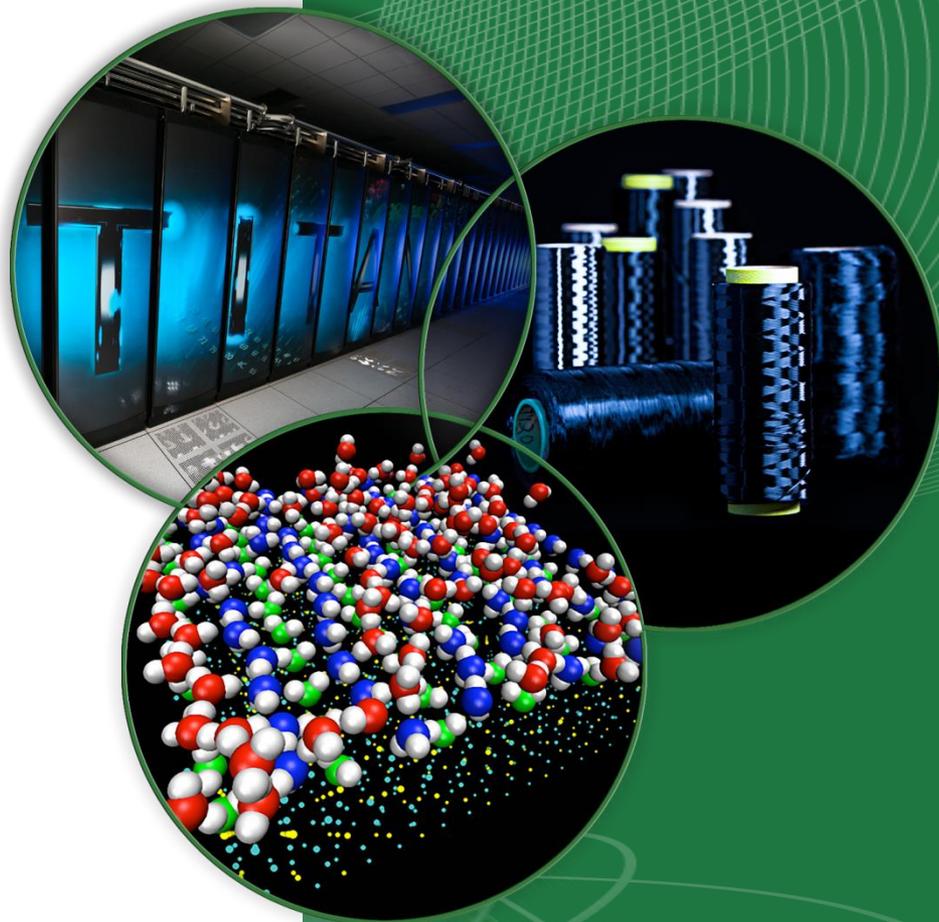


# Imaging with Neutrons

Lou Santodonato  
Instrument Scientist  
Neutron Imaging Team

19<sup>th</sup> National School on  
Neutron and X-ray Scattering  
August 5-19, 2017



# Acknowledgement

- The Neutron Imaging Team



# Goals

- See what we can do with neutron imaging
  - Compare to other imaging techniques
  - Know when to choose it
- Understand the basic instrument layout and principals of neutron image acquisition and analysis
- Learn by example
  - Review some recent neutron imaging projects

# Imaging throughout Nobel Prize History

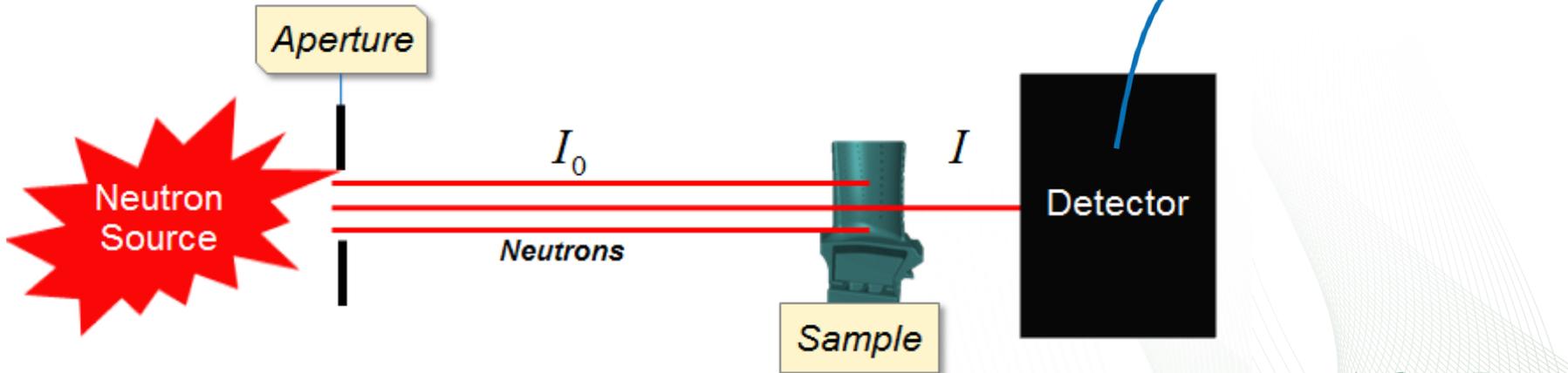
- 1901: Roentgen, FIRST Nobel Prize in Physics,  
**Discovery of X-rays**
- 1979: Cormack and Hounsfield, Nobel Prize  
in Medicine, **Computed Tomography (CT)**
- 1986: Ruska, Binnig, Rohrer, Nobel Prize in Physics,  
**Electron Microscopy**
- 2003: Lauterbur and Mansfield, Nobel Prize in Medicine,  
**Magnetic Resonance Imaging (MRI)**
- 2009: Boyle and Smith, Nobel Prize in Physics,  
**Imaging semi-conductor circuit, the CCD\* sensor**
- (\*) Charge-Coupled Device

# What about Neutron Imaging?

- The Nobel Prize for neutron imaging has yet to be won
  - An opportunity for you!
- NI started in the mid 1930's but only the past 30 years has it come to the forefront of non-destructive testing
- World conferences and workshops being held regularly

# Neutron Imaging

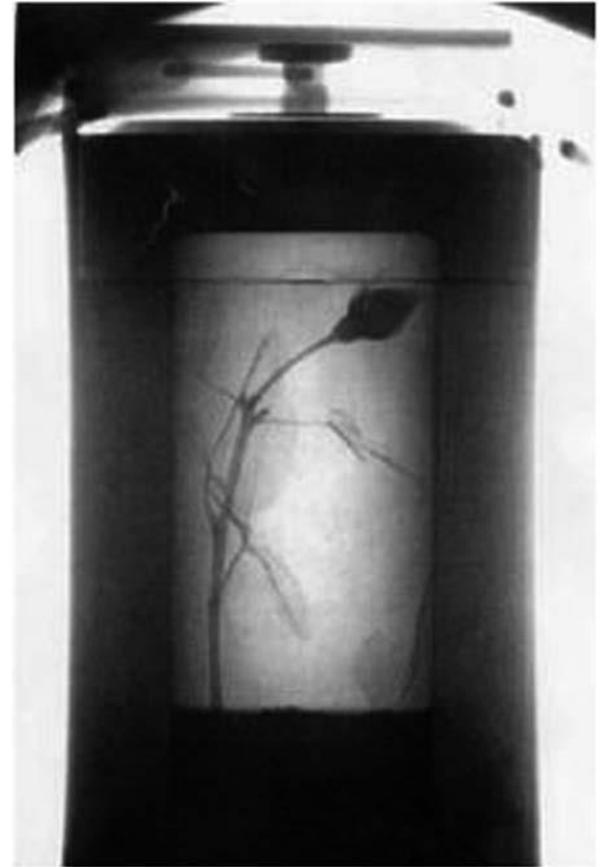
- Measures “shadows” based on neutron attenuation through the object
- One shadow is a radiograph
- These “shadows” are collected at different angles and reconstructed in 3D, called the computed tomography or CT [Watch the video](#)



# Distinctive Features of Neutron Imaging

Elemental adsorption cross sections play a key role in transmission imaging.

Huge difference between neutrons and X-rays

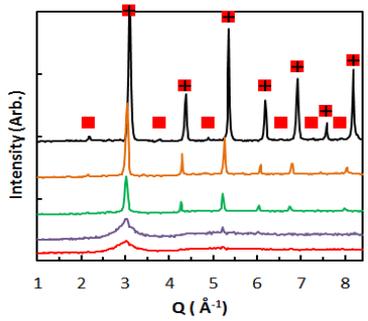


*Neutron radiograph of a rose in lead flask!*

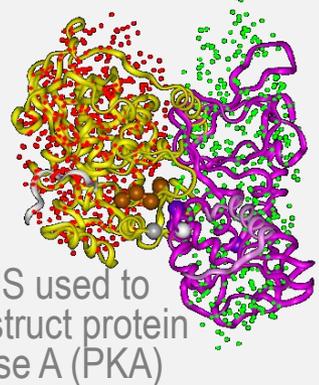
Courtesy of E. Lehmann, PSI

# Distinctive Features of Neutron Imaging

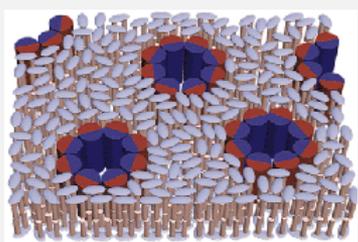
## Diffraction



## Scattering

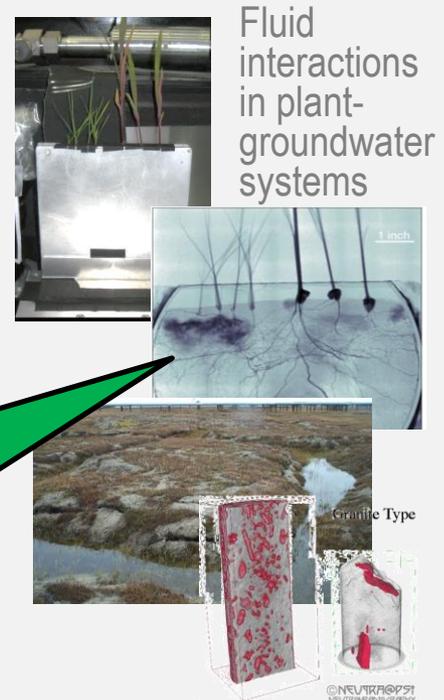


SANS used to construct protein kinase A (PKA)



Characterization of biological membranes, colloids, porosity, etc.

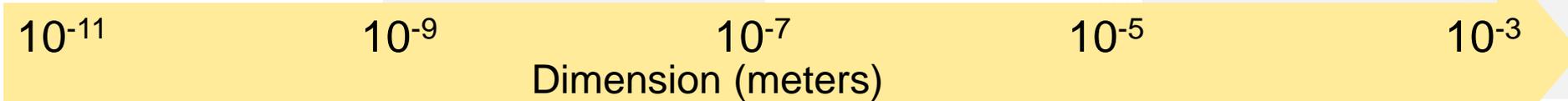
## Real-space imaging



You can directly see the structure.  
How easy!

*Inferred structure (indirect)*

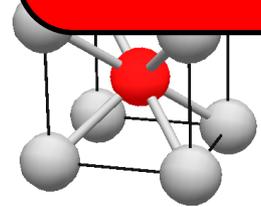
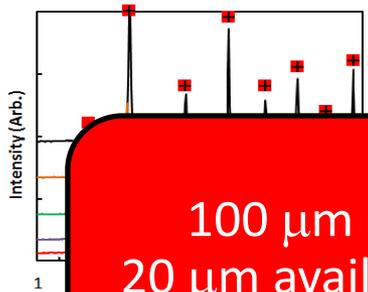
*Direct structure*



0.1 Å      1.0 nm      0.1 μm      10.0 μm      1 mm

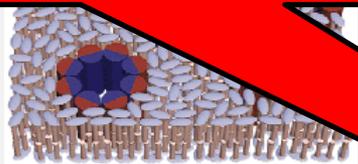
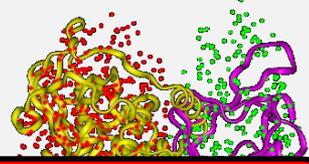
# Distinctive Features of Neutron Imaging

## Diffraction



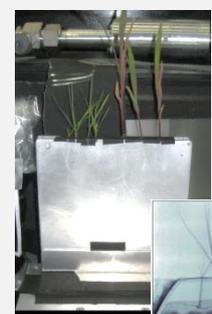
Crystal structures

## Scattering

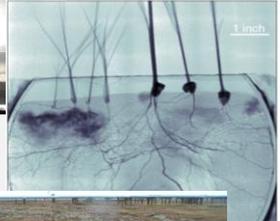


Characterization of biological membranes, colloids, porosity, etc.

## Real-space imaging



Fluid interactions in plant-groundwater systems



Ice/water segregation in permafrost structures

## Direct structure

100  $\mu\text{m}$  routinely available  
 20  $\mu\text{m}$  available with trade-off in field-of-view and acquisition times

Spatial resolution is limited!

*Inferred structure (indirect)*



# Quantitative Neutron Imaging

## Lambert-Beer Law:

$$T = \frac{I(\lambda)}{I_0(\lambda)} = e^{-\mu(\lambda)\Delta x}$$

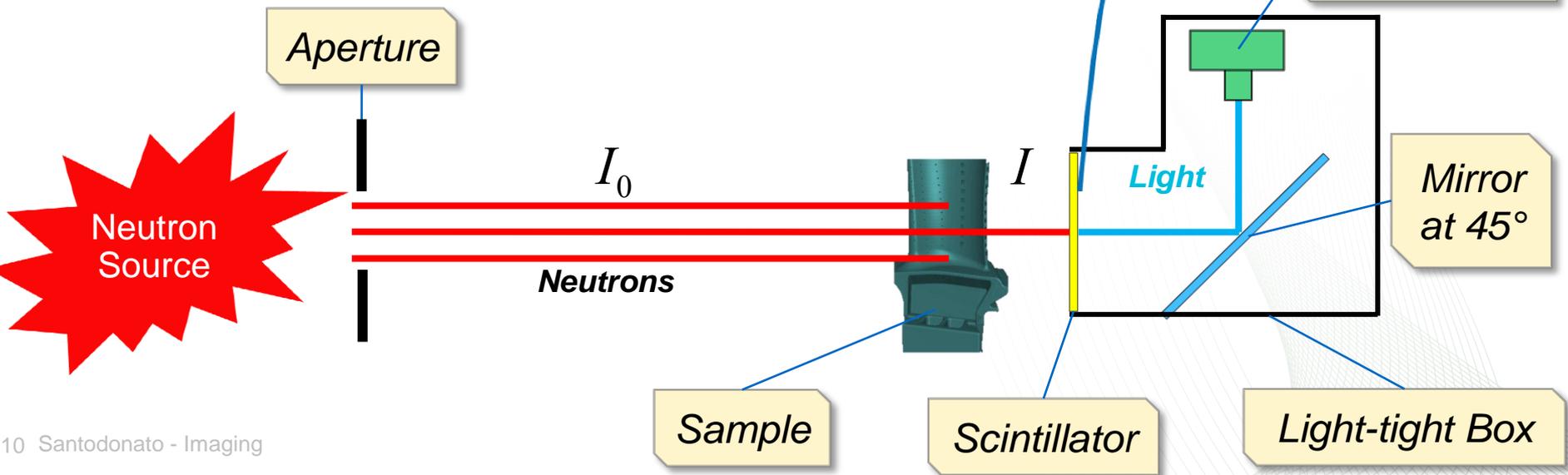
$\mu$  is the attenuation coefficient and  $\Delta x$  is the thickness of the sample

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

$\sigma_t(\lambda)$  is the material's total cross section for neutrons,  $\rho$  is its density,  $N_A$  is Avogadro's number, and  $M$  is the molar mass.

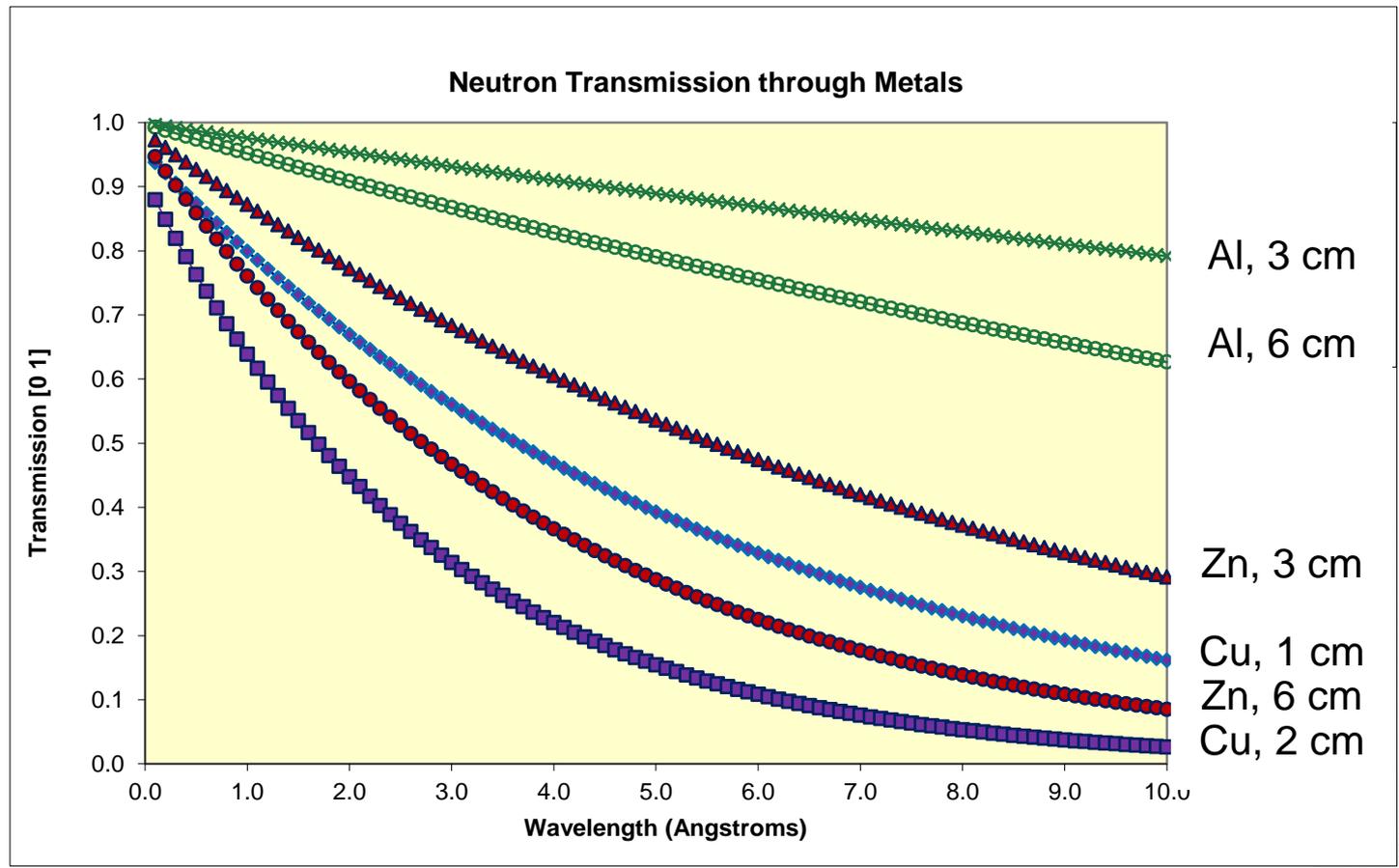


Image



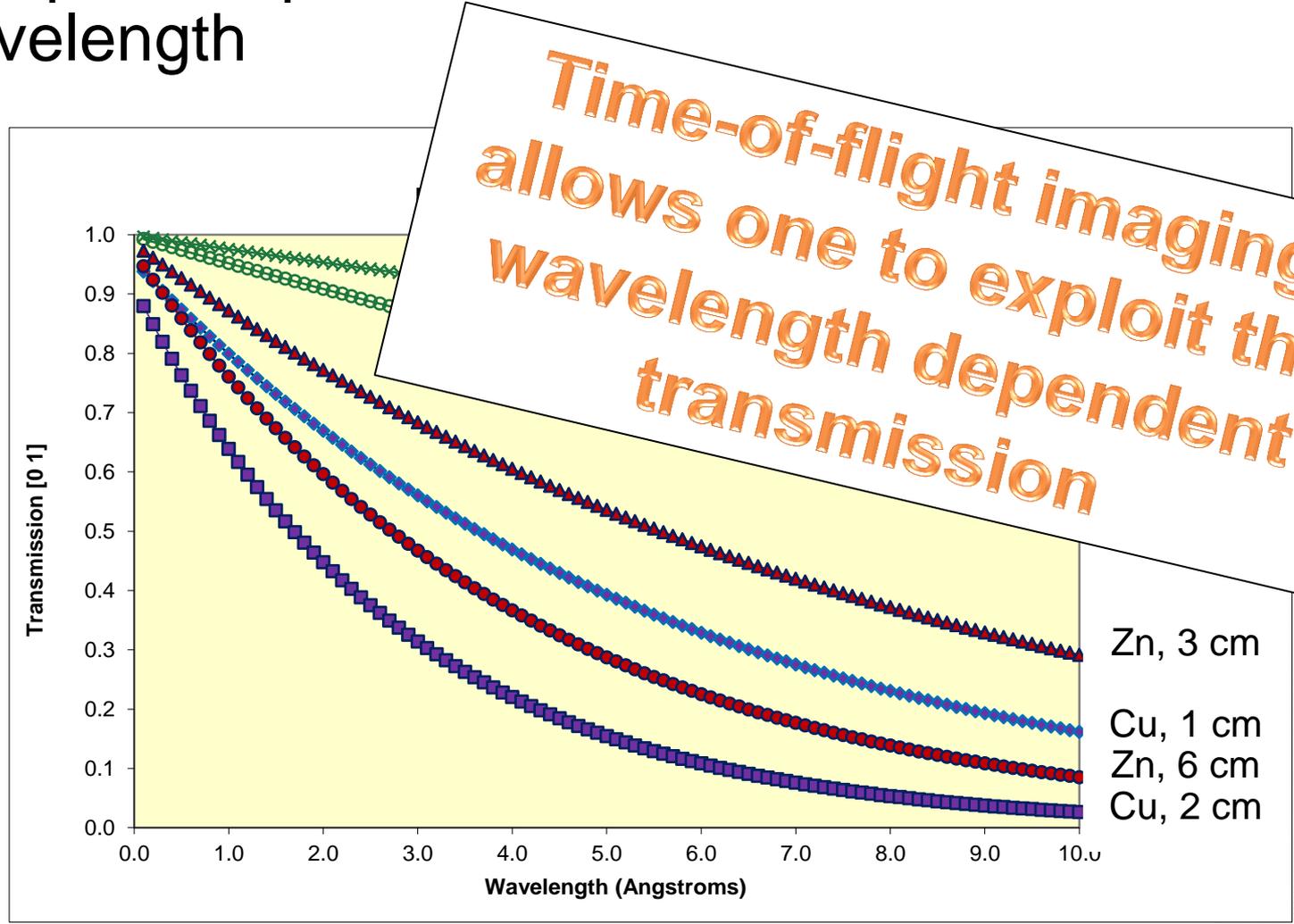
# Neutron Transmission Depends Upon . . .

- Sample composition, thickness, and neutron wavelength



# Neutron Transmission Depends Upon . . .

- Sample composition, thickness, and neutron wavelength

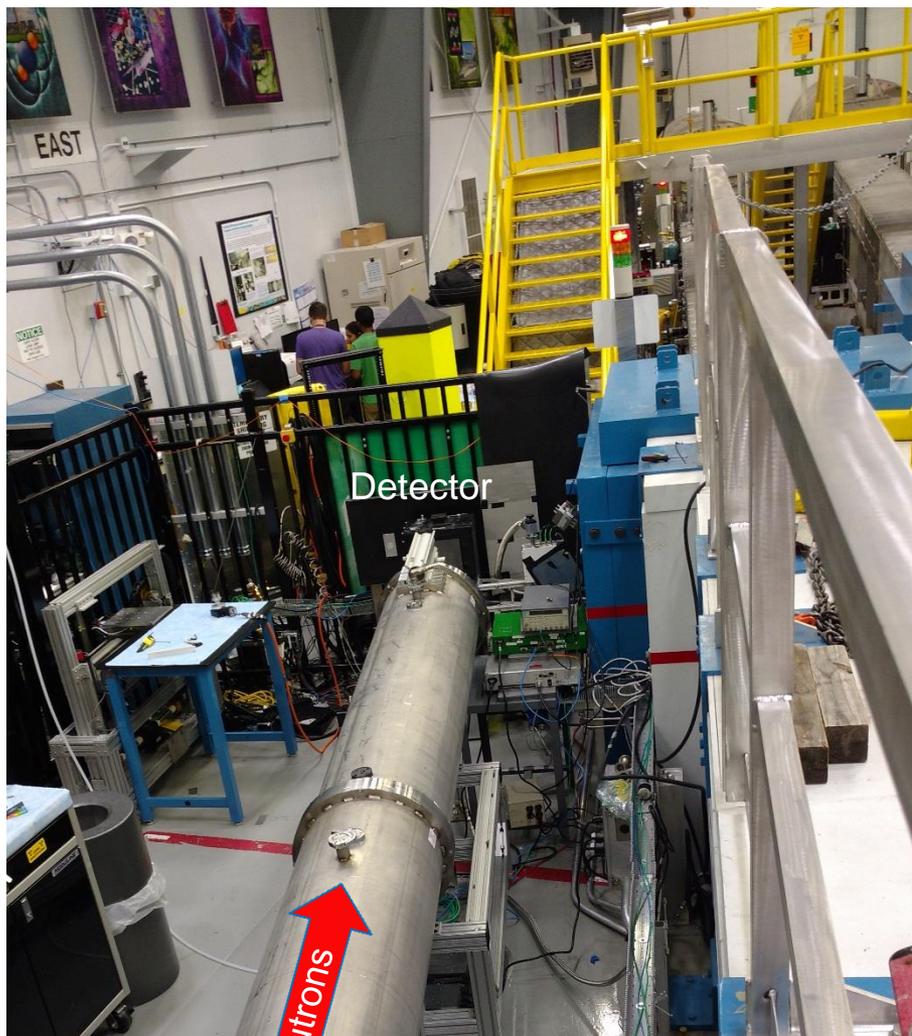


# Goals

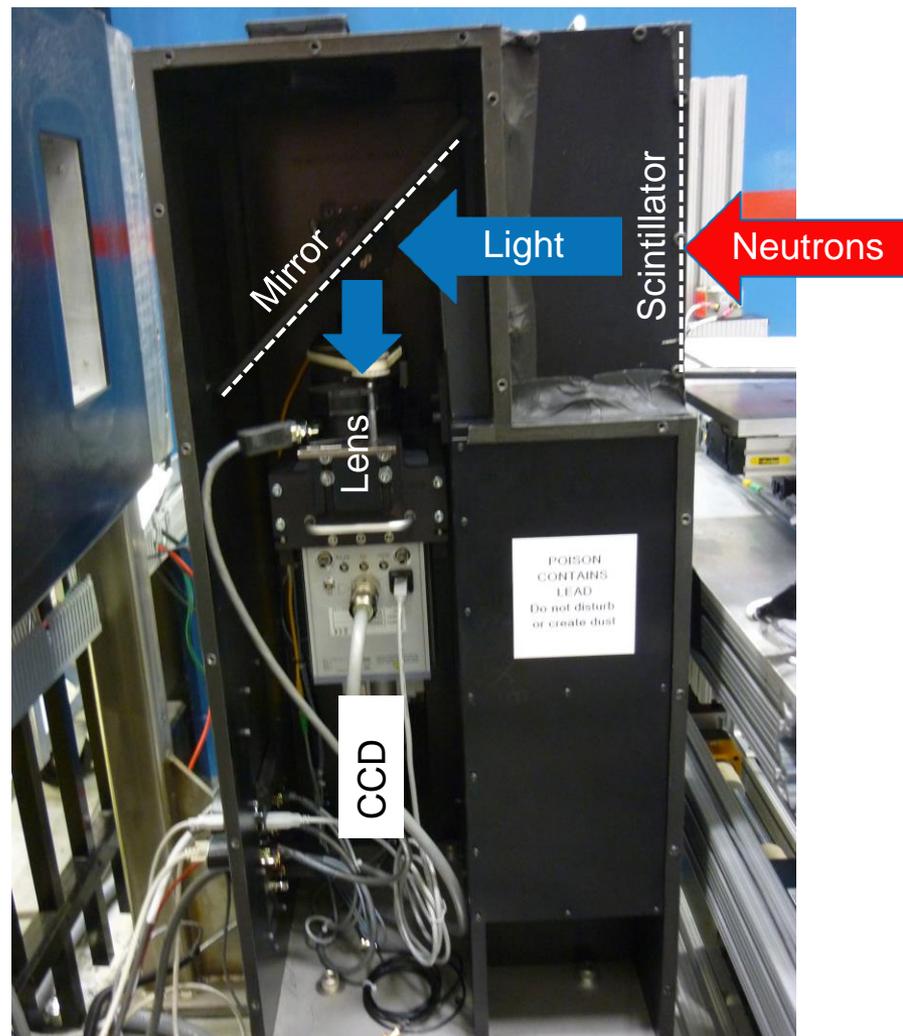
- See what we can do with neutron imaging
  - Compare to other imaging techniques
  - Know when to choose it
- Understand the basic instrument layout and principals of neutron image acquisition and analysis
- Learn by example
  - Review some recent neutron imaging projects

Let's move on.

# CG-1D Neutron Imaging Facility

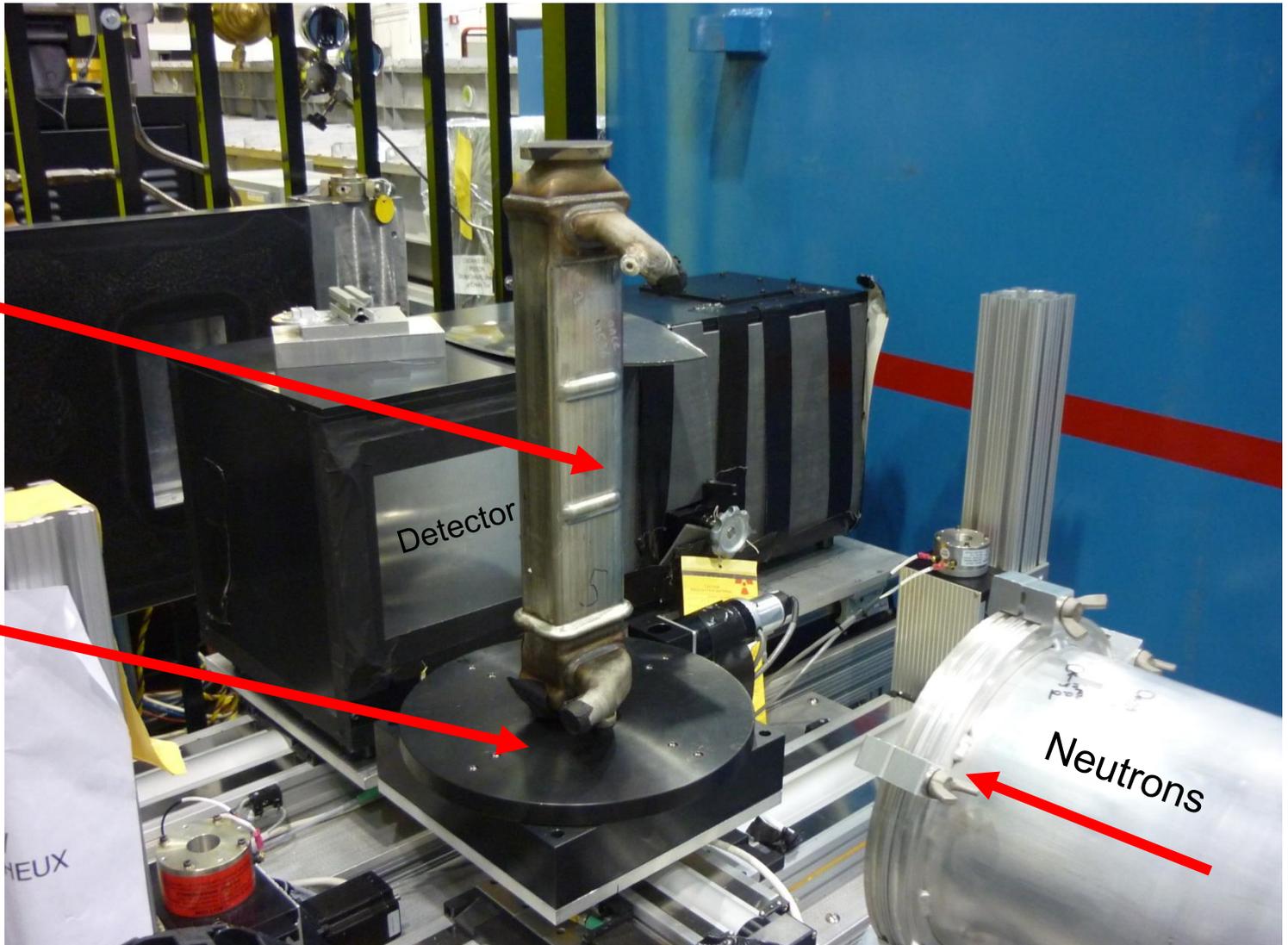


Instrument layout



Detector assembly (side view)

# Sample Area



Sample  
(Automobile  
part)

Rotation/  
Translation  
Stage

Detector

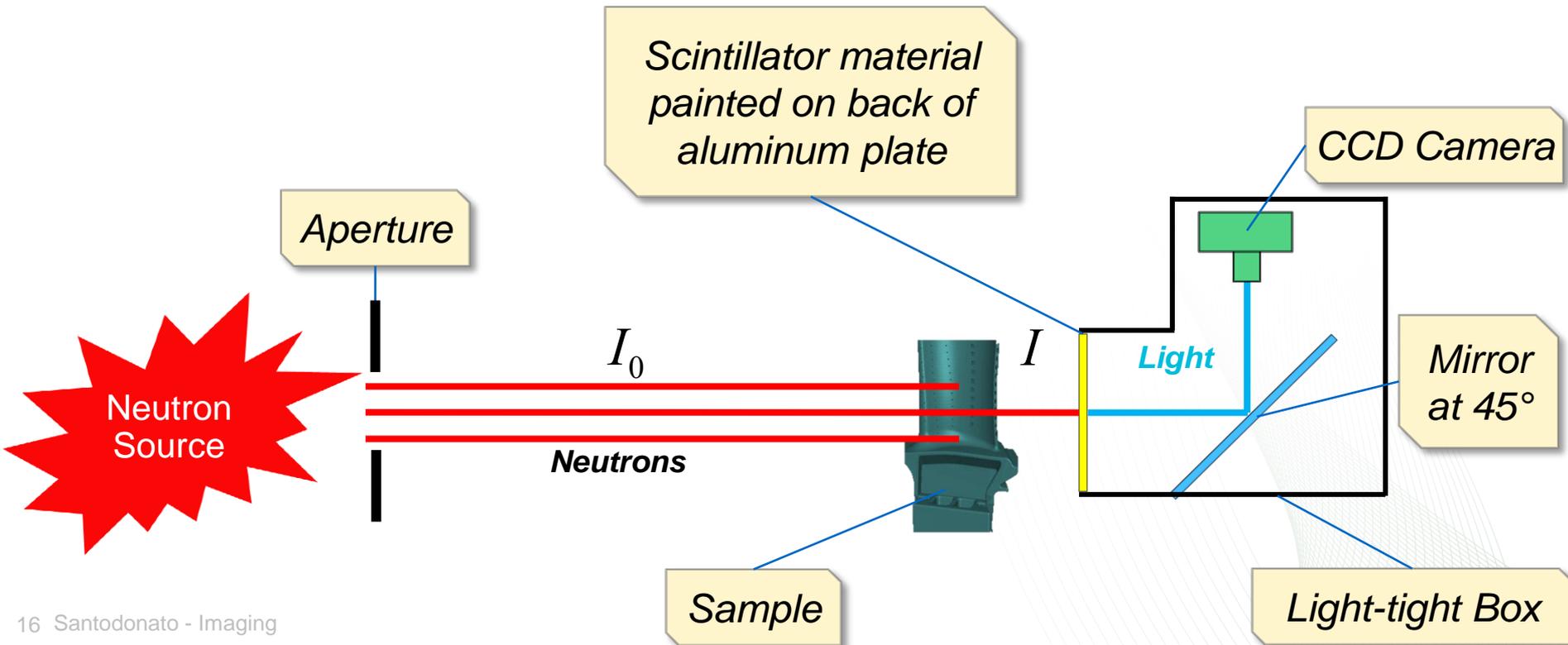
Neutrons

NEUX

# Detection of “Imaging” Neutrons

- Neutron scintillators

- Emit light after capturing neutrons
- Good signal-to-noise ratio
- Large Field Of View
- Spatial resolution limited by the dissipation of particles



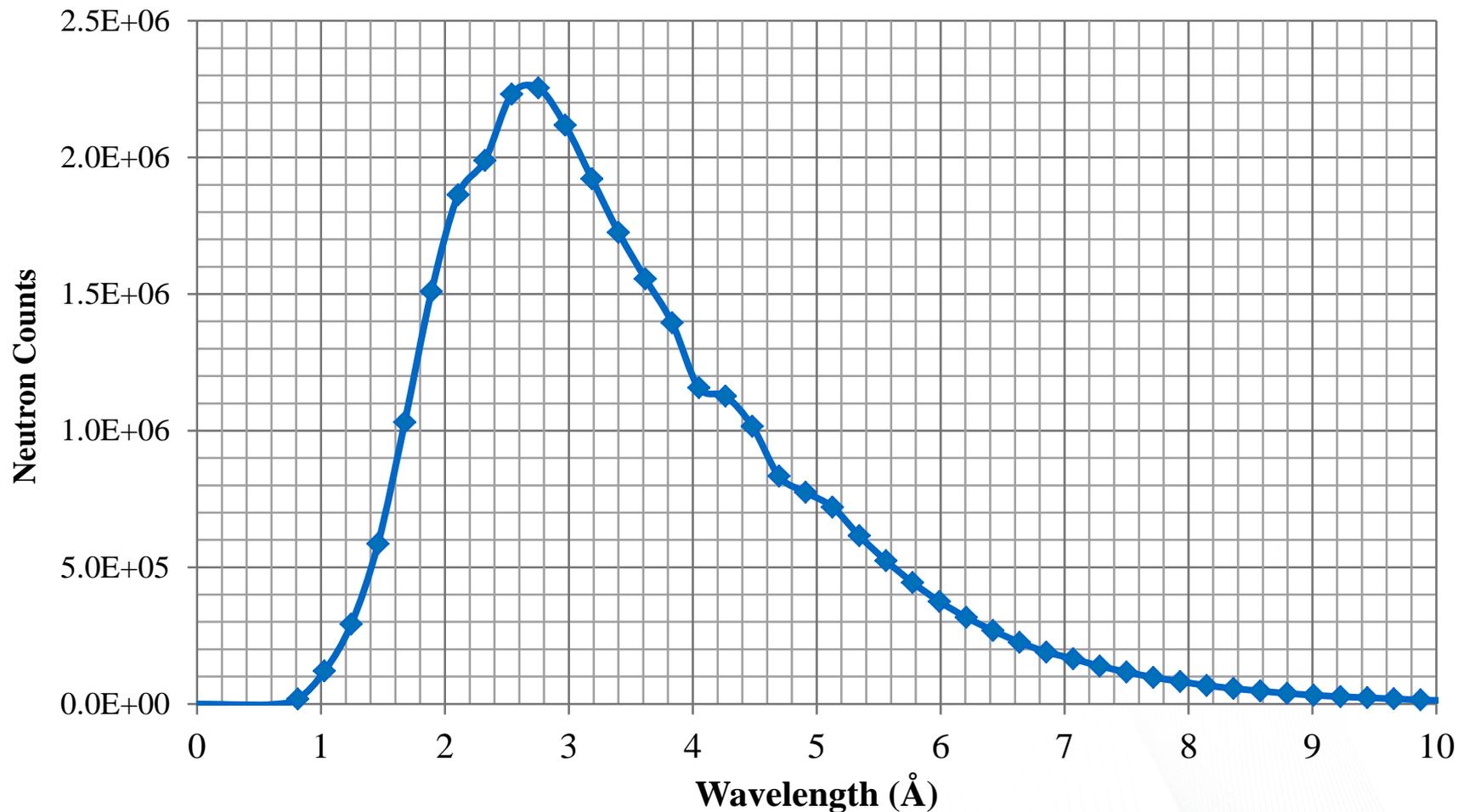
# Detection of “Imaging” Neutrons (cont’d)

- Micro-Channel Plate (MCP)

- In the direct path of the beam
- Encodes events at x, y position and time of arrival, at high temporal resolution  $\sim 1$  MHz
  - Enables time-of-flight imaging
- Detection efficiency has improved for both cold ( $\sim 70\%$ ) and thermal ( $\sim 50\%$ ) energy range
- Absence of readout noise
- Not as gamma sensitive
- Becoming commercial
- Limited FOV

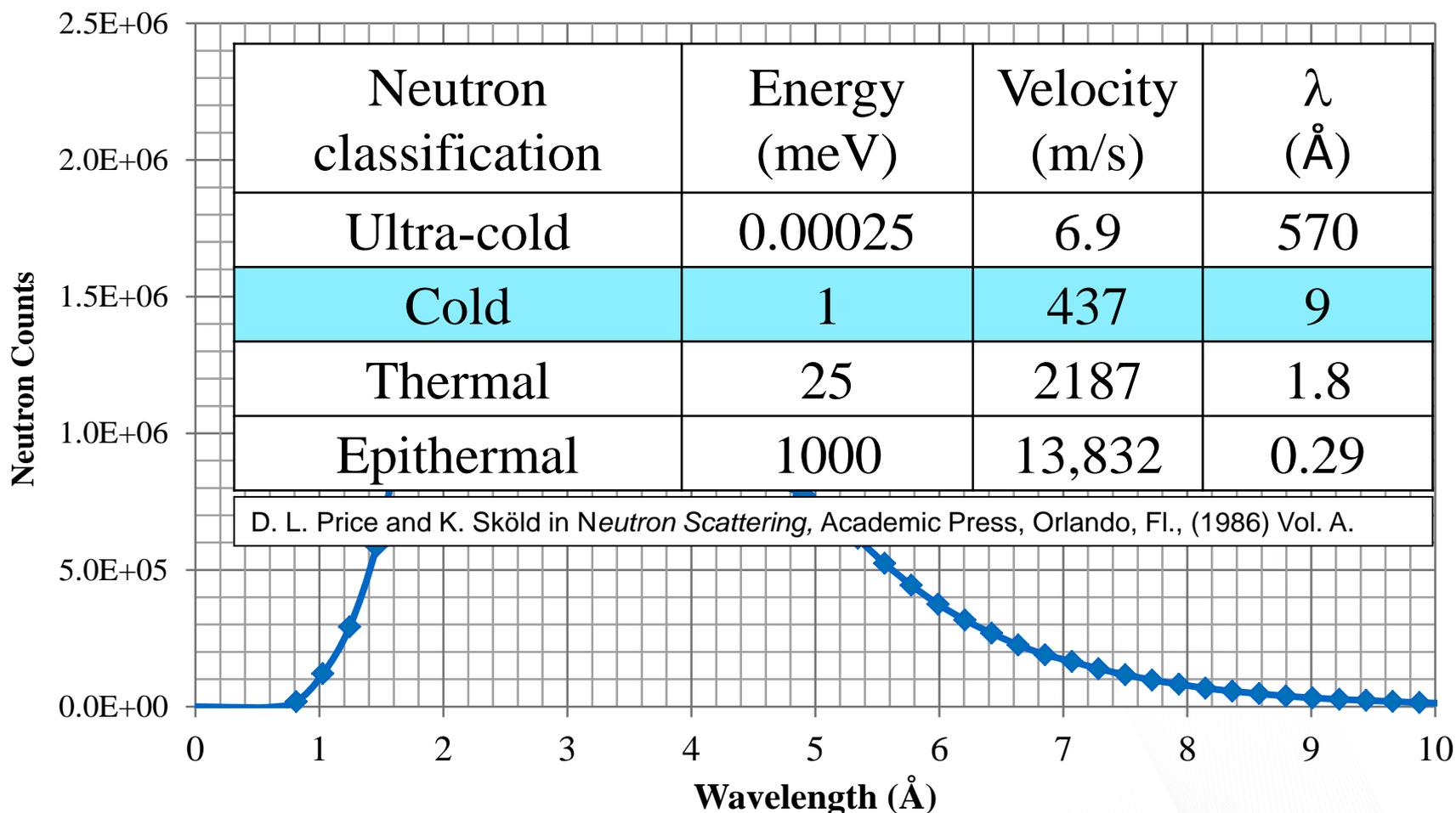


# CG-1D polychromatic beam



CG-1D spectrum measured with the MCP detector at a flight path distance of approximately 5.5 m, with the chopper running at a frequency 40 Hz and an 5 mm aperture. *[Bilheux et al., ITMNR-7, Canada, June 2012]*

# CG-1D polychromatic beam

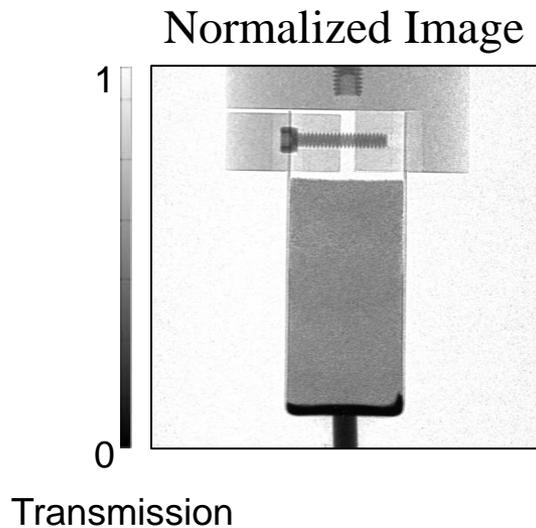


CG-1D spectrum measured with the MCP detector at a flight path distance of approximately 5.5 m, with the chopper running at a frequency 40 Hz and an 5 mm aperture. [Bilheux et al., ITMNR-7, Canada, June 2012]

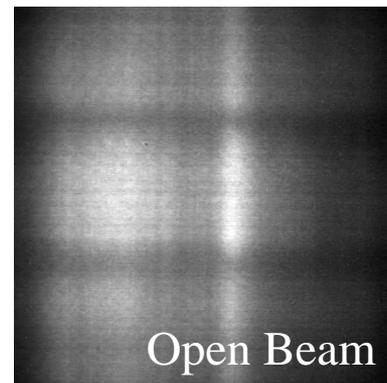
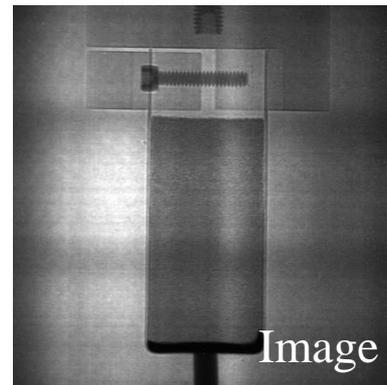
# Data Normalization for Imaging

- 2D – Radiography
  - Normalization

$$I_N(i, j) = \frac{I(i, j) - DF(i, j)}{OB(i, j) - DF(i, j)}$$



=

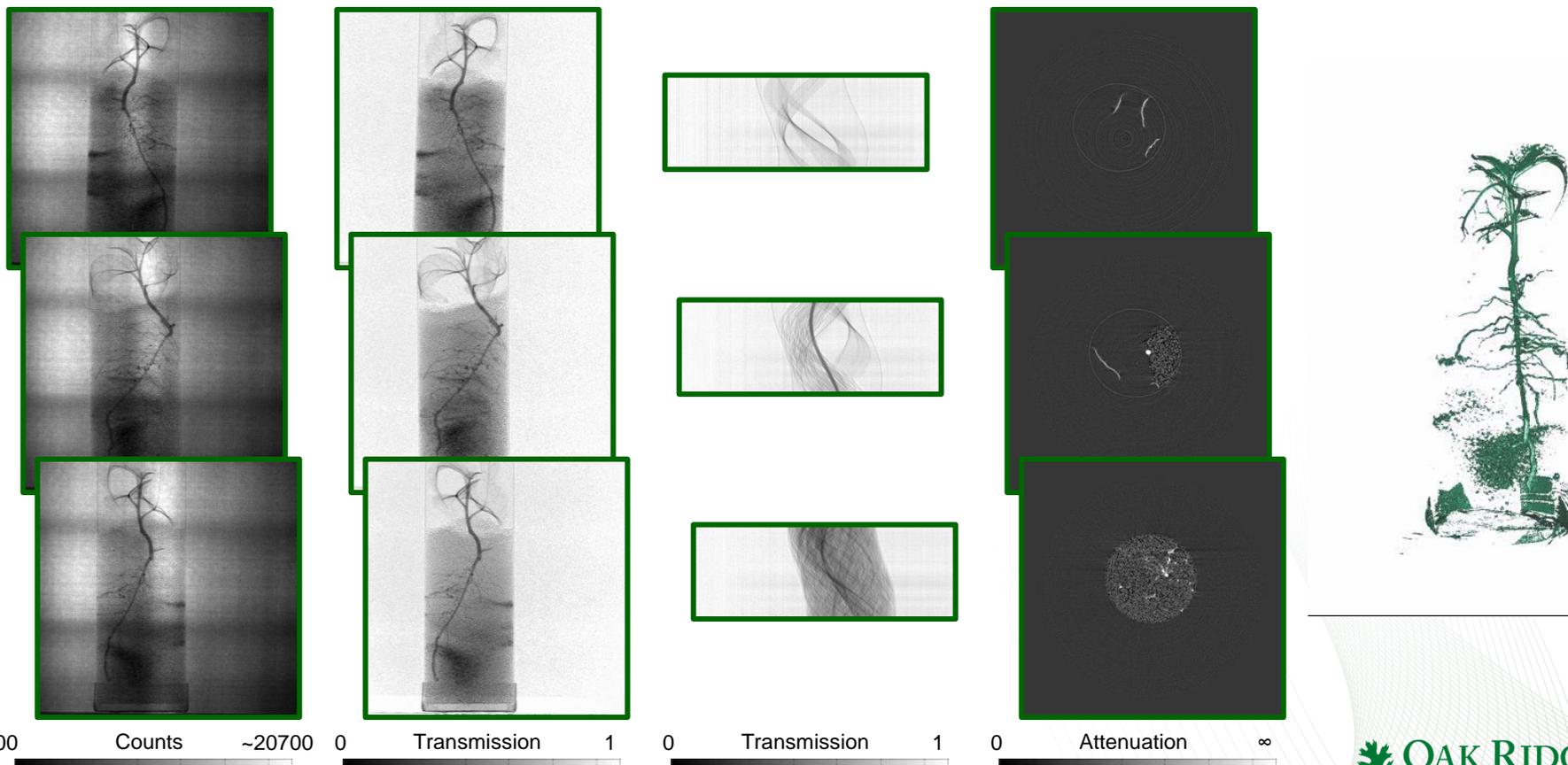


# Computed/Computerized Tomography (CT)

- Several techniques:
  - Filtered Back Projection
    - Radon transform
    - Works well with high signal to noise ratio measurements
    - Easy-to-use commercial, semi-automated software available
    - Quick
  - Iterative Reconstruction
    - Direct approach
    - Less artifacts
    - Can reconstruct incomplete data
    - High computation time

# Computed/Computerized Tomography (FBP)

- Filtered back projection method



# Conventional Neutron Imaging Techniques at Steady-State Sources

- Radiography
  - Tomography
- Routinely available at CG-1D
- Stroboscopic Imaging
  - Imaging of processes that happen fast
- Available at CG-1D using the MCP detector
- Polarized Neutron Imaging
  - Energy selective techniques possible with double-monochromator configuration
  - Phase Contrast Imaging
    - Under development
- Newly implemented at CG-1D

# Goals

- See what we can do with neutron imaging
  - Compare to other imaging techniques
  - Know when to choose it
- Understand the basic instrument layout and principals of neutron image acquisition and analysis
- Learn by example
  - Review some recent neutron imaging projects

# A Wide Range of Applications

## Applications

---

### Additive Manufacturing

Porosity; internal structure; quantitative comparative analysis of neutron-computed tomography data with engineering drawings

### Energy Storage

Ion transport in energy storage materials; three-dimensional mapping of ions in electrodes

### Technologies

Particulate deposition in vehicle parts; two-phase transport in heat pipes; multiphase constrained jet flows; metal casting; reservoir flow, creation, and production

### Plant Systems Biology

Partitioning, transport, and fate of carbon fixed by plants; carbon biosequestration; modeling impacts of rising CO2 levels; modified bioenergy feedstock plants; cavitation and gas embolism in plants

### Plant-Soil-Groundwater Systems

Transport and interactions of fluids in porous media; water infiltration and aquifer recharge; plant-plant and plant-fungal interactions; change in pore structure and voids after repeated thawing and freezing of permafrost soil

### Biological and Forensic Studies

Structural, contrast agent, and cancer research

### Food Science and Archeology



Using Our Instruments
User Program
User Laboratories
Sample Environment
Data Analysis and Management

HFIR Instruments
CG-1   DEV BEAM Instrument Development Beam Line
CG-1D   IMAGING Neutron Imaging Facility
CG-2   GP-SANS General-Purpose Small-Angle Neutron Scattering Diffraction



# CG-1D Cancer Research Application

Photograph of tissue sample

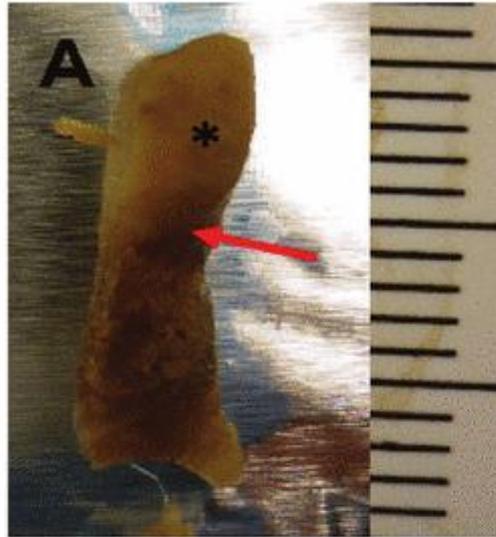
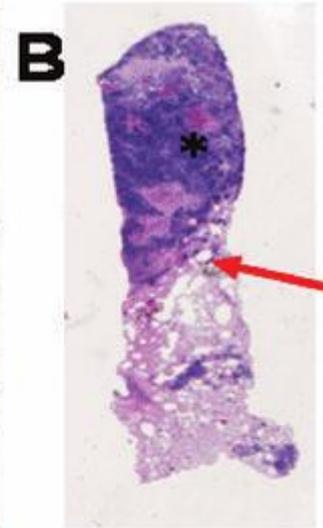
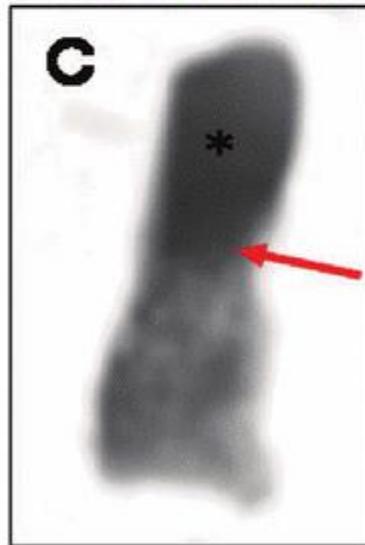


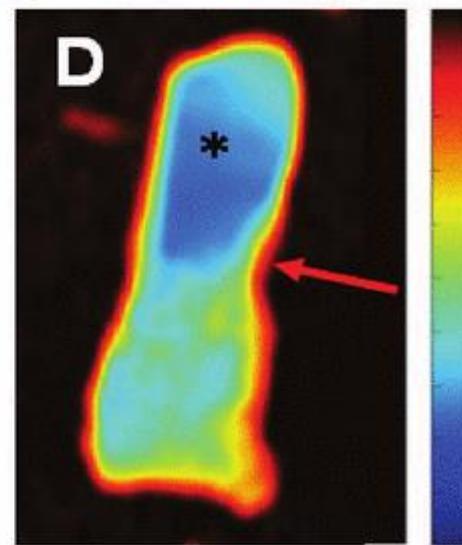
Photo of stained tissue slice



Greyscale neutron image

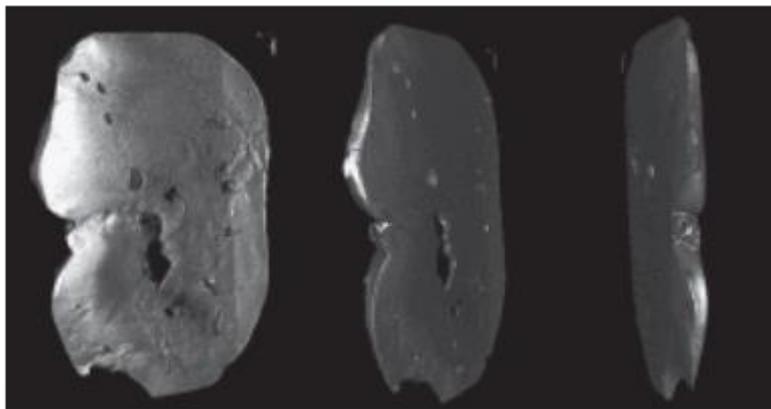


Colorized\* neutron image



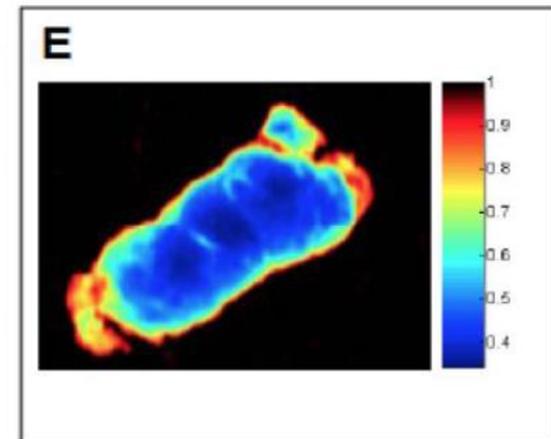
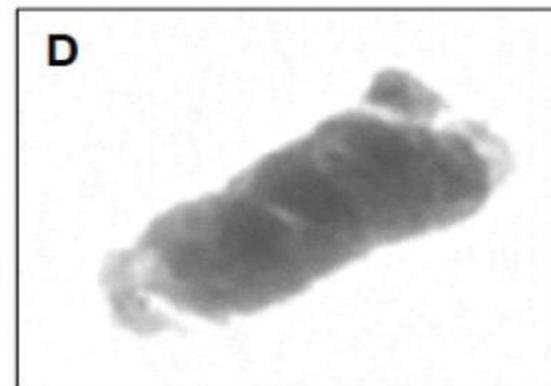
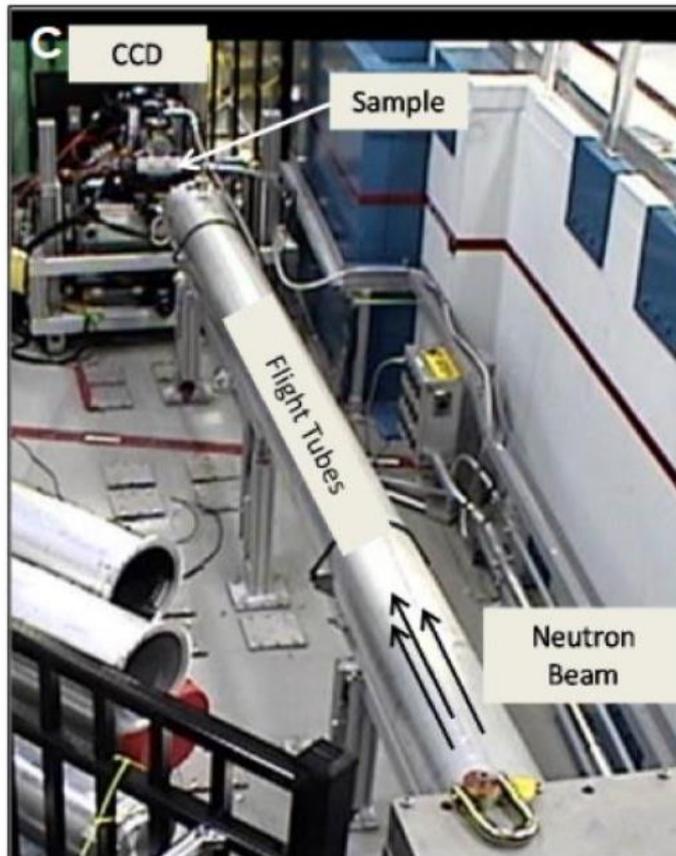
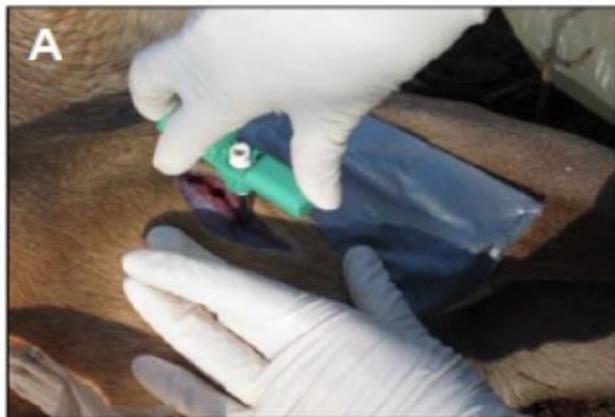
# Several Biological Tissues Have Been Studied at CG-1D

- No animals are ever hurt or sacrificed for these experiments
- Post mortem studies help researchers battle disease
- Neutrons reveal important features
- Non-destructive 3D evaluation



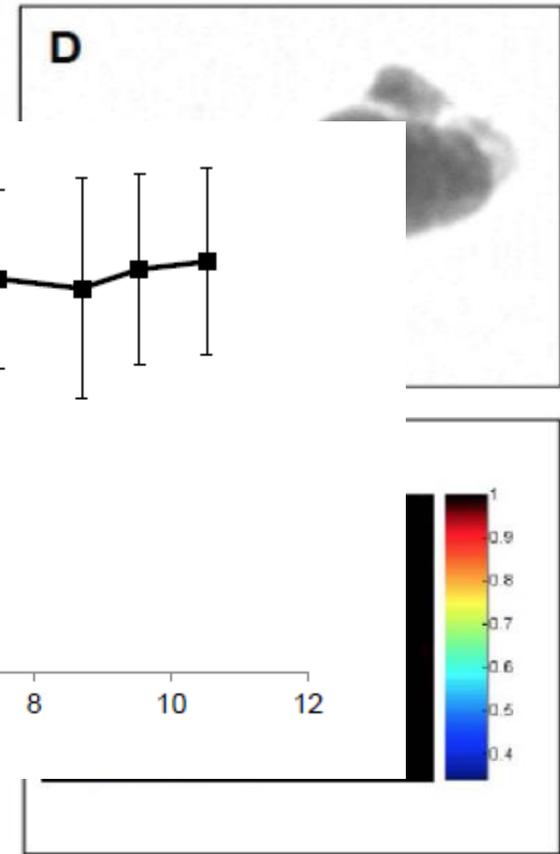
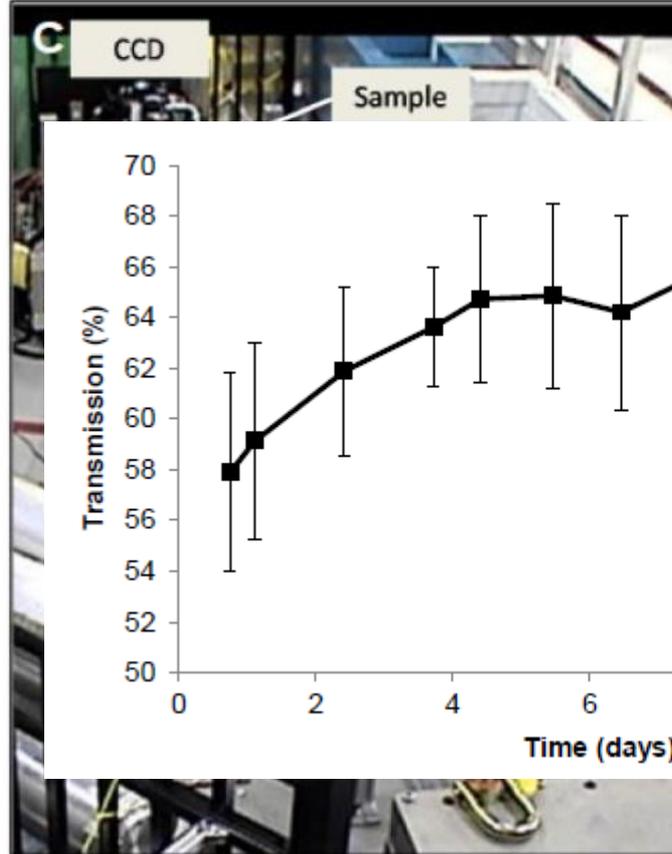
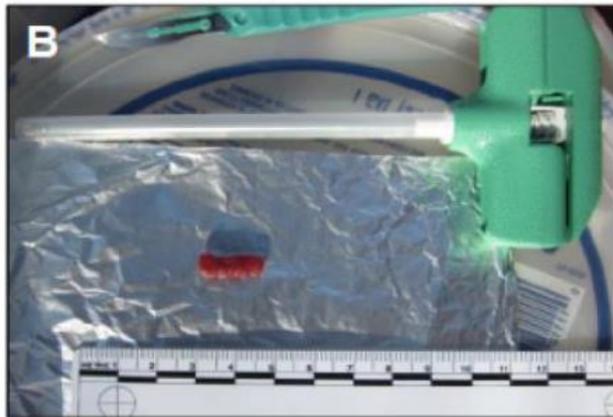
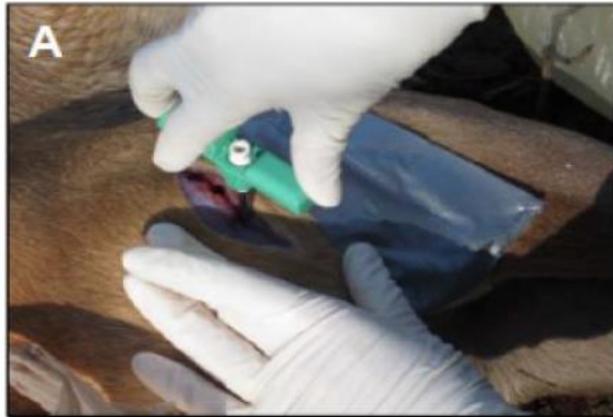
**Fig. 5.**  
Volume rendered images computed tomogram of the canine kidney slice from fig. 5.

# Forensic Science Example



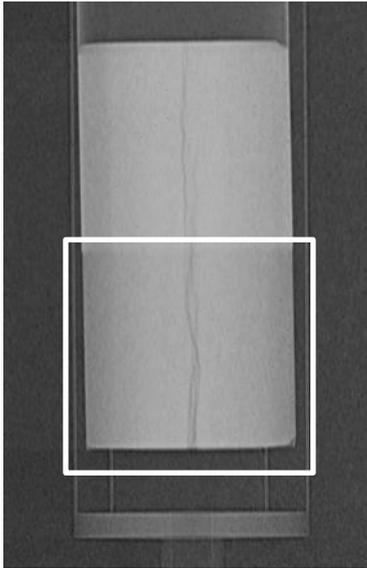
Bilheux H.Z., Cekanova M., Vass A., Nichols T., Bilheux J., Legendre A., Donnell R.L., *Investigation of a Novel Approach to Forensic Analysis Using Neutron Imaging Techniques U. S. Department of Justice 24845 (2014).*

# Forensic Science Example



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# Rapid Imbibition of Water in Fractures within Unsaturated Sedimentary Rock

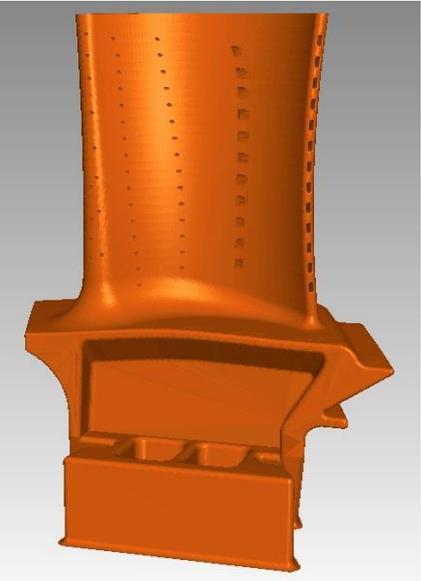


Time sequence of neutron radiographs showing the rapid uptake of water into a longitudinal, air-filled fracture zone in Berea sandstone. FOV is  $\sim 28 \times 28 \text{ mm}^2$ .

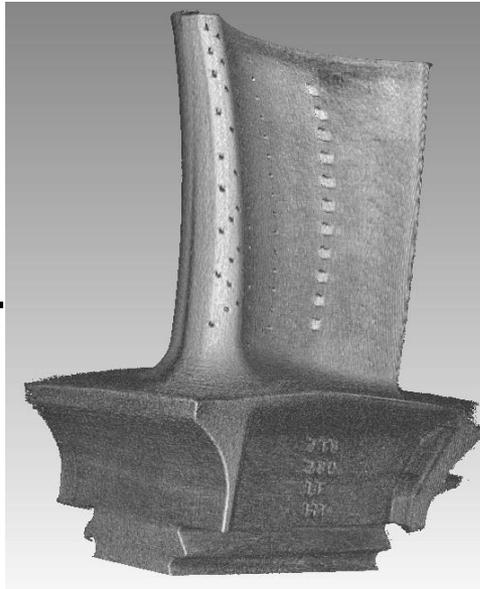
- **Dynamic neutron radiography**
  - Directly quantify the sorptivity and dispersion coefficients of liquids in fractured, porous media
  - The findings can be applied in modeling hydraulic fracturing

Work performed at the High Flux Isotope Reactor Imaging beam line (CG1D) was supported by the Scientific User Facilities Division, Office of Basic Energy Sciences, U.S. Department of Energy.

# Fabrication tolerance studies comparing CAD drawing to neutron computed tomography



+

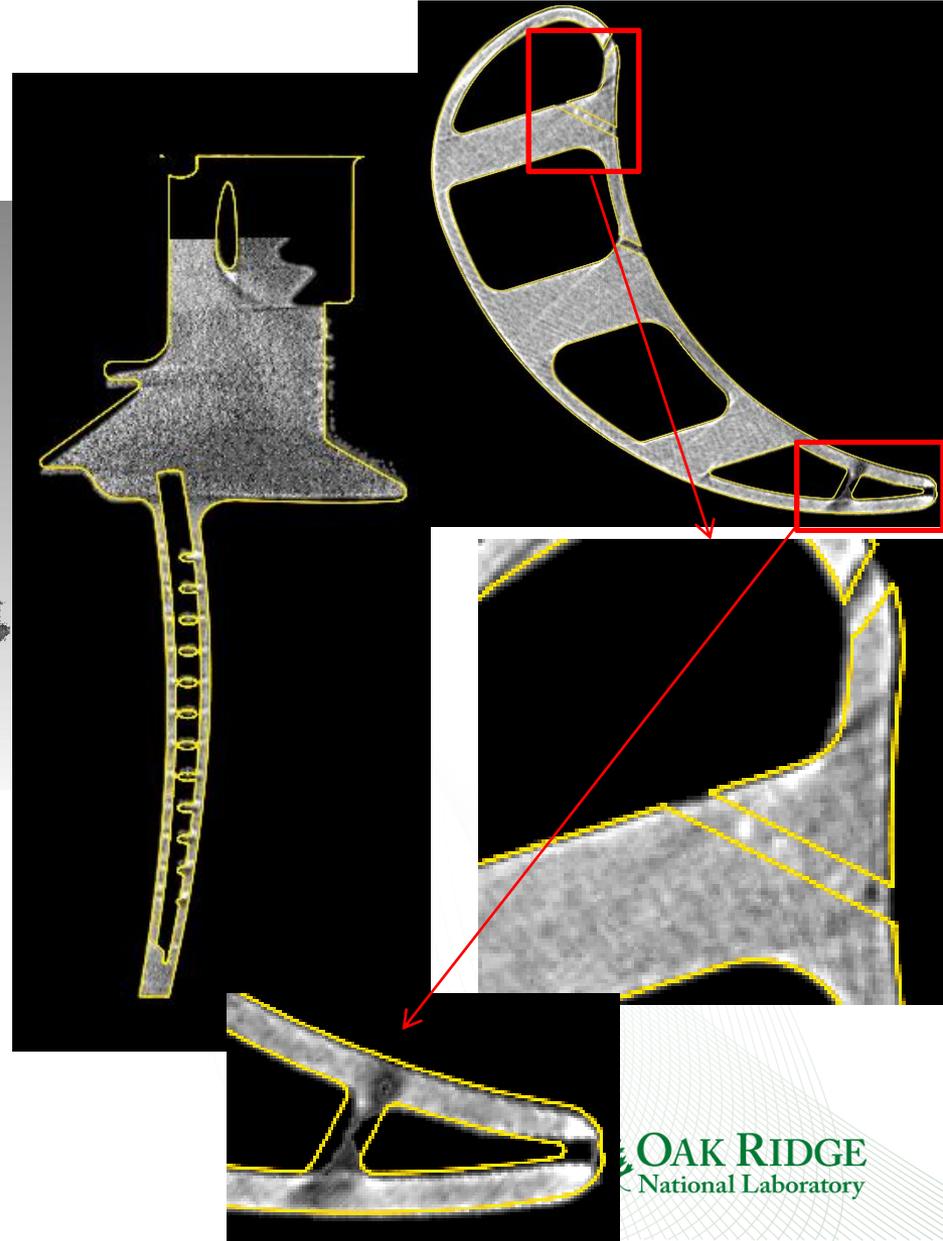


Engineering drawing

Neutron CT

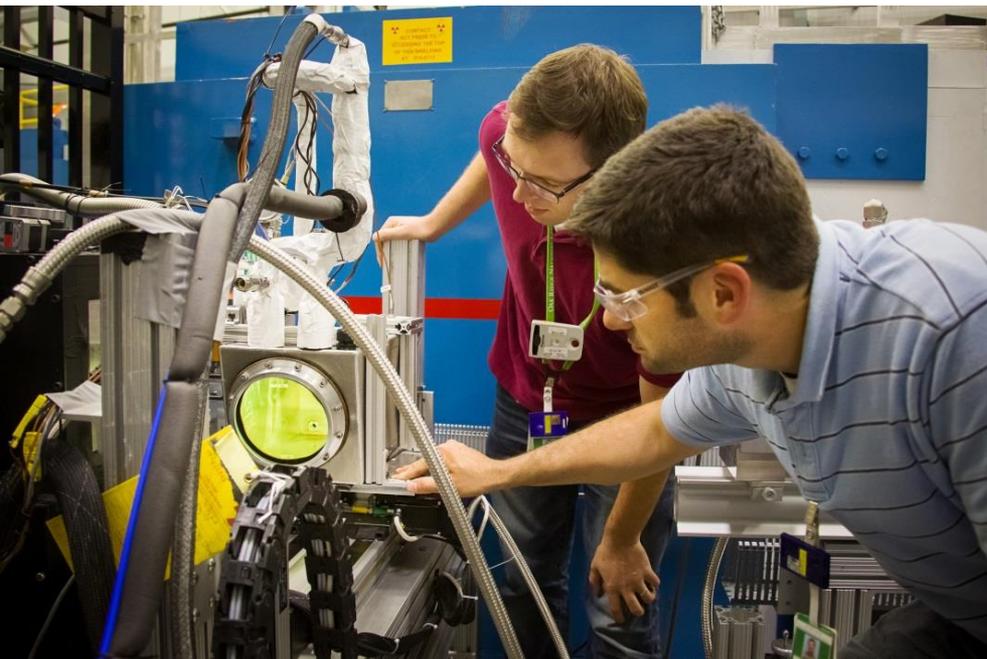
In orange/yellow: AUTOCAD outline

In gray: neutron data



# Time-resolved studies

- Rapid image acquisition and synchronization with operating devices
  - Micro-channel plate detector technology
- Recent applications include fuel injector operation and water propagation through porous media



← **Researchers  
setup a fuel  
Injector chamber**

# More Examples

- More examples may be presented at the live talk

# Summary

# Imaging is a Growing Part of the ORNL Neutron Sciences Program

## High Flux Isotope Reactor (HFIR)

Intense steady-state neutron flux and a high-brightness cold neutron source

## Spallation Neutron Source (SNS)

World's most powerful accelerator-based neutron source

Dedicated Imaging Instrument (CG-1D)  
Steadily improving capabilities  
Expanded support

Techniques such as Bragg-edge imaging are being implemented on diffraction instruments (no dedicated imaging beamline yet)

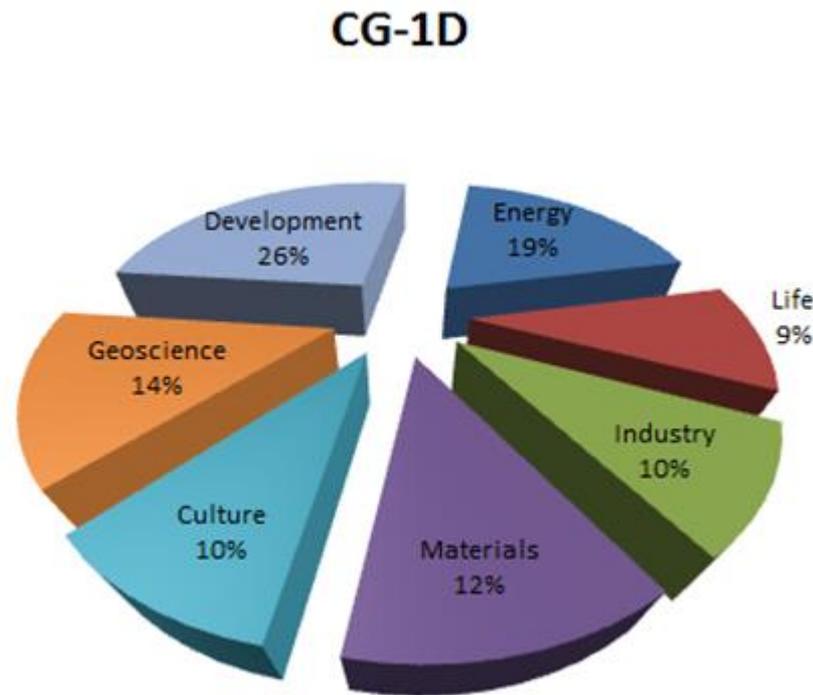
# HFIR

# SNS

 OAK RIDGE  
National Laboratory

# Diverse Science and Engineering Applications

- Trends at CG-1D are similar other facilities
- Are we missing any opportunities? Your science!



Based upon recent publications

# Summary

- Neutrons are ideal for *certain* imaging applications, especially those requiring
  - Sensitivity to hydrogen and other light elements
  - Isotope sensitivity
  - Penetration into large samples and/or sample environments
- Spatial resolution is a key consideration
  - CG-1D routine capability of  $\sim 80 \mu\text{m}$
  - Radiography at  $\sim 20 \mu\text{m}$  (with the trade-off of long counting time) is now available
- Imaging capabilities are steadily improving

# Thank you

- Lou Santodonato [SantodonatoL@ornl.gov](mailto:SantodonatoL@ornl.gov)
- Hassina Bilheux [BilheuxHN@ornl.gov](mailto:BilheuxHN@ornl.gov)

