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Nanocharacterization & Soft Matter Facilities

# X-ray Imaging and MicroCT

## Summer Course #6

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Center for Nanoscale Systems
Harvard University

7/18/2014 Friday

# X-ray Imaging and MicroCT at CNS

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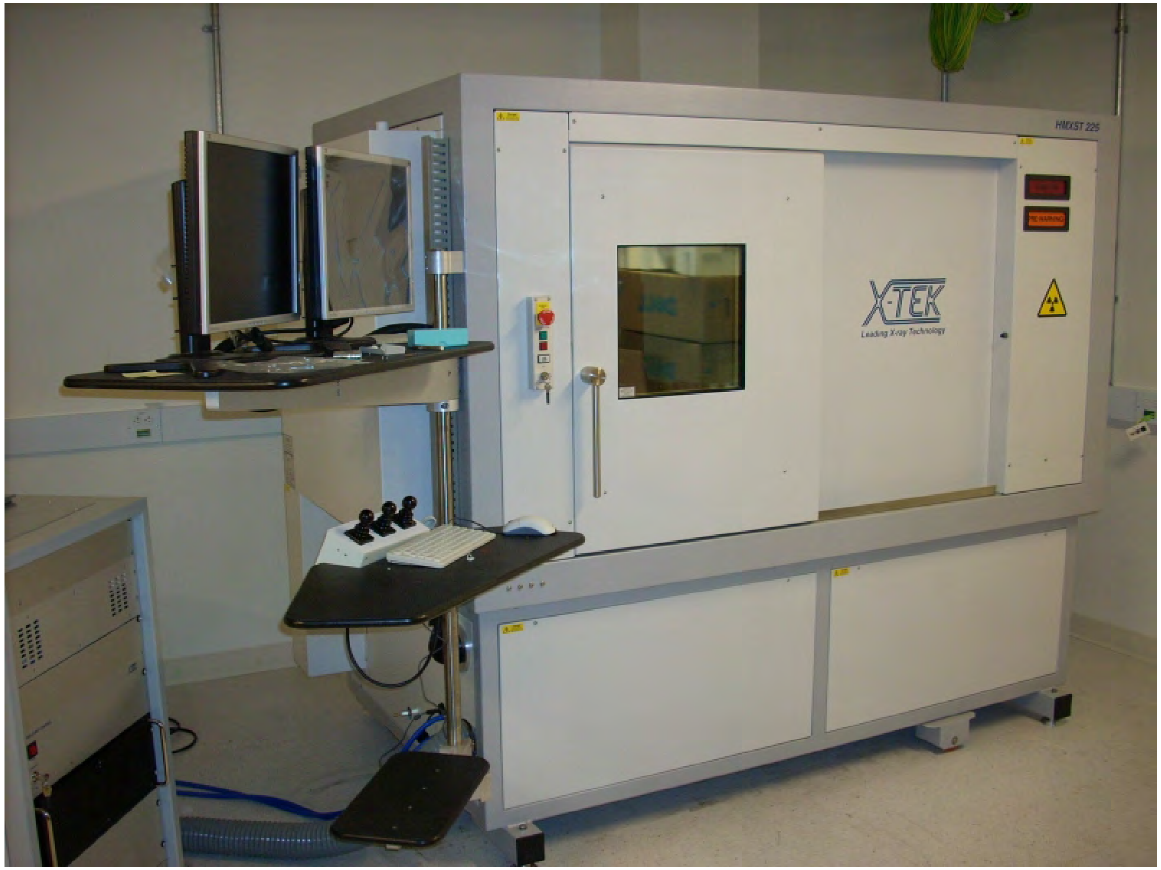
**X-TEK HMXST225 ➔ Now owned by Nikon Metrology**




Certainly THE instrument at CNS with the most diverse group of users and samples!

# X-ray Imaging and MicroCT at CNS

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A versatile and non-destructive technique for:

- 2D imaging
- 3D visualization, sectioning and comparison
- Metrology
- Quality control
- Porosity/inclusion analysis
- Defect/failure analysis
- Material density analysis
- CAD-to-prototype comparison
- Reverse engineering

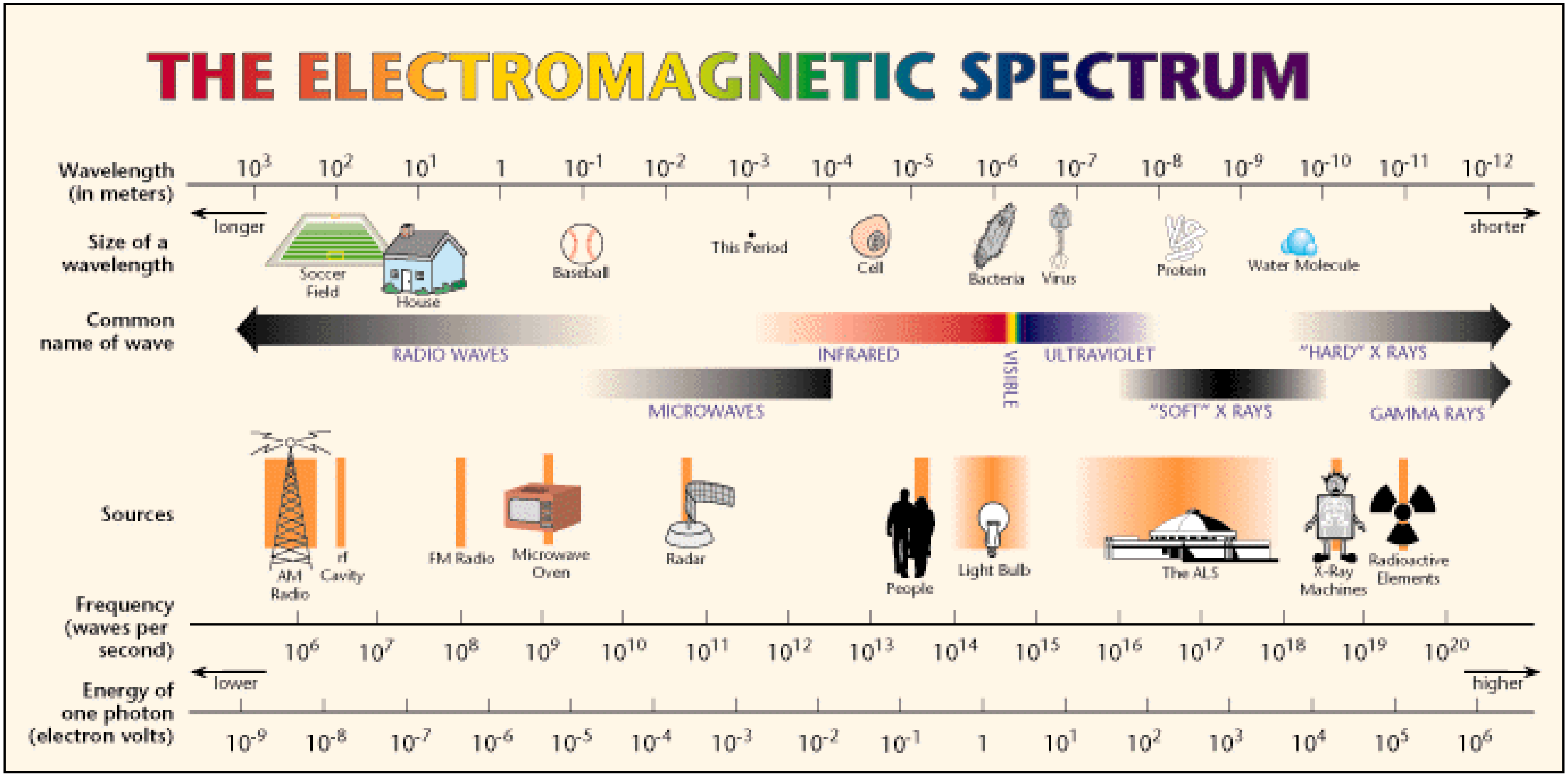
At micron scale!

# Overview

- What are X-rays, and how do we generate them?
- 2D micro-imaging using X-rays
- How does X-ray microCT work?
- How are 3D volumes reconstructed from 2D images?
- Rendering and visualizing 3D volume files
- Artifacts in X-ray microCT and how to minimize them
- Examples of X-ray imaging and microCT

# What are X-rays?

X-rays are electromagnetic radiation just like visible light, infra-red light, ultra-violet light and radio waves, but with a much shorter wavelength, hence with much higher energy, than any of these.




X-Tek X-ray sources produce energies in the range 30-450keV.

# First X-ray Image

*The discoverer of X-rays, Wilhelm Röntgen's first radiograph (1895): the low energy X-rays penetrated the bone but not the gold ring.*

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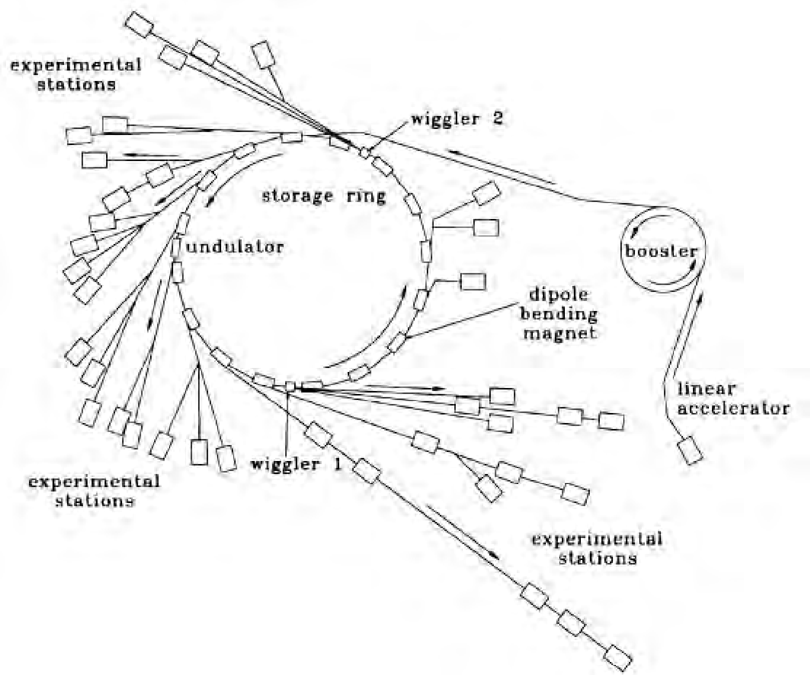
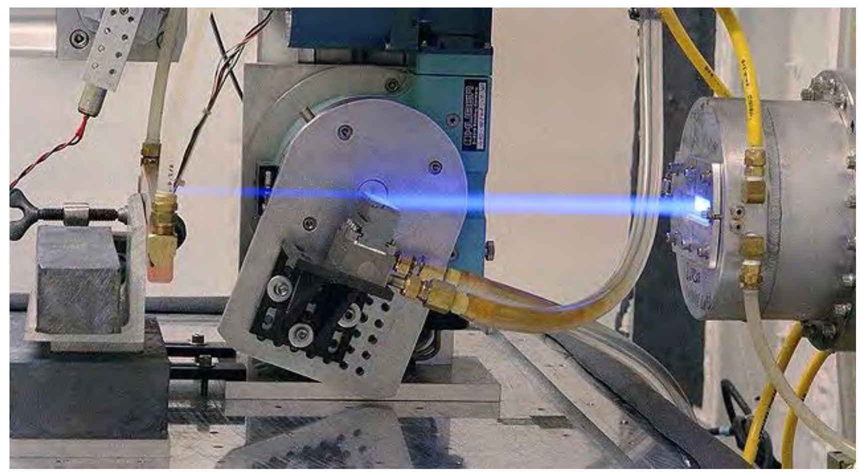
# How to generate X-rays?

**The very expensive way:**

## 1) Synchrotron radiation

- E.g. Argonne National Laboratory
- high-energy electron beam: directed into auxiliary components (e.g. bending magnets and insertion devices) supplying strong magnetic fields perpendicular to the beam



Synchrotron radiation emerging from a beam port. The blue color comes from oxygen and nitrogen atoms in the air, ionized by the X-rays (Source: Wikipedia).

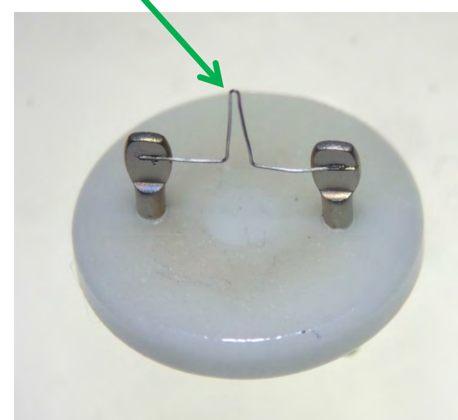
http://authors.library.caltech.edu/5456/1/hrst.mit.edu/hrs/materials/public/X-rays/sources_detectors.htm

# How to generate X-rays?

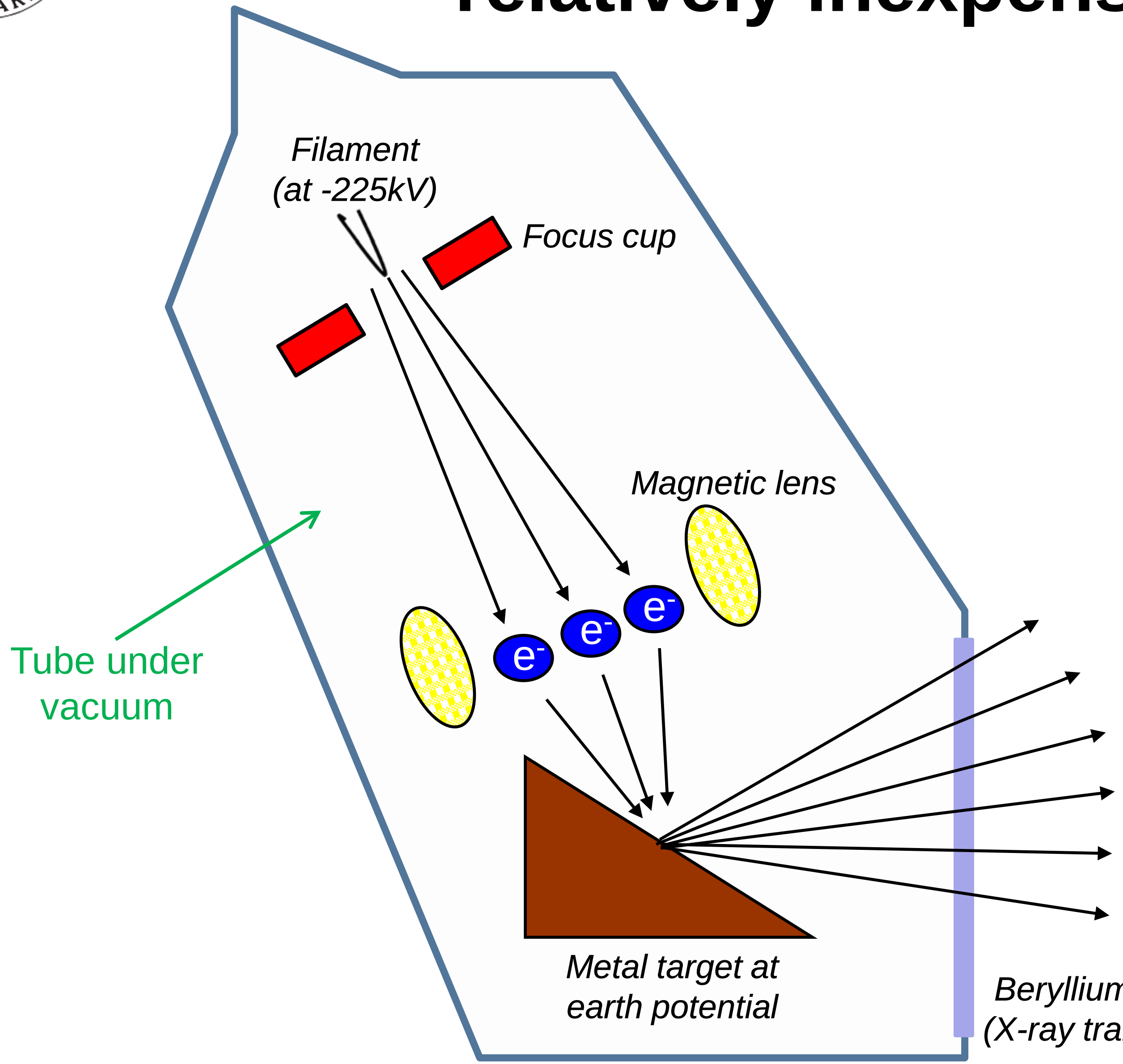
**The much less expensive way:**

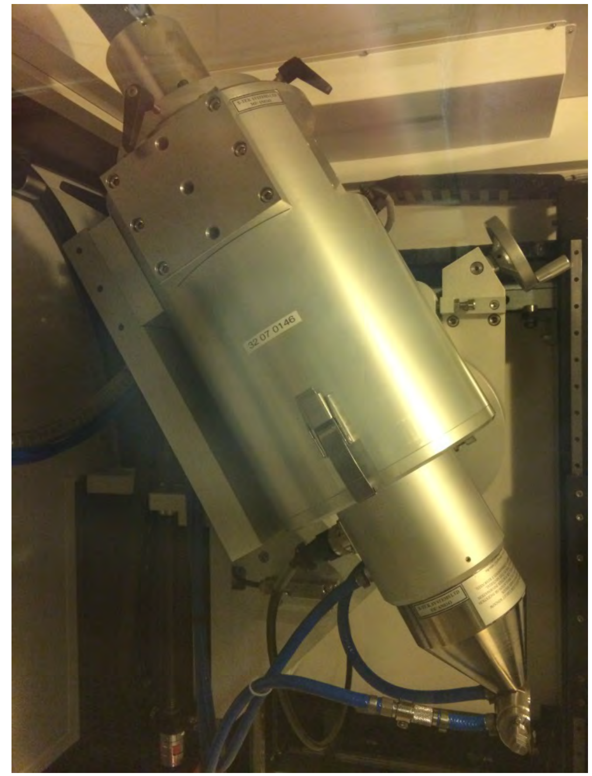
2) Firing electrons at high speed on to a metal target.

- Electrons are produced from a hot Tungsten filament (like a light bulb).
- They are accelerated using a high voltage into a beam tube.
- They travel at up to 80% the speed of light (giving them energies of 30 - 450keV).
- They are focused by a magnetic lens into a very small spot (1-5µm diameter) onto the surface of a metal target.
- The sudden deceleration of the charged electrons when they hit the target produces heat (a lot!) and X-rays (some).

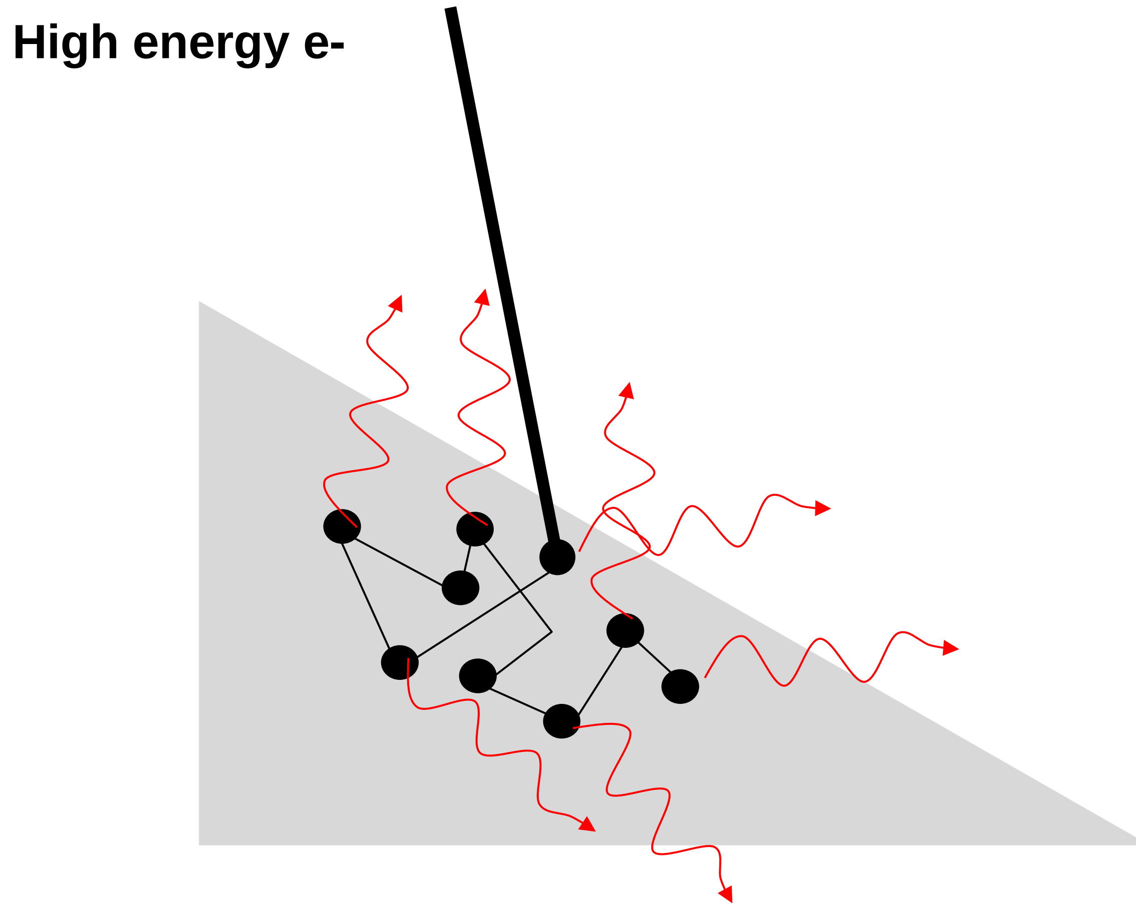


# X-ray Tubes: simple and relatively inexpensive



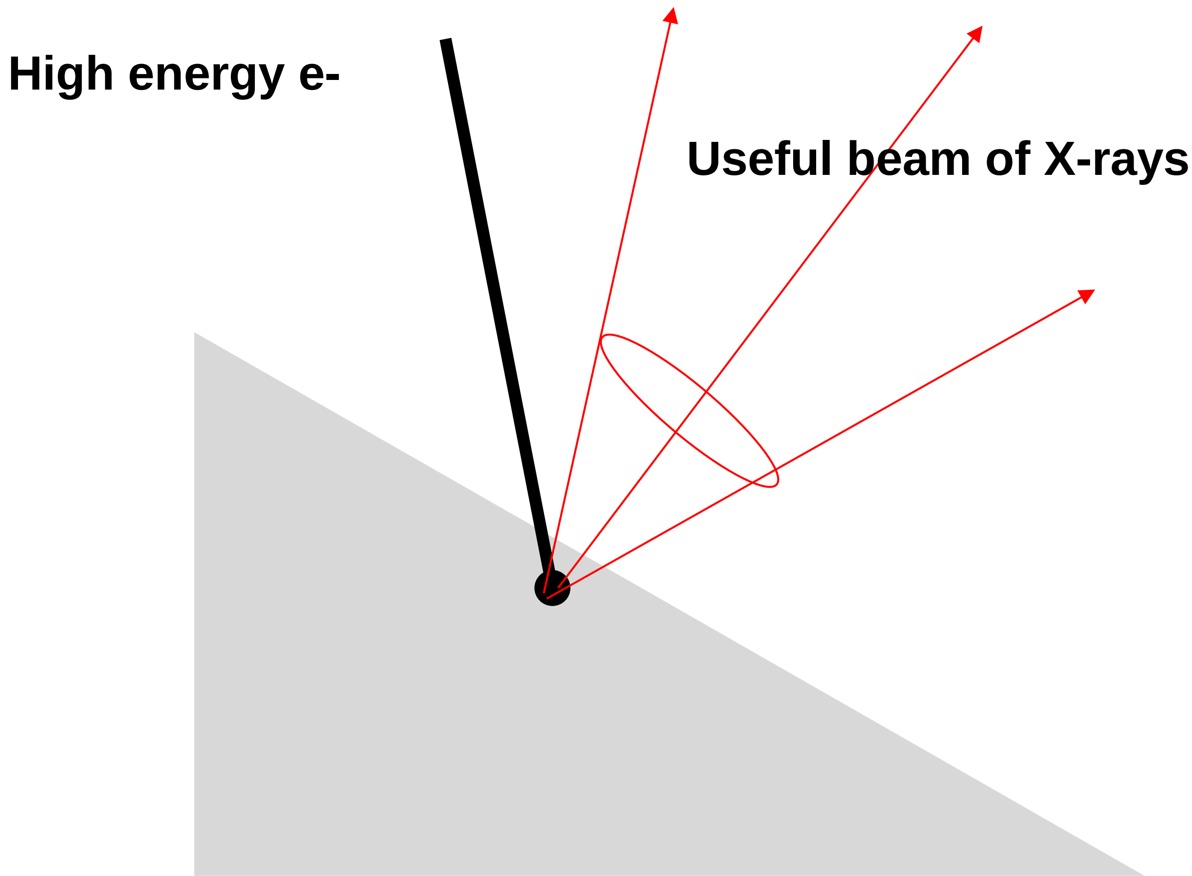



# How to generate X-rays?



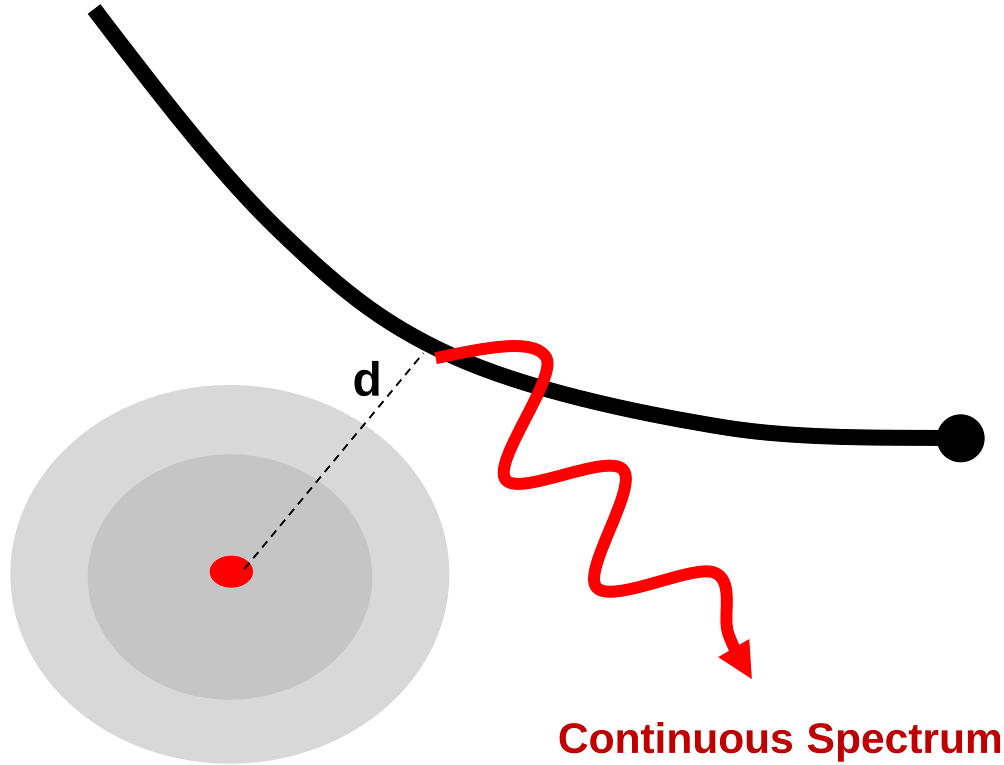

**Electron - Interactions**

# How to generate X-rays?



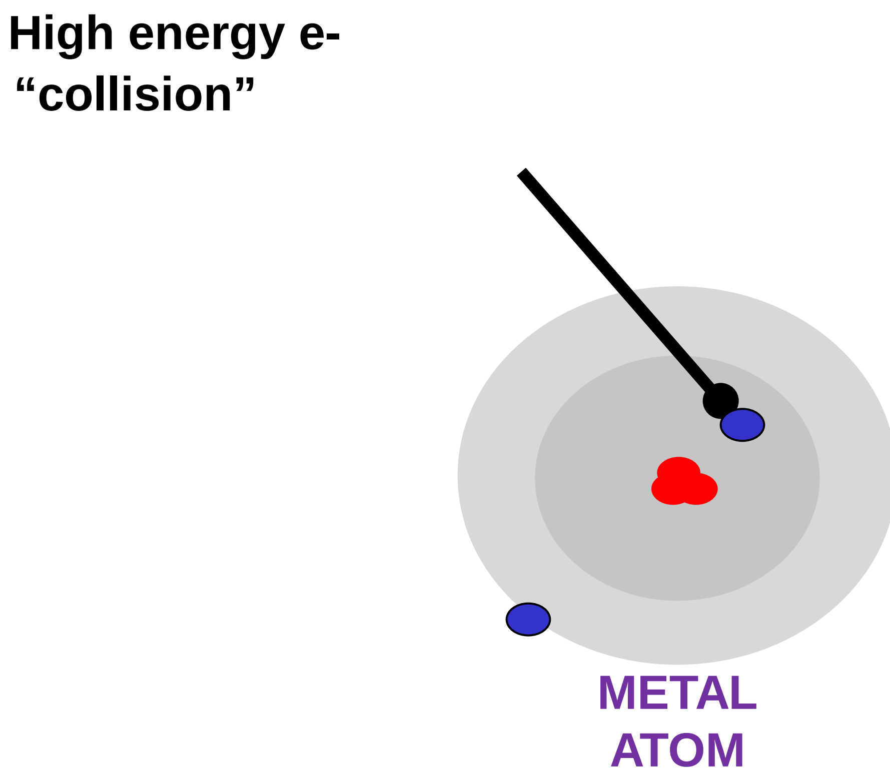

Electron - electron interactions

# Bremstrahlung



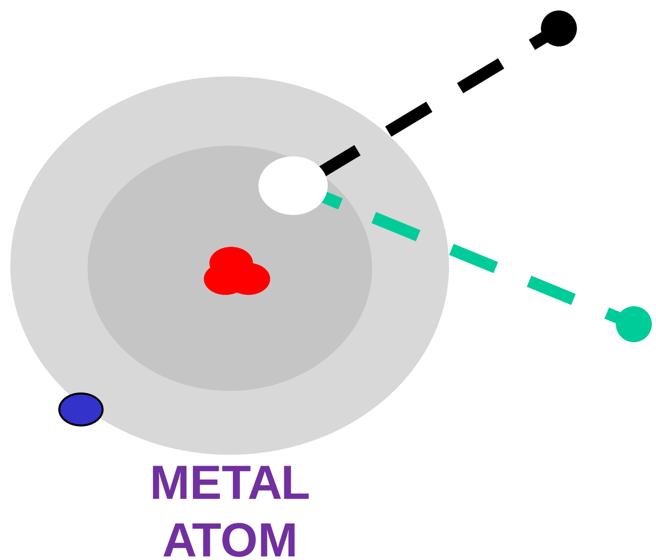

**Range of d's**
**Range of accelerations**
**Range of photon energies**
**Continuum radiation**

# Characteristic Radiation



# Characteristic Radiation

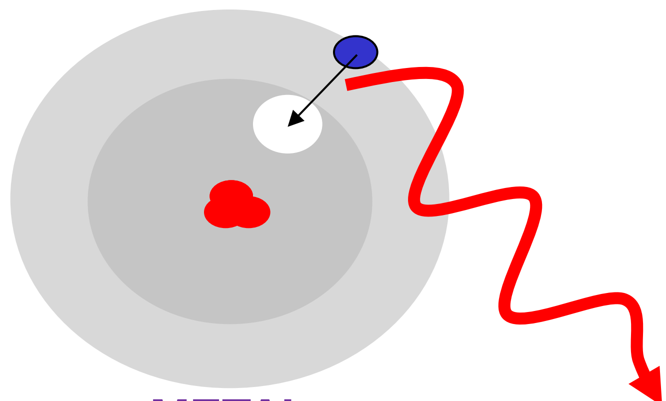
**The Collision removes an electron from the atom**



# Characteristic Radiation

**An outer electron falls to fill the "hole" and an X-ray photon emitted.**

**Photon Energy = difference between the initial and final state of the transition.**




**Electron states are dependent on the material**
**Hence – characteristic X-ray**

# Spectrum from an X-ray Tube

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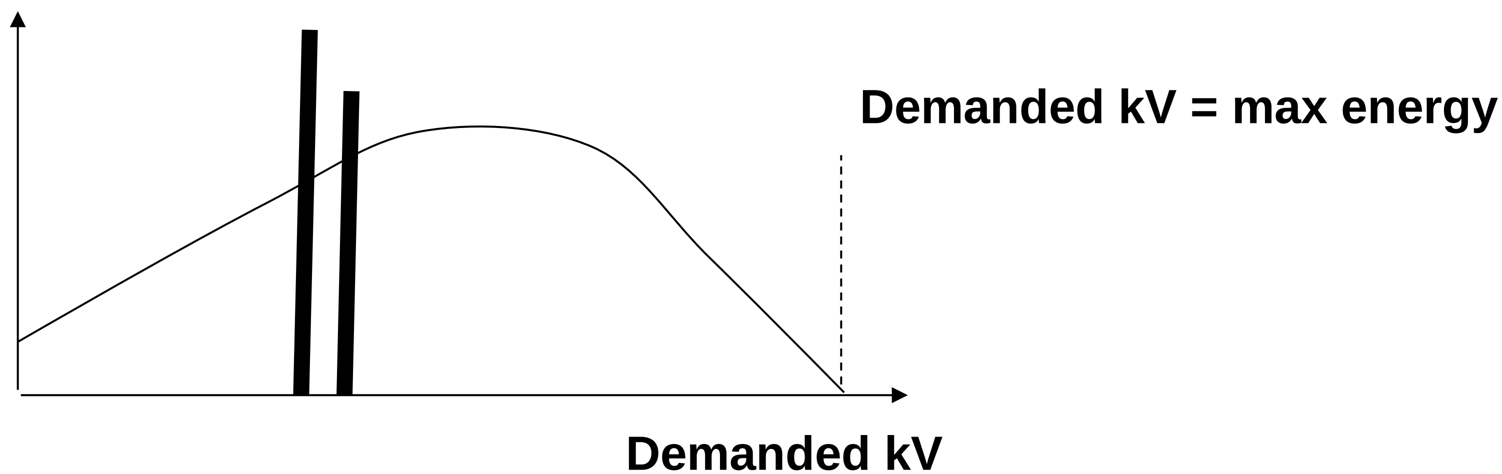
The spectrum from the source is made up of two components

1) Continuum radiation ~ 95%

2) Characteristic Lines from the target material ~ 5%



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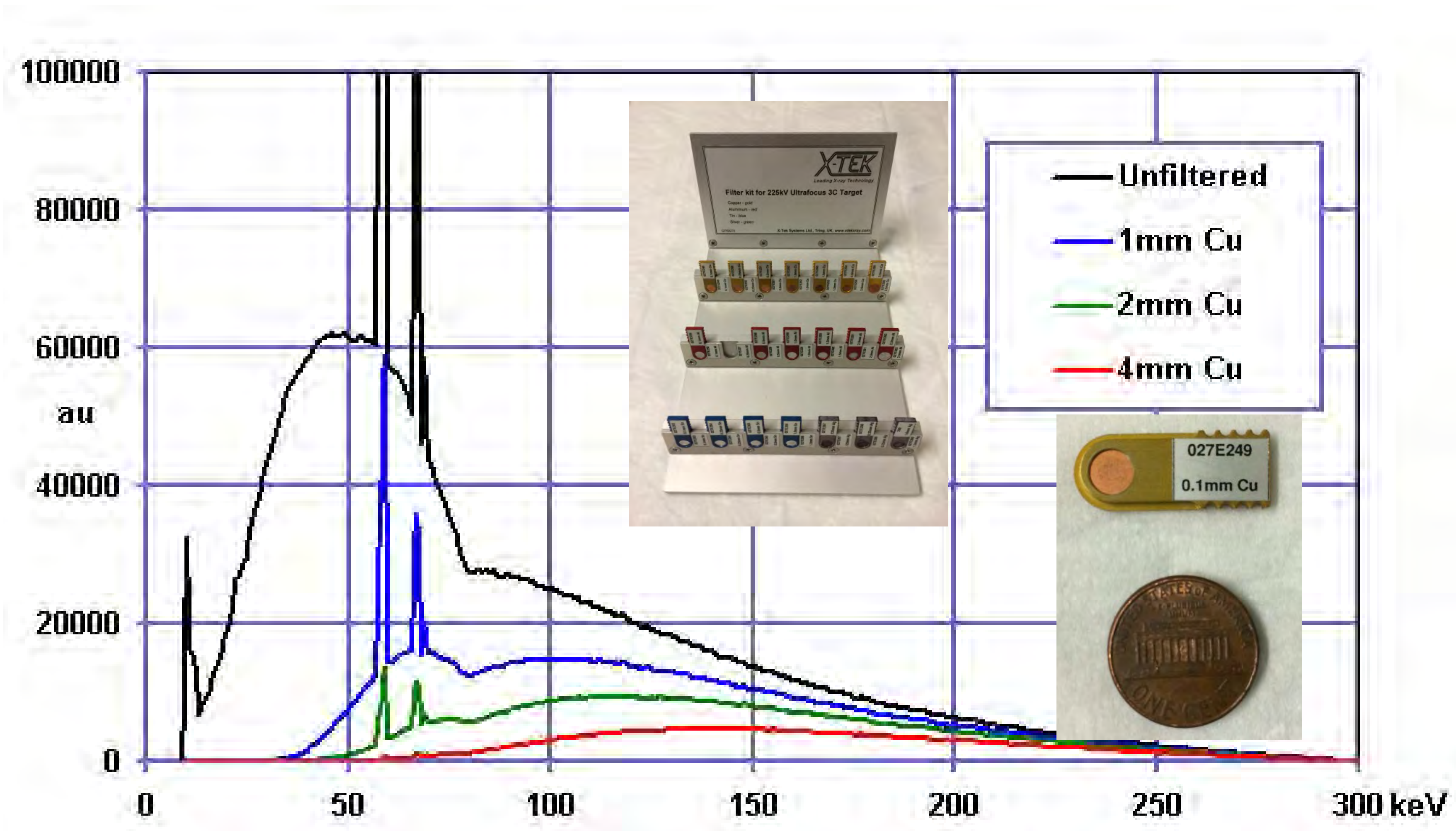
# Spectrum from an X-ray Tube



# X-ray Imaging

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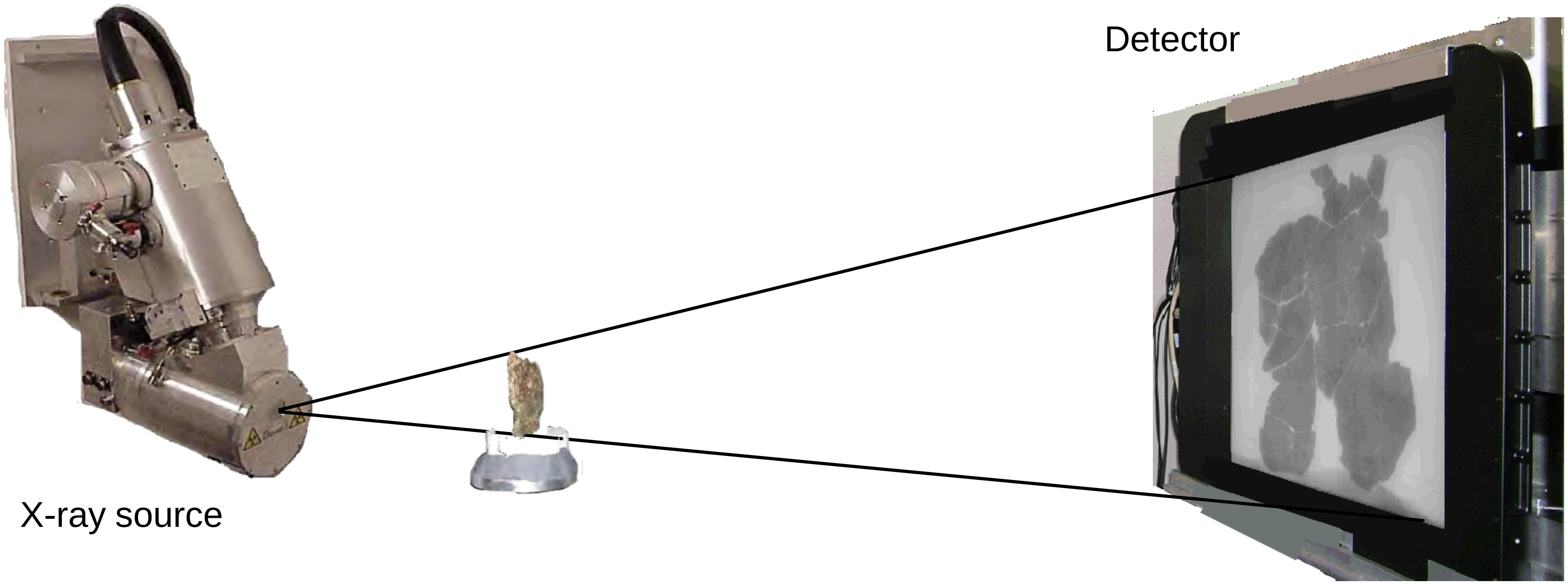
**How do we get an X-ray image?**

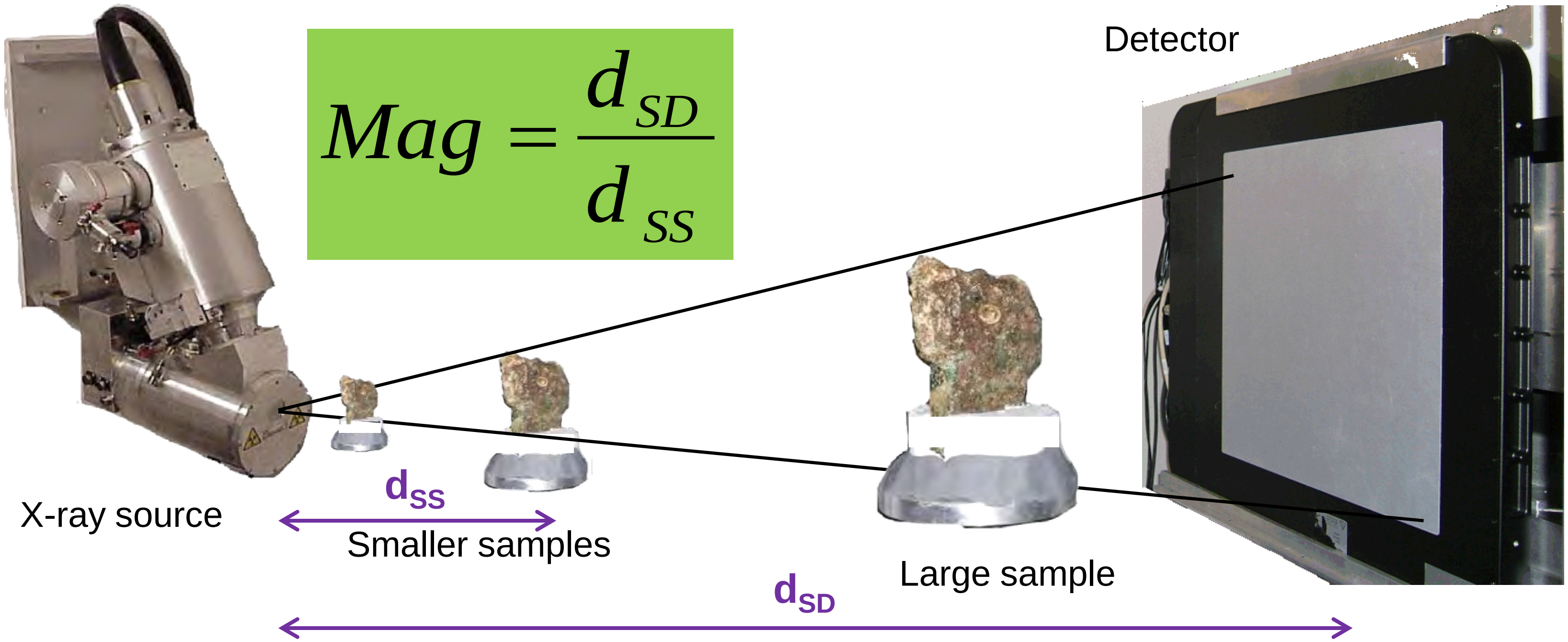



X-rays travel in straight lines and pass right through the sample. However, some of the X-rays are absorbed by the sample and so the intensity of the X-rays is reduced forming a shadow image.

# X-ray Imaging

**How do we get a magnified image?**

$$Mag = \frac{d_{SD}}{d_{SS}}$$




Just like light, X-rays travel in straight lines.
Unlike light, we cannot use a lens, so we use geometric magnification.

The magnification is increased by moving the sample closer to the X-ray source (and vice versa).

**Working distance increases as sample size increases ➔ Mag decreases!**

# X-ray Imaging

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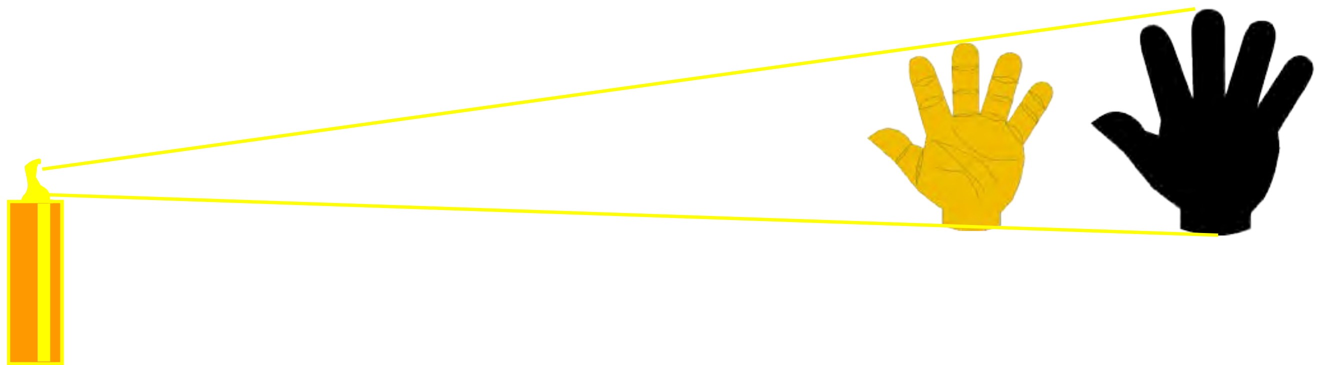
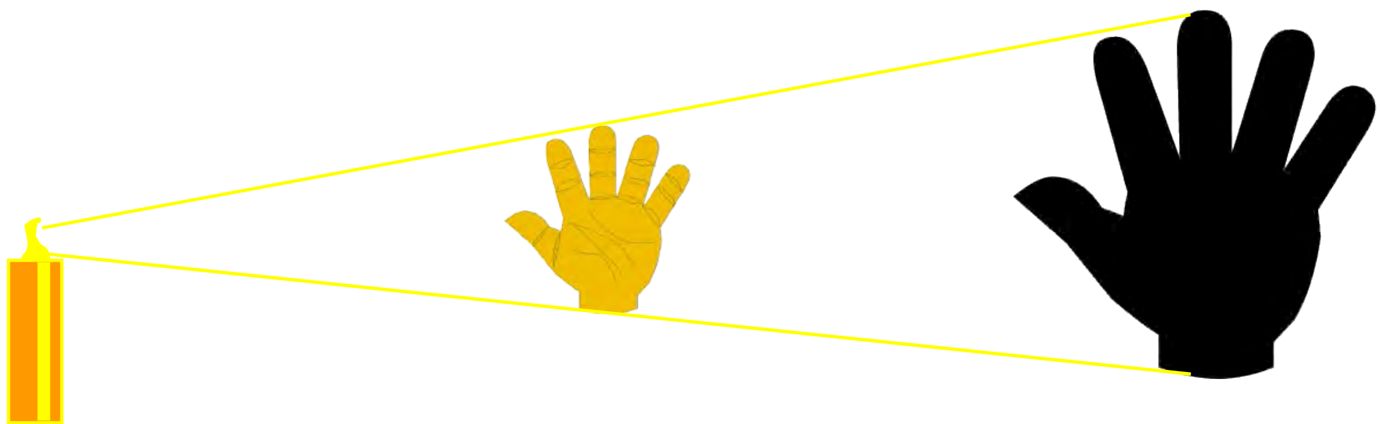
**How do we magnify the image?**



An optical analogy is the shadow cast by your hand on a wall by the light of a candle. As you move your hand closer to the candle, the shadow on the wall will get larger.

# X-ray Imaging

**How do we magnify the image?**



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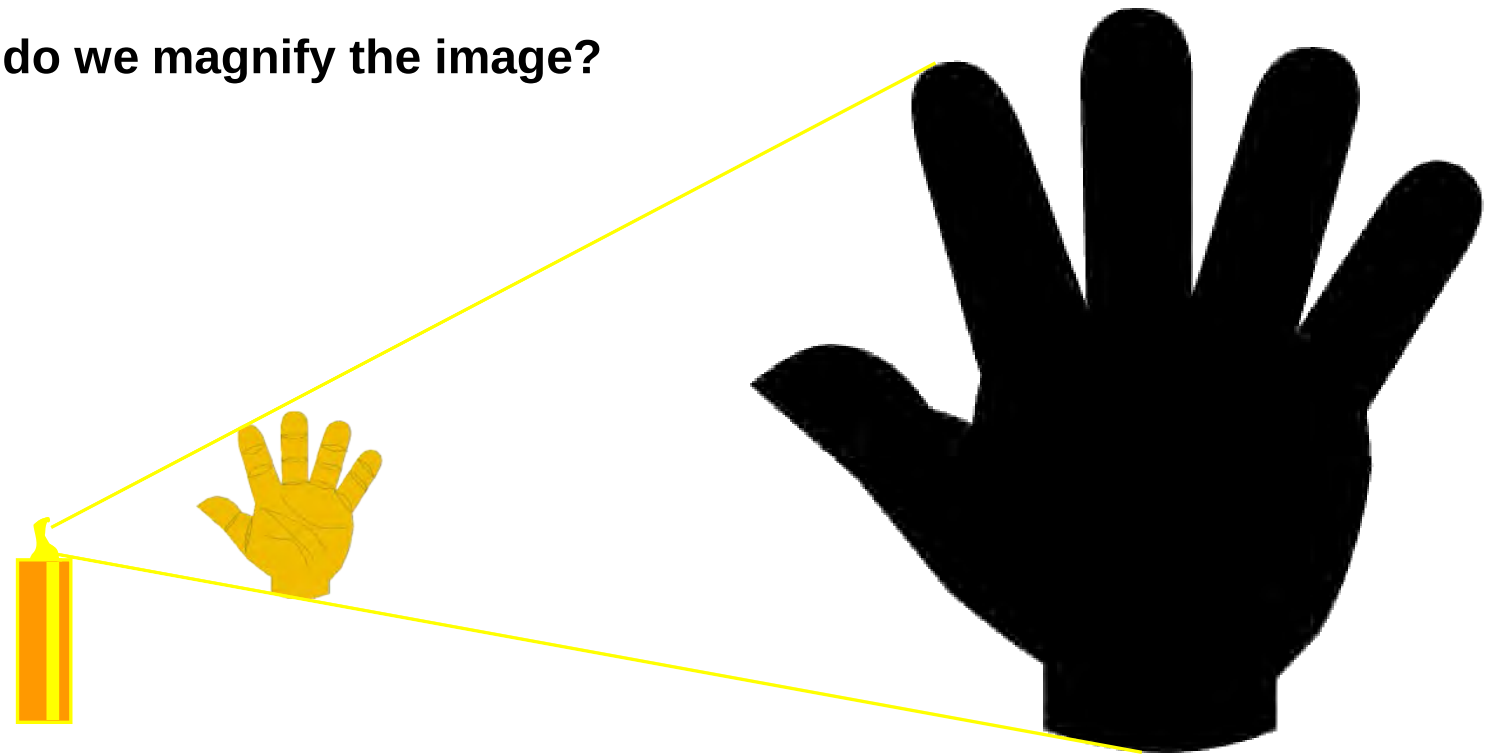
# X-ray Imaging

**How do we magnify the image?**



An optical analogy is the shadow cast by your hand on a wall by the light of a candle. As you move your hand closer to the candle, the shadow on the wall will get larger.

# X-ray Imaging

**How do we image the X-rays?**

• When X-rays hit certain materials, they cause them to fluoresce. In this process, the energy of the X-ray is absorbed and re-emitted as visible light. Usually this light is very faint and needs to be amplified, else very sensitive detectors need to be used.

• An image intensifier is coated with a fluorescent front screen which is intensified electronically on to the back screen. A CCD camera with typically 1000x1000 pixels views this back screen. The signal from this camera is digitised to an 8/10 or 12-bit image.

*A 150mm image intensifier with a CCD video camera attached*

# X-ray Imaging

**How do we image the X-rays?**

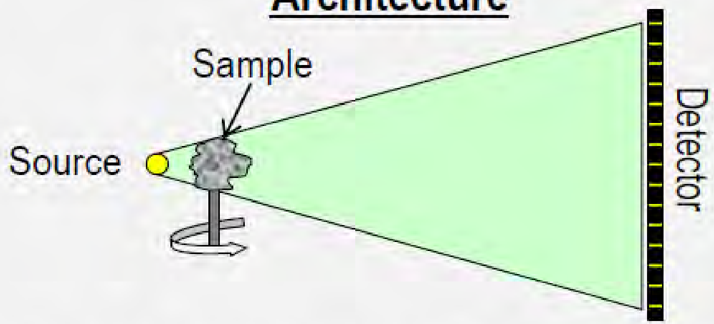
• The silicon flat panel detector has a fluorescent screen which converts the X-ray energy into light to form an image on an array of 2000x2000 light-sensitive diodes, each 200x200µm in size. Electronics allow this image to be read by the computer with a precision of 1 part in 65,536 shades of gray (16 bits).

*A 2k x 2k 16-bit amorphous silicon flat panel detector from PerkinElmer*

# Imaging Architecture Comparison

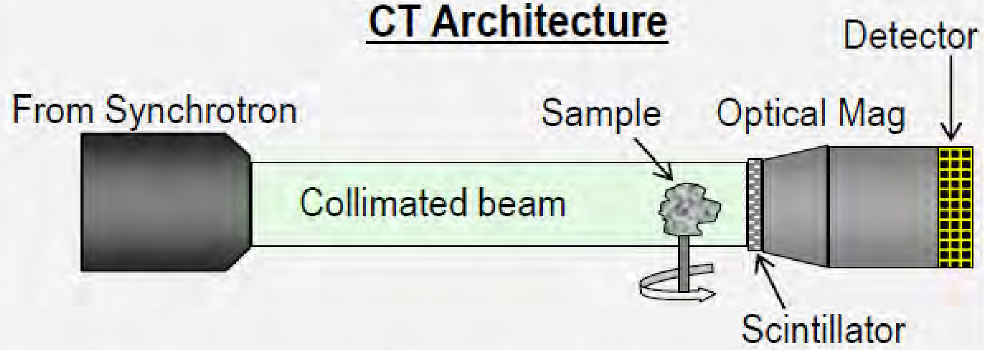
Synchrotron vs. Conventional CT vs. with Optical Magnification

## Conventional CT Architecture



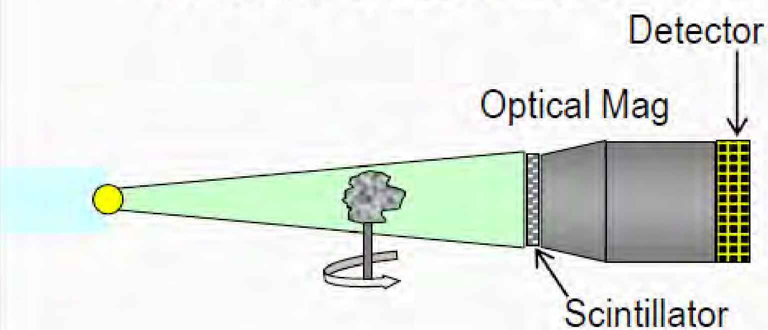

Relies on geometric magnification and small spot size for resolution. Large detector pixel.

## Synchrotron Source CT Architecture




Relies on optical magnification/small detector pixel size for resolution. Large spot size.

## Xradia Versa Architecture:




- Resolution relies on small detector pixels
- Achieves high resolution with small geometric magnification
- Flexibility to use more or less geo mag
- Does not require small spot size

(Credit: Zeiss)

# Spot Size dictates max. resolution!

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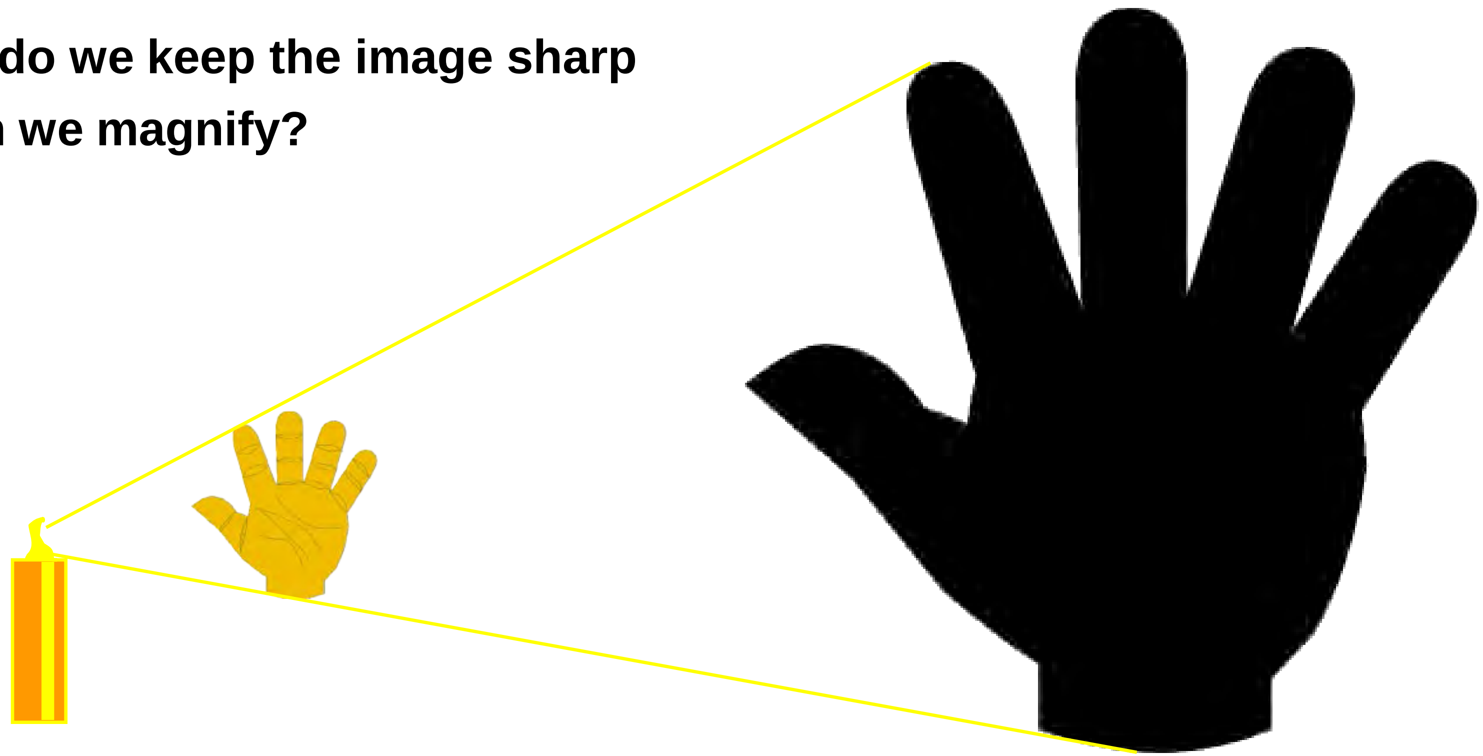
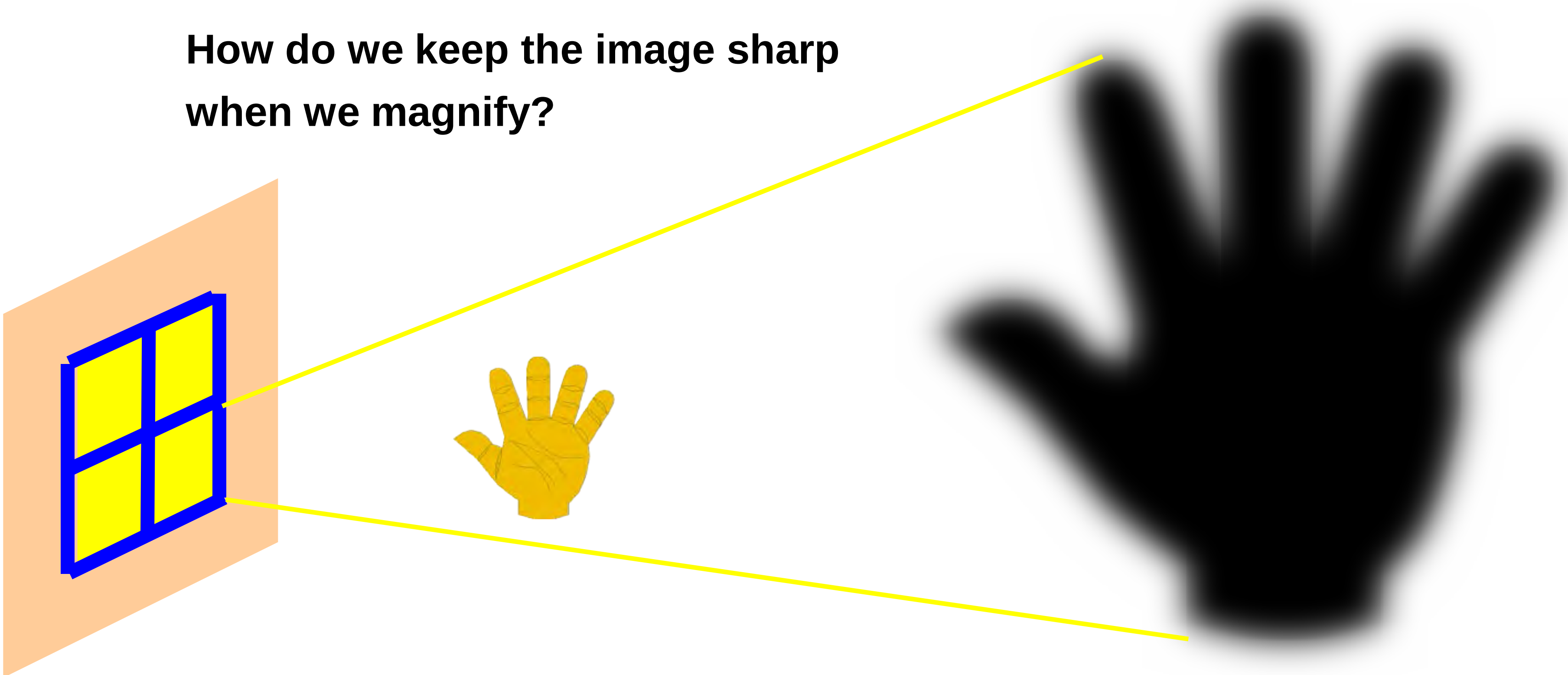
**How do we keep the image sharp when we magnify?**



An optical analogy here is the difference between the shadow cast by a small light source, such as a candle and that cast by a larger light source, such as a window.

# Spot Size dictates max. resolution!

**How do we keep the image sharp when we magnify?**

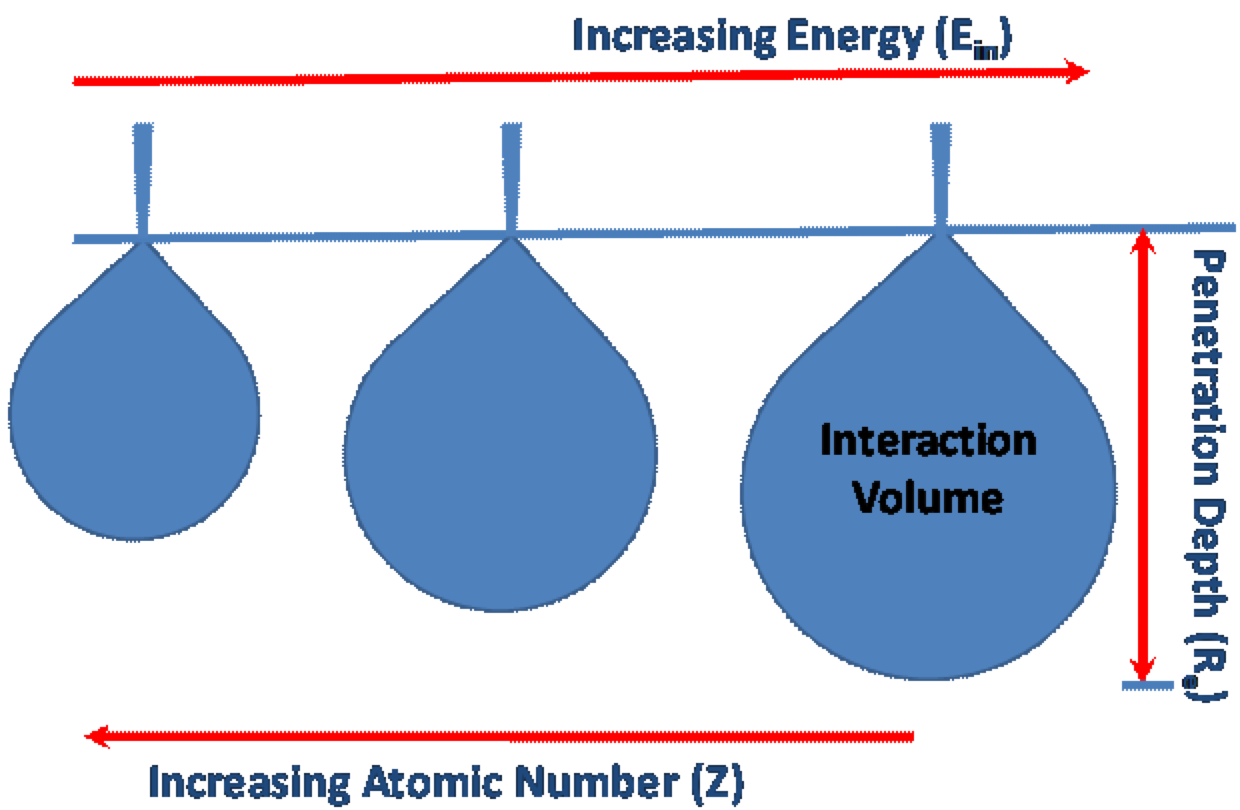


An optical analogy here is the difference between the shadow cast by a small light source, such as a candle and that cast by a larger light source, such as a window.

# Performance and Resolution

The source (i.e. X-ray spot) size depends on the energy of the electron beam, the X-ray target material, and the target geometry (thin metal layer or water-cooled metal block).

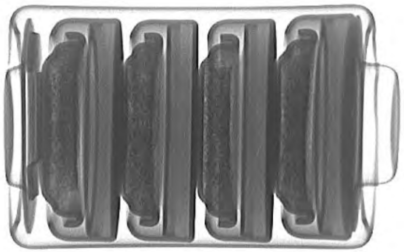
The higher the energy, the larger the interaction volume, hence the larger X-ray spot size, hence the lower the maximum attainable resolution!



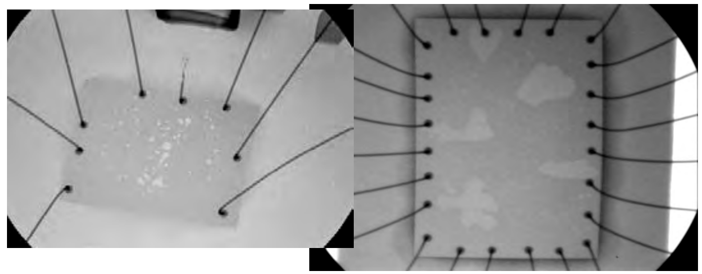

(Image from: http://materialsworld.utep.edu/Background/SCANNING%20ELECTRON%20MICROSCOPY/SccaningElectronMicroscopy.htm)

# Applications of (2D) X-ray Imaging

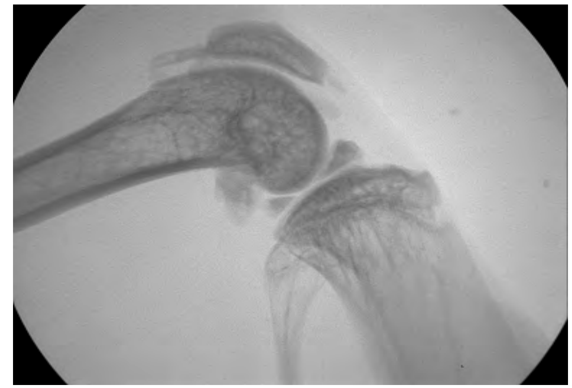




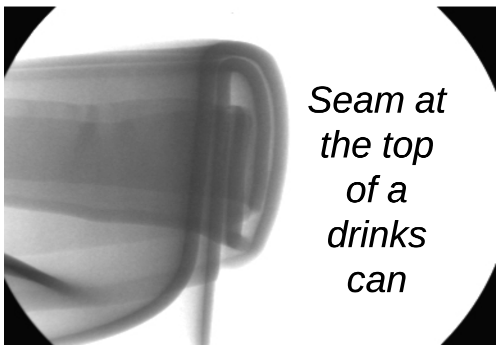
*Battery*



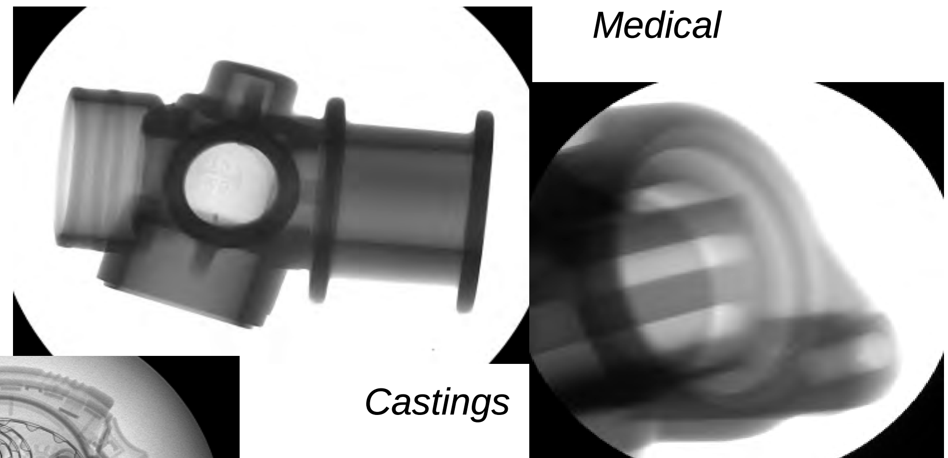
*Electronics*



*Medical*

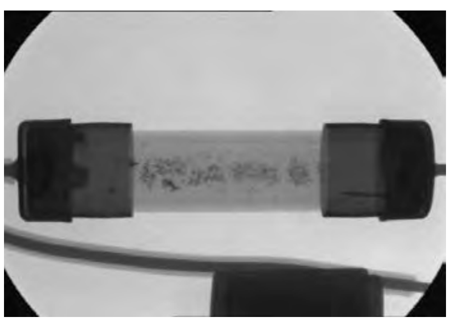


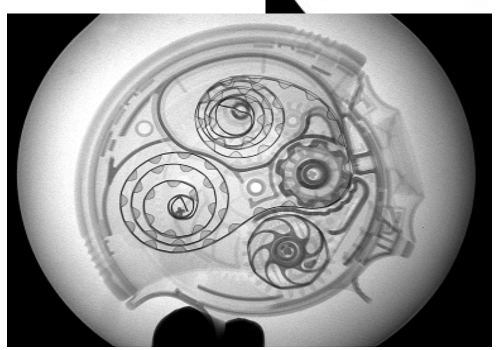
*Seam at the top of a drinks can*



*Castings*

*A blown fuse*





X-rays can be used to image many products!

*… and complex mechanisms!*

# Major drawback of 2D X-ray Imaging:

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**NO SPACIAL INFORMATION IN THE 3RD DIMENSION!**

2D X-ray image of Fitbit Flex personal activity monitor


Fitbit Flex personal activity monitor

# Major drawback of 2D X-ray Imaging:

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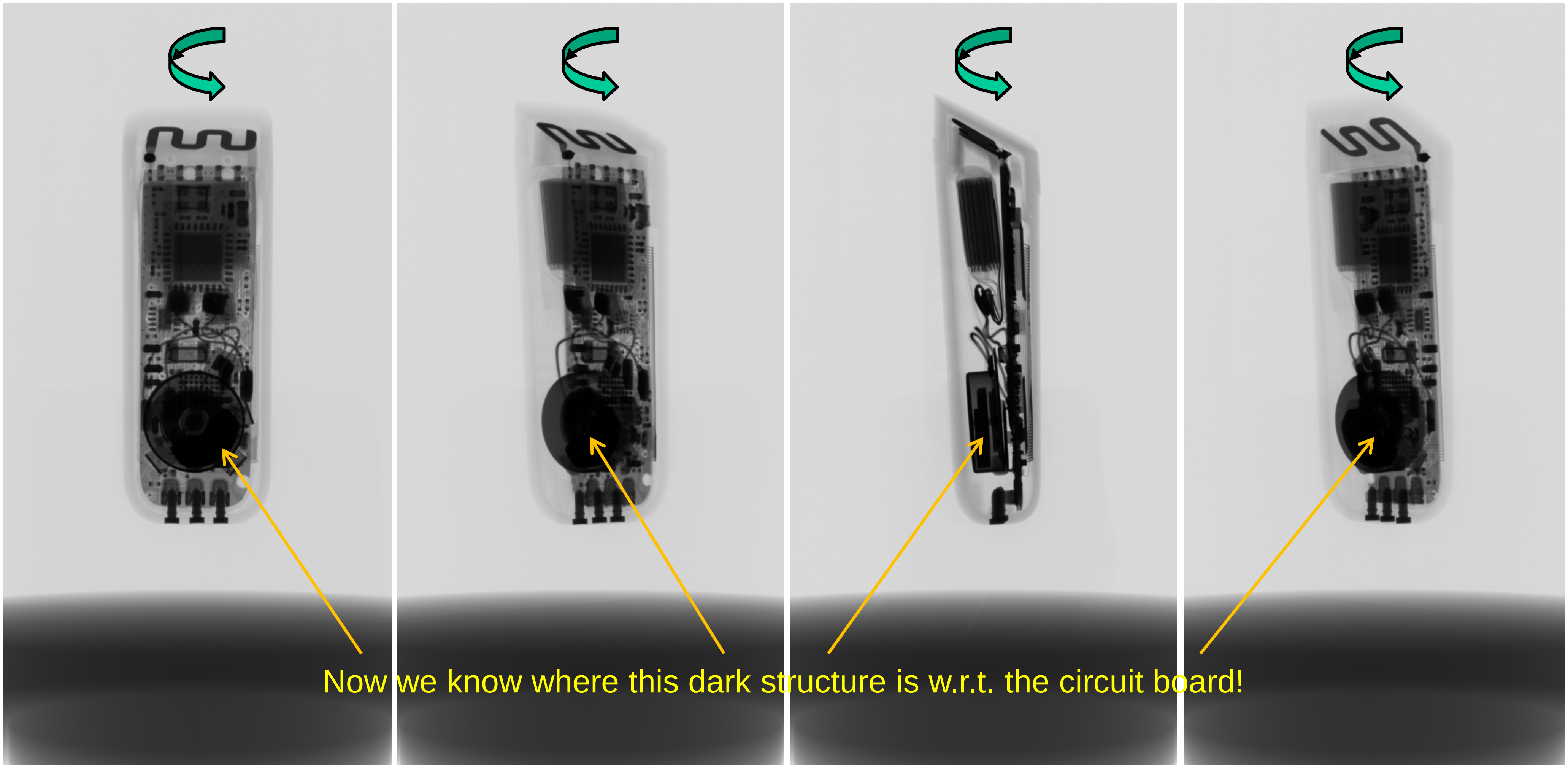
**BUT ONCE WE START ROTATING THE SAMPLE…**



# X-ray Computed Tomography

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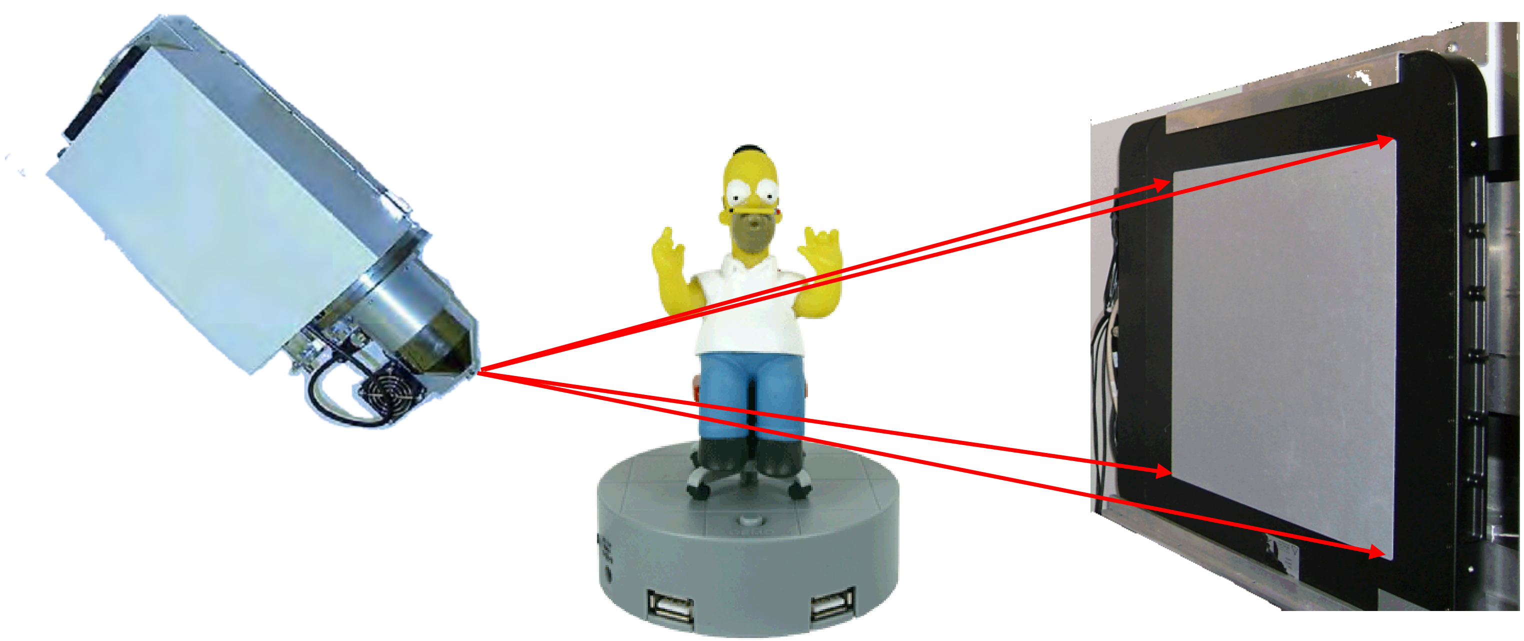
## What is X-ray Computed Tomography (or X-ray CT)?

• The process of imaging an object from all directions using penetrating X-rays and using a computer to reconstruct the internal 3-D structure of the object from the intensity values in the projected images.

• It is the process used in a medical CT scanner, though in our case we keep the source and detector stationary and rotate the object.



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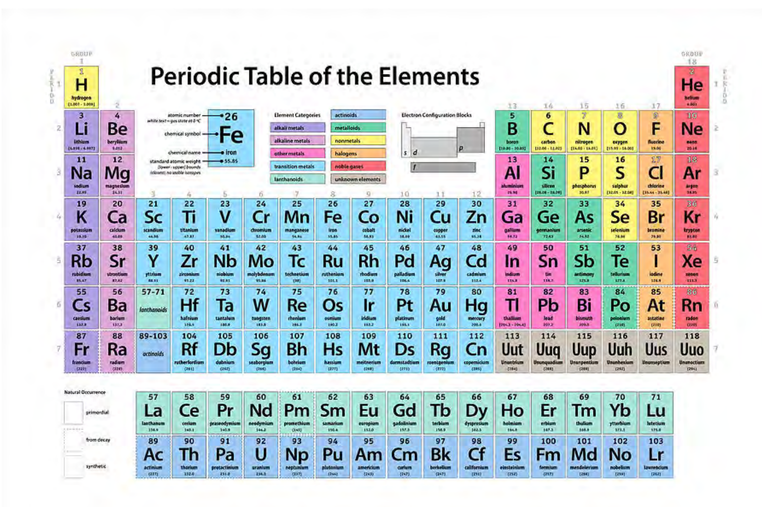
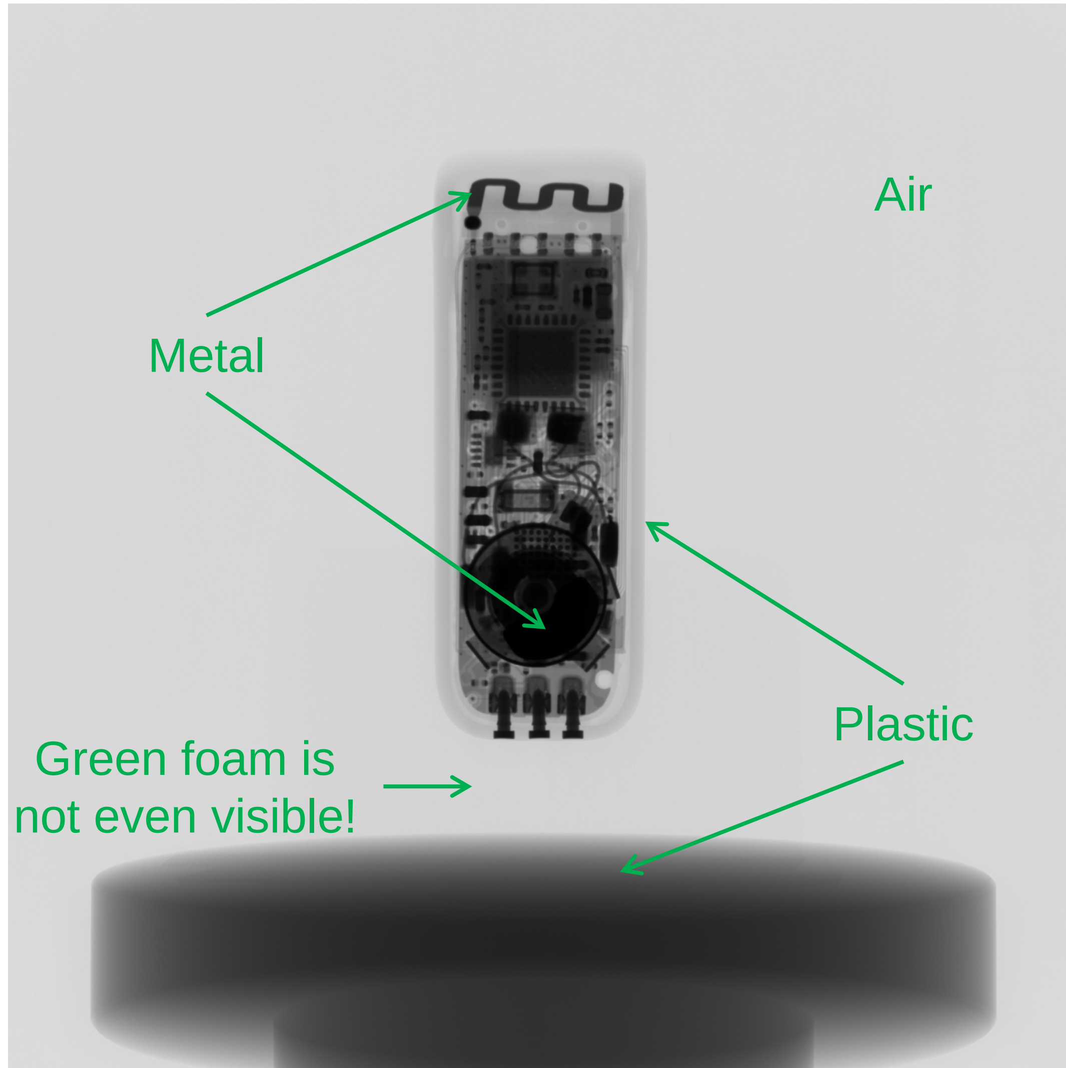
# X-ray Attenuation

**How much X-rays get attenuated is material-dependent!**



# X-ray Computed Tomography

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**What do CT volumes measure?**

The CT volumes measure *X-ray linear attenuation*. This is how much one unit of length of material reduces the X-ray intensity. It is usually measured as a logarithmic value, μ , and is in units of inverse length (e.g. $mm^{-1}$).

$I_{measured} = I_{black} + (I_{white} - I_{black}).\ \exp(-\mu\ t)$   [ t = material thickness]

So, $\mu = \ln \{ (I_{white} - I_{black}) / (I_{measured} - I_{black}) \} / t$

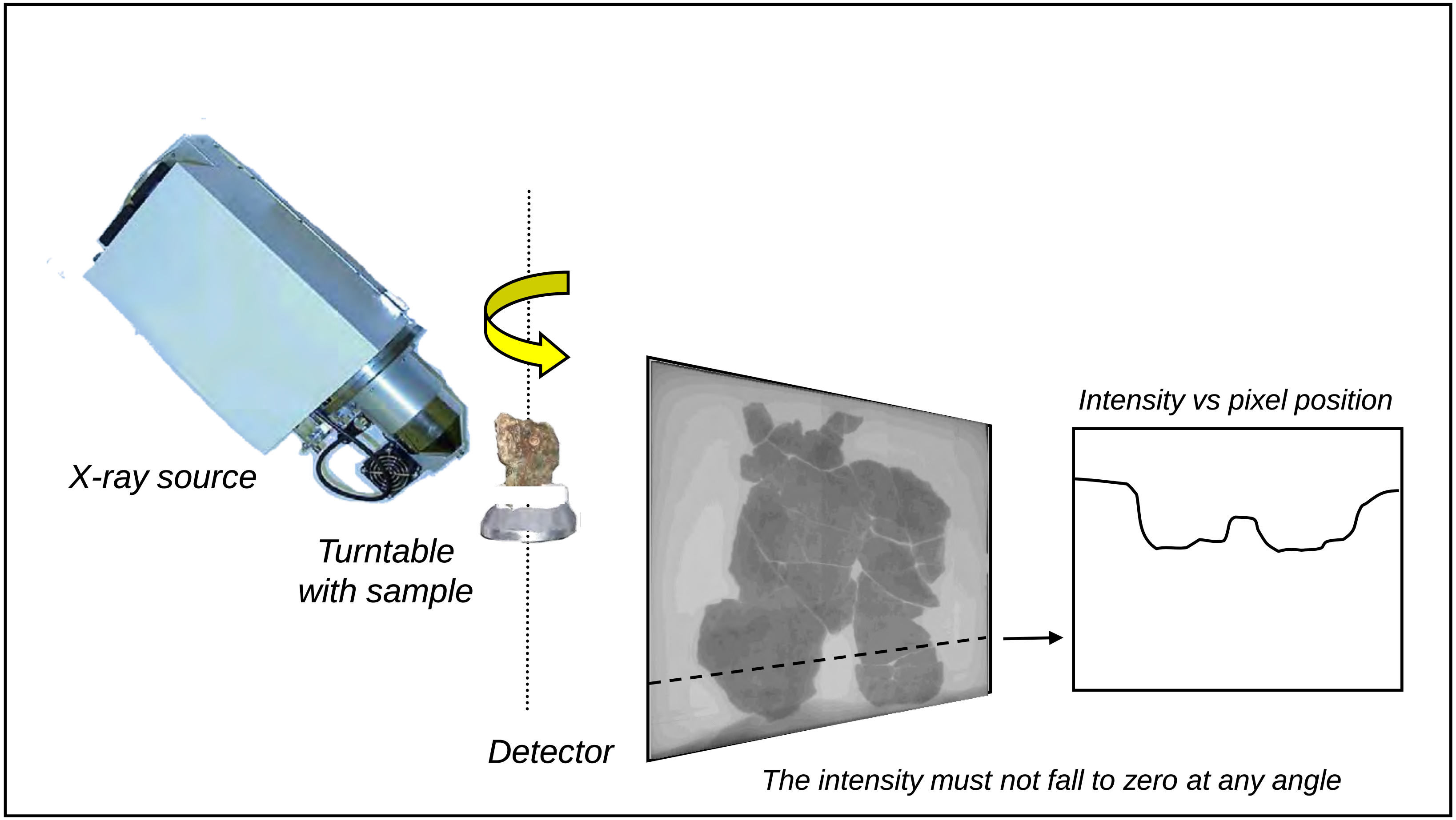
We have black and white reference images, so we can calculate μ.t for all projection image pixels.

When we reconstruct the volumes, we show the values of μ for all voxels.

→ Think of μ as the *X-ray density* of the material.

# X-ray Computed Tomography

CT requires us to penetrate the object with X-rays from all directions:



# X-ray Computed Tomography

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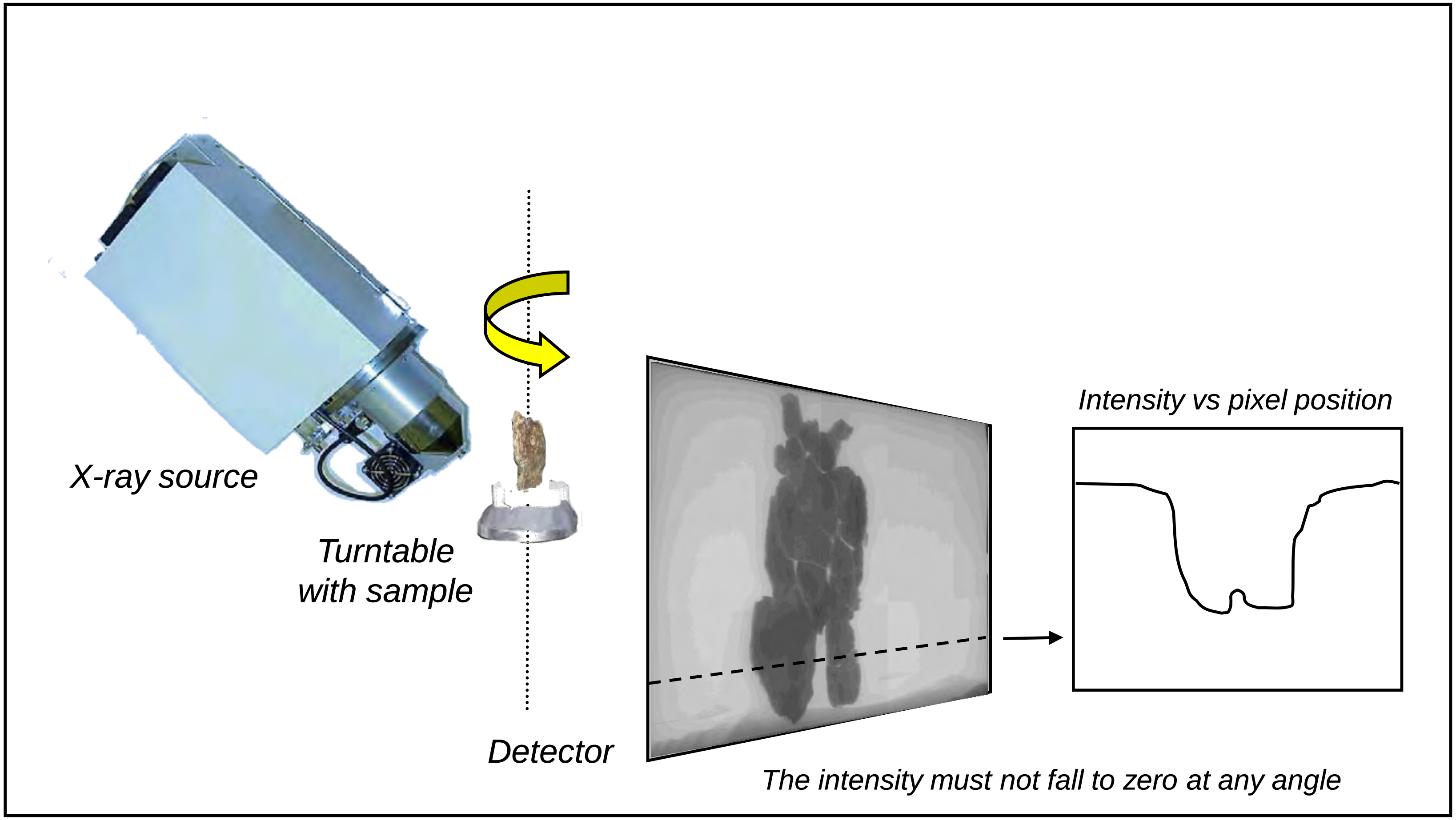

# X-ray Computed Tomography

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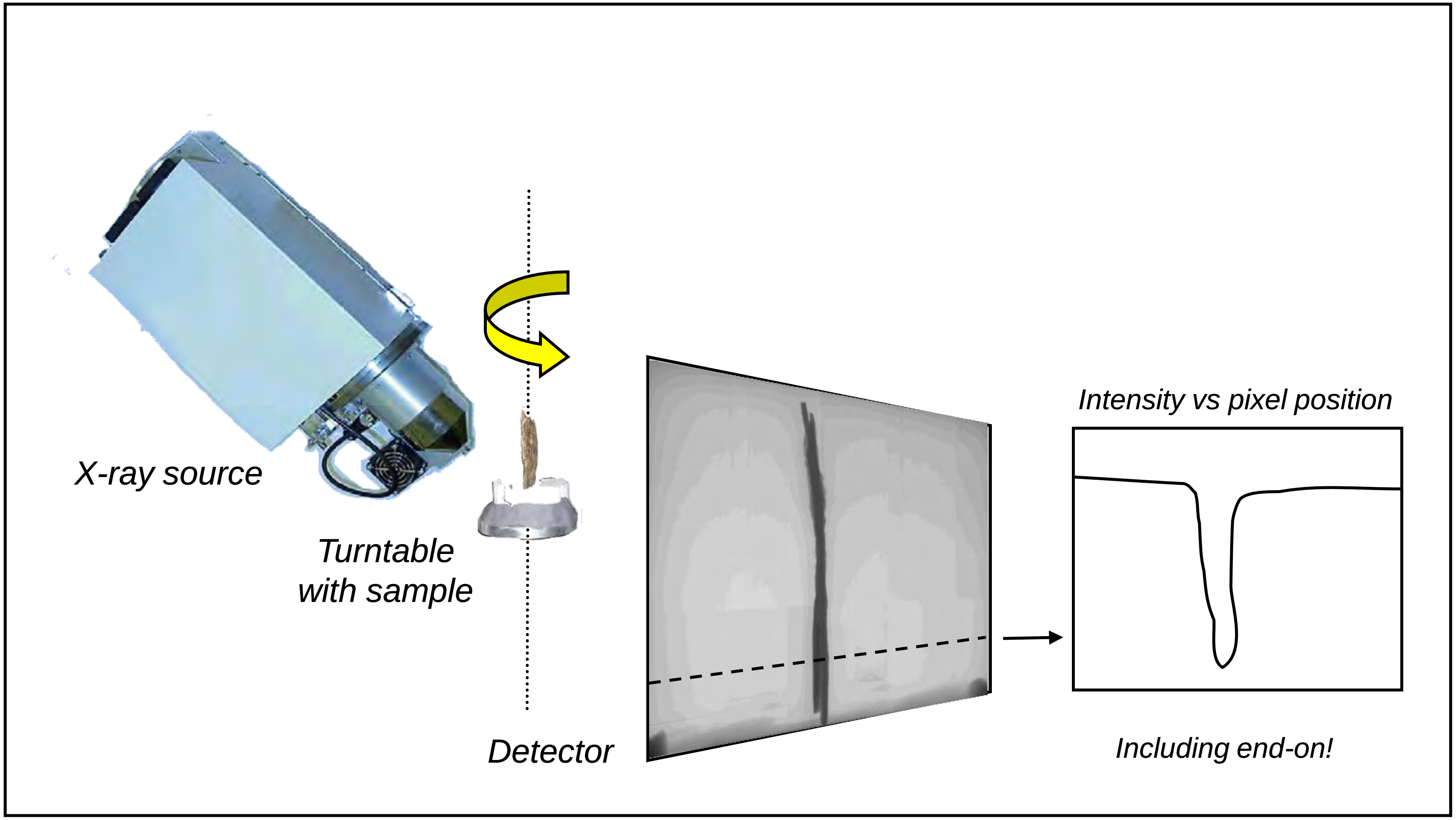
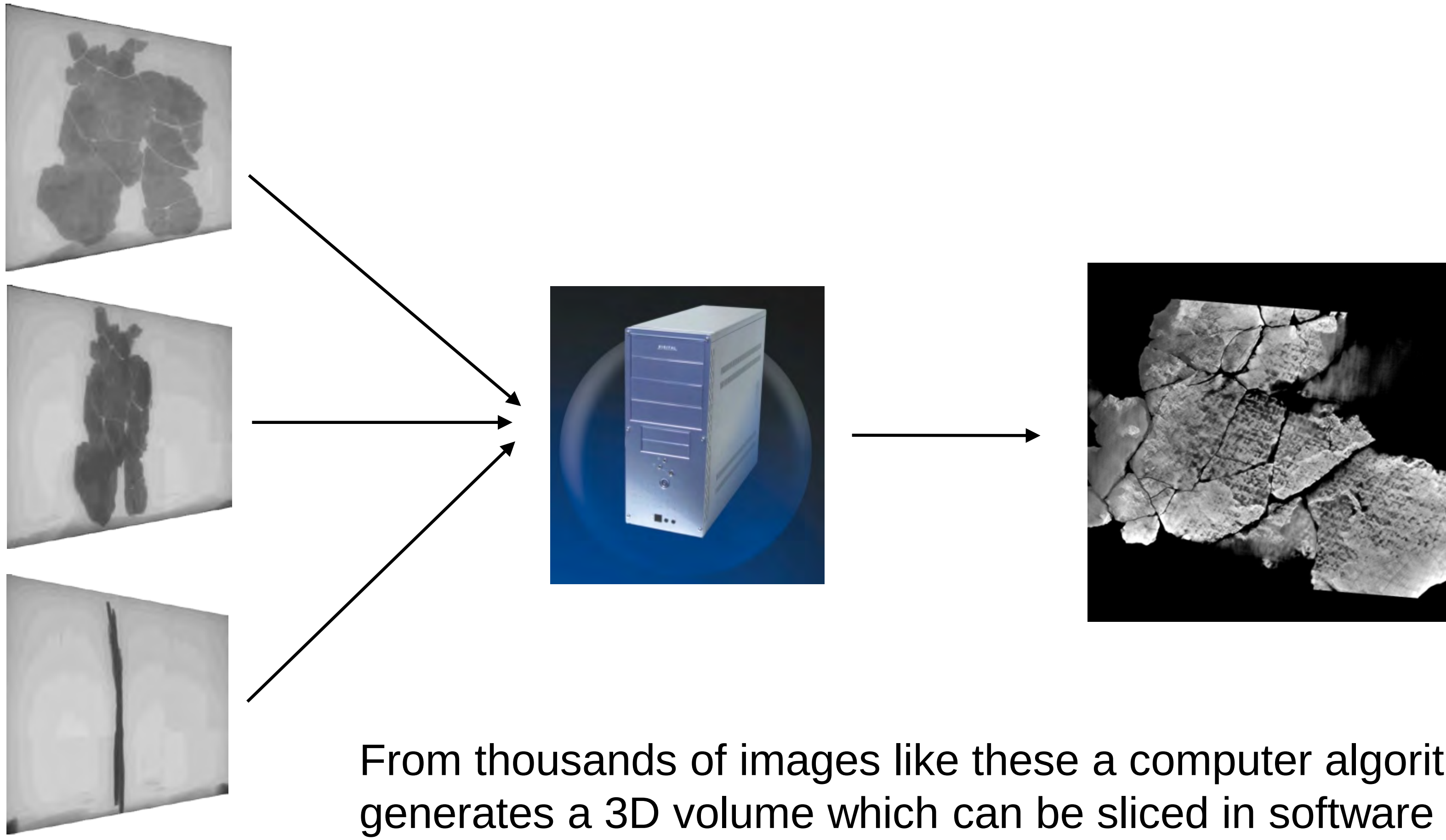


# X-ray Computed Tomography



From thousands of images like these a computer algorithm generates a 3D volume which can be sliced in software to reveal the internal structure of the object.

# X-ray Computed Tomography

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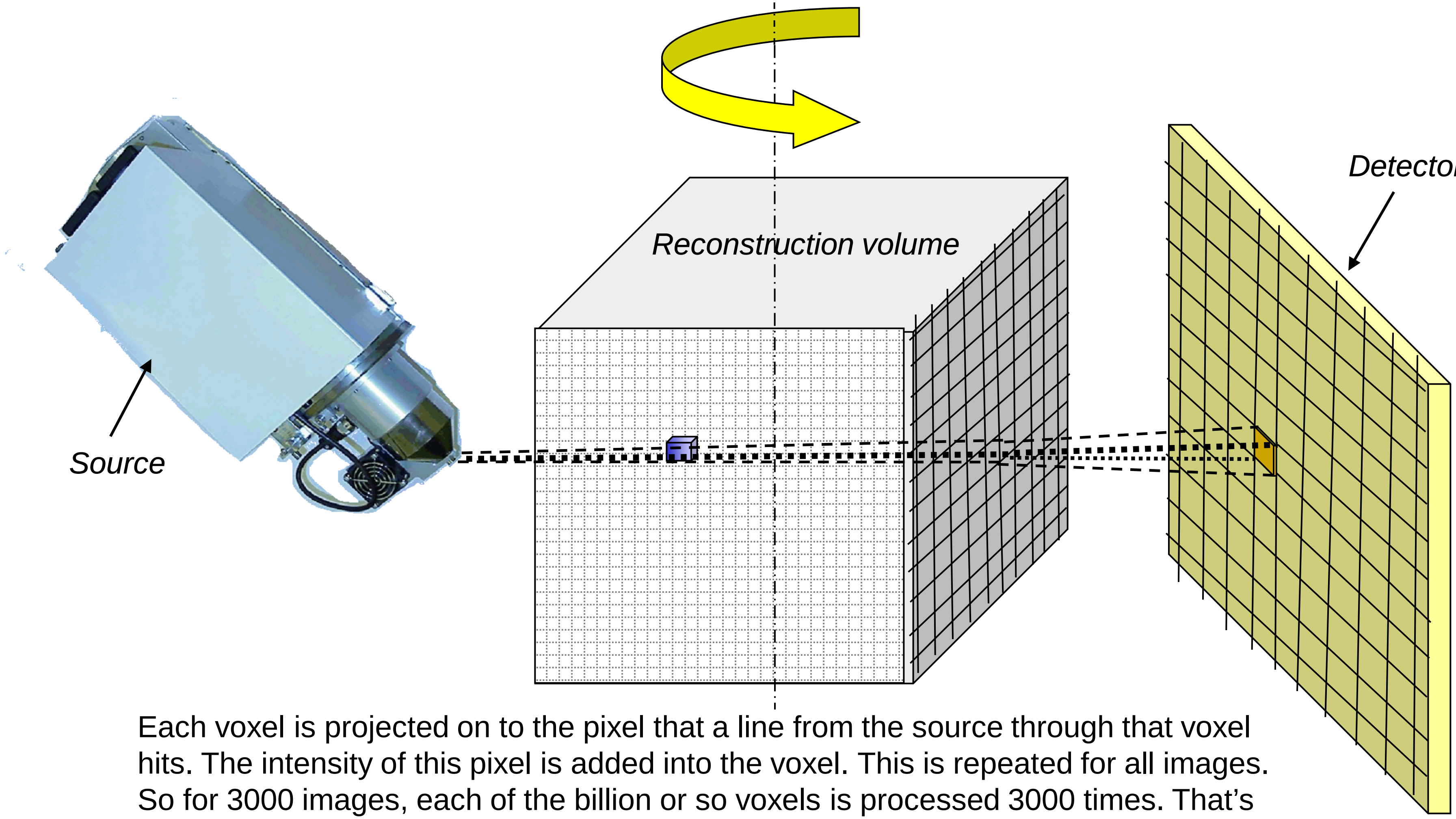
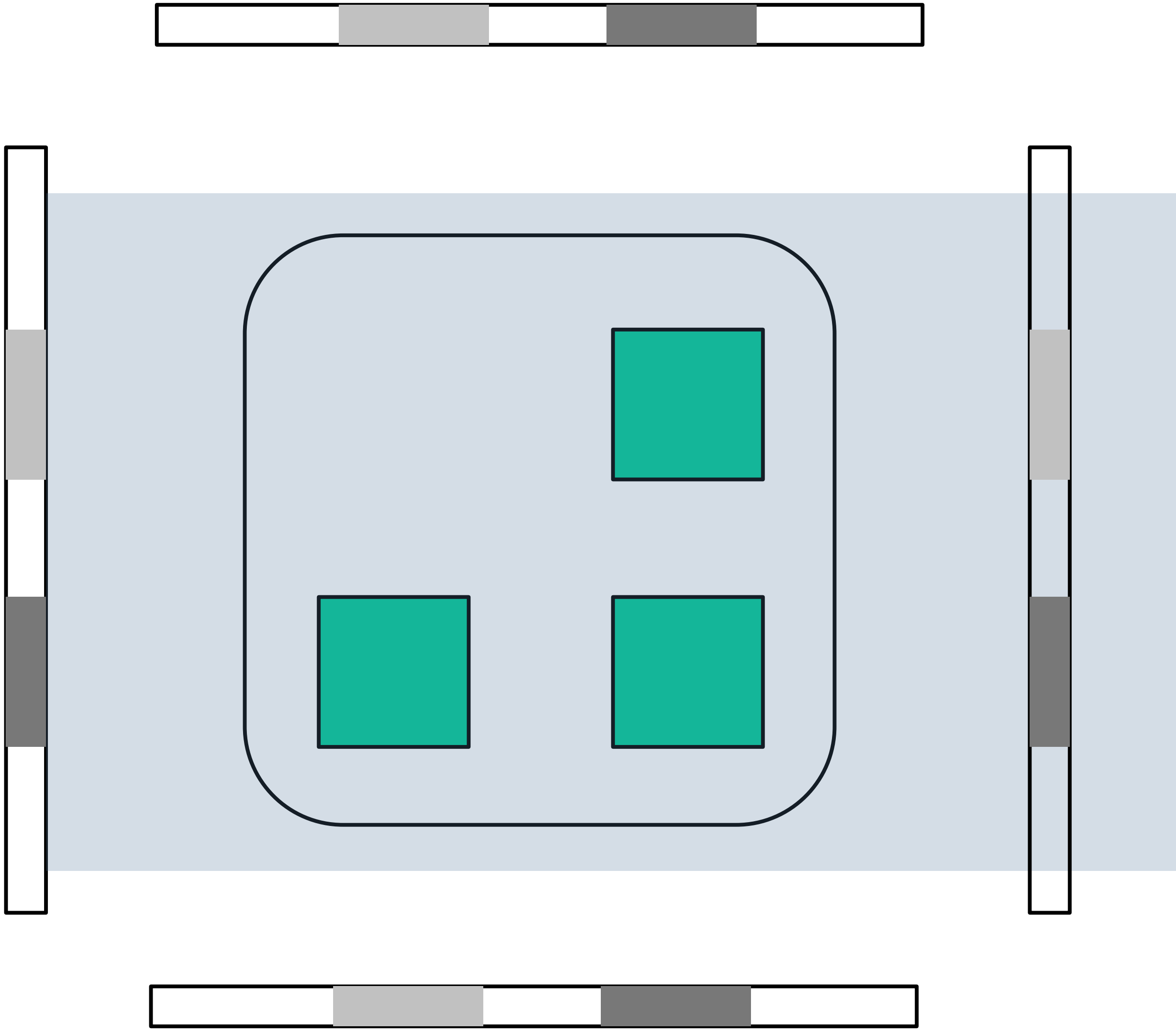
## Projecting the volume elements (voxels) onto the picture elements (pixels)




Each voxel is projected on to the pixel that a line from the source through that voxel hits. The intensity of this pixel is added into the voxel. This is repeated for all images. So for 3000 images, each of the billion or so voxels is processed 3000 times. That's why it can take a long time to reconstruct high-resolution CT volumes!

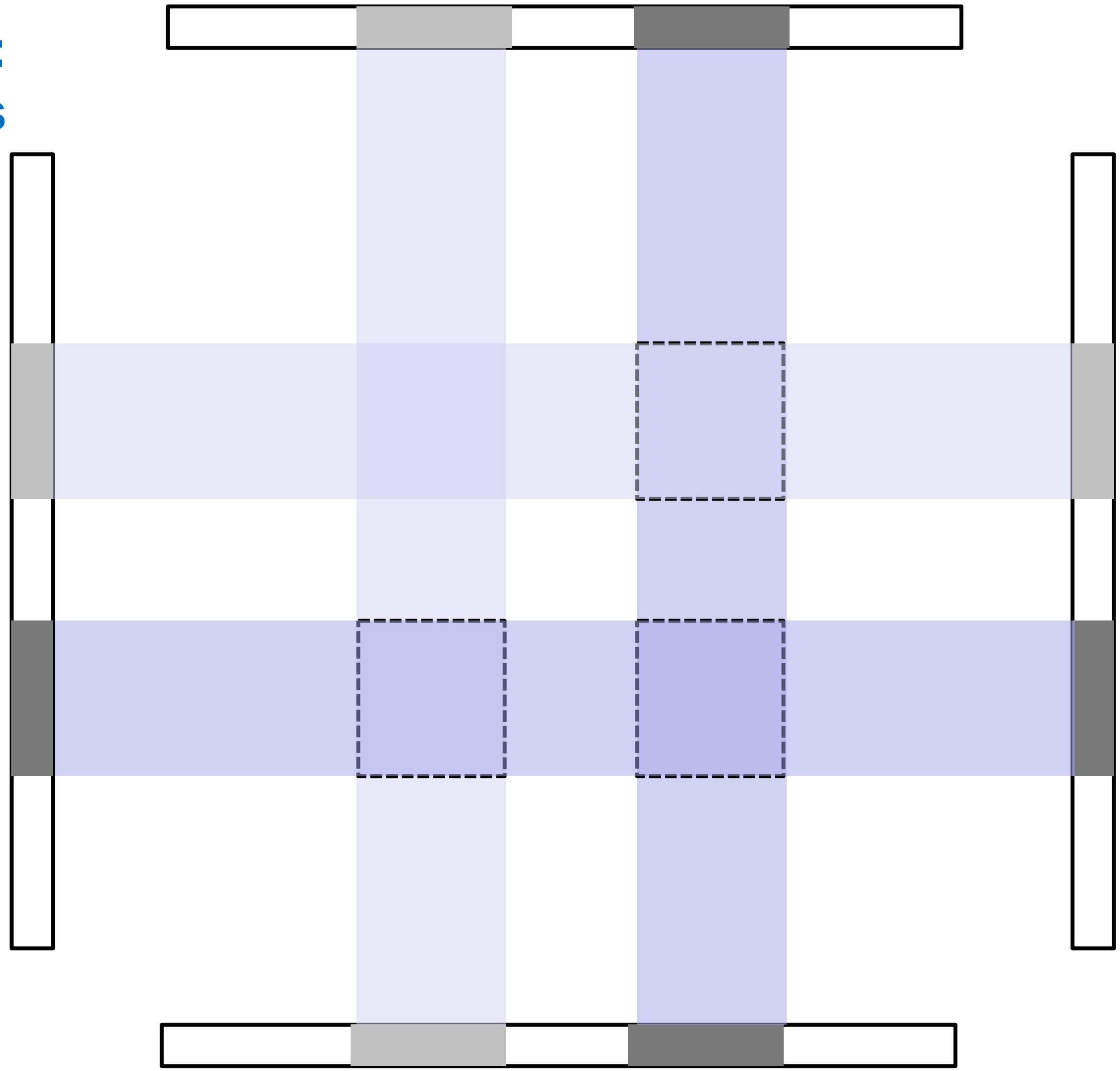
# X-ray Computed Tomography

## Scanning: projections



# X-ray Computed Tomography

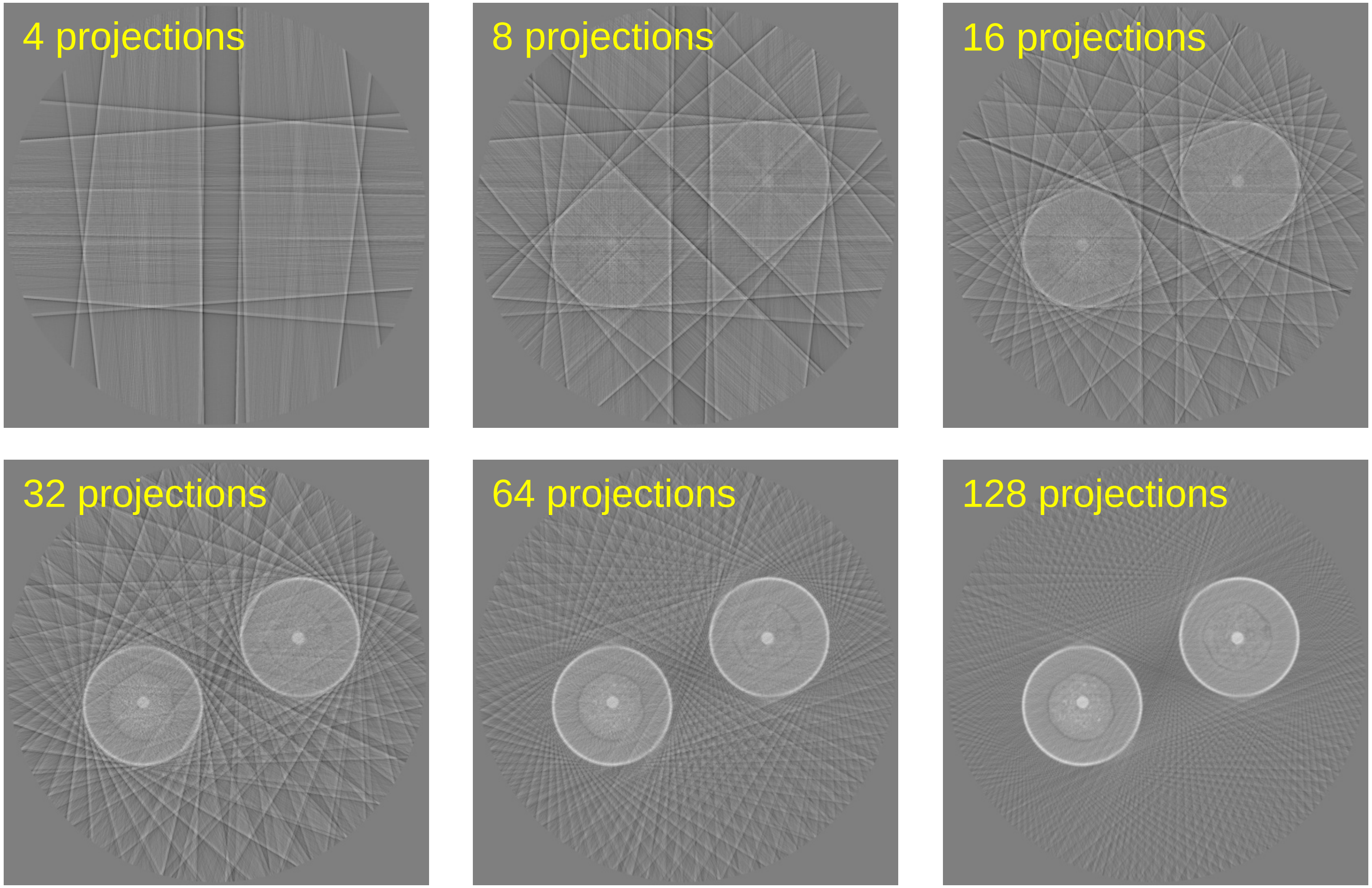
## Reconstruction: backprojections



# X-ray Computed Tomography



**Adding projections from different angles to build a volume:**




Horizontal slices through a CT volume of two E90 batteries as projections are added.

# X-ray Computed Tomography

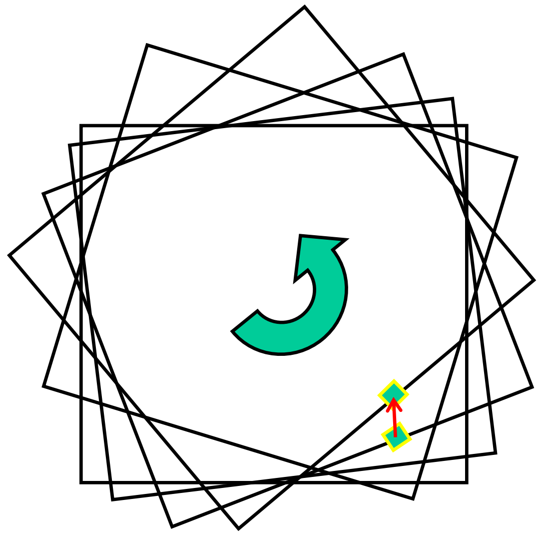


**Adding projections from different angles to build a volume:**

Horizontal slices through a CT volume of two E90 batteries as projections are added.

# Number of Projections

**How many images do we need to collect for a CT scan?**



The displacement of an edge pixel from one angle to the next must be no more than the size of one voxel (=3D pixel) in the volume.

For a good quality CT volume we need more than 1000 projection images. To collect these in a reasonable time we used continuous rotation. Typical scans are 25 min (1600 images) to 50 min (3200 images).

# Resolution: Contrast

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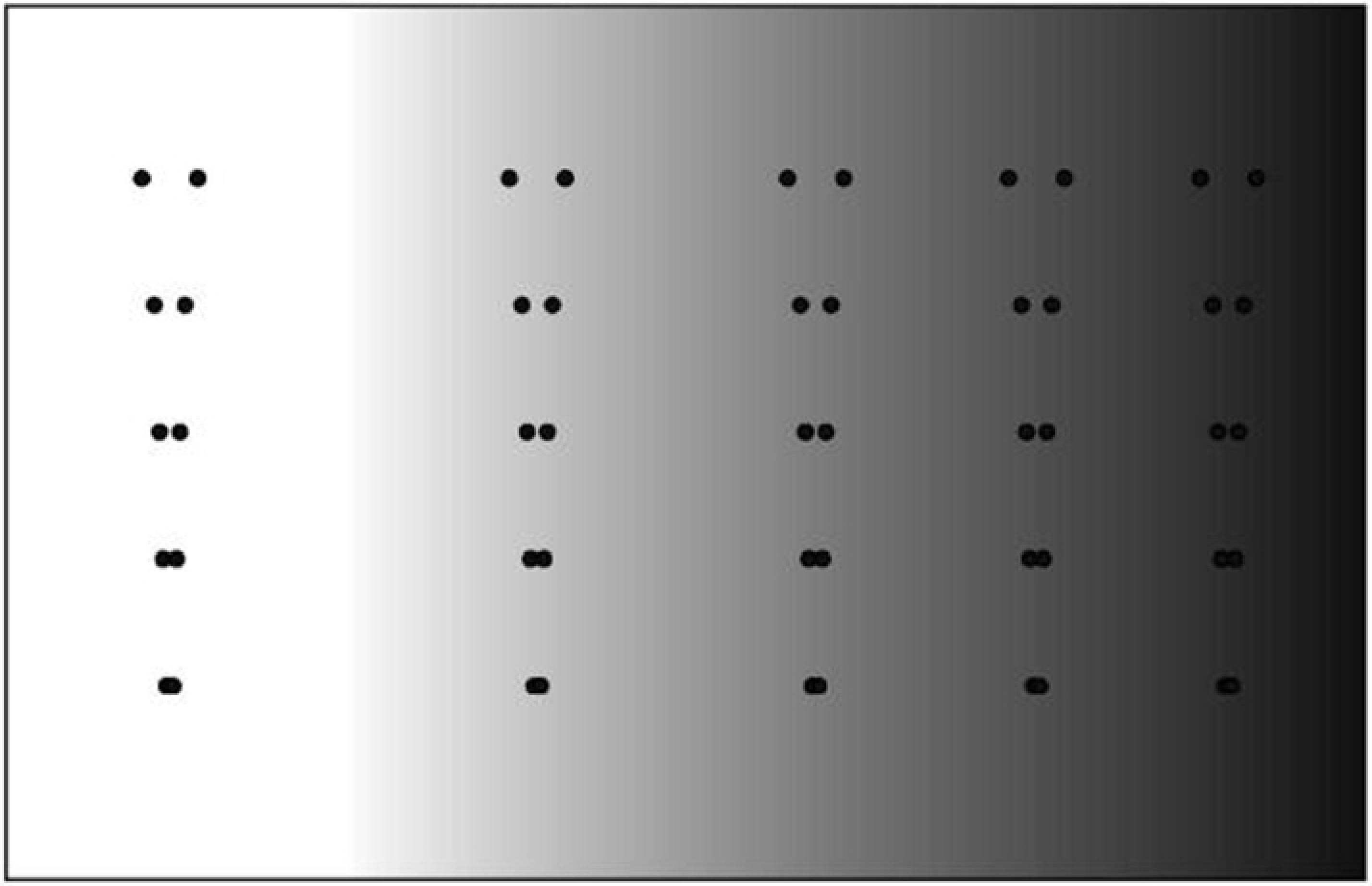


**FIGURE 2.6**
Influence of contrast on resolution of closely spaced features. The 1D gradient of background gray levels makes it more difficult to resolve the pairs of disks the farther to the right one goes.

From: MicroComputed Tomography, Stuart R. Stock

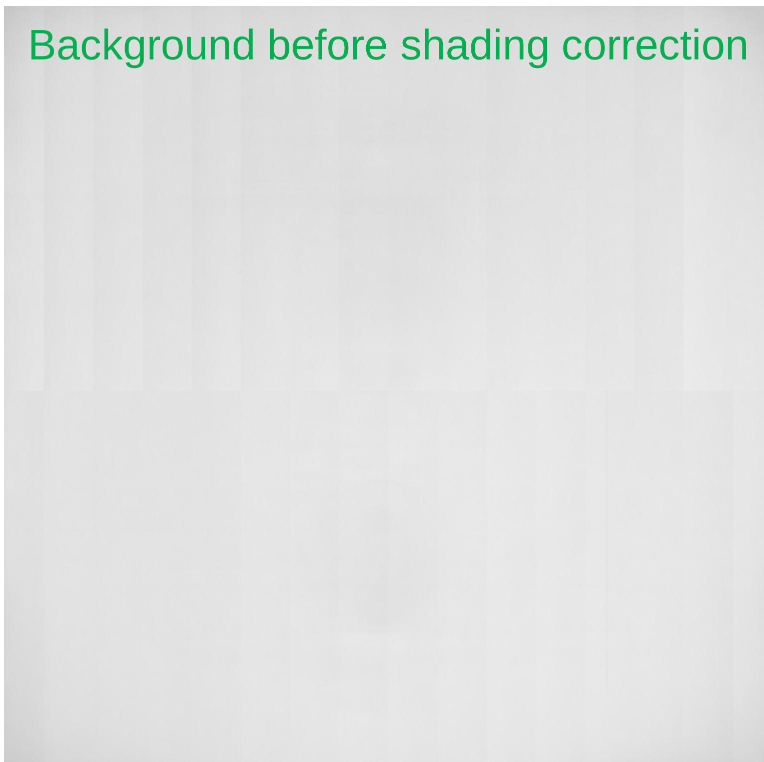
# Resolution: Contrast

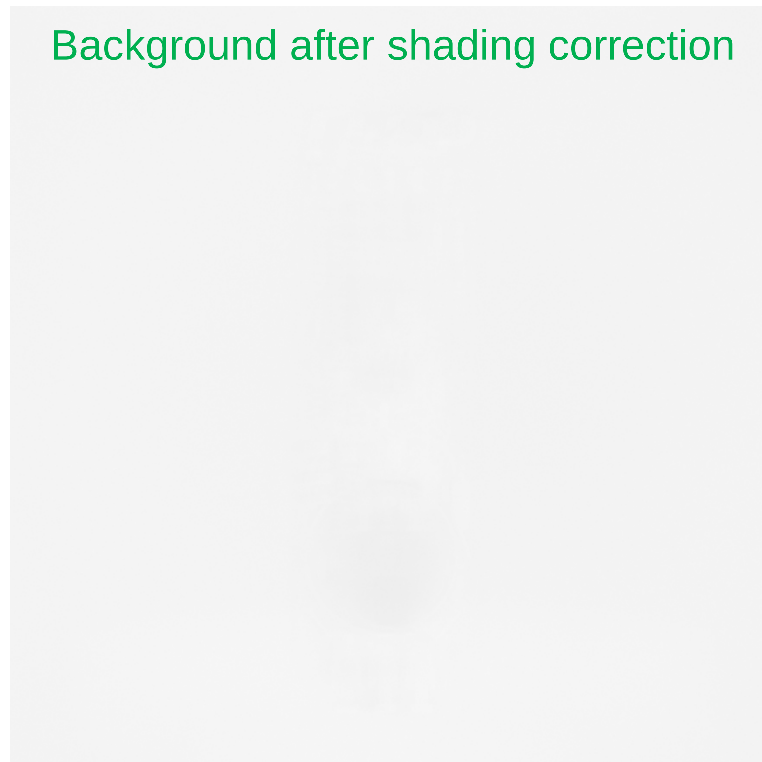
- To get good contrast:
  1. The energy of the electron beam (i.e. the voltage) must be appropriate for the sample: low for “soft” (e.g. biological, polymer) samples and higher for “hard” (e.g. mineral, metal).
  2. The sample must be penetrated by X-rays in all orientations.
  3. The X-ray flux (i.e. the current) must be adjusted to get a background grayscale value close to white.

- Getting good contrast for composite samples made of different materials could be challenging (e.g. a sample made of plastic, silicon, and several different metals).

# Shading Correction

- A detector calibration done before starting the scan to achieve a uniform background.
- Every single pixel on the detector must be calibrated to display the same grayscale value when exposed to the same X-ray conditions.
- At least two shading correction images, one black (X-rays off) and one white (X-rays on, no sample) must be collected during this step.


Background before shading correction


Background after shading correction

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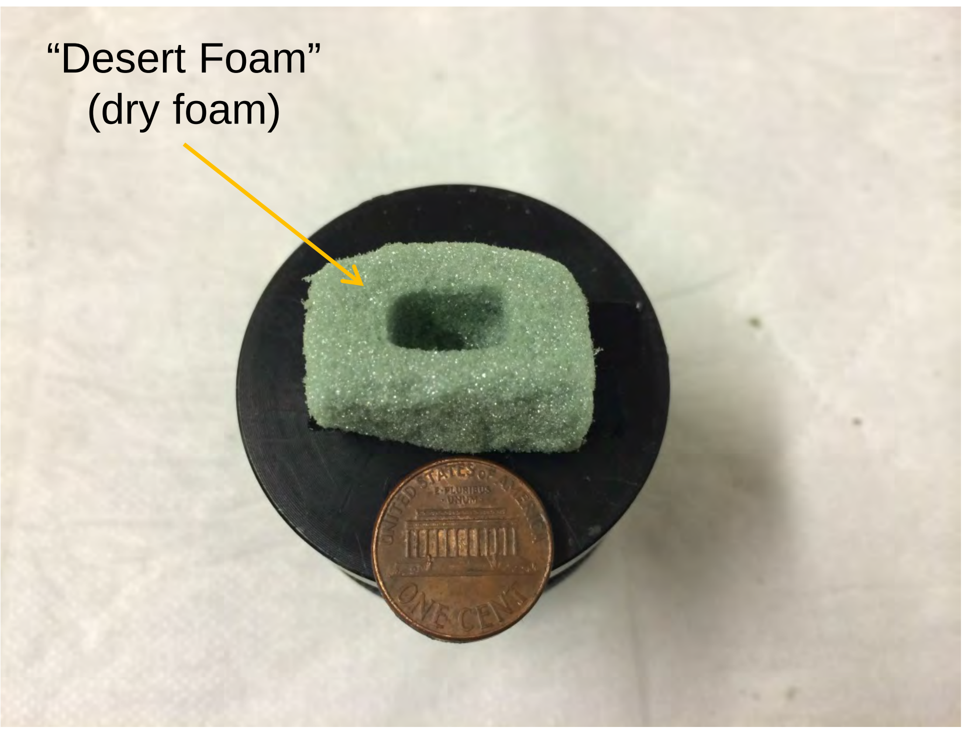
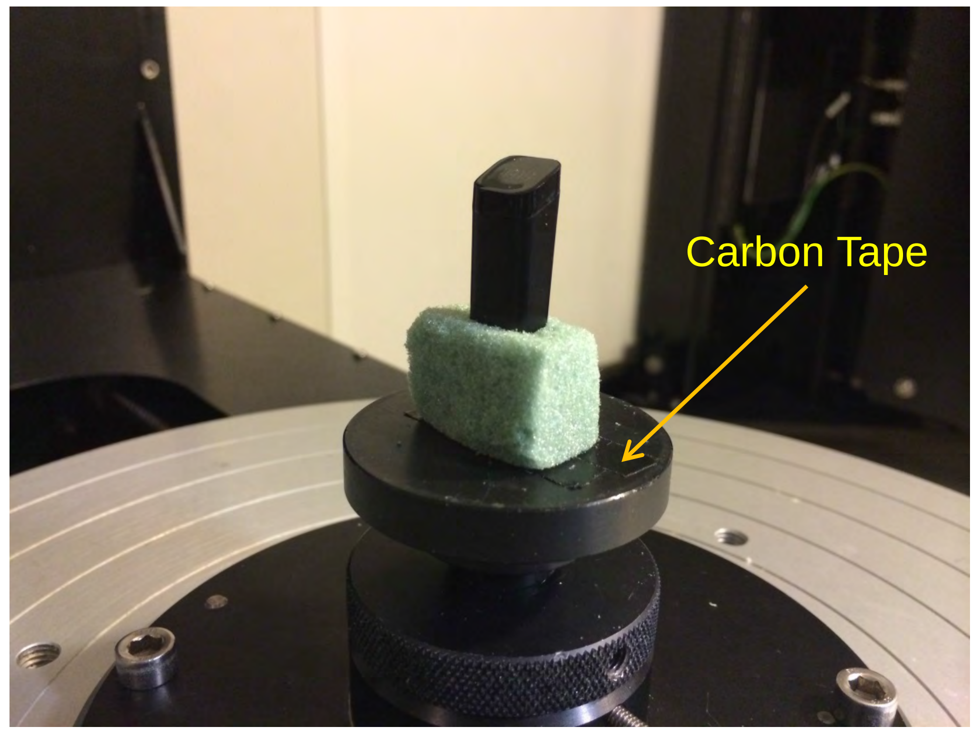
# Sample Mounting

- Poor sample mounting is the most common culprit for failed scans.
- The sample SHOULD NOT move during the entire scan (except the rotation of the sample stage).
- Especially difficult to achieve with soft, elastic or wet samples.
- Change in temperature inside the chamber of the instrument may cause the sample to move as well.



# MicroCT in Practice

**Artefacts and causes of errors in CT data**

Unfortunately, not all CT scans give optimal data.

Some of the following artefacts may be seen:

- Motion artefacts – may appear as double image, blur, or result in failed reconstruction
- Center-of-rotation errors during reconstruction – cause blurring, degraded resolution, or failed reconstruction
- Stage wobble and instability
- Undersampling
- Noise – appears as speckle in the slice images
- Ring artefacts – appear as rings in the axial slice images
- Streak artefacts – from dense structures in the sample
- Scattered radiation – brightens holes and fills in reentrants

# MicroCT in Practice

**Speed vs Quality = Time vs Noise**

The key to good CT data is good signal to noise.

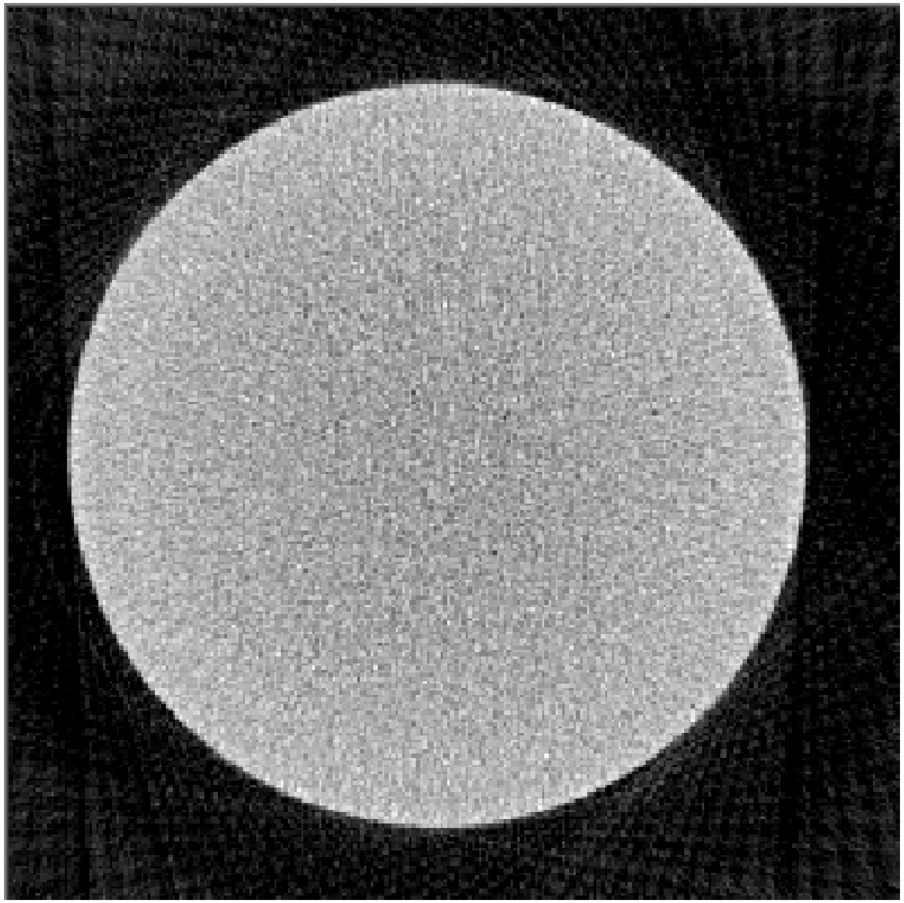
Unfortunately, CT reconstruction exaggerates noise!

Therefore, we must collect very low-noise projection images.

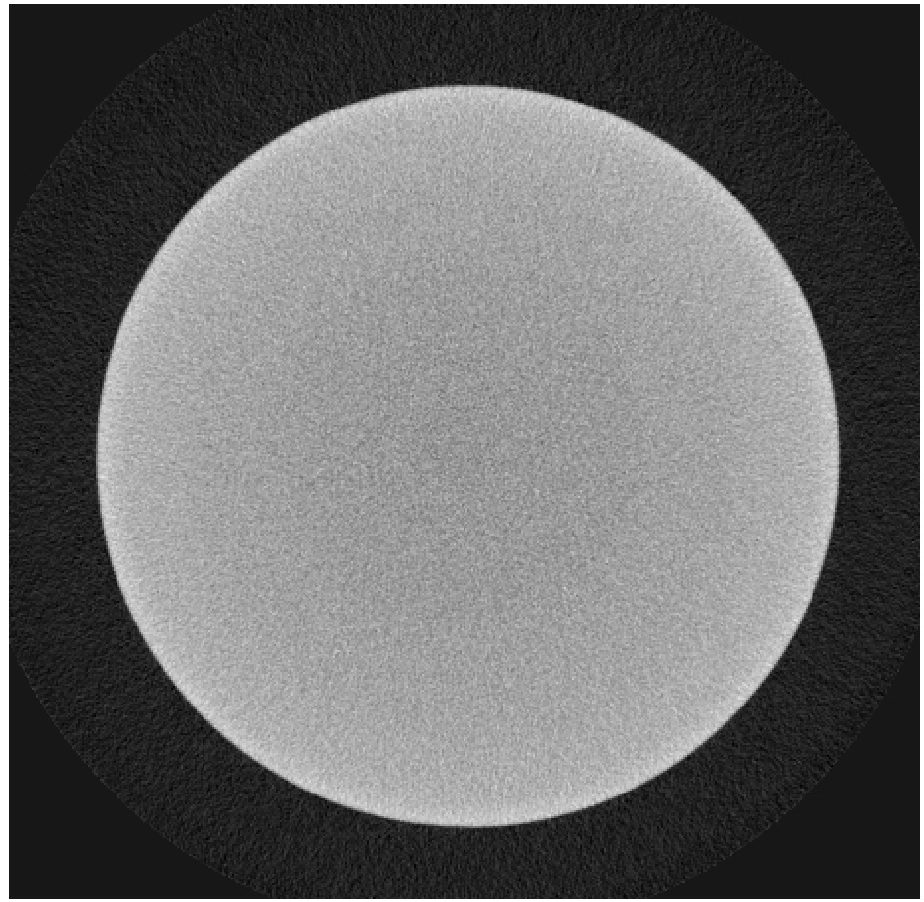
This is achieved by maximising the detected X-ray dose in each image.

# MicroCT in Practice

Random Noise



Noisy CT slice



Less noisy CT slice

# MicroCT in Practice

**CT quality is proportional to the total number of detected X-rays**

The following are measures of the detected X-ray dose:

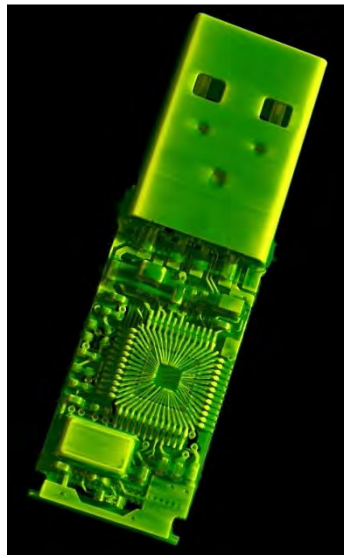
- Number of projection images (also helps resolution)
- Camera exposure for each image
- Number of frames averaged at each position
- X-ray current (µA)
- Proportion of spectrum passed by filter
- X-ray voltage (kV)

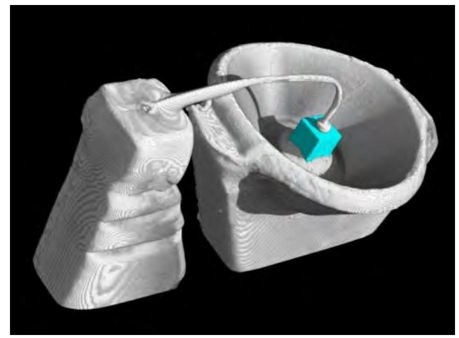
The following do NOT affect the total dose:

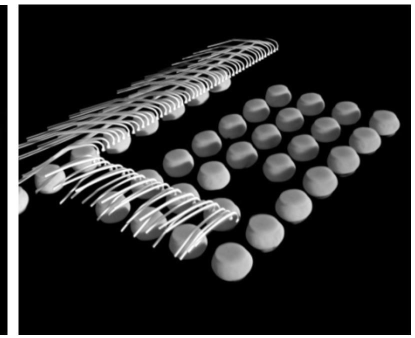
- Detector gain
- Detector binning

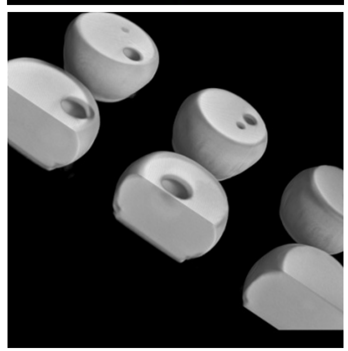
# X-ray Computed Tomography

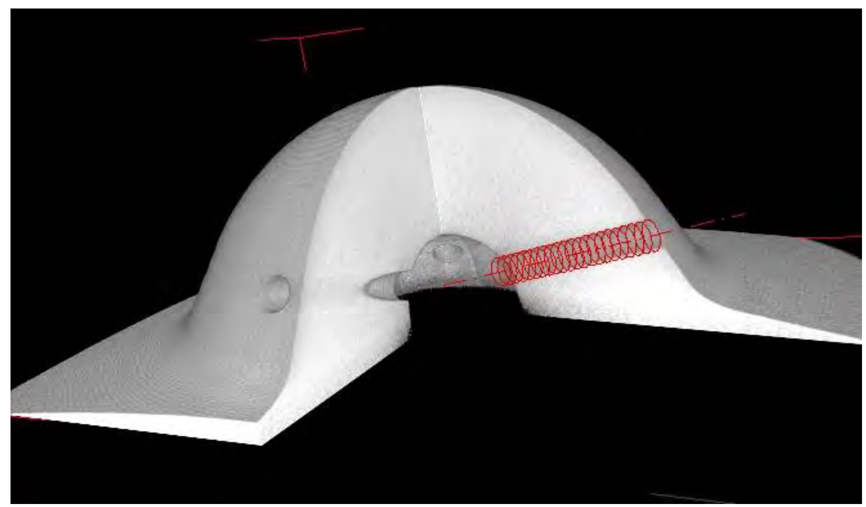
## Examples of Computed Tomography











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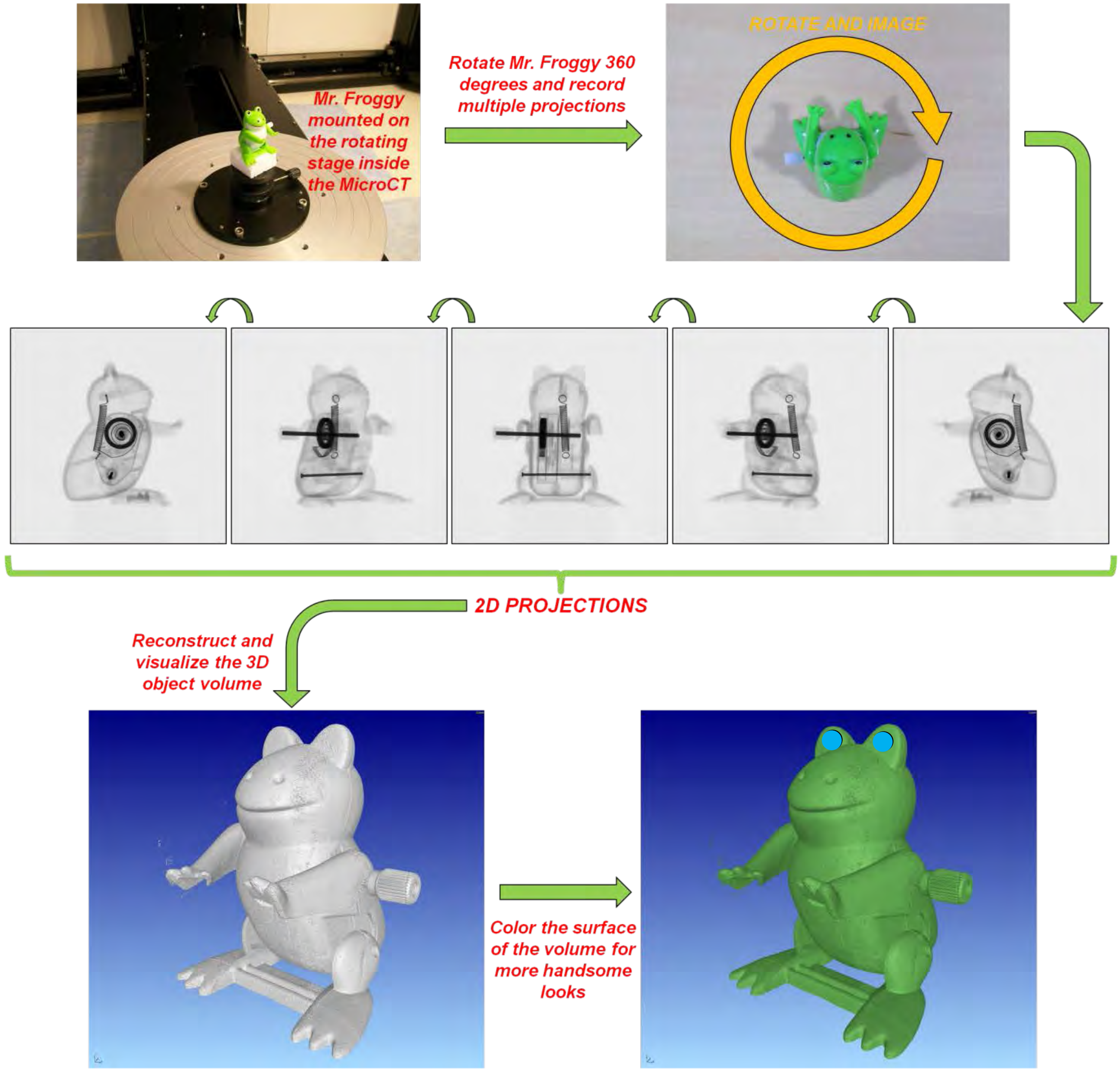
# Example: Mr. Froggy

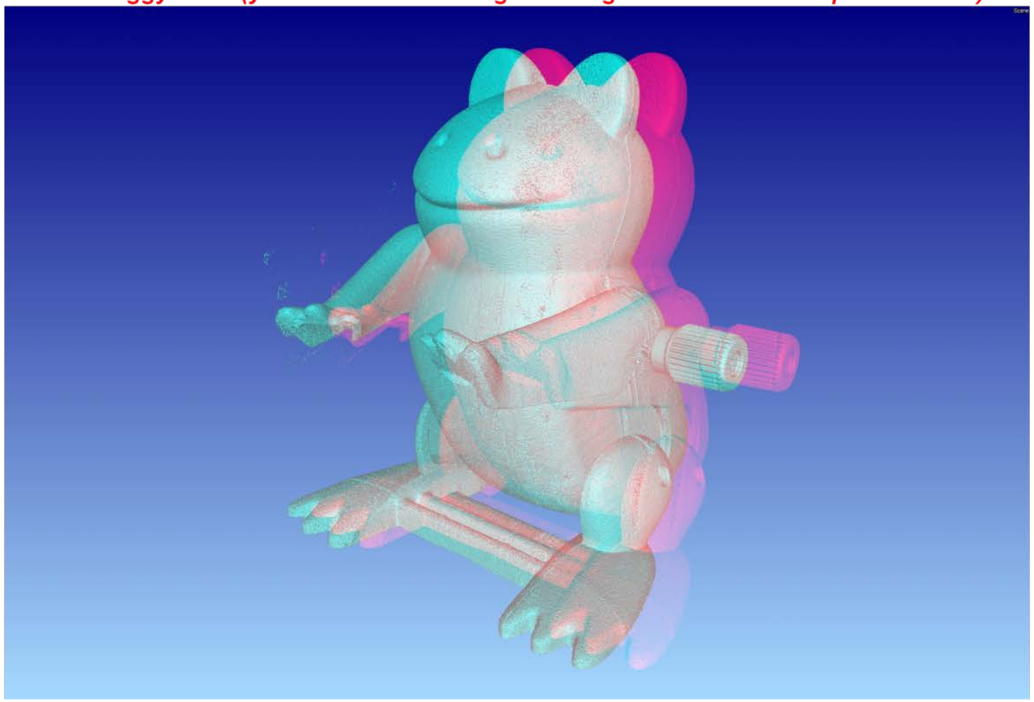


# Example: Mr. Froggy

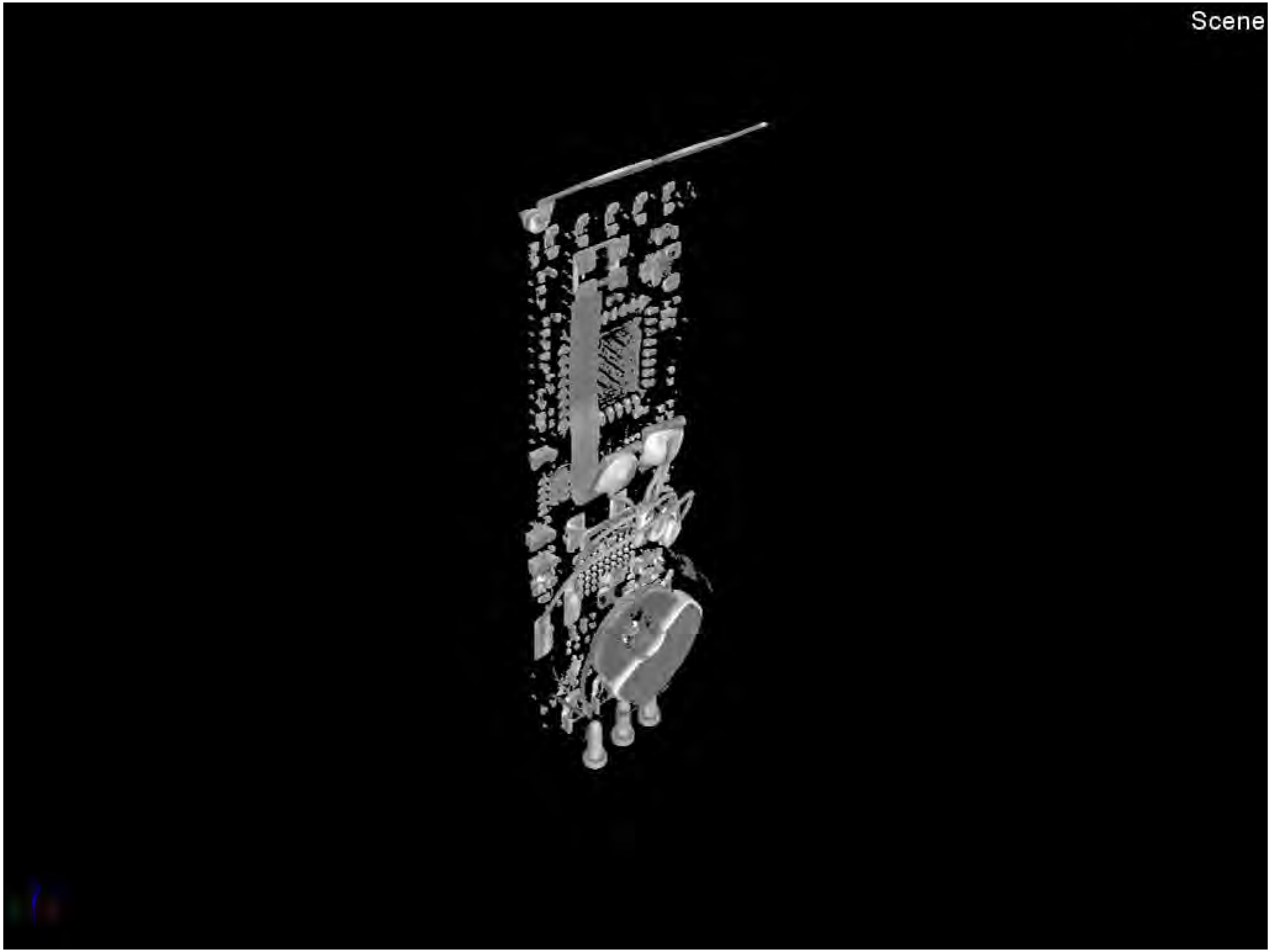



Strip away Mr. Froggy's plastic components


Mr. Froggy in 3D (you need to wear red/green 3D glasses to view this picture in 3D)



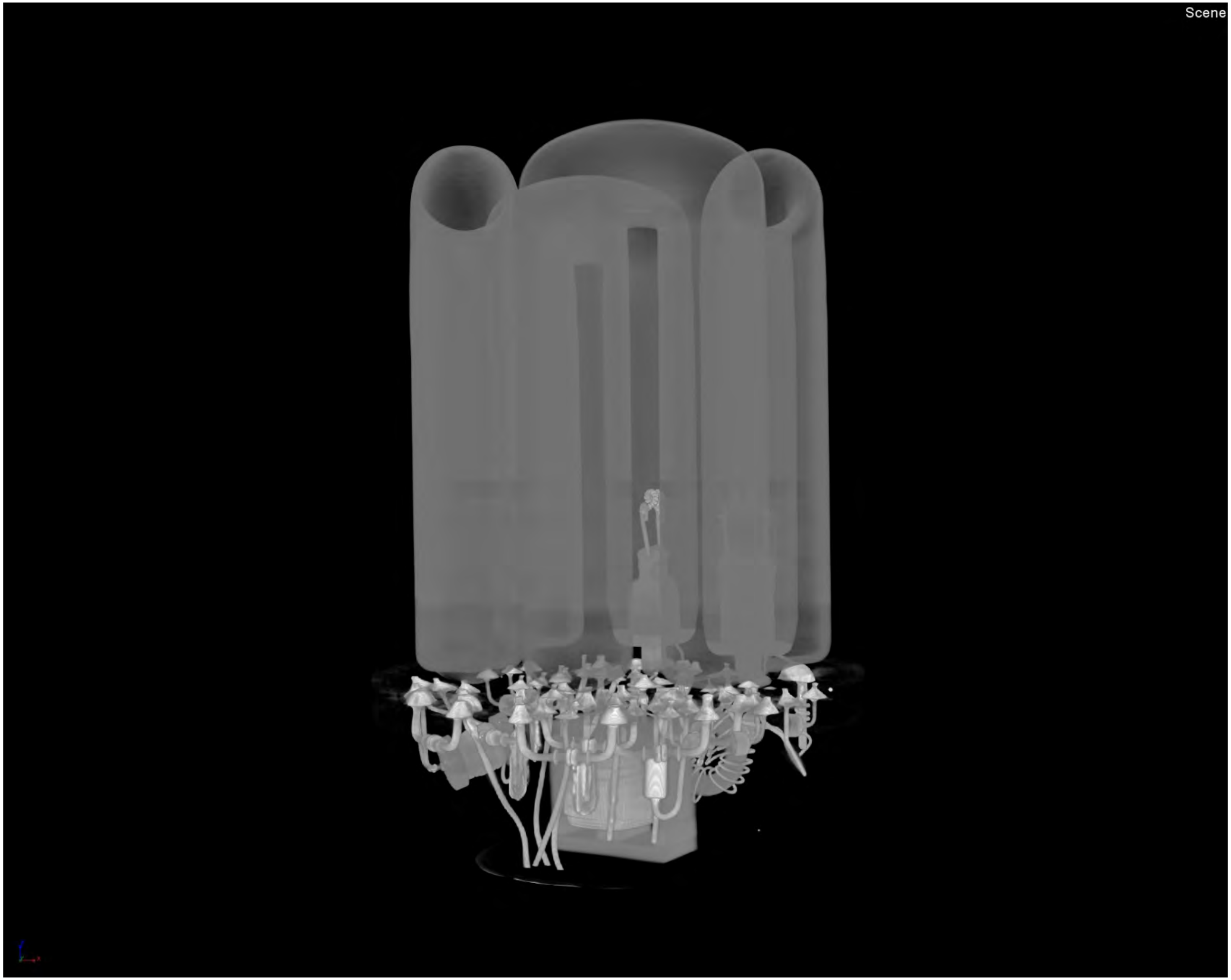
# Example: 3D Animation (Fitbit Flex)



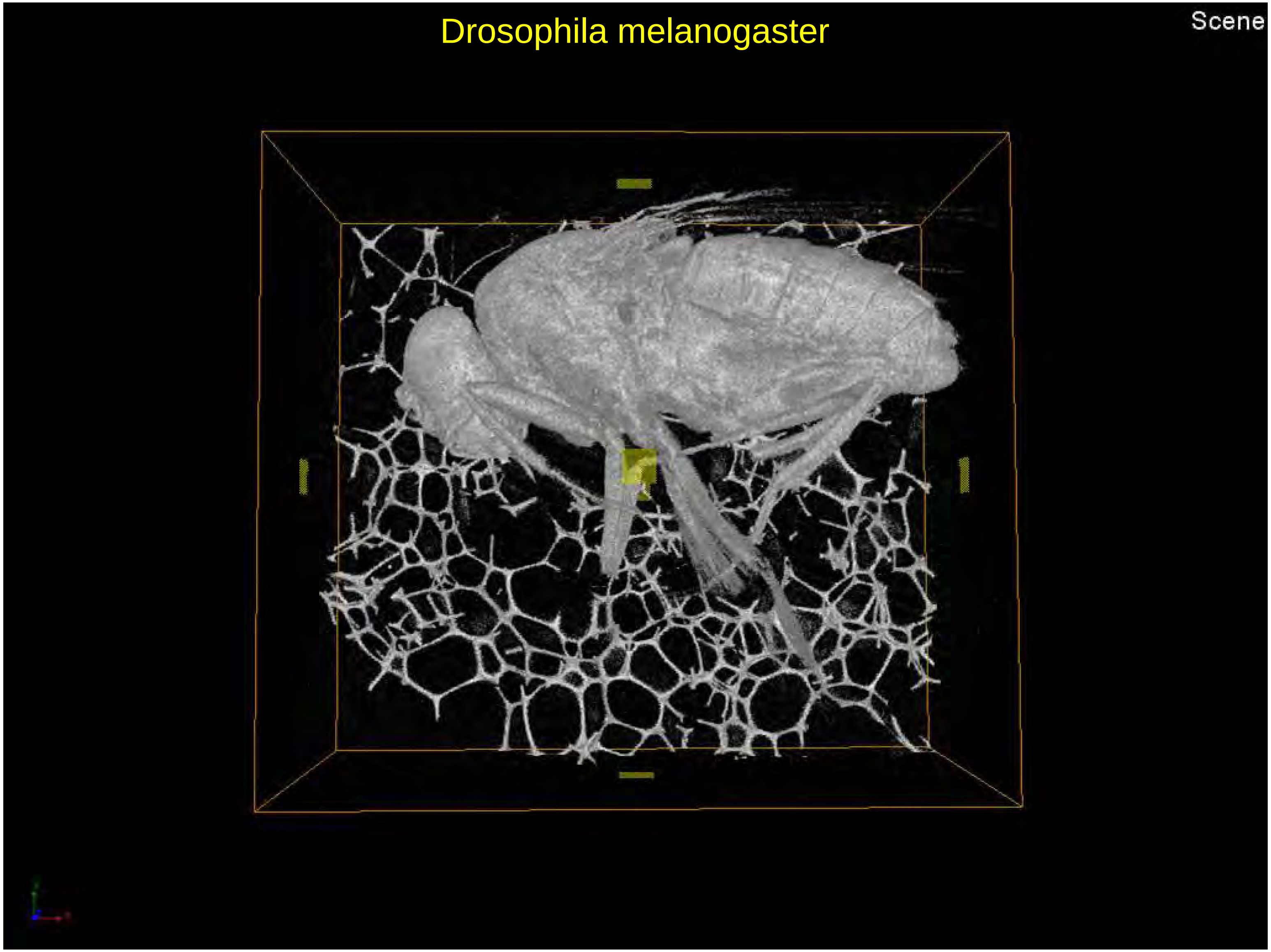
# Example: Compact Fluorescent Bulb

# Example: Compact Fluorescent Bulb

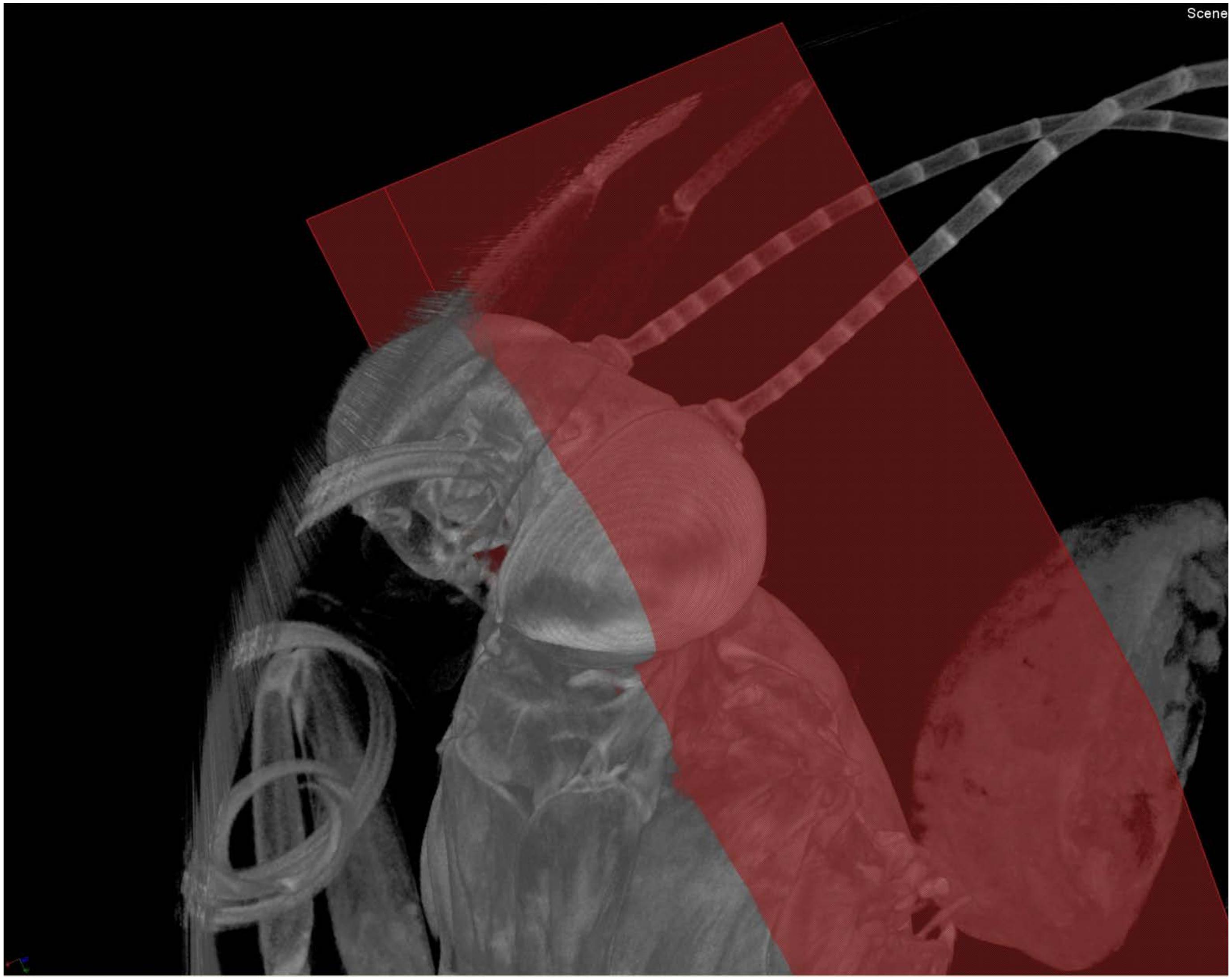




# Example: 3D Animation (Fruit Fly)



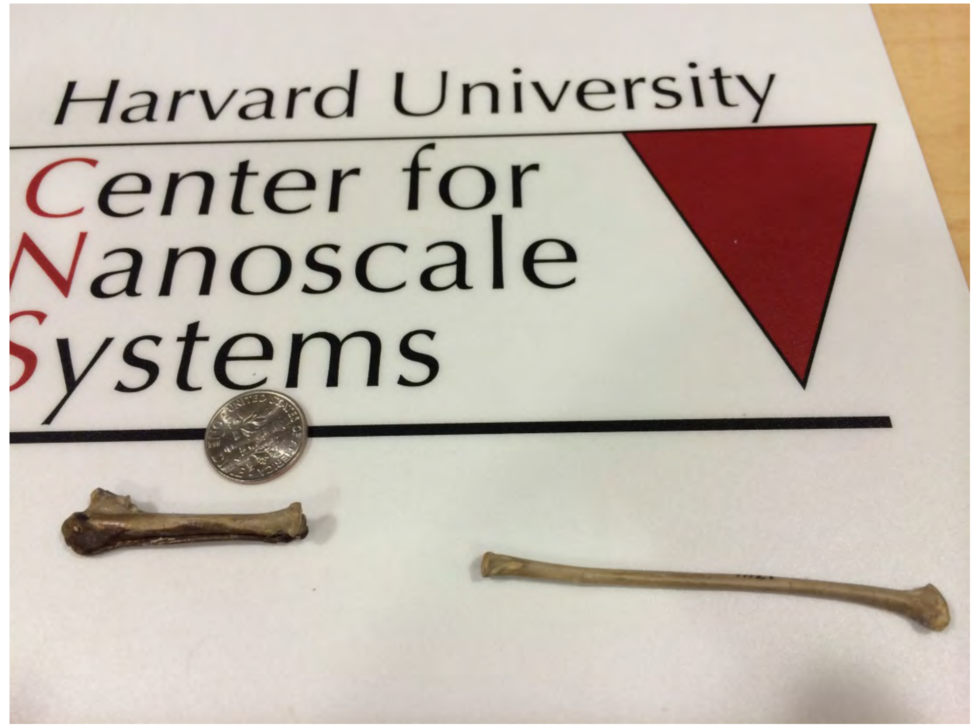
# Example: Butterfly Head




(Scan and image by Monica Zugravu @ CNS)

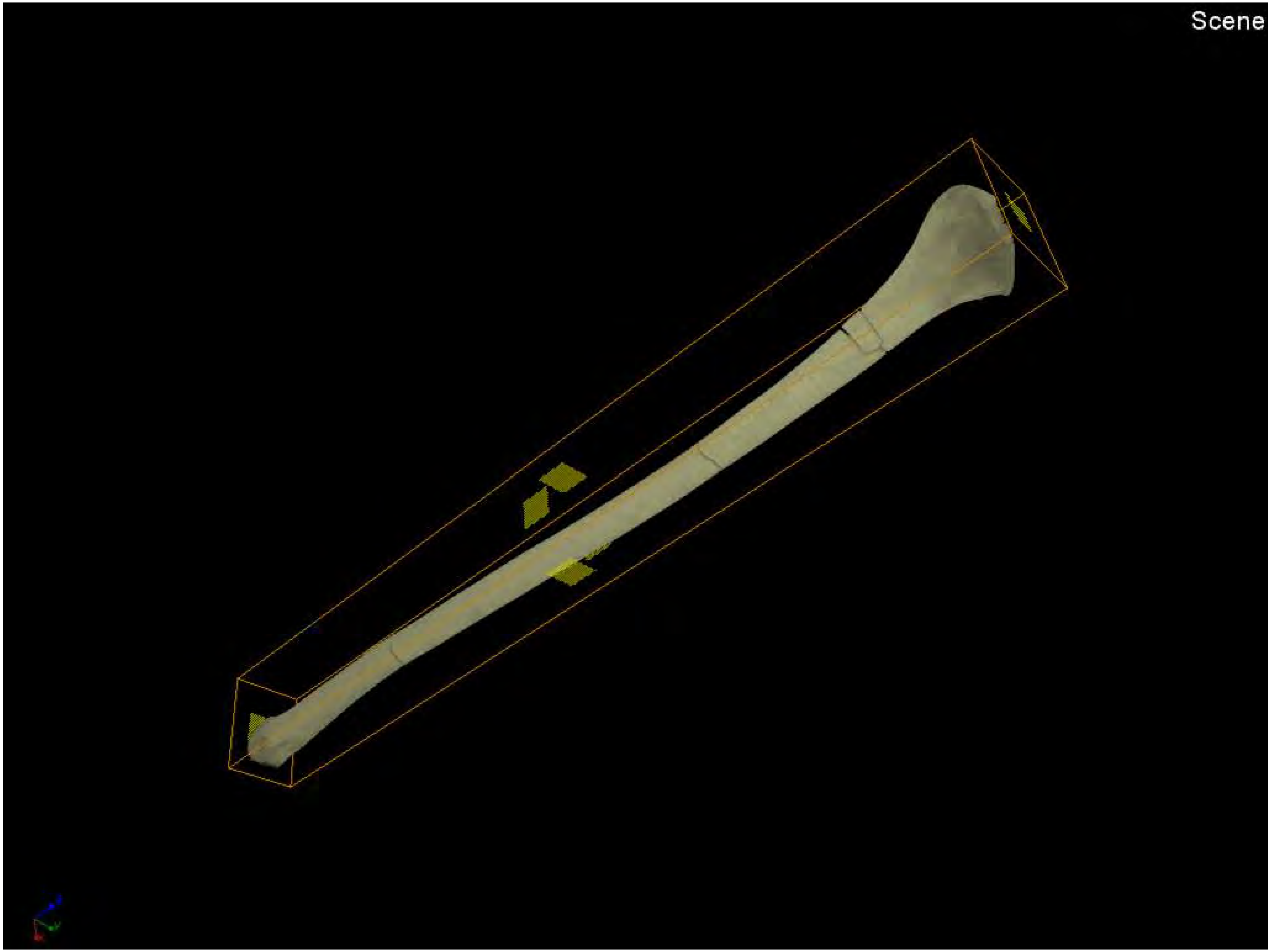
# Example: 86M y/o Bird Bones!

## Ichthyornis, a.k.a. “fishbird” (with teeth)




- Scanned by Daniel Field (from Yale) and Prof. Bhart-Anjan Singh Bhullar on our system
- From Yale Peabody Museum of Natural History collection
- Found in marine sediments in Kansas! (Kansas was a sea at that time.)
- Transitional form to modern-day birnds: like Homo erectus to humans

# Example: 86M y/o Bird Bone



# X-ray MicroCT at CNS

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LISE G27


- X-Tek HMXST225 system (225kV max)
- Three reconstruction workstations
- Software:
  - o InspectX: X-ray imaging and CT acquisition
  - o CT Pro 3D: volume reconstruction
  - o VG Studio MAX 2.2: 3D volume visualization, rendering and analysis
  - o Amira: 3D volume visualization, rendering and analysis

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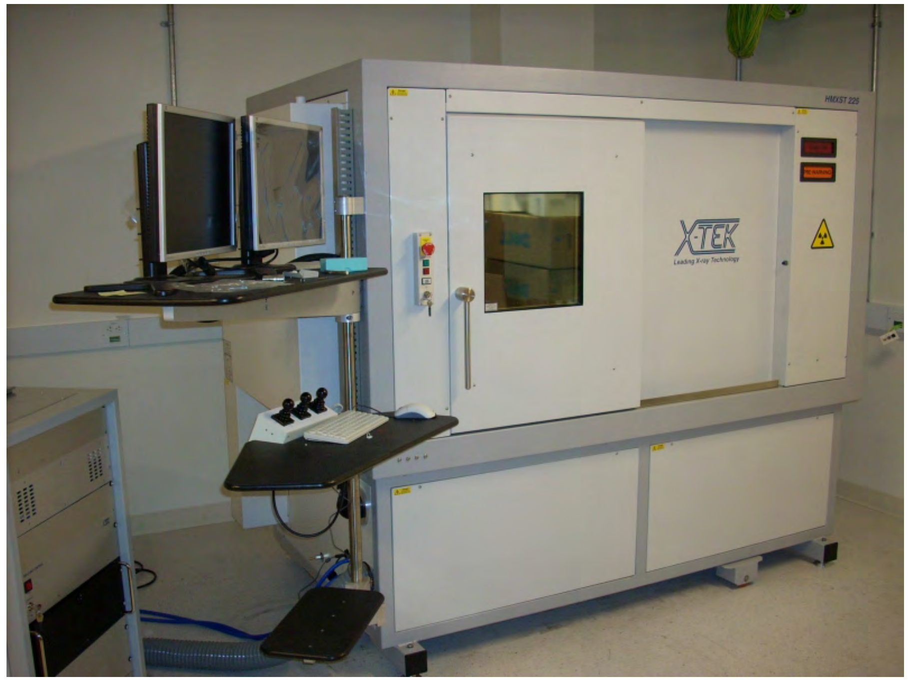
# Questions? Comments?

fkosar@cns.fas.harvard.edu




Interested? Sign up for X-ray MicroCT training on CNS website!