PAUL SCHERRER INSTITUT PSI

CCMX Competence Centre for Materials Science and Technology

IAEA International Atomic Energy Agency

Wir schaffen Wissen – heute für morgen

Manuel Morgano

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Principles of Neutron Imaging

Topics

1. Absorption-based imaging
2. How to attenuate a neutron beam: absorption vs. scattering (in brief)
3. Geometrical principles: L/D
4. Neutron collimation and exposure time
5. Main differences between x-ray and neutron imaging
6. Neutron imaging domain: big objects, hydrogen…
7. Neutron conversion to light
8. Thermal and cold neutrons: pros and cons
9. A taste of more advanced neutron imaging techniques

What is neutron imaging

Problem:

You have an object

What is neutron imaging

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You want to know what's inside this object (even the composition)

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You also want to know how much of it is inside

What is neutron imaging

Problem:

You have an object

You want to know what's inside this object (even the composition)

You also want to know how much of it is inside

And for some reasons you want to use neutrons (we'll see why later)

Solution:

What is neutron imaging

Solution:

Get yourself one of these:

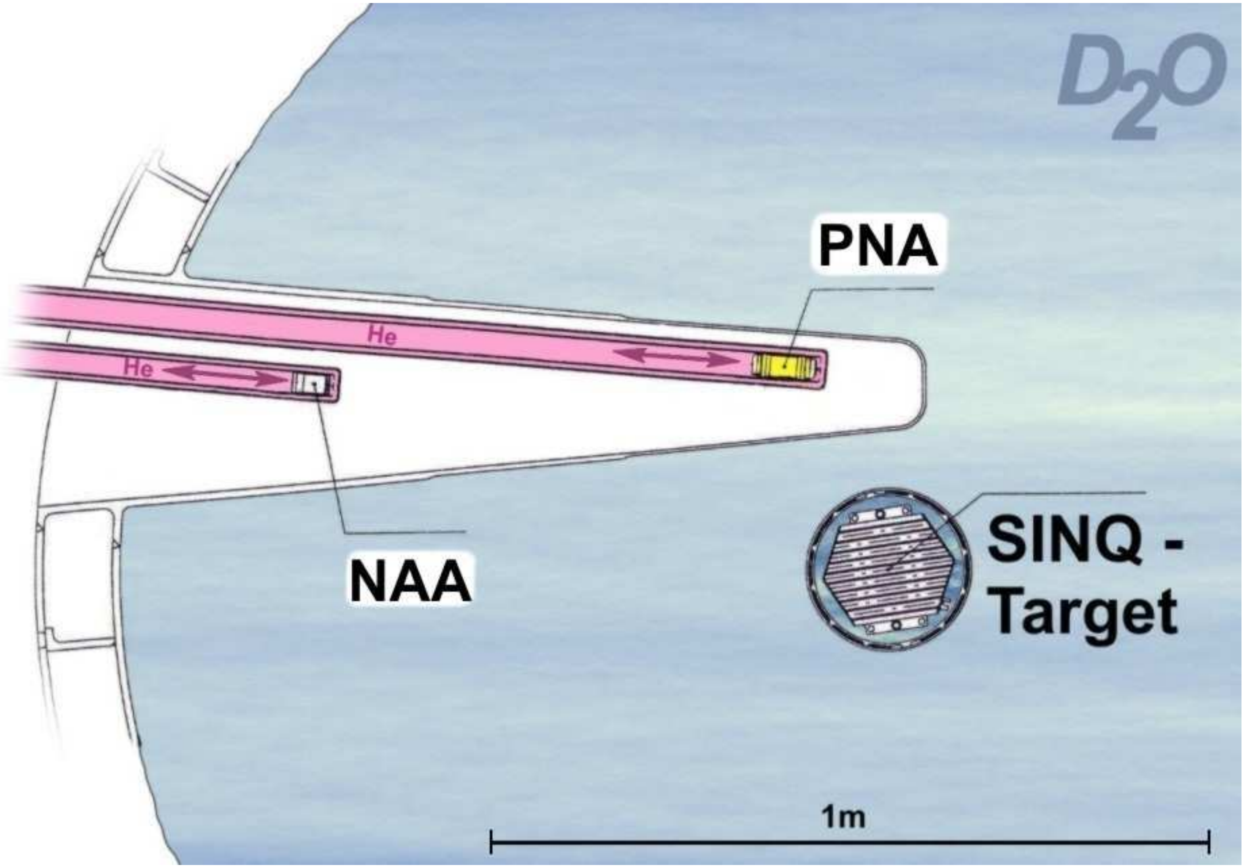
What is neutron imaging

Solution:

Or one of these:

What is neutron imaging

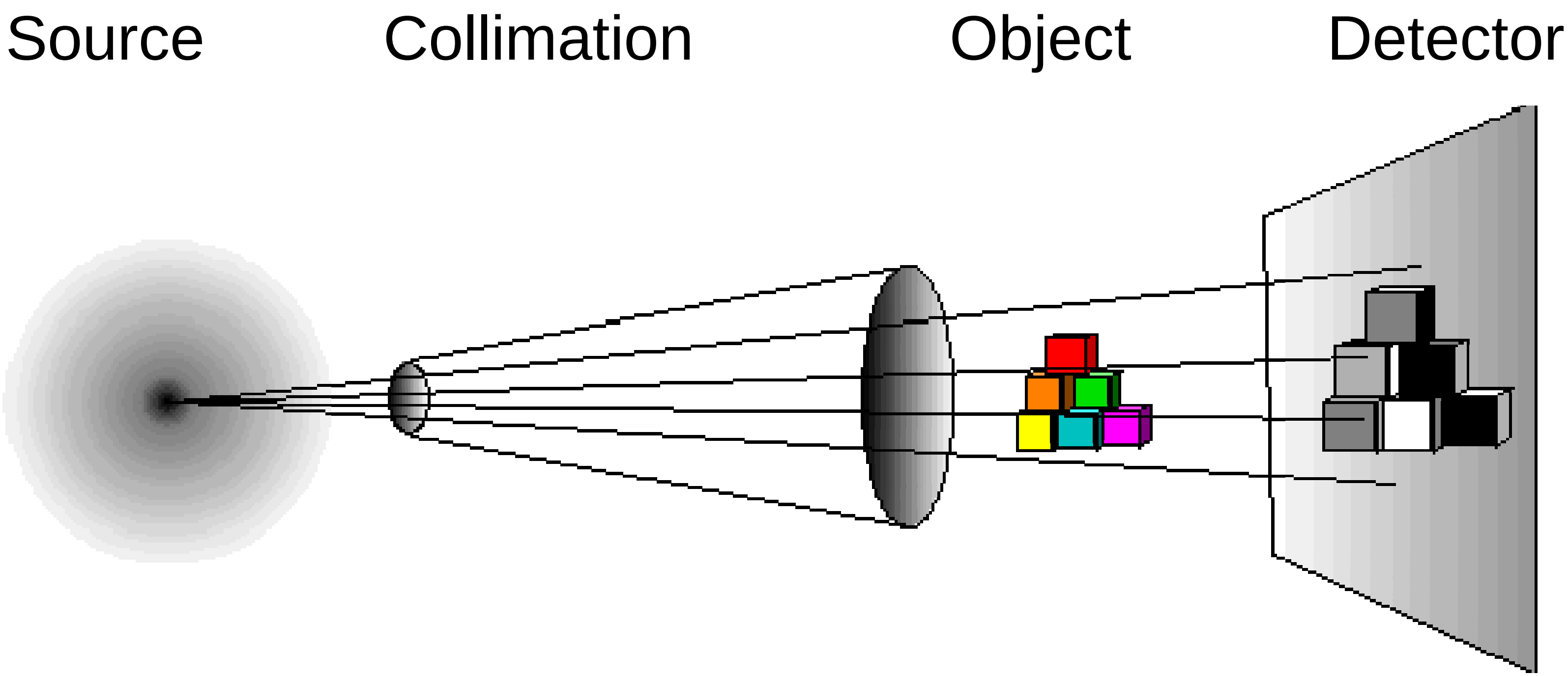
Moderate and transport the resulting neutrons



See presentations from E. Lehmann and M. Strobl about this

What is neutron imaging

Measure!



What is neutron imaging

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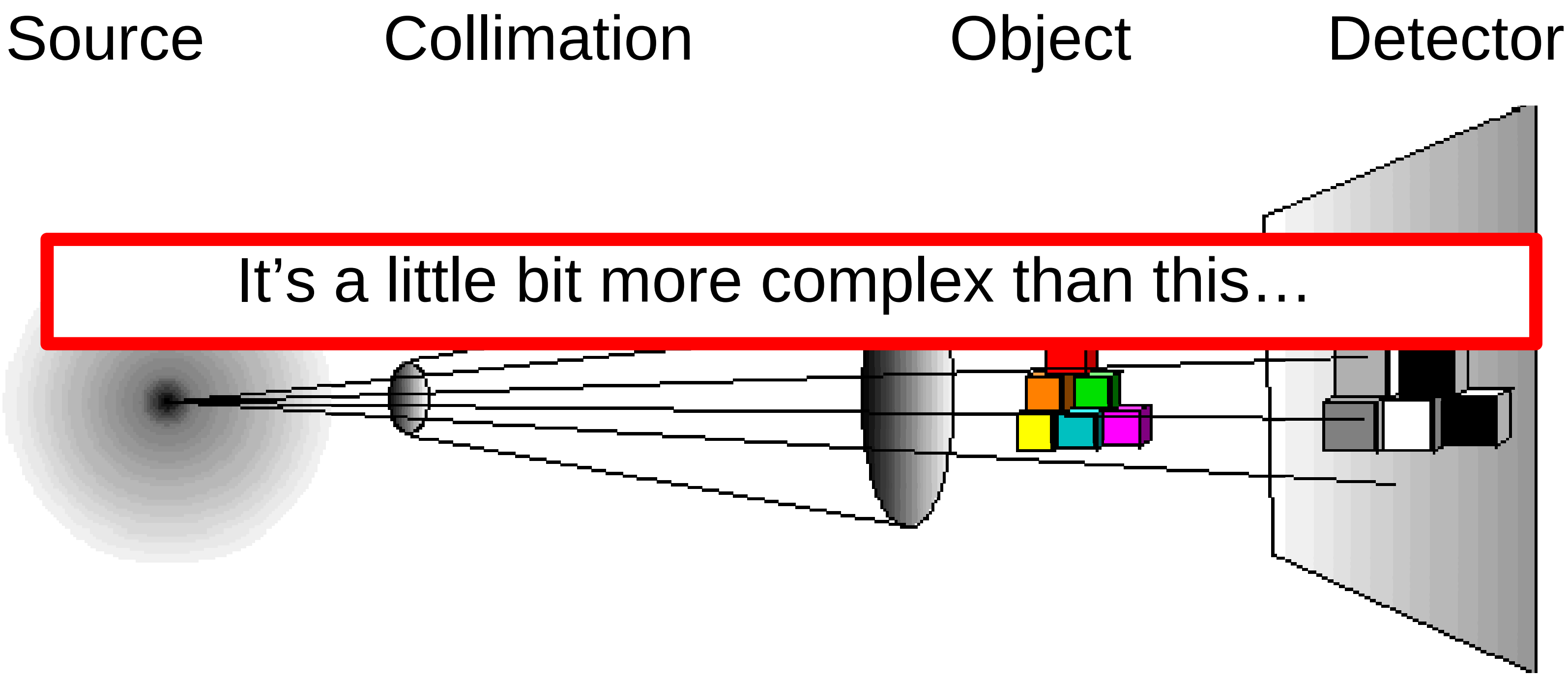

Attenuation-based imaging

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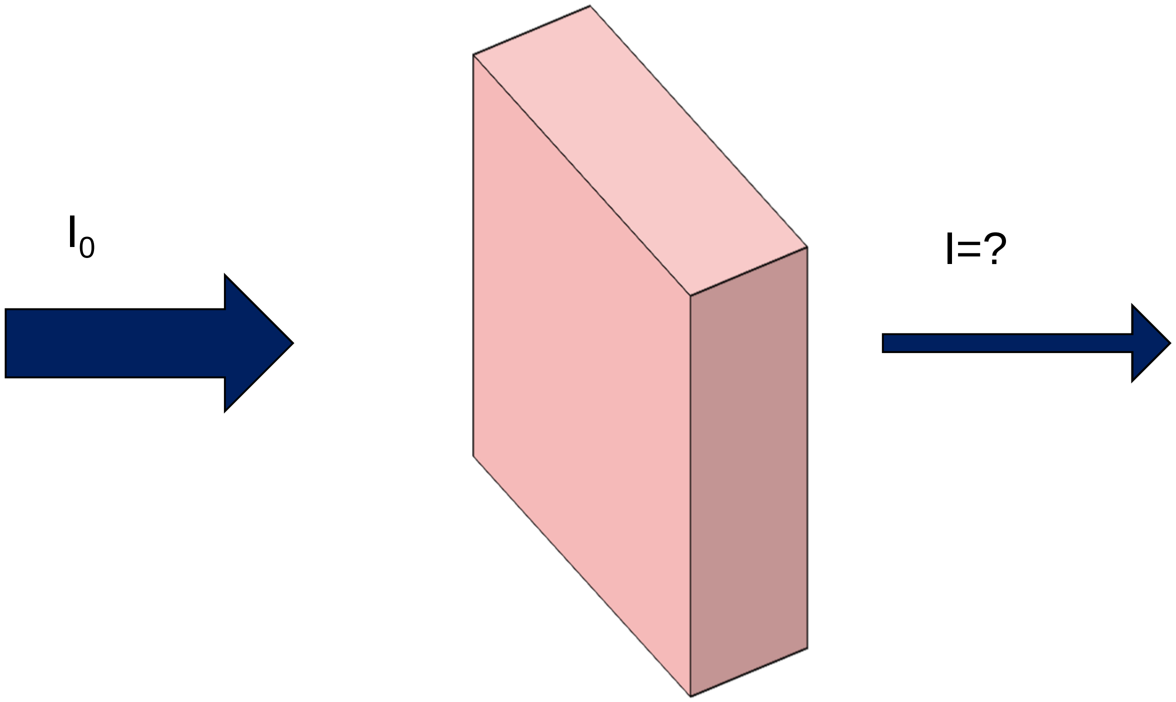
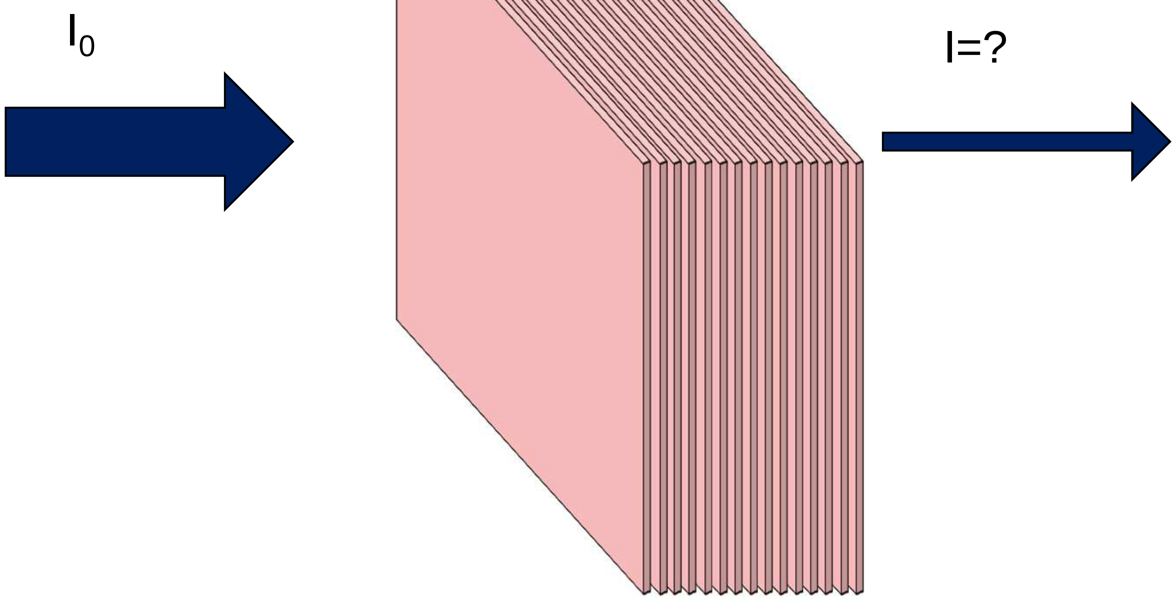


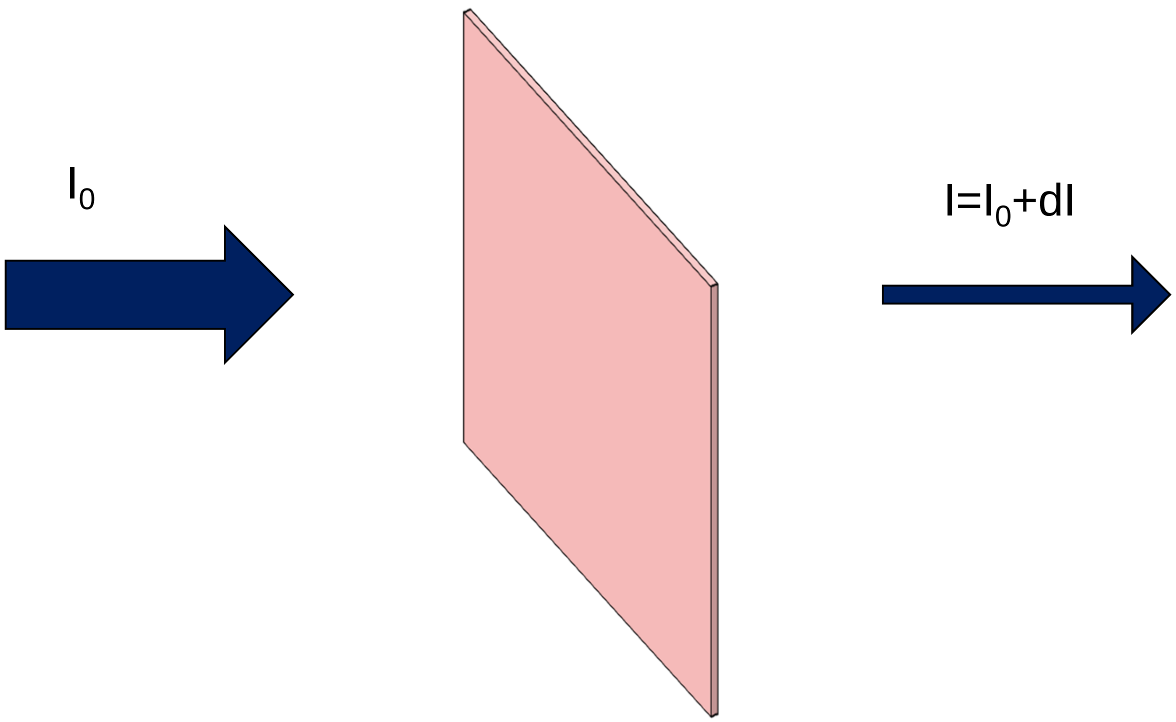
Attenuation-based imaging

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



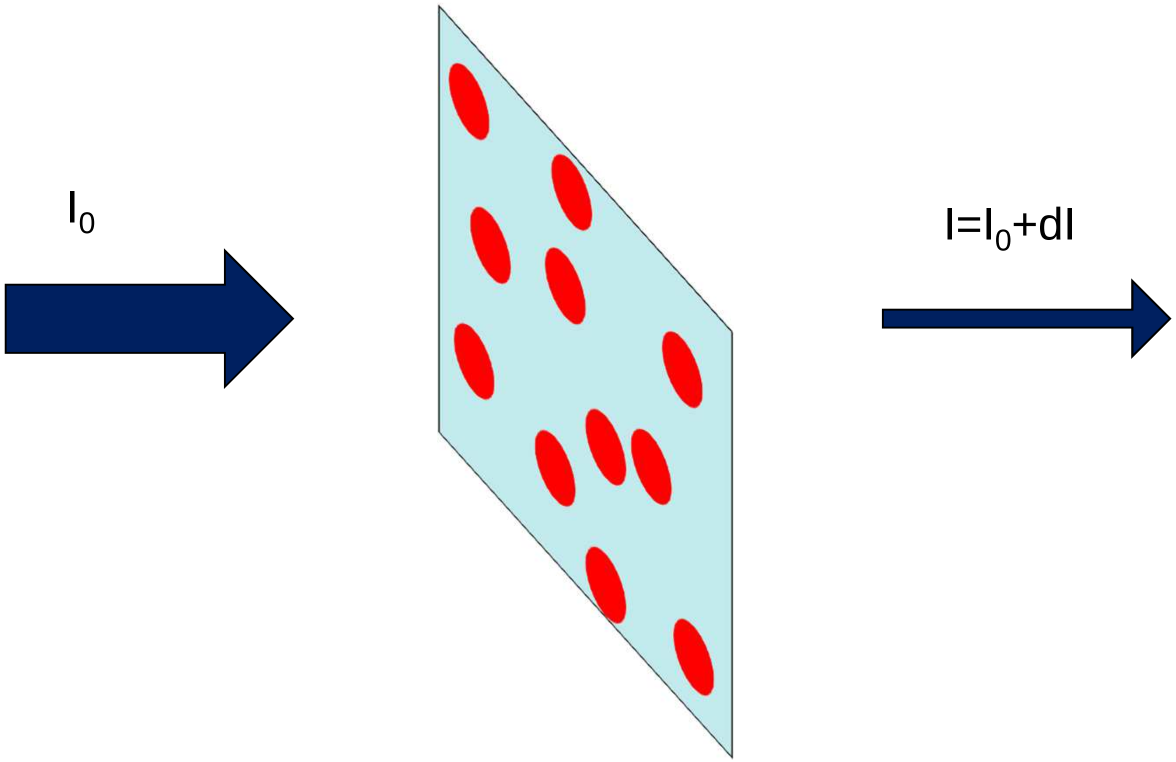
Attenuation-based imaging

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



Attenuation-based imaging

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



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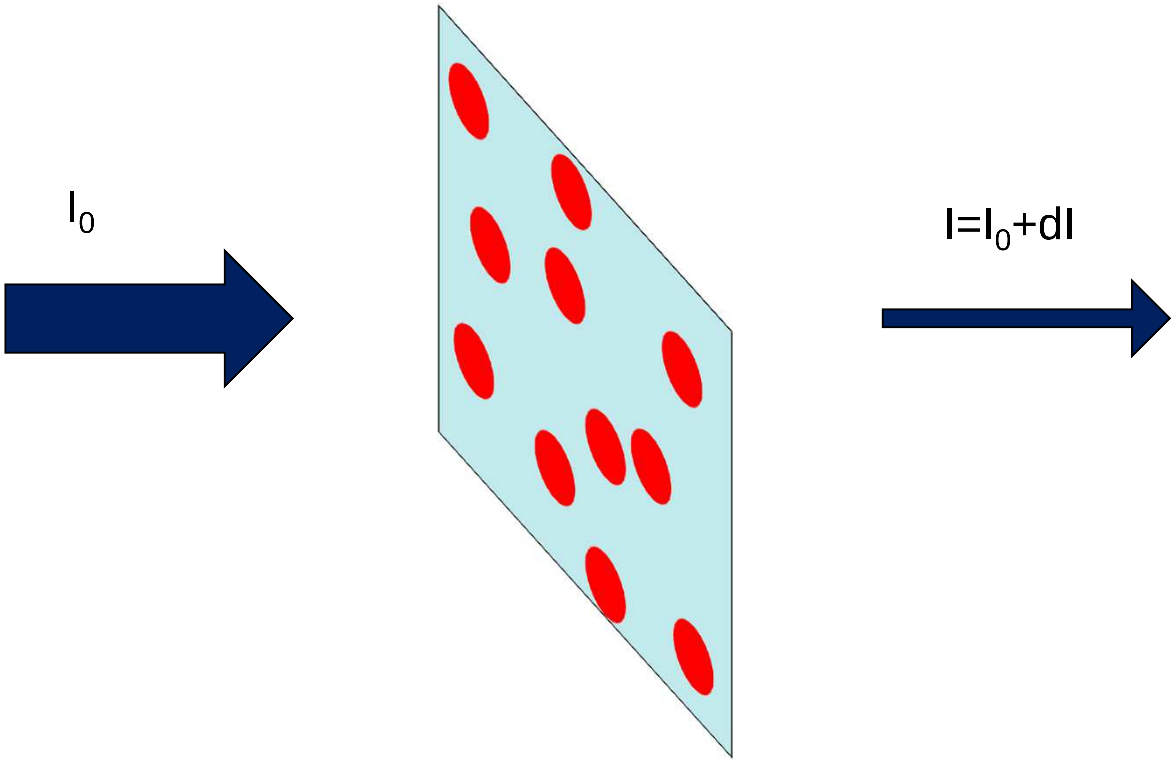
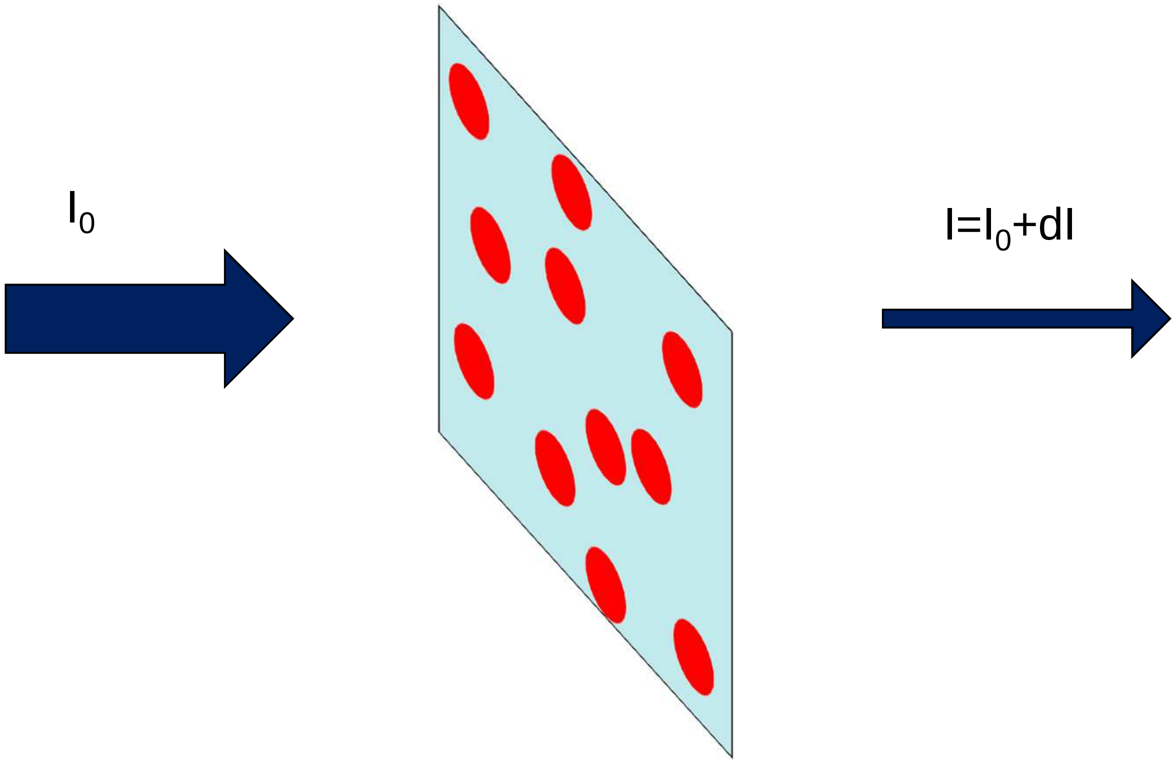


The area of each attenuator is called the (microscopic) cross section σ

Attenuation-based imaging

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



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

Attenuation-based imaging

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

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

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

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

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Beer-Lambert law

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

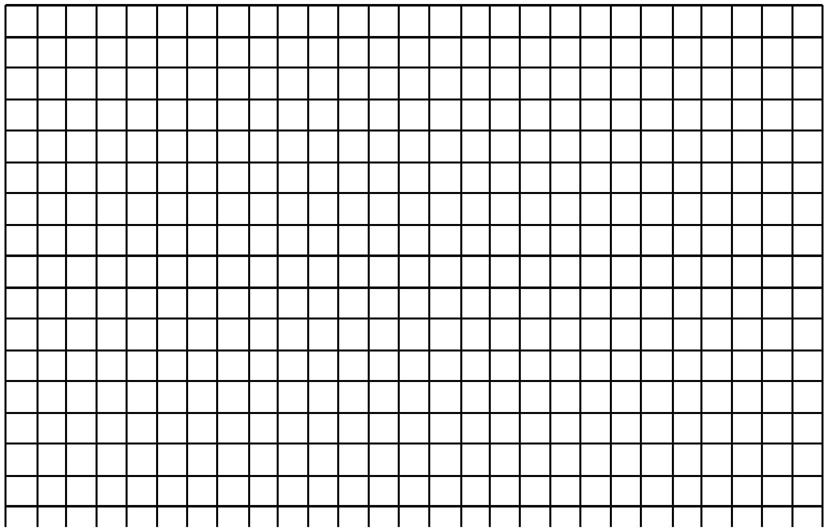
$$I = I_0 e^{-\sum_i \int_0^t N_i(x) \cdot \sigma_i(x) \cdot dx}$$ For several absorbers

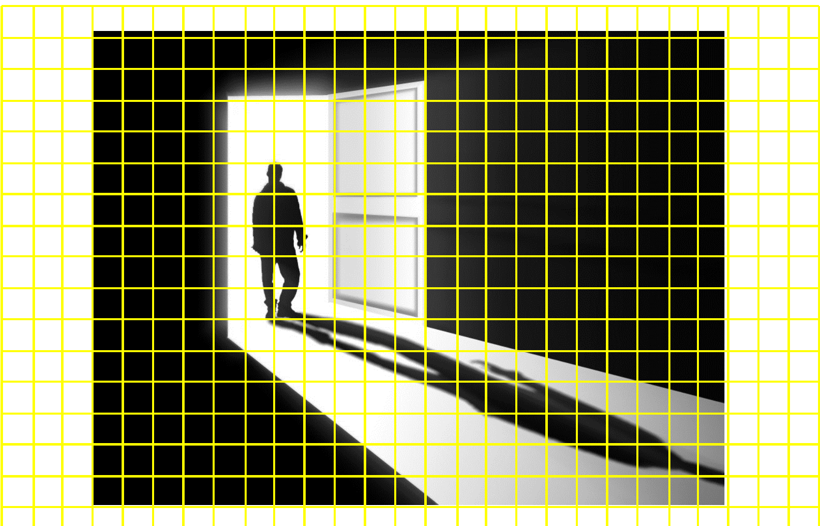
Attenuation-based imaging

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

$$I_{(i,j)} = I_{0(i,j)} e^{-\int_C N_{(i,j)}(x)\cdot\sigma_{(i,j)}(x)\cdot dx}$$

With “C” the line, of length t, in front of pixel (i,j)





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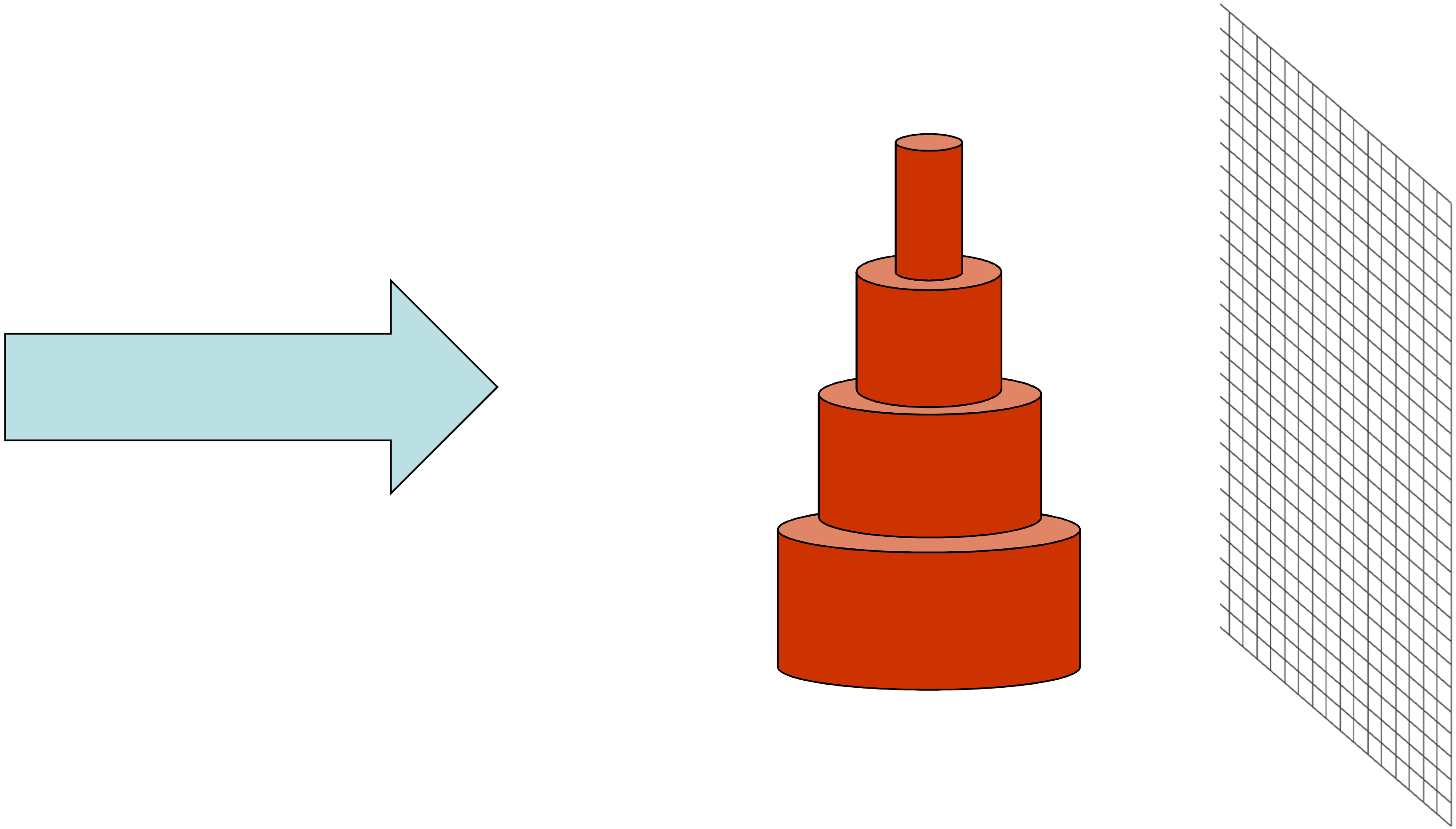

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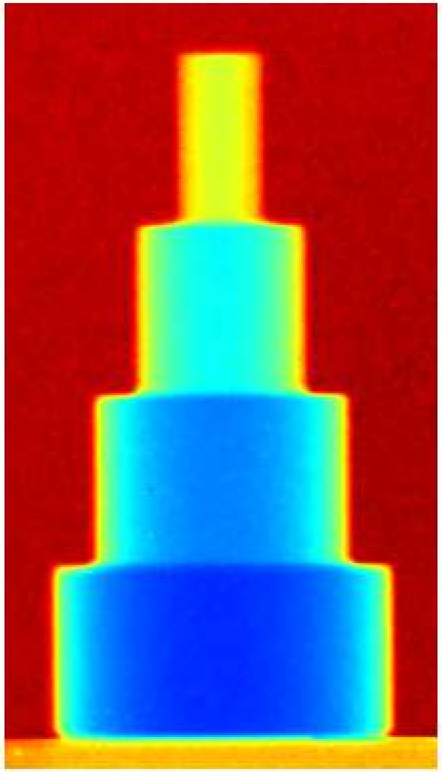

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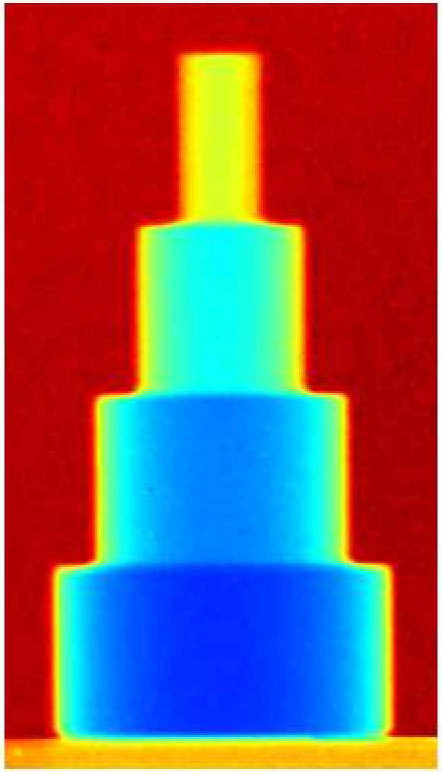

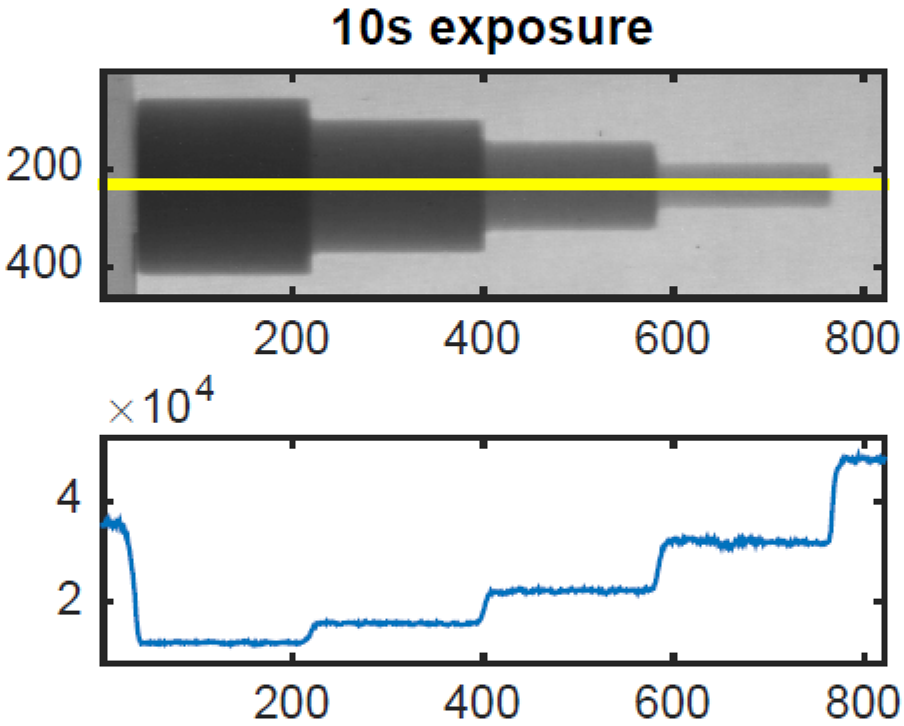

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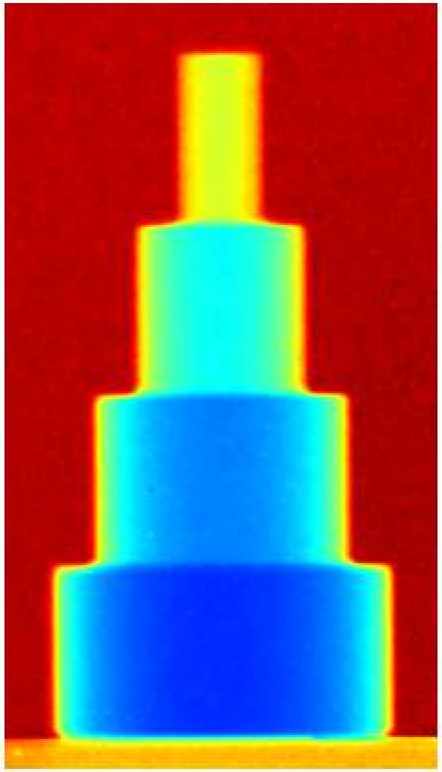

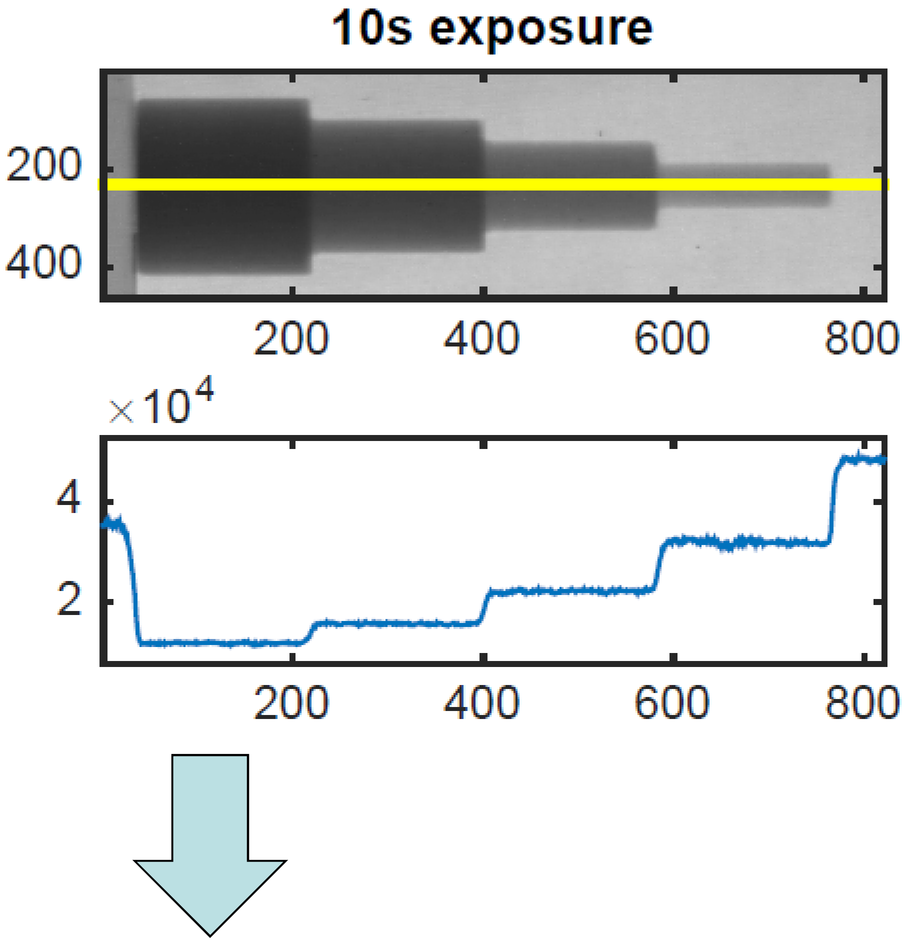

From this to quantification of the amount of material

Attenuation-based imaging

A number of assumptions have been made:

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For (thermal and cold) neutrons:

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True for most applications

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For (thermal and cold) neutrons:

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True for most elements

The equation needs to be modified:

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

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Also beam hardening

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(Almost) true for imaging

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For (thermal and cold) neutrons:

- True for most applications
- True for most elements
- The equation needs to be modified:
  $$I = I_0 e^{-\int_0^t \int_{\lambda_{min}}^{\lambda_{max}} N(x)\sigma(x,\lambda)\,dx\,d\lambda}$$
- (Almost) true for imaging
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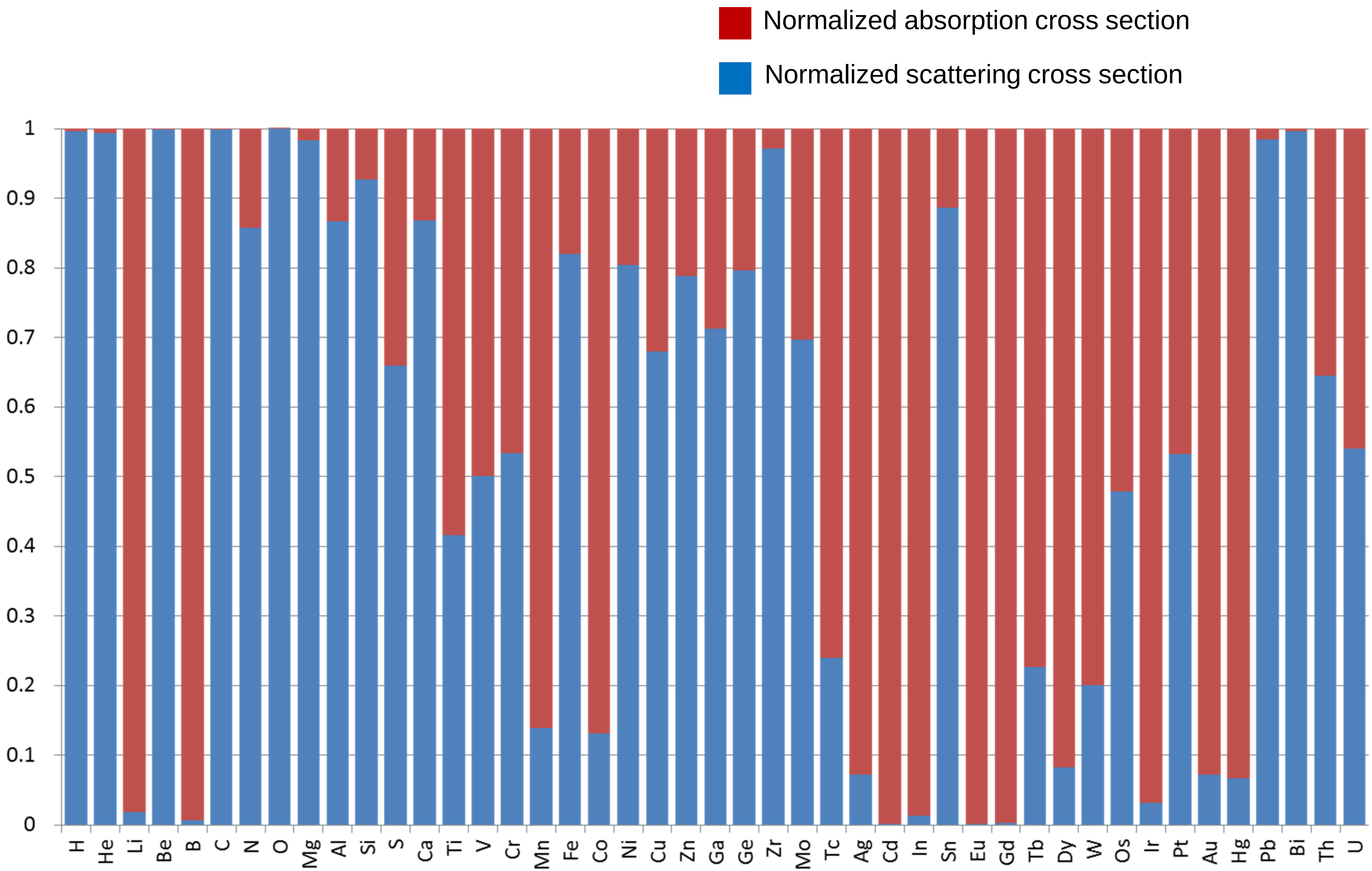
True for most elements

Plain wrong for most elements

Absorption vs. Scattering



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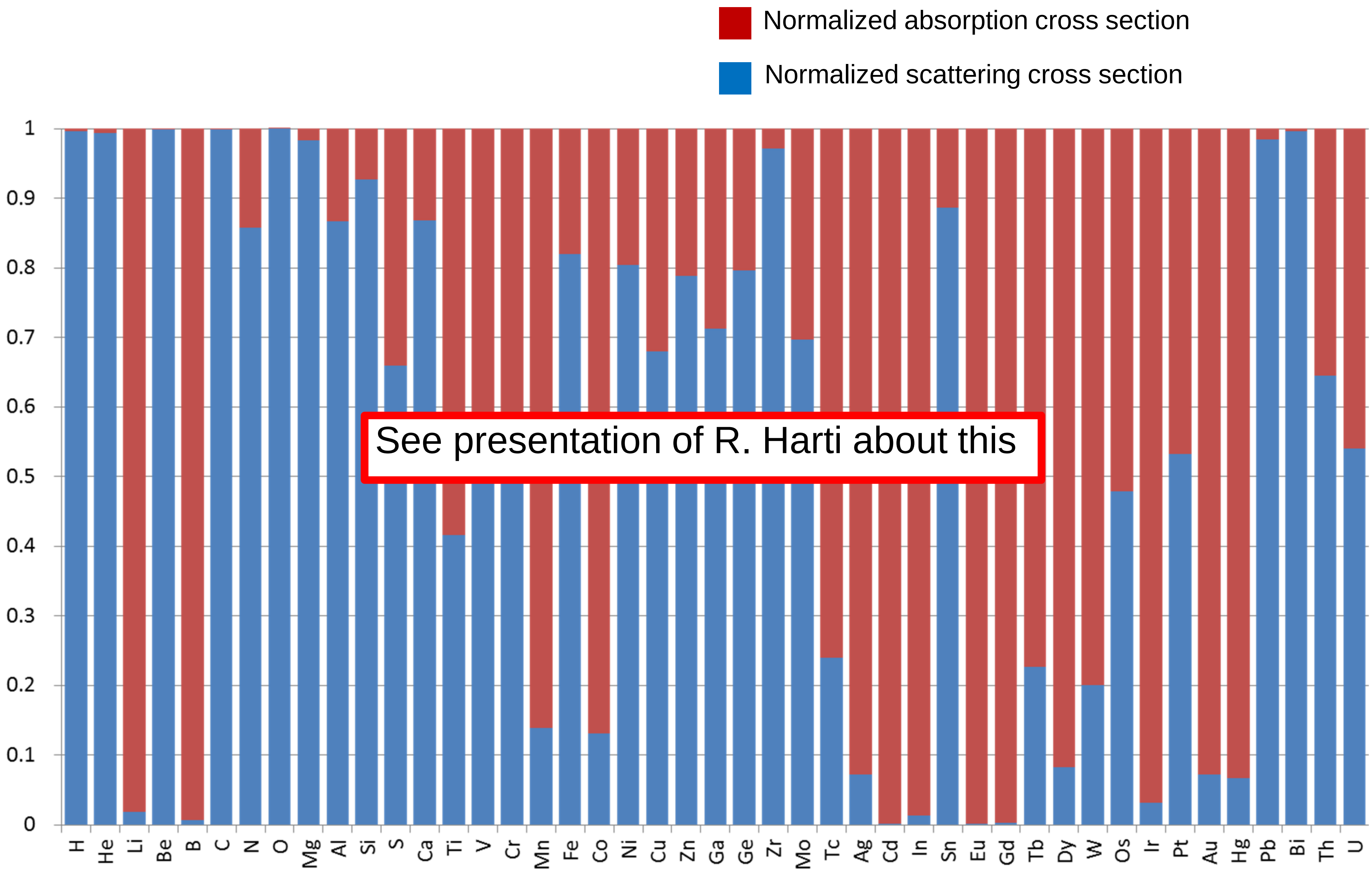

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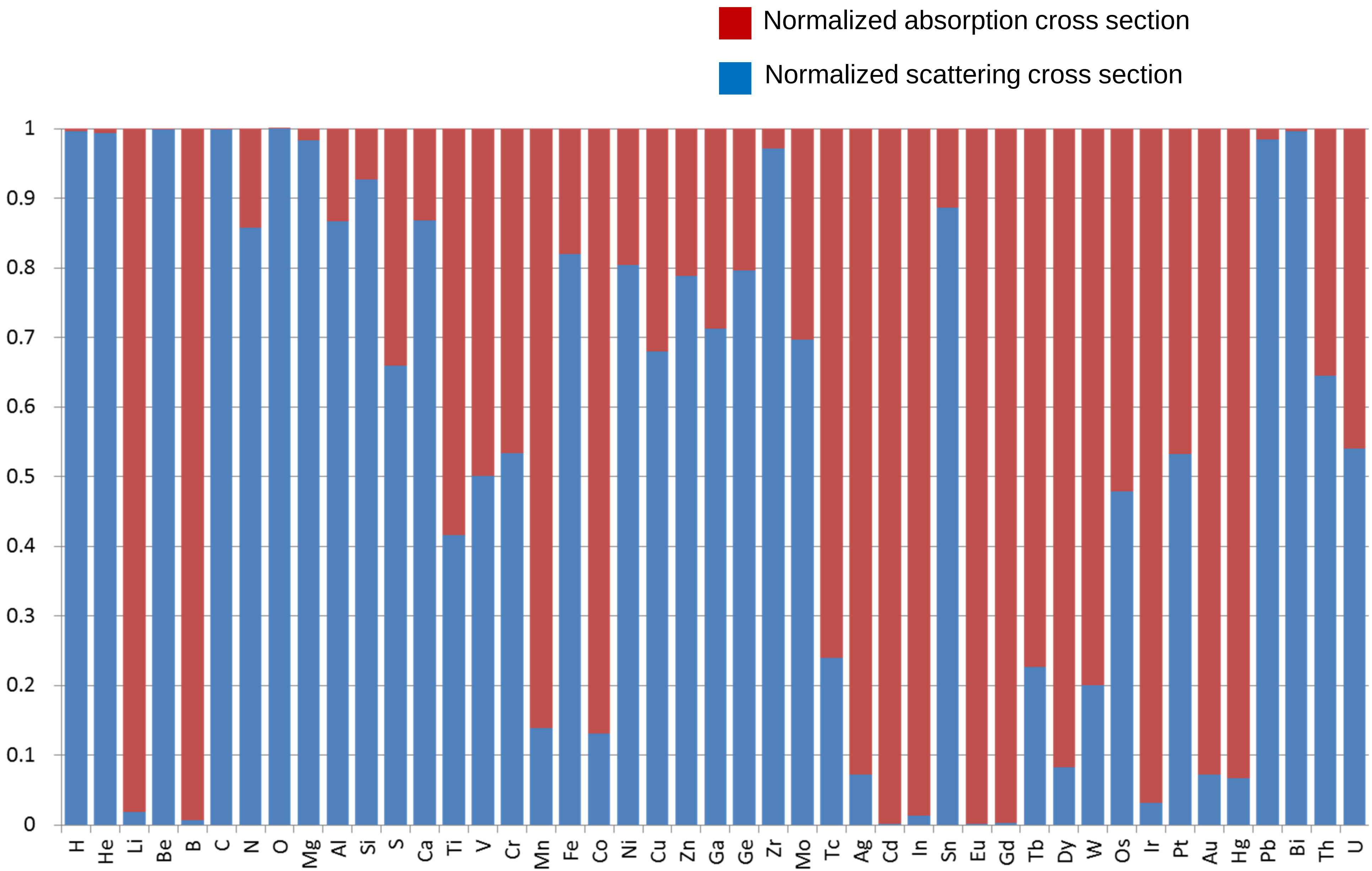

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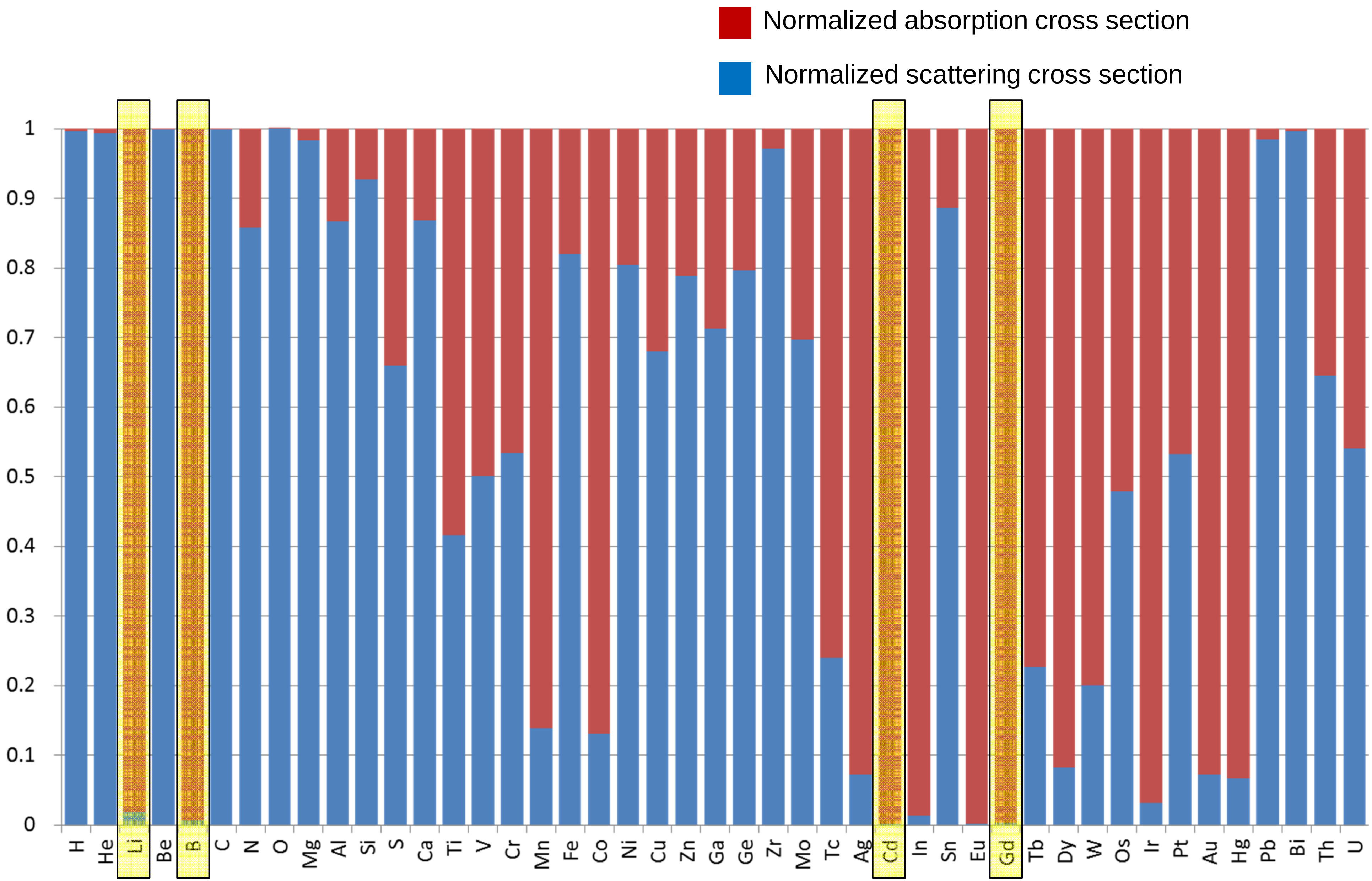

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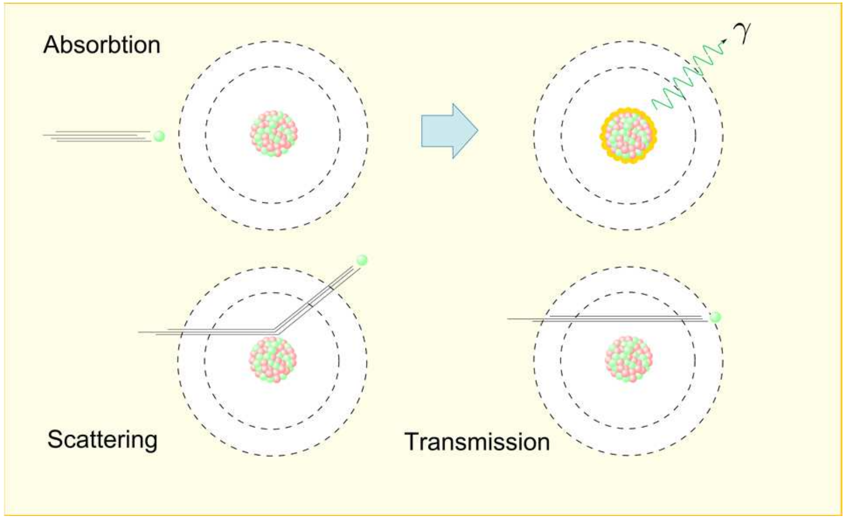

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How to solve this problem:

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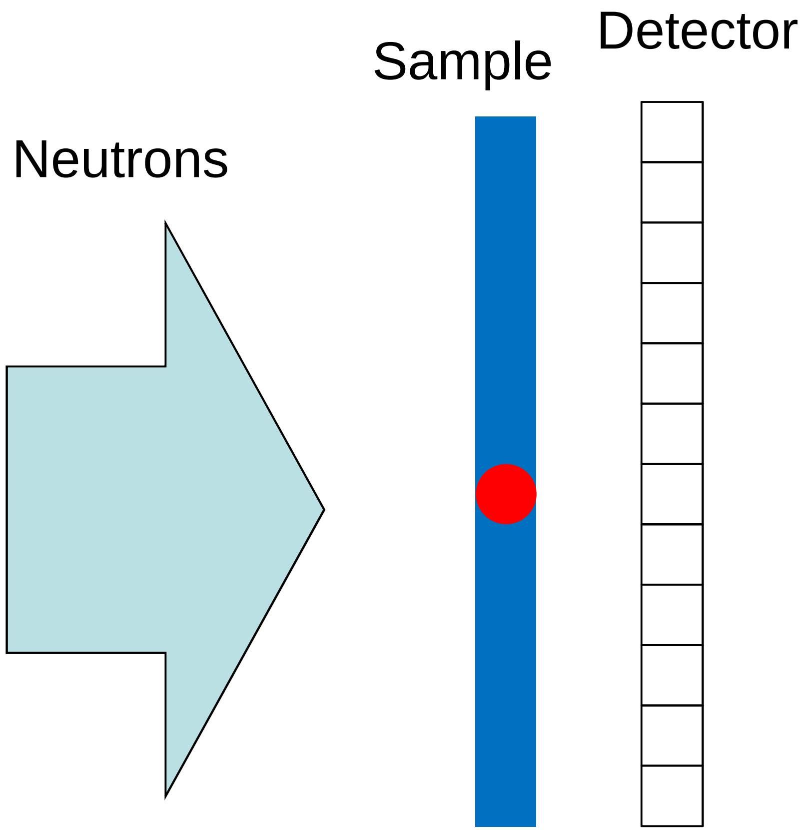
2. Flat samples are easier



Assume 4 π scatterer (red)

Absorption vs. Scattering

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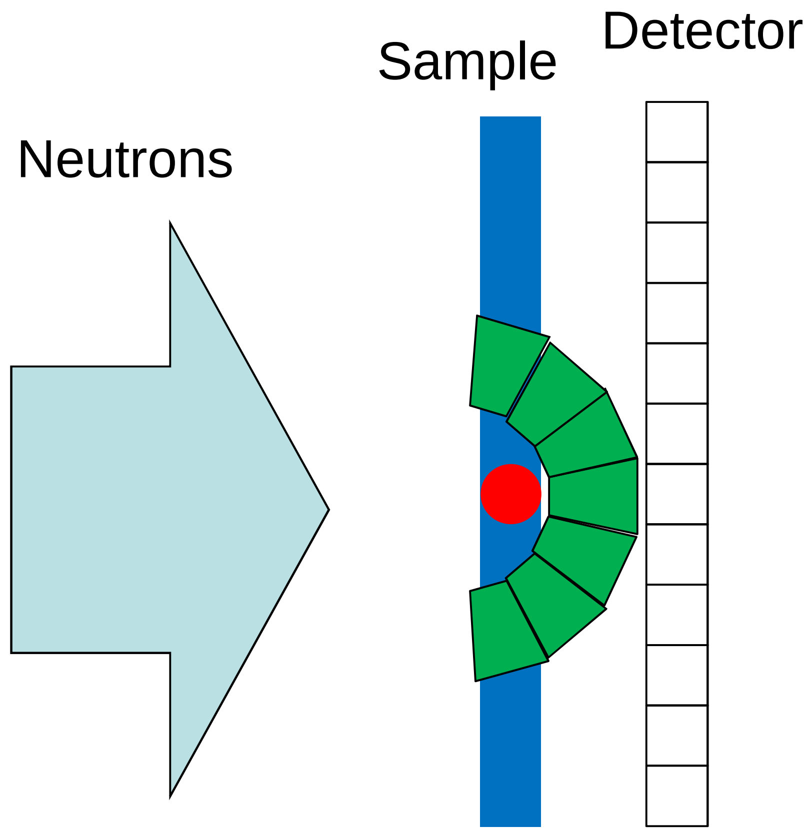

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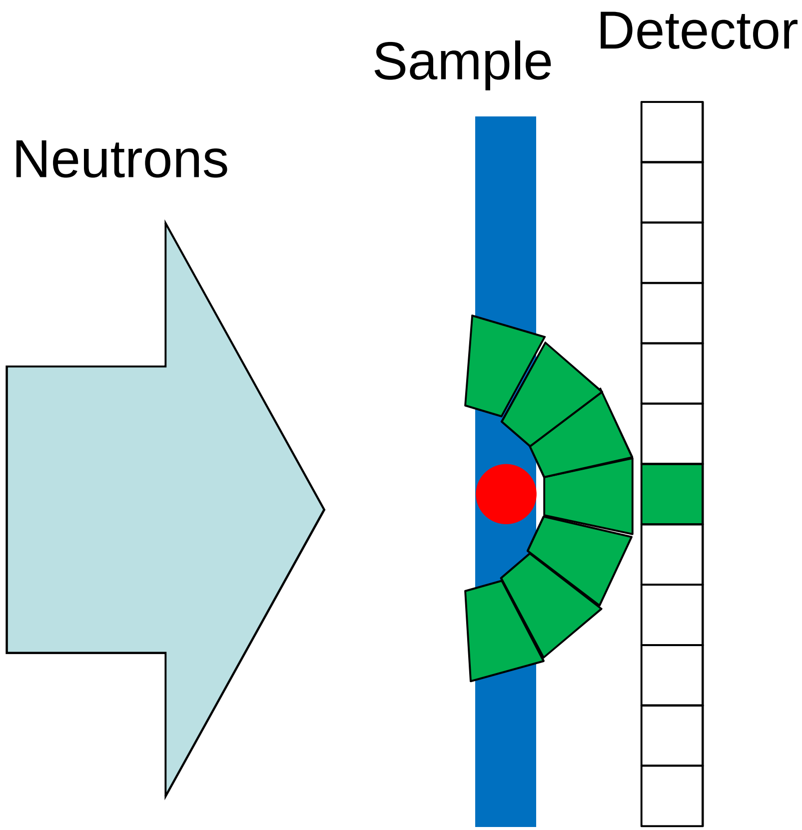

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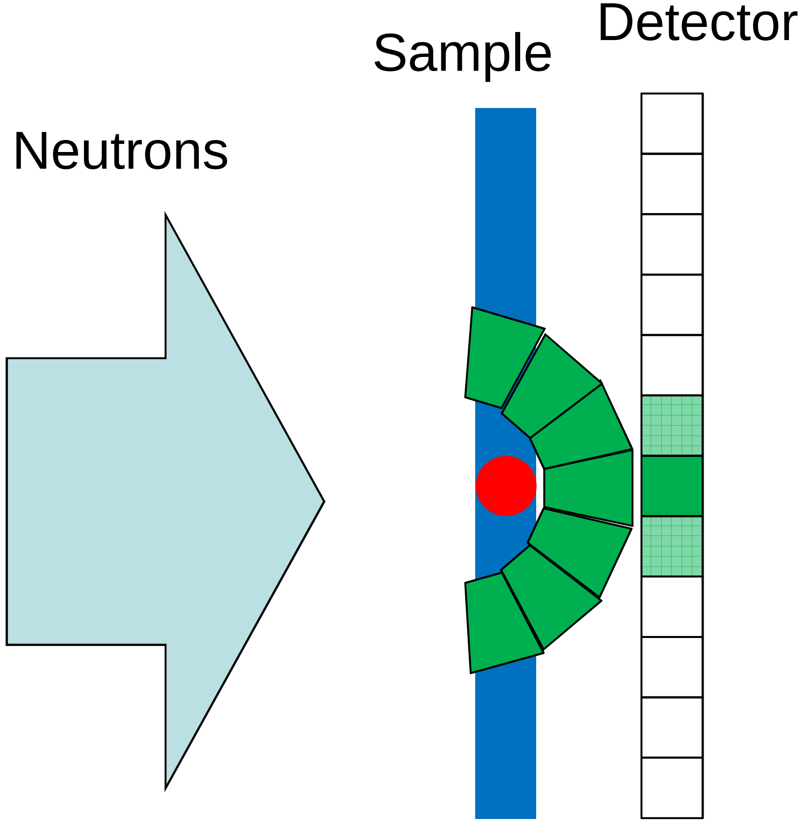

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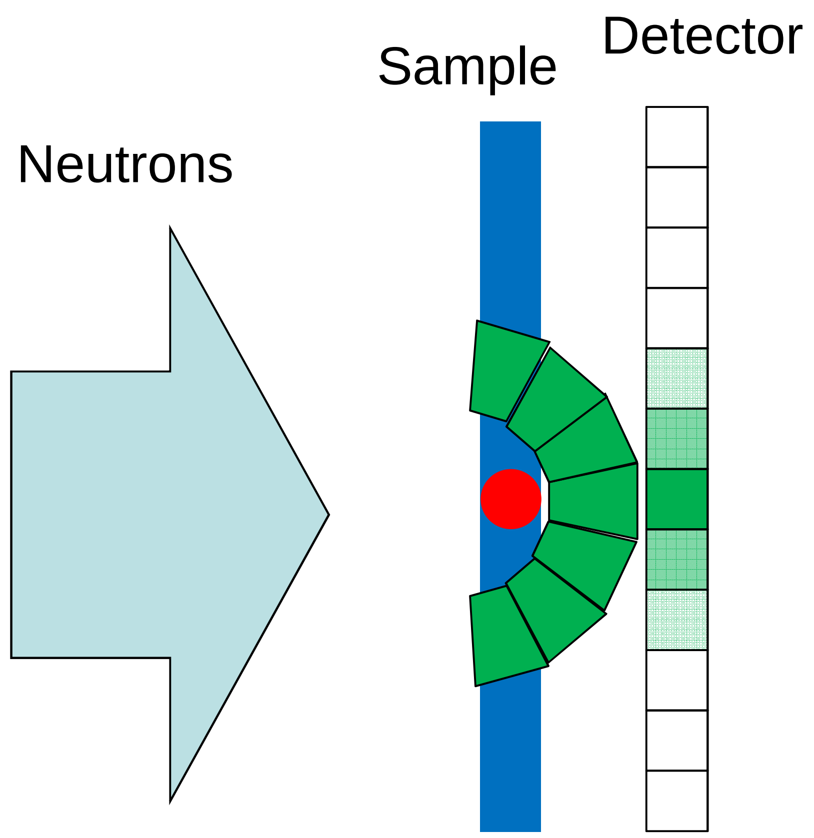
The pixel-wise solid angle quickly becomes small



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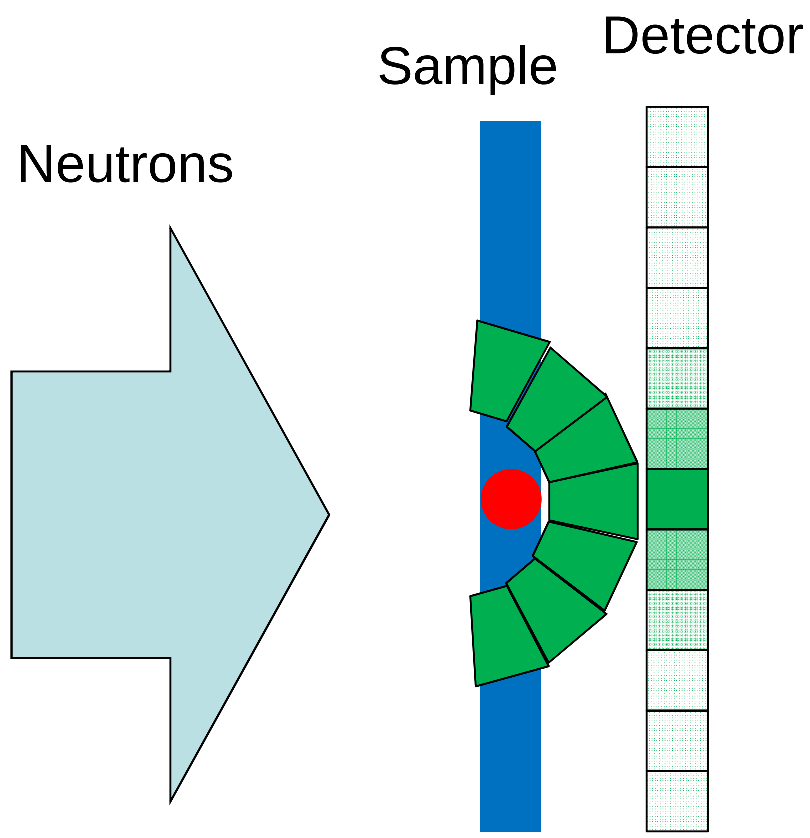
The pixel-wise solid angle quickly becomes small➔

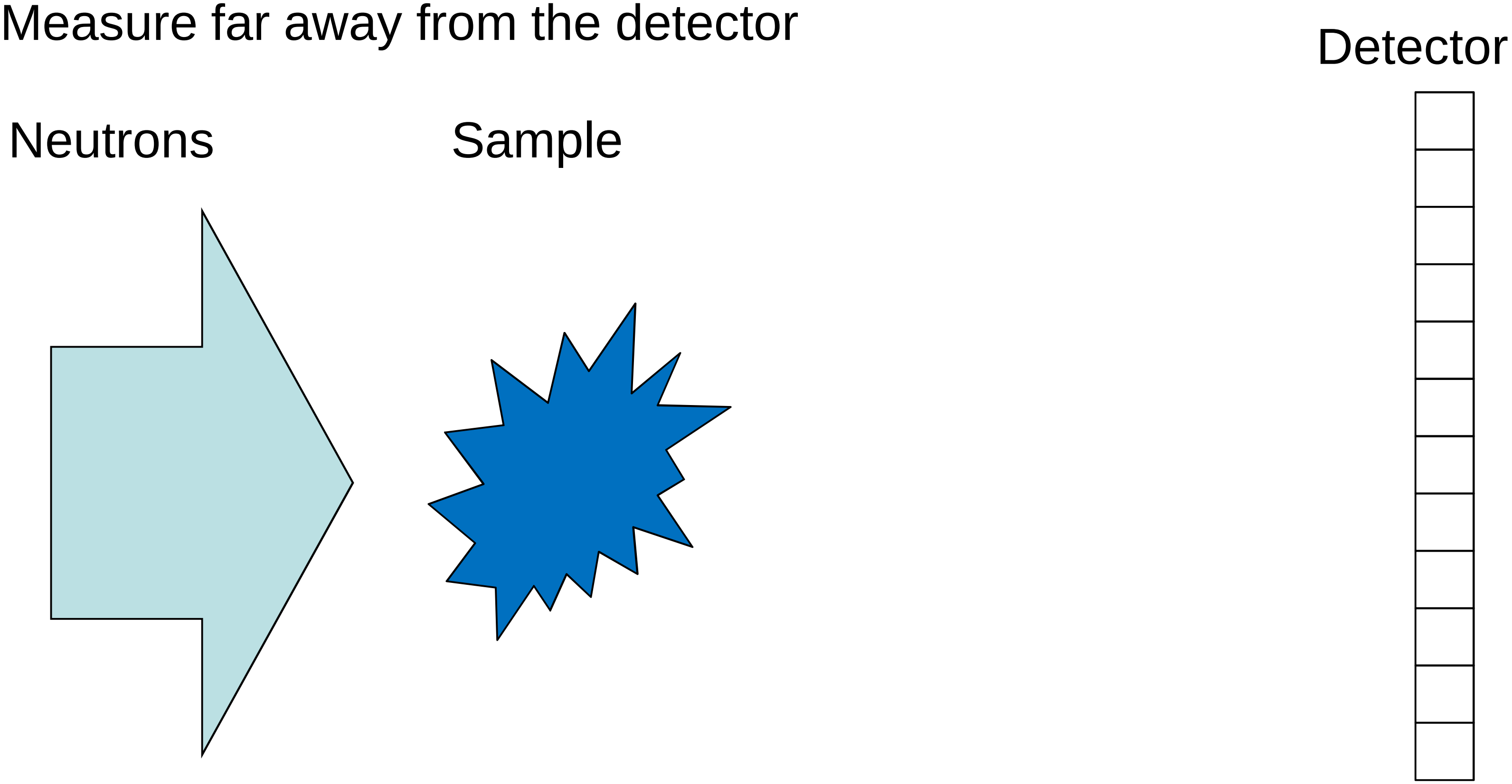
The cross talk quickly tapers off



Absorption vs. Scattering

How to solve this problem:

1. Accept it: quantification of highly scattering elements through imaging is difficult
2. Flat samples are easier
3. Measure far away from the detector



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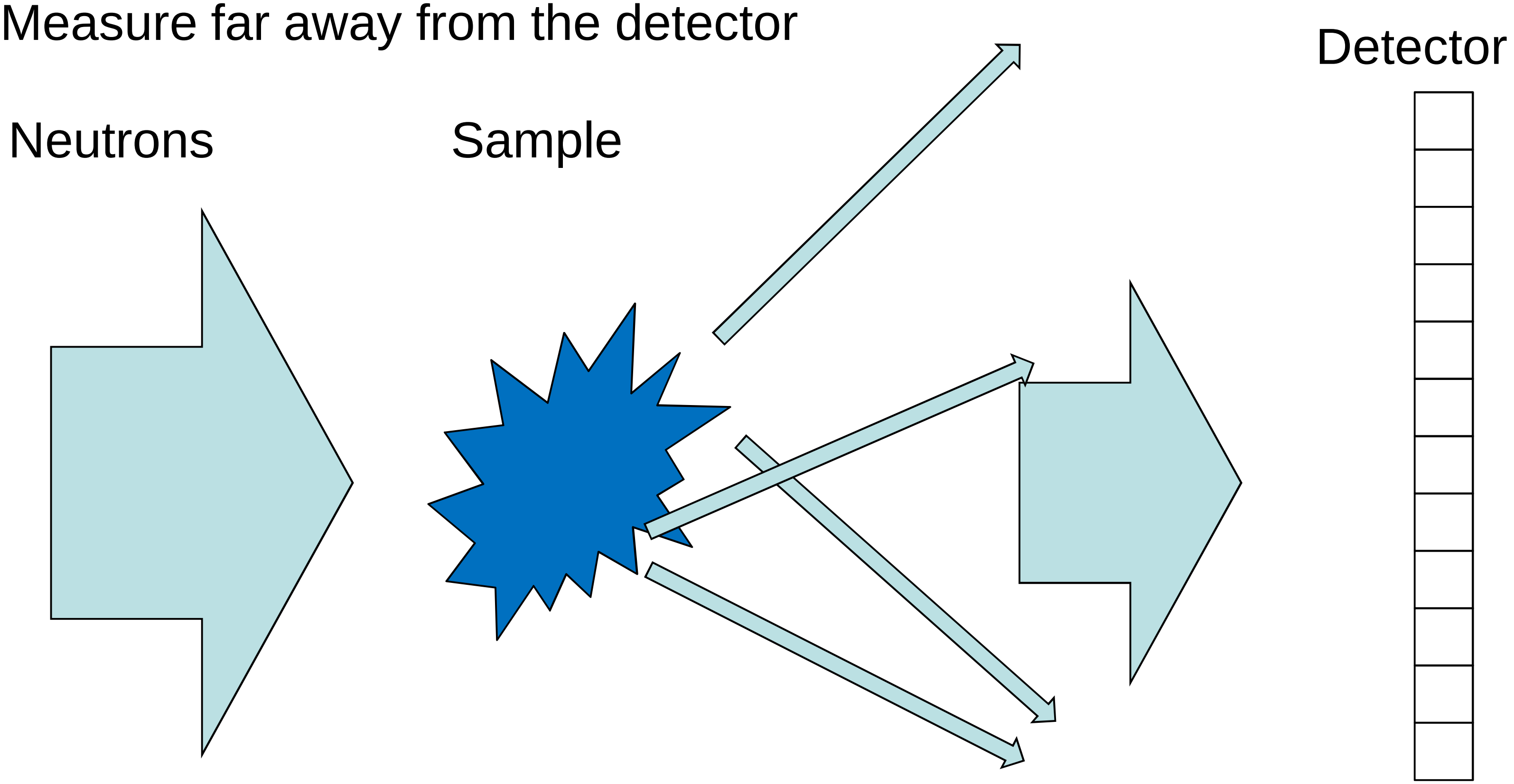

Absorption vs. Scattering

How to solve this problem:

1. Accept it: quantification of highly scattering elements through imaging is difficult
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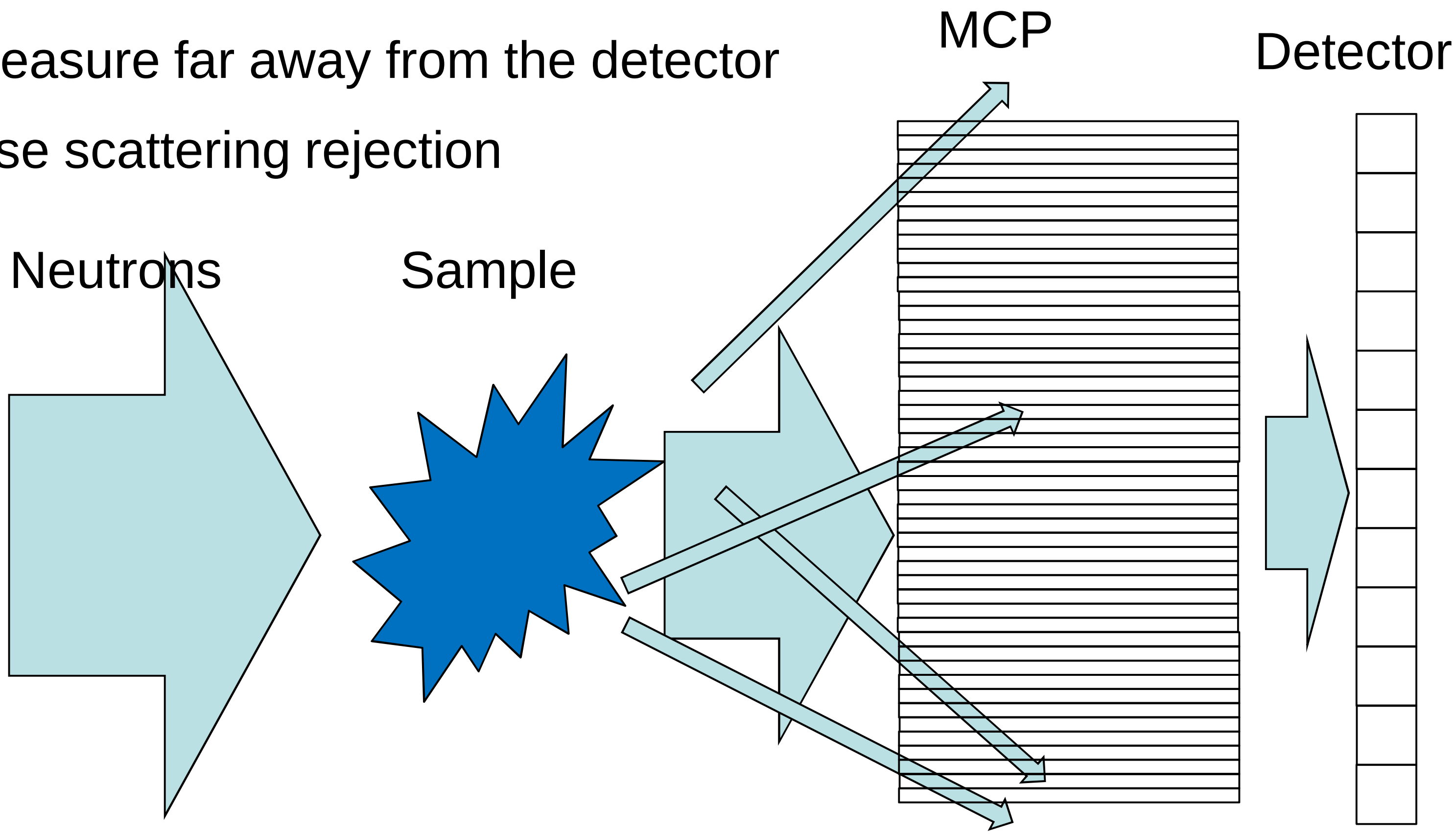
4. Use scattering rejection



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1. Accept it: quantification of highly scattering elements through imaging is difficult
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5. Modelling tools and simulations for ex-post correction

See presentation of P. Vontobel about this

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See presentation of B. Betz about this

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Seems the easiest! Let's do that!

Geometric principles

Depends on what you want to end up with:

Geometric principles

Depends on what you want to end up with:

This

Geometric principles

Depends on what you want to end up with:

This or this

Geometric principles

The reason is: <u>the neutron beam is never parallel</u>

Geometric principles

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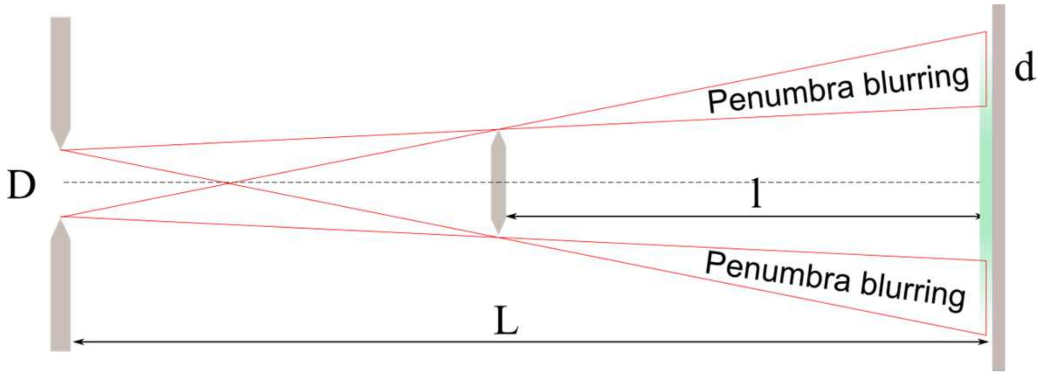

Geometric principles

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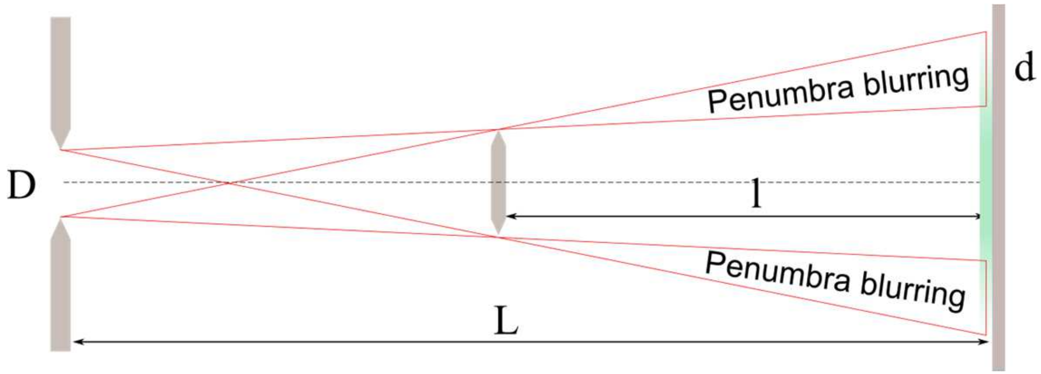
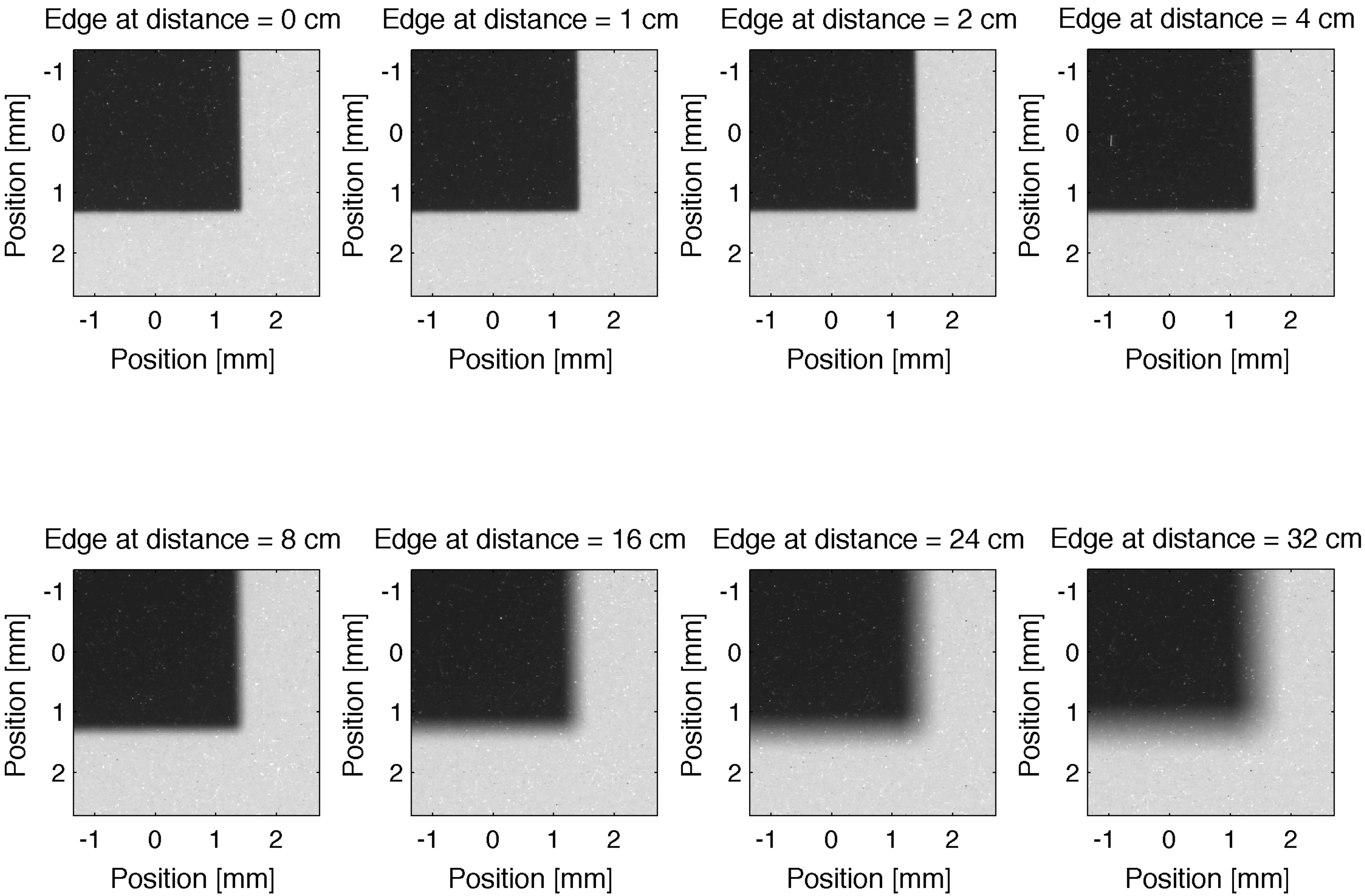


$$\frac{l}{d} = \frac{L}{D}$$

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

Geometric principles



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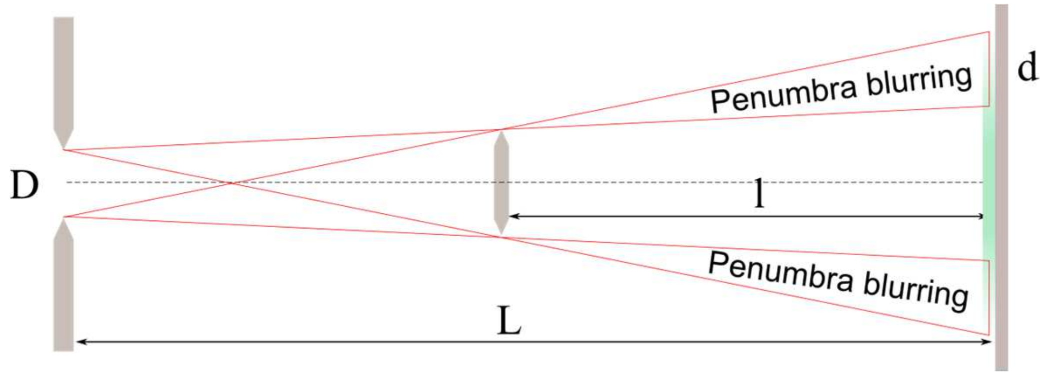

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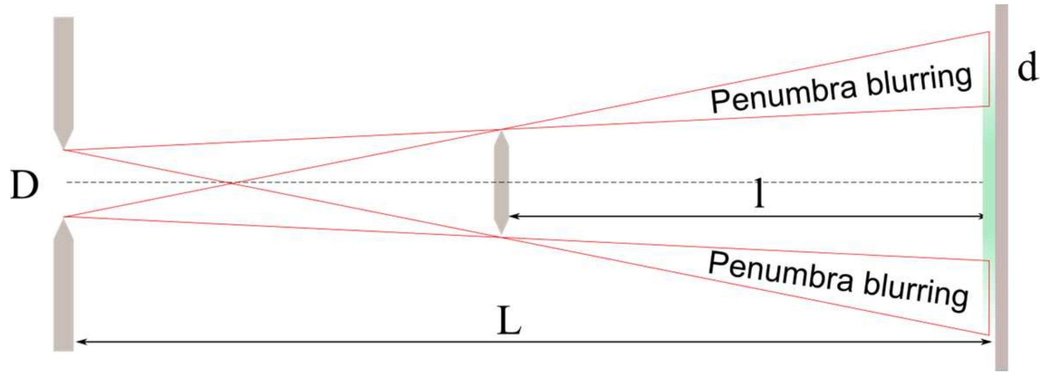

$$\frac{l}{d} = \frac{L}{D}$$

Minimize this! $d = \frac{l}{L/D}$

Geometric principles

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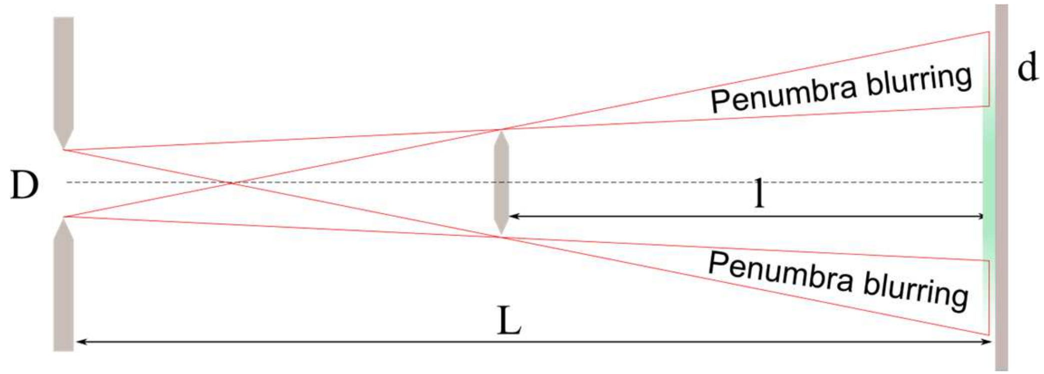

$$\frac{l}{d} = \frac{L}{D}$$

Minimize this!

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

Minimize these!

Geometric principles

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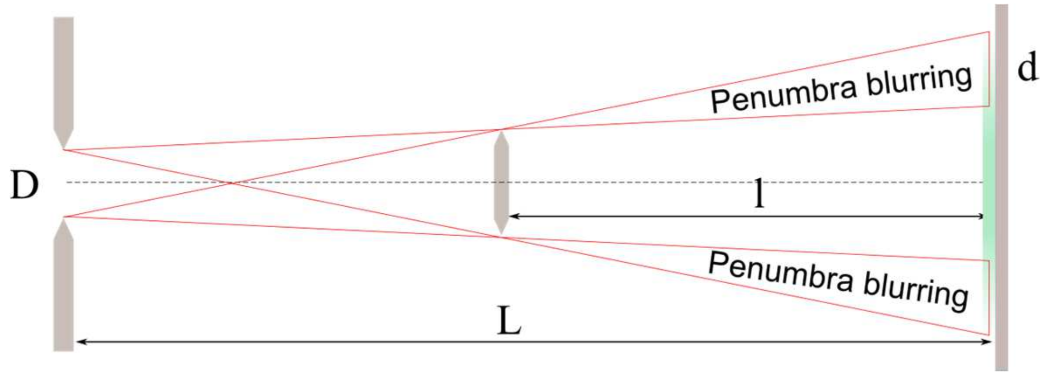

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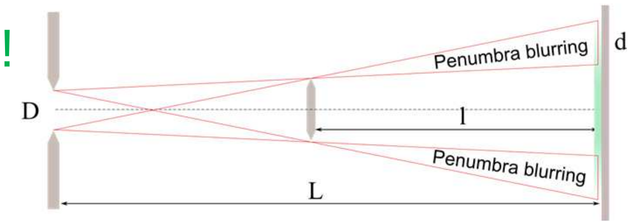

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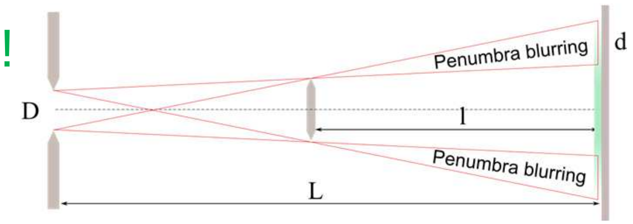

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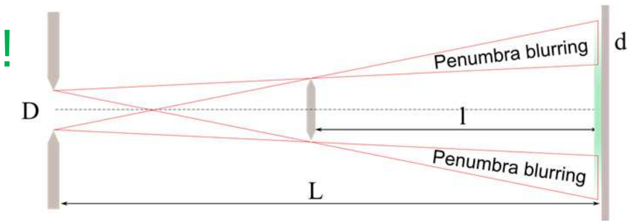

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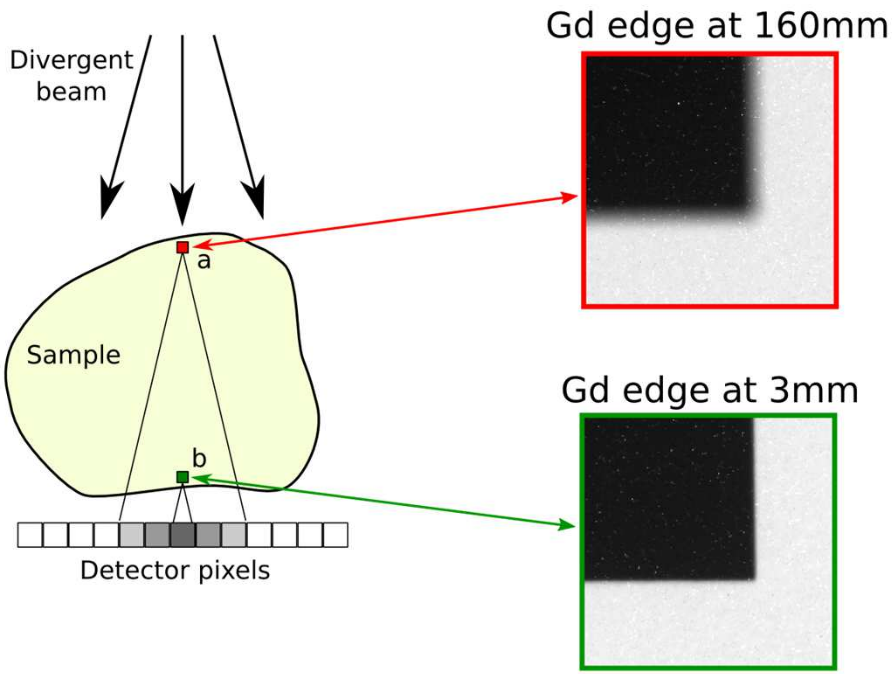
…but it only gets you so far



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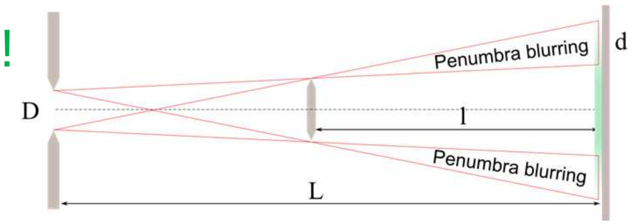

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Maximize L: The source is a 4π emitter: flux tapers off as R^{-2}

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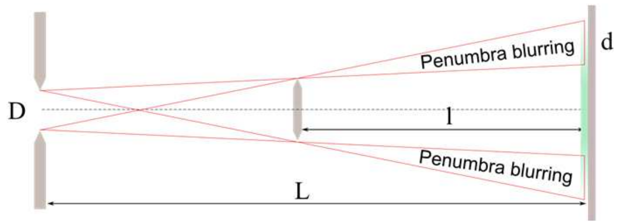

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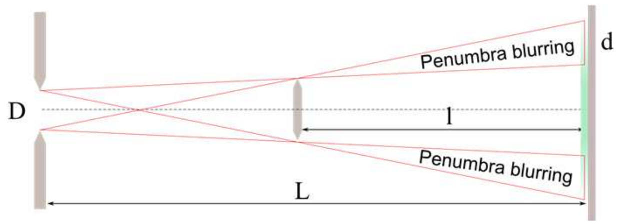

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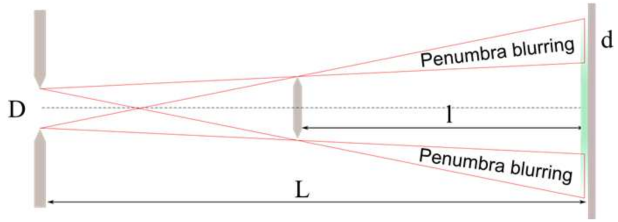

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Data acquisition time extended

Neutron collimation and exposure time

A compromise has to be found for the optimal L/D-resolution-data taking time:

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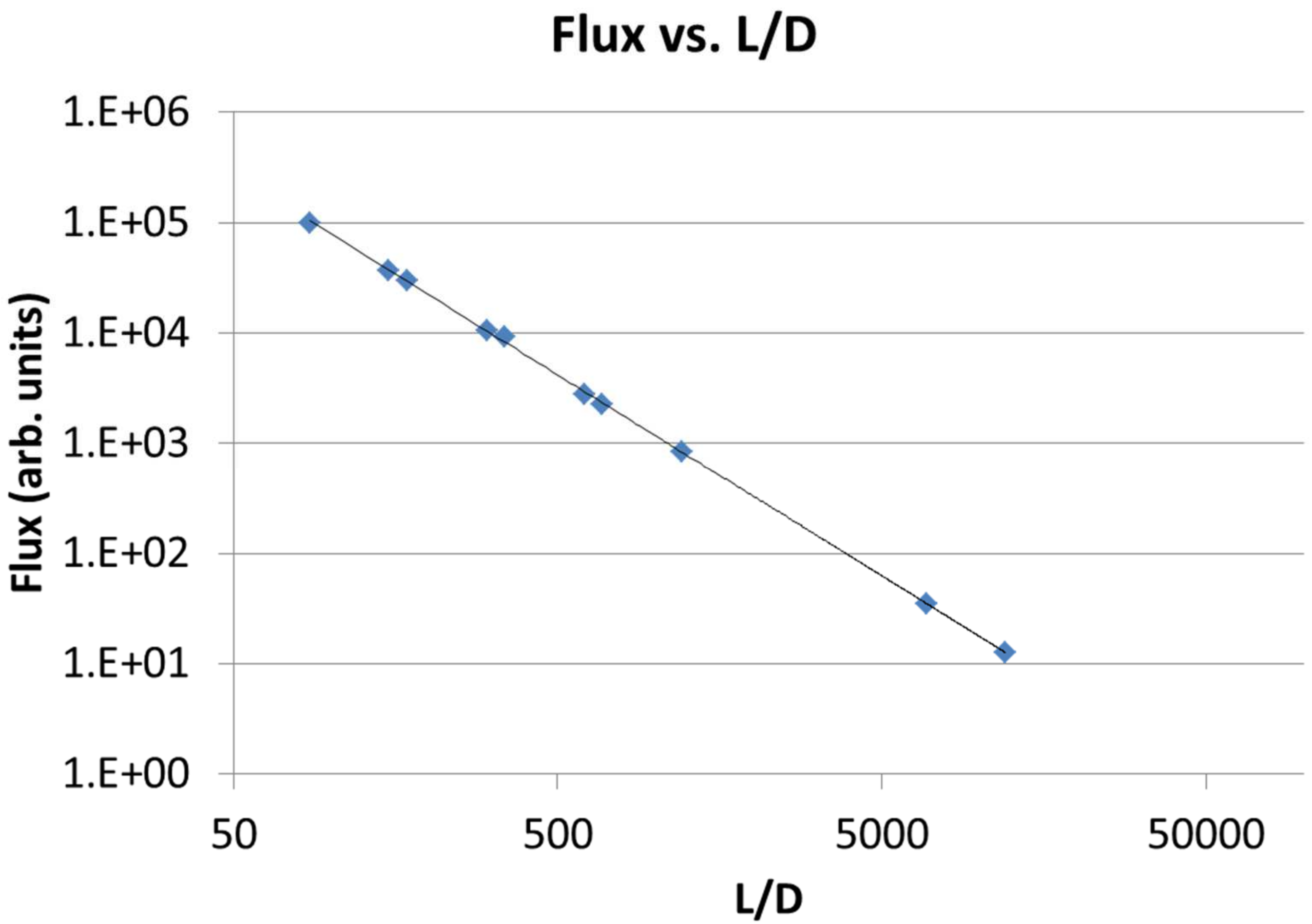

Neutrons vs. X-rays

Why are we so concerned about the flux?

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TOMCAT beamline at PSI

$$Flux = {}^{10^{16}}/_{ph \cdot s \cdot cm^2}$$

Neutrons vs. X-rays

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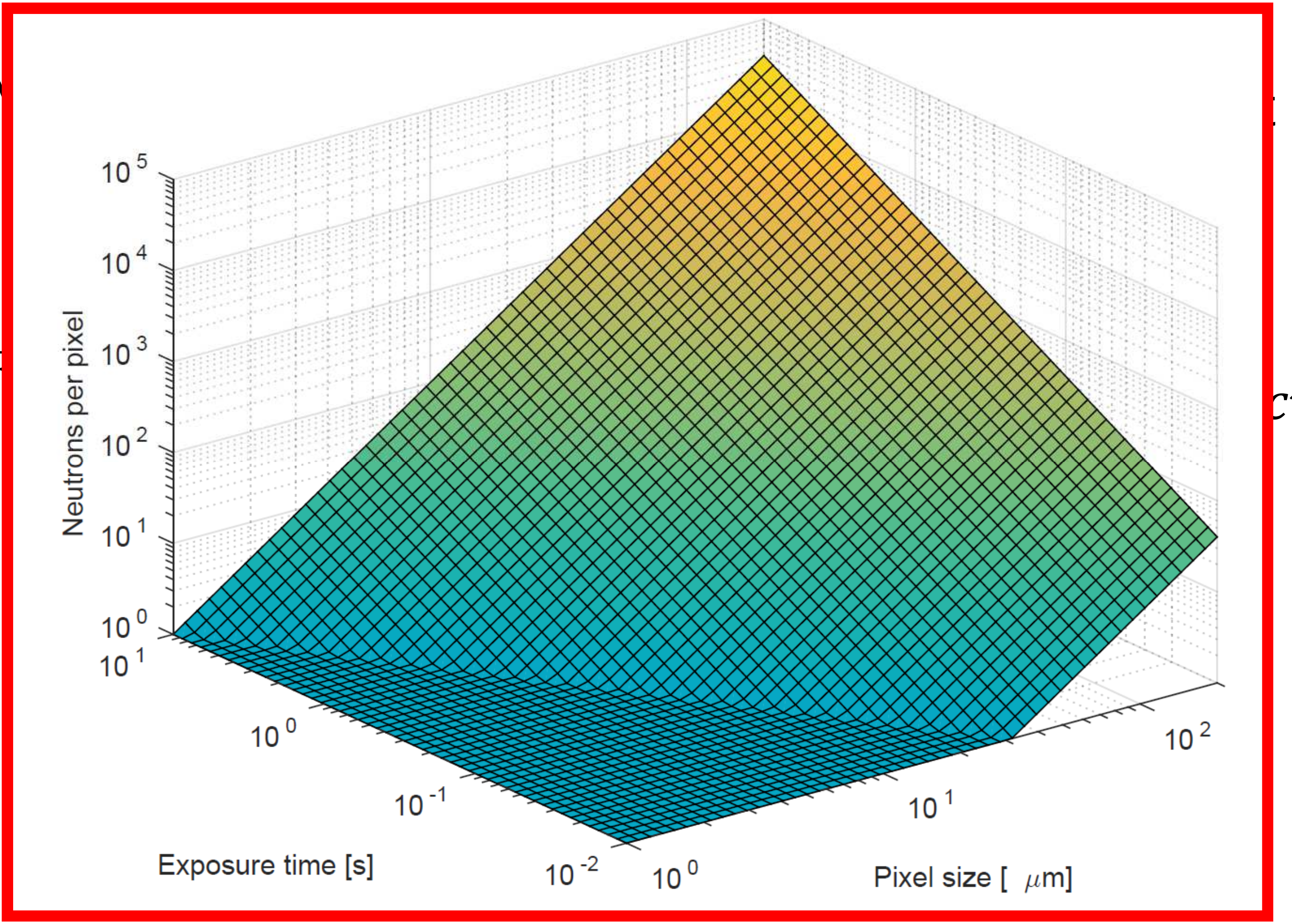

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Group → / ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	H 0.02																	He 0.02
2	Li 0.06	Be 0.22											B 0.28	C 0.27	N 0.11	O 0.16	F 0.14	Ne 0.17
3	Na 0.13	Mg 0.24											Al 0.38	Si 0.33	P 0.25	S 0.30	Cl 0.23	Ar 0.20
4	K 0.14	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
5	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
6	Cs 1.47	Ba 2.73		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
7	Fr -	Ra 11.80		Rf -	Db -	Sg -	Bh -	Hs -	Mt -	Ds -	Rg -	Uub -	Uut -	Uuq -	Uup -	Uuh -	Uus -	Uuo -
Lanthanides				La 5.04	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 10.17	Er 11.70	Tm 12.49	Yb 9.32	Lu 14.07
Actinides				Ac 24.47	Th 28.95	Pa 39.65	U 49.08	Np -	Pu -	Am -	Cm -	Bk -	Cf -	Es -	Fm -	Md -	No -	Lr -

Group → / ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	H 3.44																	He 0.02
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4	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
5	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 115.1	In 7.58	Sn 0.21	Sb 0.30	Te 0.25	I 0.23	Xe 0.43
6	Cs 0.29	Ba 0.07		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 -
7	Fr -	Ra 0.34		Rf -	Db -	Sg -	Bh -	Hs -	Mt -	Ds -	Rg -	Uub -	Uut -	Uuq -	Uup -	Uuh -	Uus -	Uuo -
Lanthanides				La 0.52	Ce 0.14	Pr 0.41	Nd 1.87	Pm 5.72	Sm 171.47	Eu 94.58	Gd 1479.0	Tb 0.93	Dy 32.42	Ho 2.25	Er 5.48	Tm 3.53	Yb 1.40	Lu 2.75
Actinides				Ac -	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 -

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Neutrons vs. X-rays

X-rays:

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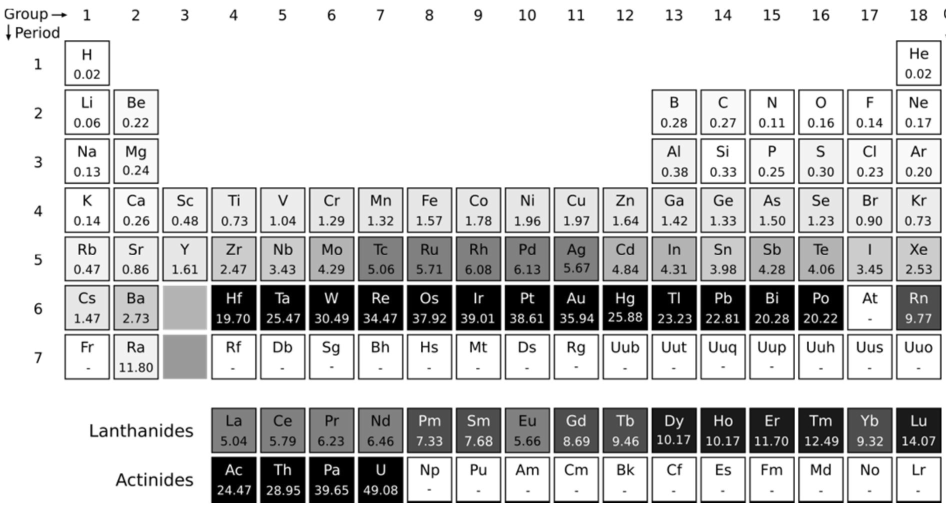
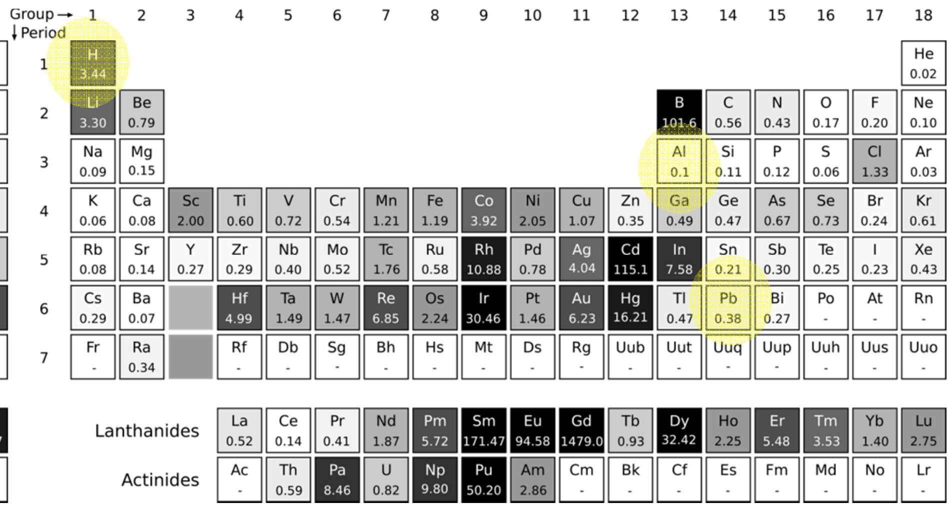
Neutrons:

- Interacting with the nucleus





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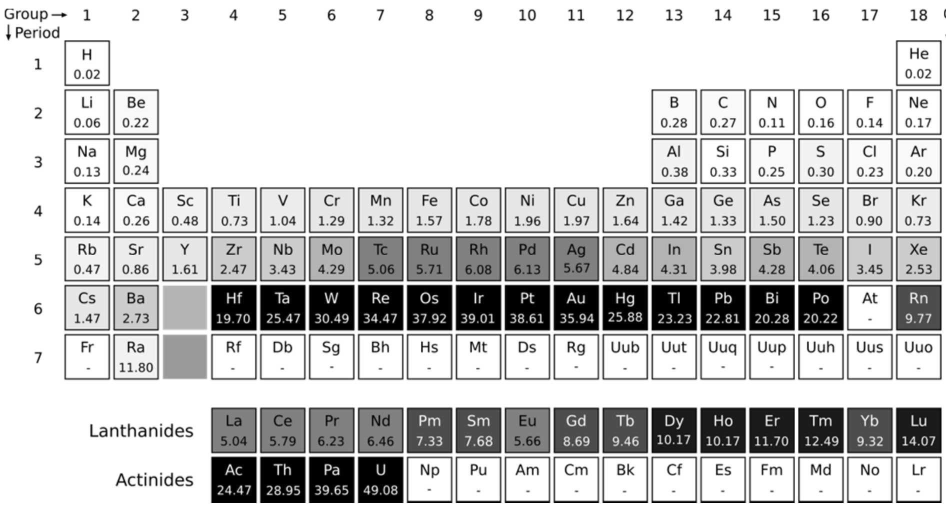

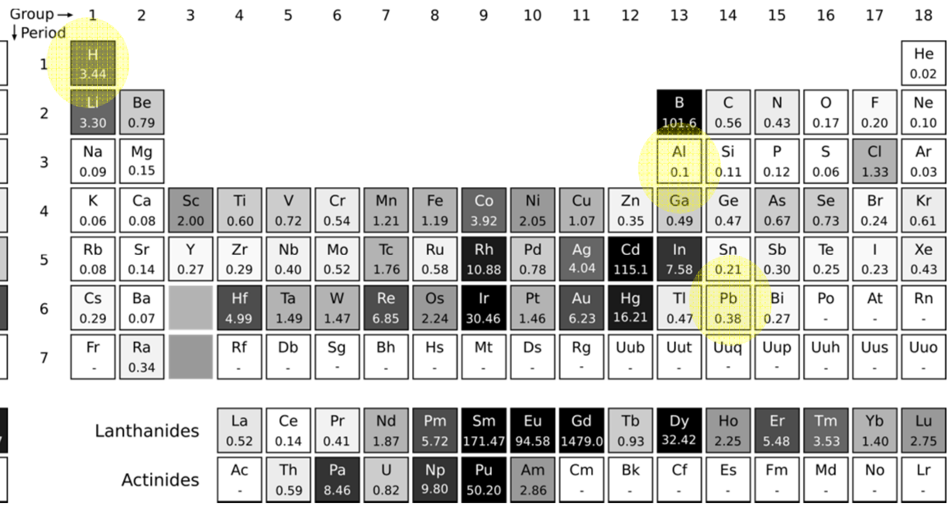

Already this creates a clear domain for neutron imaging!

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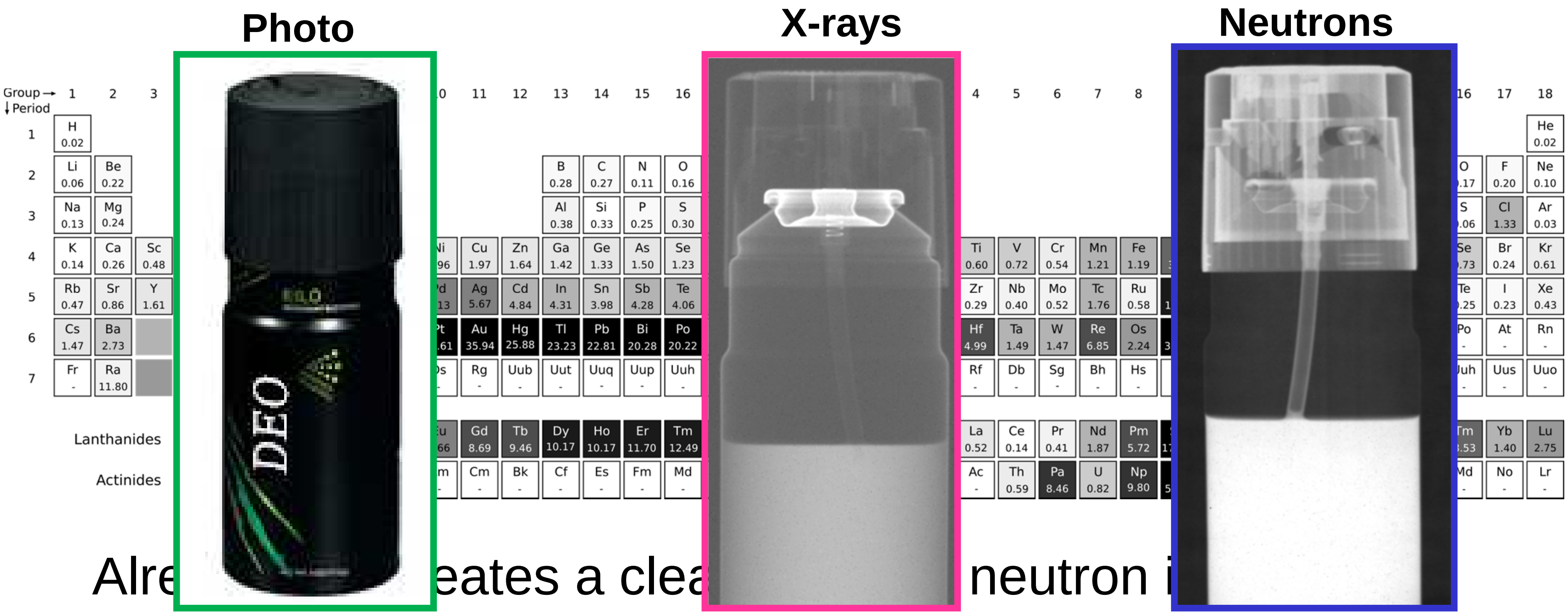

Alre… eates a clea… neutron i…

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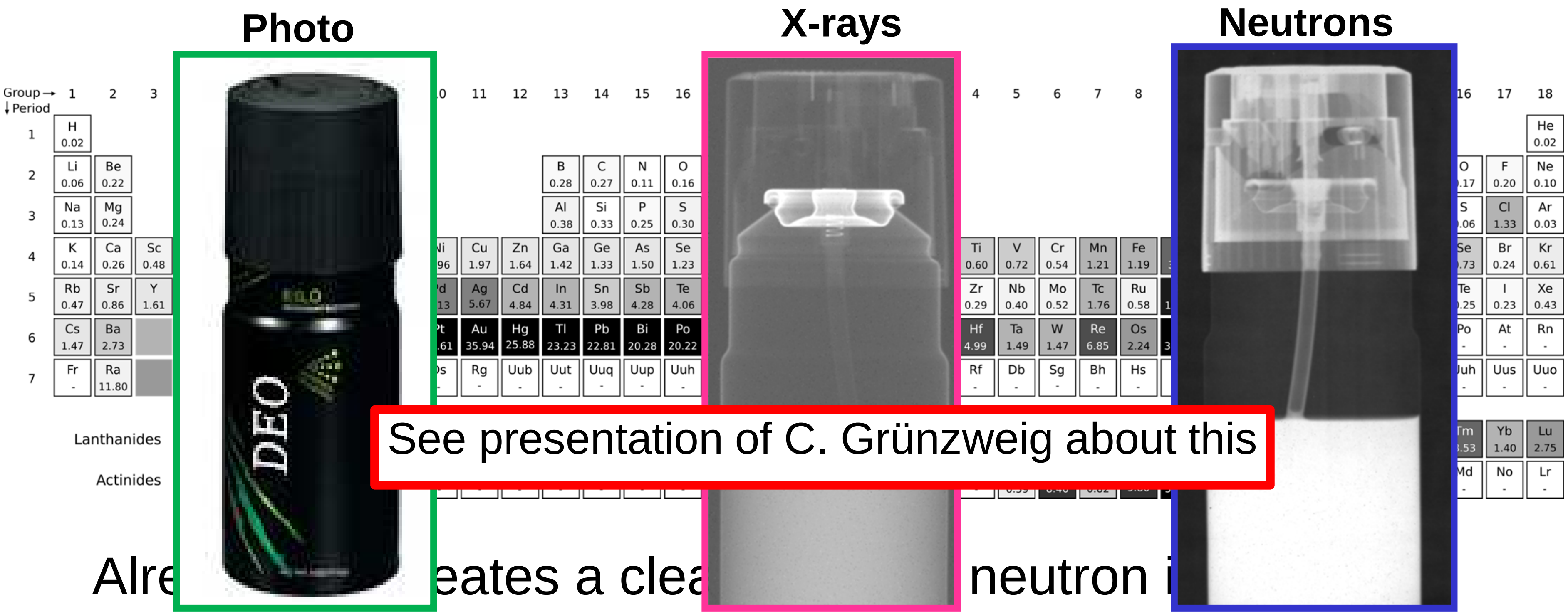

See presentation of C. Grünzweig about this

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See presentation of S. Peetermans about this

Neutrons vs. X-rays

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See presentation of N. Kardjilov about this

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This has an influence on the way you convert neutrons into visible light

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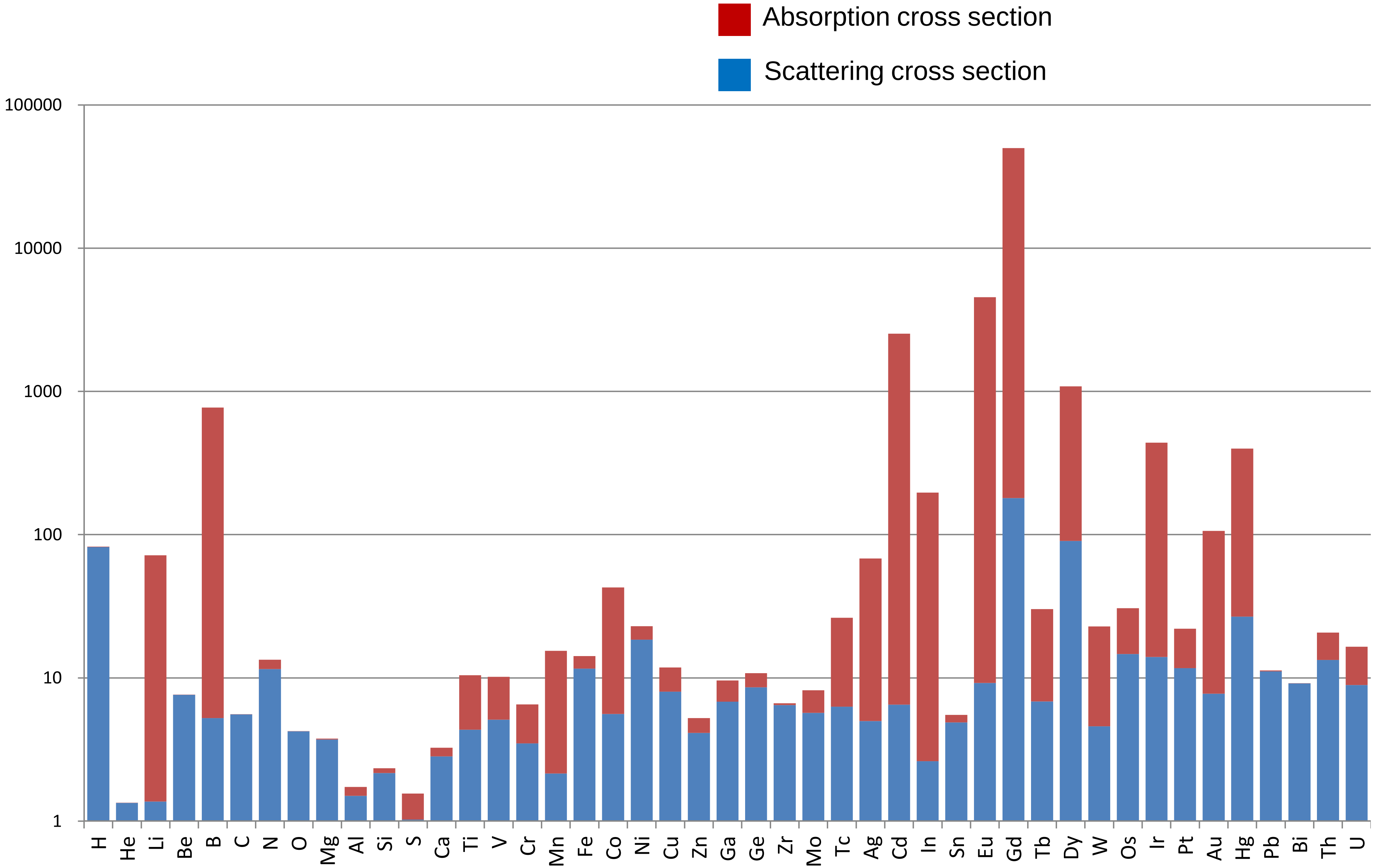
(even though you can avoid going through visible light altogether i.e. MCP based detectors)

Neutron conversion to light



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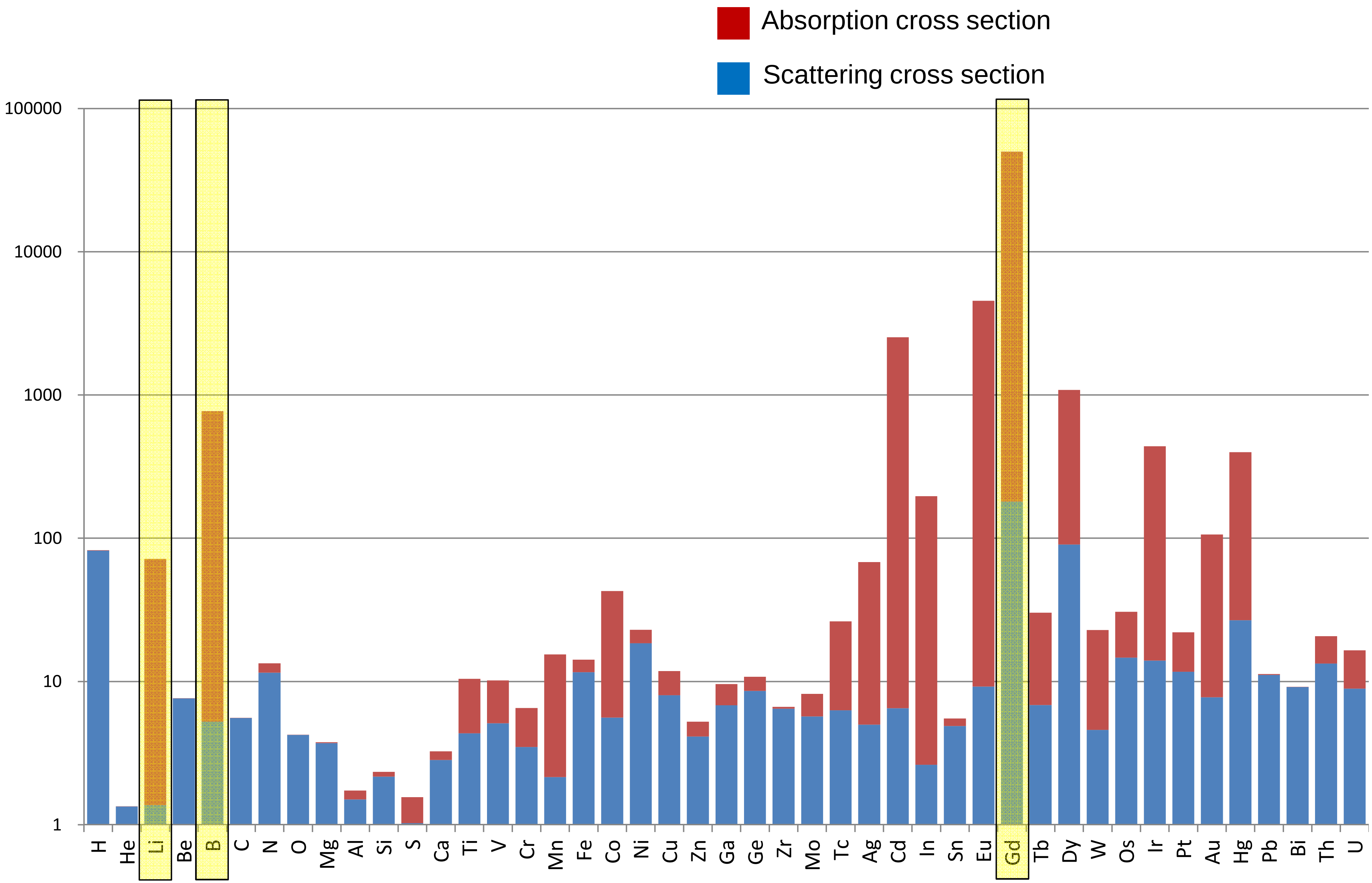

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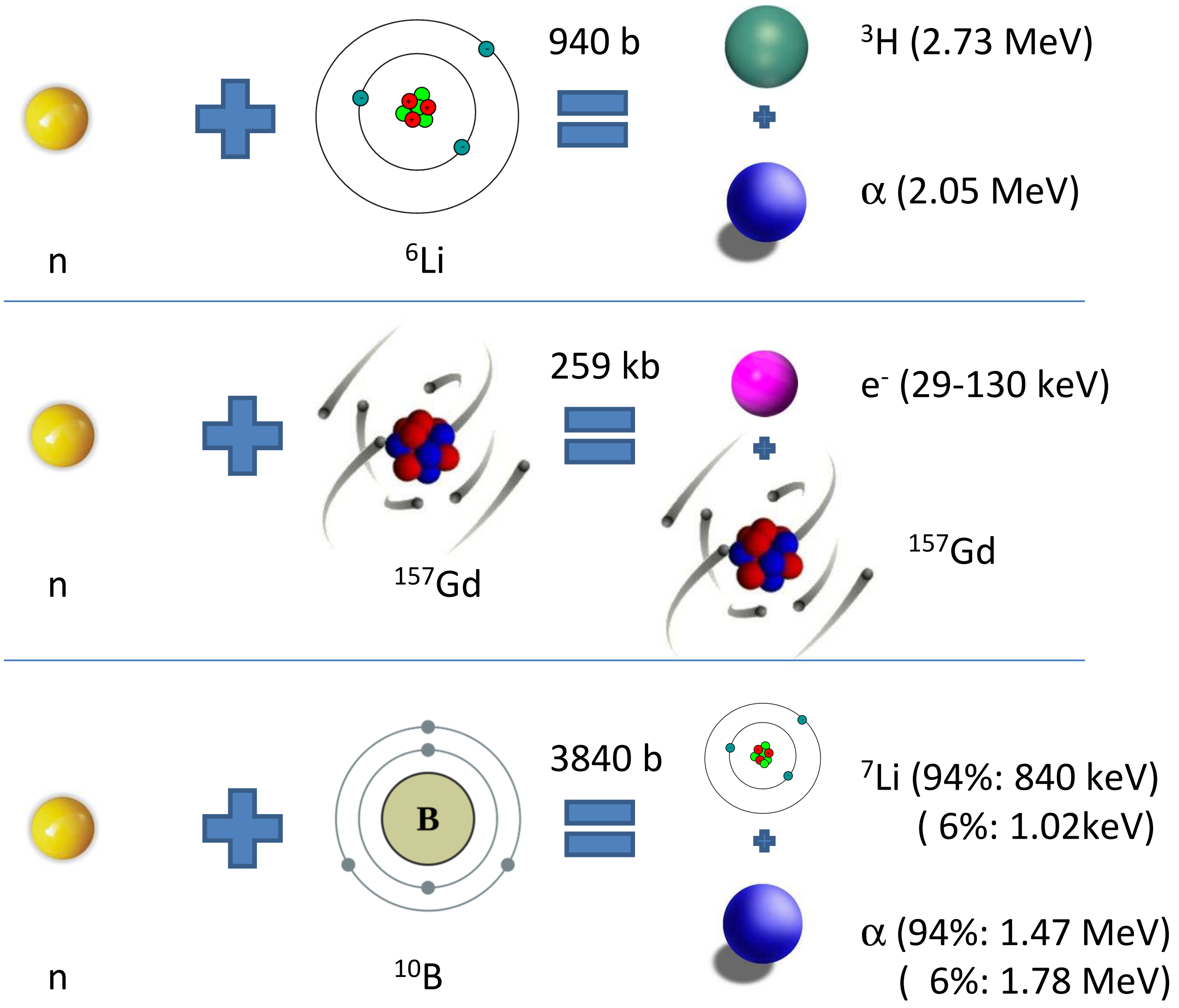

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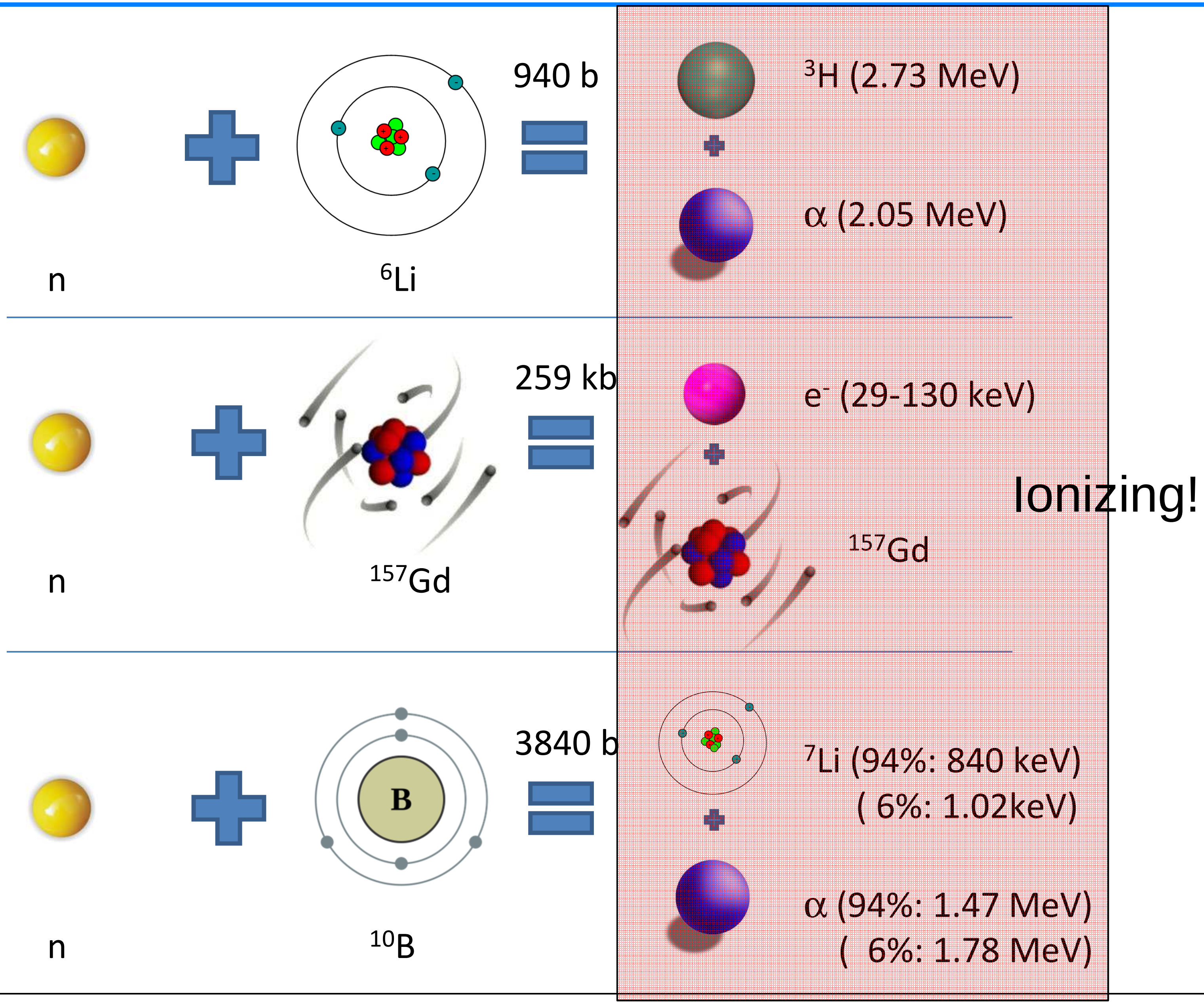

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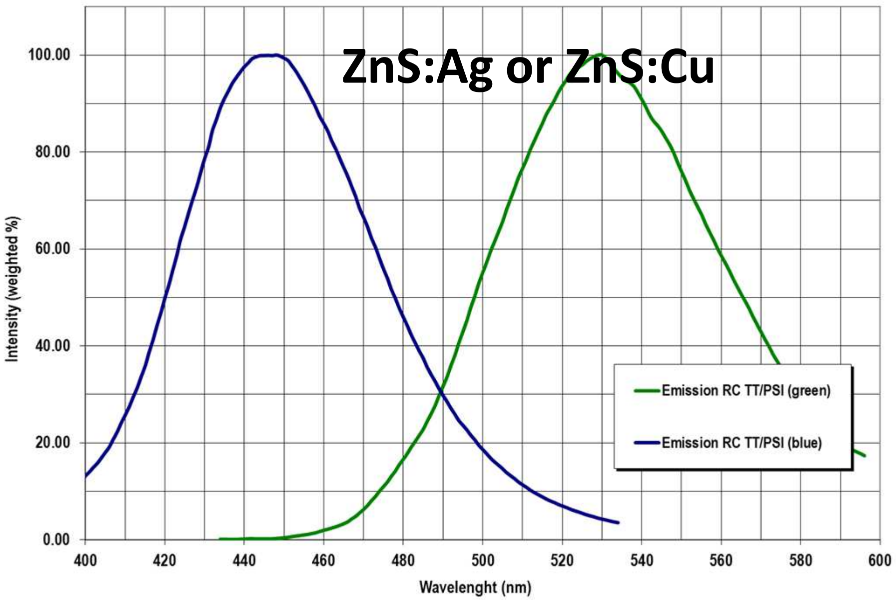

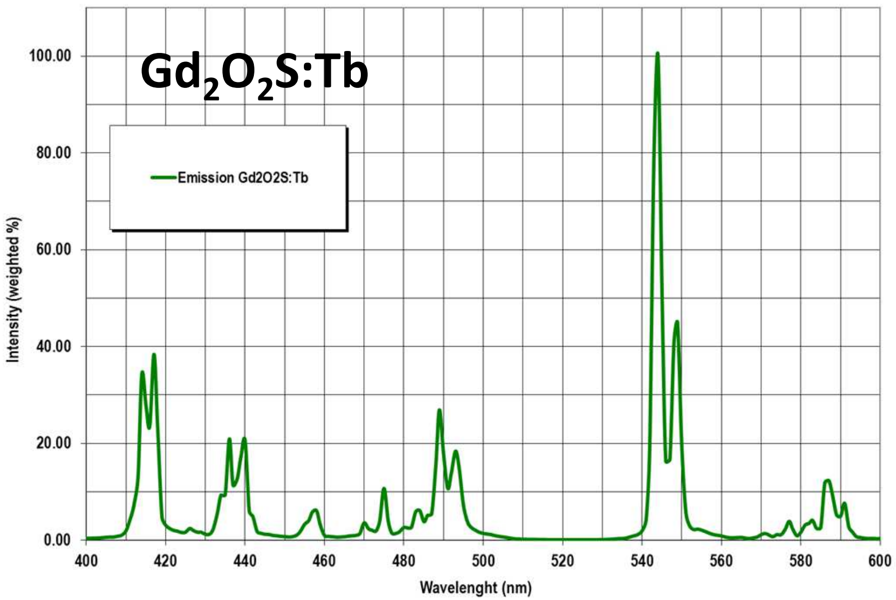

Slide from B. Walfort, WCNR-10, Grindelwald (CH) (2014)

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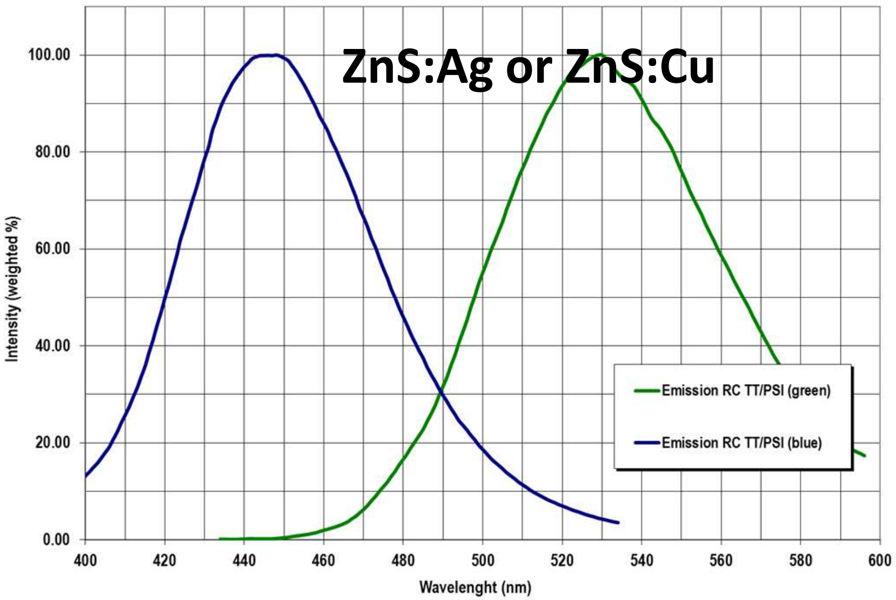
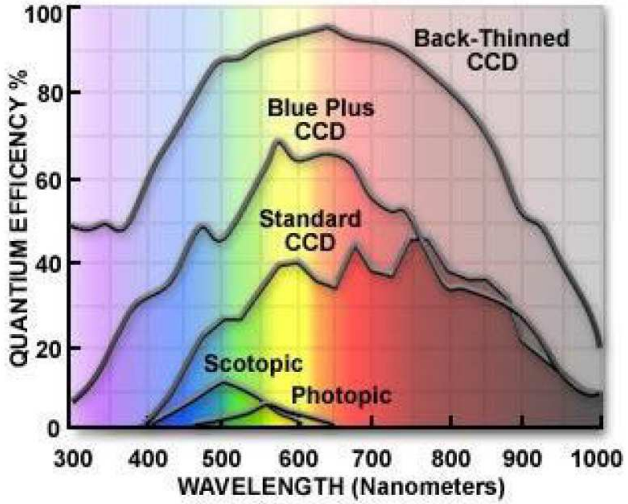
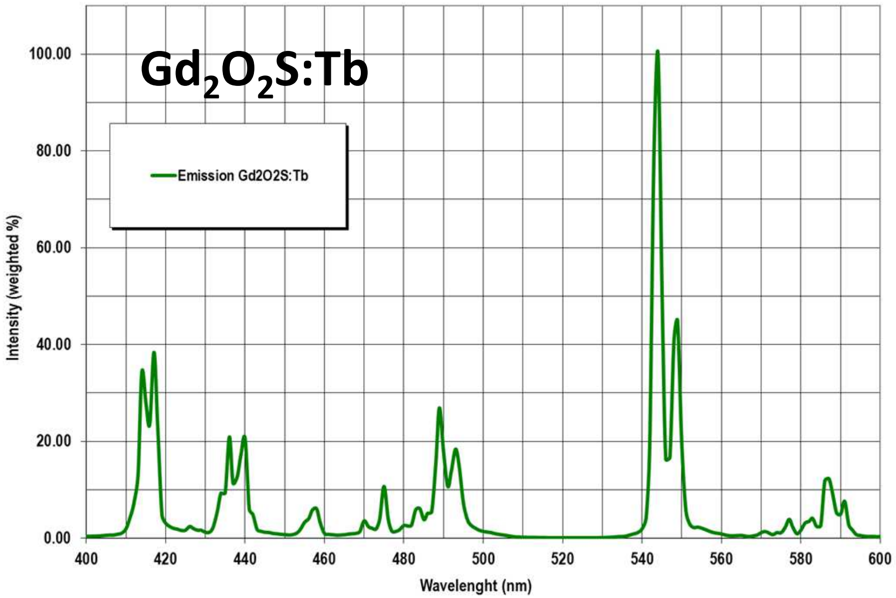




Photosensitivity of CCD



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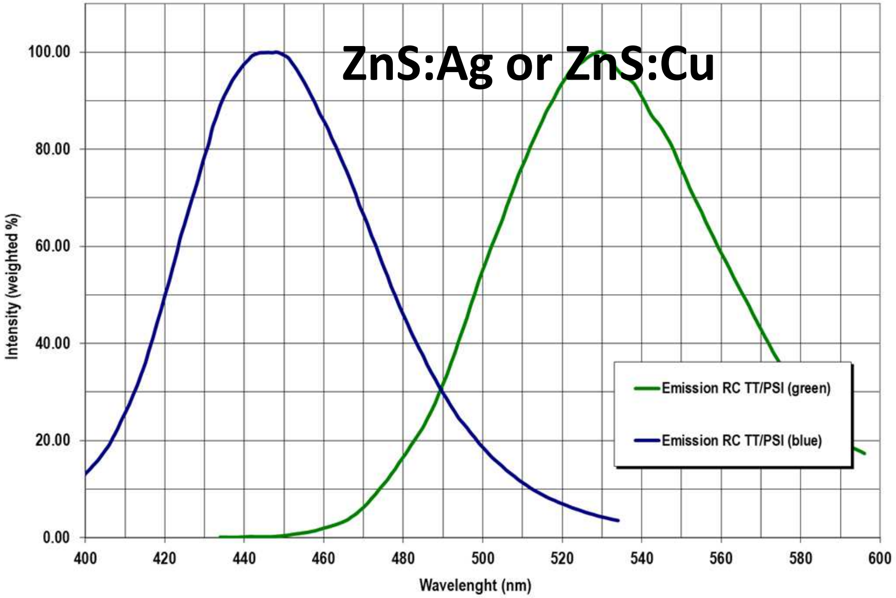

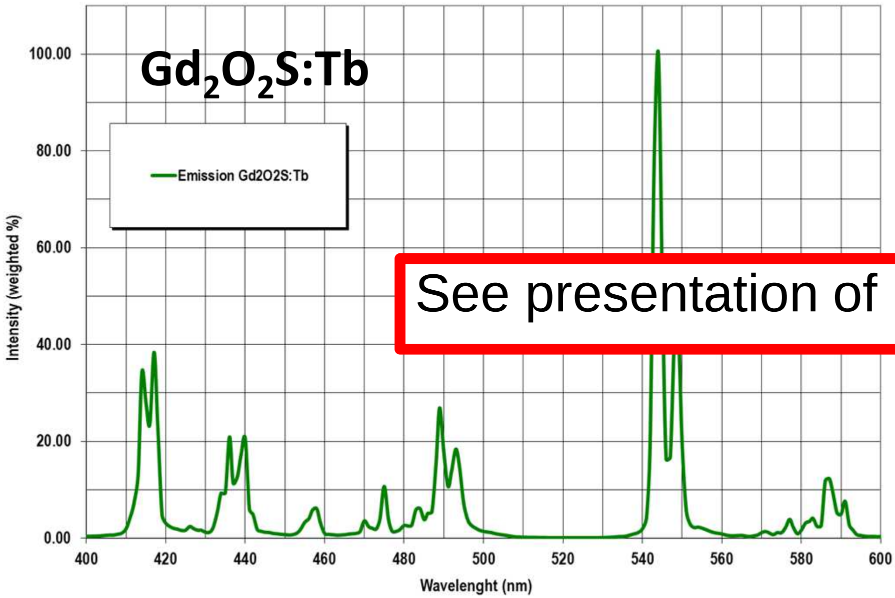

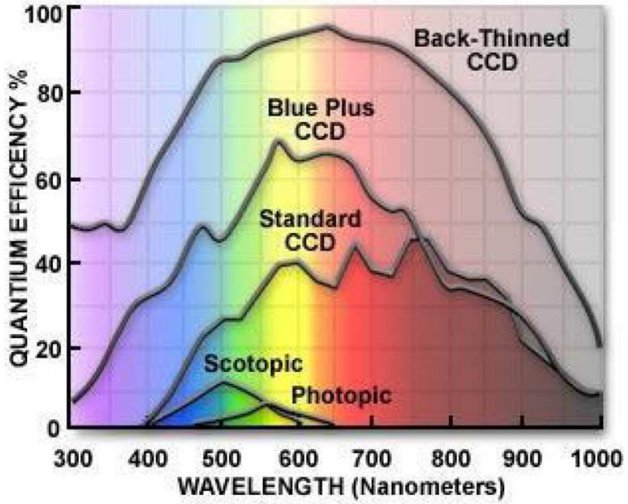

Photosensitivity of CCD

See presentation of P. Trtik about this

Slide from B. Walfort, WCNR-10, Grindelwald (CH) (2014)

Neutron conversion to light

How do you choose which absorber?

Neutron conversion to light

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

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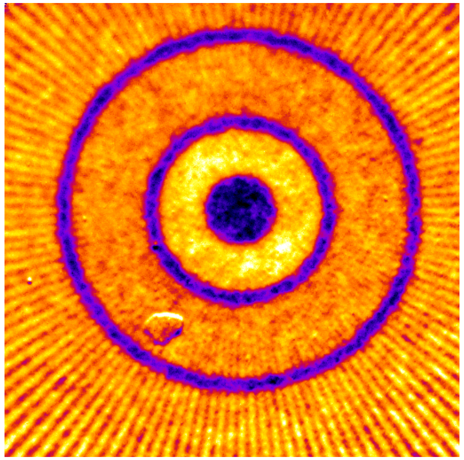
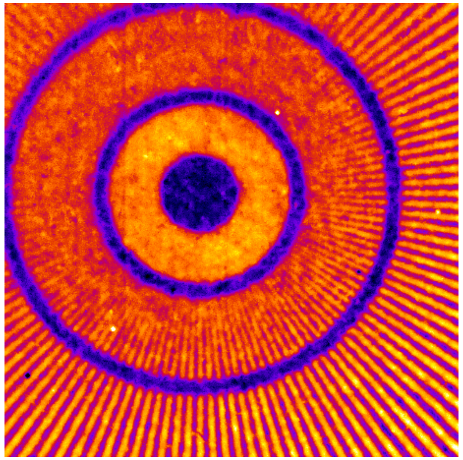
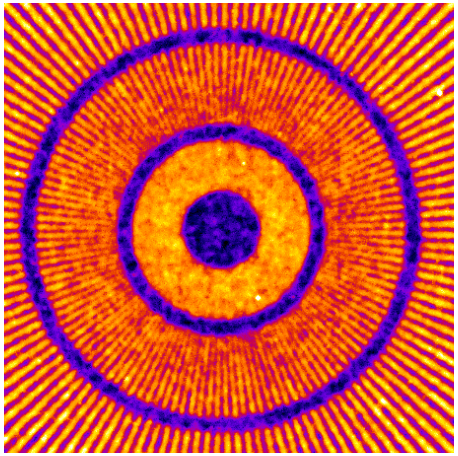


1mm

20um-Gadox



10um-Gadox



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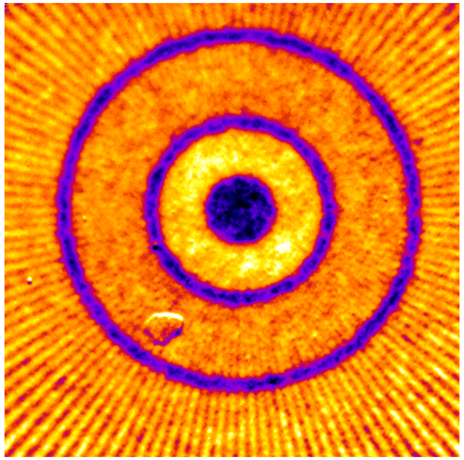

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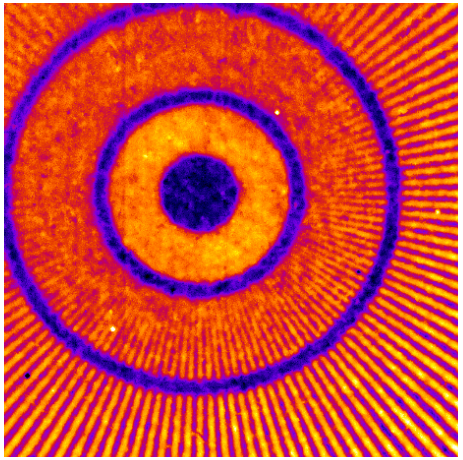
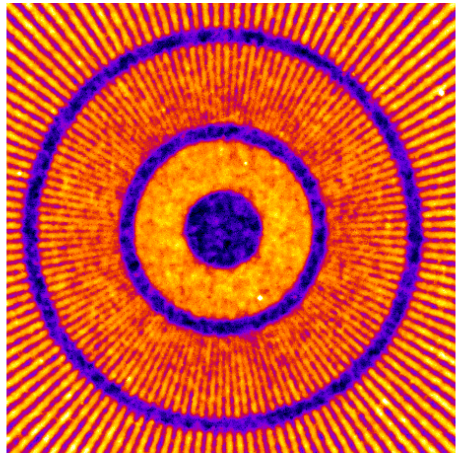
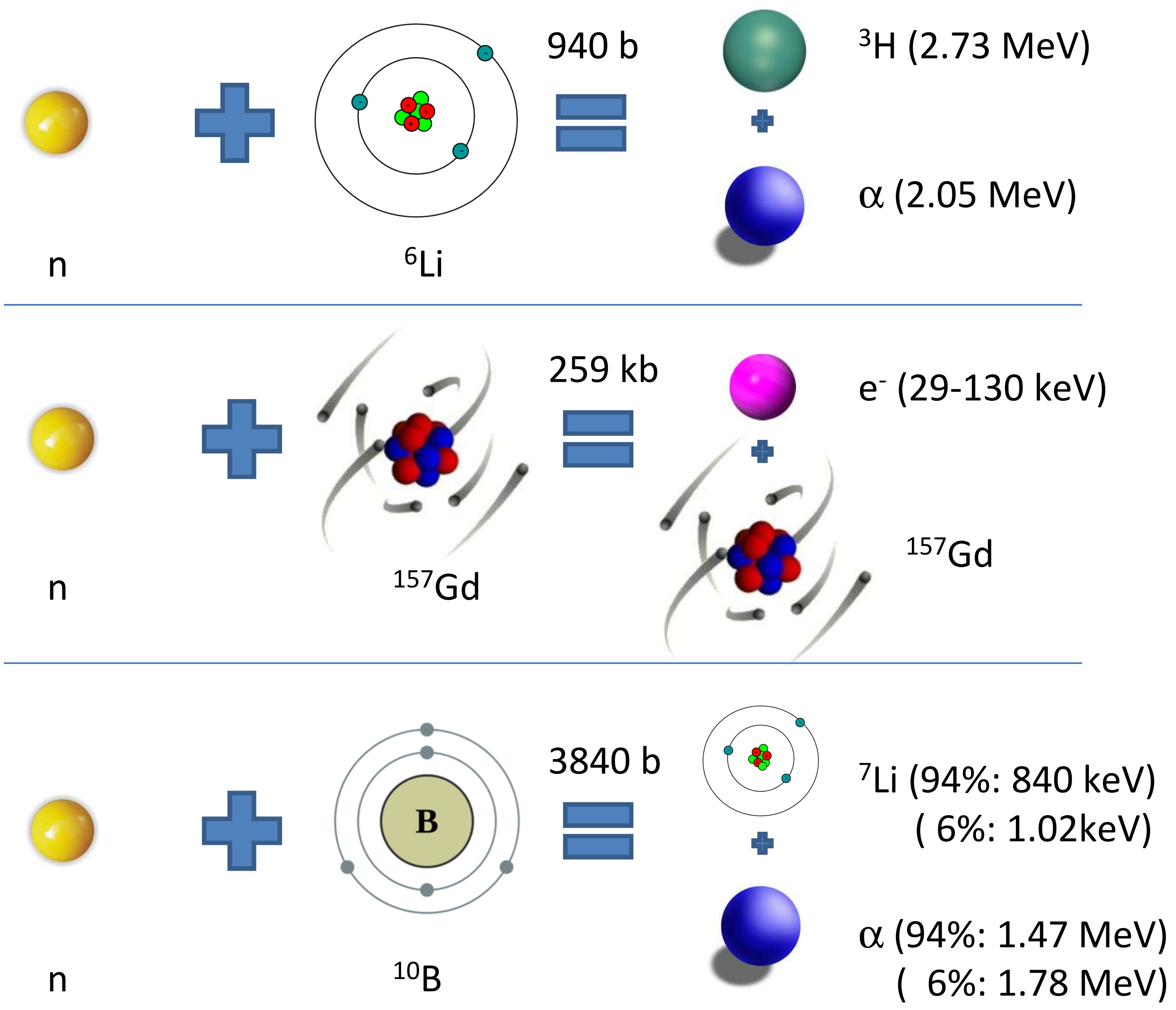


10um-Gadox



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

Neutron conversion to light



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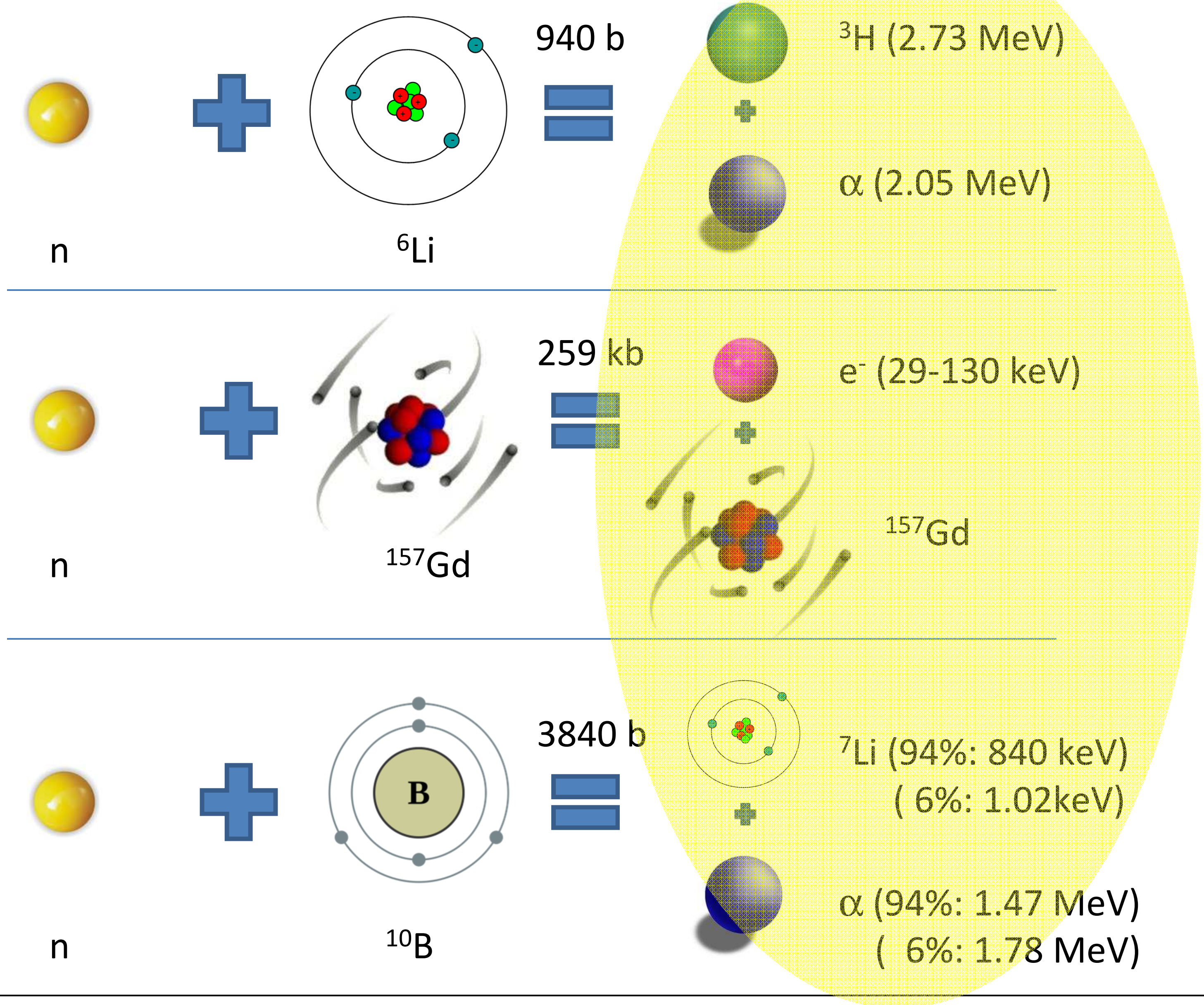

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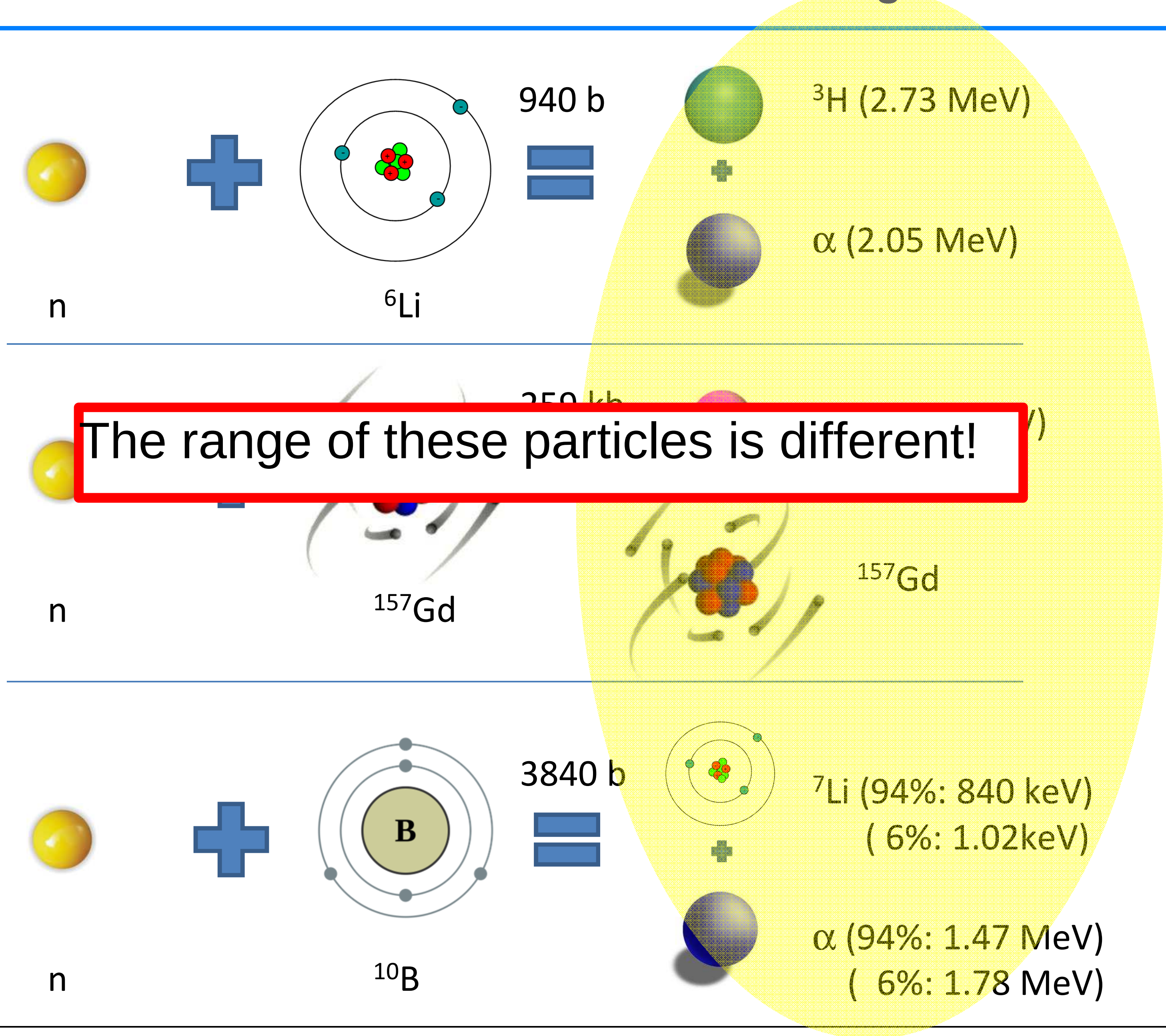

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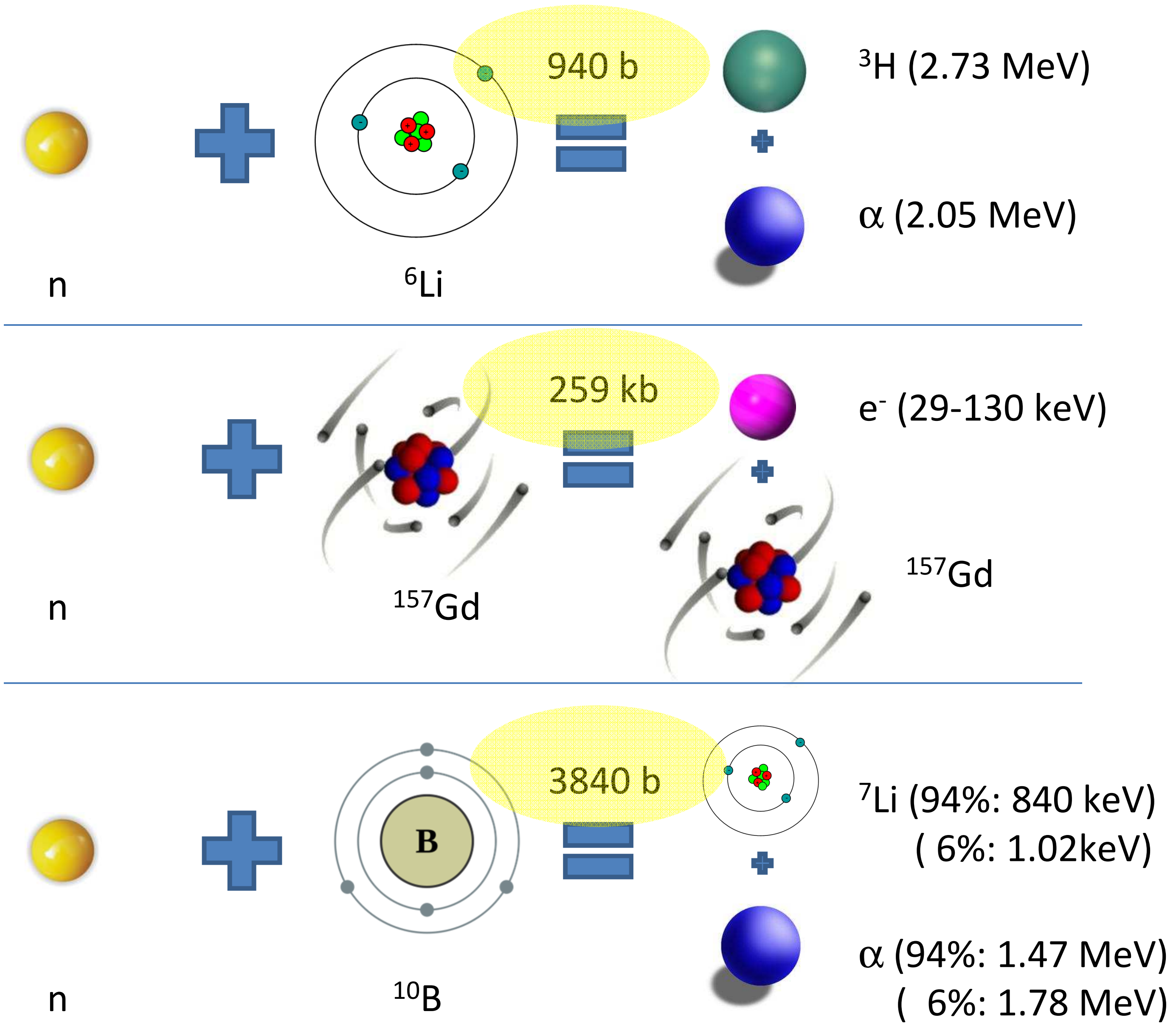

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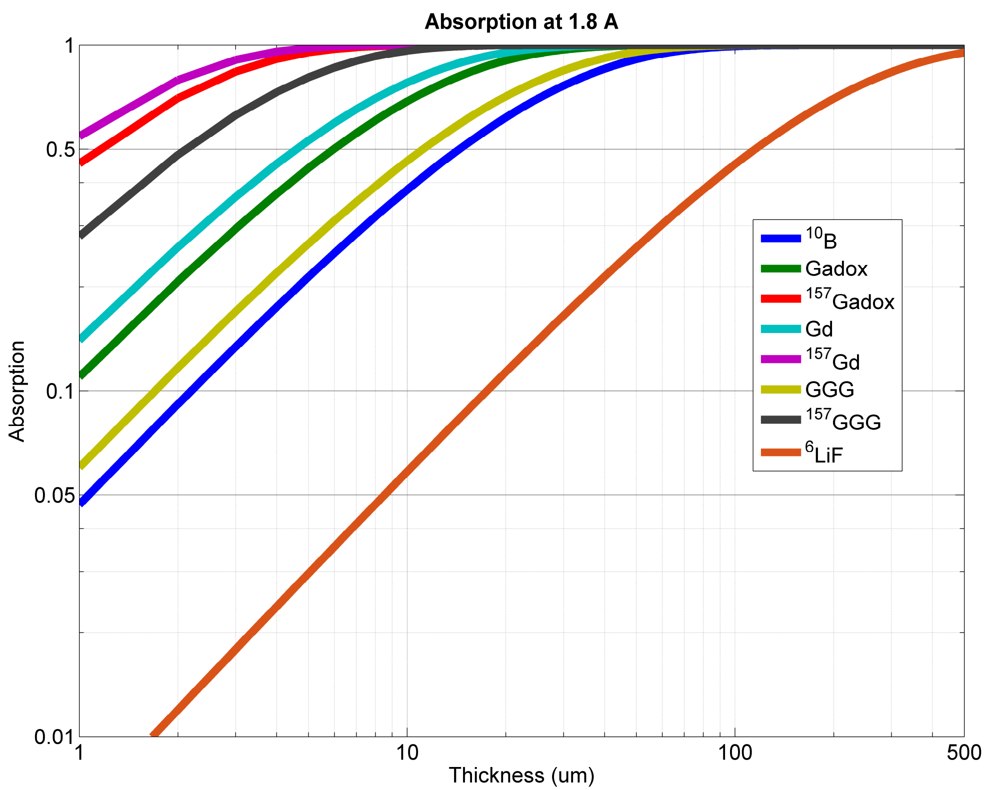
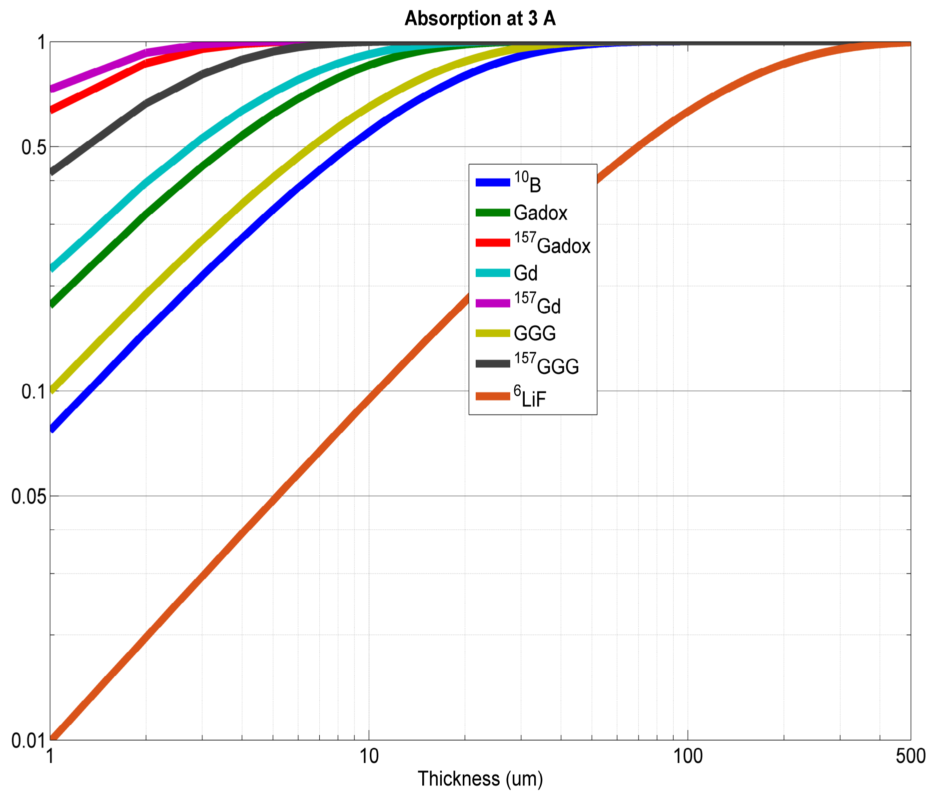
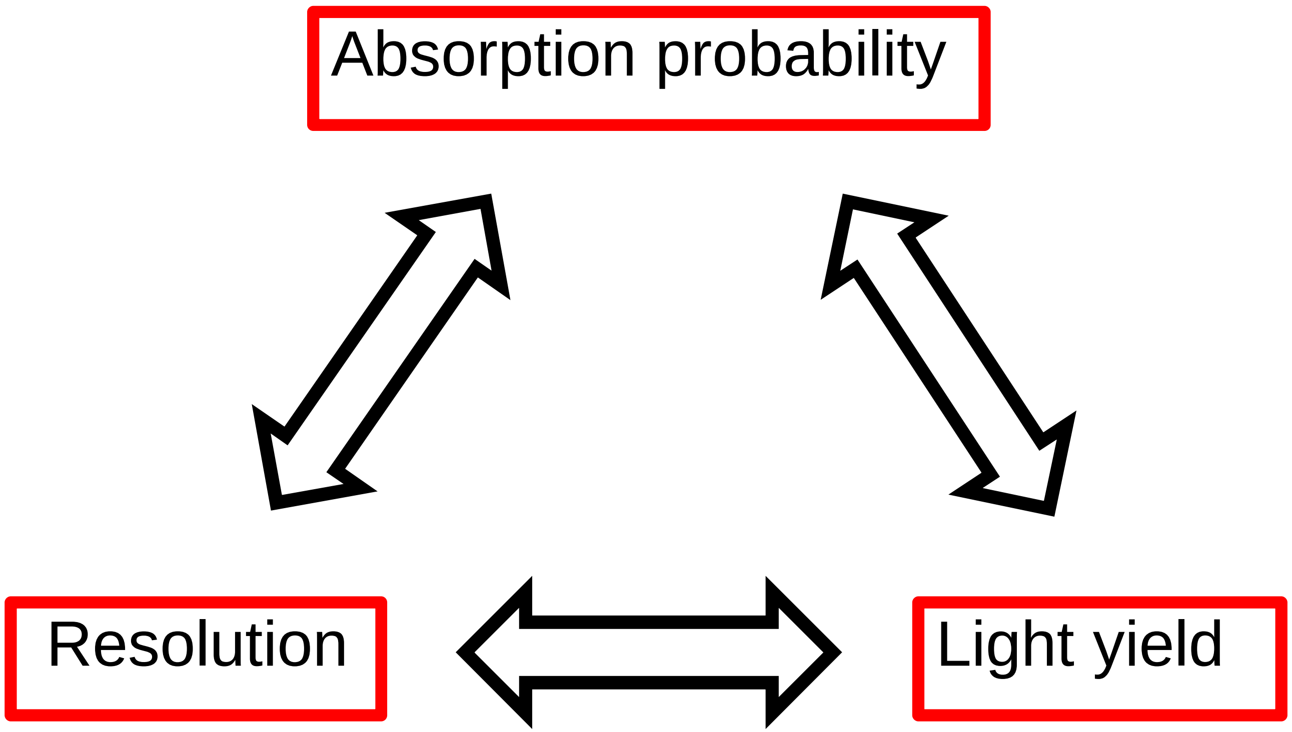
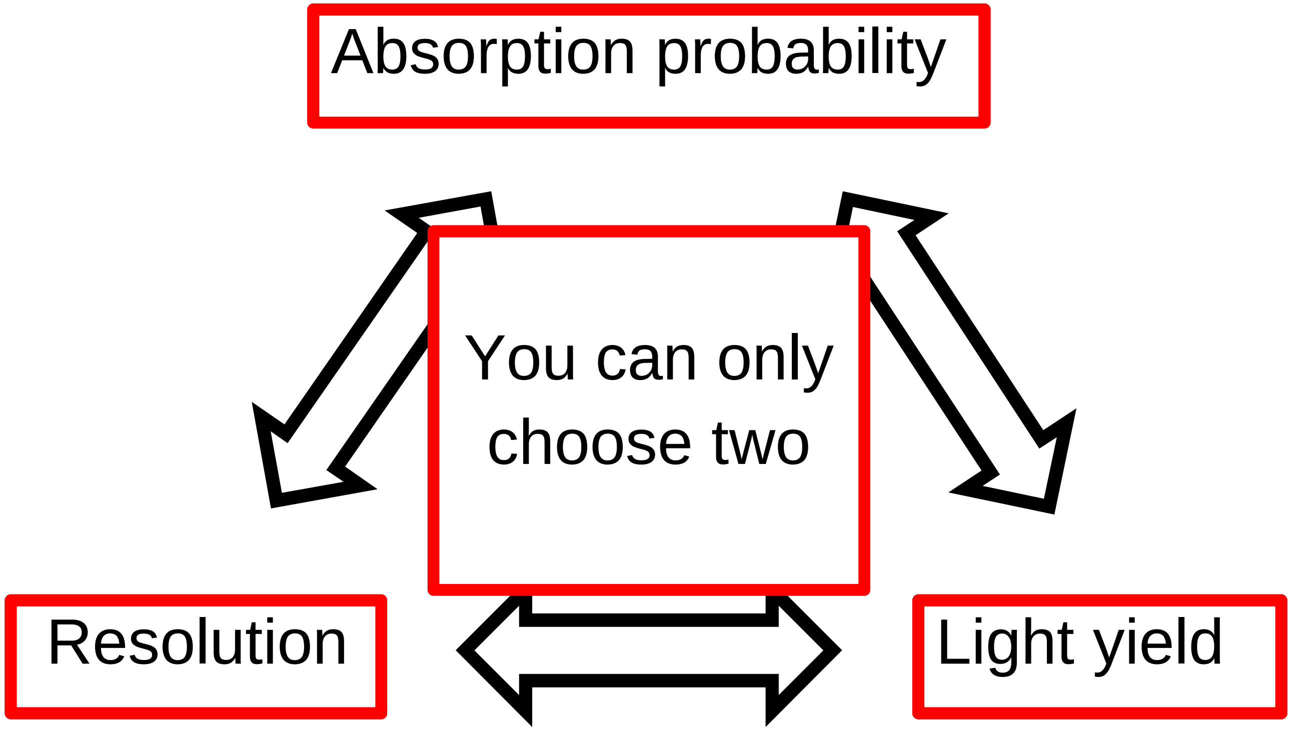




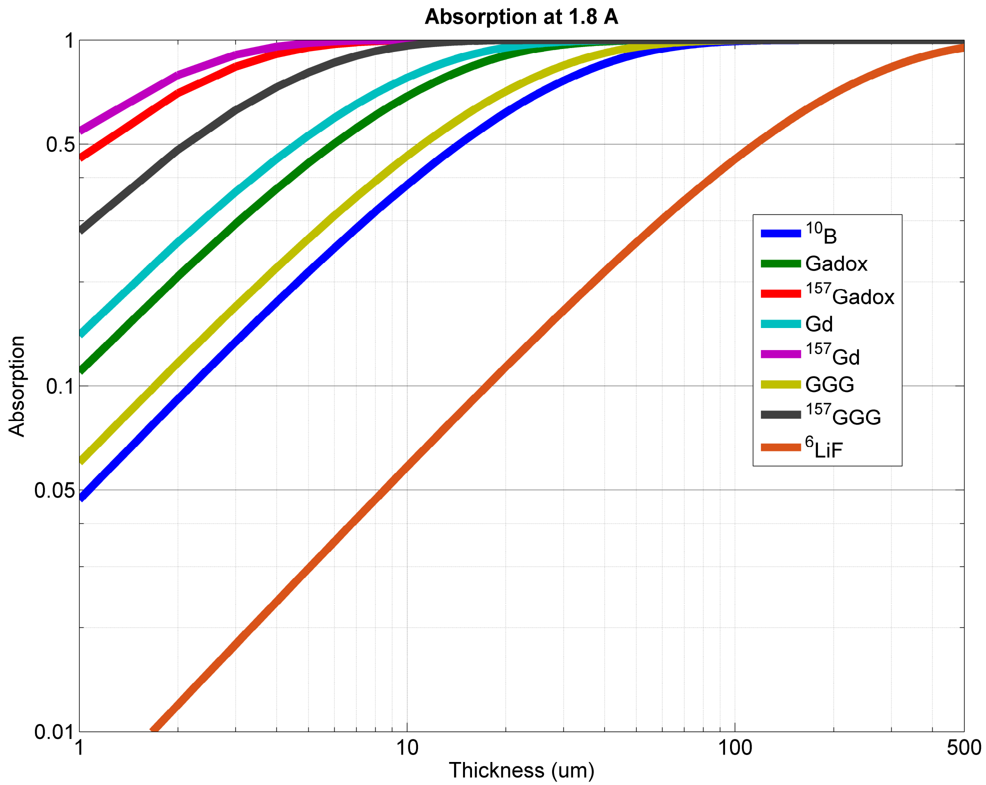
Neutron conversion to light

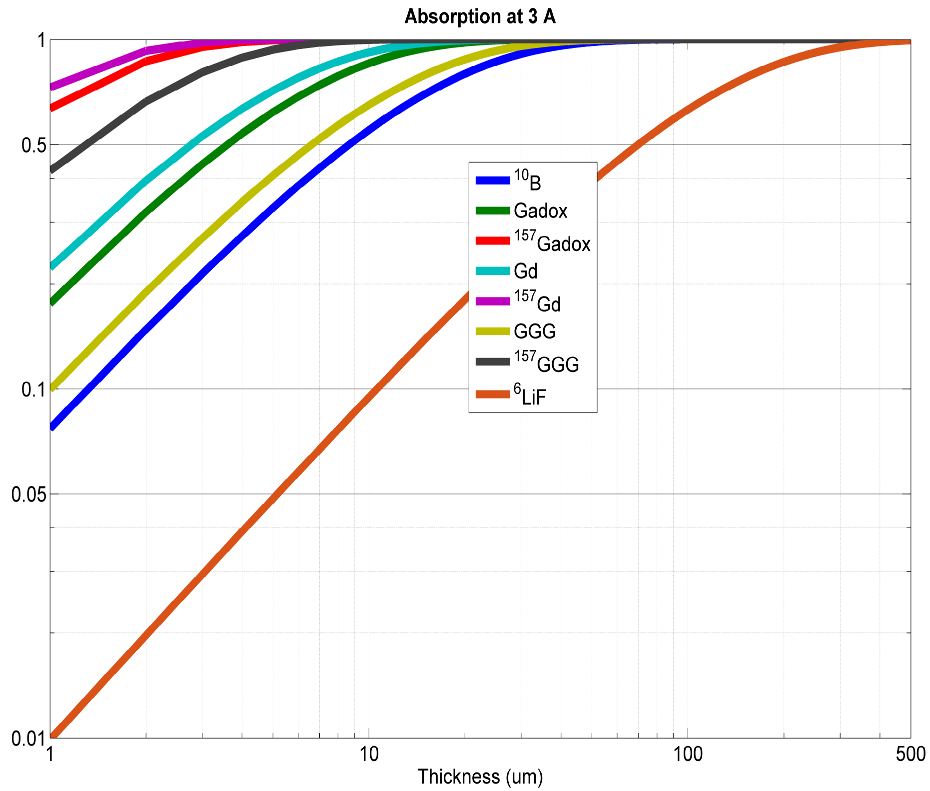


Neutron conversion to light



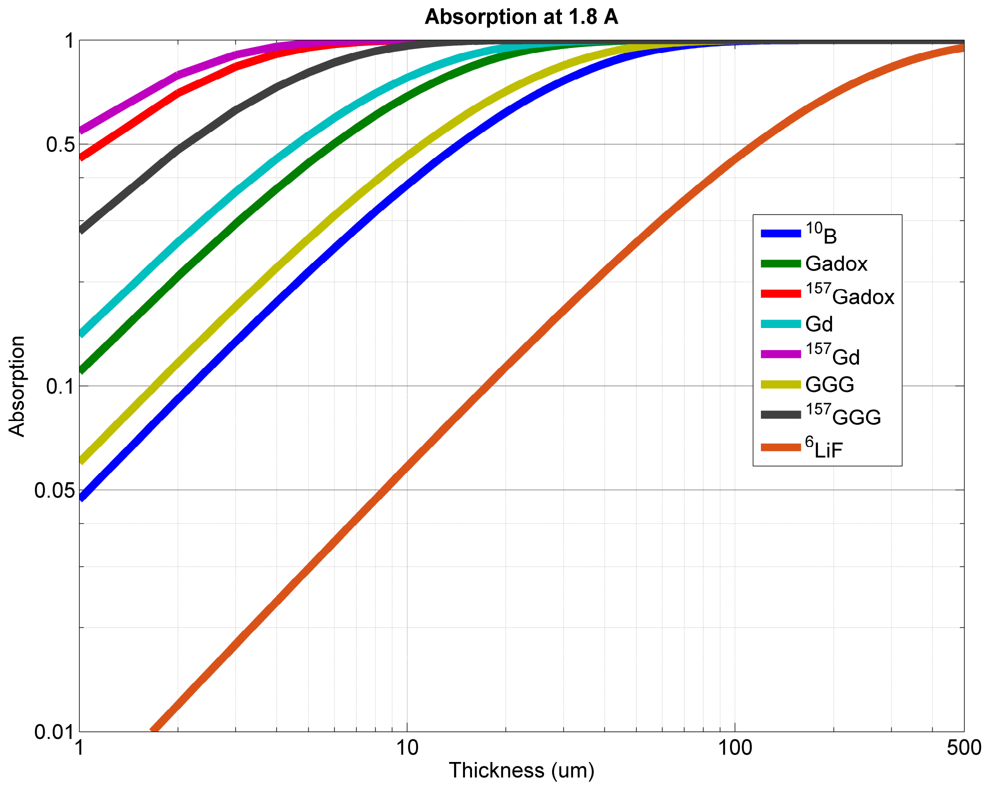
Neutron conversion to light



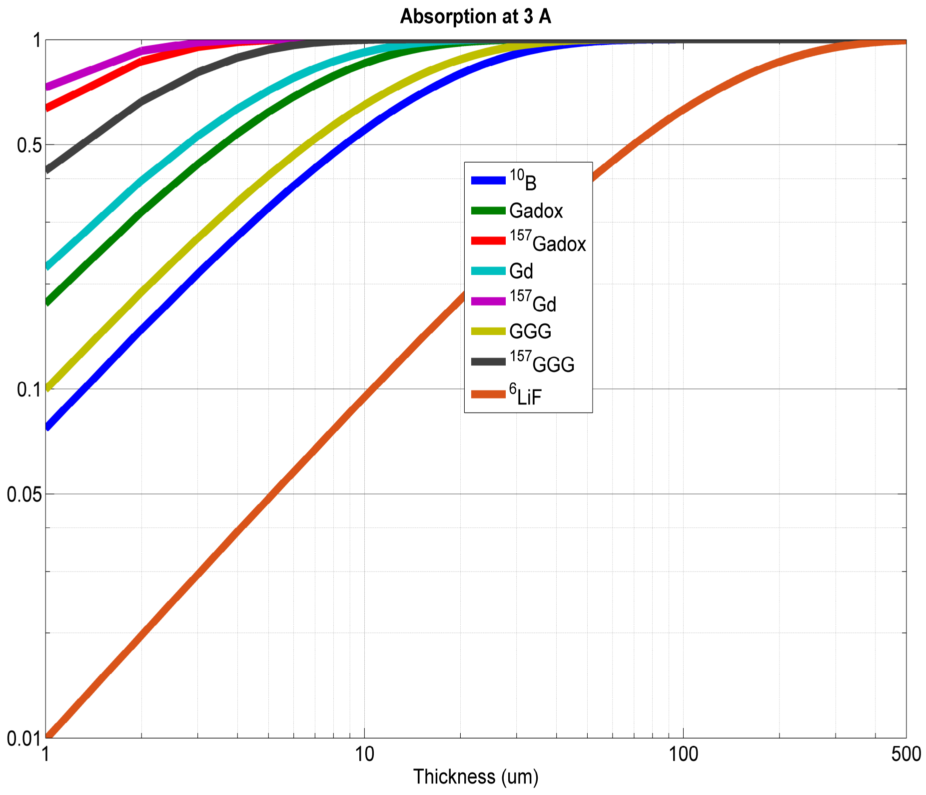


Thermal and cold neutrons

Thermal neutrons



Cold neutrons



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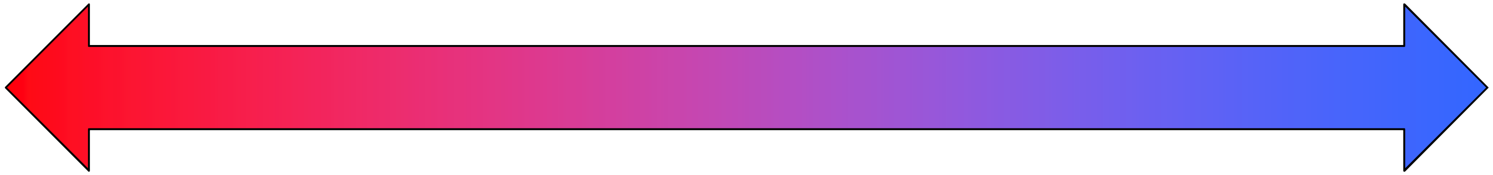
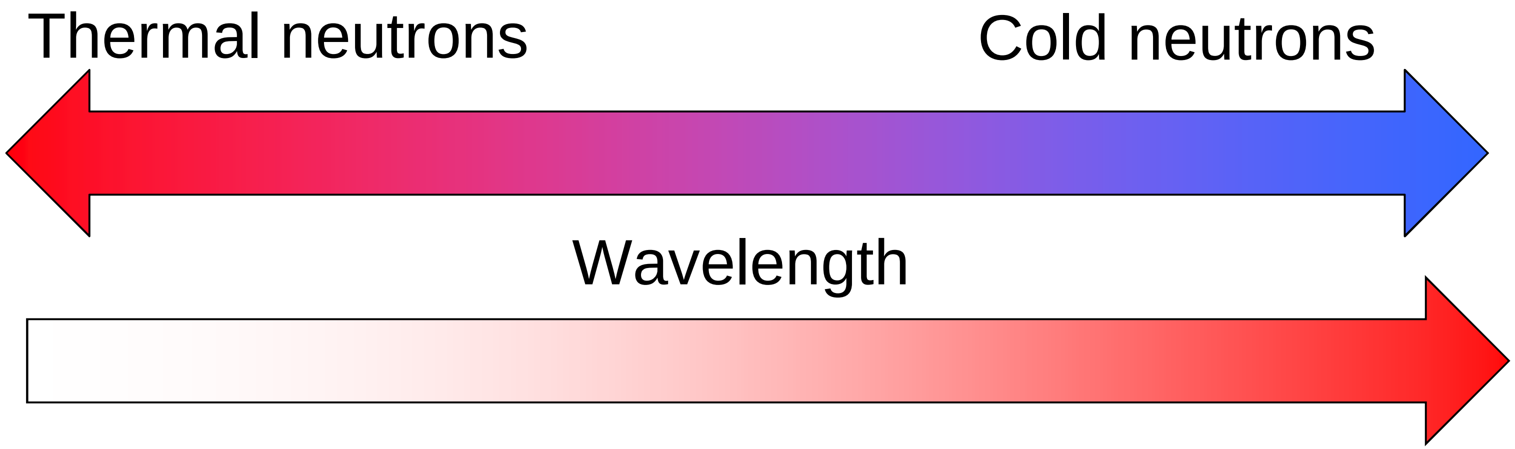
Thermal and cold neutrons

Thermal neutrons

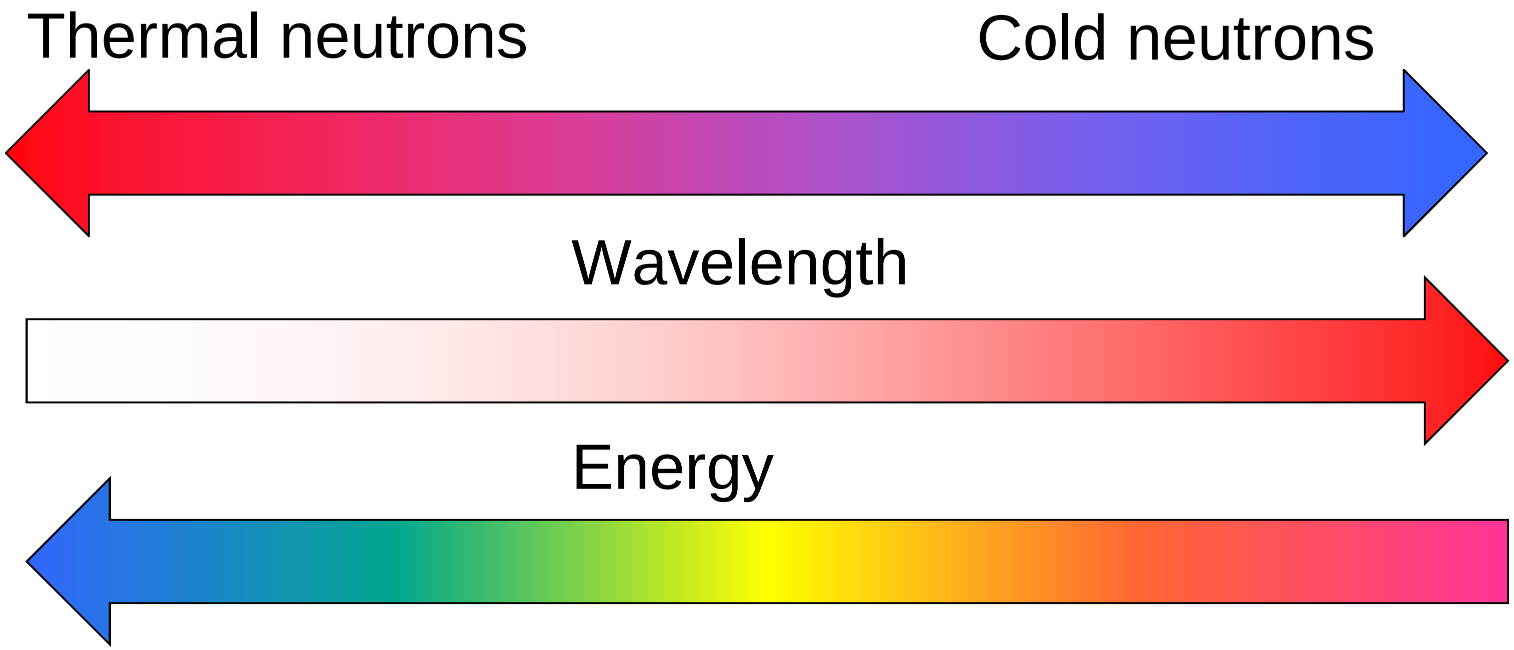
Cold neutrons



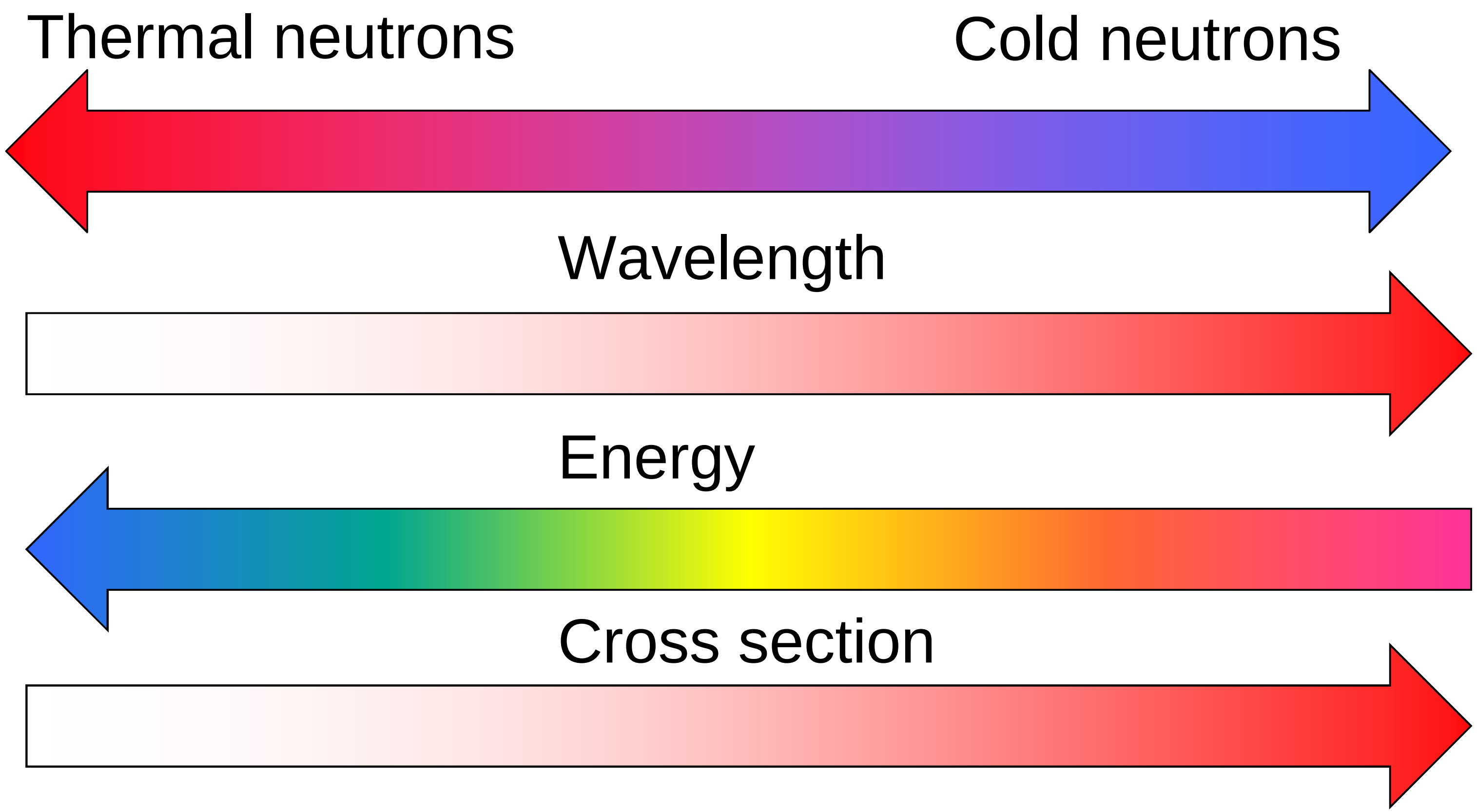
Thermal and cold neutrons



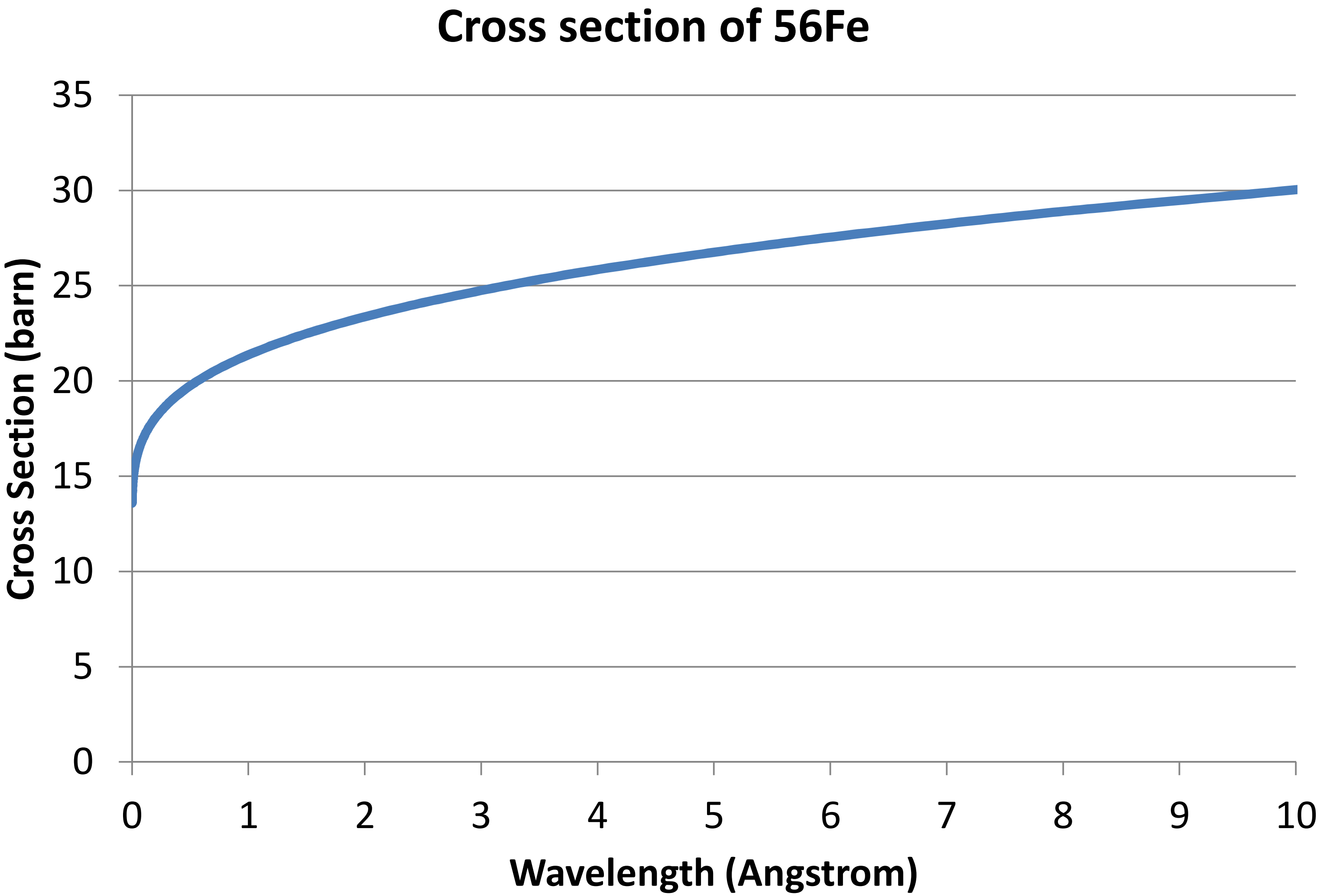
Thermal and cold neutrons



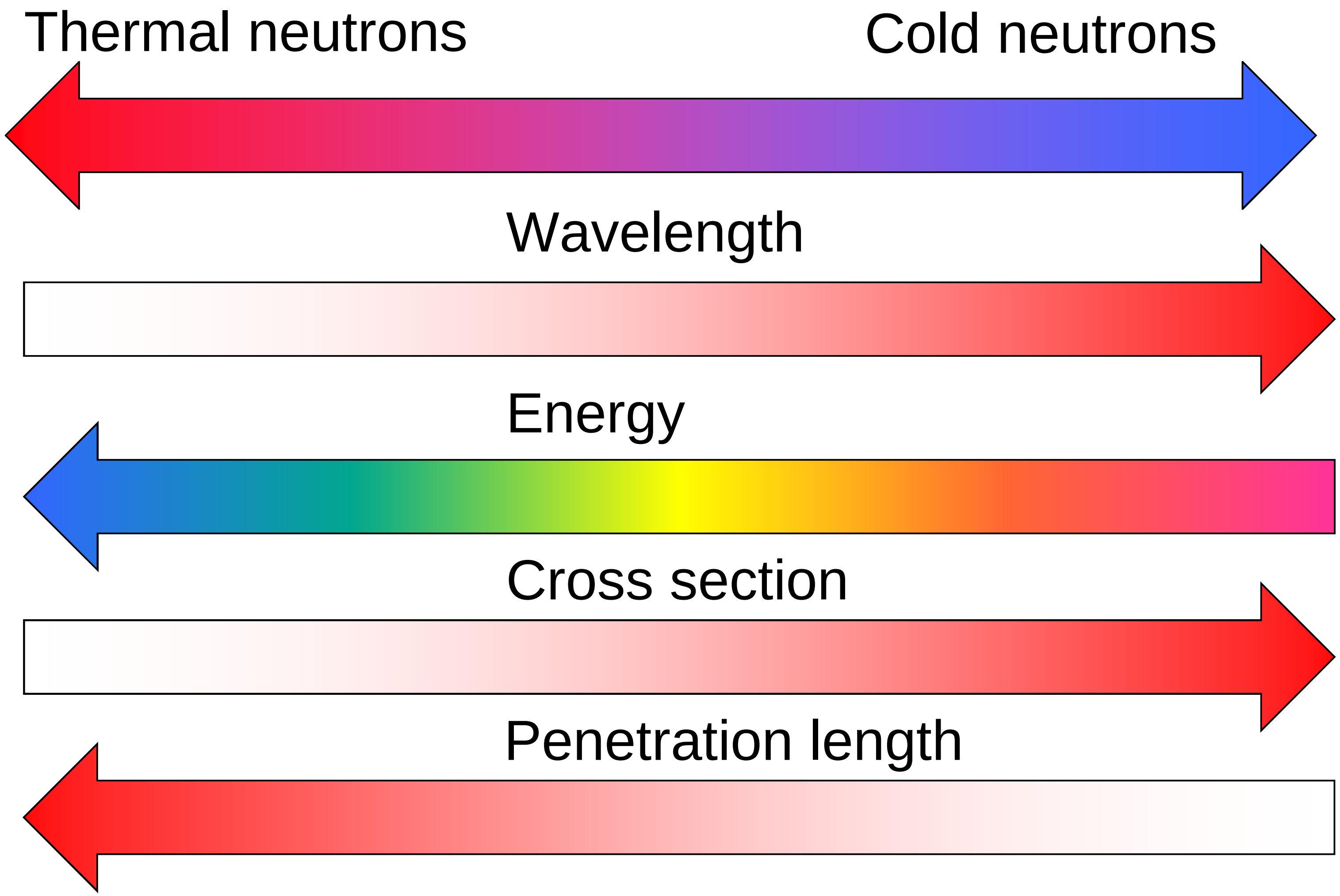
Thermal and cold neutrons



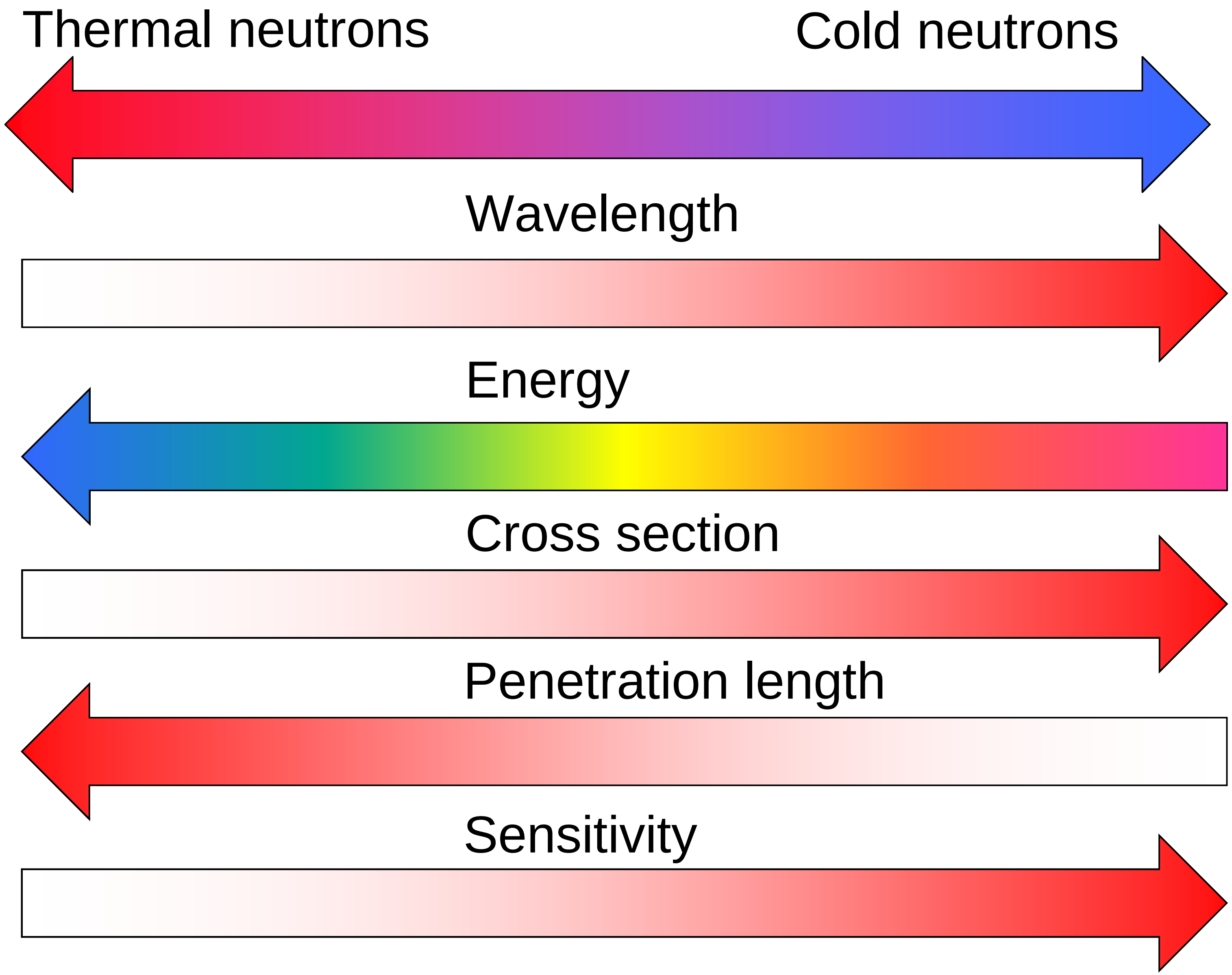
Thermal and cold neutrons



Thermal and cold neutrons



Thermal and cold neutrons



Examples

Coffee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PSI
neutron imaging & activation group
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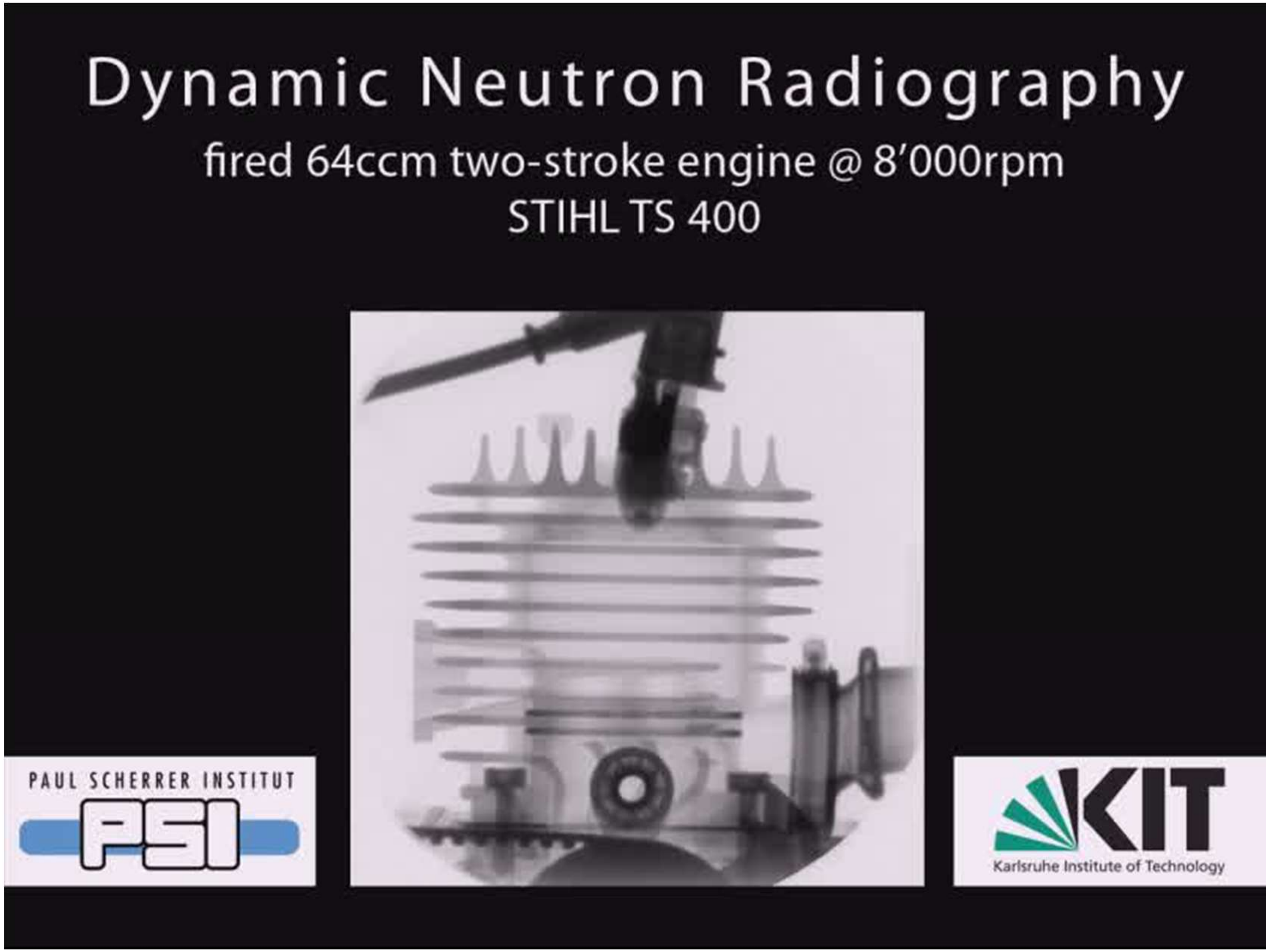
Engine running



See presentation of P. Boillat about this

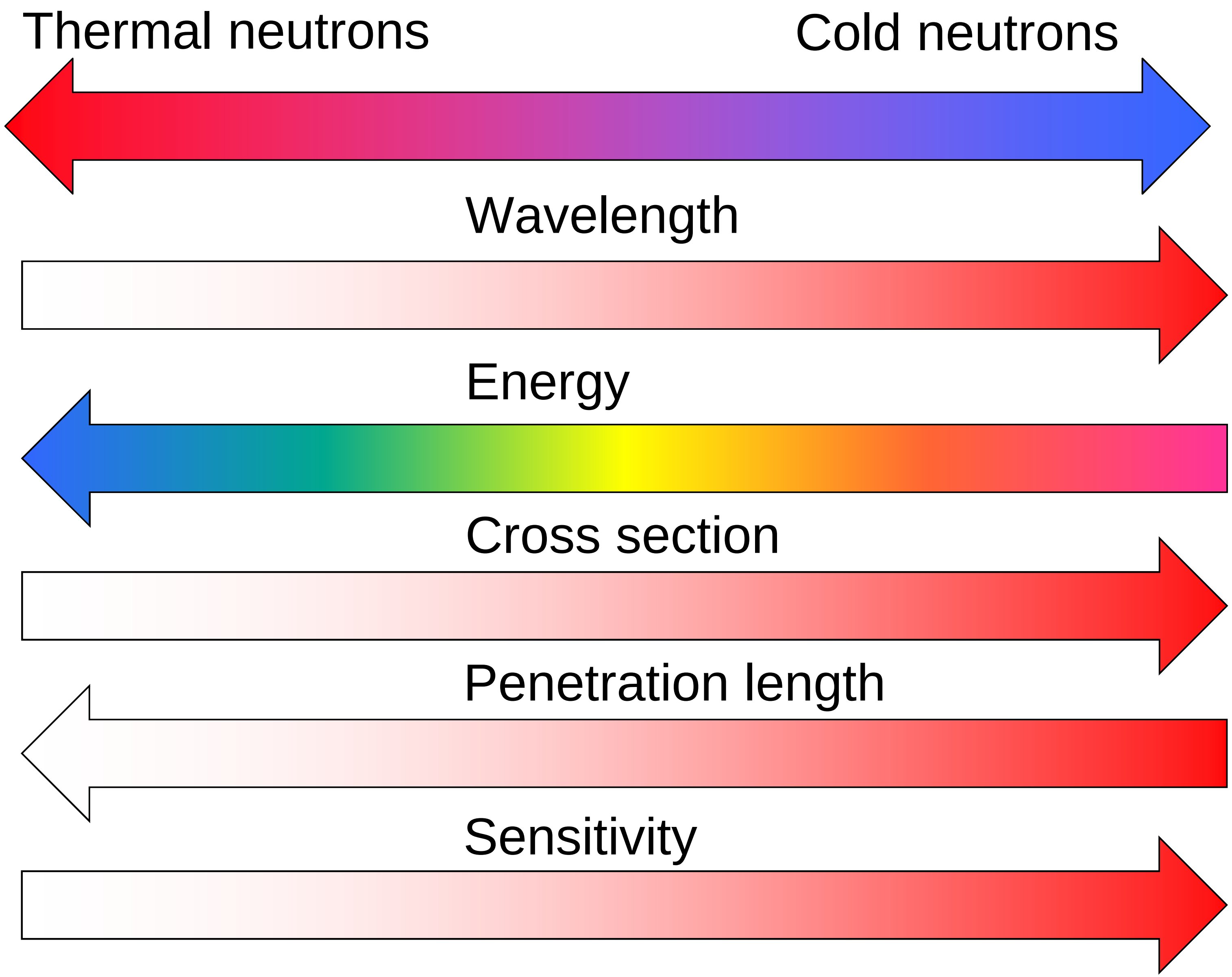
Buddha

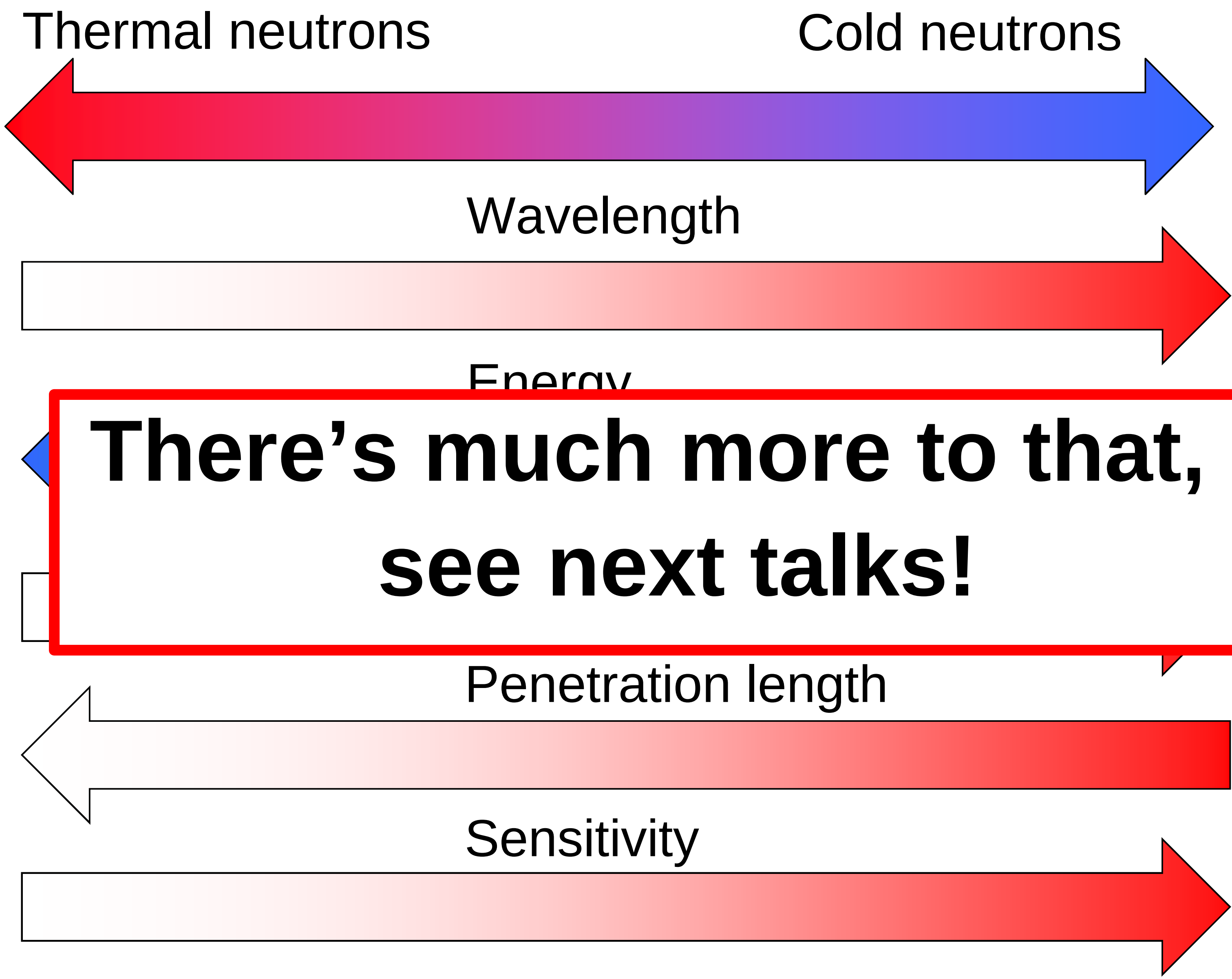
See presentation of D. Mannes about this

Army-knife

See presentation of A. Kaestner about this

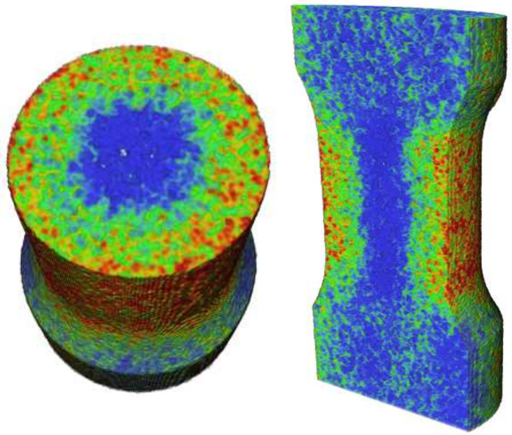
Fly

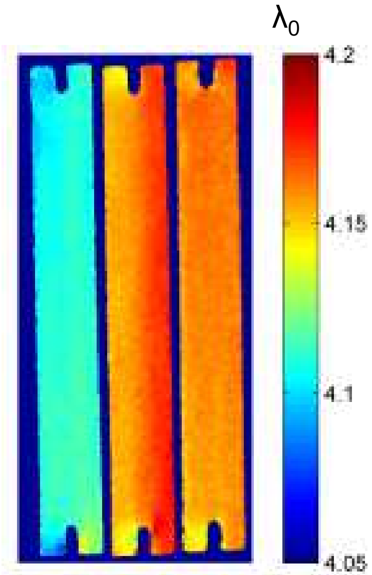

Thermal neutrons
Cold neutrons
Wavelength
Energy
Cross section
Penetration length
Sensitivity

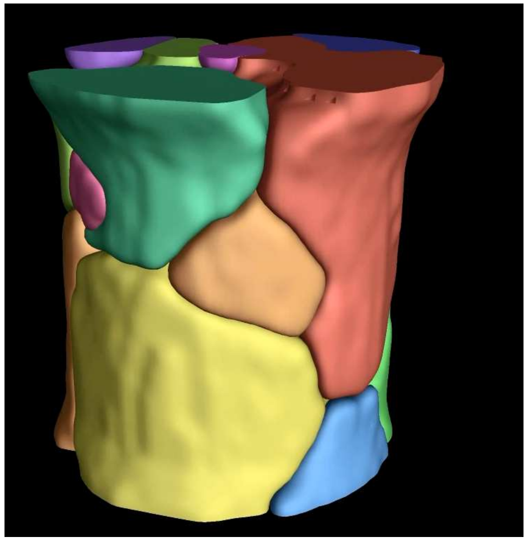


There's much more to that, see next talks!

Other great stuff with neutrons







See presentations of S. Peetermans and M. Raventos about these