SWEDNESS/LINXS Doctoral-level course on neutron imaging

Monday, 17 May 2021

Introduction to neutron imaging

- basic concepts/definitions
- interaction mechanisms
- introduction to different modalities

ROBIN.WORACEK@ESS.EU

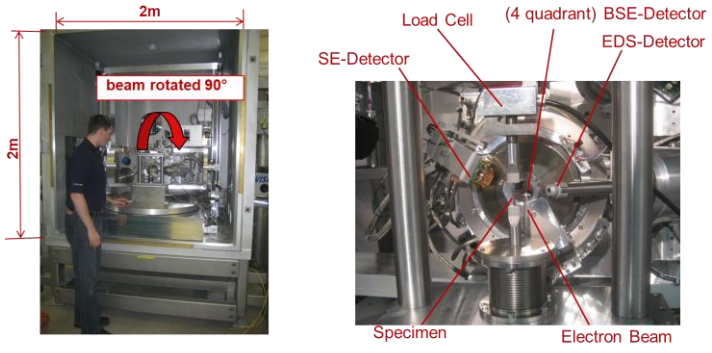
Introduction to neutron imaging

- ❑ Characterization Techniques, Definitions, Neutron Sources
- ❑ Neutron Methods & Length Scales
- ❑ How is an image recorded?
- ❑ Beer–Lambert law for attenuation based imaging
- ❑ The neutron imaging setup: geometrical considerations & Scattering vs Absorption
- ❑ Principles of Tomography
- ❑ Advanced Neutron Imaging Methods
- ❑ Neutron Detection

A little bit about how I got here…

- ➢ Trained Mechanical Engineer (Dipl. Ing.) & Automotive Industry, Germany (2002-2006)

- ➢ Fulbright scholar: MS + PhD at The University of Tennessee, Knoxville, TN, USA (206-2015)
  - MS project: loading system (80kN) for Large-Chamber SEM
  - PhD (2009-2014): collaboration with Neutron Imaging group at Helmholtz Zentrum Berlin



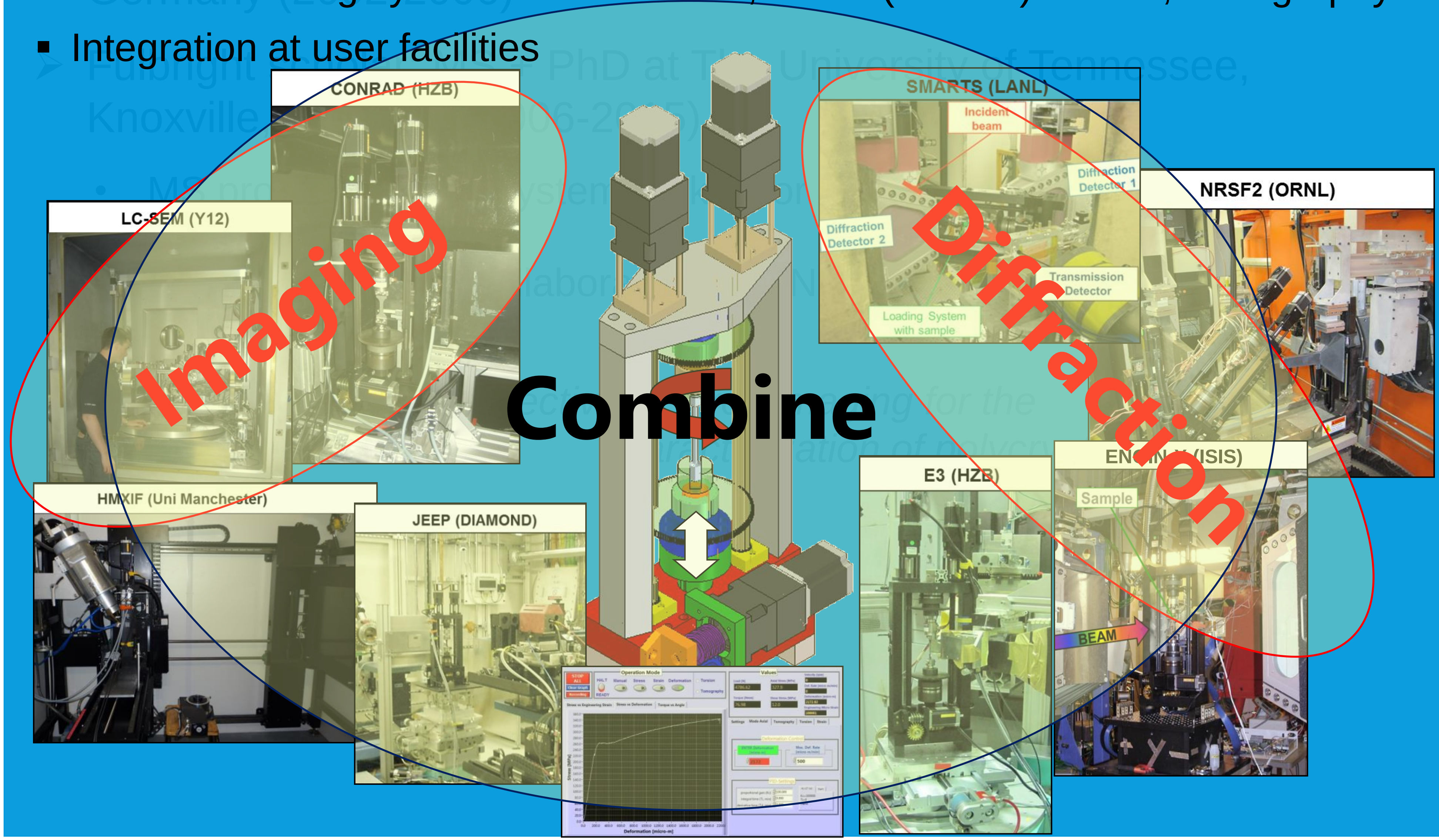
"Energy selective neutron imaging for the characterization of polycrystalline materials"

- ➢ Since February 2015: At ESS

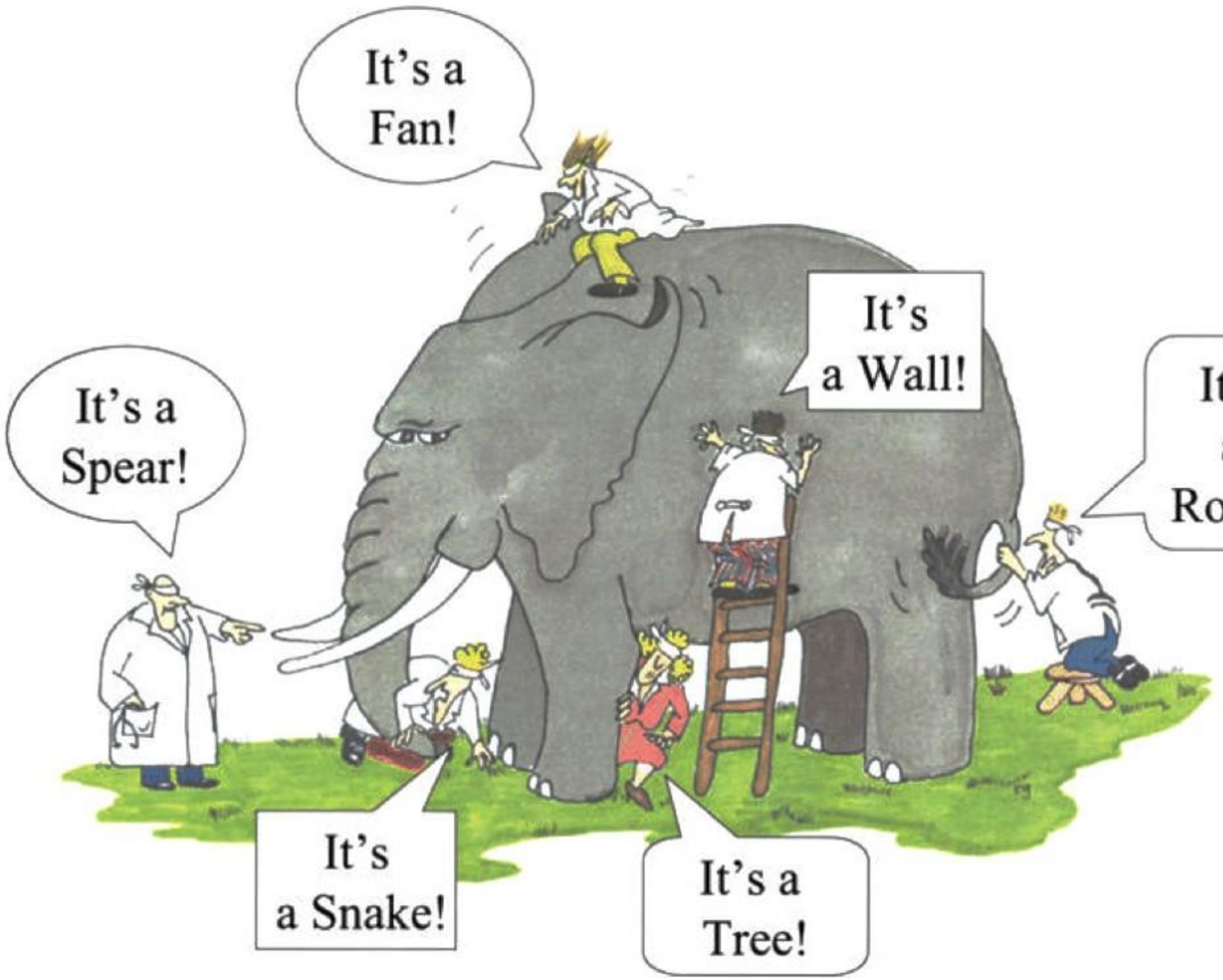
- ➢ My interest: How to enable useful material characterization techniques that create a positive impact to our life on spaceship earth ☺

A little bit about how I got here…

- Modified loading system: 44kN tension, 11Nm (110Nm) torsion, tomography
- Integration at user facilities



Array of characterization techniques



The six blind men and the elephant

Array of characterization techniques

Traditional lab methods

Optical microscopy

SEM

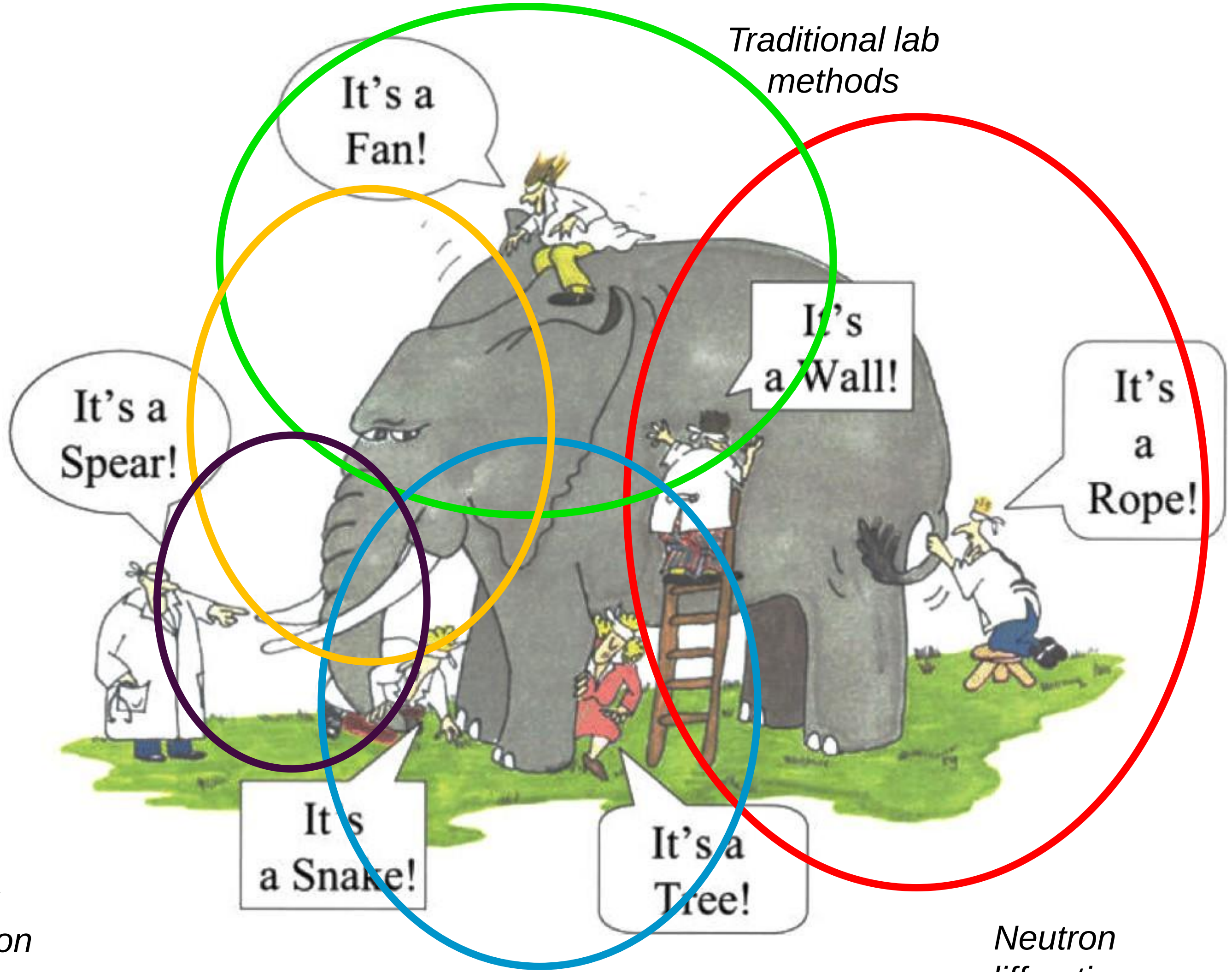
TEM

Atom probe

SANS/SAXS

X-ray diffraction

X-ray imaging

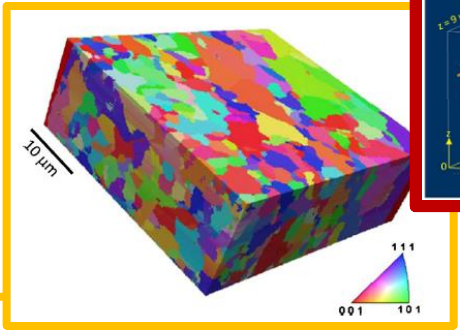


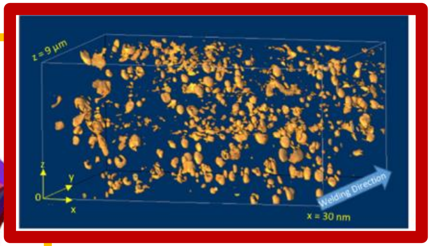
....many methods..

Neutron Imaging

Neutron diffraction

Array of characterization techniques: Tomography





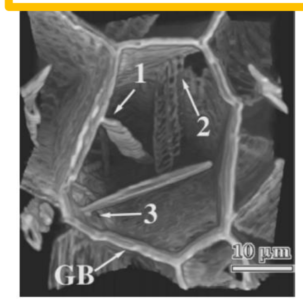
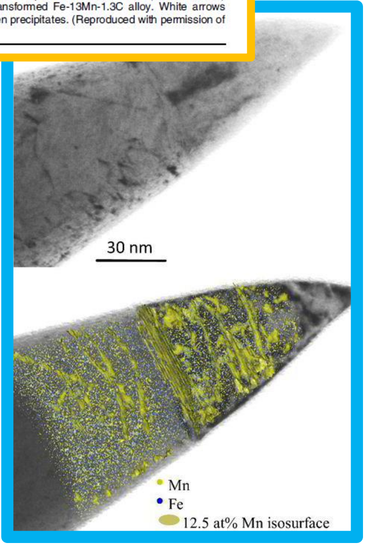


Fig. 2. 3D reconstruction of proeutectoid cementite (white features) in an isothermally transformed Fe-13Mn-1.3C alloy. White arrows point to Widmanstätten precipitates. (Reproduced with permission of Ref. 54).



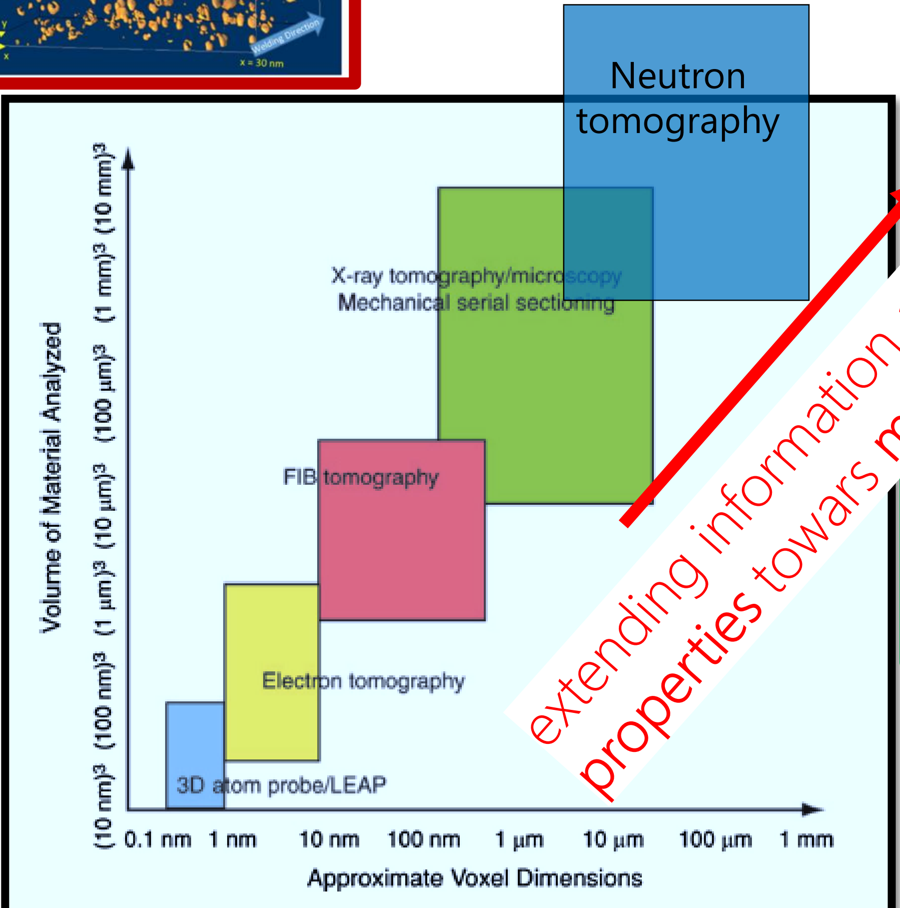
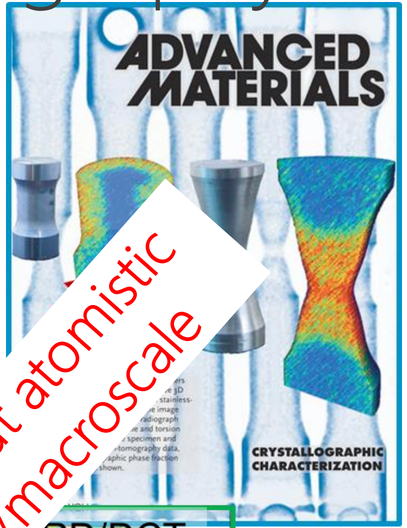
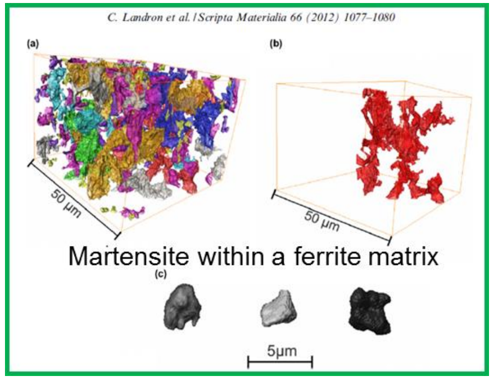


Fig. 3. Graphical representation of the resolution and typical volume analyzed per experiment for modern tomographic characterization methods. (Reproduced with permission of Ref. 59).

extending information about atomistic properties towards meso-/macroscale





S.N. Monteiro, S. Paciornik. "From Historical Backgrounds to Recent Advances in 3D Characterization of Materials: An Overview." JOM 69.1 (2017): 84-92.

Neutron Imaging (NI): Definition

- is a technology to produce visible information of objects and structures by using beams of free neutrons
- due to the high penetration power of neutrons for most of the observed materials also inner features can be visualized
- NI is therefore a suitable tool for non-destructive testing and for applied research

Neutron Imaging (NI): Aims

- non-destructive/non-invasive
- visualization and
- quantitative determination
- of material distributions and properties
- of macroscopic samples/objects (resolution > 1 µm; object size 1 … 20 cm)

Neutron Imaging (NI): Physical Background

- Matter is in general not transparent for visible light (exceptions: water, glass, plastics, …)
- Other types of radiation are also able to penetrate matter and enable the visualization of the inner of objects non-destructively. (complementarity information)
- In particular neutrons can penetrate thick (several cm) layers of material (e.g. metals, rocks, etc.) while being sensitive to small amounts of organic matter like liquids, plastics and plants.

X-rays and Neutrons

- **Neutrons** interact with the **nuclei** of the atoms: **strong nuclear force**.
- Different to **light** and **X-rays,** which interact with **the electron clouds** surrounding the nuclei: **electromagnetic force**.

- We can imagine the **nucleus** of the size of a **marble**.

Courtesy J. Houston, ESS

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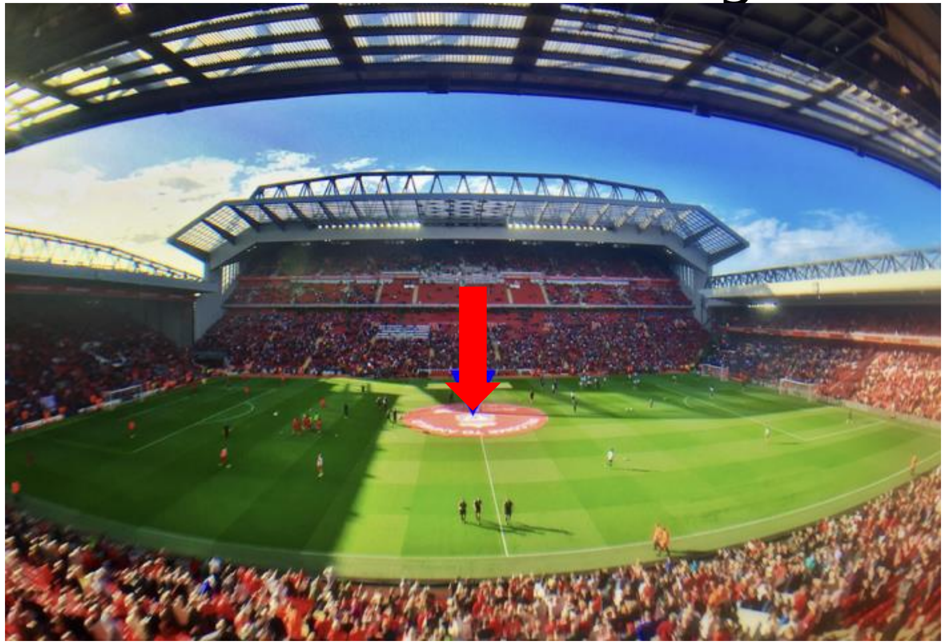
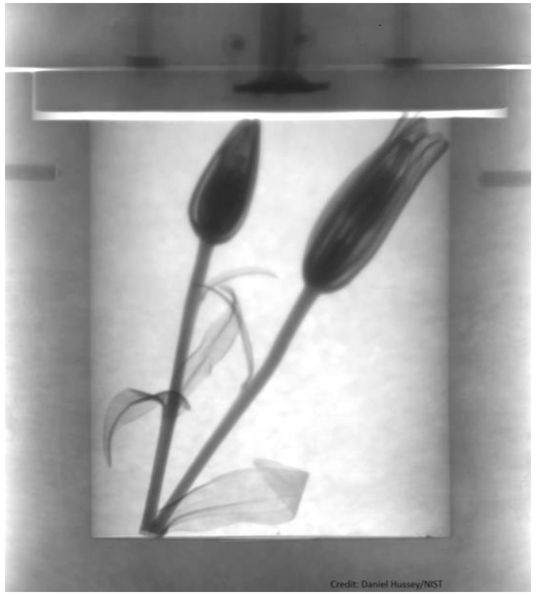


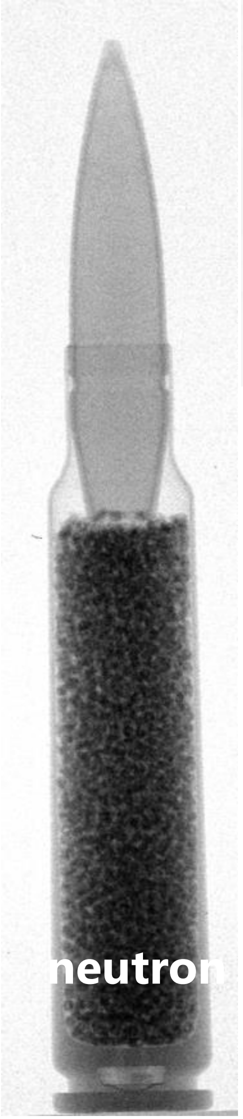
- We can imagine the **nucleus** of the size of a **marble**.
- The **atom** in proportion will be as big as a football **stadium**.
- **Neutrons interact** with the sample **only** when they **hit the nucleus**.

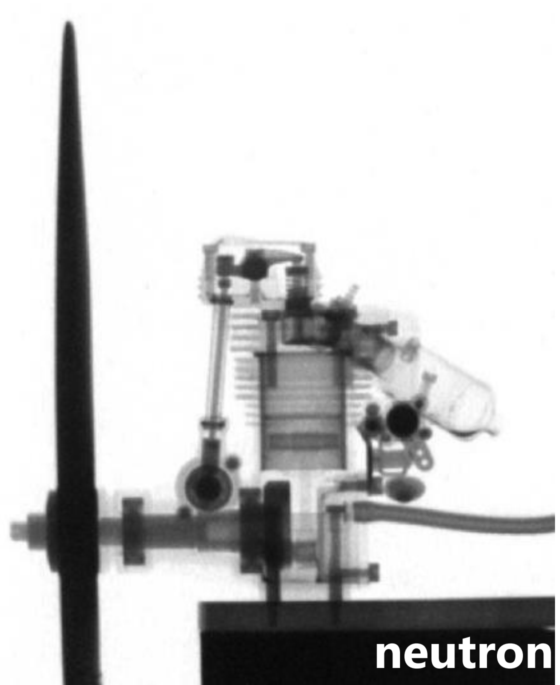
Courtesy J. Houston, ESS

X-rays and Neutrons

Neutrons 'see' light elements







Courtesy of NIST, PSI

X-rays and Neutrons

For X-rays = proportional increase!

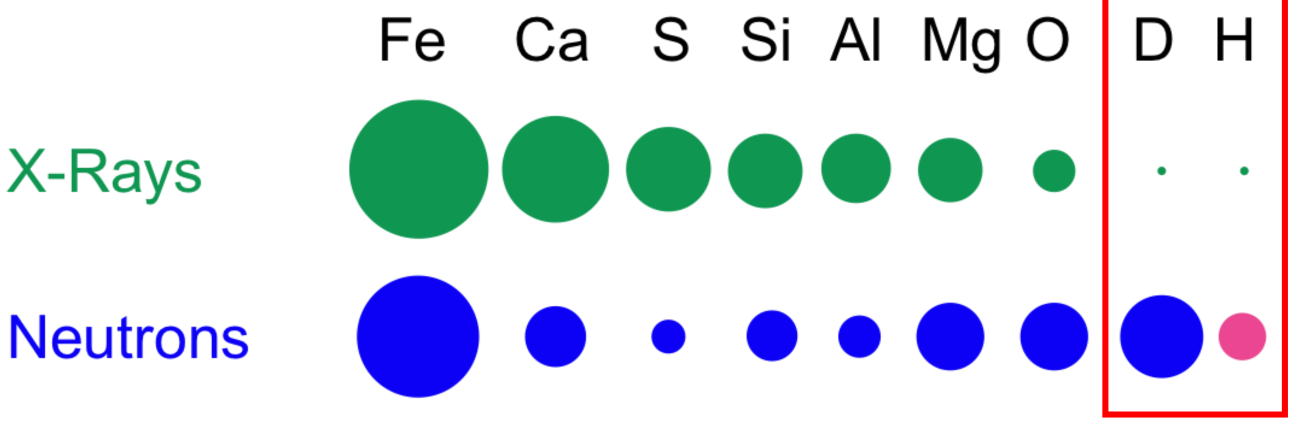
Attenuation coefficients with X-ray [cm?¹]

1a	2a	3b	4b	5b	6b	7b	8			1b	2b	3a	4a	5a	6a	7a	0
H 0.02																	He 0.02
Li 0.06	Be 0.22											B 0.28	C 0.27	N 0.11	O 0.16	F 0.14	Ne 0.17
Na 0.13	Mg 0.24											Al 0.38	Si 0.33	P 0.25	S 0.30	Cl 0.23	Ar 0.20
K 0.14	Ca 0.26	Sc 0.48	Ti 0.73	V 1.04	Cr 1.29	Mn 1.32	Fe 1.57	Co 1.78	Ni 1.96	Cu 1.97	Zn 1.64	Ga 1.42	Ge 1.33	As 1.50	Se 1.23	Br 0.90	Kr 0.73
Rb 0.47	Sr 0.86	Y 1.61	Zr 2.47	Nb 3.43	Mo 4.29	Tc 5.06	Ru 5.71	Rh 6.08	Pd 6.13	Ag 5.67	Cd 4.84	In 4.31	Sn 3.98	Sb 4.28	Te 4.06	I 3.45	Xe 2.53
Cs 1.42	Ba 2.73	La 5.04	Hf 19.70	Ta 25.47	W 30.49	Re 34.47	Os 37.92	Ir 39.01	Pt 38.61	Au 35.94	Hg 25.88	Tl 23.23	Pb 22.81	Bi 20.28	Po 20.22	At	Rn 9.77
Fr	Ra 11.80	Ac 24.47	Rf	Ha													
Lanthanides	Ce 5.79	Pr 6.23	Nd 6.46	Pm 7.33	Sm 7.68	Eu 5.66	Gd 8.69	Tb 9.46	Dy 10.17	Ho 10.91	Er 11.70	Tm 12.49	Yb 9.32	Lu 14.07			
Actinides	Th 28.95	Pa 39.65	U 49.08	Np	Pu	Am	Cm	Bk	Vf	Es	Fm	Md	No	Lr x-ray			

For neutrons = completely unsystematic!

Attenuation coefficients with neutrons [cm?¹]

1a	2a	3b	4b	5b	6b	7b	8			1b	2b	3a	4a	5a	6a	7a	0
H 3.44																	He 0.02
Li 3.30	Be 0.79											B 101.60	C 0.56	N 0.43	O 0.17	F 0.20	Ne 0.10
Na 0.09	Mg 0.15											Al 0.10	Si 0.11	P 0.12	S 0.06	Cl 1.33	Ar 0.03
K 0.06	Ca 0.08	Sc 2.00	Ti 0.60	V 0.72	Cr 0.54	Mn 1.21	Fe 1.19	Co 3.92	Ni 2.05	Cu 1.07	Zn 0.35	Ga 0.49	Ge 0.47	As 0.67	Se 0.73	Br 0.24	Kr 0.61
Rb 0.08	Sr 0.14	Y 0.27	Zr 0.29	Nb 0.40	Mo 0.52	Tc 1.76	Ru 0.58	Rh 10.88	Pd 0.78	Ag 4.04	Cd 115.11	In 7.58	Sn 0.21	Sb 0.30	Te 0.25	I 0.23	Xe 0.43
Cs 0.29	Ba 0.07	La 0.52	Hf 4.99	Ta 1.49	W 1.47	Re 6.85	Os 2.24	Ir 30.46	Pt 1.46	Au 6.23	Hg 16.21	Tl 0.47	Pb 0.38	Bi 0.27	Po	At	Rn
Fr	Ra 0.34	Ac	Rf	Ha													
*Lanthanides	Ce 0.14	Pr 0.41	Nd 1.87	Pm 5.72	Sm 171.47	Eu 94.58	Gd 1479.04	Tb 0.93	Dy 32.42	Ho 2.25	Er 5.48	Tm 3.53	Yb 1.40	Lu 2.75			
**Actinides	Th 0.59	Pa 8.46	U 0.82	Np 9.80	Pu 50.20	Am 2.86	Cm	Bk	Cf	Es	Fm	Md	No	Lr neut.			



...even for different isotopes of the same element!

X-rays and Neutrons

Attenuation coefficients with X-ray [cm?^{1}]

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Attenuation coefficients with neutrons [cm?^{1}]

For neutrons = completely unsystematic!

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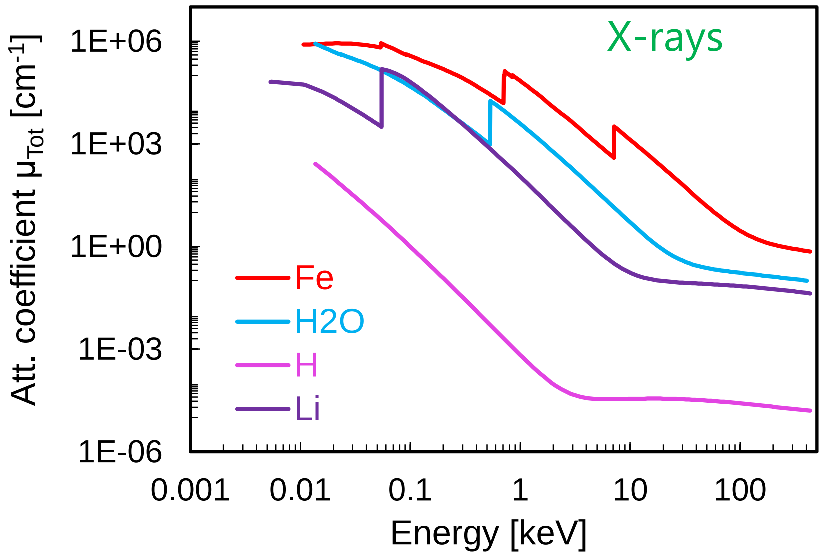
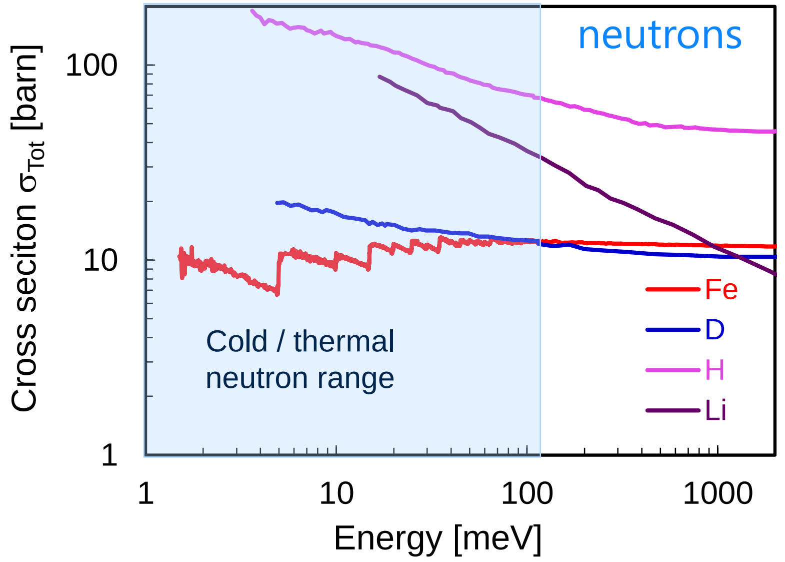
The cross section (& attenuation) is energy (wavelength) dependent for most materials!





$$\sigma_{\text{tot}}(\lambda) = \sigma_{\text{coh}}(\lambda) + \sigma_{\text{incoh}}(\lambda) + \sigma_{\text{abs}}(\lambda)$$

Properties of the free neutron

Mean diameter: $1.6 * 10^{-15}$ m

Mass: $1.674927351(74) * 10^{-27}$ kg

Charge: 0

Spin: ½ (two states possible)

Velocity: few m/s (ultra cold) to speed of light (very fast)

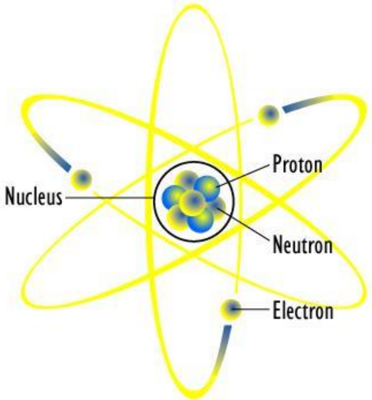
Elementary composition: 3 Quarks up-down-down

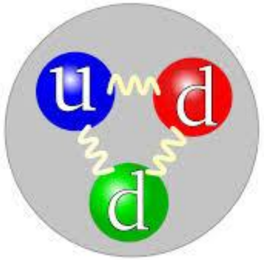
Magnetic moment: $-1.913\ \mu_N$

Interaction with matter: nuclear reactions: absorption, scattering, fission

Classification: Baryon, Fermion

Half-life: 881.5 s





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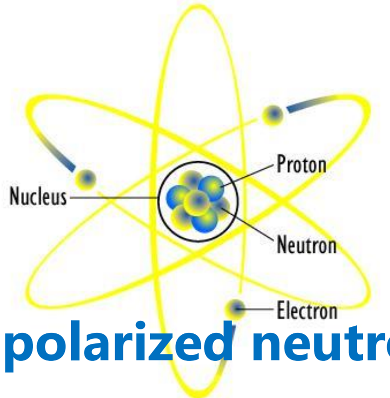
Mass: $1.674927351(74) * 10^{-27}$ kg

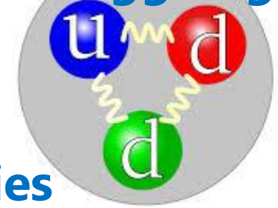
Charge: **0** — **deep penetration into matter**



Spin: ½ (two states possible) — **imaging with polarized neutrons**

Velocity: few m/s (ultra cold) to speed of light (very fast) — **energy – selected neutron imaging (e.g. at Bragg edges; contrast variation)**

Elementary composition: 3 Quarks up-down-down



Magnetic moment: $-1.913\ \mu_N$ — **study of magnetic properties**

Interaction with matter: nuclear reactions: absorption, scattering, fission
needed for efficient neutron detection

Classification: Baryon, Fermion

Half-life: 881.5 s

Text in red: with relevance for neutron imaging

Neutron parameters – and conversion

$$E = \frac{mv^2}{2} = \frac{h^2}{2m} \cdot \frac{1}{\lambda^2} \Rightarrow E[meV] = \frac{81.82}{(\lambda[\text{Å}])^2}$$ **energy**

$$\lambda[\text{Å}] = \frac{9.045}{\sqrt{E[meV]}}$$ **wavelength**

$$v[m/s] = \frac{3956}{\lambda[\text{Å}]} = 437 \cdot \sqrt{E[meV]}$$ **velocity**

https://www.psi.ch/en/niag/neutron-physics

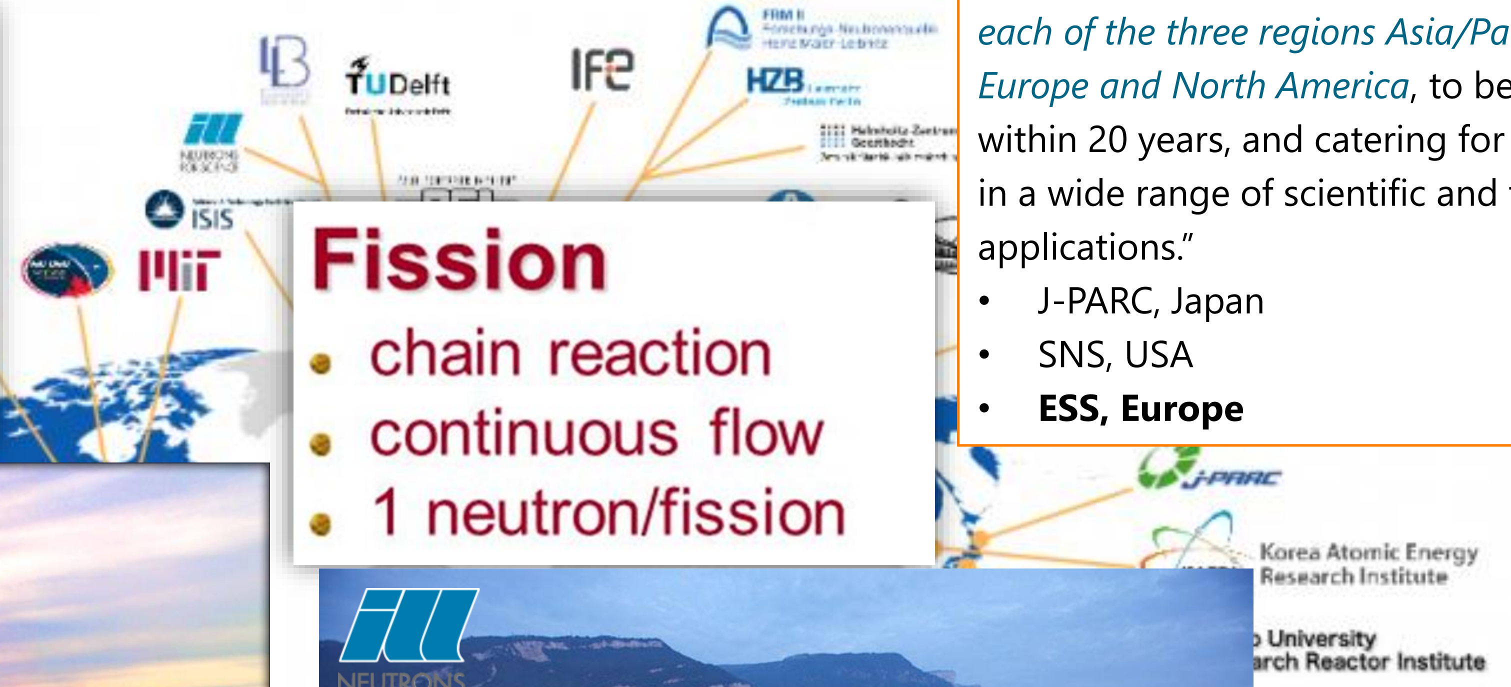
How do I get free neutrons?

Access by beam time proposal: Exercise this week!

How do I get free neutrons?

Spallation

- no chain reaction
- pulsed operation
- 30 neutrons/proton
- Time resolved exp.



Fission

- chain reaction
- continuous flow
- 1 neutron/fission

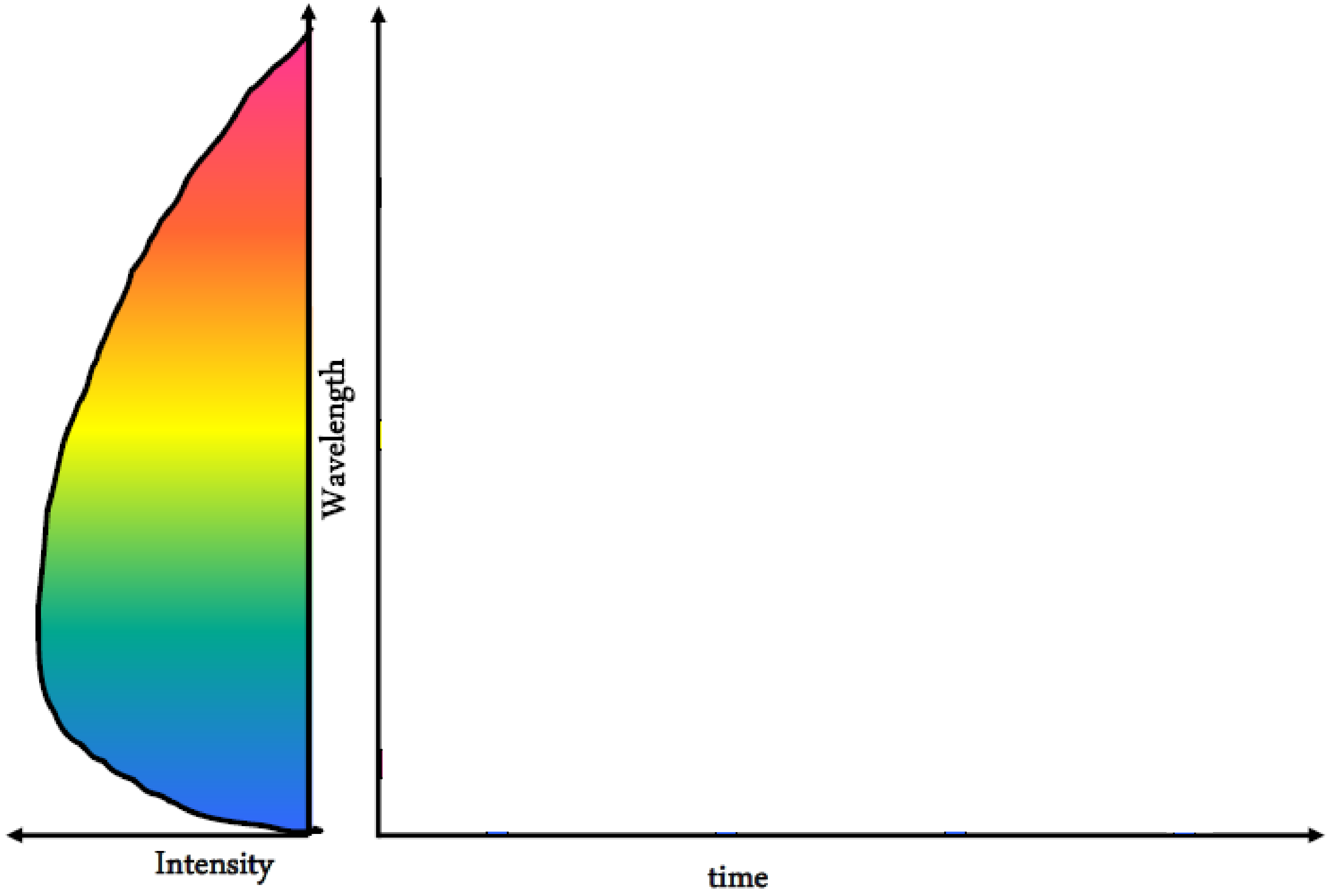
OECD recommendation 2006

"The Neutron Sources Working Group recommends a scenario which aims at the construction of advanced *neutron sources in each of the three regions Asia/Pacific rim, Europe and North America*, to be operational within 20 years, and catering for regional needs in a wide range of scientific and technological applications."

- J-PARC, Japan
- SNS, USA
- **ESS, Europe**

How do I get free neutrons?

Reactor or pulsed source?



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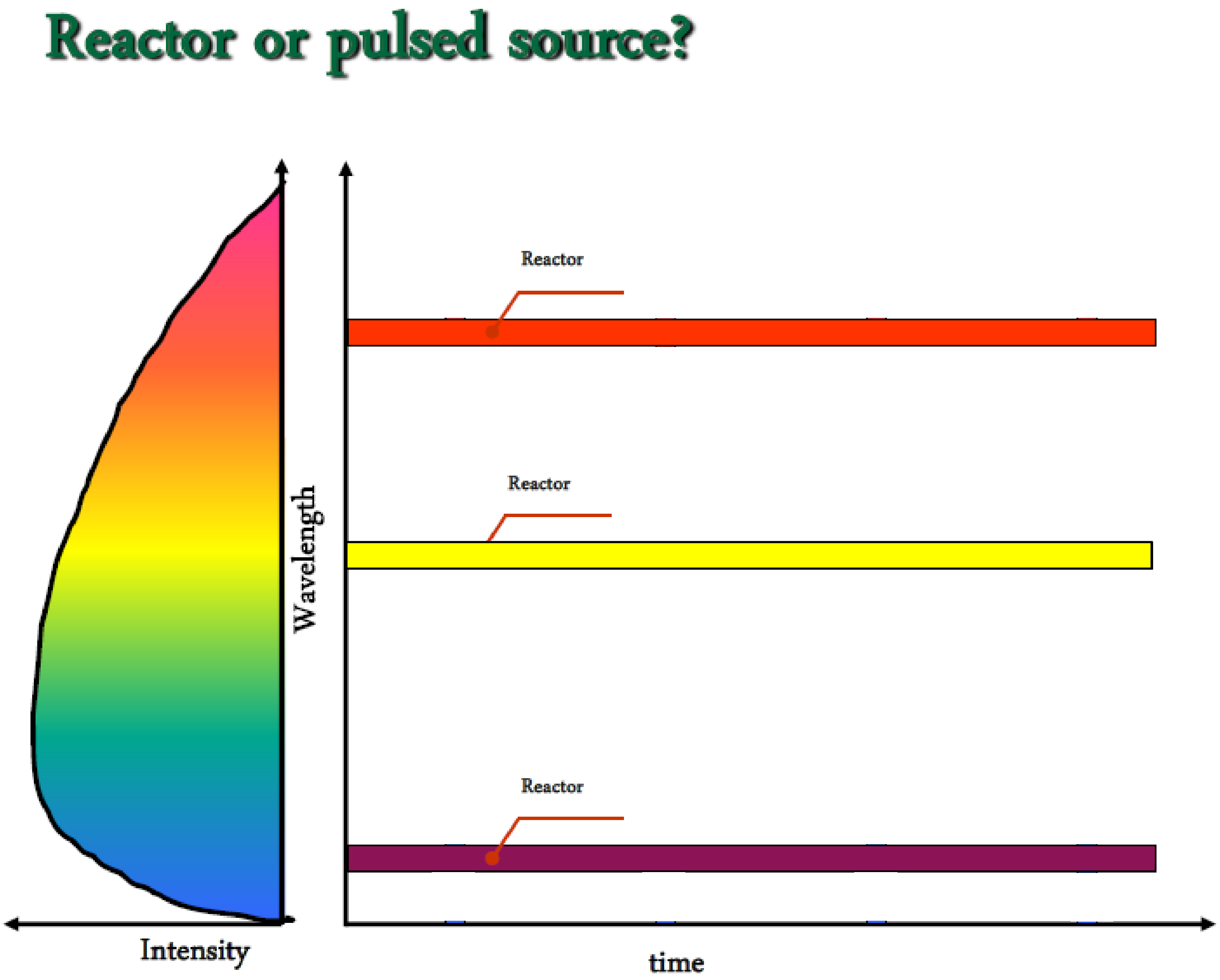
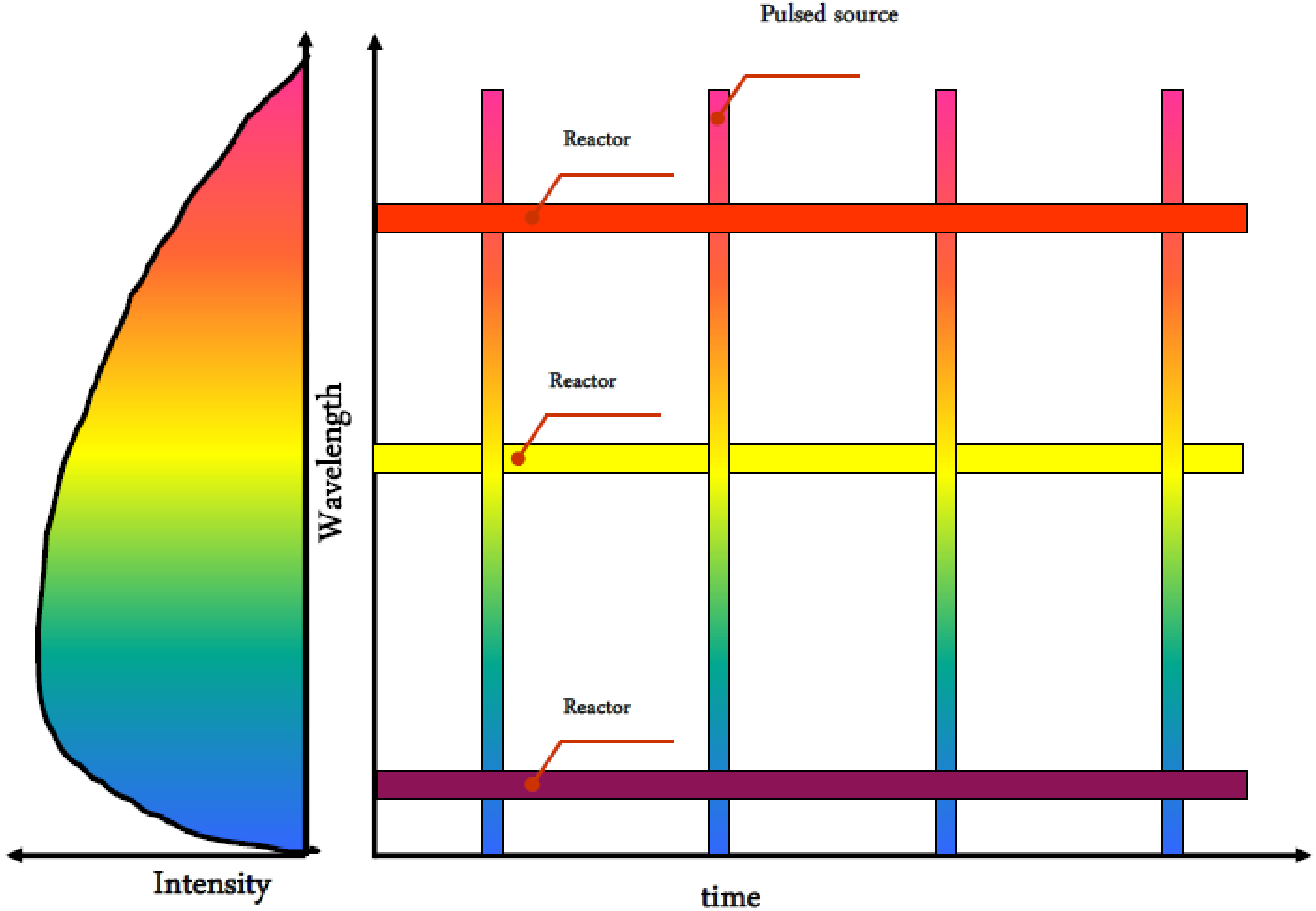
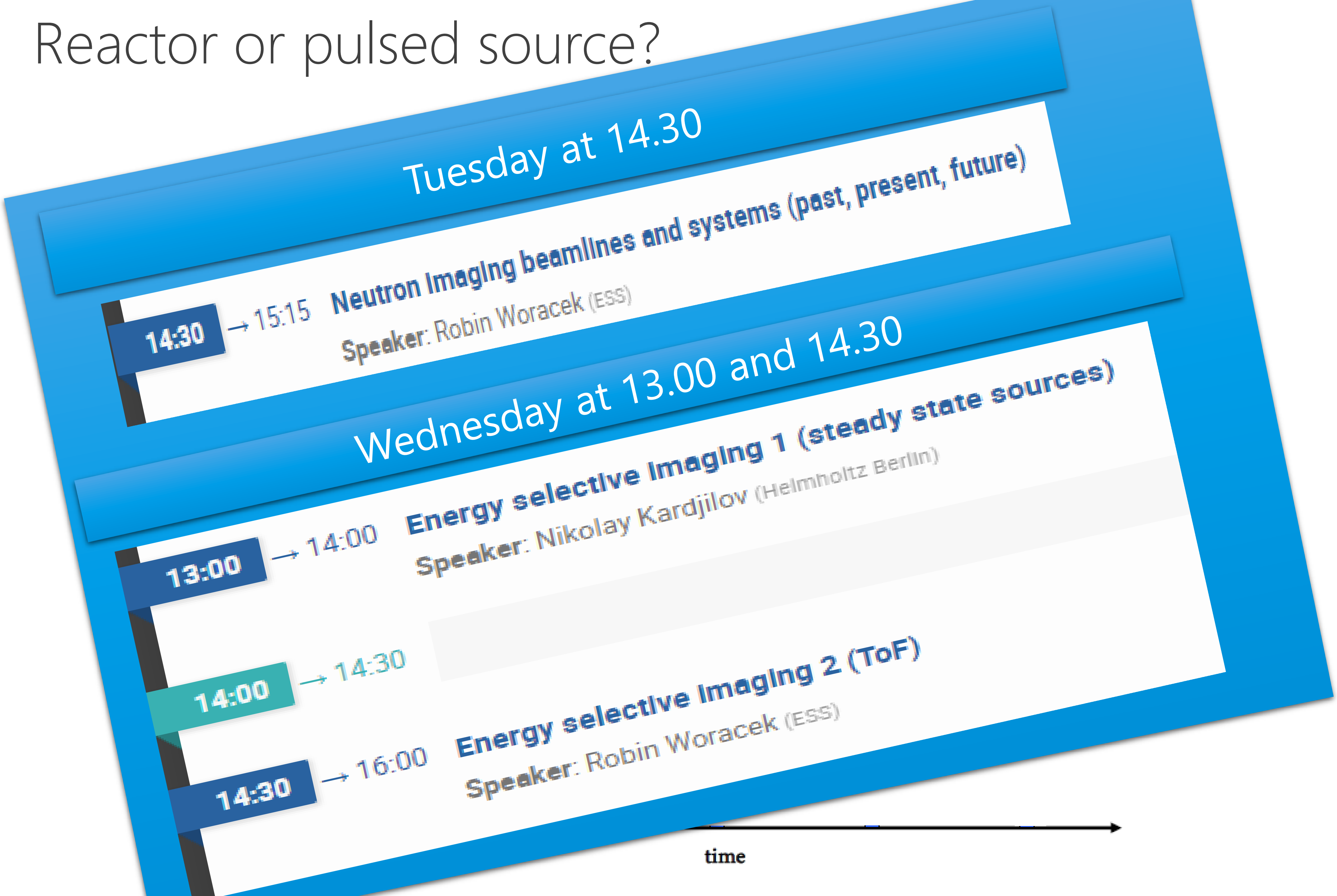


How do I get free neutrons?

Reactor or pulsed source?



Reactor or pulsed source?



Neutron Utilization for Research

ADVANTAGES

- no charge: often deeper penetration
- magnetic moment: magnetic interaction with nuclei → polarized neutrons
- high sensitivity for light elements
- different isotopes can be distinguished (D:H, B-10:B-11, Li-6: Li-7, U-235:U-238)
- energy selection using time-of-flight (at pulsed sources)

DISADVANTAGES

- neutron intensity limited
- no direct detection – a secondary process is needed (limiting spatial resolution)
- no charge: no focusing and guiding by el.-magnetic fields possible
- risks of samples activation

Introduction to neutron imaging

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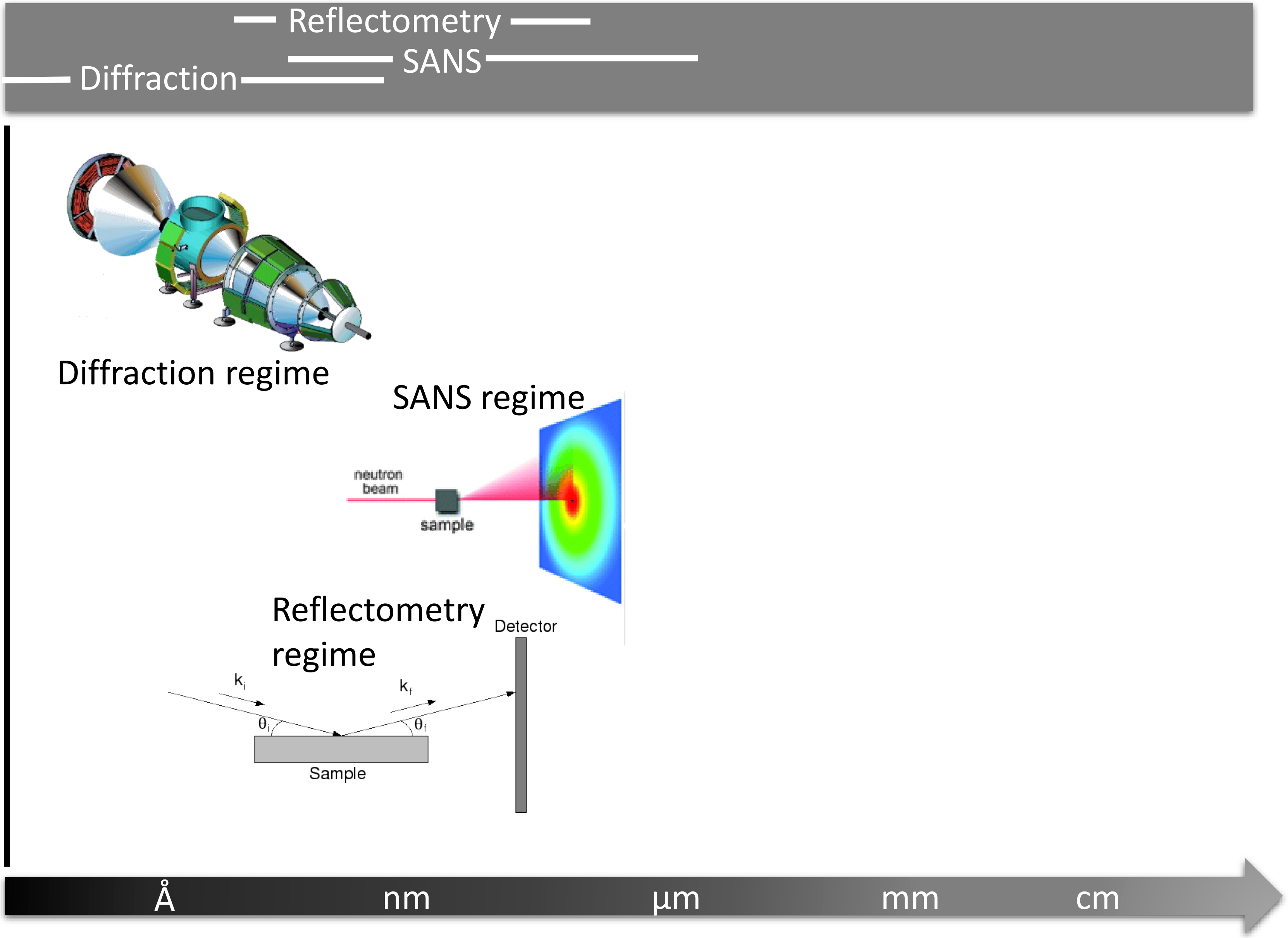
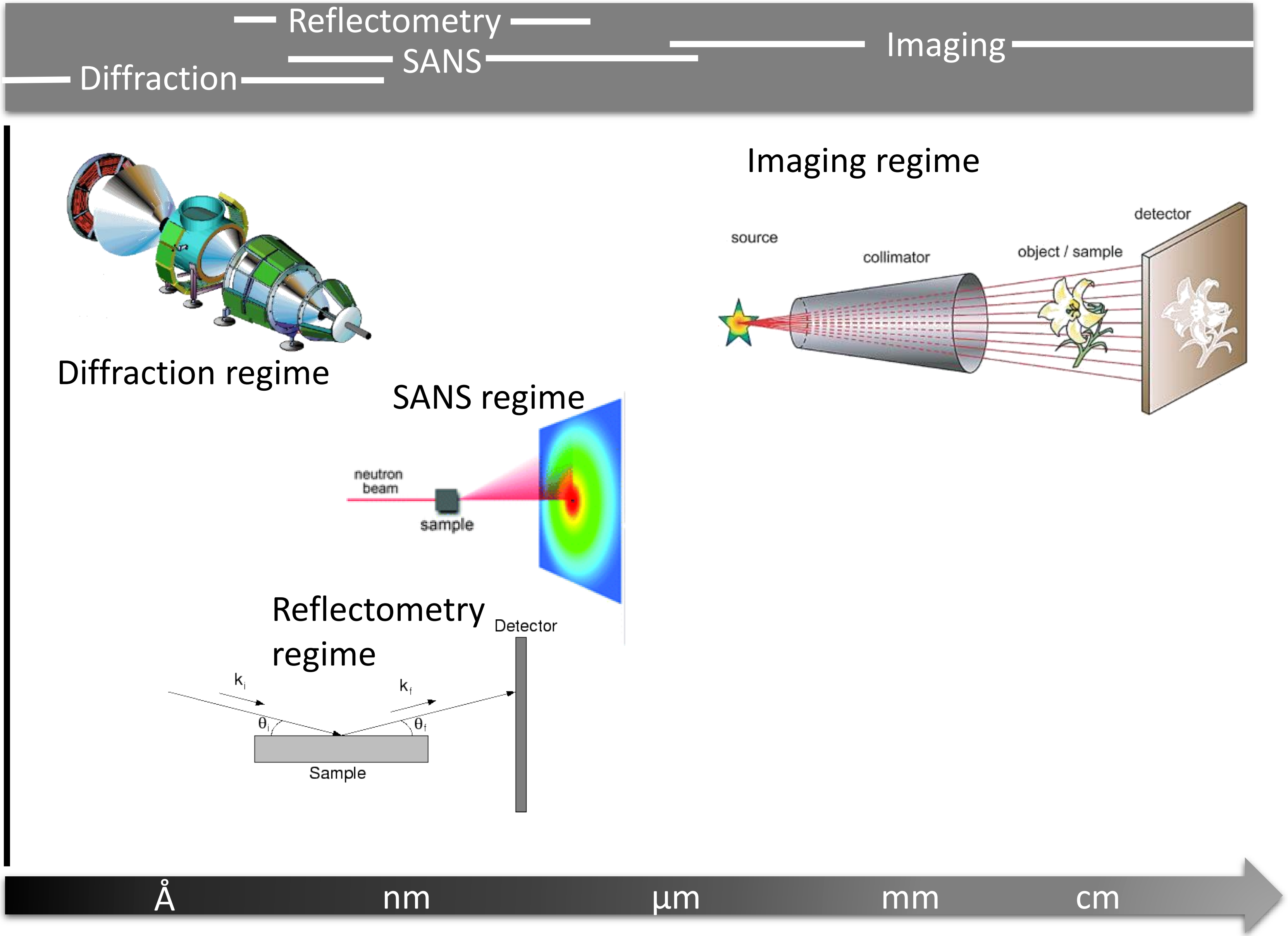
Neutron Methods & Length Scales

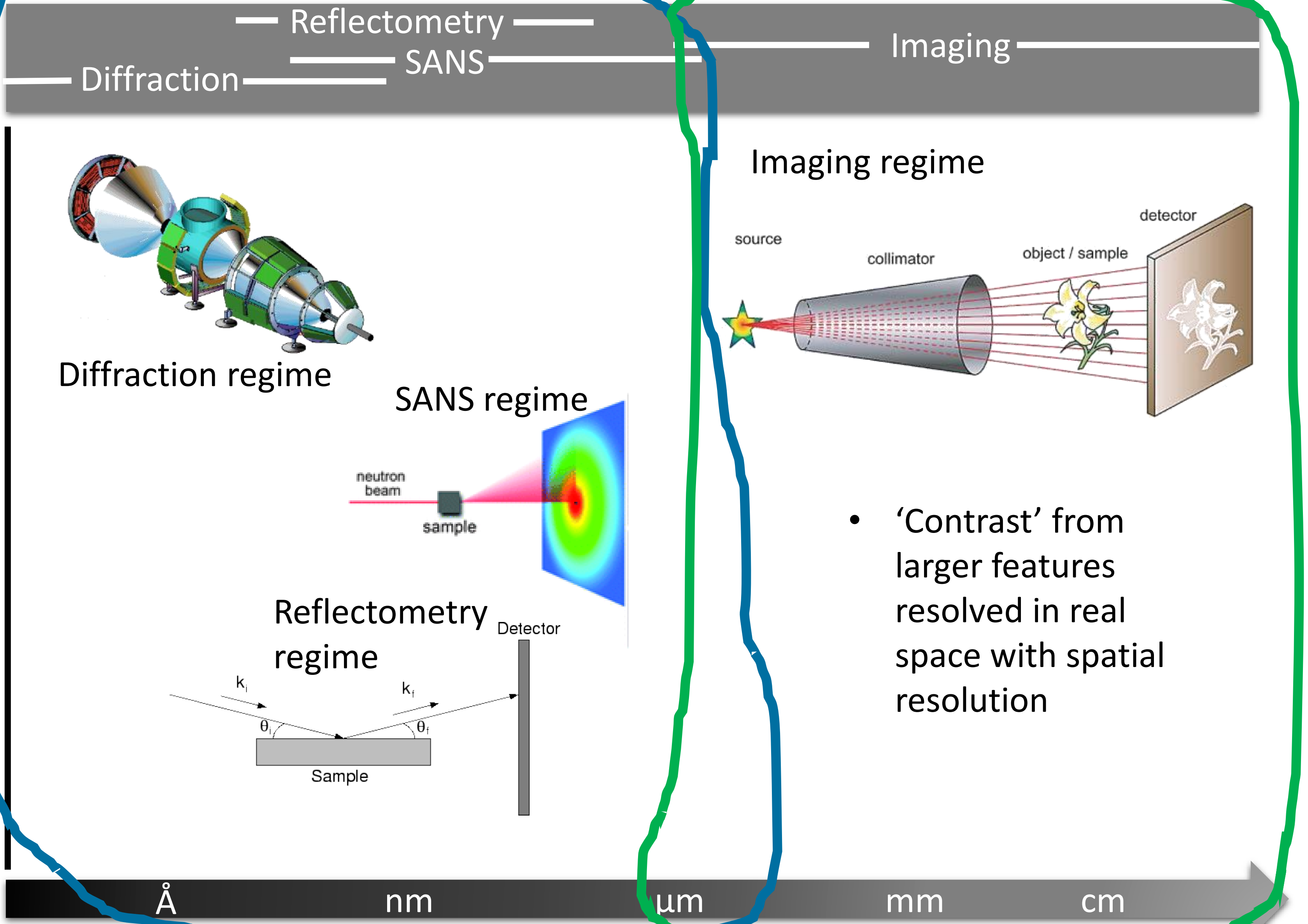


Neutron Methods & Length Scales



Neutron Methods & Length Scales

- ‘Contrast’ due to small spatial features
- Usually averaged over several mm^3



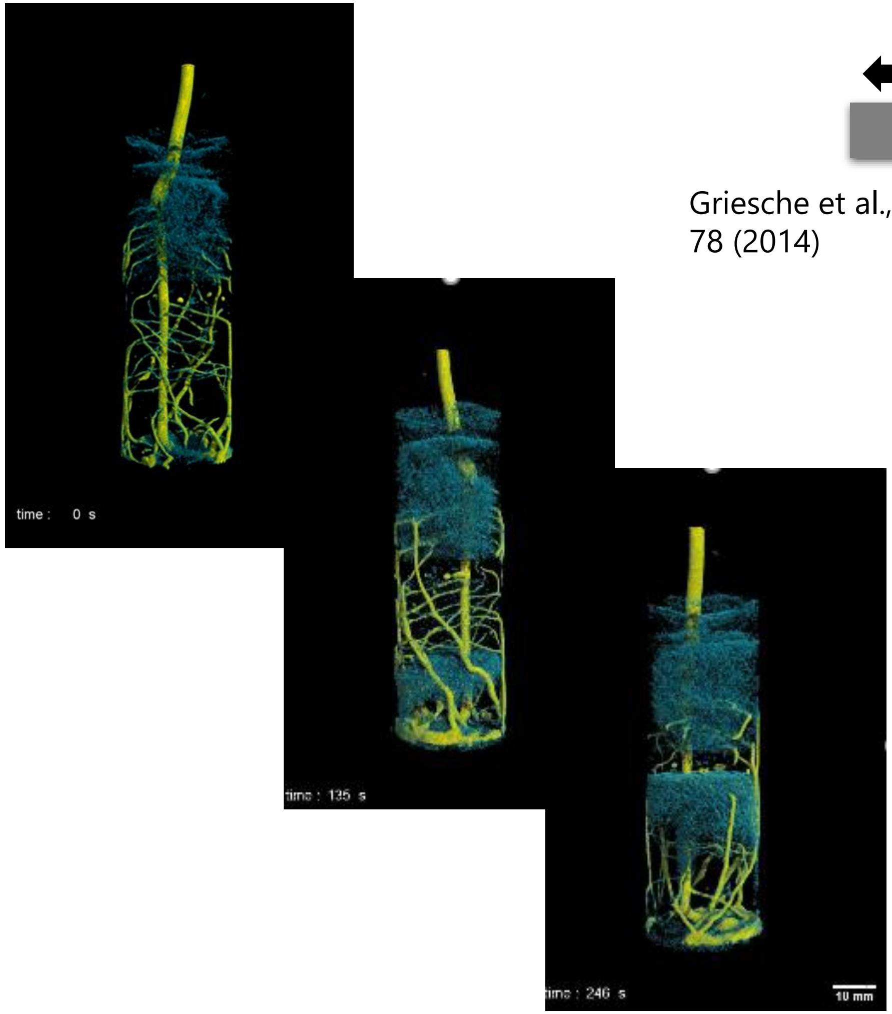
- ‘Contrast’ from larger features resolved in real space with spatial resolution

Neutron Methods & Length Scales

Neutron Imaging

Applications

- Metals/ Engineering
- Hydrogen
- Energy Storage
- Cultural Heritage

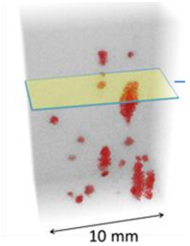


Imaging regime

Attenuation

Griesche et al., Acta Materialia 78 (2014)

Hydrogen in metals



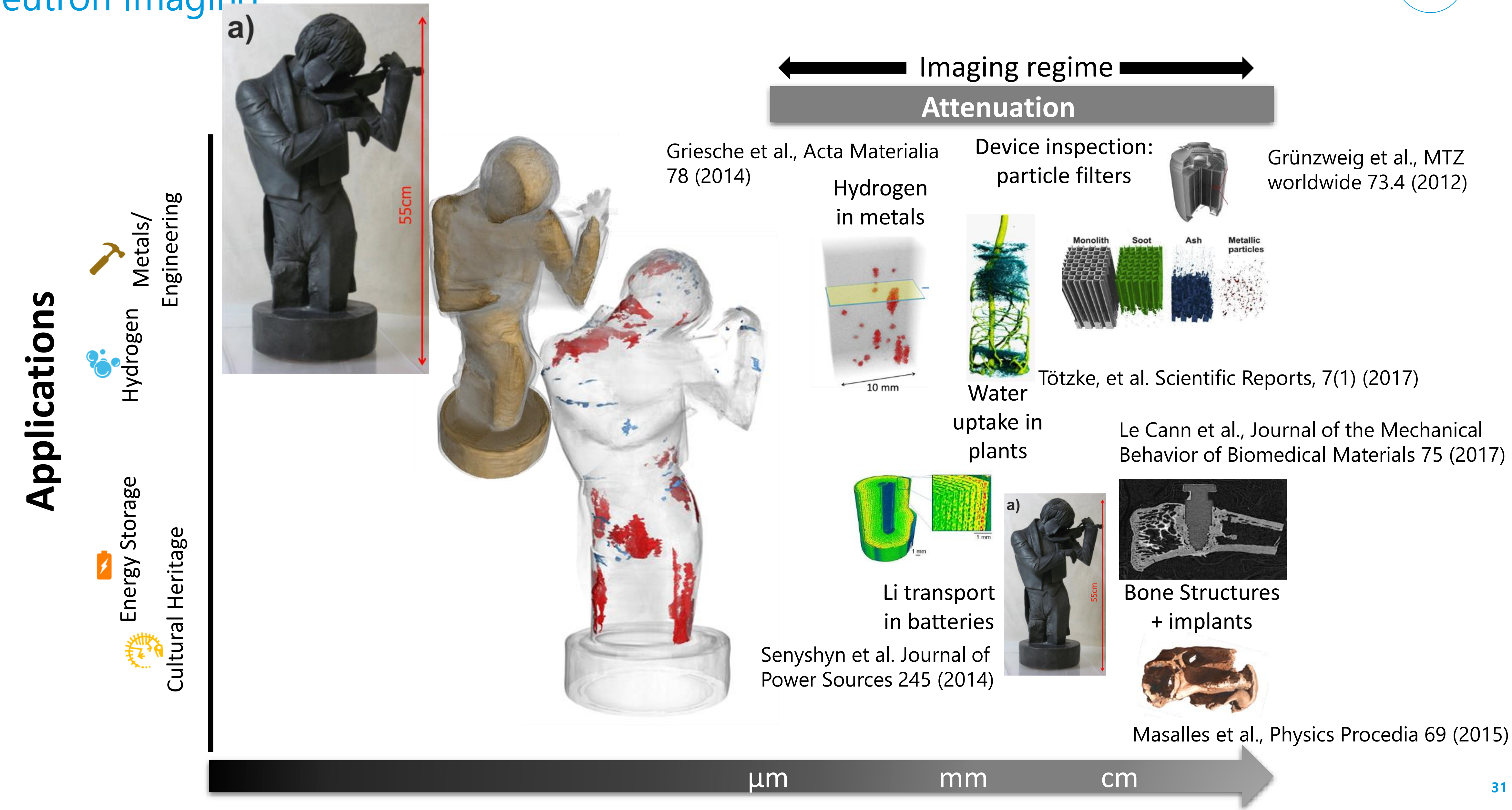
Water uptake in plants

Tötzke, et al. Scientific Reports, 7(1) (2017)

µm mm cm

Neutron Methods & Length Scales

Neutron Imaging



Neutron Methods & Length Scales

Neutron Imaging

Kardjilov, Manke, Woracek, Banhart,. Advances in neutron imaging. Materials Today 21 (2018)

Imaging regime

Attenuation

Applications

Metals/ Engineering

Hydrogen

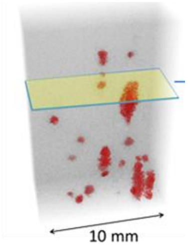
Energy Storage

Cultural Heritage

Fine then… let us have a look at some applications in more detail!

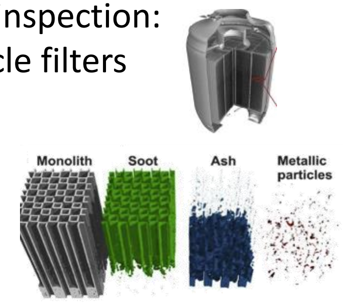
Let him first explain some peculiarities of neutron imaging …

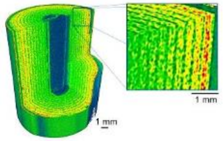
Hydrogen in metals



Water uptake in plants

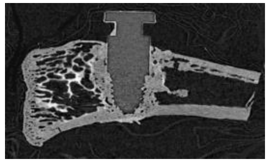
Device inspection: particle filters





Li transport in batteries

Corrosion



Bone Structures + implants

µm mm cm

Introduction to neutron imaging

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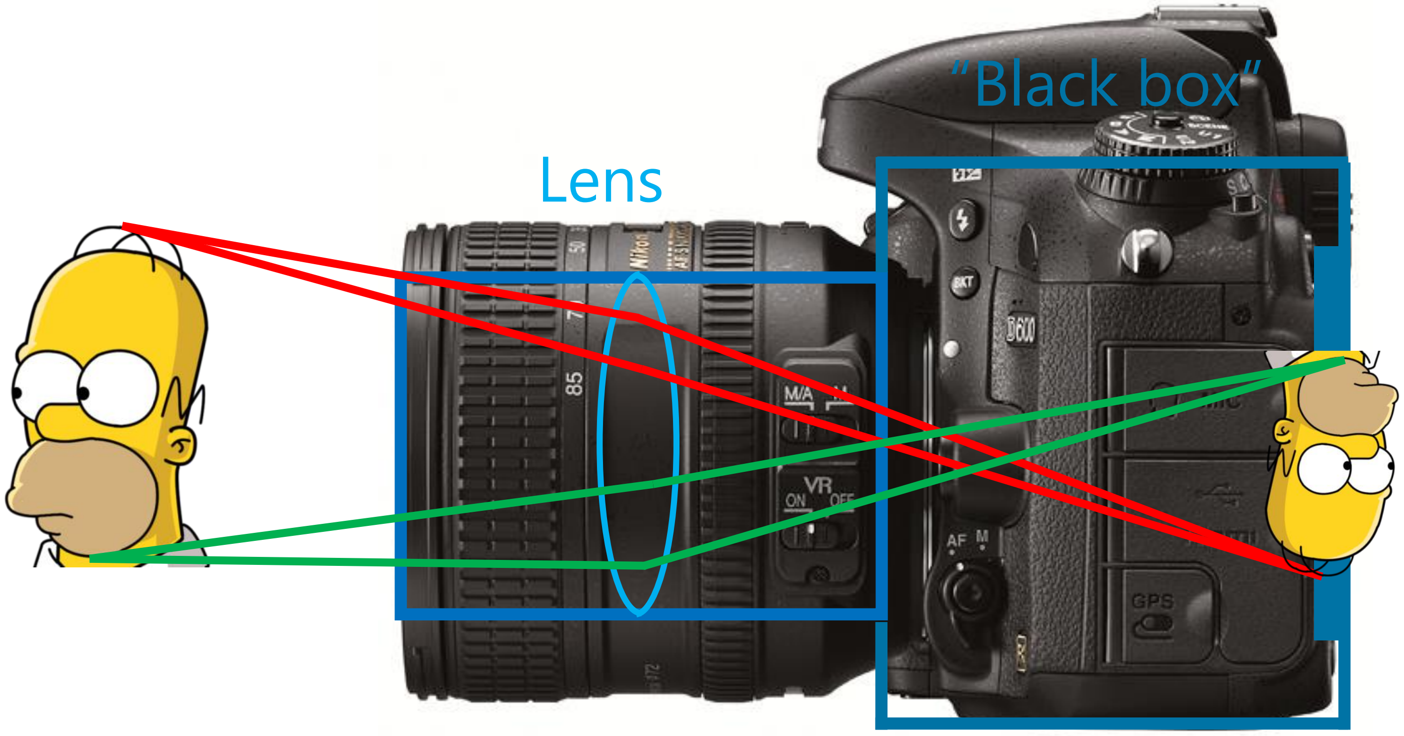
- ❑ Beer–Lambert law for attenuation based imaging
- ❑ The neutron imaging setup: geometrical considerations & Scattering vs Absorption
- ❑ Principles of Tomography
- ❑ Advanced Neutron Imaging Methods
- ❑ Neutron Detection

Neutron Imaging

How is an image recorded?

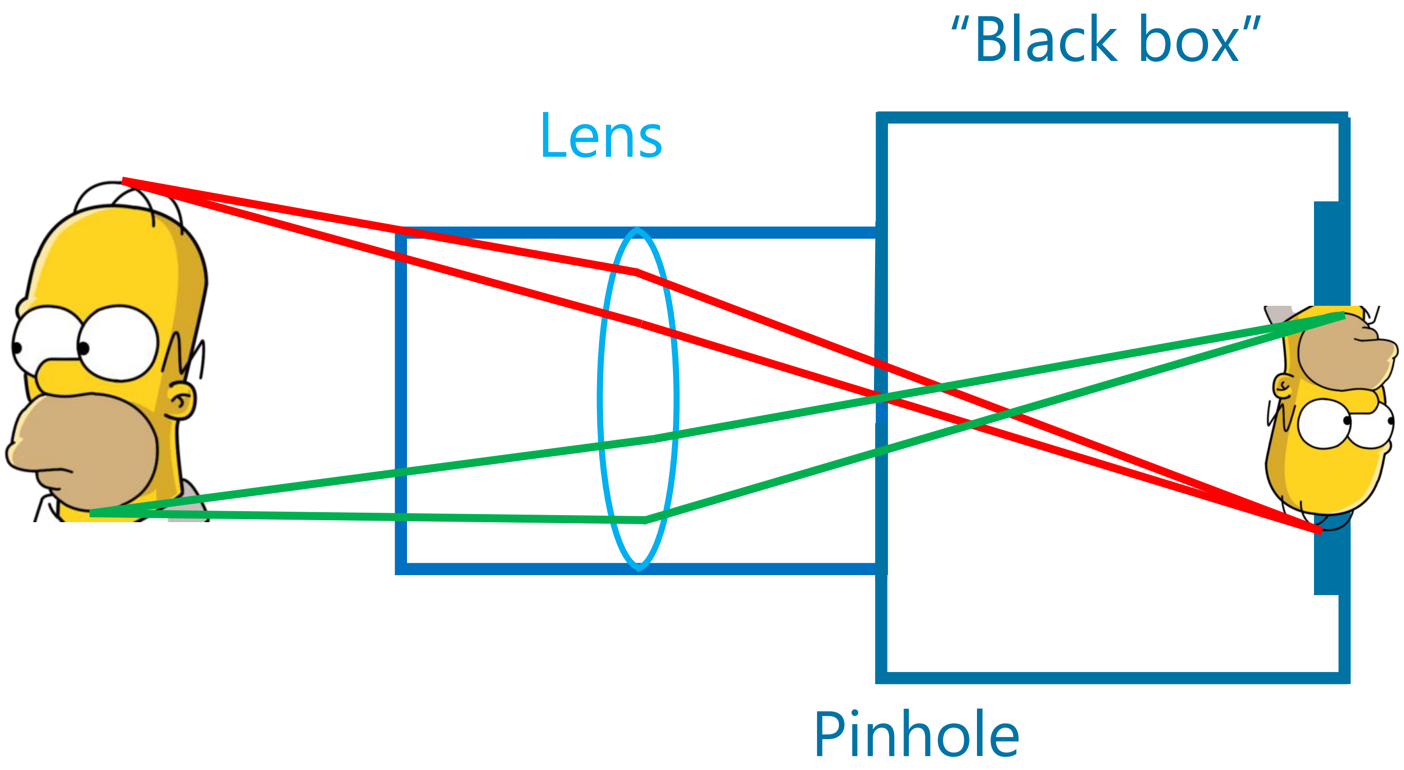
Neutron Imaging

How is an image recorded?



Neutron Imaging

How is an image recorded?



Neutron Imaging

How is an image recorded?

Pop-Up Quiz:
How can we record an image without a lens?

No optics!?!

“Black box”

- Minimize the distance between object and box
- Maximize the distance between object and box
- Using a small pinhole

Pinhole

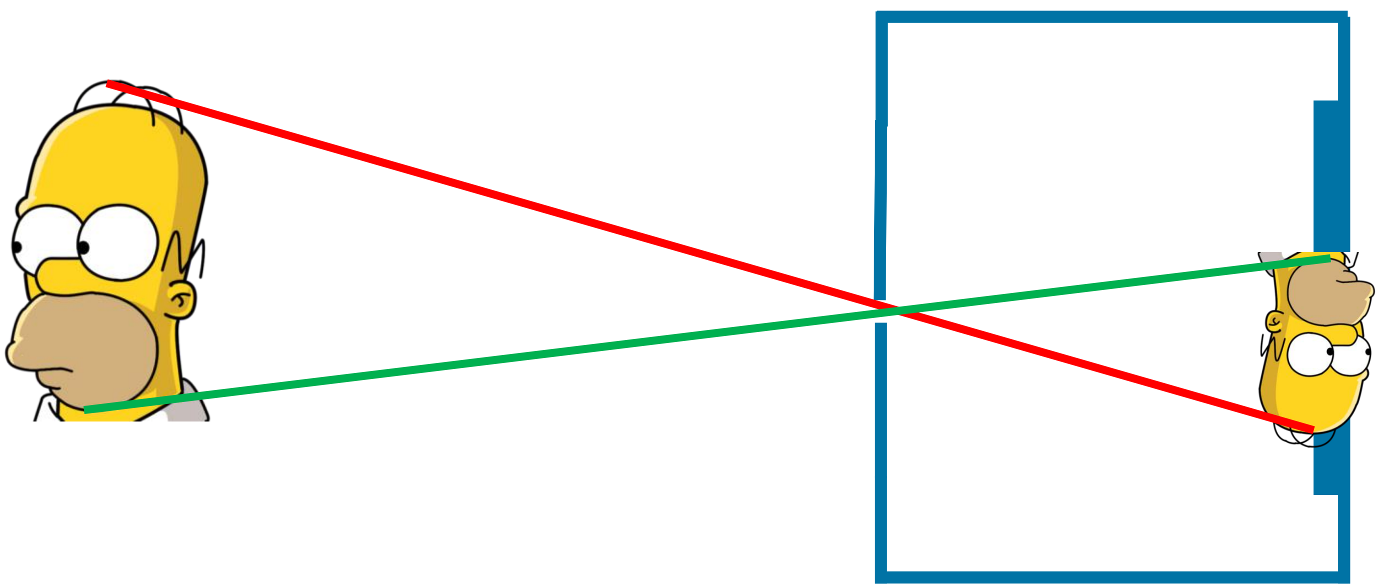
Neutron Imaging

How is an image recorded?
Transmission

Pop-Up Quiz:
How can we record an image without a lens?

No optics!?!

“Black box”



Pinhole

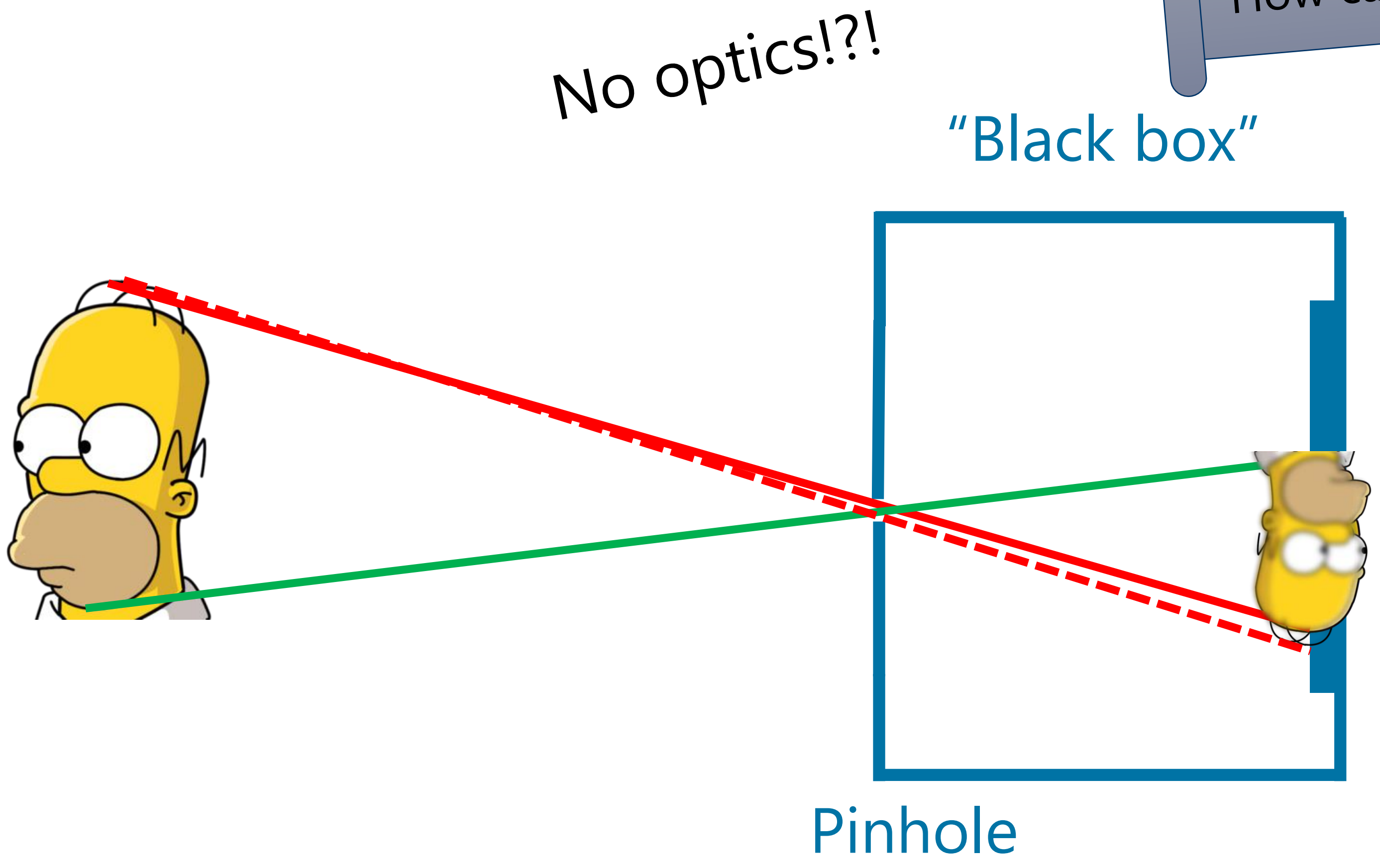
- Minimize the distance between object and box
- Maximize the distance between object and box
- Using a small pinhole

Neutron Imaging

How is an image recorded?

Transmission

Pop-Up Quiz:
How can we record an image without a lens?



- Minimize the distance between object and box
- Maximize the distance between object and box
- Using a small pinhole

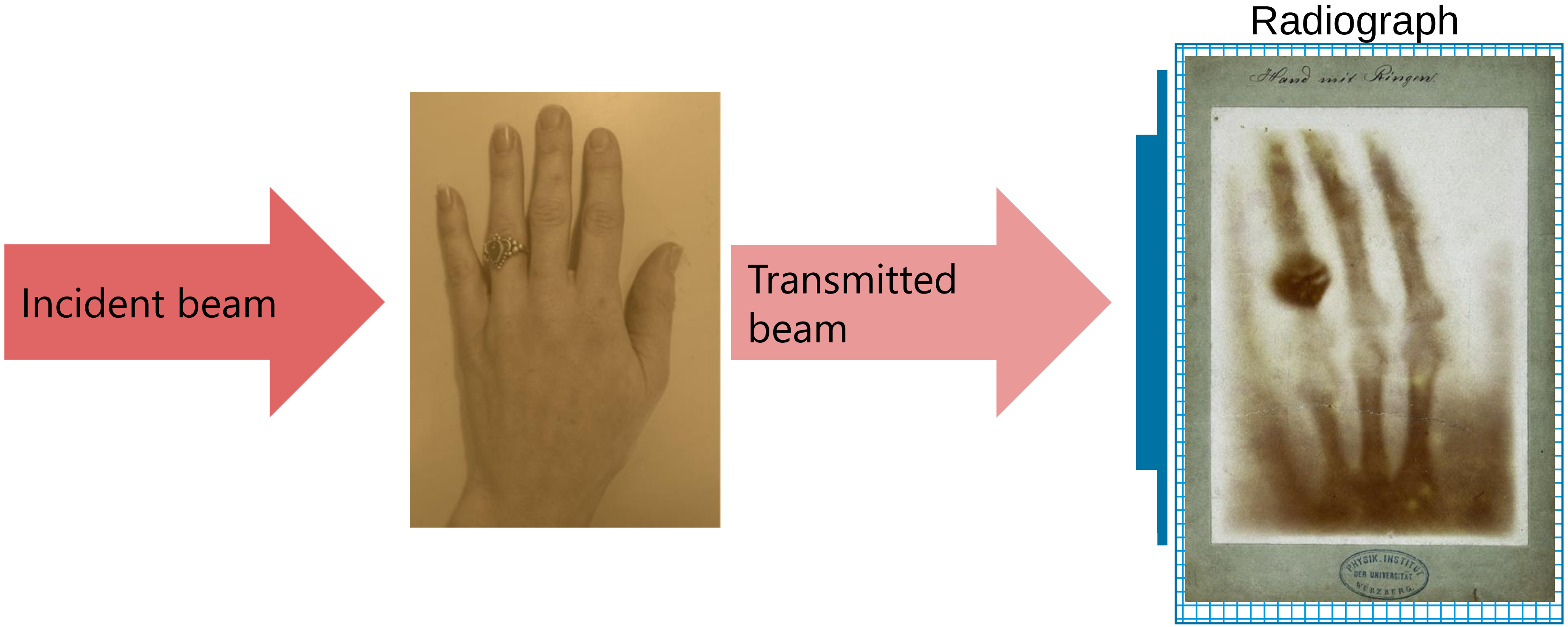
Neutron Imaging

How is a Transmission image recorded?

No optics!?!

Neutron Imaging

How is a Transmission image recorded?



Neutron Imaging

How is a Transmission image recorded?

X-ray

First experiments with a new kind of radiation were performed by Konrad Röntgen in 1895 during investigations with cathode-ray tubes.

He found the new ray could pass through most substances casting shadows of solid objects.

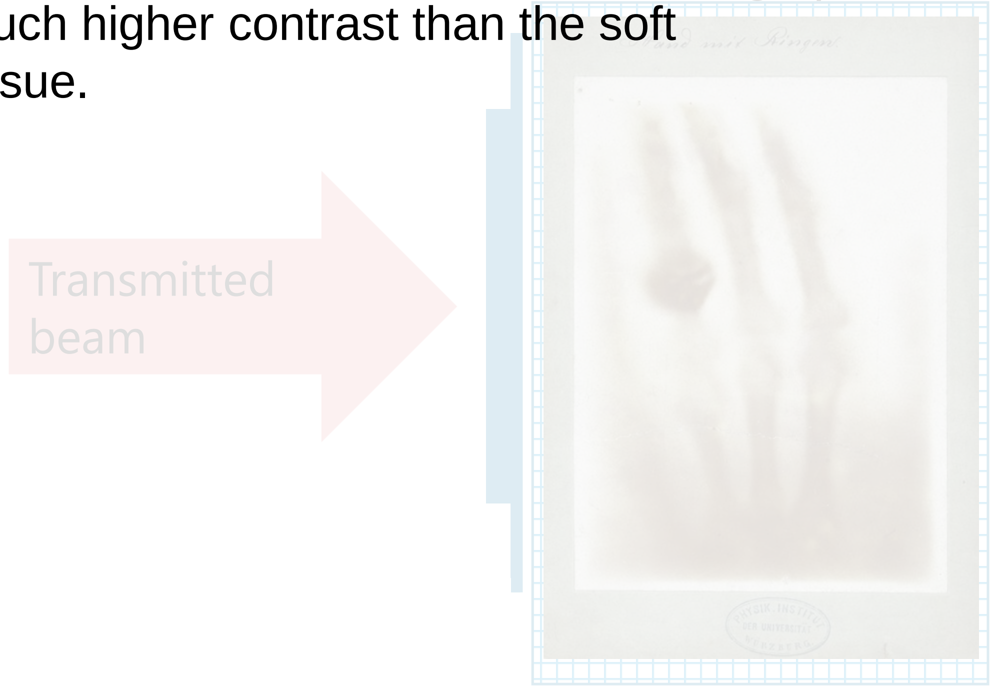
In conjunction with a photographic plate, a picture of interior body parts can be obtained when human tissue will be investigated.

Neutron Imaging

How is a Transmission image recorded?

One of the first experiments late in 1895 was a film of a hand of his wife.

The bones and also finger rings deliver much higher contrast than the soft tissue.

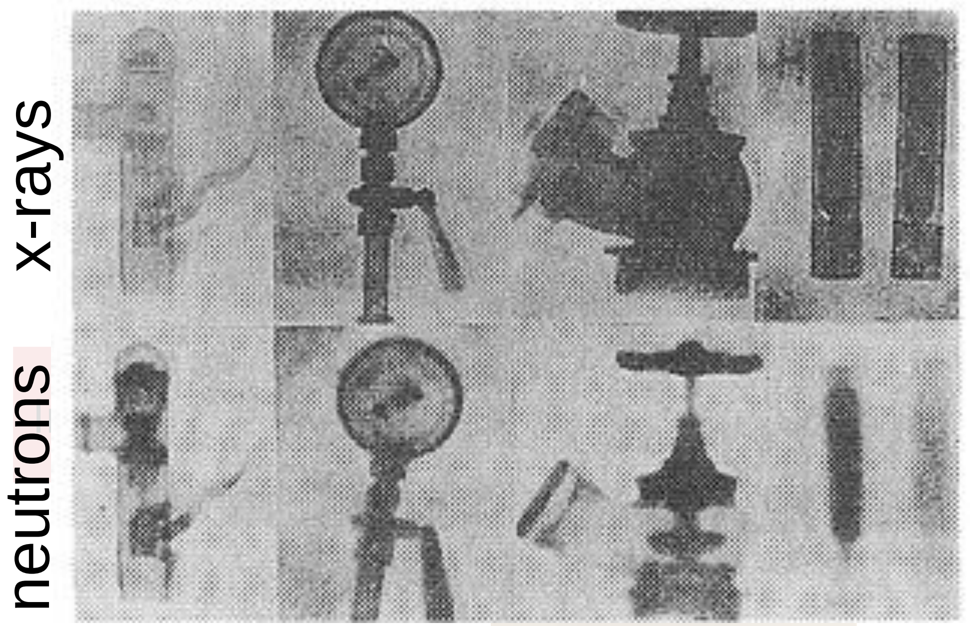


Neutron Imaging

How is a Transmission image recorded?

First neutron radiographs

Comparison between x-ray and neutron images



Berlin, 1935 – 1938
H. Kallmann & Kuhn with Ra-Be and neutron generator

Berlin until Dec. 1944
O. Peter with an accelerator neutron source

But the real programs with neutrons started after World War II at research reactors

Neutron Imaging

How is a Transmission image...

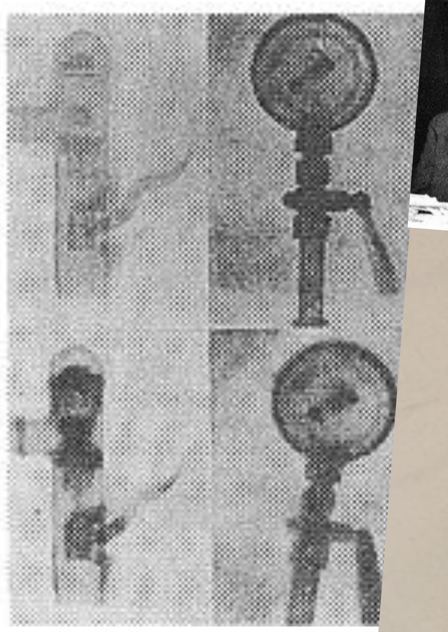
Pop-Up Quiz:
Does anyone know who discovered the neutron and when?

First n...

Comparison between x-ray and neutron images

x-rays

neutrons



Letters to the Editor

[The Editor does not hold himself responsible for opinions expressed by his correspondents. Neither can he undertake to return, nor to correspond with the writers of, rejected manuscripts intended for this or any other part of NATURE. No notice is taken of anonymous communications.]

Possible Existence of a Neutron

IT has been shown by Bothe and others that beryllium when bombarded by α-particles of polonium emits a radiation of great penetrating power, which has an absorption coefficient in lead of about 0·3 (cm.)$^{-1}$. Recently Mme. Curie-Joliot and M. Joliot found, when measuring the ionisation produced by this beryllium radiation in a vessel with a thin window, that the ionisation increased when matter containing hydrogen was placed in front of the window. The effect appeared to be due to the ejection of protons with velocities up to a maximum of nearly 3×10^9 cm. per sec. They suggested that the transference of energy to the proton was by a process similar to the Compton effect, and estimated that the beryllium radiation had a quantum energy of 50×10^6 electron volts.

I have made some experiments using the valve counter to examine the properties of this radiation excited in beryllium. The valve counter consists of a small ionisation chamber connected to an amplifier,

This again receives a simple explanation on the neutron hypothesis.

If it be supposed that the radiation consists of quanta, then the capture of the α-particle by the Be^9 nucleus will form a C^{13} nucleus. The mass defect of C^{13} is known with sufficient accuracy to show that the energy of the quantum emitted in this process cannot be greater than about 14×10^6 volts. It is difficult to make such a quantum responsible for the effects observed.

It is to be expected that many of the effects of a neutron in passing through matter should resemble those of a quantum of high energy, and it is not easy to reach the final decision between the two hypotheses. Up to the present, all the evidence is in favour of the neutron, while the quantum hypothesis can only be upheld if the conservation of energy and momentum be relinquished at some point.

J. CHADWICK.

Cavendish Laboratory,
Cambridge, Feb. 17.

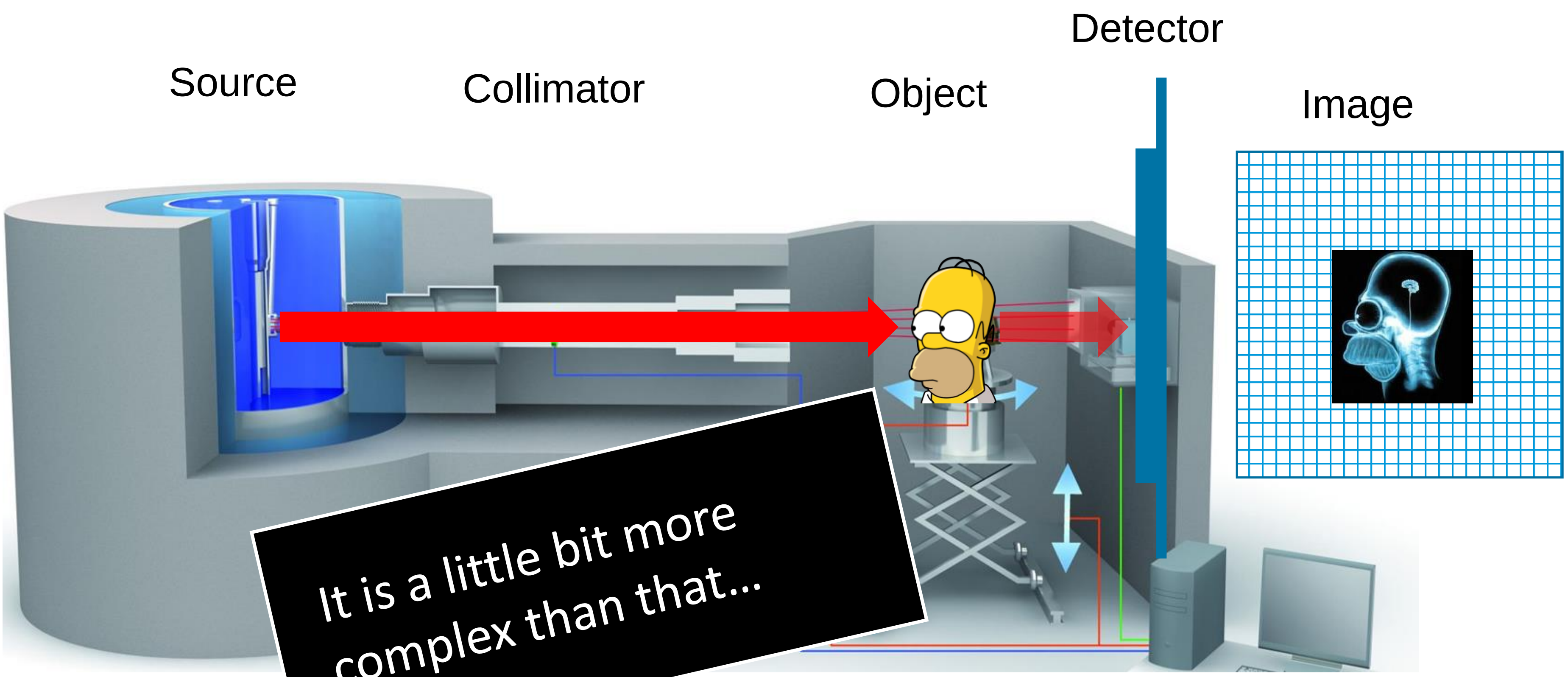
The Oldoway Human Skeleton

A LETTER appeared in NATURE of Oct. 24, 1931 signed by Messrs. Leakey, Hopwood, and Reck, in which, among other conclusions, it is stated that "there is no possible doubt that the human skeleton came from Bed No. 2 and not from Bed No. 4". This must be taken to mean that the skeleton is to be considered as a natural deposit in Bed No. 2, which

But the real programs with neutrons started...

Neutron Imaging

Let’s go and measure then!



It is a little bit more complex than that…

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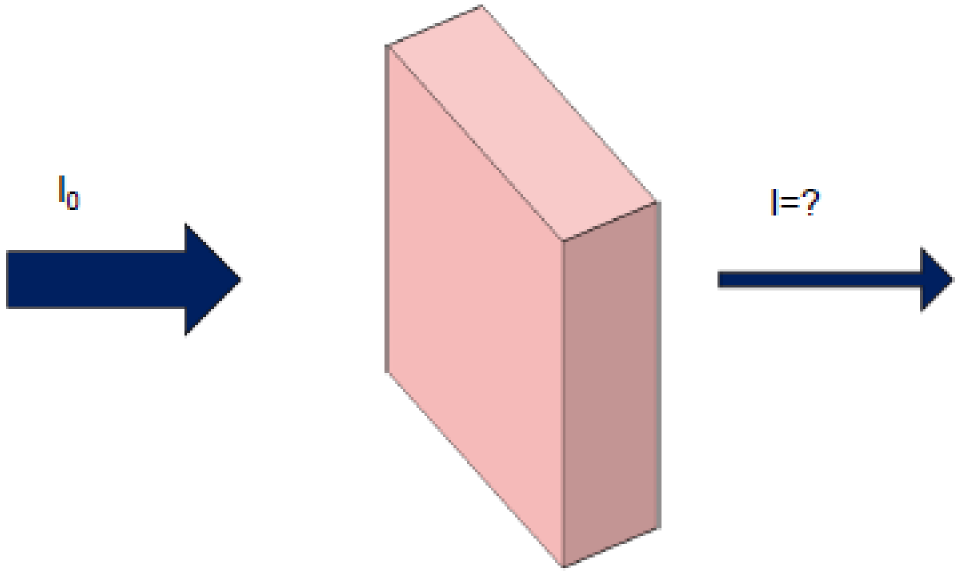
- ❑ Neutron Detection

Neutron Imaging

Beer–Lambert law

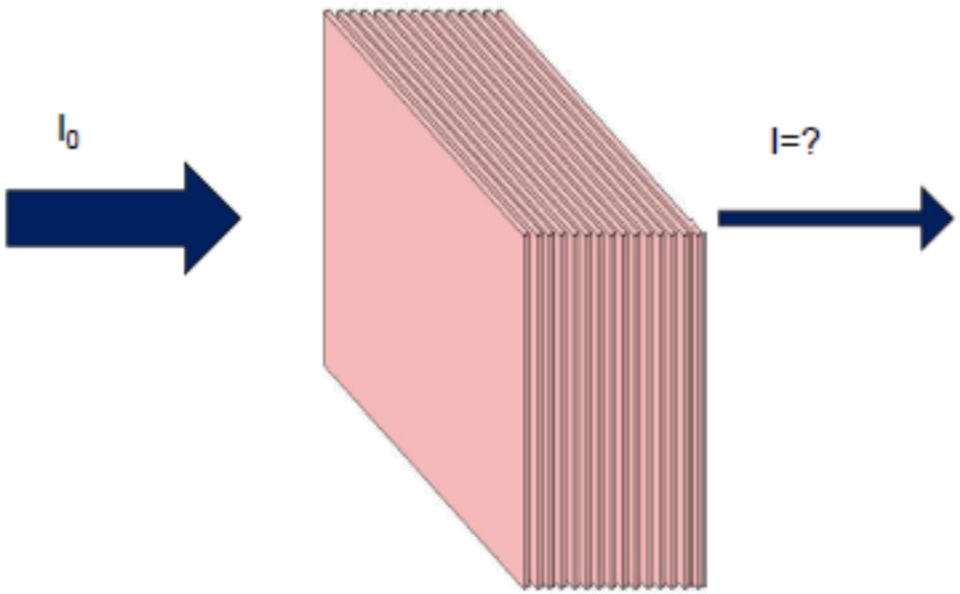
Problem:



Neutron Imaging

Beer–Lambert law

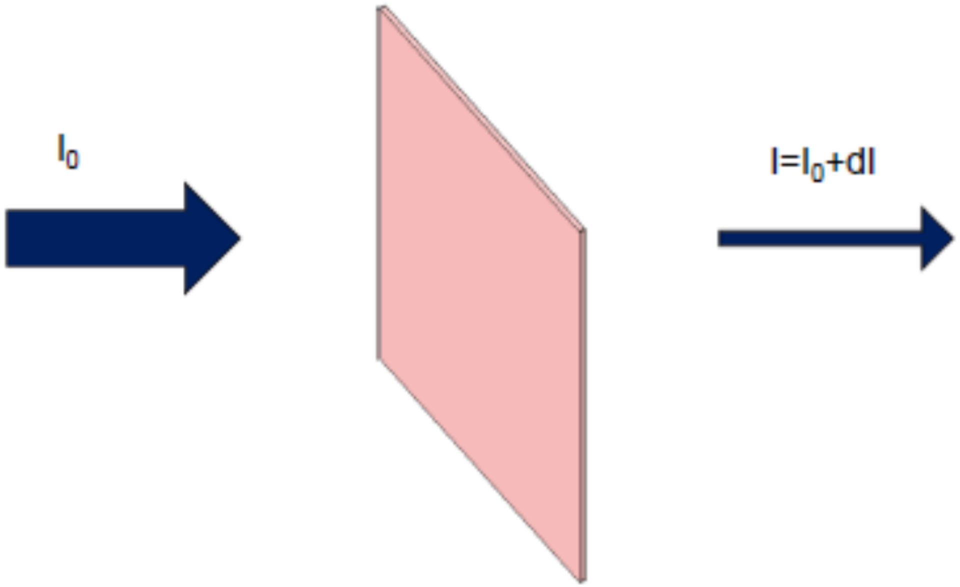
1st: let's divide the bulk into thin (differential) slices



Neutron Imaging

Beer–Lambert law

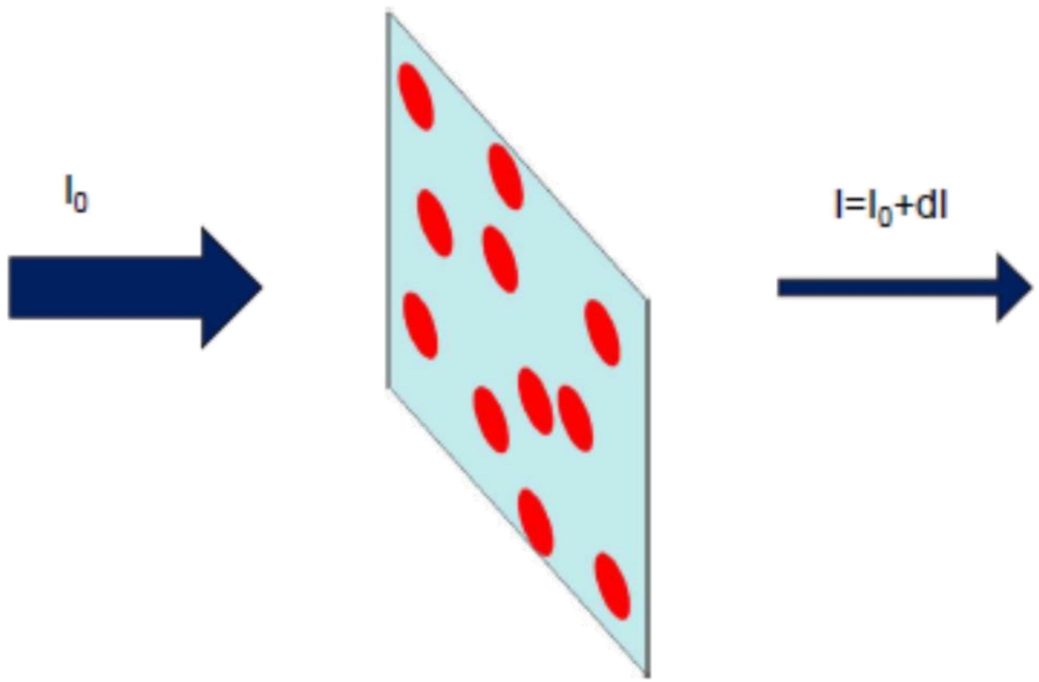
Let's consider one slab at a time (we'll sum the effect of each of them eventually)



Neutron Imaging

Beer–Lambert law

In reality, a slab is made of discrete attenuators separated by vacuum



Neutron Imaging

Beer–Lambert law

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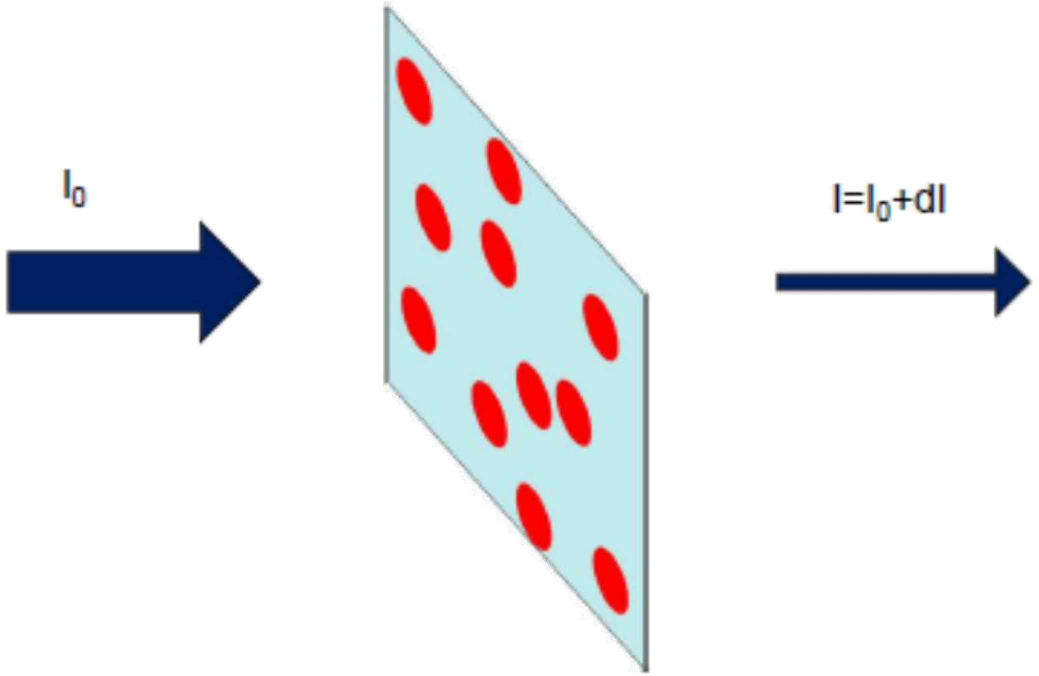
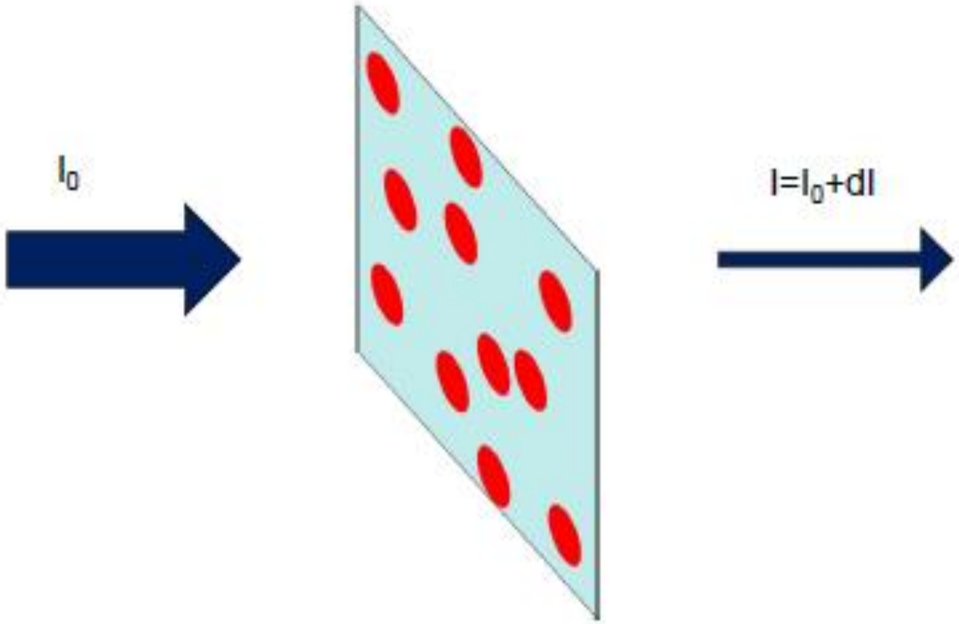


- The strength of the interaction with matter is expressed by „*microscopic cross-sections*" – **σ** , the unit is „barn = 10^{-24} cm^2"

Neutron Imaging

Beer–Lambert law

If we have N absorber per unit volume and the slab has a thickness of dx



we can express $dI = -I_0 \cdot N(x) \cdot \sigma(x) \cdot dx$

Neutron Imaging

Beer–Lambert law

We can solve the equation and integrate over the thickness t:

$$dI = -I_0 \cdot N \cdot \sigma \cdot dx$$

$$dI/_{I_0} = -N \cdot \sigma \cdot dx$$

$$\int_{I0}^{I} dI/_{I_0} = \int_0^t -N \cdot \sigma \cdot dx$$

$$I = I_0 e^{-\int_0^t N(x)\cdot\sigma(x)\cdot dx}$$

Beer-Lambert law

$$I = I_0 e^{-\sum_i \int_0^t N_i(x)\cdot\sigma_i(x)\cdot dx}$$

For several absorbers

$$I = I_0 \, e^{-\mu z}$$

$$\mu = \mu_{\text{abs}} + \mu_{\text{scatt}}$$

attenuation coefficient (cm^{-1})

sample thickness (cm)

- The *"macroscopic cross-section"* Σ is defined as : **Σ= N* σ**, the unit is cm^{-1}

  N = nuclear density = **(ρ*A)/M** (A=Avogadro's number, M=mass)

- also called *"attenuation coefficient" and expressed as* $\mu = \sigma_{total}(\lambda) \cdot N$

Neutron Imaging

Beer–Lambert law

Today at 15.00

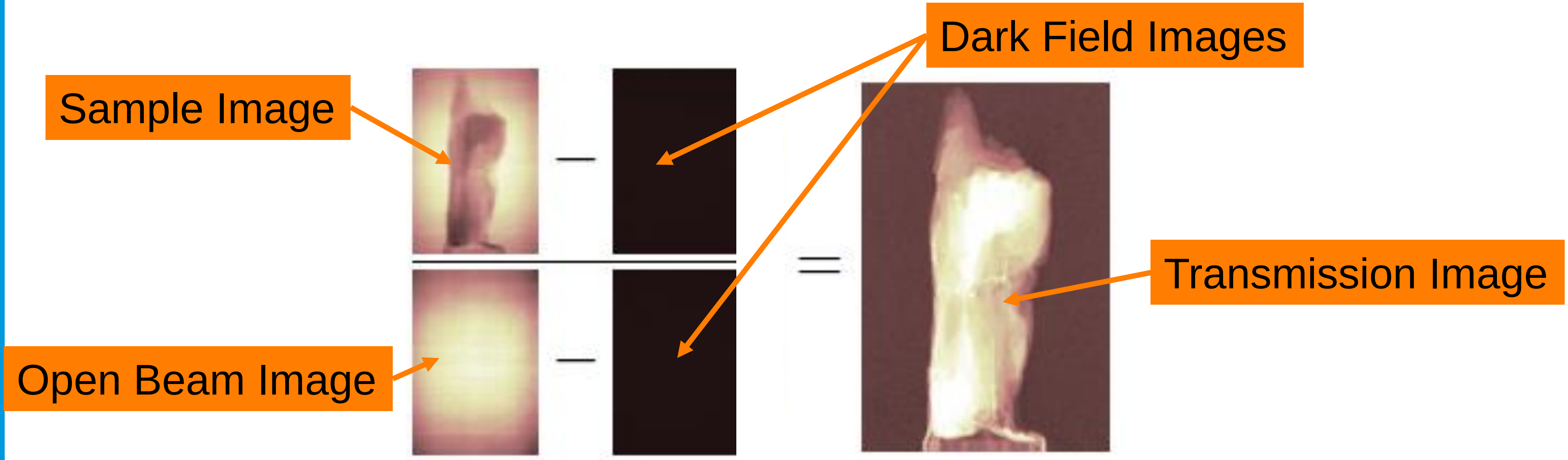
A. Kaestner :: Paul Scherrer Institut

Introduction to computed tomography

Theory and practical details for the experimentalist

Transmission

$$T = \frac{I}{I_0} = e^{-\Sigma \cdot d} = e^{-\sigma \cdot N \cdot d}$$



Neutron Imaging

Beer–Lambert law

Transmission

$$T = \frac{I}{I_0} = e^{-\Sigma \cdot d} = e^{-\sigma \cdot N \cdot d}$$

and inverted …

$$\Sigma \cdot d = \ln\left(\frac{I_0}{I}\right)$$

Thickness d can be obtained when Σ is known

Density or composition derived if thickness d is known

Neutron Imaging

A number of assumptions have been made:

A number of assumptions have been made:

1) The absorbers are independent on each other ✓ True for most applications

2) The absorbers are "diluted" e.g. they do not shadow each other from one slab to the other ✓ True for most elements

3) The attenuation does not depend on the wavelength or the beam is monochromatic 🚫 Equation needs to be modified

$$I = I_0 e^{-\int_0^t \int_{\lambda_{min}}^{\lambda_{max}} N(x)\sigma(x,\lambda)dxd\lambda}$$

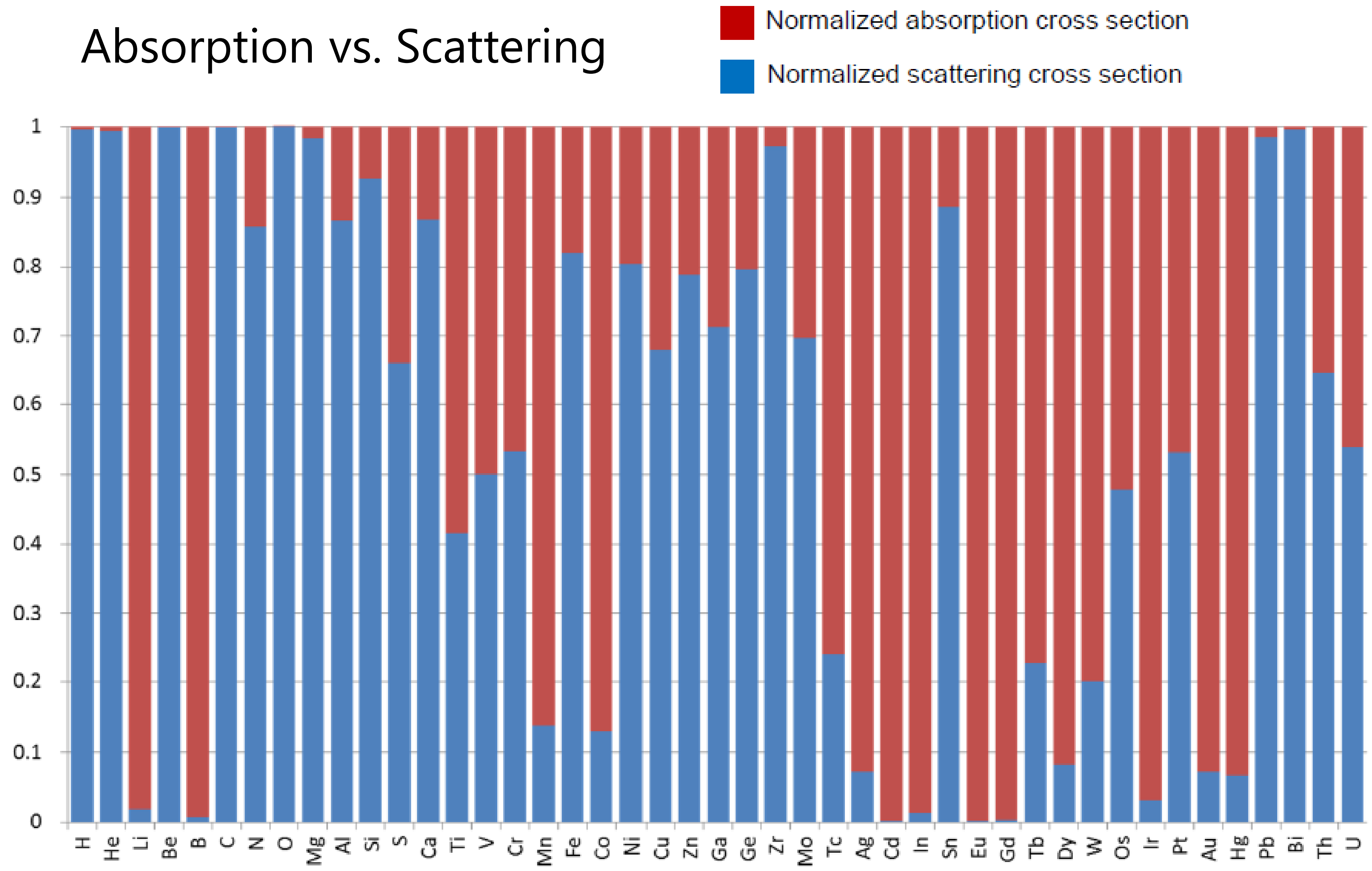
4) The beam is somewhat parallel ✓ Almost true…

5) The absorbers are not influenced by the radiation (i.e. no fission in the material) ✓ True for most elements

6) No scattering is present 🚫 Plain wrong for most elements

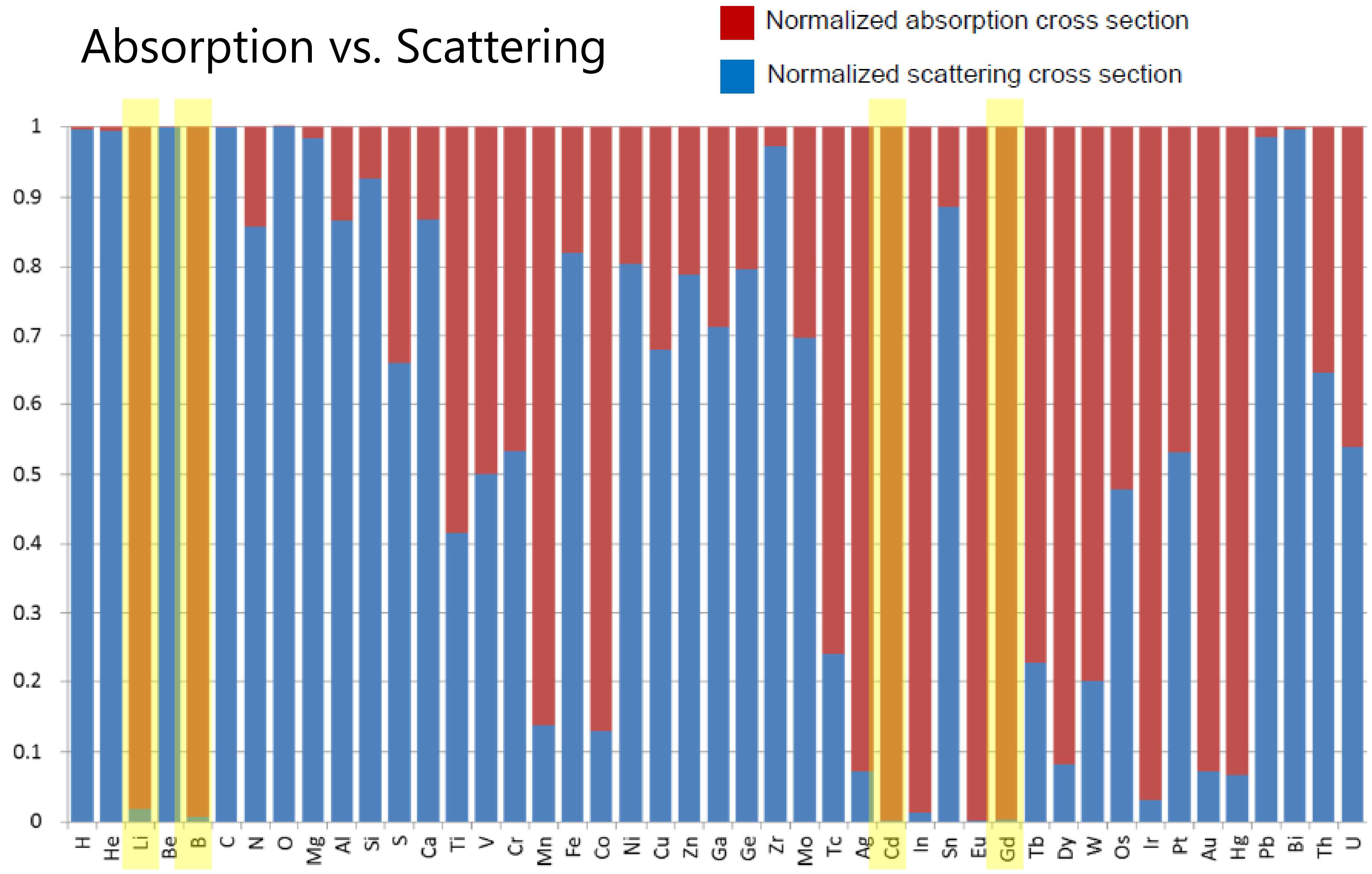
Neutron Imaging

A number of assumptions have been made:



Neutron Imaging

A number of assumptions have been made:



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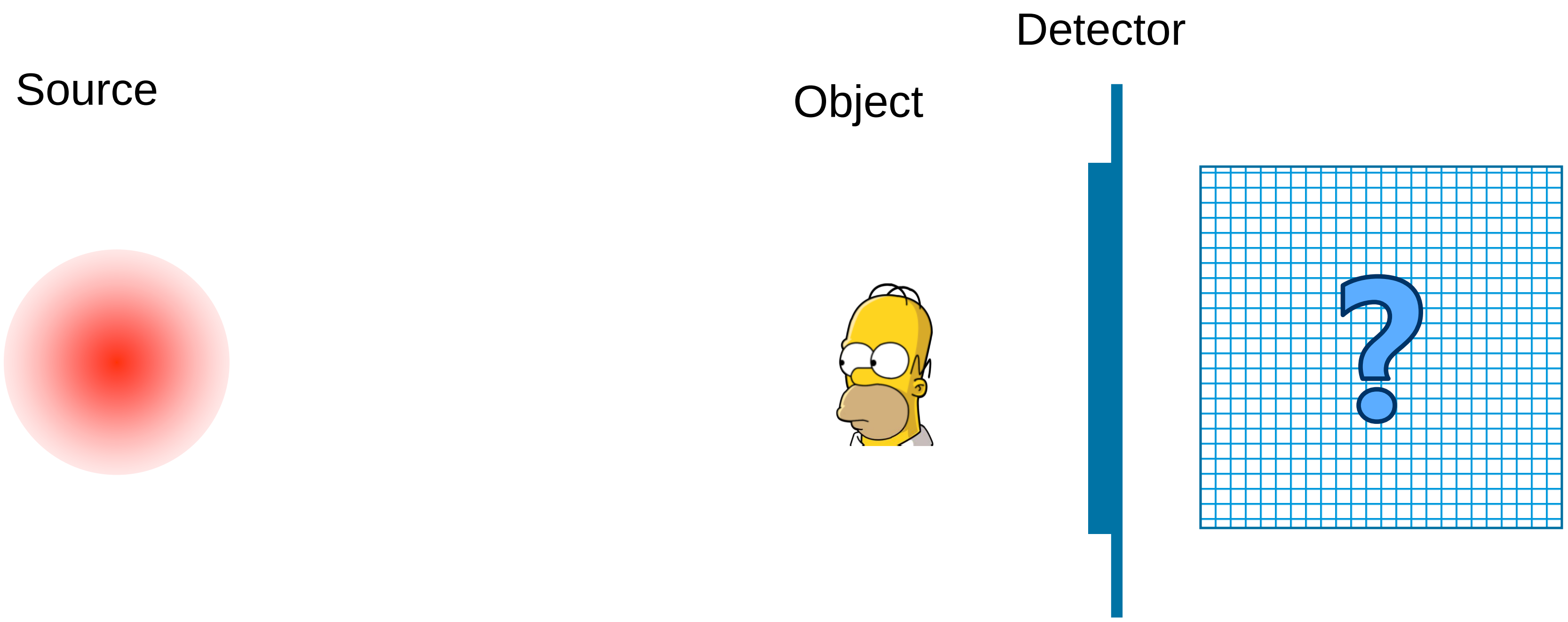
Neutron Imaging

The neutron imaging setup



Neutron Imaging

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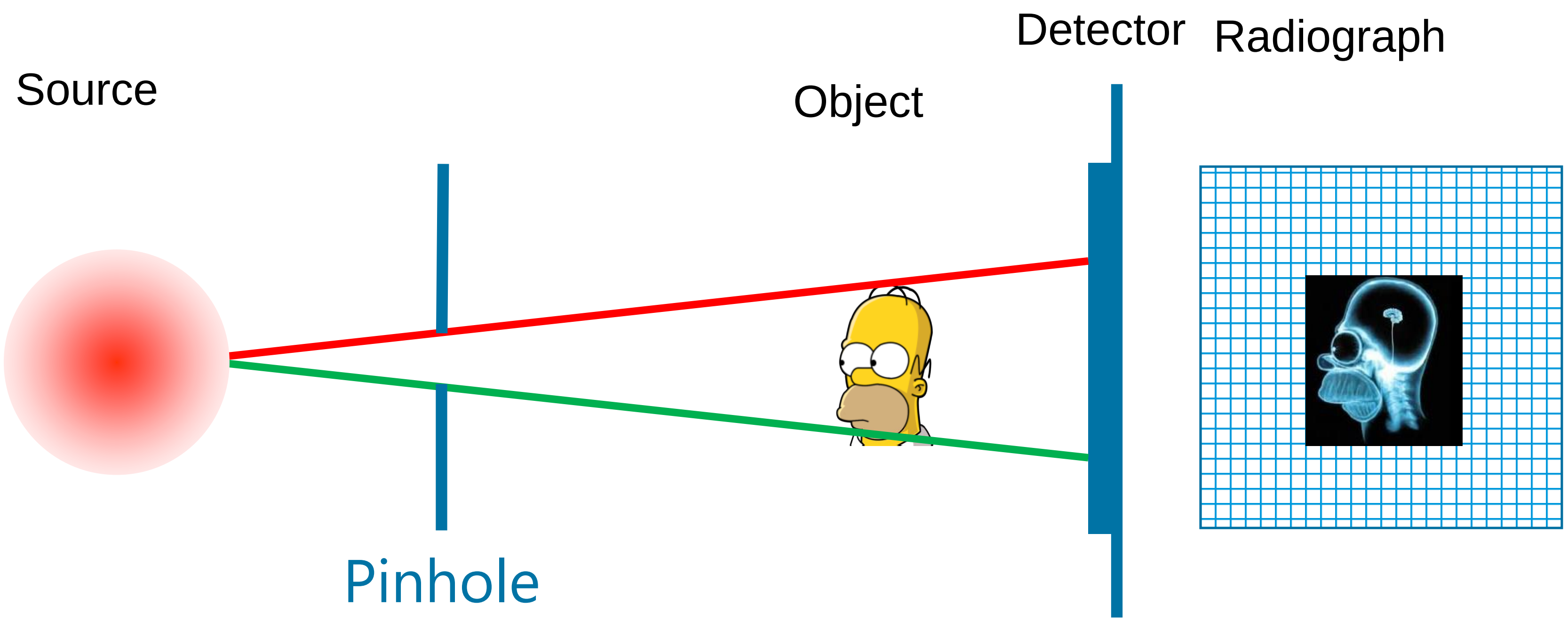
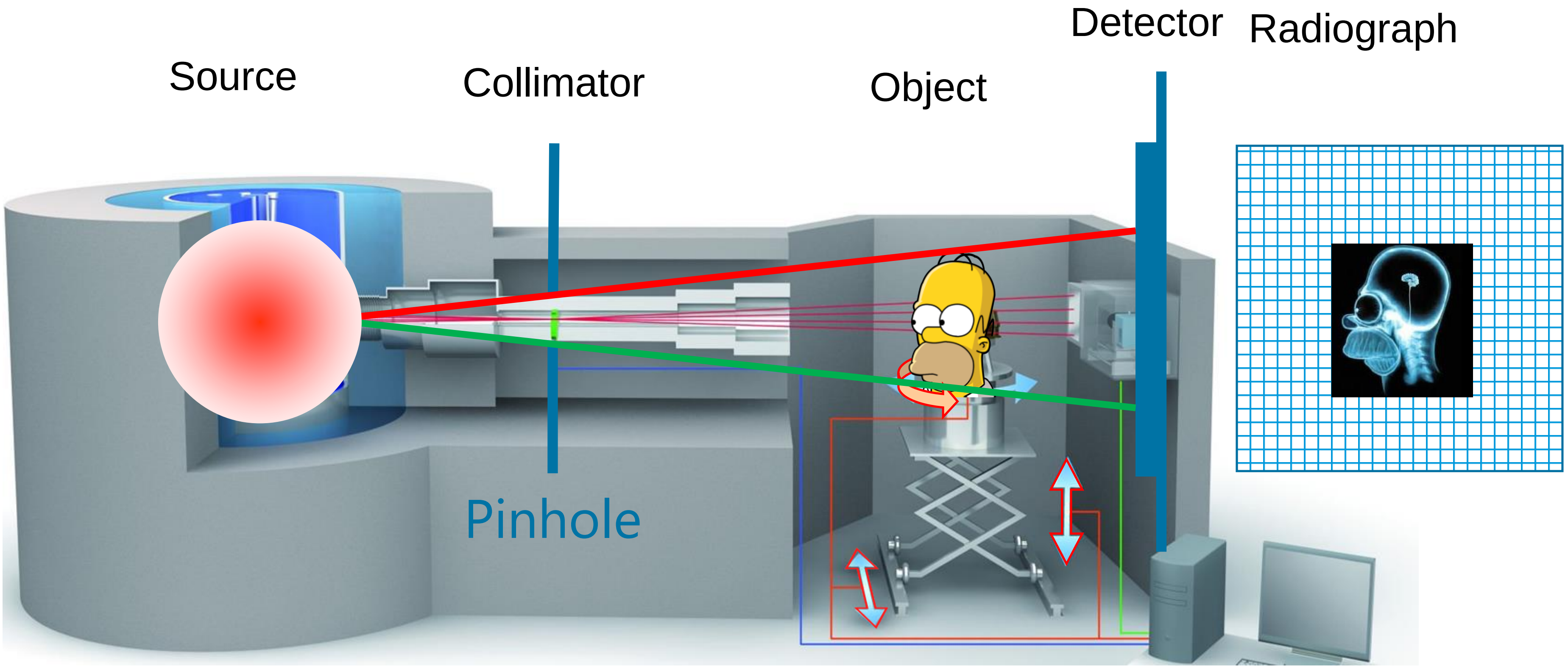


Neutron Imaging

The neutron imaging setup



Neutron Imaging

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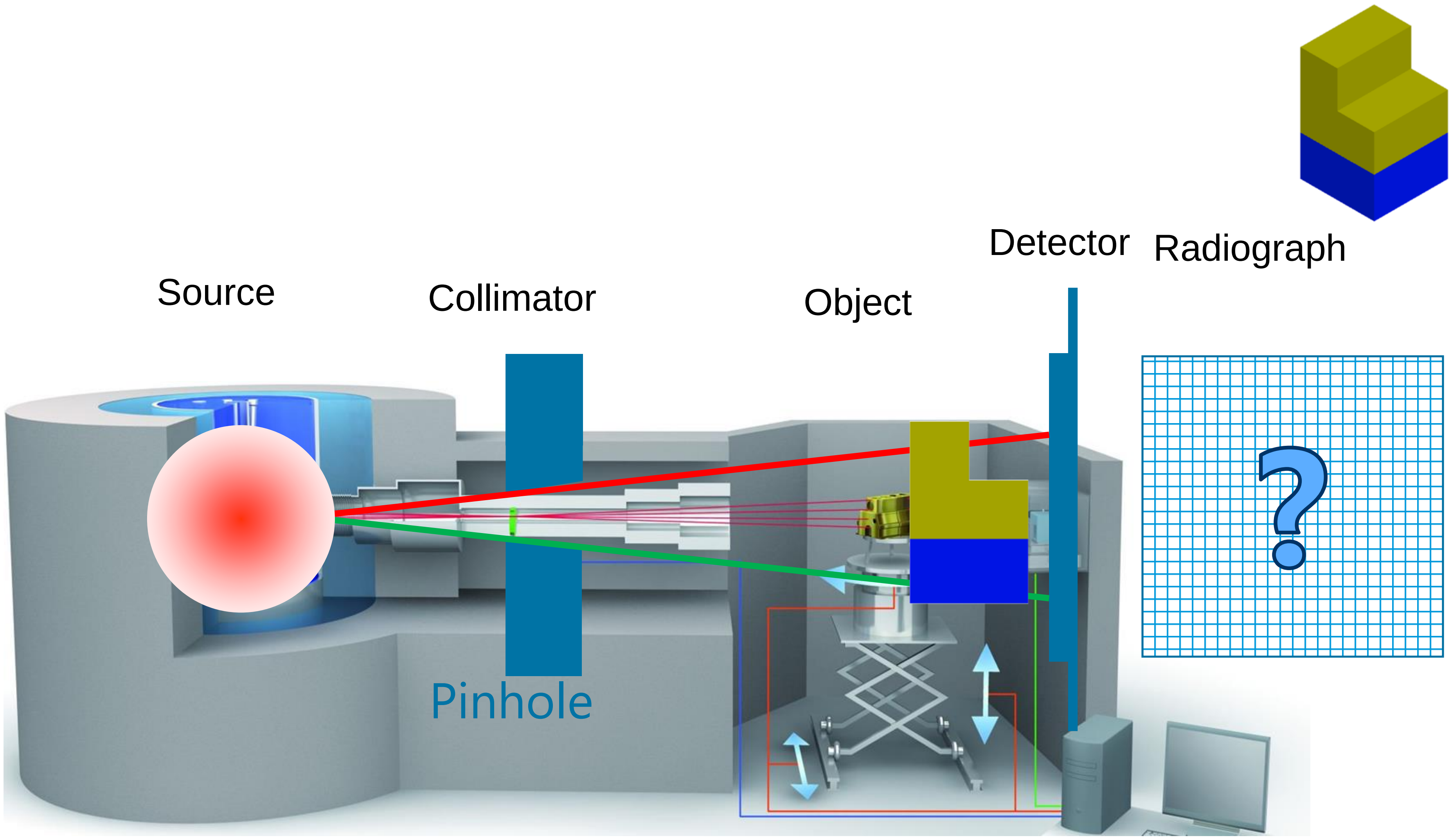

Neutron Imaging

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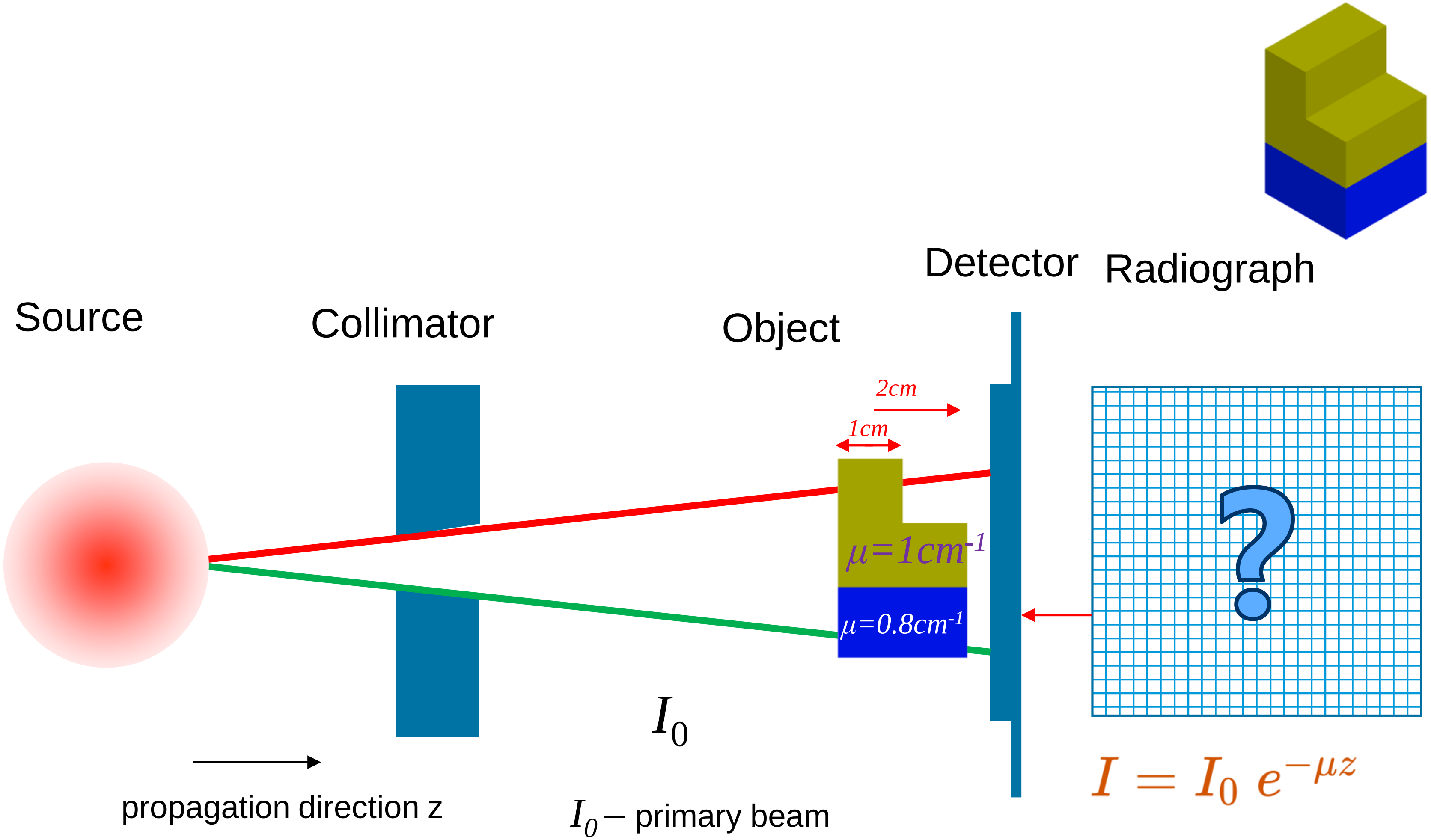


$$I = I_0 \, e^{-\mu z}$$

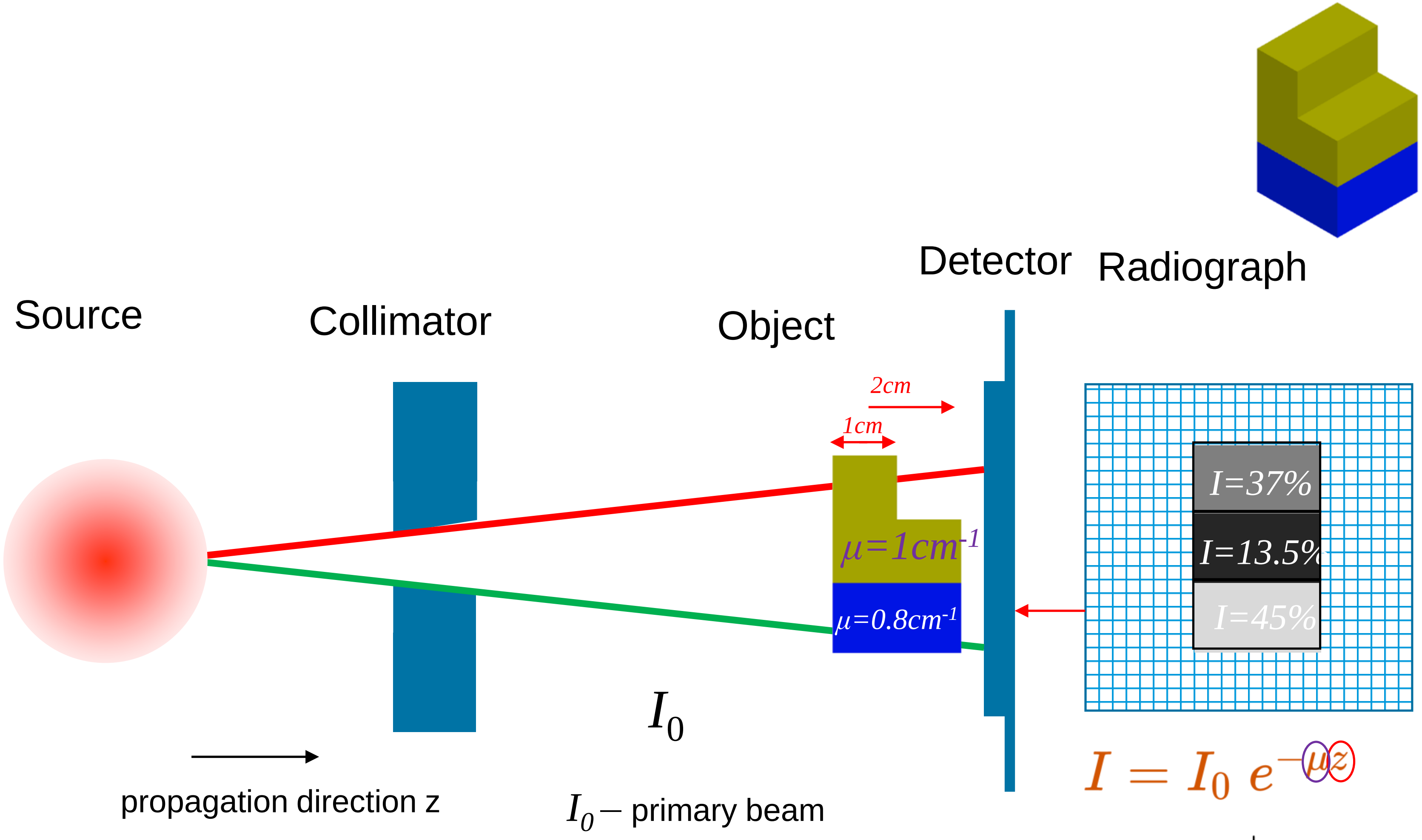
$$\mu = \mu_{\text{abs}} + \mu_{\text{scatt}}$$

attenuation coefficient (cm^{-1})

sample thickness (cm)

Neutron Imaging

The neutron imaging setup



$$I = I_0\, e^{-\mu z}$$

$$\mu = \mu_{\text{abs}} + \mu_{\text{scatt}}$$

attenuation coefficient (cm^{-1})

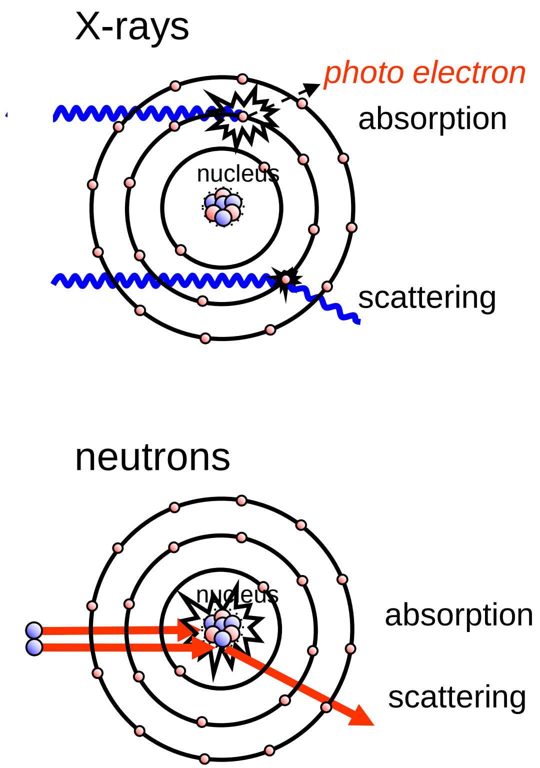
sample thickness (cm)

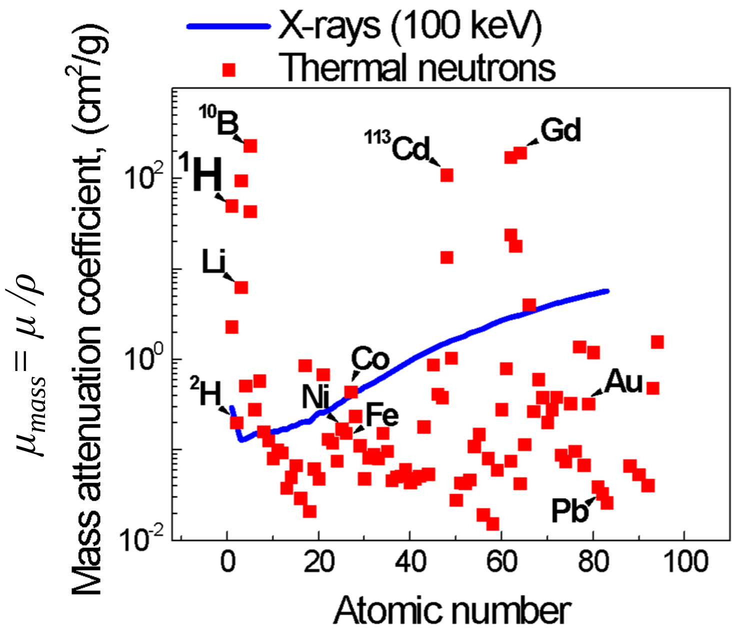
Neutron Imaging

Neutron attenuation & cross section

$$\mu = \mu_{\text{abs}} + \mu_{\text{scatt}}$$

$$\mu = \sigma_{total}(\lambda) \cdot N$$





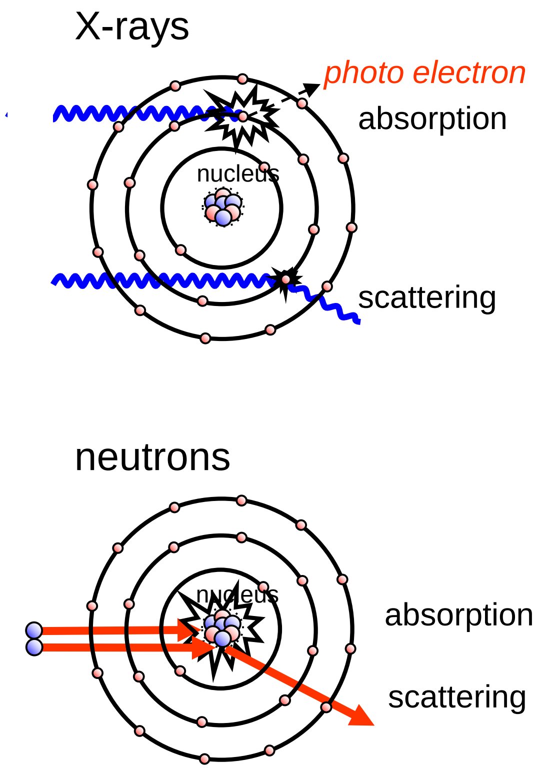
$$\sigma_{total}(\lambda) = \sigma_{absorption}(\lambda) + \sigma_{coherent\_scatt}(\lambda) + \sigma_{incoherent\_scatt}(\lambda)$$

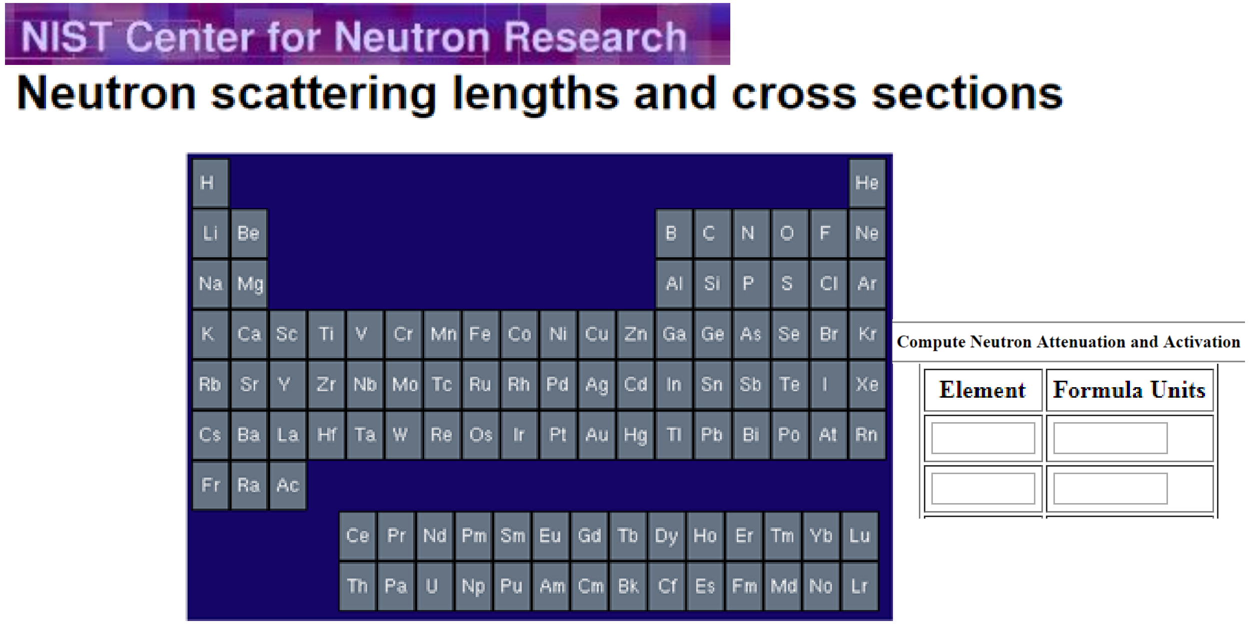
Neutron Imaging

Neutron attenuation & cross section

$$\mu = \mu_{\text{abs}} + \mu_{\text{scatt}}$$

$$\mu = \sigma_{total}(\lambda) \cdot N$$





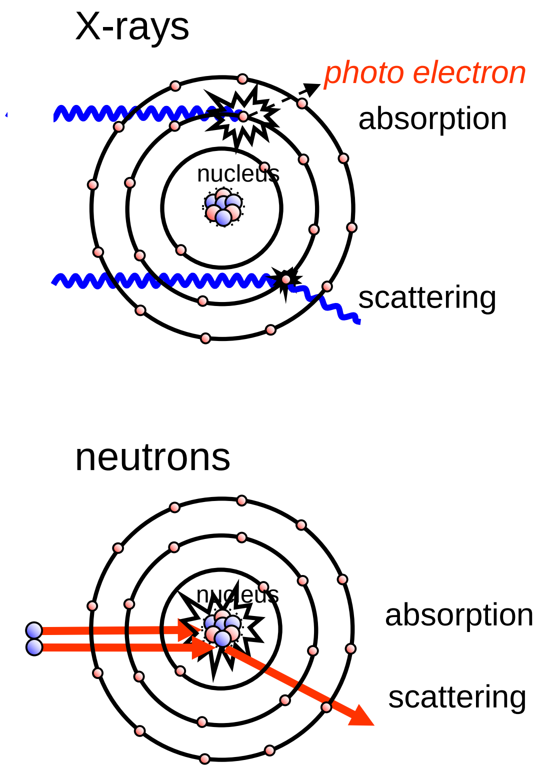
www.ncnr.nist.gov/resources/n-lengths/
www.ncnr.nist.gov/instruments/bt1/neutron.html

$$\sigma_{total}(\lambda) = \sigma_{absorption}(\lambda) + \sigma_{coherent\_scatt}(\lambda) + \sigma_{incoherent\_scatt}(\lambda)$$

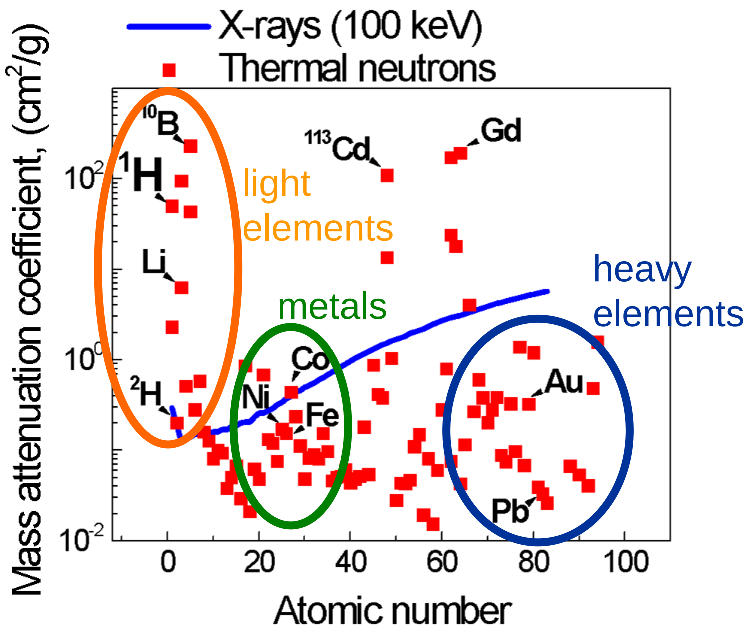
Neutron Imaging

Neutron attenuation & cross section

$$\mu = \mu_{\text{abs}} + \mu_{\text{scatt}}$$



→ High attenuation for heavy elements
→ High transparency for hydrogenous / organic material

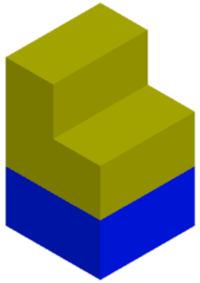


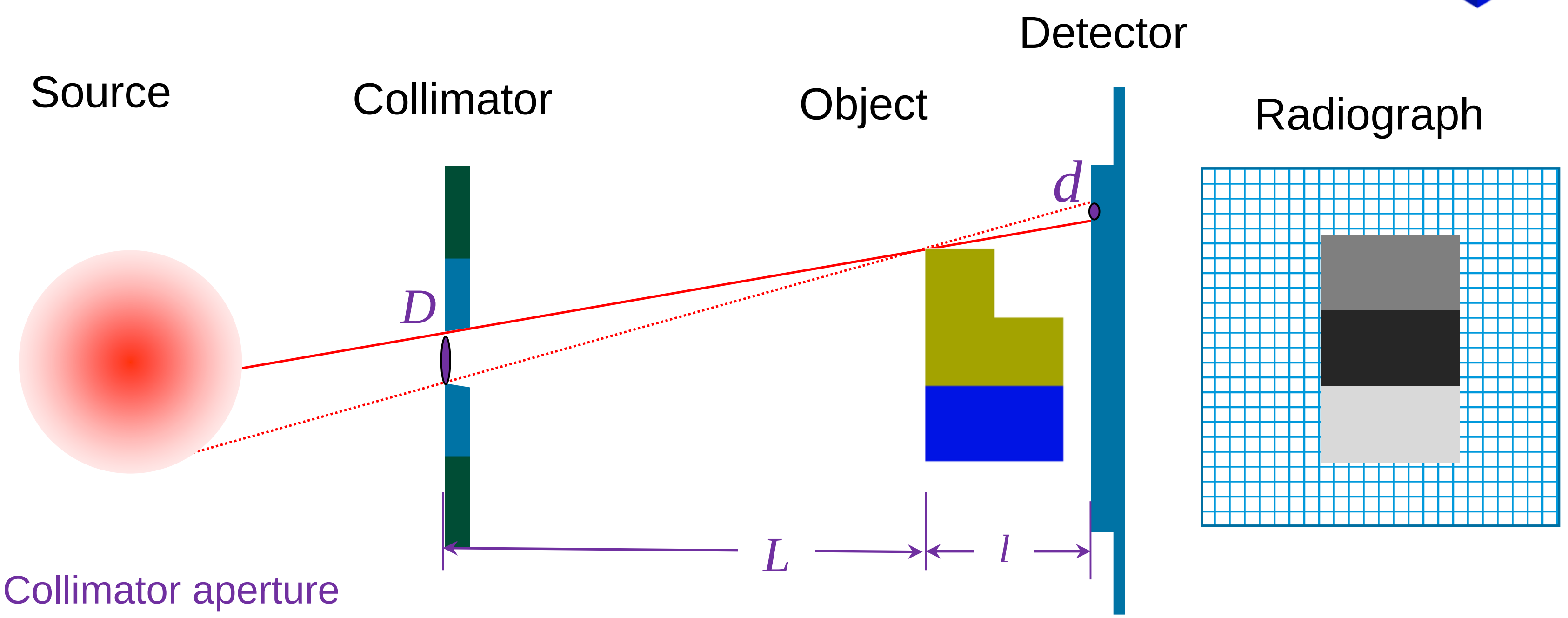
→ High attenuation for hydrogenous / organic material
→ High transparency for heavy elements

Neutron Imaging

The L/D ratio

$$d = \frac{l}{L/D}$$





D – Collimator aperture

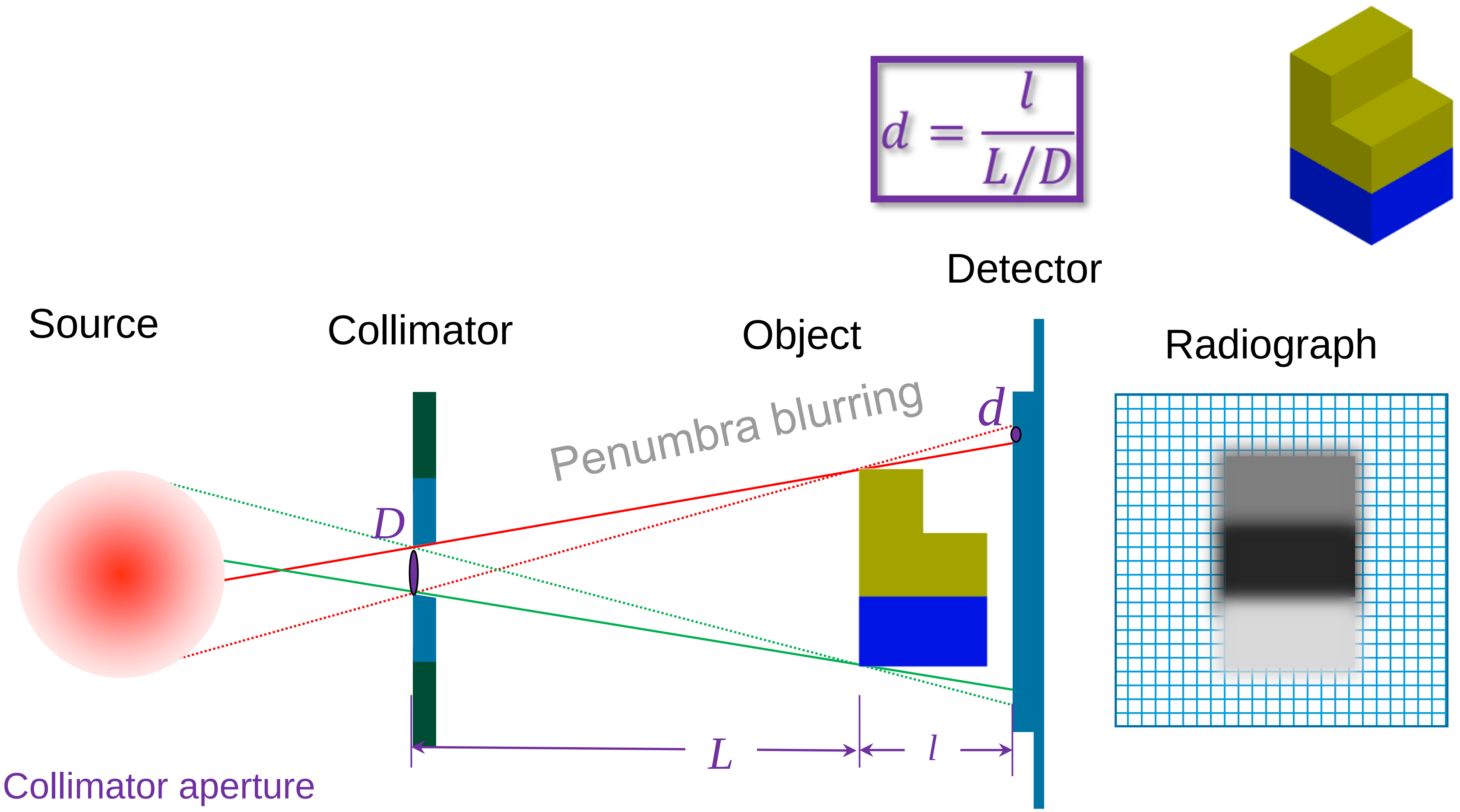
L – Distance Collimator-Object

l – Distance Object-Detector

Neutron Imaging

The L/D ratio

$$d = \frac{l}{L/D}$$



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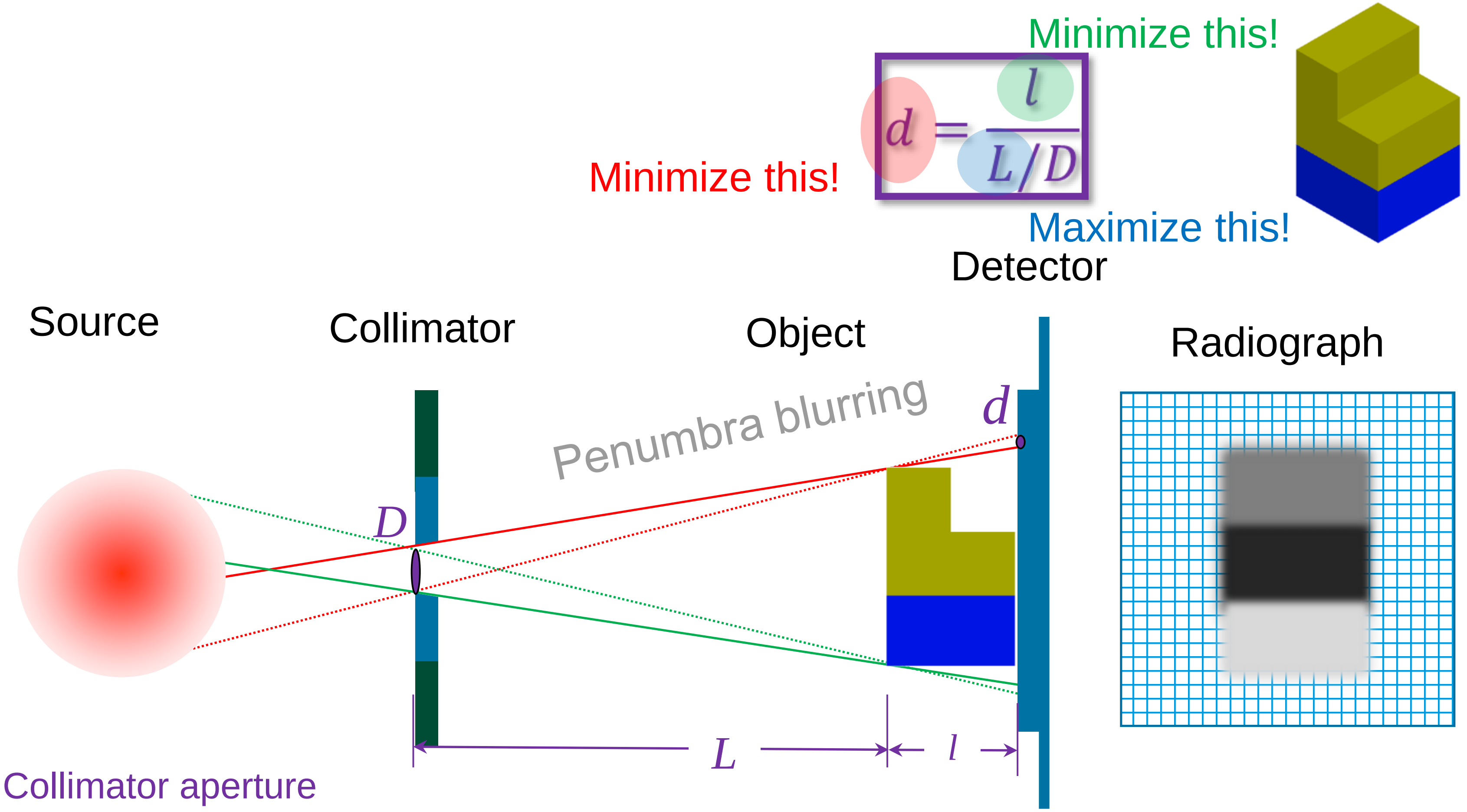
Neutron Imaging

The L/D ratio



D – Collimator aperture

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l – Distance Object-Detector

Neutron Imaging

The L/D ratio

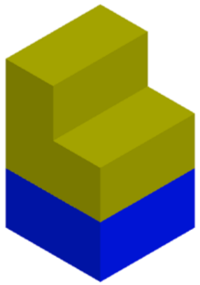
Minimize this!

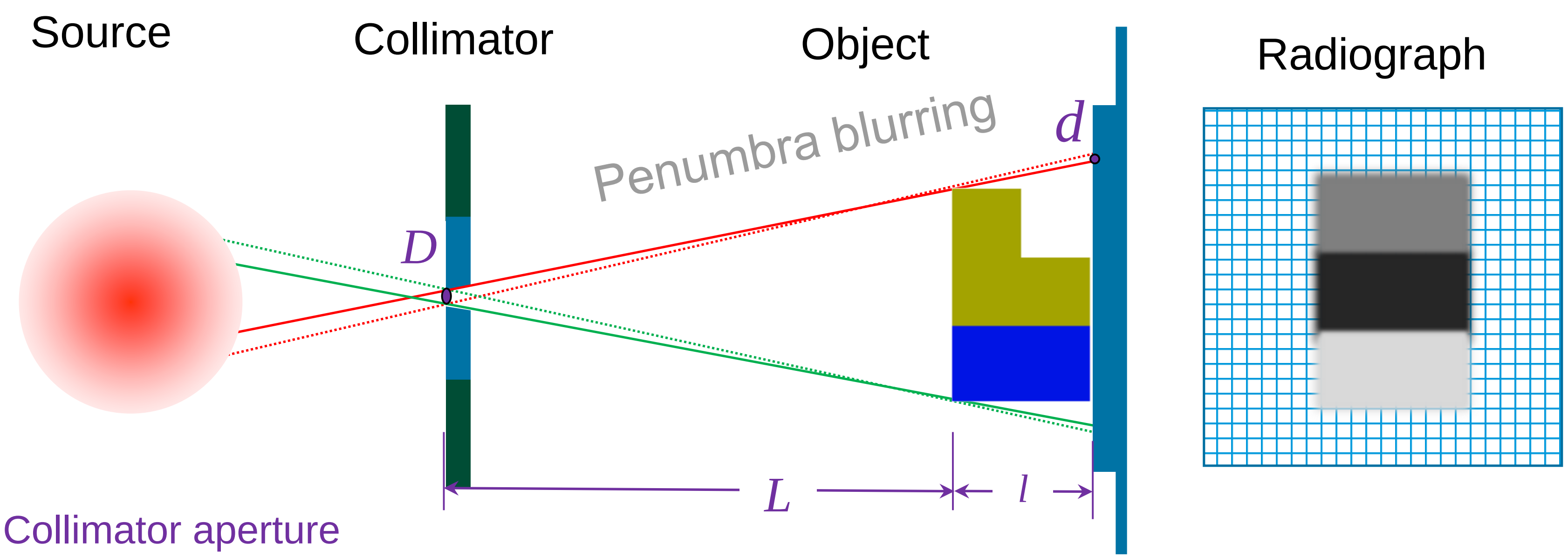
$$d = \frac{l}{L/D}$$

Minimize this!

Minimize this!

Maximize this!





D – Collimator aperture

L – Distance Collimator-Object

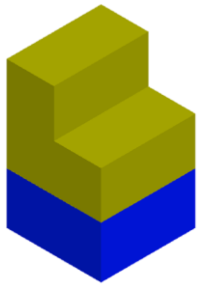
l – Distance Object-Detector

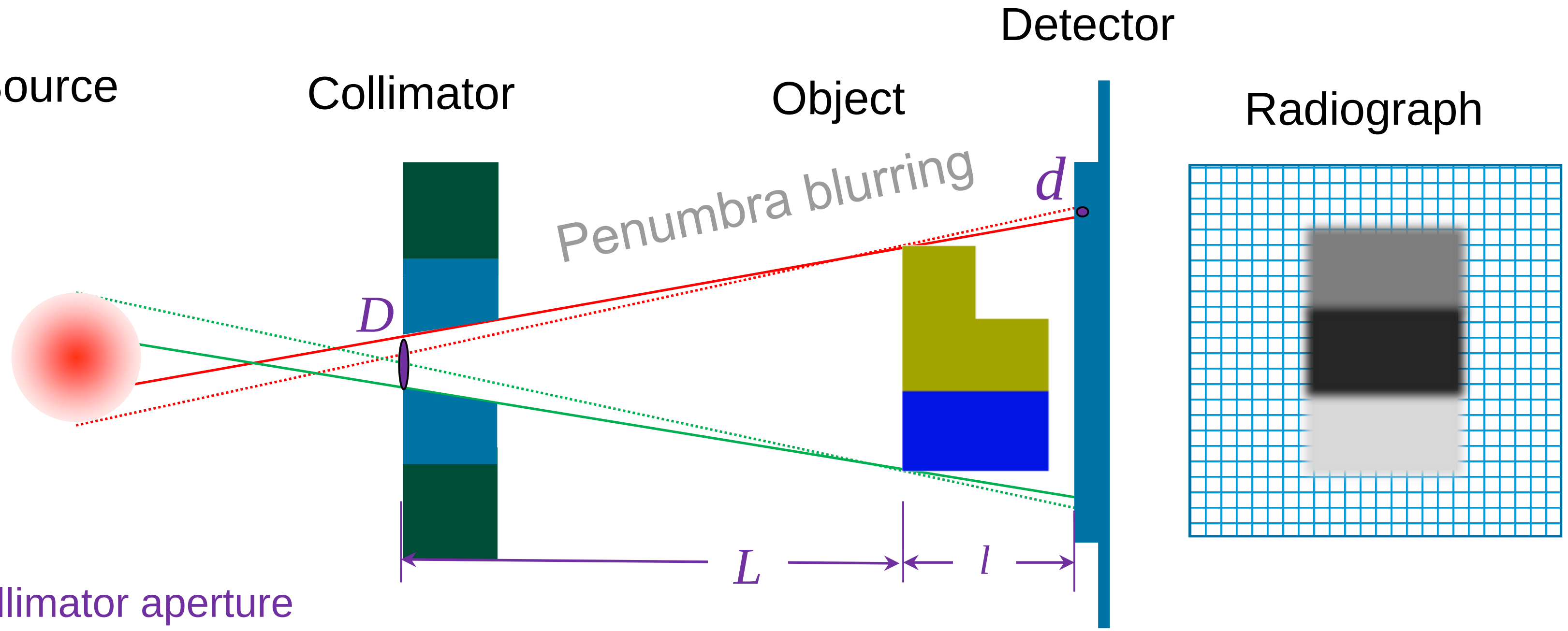
Find compromise for the optimal L/D ratio (resolution vs data acquisition time)

Neutron Imaging

The L/D ratio

$$d = \frac{l}{L/D}$$





D – Collimator aperture

L – Distance Collimator-Object

l – Distance Object-Detector

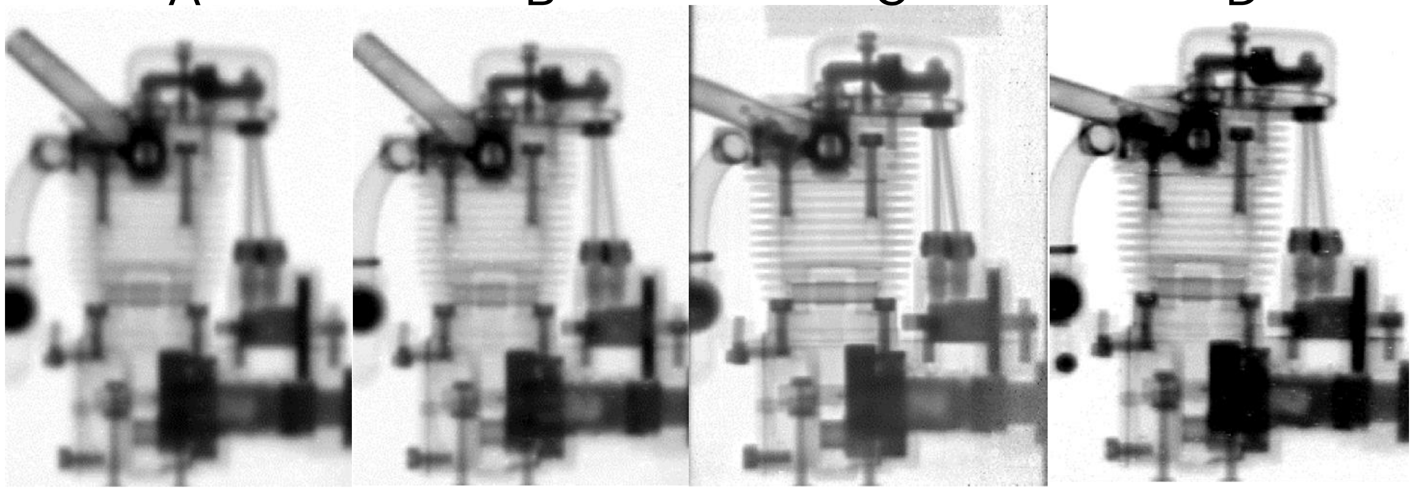
Neutron Imaging

The L/D ratio

Pop-Up Quiz:
Which image has the highest and which one the lowest L/D ratio?

$$d = \frac{l}{L/D}$$

A B C D



D – Collimator aperture

L – Distance Collimator-Object

l – Distance Object-Detector

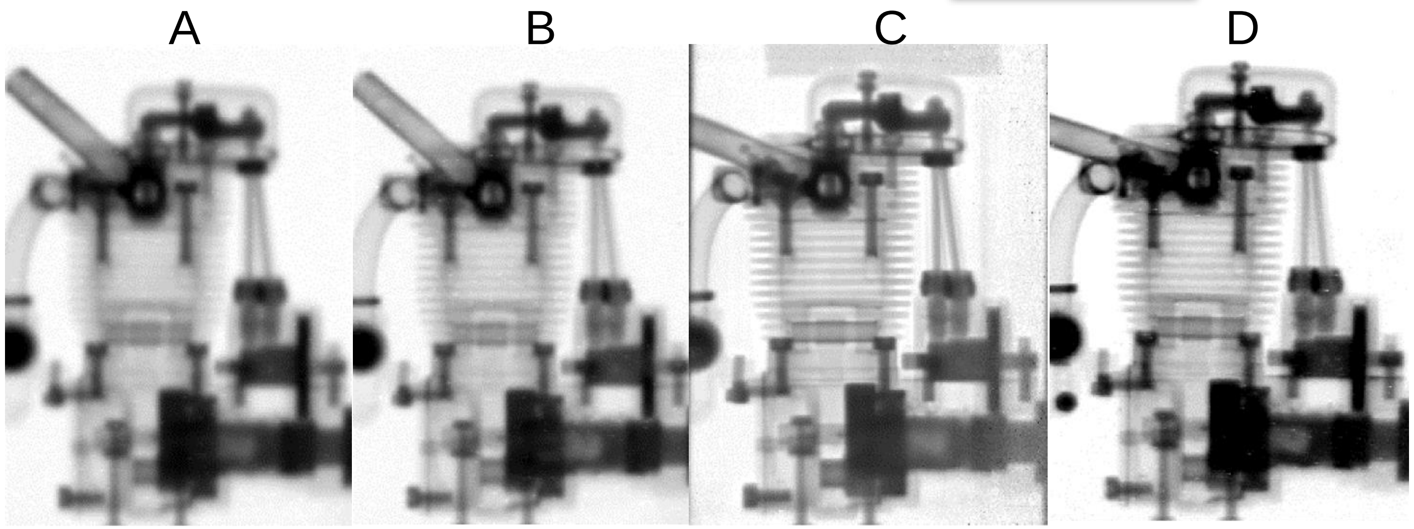
Source: B. Schillinger, Estimation and measurement of L/D on a cold and thermal neutron guide, in: Nondestructive Testing and Evaluation, World Conference on Neutron Radiography, vol. 16, Osaka, 1999, pp. 141–150

Neutron Imaging

The L/D ratio

Pop-Up Quiz:
Which image has the highest and which one the lowest L/D ratio?

$$d = \frac{l}{L/D}$$



L/D=71 | L/D=115 | L/D=320 | L/D>500

D – Collimator aperture

L – Distance Collimator-Object

l – Distance Object-Detector

Source: B. Schillinger, Estimation and measurement of L/D on a cold and thermal neutron guide, in: Nondestructive Testing and Evaluation, World Conference on Neutron Radiography, vol. 16, Osaka, 1999, pp. 141–150

Introduction to neutron imaging

- ❑ Characterization Techniques, Definitions, Neutron Sources
- ❑ Neutron Methods & Length Scales
- ❑ How is an image recorded?
- ❑ Beer–Lambert law for attenuation based imaging
- ❑ The neutron imaging setup: geometrical considerations & Scattering vs Absorption
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- ❑ Neutron Detection

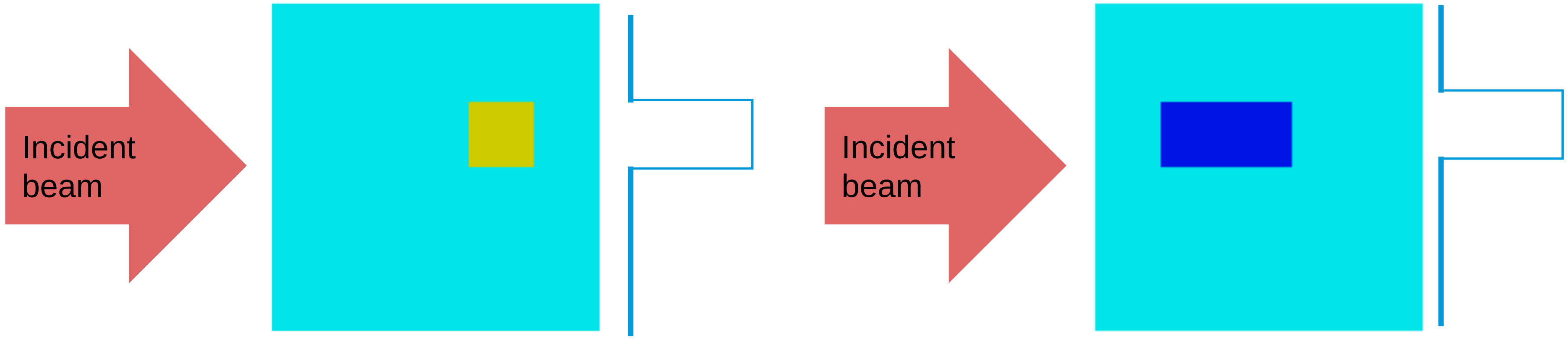
Neutron Imaging

Principles of Tomography

Radiography

Single projections

→ several solutions

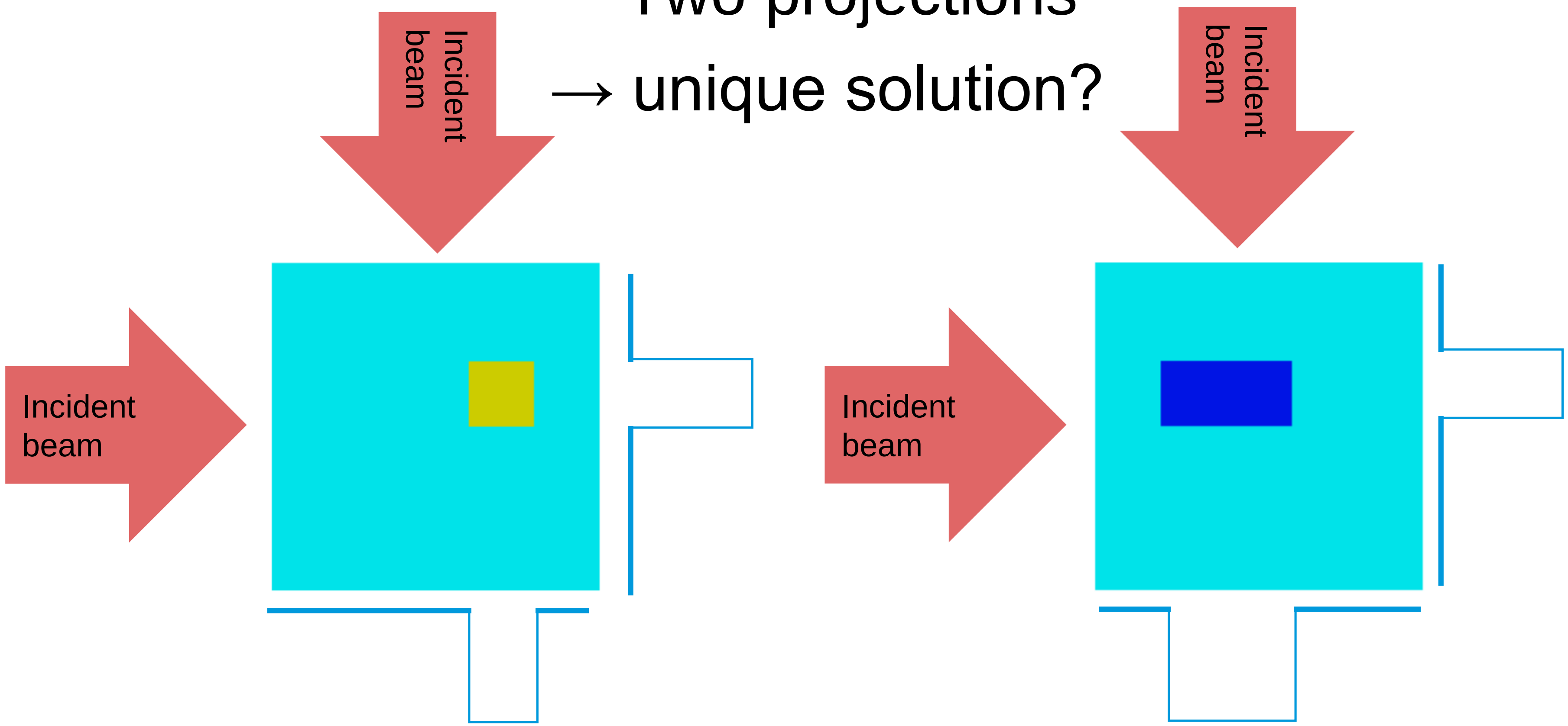


Neutron Imaging

Principles of Tomography

Stereography

Two projections
→ unique solution?



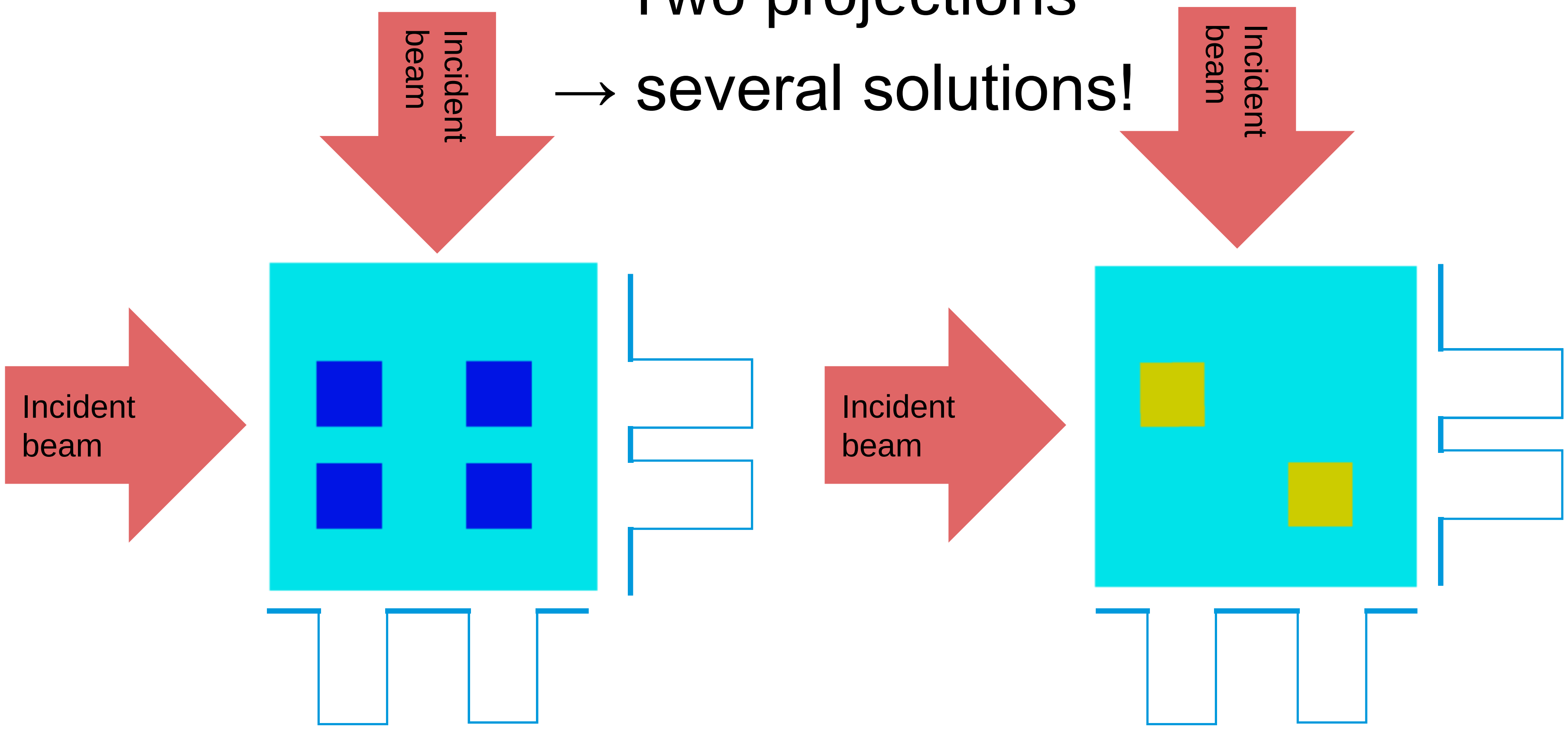
Neutron Imaging

Principles of Tomography

Stereography

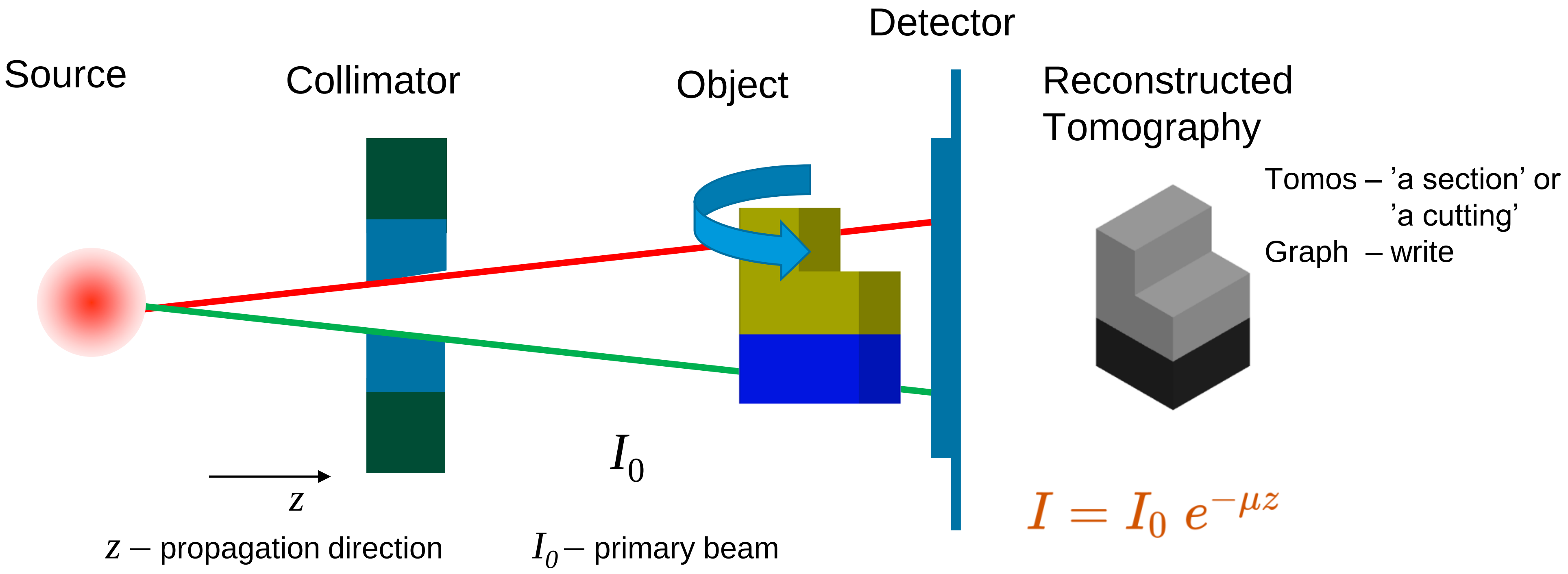
Two projections

→ several solutions!



Tomography

→ A unique solution would exist only for an infinite number of noiseless continuous projections



$$I = I_0\, e^{-\mu z}$$

Neutron Imaging

Principles of Tomogr

Tom

→ A
of n

Today at 15.00

PAUL SCHERRER INSTITUT
PSI

A. Kaestner :: Paul Scherrer Institut

Introduction to computed tomography

Theory and practical details for the experimentalist

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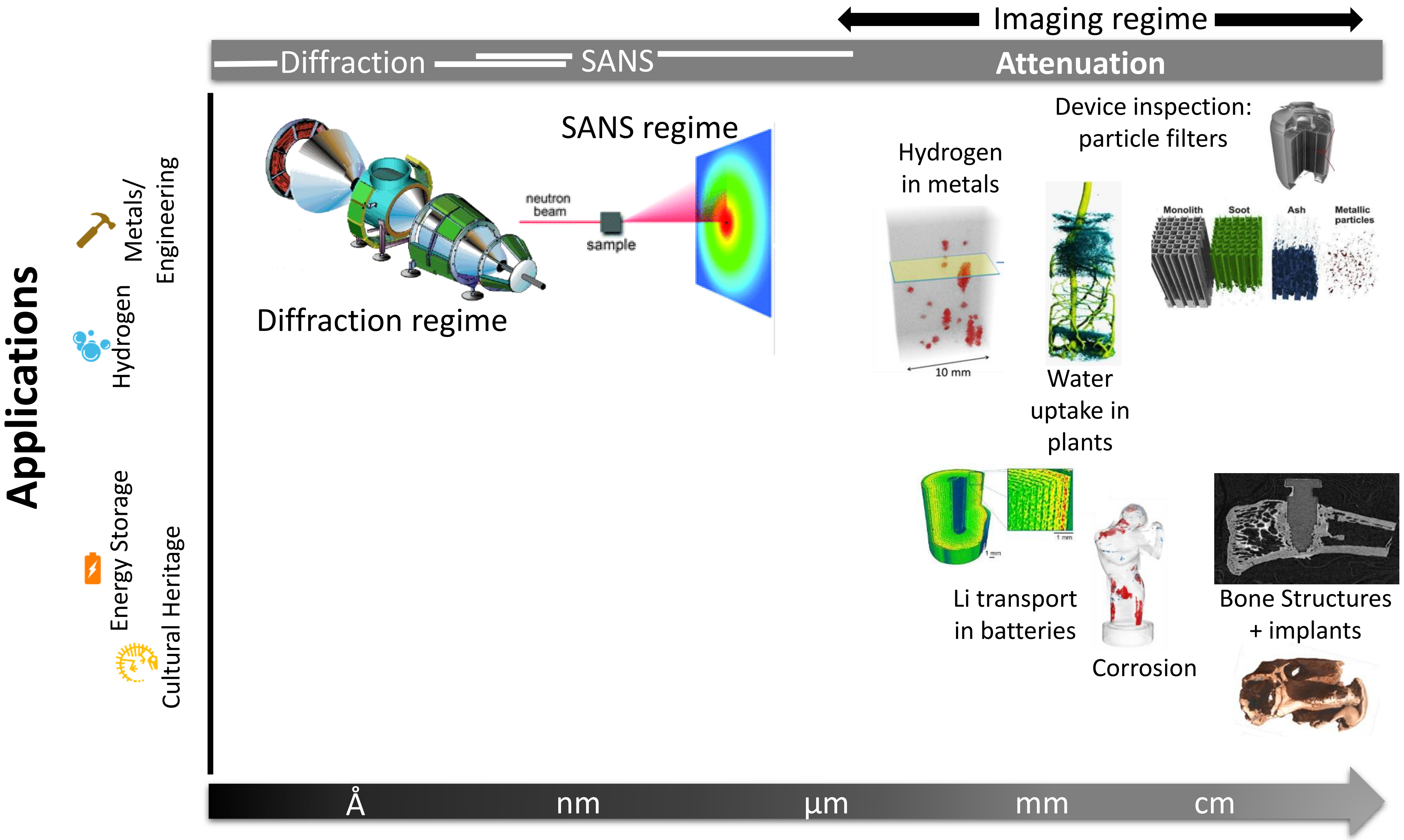
Advanced Neutron Imaging Methods

Kardjilov, Manke, Woracek, Banhart,. Advances in neutron imaging. Materials Today 21 (2018)



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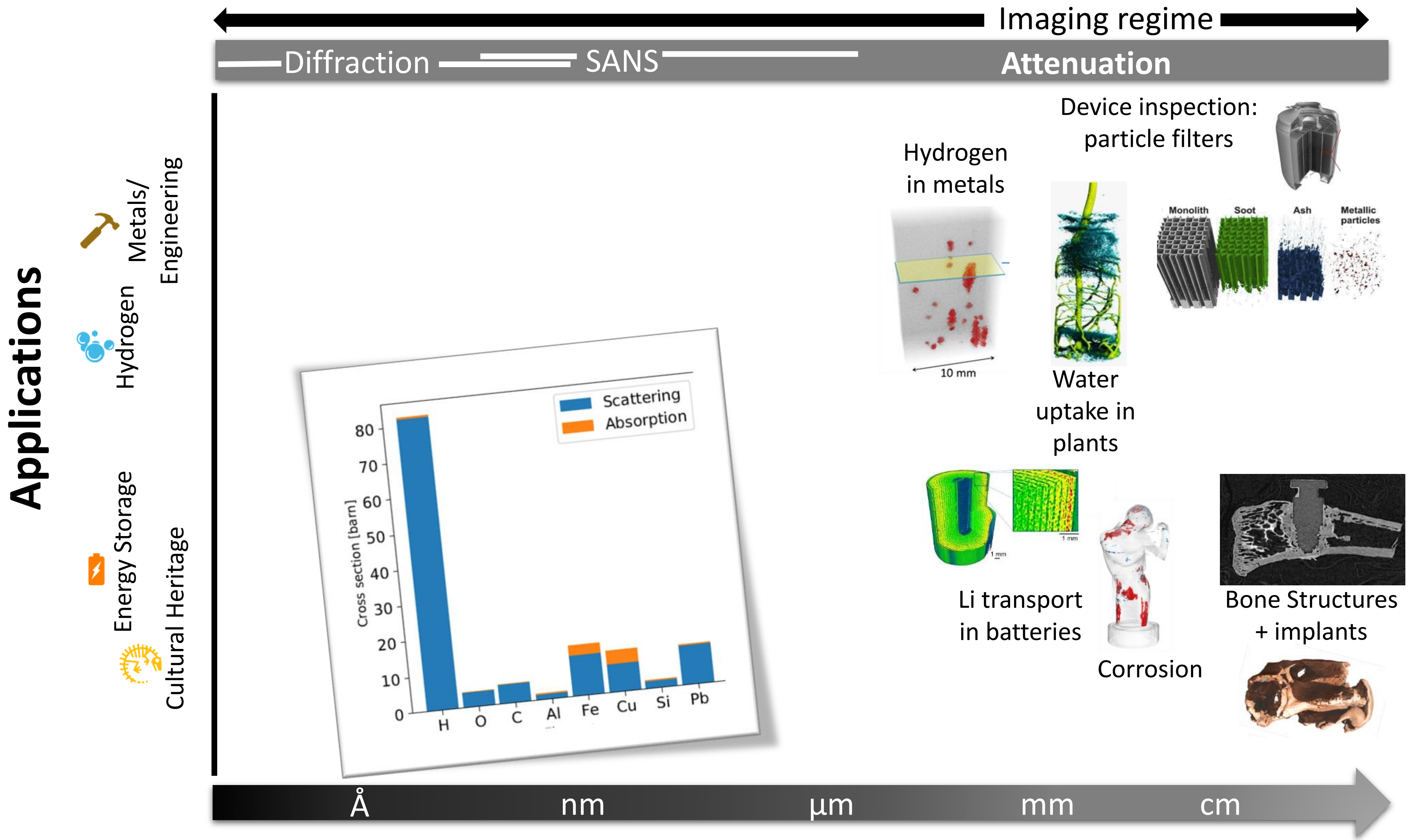

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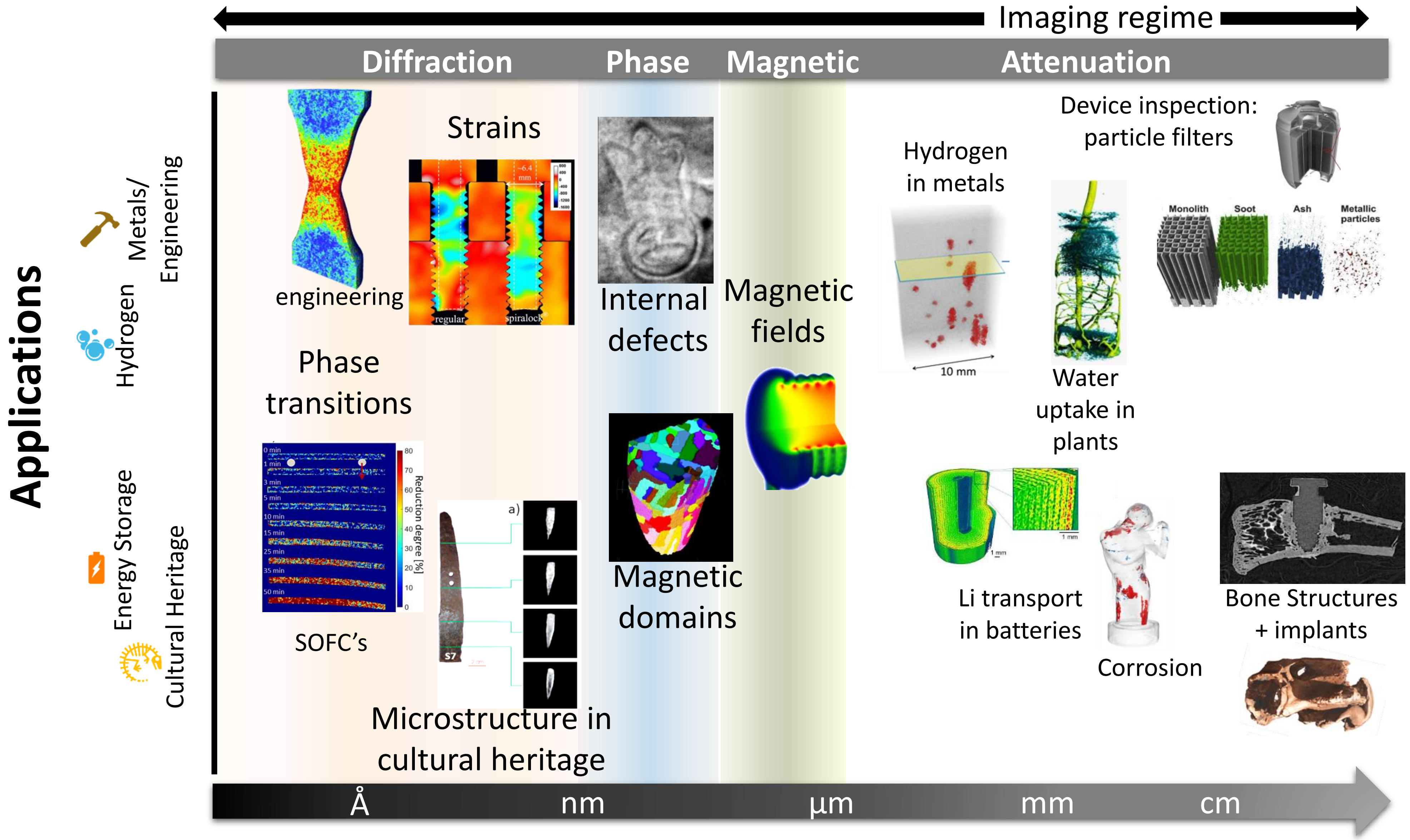

Advanced Neutron Imaging Methods

(2018)

Wednesday

13:00 → 14:00 **Energy selective imaging 1 (steady state sources)**
Speaker: Nikolay Kardjilov (Helmholtz Berlin)

14:00 → 14:30 **Coffee Break**

14:30 → 16:00 **Energy selective imaging 2 (ToF)**
Speaker: Robin Woracek (ESS)

Thursday

13:00 → 14:30 **Scattering and magnetic contrast: Phase contrast, grating interferometry, SEMSANS, polarized imaging**
Speaker: Nikolay Kardjilov (Helmholtz Berlin)

14:30 → 15:00 **Coffee Break**

15:00 → 16:30 **Neutron tomography application examples from archeology and food to battery processes and strain evolution in metals**
Speakers: Robin Woracek (ESS), Stephen Hall (LINXS)

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Neutron Detectors

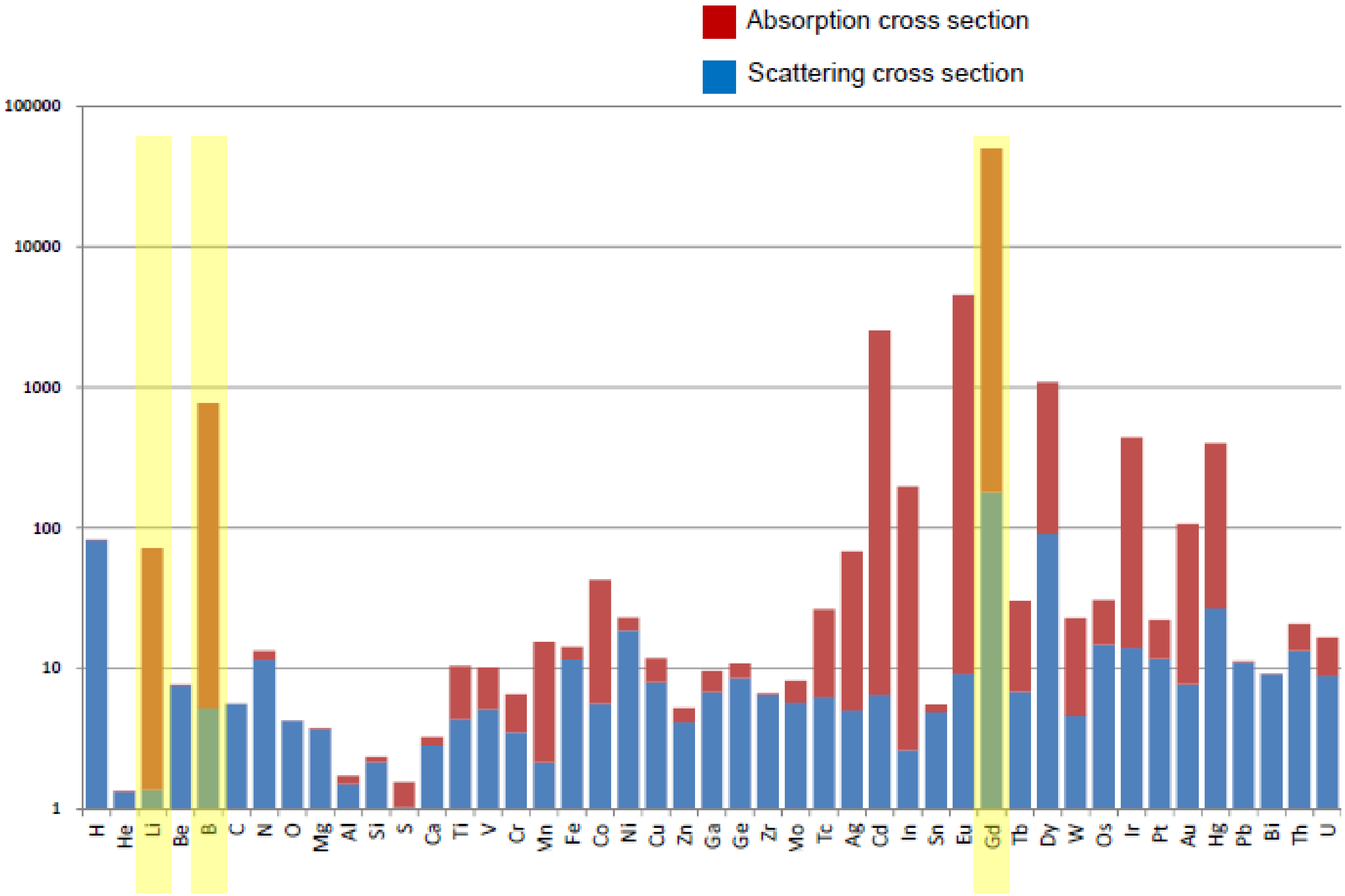
- How does one “detect” a neutron?
  - Can’t directly detect slow neutrons (neutrons relevant to materials science, that is)—they carry too little energy
  - Need to produce some sort of measurable quantitative (countable) electrical signal
- Need to use nuclear reactions to convert neutrons into charged particles
- Then one can use some of the many types of charged particle detectors
  - Gas proportional counters and ionization chambers
  - Scintillation detectors
  - Semiconductor detectors

Neutron Detection

A common method for detecting neutrons involves converting the energy released from neutron capture reactions into electrical signals. Certain nuclides have a high neutron capture cross section, which is the probability of absorbing a neutron. Upon neutron capture, the compound nucleus emits more easily detectable radiation, for example an alpha particle, which is then detected.

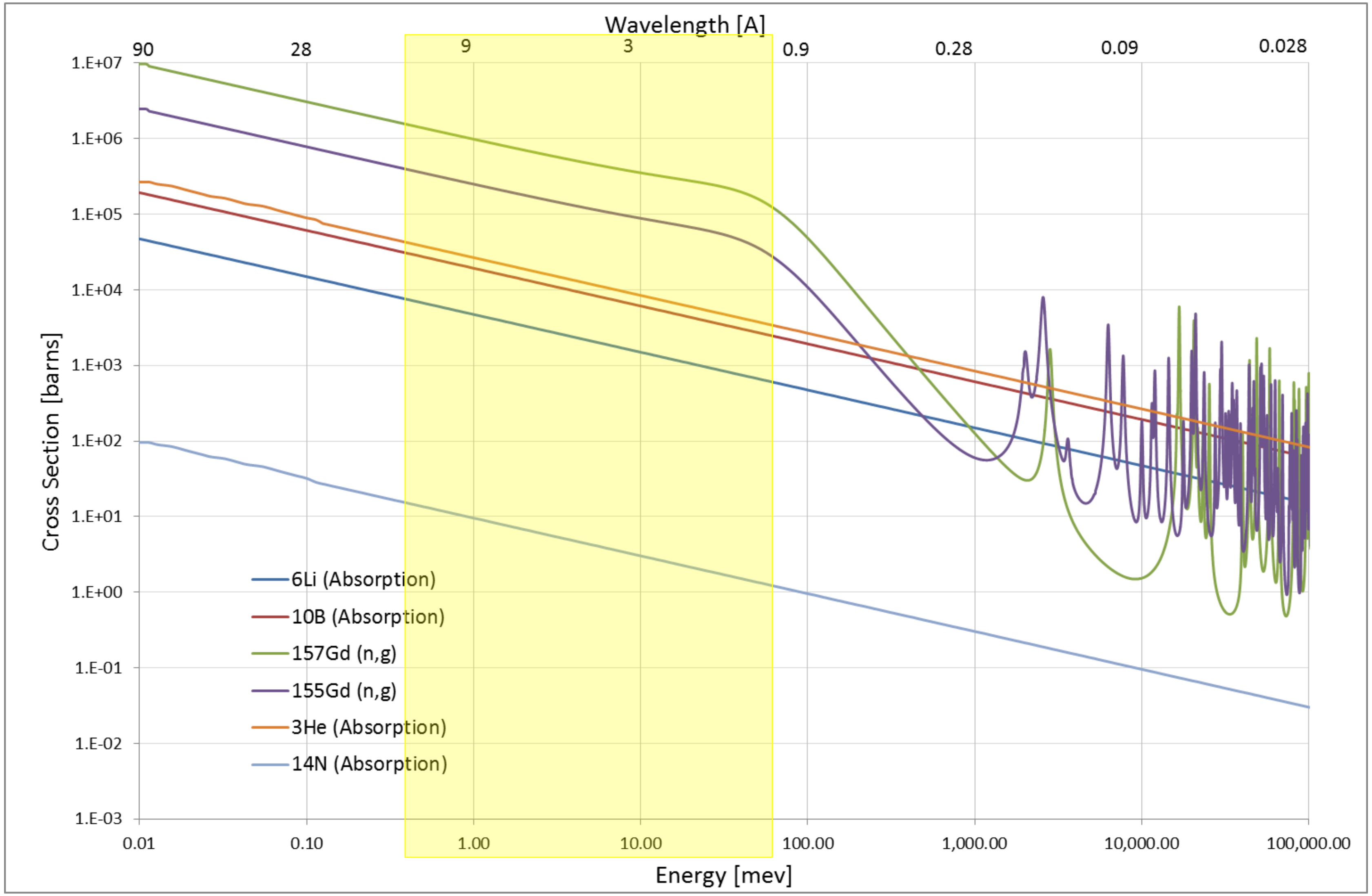
- **Since neutrons have zero charge they cannot be detected directly, instead a charge particle needs to be produced and then detected.**

Neutron Detection



Neutron Detection

The Cross Sections also depends on the energy



Courtesy: D. Pooley

Neutron Detection

Capture reactions for thermal / cold neutrons

$^{3}He + {}^{1}n \Rightarrow {}^{3}He + {}^{1}p + 0.77\ MeV$

→ $^{6}Li + {}^{1}n \Rightarrow {}^{3}H + {}^{4}He + 4.79\ MeV$

→ $^{10}B + {}^{1}n \Rightarrow {}^{7}Li + {}^{4}He + 2.78\ MeV$ (7%)

$\Rightarrow {}^{7}Li^{*} + {}^{4}He + 2.30\ MeV$ (93%)

→ $^{155}Gd + {}^{1}n \Rightarrow {}^{156}Gd + \gamma's + CE's$ (7.9 MeV)

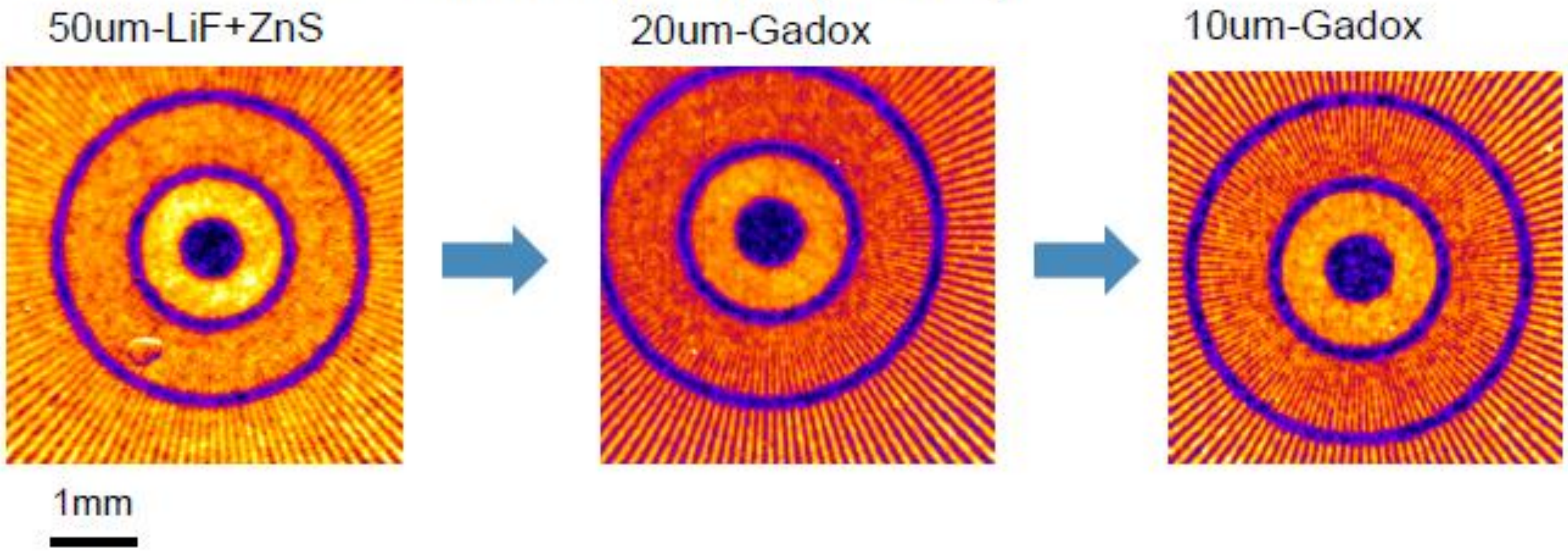
$^{157}Gd + {}^{1}n \Rightarrow {}^{158}Gd + \gamma's + CE's$ (8.5 MeV)

^{235}U, ^{239}Pu $^{1}n \Rightarrow$ fission products + 80 MeV

Neutron Detection

How do you choose which absorber and which thickness for a scintillator?

Rule-of-thumb: thickness = spatial resolution (valid because these scintillators are powder)



That's not the end of the story (of course)

Neutron Detection

How do you choose which absorber
scintillat

Thank you!

Questions?

Website : **http://www.europeanspallationsource.se**

Contact me : **robin.woracek@ess.eu**