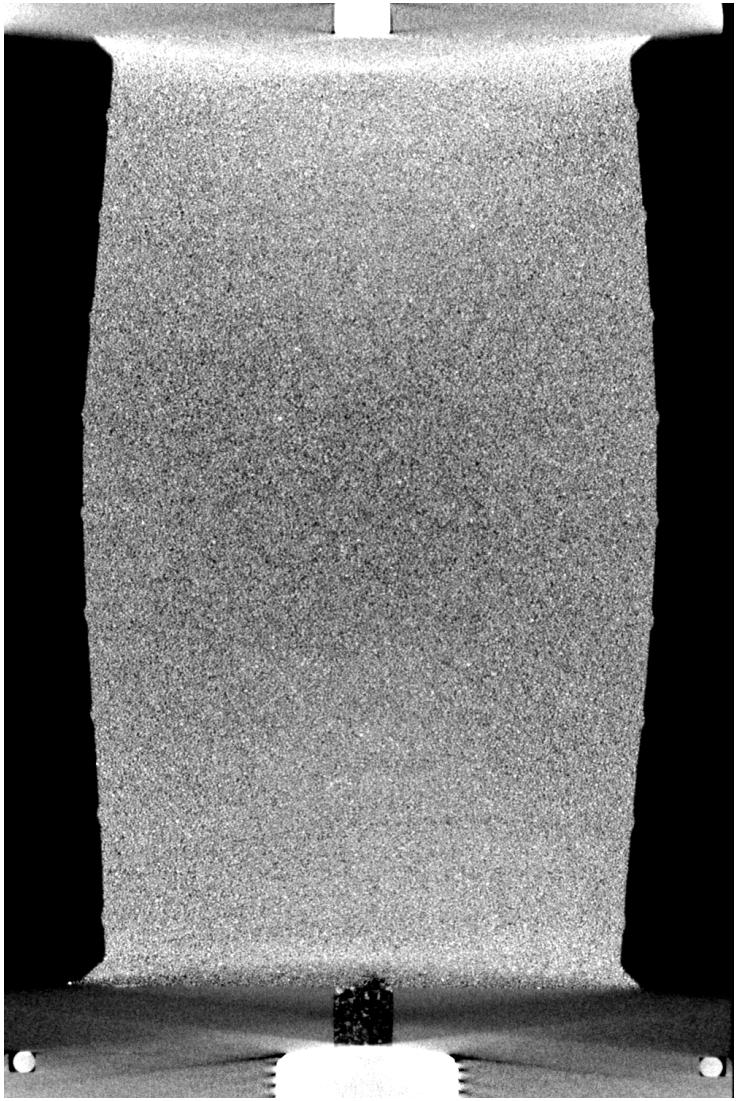

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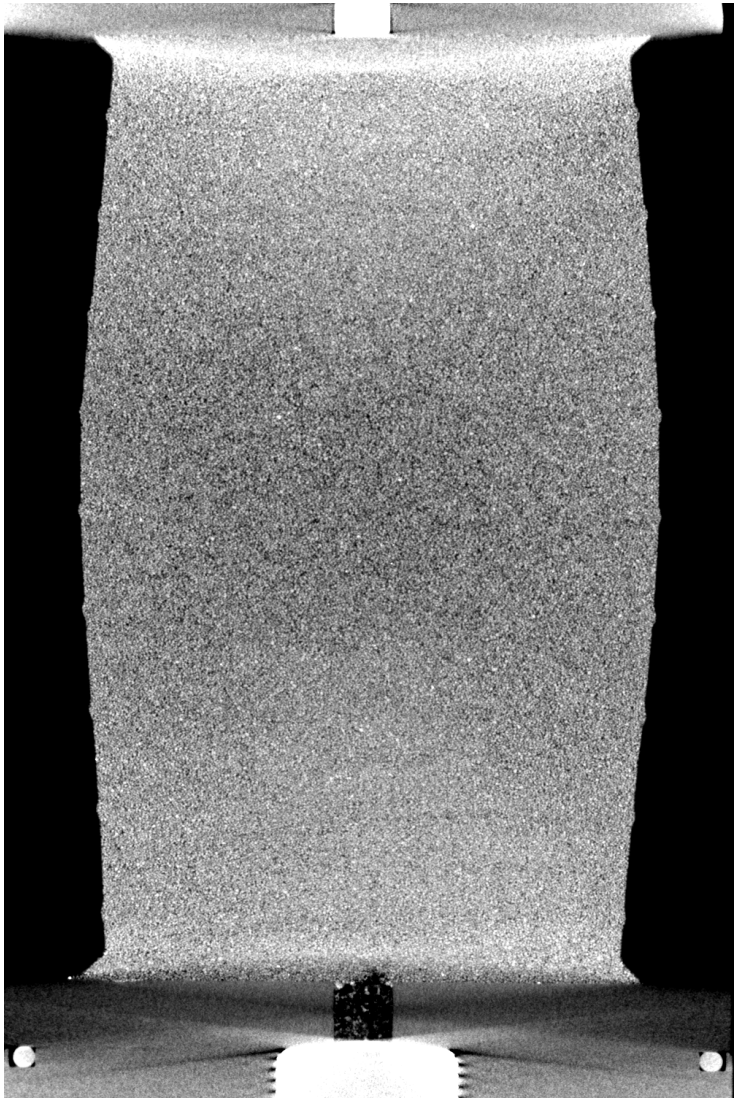

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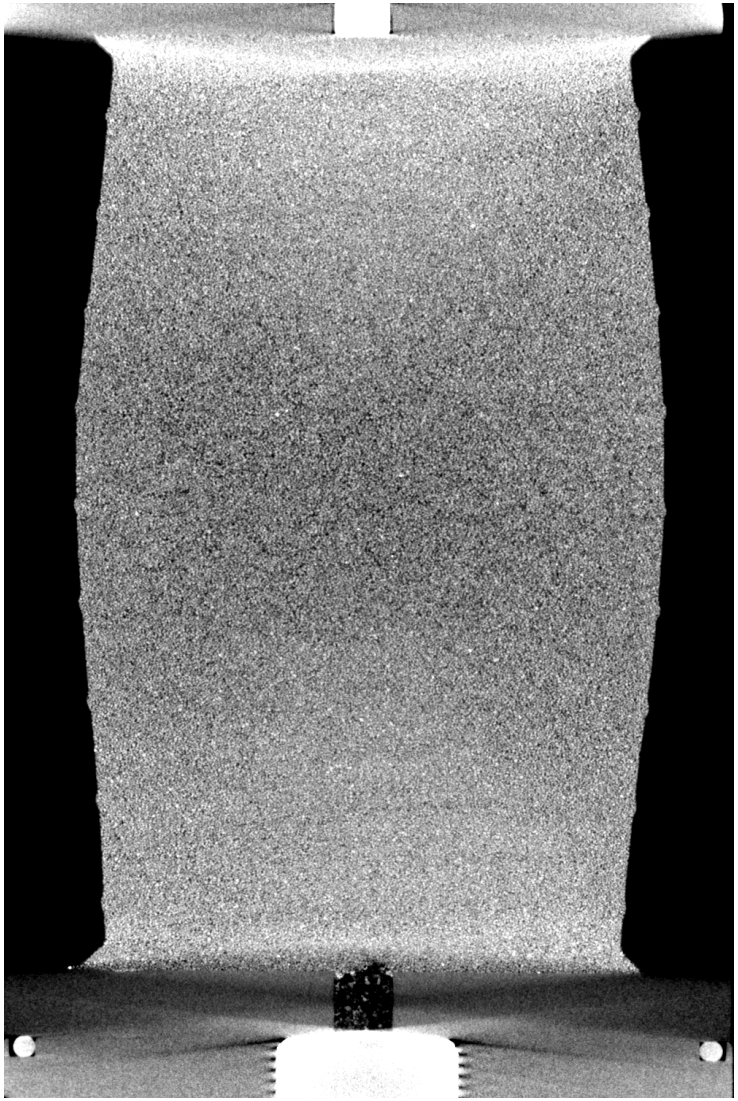

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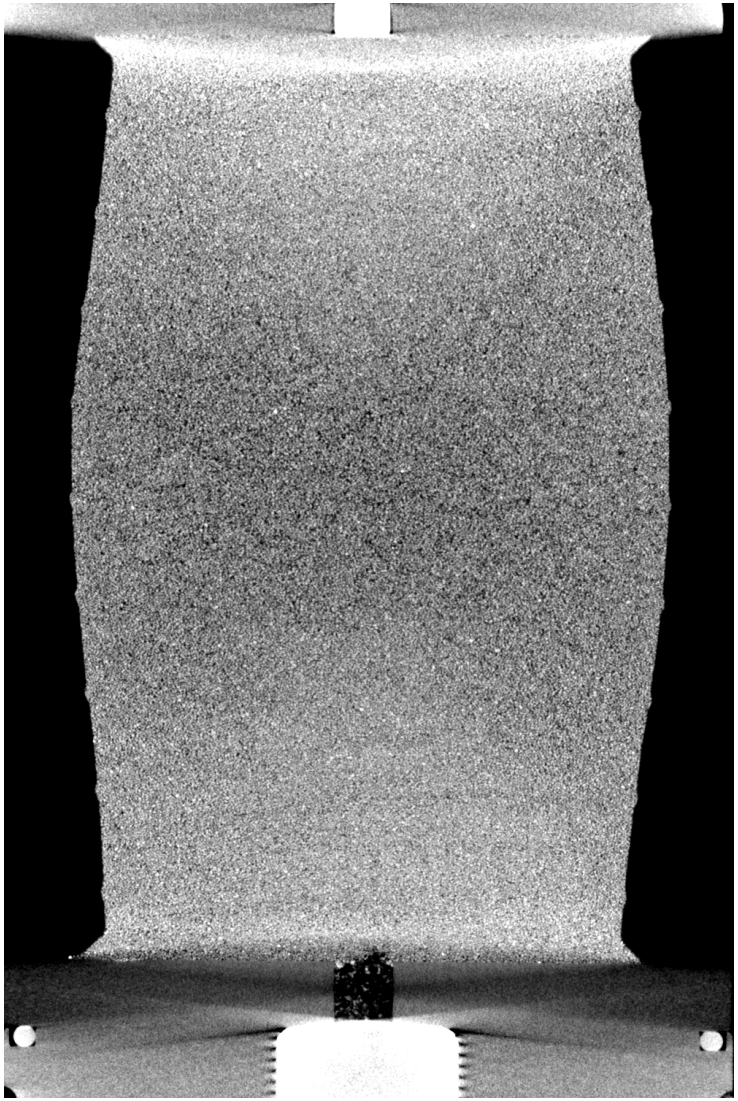

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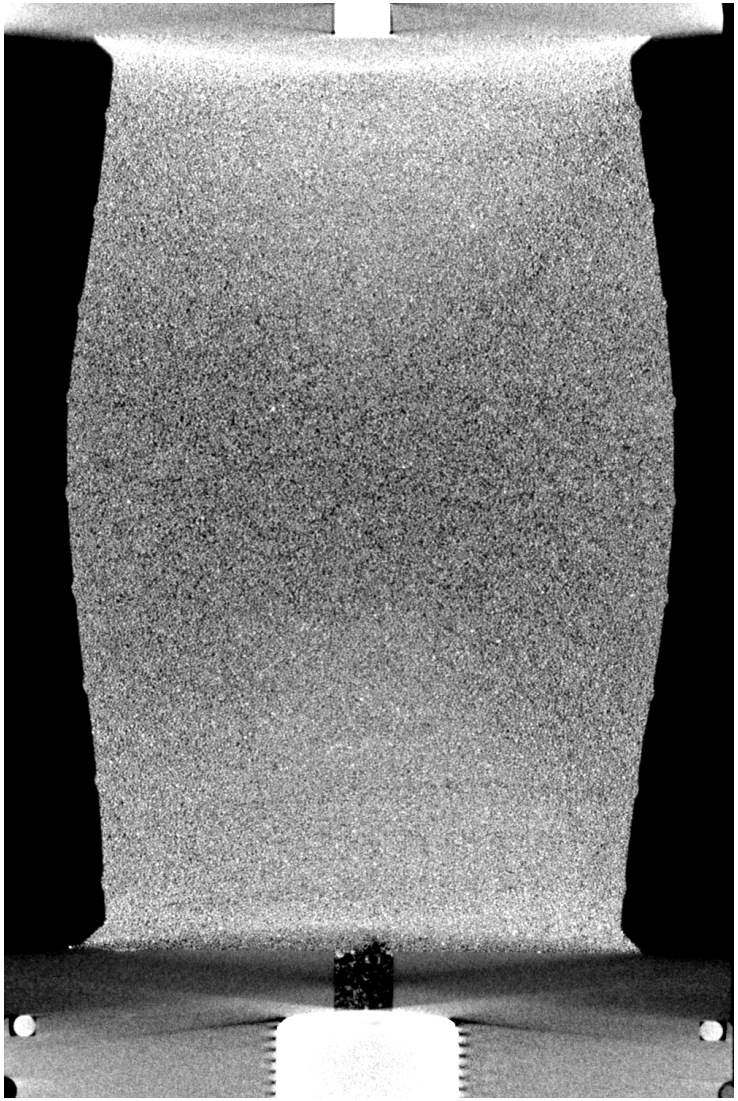

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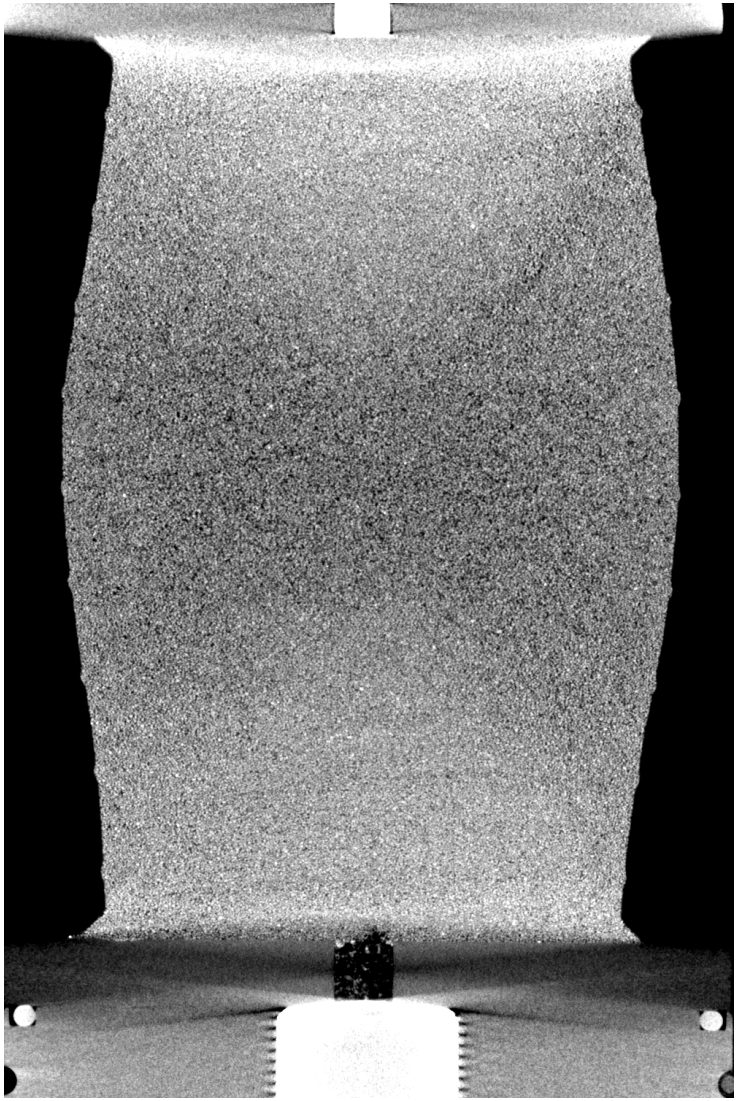

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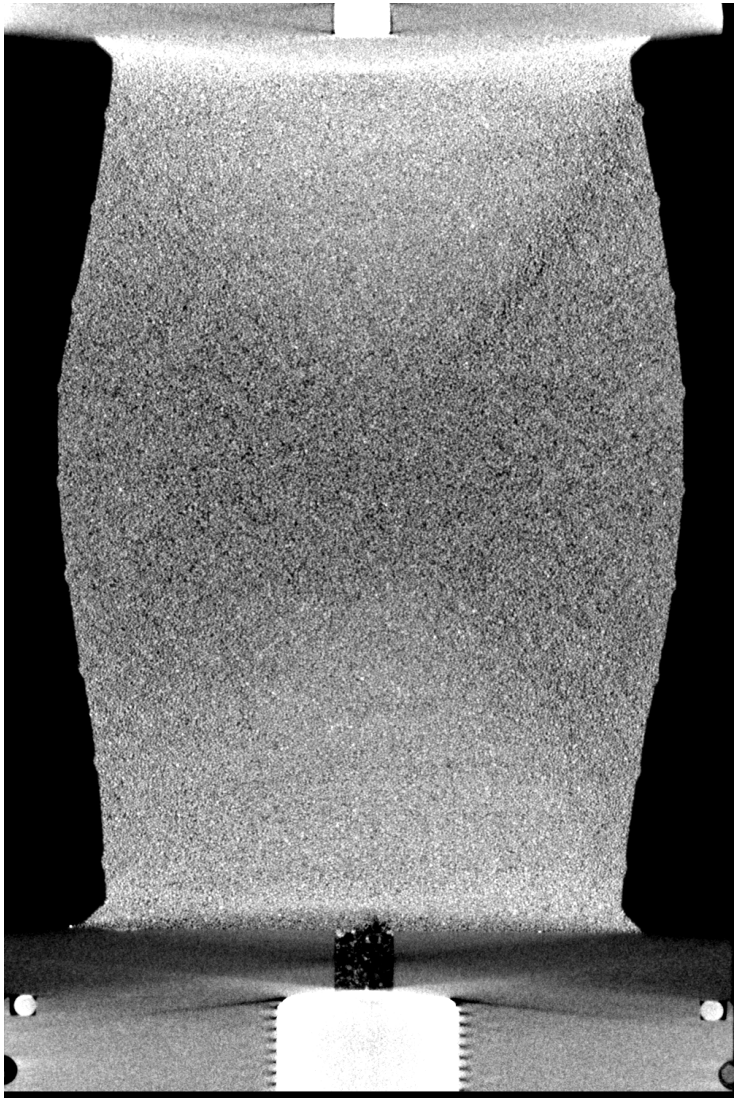

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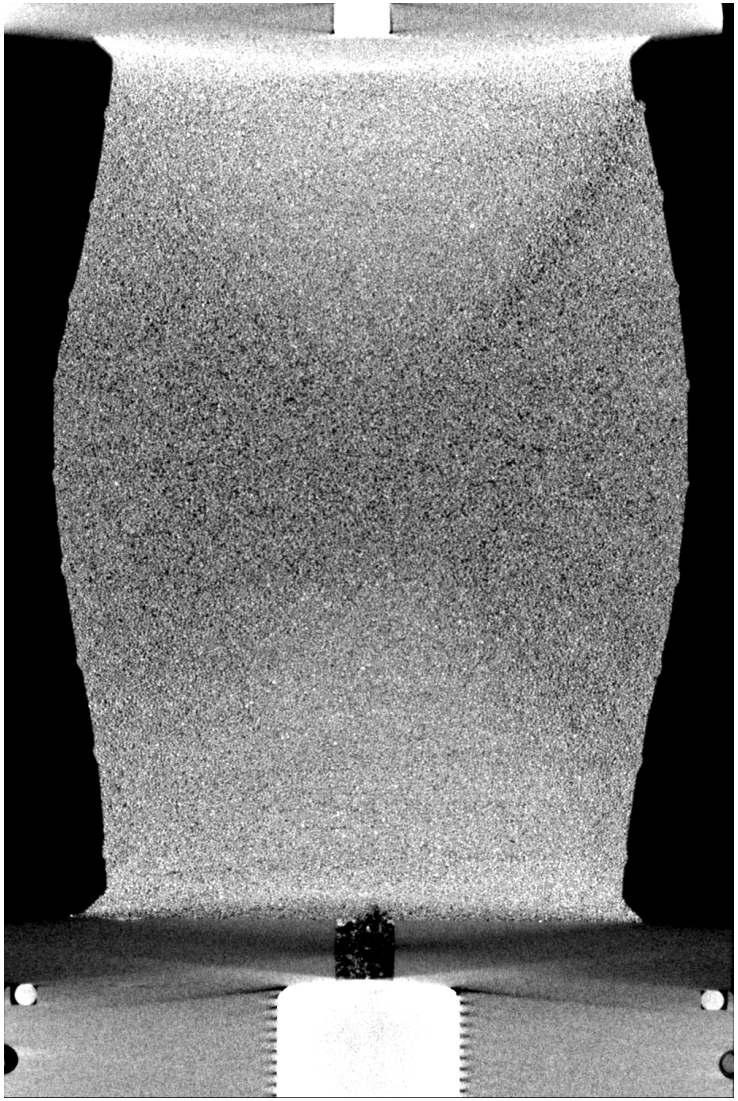

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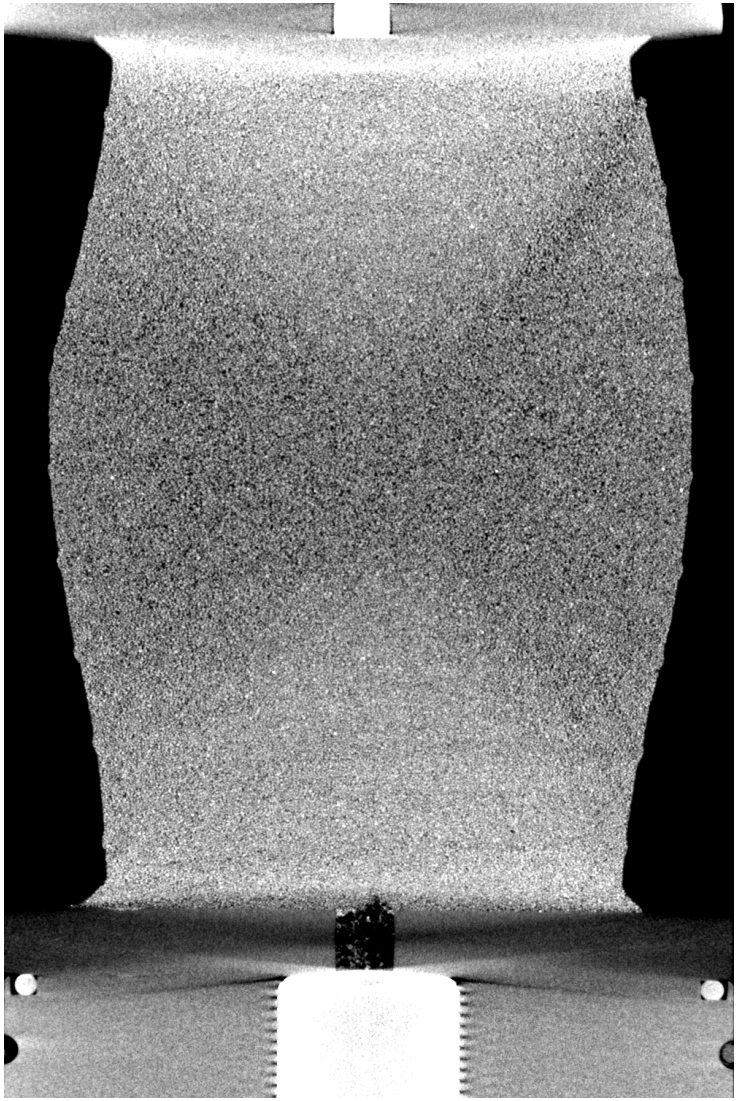

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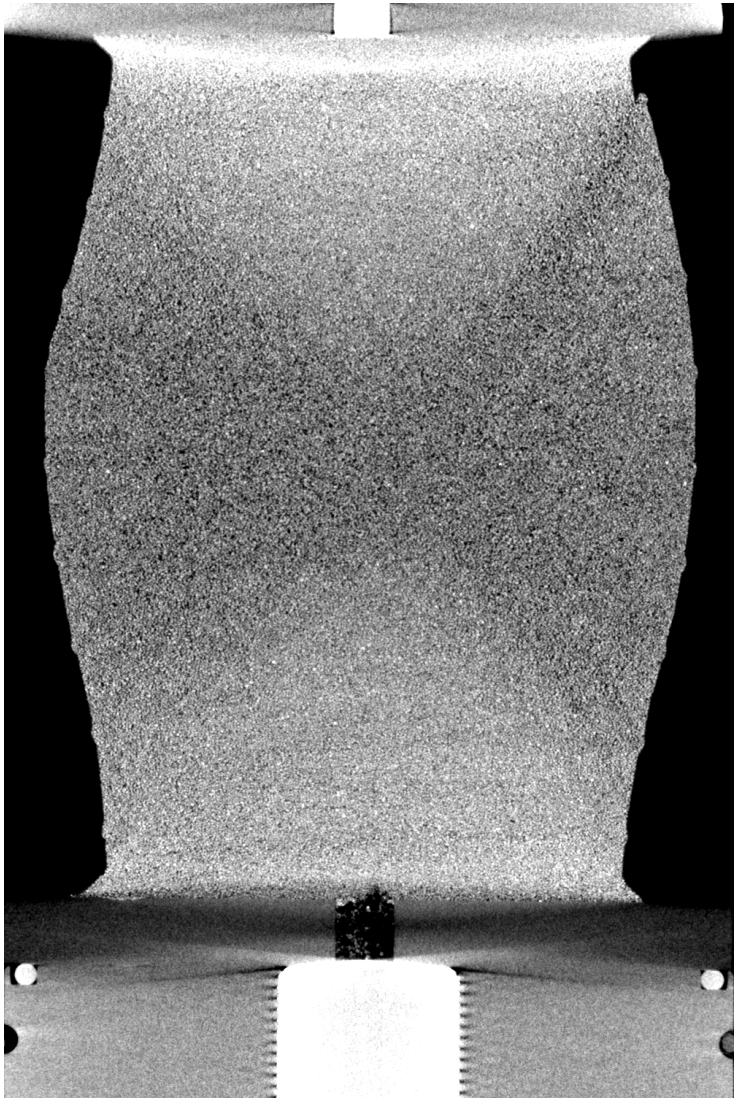

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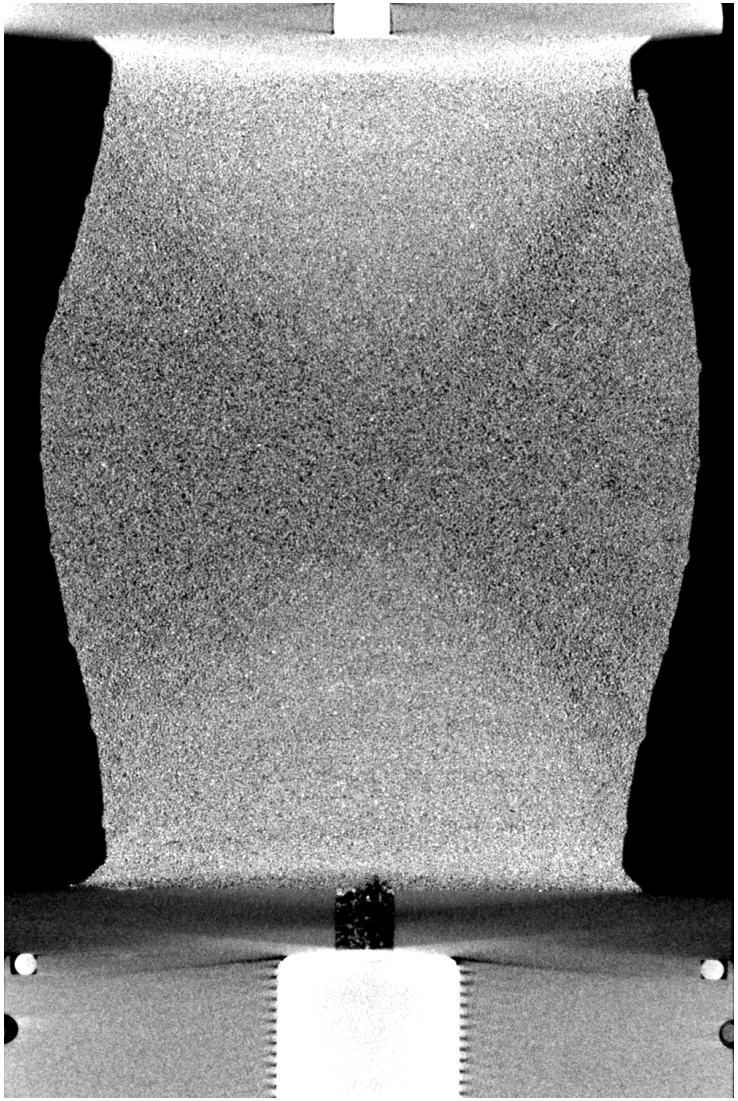

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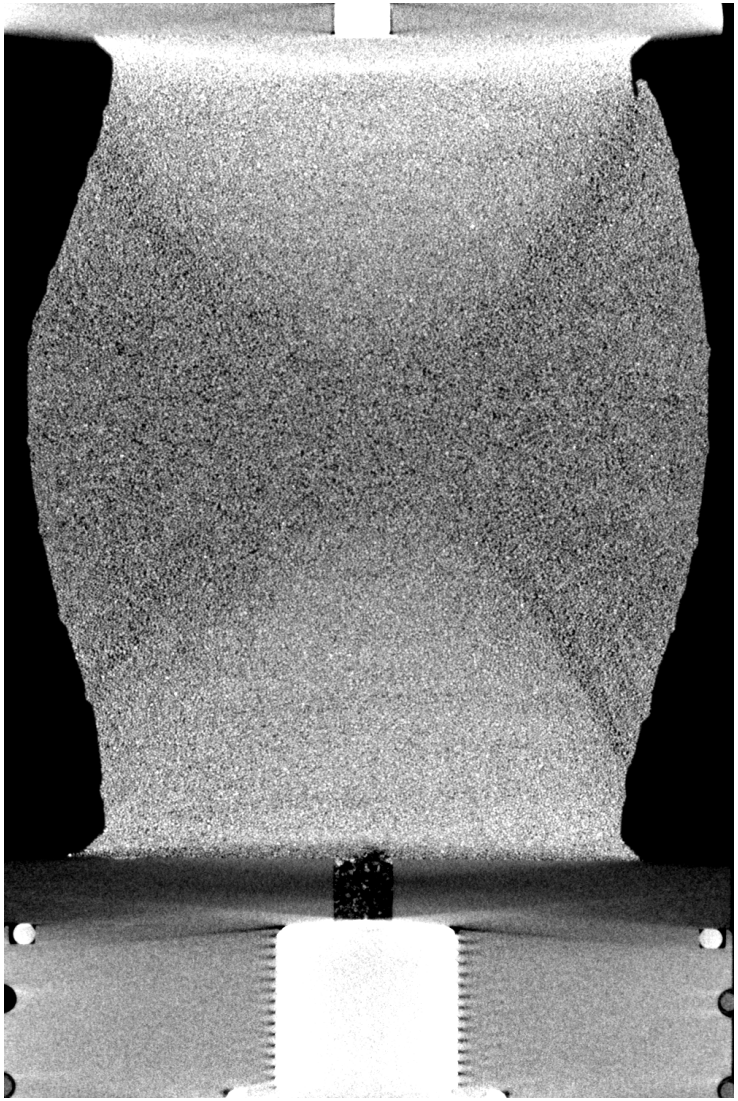

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Wow! New way of looking at experiments!

What to do with the data?

Starting from the 3D+Time volumes acquired may things are possible, we will discuss two:

1. Characterisation of grains (size, shape, position)
2. Kinematics (transformation with time)

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In Grenoble we develop and share our tools to do this:

Software for Practical Analysis of Materials

`https://ttk.gricad-pages.univ-grenoble-alpes.fr/spam/intro.html`

Particle identification

Using the language from before we need sufficiently **sharp** and **noise-free** image to be able to detect grains.

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Need sufficiently small pixel size (at least $\frac{D_{50}}{10}$).

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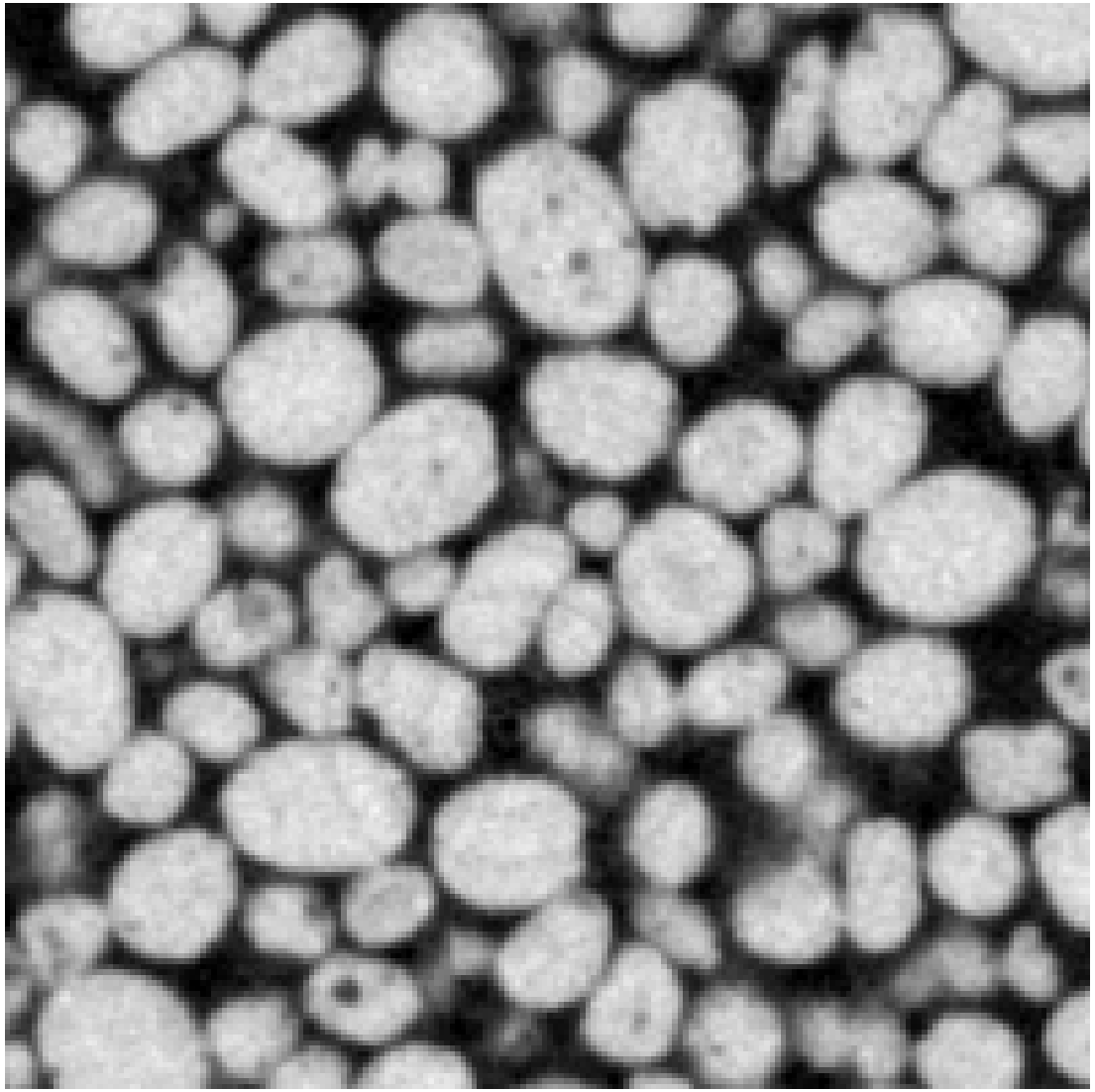
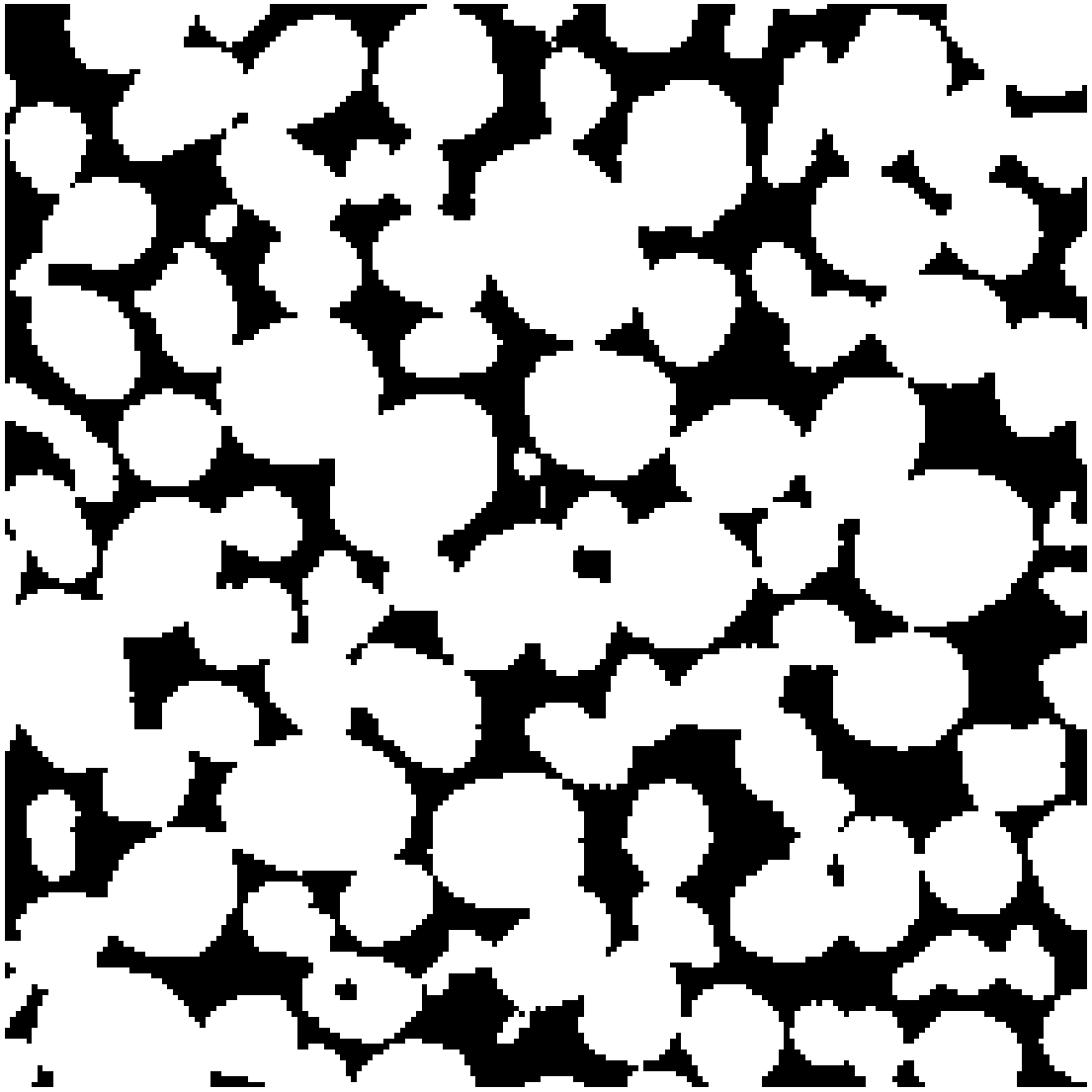
This is more like the first experiment than the second.

Step 1: separate pores and solids

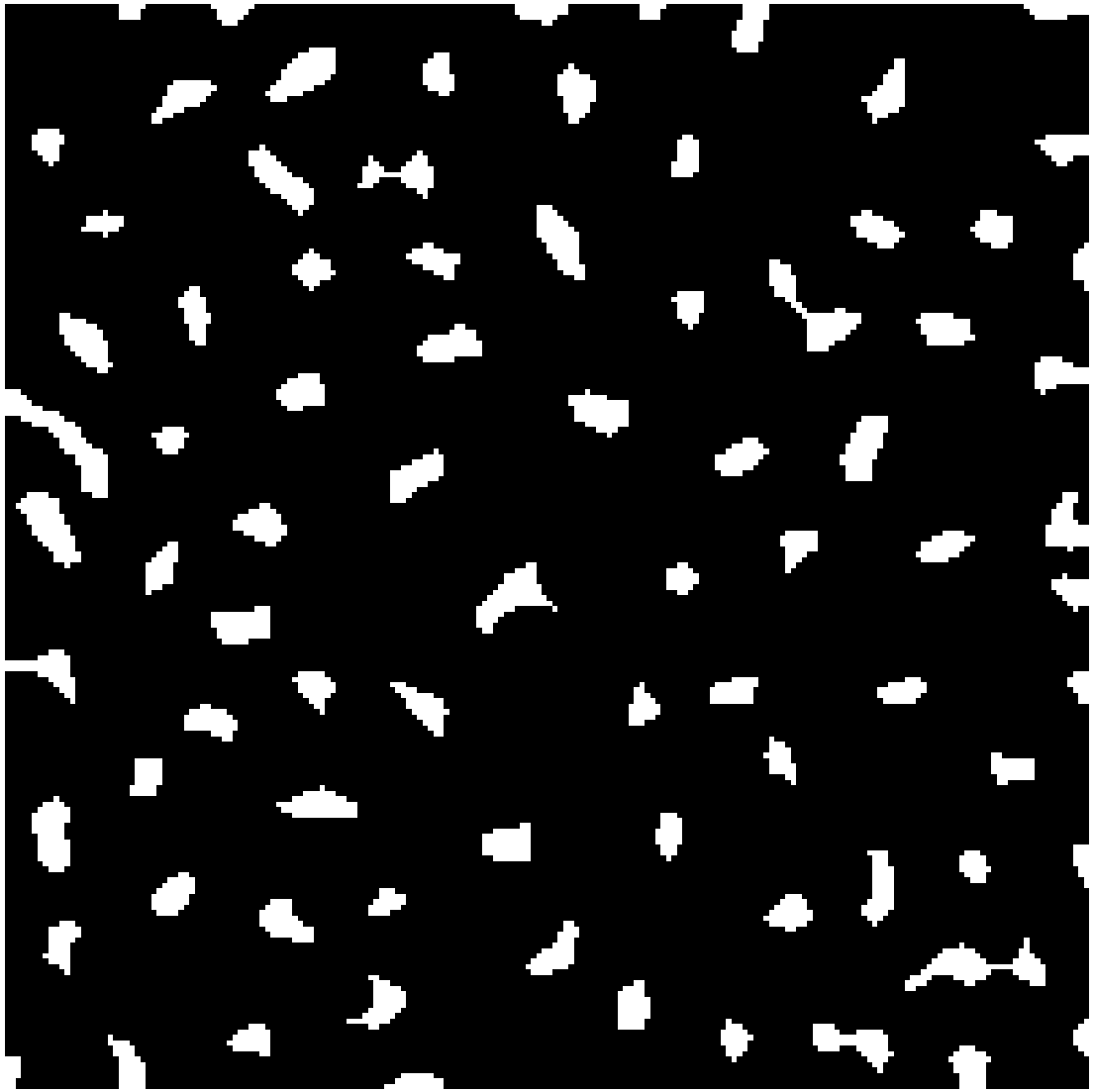
Reconstructed x-ray attenuation field



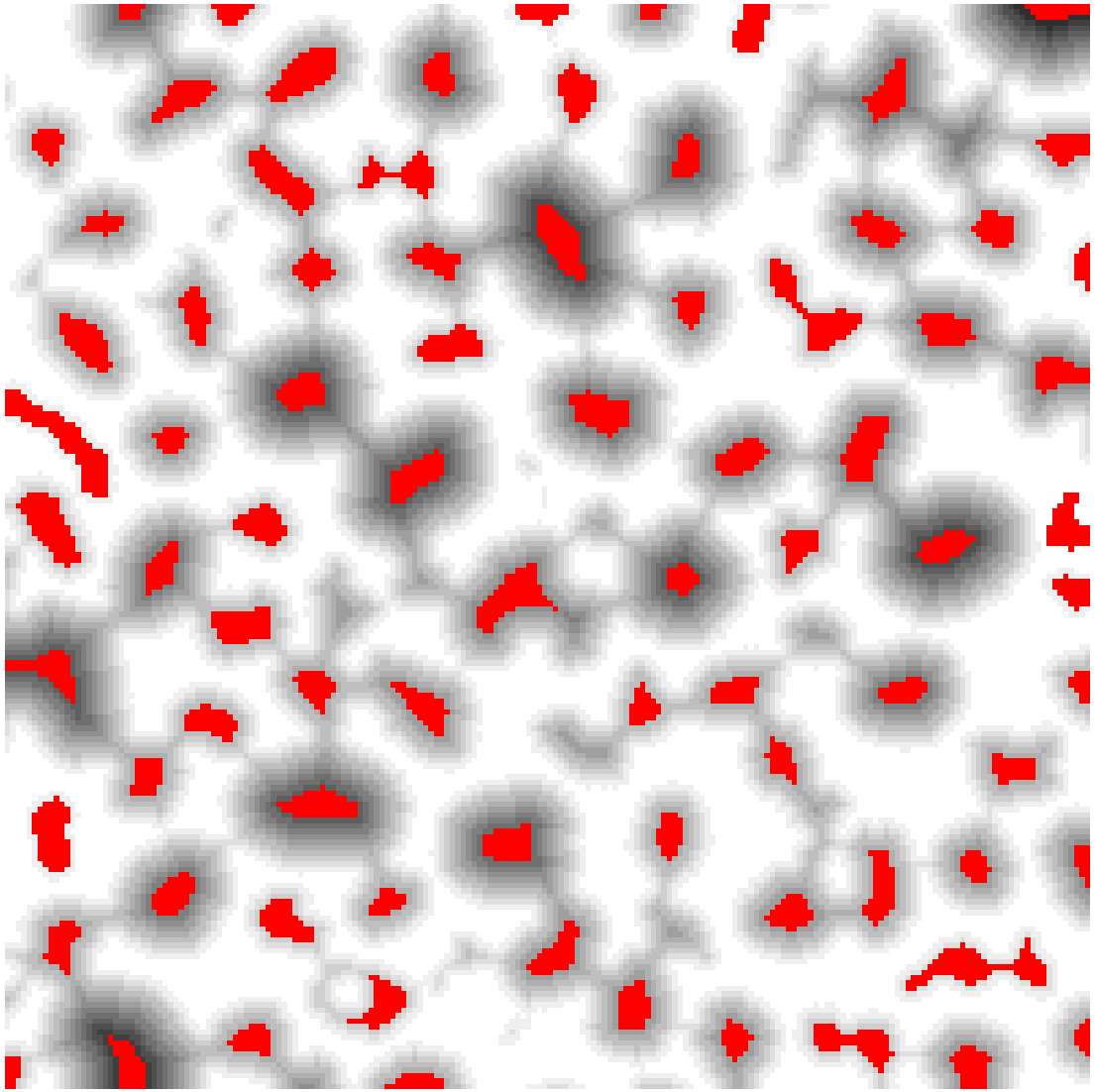
Apply threshold to this field



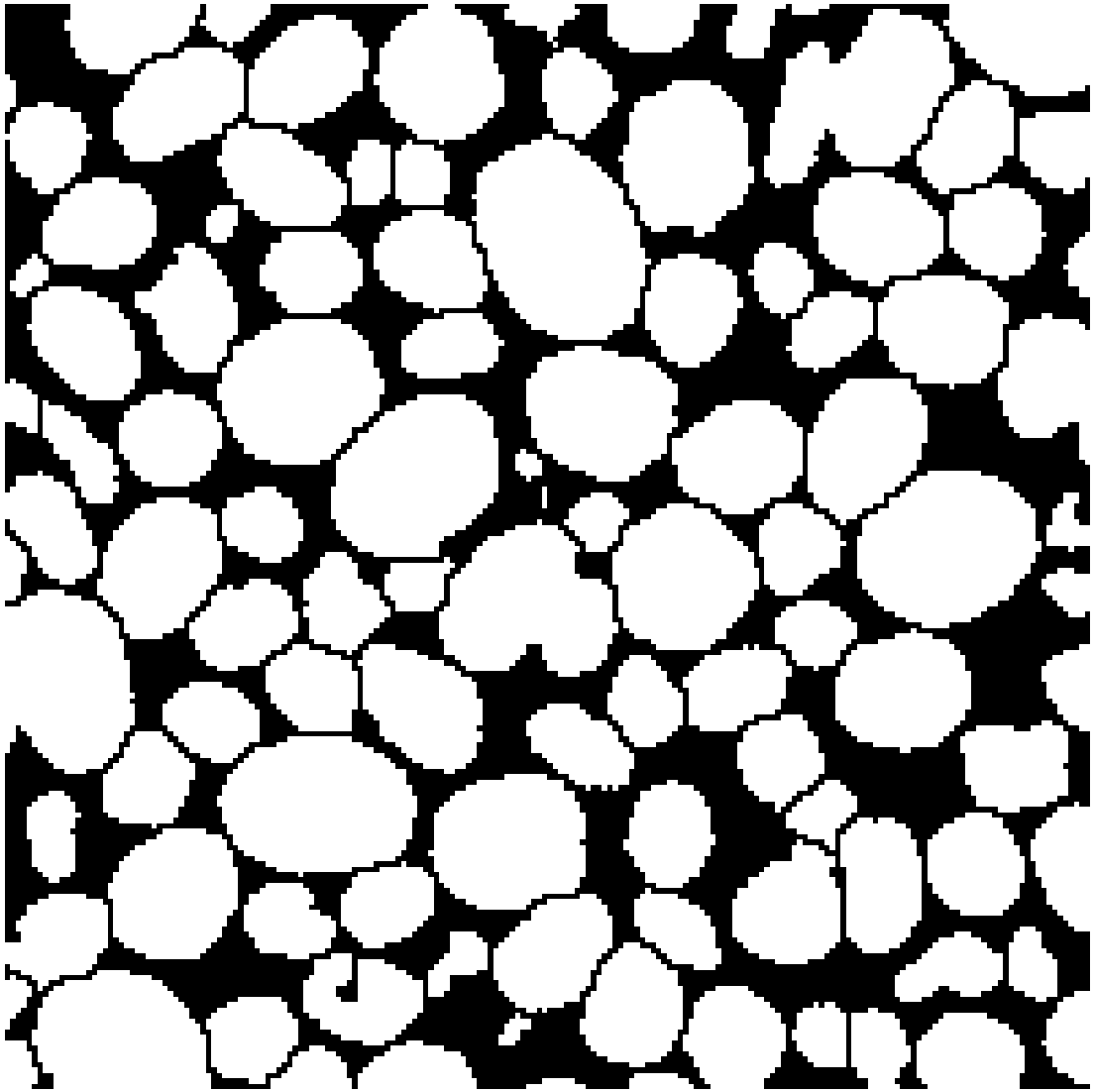
Erode particles to find centre, number these non-touching objects



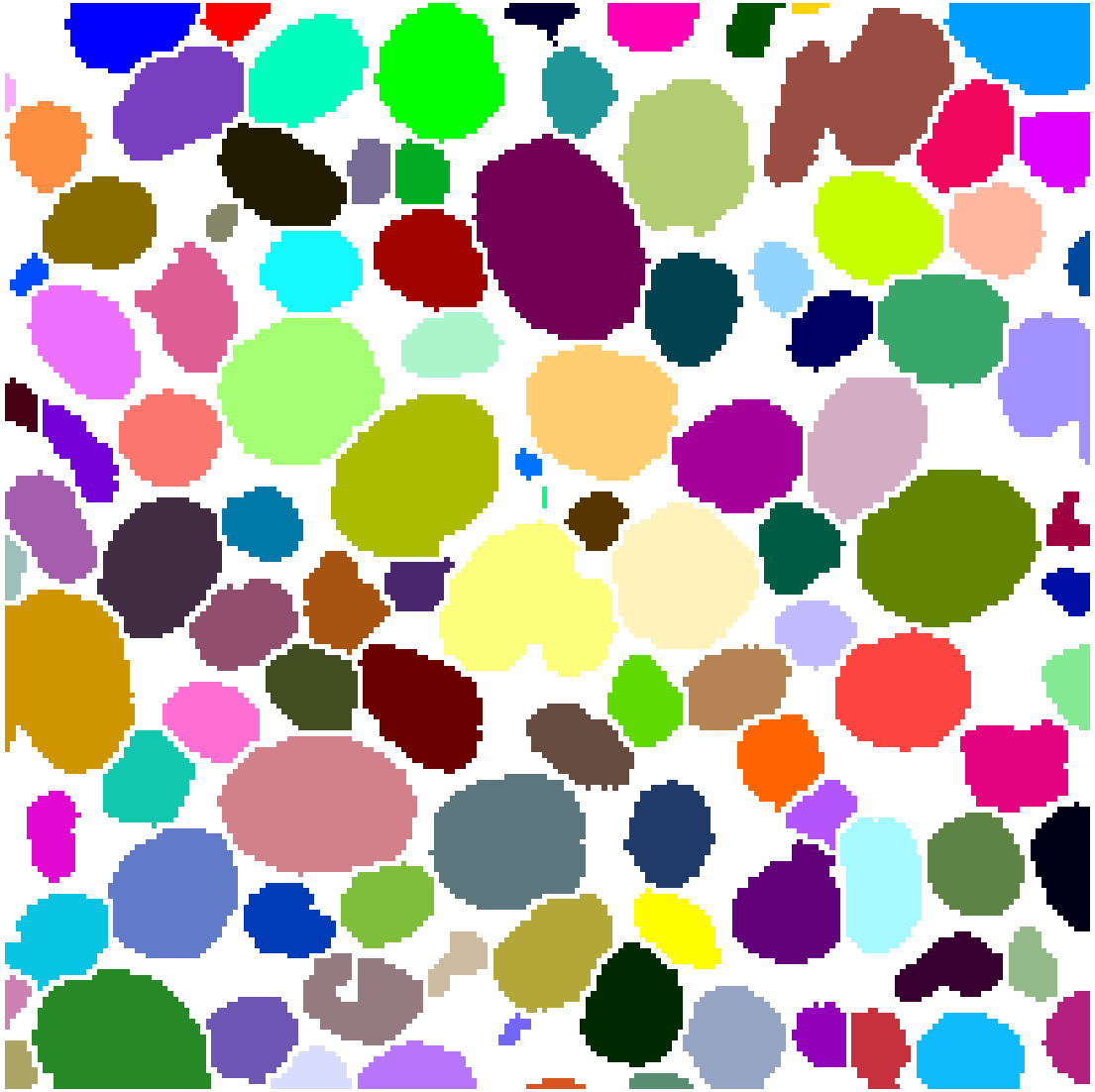
Grow them back to full size



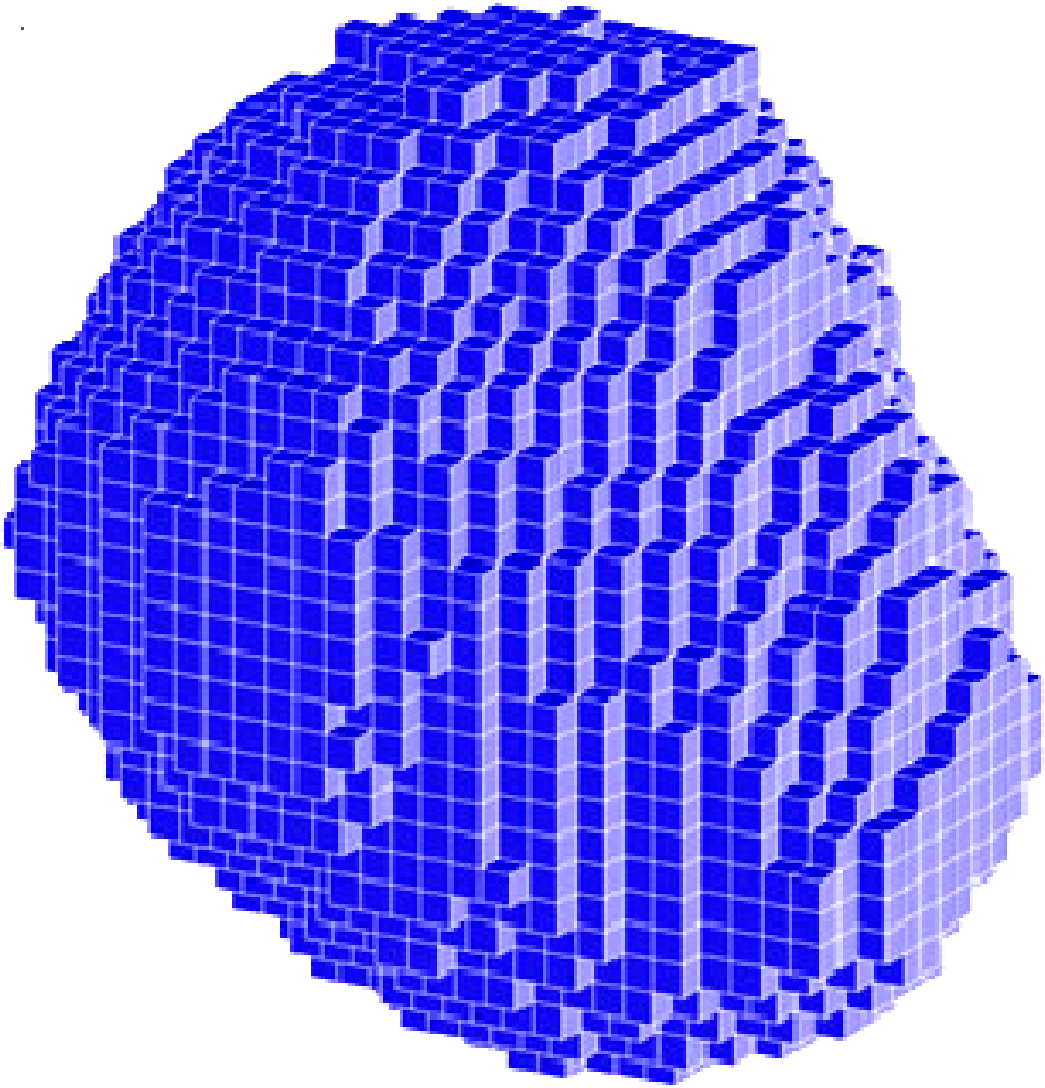
(Optional) Cut the interface voxels



"Label" *i.e.*, Number all particles



3D result selecting a single particle



This “grain” is just a contiguous block of voxels!

All this becomes:

```
labelledArray = spam.label.watershed(binaryArray)
```

With such a labelled image it is easy to measure properties of these objects:
(Discrete Maths!)

- Centre of Mass $\frac{1}{N} \sum_{i=0..N} (\vec{X}(N))$
- Volume (N)
- Elongation/sphericity/orientation/*etc.*

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Where:

- N is the voxel numbers of the particle
- $\vec{X}$ is the coordinate of a voxel

R. Rorato, M. Arroyo, E. Andò, A. Gens, *Sphericity measures of sand grains*, EG - 2019

This makes a particle-size-distribution trivial, and shape analysis (at least at the coarse level) extremely easy.

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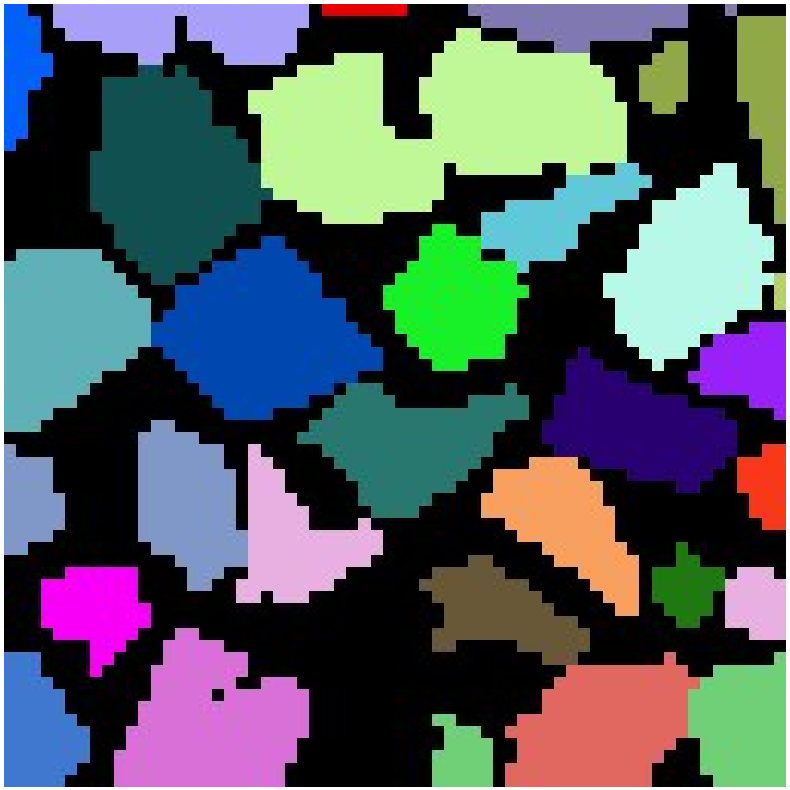
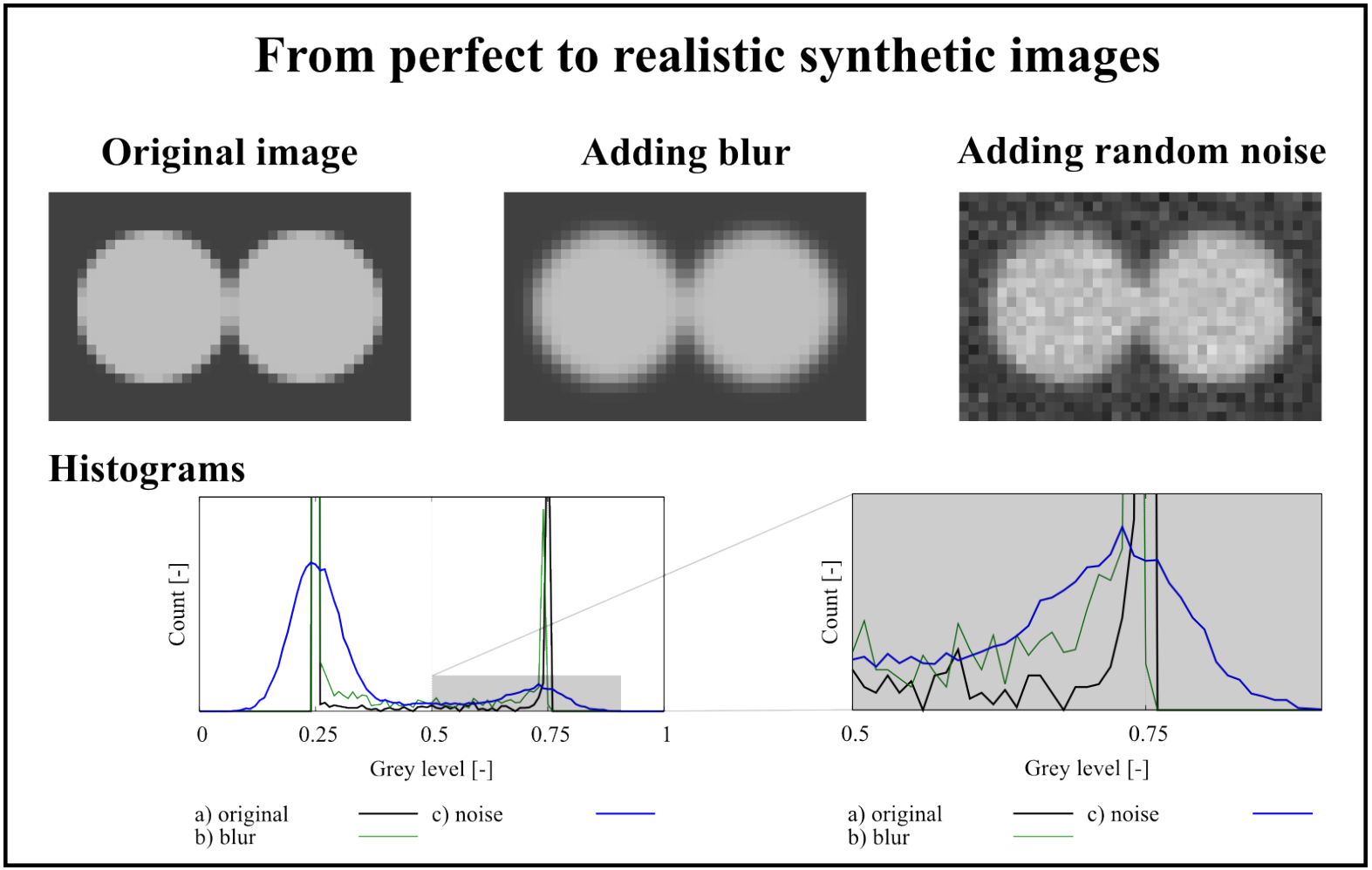
How can we tell if two particles are in contact?

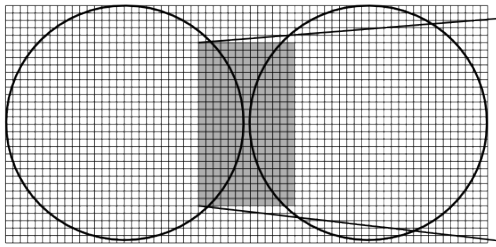


PhD of M. Wiebicke



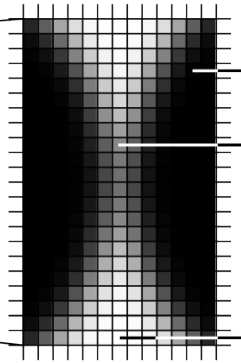
Creation of synthetic images

Spheres
with a distance of 1 pixel



creation of an image of the spheres respecting the partial volume effect: Kalisphera

Greyscale Spheres

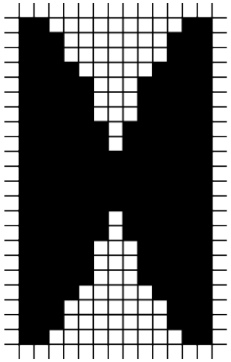


solid voxel

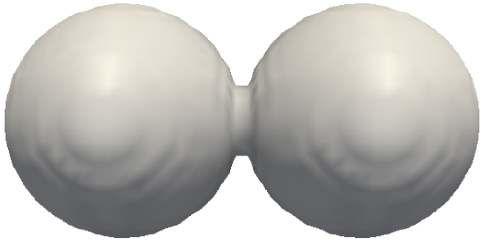
voxel partially filled with solid and void

void voxel

binarization of the greyscale image based on a chosen threshold



Binary Spheres



3D rendering of the image

Creation of synthetic images

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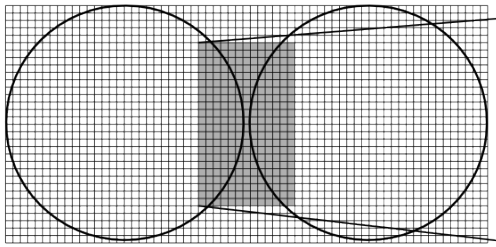

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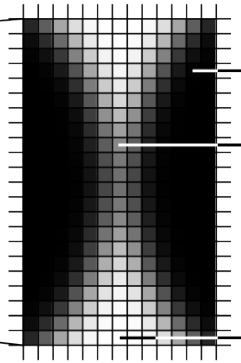

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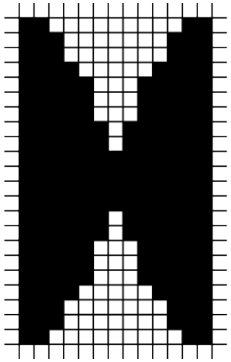

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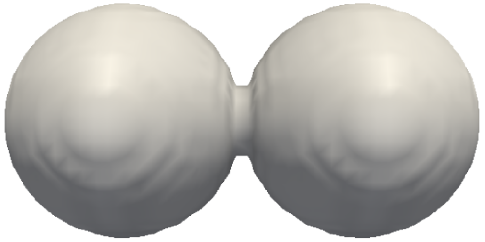

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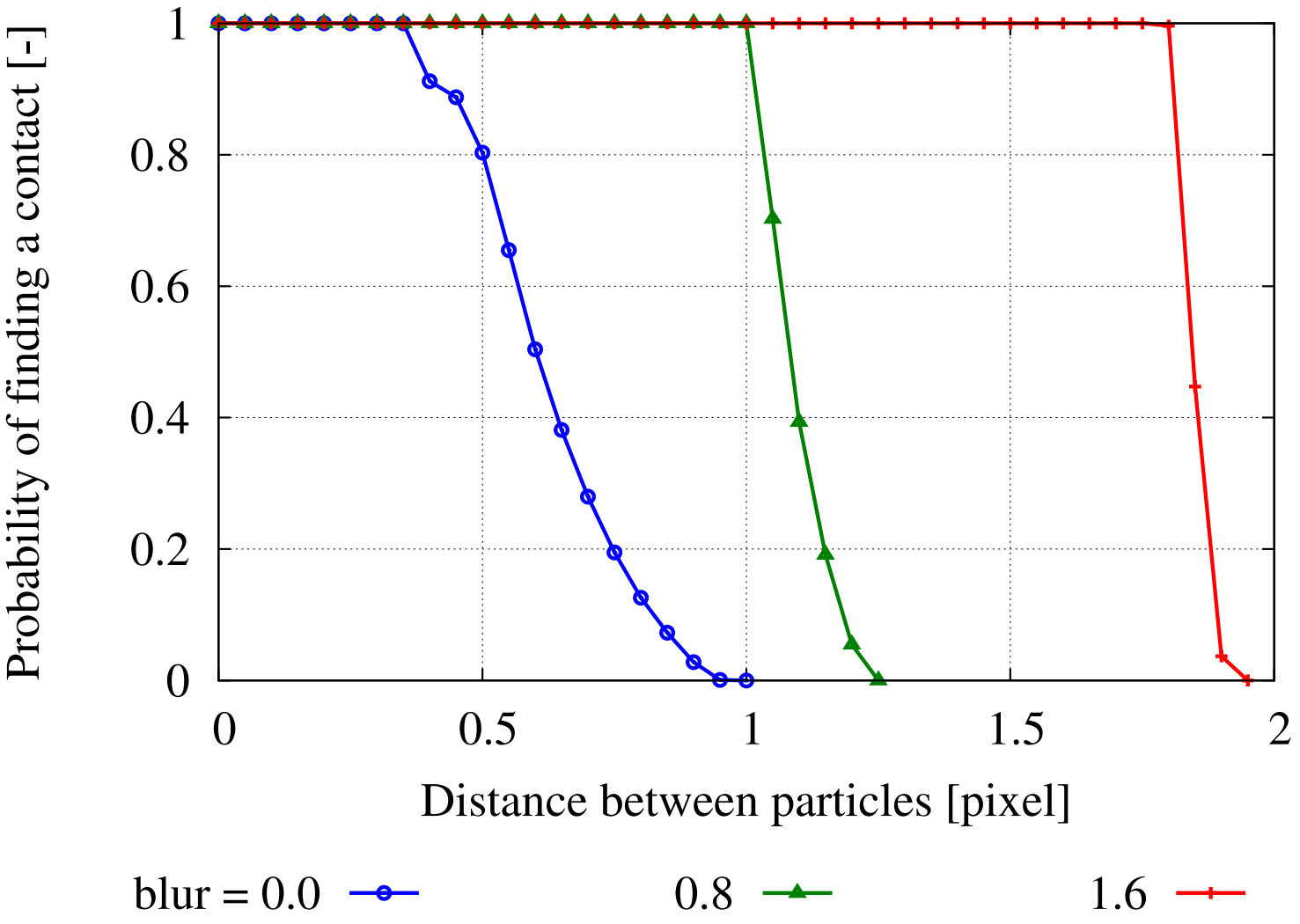
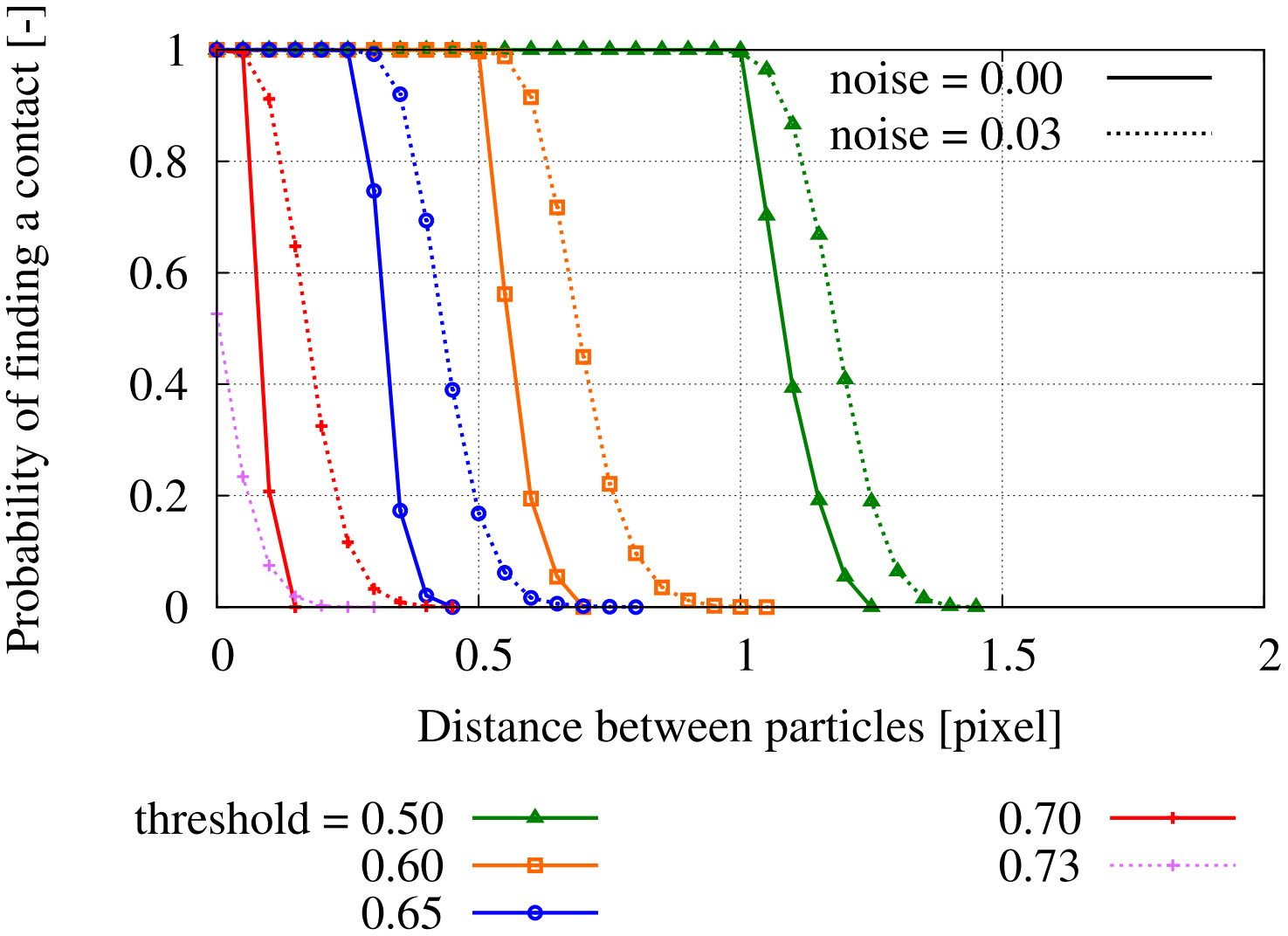

Probability of finding a contact [-]
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
Distance between particles [pixel]
blur = 0.0
0.8
1.6



Wiebicke *et al.* 2017

Conclusions:

- (That's just the beginning of the story, see orientations, non-spherical...)
- Error is not symmetric, and so in this topology despite improvement we're always overestimating
- This was really worth doing, now we know better how much we can trust this measurement.

Now let's try to characterise how grains move.

Measuring transformations between two 3D images (formally):

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We want to find Φ to satisfy:

$$\sum_{\vec{X} \in ROI} (im1(\Phi \cdot \vec{X}) - im2(\vec{X})) = 0$$

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- What is ROI?

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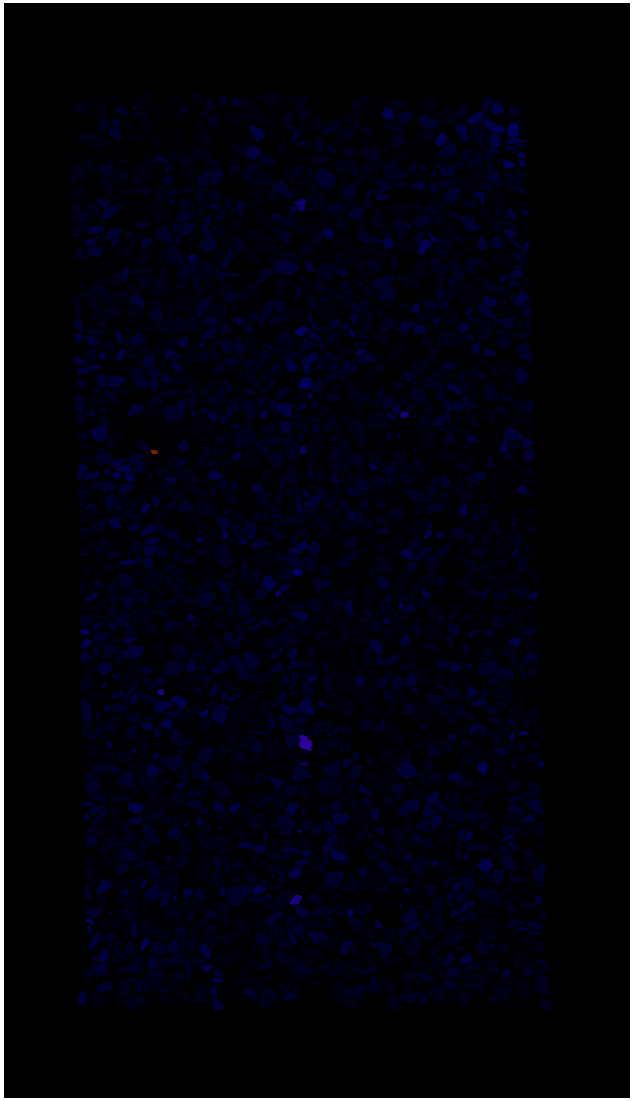
- How close do we need to be? How do we get close?
- What is *ROI*?

```
spam.DIC.lucasKanade(im1, im2)
```

If *ROI* is labelled image: "Discrete Correlation"
Example: Particle rotations



spam-ddic

R. Rorato *et al.*, *Particle shape and rotation during triaxial shearing*, Géotechnique Submitted - 2019

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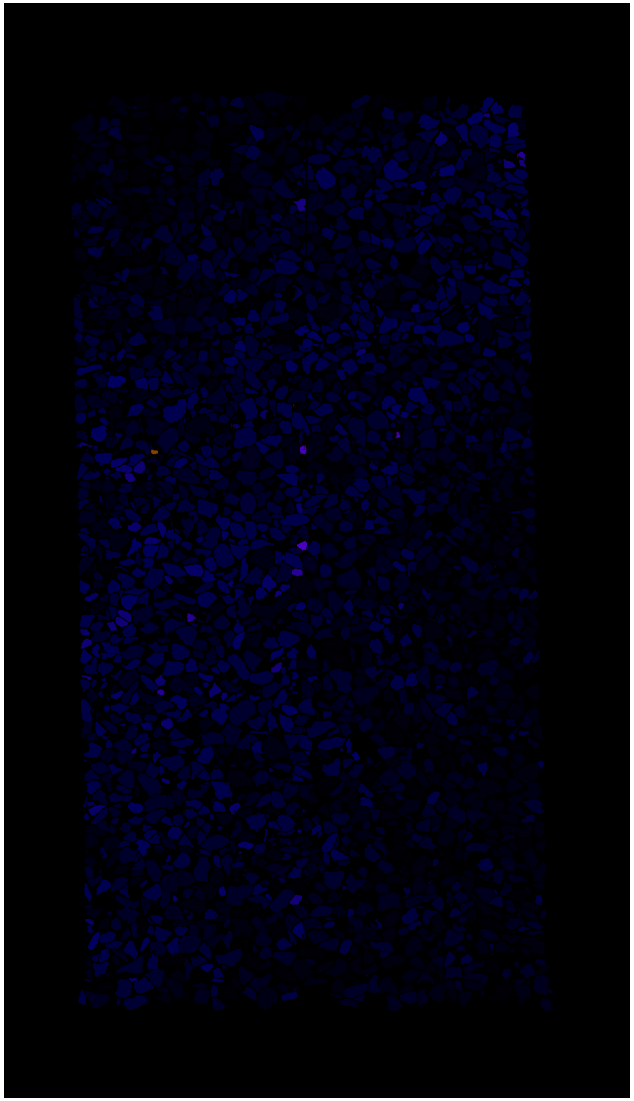

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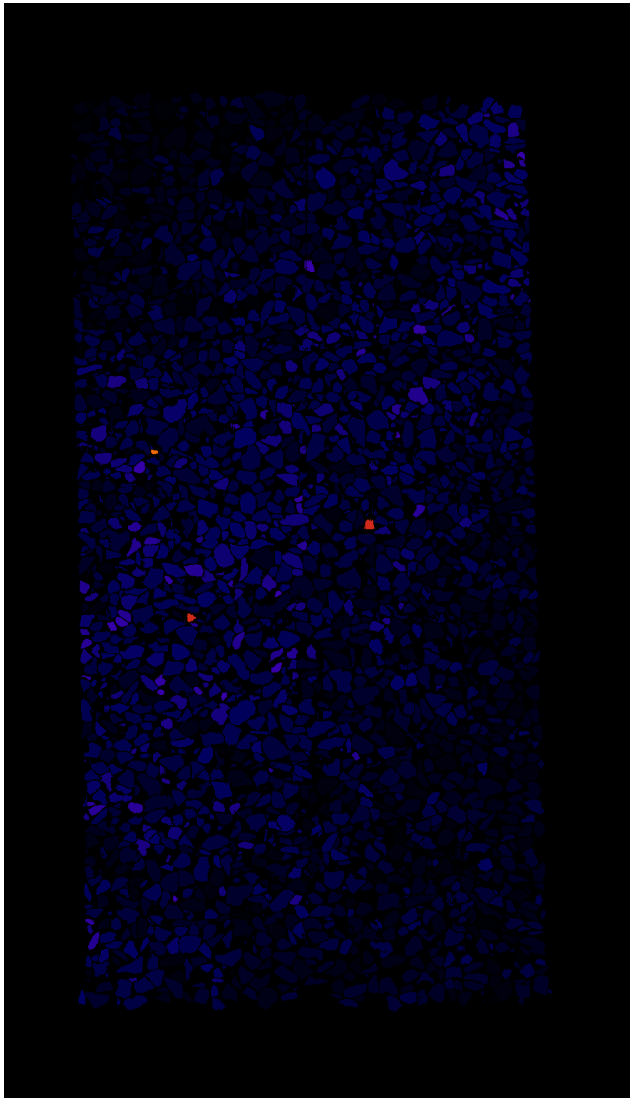

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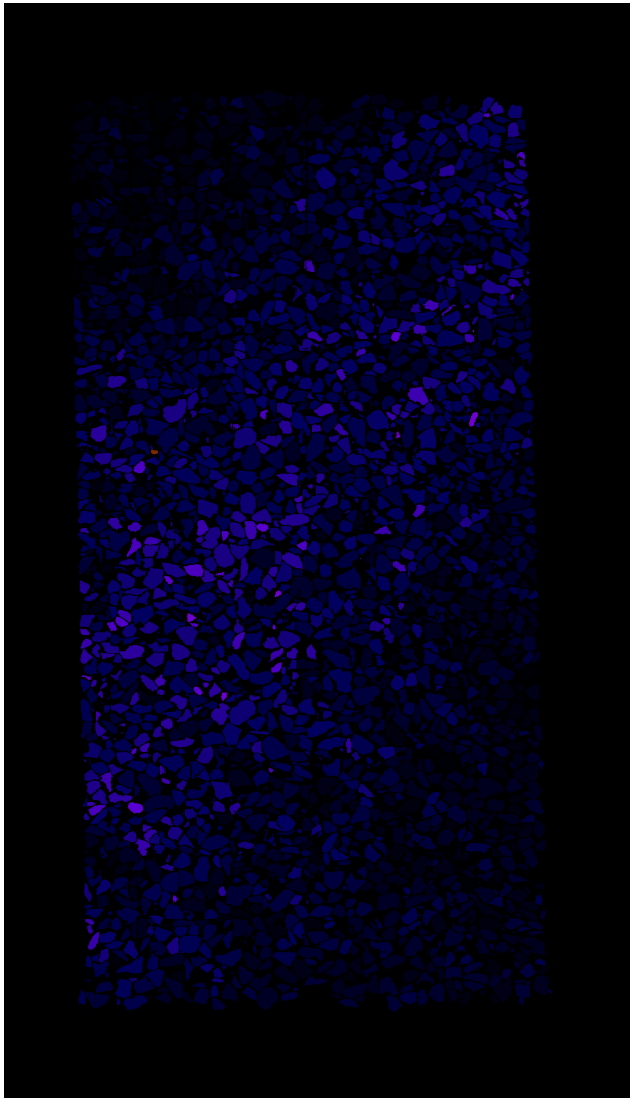

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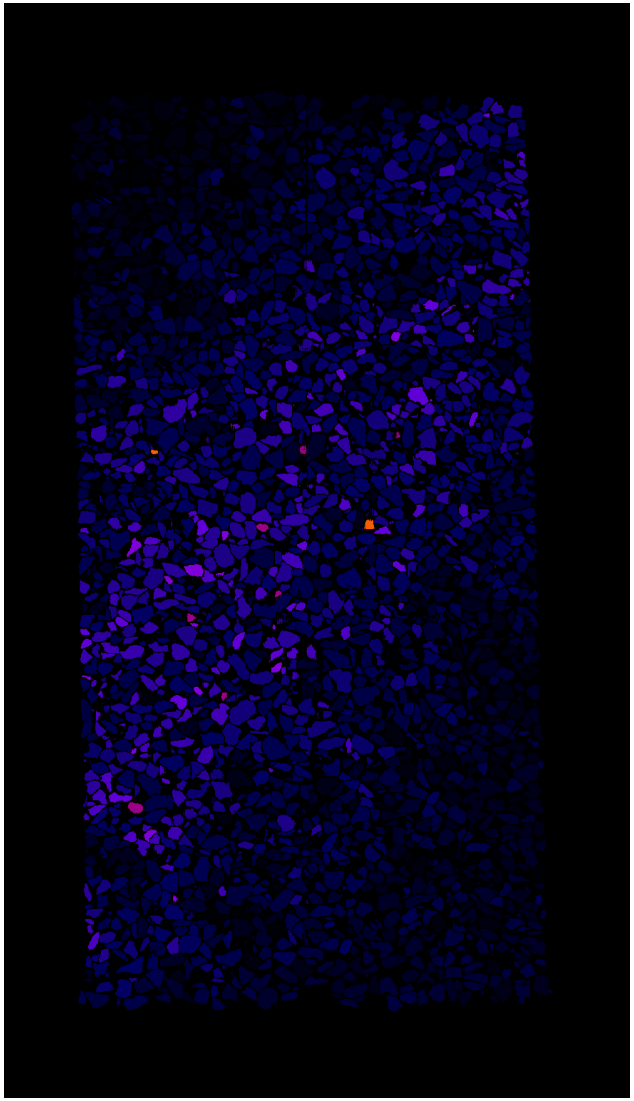

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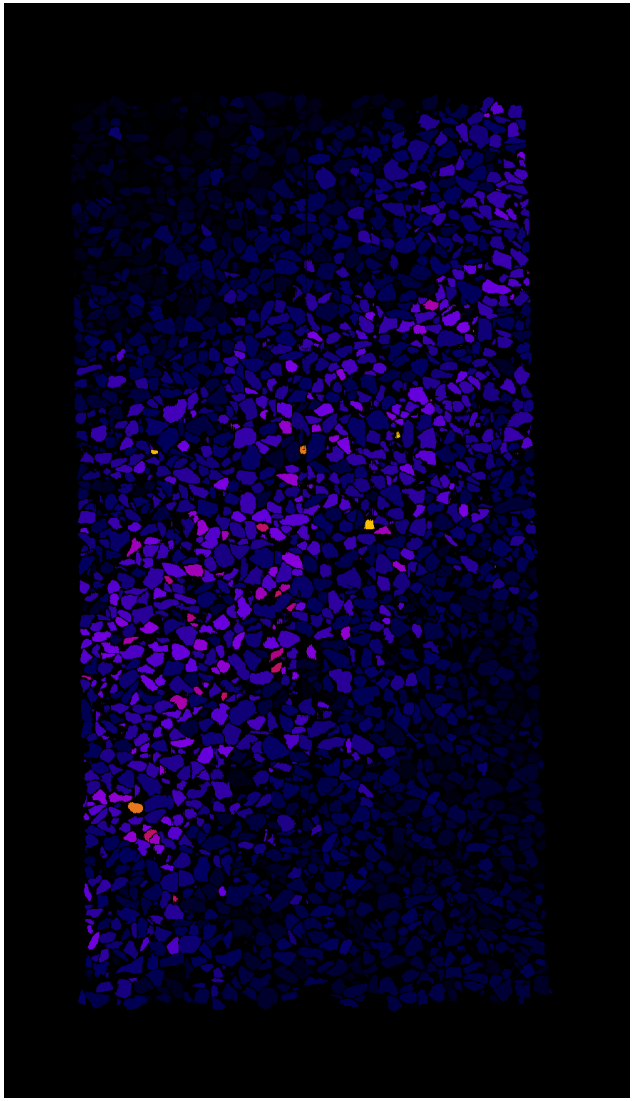

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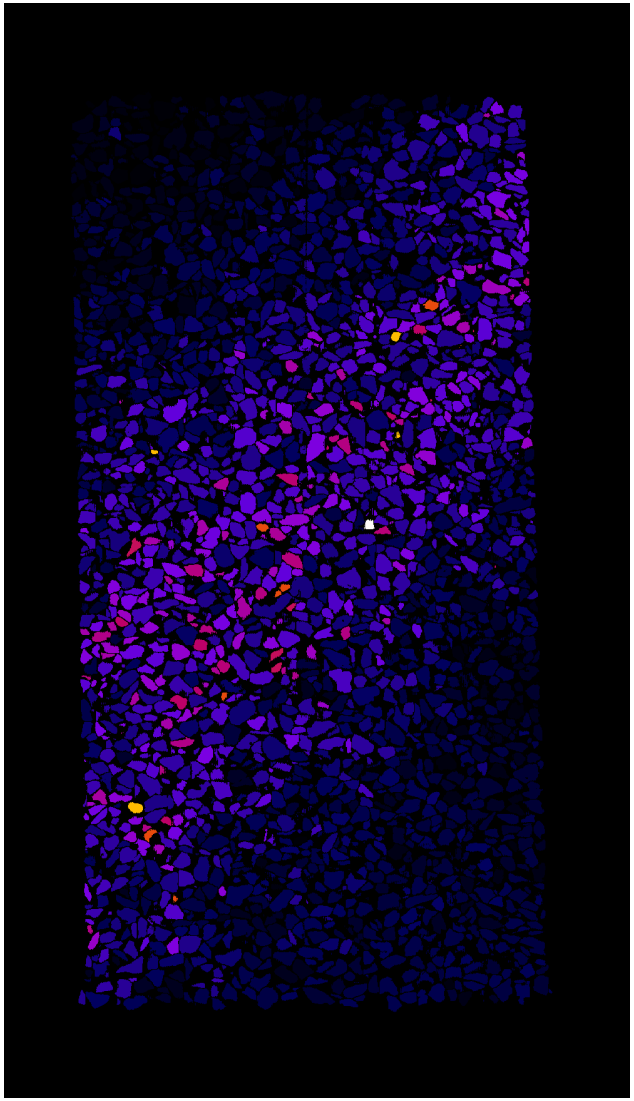

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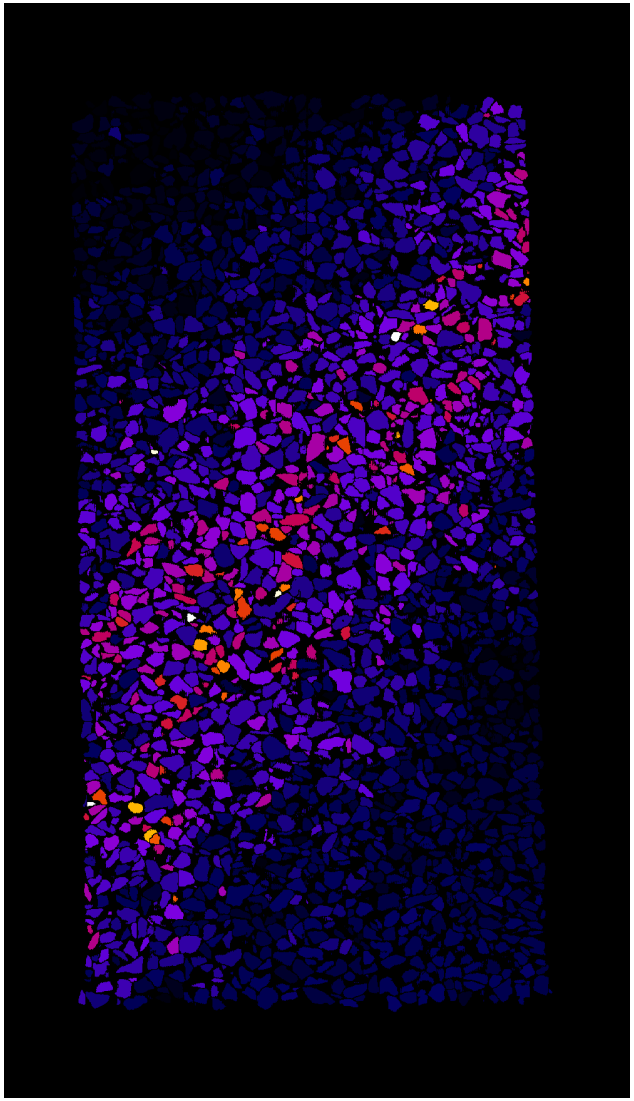

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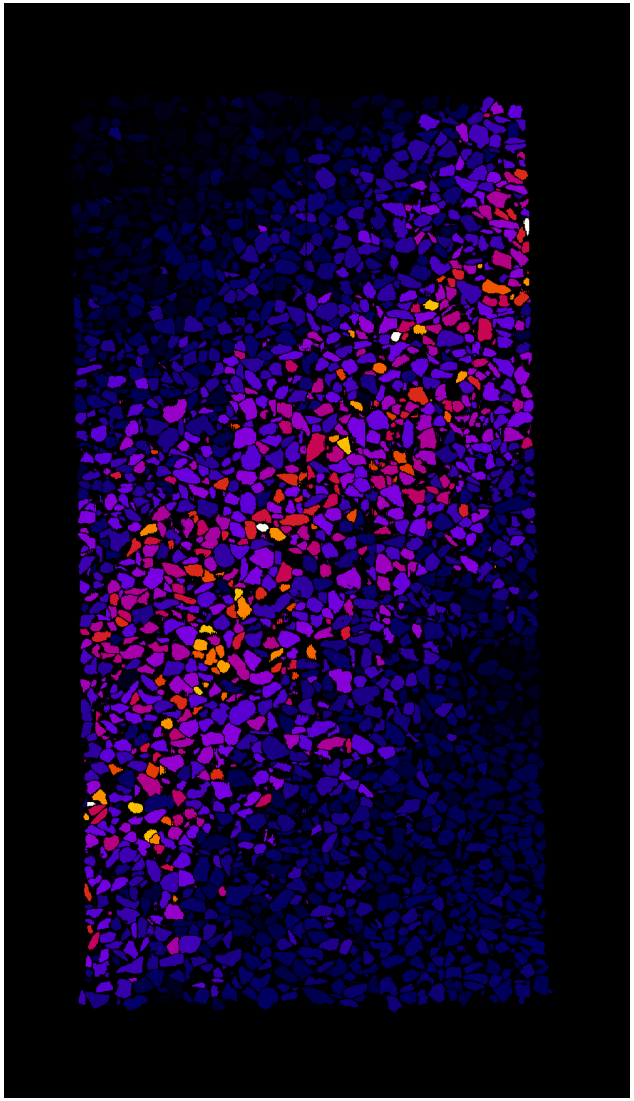

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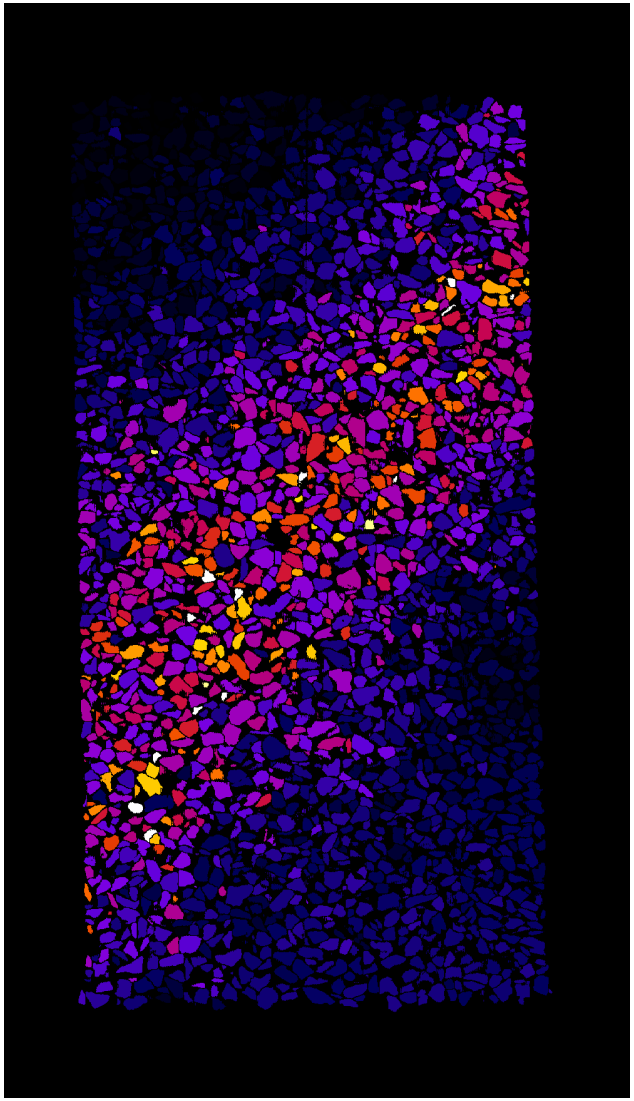

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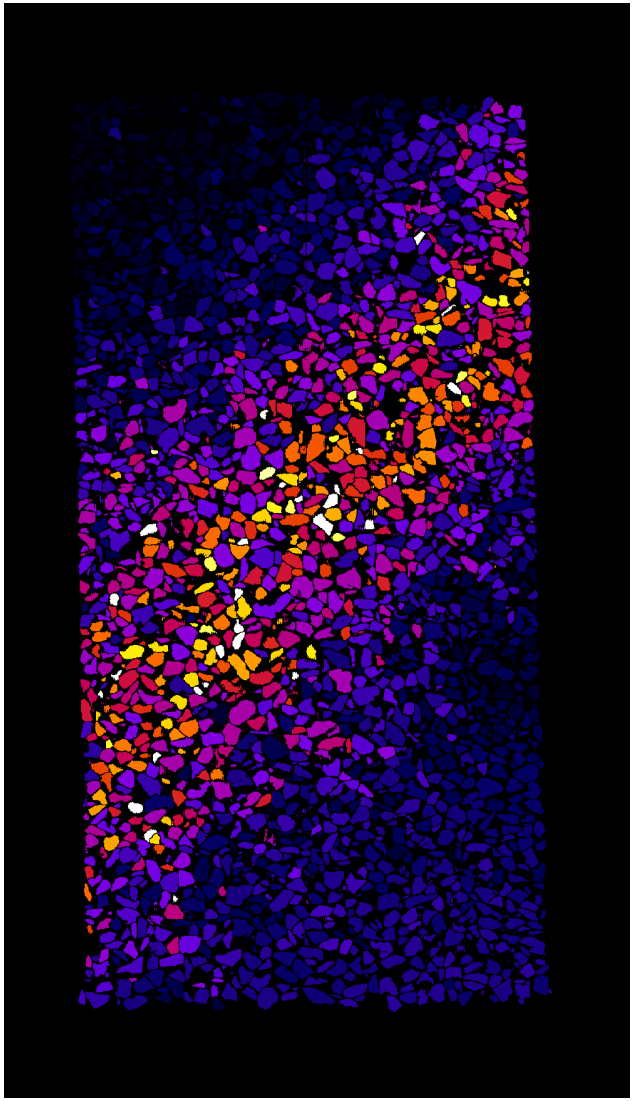

spam-ddic

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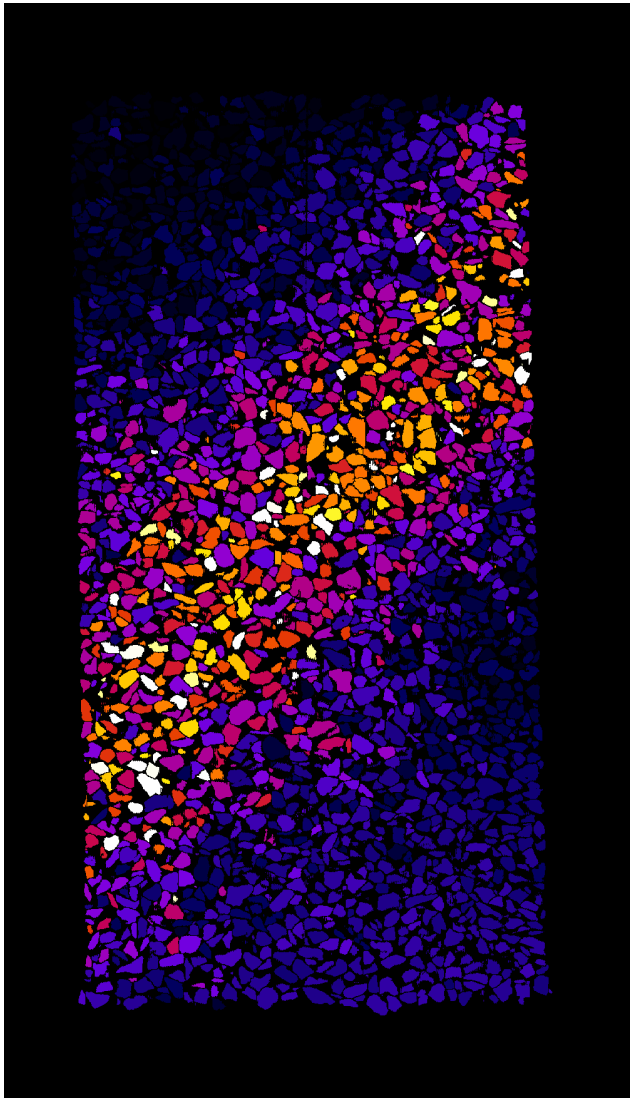

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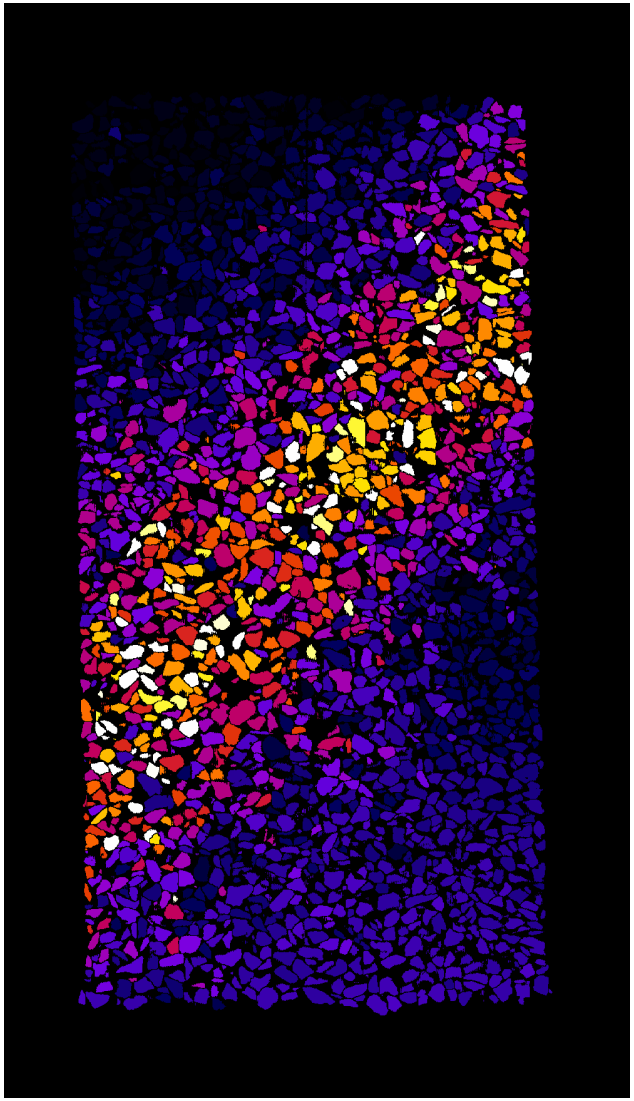

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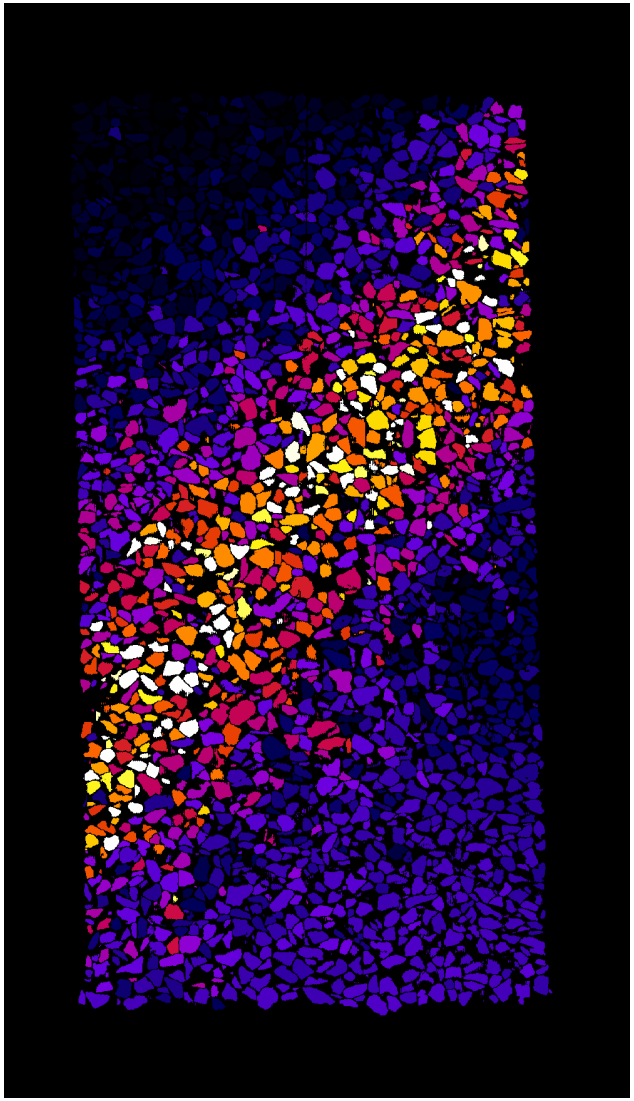


spam-ddic

R. Rorato *et al.*, *Particle shape and rotation during triaxial shearing*, Géotechnique Submitted - 2019

Summarising for this experiment

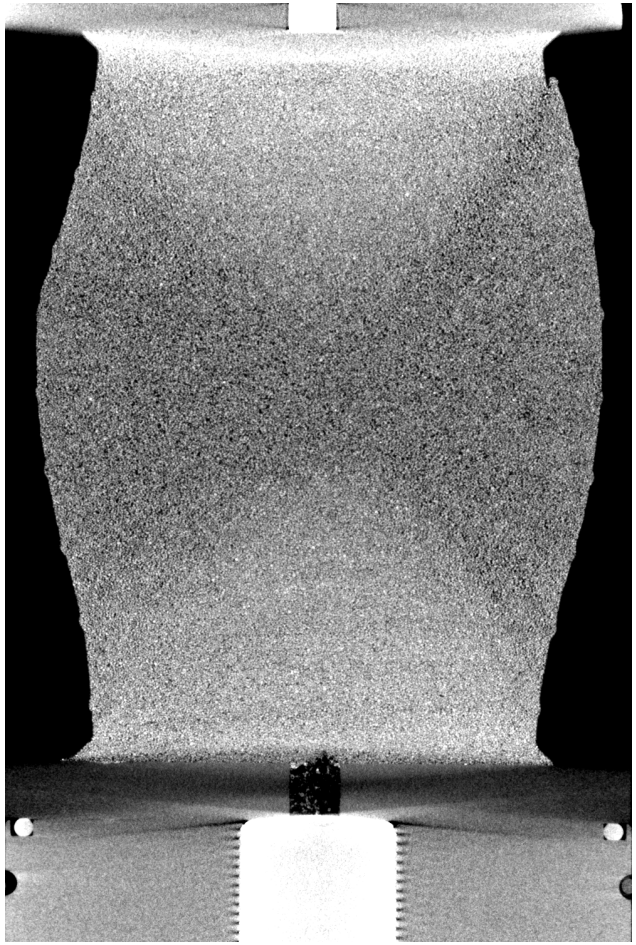
We can characterise positions, shapes, *etc.* of *each* grain

We can obtain a reliable kinematic history

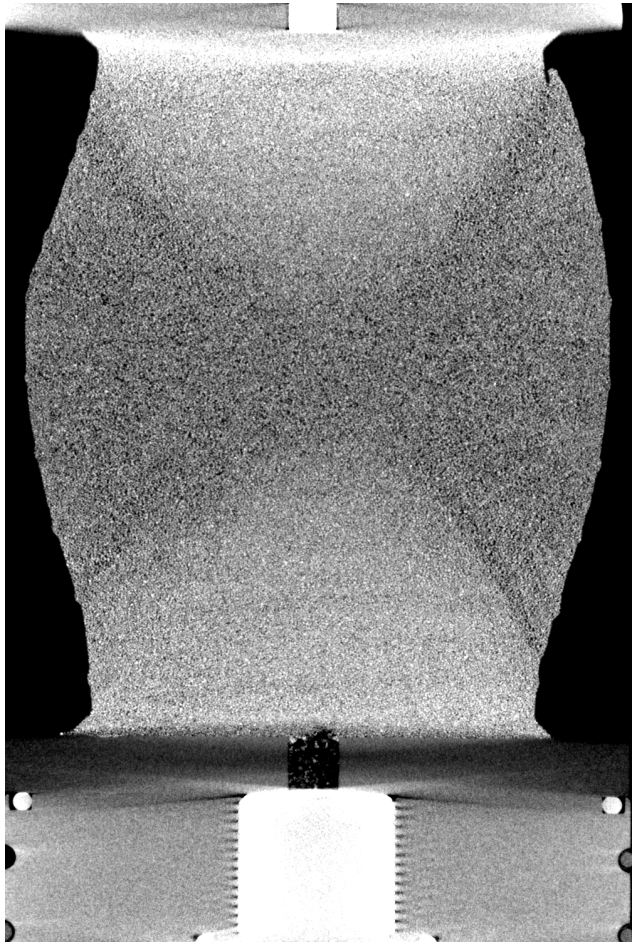
This reveals some interesting features about shear bands in these materials

If *ROI* is regularly-spaced subvolumes: "Local Correlation"

Step 26

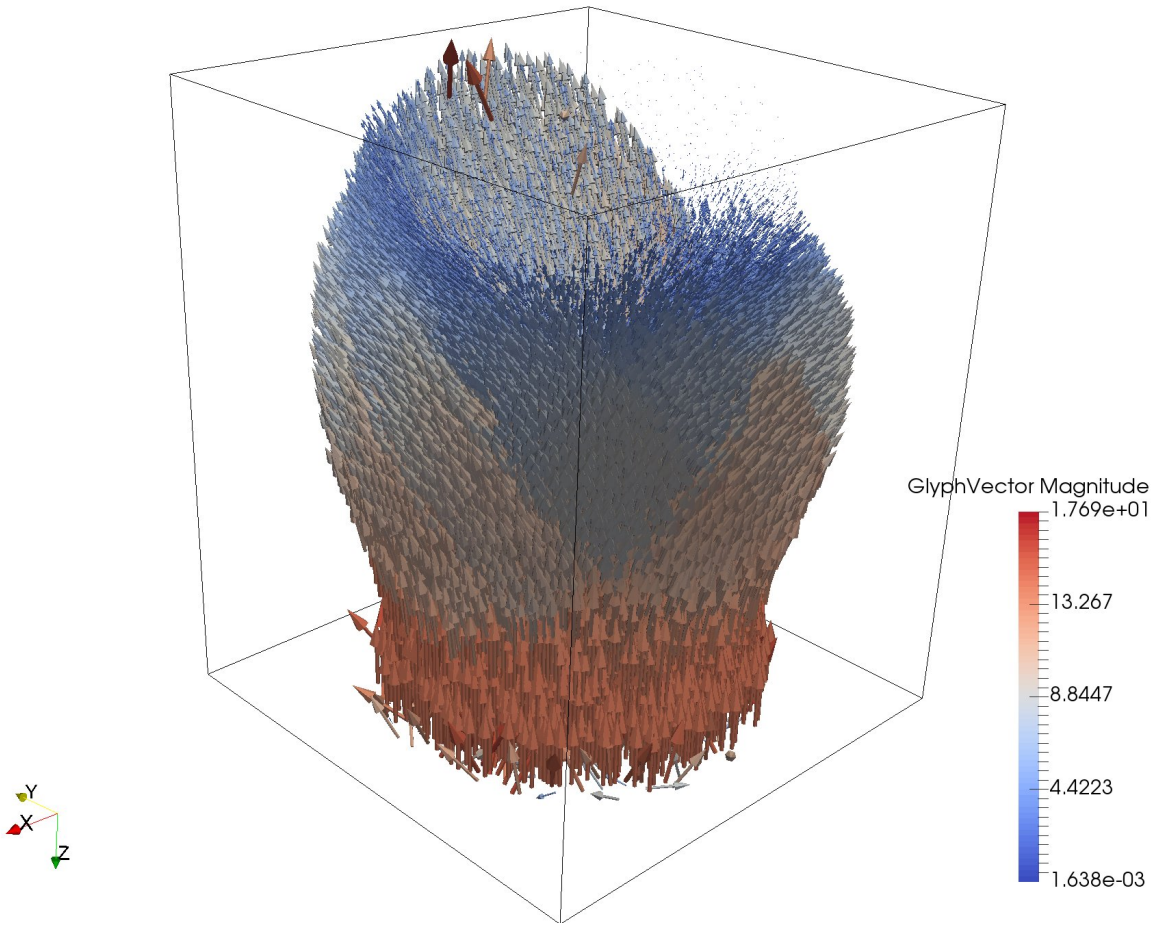


Step 27



J. Desrues *et al.*, *How does strain localise in standard triaxial tests on sand: Revisiting the mechanism 20 years on*, MRC 2018

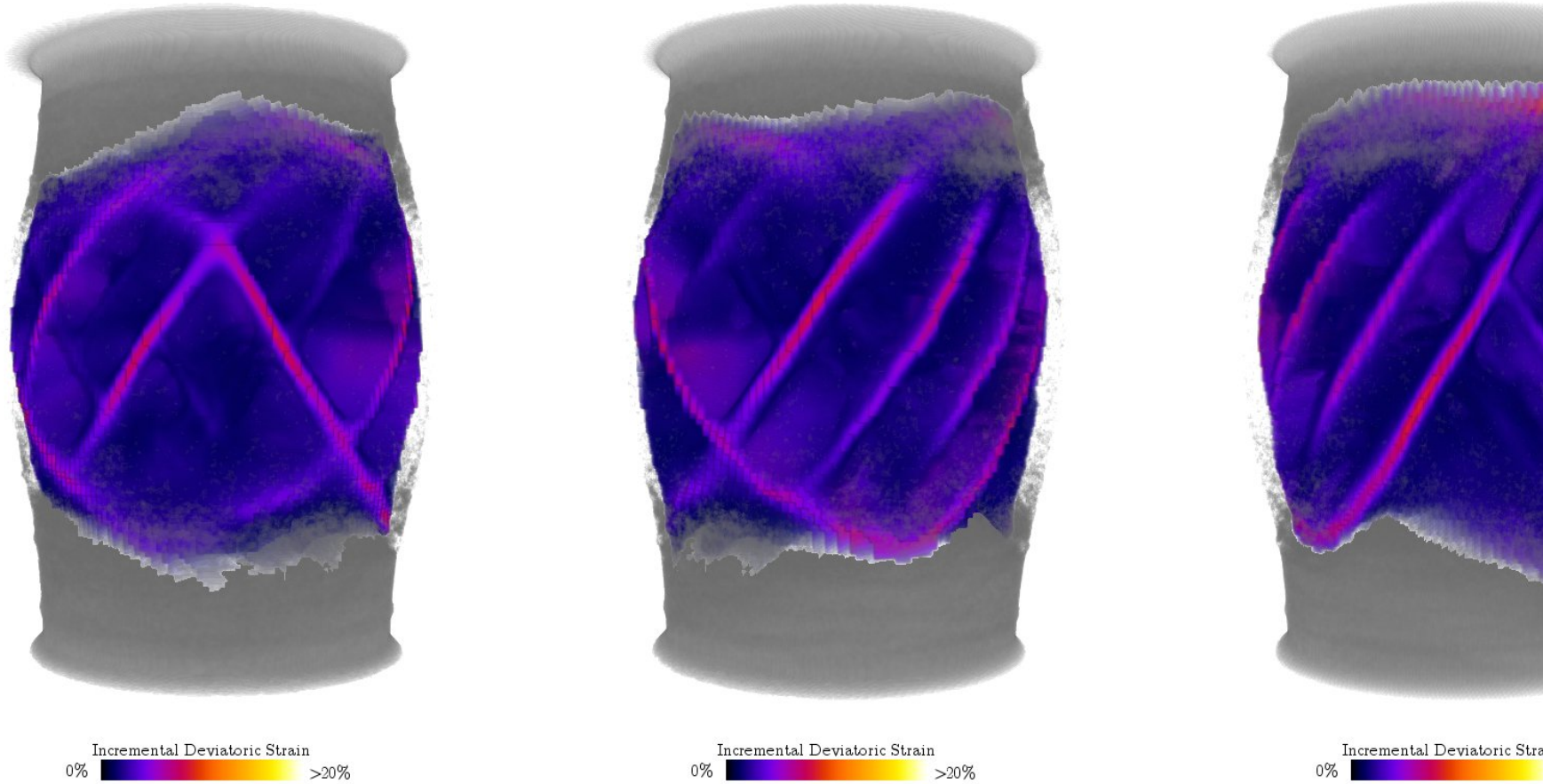
If *ROI* is regularly-spaced subvolumes: "Local Correlation" Displacement Field



`spam-ldic im1 im2`

J. Desrues *et al.*, *How does strain localise in standard triaxial tests on sand: Revisiting the mechanism 20 years on*, MRC 2018

If *ROI* is regularly-spaced subvolumes: "Local Correlation" Deviatoric strain field



`spam-regularStrains`

J. Desrues *et al.*, *How does strain localise in standard triaxial tests on sand: Revisiting the mechanism 20 years on*, MRC 2018

Summarising for this experiment

OK that wasn't at the grain scale, but it was cool

These structures are complicated even after a lot of shearing!

Excellent – apply this to all possible sands?

The combination of **high res x-ray tomography** + **particle detection** + **particle tracking with image correlation** gives a pretty complete complete picture of the kinematics, for stoppable processes.

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Revolution in granular mechanics? Not yet, we have "effects" but we don't have any "causes".

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Why not? There is a technique to go from grain-strains to contact forces (GEM, Andrade *et al.* 2012), why don't we measure grain strains with DVC?

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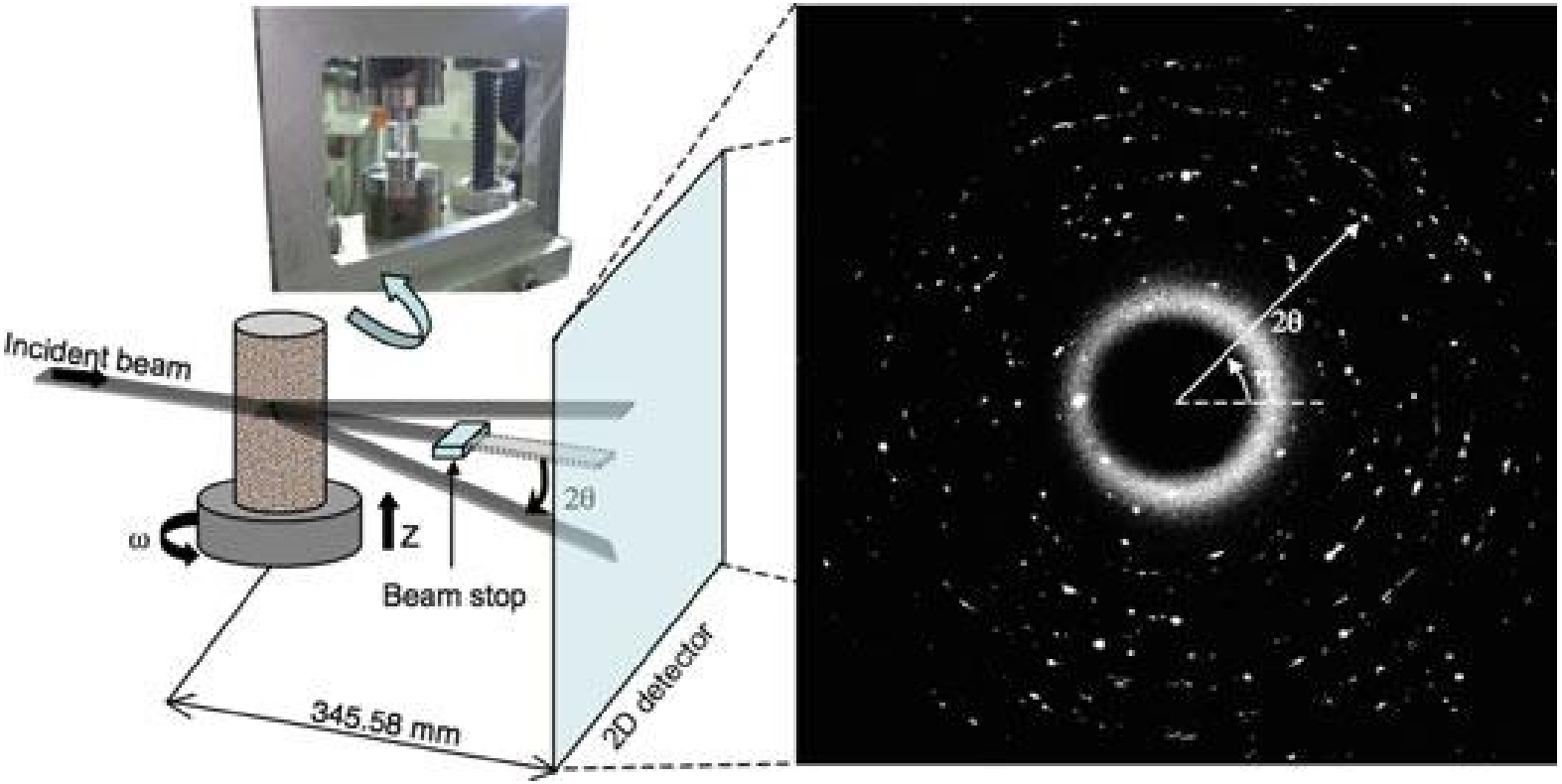
Why not? There is a technique to go from grain-strains to contact forces (GEM, Andrade *et al.* 2012), why don't we measure grain strains with DVC? Is there any other alternative?

Let's measure grain strains in another way

We'll use Bragg's law – in crystals, incoming radiation is *diffracted* out in a different direction as a function of the crystal spacing:



Hall *et al.* 2011

3DXRD

(but also see Neutron Diffraction – Wensrich and Athanasopoulos)
Now for each grain we have a number of spots.

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Movement of spots gives an idea of crystal deformation, full per-grain strain tensor can be reconstructed.

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Movement of spots gives an idea of crystal deformation, full per-grain strain tensor can be reconstructed.

Remembering that crystals have different stiffnesses in different directions, this matches strain.

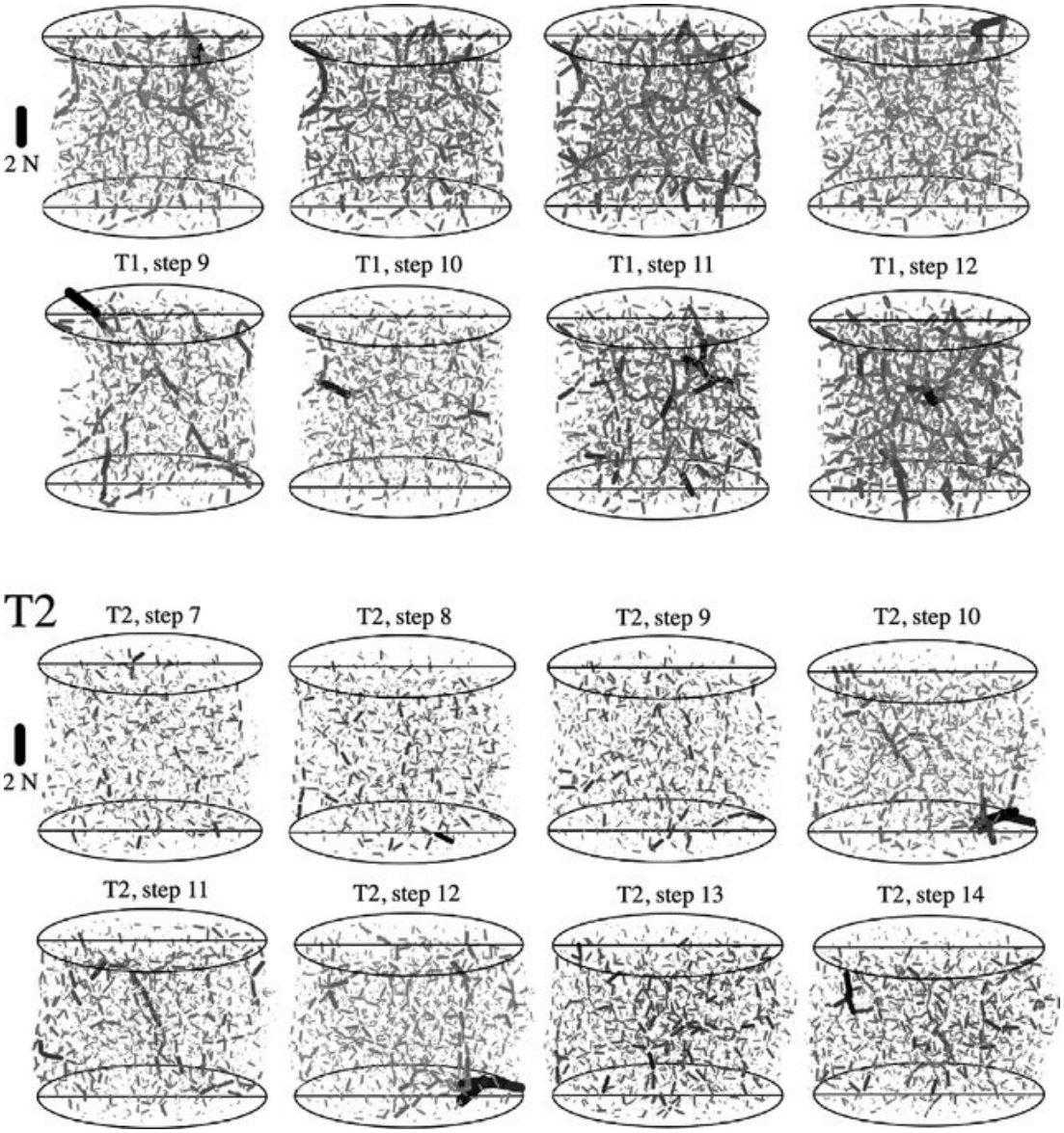
3DXRD

(but also see Neutron Diffraction – Wensrich and Athanasopoulos)
Now for each grain we have a number of spots.

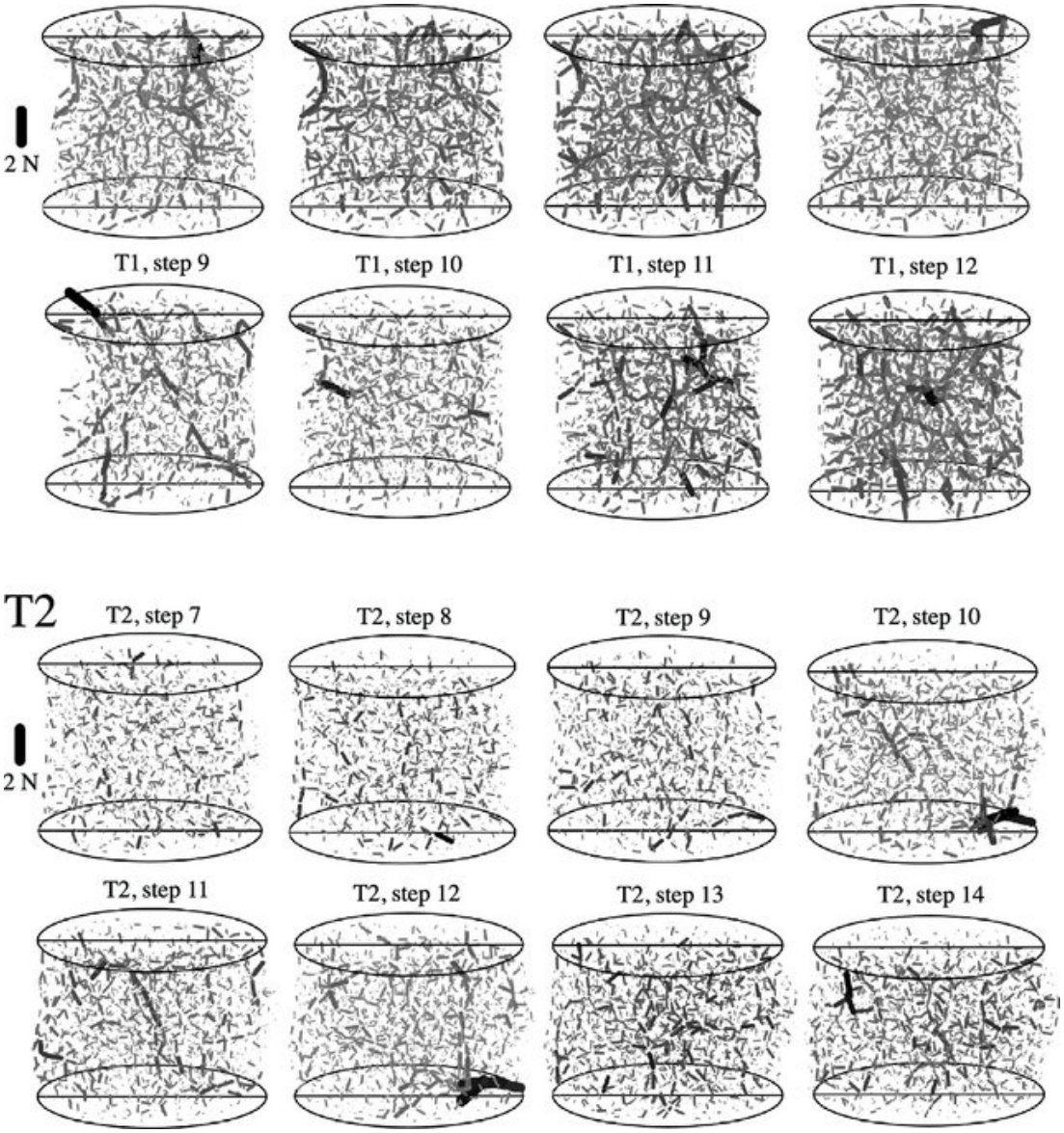
Movement of spots gives an idea of crystal deformation, full per-grain strain tensor can be reconstructed.

Remembering that crystals have different stiffnesses in different directions, this matches strain.

Using GEM, forces at contacts can be reconstructed:



Zhai *et al.* 2019



Zhai *et al.* 2019
Wow!!

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