PAUL SCHERRER INSTITUT

PSI

CCMX Competence Centre for Materials Science and Technology

IAEA International Atomic Energy Agency

Wir schaffen Wissen – heute für morgen

Marc Raventós

Neutron Imaging & Activation Group, Paul Scherrer Institut, Switzerland

Diffractive Neutron Imaging

OUTLINE

1. Introduction
2. Neutron interactions
3. Bragg edge scattering
4. Energy selection
5. Detector setup
6. Applications

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1. **Introduction**
2. Neutron interactions
3. Bragg edge scattering
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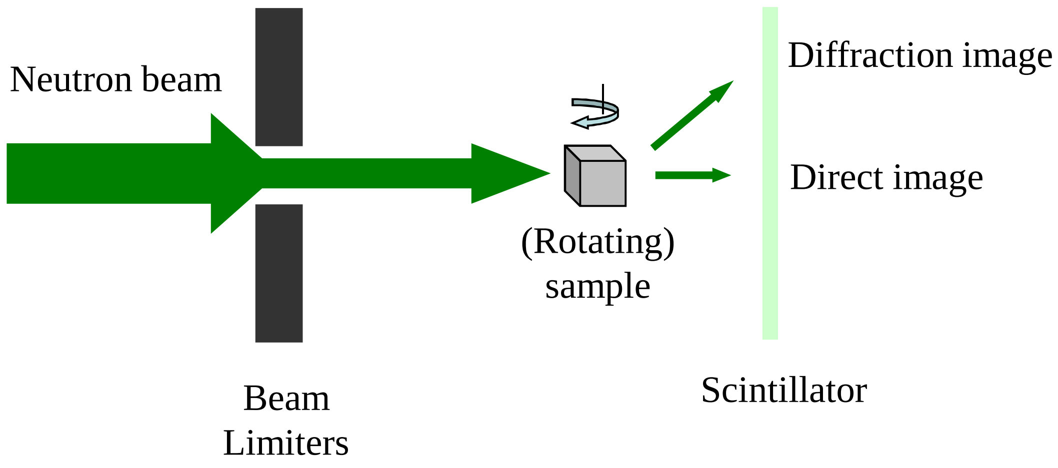
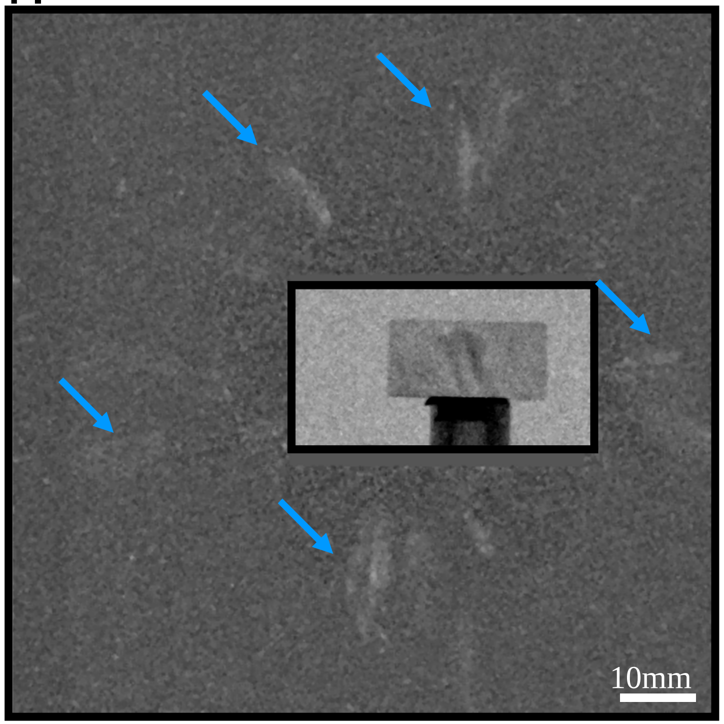
INTRODUCTION - Motivation

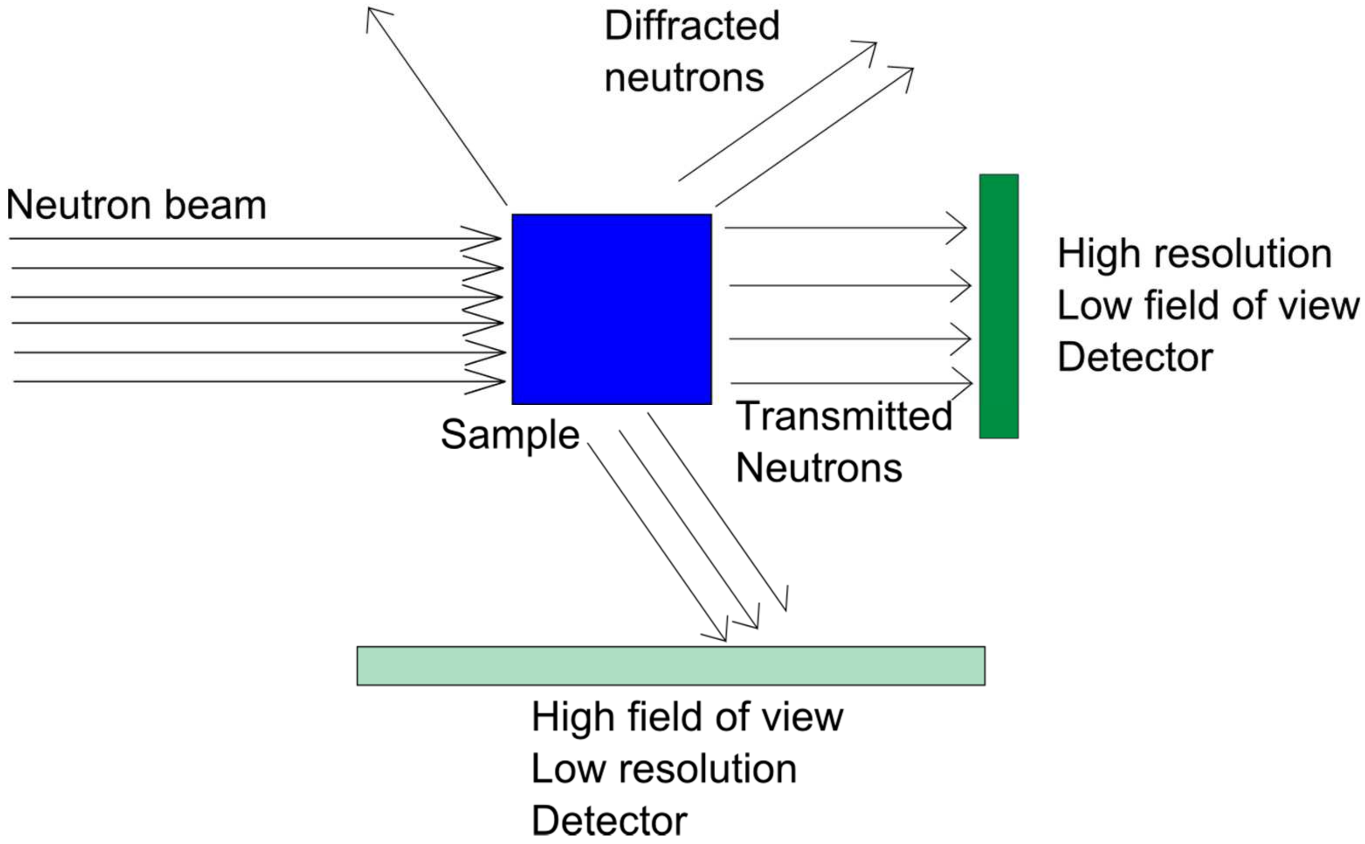
What information is present on scattered neutrons? Where do these neutrons go? Can we detect them?

First proof of principle:
everything on one detector





INTRODUCTION – Example: Pyrite single crystal

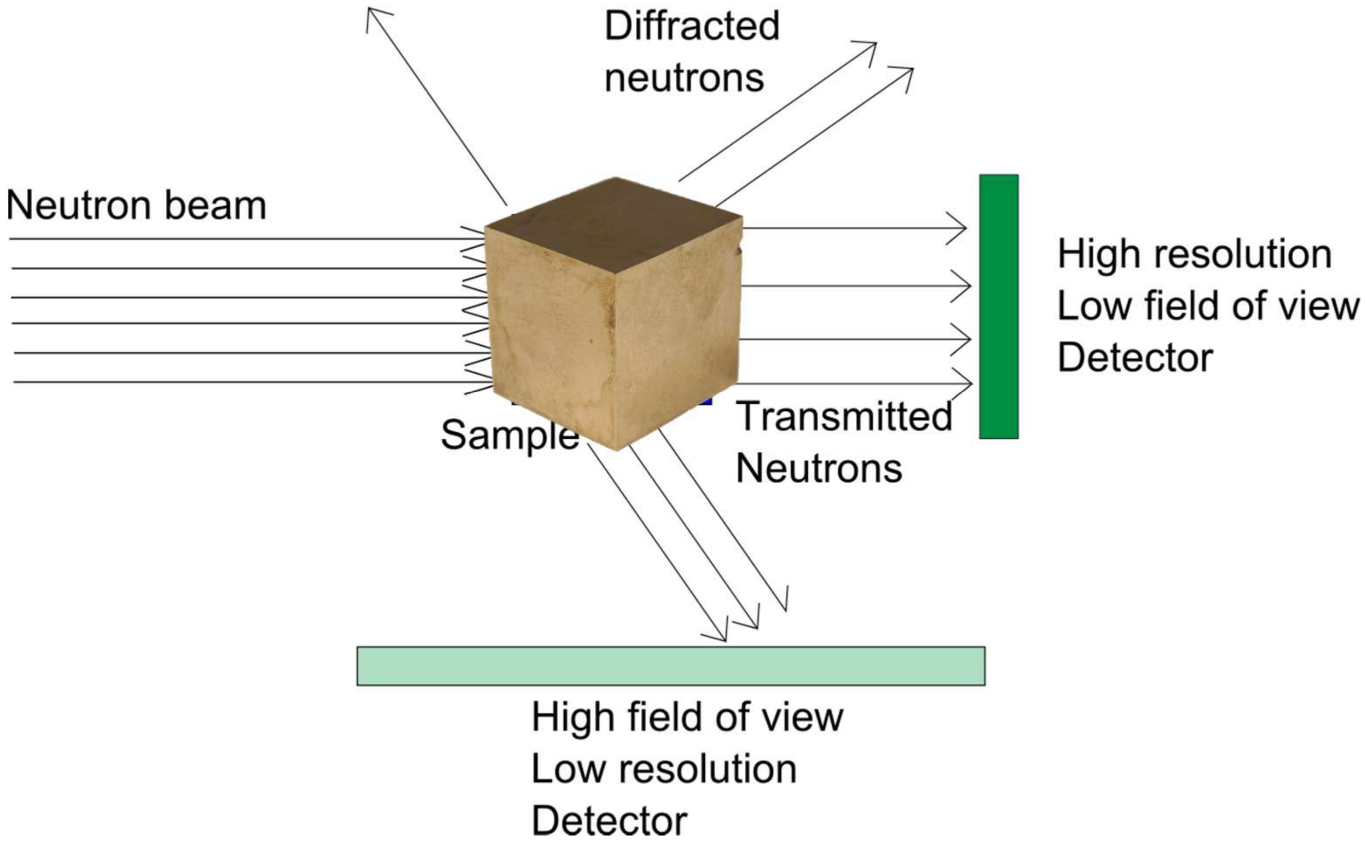


INTRODUCTION – Example: Pyrite single crystal

FeS_2

Primitive cubic structure

INTRODUCTION – Example: Pyrite single crystal



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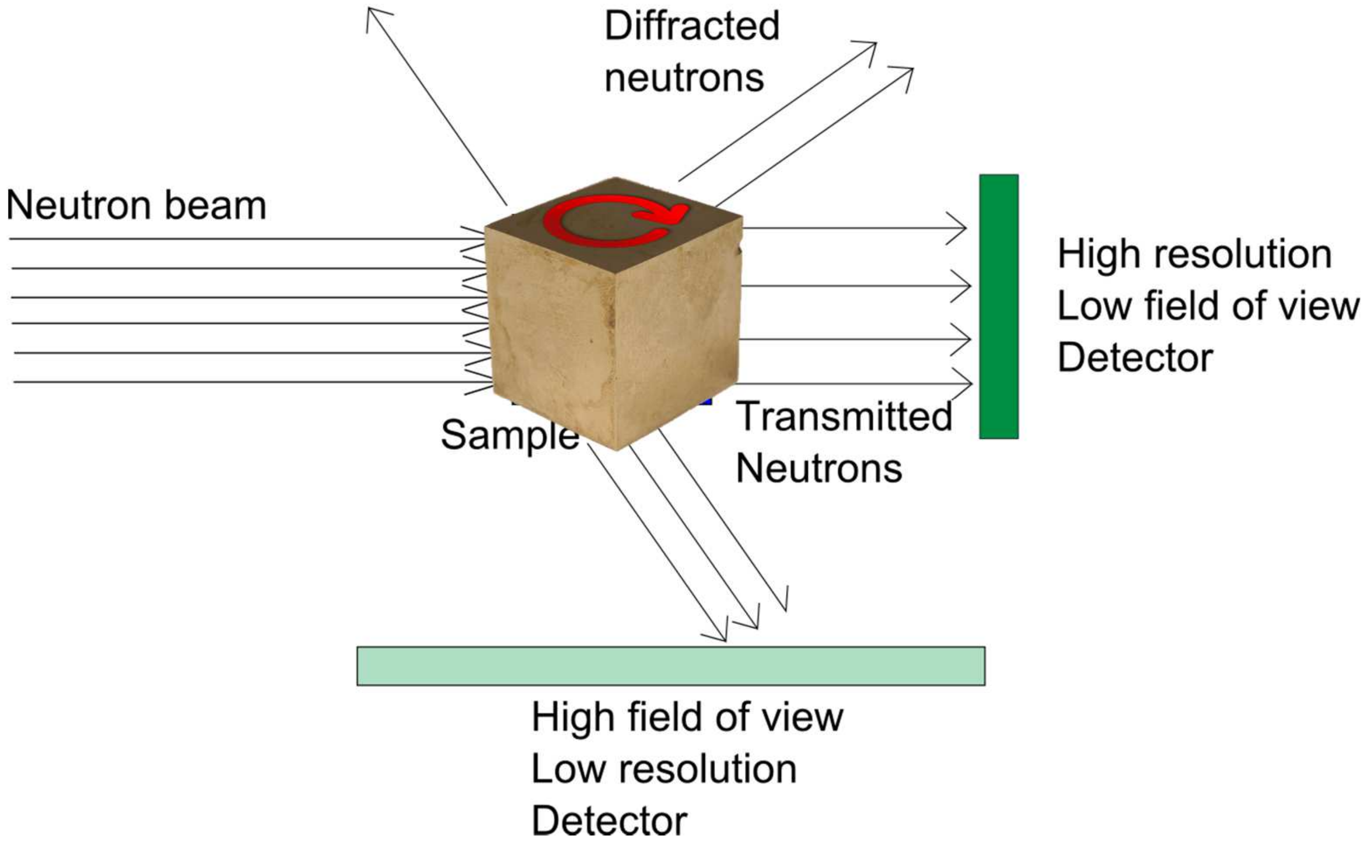

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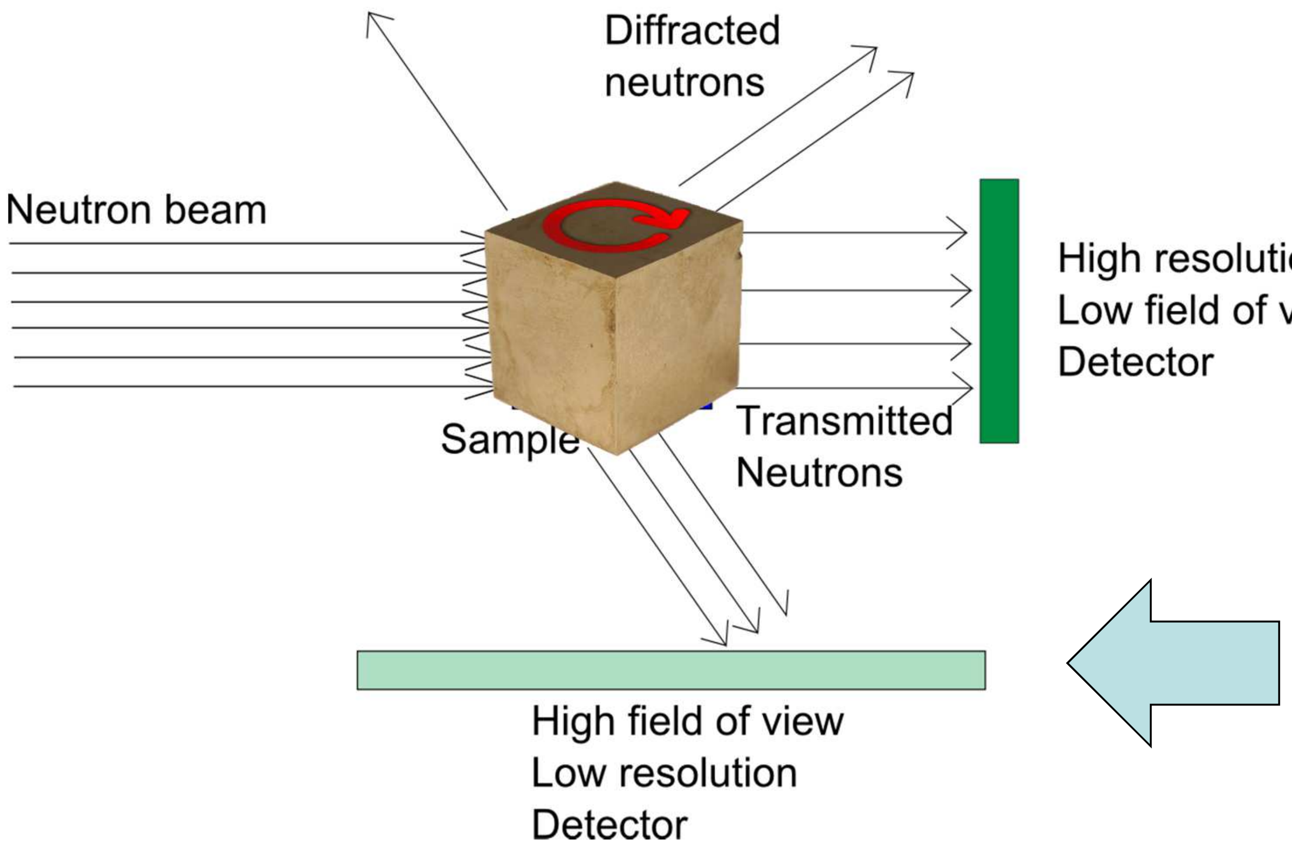

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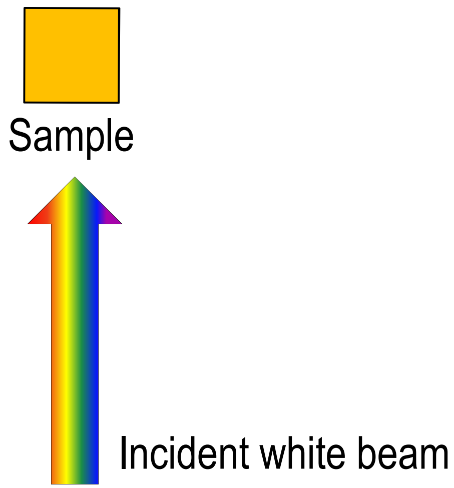

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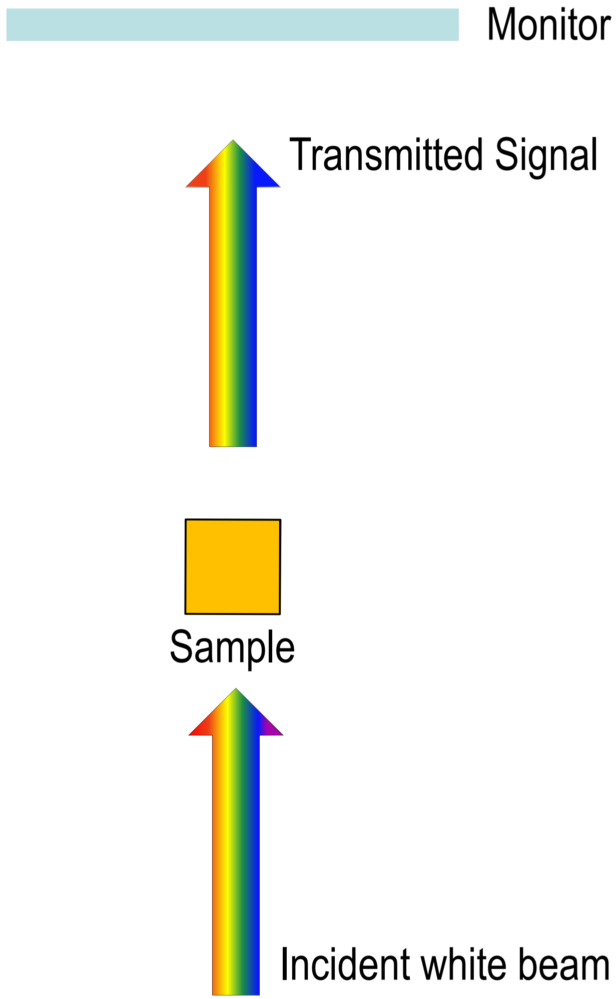

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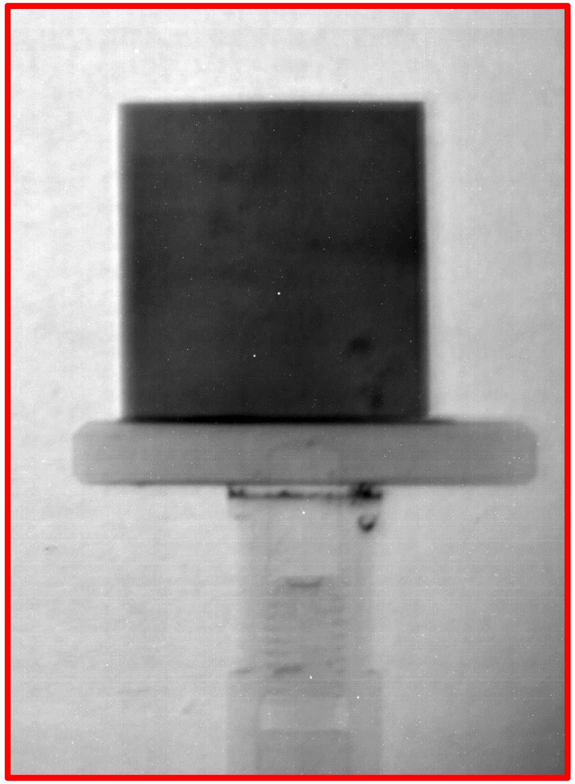
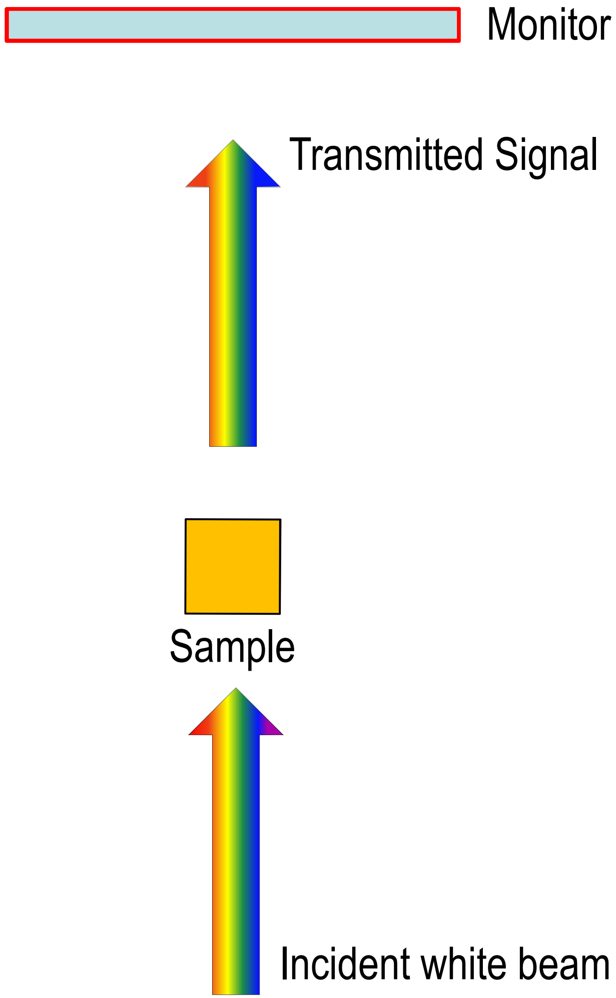


Transmitted Image



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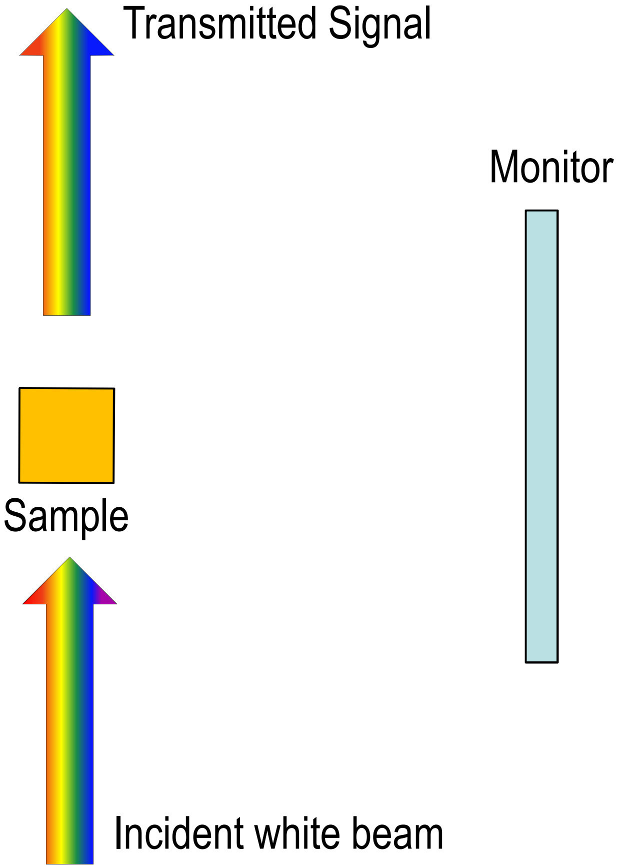

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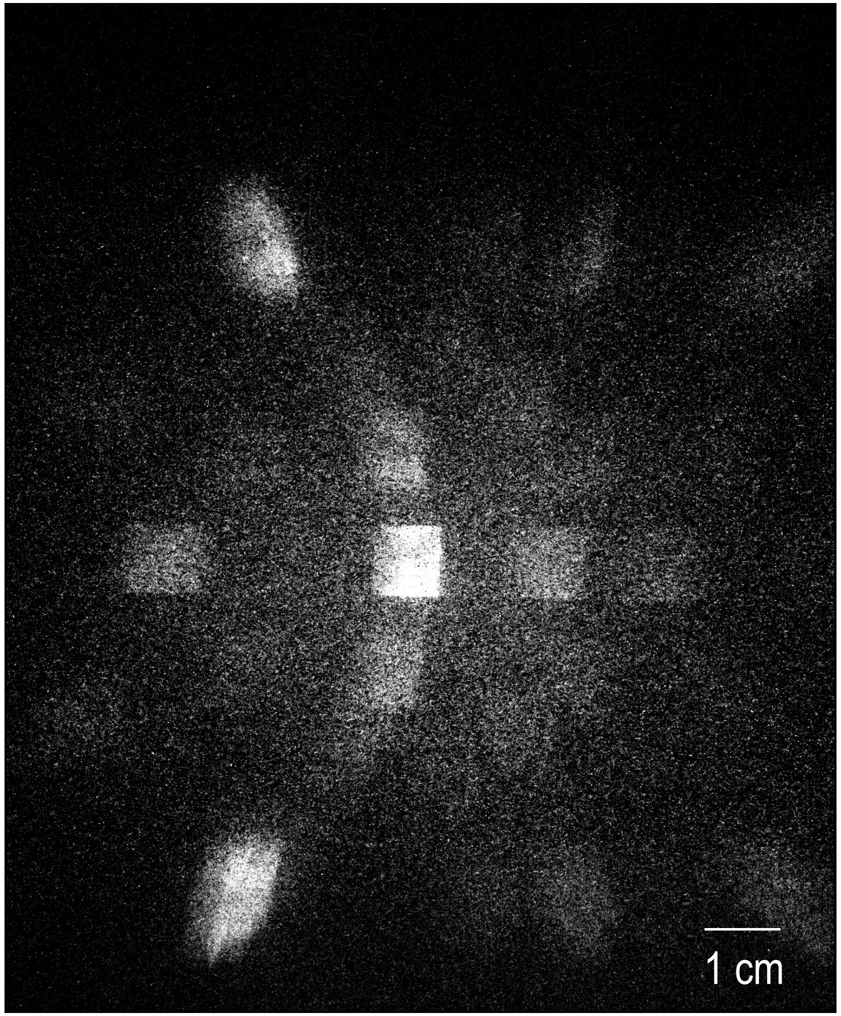
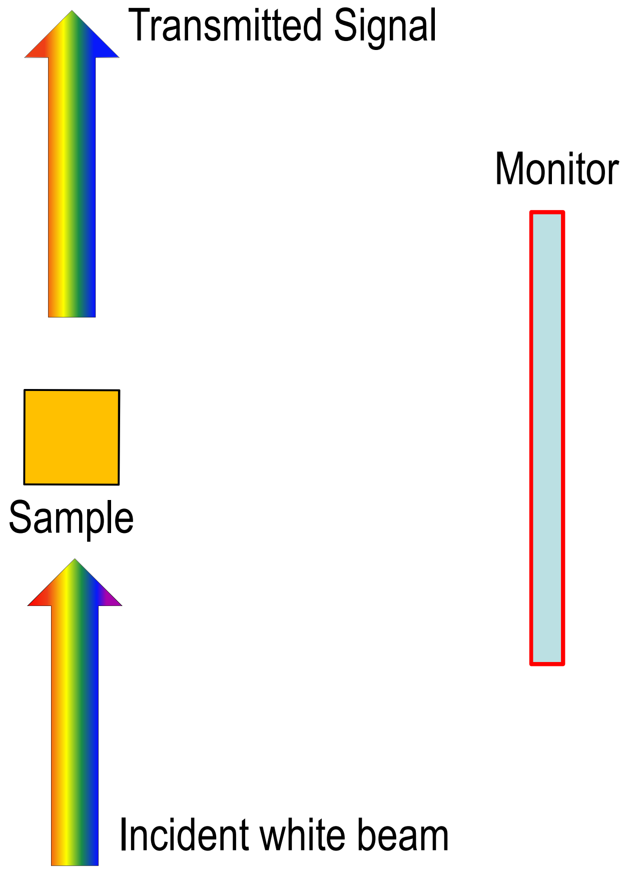


Diffractive Image



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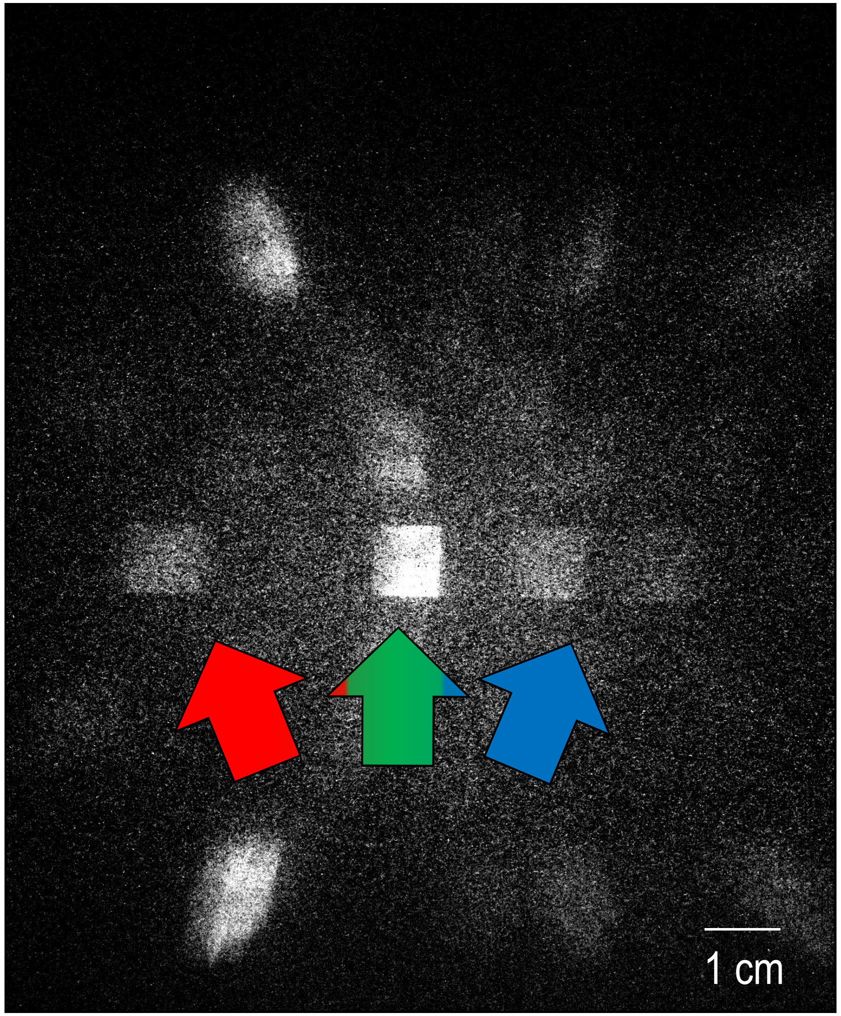

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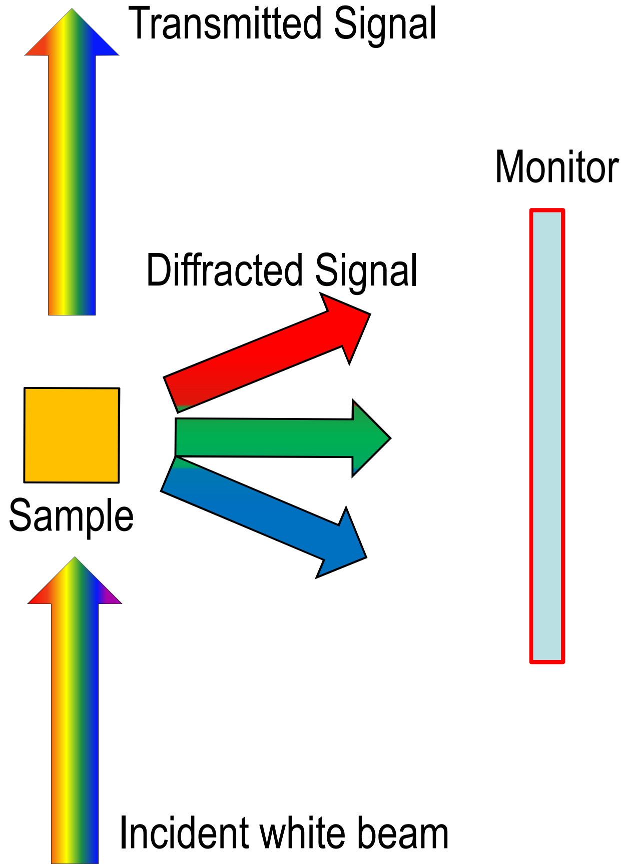

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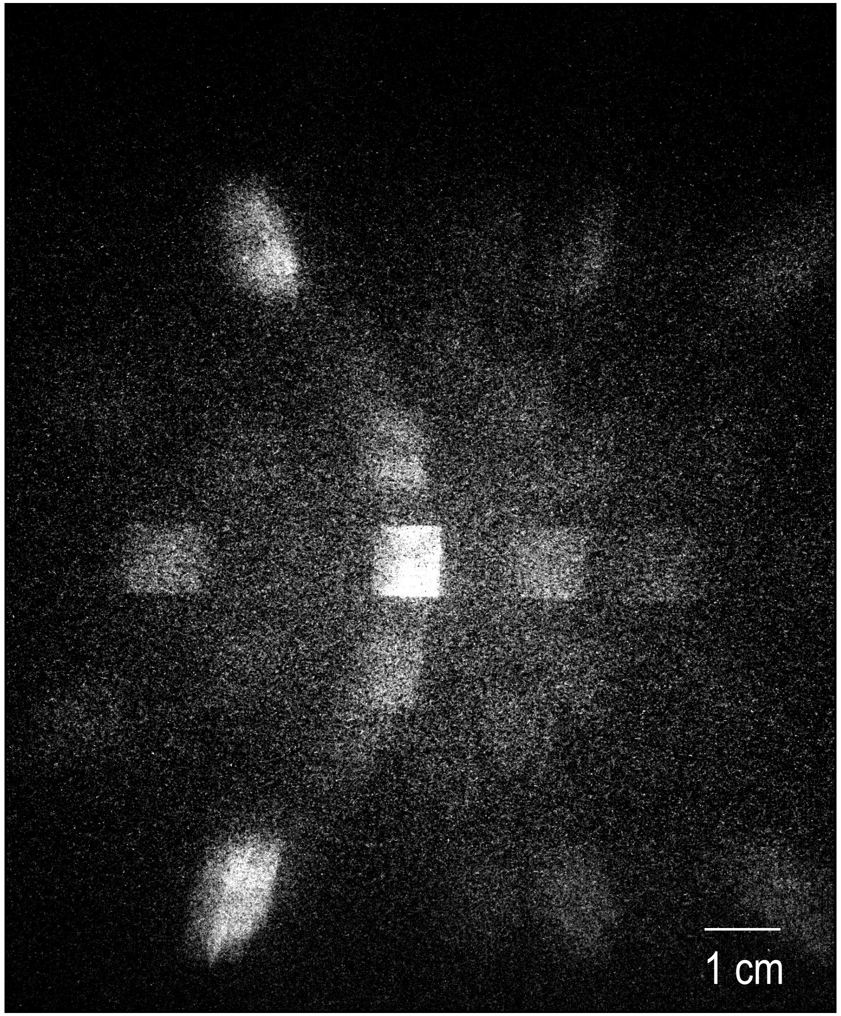

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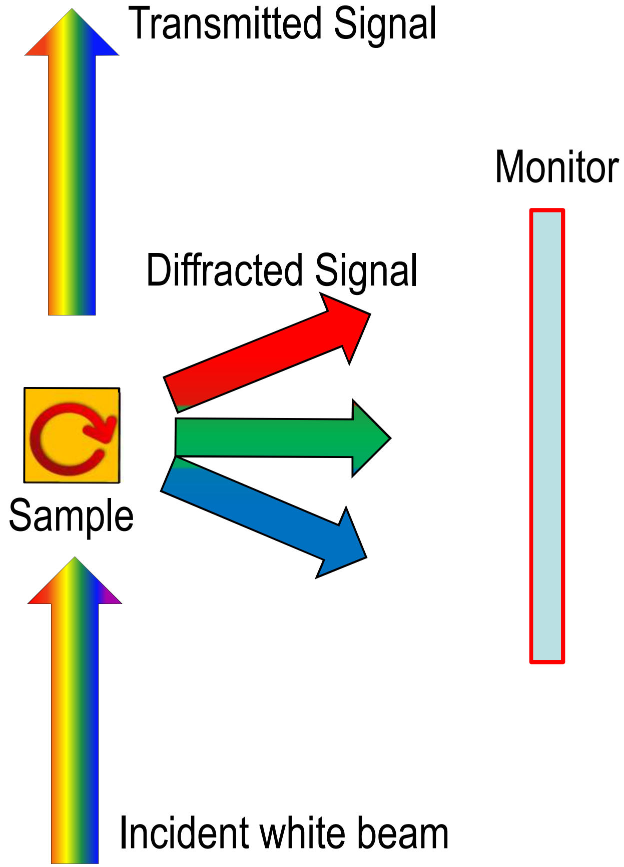

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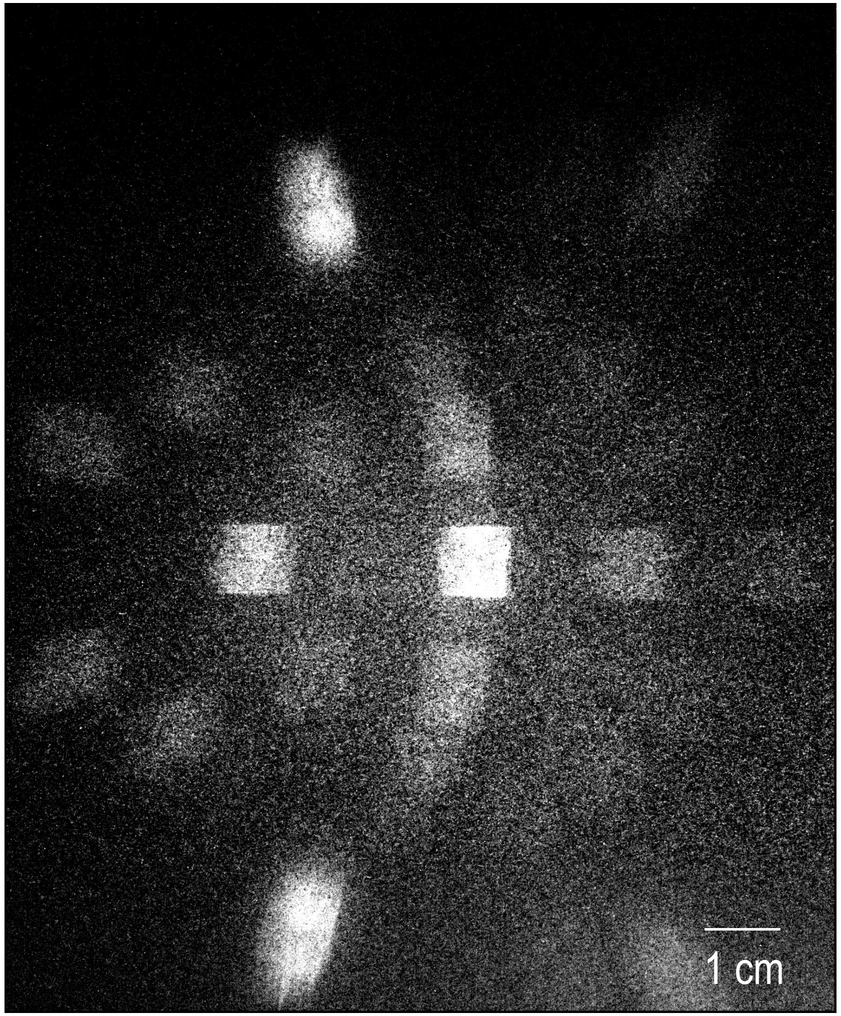

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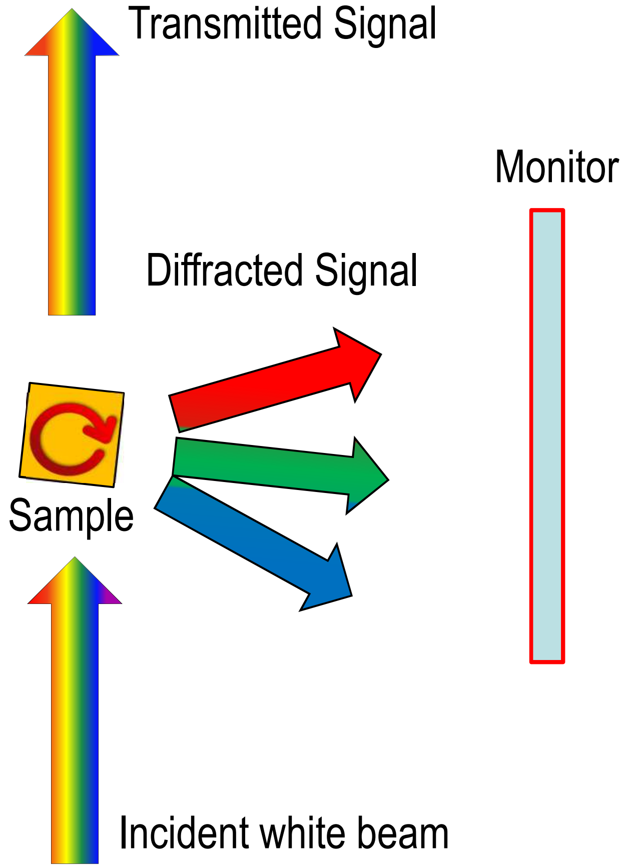

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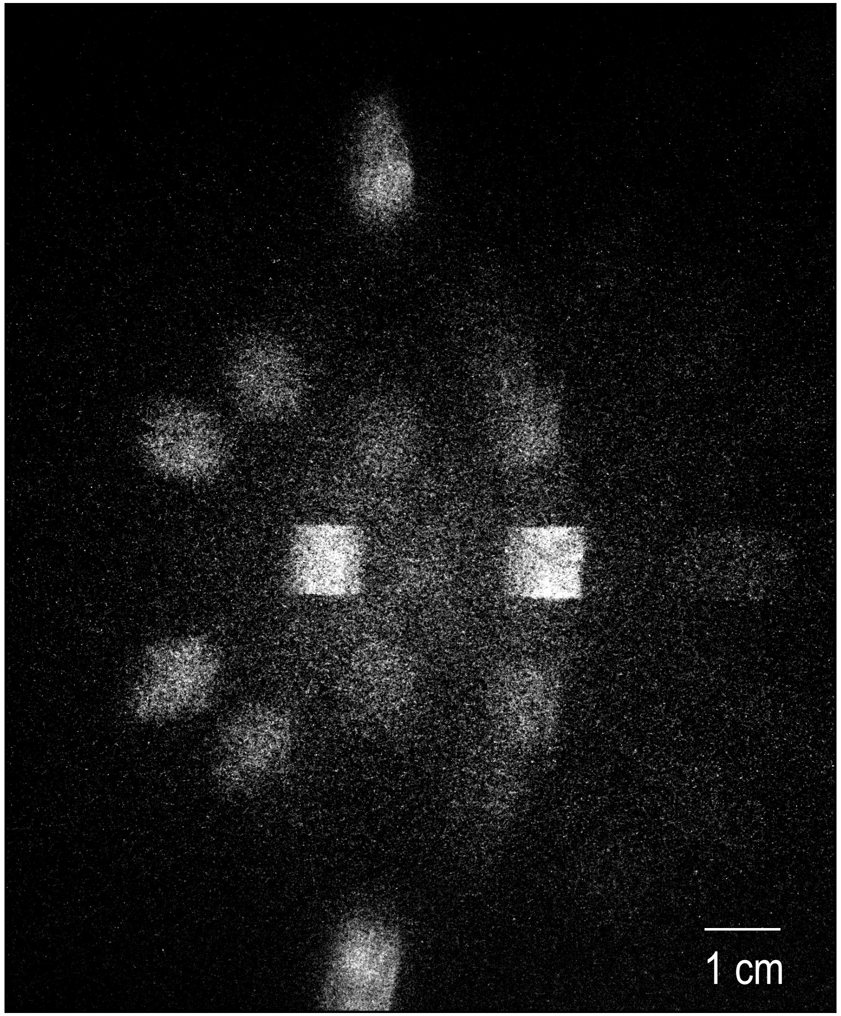

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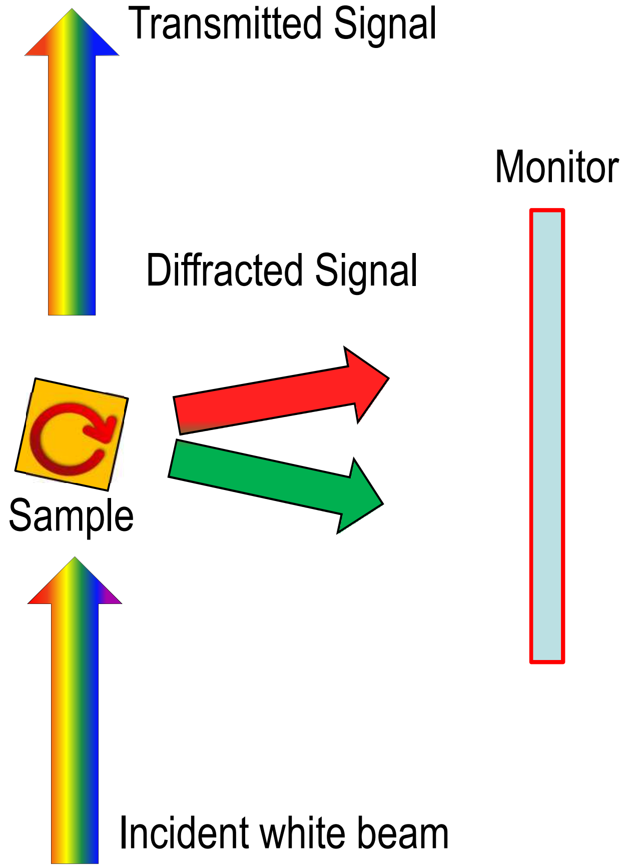

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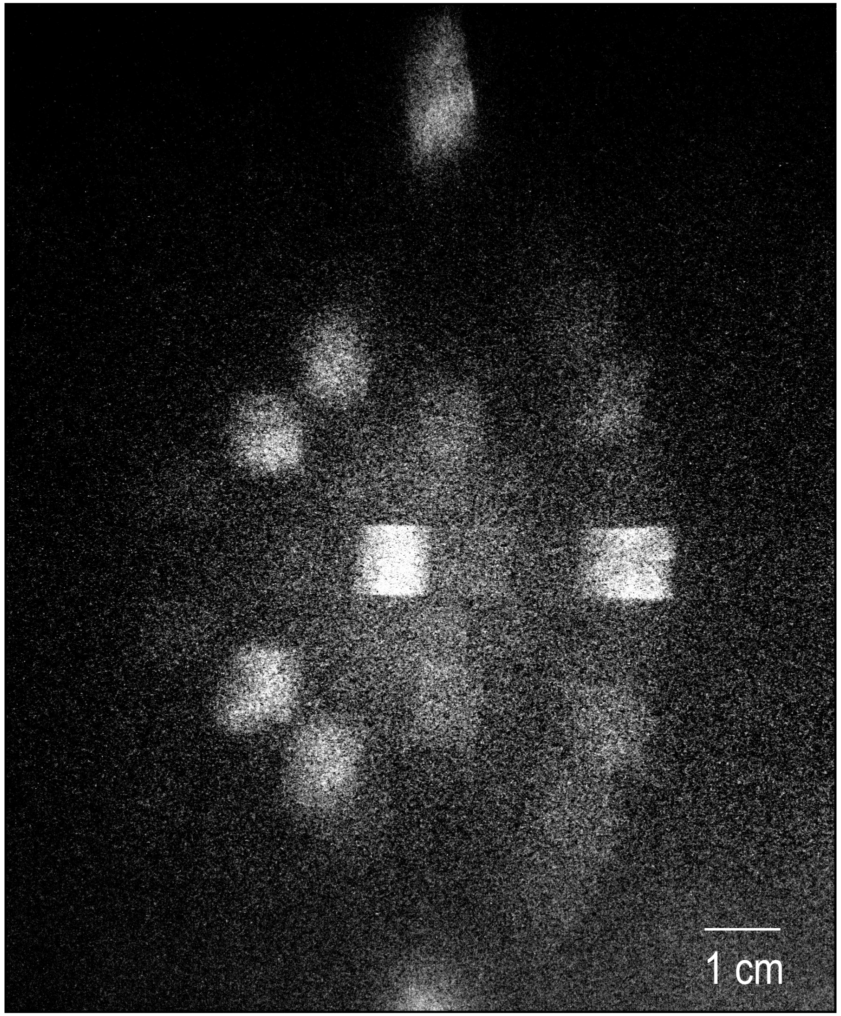

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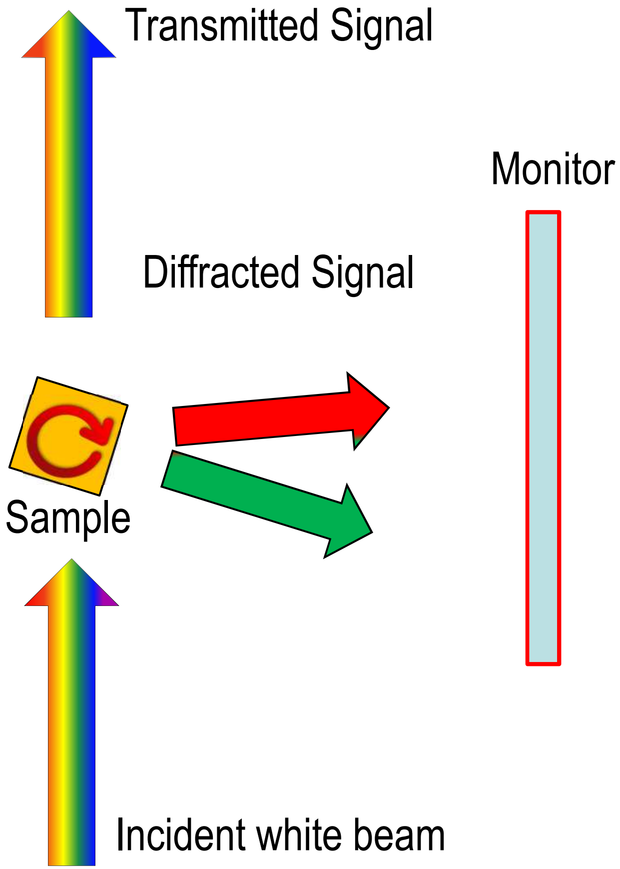

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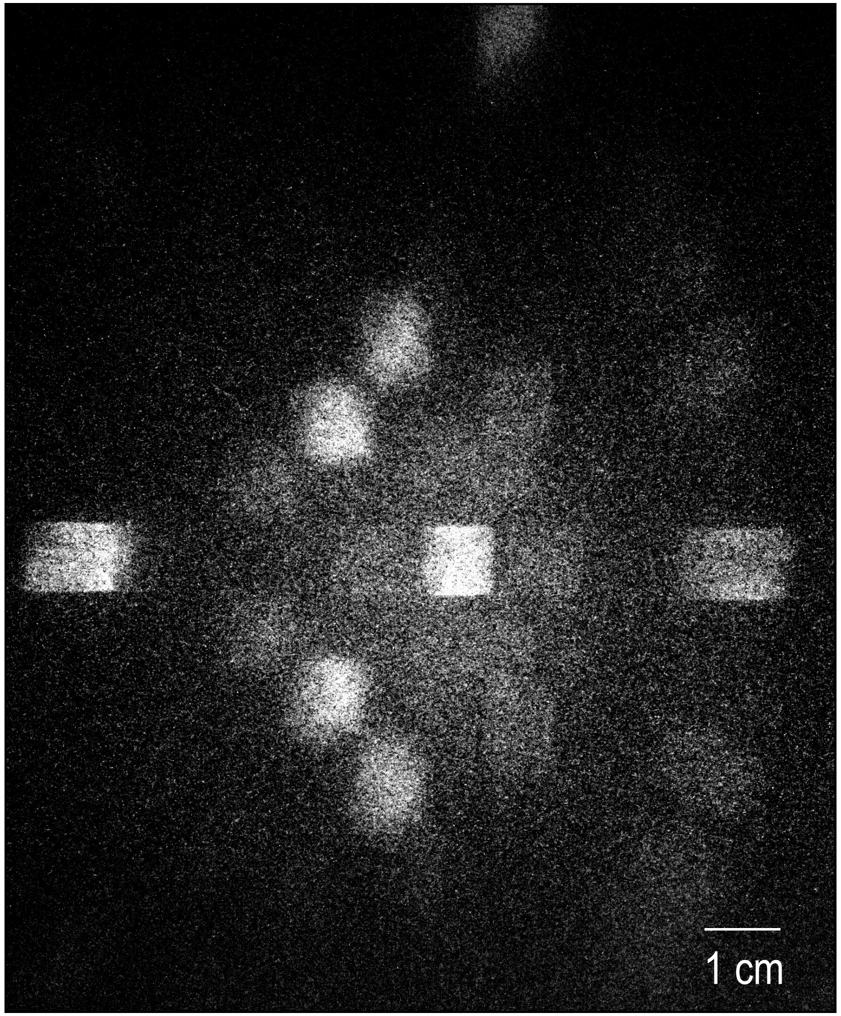

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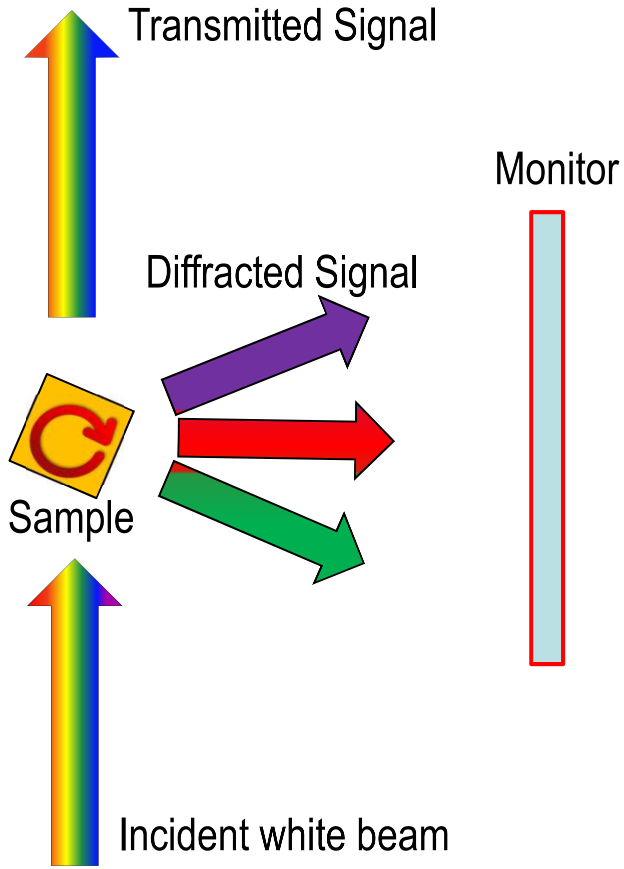

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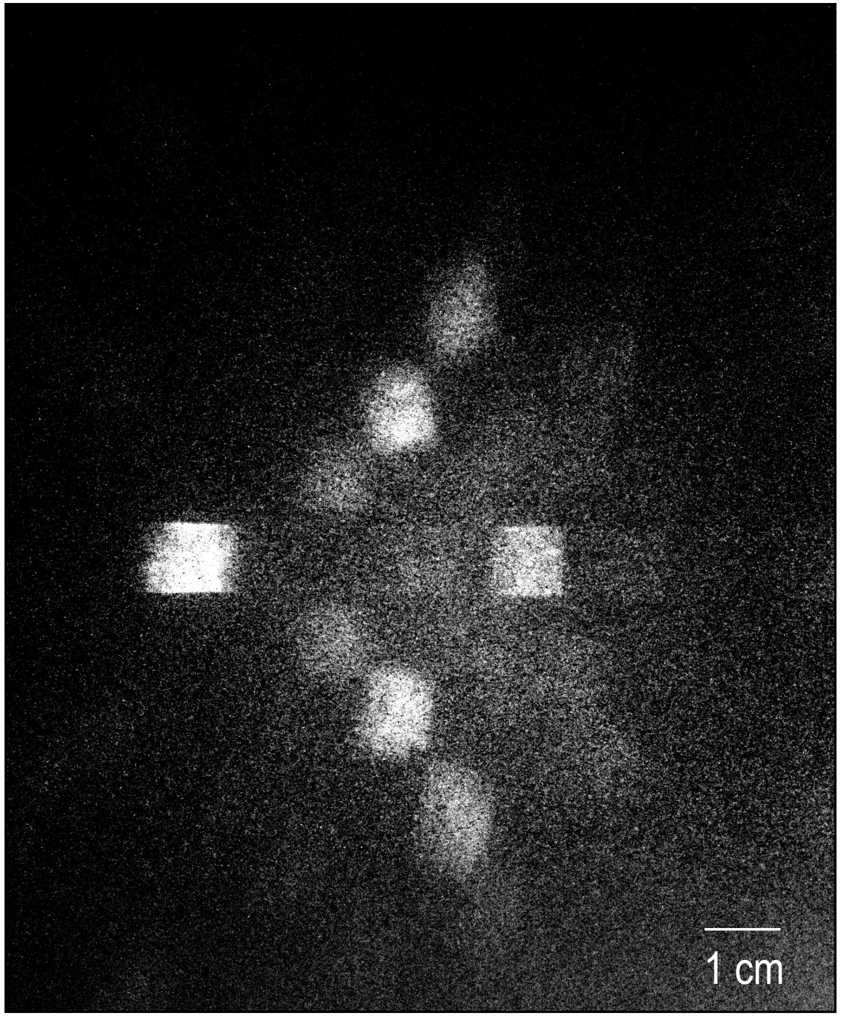

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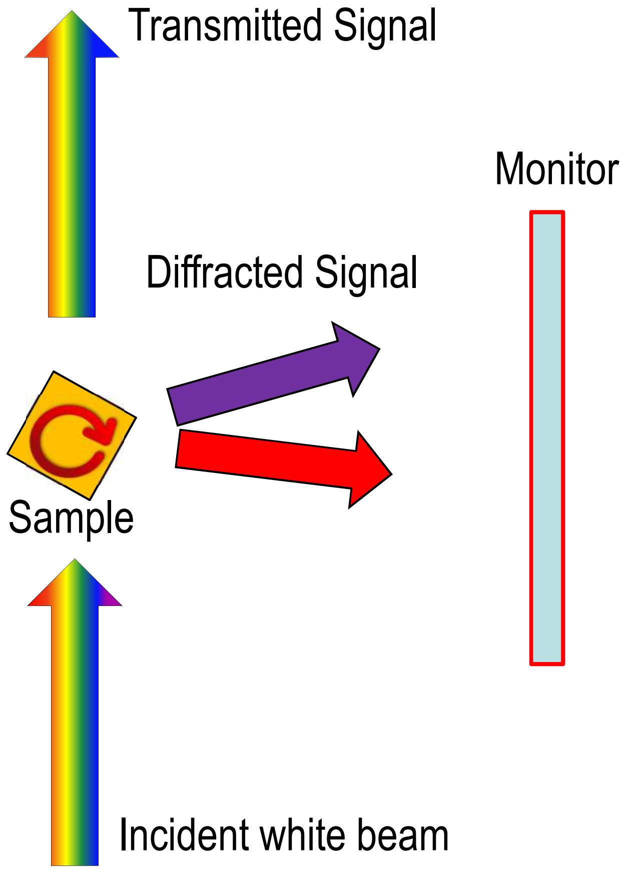

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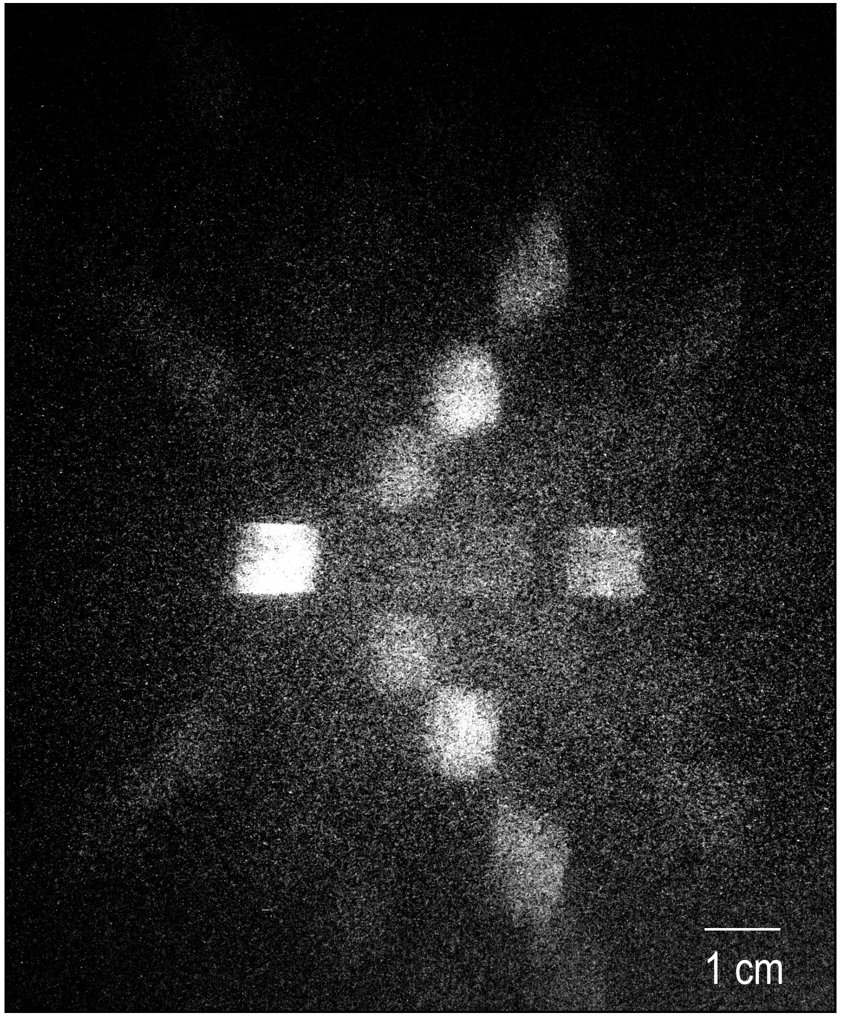

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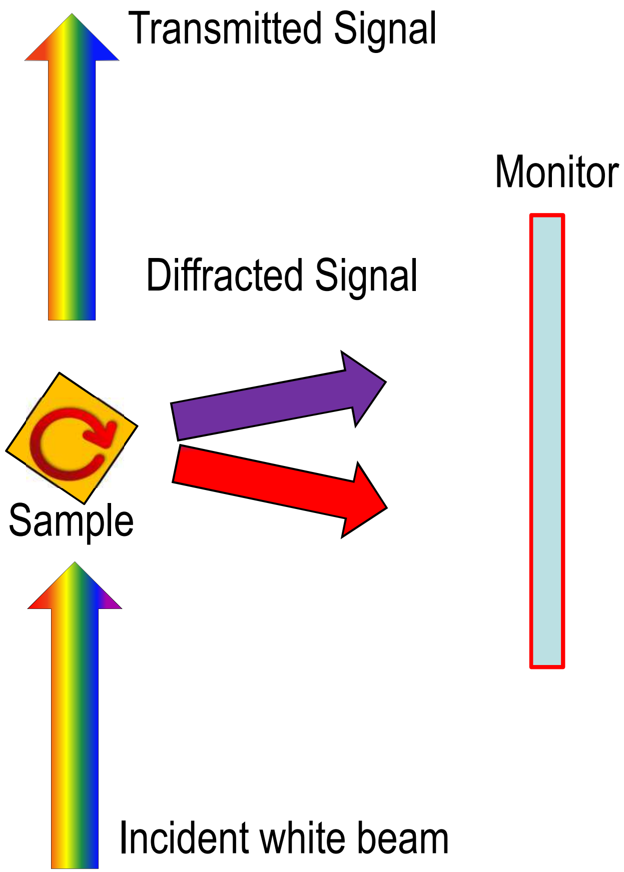

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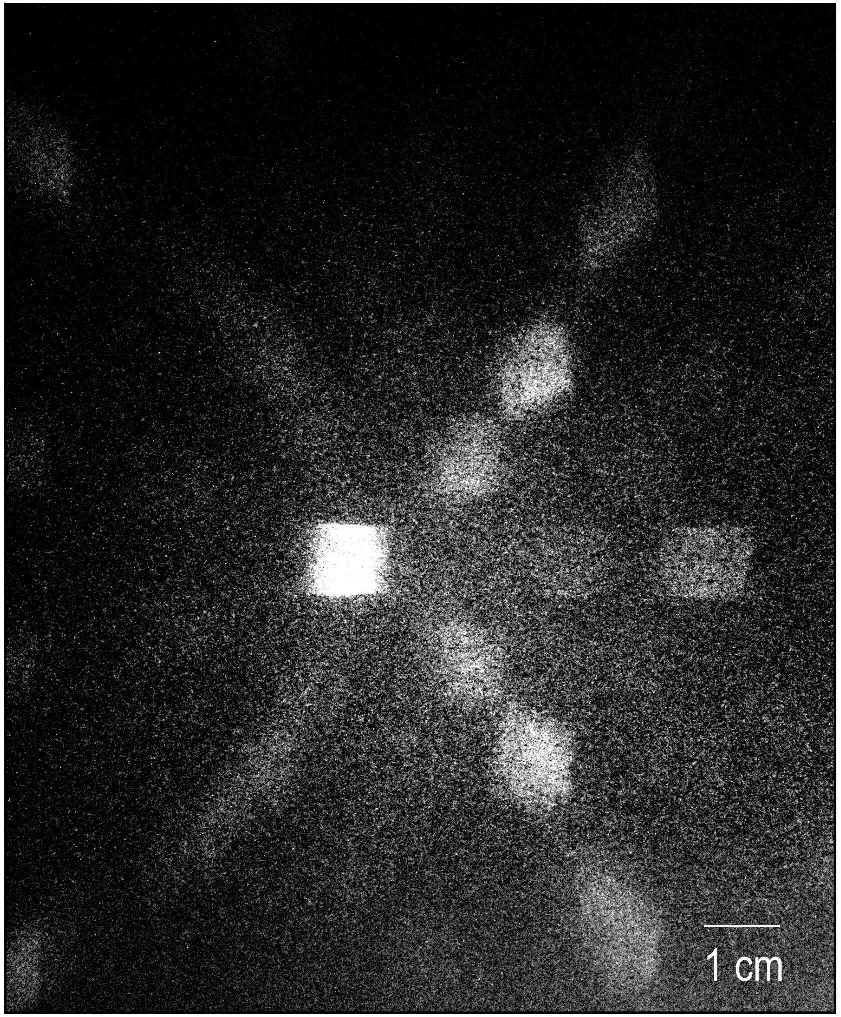

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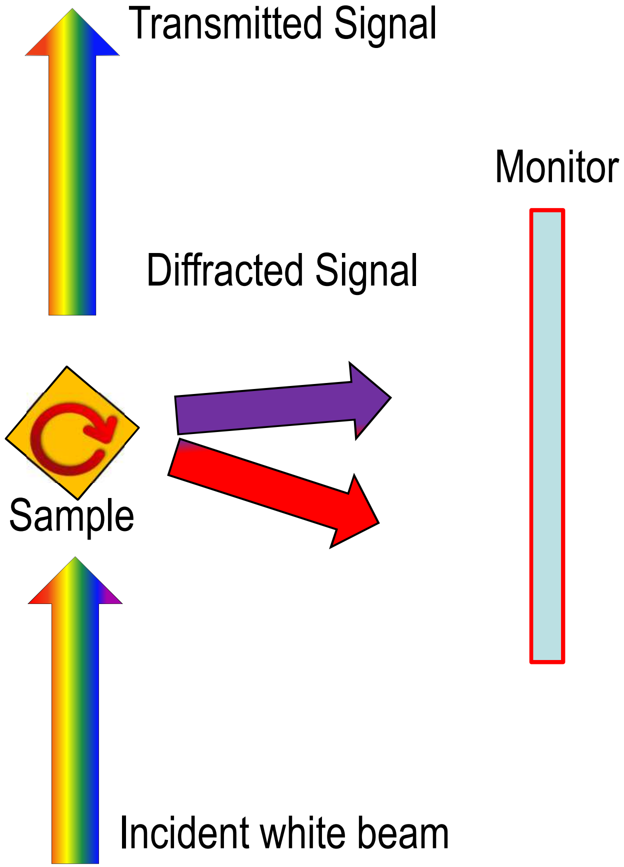

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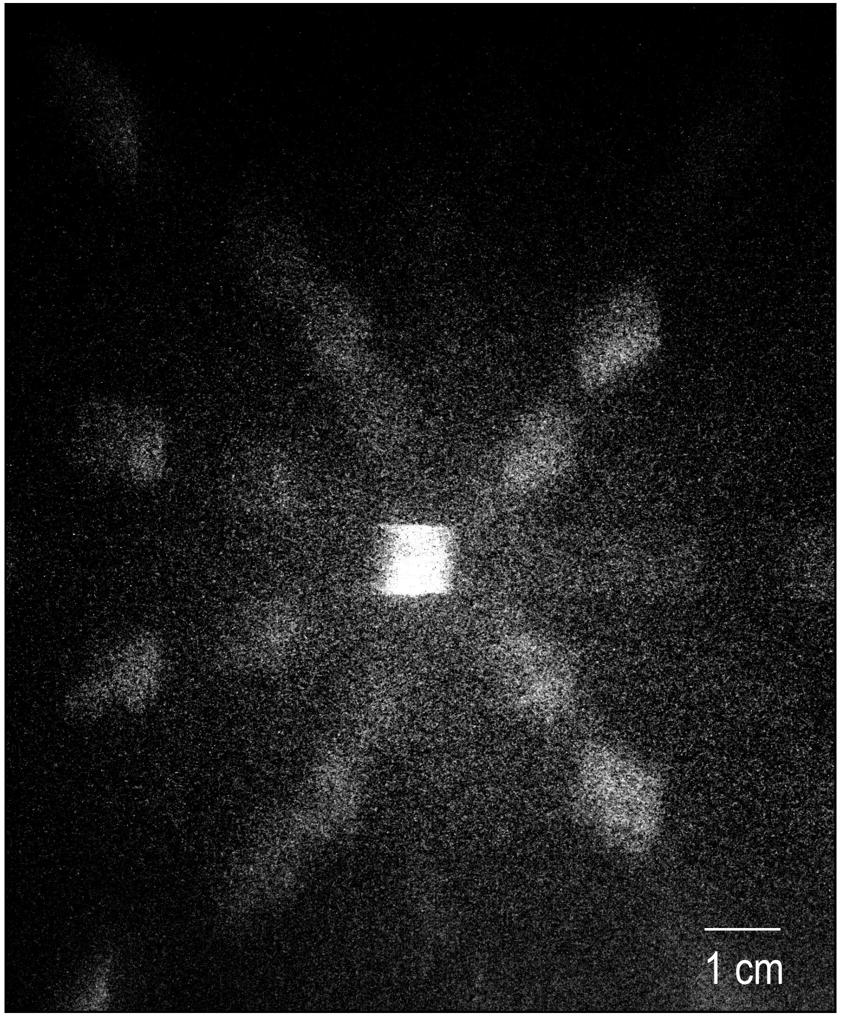

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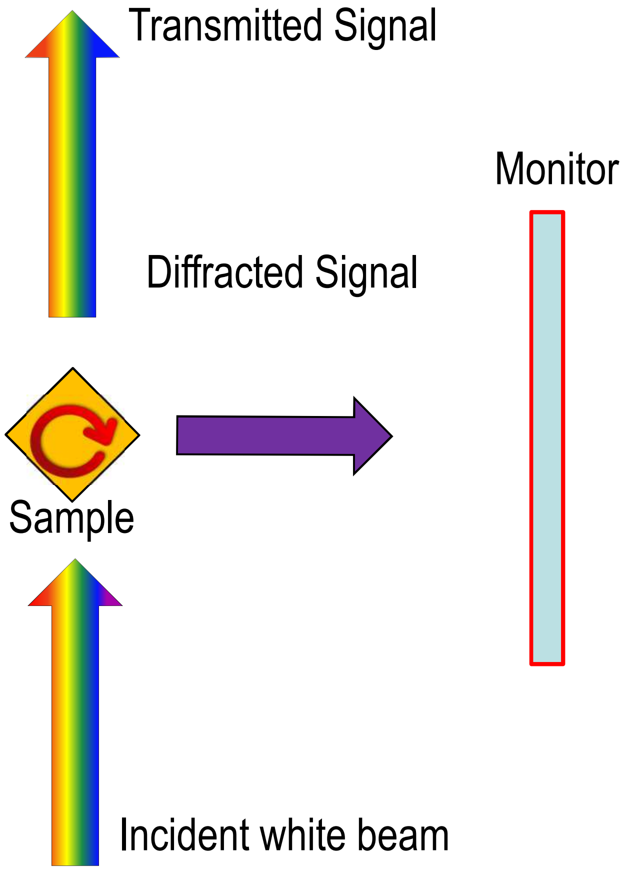

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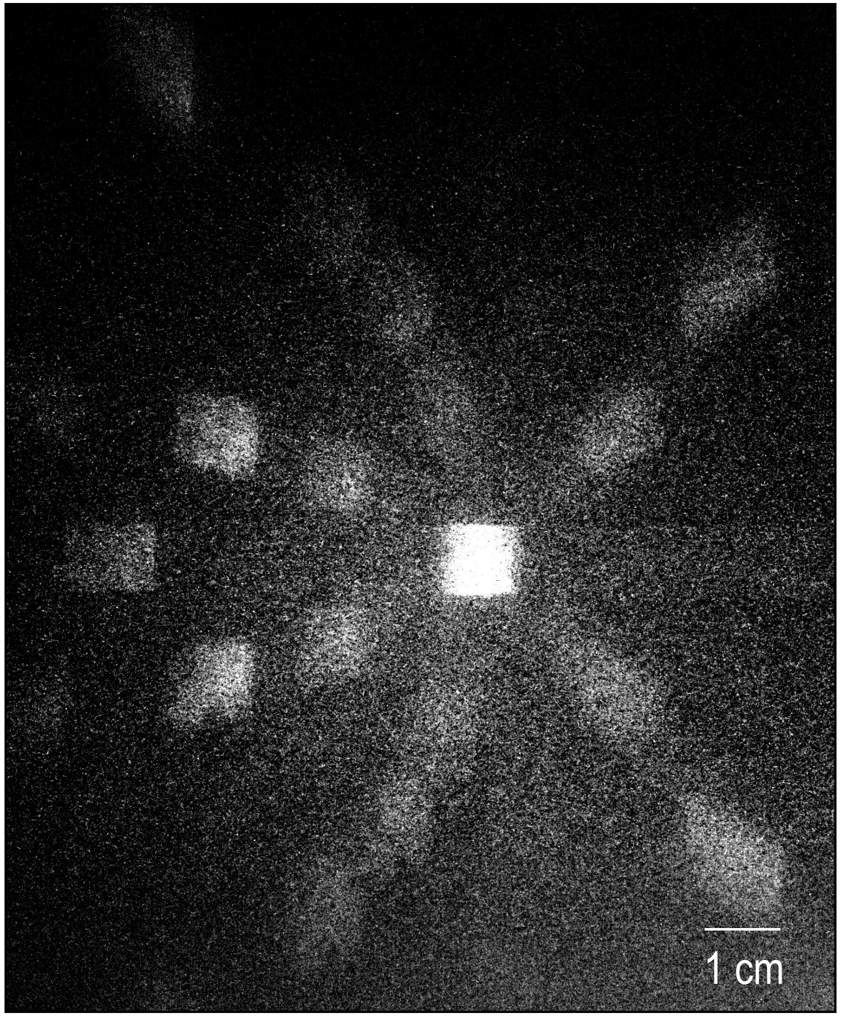

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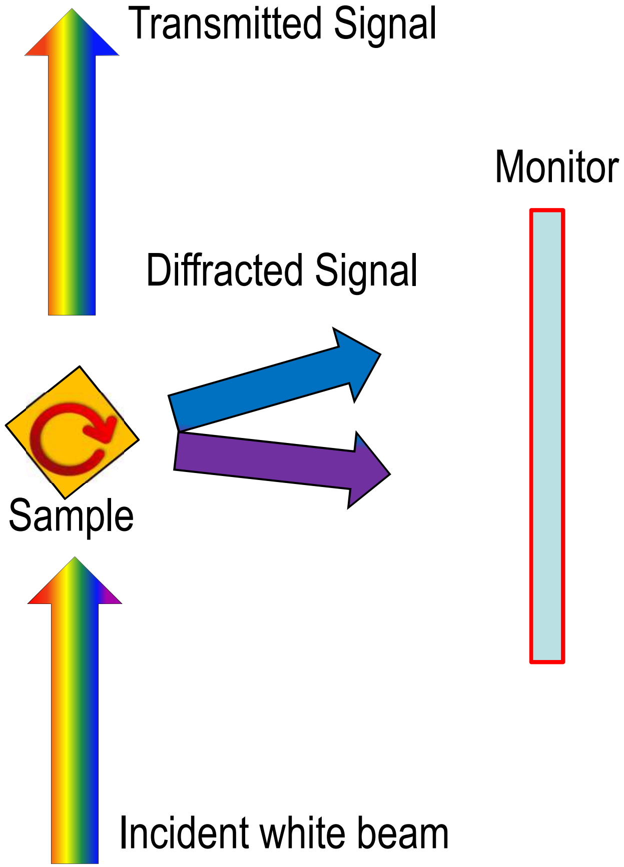

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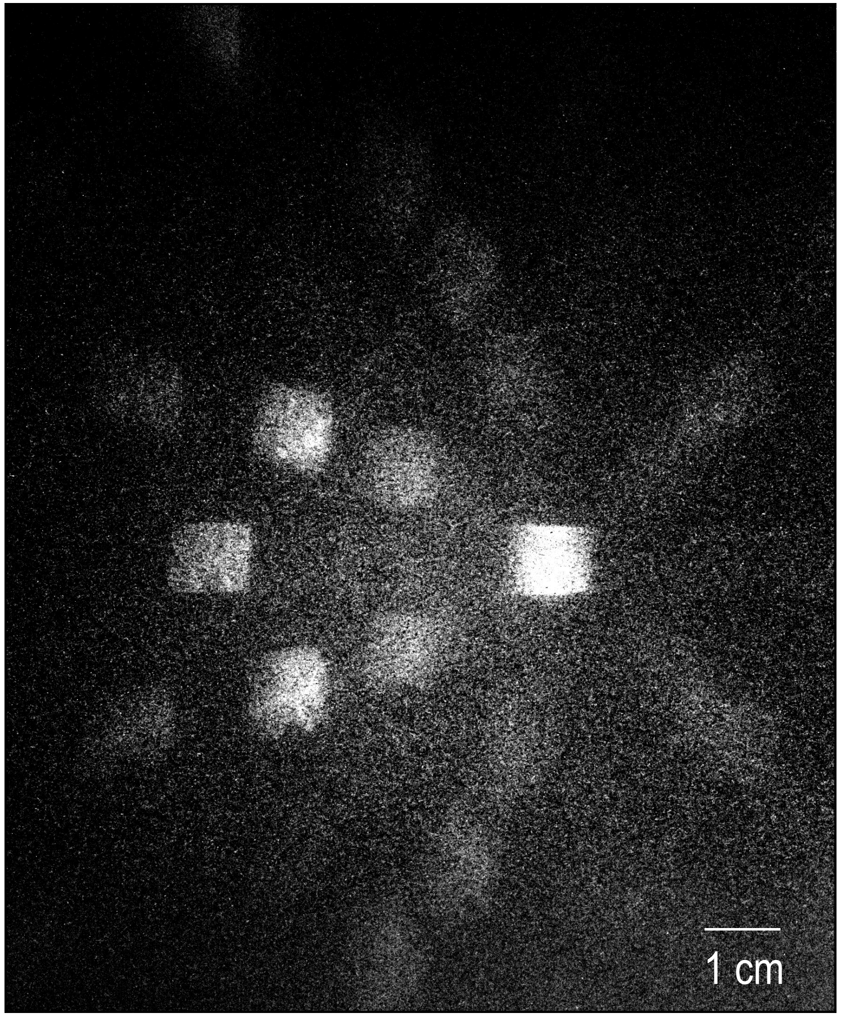

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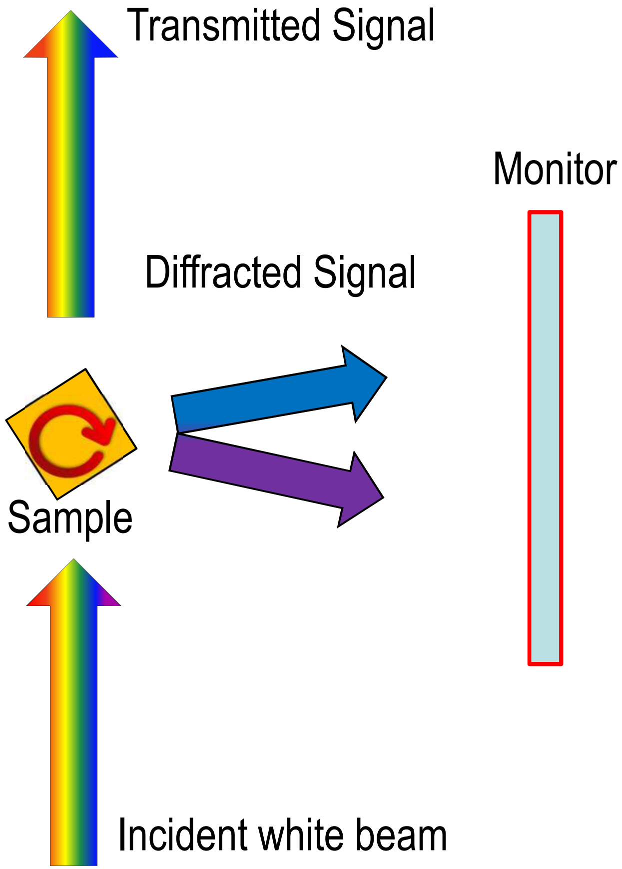

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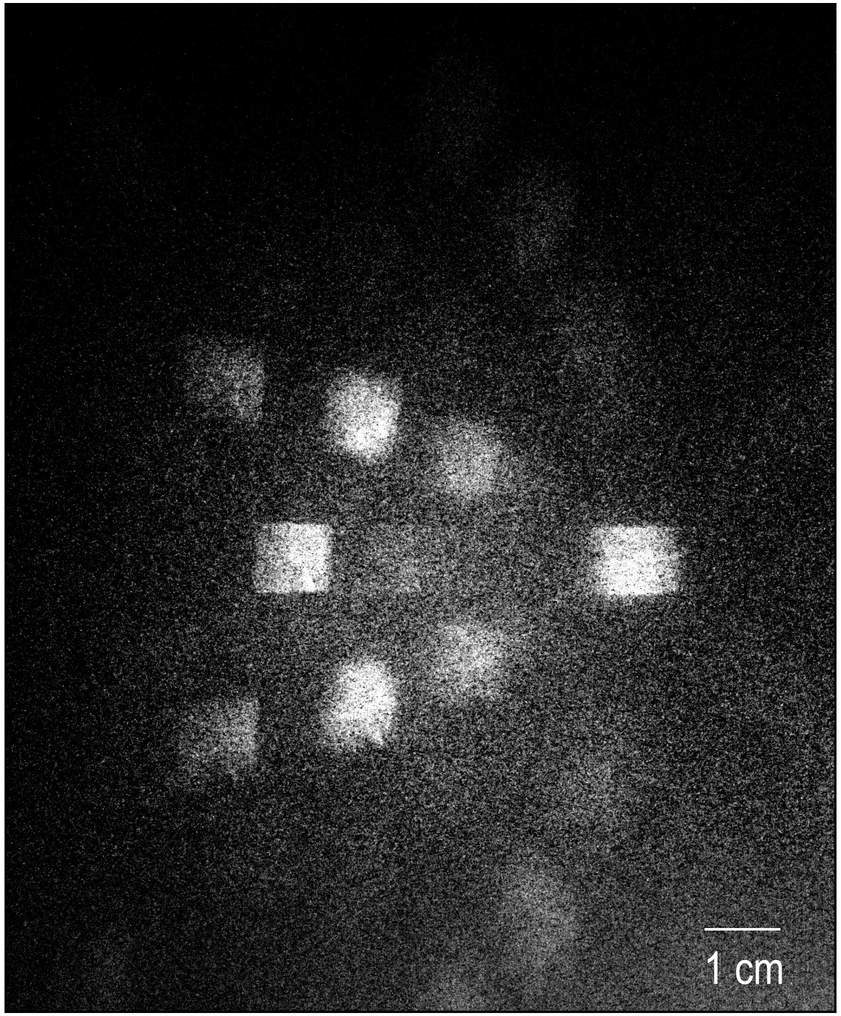

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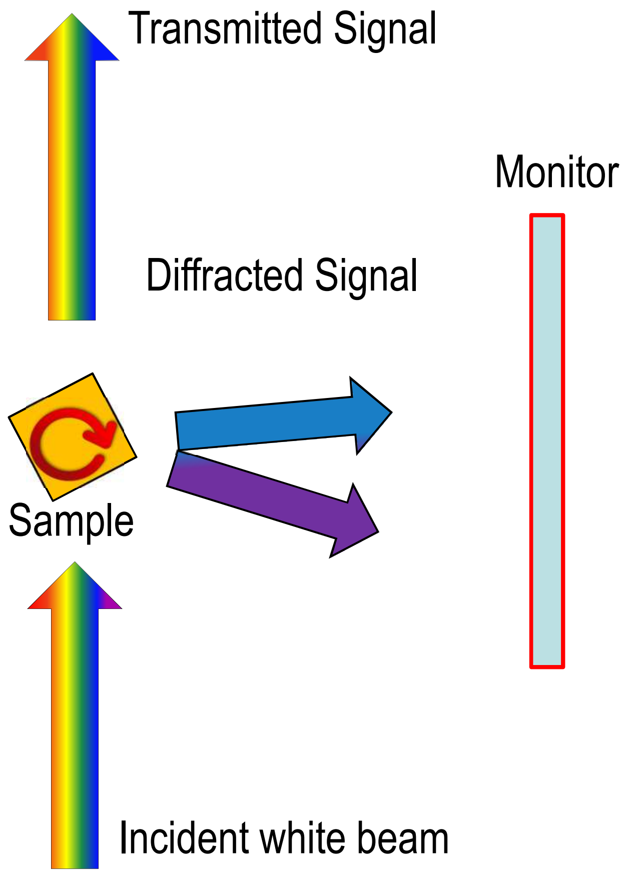

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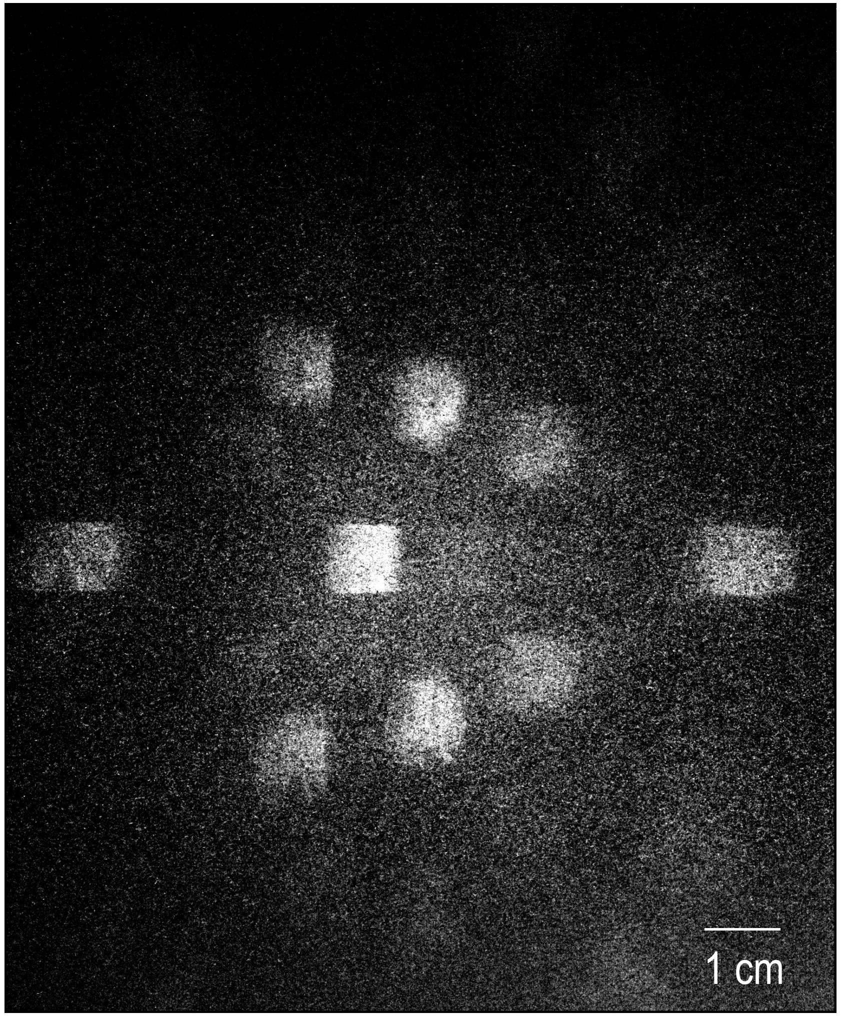

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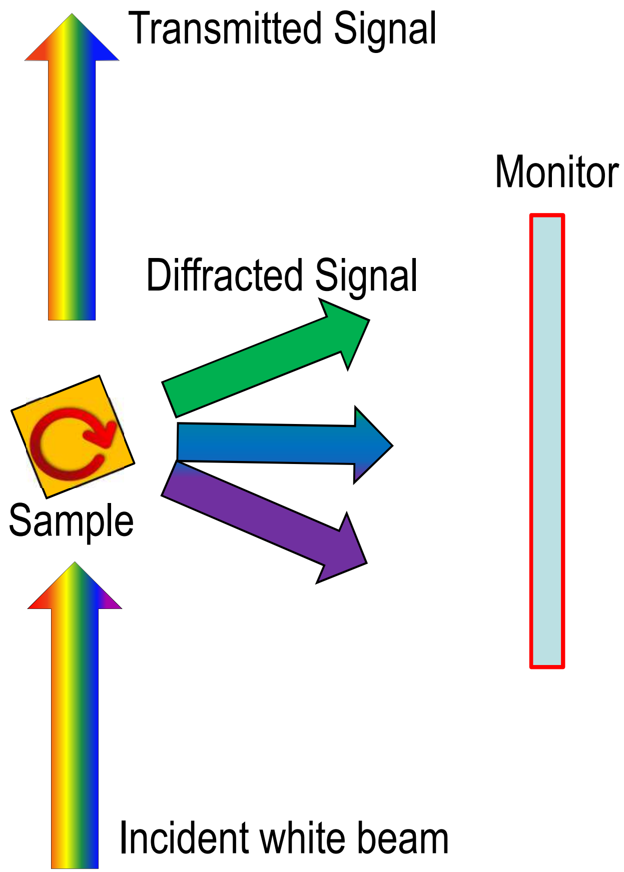

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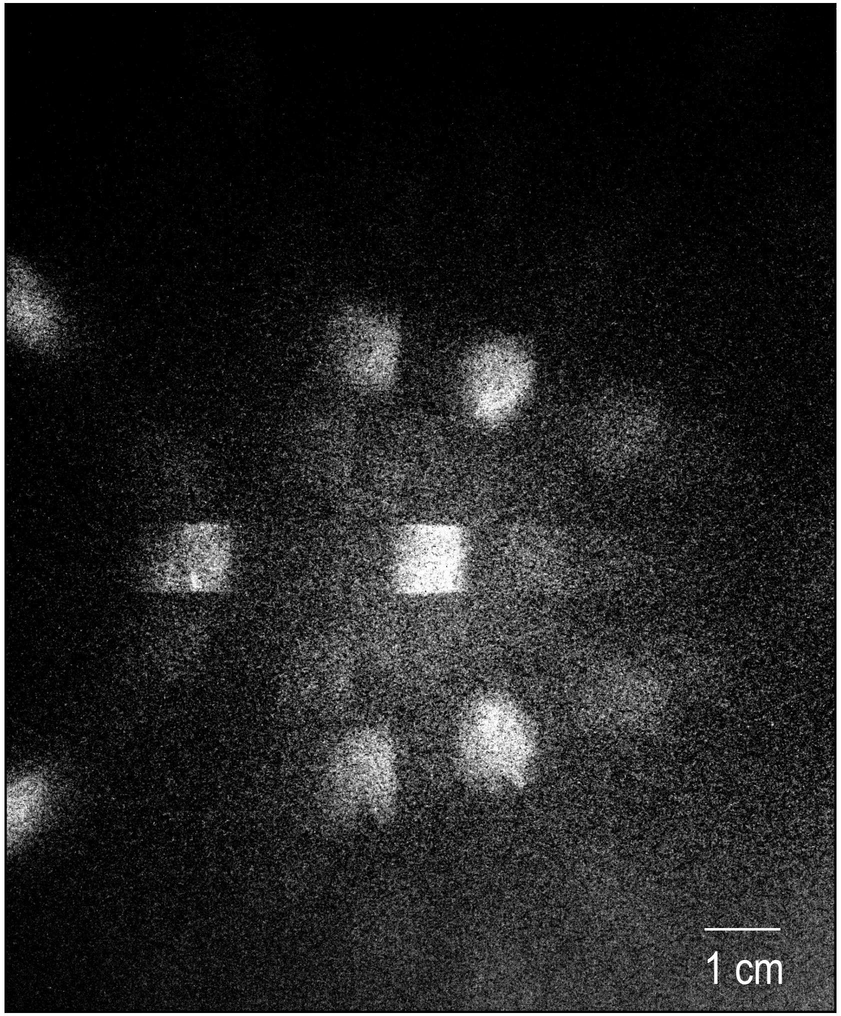
INTRODUCTION – Example: Pyrite single crystal



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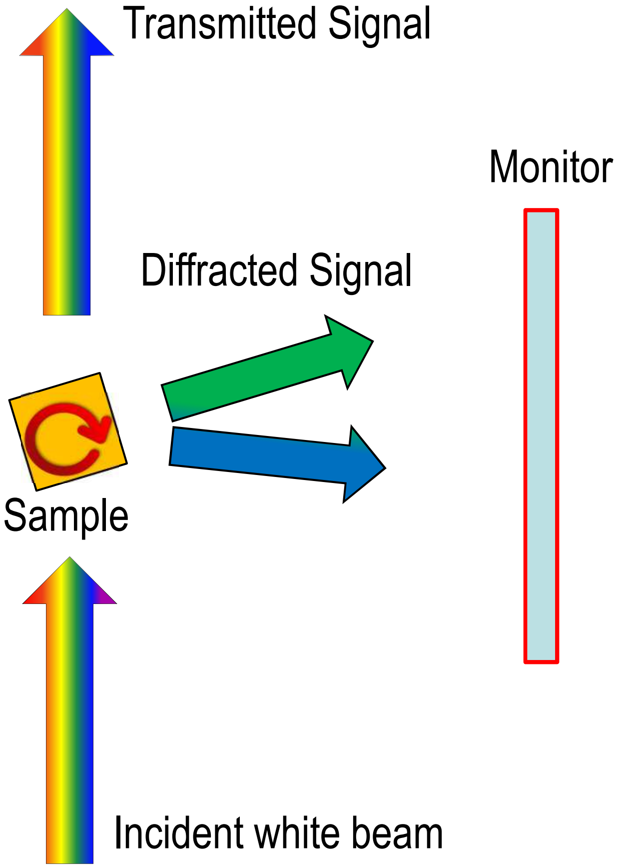

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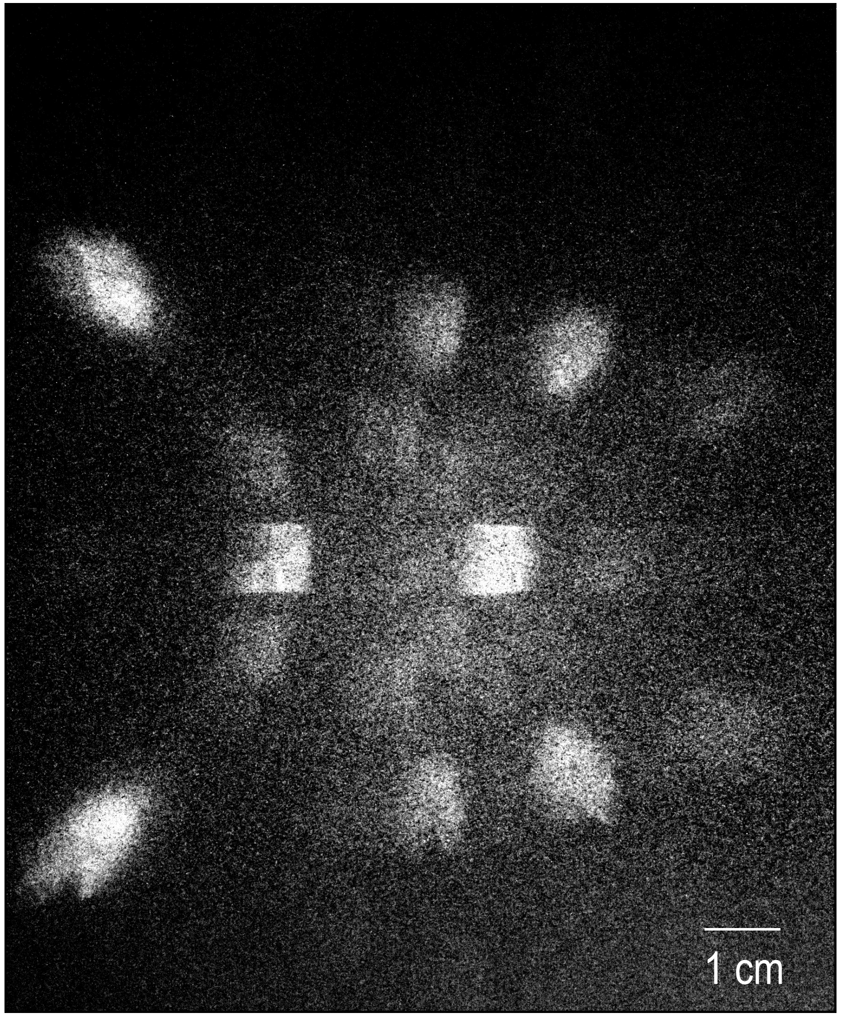

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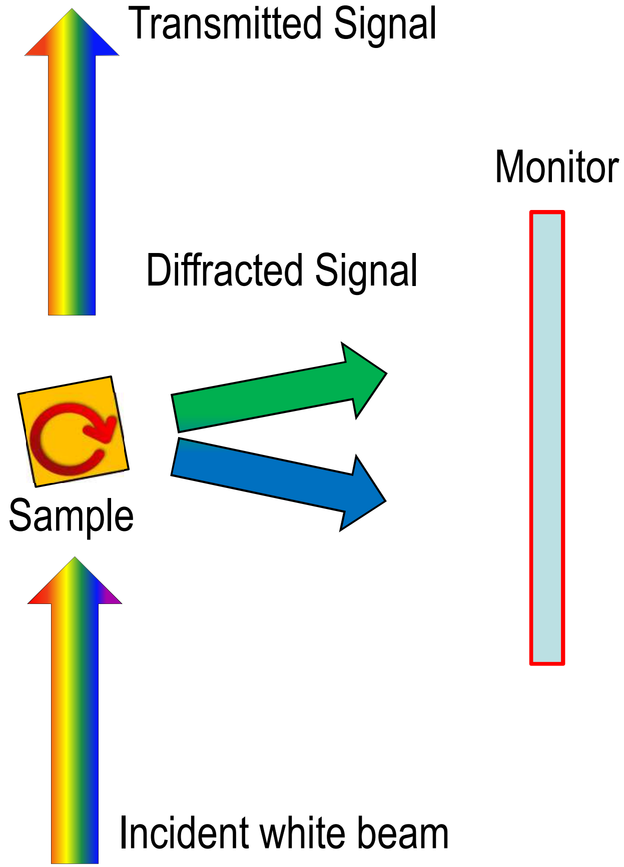

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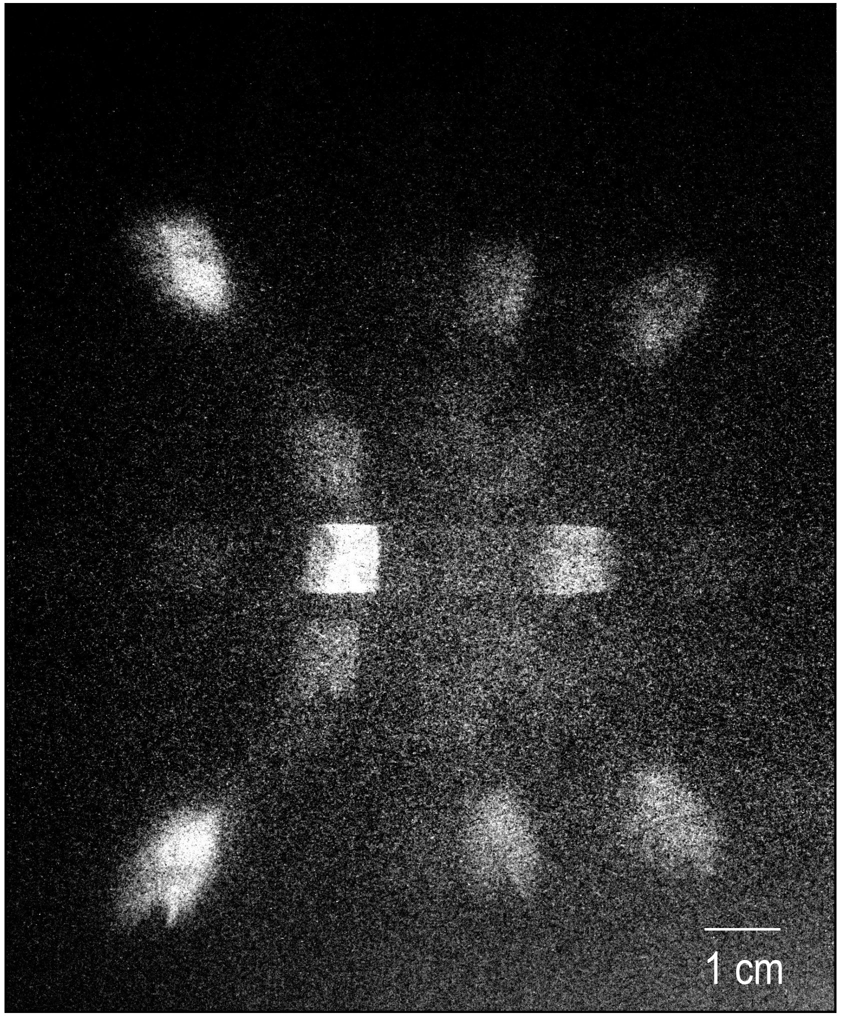

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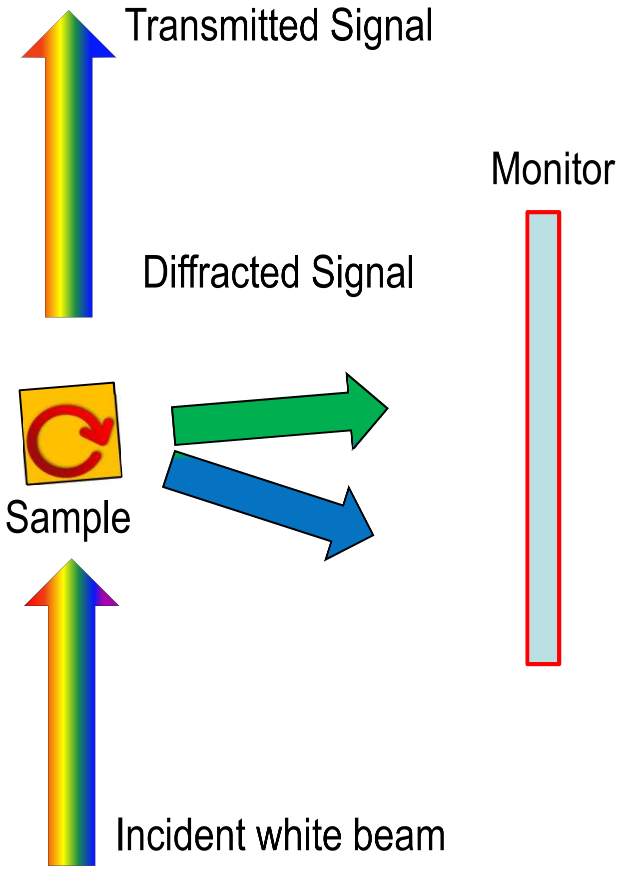

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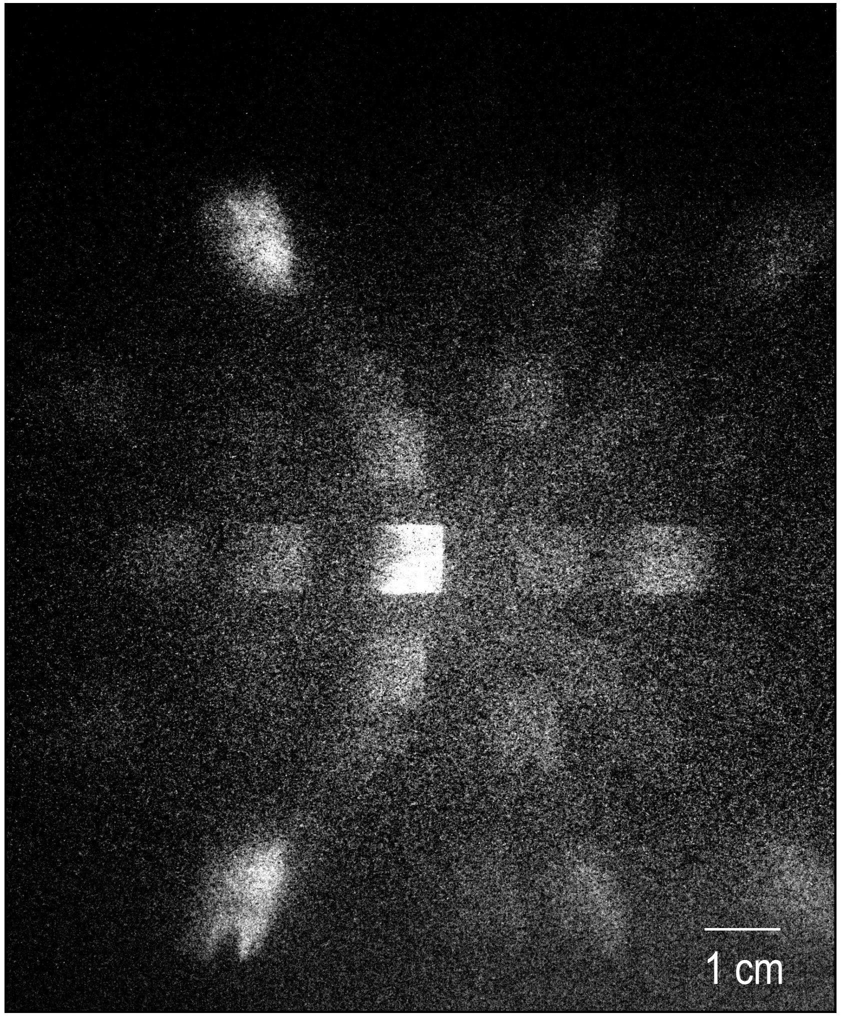

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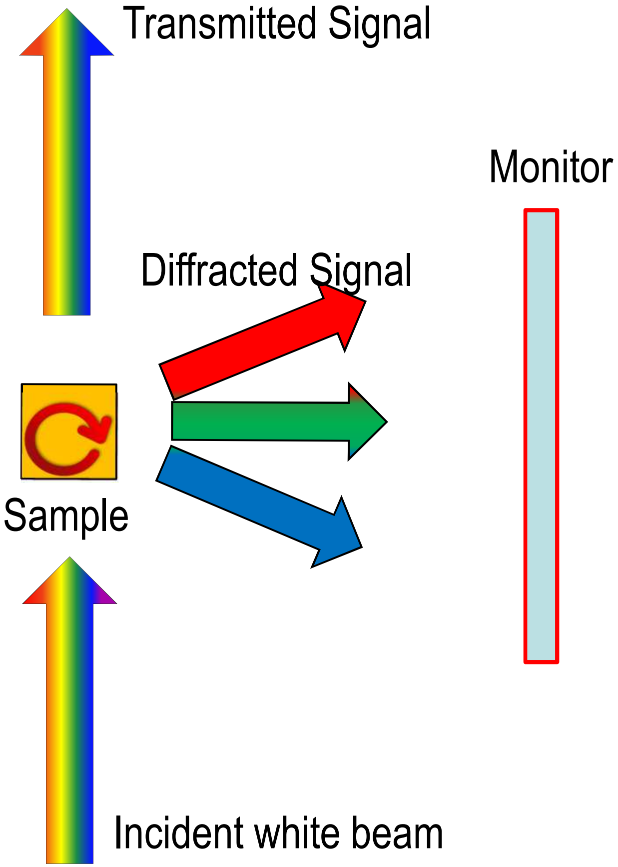

INTRODUCTION – Scope of the technique

- Study of crystal orientation and crystalline properties of **bulky samples**

- Applicable to single crystals and coarse polycrystals

- Privileged position of neutrons thanks to their wavelength

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2. **Neutron interactions**
3. Bragg edge scattering
4. Energy selection
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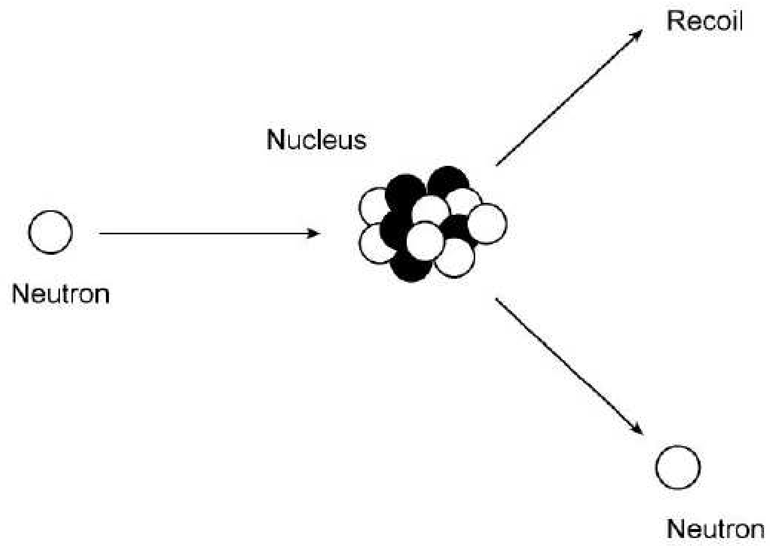
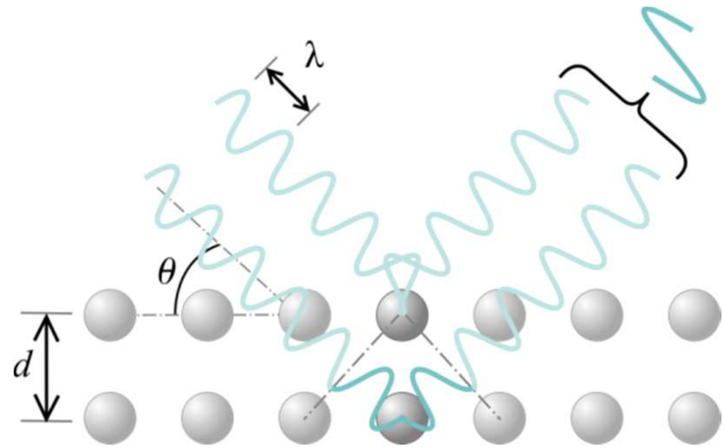
NEUTRON INTERACTIONS – Nuclear or crystalline

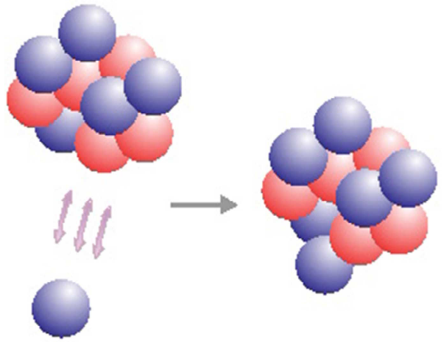


INCOHERENT SCATTERING

$$n\lambda = 2dSin\theta$$

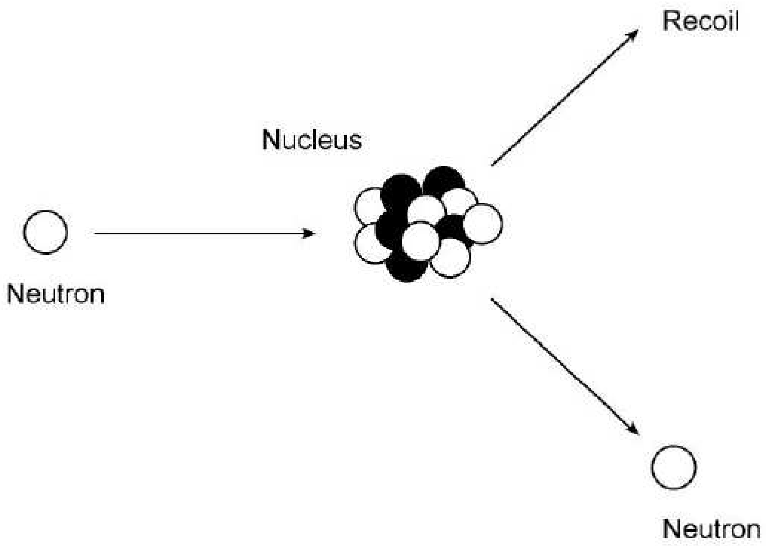


COHERENT SCATTERING



ABSORPTION

NEUTRON INTERACTIONS – Overview



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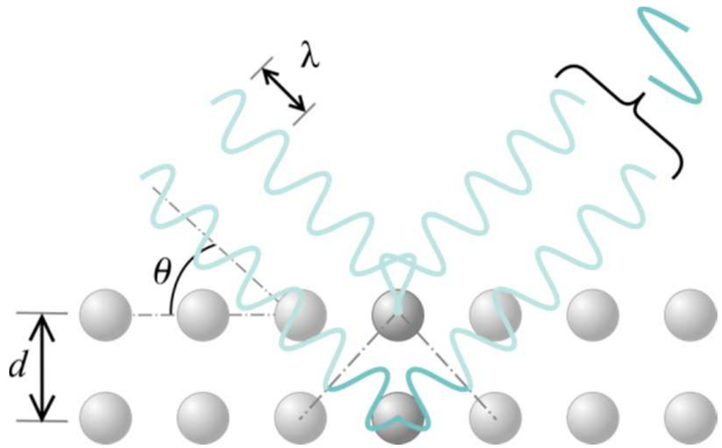

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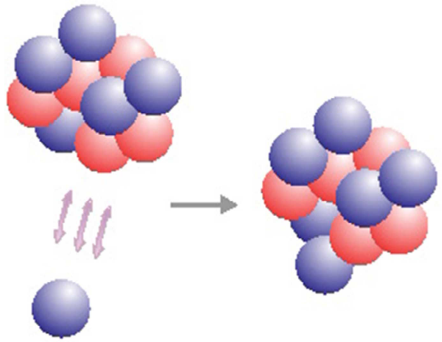
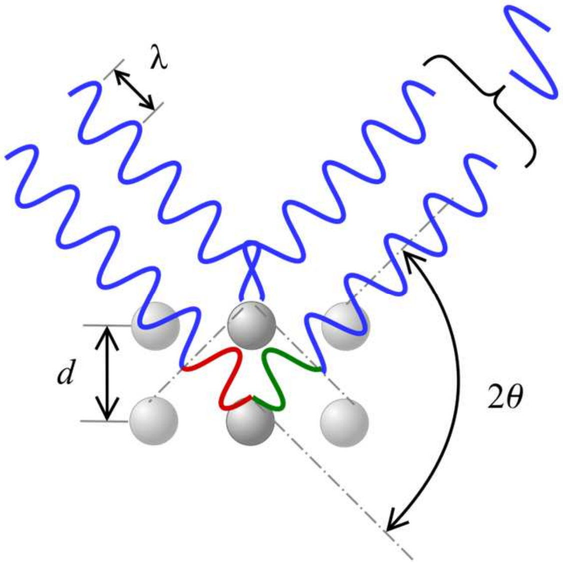


ABSORPTION

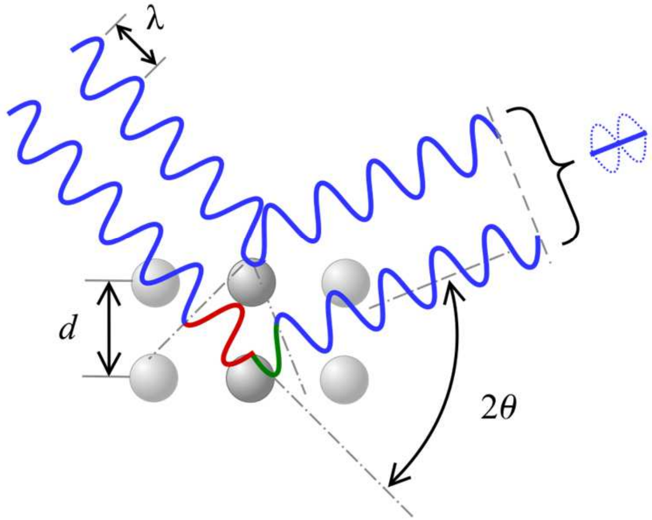
NEUTRON INTERACTIONS – Coherent scattering

CONSTRUCTIVE INTERFERENCE



$$n\lambda = 2dSin\theta$$

DESTRUCTIVE INTERFERENCE



$$n\lambda \cancel{=} 2dSin\theta$$

NEUTRON INTERACTIONS – Coherent scattering

And what can we know from this? $n\lambda = 2dSin\theta$

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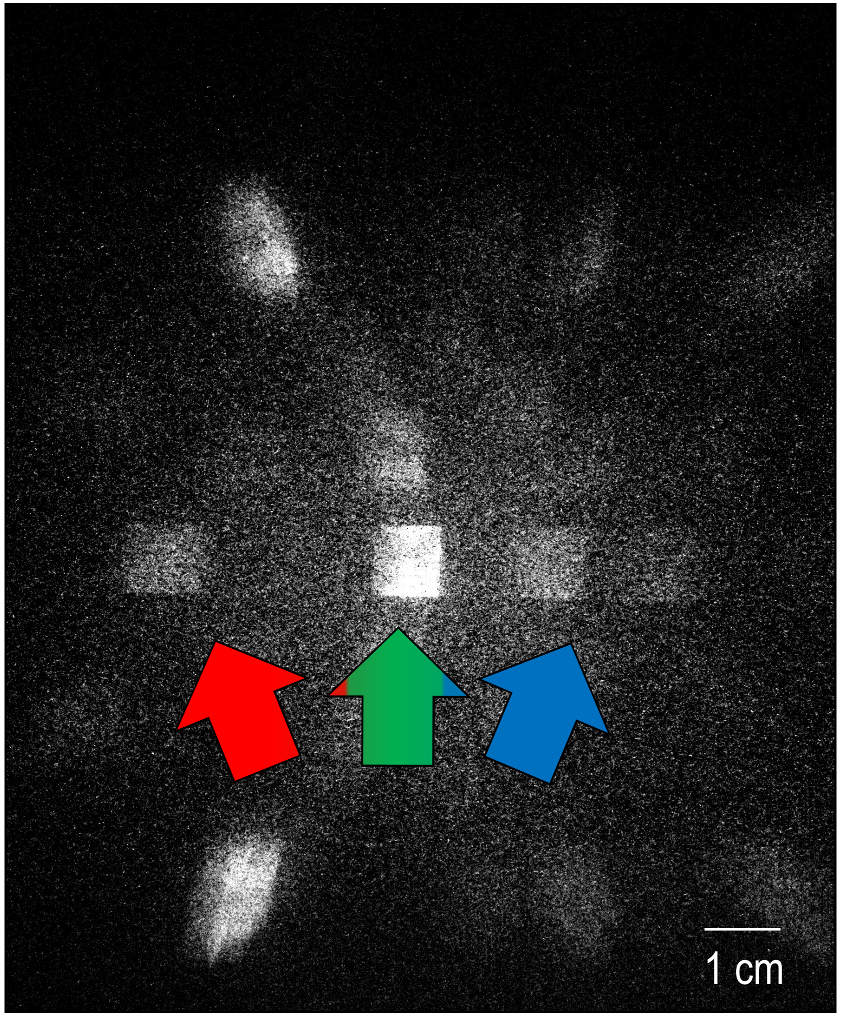

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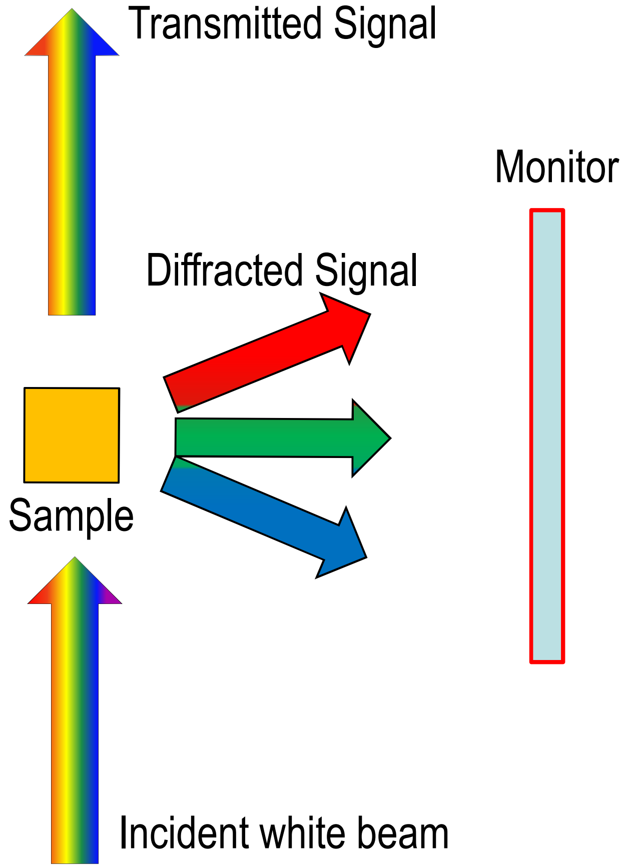

NEUTRON INTERACTIONS – Coherent scattering

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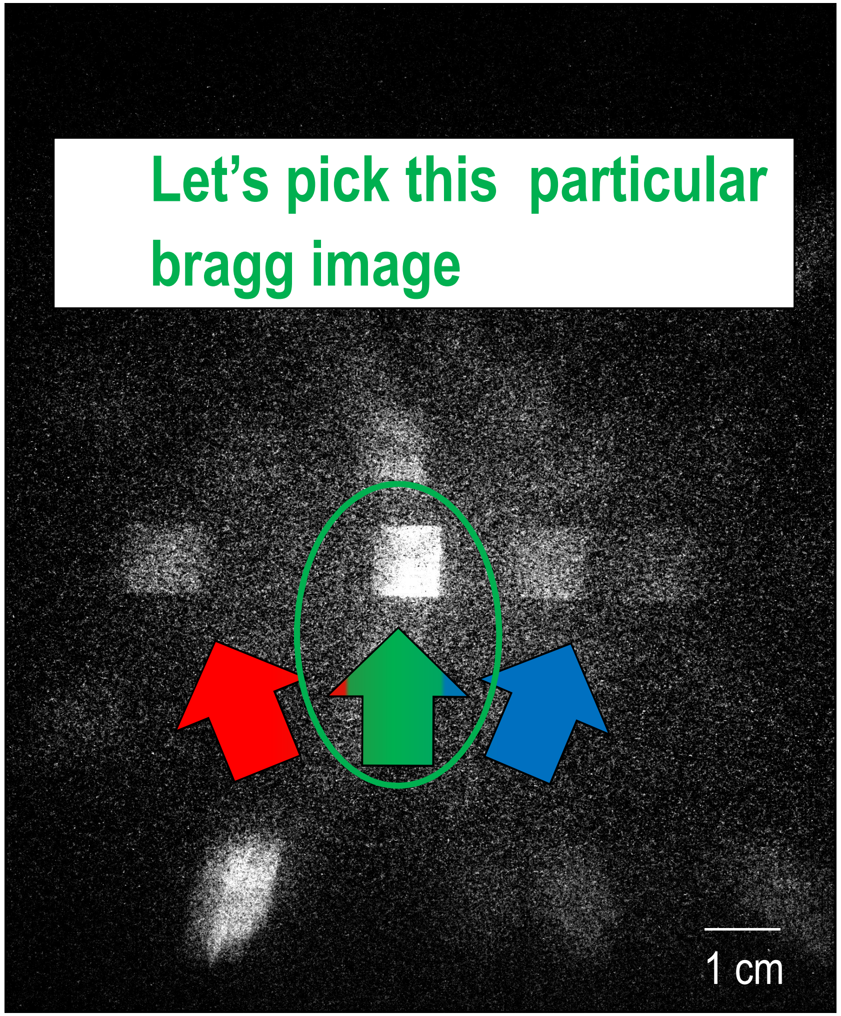

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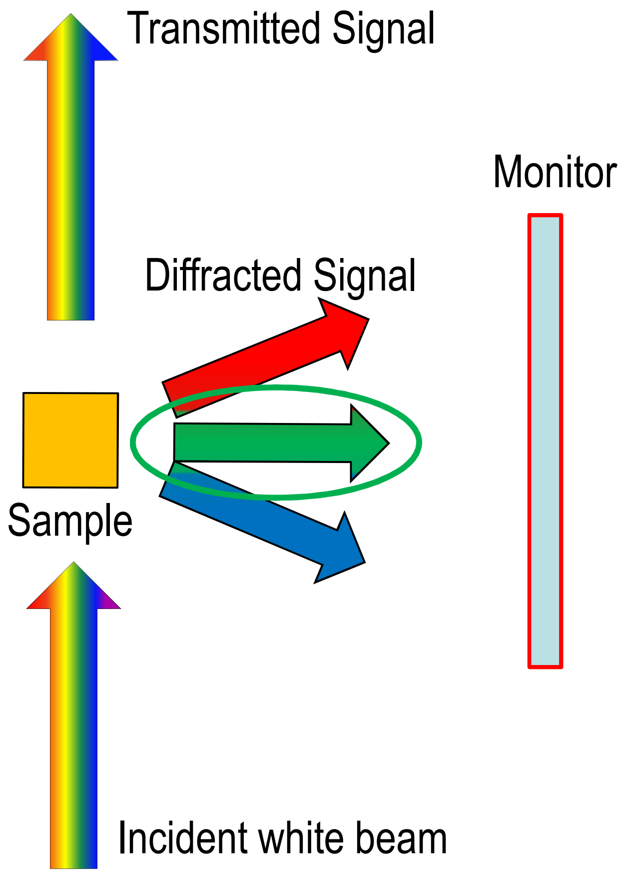

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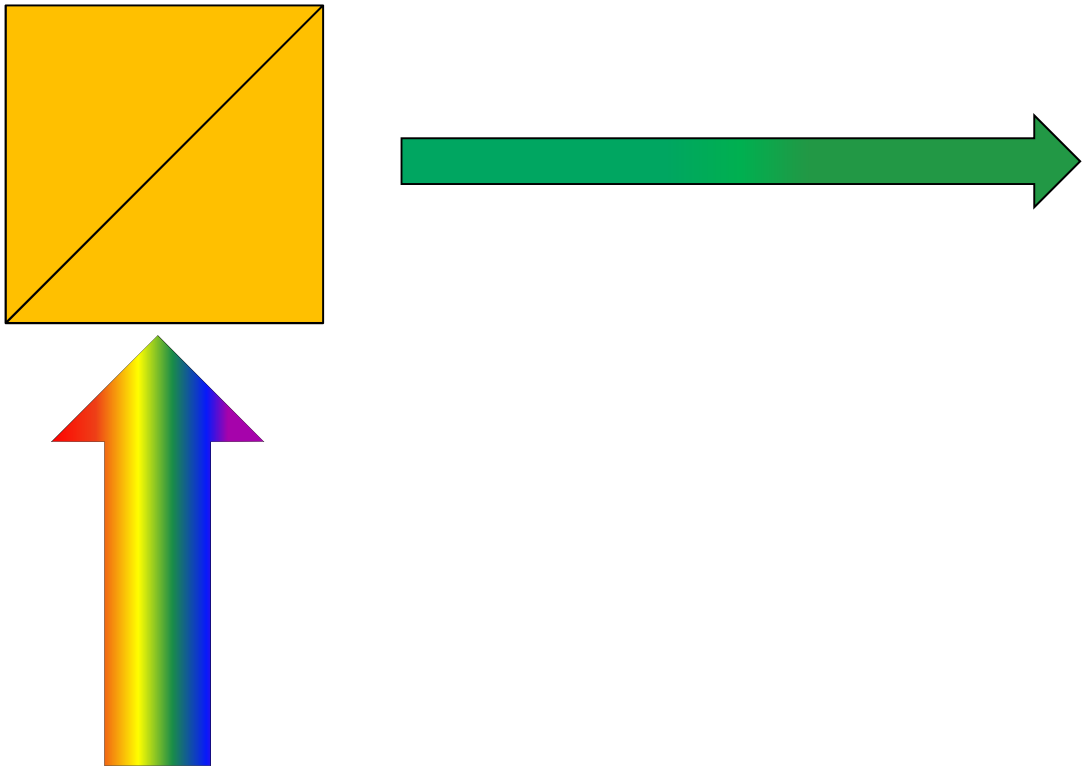
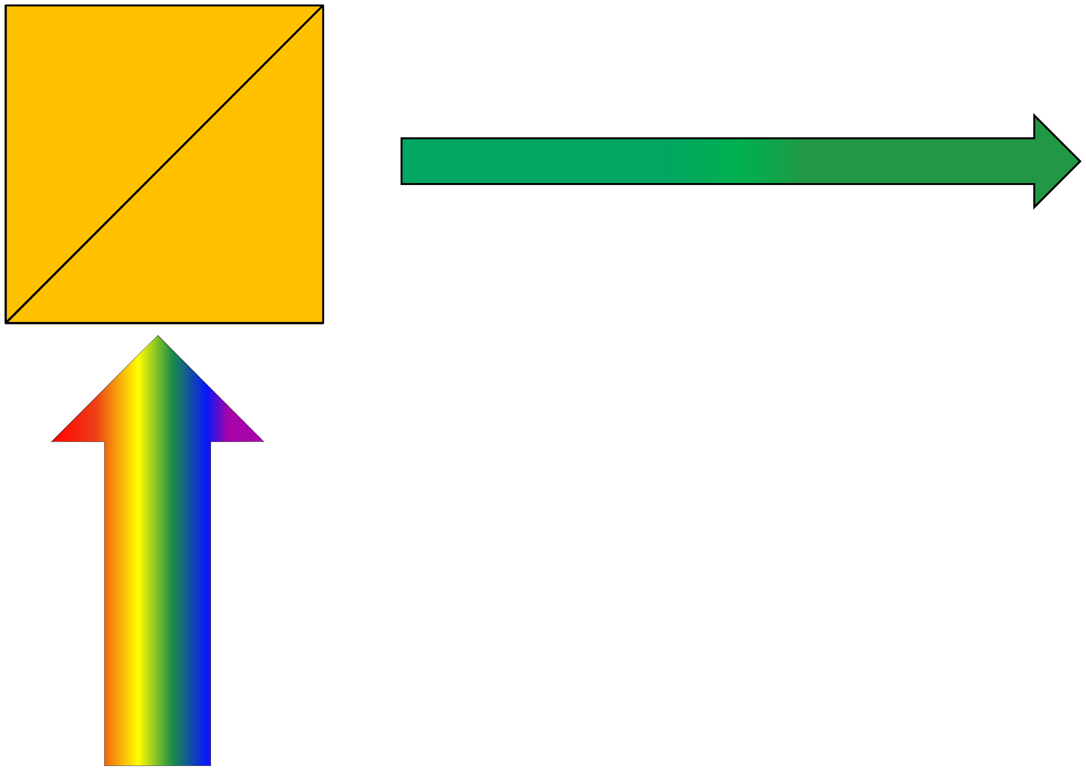


NEUTRON INTERACTIONS – Coherent scattering

And what can we know from this? $n\lambda = 2dSin\theta$

Interplanar distance of [1 1 0] plane for pyrite? → 3.831 Å



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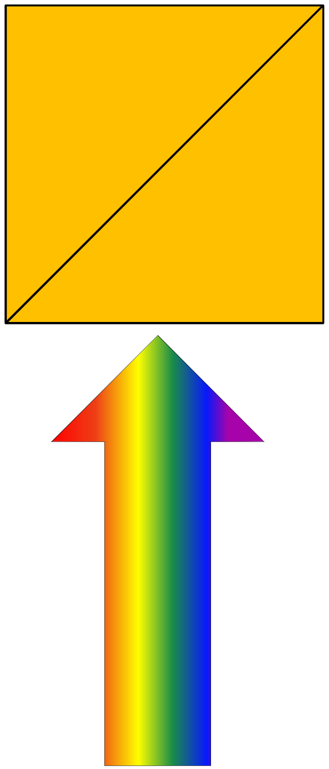

Neutron wavelengths selected:

$$\lambda = \frac{2 \cdot 3.831 \cdot Sin45}{n}$$

n	λ [Å]
1	5.418
2	2.709
3	1.806
4	1.354
5	1.083
…	…

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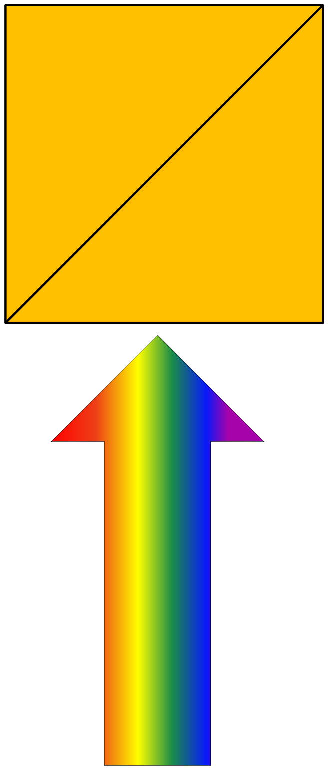

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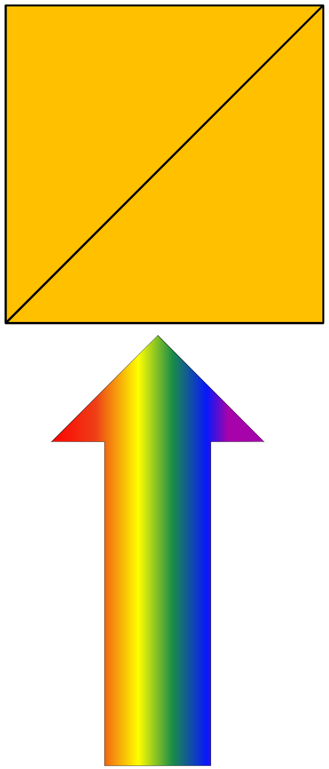
…	…

- Knowing crystal orientation and interplanar distances, energy can be known

NEUTRON INTERACTIONS – Coherent scattering

And what can we know from this? $n\lambda = 2dSin\theta$

Interplanar distance of [1 1 0] plane for pyrite? → 3.831 Å



Neutron wavelengths selected:

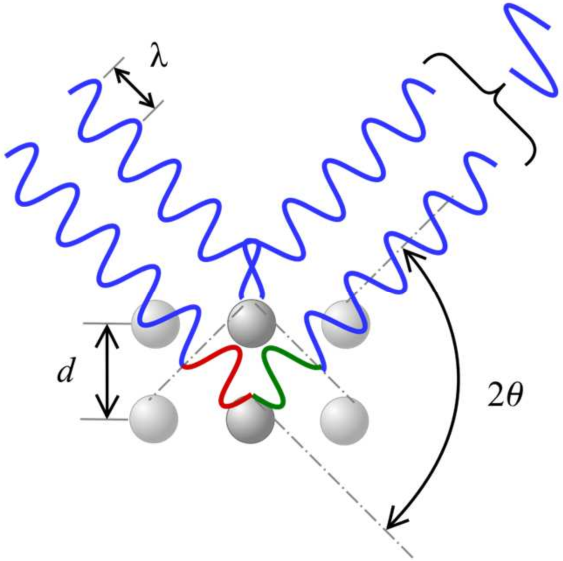
$$\lambda = \frac{2 \cdot 3.831 \cdot Sin45}{n}$$

n	λ [Å]
1	5.418
2	2.709
3	1.806
4	1.354
5	1.083
...	...

- Knowing crystal orientation and interplanar distances, energy can be known
- **Knowing energy and interplanar distances, crystal orientation can be known**

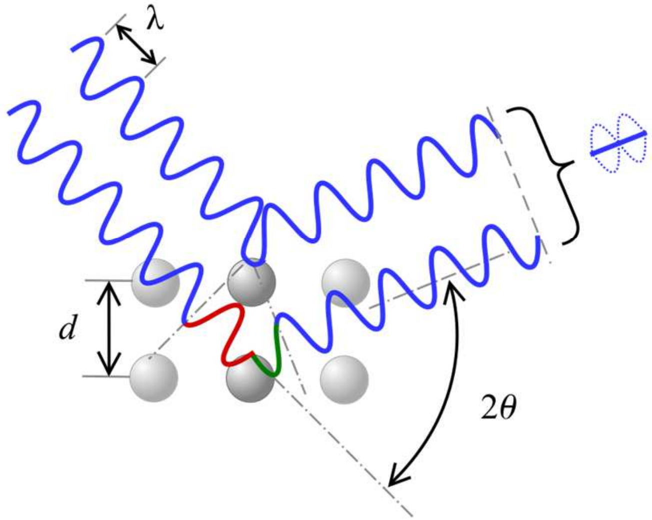
NEUTRON INTERACTIONS – Coherent scattering

CONSTRUCTIVE INTERFERENCE



$$n\lambda = 2dSin\theta$$

DESTRUCTIVE INTERFERENCE



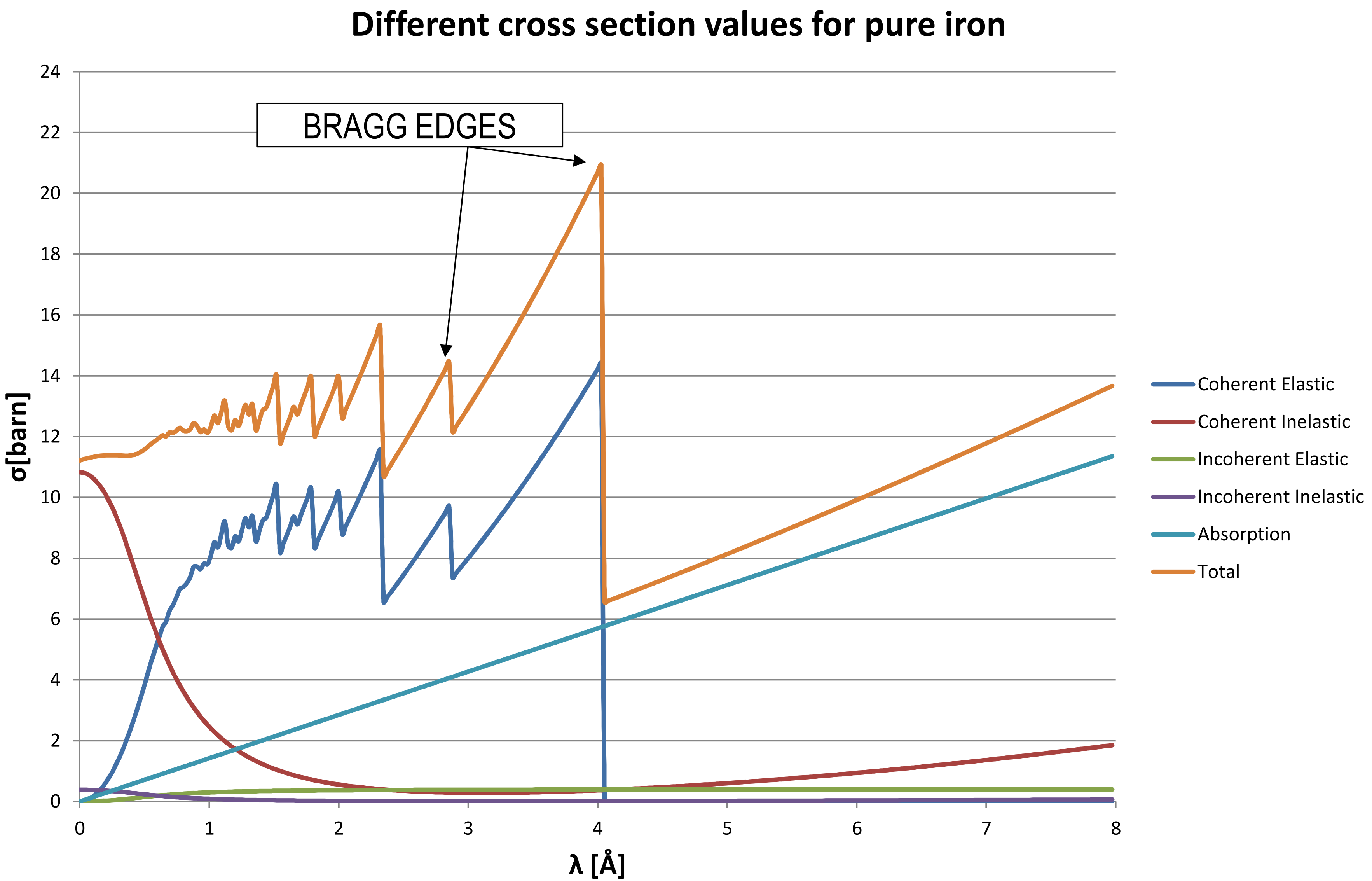
$$n\lambda \cancel{=} 2dSin\theta$$

When the neutrons satisfy the bragg condition for a certain interplanar distance, there is a local maximum in the coherent scattering cross section (**Bragg edge).**

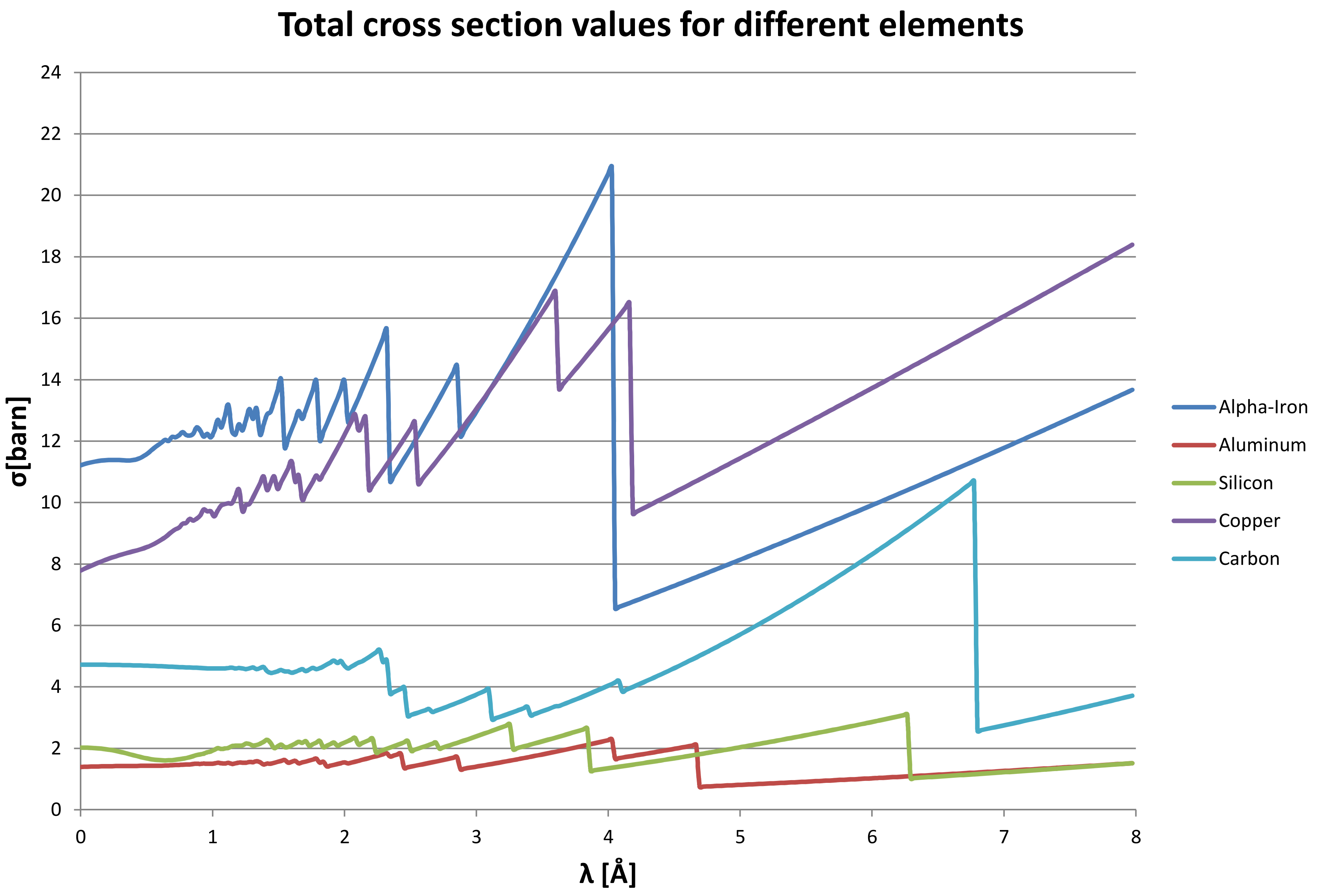
OUTLINE

1. Introduction
2. Neutron interactions
3. **Bragg edge scattering**
4. Energy selection
5. Detector setup
6. Applications

BRAGG EDGE SCATTERING – Cross sections



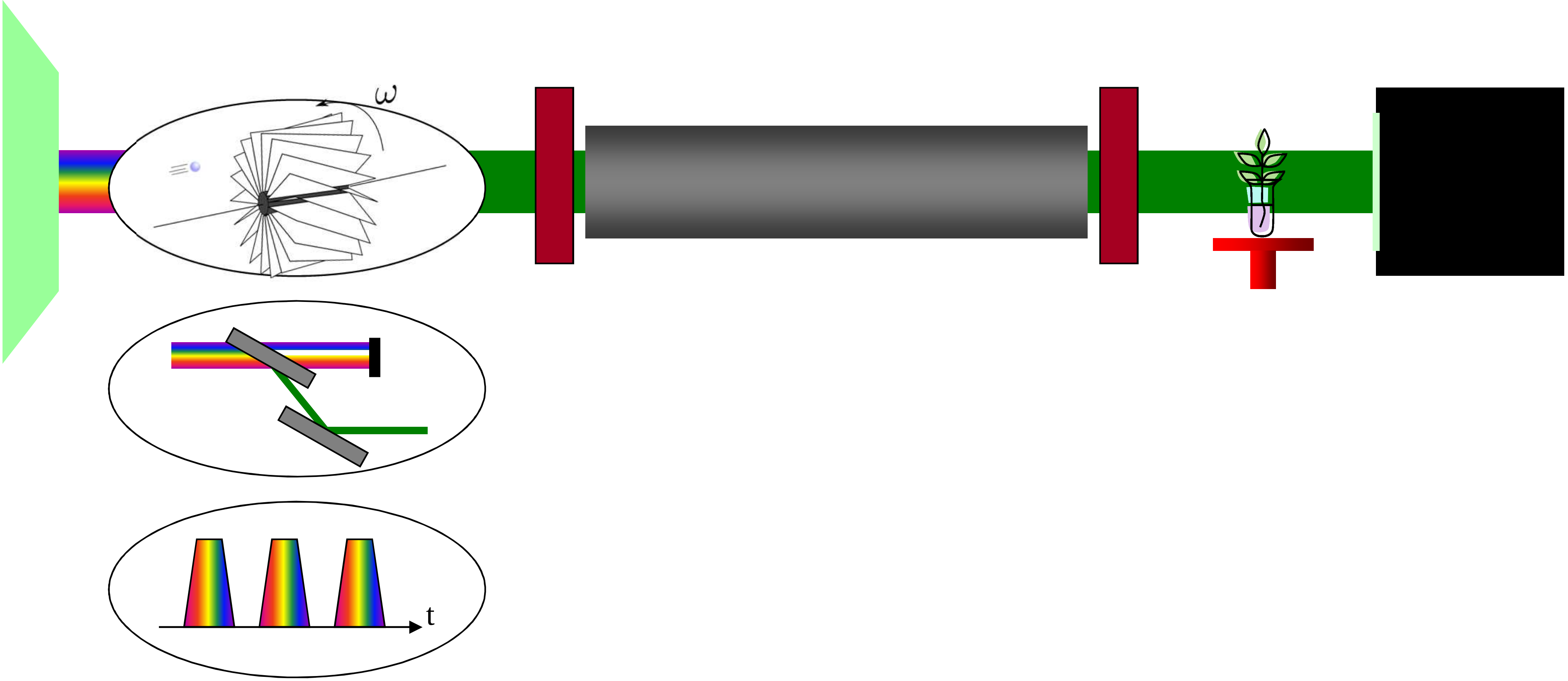
BRAGG EDGE SCATTERING – Different metals



PAUL SCHERRER INSTITUT

OUTLINE

ENERGY SELECTION - Methods



	Monochromaticity	Exposure time	Wavelength shift	Availability
Velocity Selector	15%	1 min	1 Å	ICON
Double Crystal	2.5%	5 min	0.1 Å	BOA
Time Of Flight	<0.5%	2.5 h		BOA

OUTLINE

1. Introduction
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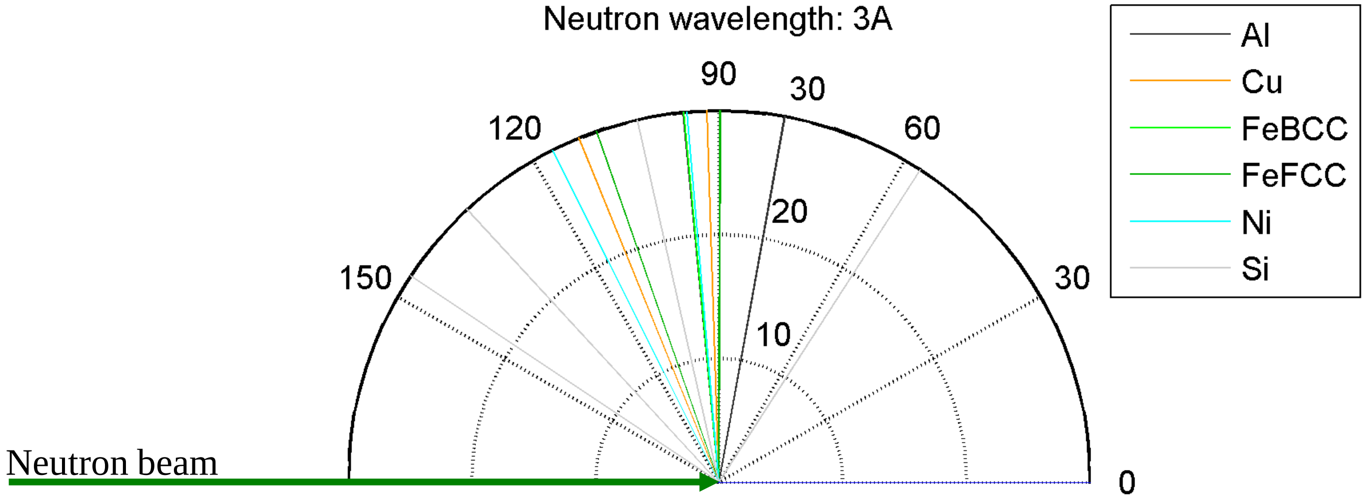
Contradictory requirements

Transmission	Diffracted neutrons
Small FOV	Large FOV (large angular range many grains)
High resolution	Resolution not crucial
In beam direction	Perpendicular to direct beam lower background favoured diffraction direction

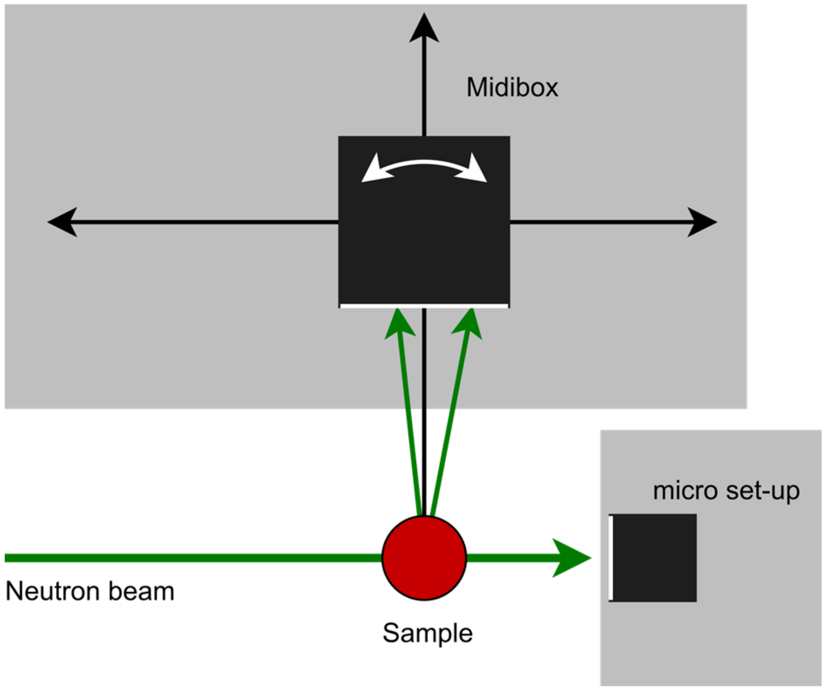


DETECTOR SETUP

Two camera systems desired:

1) high-resolution imaging
2) larger FOV

… already existing at the ICON beamline (PSI): micro set-up and midi set-up.



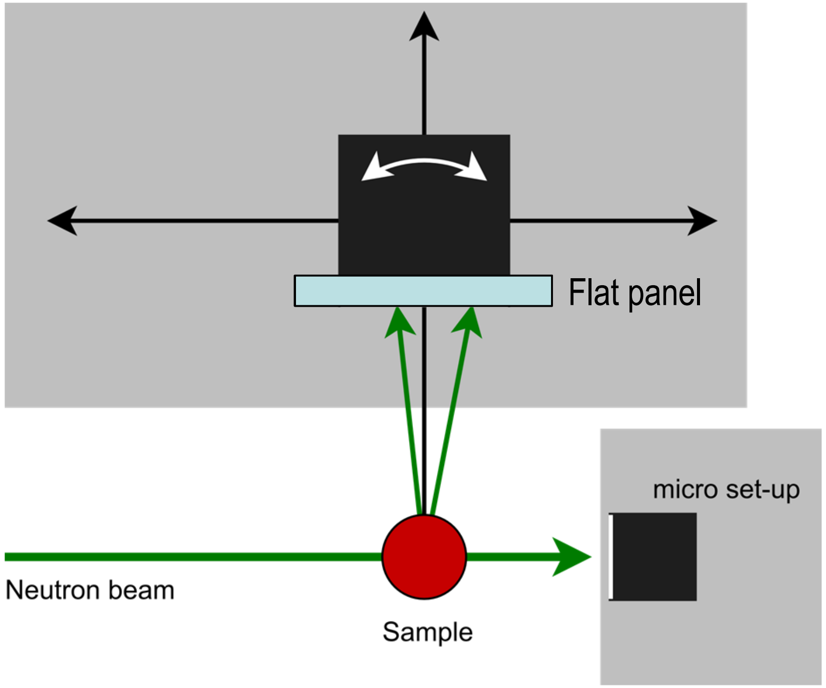
DETECTOR SETUP

Two camera systems desired:

1) high-resolution imaging
2) larger FOV

… already existing at the ICON beamline (PSI): micro set-up and FLAT PANEL.

NEW 2015!



DETECTOR SETUP – Flat Panel

- Gadox scintillator
- Fast acquisition
- Neutron imaging
- X-Ray imaging
- Compact
- FoV: 24.9 x 30.2 cm
- Pixel size 139 µm
- Now available at ICON!

OUTLINE

1. Introduction
2. Neutron interactions
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4. Energy selection
5. Detector setup
6. **Applications**

OUTLINE

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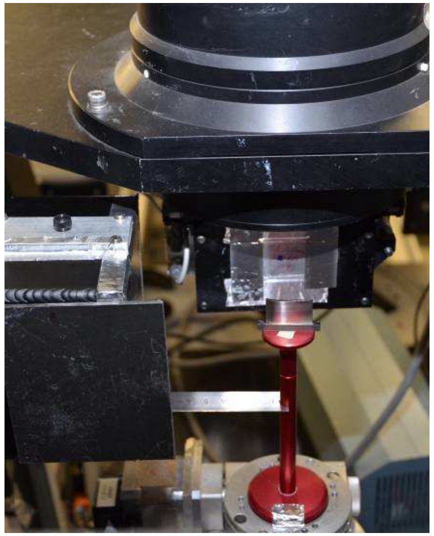
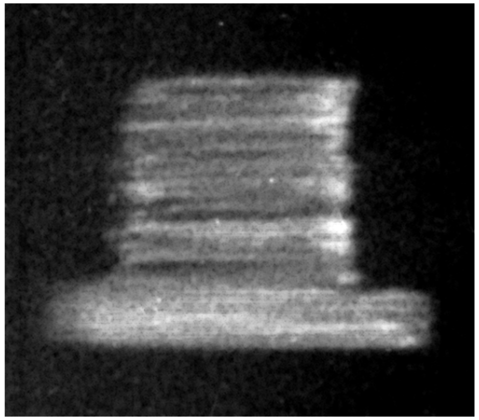
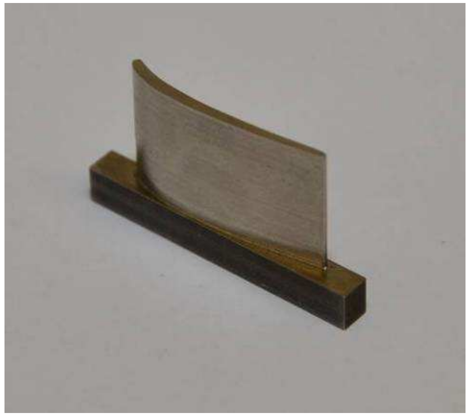
5. Detector setup
6. **Applications**

APPLICATIONS – Crystal orientation

SX 4

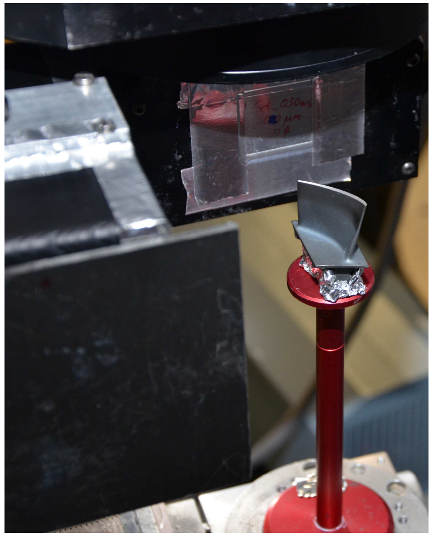


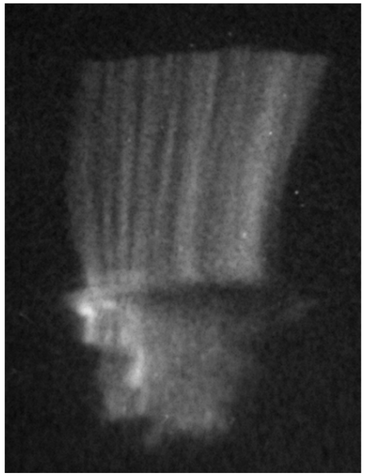




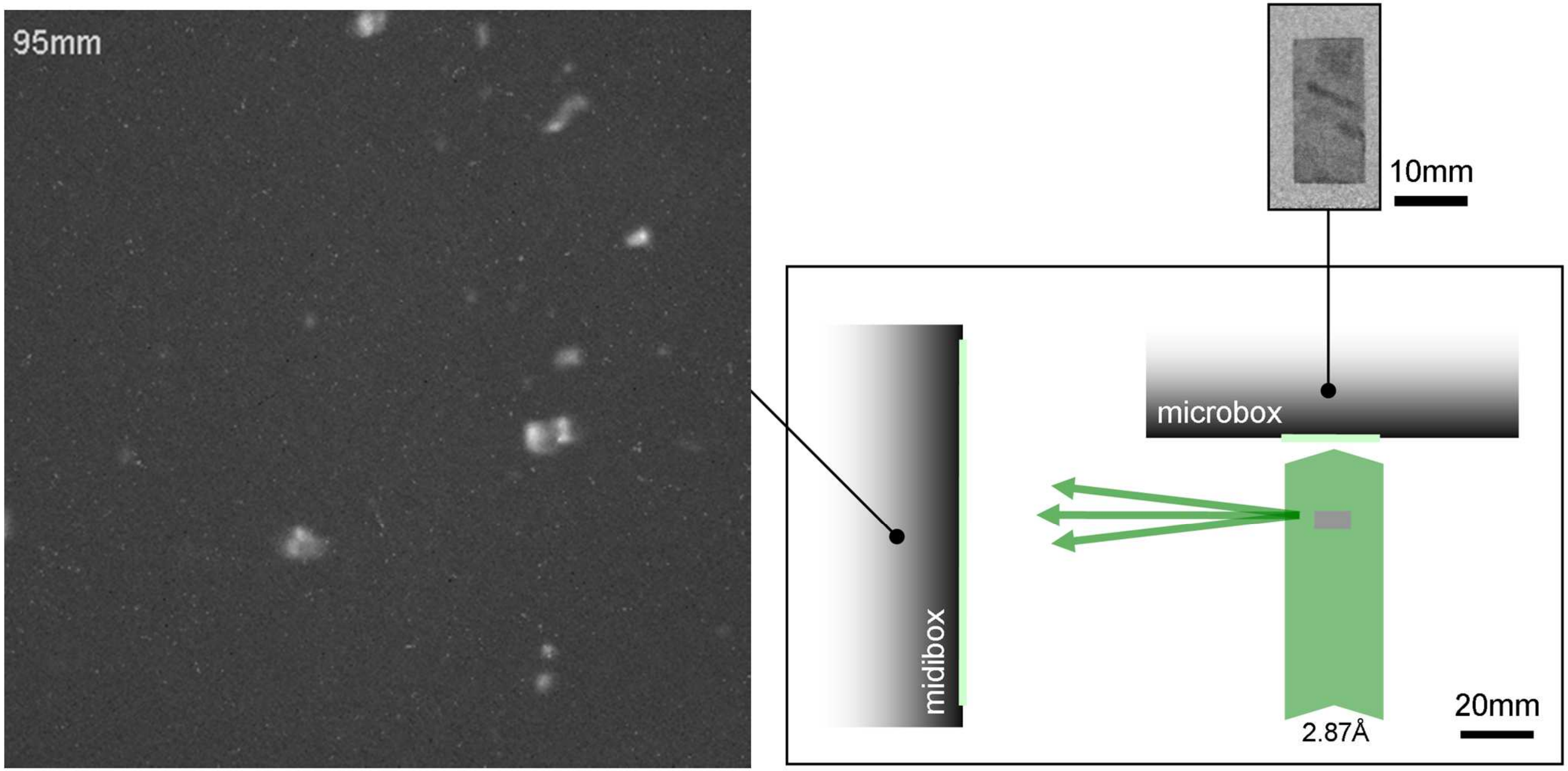
Different solidification directions

SX 5

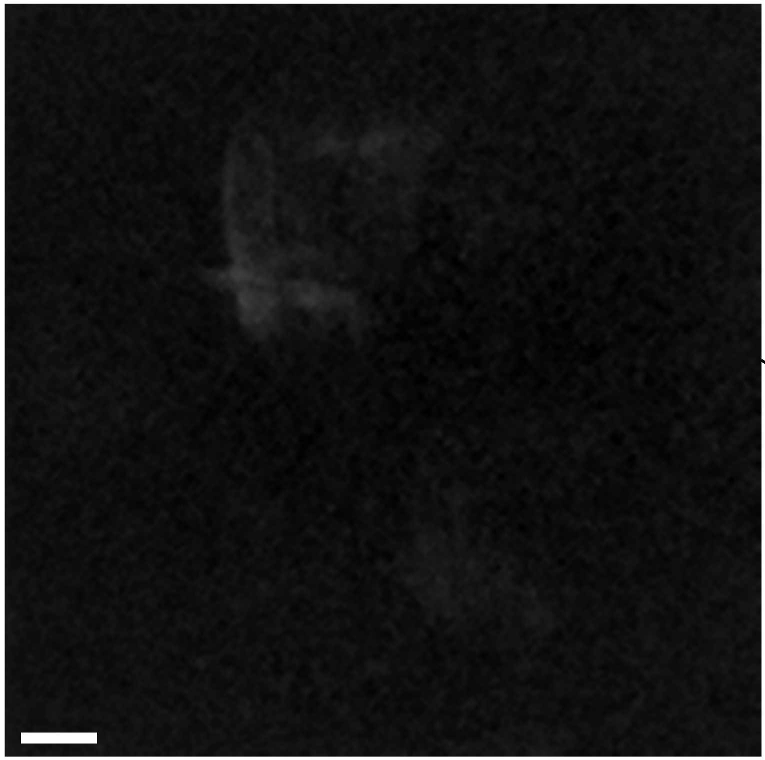


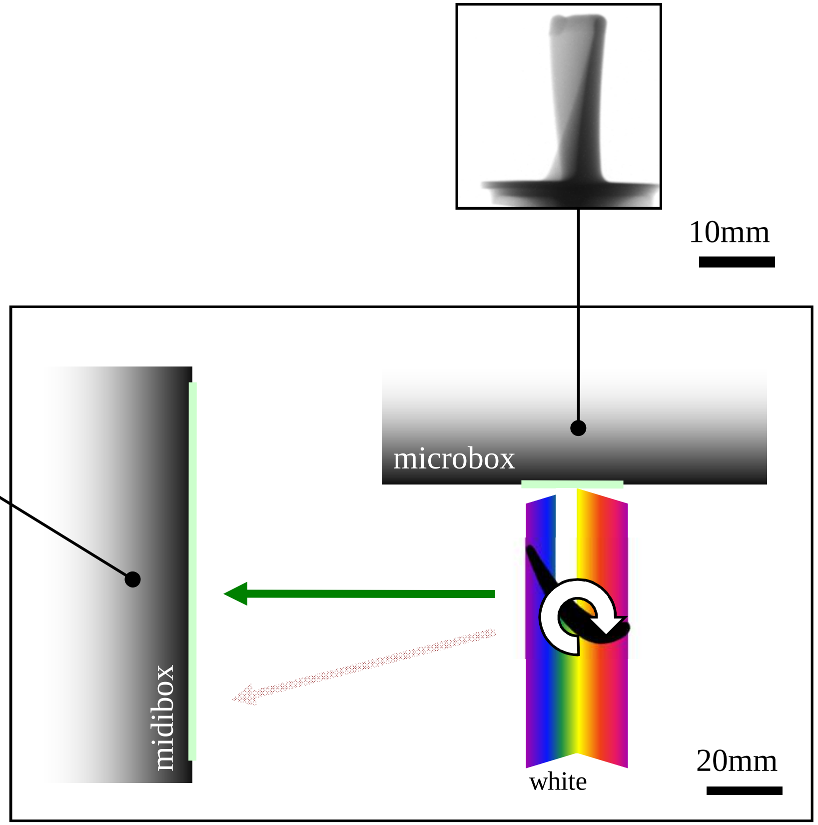


Vary midibox to sample distance for ray-tracing



Rotate the sample (standard transmission tomography)

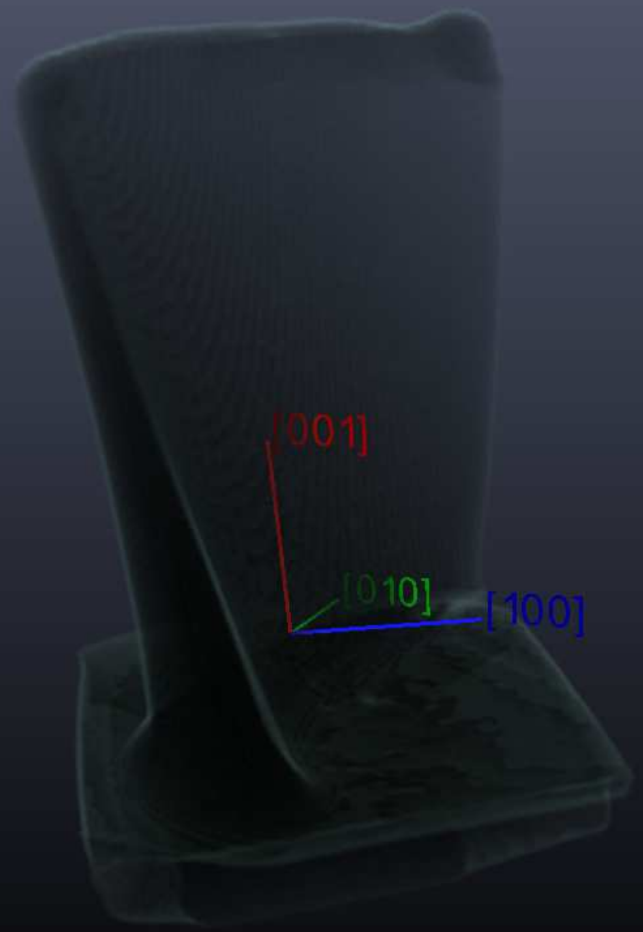




Sample projections under different angles
Tomographic reconstruction?

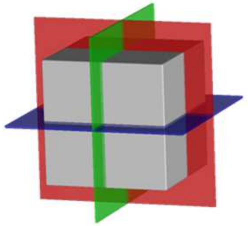
APPLICATIONS – Tomography

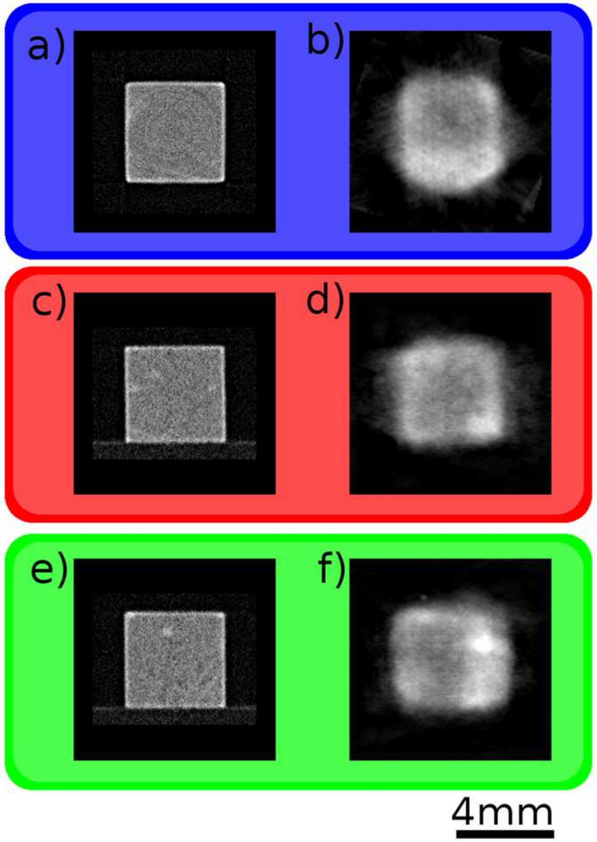
Geometry from transmitted tomography



Crystal orientation from diffractive tomography

APPLICATIONS – Single crystal nDCT

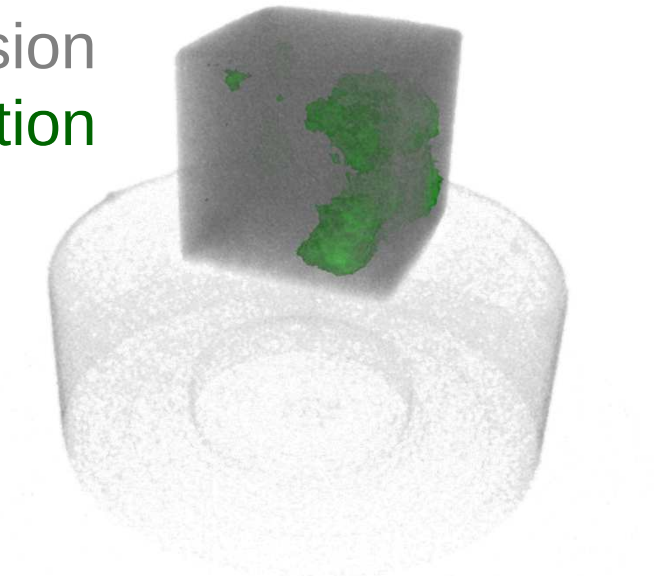




Mapping of local reflectivity (3D, non-destructive) in bulk metallic single crystals.

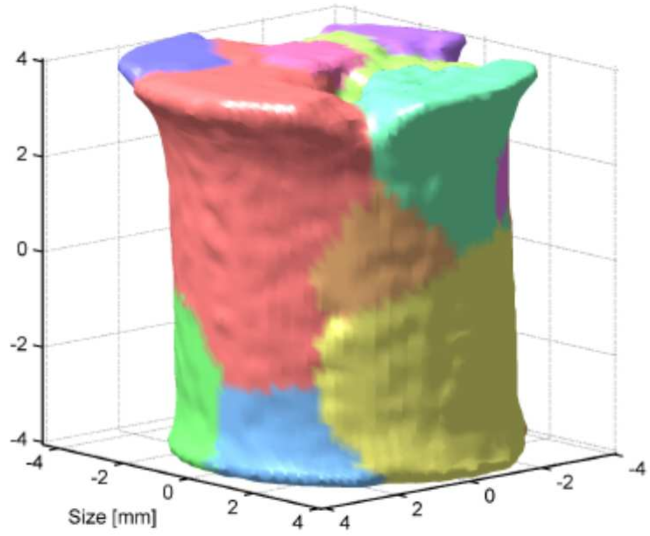
Combine with transmission data

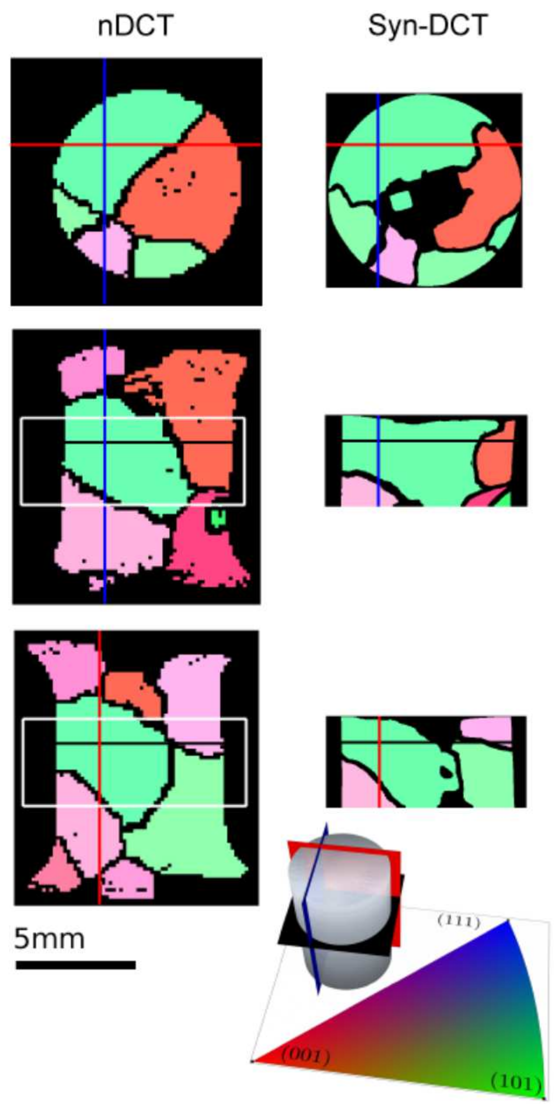
Transmission
& Diffraction



Peetermans, S. & Lehmann, E. H. Simultaneous neutron transmission and diffraction contrast tomography as a non-destructive 3D method for bulk single crystal quality investigations. *Journal of Applied Physics, 114, 124905 (2013)*

APPLICATIONS – Polycrystal nDCT

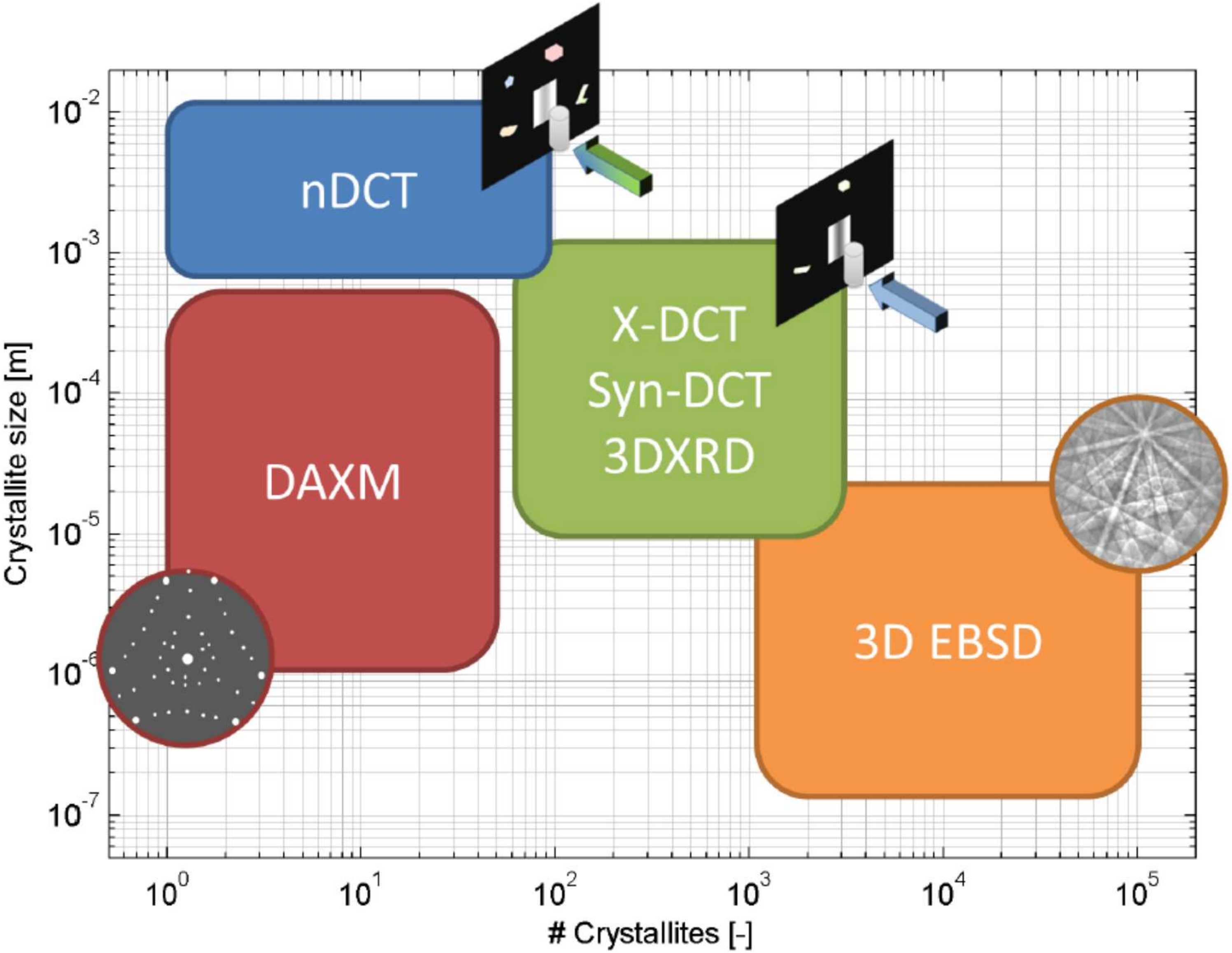




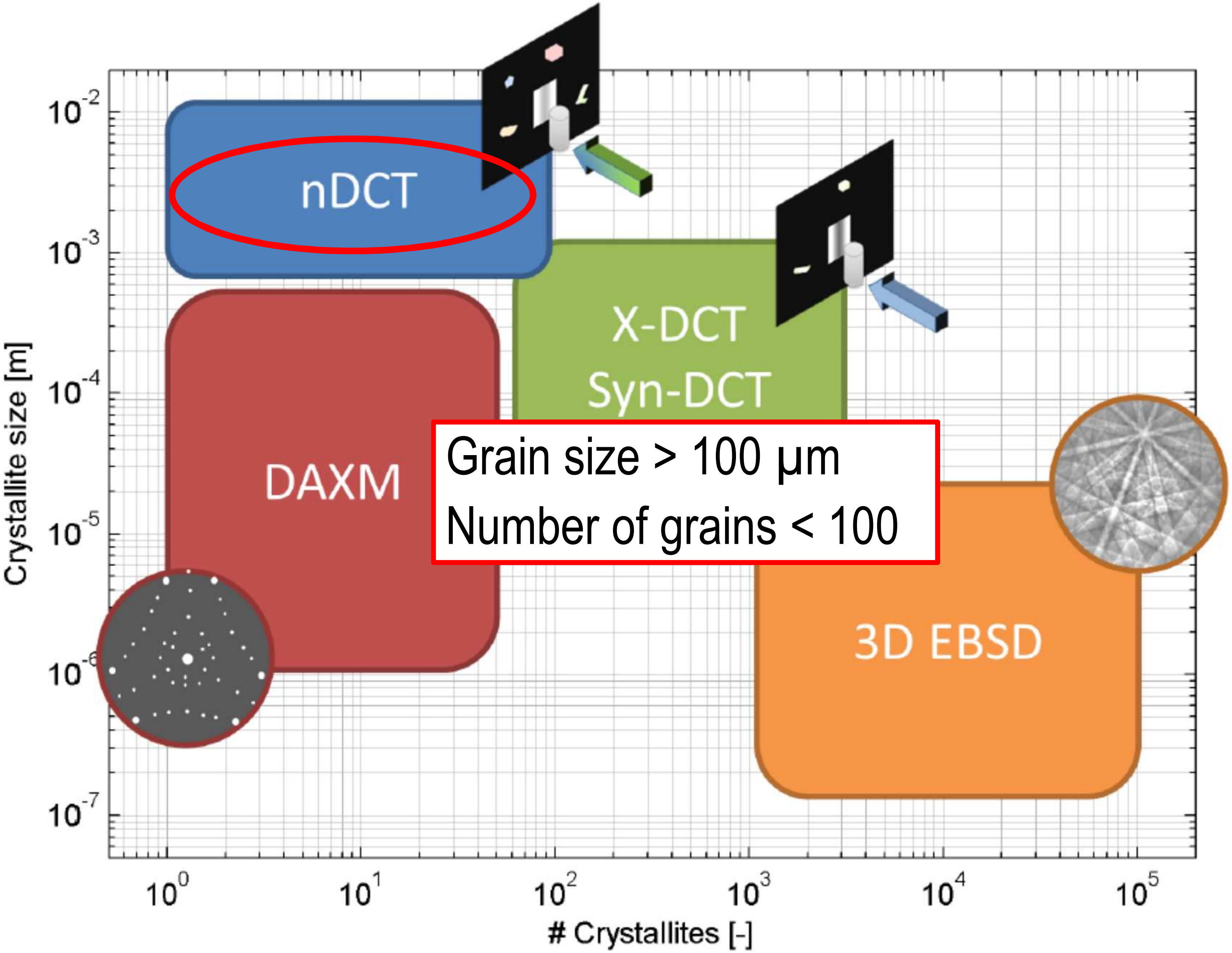
Grain mapping of polycrystalline bulky aluminum cylindric sample.

Peetermans, S. Energy selective neutron imaging for material science. *PhD Thesis presented 18 December 2014. École Polytechnique Federale de Lausanne.*

APPLICATIONS – nDCT Limitations



APPLICATIONS – nDCT Limitations



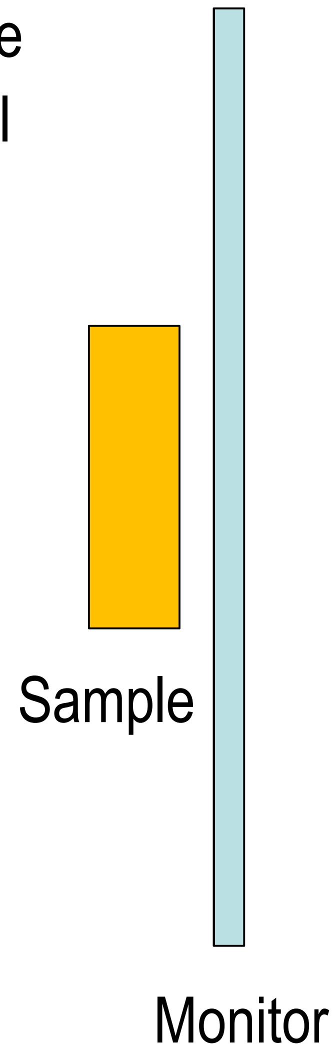
Grain size > 100 µm
Number of grains < 100

Thanks!

- Most of the work shown in this presentation belongs to Dr. Steven Peetermans. Thanks to him for letting me use it for the lecture.

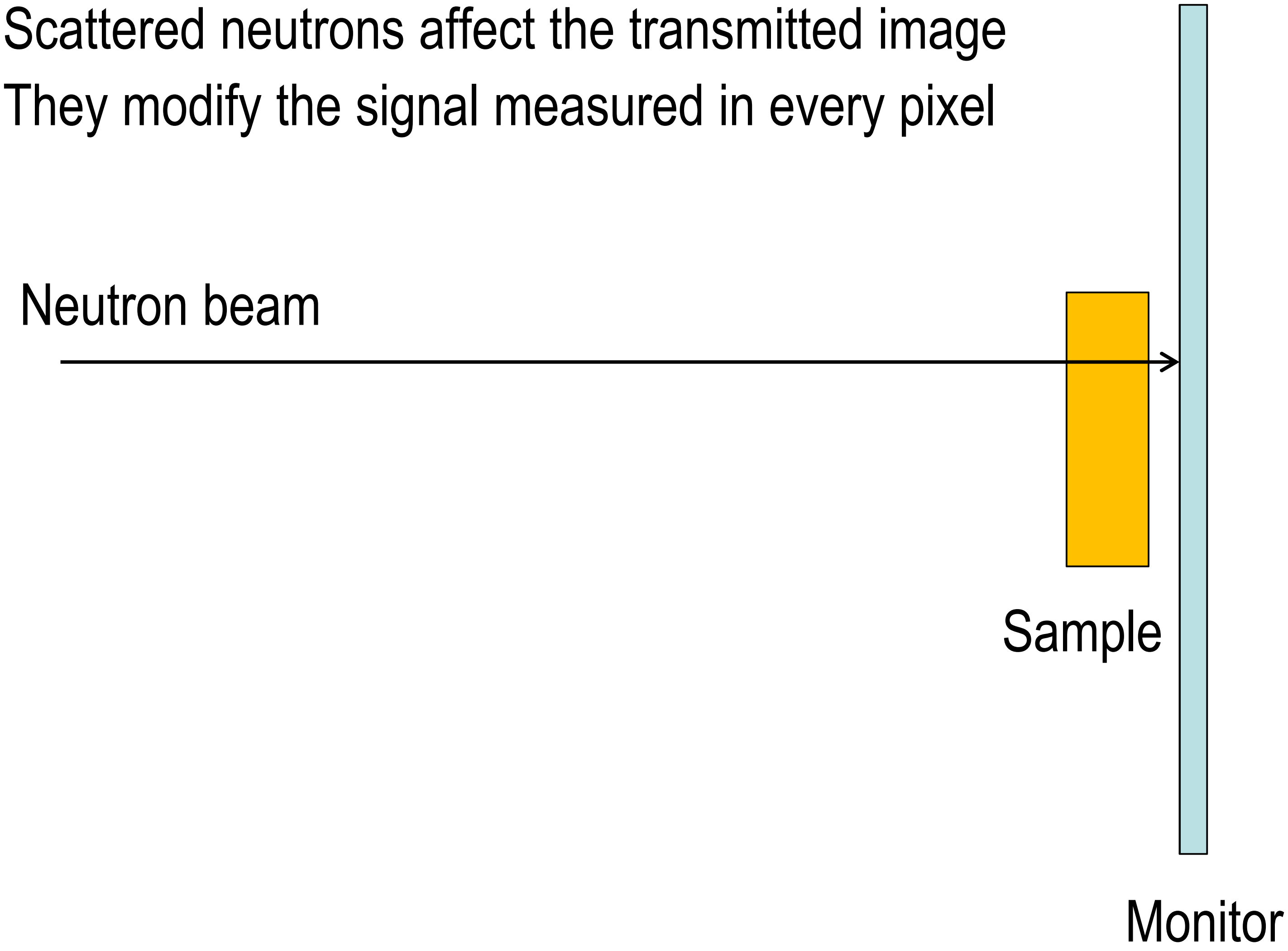
- Thanks for your attention!

- Scattered neutrons affect the transmitted image
- They modify the signal measured in every pixel



QUANTITATIVE NEUTRON IMAGING

- Scattered neutrons affect the transmitted image
- They modify the signal measured in every pixel



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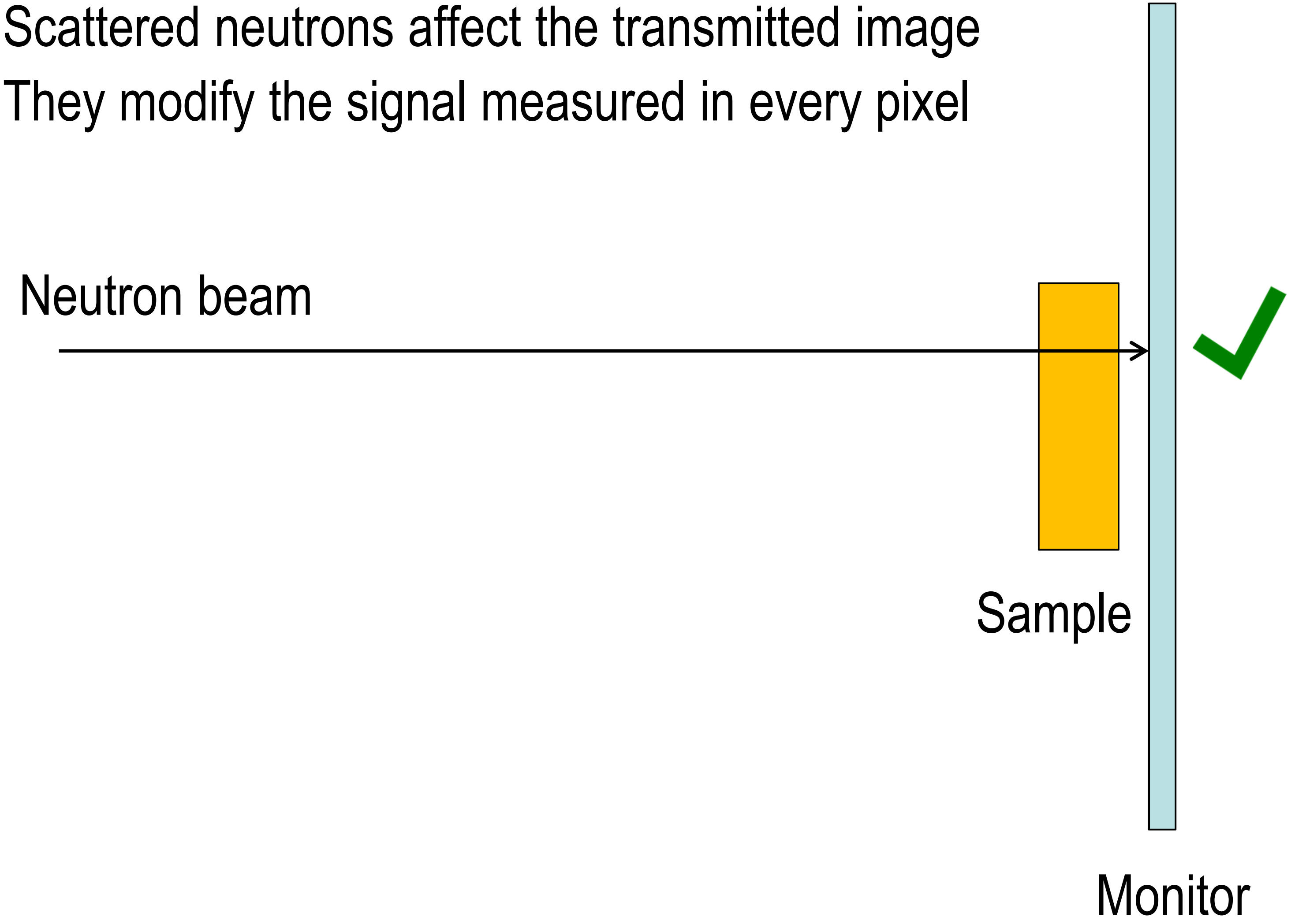

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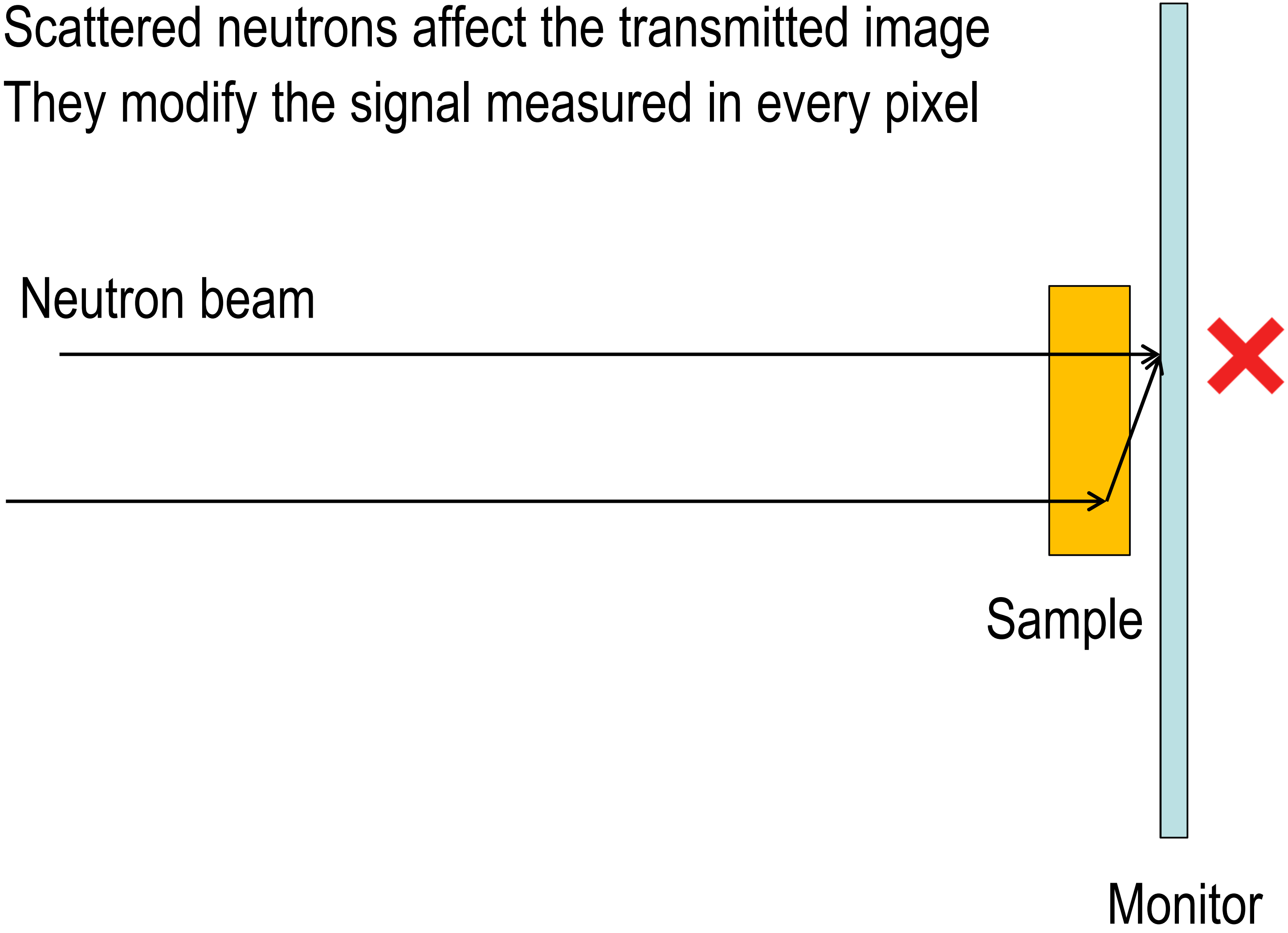
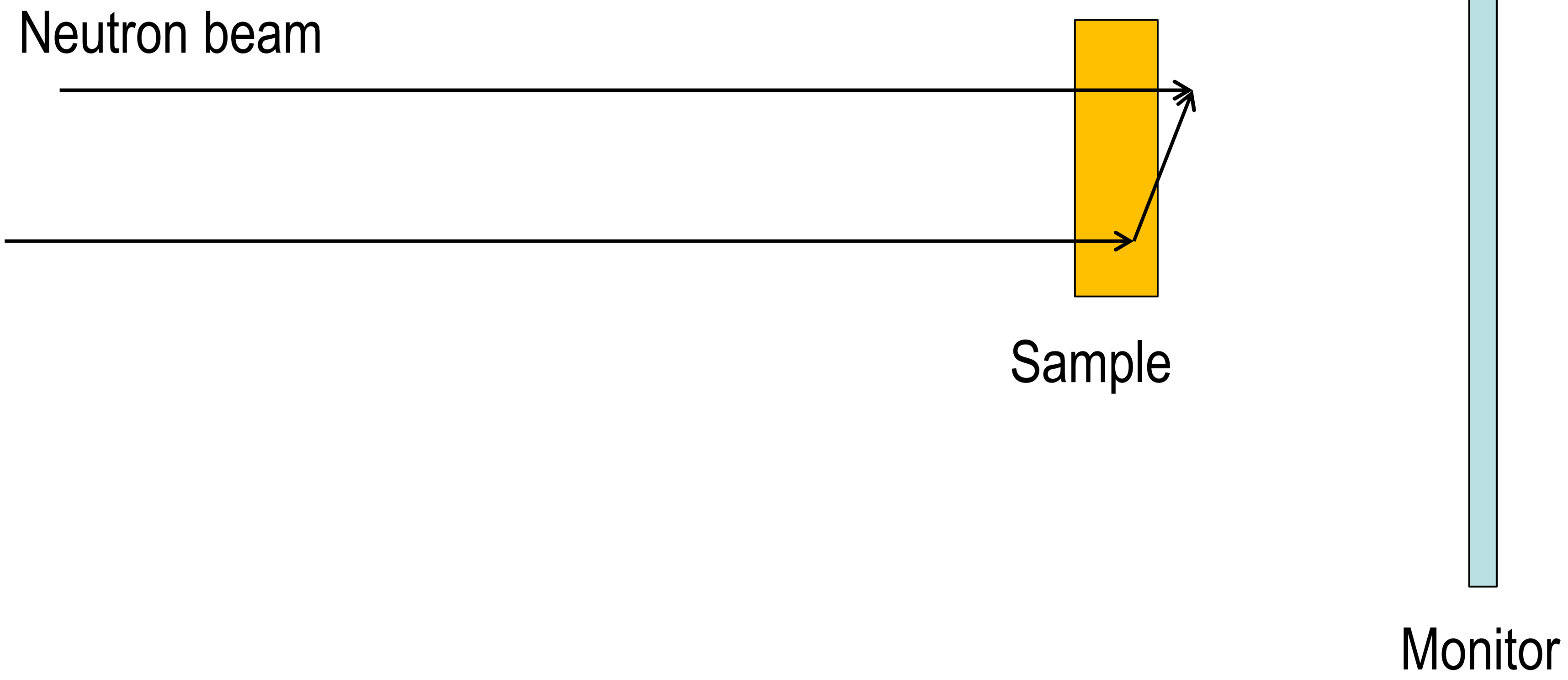


QUANTITATIVE NEUTRON IMAGING

- Scattered neutrons affect the transmitted image
- They modify the signal measured in every pixel
- Increase sample to detector distance?



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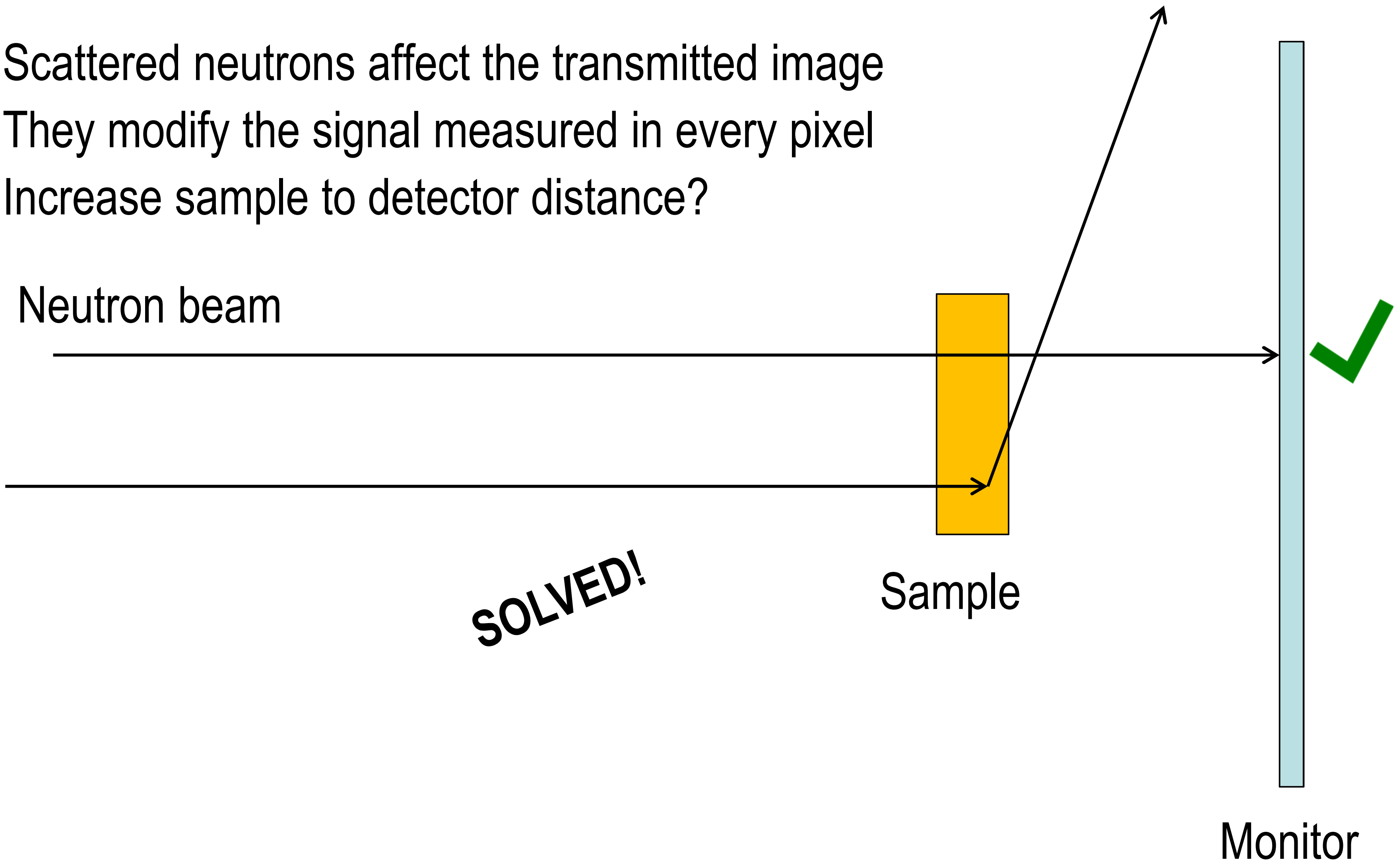

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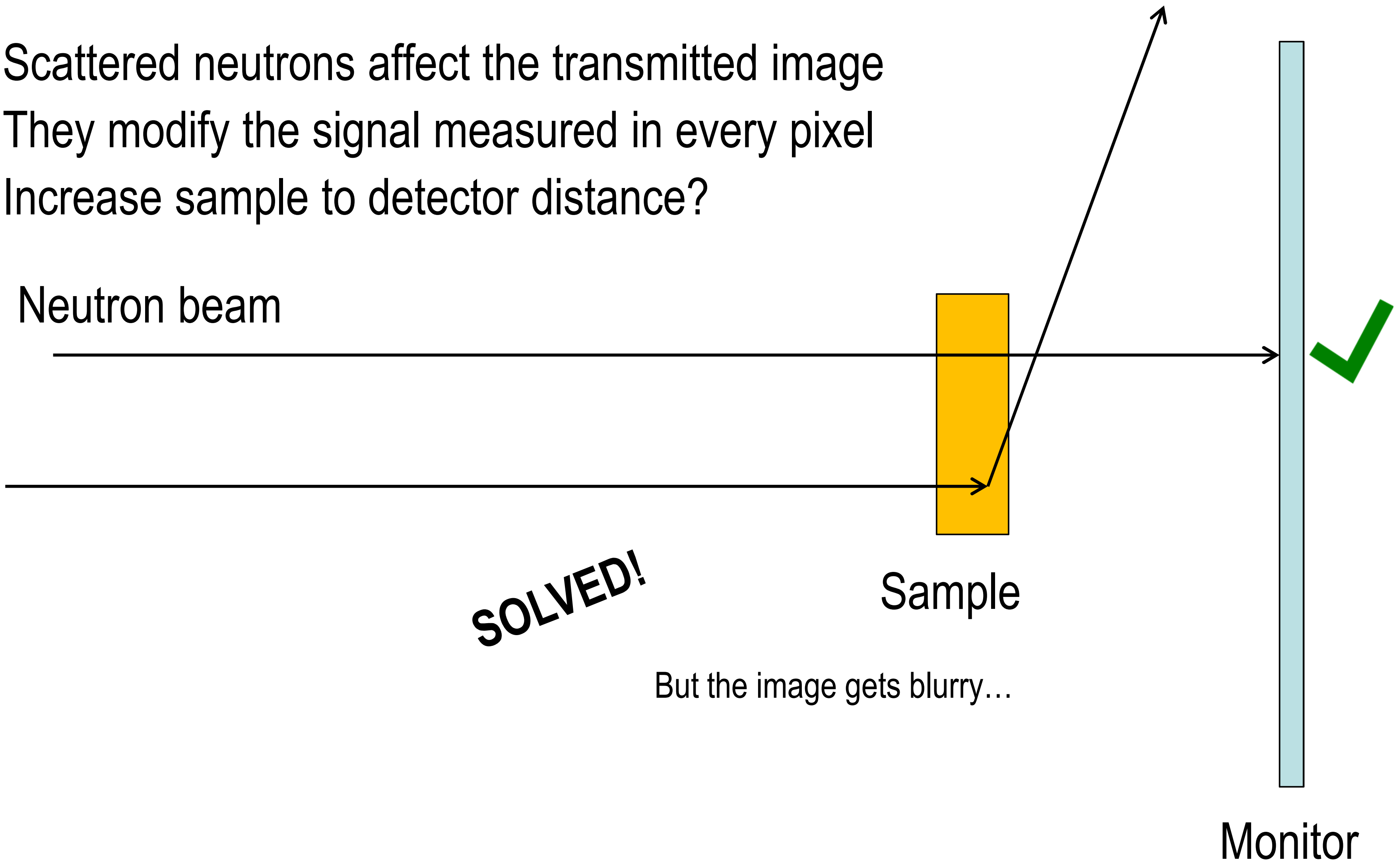

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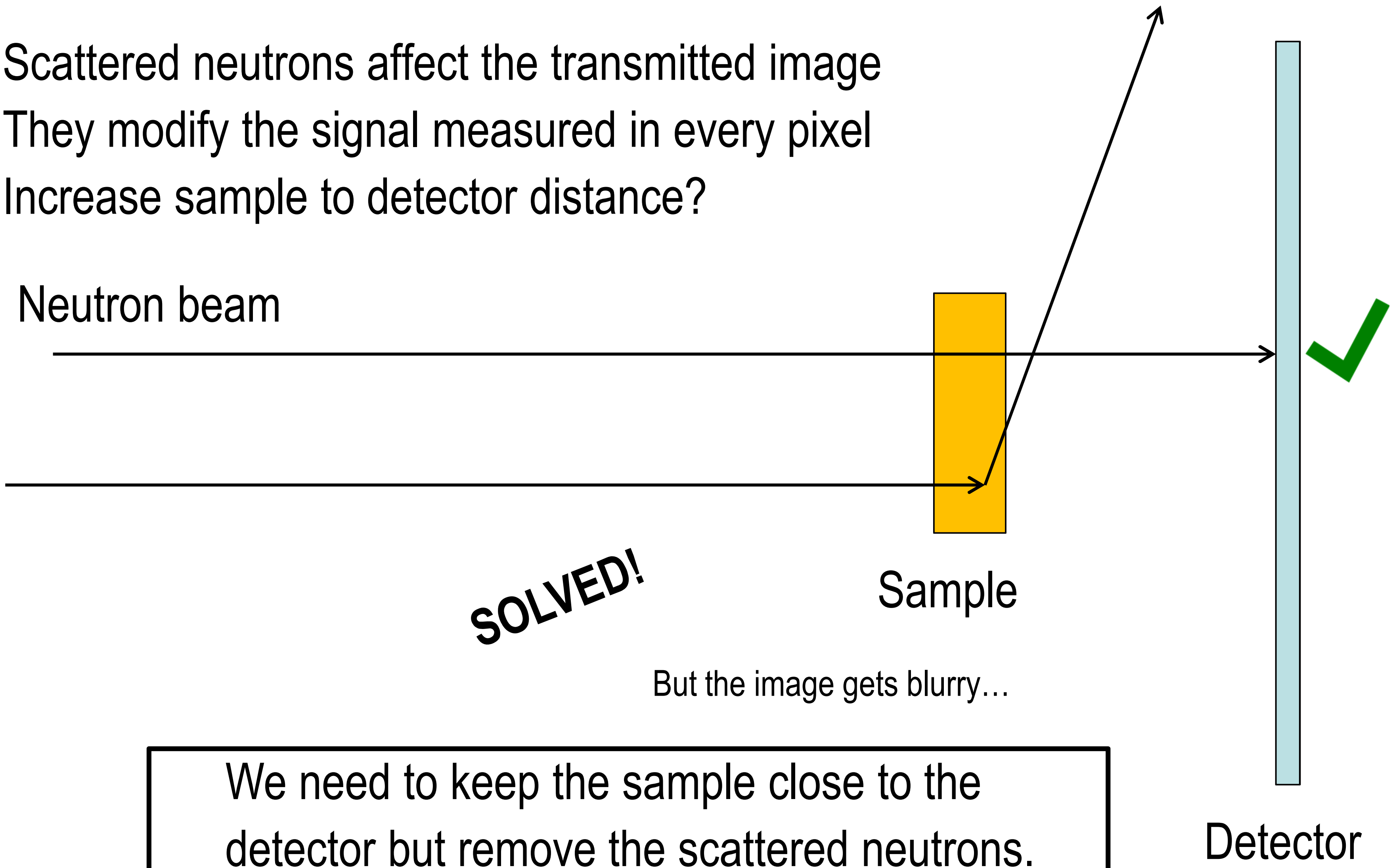
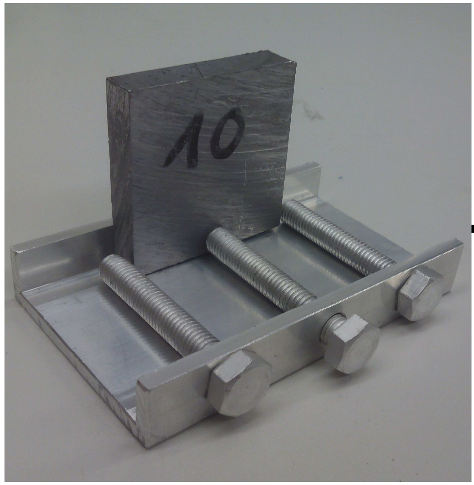
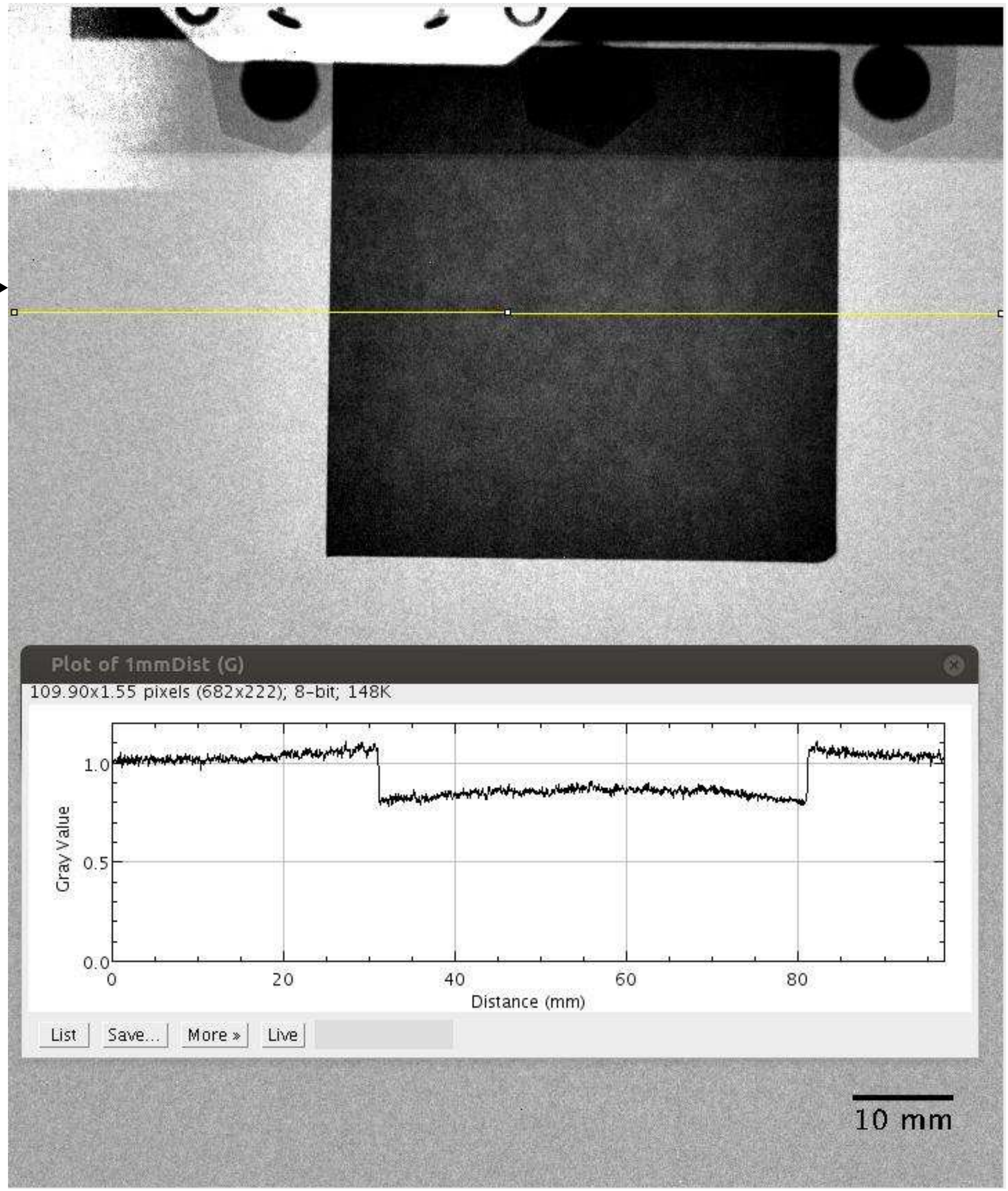


But the image gets blurry…

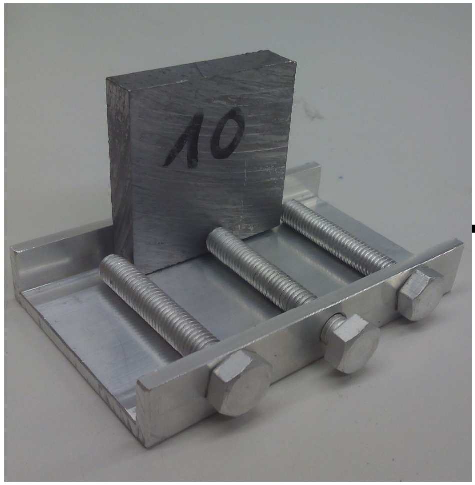
We need to keep the sample close to the detector but remove the scattered neutrons.

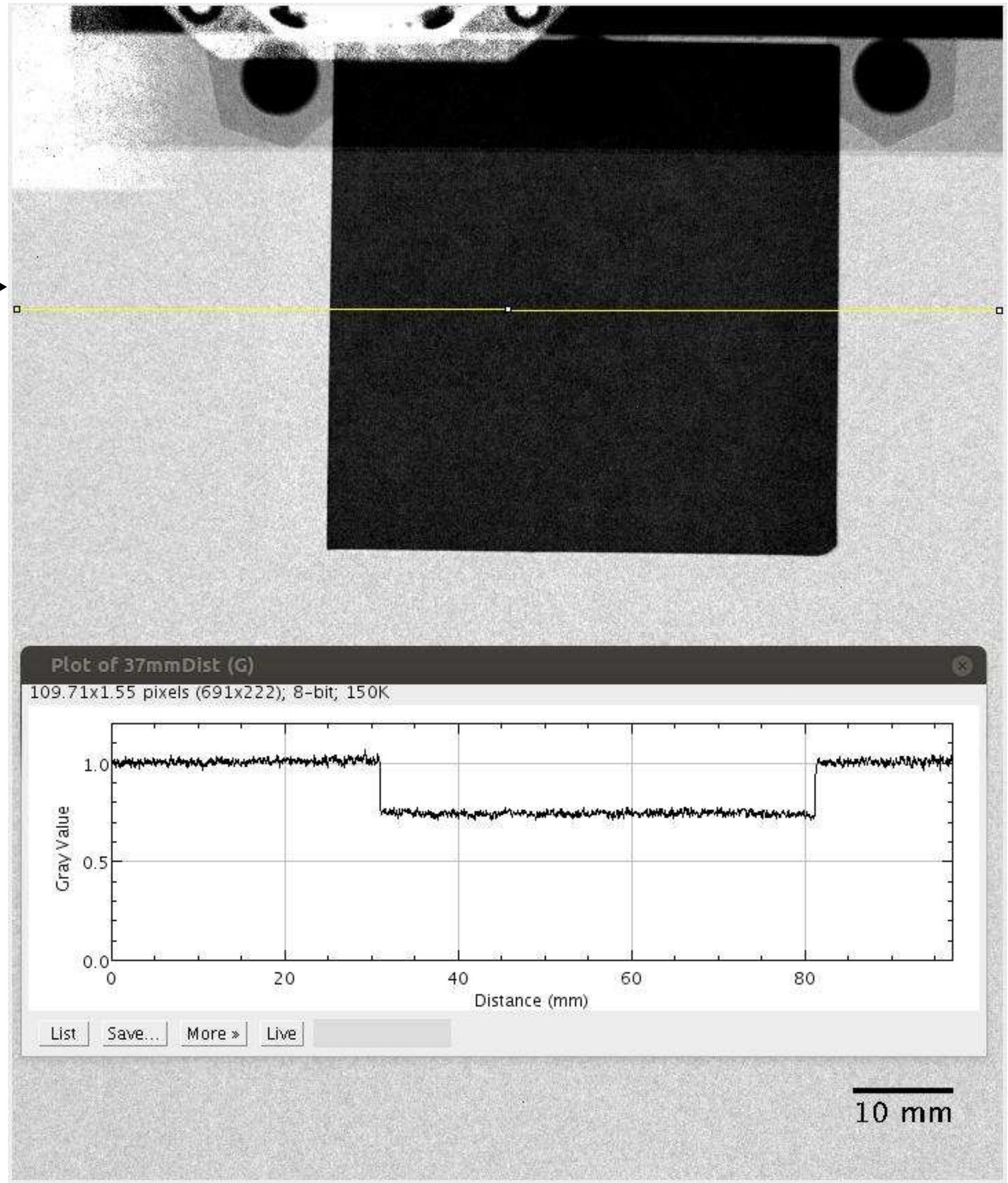




- Lead slab used as sample
- Dimensions: 50mm x 50mm x 10mm
- Close contact with detector

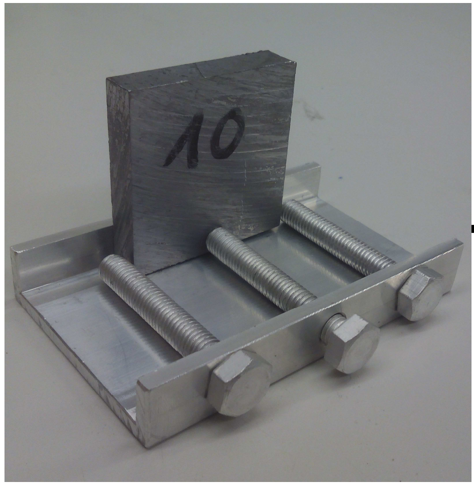
QUANTITATIVE NEUTRON IMAGING

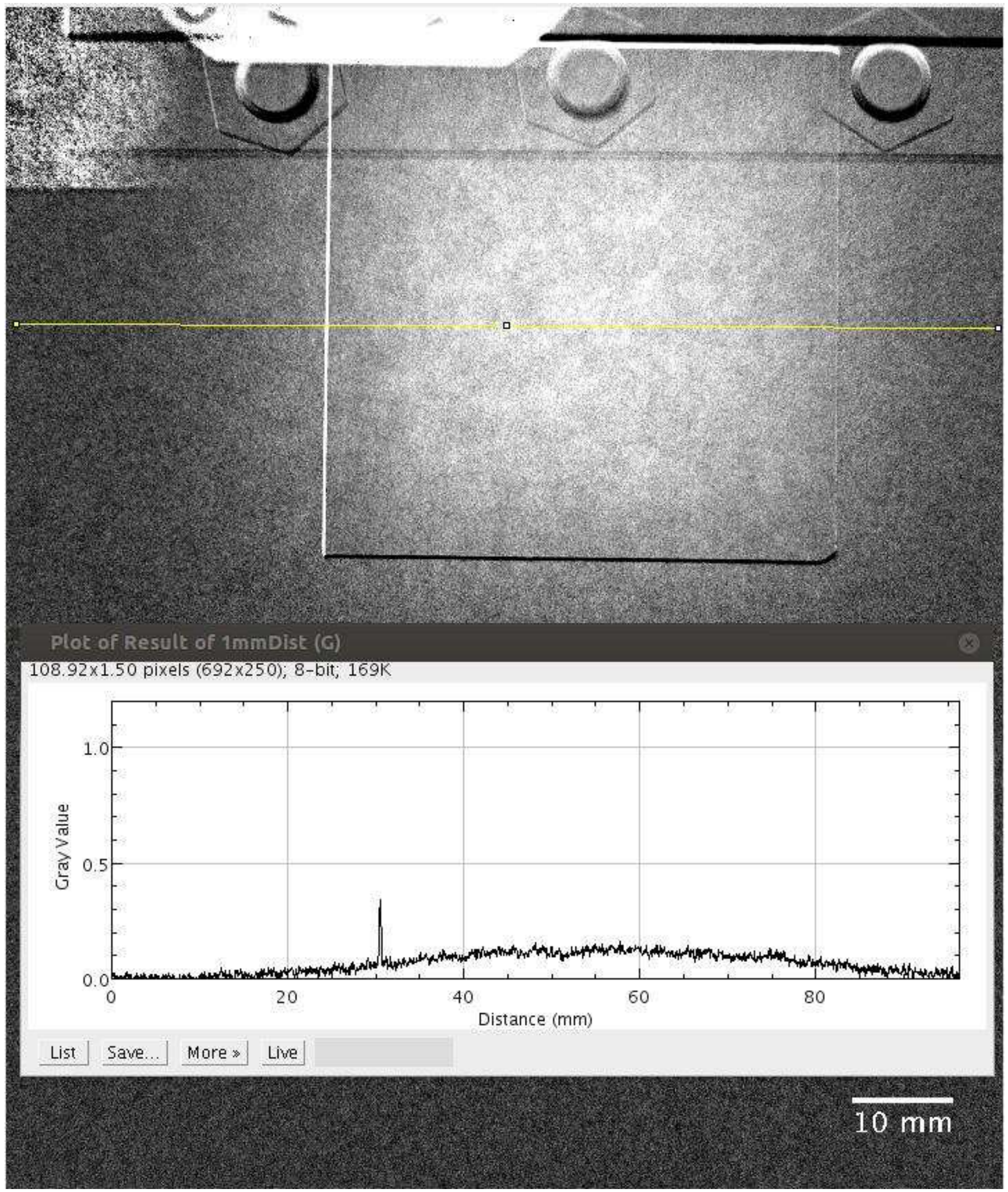




- Lead slab used as sample
- Dimensions: 50mm x 50mm x 10mm
- 40 mm distance with detector

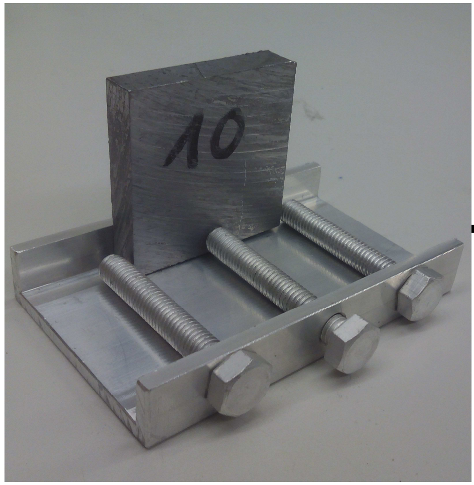
QUANTITATIVE NEUTRON IMAGING

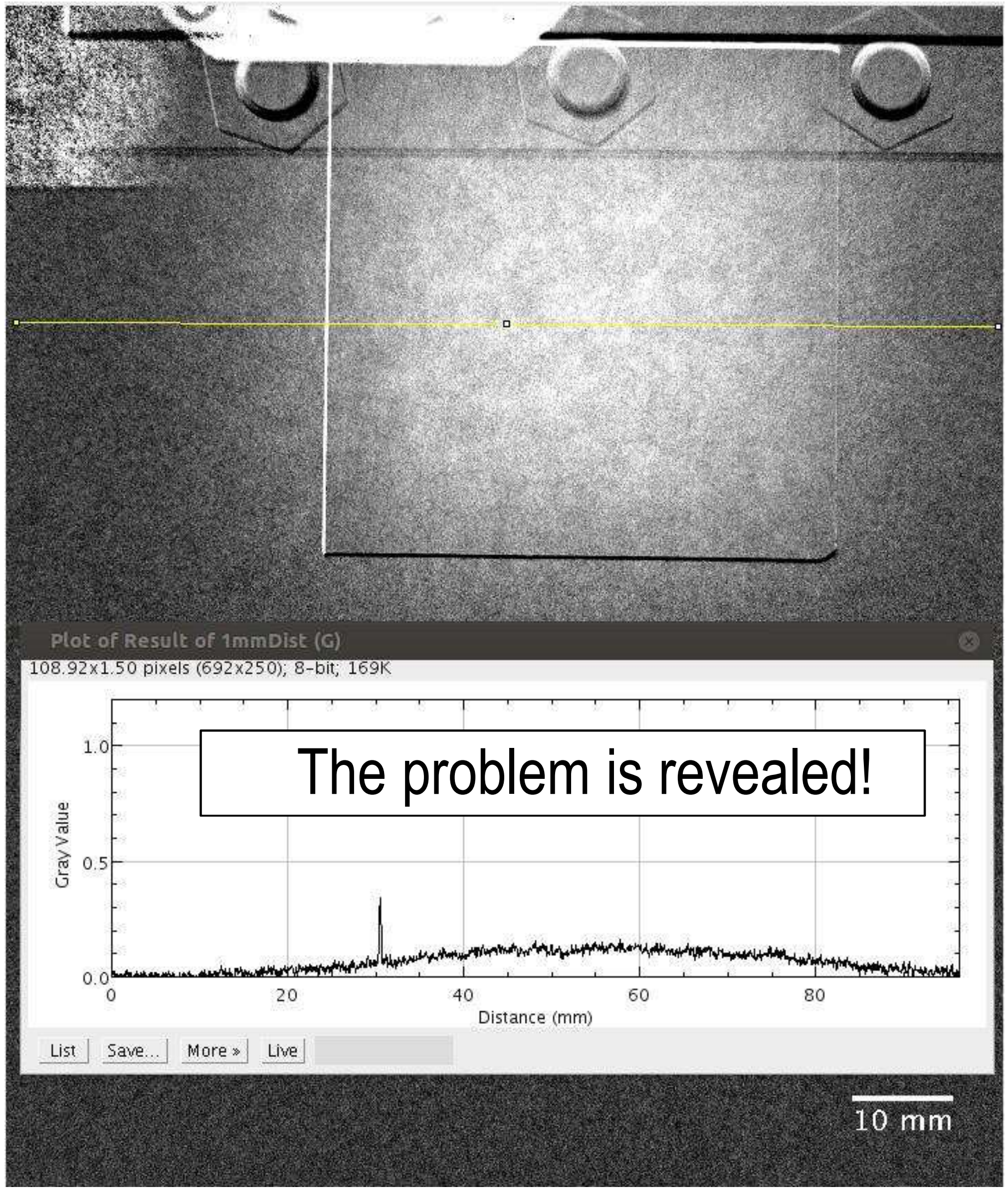




- Lead slab used as sample
- Dimensions: 50mm x 50mm x 10mm
- Previous signals subtracted

QUANTITATIVE NEUTRON IMAGING





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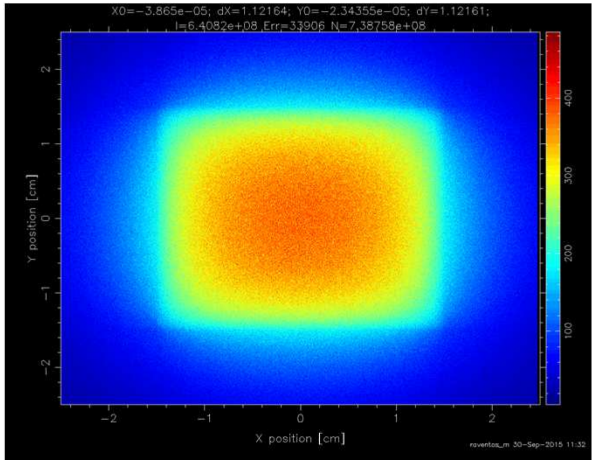
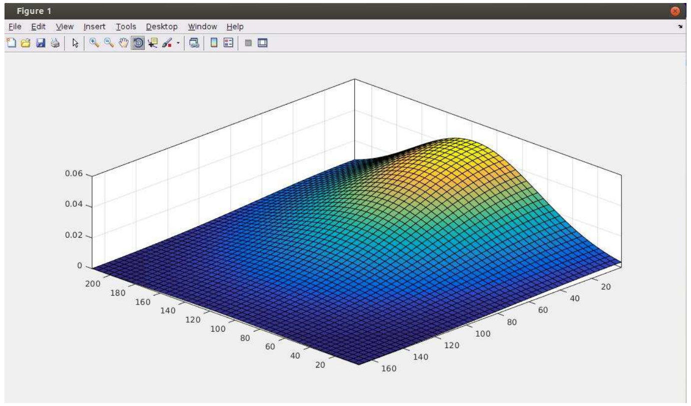
But how to tackle it?

But how to tackle it?



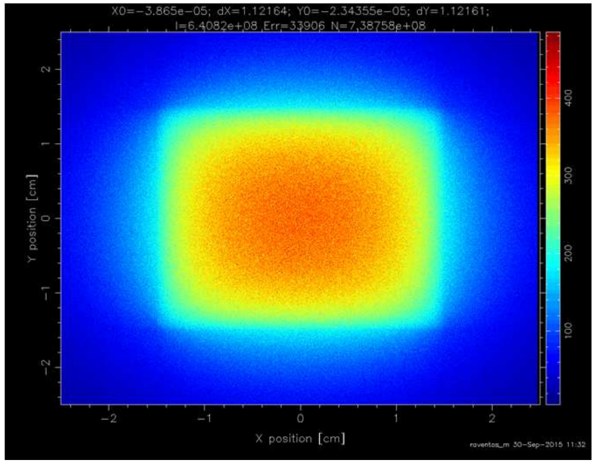
Monte-Carlo simulations



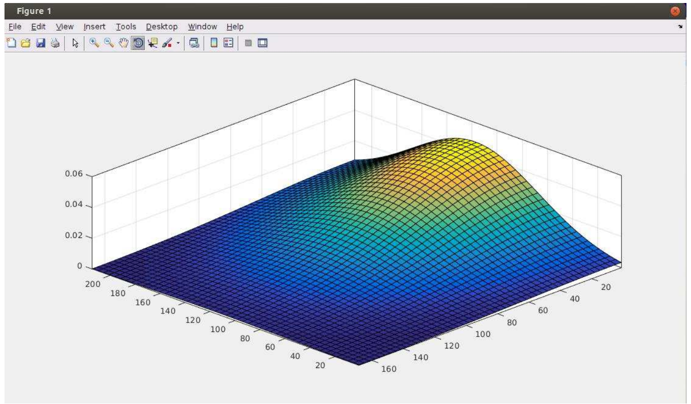
Robust curve fitting

Filtering with gratings

But how to tackle it?



Monte-Carlo simulations



Robust curve fitting

Filtering with gratings

- For scattering from water

Correction Methods for the Quantitative Evaluation of Thermal Neutron Tomography
R. Hassanein (2006)

- For other scatterers

Coming soon…