# Transmission imaging 1
# HL1202

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Office hours (för frågor) denna vecka: *https://kth-se.zoom.us/j/63298493978*

Onsdag 8 feb 12:00-13:00
Fredag 10 feb 13:00-14:00

This is what you should know after this lecture + own work:

1. Def. of ionising radiation
2. Basic principles of transmission imaging
3. Fundamentals of interaction of radiation with matter of interest for transmission imaging (kinds of interaction, energy dependence)
4. Attenuation of photons: primary, attenuated, absorbed photons
5. Beer's law and how to apply it
6. Definition of linear and mass attenuation coefficient
7. Definition of object contrast
8. Image contrast vs object contrast
9. Signal Difference to Noise Ratio (SDNR)
10. Influence of Compton on contrast
11. Influence of x-ray energy on contrast
12. Energy dependence of attenuation, Photo Effect, Compton and Pair Production

# Intro: orientation chart & lecture organisation

Transmission imaging

# Intro: orientation chart & lecture organisation

## Transcission imaging

interaction radiation with matter

1. photoeffect, compton, pair prod., ...
2. linear or mass absorption coeff.
3. dose
4. ...

image quality

1. contrast (hounsfield units)
2. SNR, SDNR
3. ...

sources

1. spectrum, decay schemes
2. beam hardening
3. engineering challenges
4. ...

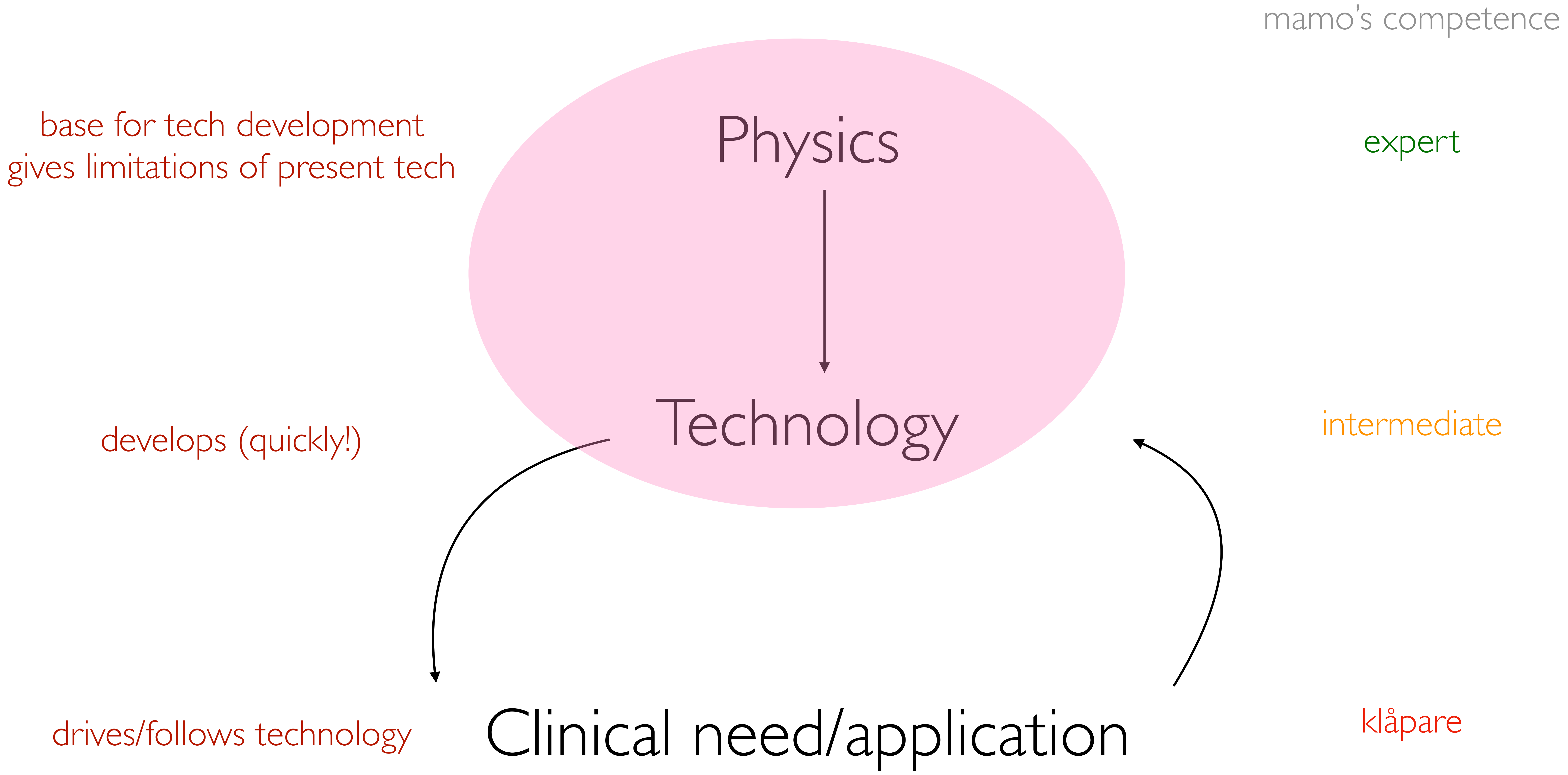
detectors

1. types
2. efficiency
3. resolution (spatial, energy)
4. ...

CT: 3D

1. projections
2. image reconstruction
3. acquisition geometry, different generations
4. ...

# Philosophy of the course and motivation for it



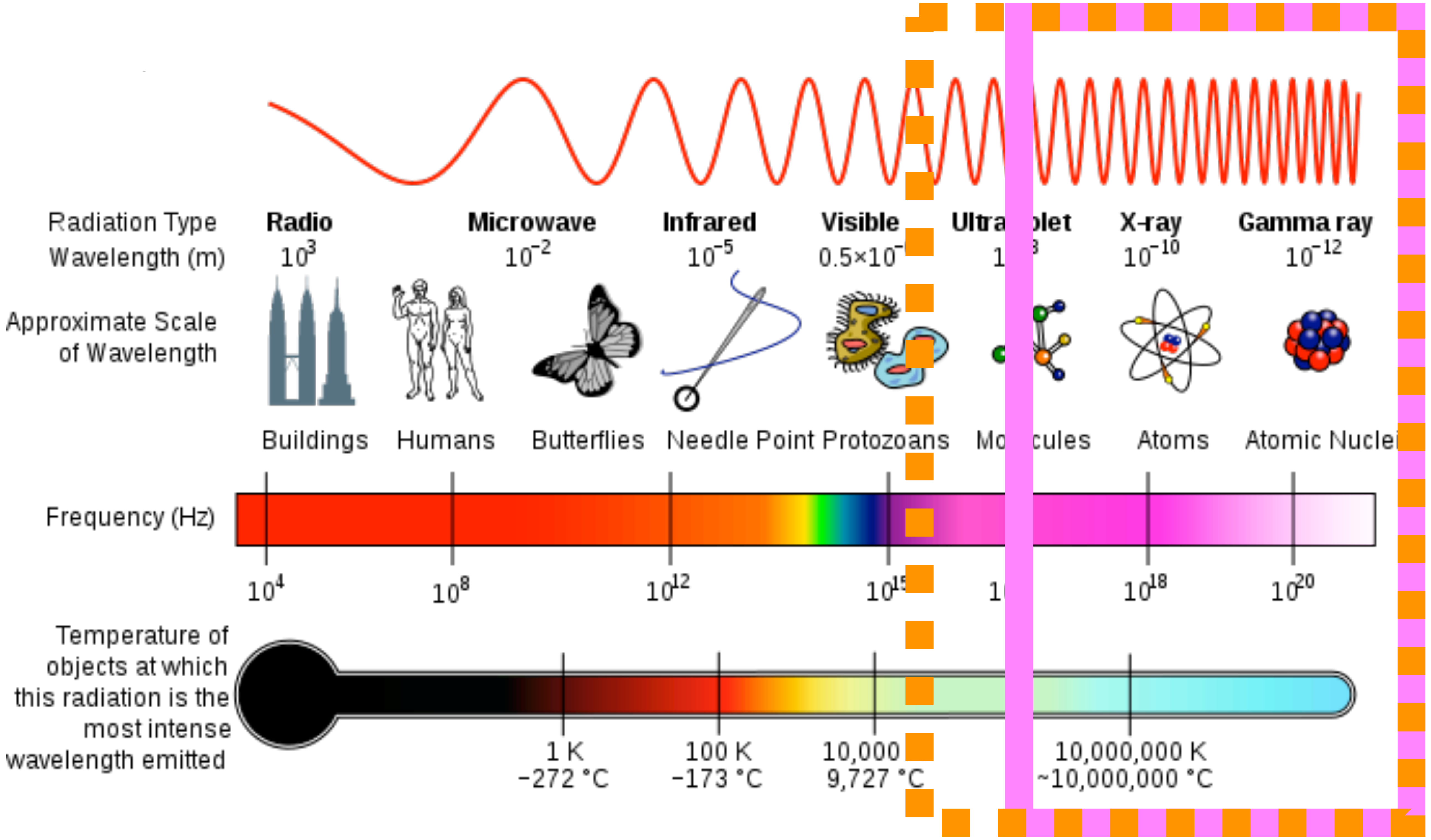

… but we will jump back and forth among these 3

Warning: the material in this lecture is at exactly the same level as you should know it in order to pass the exam (that is, I am not presenting things that are "just so you know it and have a vague idea")

# Let's get started: panorama view of 2D transmission imaging with ionising radiation

# ionising radiation?

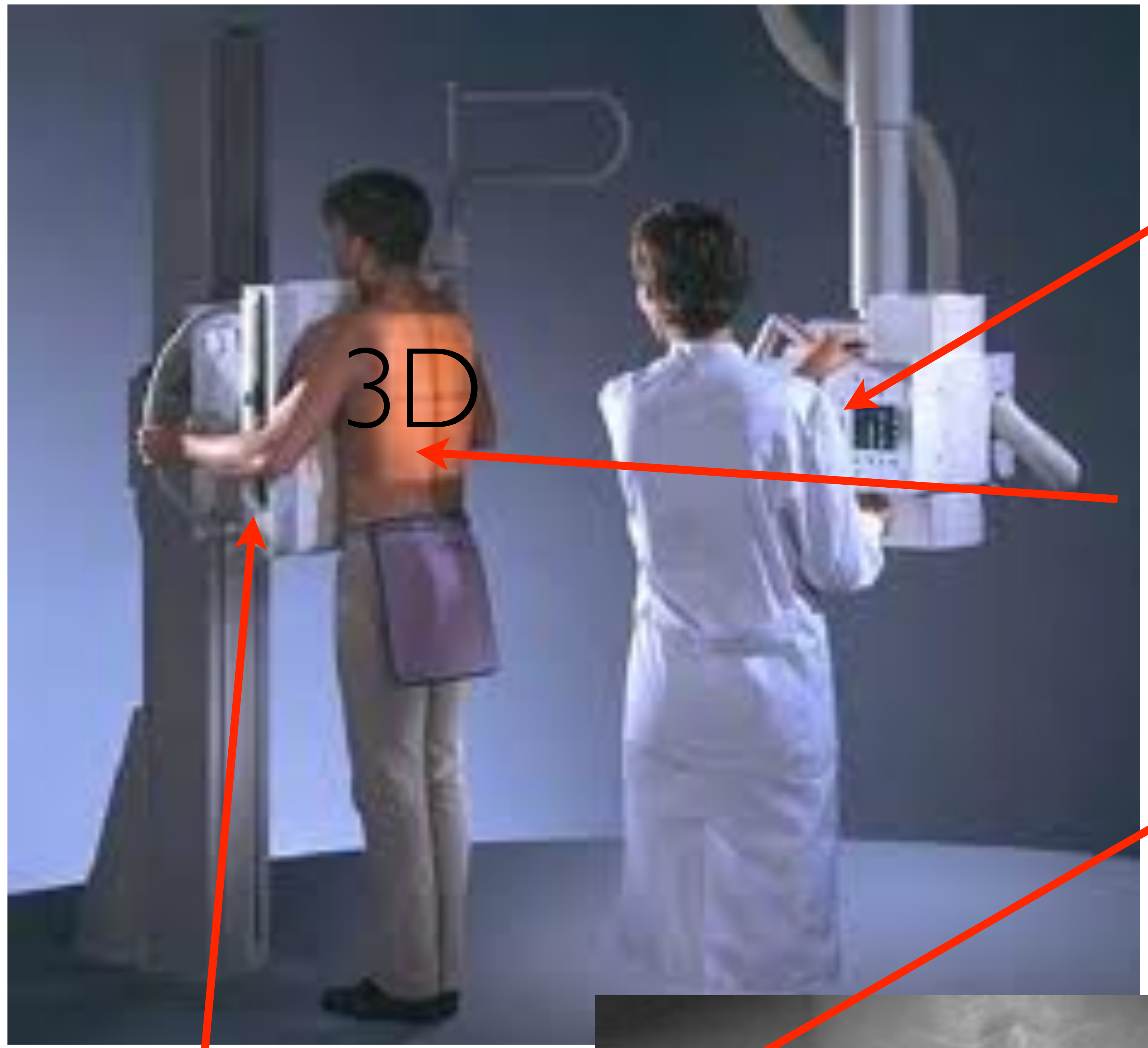
EM-strålning med tillräckligt hög energi för att jonisera atomer

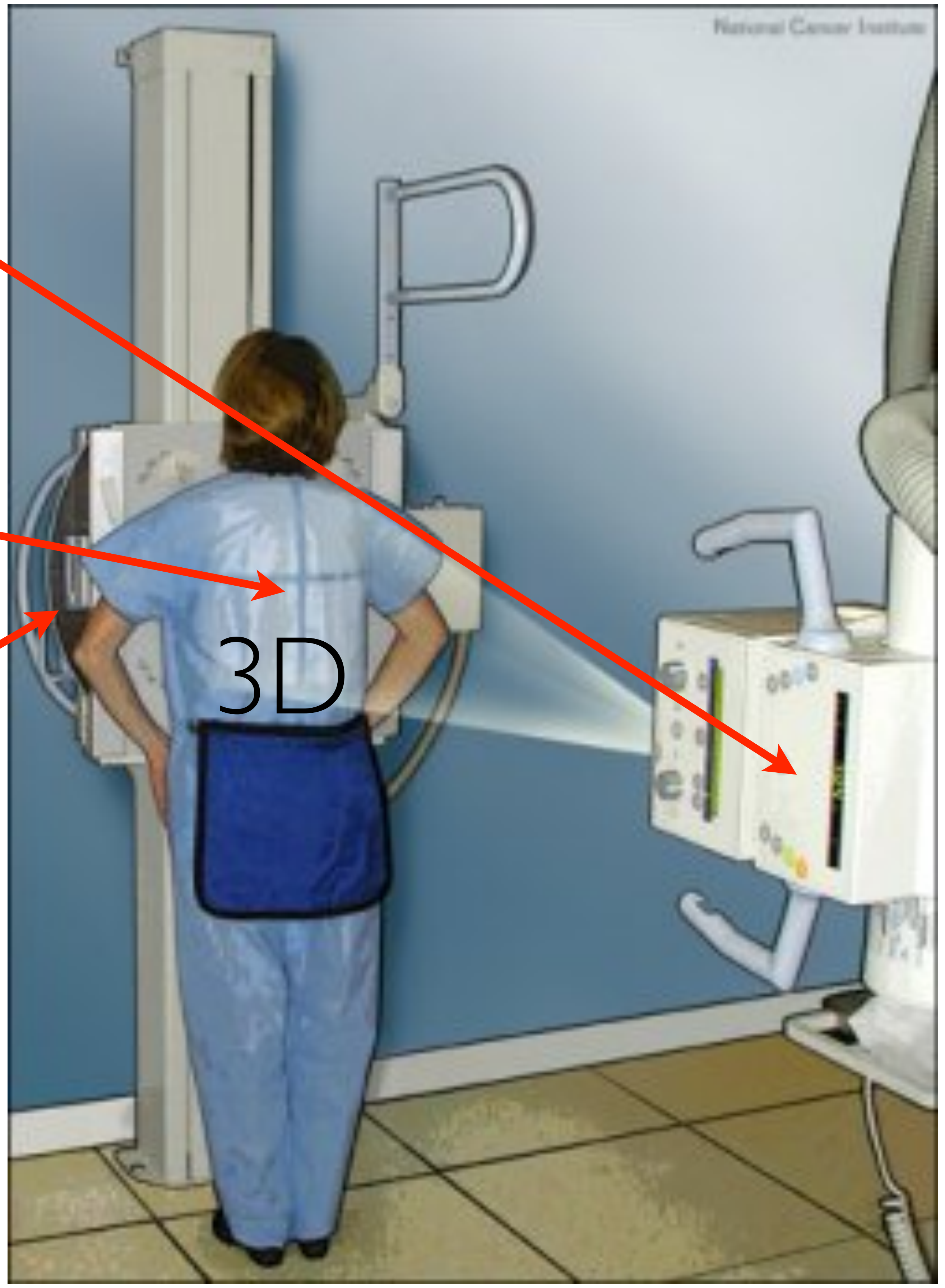



> 100 eV

# Let's jump to clinical practice

# Transmission imaging fundamental elements

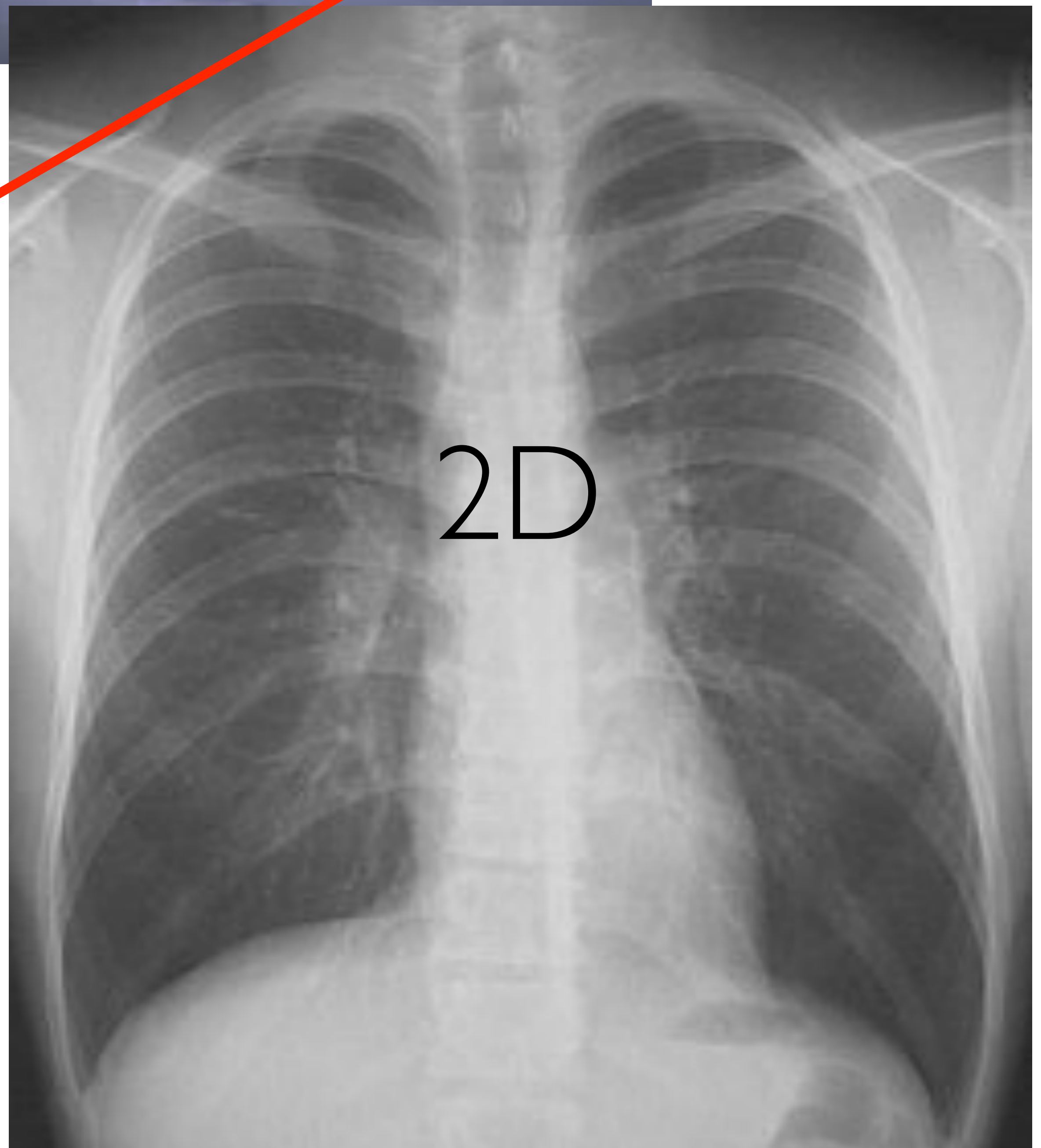



source

object

detector




property of the object measured:
transparency to x-ray

What is absolutely necessary for obtaining the kind of x-ray of the chest shown in the picture?:

1. All of the transmitted photons must be detected by the detector

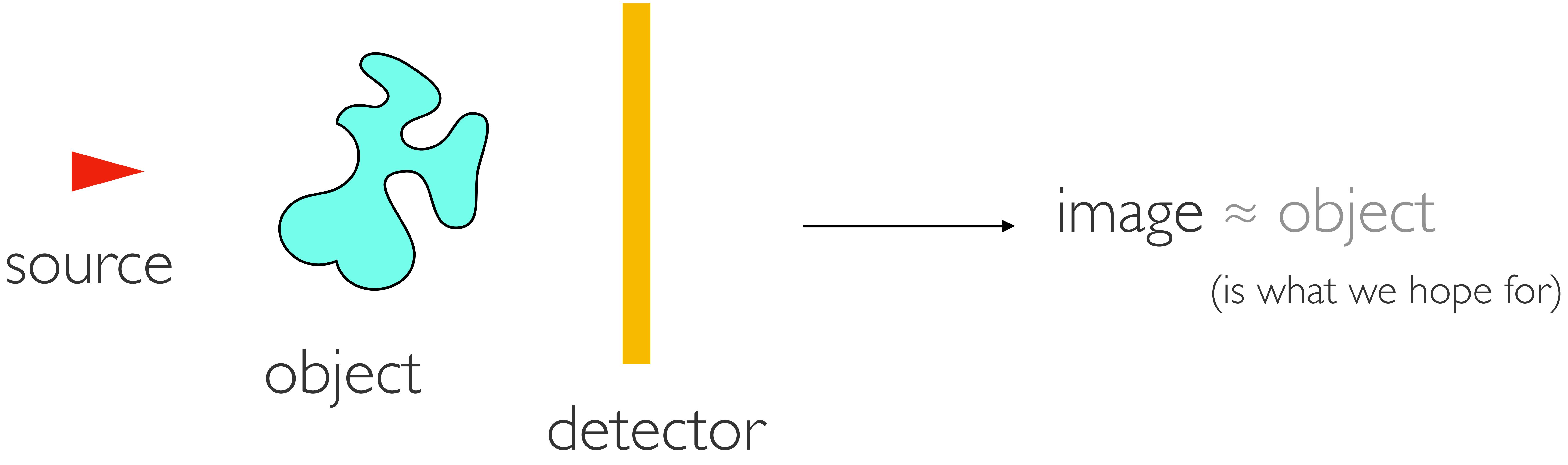
2. Bones and soft tissues must transmit x-ray in a different way

3. Some of the photons must be absorbed in the object

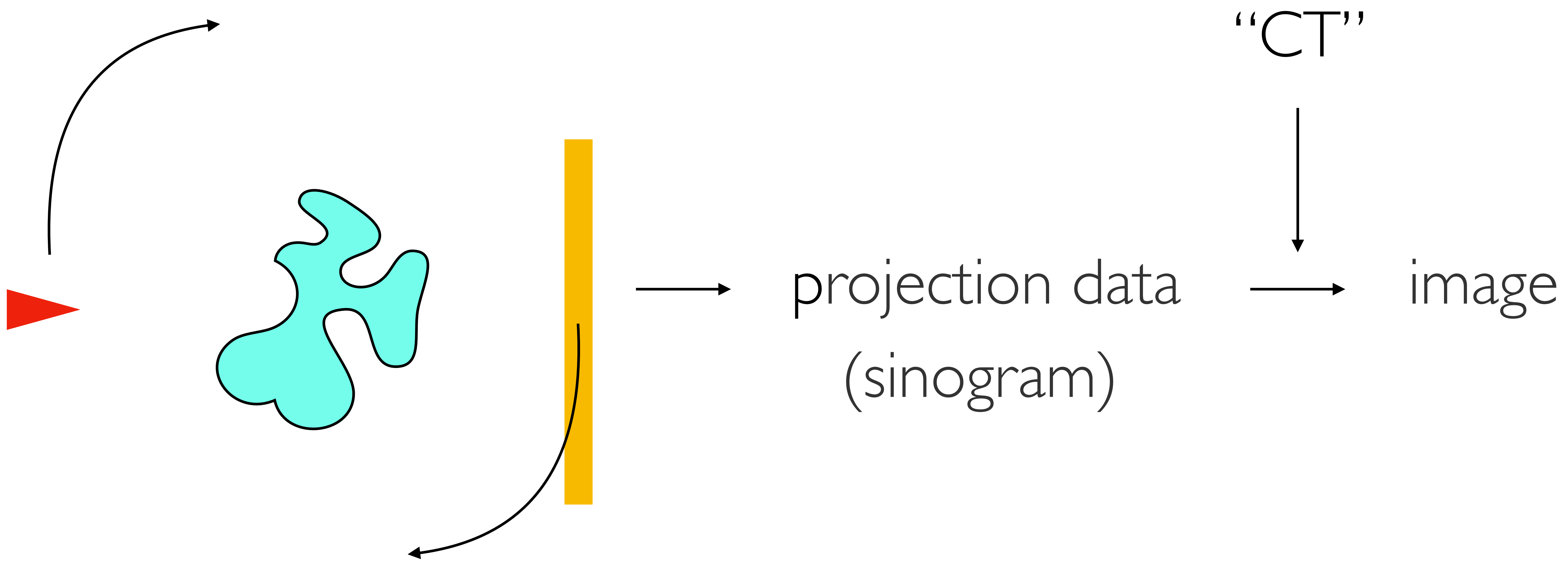
4. The patient must be alive

Still clinical, but simplified
(hint that we’ll be heading
towards Physics soon!)

# 2D X-ray




# 3D: CT (or X-ray CT)

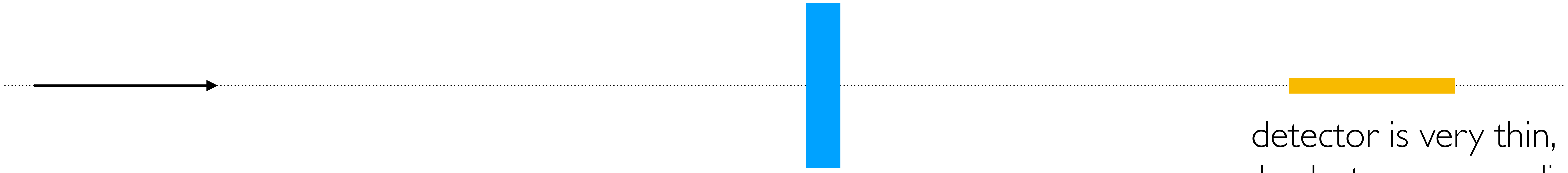


# Physics!

So now we're going to look at very simple cases but we will dig very deep into details. The goal is to understand how these details are going to be important for the clinical setting

Let’s consider a simple case:

object: homogeneous material, thickness t



shoot 1 photon at the time, always along same direction

detector is very thin, only photons proceeding in same direction as emitted can be detected

(Keep clinical application in mind: will the detector signal change if I remove or change in any way the object? How? Why? Can I change something in the object without changing the detector output?)

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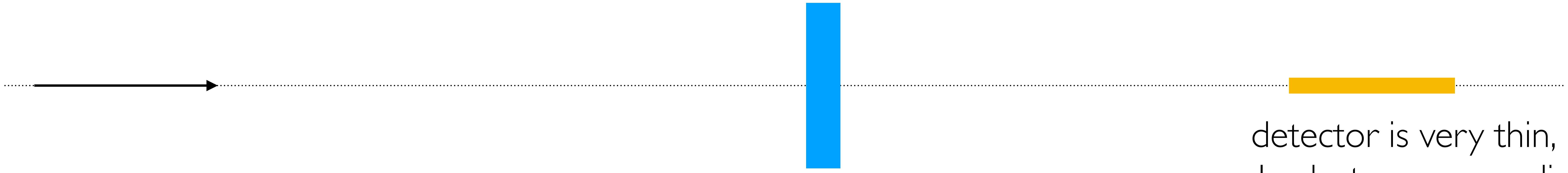

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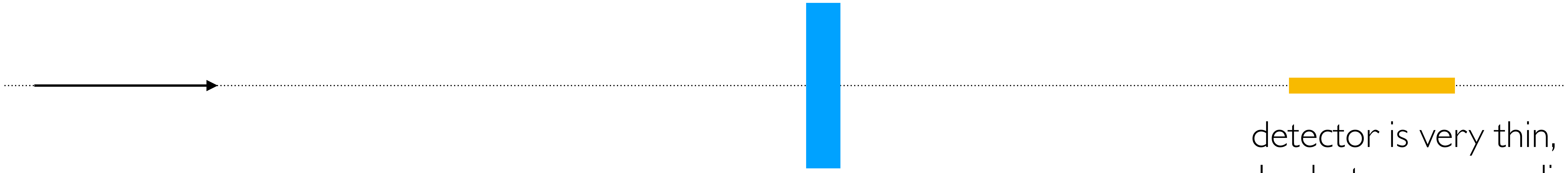

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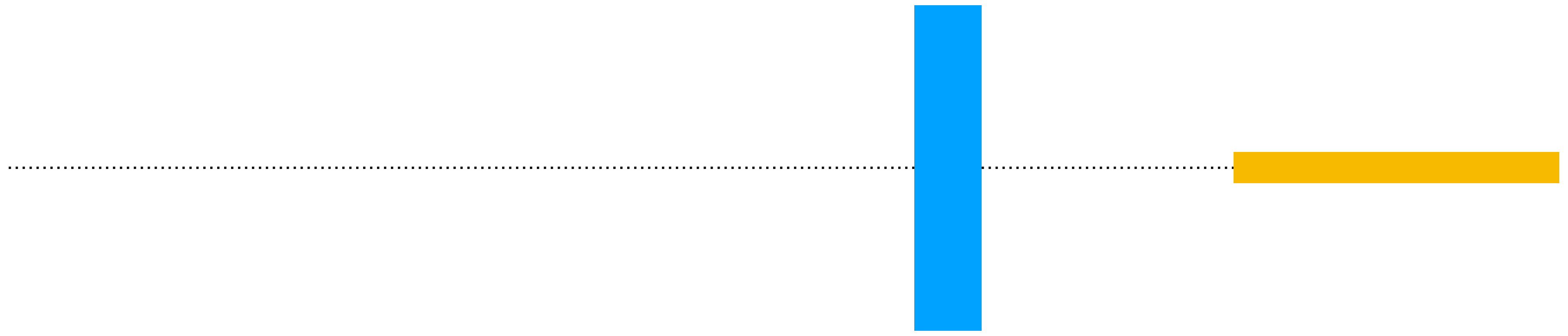

photon absorbed (PE)

detector signal = 0

E dep ≠ 0

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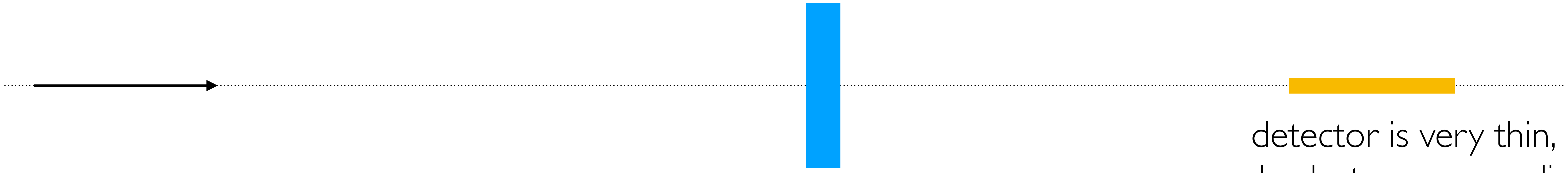

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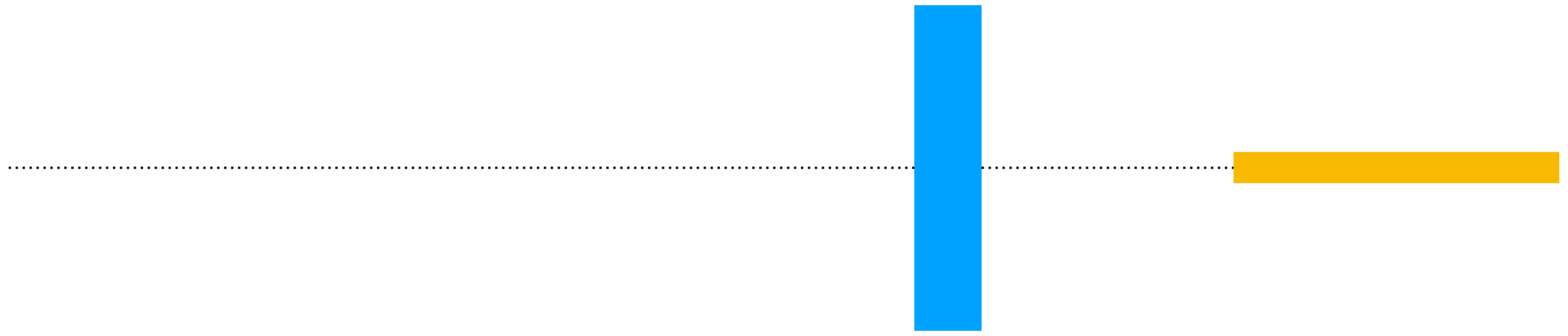

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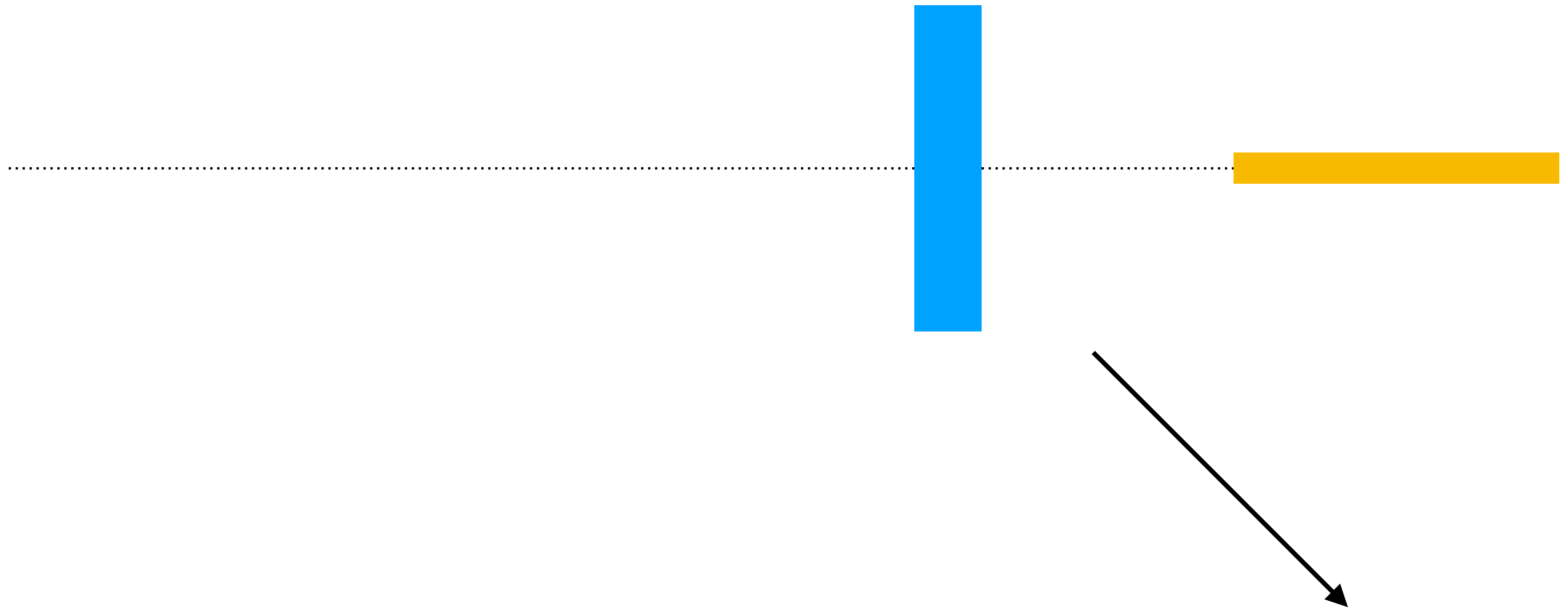

photon scattered (Compton) | detector signal = 0 | E dep ≠ 0

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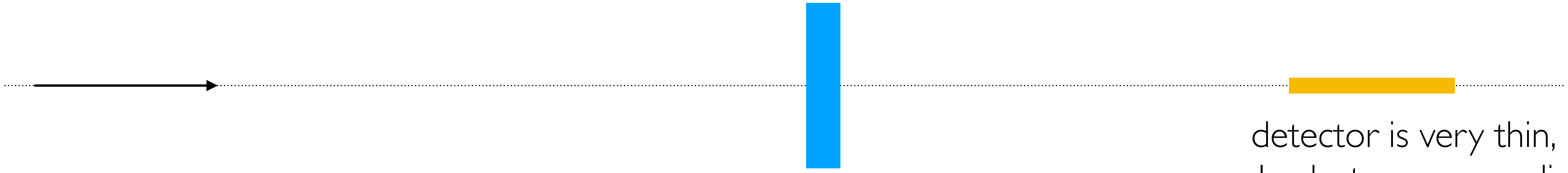

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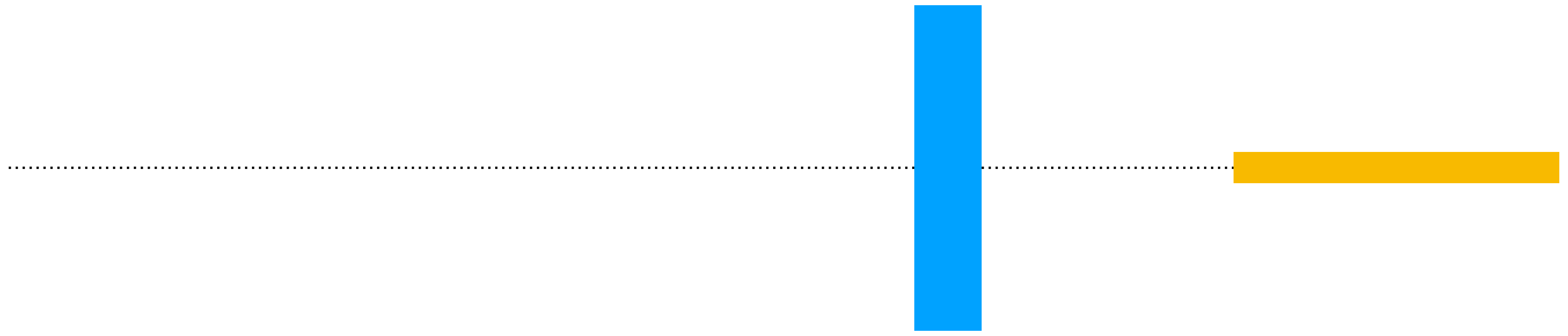
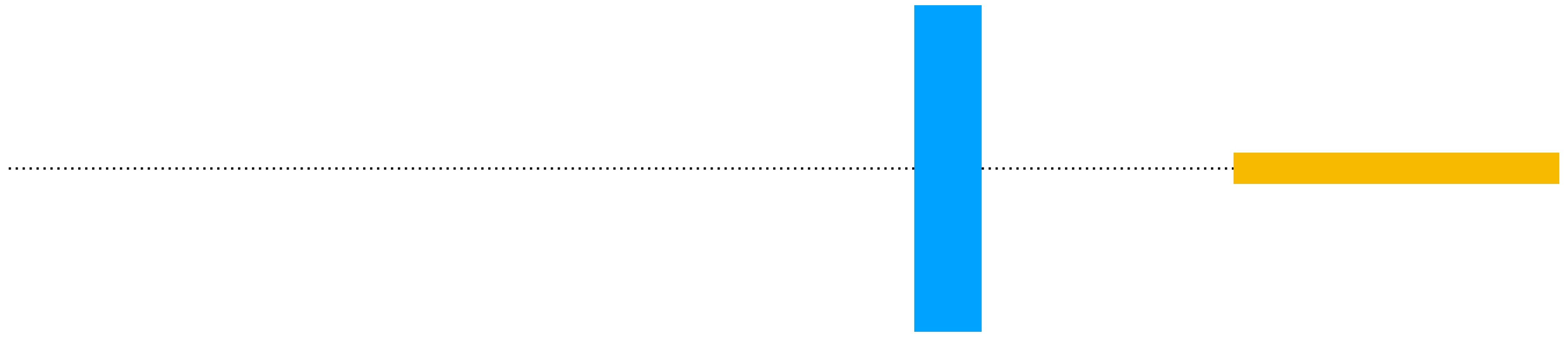


photon absorbed (PE) — detector signal = 0 — E dep ≠ 0



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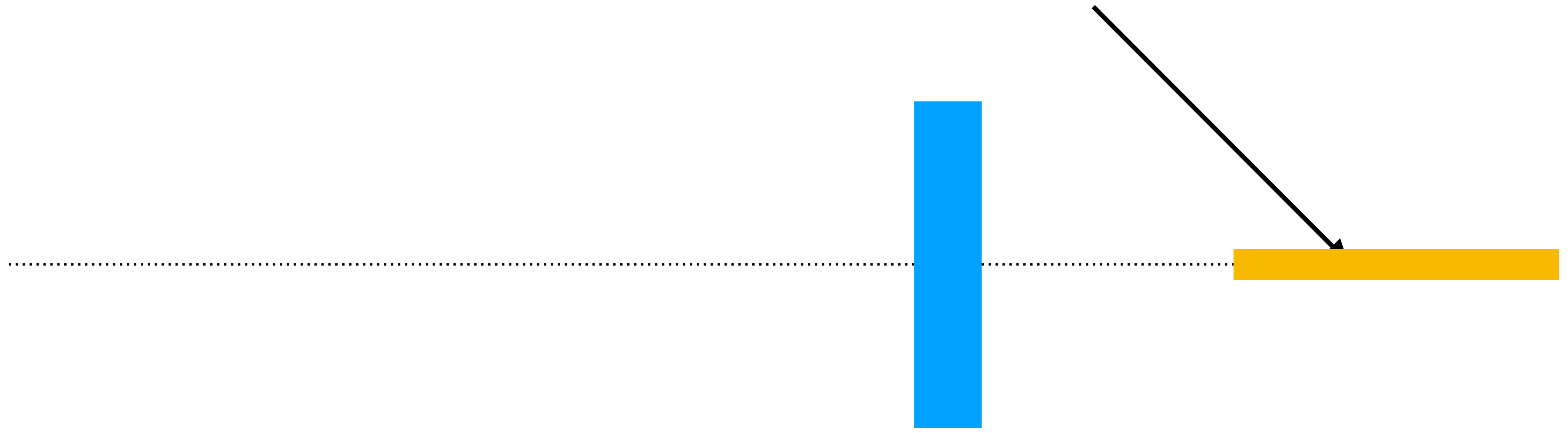
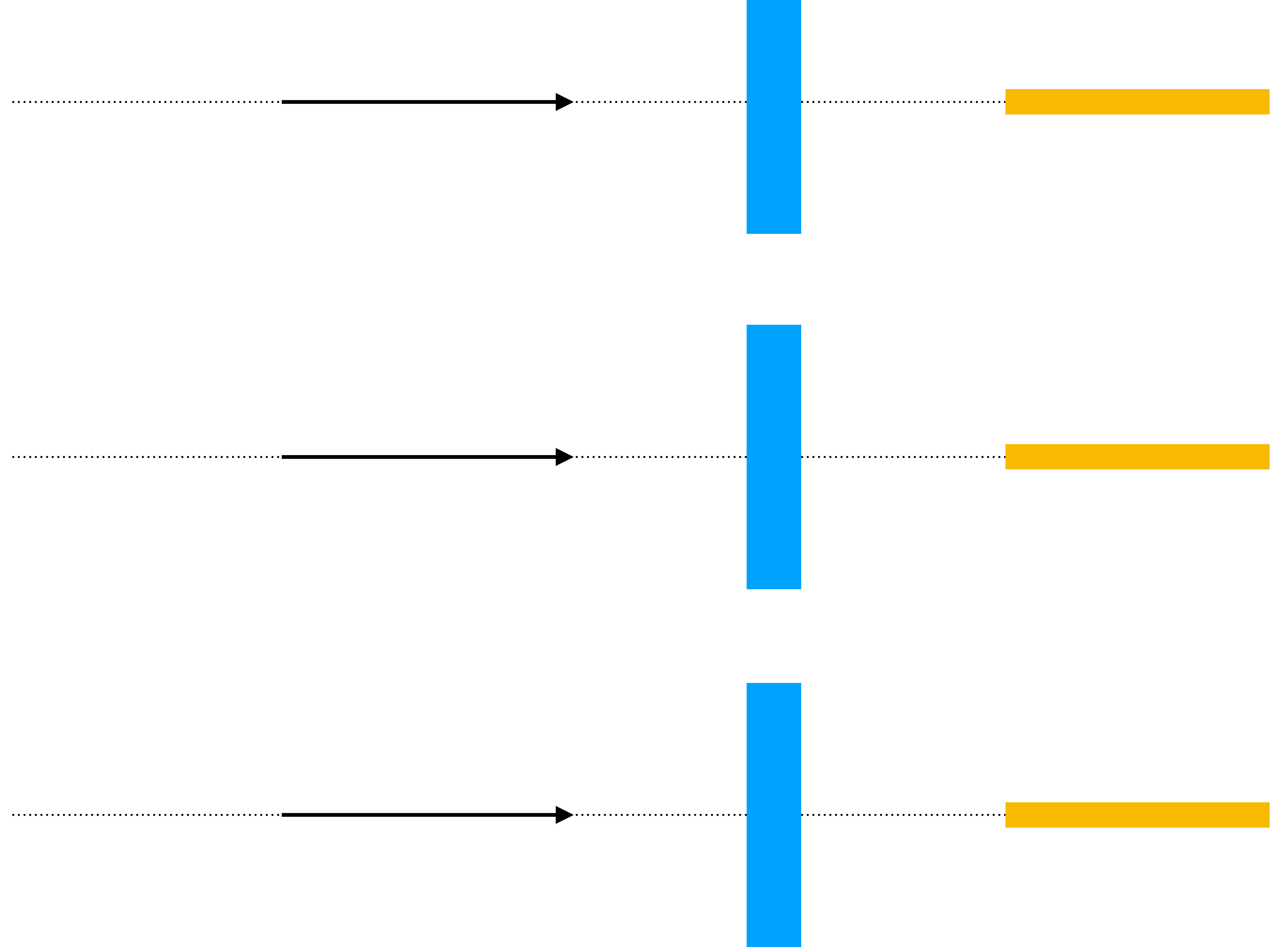


photon not interacting — detector signal ≠ 0 — E dep = 0

# Definitions ahead



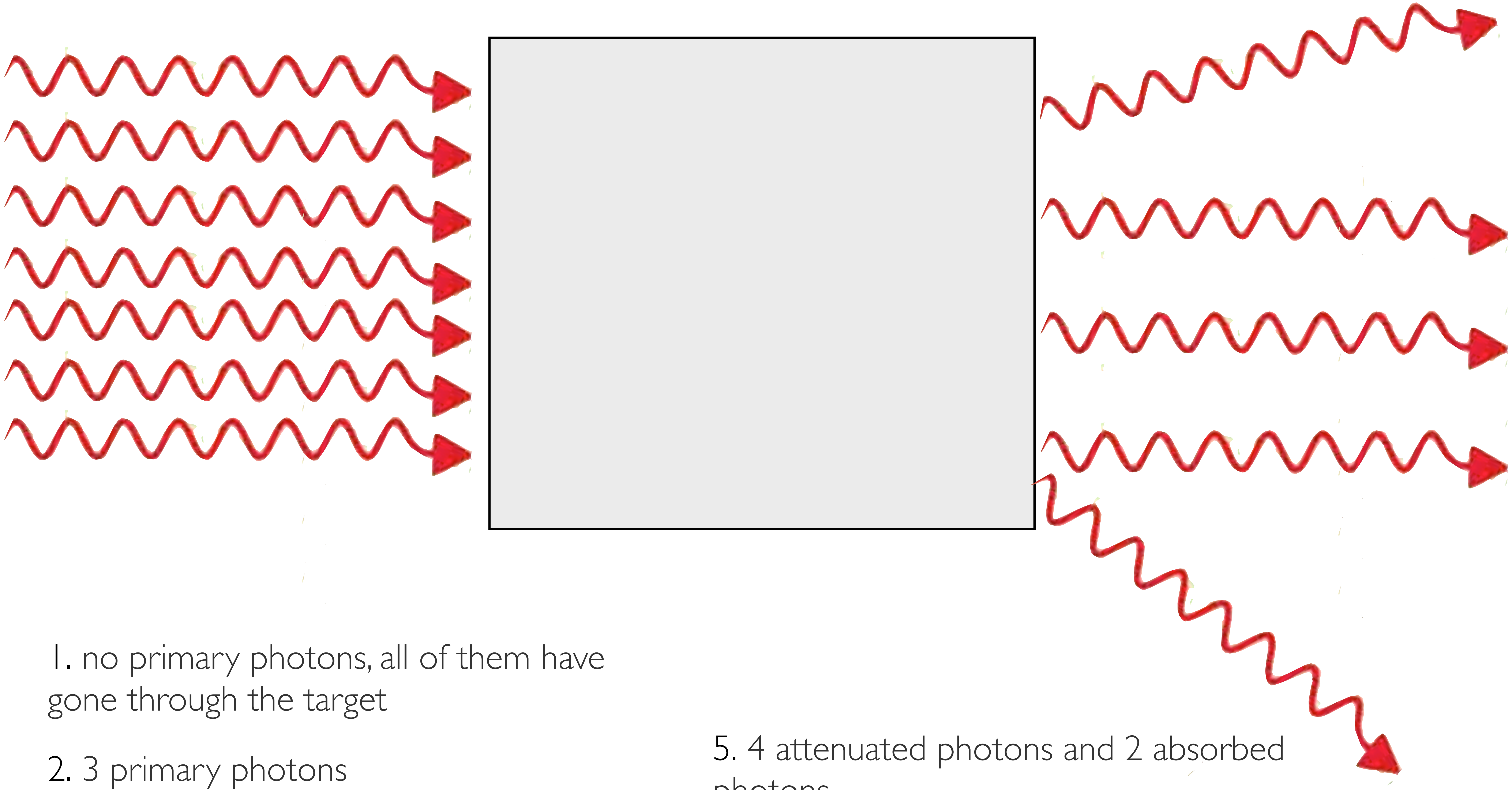
| | | |
|---|---|---|
| photon absorbed (PE) | detector signal = 0 | E dep ≠ 0 |
| photon scattered (Compton) | detector signal = 0 | E dep ≠ 0 |
| photon not interacting | detector signal ≠ 0 | E dep = 0 |

**Def 1:** Photons interacting in the object, that is photons deposing energy in the object are called *attenuated photons*

**Def 2:** Photons not interacting in the object, are called *primary photons*

**Question:** Could I equivalently define attenuated photons as photons not deposing energy in the detector? Hint: to answer the question, try to design at least a case in which scattered photons end up interacting in the detector

In the situation in the figure there are:



1. no primary photons, all of them have gone through the target

2. 3 primary photons

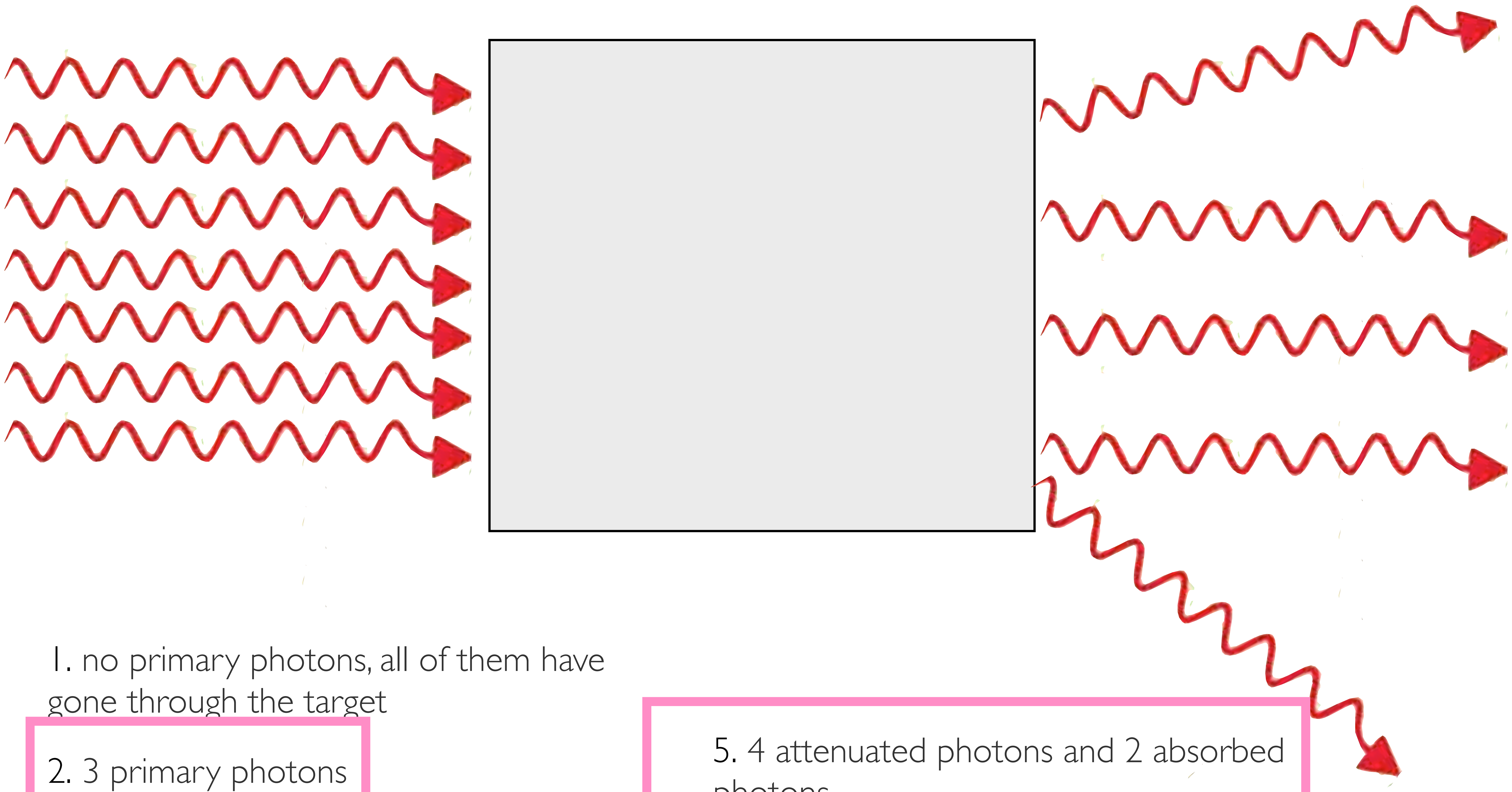
3. 5 primary photons

4. 2 attenuated photons and 2 absorbed photons

5. 4 attenuated photons and 2 absorbed photons

6. more information is needed to decide

# In the situation in the figure there are:



1. no primary photons, all of them have gone through the target

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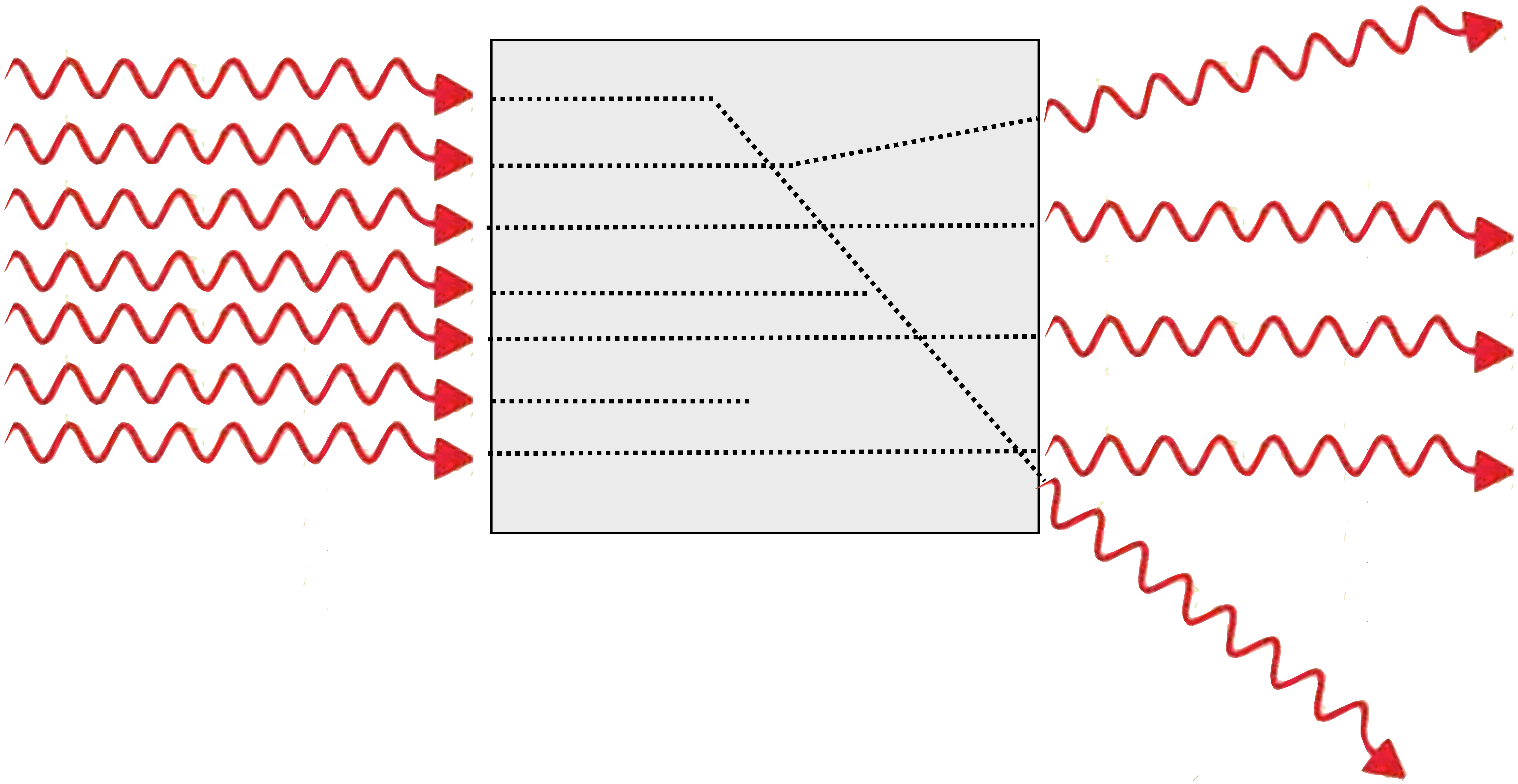
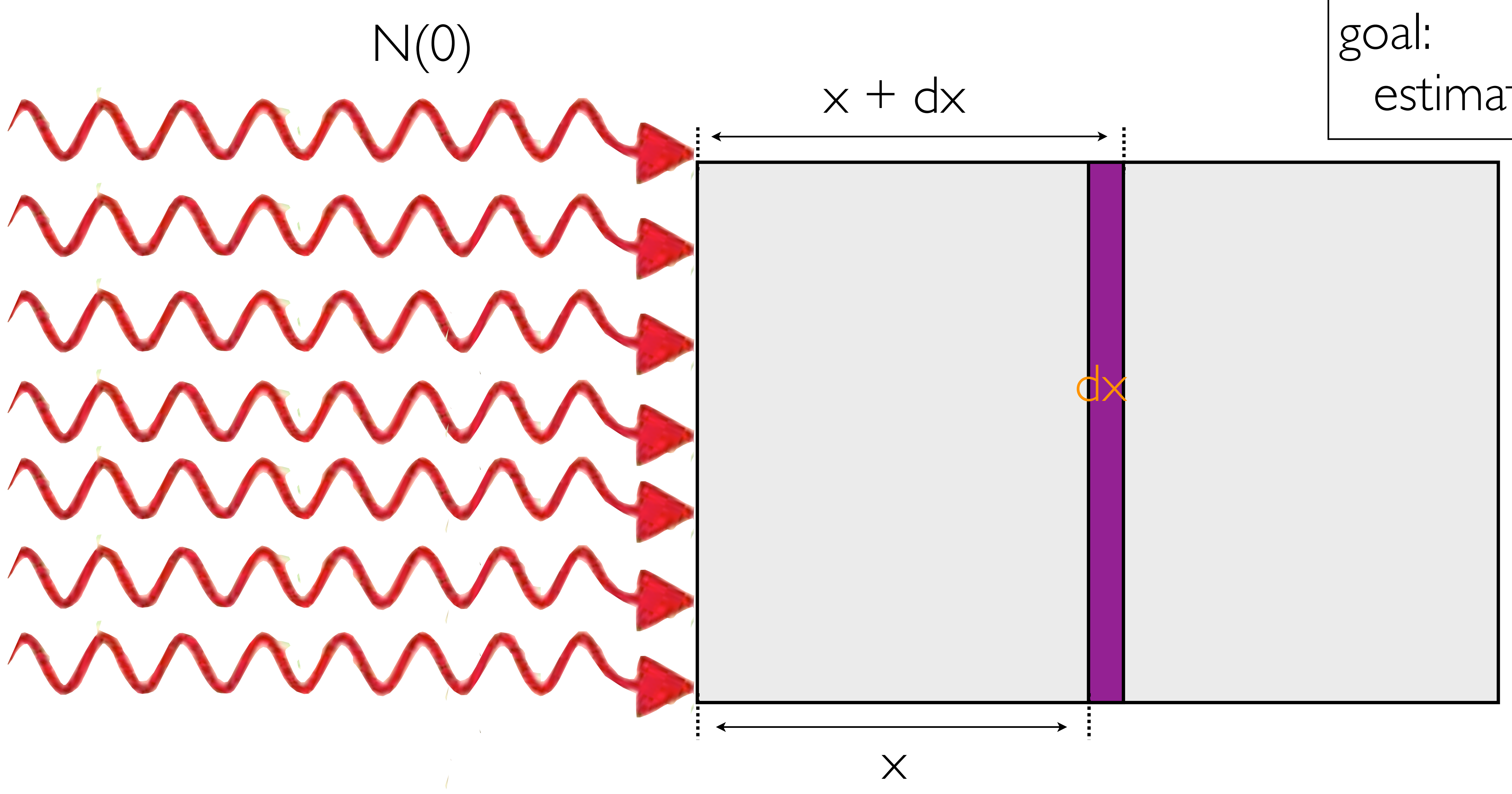
# Let us sort out the answer to the previous question



# Beer's law

goal:
estimate # of primary photons reaching distance x




(only primary photons ⇨ E constant)

let σ be the probability of interaction with 1 electron in the material

let D be the density of electrons in the material

there will be Ddx electrons available for scattering in a slice of thickness dx (per unit area of the material) ⇒ probability of interaction in that slice is Dσdx

let P(x) be the probability of having travelled **without** interaction to x

⇒ the probability of interaction in the slab between x & x+dx will be:

$P(x)\, D\sigma dx$

⇒ the probability of travelling to x+dx **without** interaction will be:

$P(x+dx) = P(x)(1 - D\sigma dx)$ ⇨ $P(x) = e^{-D\sigma x}$

# Q: We have derived the equation:
# $P(x+dx) = P(x)(1-D\sigma dx)$
# P(x) is found by observing that:

1. $$\frac{P(x+dx) - P(x)}{dx} = -P(x)D\sigma$$

2. the derivative of P(x) is equal to itself times a constant

3. the probability of interaction for primary photons is independent of the distance travelled

4. none of the above, P(x) is experimentally determined

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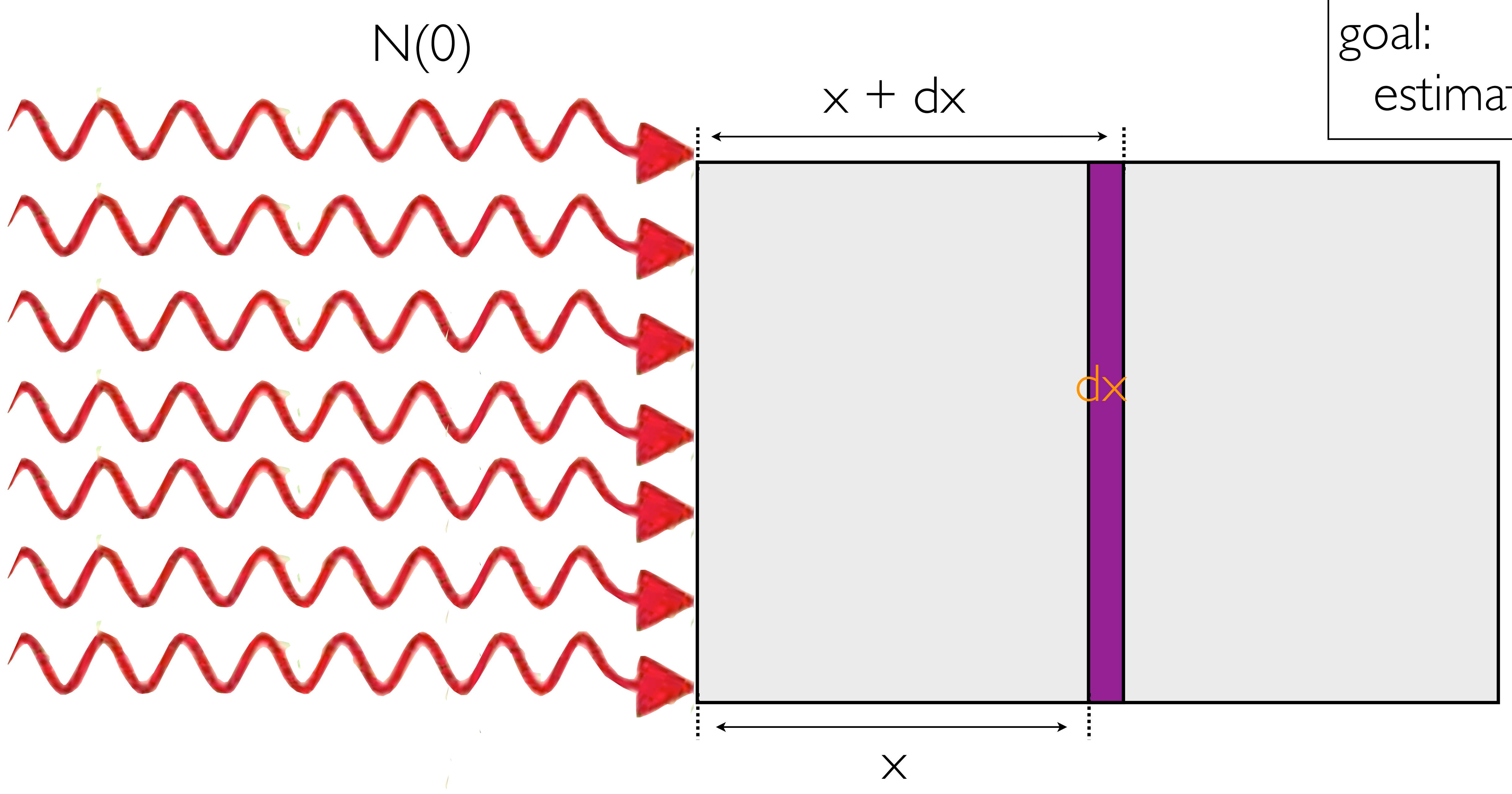


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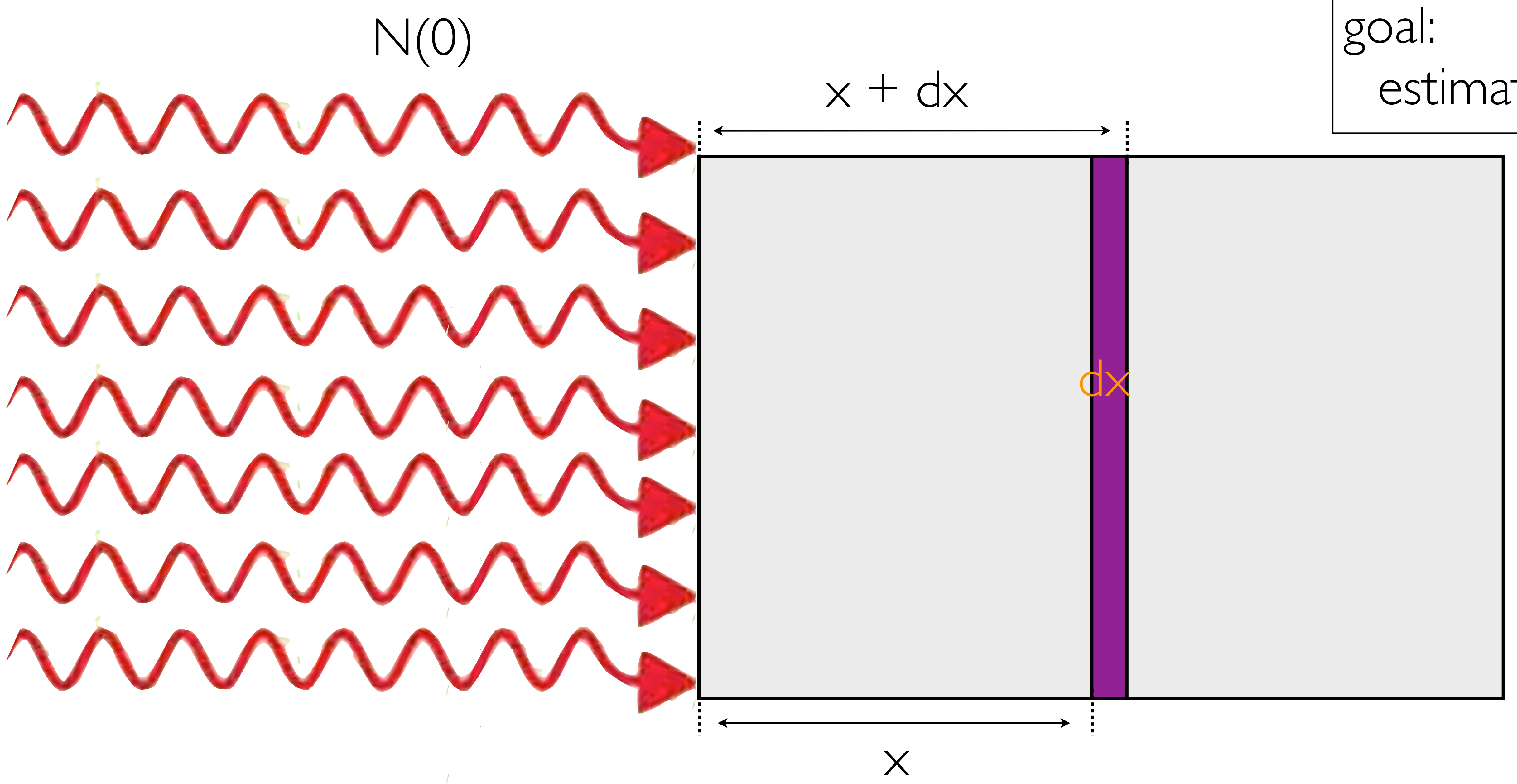
Beer's law

$N(x) = N(0)e^{-\mu x}$

# Beer's law

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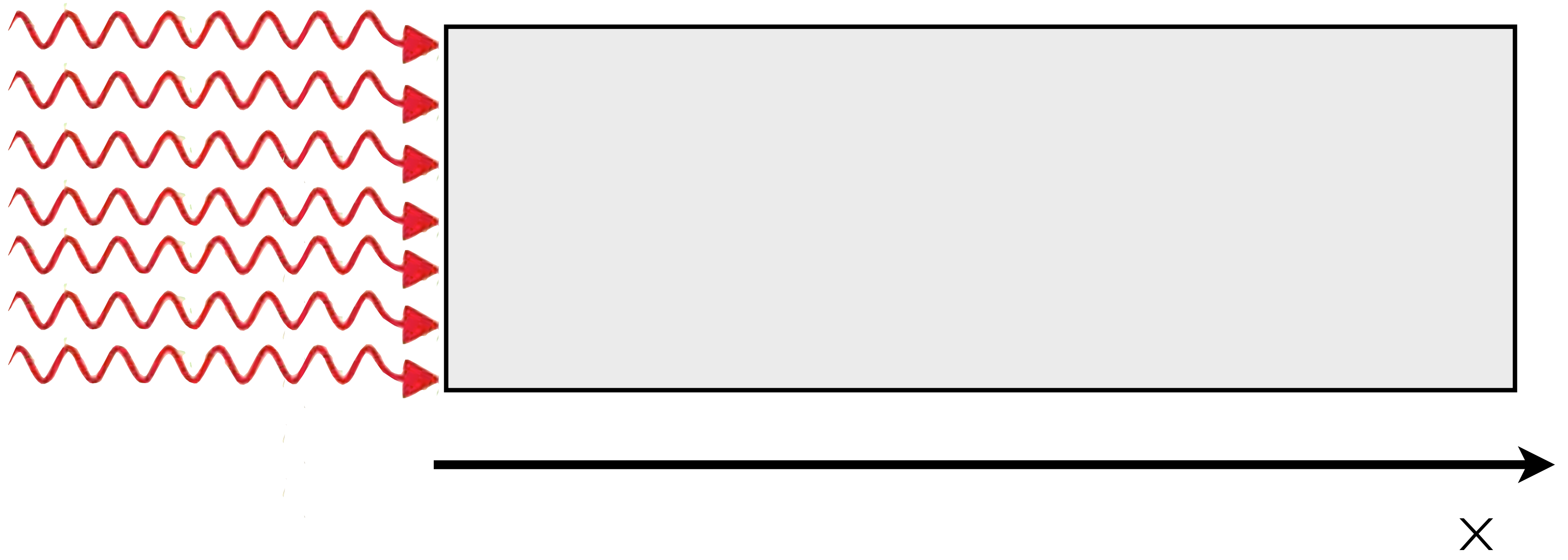
linear attenuation coefficient

Beer's law

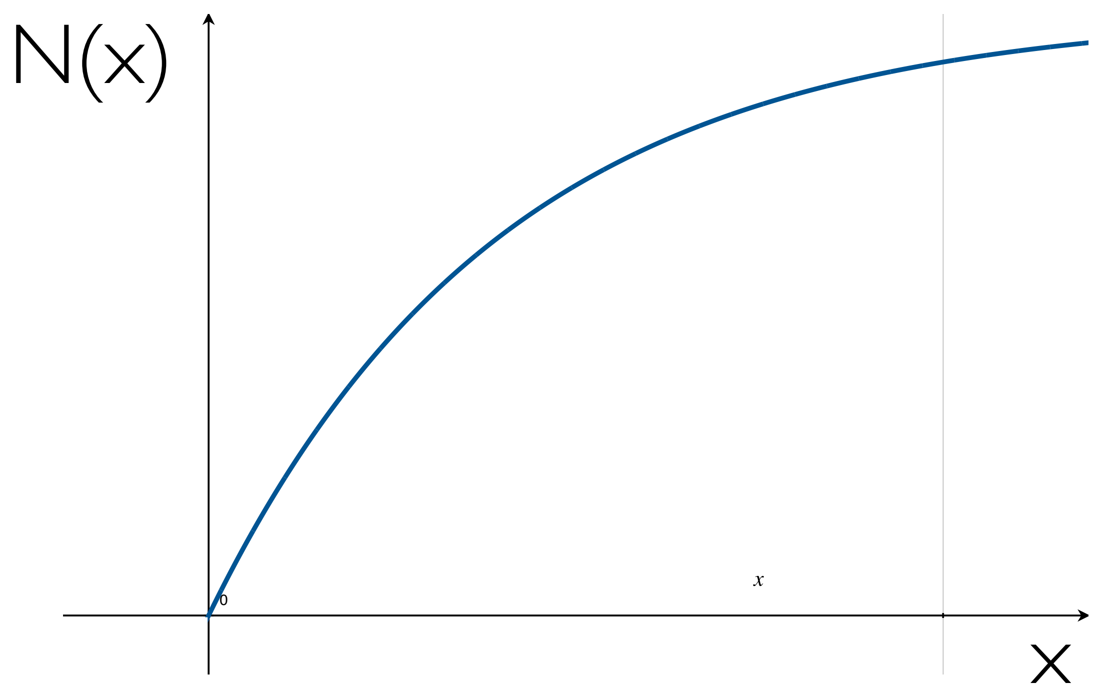
$N(x) = N(0)e^{-\mu x}$

**Q:**

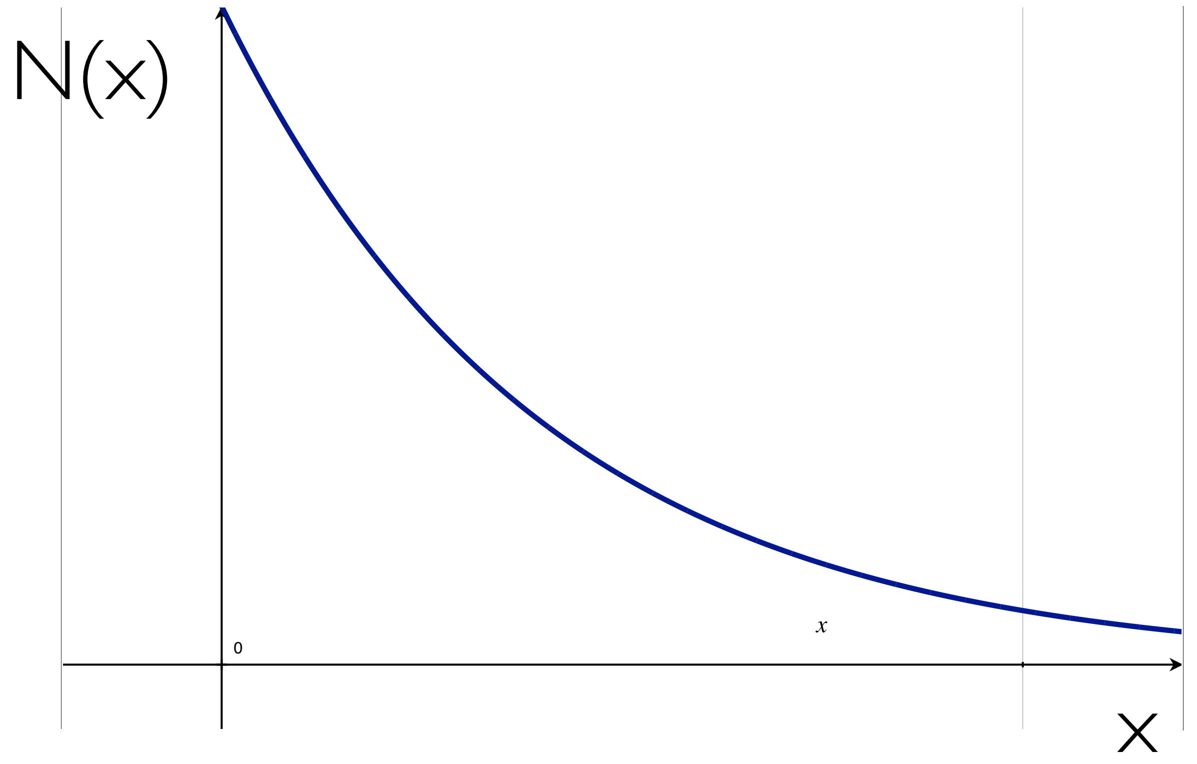
N(0)



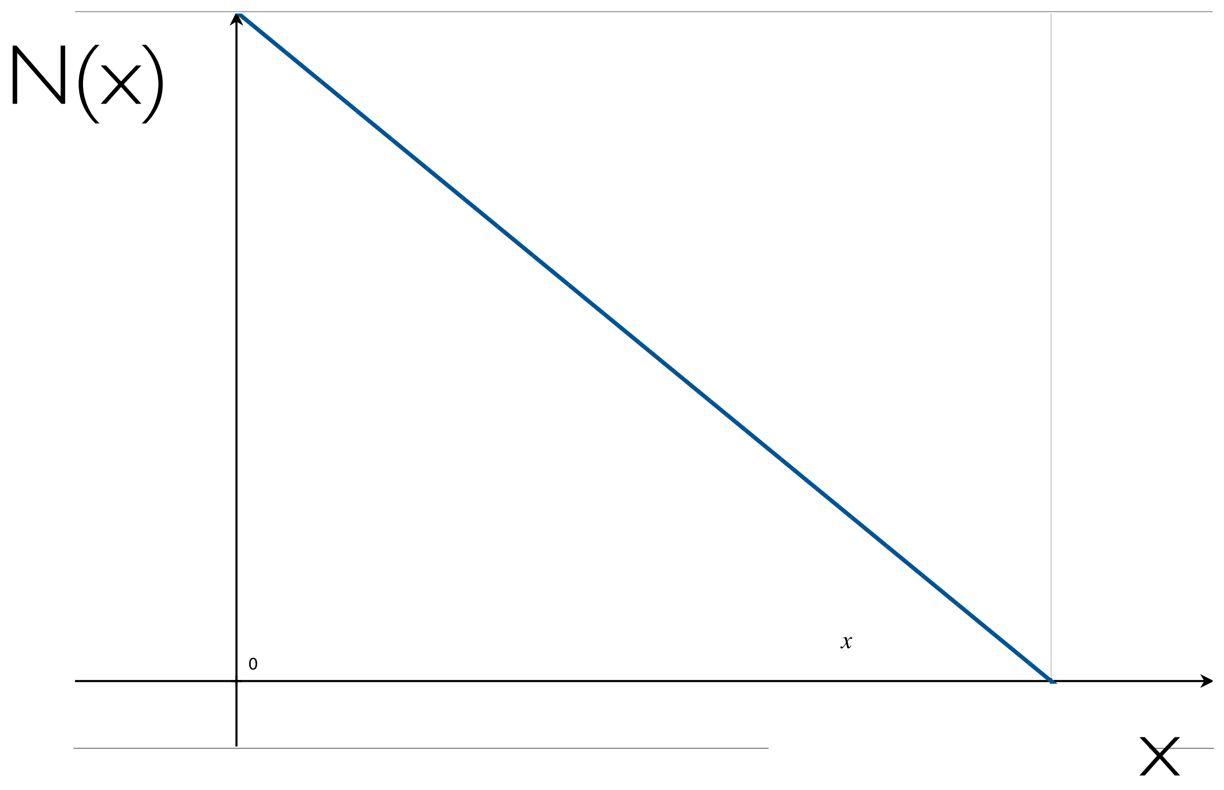

N(x) looks like:



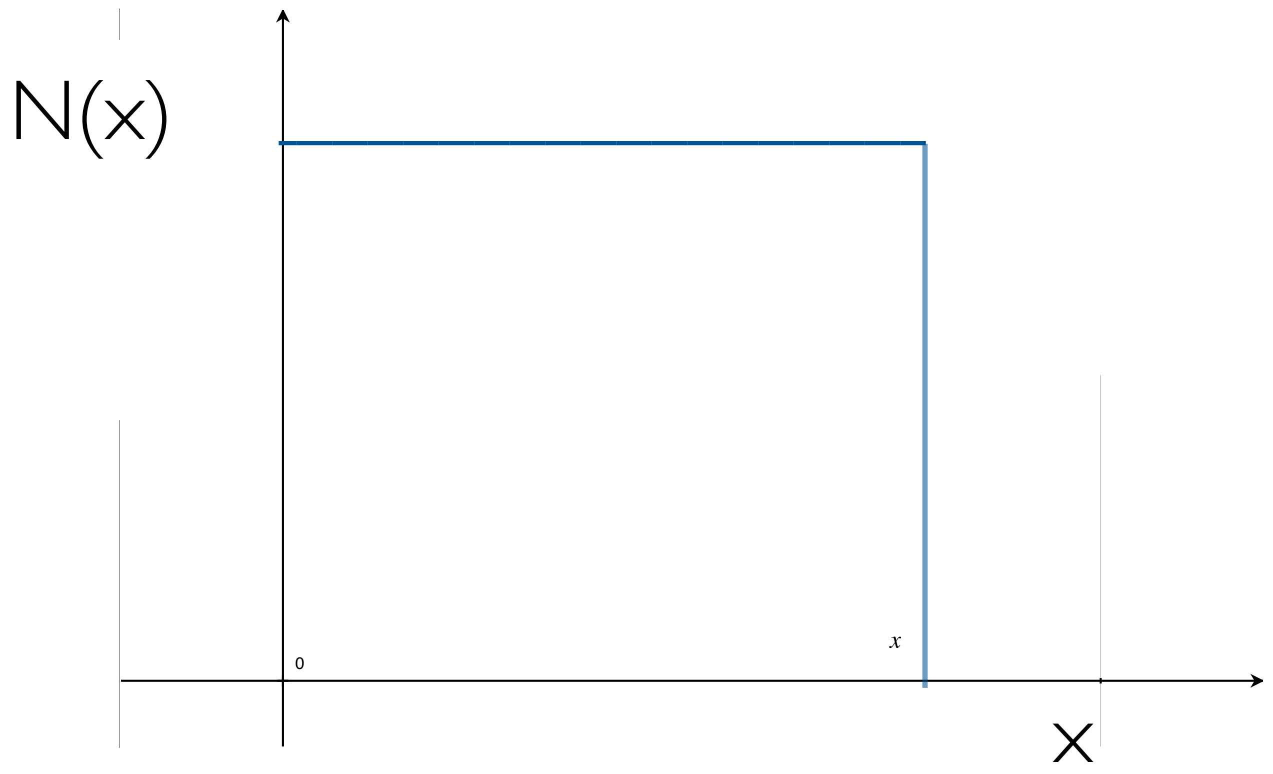

1




2

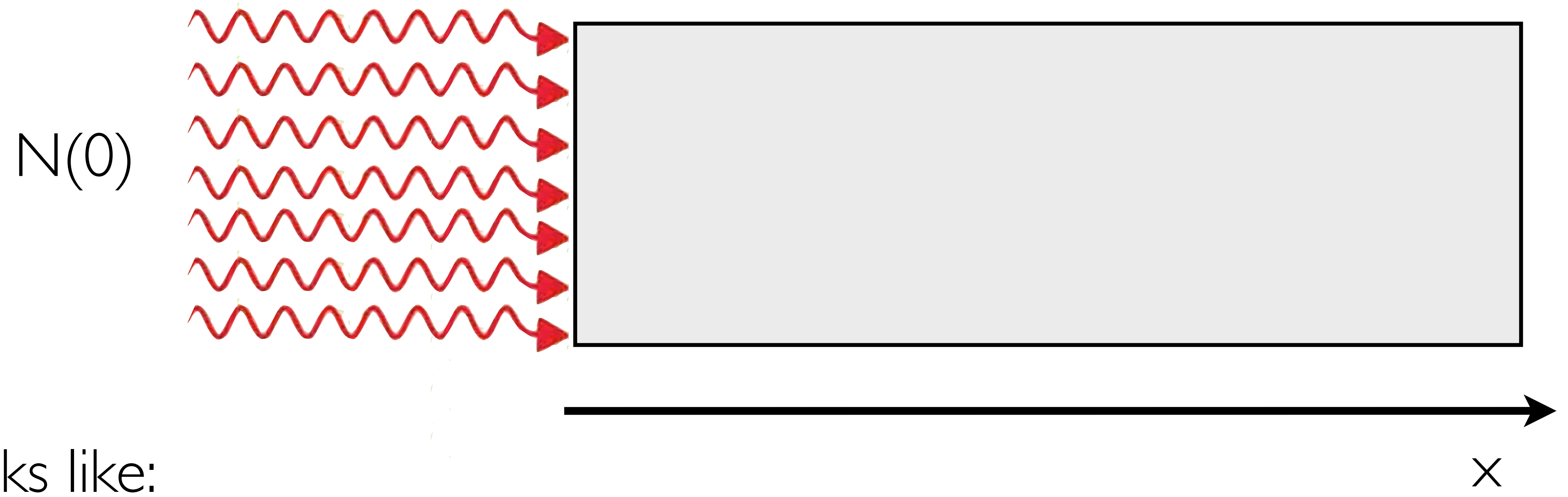



3




4

**Q:**

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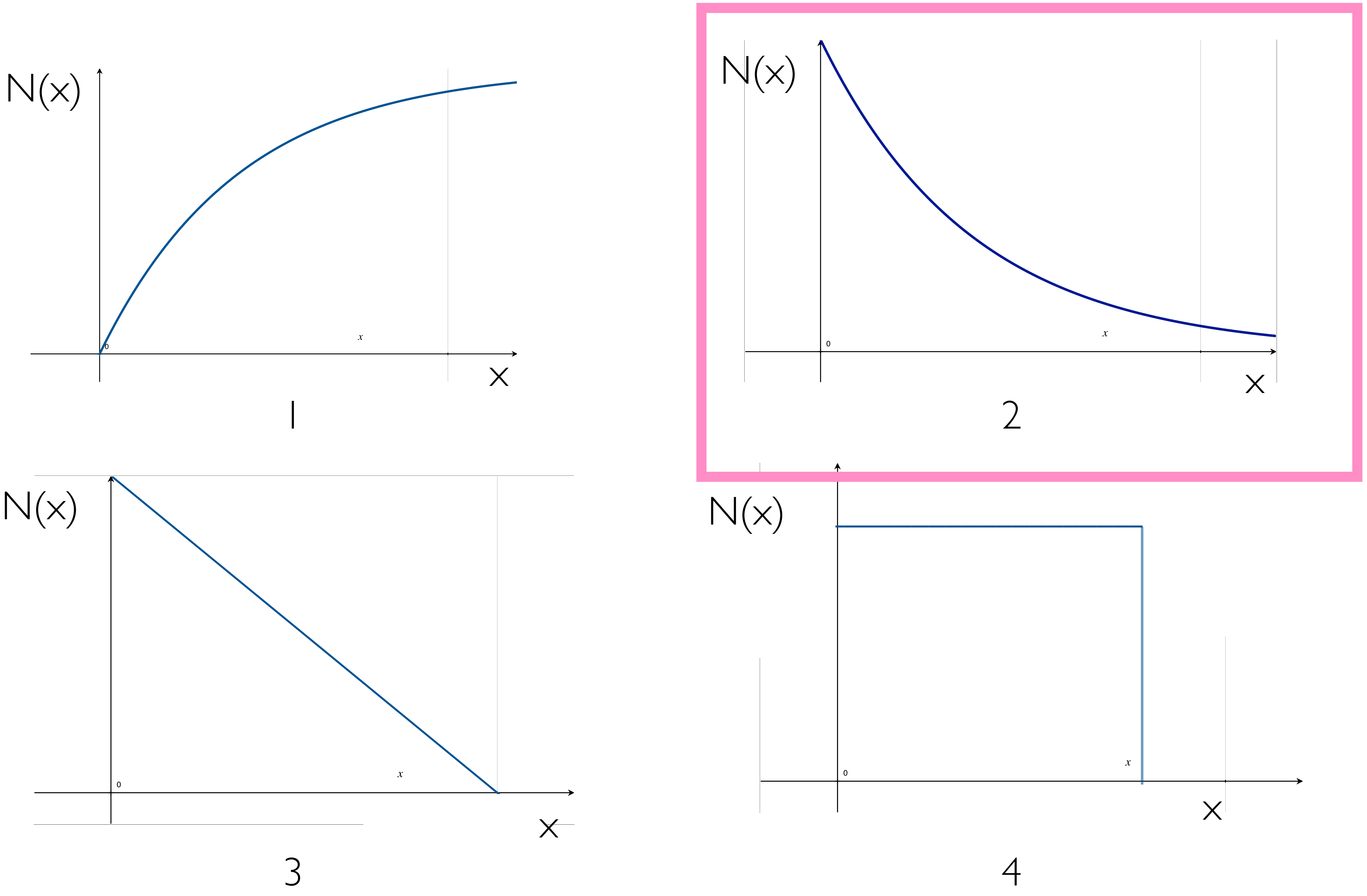

Q: How many photons are attenuated in a material with linear attenuation coefficient $\mu$ and thickness d, if $N_0$ photons impinge on it?

1. $N_0$
2. $N_0/2$
3. $N_0 e^{-\mu d}$
4. $N_0 - N_0 e^{-\mu d}$
5. $N_0 e^{-2\mu d}$
6. not sufficient data

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# Definitions ahead

The fraction of incoming photons of energy E, going through a target of thickness t and linear attenuation coefficient μ, without interaction (or, equivalently the fraction of primary photons through a target):

$$\frac{N}{N_0} = e^{-\mu(E)t}$$

is called *attenuation factor*

**It's confusing, I know! But we're not here to change the world**

The fraction of attenuated photons by a target is instead:

$$\frac{N_0 - N}{N_0} = 1 - e^{-\mu(E)t}$$

understanding at
macroscopic level
(Physics)

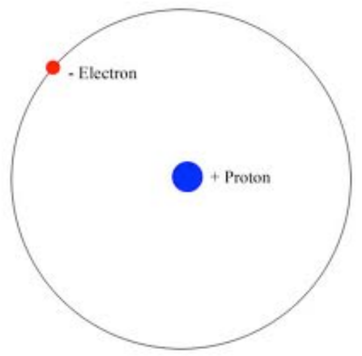
Compton scattering & Photoelectric effect are interactions between photons & electrons

⇩

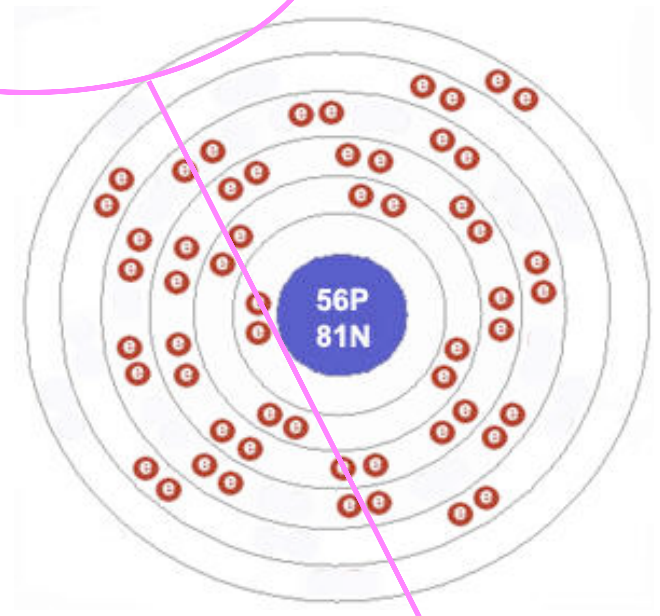
attenuation probability is proportional to electron density of the material

H

1 proton (Z = 1)
1 electron



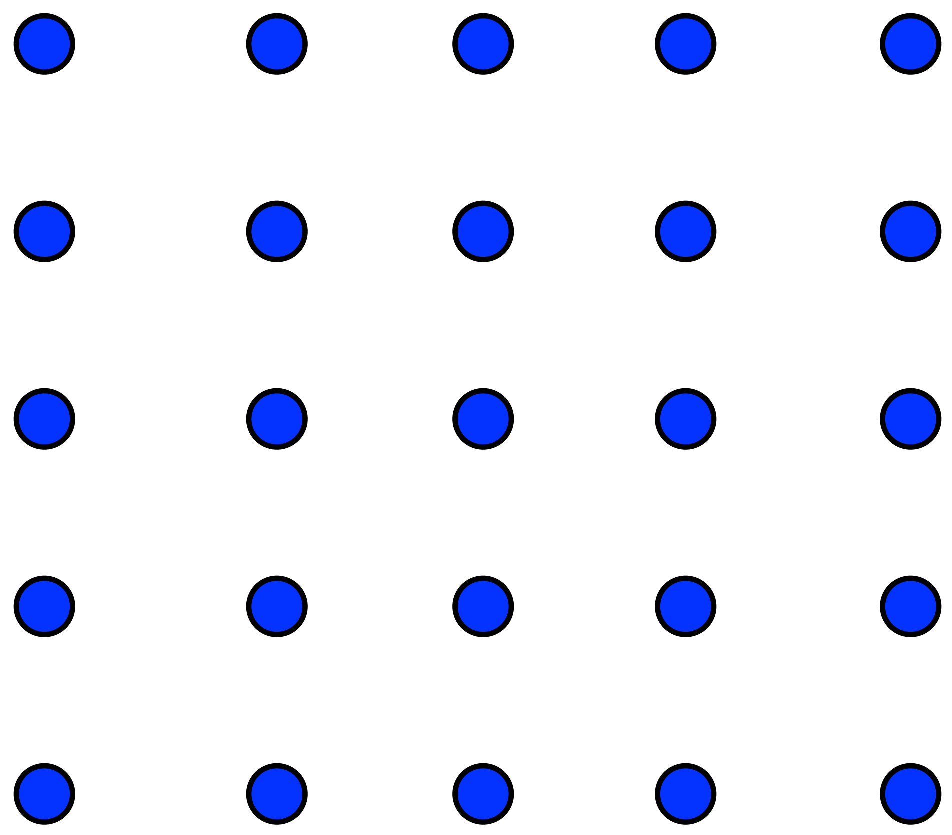

vs



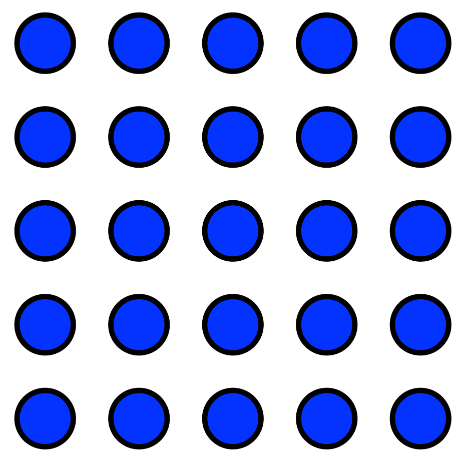

Ba

56 protons (Z = 56)
56 electrons
(81 neutrons)

low density



vs



high density

⇩

# attenuation probability is proportional to Z & ρ

# mass attenuation coefficient

linear attenuation coefficient, μ, depends on Z & ρ

⇩

same material in different phases or pressure will have different μ

⇩

more convenient to tabulate $\mu_\rho = \mu/\rho$

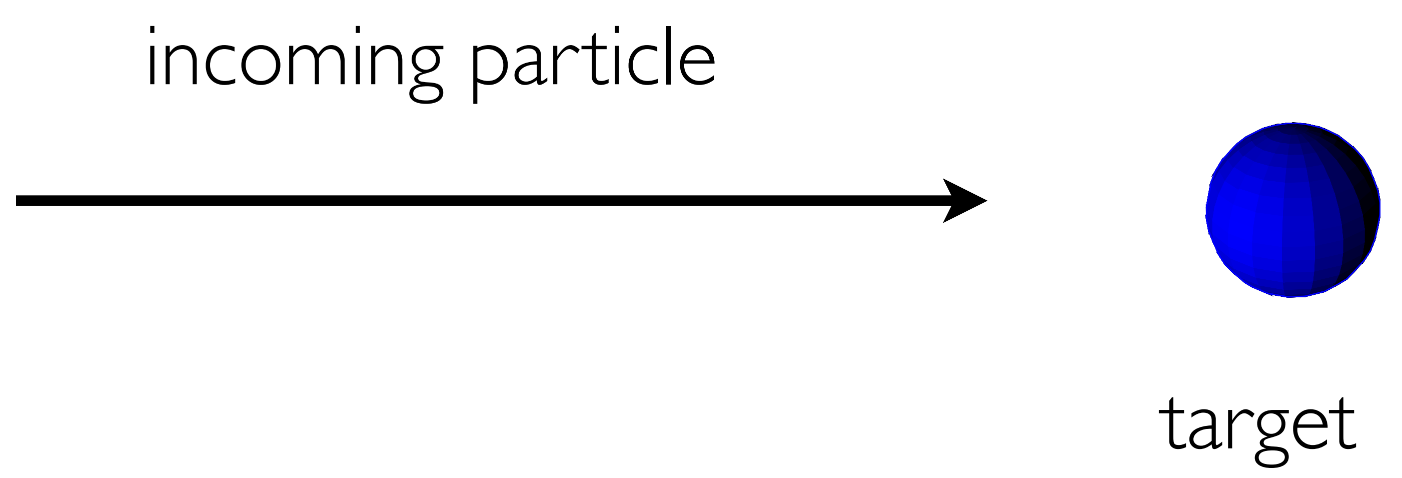
mass attenuation coefficient

http://www.nist.gov/pml/data/xraycoef/

(google: mass attenuation coefficient NIST)

# Physics:
# Let’s go microscopic!

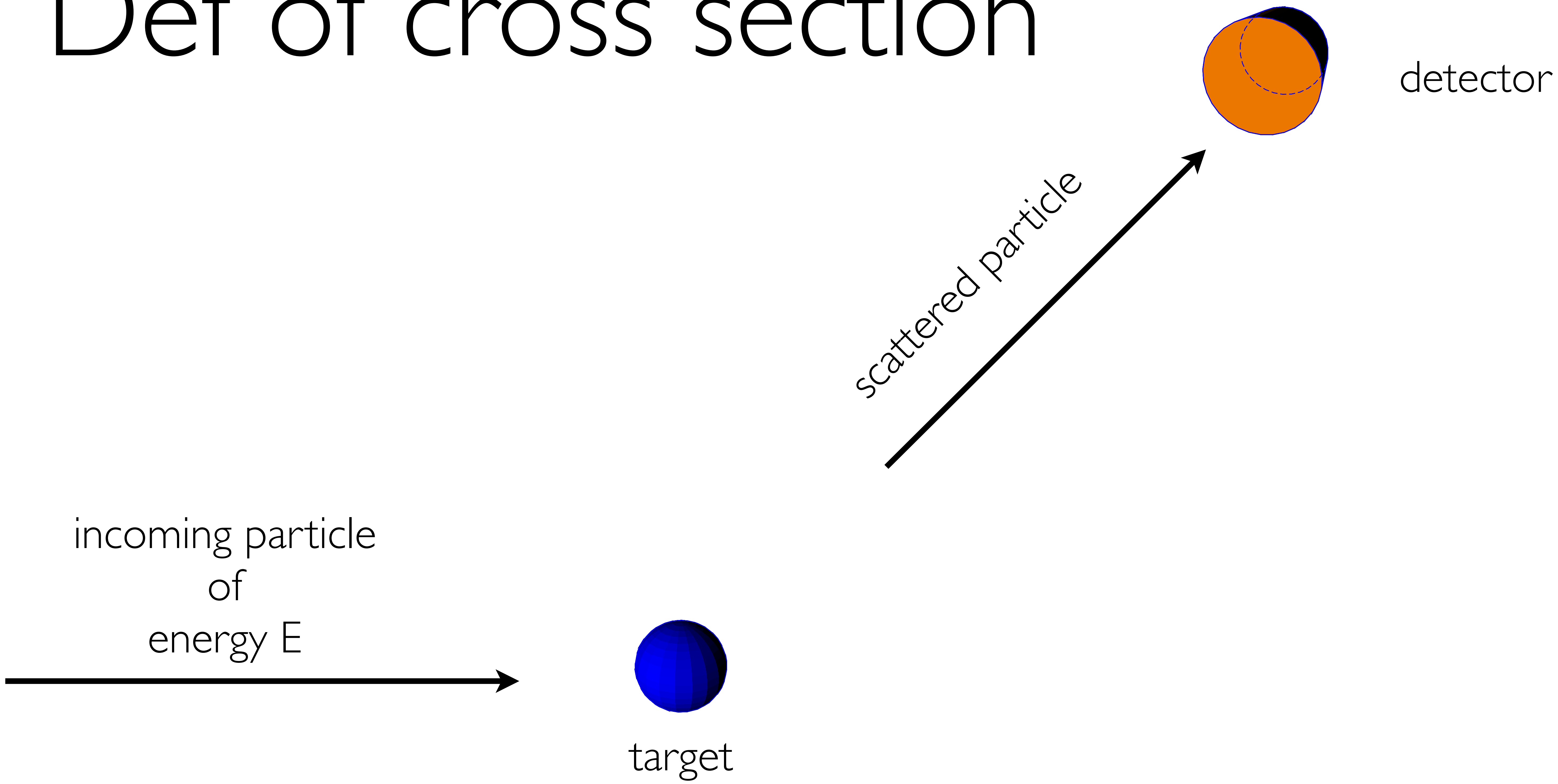
# cross section




Prob. of scattering particle?
(prob of interaction)

Prob. of scattering particle of energy E ?

# Def of cross section



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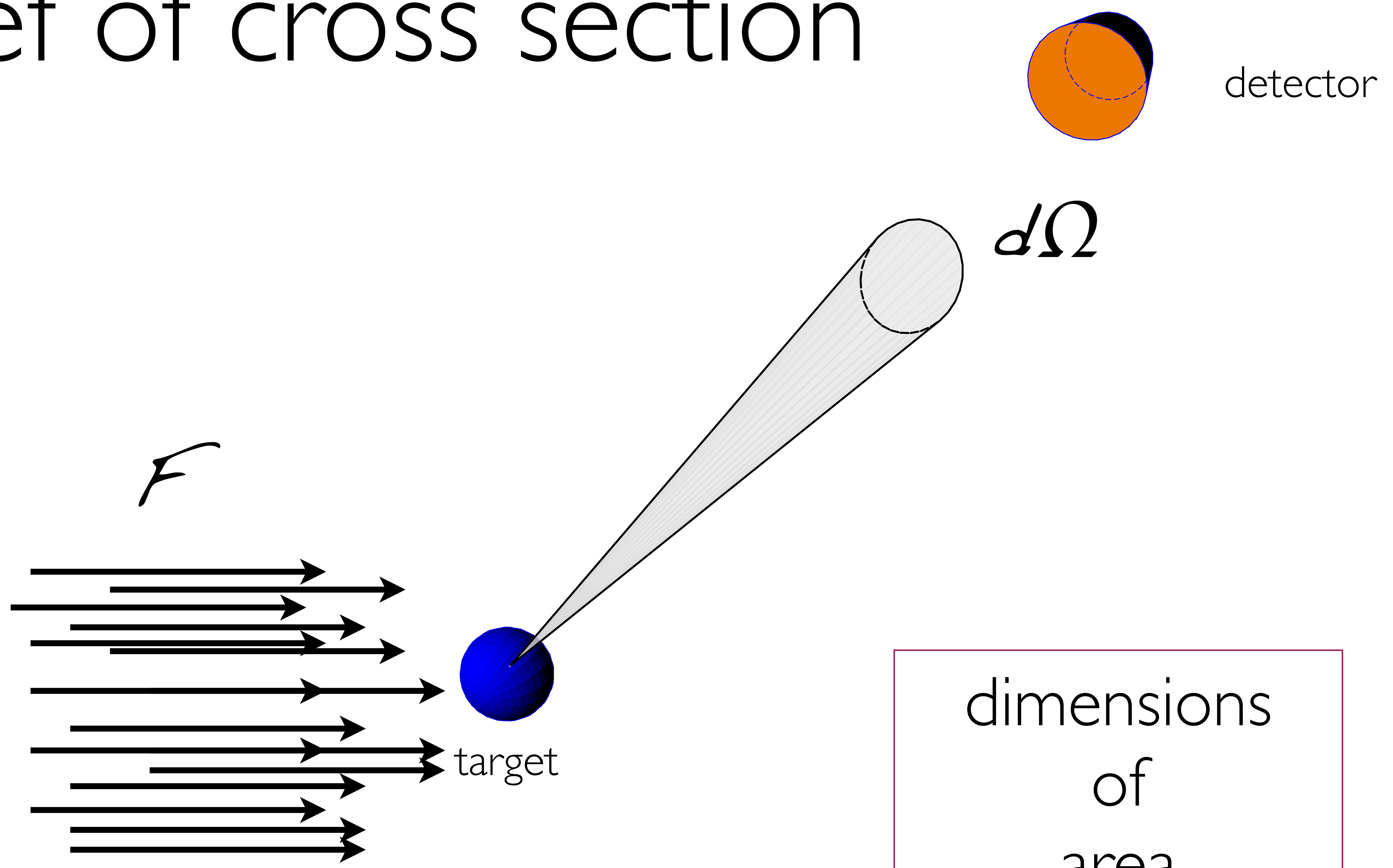


dimensions of area

Prob. of scattering particle of energy E to angle Ω:

$$\frac{d\sigma(E,\Omega)}{d\Omega} \stackrel{\text{Def}}{\equiv} \frac{1}{F}\frac{dN}{d\Omega}$$

Integrate over all angles (measure at all Ω)
=> prob. of scattering particle of energy E:

$$\sigma(E,\Omega)$$

# Mer om sambandet mellan σ, $\mu_\rho$ ,μ

1g av materia av isotopen ${}^{A}_{Z}\mathrm{X}$ innehåller $\frac{N_{\mathrm{Avogadro}}}{A}$ atomer (till exempel ${}^{26}_{13}\mathrm{Al}$, ${}^{19}_{13}\mathrm{Al}$)

och därför $\frac{N_{\mathrm{Avogadro}}}{A}Z$ elektroner

# Note on mass and linear attenuation coefficient

$$\sigma = \text{ area / electron} \qquad [L^2]$$

$$N_A \frac{m}{m_{molar} V} \qquad Z\sigma = \text{ area / atom} \qquad [L^2]$$

$$N_A \frac{\rho}{m_{molar}} Z\sigma = \text{ area / volume} \qquad [L^{-1}]$$

# Note on mass and linear attenuation coefficient

$$\sigma = \text{ area / electron} \qquad [L^2]$$

$$Z\sigma = \text{ area / atom} \qquad [L^2]$$

linear attenuation coefficient $\mu$

$$\boxed{N_A \frac{\rho}{m_{molar}} Z\sigma} = \text{ area / volume} \qquad [L^{-1}]$$

mass attenuation coefficient $\mu_\rho$

$$\boxed{N_A \frac{1}{m_{molar}} Z\sigma} = \text{ area / mass} \qquad [\frac{L^2}{M}]$$

**Tabulated!**
**Google: NIST mass attenuation coefficient**
**(till government shutdown är last titta på pdf I CANVAS)**

Let’s see if we understand how to use this for clinical applications!

Q: In order to better image veins a water solution of Ba is injected to patients before an x-ray examination. What is the reason for this?

1. Ba has high Z, this will result in a much higher x-ray absorption than in surrounding tissue
2. Ba in standard condition has around 3,5 times the density of blood => the higher density will produce much higher absorption
3. both 1 and 2

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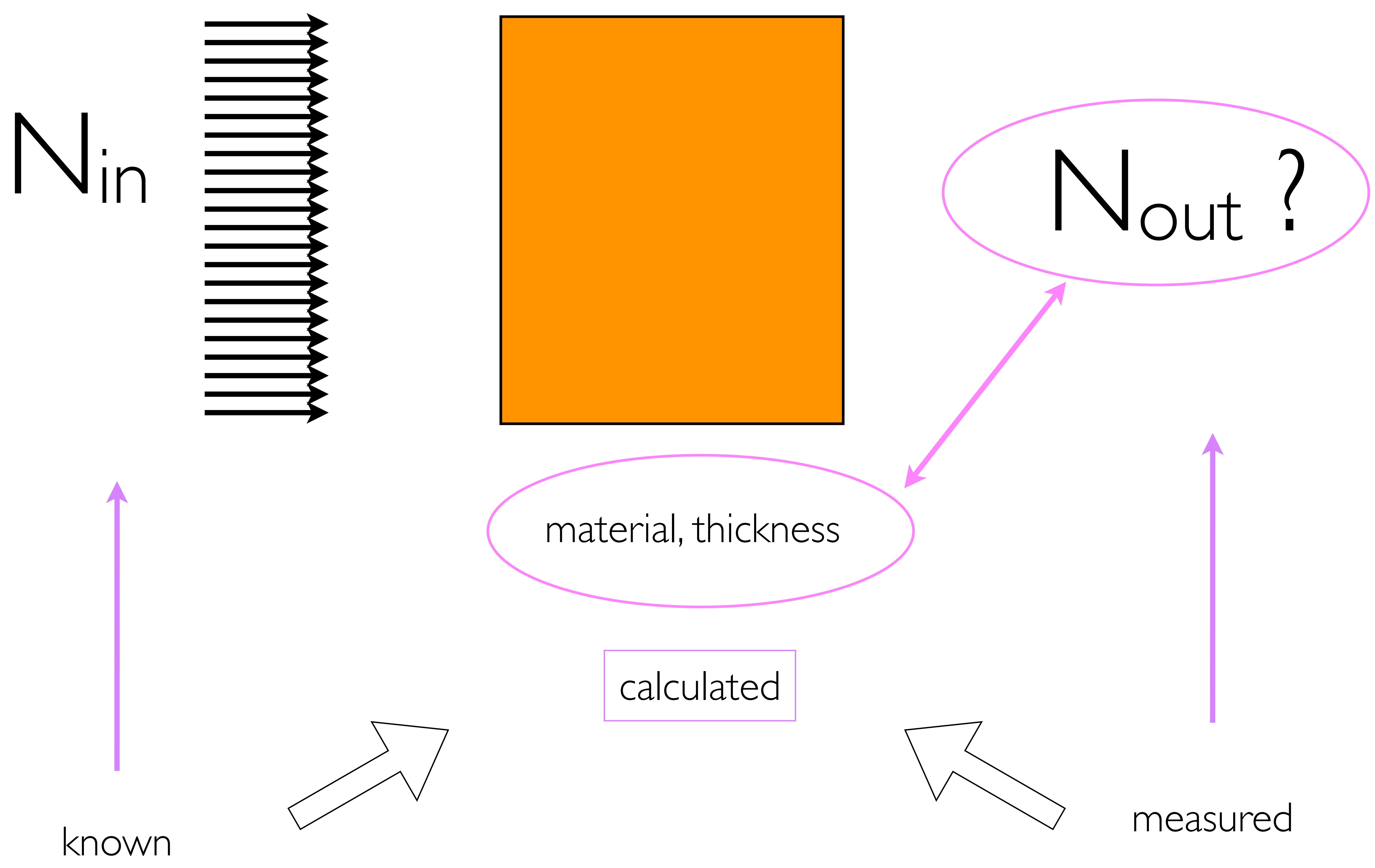
Physics:
back to a macroscopic

# Transmission basic idea

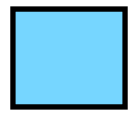
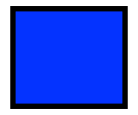


# toy model

# toy model

# toy model


in order to hope to get an image:

1.  and  must attenuate x-ray differently
2. D must translate x-rays in something visible or measurable
3. a lot of other things you'll know by the end of this week

# toy model


object contrast defined as: $$\frac{Nb - Na}{Nb}$$

# toy model


object contrast defined as: $$\frac{Nb - Na}{Nb}$$

# toy model


object contrast depends on:

1. energy of incoming photons
2. thickness of b
3. thickness of a
4. difference in linear attenuation coefficient between a and b

recall: $\mu \equiv N_A \frac{\rho}{m_{\text{molar}}} Z\sigma(E)$

# toy model


object contrast depends on:

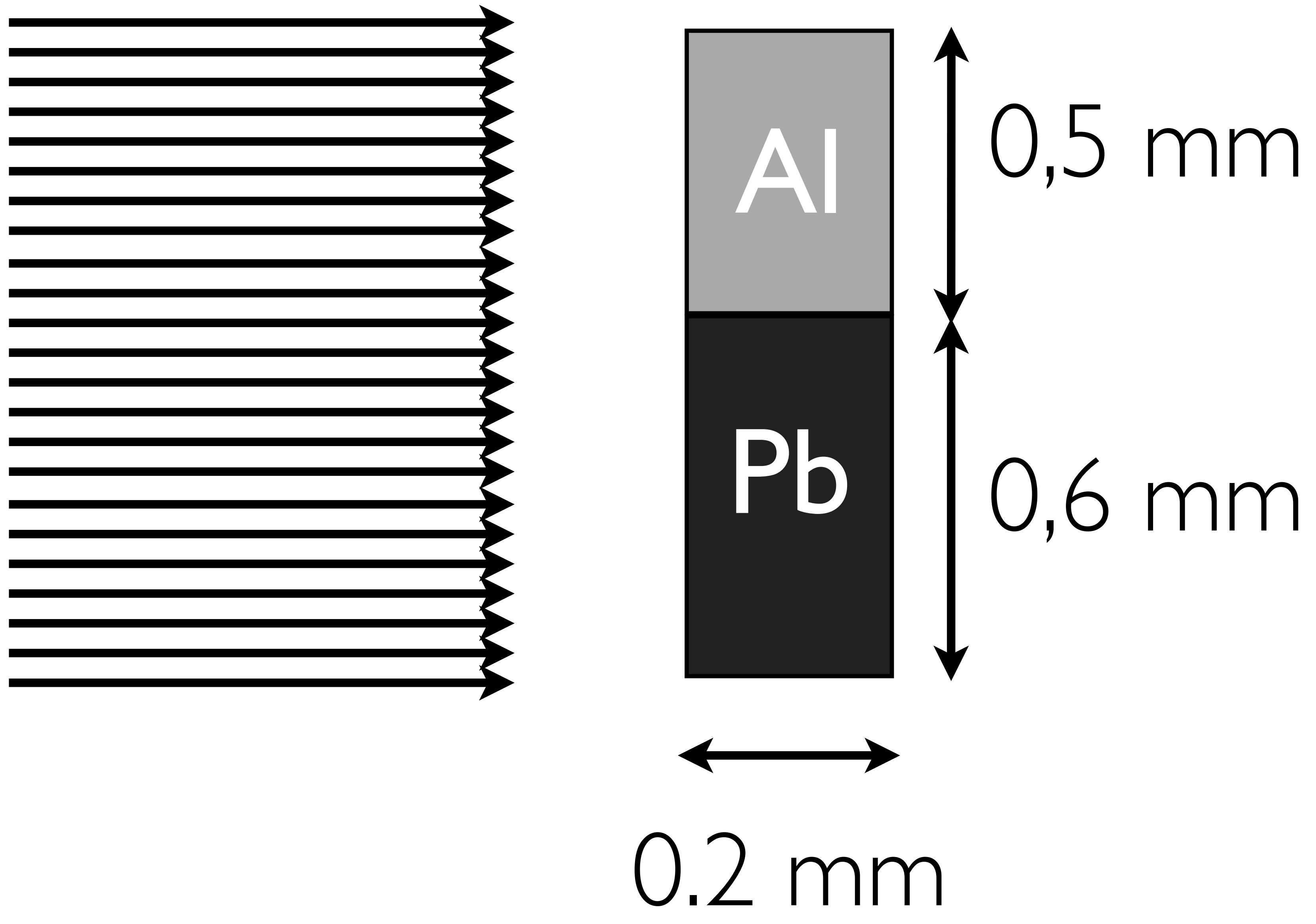
1. energy of incoming photons
2. ~~thickness of b~~
3. thickness of a
4. difference in linear attenuation coefficient between a and b

recall: $\mu \equiv N_A \frac{\rho}{m_{\mathrm{molar}}} Z\sigma(E)$

# object contrast:

# object contrast: numerisk uppgift

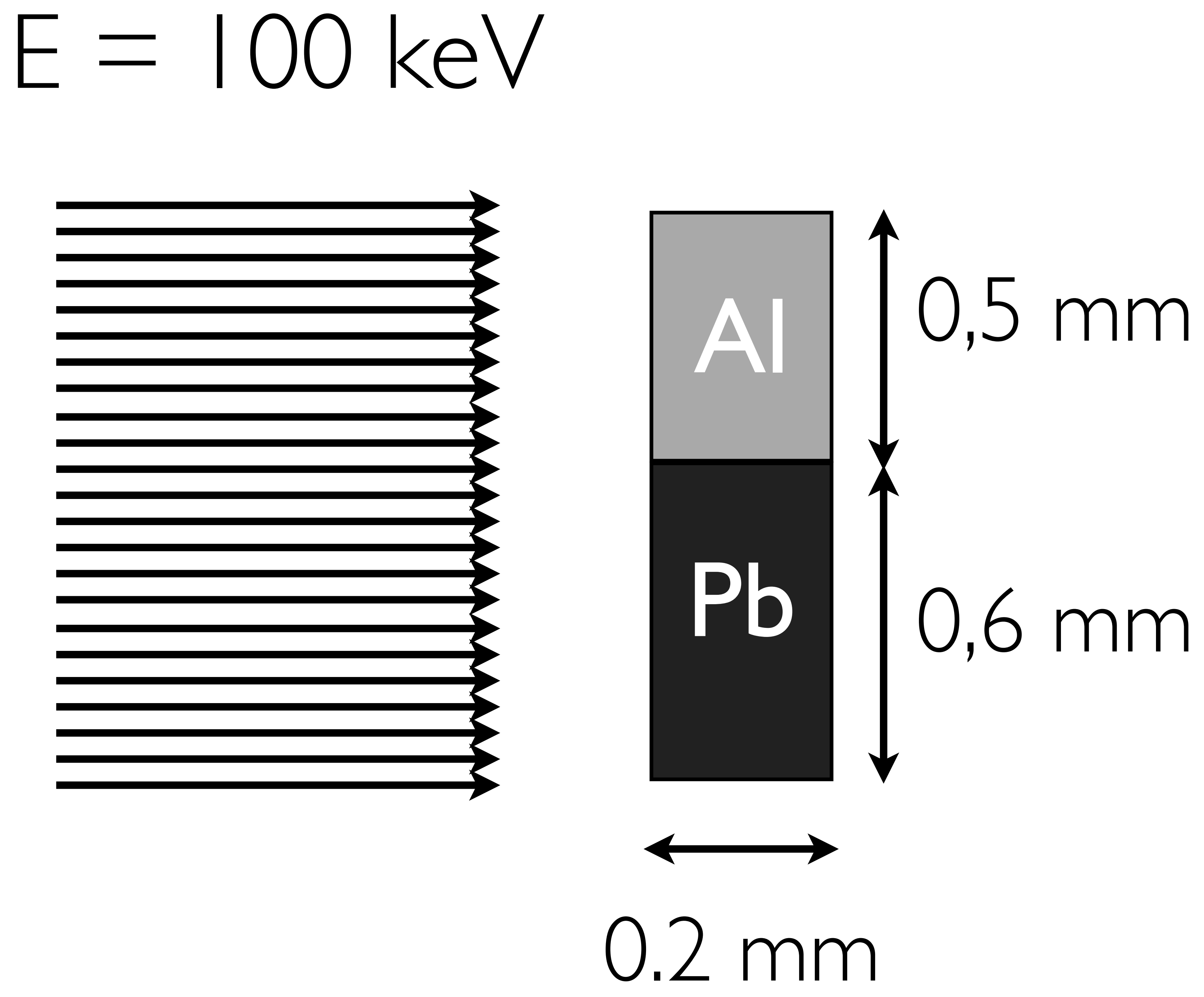
E = 100 keV




Contrast?

$$= \frac{N_0 e^{-\mu_{Al}(100\ \mathrm{keV}) t_{Al}} - N_0 e^{-\mu_{Pb}(100\ \mathrm{keV}) t_{Pb}}}{N_0 e^{-\mu_{Al}(100\ \mathrm{keV}) t_{Al}}} = 1 - e^{-(\mu_{Pb}(100\ \mathrm{keV}) - \mu_{Al}(100\ \mathrm{keV})) t_{Al}}$$

# object contrast: numerisk uppgift




Contrast?

$$\text{Object contrast} = \frac{\text{N through Al} - \text{N through Pb}}{\text{N through Al}} = \frac{N_0 e^{-\mu_{Al}(100\ \text{keV}) t_{Al}} - N_0 e^{-\mu_{Pb}(100\ \text{keV}) t_{Pb}}}{N_0 e^{-\mu_{Al}(100\ \text{keV}) t_{Al}}} = 1 - e^{-(\mu_{Pb}(100\ \text{keV}) - \mu_{Al}(100\ \text{keV})) t_{Al}}$$

tables given by Hubbell in the International Journal of Applied Radiation and Isotopes **33,** 1269 (1982).

Note on NIST X-ray Attenuation Databases

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*Work supported by the Standard Reference Data Program of NIST.
+Work carried out for NIST under contract 43NANB412756.


**U.S. DEPARTMENT OF COMMERCE** - Mickey Kantor, *Secretary*
**Technology Administration** - Mary L. Good, *Under Secretary for Technology*
**National Institute of Standards and Technology** - Arati Prabhakar, *Director*

Elemental Media

or

Compounds & Mixtures


NIST Standard Reference Database 126
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**Online:** May 1996 - **Last update:** July 2004


## Contact


Stephen Seltzer
Radiation and Biomolecular Physics Division
phone: 301-975-5552
fax: 301-869-7682

100 Bureau Drive, M/S 8460
Gaithersburg, MD 20899-8460

edges are indicated by the shell designation.

| Z | Element | | Z | Element | | Z | Element | | Z | Element | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | H | Hydrogen | 24 | Cr | Chromium | 47 | Ag | Silver | 70 | Yb | Ytterbium |
| 2 | He | Helium | 25 | Mn | Manganese | 48 | Cd | Cadmium | 71 | Lu | Lutetium |
| 3 | Li | Lithium | 26 | Fe | Iron | 49 | In | Indium | 72 | Hf | Hafnium |
| 4 | Be | Beryllium | 27 | Co | Cobalt | 50 | Sn | Tin | 73 | Ta | Tantalum |
| 5 | B | Boron | 28 | Ni | Nickel | 51 | Sb | Antimony | 74 | W | Tungsten |
| 6 | C | Carbon, Graphite | 29 | Cu | Copper | 52 | Te | Tellurium | 75 | Re | Rhenium |
| 7 | N | Nitrogen | 30 | Zn | Zinc | 53 | I | Iodine | 76 | Os | Osmium |
| 8 | O | Oxygen | 31 | Ga | Gallium | 54 | Xe | Xenon | 77 | Ir | Iridium |
| 9 | F | Fluorine | 32 | Ge | Germanium | 55 | Cs | Cesium | 78 | Pt | Platinum |
| 10 | Ne | Neon | 33 | As | Arsenic | 56 | Ba | Barium | 79 | Au | Gold |
| 11 | Na | Sodium | 34 | Se | Selenium | 57 | La | Lanthanum | 80 | Hg | Mercury |
| 12 | Mg | Magnesium | 35 | Br | Bromine | 58 | Ce | Cerium | 81 | Tl | Thallium |
| 13 | Al | Aluminum | 36 | Kr | Krypton | 59 | Pr | Praseodymium | 82 | Pb | Lead |
| 14 | Si | Silicon | 37 | Rb | Rubidium | 60 | Nd | Neodymium | 83 | Bi | Bismuth |
| 15 | P | Phosphorus | 38 | Sr | Strontium | 61 | Pm | Promethium | 84 | Po | Polonium |
| 16 | S | Sulfur | 39 | Y | Yttrium | 62 | Sm | Samarium | 85 | At | Astatine |
| 17 | Cl | Chlorine | 40 | Zr | Zirconium | 63 | Eu | Europium | 86 | Rn | Radon |
| 18 | Ar | Argon | 41 | Nb | Niobium | 64 | Gd | Gadolinium | 87 | Fr | Francium |
| 19 | K | Potassium | 42 | Mo | Molybdenum | 65 | Tb | Terbium | 88 | Ra | Radium |
| 20 | Ca | Calcium | 43 | Tc | Technetium | 66 | Dy | Dysprosium | 89 | Ac | Actinium |
| 21 | Sc | Scandium | 44 | Ru | Ruthenium | 67 | Ho | Holmium | 90 | Th | Thorium |
| 22 | Ti | Titanium | 45 | Rh | Rhodium | 68 | Er | Erbium | 91 | Pa | Protactinium |
| 23 | V | Vanadium | 46 | Pd | Palladium | 69 | Tm | Thulium | 92 | U | Uranium |

# Al

| | Energy (MeV) | $\mu/\rho$ ($cm^2/g$) | $\mu_{en}/\rho$ ($cm^2/g$) |
|---|---|---|---|
| | 1.00000E-03 | 1.185E+03 | 1.183E+03 |
| | 1.50000E-03 | 4.022E+02 | 4.001E+02 |
| | 1.55960E-03 | 3.621E+02 | 3.600E+02 |
| K | 1.55960E-03 | 3.957E+03 | 3.829E+03 |
| | 2.00000E-03 | 2.263E+03 | 2.204E+03 |
| | 3.00000E-03 | 7.880E+02 | 7.732E+02 |
| | 4.00000E-03 | 3.605E+02 | 3.545E+02 |
| | 5.00000E-03 | 1.934E+02 | 1.902E+02 |
| | 6.00000E-03 | 1.153E+02 | 1.133E+02 |
| | 8.00000E-03 | 5.033E+01 | 4.918E+01 |
| | 1.00000E-02 | 2.623E+01 | 2.543E+01 |
| | 1.50000E-02 | 7.955E+00 | 7.487E+00 |
| | 2.00000E-02 | 3.441E+00 | 3.094E+00 |
| | 3.00000E-02 | 1.128E+00 | 8.778E-01 |
| | 4.00000E-02 | 5.685E-01 | 3.601E-01 |
| | 5.00000E-02 | 3.681E-01 | 1.840E-01 |
| | 6.00000E-02 | 2.778E-01 | 1.099E-01 |
| | 8.00000E-02 | 2.018E-01 | 5.511E-02 |
| | 1.00000E-01 | 1.704E-01 | 3.794E-02 |
| | 1.50000E-01 | 1.378E-01 | 2.827E-02 |
| | 2.00000E-01 | 1.223E-01 | 2.745E-02 |
| | 3.00000E-01 | 1.042E-01 | 2.816E-02 |
| | 4.00000E-01 | 9.276E-02 | 2.862E-02 |
| | 5.00000E-01 | 8.445E-02 | 2.868E-02 |
| | 6.00000E-01 | 7.802E-02 | 2.851E-02 |
| | 8.00000E-01 | 6.841E-02 | 2.778E-02 |
| | 1.00000E+00 | 6.146E-02 | 2.686E-02 |
| | 1.25000E+00 | 5.496E-02 | 2.565E-02 |
| | 1.50000E+00 | 5.006E-02 | 2.451E-02 |

| | Energy (MeV) | $\mu/\rho$ ($cm^2/g$) | $\mu_{en}/\rho$ ($cm^2/g$) |
|---|---|---|---|
| | 1.00000E-03 | 1.185E+03 | 1.183E+03 |
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| | 2.00000E-03 | 2.263E+03 | 2.204E+03 |
| | 3.00000E-03 | 7.880E+02 | 7.732E+02 |
| | 4.00000E-03 | 3.605E+02 | 3.545E+02 |
| | 5.00000E-03 | 1.934E+02 | 1.902E+02 |
| | 6.00000E-03 | 1.153E+02 | 1.133E+02 |
| | 8.00000E-03 | 5.033E+01 | 4.918E+01 |
| | 1.00000E-02 | 2.623E+01 | 2.543E+01 |
| | 1.50000E-02 | 7.955E+00 | 7.487E+00 |
| | 2.00000E-02 | 3.441E+00 | 3.094E+00 |
| | 3.00000E-02 | 1.128E+00 | 8.778E-01 |
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| | 1.25000E+00 | 5.496E-02 | 2.565E-02 |
| | 1.50000E+00 | 5.006E-02 | 2.451E-02 |
| | 2.00000E+00 | 4.324E-02 | 2.266E-02 |
| | 3.00000E+00 | 3.541E-02 | 2.024E-02 |
| | 4.00000E+00 | 3.106E-02 | 1.882E-02 |
| | 5.00000E+00 | 2.836E-02 | 1.795E-02 |
| | 6.00000E+00 | 2.655E-02 | 1.739E-02 |
| | 8.00000E+00 | 2.437E-02 | 1.678E-02 |
| | 1.00000E+01 | 2.318E-02 | 1.650E-02 |
| | 1.50000E+01 | 2.195E-02 | 1.631E-02 |
| | 2.00000E+01 | 2.168E-02 | 1.633E-02 |

# Al

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| | 1.55960E-03 | 3.621E+02 | 3.600E+02 |
| K | 1.55960E-03 | 3.957E+03 | 3.829E+03 |
| | 2.00000E-03 | 2.263E+03 | 2.204E+03 |
| | 3.00000E-03 | 7.880E+02 | 7.732E+02 |
| | 4.00000E-03 | 3.605E+02 | 3.545E+02 |
| | 5.00000E-03 | 1.934E+02 | 1.902E+02 |
| | 6.00000E-03 | 1.153E+02 | 1.133E+02 |
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| | 1.00000E-02 | 2.623E+01 | 2.543E+01 |
| | 1.50000E-02 | 7.955E+00 | 7.487E+00 |
| | 2.00000E-02 | 3.441E+00 | 3.094E+00 |
| | 3.00000E-02 | 1.128E+00 | 8.778E-01 |
| | 4.00000E-02 | 5.685E-01 | 3.601E-01 |
| | 5.00000E-02 | 3.681E-01 | 1.840E-01 |
| | 6.00000E-02 | 2.778E-01 | 1.099E-01 |
| | 8.00000E-02 | 2.018E-01 | 5.511E-02 |
| 100 keV | 1.00000E-01 | 1.704E-01 | 3.794E-02 |
| | 1.50000E-01 | 1.378E-01 | 2.827E-02 |
| | 2.00000E-01 | 1.223E-01 | 2.745E-02 |
| | 3.00000E-01 | 1.042E-01 | 2.816E-02 |
| | 4.00000E-01 | 9.276E-02 | 2.862E-02 |
| | 5.00000E-01 | 8.445E-02 | 2.868E-02 |
| | 6.00000E-01 | 7.802E-02 | 2.851E-02 |
| | 8.00000E-01 | 6.841E-02 | 2.778E-02 |
| | 1.00000E+00 | 6.146E-02 | 2.686E-02 |
| | 1.25000E+00 | 5.496E-02 | 2.565E-02 |
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| | 1.50000E-03 | 4.022E+02 | 4.001E+02 |
| | 1.55960E-03 | 3.621E+02 | 3.600E+02 |
| K | 1.55960E-03 | 3.957E+03 | 3.829E+03 |
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| | 3.00000E-03 | 7.880E+02 | 7.732E+02 |
| | 4.00000E-03 | 3.605E+02 | 3.545E+02 |
| | 5.00000E-03 | 1.934E+02 | 1.902E+02 |
| | 6.00000E-03 | 1.153E+02 | 1.133E+02 |
| | 8.00000E-03 | 5.033E+01 | 4.918E+01 |
| | 1.00000E-02 | 2.623E+01 | 2.543E+01 |
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| | 6.00000E-01 | 7.802E-02 | 2.851E-02 |
| | 8.00000E-01 | 6.841E-02 | 2.778E-02 |
| | 1.00000E+00 | 6.146E-02 | 2.686E-02 |
| | 1.25000E+00 | 5.496E-02 | 2.565E-02 |
| | 1.50000E+00 | 5.006E-02 | 2.451E-02 |
| | 2.00000E+00 | 4.324E-02 | 2.266E-02 |
| | 3.00000E+00 | 3.541E-02 | 2.024E-02 |
| | 4.00000E+00 | 3.106E-02 | 1.882E-02 |
| | 5.00000E+00 | 2.836E-02 | 1.795E-02 |
| | 6.00000E+00 | 2.655E-02 | 1.739E-02 |
| | 8.00000E+00 | 2.437E-02 | 1.678E-02 |
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tables given by Hubbell in the International Journal of Applied Radiation and Isotopes **33**, 1269 (1982).

**Note on NIST X-ray Attenuation Databases**

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**U.S. DEPARTMENT OF COMMERCE** - Mickey Kantor, *Secretary*
**Technology Administration** - Mary L. Good, *Under Secretary for Technology*
**National Institute of Standards and Technology** - Arati Prabhakar, *Director*

Elemental Media

or

Compounds & Mixtures


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## Contact


Stephen Seltzer
Radiation and Biomolecular Physics Division
phone: 301-975-5552
fax: 301-869-7682

100 Bureau Drive, M/S 8460
Gaithersburg, MD 20899-8460

| Z | | Element | Z/A | I (eV) | Density ($g/cm^3$) |
|---|---|---|---|---|---|
| 1 | H | Hydrogen | 0.99212 | 19.2 | 8.375E-05 |
| 2 | He | Helium | 0.49968 | 41.8 | 1.663E-04 |
| 3 | Li | Lithium | 0.43221 | 40.0 | 5.340E-01 |
| 4 | Be | Beryllium | 0.44384 | 63.7 | 1.848E+00 |
| 5 | B | Boron | 0.46245 | 76.0 | 2.370E+00 |
| 6 | C | Carbon, Graphite | 0.49954 | 78.0 | 1.700E+00 |
| 7 | N | Nitrogen | 0.49976 | 82.0 | 1.165E-03 |
| 8 | O | Oxygen | 0.50002 | 95.0 | 1.332E-03 |
| 9 | F | Fluorine | 0.47372 | 115.0 | 1.580E-03 |
| 10 | Ne | Neon | 0.49555 | 137.0 | 8.385E-04 |
| 11 | Na | Sodium | 0.47847 | 149.0 | 9.710E-01 |
| 12 | Mg | Magnesium | 0.49373 | 156.0 | 1.740E+00 |
| 13 | Al | Aluminum | 0.48181 | 166.0 | 2.699E+00 |
| 14 | Si | Silicon | 0.49848 | 173.0 | 2.330E+00 |
| 15 | P | Phosphorus | 0.48428 | 173.0 | 2.200E+00 |
| 16 | S | Sulfur | 0.49897 | 180.0 | 2.000E+00 |
| 17 | Cl | Chlorine | 0.47951 | 174.0 | 2.995E-03 |
| 18 | Ar | Argon | 0.45059 | 188.0 | 1.662E-03 |
| 19 | K | Potassium | 0.48595 | 190.0 | 8.620E-01 |
| 20 | Ca | Calcium | 0.49903 | 191.0 | 1.550E+00 |

| Z | | Element | Z/A | I (eV) | Density (g/cm³) |
|---|---|---|---|---|---|
| 1 | H | Hydrogen | 0.99212 | 19.2 | 8.375E-05 |
| 2 | He | Helium | 0.49968 | 41.8 | 1.663E-04 |
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# Pb

HTML table format

| | Energy (MeV) | $\mu/\rho$ ($cm^2/g$) | $\mu_{en}/\rho$ ($cm^2/g$) |
|---|---|---|---|
| | 1.00000E-03 | 5.210E+03 | 5.197E+03 |
| | 1.50000E-03 | 2.356E+03 | 2.344E+03 |
| | 2.00000E-03 | 1.285E+03 | 1.274E+03 |
| | 2.48400E-03 | 8.006E+02 | 7.895E+02 |
| M5 | 2.48400E-03 | 1.397E+03 | 1.366E+03 |
| | 2.53429E-03 | 1.726E+03 | 1.682E+03 |
| | 2.58560E-03 | 1.944E+03 | 1.895E+03 |
| M4 | 2.58560E-03 | 2.458E+03 | 2.390E+03 |
| | 3.00000E-03 | 1.965E+03 | 1.913E+03 |
| | 3.06640E-03 | 1.857E+03 | 1.808E+03 |
| M3 | 3.06640E-03 | 2.146E+03 | 2.090E+03 |
| | 3.30130E-03 | 1.796E+03 | 1.748E+03 |
| | 3.55420E-03 | 1.496E+03 | 1.459E+03 |
| M2 | 3.55420E-03 | 1.585E+03 | 1.546E+03 |
| | 3.69948E-03 | 1.442E+03 | 1.405E+03 |
| | 3.85070E-03 | 1.311E+03 | 1.279E+03 |
| M1 | 3.85070E-03 | 1.368E+03 | 1.335E+03 |
| | 4.00000E-03 | 1.251E+03 | 1.221E+03 |
| | 5.00000E-03 | 7.304E+02 | 7.124E+02 |
| | 6.00000E-03 | 4.672E+02 | 4.546E+02 |
| | 8.00000E-03 | 2.287E+02 | 2.207E+02 |
| | 1.00000E-02 | 1.306E+02 | 1.247E+02 |
| | 1.30352E-02 | 6.701E+01 | 6.270E+01 |
| L3 | 1.30352E-02 | 1.621E+02 | 1.291E+02 |
| | 1.50000E-02 | 1.116E+02 | 9.100E+01 |
| | 1.52000E-02 | 1.078E+02 | 8.807E+01 |
| L2 | 1.52000E-02 | 1.485E+02 | 1.131E+02 |
| | 1.55269E-02 | 1.416E+02 | 1.083E+02 |
| | 1.58608E-02 | 1.344E+02 | 1.032E+02 |
| L1 | 1.58608E-02 | 1.548E+02 | 1.180E+02 |
| | 2.00000E-02 | 8.636E+01 | 6.899E+01 |
| | 3.00000E-02 | 3.032E+01 | 2.536E+01 |
| | 4.00000E-02 | 1.436E+01 | 1.211E+01 |
| | 5.00000E-02 | 8.041E+00 | 6.740E+00 |
| | 6.00000E-02 | 5.021E+00 | 4.149E+00 |
| | 8.00000E-02 | 2.419E+00 | 1.916E+00 |
| | 8.80045E-02 | 1.910E+00 | 1.482E+00 |
| K | 8.80045E-02 | 7.683E+00 | 2.160E+00 |
| | 1.00000E-01 | 5.549E+00 | 1.976E+00 |
| | 1.50000E-01 | 2.014E+00 | 1.056E+00 |
| | 2.00000E-01 | 9.985E-01 | 5.870E-01 |
| | 3.00000E-01 | 4.031E-01 | 2.455E-01 |
| | 4.00000E-01 | 2.323E-01 | 1.370E-01 |
| | 5.00000E-01 | 1.614E-01 | 9.128E-02 |
| | 6.00000E-01 | 1.248E-01 | 6.819E-02 |
| | 8.00000E-01 | 8.870E-02 | 4.644E-02 |
| | 1.00000E+00 | 7.102E-02 | 3.654E-02 |
| | 1.25000E+00 | 5.876E-02 | 2.988E-02 |

ASCII format

| | Energy (MeV) | $\mu/\rho$ ($cm^2/g$) | $\mu_{en}/\rho$ ($cm^2/g$) |
|---|---|---|---|
| | 1.00000E-03 | 5.210E+03 | 5.197E+03 |
| | 1.50000E-03 | 2.356E+03 | 2.344E+03 |
| | 2.00000E-03 | 1.285E+03 | 1.274E+03 |
| | 2.48400E-03 | 8.006E+02 | 7.895E+02 |
| M5 | 2.48400E-03 | 1.397E+03 | 1.366E+03 |
| | 2.53429E-03 | 1.726E+03 | 1.682E+03 |
| | 2.58560E-03 | 1.944E+03 | 1.895E+03 |
| M4 | 2.58560E-03 | 2.458E+03 | 2.390E+03 |
| | 3.00000E-03 | 1.965E+03 | 1.913E+03 |
| | 3.06640E-03 | 1.857E+03 | 1.808E+03 |
| M3 | 3.06640E-03 | 2.146E+03 | 2.090E+03 |
| | 3.30130E-03 | 1.796E+03 | 1.748E+03 |
| | 3.55420E-03 | 1.496E+03 | 1.459E+03 |
| M2 | 3.55420E-03 | 1.585E+03 | 1.546E+03 |
| | 3.69948E-03 | 1.442E+03 | 1.405E+03 |
| | 3.85070E-03 | 1.311E+03 | 1.279E+03 |
| M1 | 3.85070E-03 | 1.368E+03 | 1.335E+03 |
| | 4.00000E-03 | 1.251E+03 | 1.221E+03 |
| | 5.00000E-03 | 7.304E+02 | 7.124E+02 |
| | 6.00000E-03 | 4.672E+02 | 4.546E+02 |
| | 8.00000E-03 | 2.287E+02 | 2.207E+02 |
| | 1.00000E-02 | 1.306E+02 | 1.247E+02 |
| | 1.30352E-02 | 6.701E+01 | 6.270E+01 |
| L3 | 1.30352E-02 | 1.621E+02 | 1.291E+02 |
| | 1.50000E-02 | 1.116E+02 | 9.100E+01 |
| | 1.52000E-02 | 1.078E+02 | 8.807E+01 |
| L2 | 1.52000E-02 | 1.485E+02 | 1.131E+02 |
| | 1.55269E-02 | 1.416E+02 | 1.083E+02 |
| | 1.58608E-02 | 1.344E+02 | 1.032E+02 |
| L1 | 1.58608E-02 | 1.548E+02 | 1.180E+02 |
| | 2.00000E-02 | 8.636E+01 | 6.899E+01 |
| | 3.00000E-02 | 3.032E+01 | 2.536E+01 |
| | 4.00000E-02 | 1.436E+01 | 1.211E+01 |
| | 5.00000E-02 | 8.041E+00 | 6.740E+00 |
| | 6.00000E-02 | 5.021E+00 | 4.149E+00 |
| | 8.00000E-02 | 2.419E+00 | 1.916E+00 |
| | 8.80045E-02 | 1.910E+00 | 1.482E+00 |
| K | 8.80045E-02 | 7.683E+00 | 2.160E+00 |
| | 1.00000E-01 | 5.549E+00 | 1.976E+00 |
| | 1.50000E-01 | 2.014E+00 | 1.056E+00 |
| | 2.00000E-01 | 9.985E-01 | 5.870E-01 |
| | 3.00000E-01 | 4.031E-01 | 2.455E-01 |
| | 4.00000E-01 | 2.323E-01 | 1.370E-01 |
| | 5.00000E-01 | 1.614E-01 | 9.128E-02 |
| | 6.00000E-01 | 1.248E-01 | 6.819E-02 |
| | 8.00000E-01 | 8.870E-02 | 4.644E-02 |
| | 1.00000E+00 | 7.102E-02 | 3.654E-02 |
| | 1.25000E+00 | 5.876E-02 | 2.988E-02 |
| | 1.50000E+00 | 5.222E-02 | 2.640E-02 |
| | 2.00000E+00 | 4.606E-02 | 2.360E-02 |
| | 3.00000E+00 | 4.234E-02 | 2.322E-02 |
| | 4.00000E+00 | 4.197E-02 | 2.449E-02 |
| | 5.00000E+00 | 4.272E-02 | 2.600E-02 |
| | 6.00000E+00 | 4.391E-02 | 2.744E-02 |
| | 8.00000E+00 | 4.675E-02 | 2.989E-02 |
| | 1.00000E+01 | 4.972E-02 | 3.181E-02 |
| | 1.50000E+01 | 5.658E-02 | 3.478E-02 |
| | 2.00000E+01 | 6.206E-02 | 3.595E-02 |

$$C = \frac{e^{-\mu_{Al} x_{Al}} - e^{-\mu_{Pb} x_{Pb}}}{e^{-\mu_{Al} x_{Al}}}$$

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$$\mu_{Al} = \mu_{\rho Al} \rho_{Al}$$

$$C = \frac{e^{-\mu_{Al} x_{Al}} - e^{-\mu_{Pb} x_{Pb}}}{e^{-\mu_{Al} x_{Al}}}$$

$$\mu_{Pb} = \mu_{\rho Pb} \rho_{Pb}$$

$$\mu_{Al} = \mu_{\rho Al} \rho_{Al}$$

$$C = \frac{e^{-\mu_{Al} x_{Al}} - e^{-\mu_{Pb} x_{Pb}}}{e^{-\mu_{Al} x_{Al}}}$$

$$\mu_{Pb} = \mu_{\rho Pb} \rho_{Pb}$$

$$\mu_{Al} = \mu_{\rho Al} \rho_{Al}$$

$$C =$$

$$C = \frac{e^{-\mu_{Al}x_{Al}} - e^{-\mu_{Pb}x_{Pb}}}{e^{-\mu_{Al}x_{Al}}}$$

$$\mu_{Pb} = \mu_{\rho Pb}\rho_{Pb}$$

$$\mu_{Al} = \mu_{\rho Al}\rho_{Al}$$

$$C = 1 -$$

$$C = \frac{e^{-\mu_{Al} x_{Al}} - e^{-\mu_{Pb} x_{Pb}}}{e^{-\mu_{Al} x_{Al}}}$$

$$\mu_{Pb} = \mu_{\rho Pb} \rho_{Pb}$$

$$\mu_{Al} = \mu_{\rho Al} \rho_{Al}$$

$$C = 1 - e^{-(\mu_{Pb} - \mu_{Al})x}$$

$$C = \frac{e^{-\mu_{Al} x_{Al}} - e^{-\mu_{Pb} x_{Pb}}}{e^{-\mu_{Al} x_{Al}}}$$

$$\mu_{Pb} = \mu_{\rho Pb} \rho_{Pb}$$

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$$C = 1 - e^{-(\mu_{Pb} - \mu_{Al}) x}$$

$$C = \frac{e^{-\mu_{Al}x_{Al}} - e^{-\mu_{Pb}x_{Pb}}}{e^{-\mu_{Al}x_{Al}}}$$

$$\mu_{Pb} = \mu_{\rho Pb}\rho_{Pb}$$

$$\mu_{Al} = \mu_{\rho Al}\rho_{Al}$$

$$x = x_{Al} = x_{Pb}$$

$$C = 1 - e^{-(\mu_{Pb} - \mu_{Al})x}$$

Med numeriska värden:

$$C = 1 - e^{-(5,549*11,35-0,1704*2,699)0,02}$$

$$C = \frac{e^{-\mu_{Al}x_{Al}} - e^{-\mu_{Pb}x_{Pb}}}{e^{-\mu_{Al}x_{Al}}}$$

$$\mu_{Pb} = \mu_{\rho Pb}\rho_{Pb}$$

$$\mu_{Al} = \mu_{\rho Al}\rho_{Al}$$

$$x = x_{Al} = x_{Pb}$$

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$$\mu_{Pb} = \mu_{\rho Pb}\rho_{Pb}$$

$$\mu_{Al} = \mu_{\rho Al}\rho_{Al}$$

$$x = x_{Al} = x_{Pb}$$

$$C = 1 - e^{-(\mu_{Pb} - \mu_{Al})x}$$

Med numeriska värden:

$$C = 1 - e^{-(5,549*11,35-0,1704*2,699)0,02}$$

$$C = \frac{e^{-\mu_{Al} x_{Al}} - e^{-\mu_{Pb} x_{Pb}}}{e^{-\mu_{Al} x_{Al}}}$$

$$\mu_{Pb} = \mu_{\rho Pb}\, \rho_{Pb}$$

$$\mu_{Al} = \mu_{\rho Al}\, \rho_{Al}$$

$$x = x_{Al} = x_{Pb}$$

$$C = 1 - e^{-(\mu_{Pb} - \mu_{Al})x}$$

Med numeriska värden:

$$C = 1 - e^{-(5,549 * 11,35 - 0,1704 * 2,699)0,02}$$

$$C = \frac{e^{-\mu_{Al}x_{Al}} - e^{-\mu_{Pb}x_{Pb}}}{e^{-\mu_{Al}x_{Al}}}$$

$$\mu_{Pb} = \mu_{\rho Pb}\rho_{Pb}$$

$$\mu_{Al} = \mu_{\rho Al}\rho_{Al}$$

$$x = x_{Al} = x_{Pb}$$

$$C = 1 - e^{-(\mu_{Pb} - \mu_{Al})x}$$

Med numeriska värden:

$$C = 1 - e^{-(5{,}549*11{,}35-0{,}1704*2{,}699)0{,}02}$$

$$\mu_{Pb} = \mu_{\rho Pb} \rho_{Pb}$$

$$C = \frac{e^{-\mu_{Al} x_{Al}} - e^{-\mu_{Pb} x_{Pb}}}{e^{-\mu_{Al} x_{Al}}}$$

$$\mu_{Al} = \mu_{\rho Al} \rho_{Al}$$

$$x = x_{Al} = x_{Pb}$$

$$C = 1 - e^{-(\mu_{Pb} - \mu_{Al})x}$$

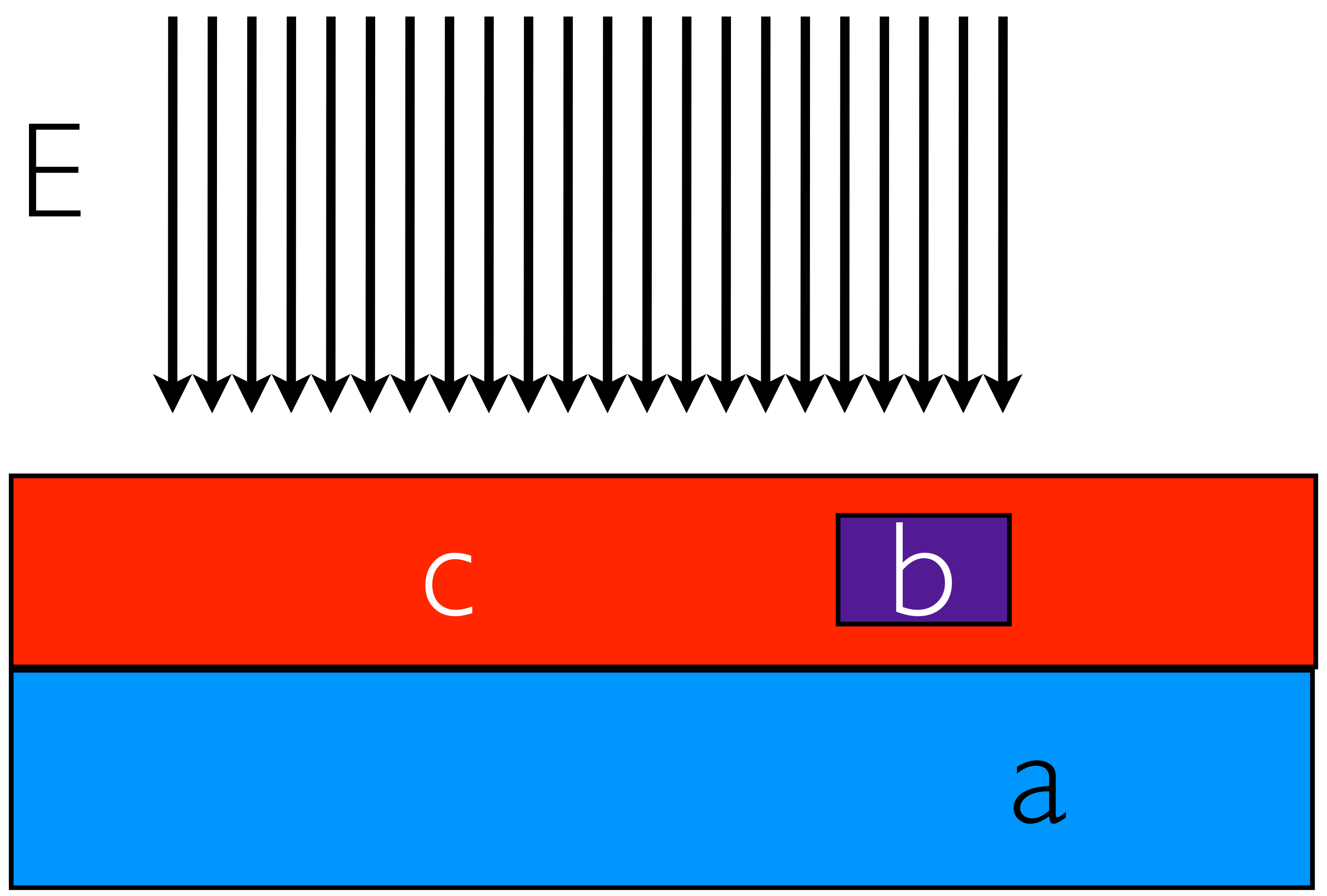
0,2 mm

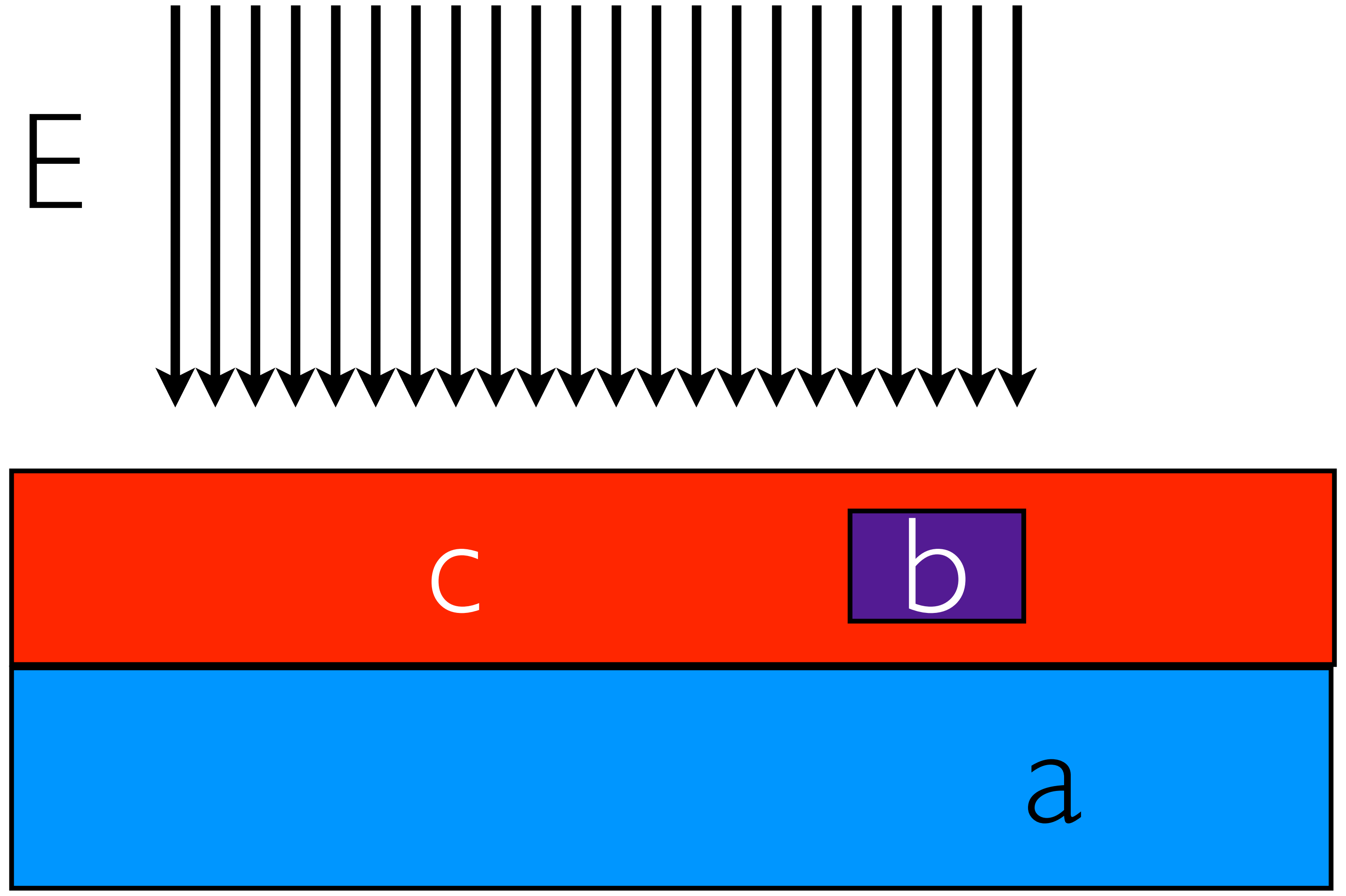
Med numeriska värden:

$$C = 1 - e^{-(5{,}549 * 11{,}35 - 0{,}1704 * 2{,}699) 0{,}02}$$

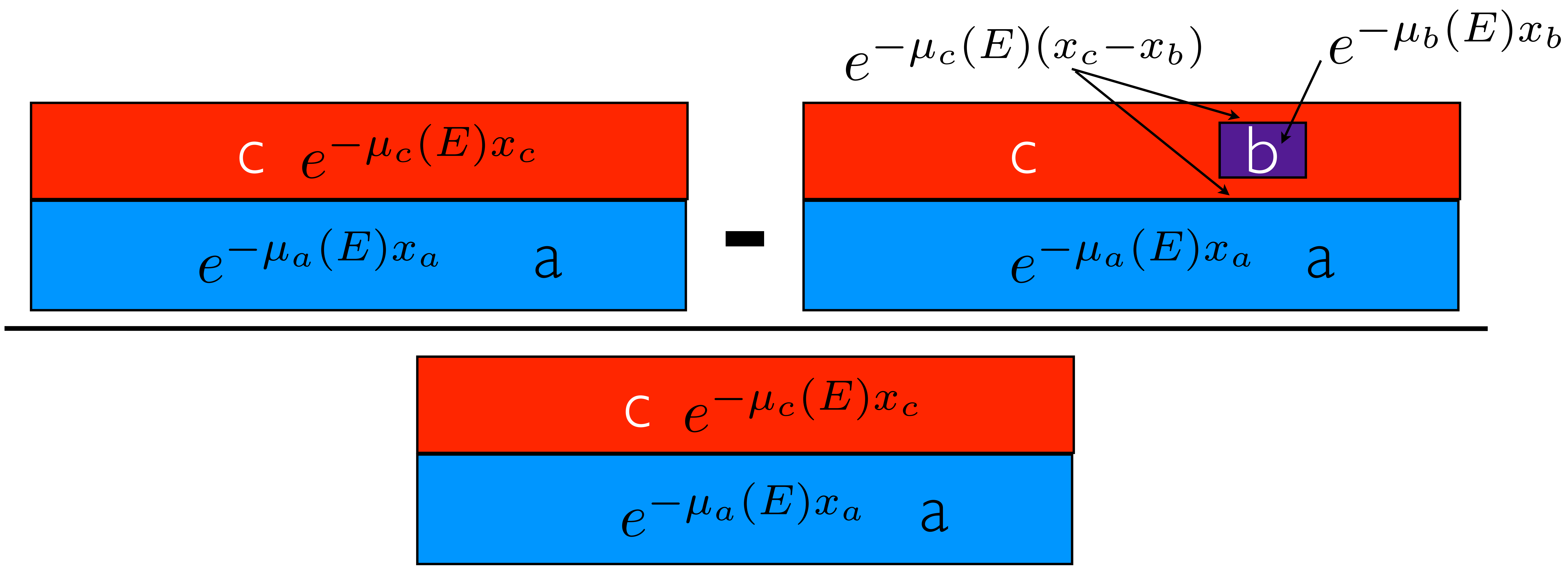
$$C \approx 70\%$$

Assume c attenuates less than b and calculate object contrast:

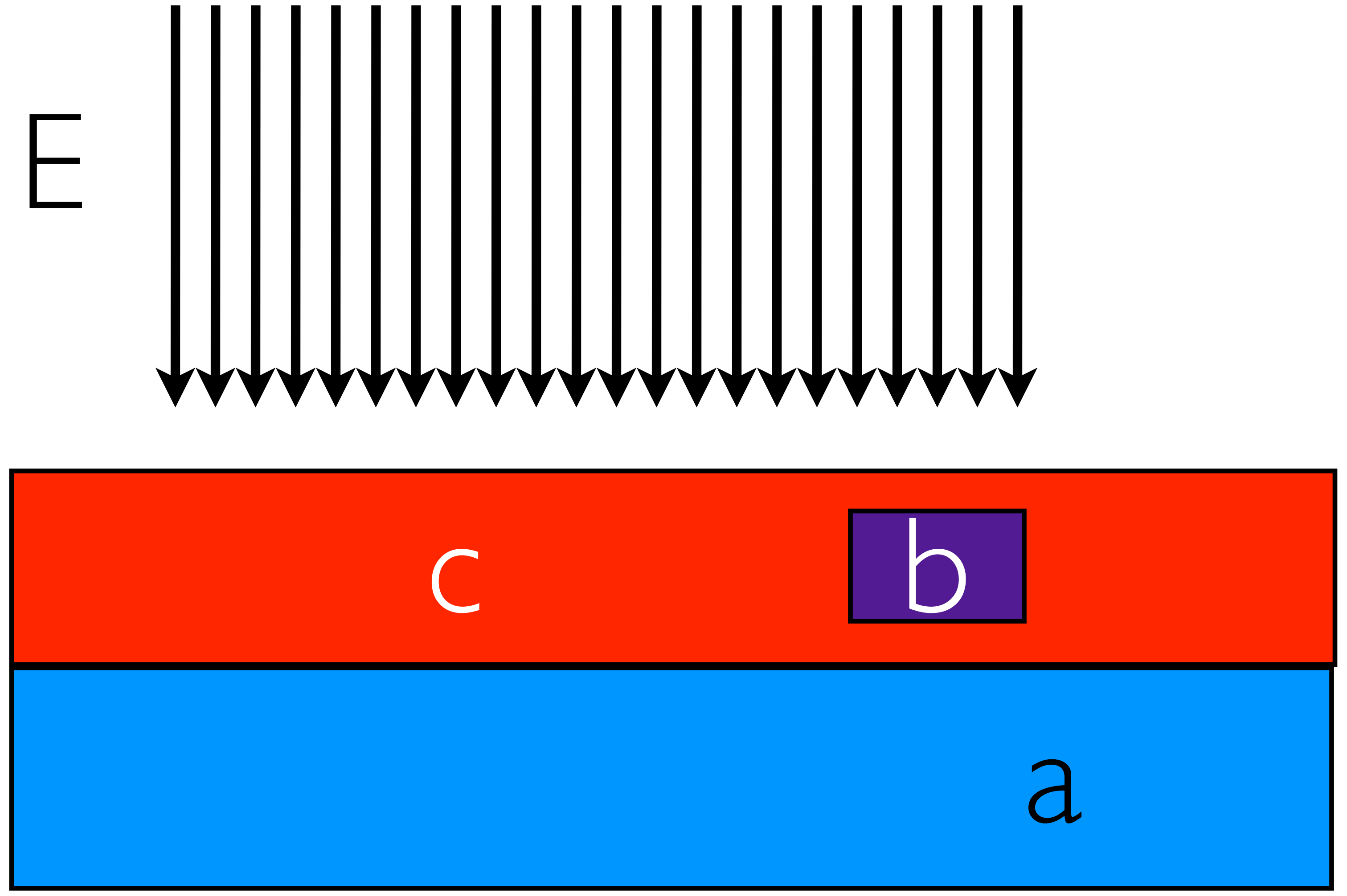





Assume c attenuates less than b and calculate object contrast:




$$C = 1 - e^{[\mu_b(E)-\mu_c(E)]x_b}$$



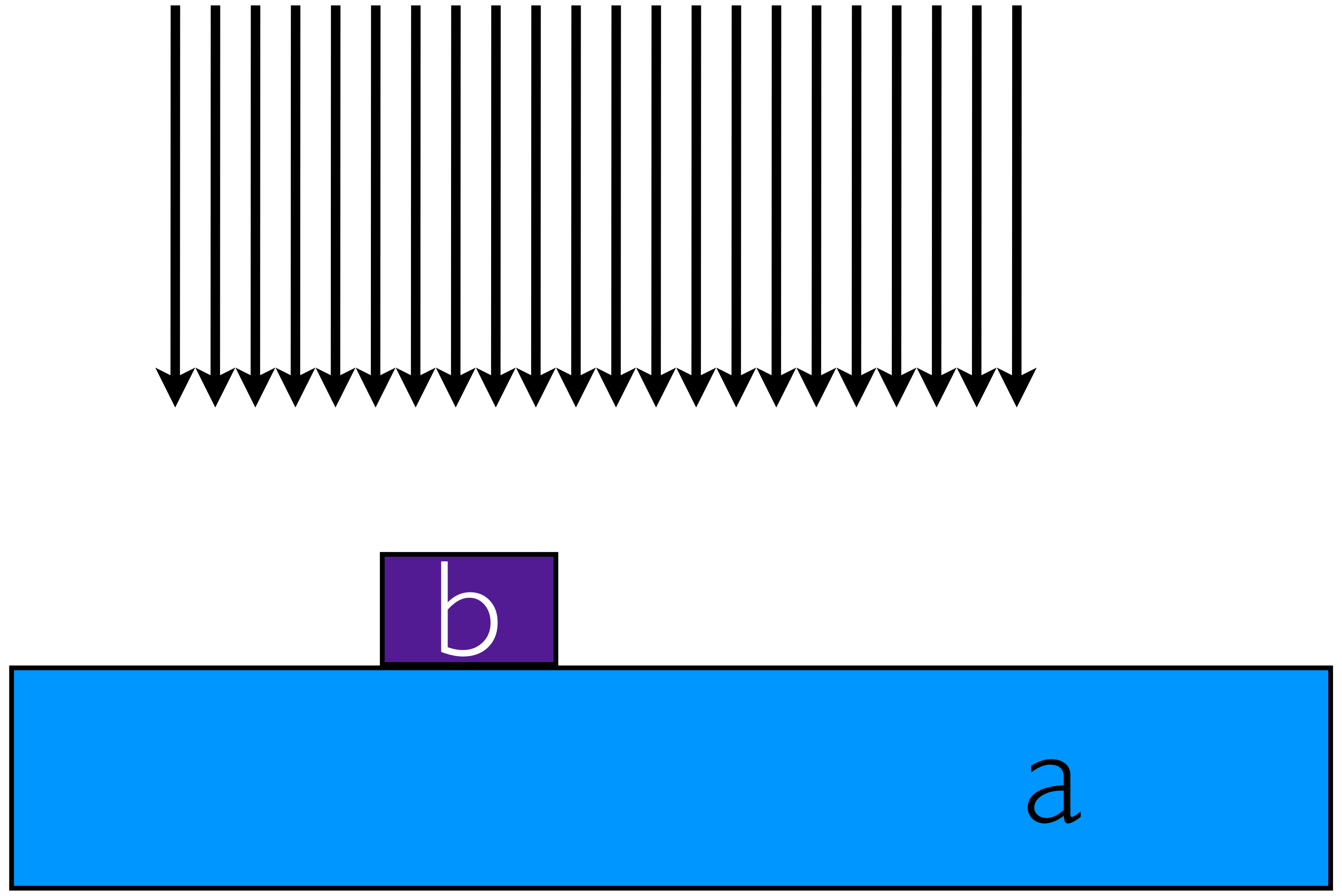

Assume c attenuates less than b and calculate object contrast:

$e^{-\mu_b(E)x_b}$

$e^{-\mu_c(E)x_b}$ −

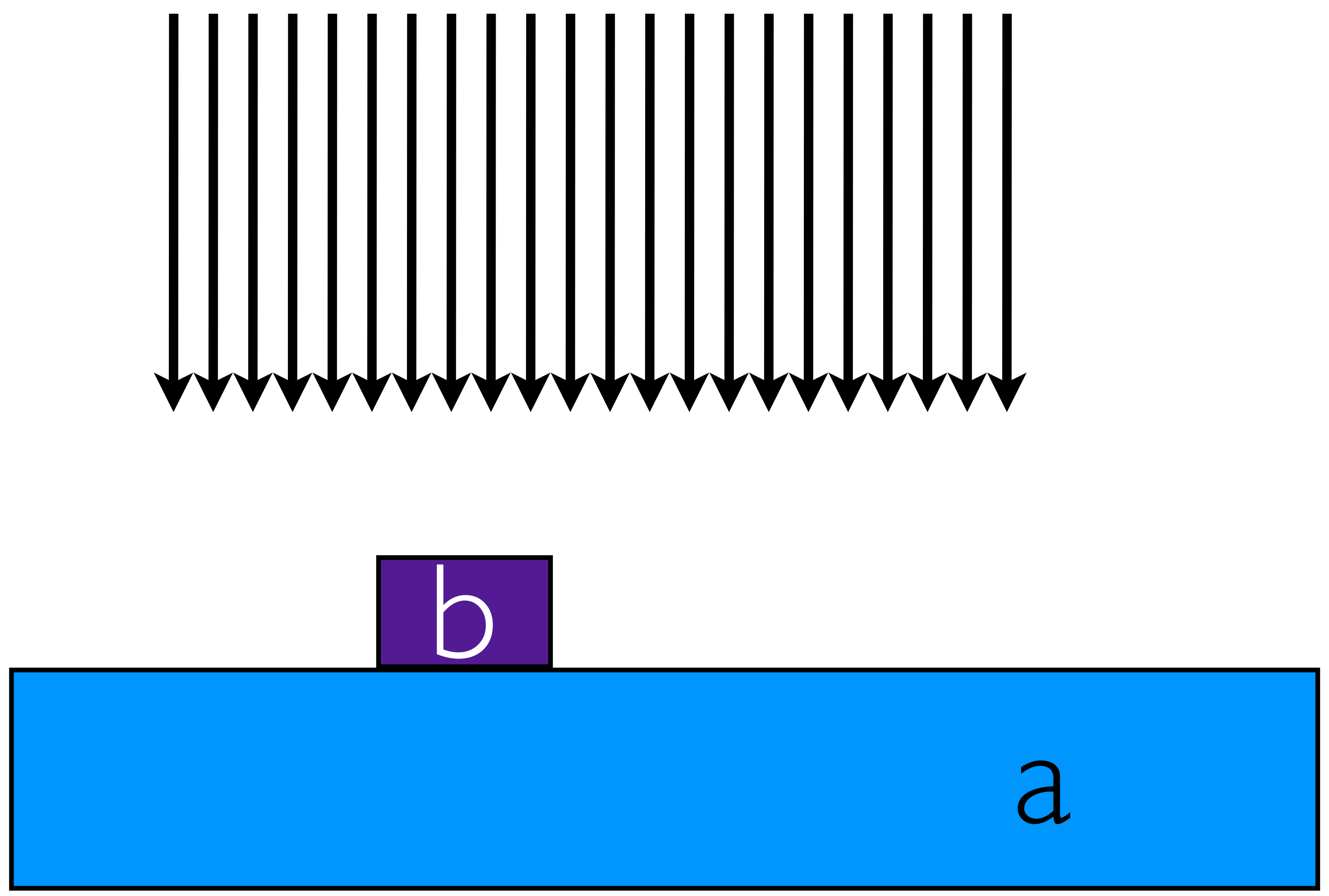
$e^{-\mu_c(E)x_b}$

$$C = 1 - e^{[\mu_b(E) - \mu_c(E)]x_b}$$



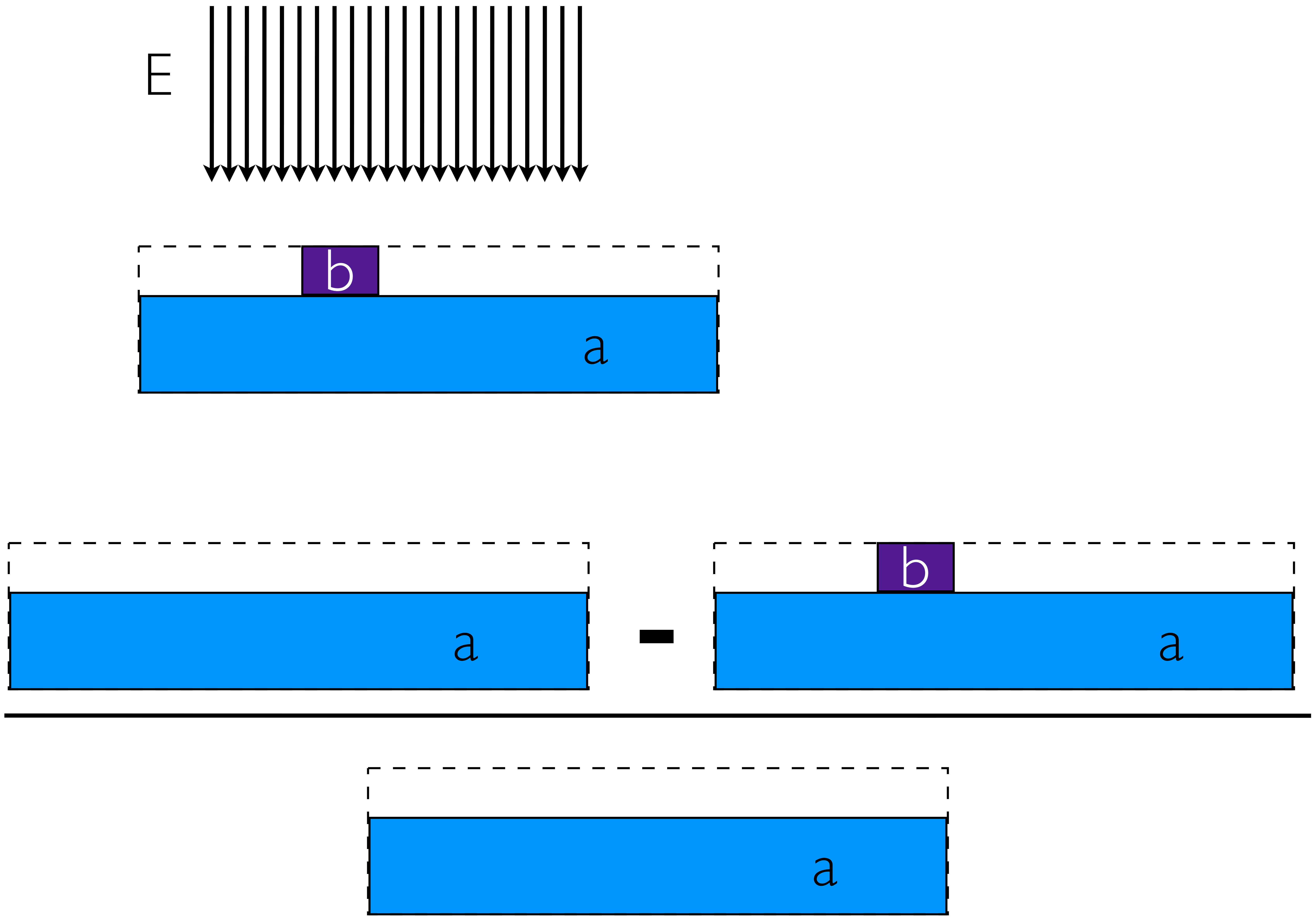

Object b is on background a. The contrast of object b will depend on:

1. linear attenuation coefficient and thickness of both a and b
2. difference in linear attenuation coefficient between a and b and thickness of b
3. thickness and linear attenuation coefficient of a
4. thickness and linear attenuation coefficient of b

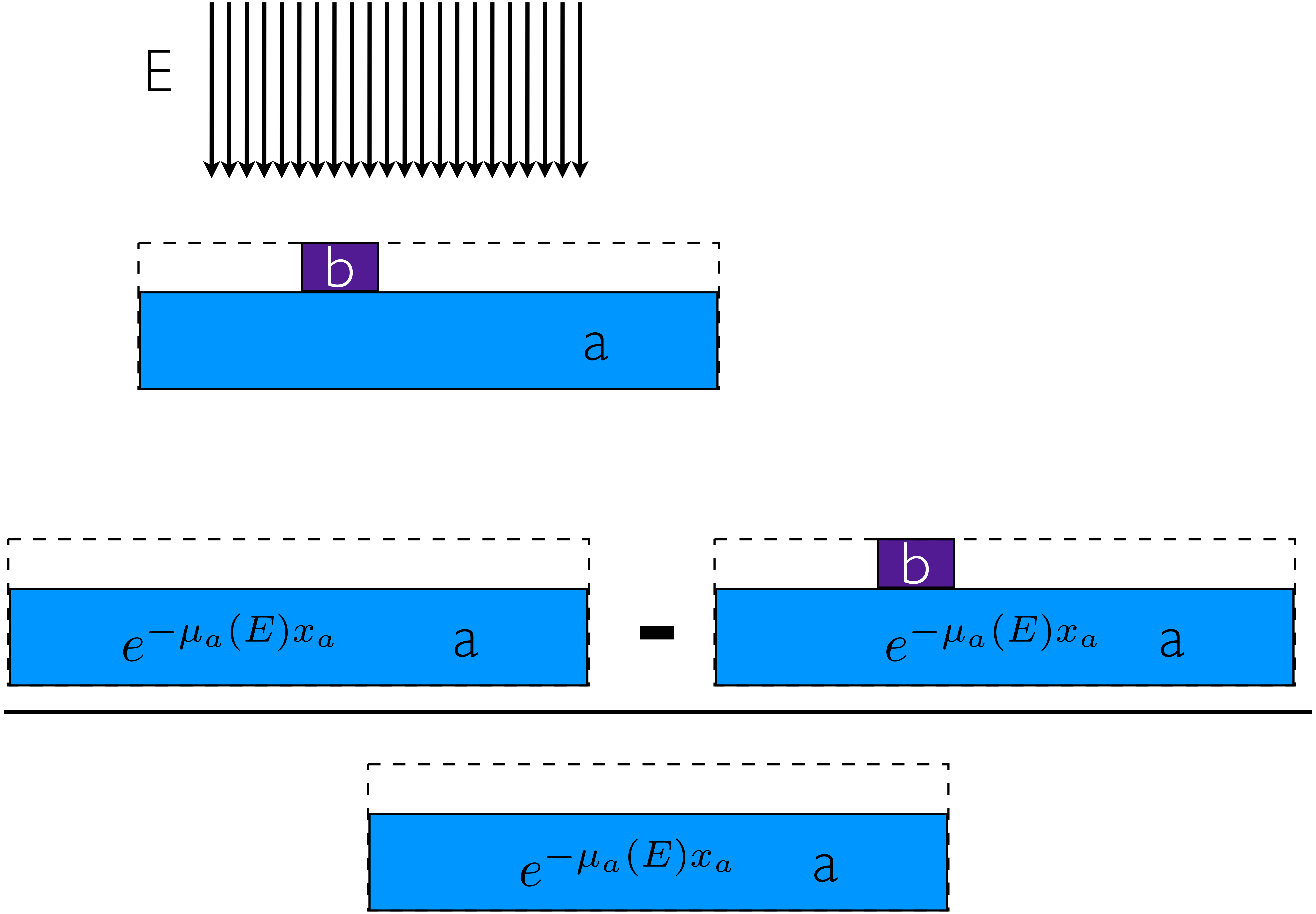



Object b is on background a. The contrast of object b will depend on:

1. linear attenuation coefficient and thickness of both a and b
2. difference in linear attenuation coefficient between a and b and thickness of b
3. thickness and linear attenuation coefficient of a
4. thickness and linear attenuation coefficient of b




bara för att lin. att. coeff.
för luft är 0! => lin. att. skillnad
är samma som lin. att av b

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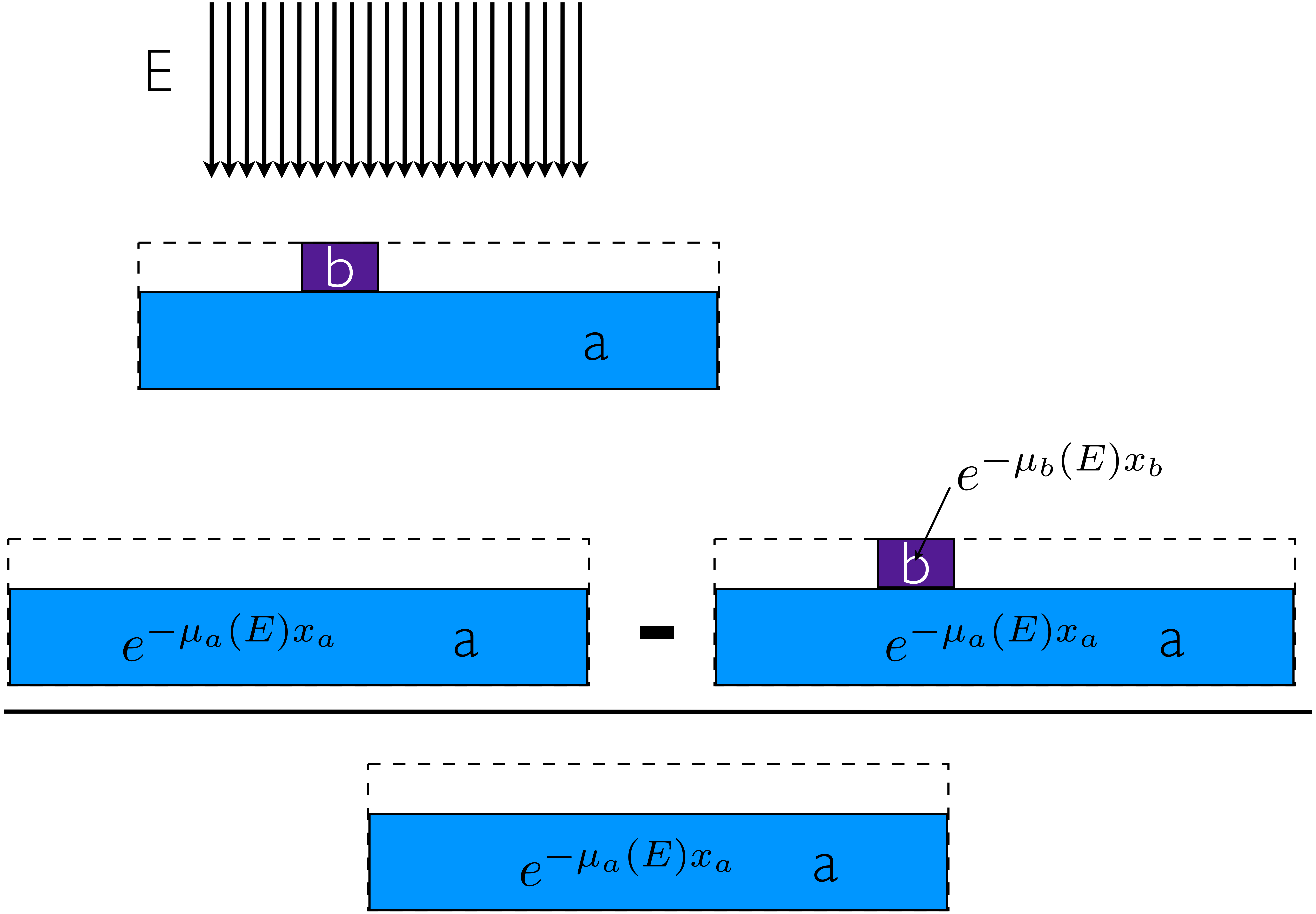
är samma som lin. att av b

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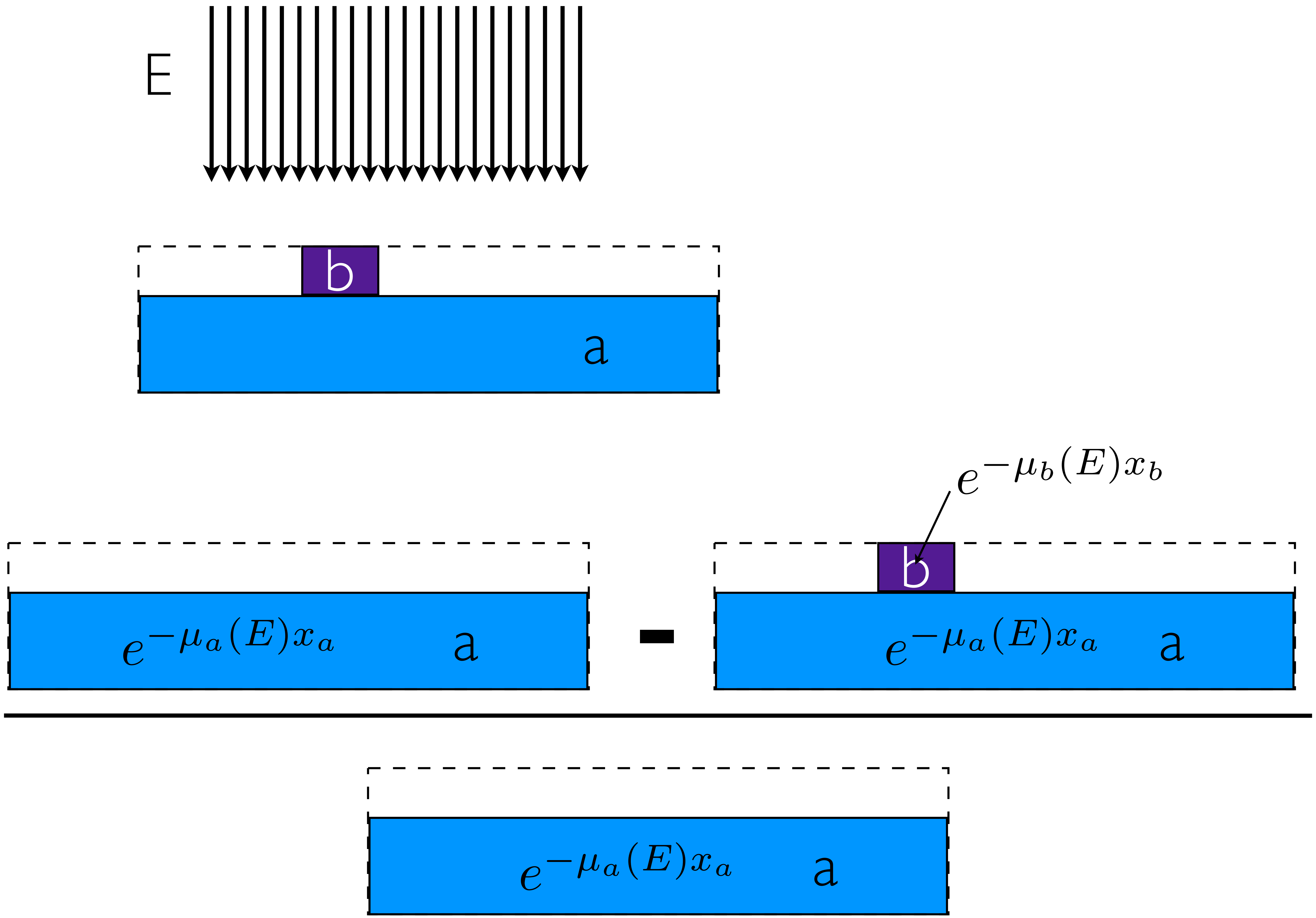
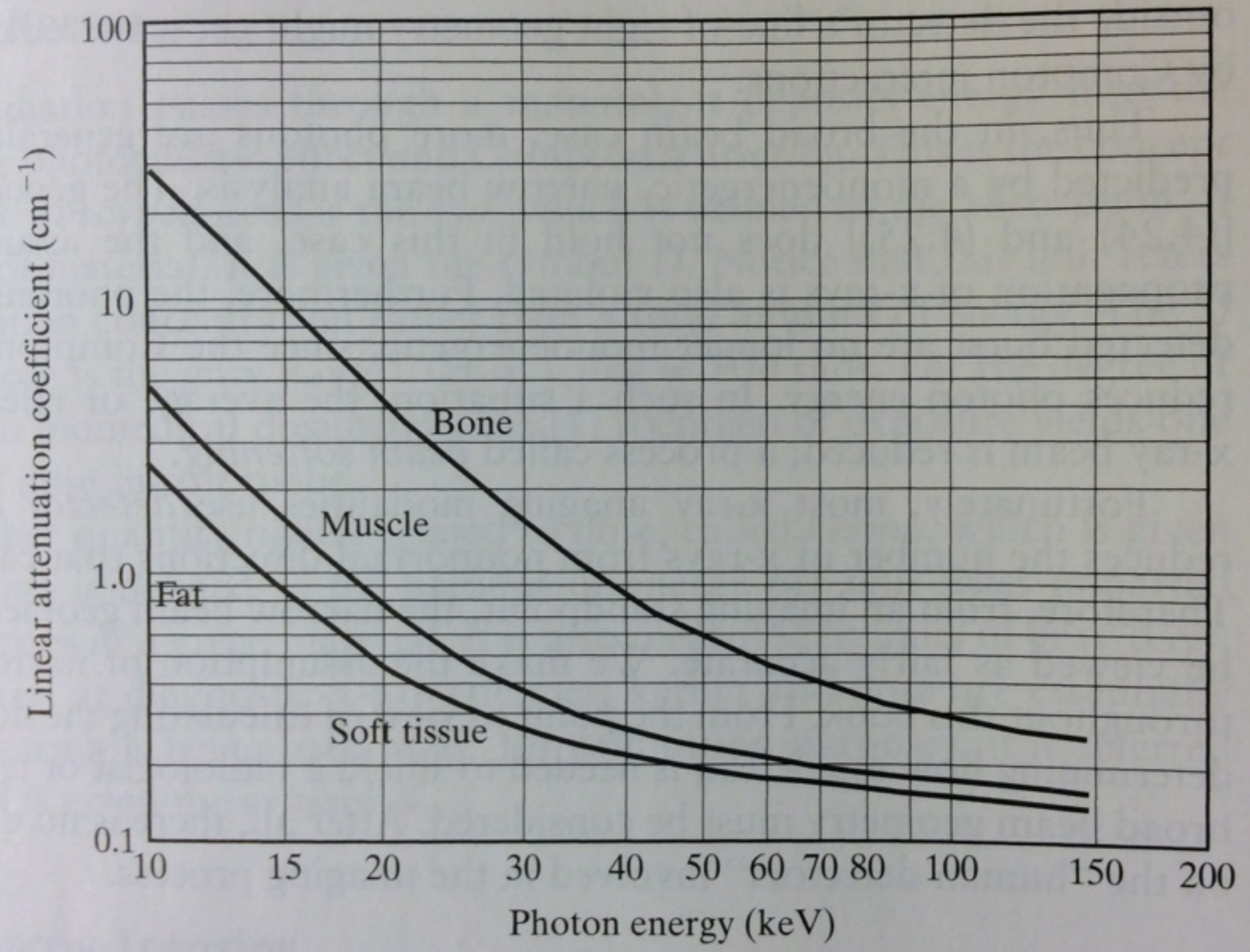


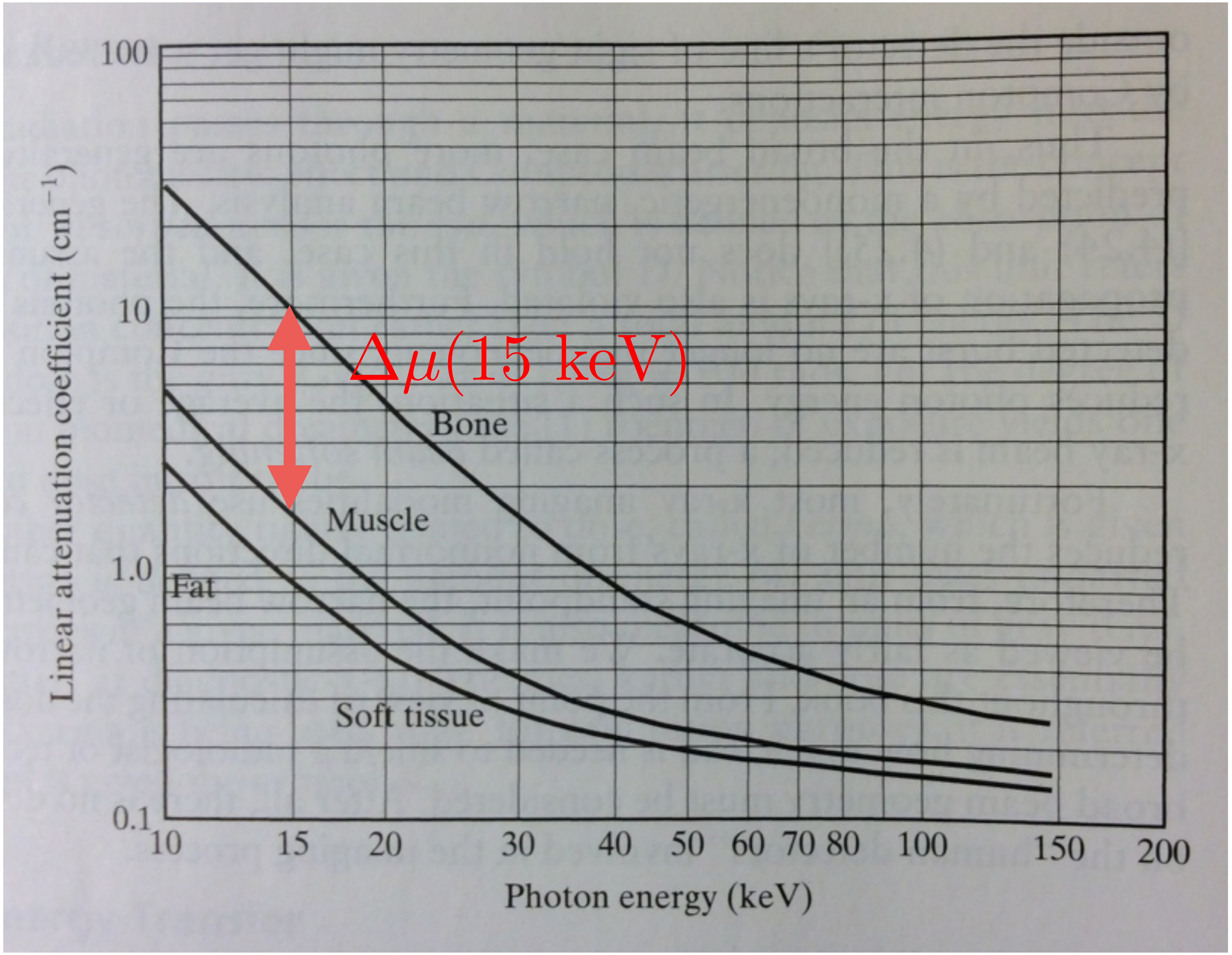

$$C = 1 - e^{-\mu_b(E)x_b}$$

bara för att lin. att. coeff.
för luft är 0! => lin. att. skillnad
är samma som lin. att av b

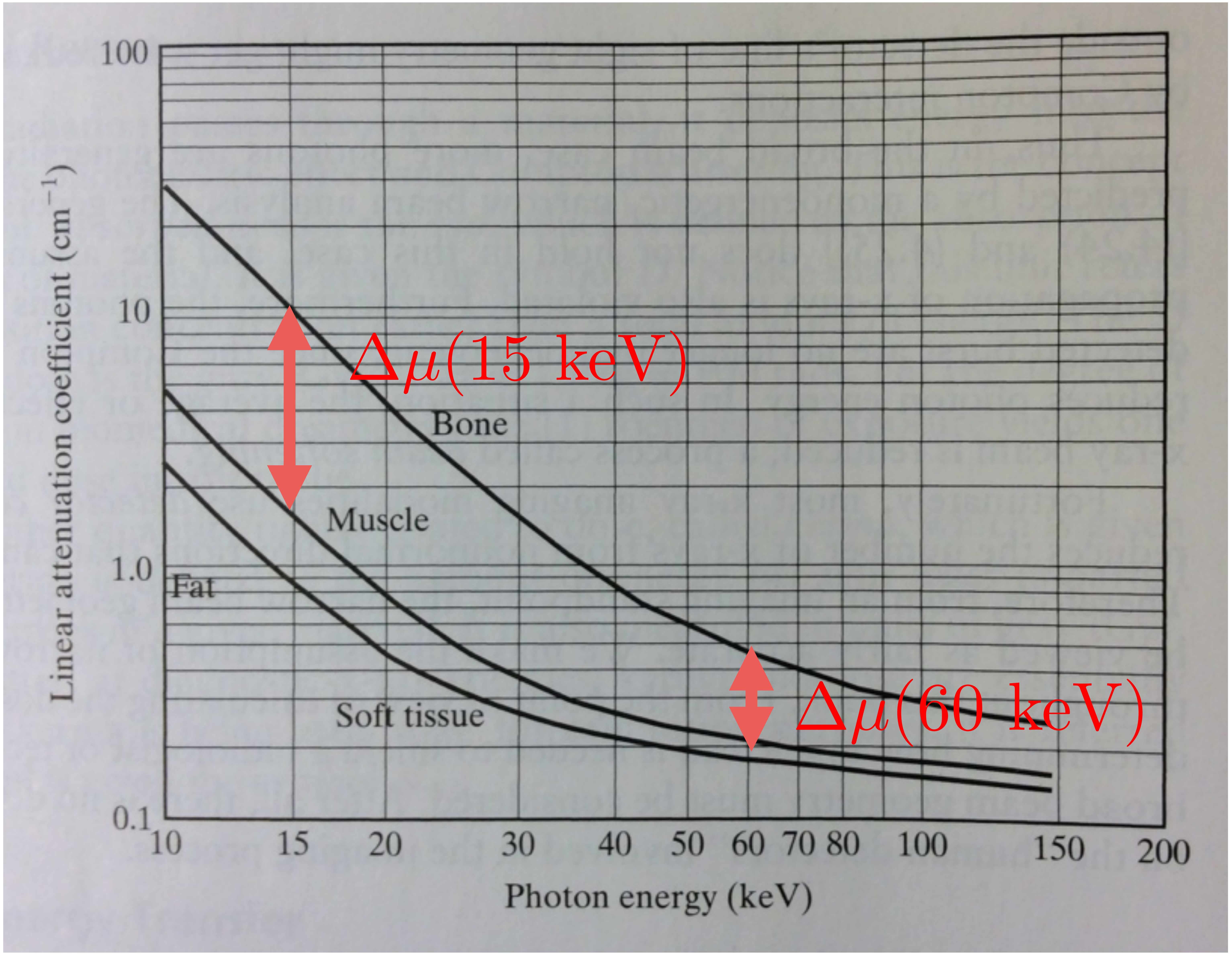
Hur påverkas transmissionsavbildning av fotonernas energi?



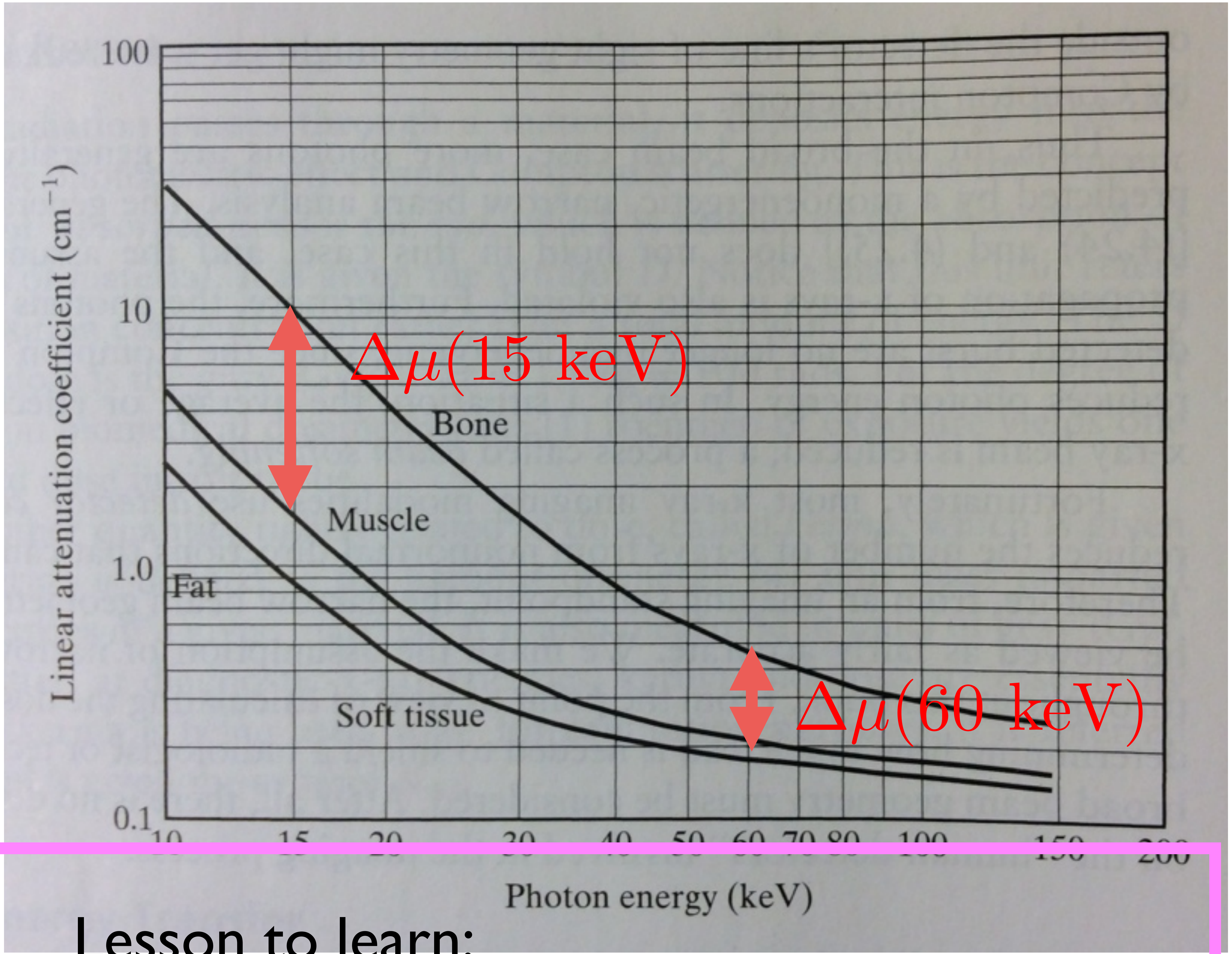
Linear attenuation coefficient (cm$^{-1}$)
100
10
1.0
0.1
Bone
Muscle
Fat
Soft tissue
10
15
20
30
40
50
60
70
80
100
150
200
Photon energy (keV)



100
10
1.0
0.1
Linear attenuation coefficient (cm$^{-1}$)
$\Delta\mu(15\ \mathrm{keV})$
Bone
Muscle
Fat
Soft tissue
10
15
20
30
40
50
60
70
80
100
150
200
Photon energy (keV)



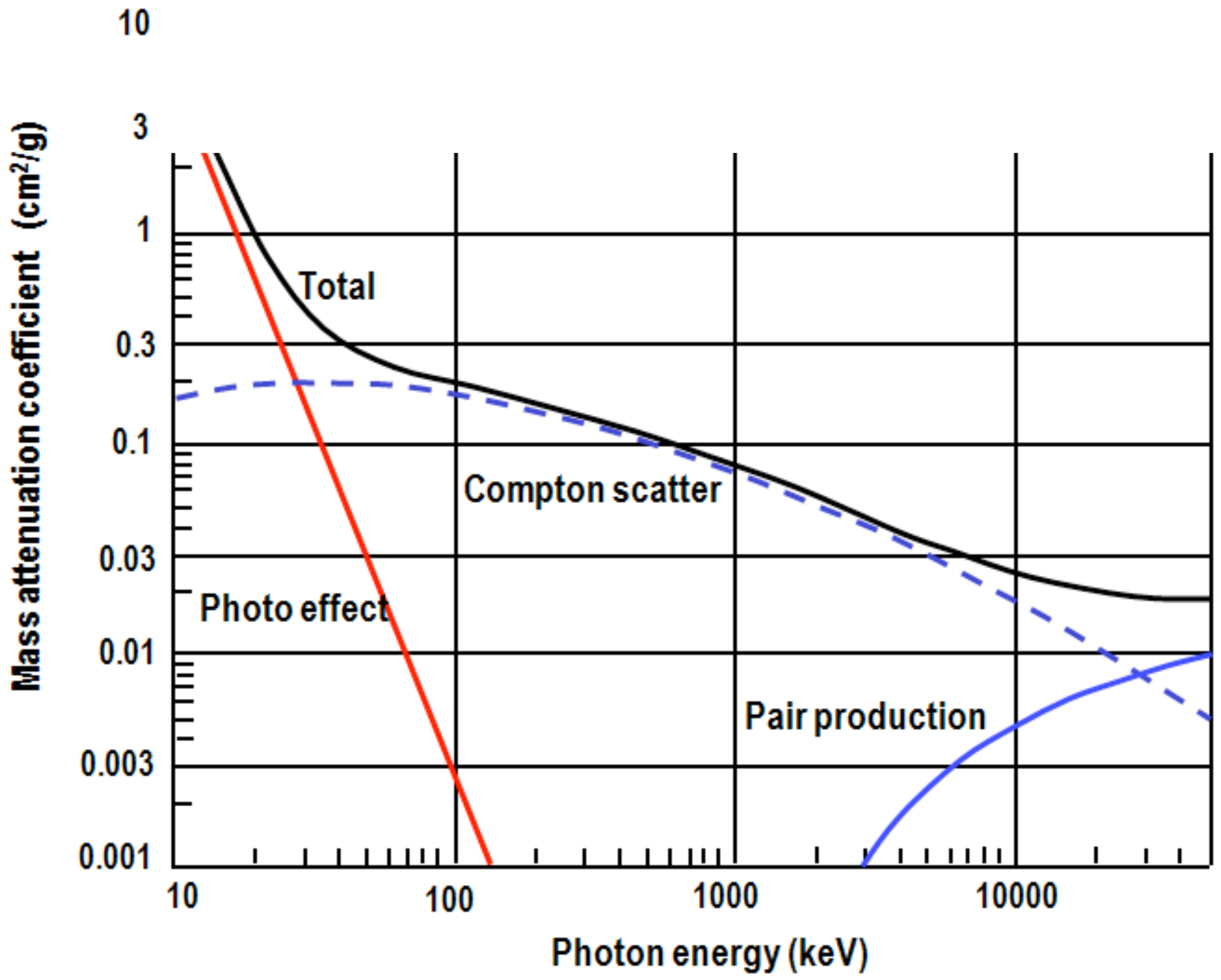
100
10
1.0
0.1
Linear attenuation coefficient (cm$^{-1}$)
$\Delta\mu(15\text{ keV})$
Bone
Muscle
Fat
Soft tissue
$\Delta\mu(60\text{ keV})$
10
15
20
30
40
50
60
70
80
100
150
200
Photon energy (keV)



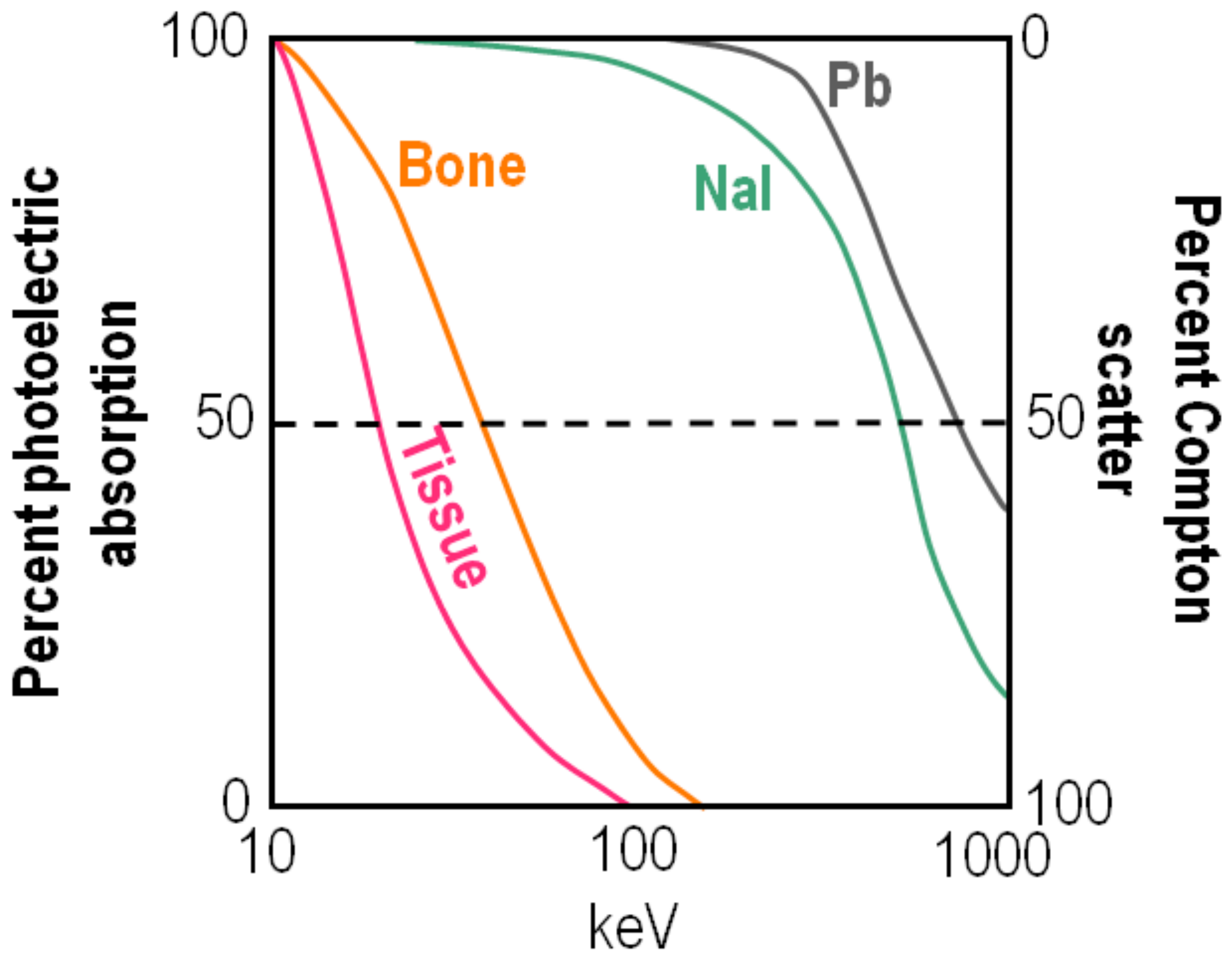

Lesson to learn:

Energi påverkar object contrast!

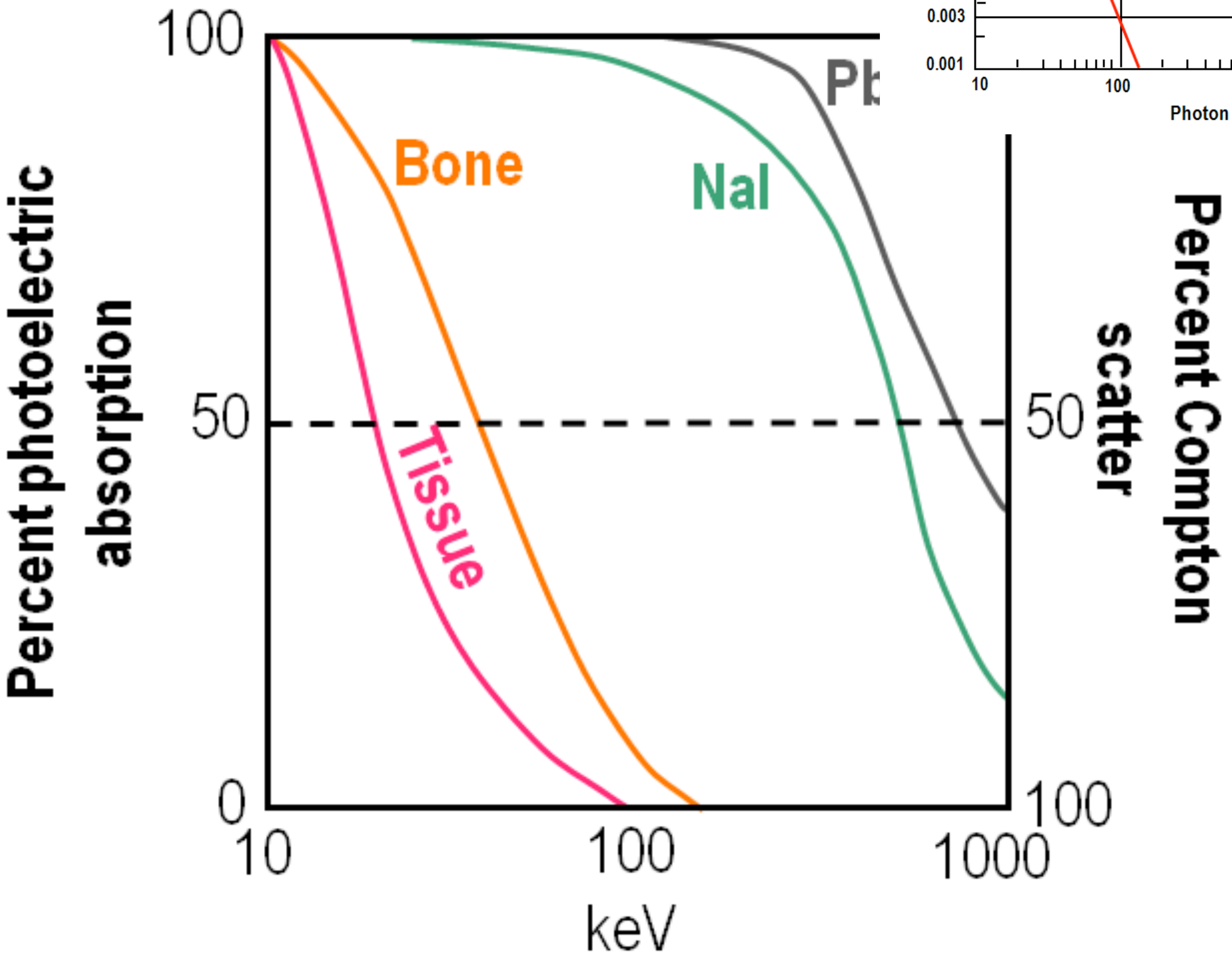
# Mass attenuation coefficient: Energy dependence

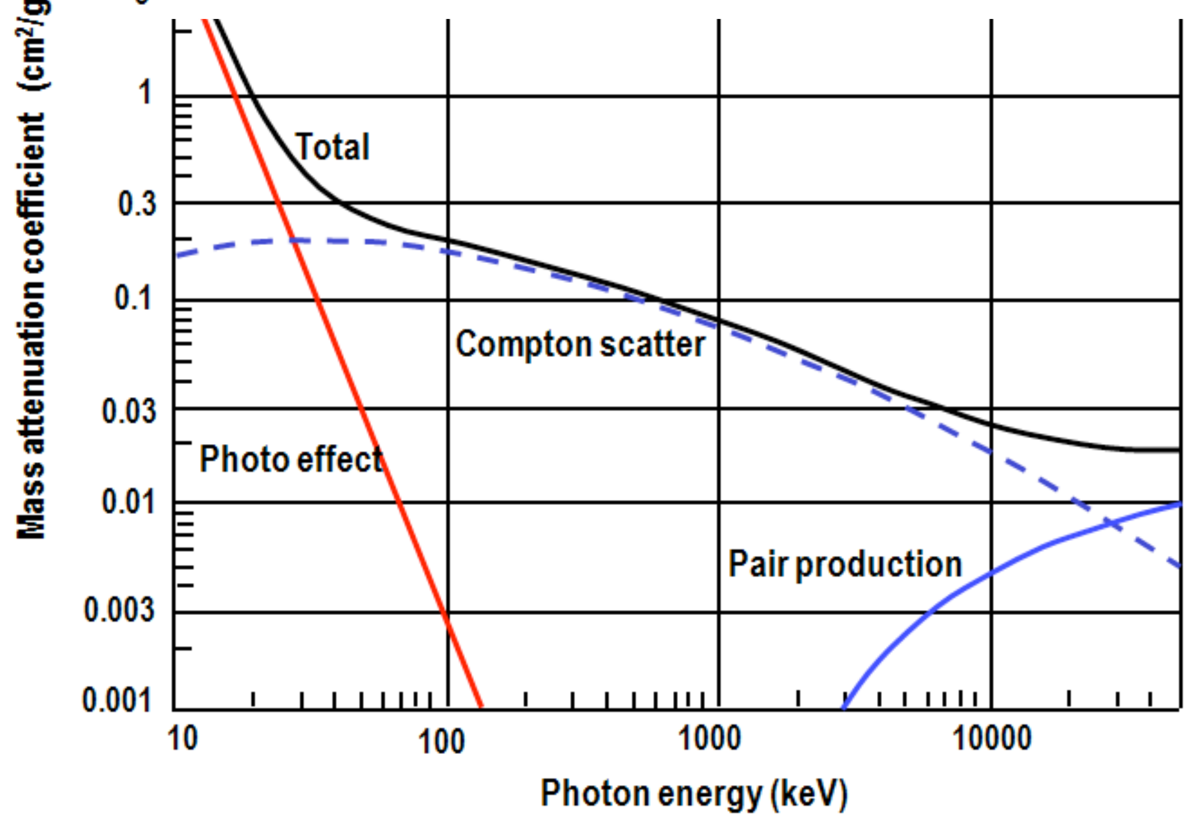


# PE vs Comptons for different materials

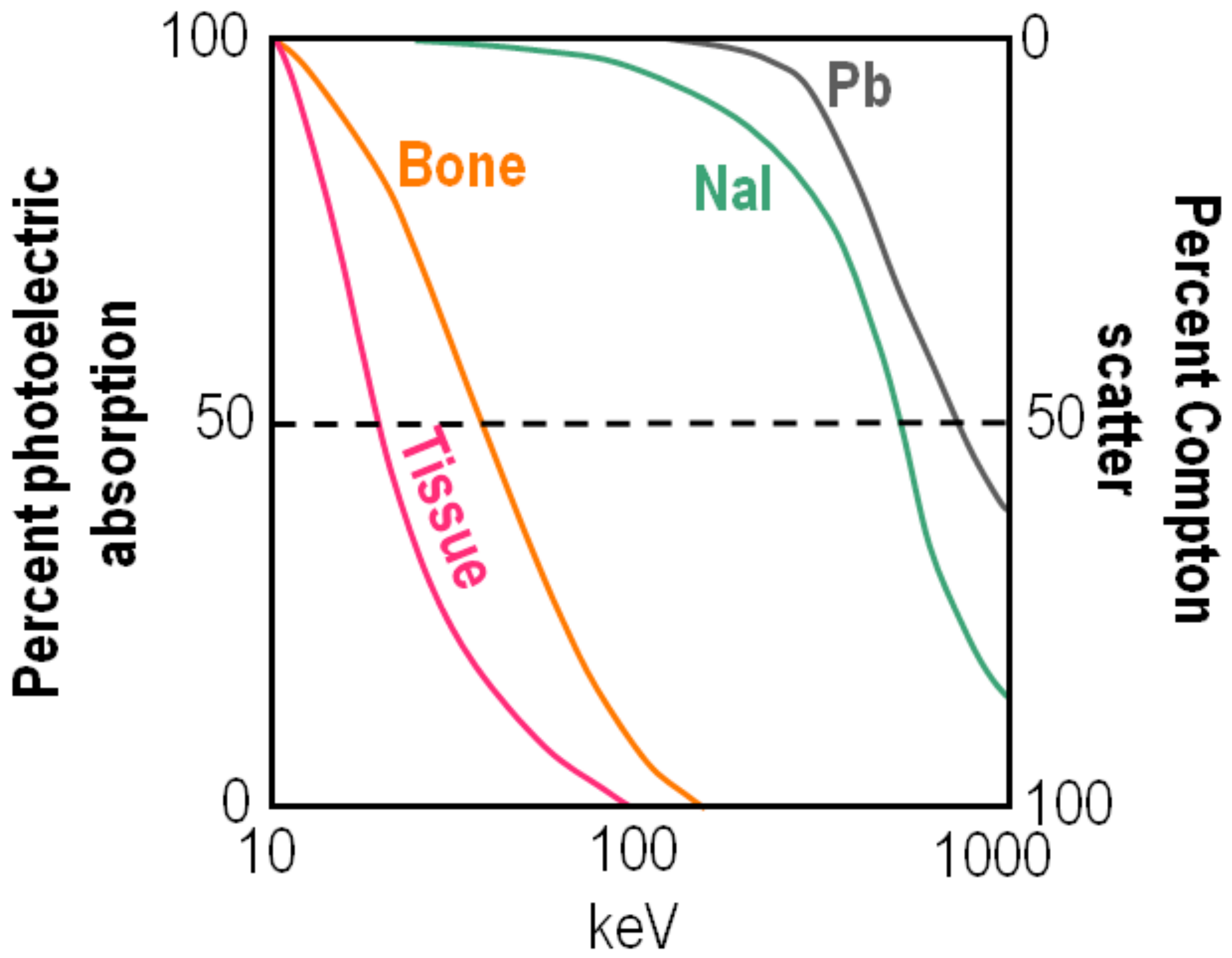


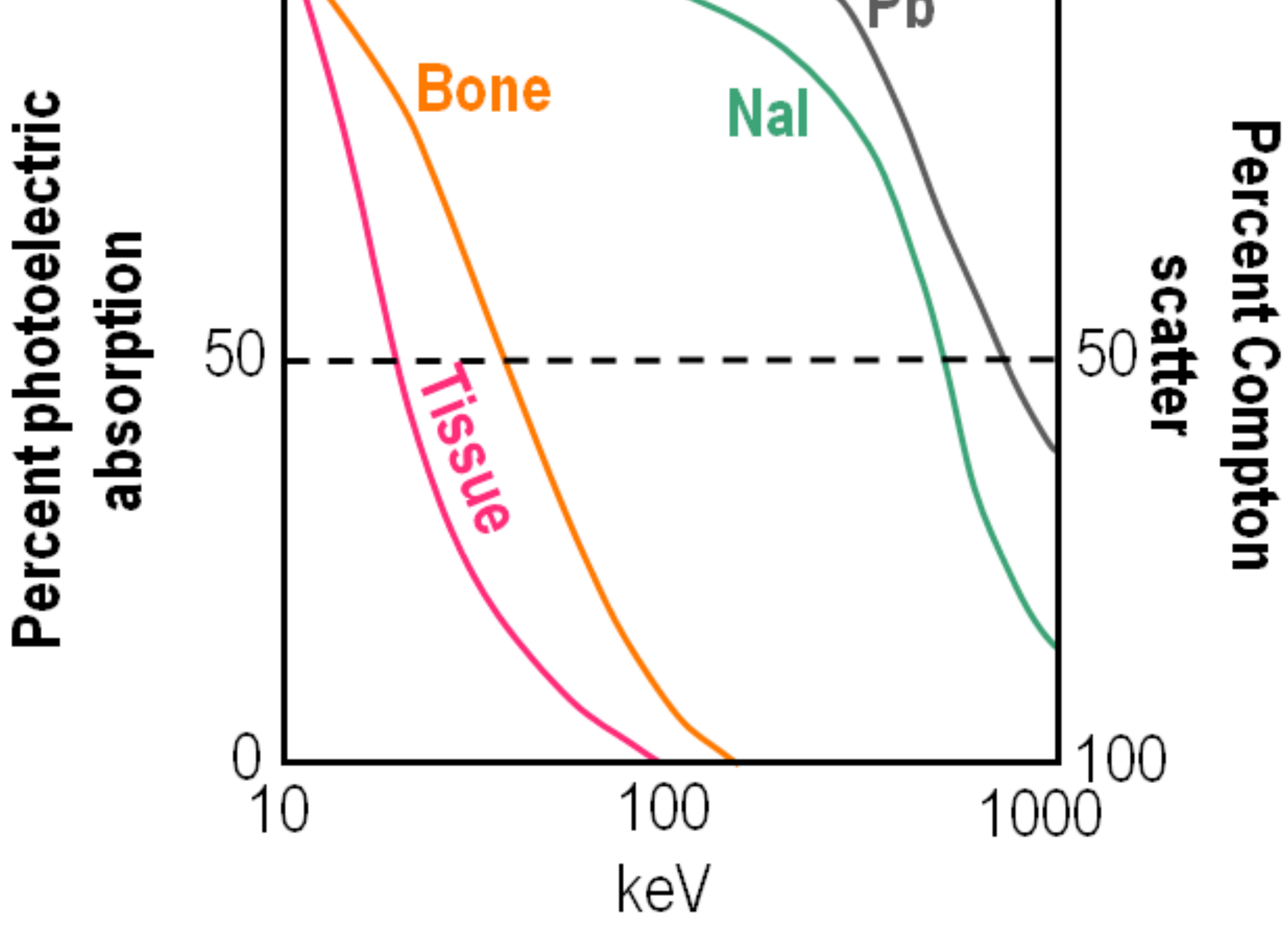
# PE vs Comptons for c



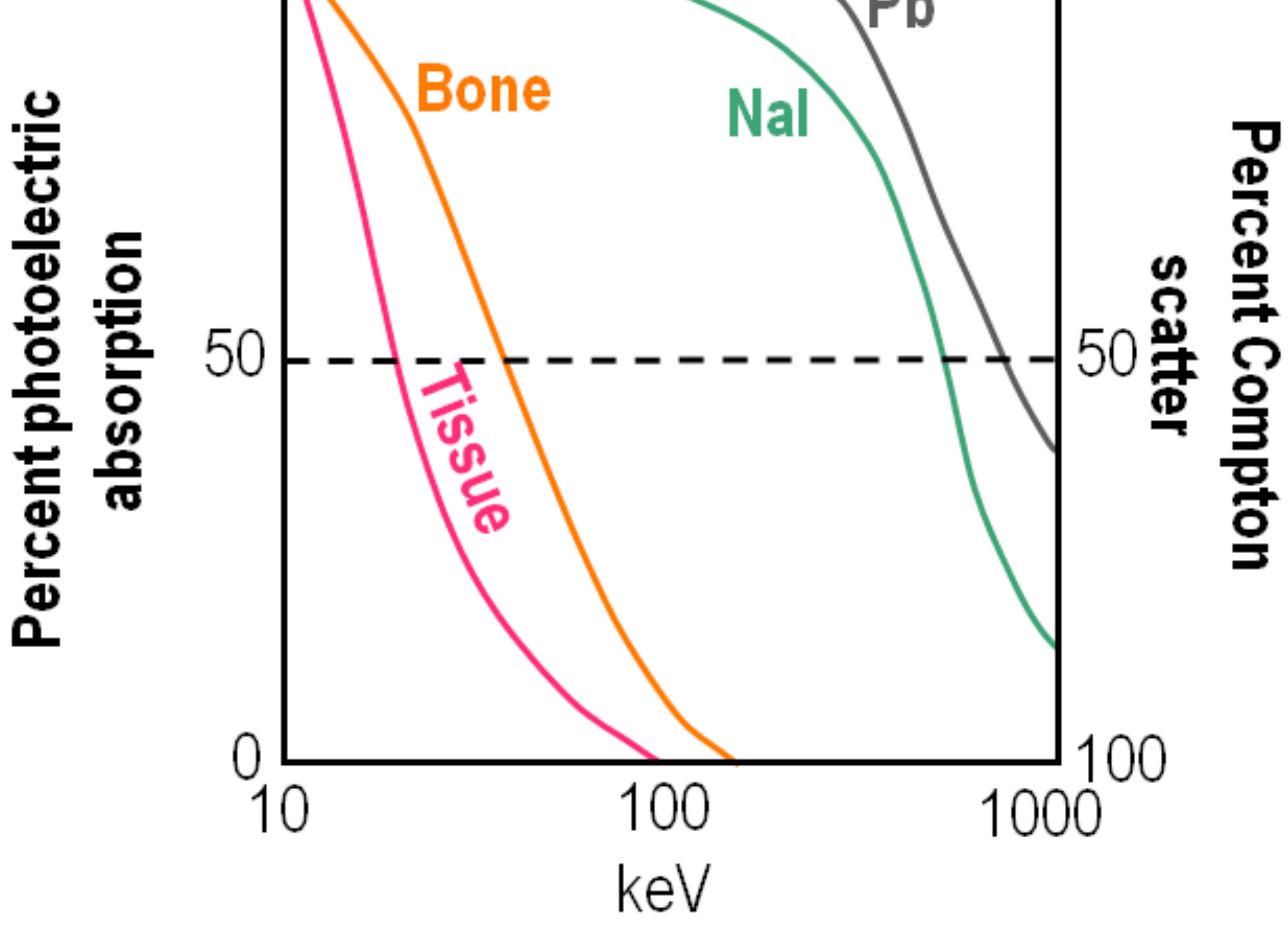
# PE vs Comptons for different materials






Which of the following energies would you choose for chest x-ray if you want to minimise Compton scattering?

1. 30 keV
2. 50 keV
3. 100 keV
4. anything between 120 keV and 200 keV will do
5. it doesn't matter, the probability of undergoing Compton scattering is a property of the material




Which of the following energies would you choose for chest x-ray if you want to maximise object contrast?

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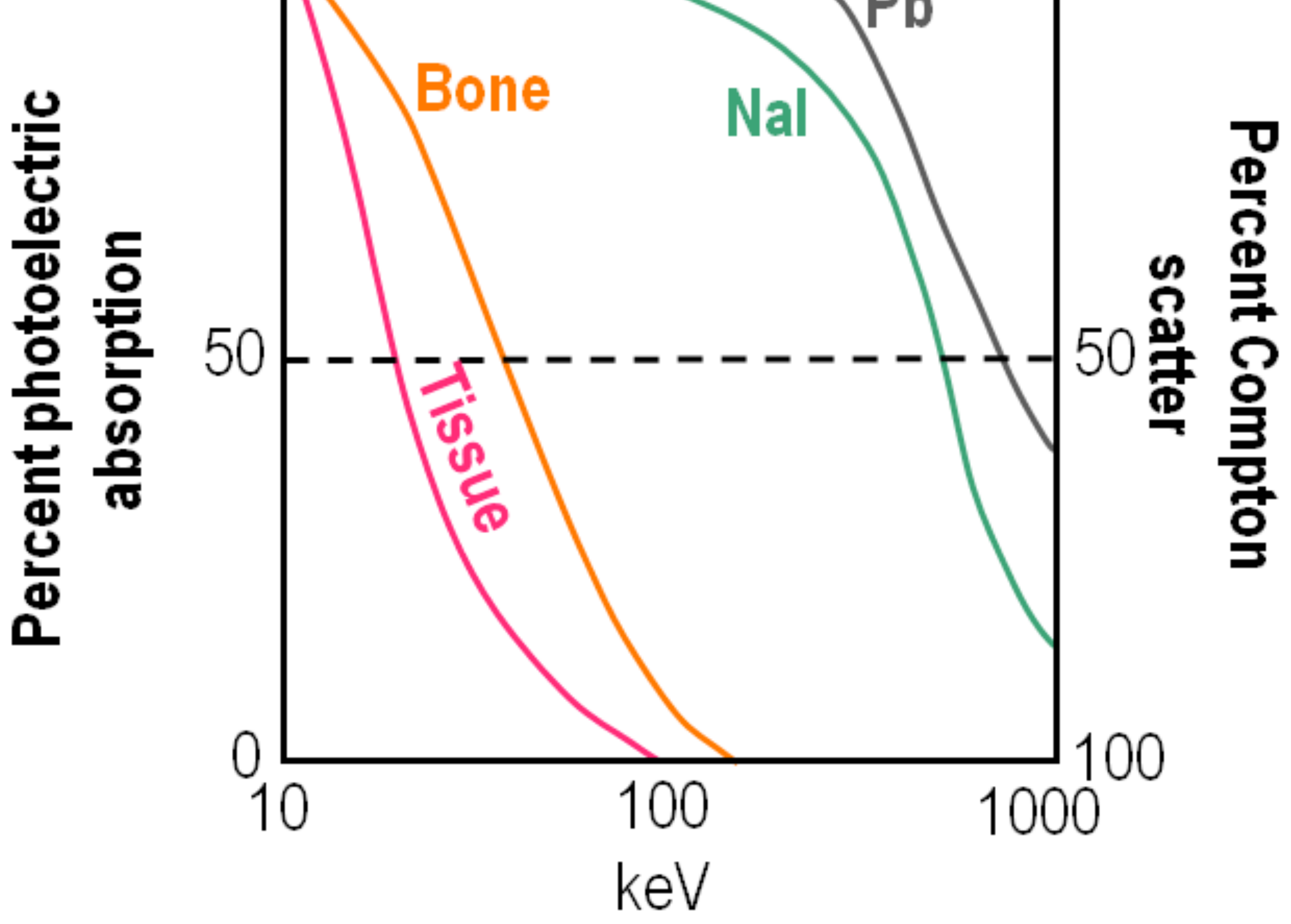



Which of the following energies would you choose for chest x-ray if you want to maximise number of primary photons reaching the detector (that is also minimising energy deposited on patient)?

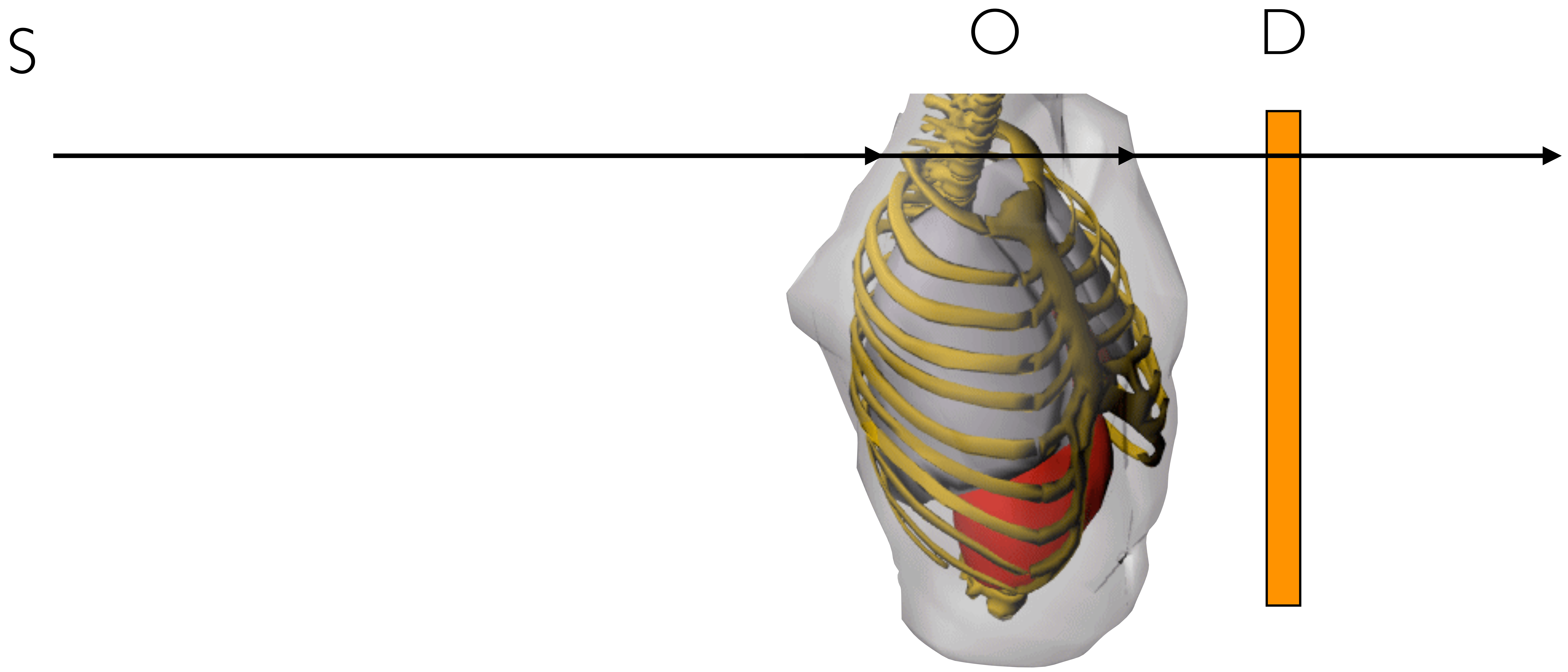
1. 30 keV
2. 50 keV
3. 100 keV
4. anything between 120 keV and 200 keV will do
5. it doesn't matter, the probability of undergoing Compton scattering is a property of the material

Lessons learned: Object contrast is maximum at low energy, Compton/PE fraction is minimal at low energy, detector signal is maximum at high energy, (dose to the patient is maximum at low energy)

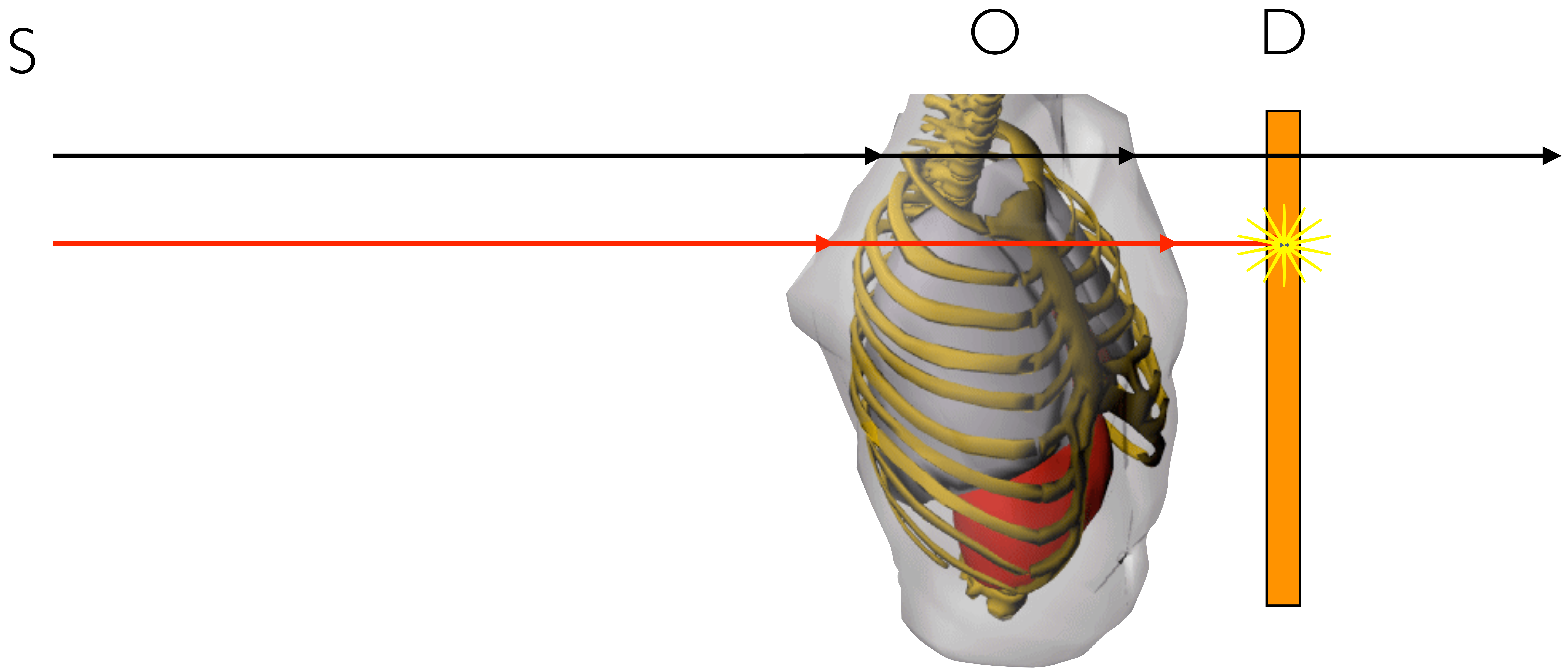
**We need an engineer!**

# Quick jump to clinical applications

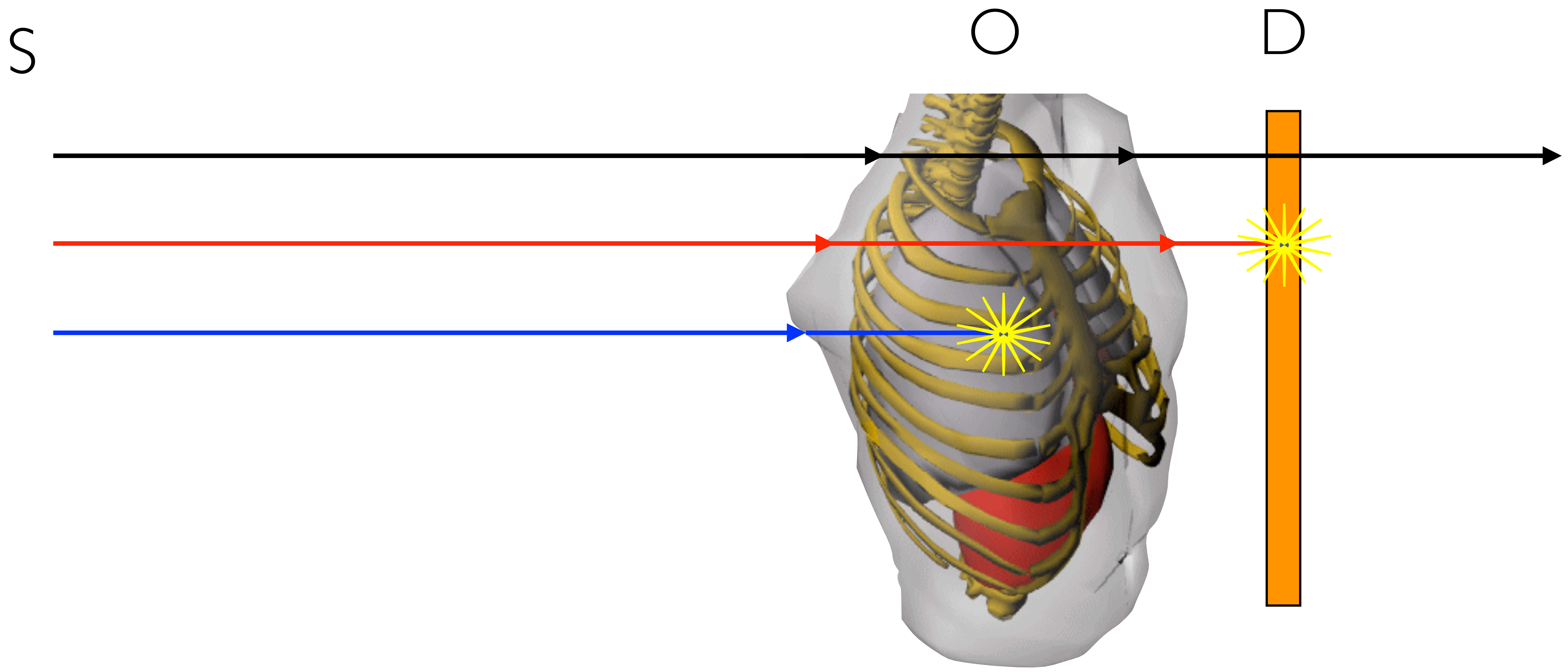
# Possible outcomes



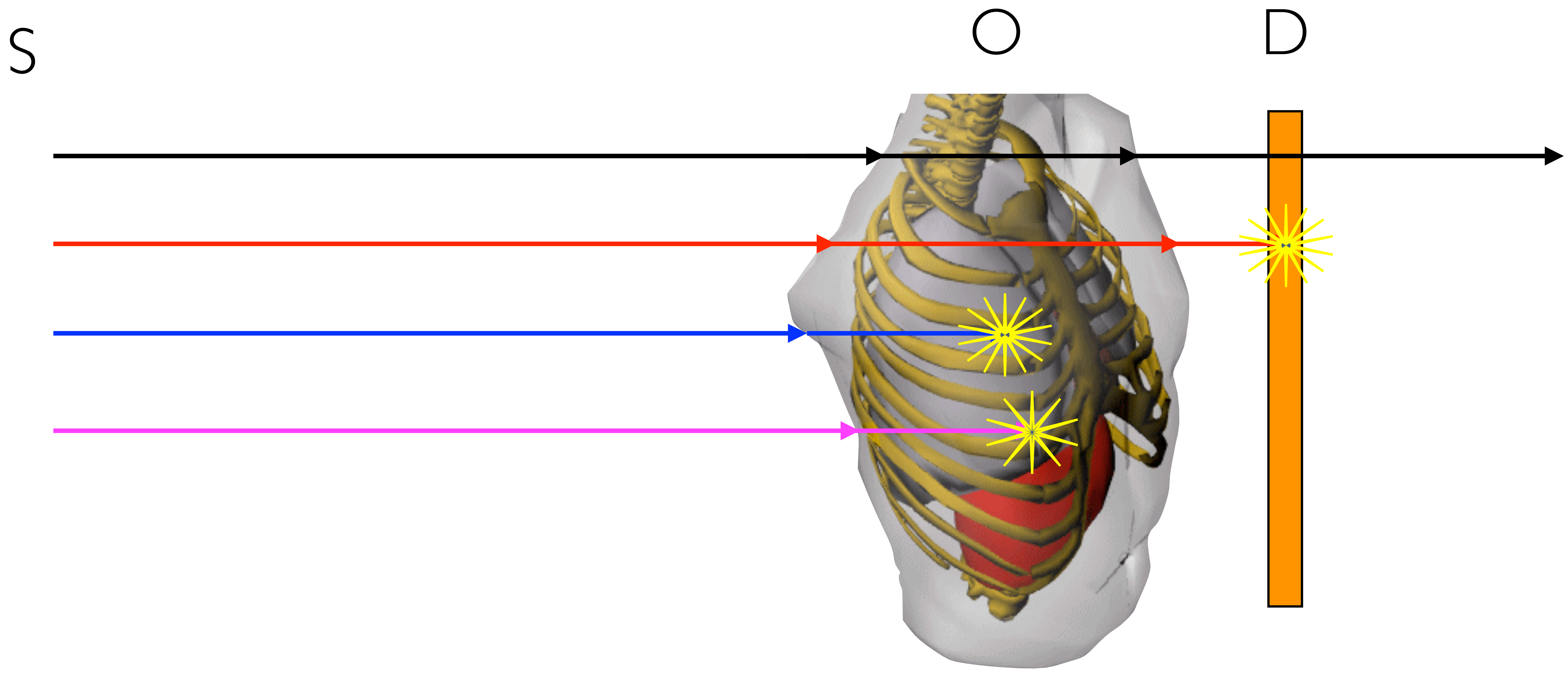
# Possible outcomes



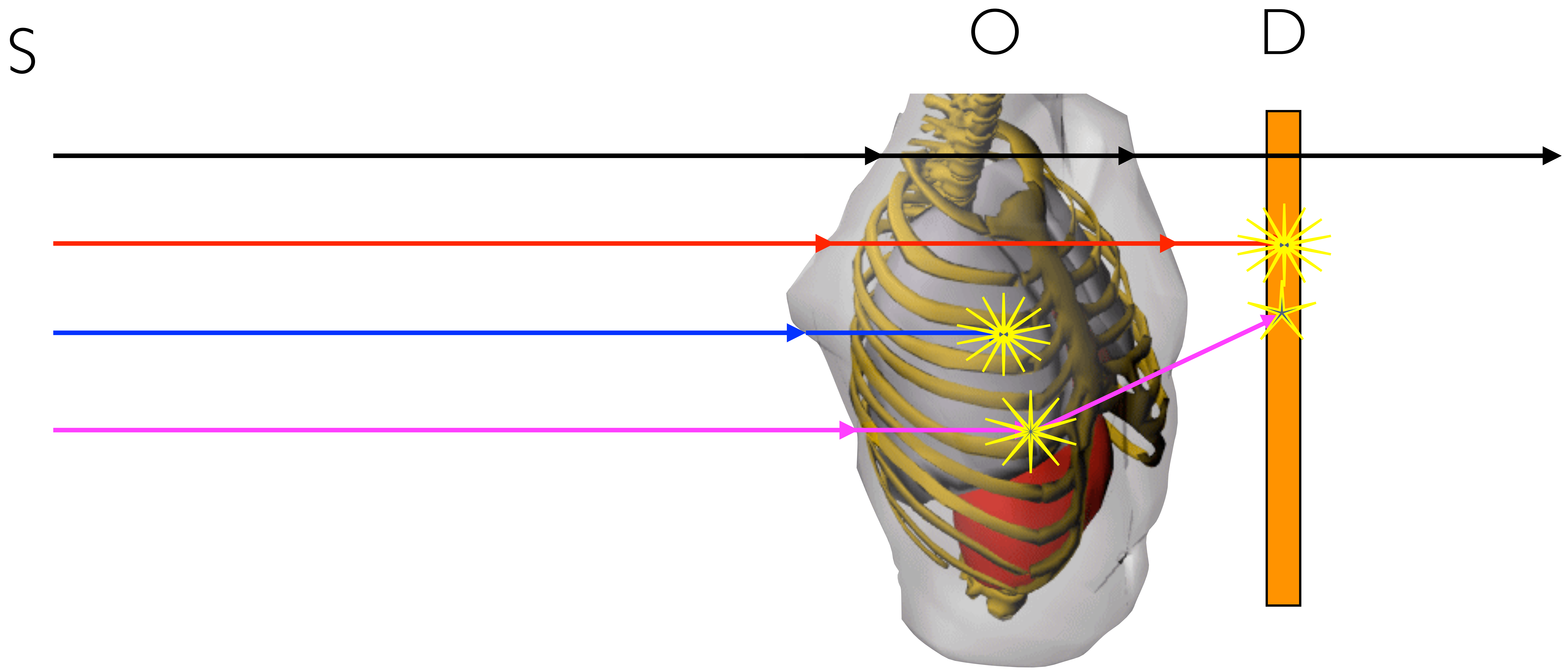
# Possible outcomes



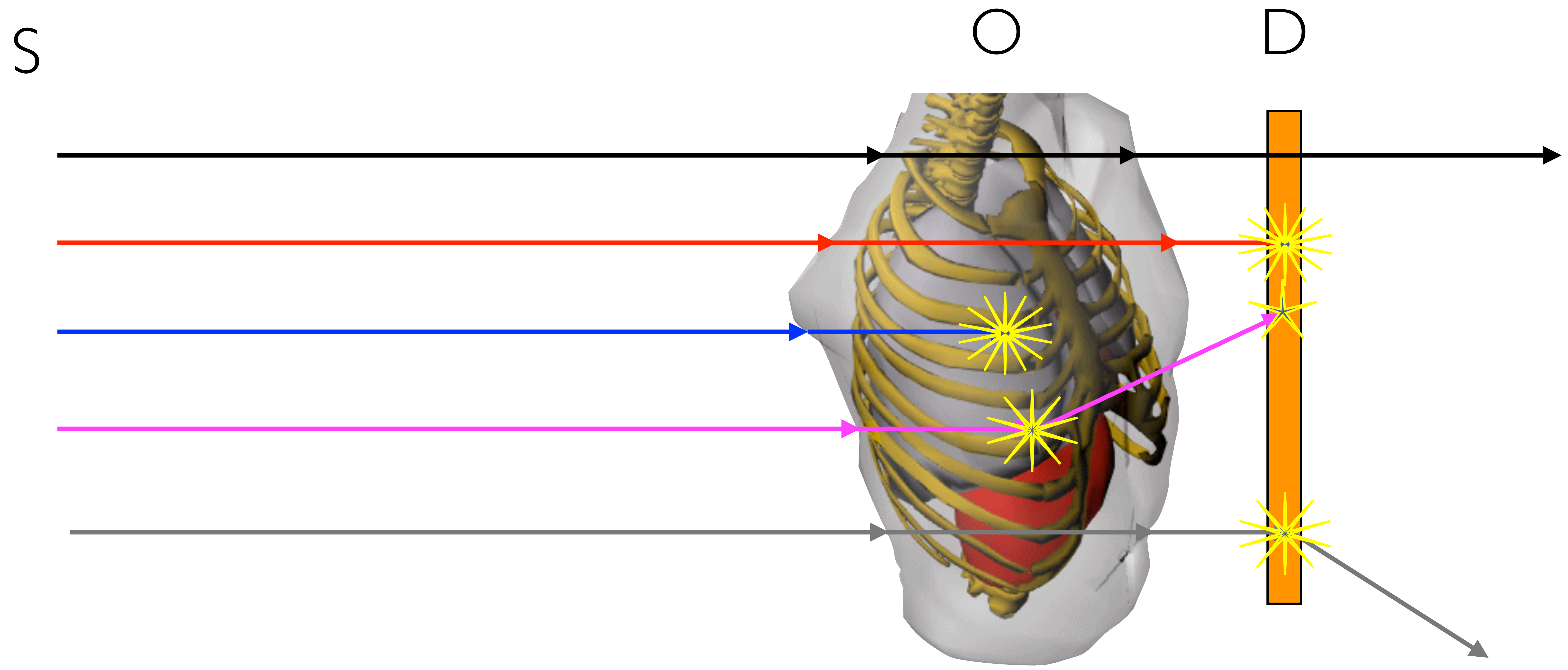
# Possible outcomes



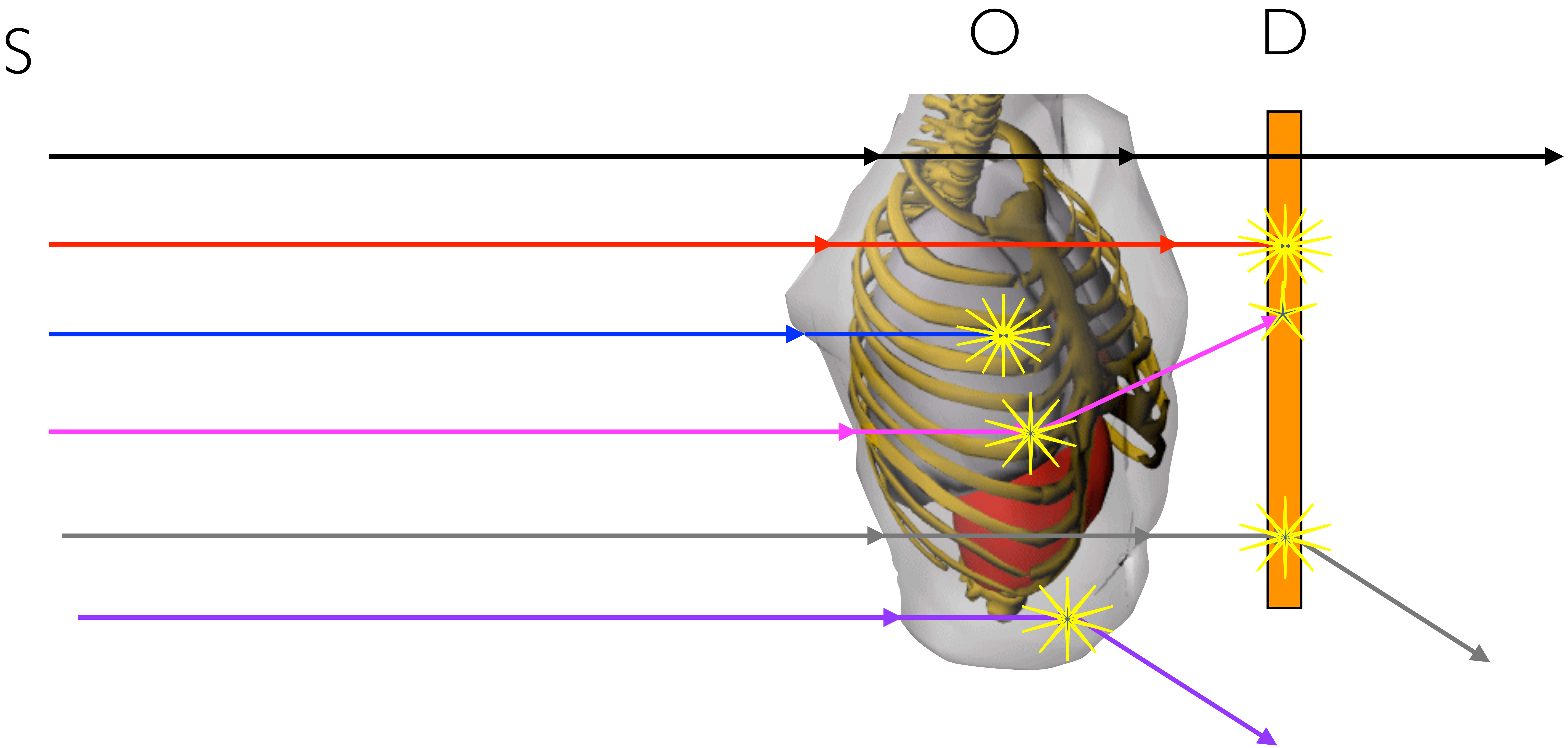
# Possible outcomes



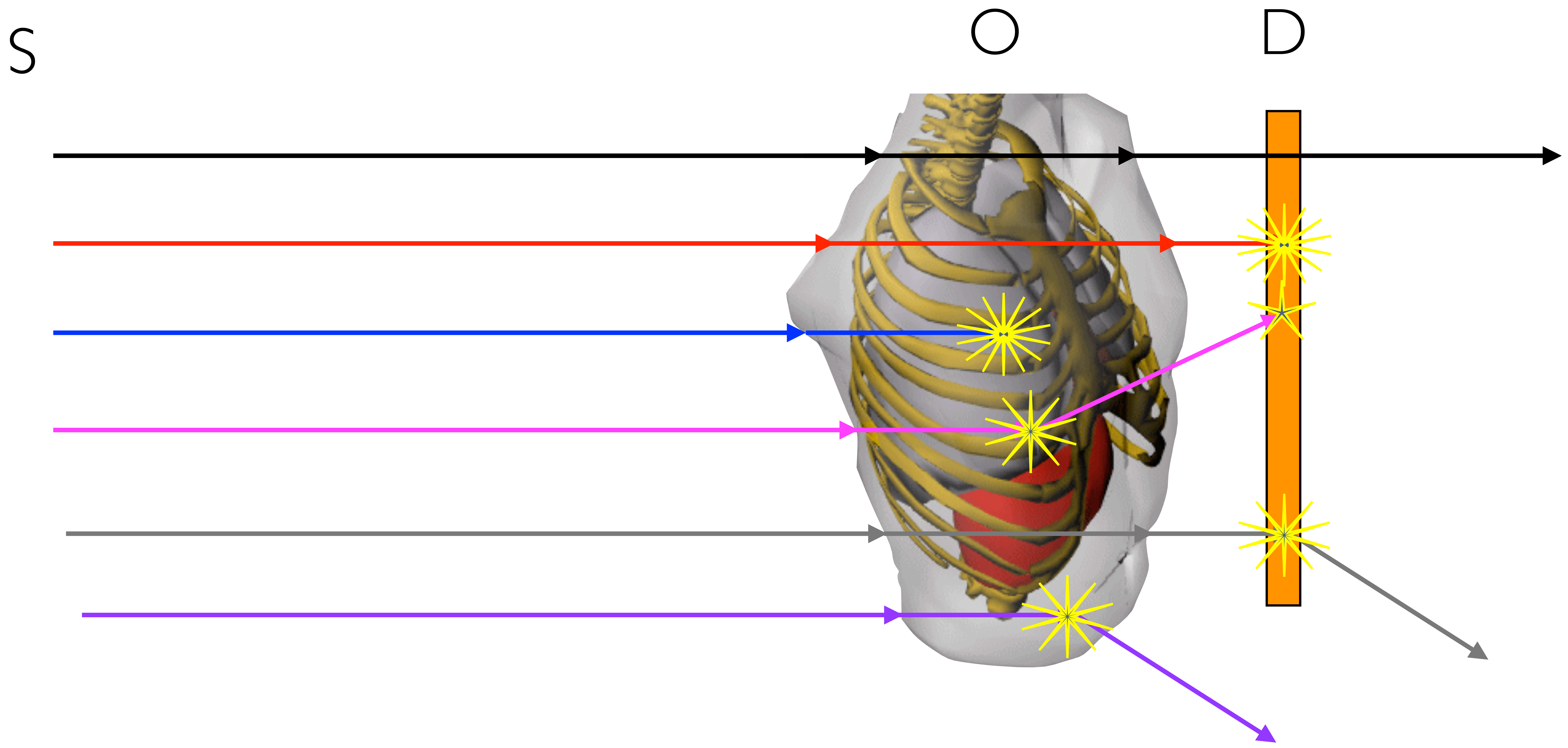
# Possible outcomes



# Possible outcomes

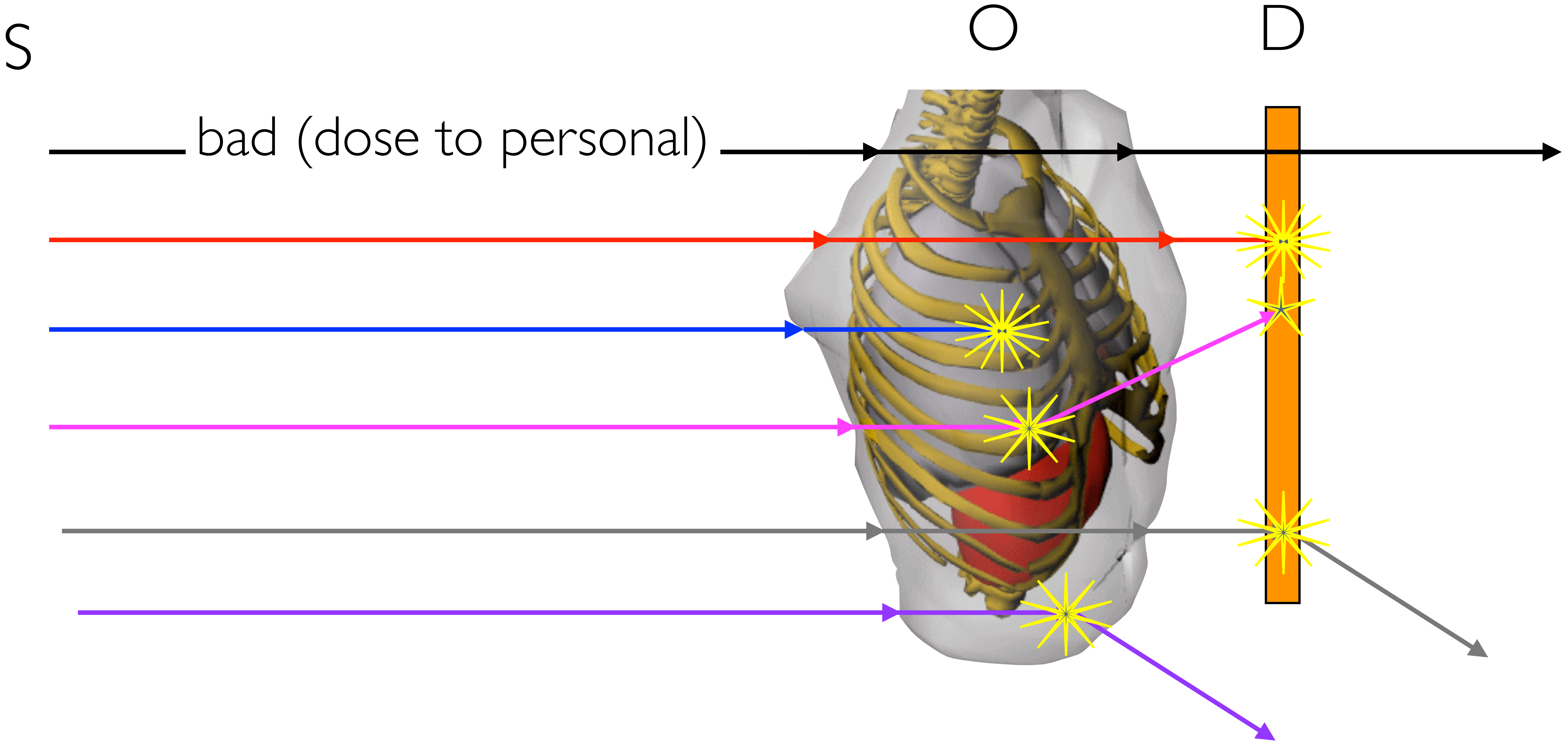


# Possible outcomes




Which are the "good "ones and which are the "bad" ones?

# Possible outcomes

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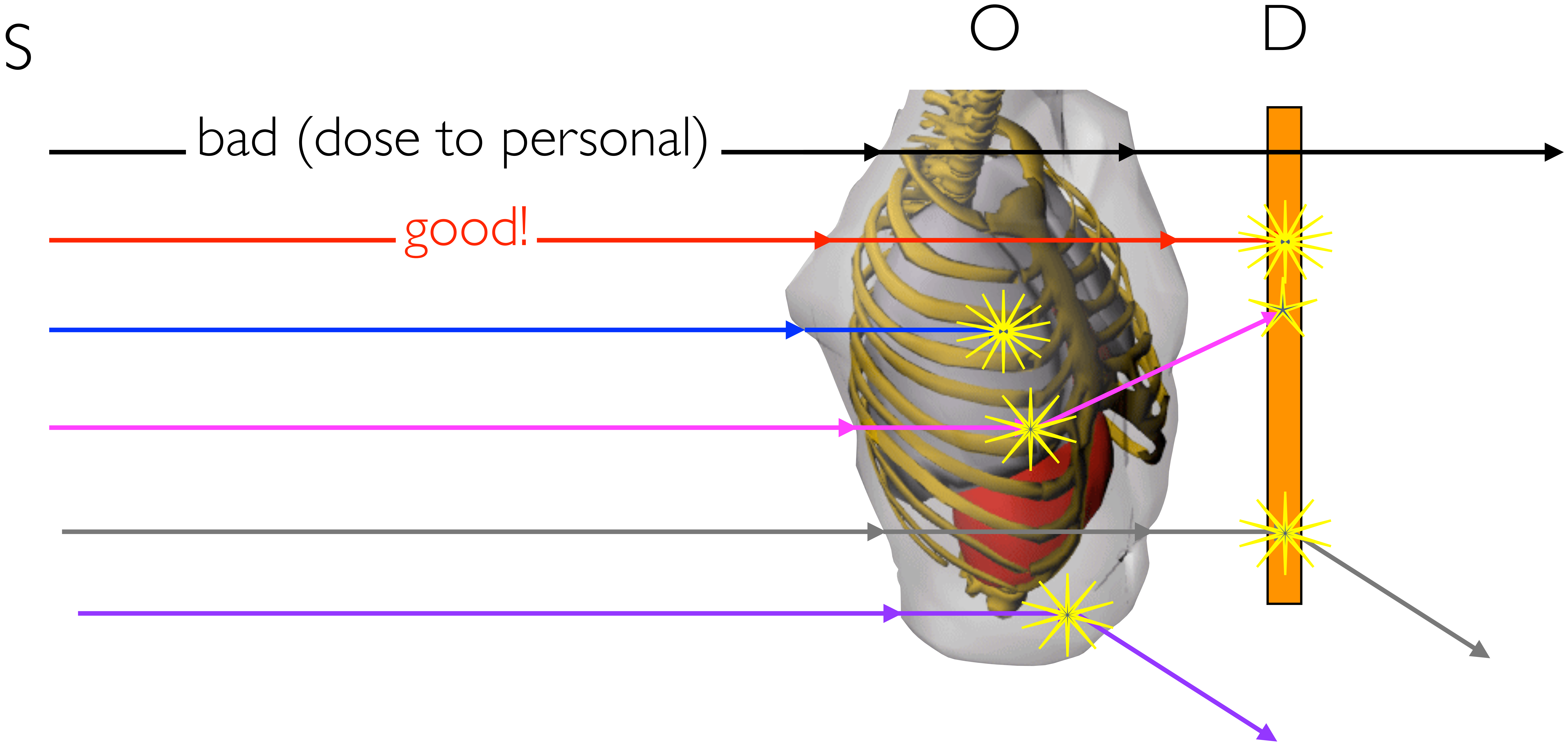
# Possible outcomes

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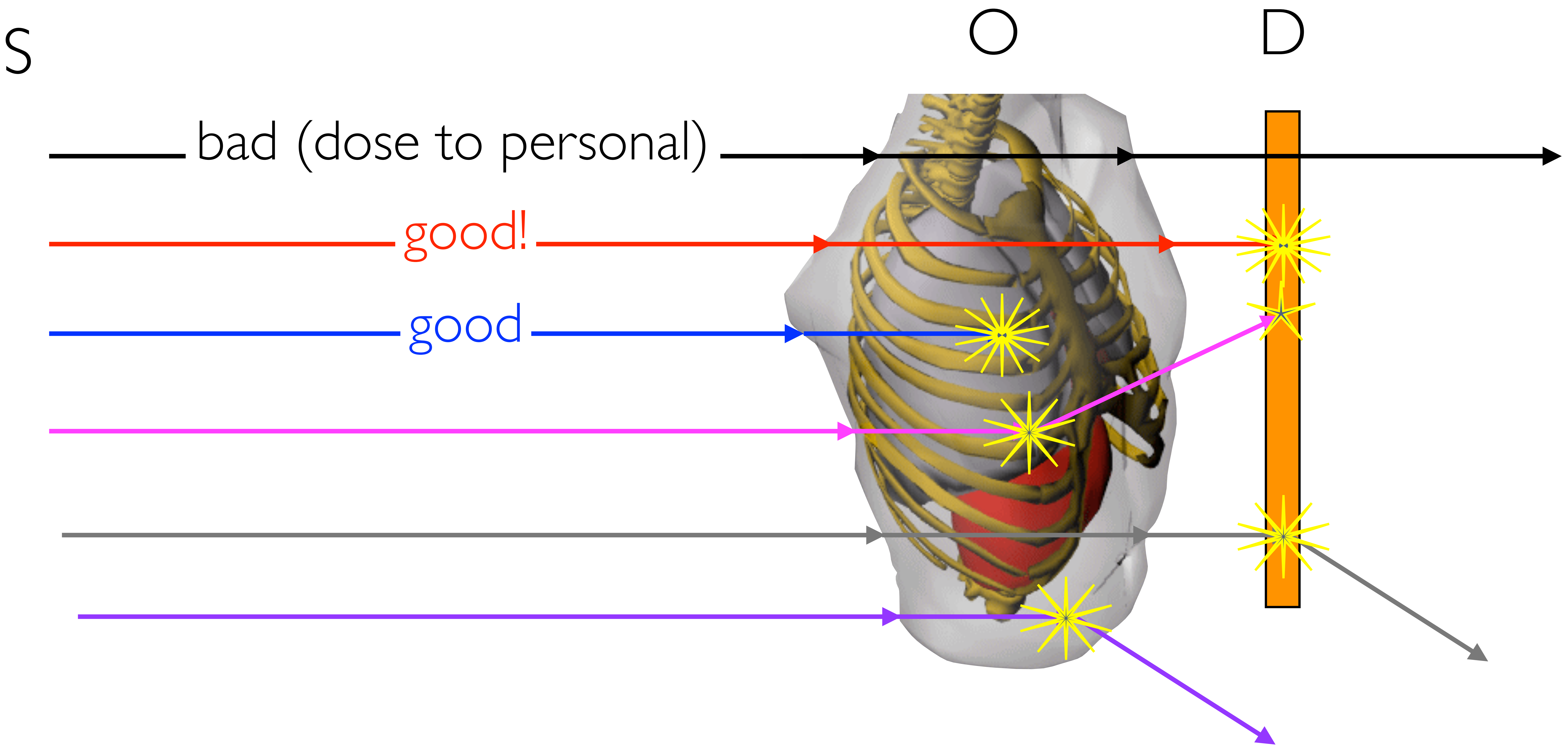
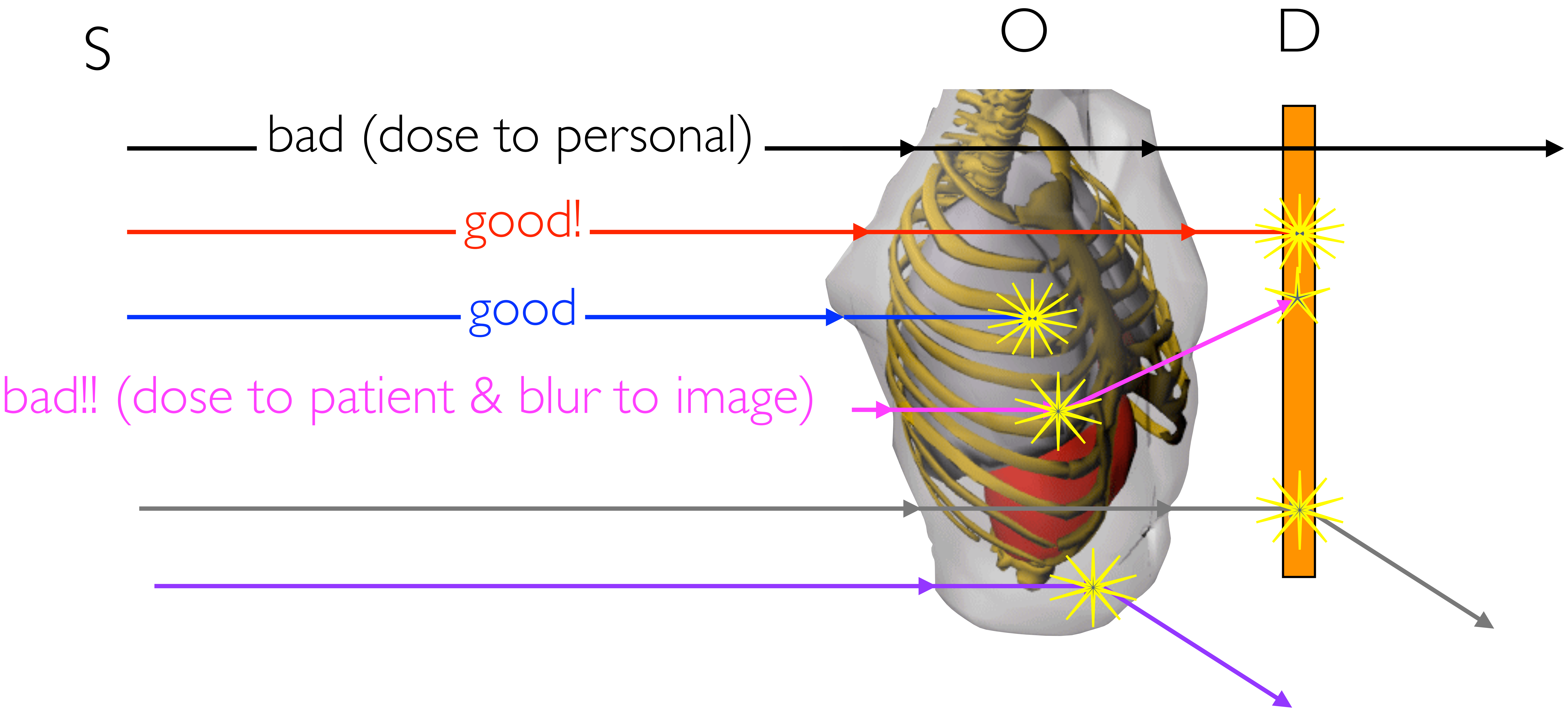
# Possible outcomes



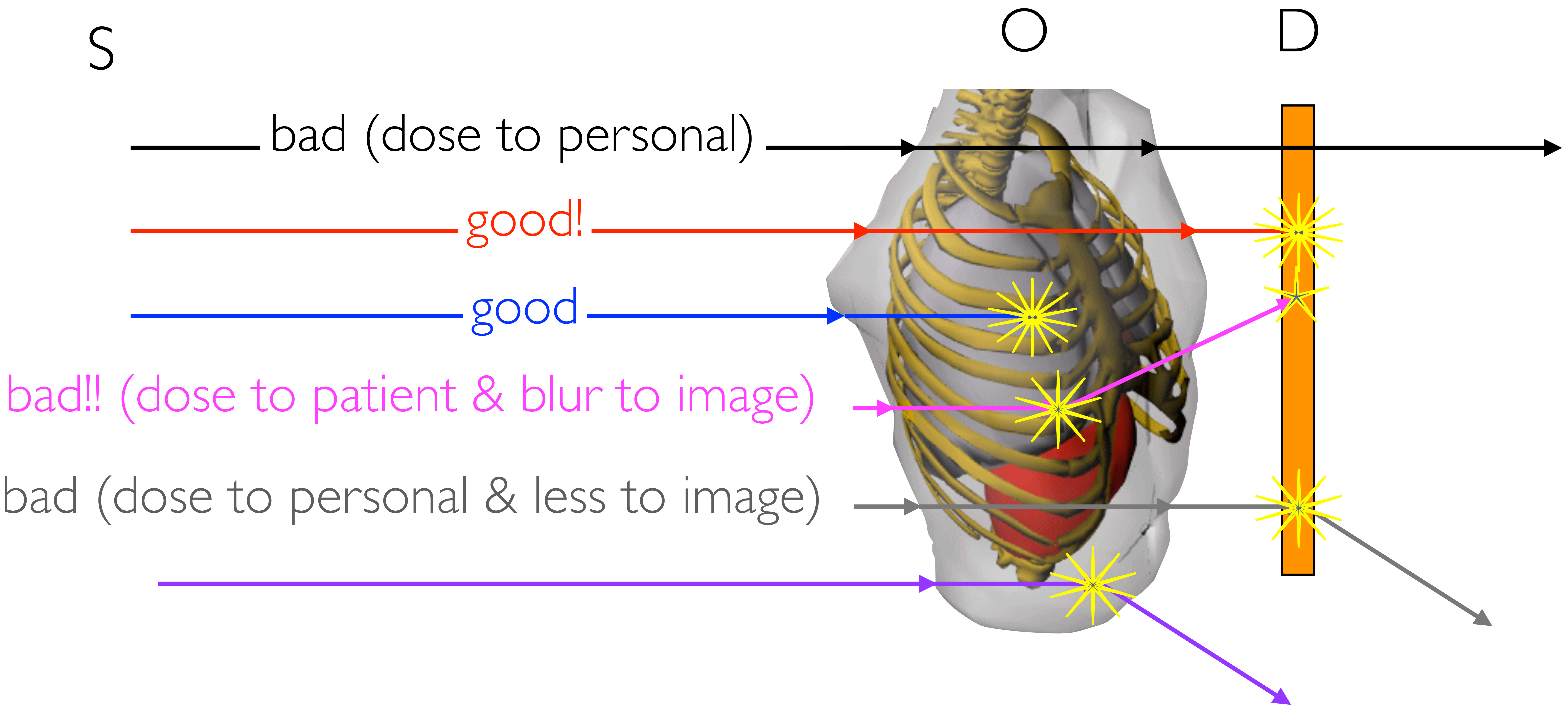

Which are the "good "ones and which are the "bad" ones?

# Possible outcomes



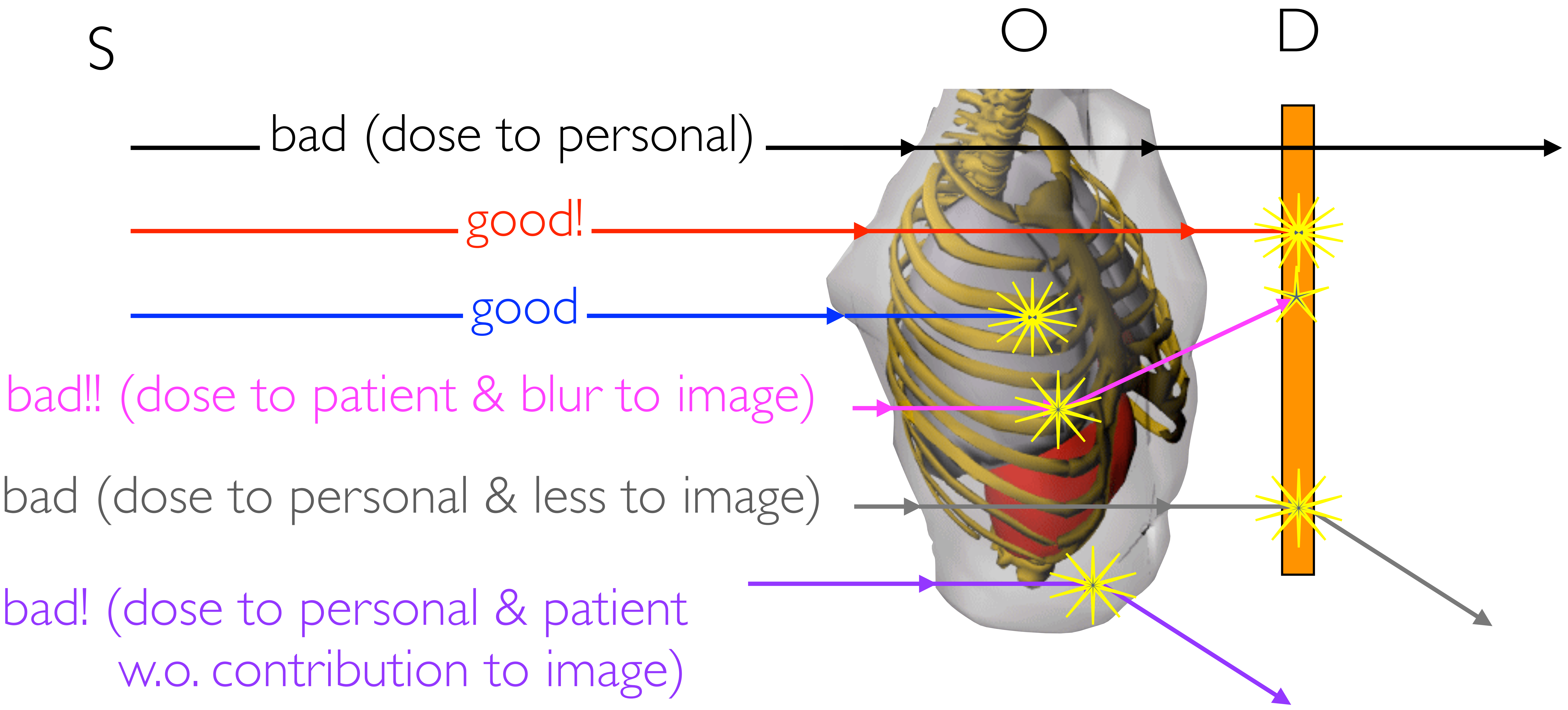

Which are the "good "ones and which are the "bad" ones?

# Possible outcomes

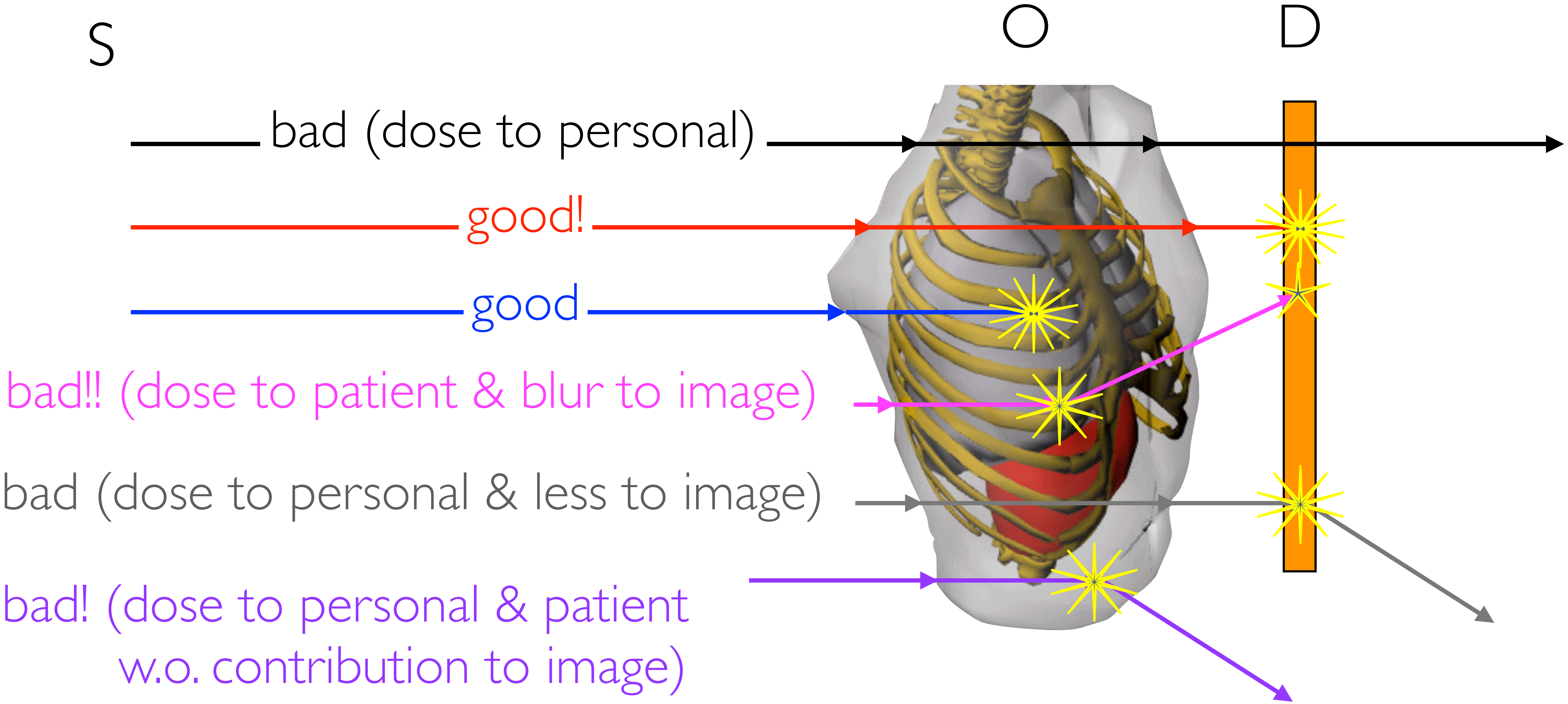



Which are the "good "ones and which are the "bad" ones?

# Possible outcomes



# Possible outcomes




Lessons to learn:

1. avoid compton in patient and detector!
2. x-rays should absorb ~100% in detector

Next we will talk about the elephant in the room: Noise!
This will add yet another factor to consider and will be an important player in distinguishing between object contrast and image contrast.

# Object contrast vs image contrast

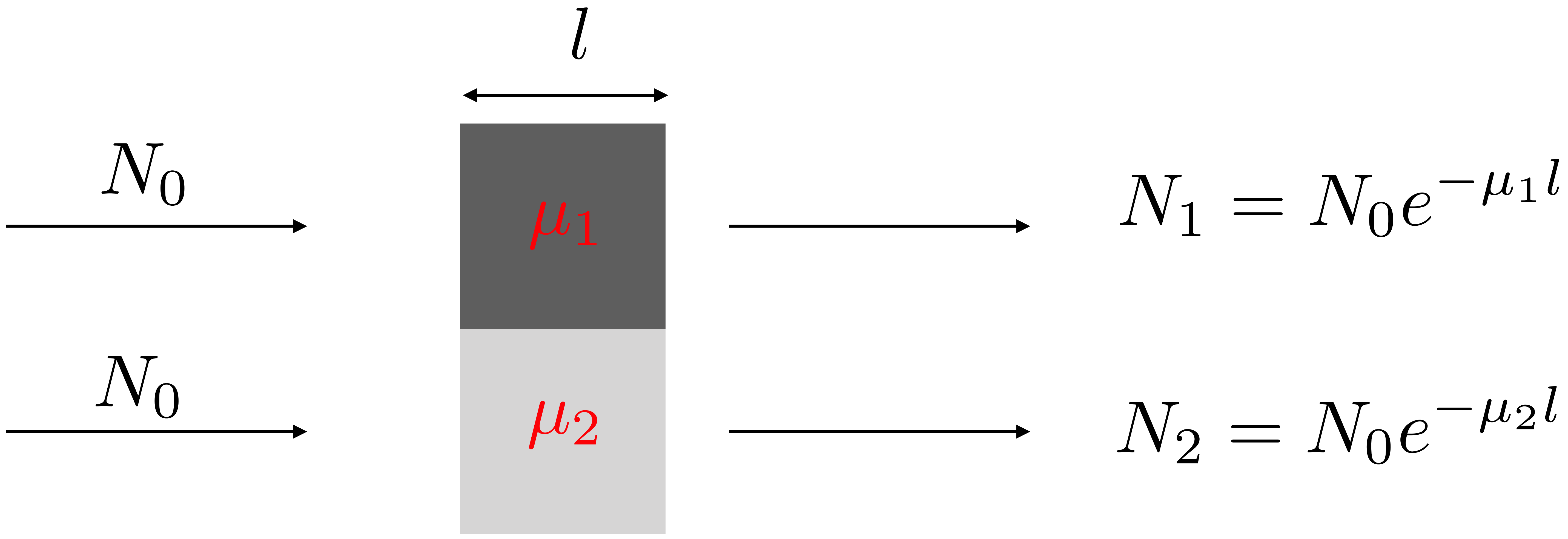
**Object contrast:** relative difference in attenuation between object and background

→ it is a property of the object and only the object!

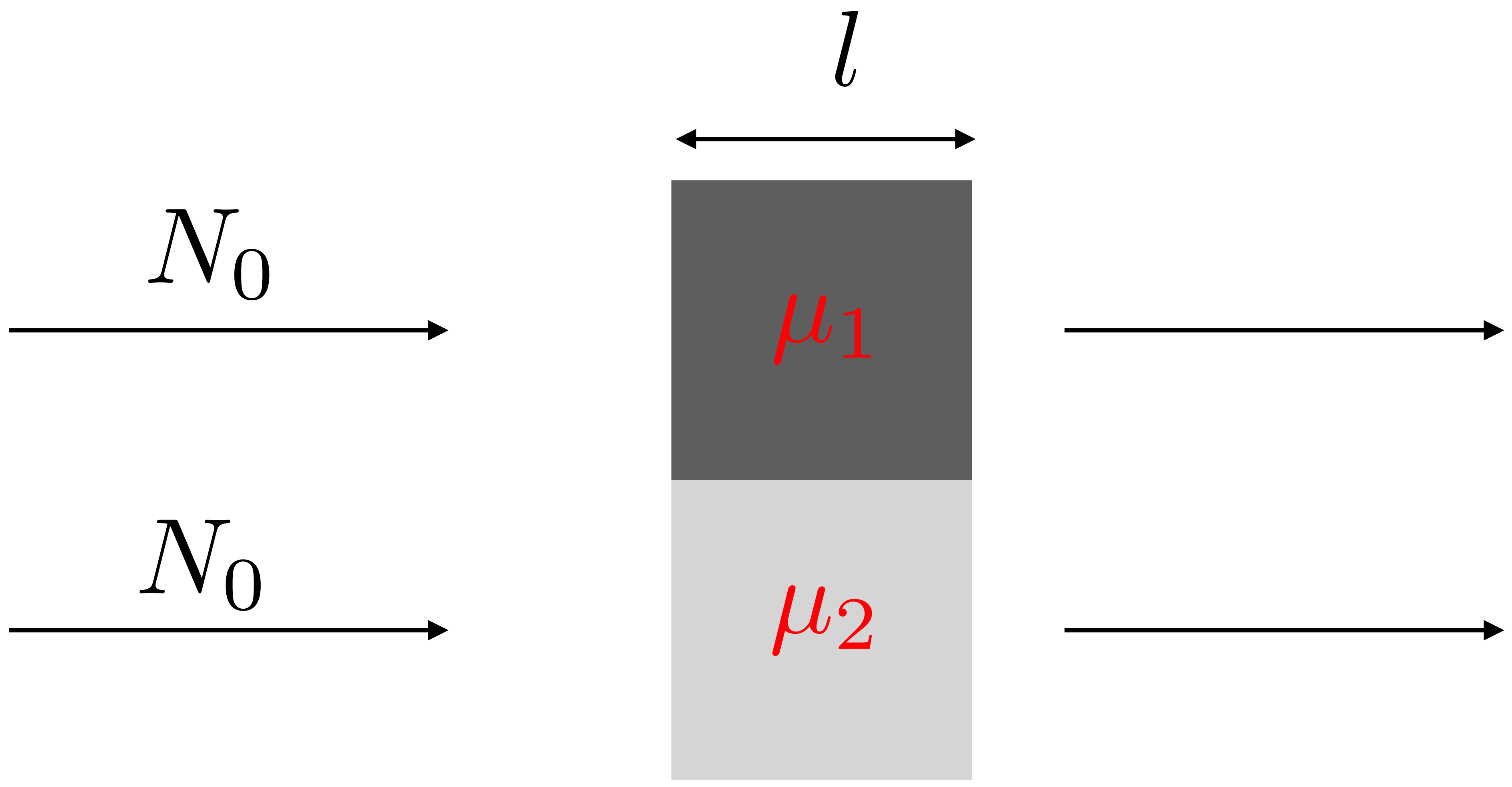
**Image contrast:** relative difference in grey scale or pixel value in the image between object and background

→ depends on the object **and** imaging *set up* (protocol + imaging system)

# Let's discuss a simple example



# Let's discuss a simple example

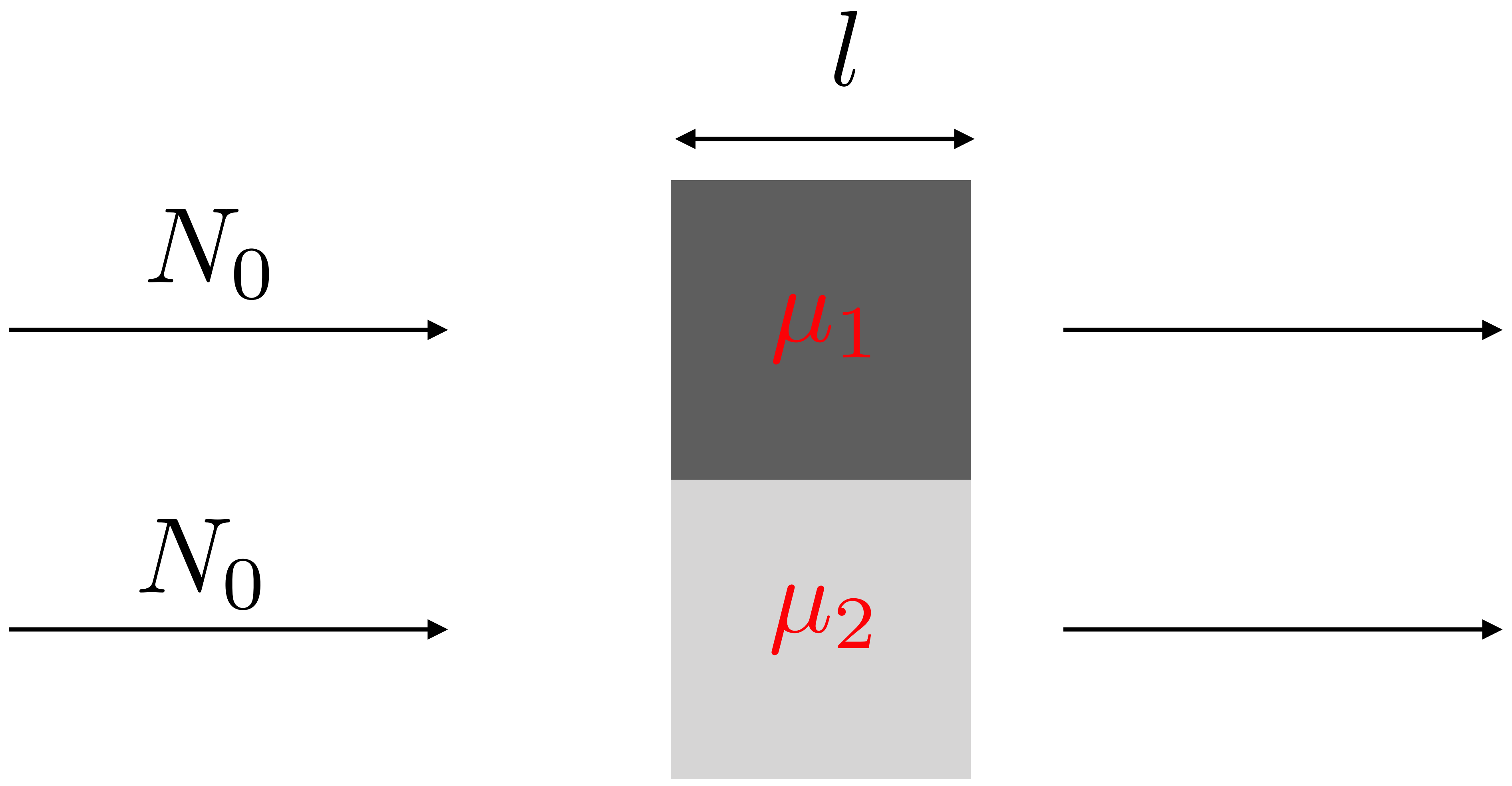



$$N_1 = N_0 e^{-\mu_1 l}$$

$$N_2 = N_0 e^{-\mu_2 l}$$

$$OC = \frac{N_1 - N_2}{N_1} = \frac{N_0 (e^{-\mu_1 l} - e^{-\mu_2 l})}{N_0 e^{-\mu_1 l}} = 1 - e^{-(\mu_2 - \mu_1) l}$$

# Let's discuss a simple example




$$N_1 = N_0 e^{-\mu_1 l}$$

$$N_2 = N_0 e^{-\mu_2 l}$$

size of object

$$OC = \frac{N_1 - N_2}{N_1} = \frac{N_0(e^{-\mu_1 l} - e^{-\mu_2 l})}{N_0 e^{-\mu_1 l}} = 1 - e^{-(\mu_2 - \mu_1) l}$$

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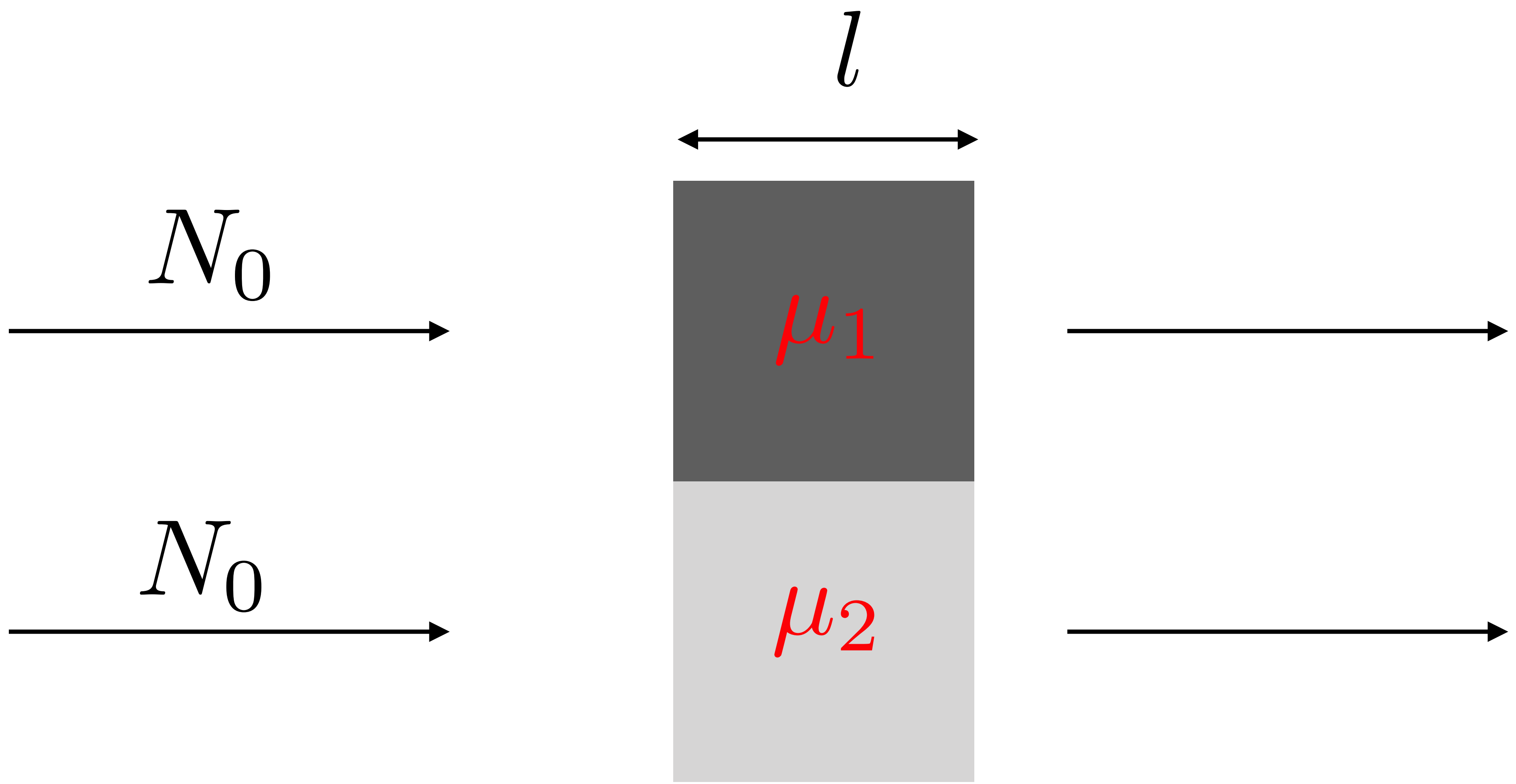


$$N_1 = N_0 e^{-\mu_1 l}$$

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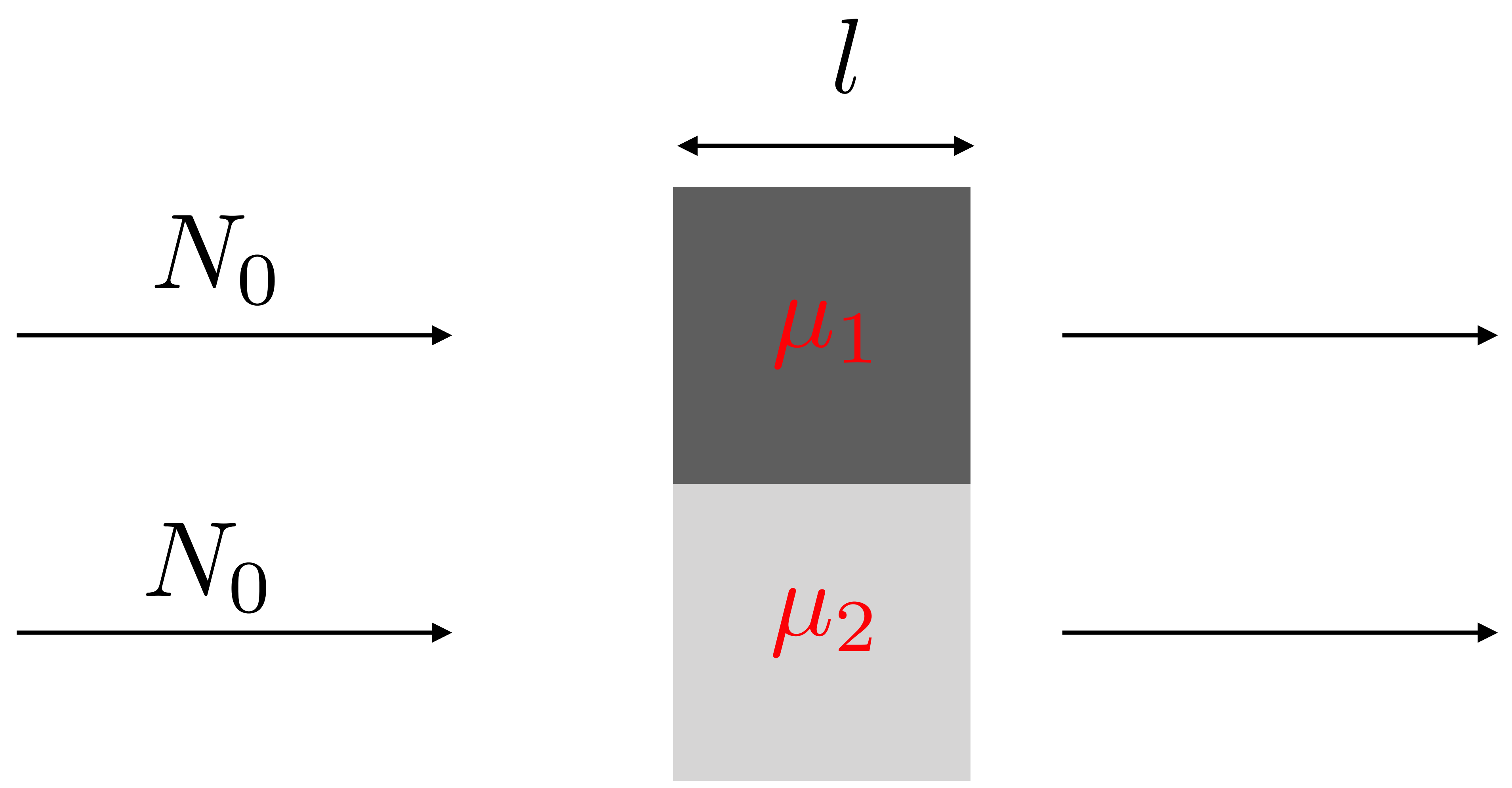
attenuation difference

# Let's discuss a simple example

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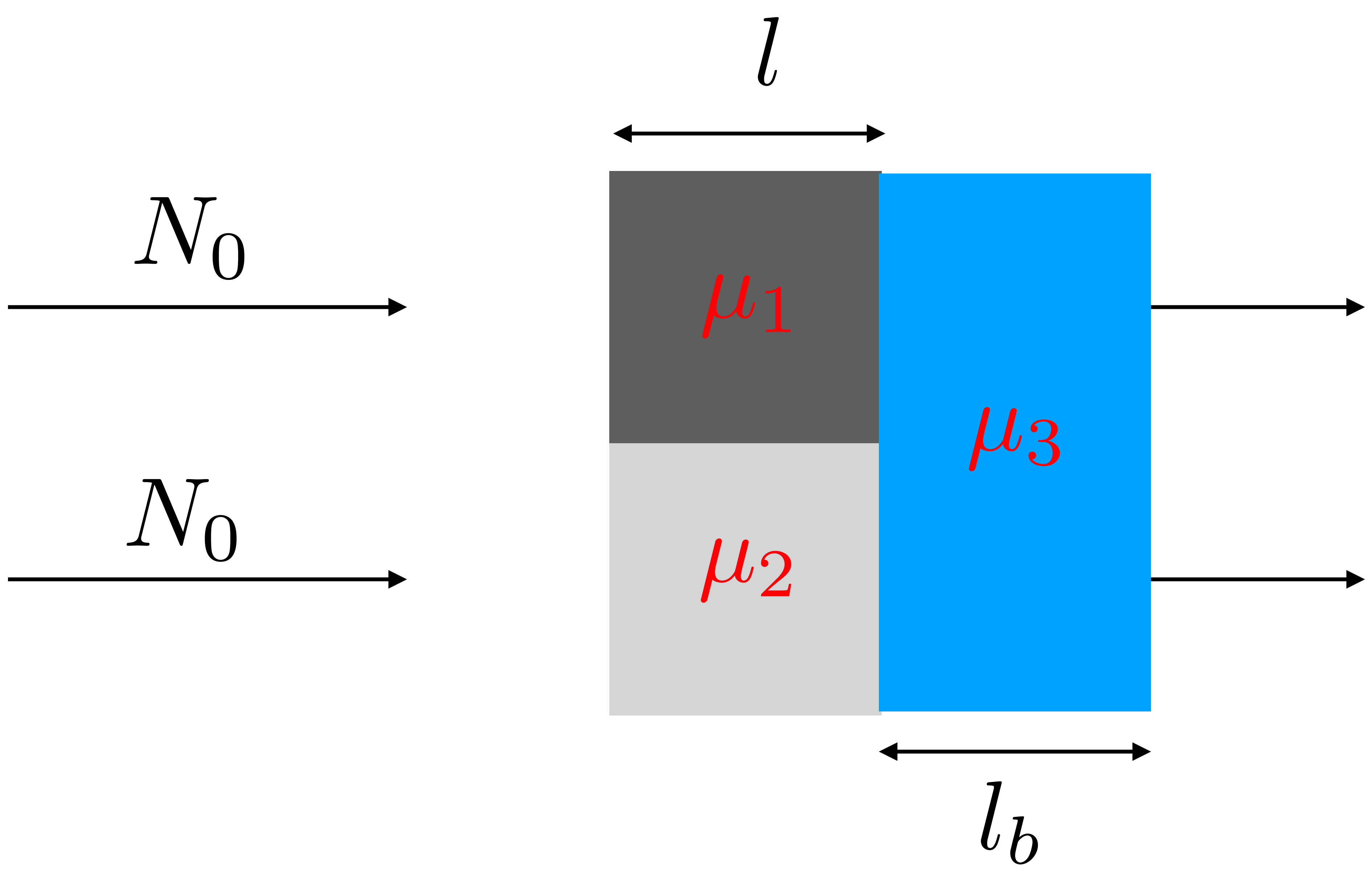
attenuation difference

independent on number of photons!

# Let's discuss a simple example

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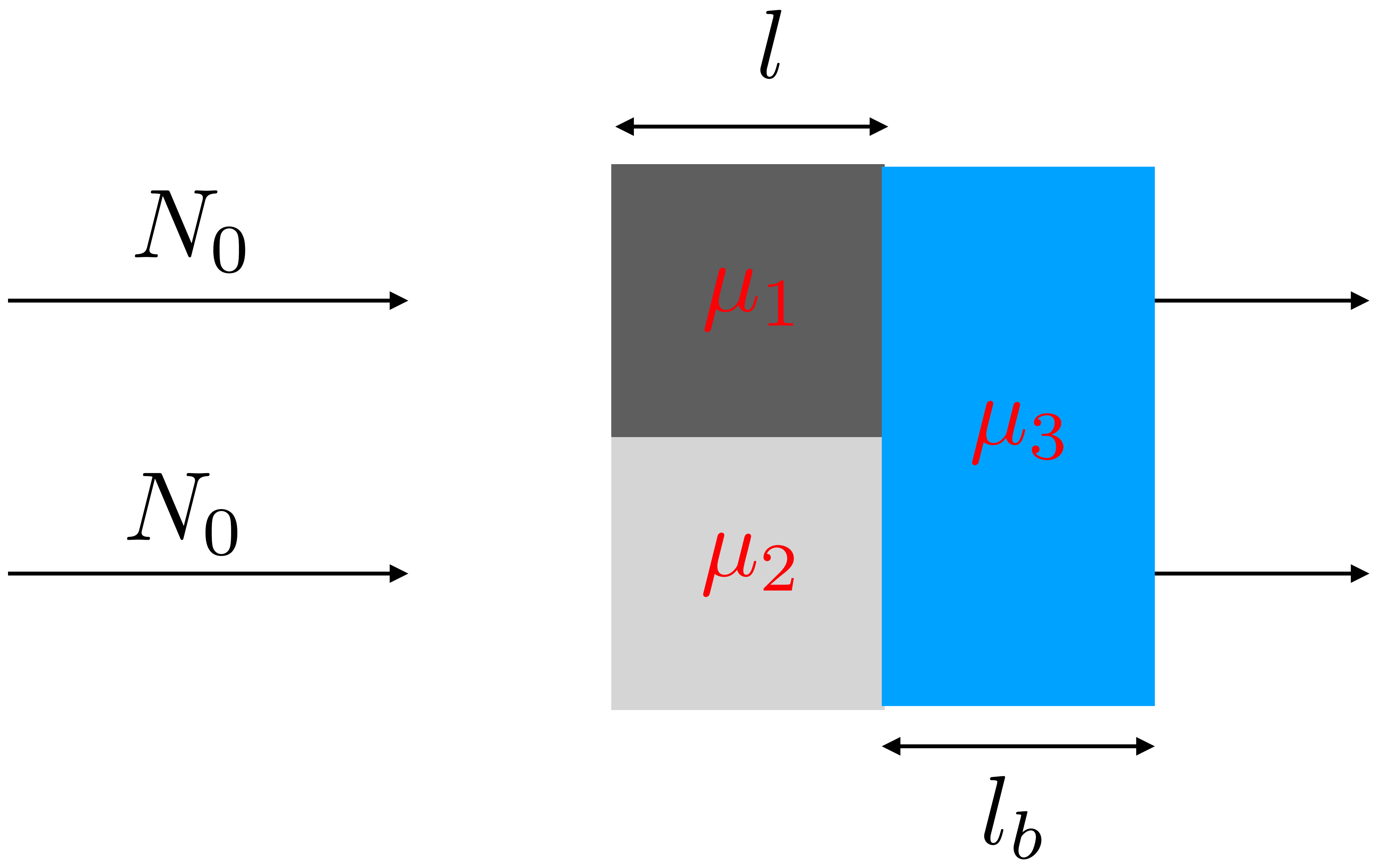
size of object

attenuation difference

independent on number of photons!

# Let's discuss a simple example




$$N_1 = N_0 e^{-\mu_1 l} \; e^{-\mu_3 l_b}$$

$$N_2 = N_0 e^{-\mu_2 l} \; e^{-\mu_3 l_b}$$

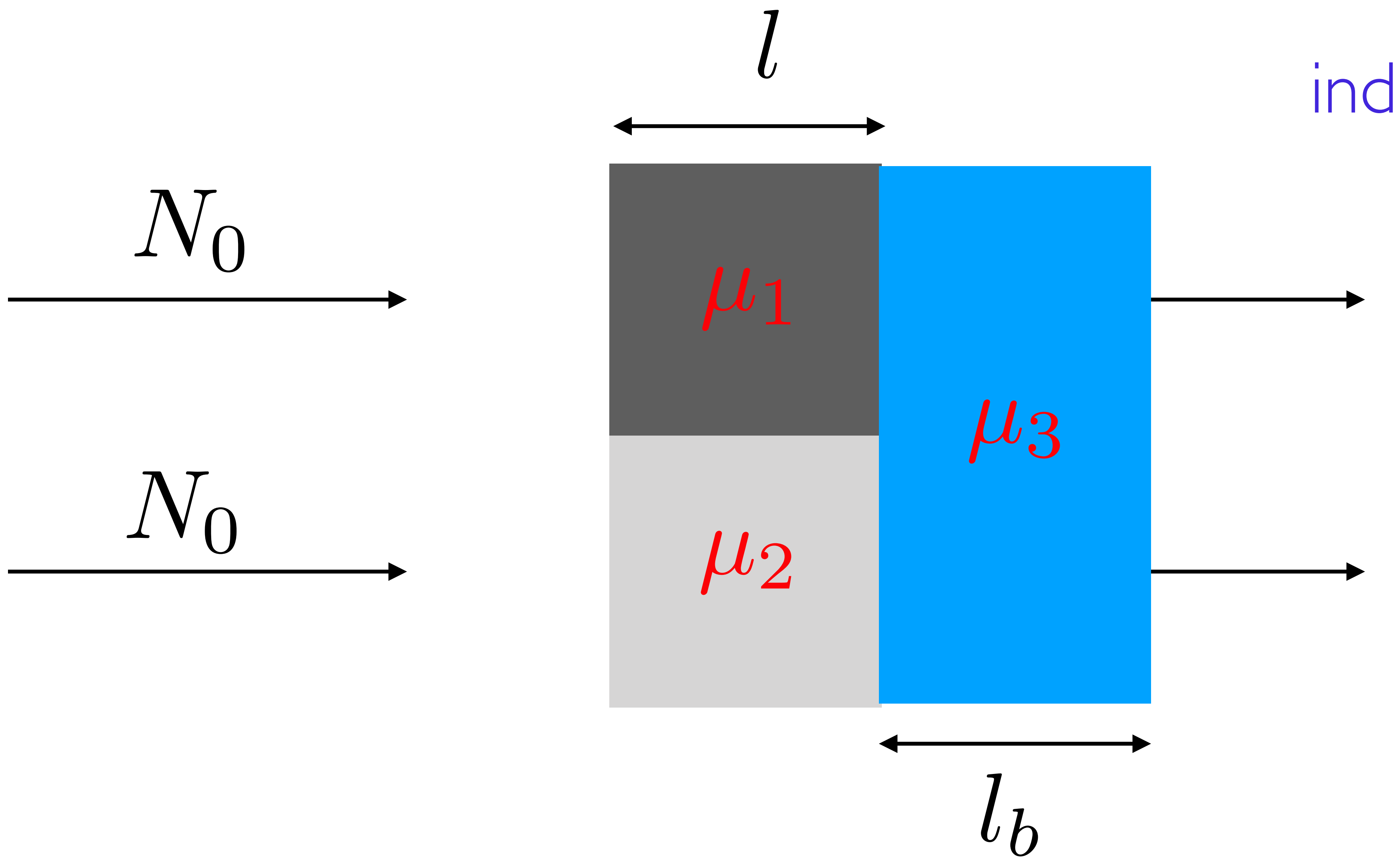
size of object

$$OC = \frac{N_1 - N_2}{N_1} = \frac{N_0 (e^{-\mu_1 l} - e^{-\mu_2 l})}{N_0 e^{-\mu_1 l}} = 1 - e^{-(\mu_2 - \mu_1) l}$$

attenuation difference

independent on number of photons!

# Let's discuss a simple example




independent on background!!!!11112121212

$$N_1 = N_0 e^{-\mu_1 l} \; e^{-\mu_3 l_b}$$

$$N_2 = N_0 e^{-\mu_2 l} \; e^{-\mu_3 l_b}$$

size of object

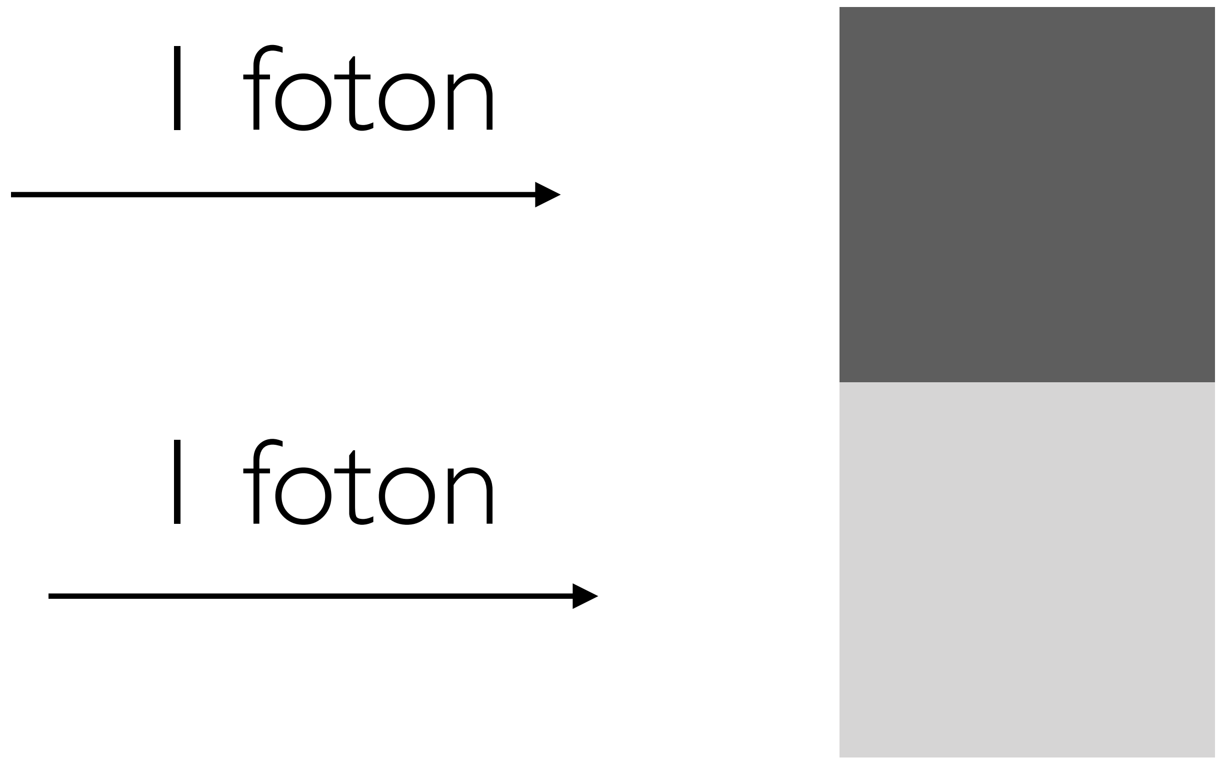
$$OC = \frac{N_1 - N_2}{N_1} = \frac{N_0 (e^{-\mu_1 l} - e^{-\mu_2 l})}{N_0 e^{-\mu_1 l}} = 1 - e^{-(\mu_2 - \mu_1) l}$$

attenuation difference

independent on number of photons!

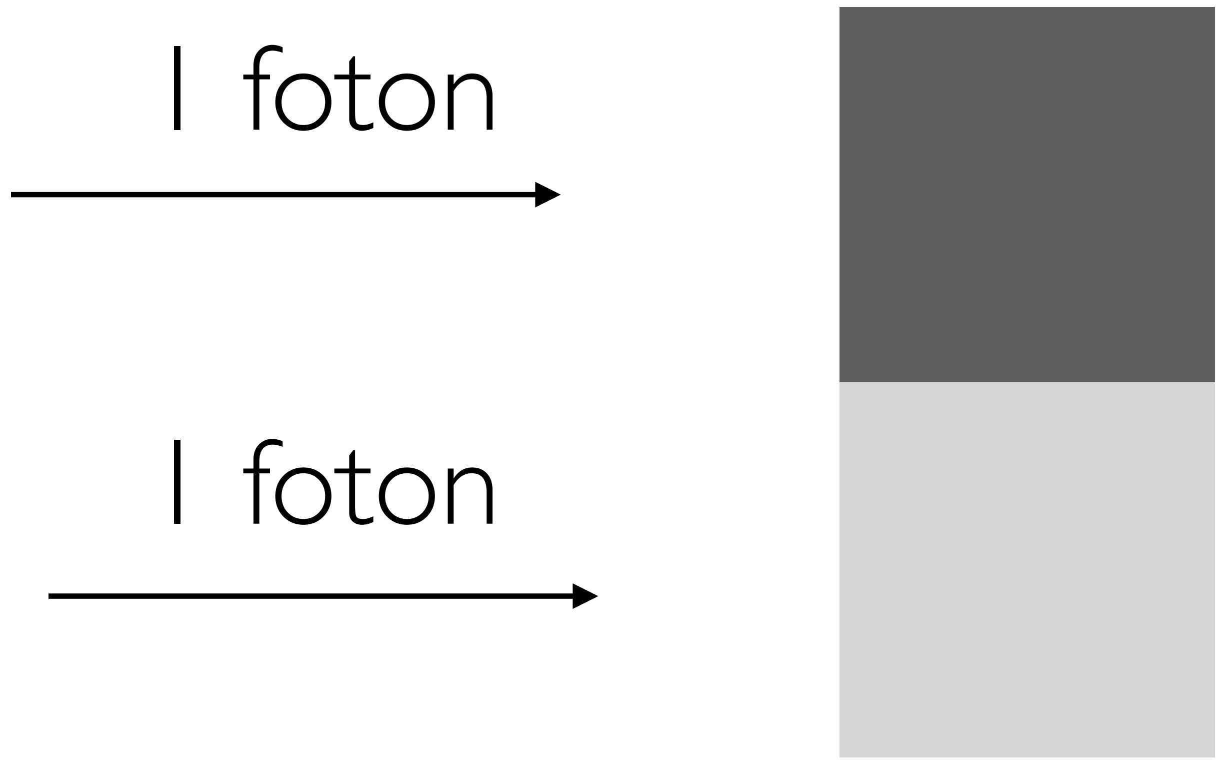
# Let’s do a “*reality check*”

possible outcomes



# Let’s do a “*reality check*”

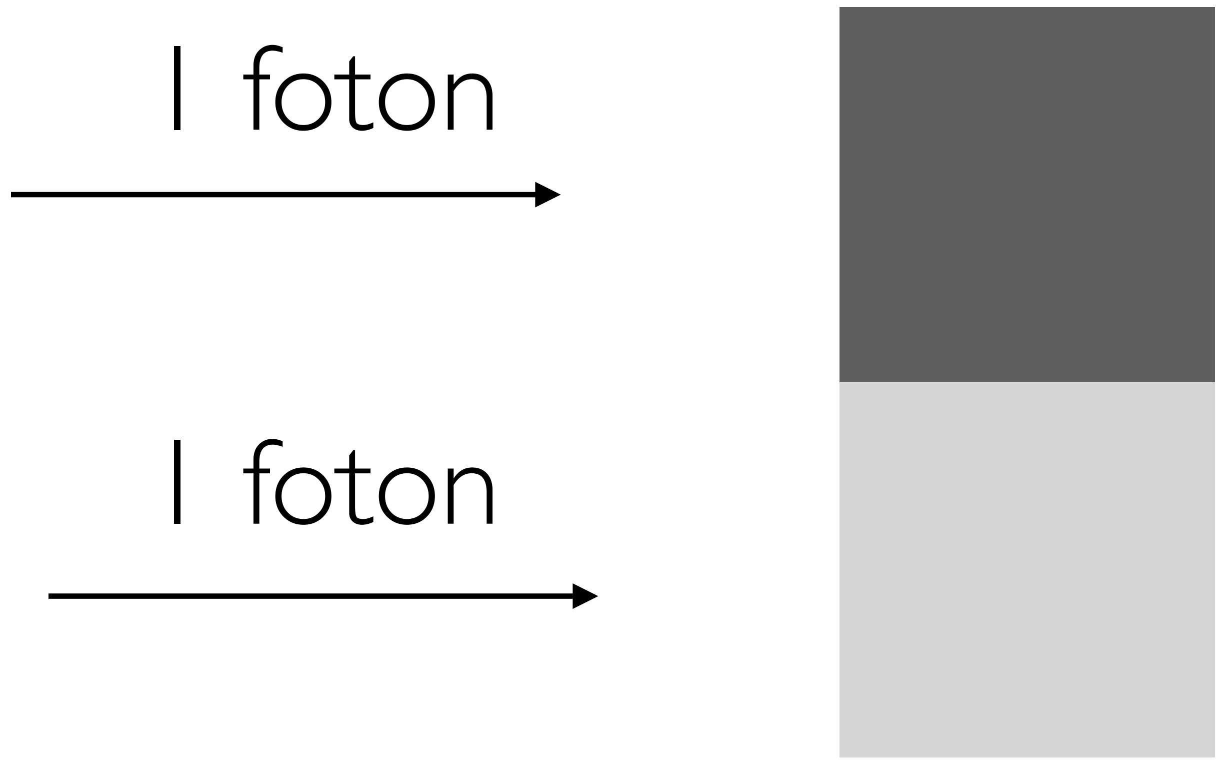
possible outcomes




0

0

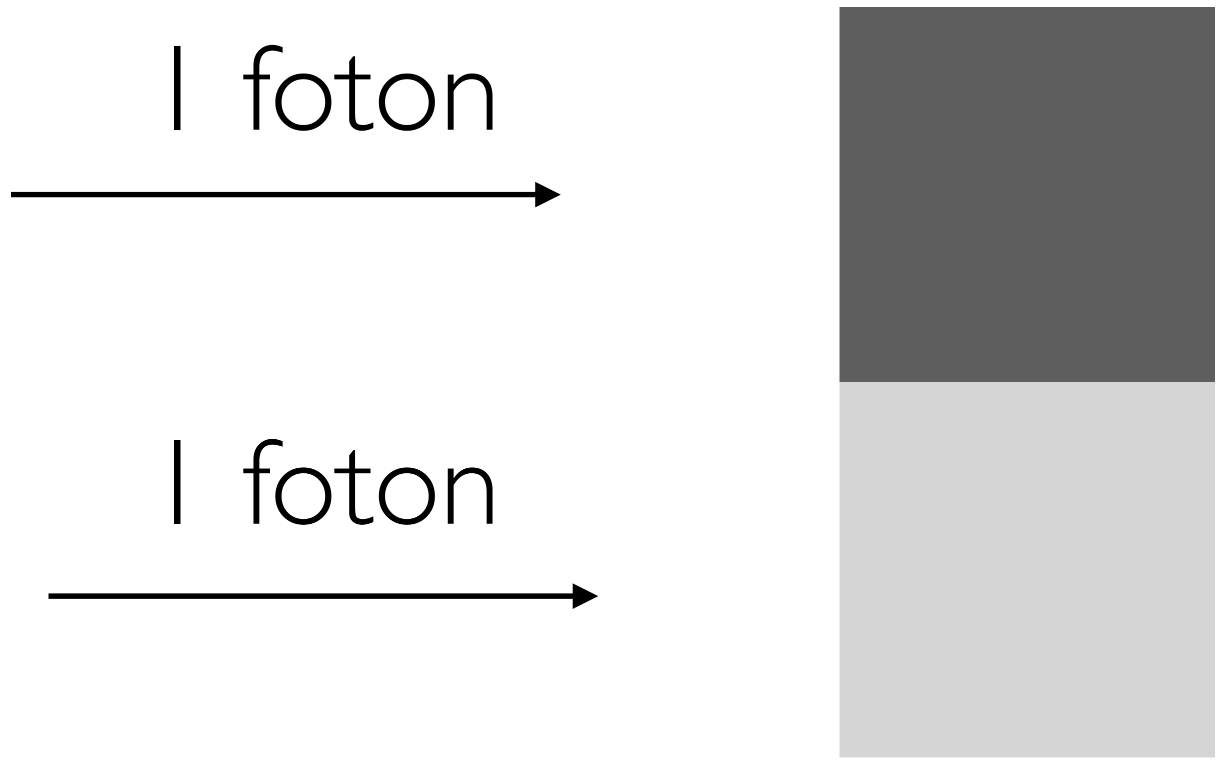
Let's do a "*reality check*"




possible outcomes

| | |
|---|---|
| 0 | 1 |
| 0 | 0 |

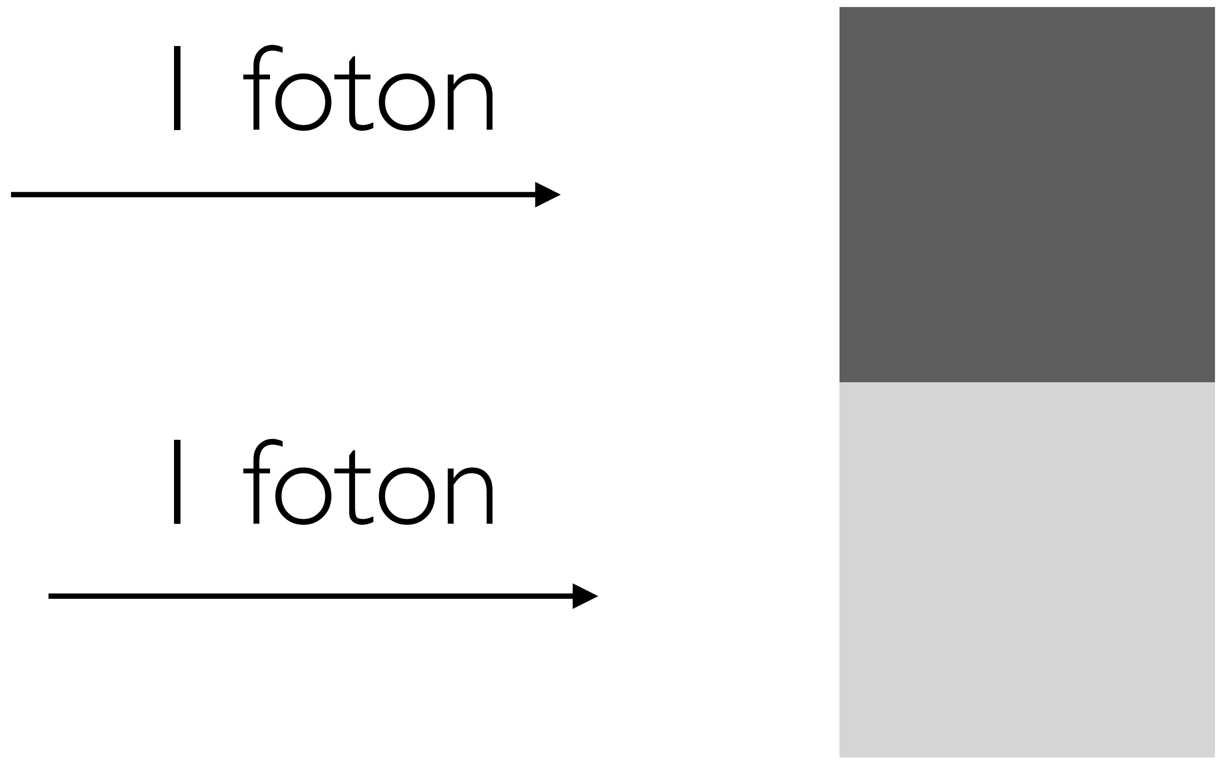
# Let's do a "*reality check*"




possible outcomes

| | | |
|---|---|---|
| 0 | 1 | 0 |
| 0 | 0 | 1 |

# Let’s do a “*reality check*”

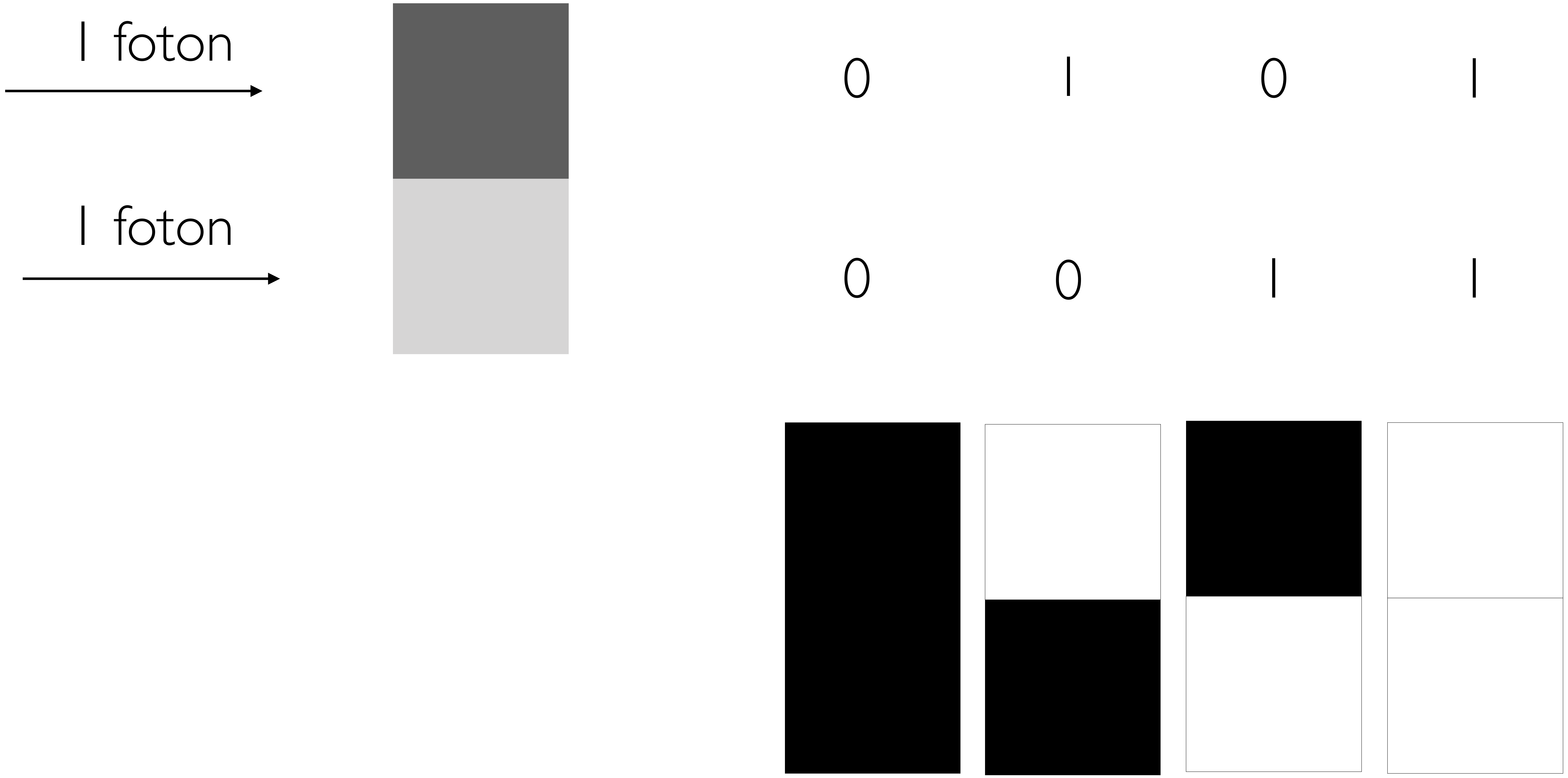



possible outcomes

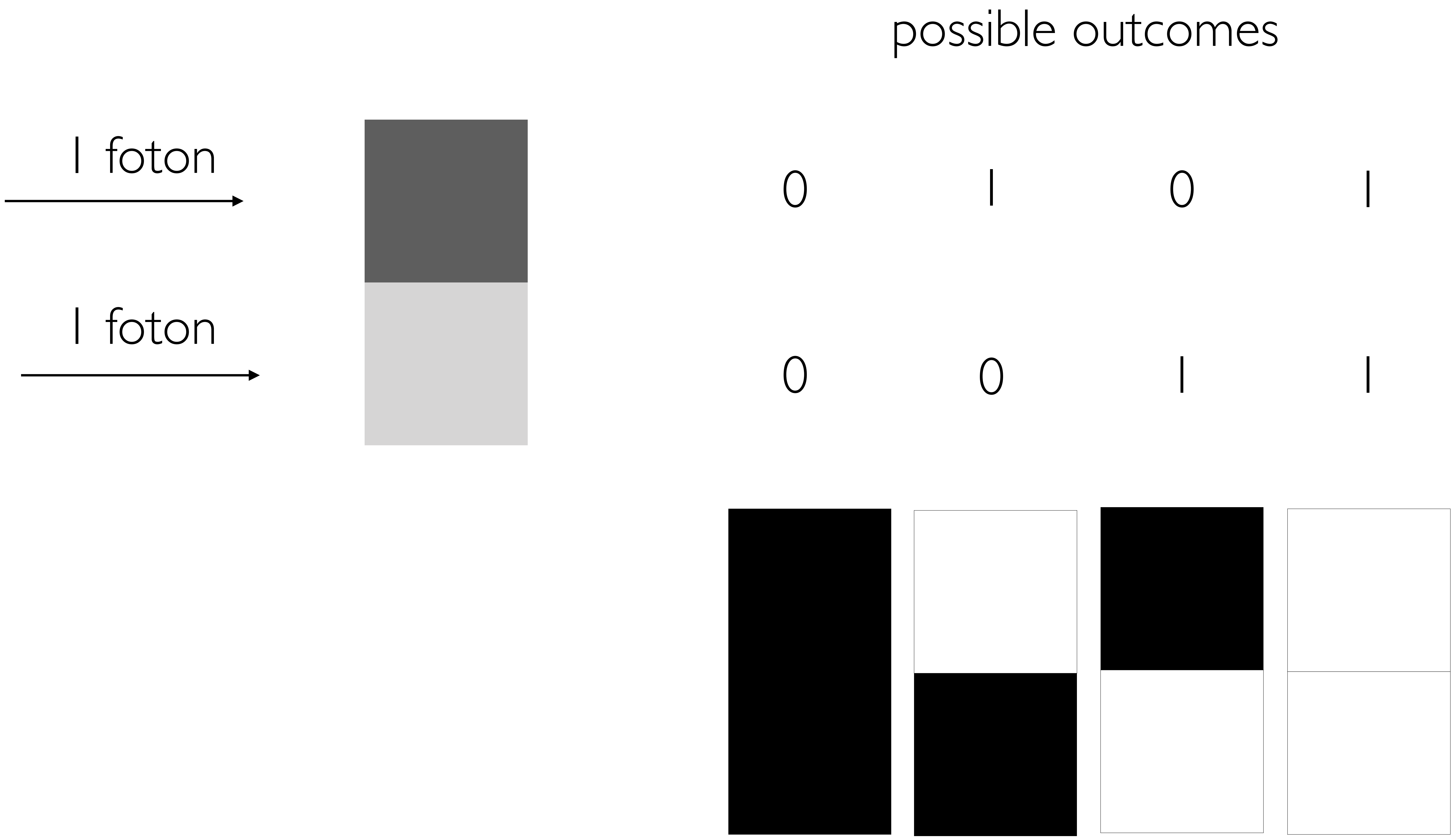
| | | | |
|---|---|---|---|
| 0 | 1 | 0 | 1 |
| 0 | 0 | 1 | 1 |

# Let's do a "*reality check*"

possible outcomes



Let's do a "*reality check*"




Since the two plates have different attenuation => the 4 outcomes have not the same probability, but wit
measurement this will not show!

simulation time!

All have the same object contrast!

object

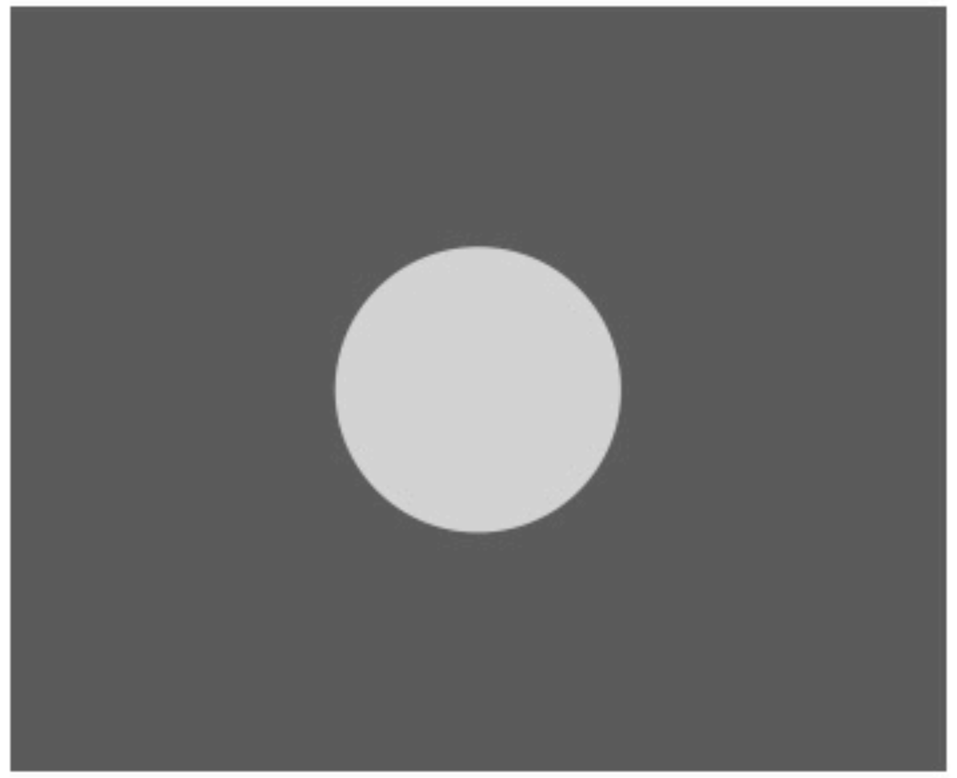


Image A

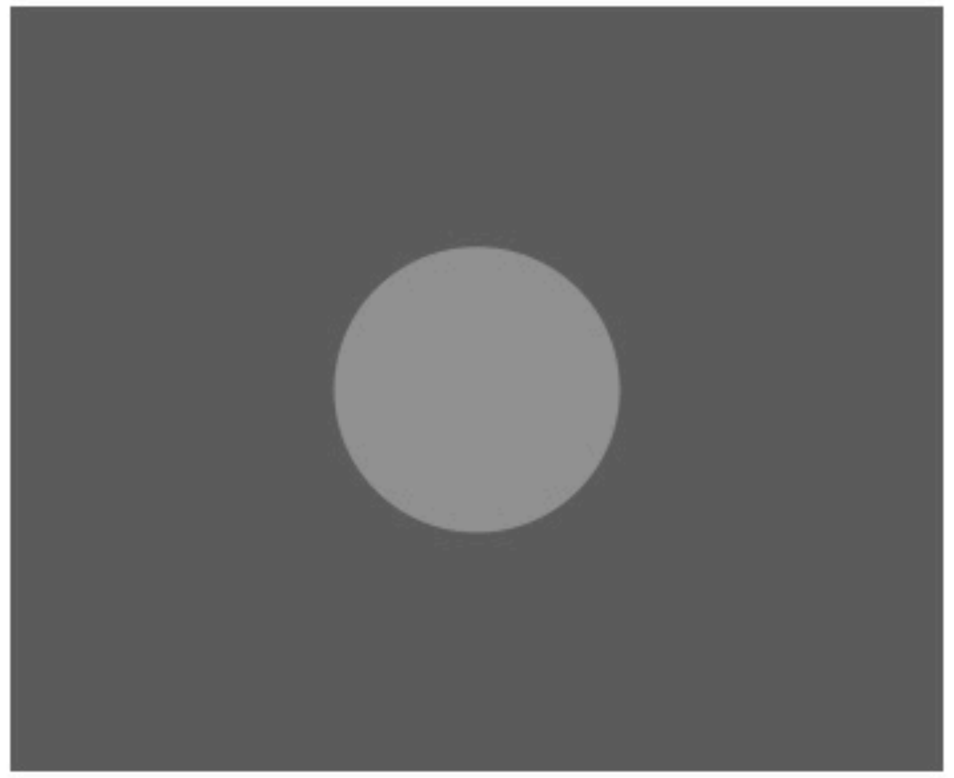


Image B

images

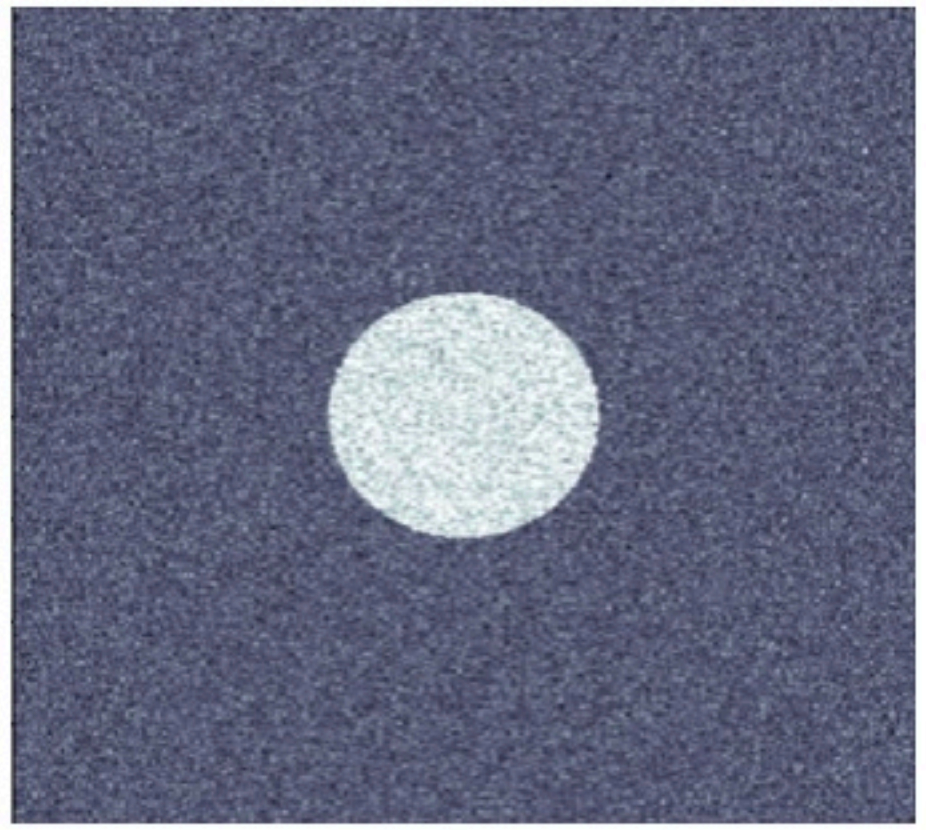


Image A

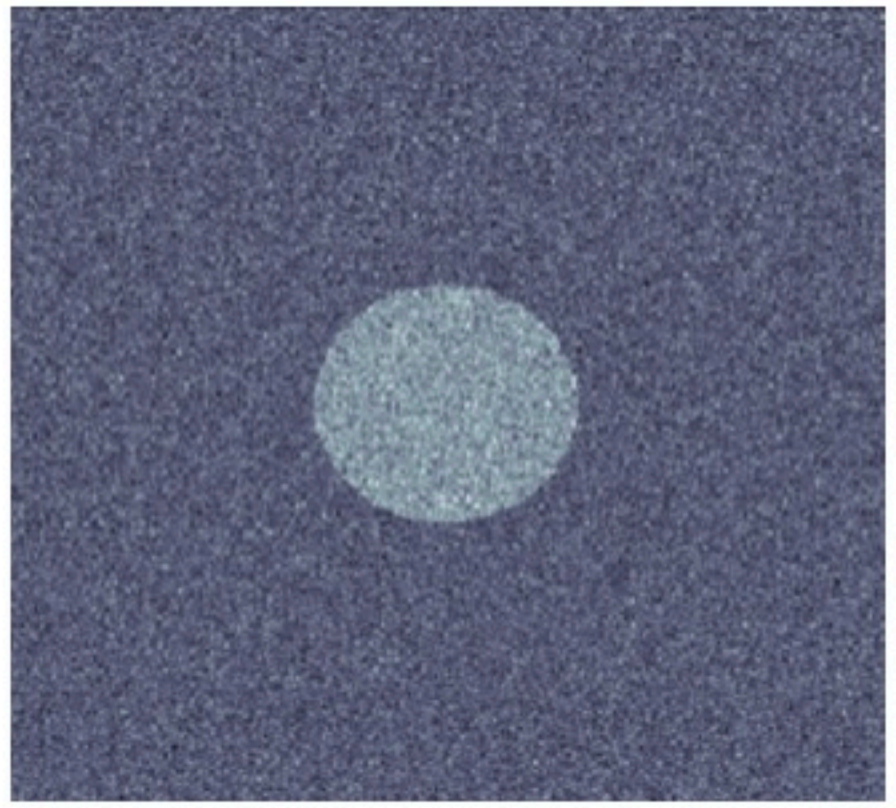


Image B

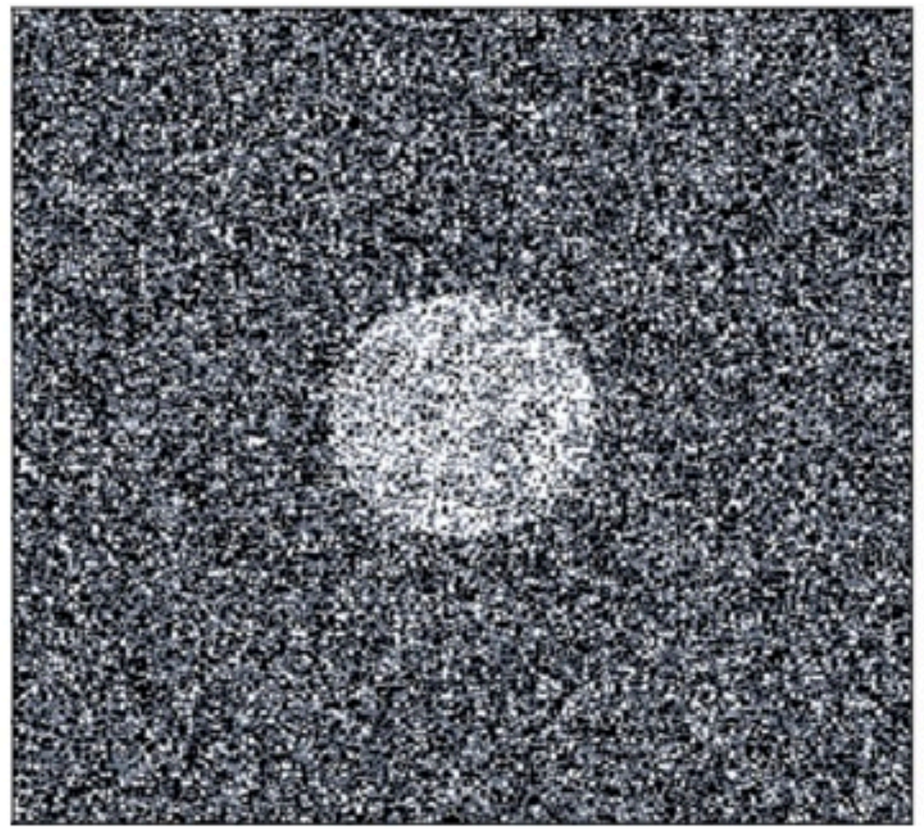


Image A

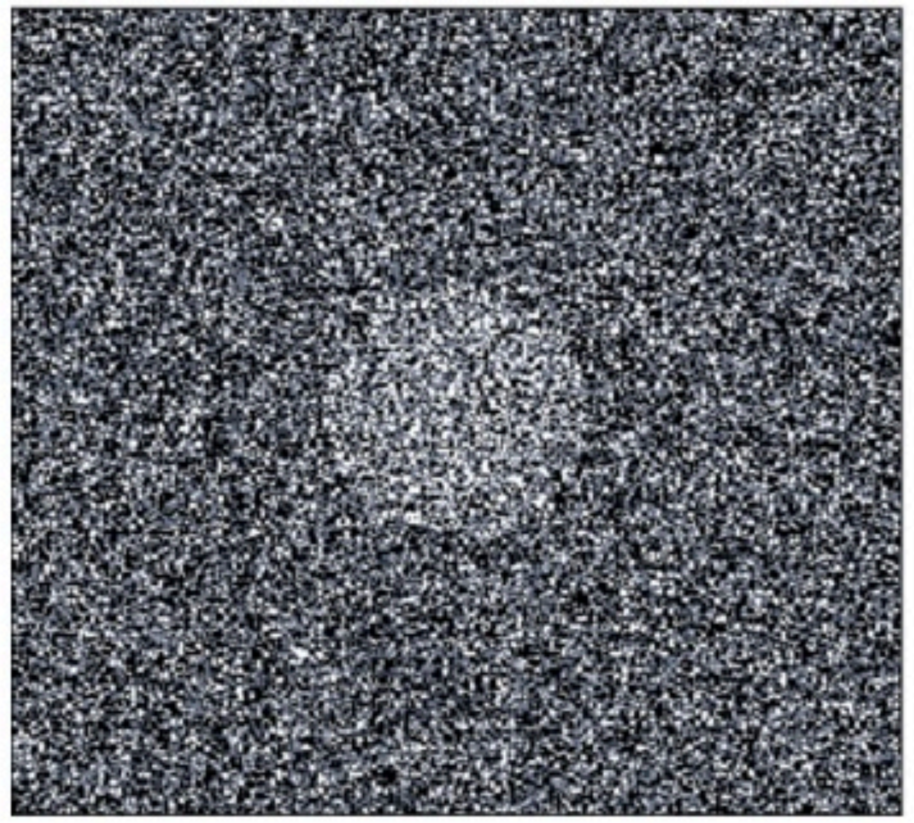


Image B

object

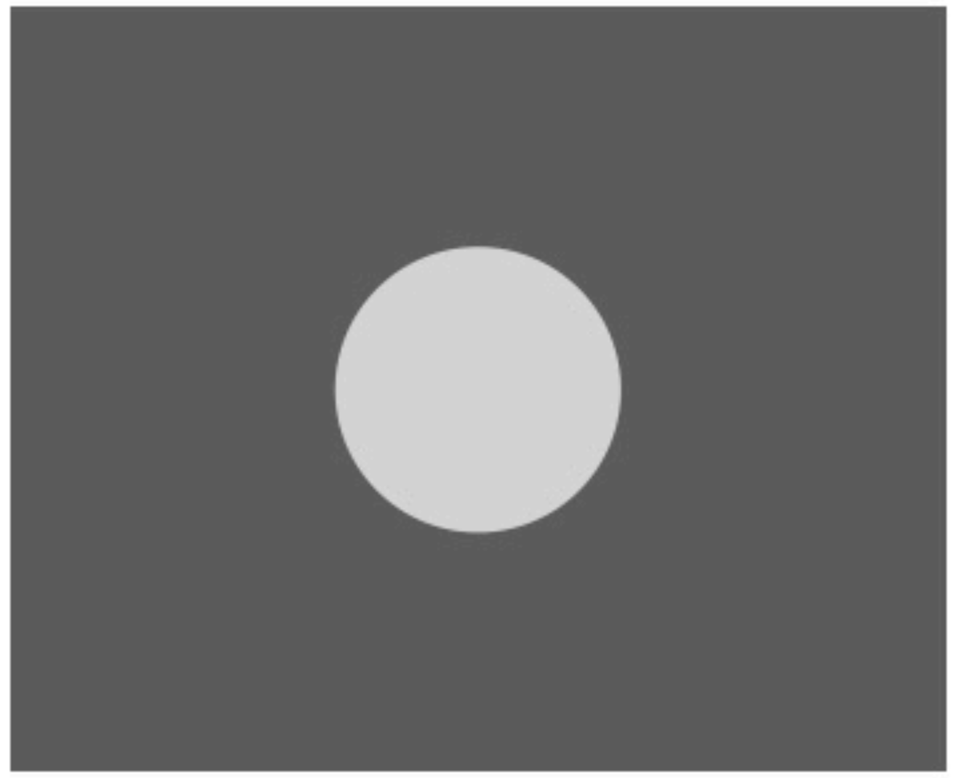


Image A

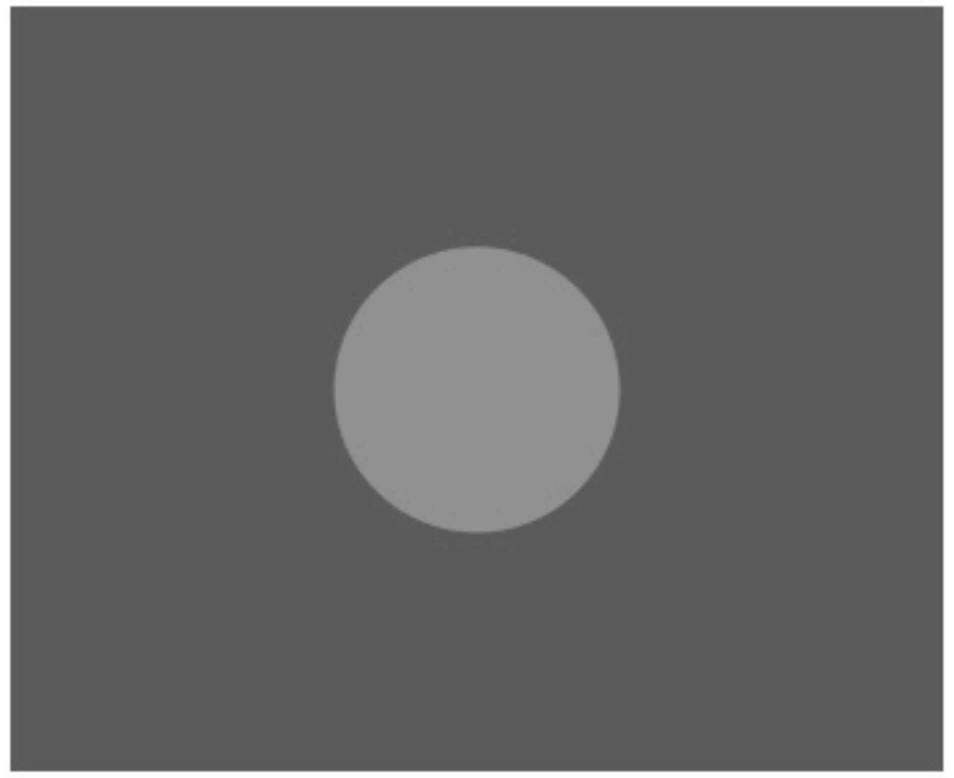


Image B

infinite number of photons

All have the same object contrast!

images

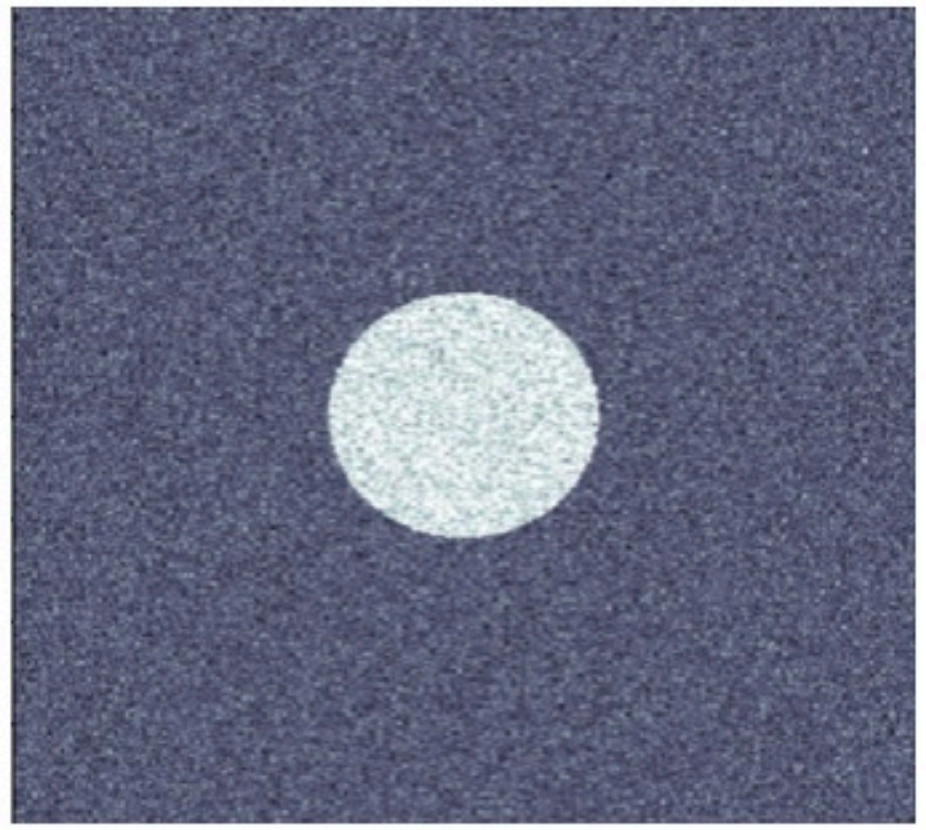


Image A

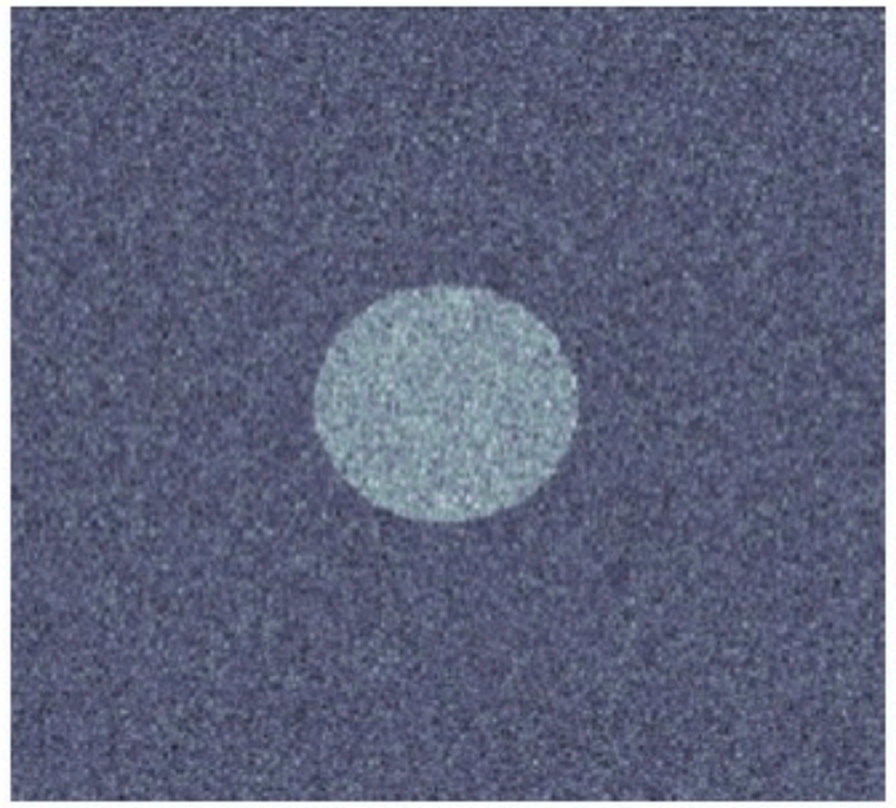


Image B

"many" photons

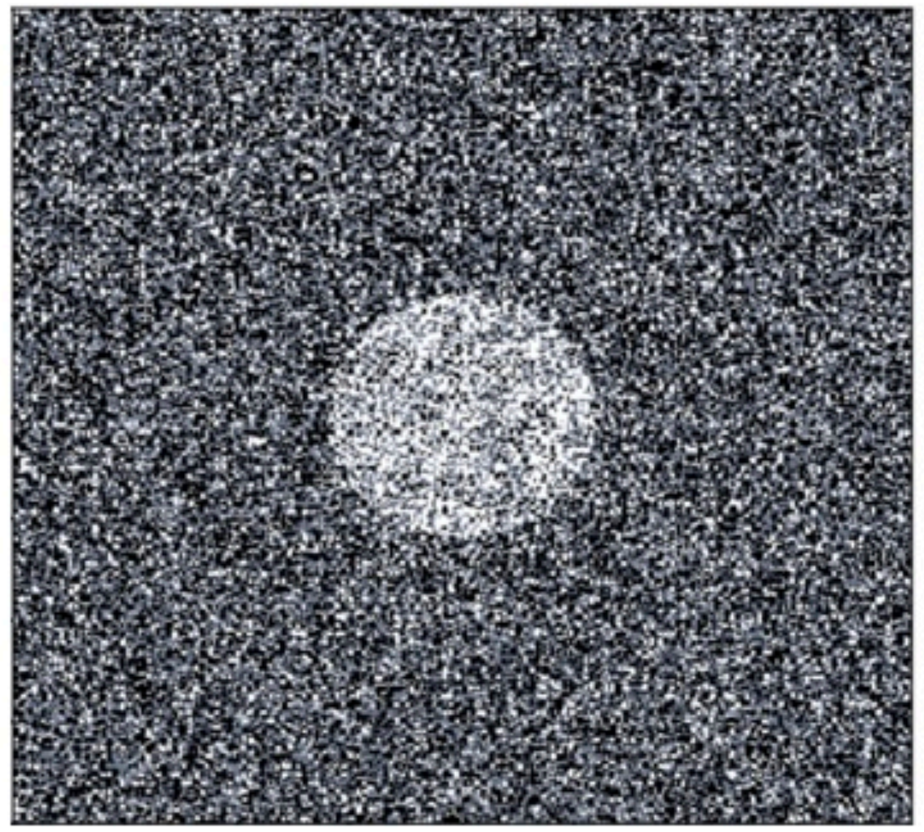


Image A

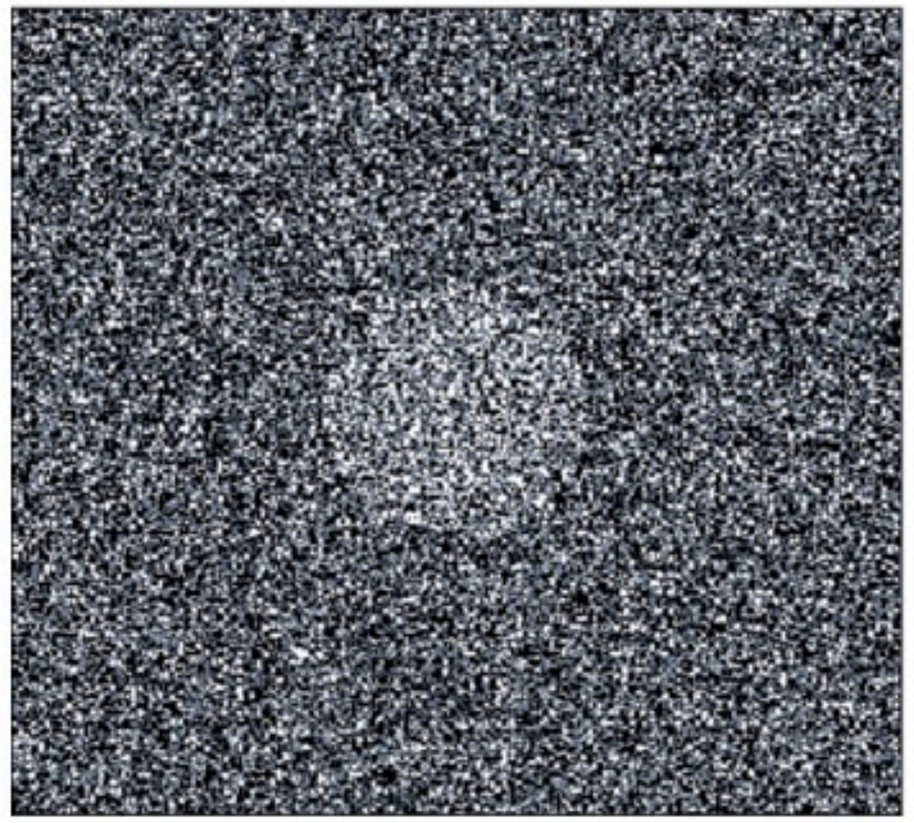


Image B

"few" photons

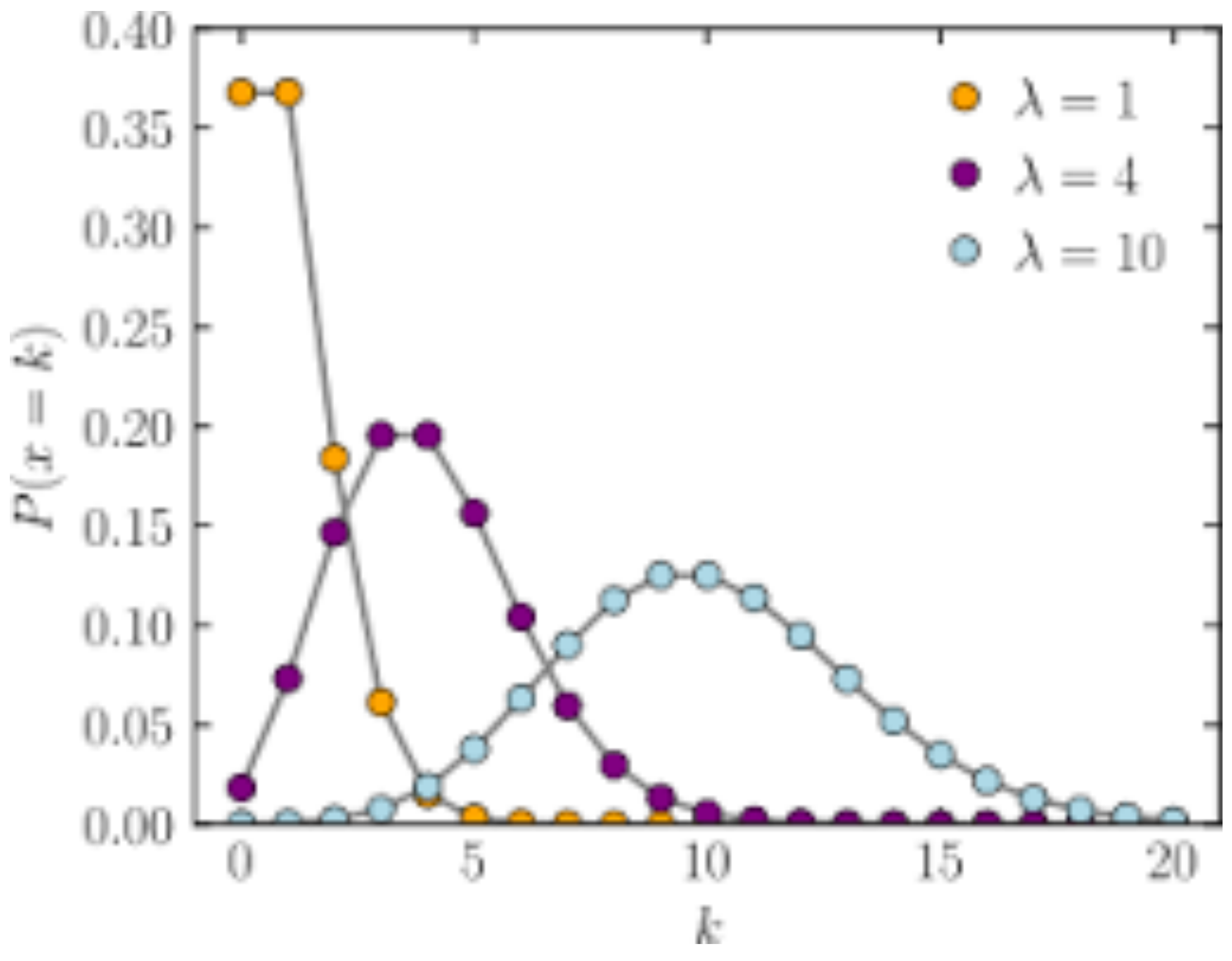
# Poisson distribution and counting statistics

Each time one has events happening randomly at a fixed rate and independently on the past then the number of events follows: → Poisson distribution

$$Pr(X = k) = \frac{\lambda^k e^{-\lambda}}{k!}$$

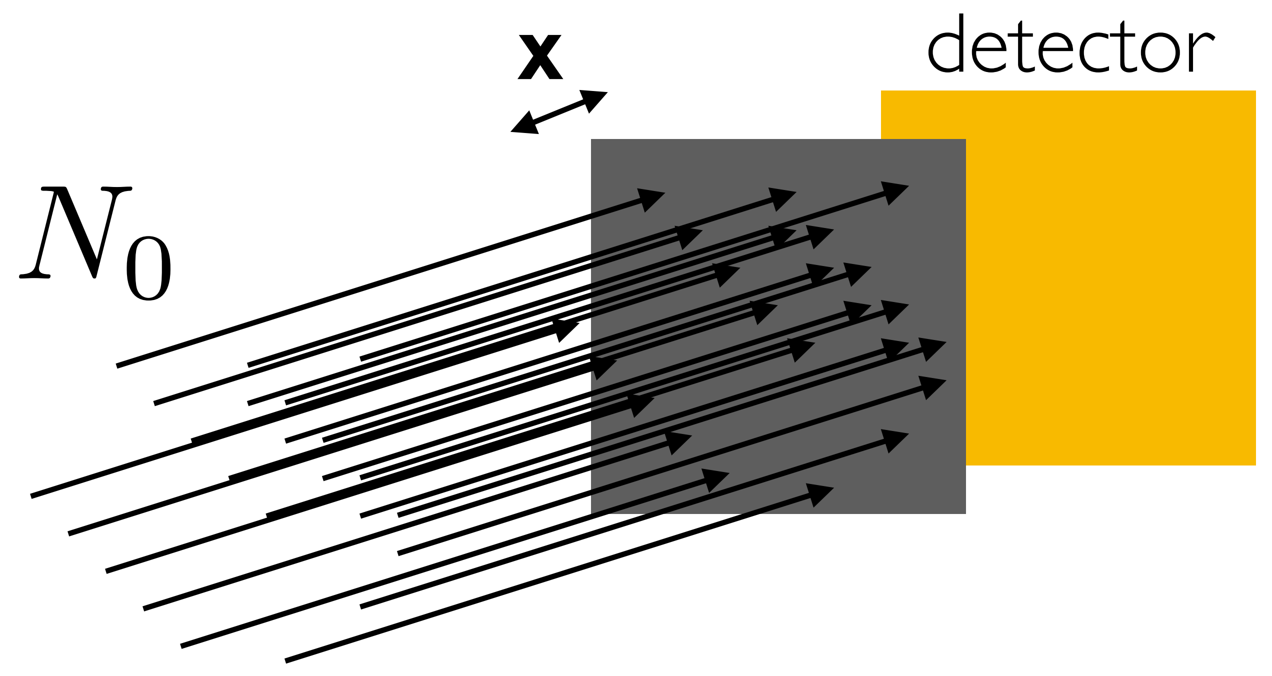
**Most relevant for us**

**In a Poisson distribution the variance equals the expected value**

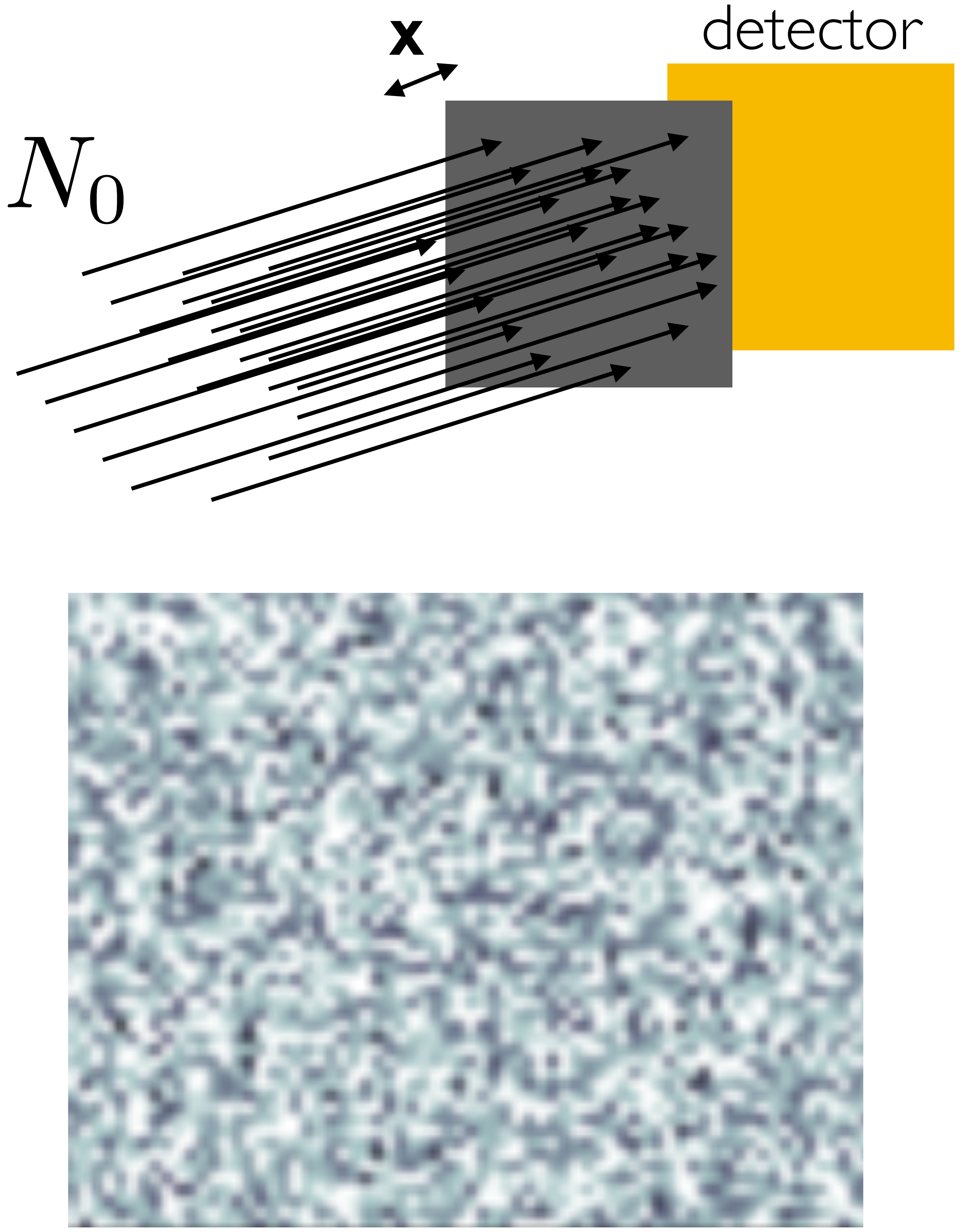



If the expected value of the number of photons through an object is N, and I repeat the experiment many times I should expect:

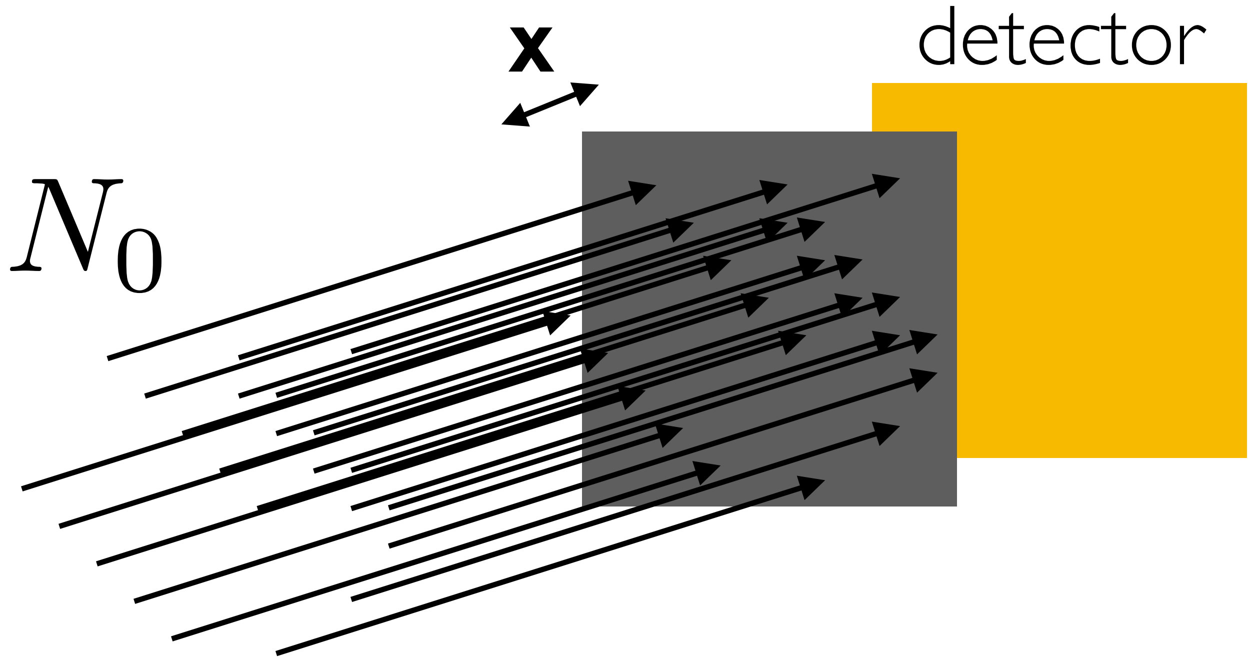
1. The average number of photons through the object is N
2. The standard deviation is $\sqrt{N}$
3. In around 67% of the cases the measured number of photons will be in the interval $N \pm \sqrt{N}$
4. In around 95% of the cases the measured number of photons will be in the interval $N \pm 2\sqrt{N}$
5. In around 99% of the cases the measured number of photons will be in the interval $N \pm 3\sqrt{N}$

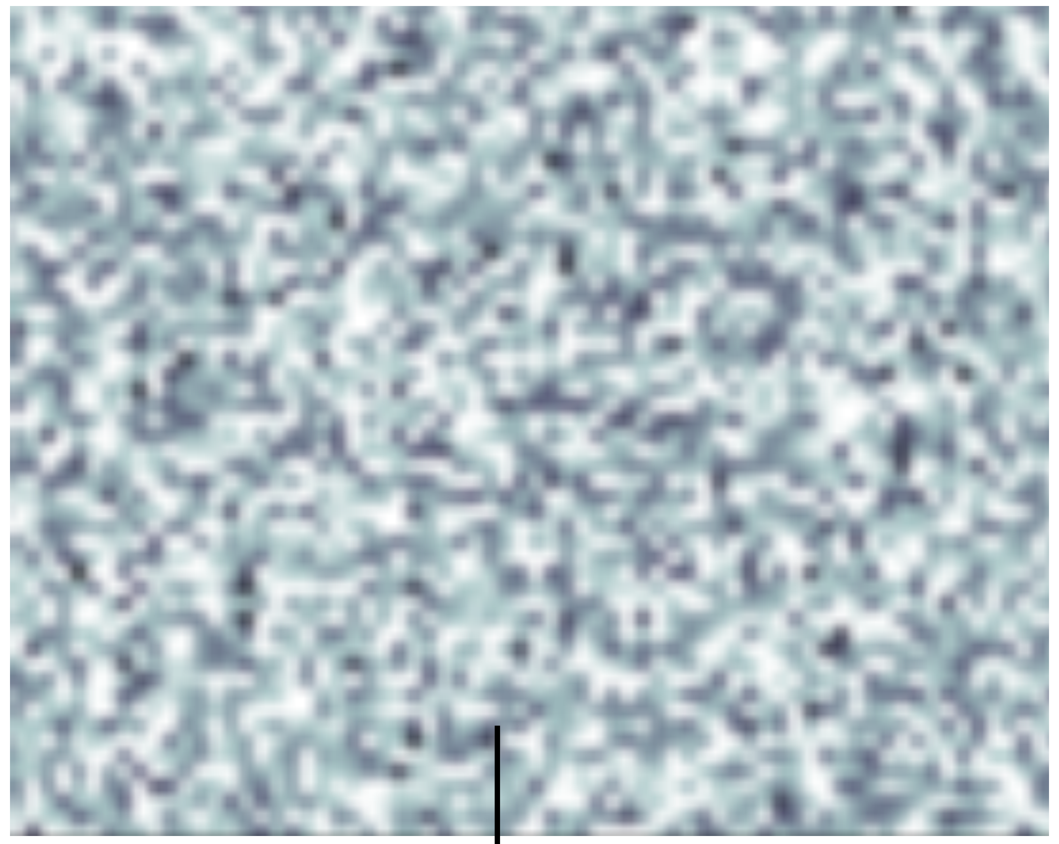


x
detector
$N_0$


x
detector
$N_0$

An image is an array $N_x \times N_y$ (e.g. 256 × 256, 512 × 512, ...)

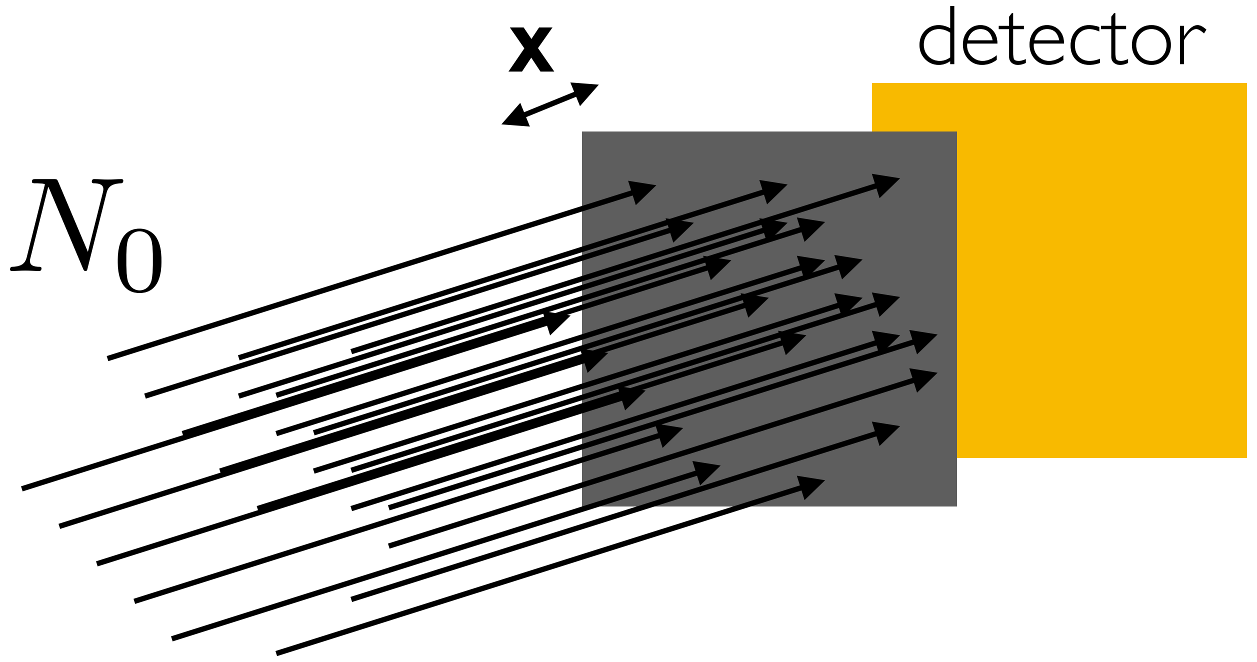


$I_{11}$   $I_{12}$   …   …   $I_{1N_x}$

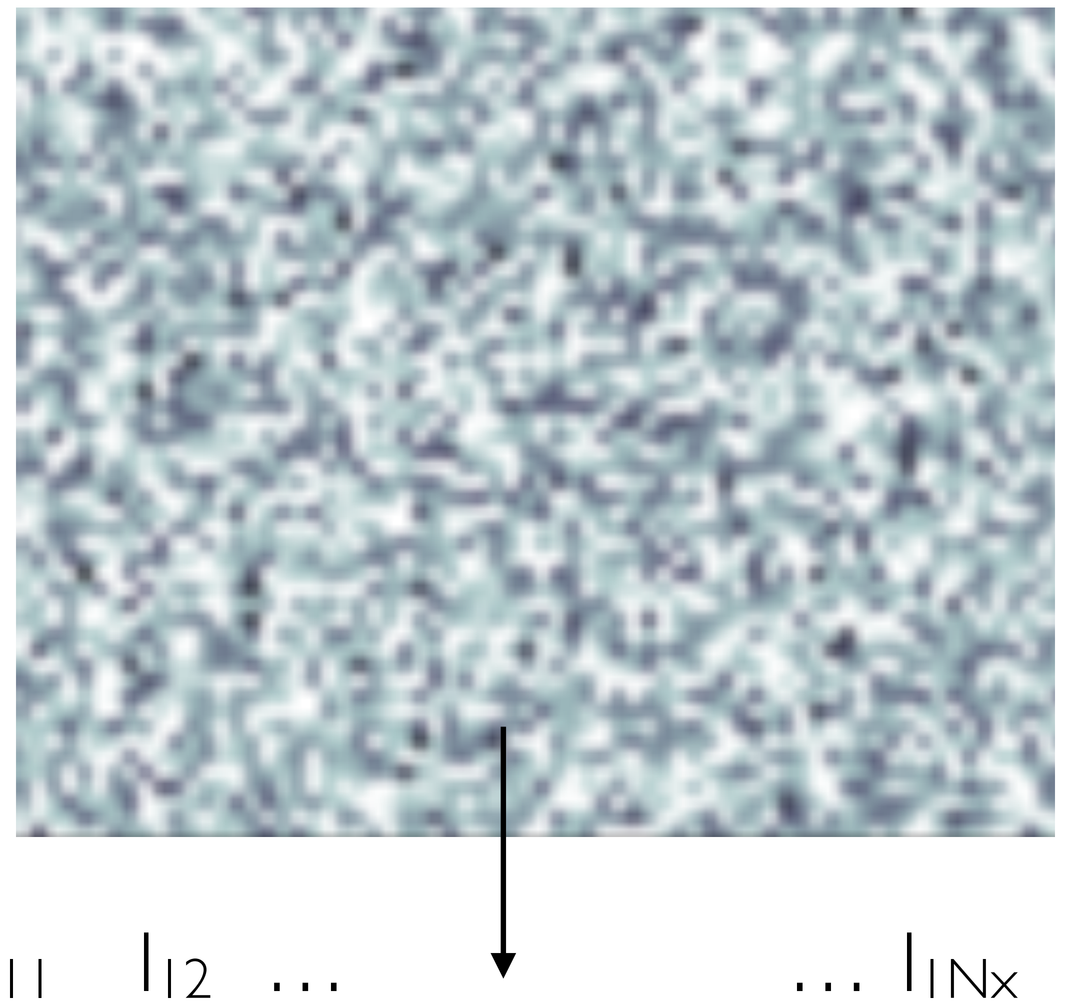
$I_{21}$   $I_{22}$   …   …   $I_{2N_x}$

$I_{N_y1}$   $I_{N_y2}$   …   …   $I_{N_yN_x}$



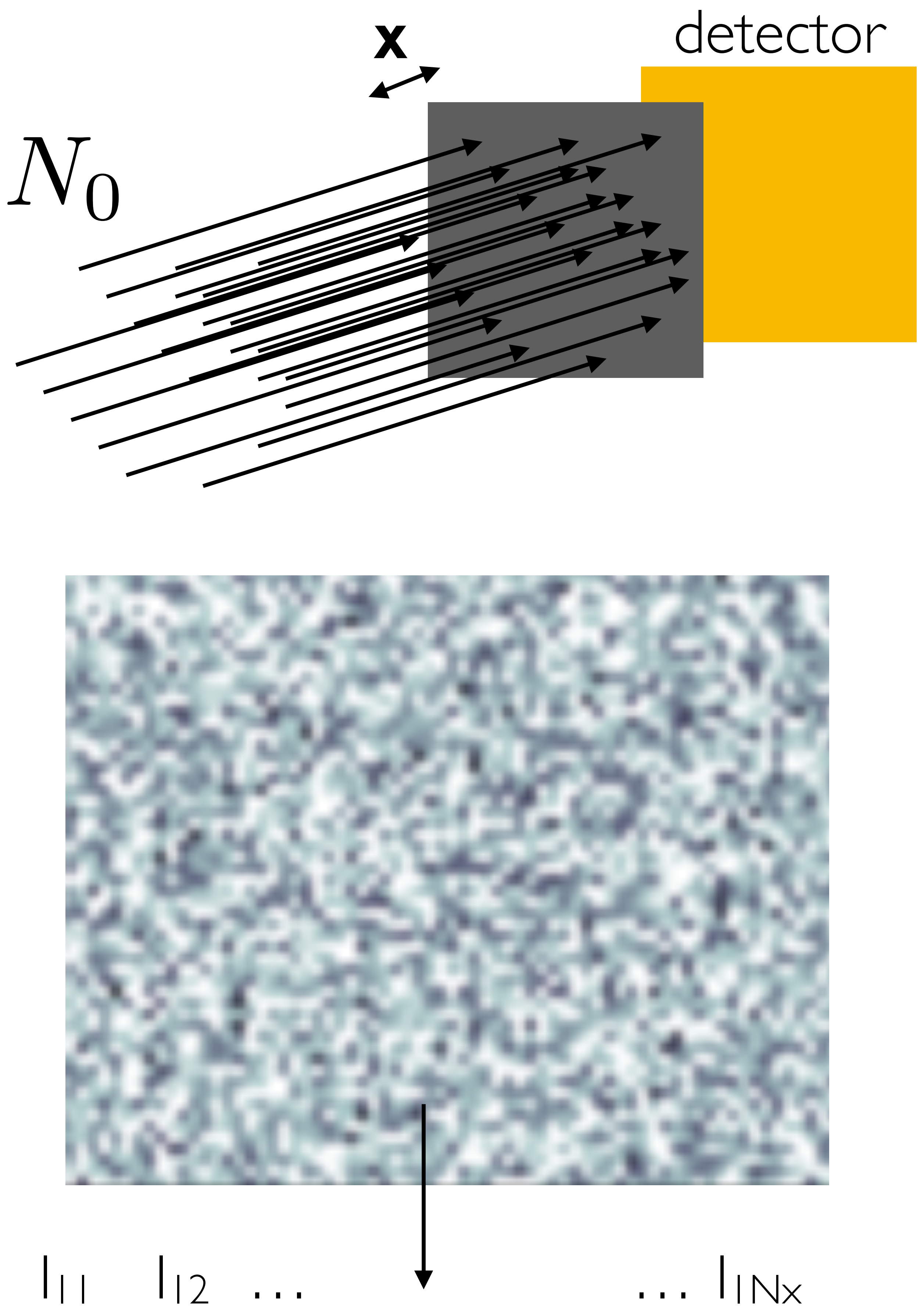

expected number of photons on each pixel: $N = N_0 e^{-\mu x}$

An image is an array $N_x \times N_y$ (e.g. 256 × 256, 512 × 512, …)



$$
\begin{matrix}
I_{11} & I_{12} & \dots & \dots & I_{1N_x} \\
I_{21} & I_{22} & \dots & \dots & I_{2N_x} \\
 & & & & \\
I_{N_y1} & I_{N_y2} & \dots & \dots & I_{N_yN_x}
\end{matrix}
$$

An image is an array $N_x \times N_y$ (e.g. 256 × 256, 512 × 512, ...)




$I_{11}$ $I_{12}$ … … $I_{1Nx}$

$I_{21}$ $I_{22}$ … … $I_{2Nx}$

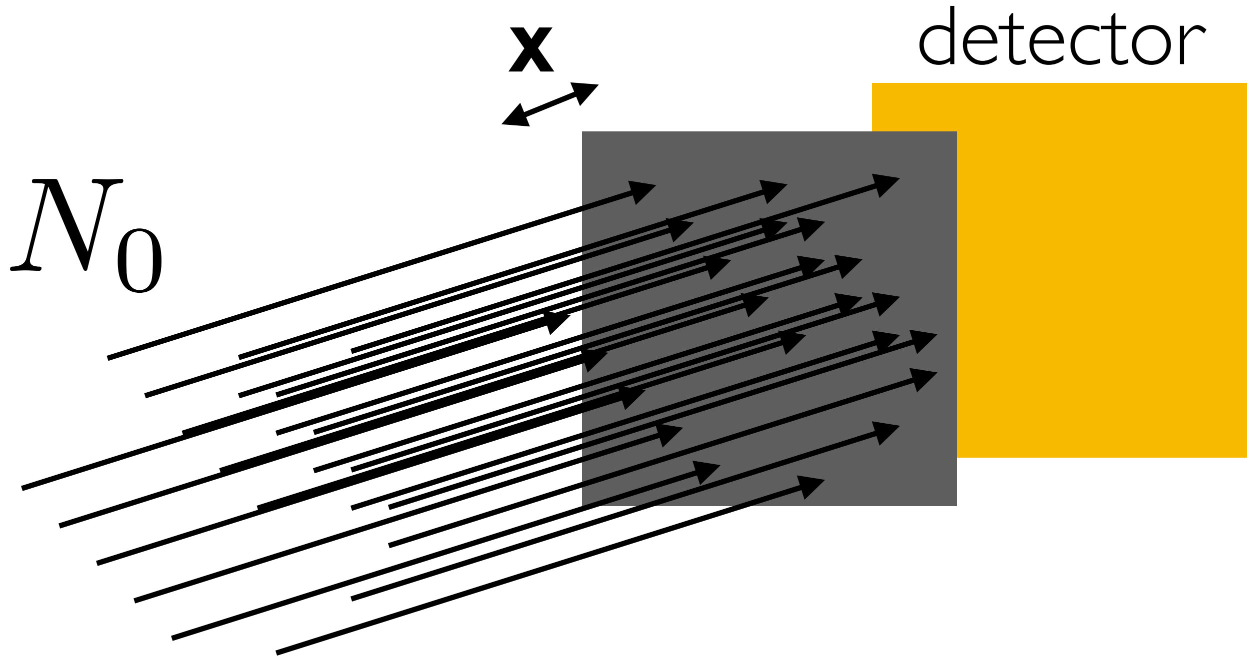
$I_{Ny1}$ $I_{Ny2}$ … … $I_{NyNx}$

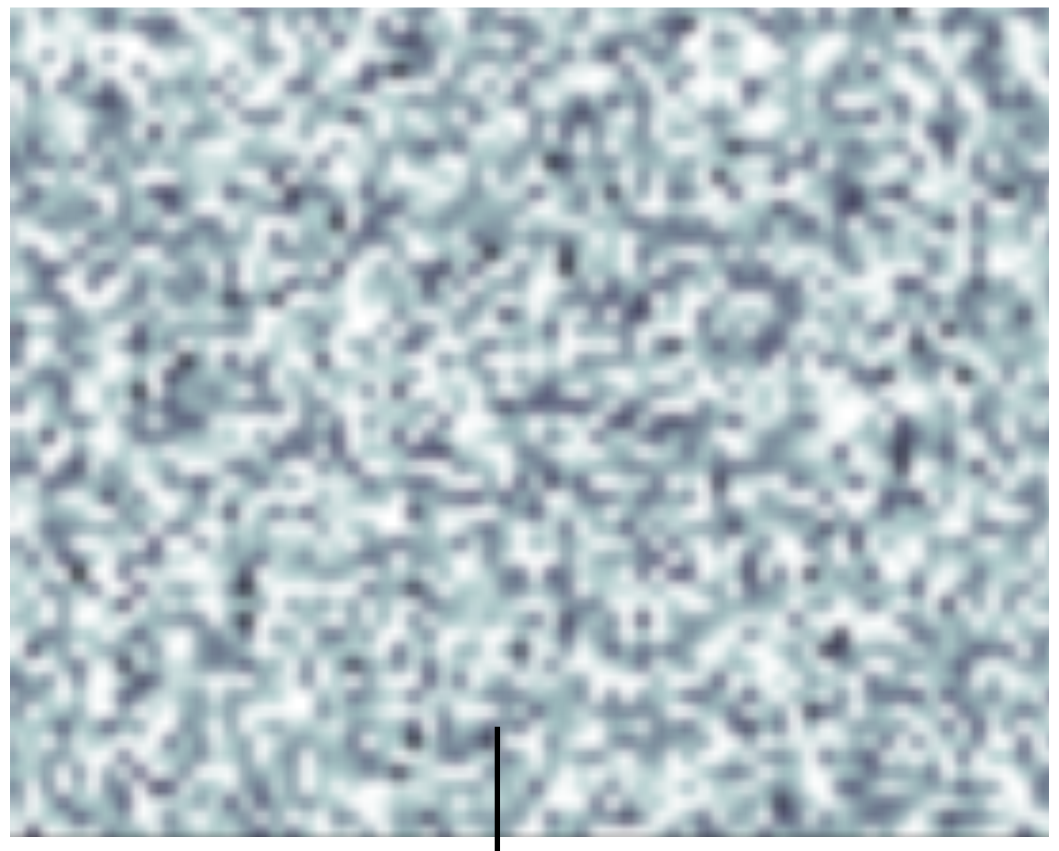
expected number of photons on each pixel: $N = N_0 e^{-\mu x}$

average value: $\dfrac{\sum_{ij} I_{ij}}{N_x N_y} \approx N$

variance: $\dfrac{\sum_{ij} (I_{ij} - N)^2}{N_x N_y} \approx N$

An image is an array $N_x \times N_y$ (e.g. 256 × 256, 512 × 512, …)



$I_{11}$ $I_{12}$ … … $I_{1N_x}$

$I_{21}$ $I_{22}$ … … $I_{2N_x}$

$I_{N_y1}$ $I_{N_y2}$ … … $I_{N_yN_x}$

expected number of photons on each pixel: $$N = N_0 e^{-\mu x}$$

average value: $$\frac{\sum_{ij} I_{ij}}{N_x N_y} \approx N$$

Poisson!

variance: $$\frac{\sum_{ij} (I_{ij} - N)^2}{N_x N_y} \approx N$$

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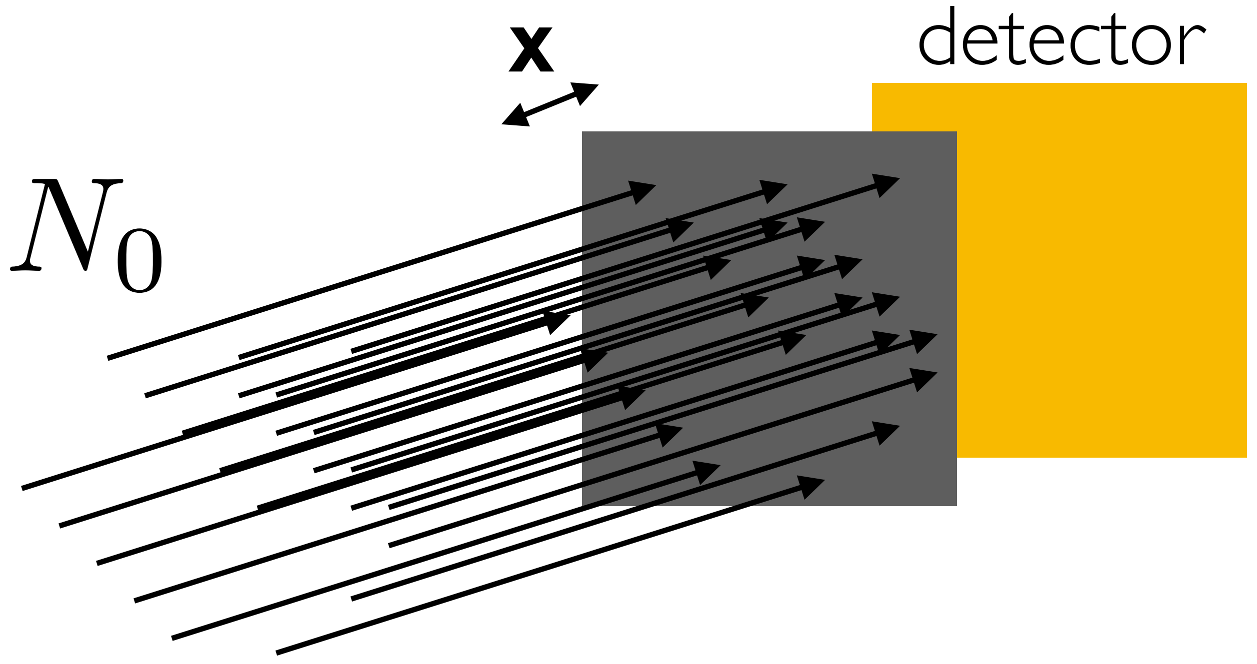


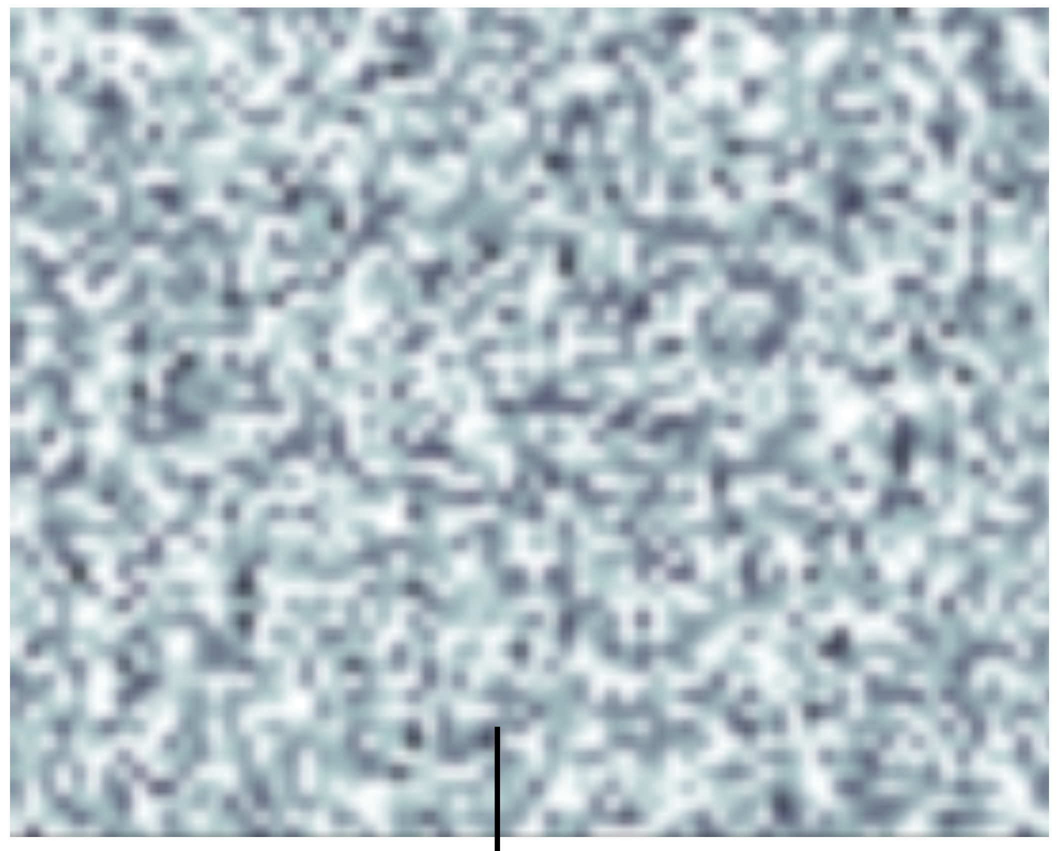

$I_{11}$ $I_{12}$ ... ... $I_{1N_x}$

$I_{21}$ $I_{22}$ ... ... $I_{2N_x}$

$I_{N_y1}$ $I_{N_y2}$ ... ... $I_{N_yN_x}$

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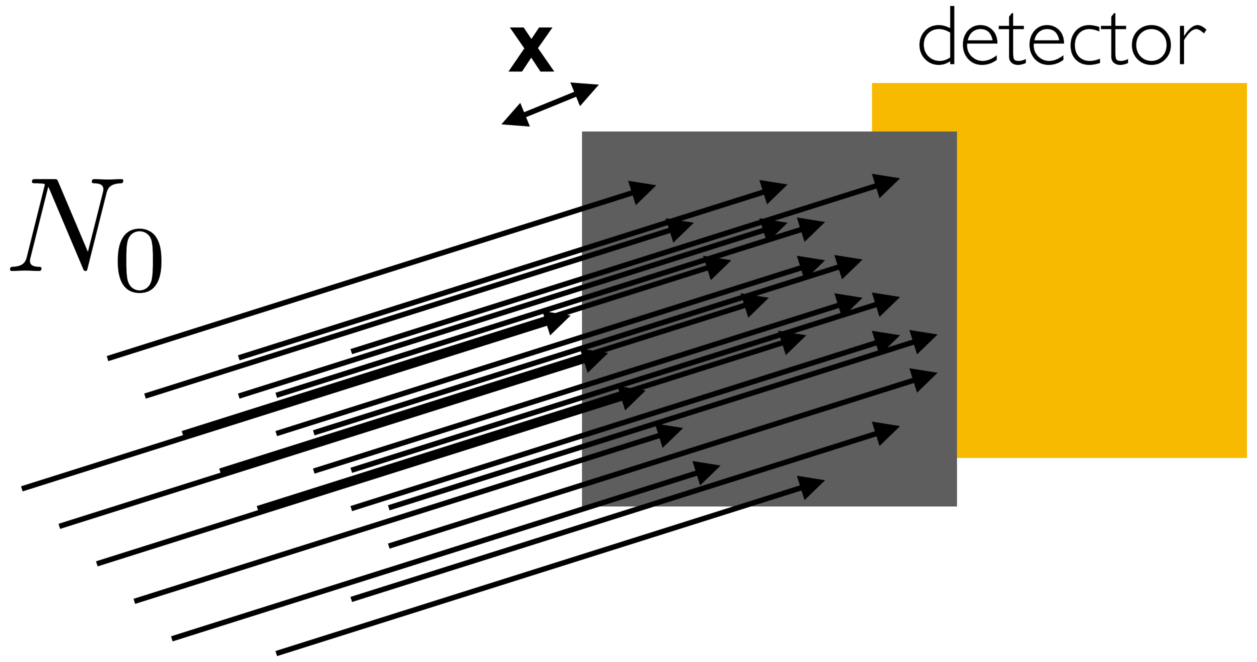
Poisson!

pixel value




expected number of photons on each pixel: $N = N_0 e^{-\mu x}$

average value: $\frac{\sum_{ij} I_{ij}}{N_x N_y} \approx N$

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Poisson!

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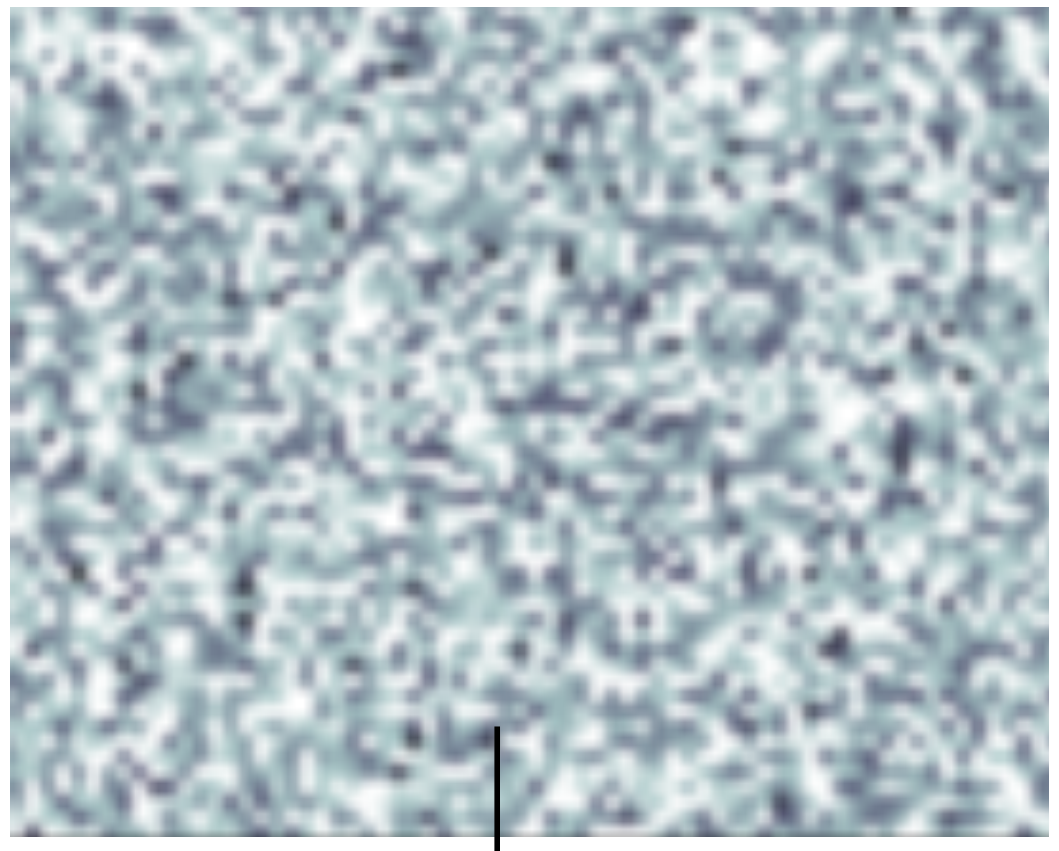
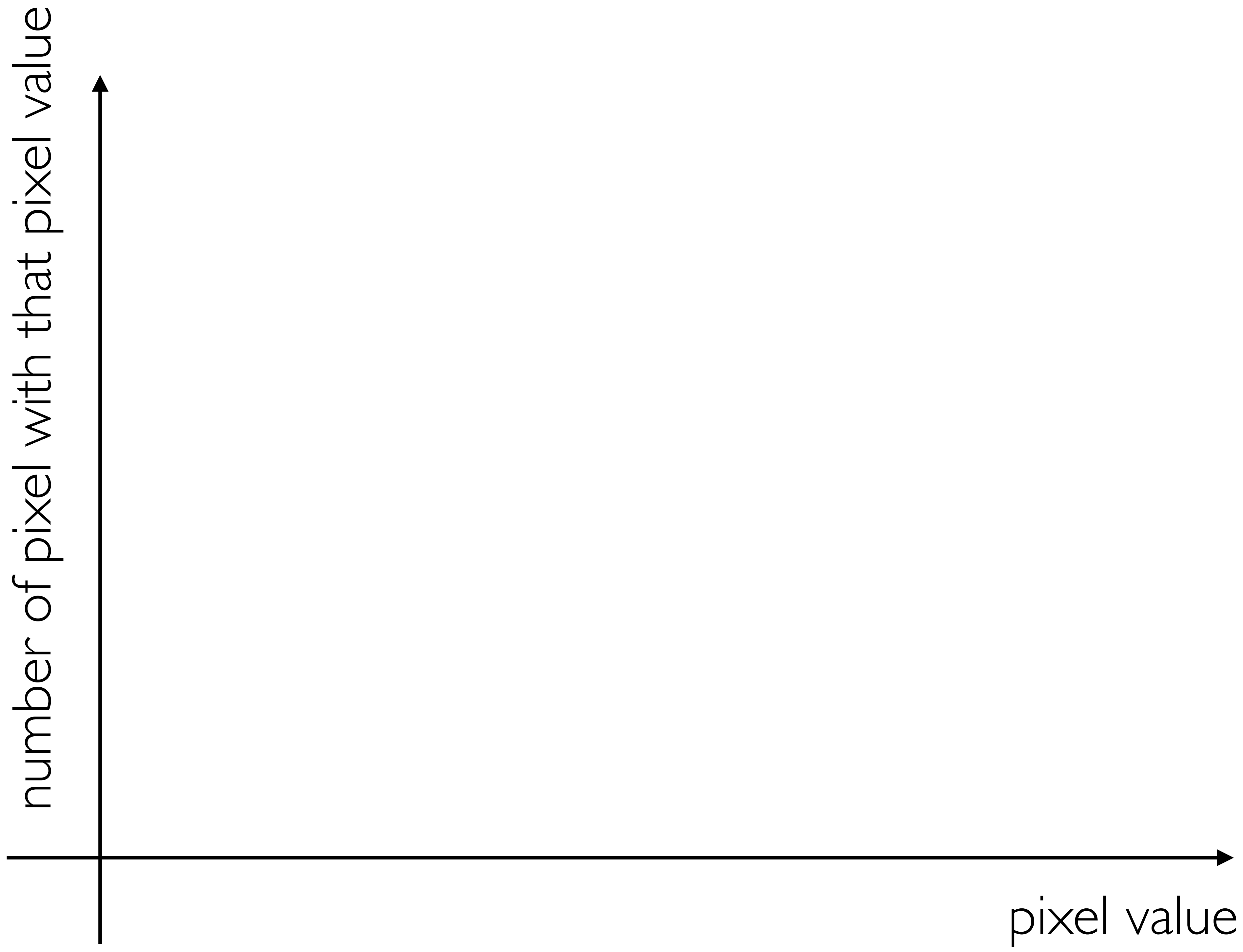
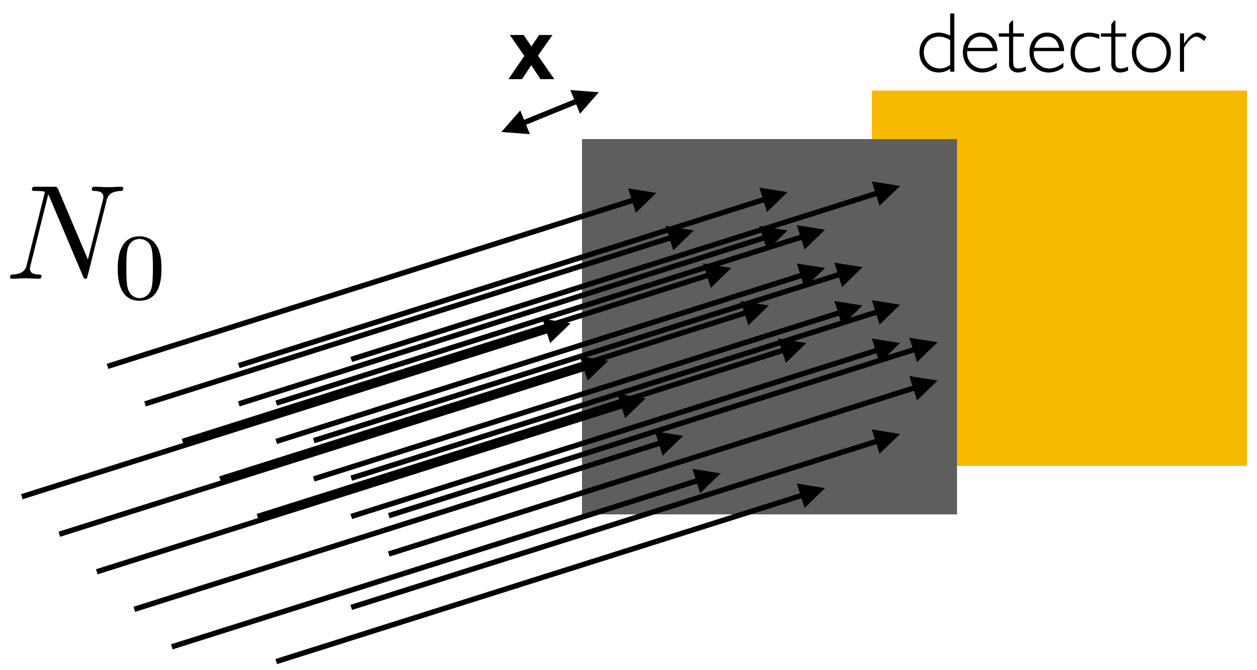


$I_{11}$ $I_{12}$ … … $I_{1Nx}$

$I_{21}$ $I_{22}$ … … $I_{2Nx}$

$I_{Ny1}$ $I_{Ny2}$ … … $I_{NyNx}$






expected number of photons on each pixel: $$N = N_0 e^{-\mu x}$$

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Poisson!

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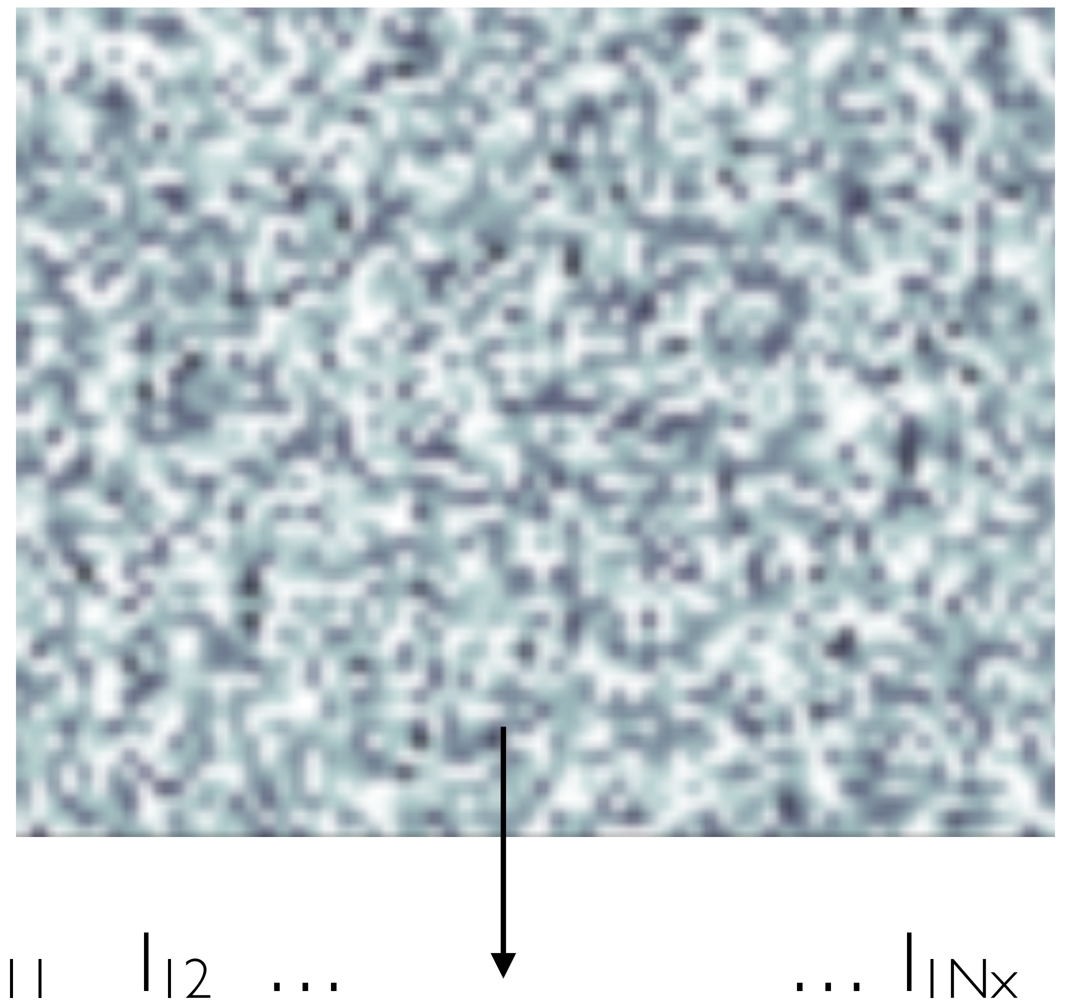

$I_{11}$ $I_{12}$ … … $I_{1N_x}$

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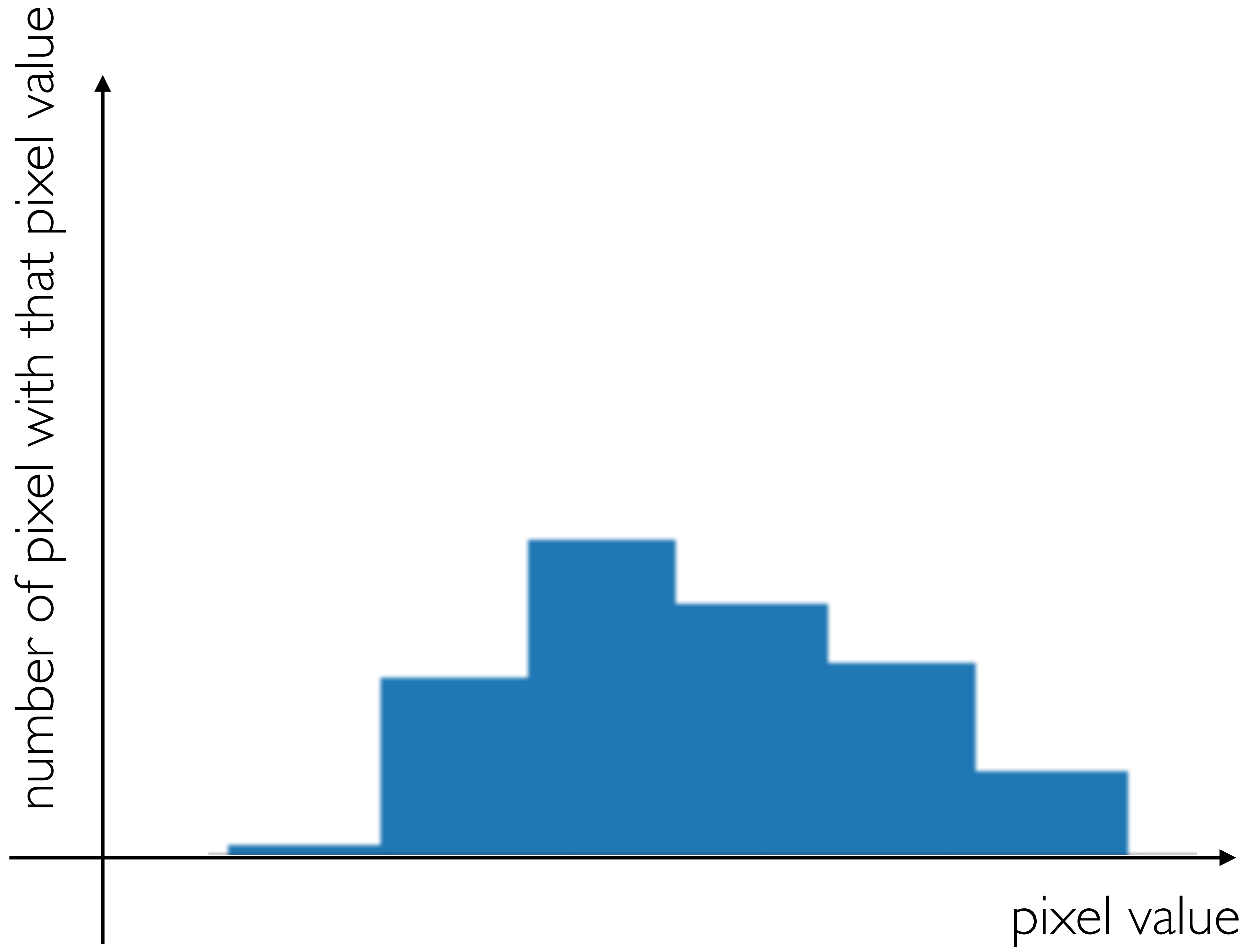
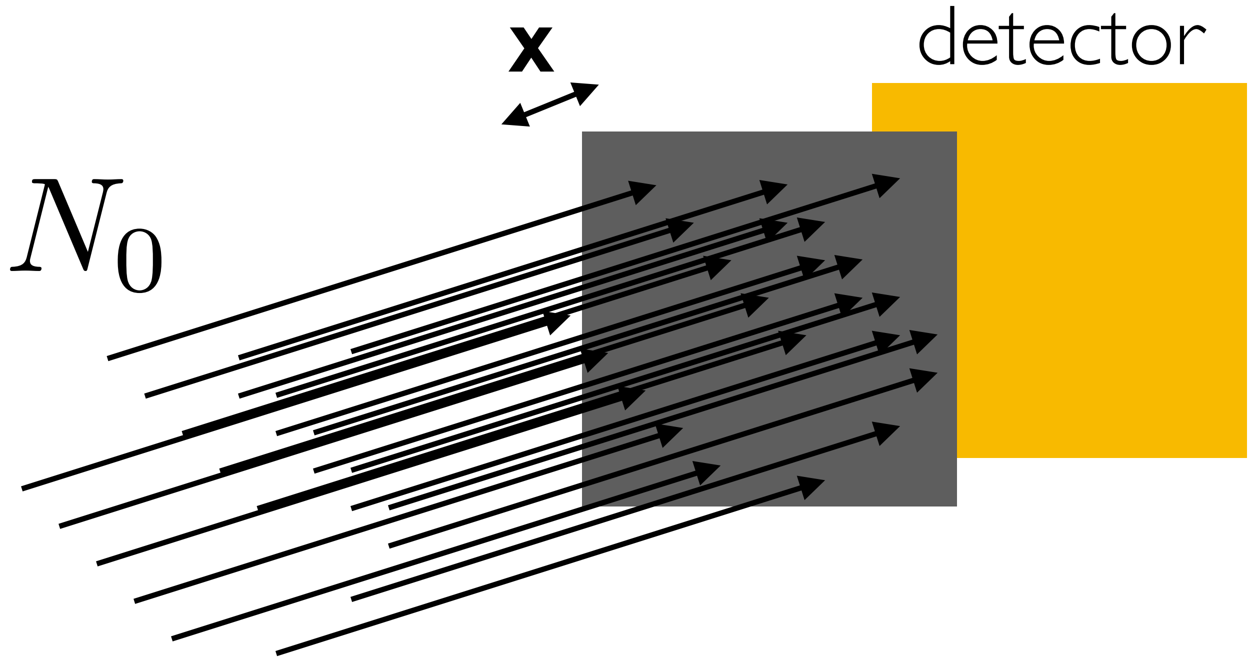
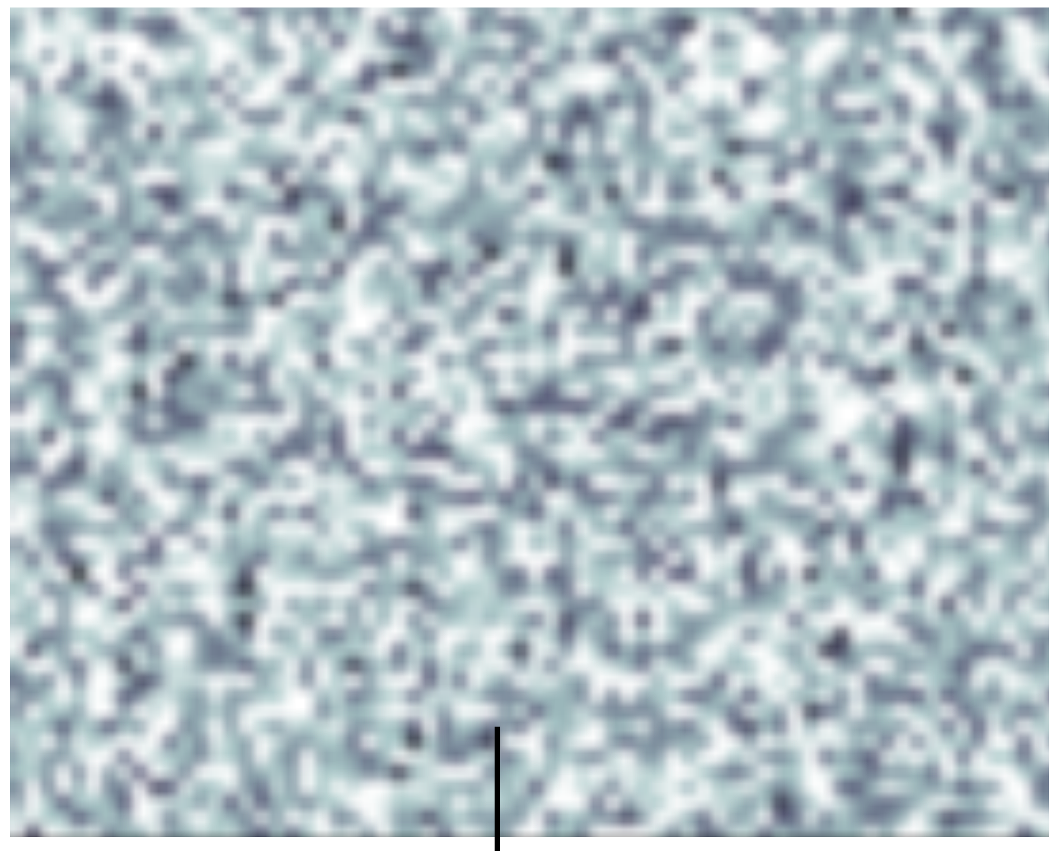
$I_{N_y1}$ $I_{N_y2}$ … … $I_{N_yN_x}$



An image is an array $N_x \times N_y$ (e.g. $256 \times 256$, $512 \times 512$, …)



$I_{11}$ $I_{12}$ … … $I_{1Nx}$

$I_{21}$ $I_{22}$ … … $I_{2Nx}$

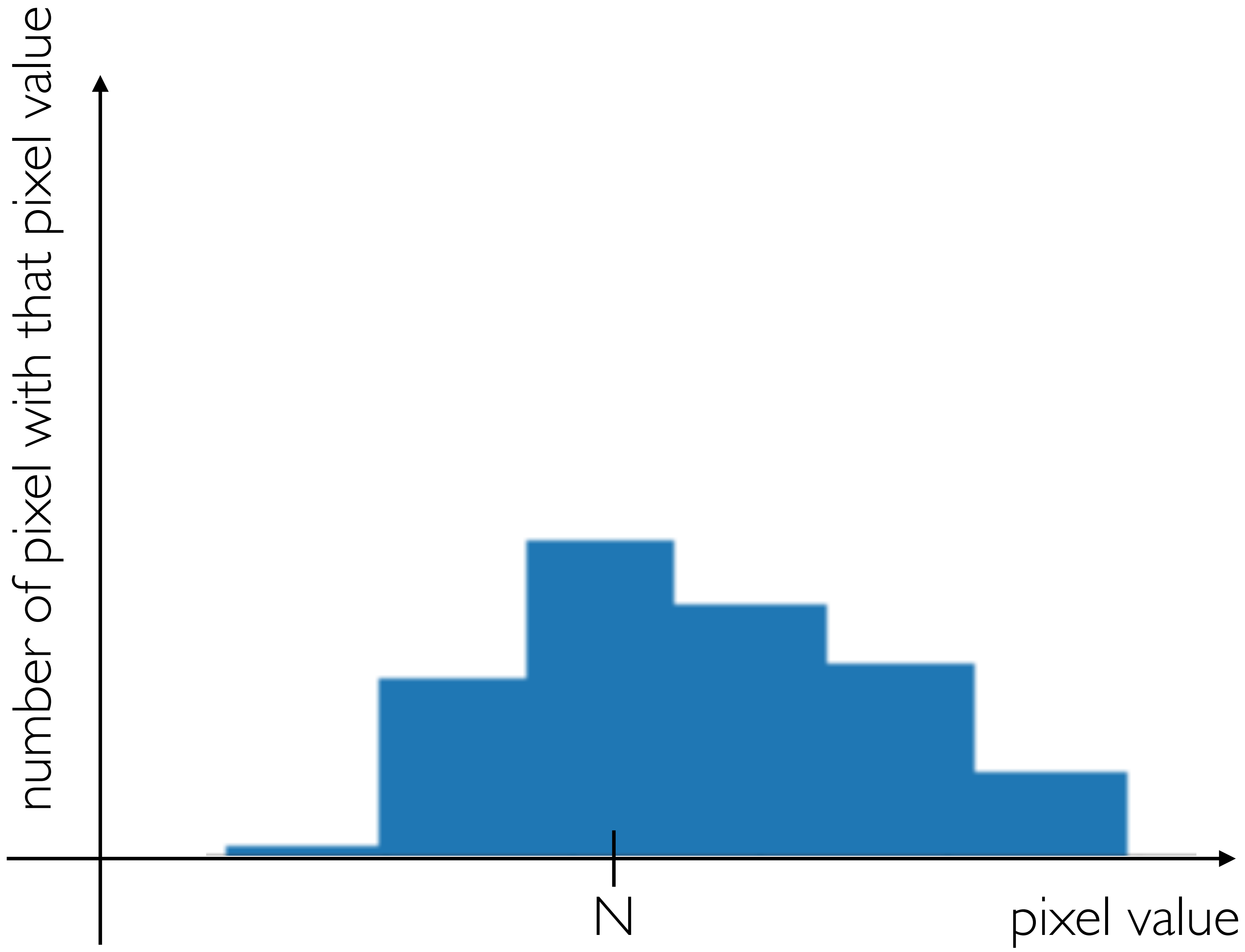
$I_{Ny1}$ $I_{Ny2}$ … … $I_{NyNx}$

expected number of photons on each pixel: $N = N_0 e^{-\mu x}$

average value: $\dfrac{\sum_{ij} I_{ij}}{N_x N_y} \approx N$

variance: $\dfrac{\sum_{ij} (I_{ij} - N)^2}{N_x N_y} \approx N$

Poisson!



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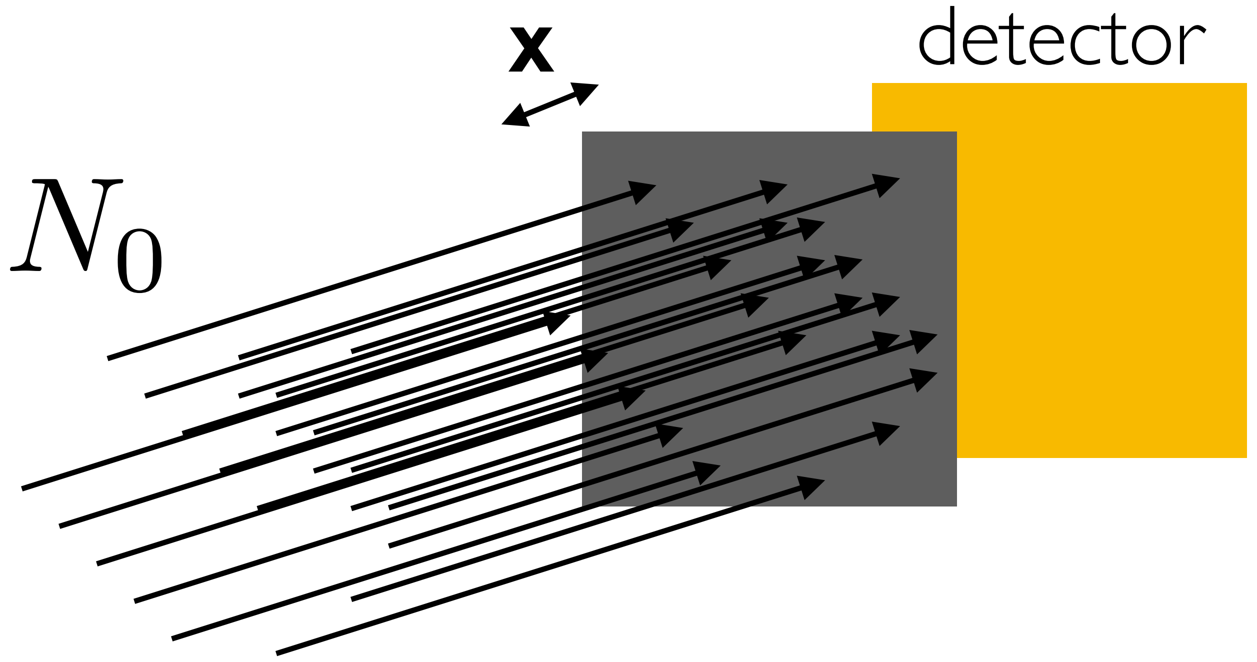


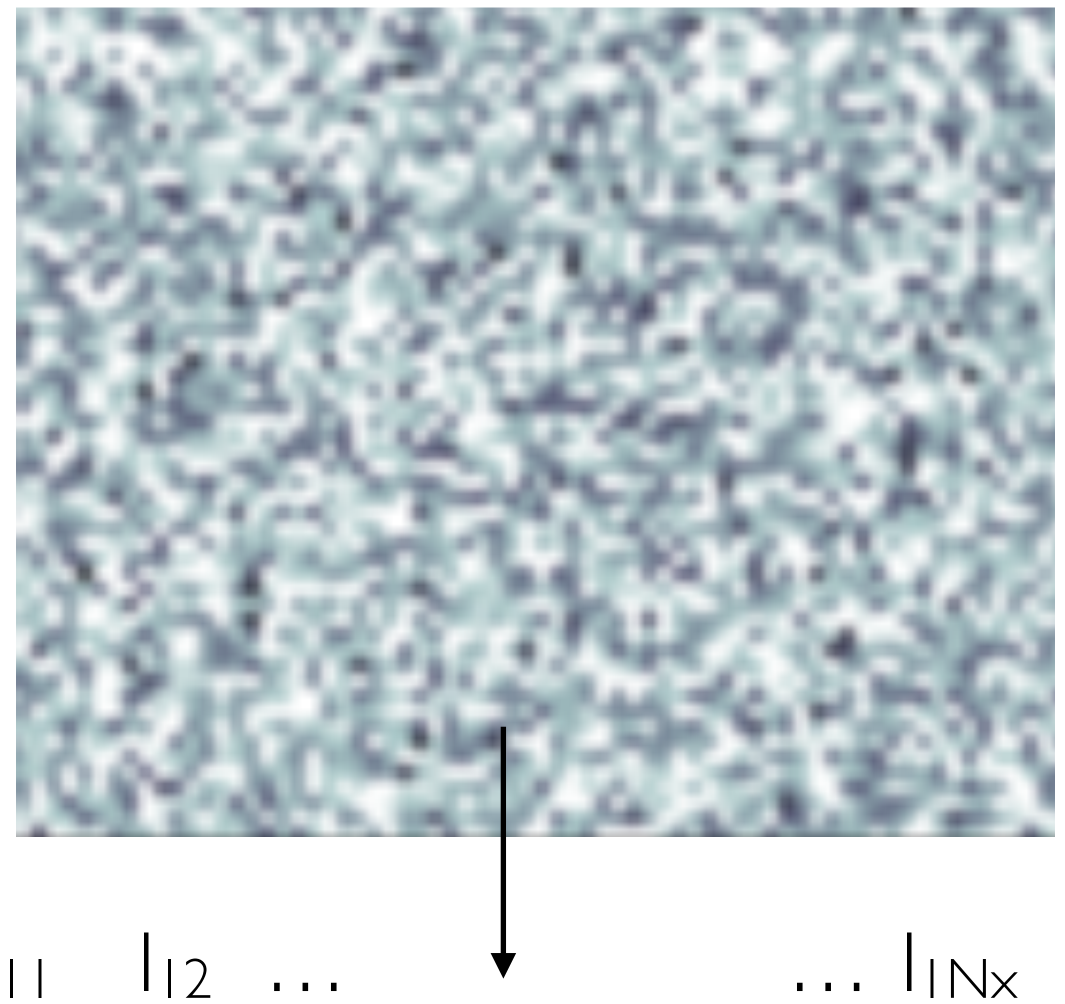

| | | | |
|---|---|---|---|
| $I_{11}$ | $I_{12}$ … | | … $I_{1N_x}$ |
| $I_{21}$ | $I_{22}$ … | | … $I_{2N_x}$ |
| $I_{N_y1}$ | $I_{N_y2}$ … | | … $I_{N_yN_x}$ |

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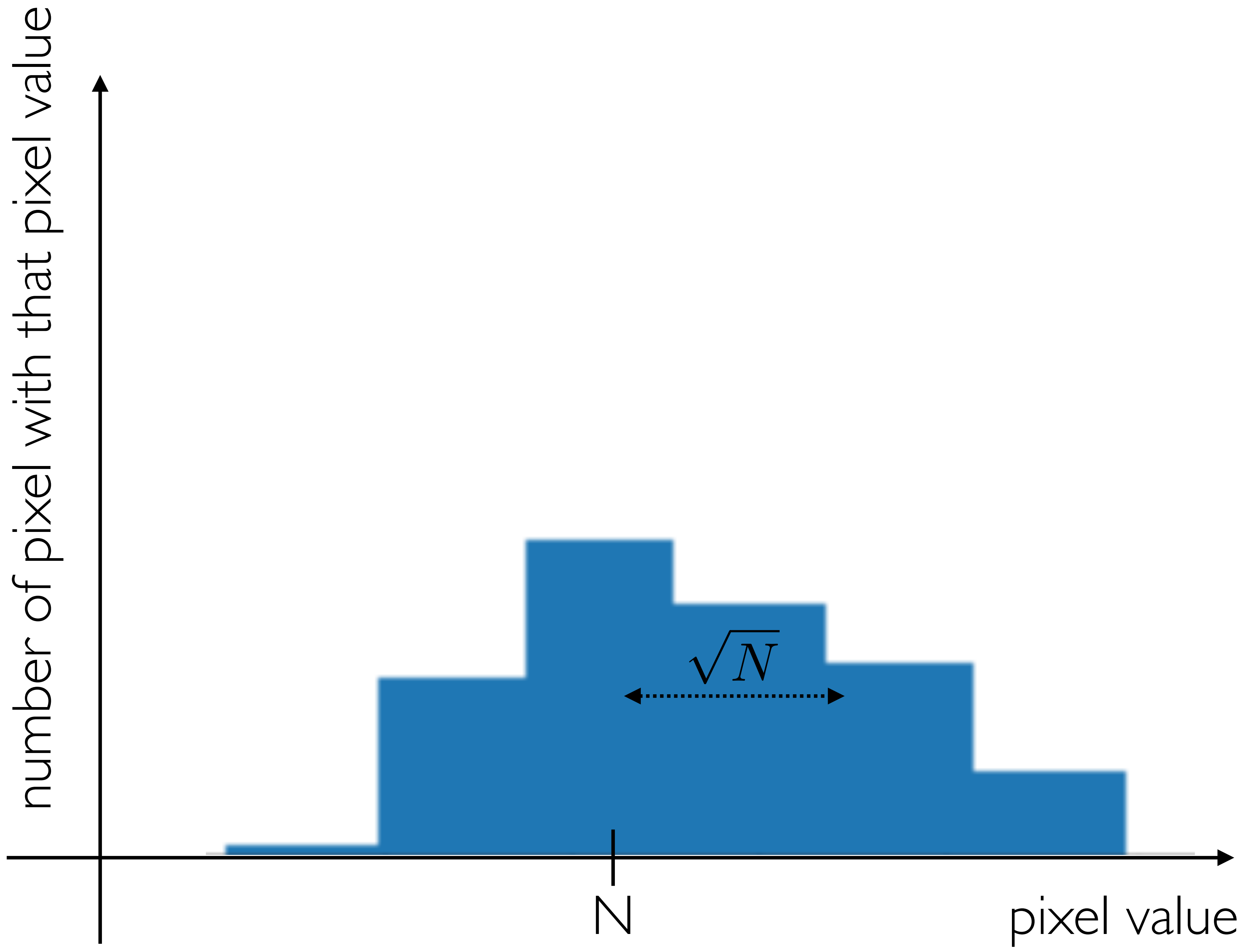

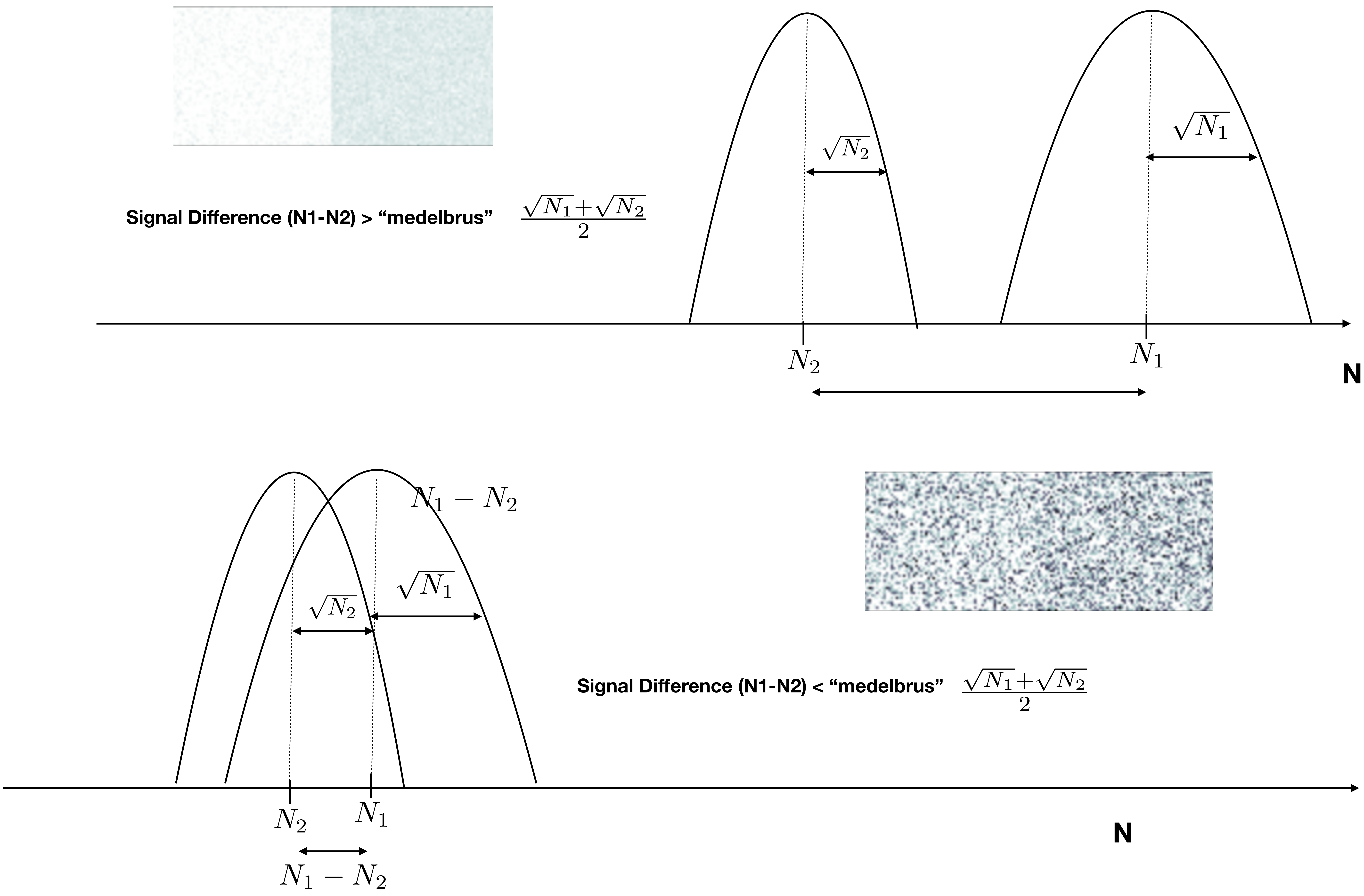

Signal Difference (N1-N2) > "medelbrus" $\frac{\sqrt{N_1}+\sqrt{N_2}}{2}$
$\sqrt{N_2}$
$\sqrt{N_1}$
$N_2$
$N_1$
N
$N_1 - N_2$
$\sqrt{N_2}$
$\sqrt{N_1}$
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$N_1$
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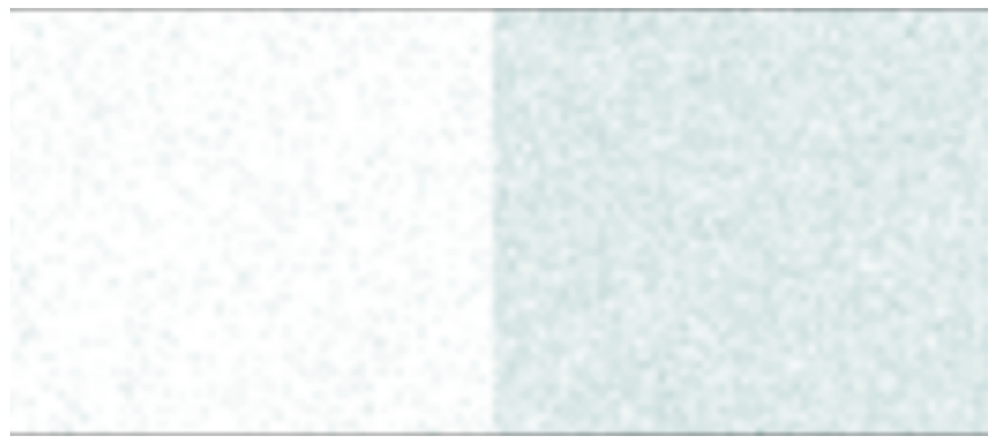
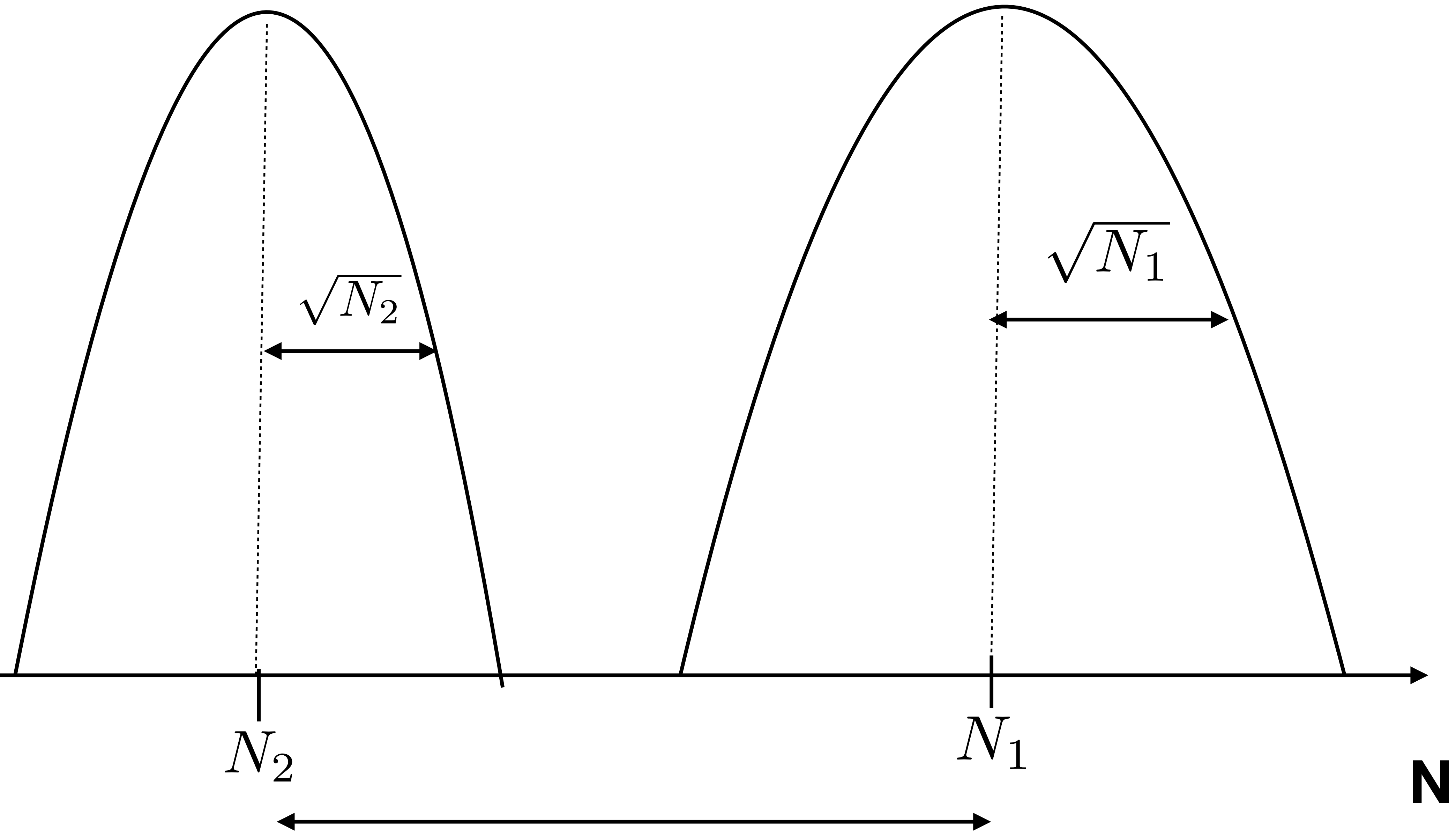
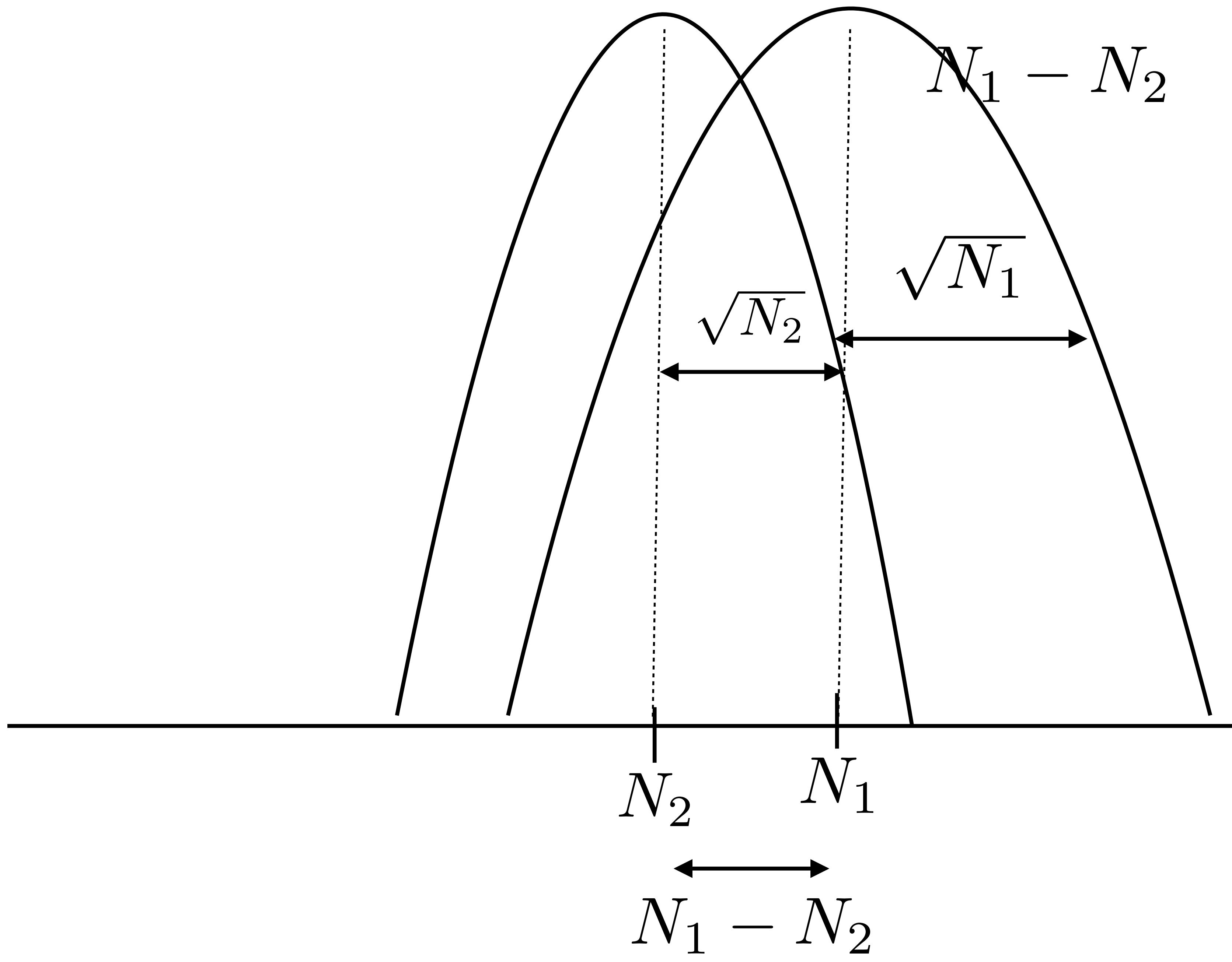
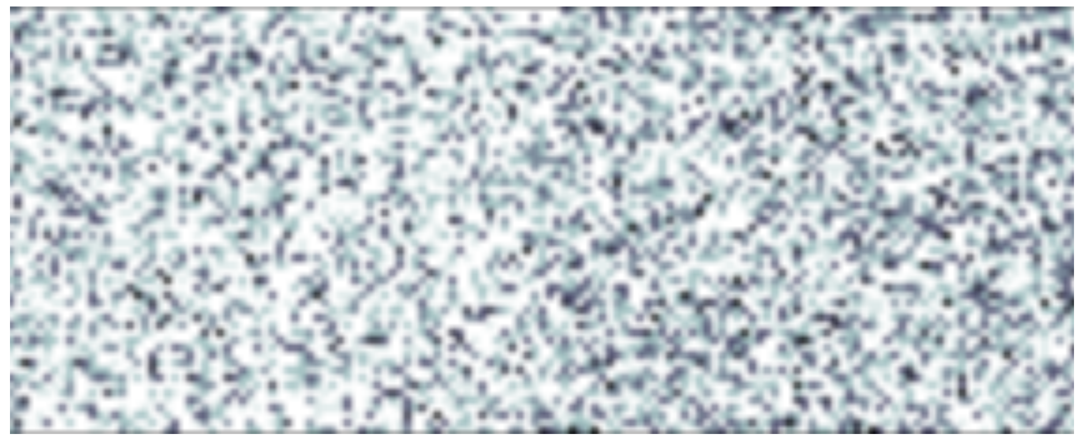





**Signal Difference (N1-N2) > "medelbrus"** $\frac{\sqrt{N_1}+\sqrt{N_2}}{2}$

OBS: samma objektkontrast!



**Signal Difference (N1-N2) < "medelbrus"** $\frac{\sqrt{N_1}+\sqrt{N_2}}{2}$

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$$\mathrm{SDNR} = \frac{N_1 - N_2}{\sqrt{N_1} + \sqrt{N_2}}$$

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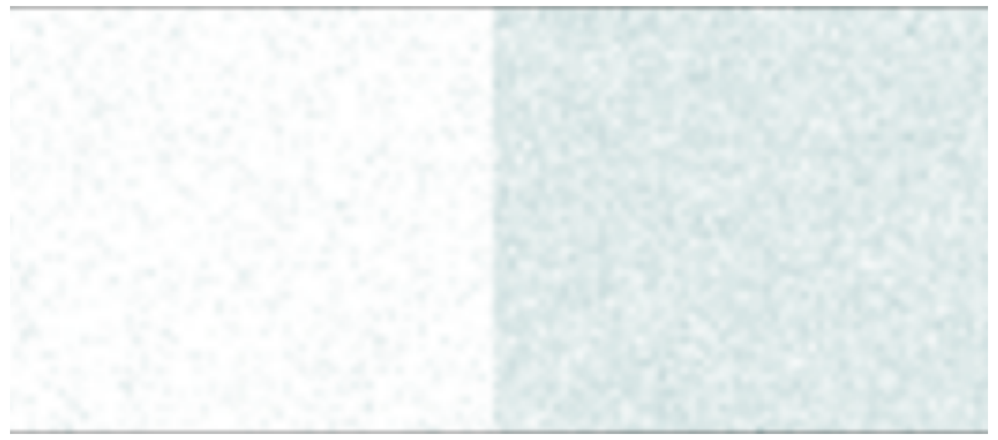

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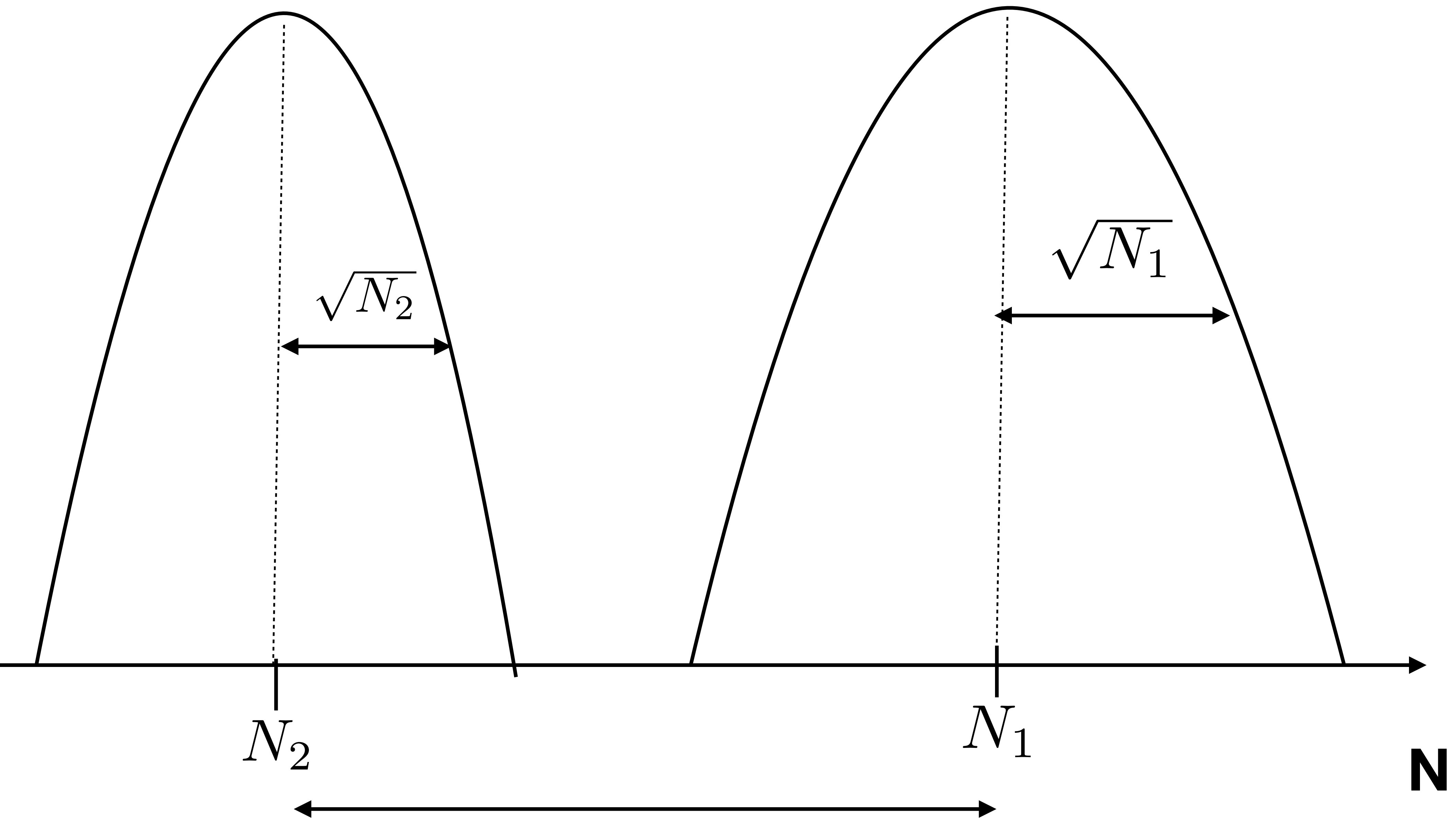

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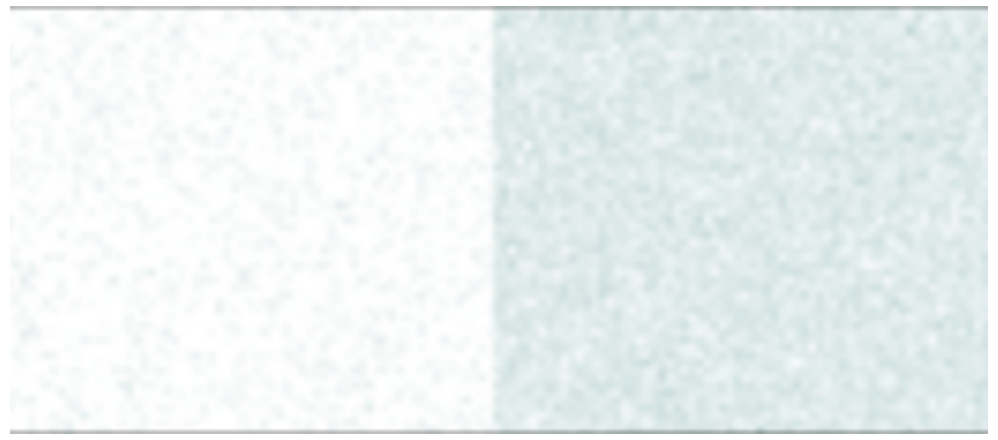

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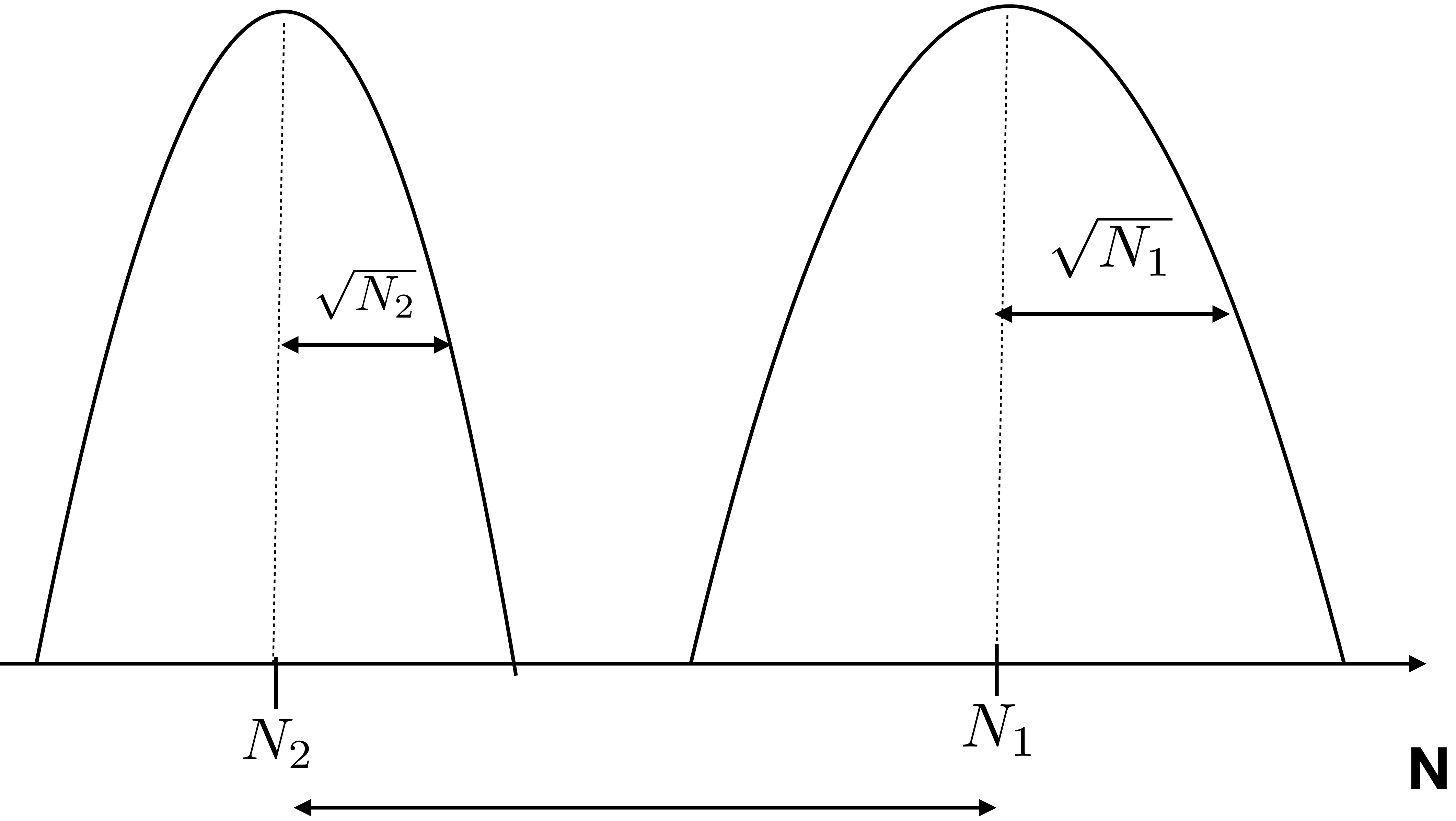


In this case SDNR is:

1. around 0
2. greater than 0, but lower than 1
3. around 1
4. greater than 1

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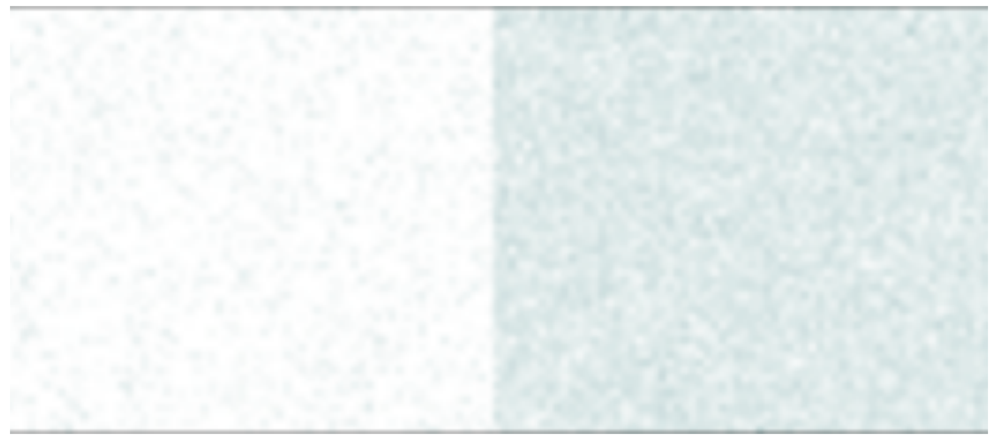

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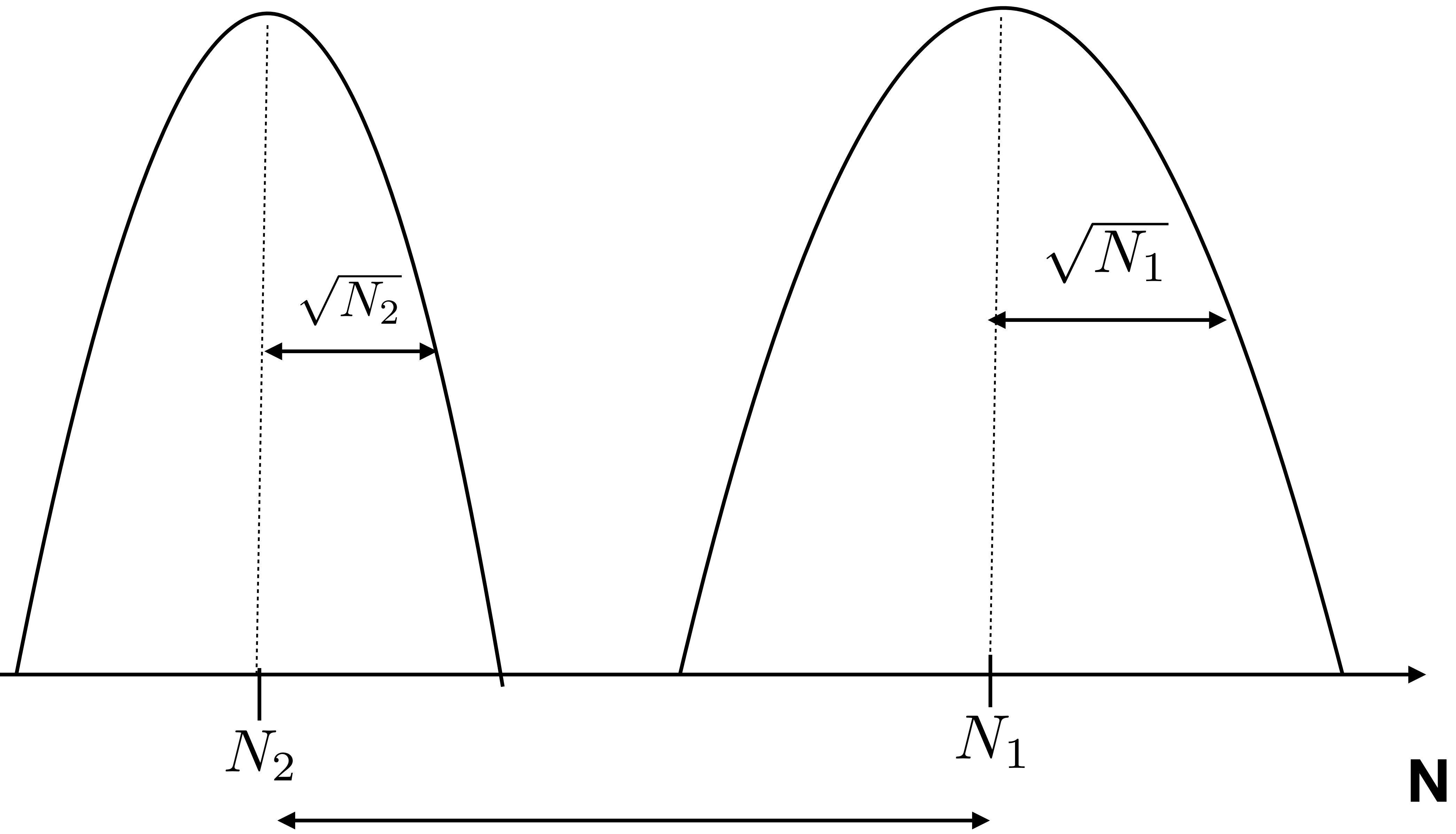


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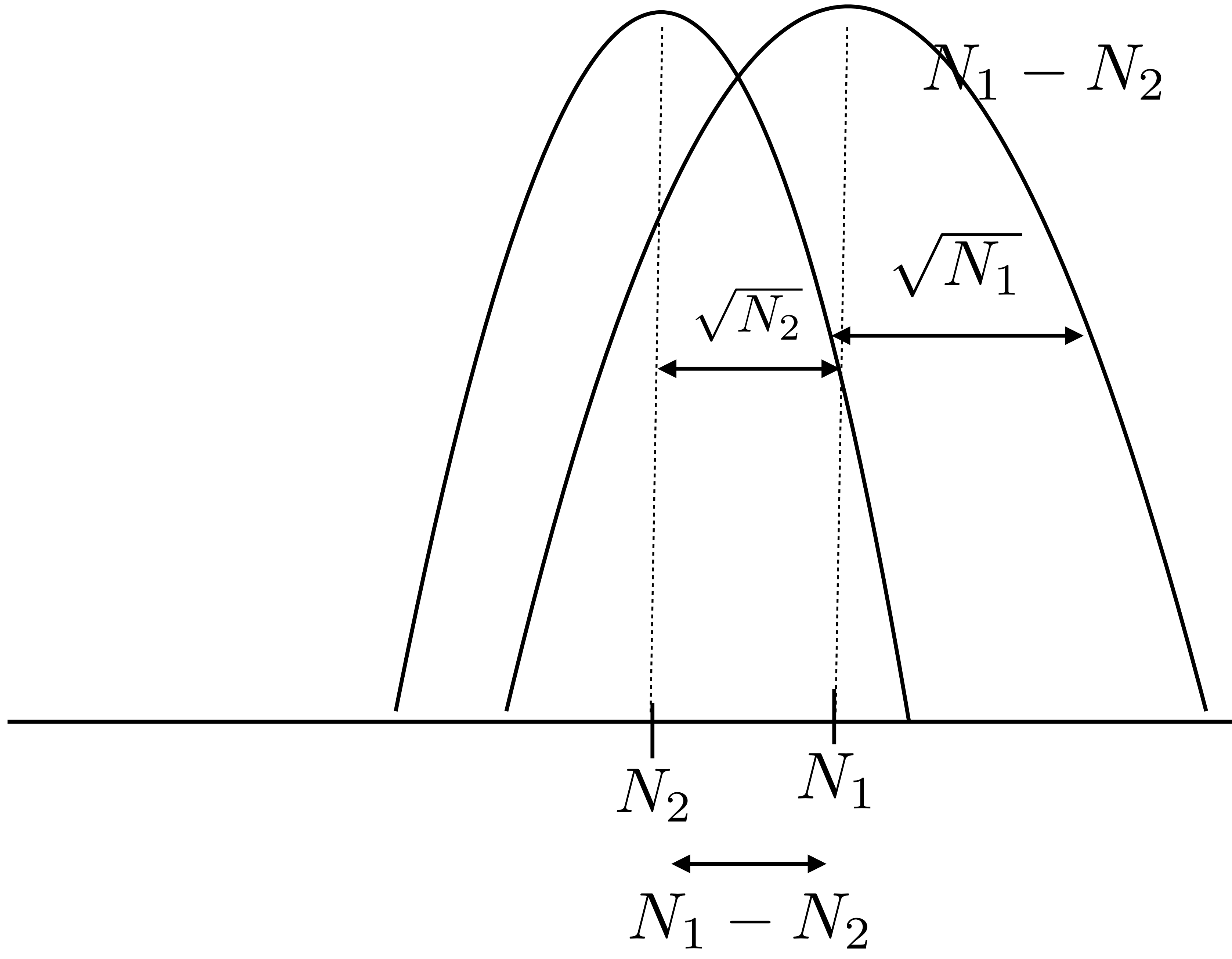


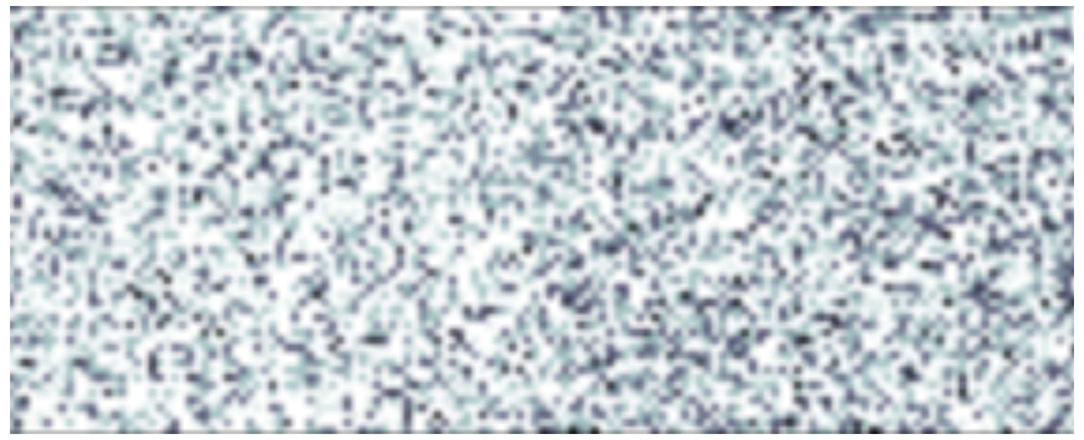

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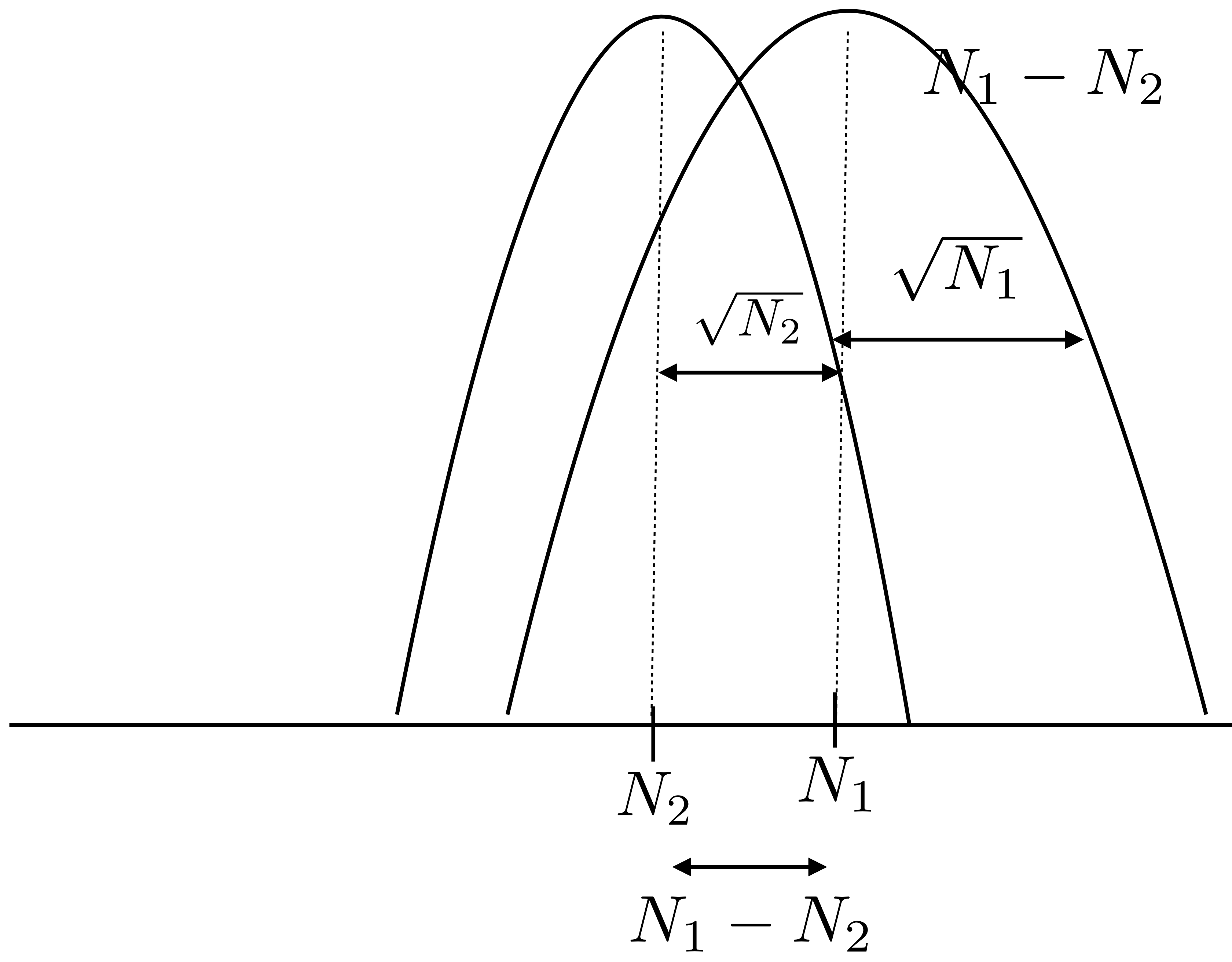


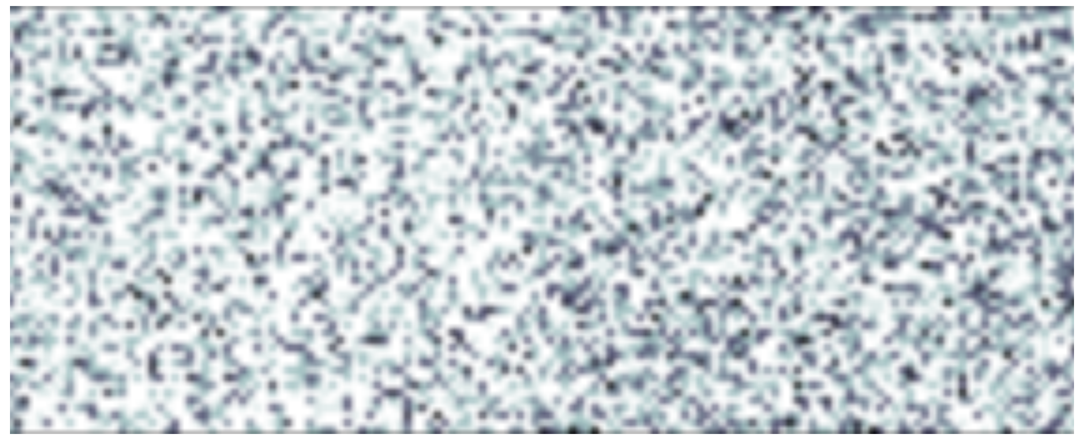

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# Rose model: An object is visible if SDNR ≥ 5

(Semi-empiric model, value 5 from experiment)

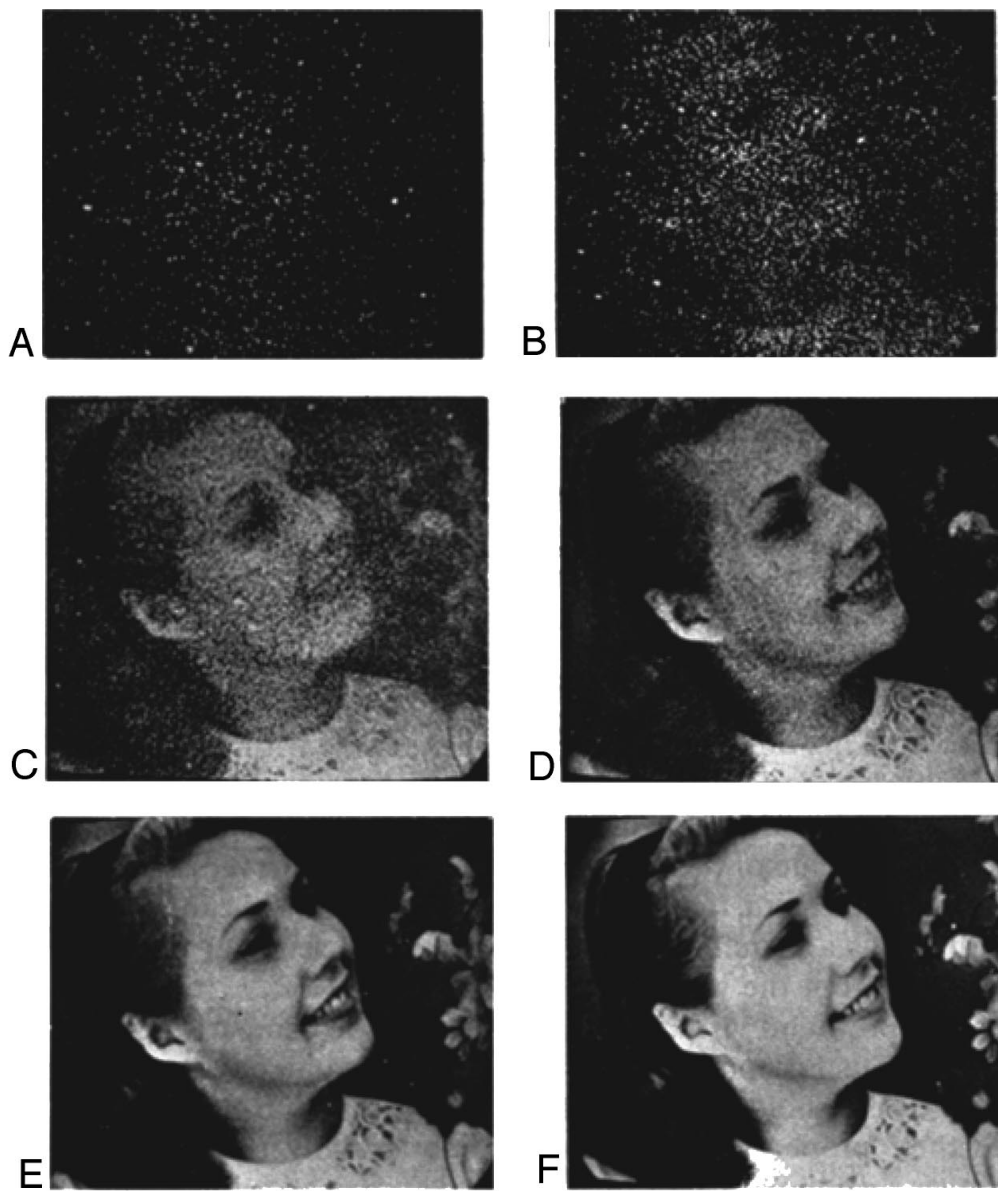


Fig. 1. Picture used by Rose,[4] of woman with flowers, to demonstrate the maximum amount of information that can be represented with varying numbers of photons. A, $3 \times 10^3$; B, $1.2 \times 10^4$; C, $9.3 \times 10^5$; D, $7.6 \times 10^5$; E, $3.6 \times 10^5$; F, $2.8 \times 10^7$. Each photon is represented as a discrete visible speck. The inherent statistical fluctuations in photon density limit one's ability to detect or identify features in the original scene.

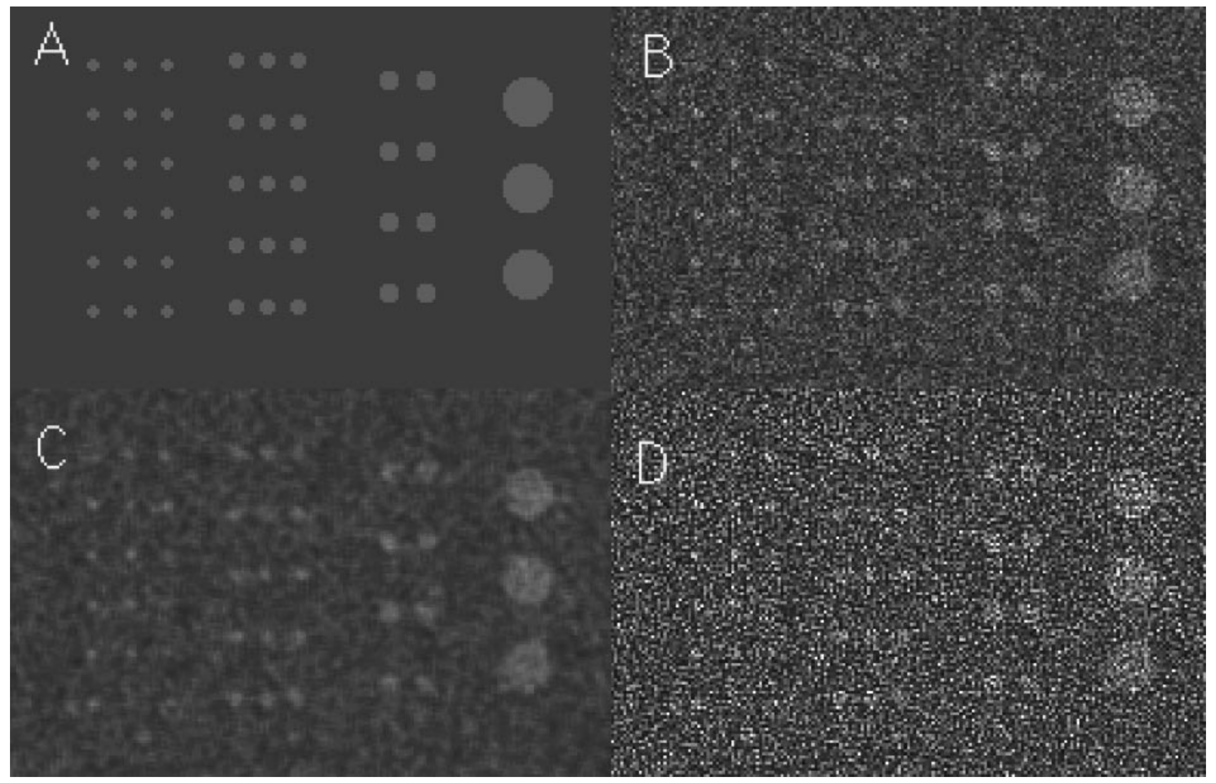


Fig. 4. Demonstration that pixel SNR ($SNR_p$) is not a good primary measure of image quality. $SNR_p$ is defined as the ratio of peak signal amplitude and noise standard deviation, $\sigma_p$, per pixel. This figure also shows that signal appearance is highly variable at low SNR, as is expected, given the statistical nature of the images. A, Signal array of disks (diameters of 4, 5, 6, 16 pixels) with amplitude of 24 gray levels. B, Same signal array with added zero-mean white noise ($\sigma_p$ of 24 gray levels), so $SNR_p = 1.0$ for all the signals. The Rose model and the ideal observer SNR's are 3.5, 4.6, 5.7, and 14.4. C, After smoothing of portion *B*. The low-pass-filtered noise has $\sigma_p$ of 8.2 gray levels, so $SNR_p = 2.9$ for all the signals. D, After edge enhancement of portion *B*, resulting in a $\sigma_p$ value of 39.6 gray levels and a $SNR_p$ value of 0.6. The filtering would have no effect on ideal observer SNR. The Rose model is not a valid method for calculating SNR with filtered images.

figures from Burgess AE. The Rose model, revisited. JOSA A. 1999 Mar 1;16(3):633-46.

# SDNR and dose

$$\mathrm{SDNR} = \frac{N_1 - N_2}{\sqrt{N_1} + \sqrt{N_2}} \quad \propto \sqrt{N}$$

dose $\propto N$

For att förbättra SDNR med en faktor 2, allt annat oförändrat, måste man öka dosen med e

1. 1
2. 2
3. 3
4. 4
5. Det går ej att säga

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Övningar:
att göras innan nästa
föreläsning!

# Övning

Antag att fotoner med energin 100 keV ska gå genom en filter gjord av 5 mm Al.

1. Rita en figur av detta.
2. Beteckna de nödvändiga storheterna
3. Bestäm linear attenuation coefficient för 5 mm Al (tag hjälp av NIST tabeller)
4. Bestäm attenueringsfaktor i detta fall
5. Bestäm andel primary photons genom Al-filter
6. Bestäm andel attenuated photons i Al-filter

Fråga Mamo om du behöver hjälp!

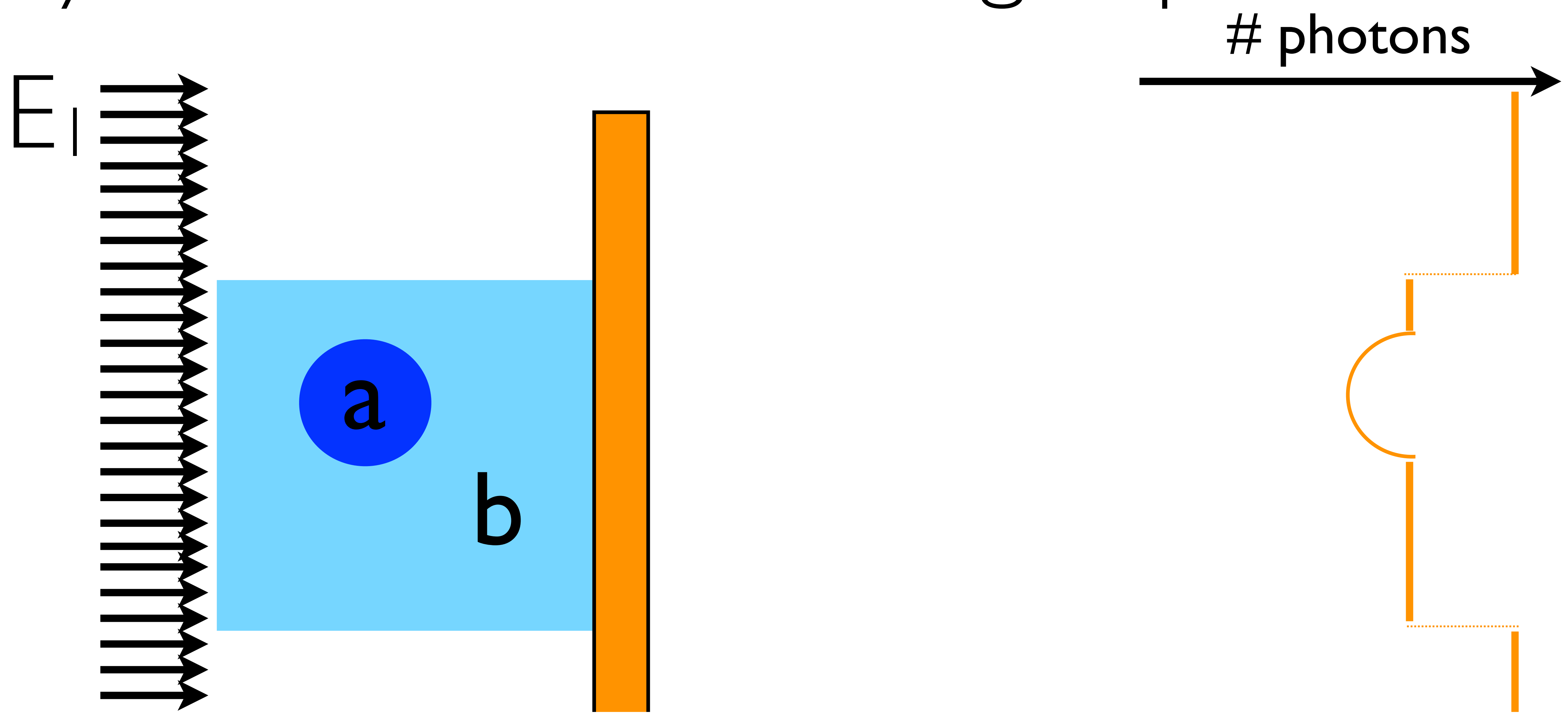
Q: the linear attenuation coefficient of lead for photons of energy of 500 keV is:

1. 0,1614
2. 0,1614 $cm^2/g$
3. 1,1832
4. 1,1832 $cm^{-1}$

Q: what is the attenuation factor of 1 mm of lead for 500 keV photons?

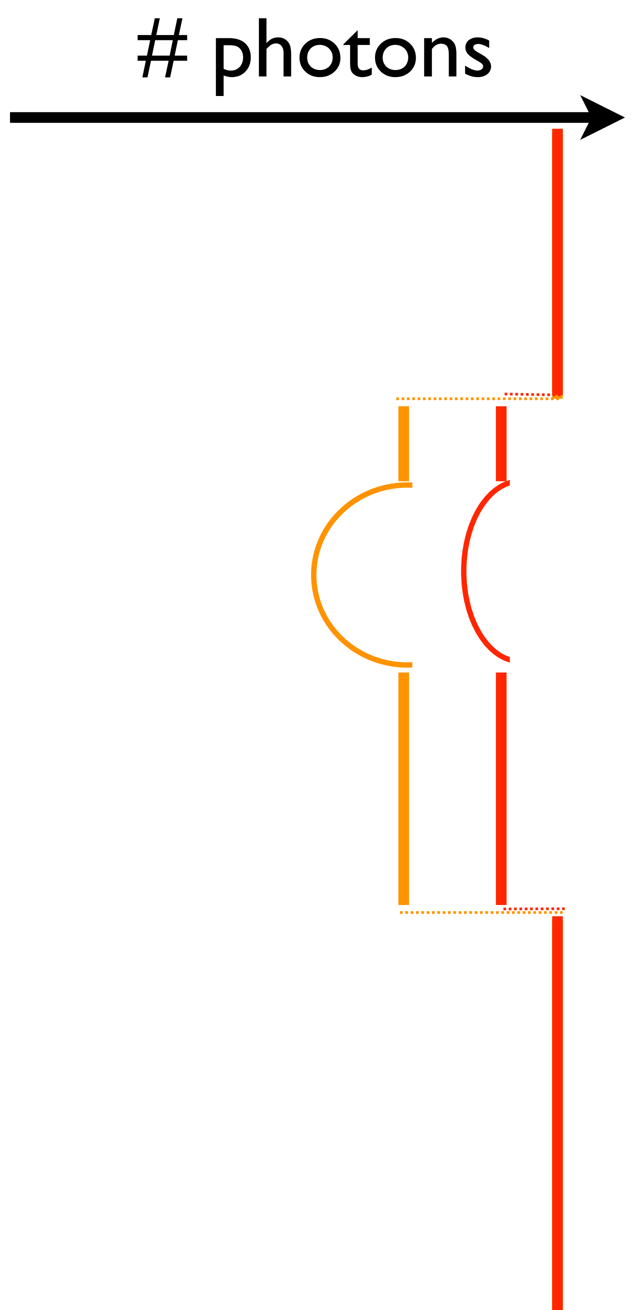
Q: what is the lead thickness needed in order to attenuate 90% of incoming 500 keV photons?

suppose you make the following experiment:

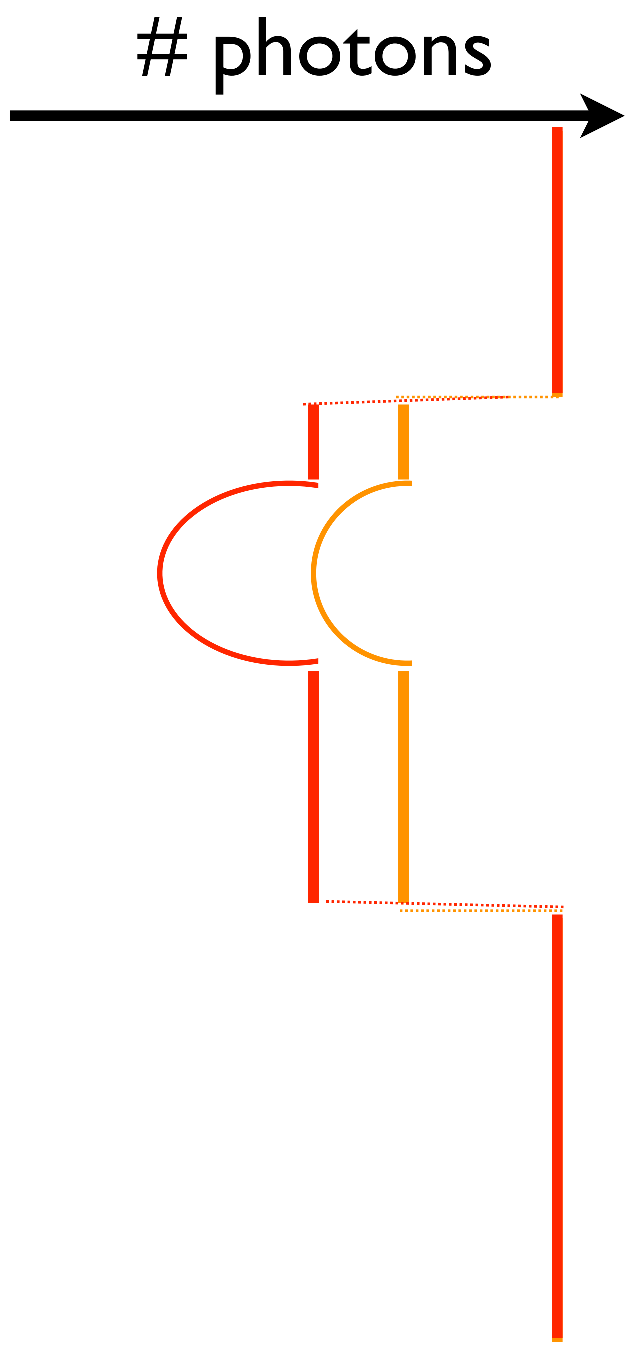



Now you increase the energy of the incoming photons.
What will be the result? (red line is the new result)

1.

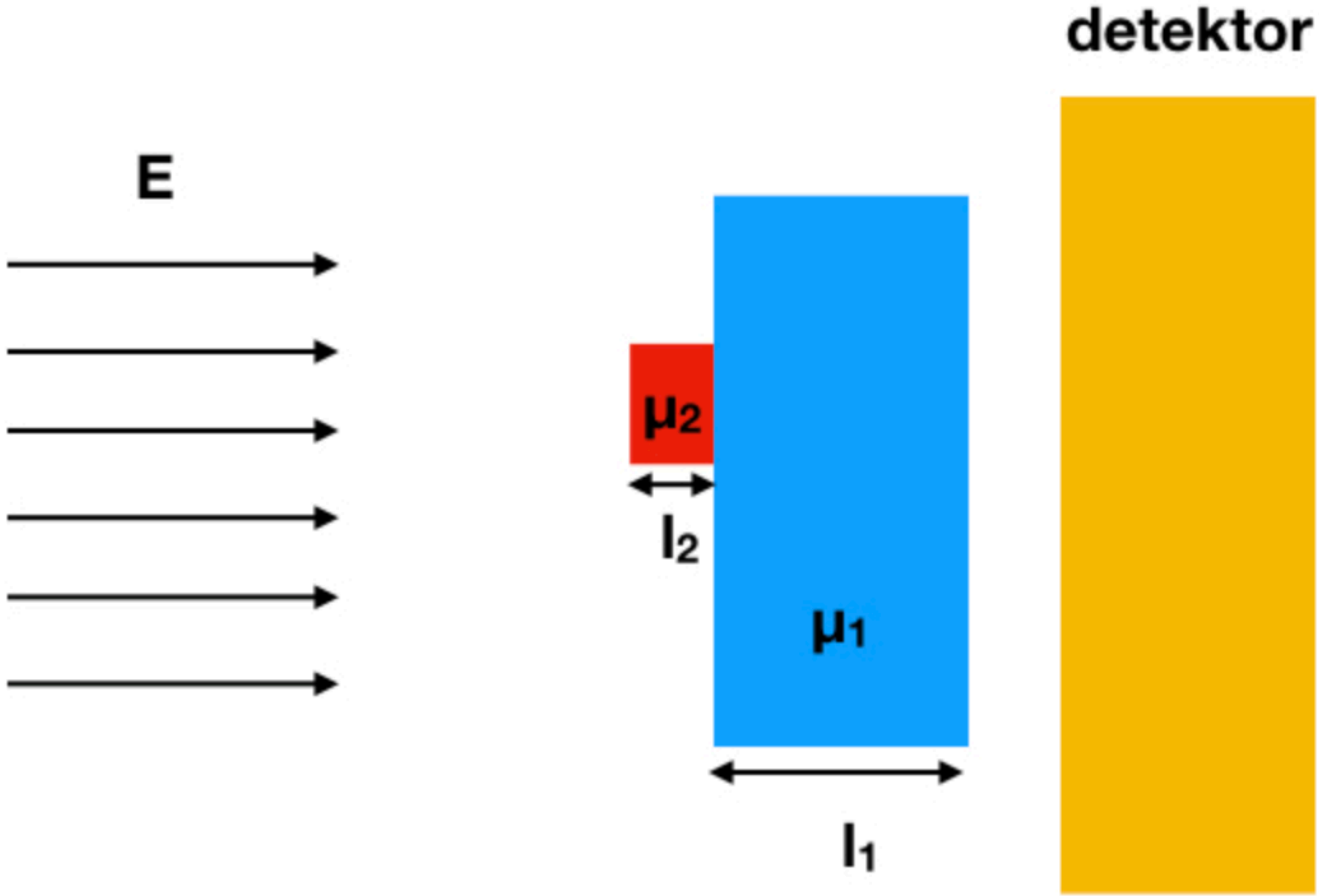


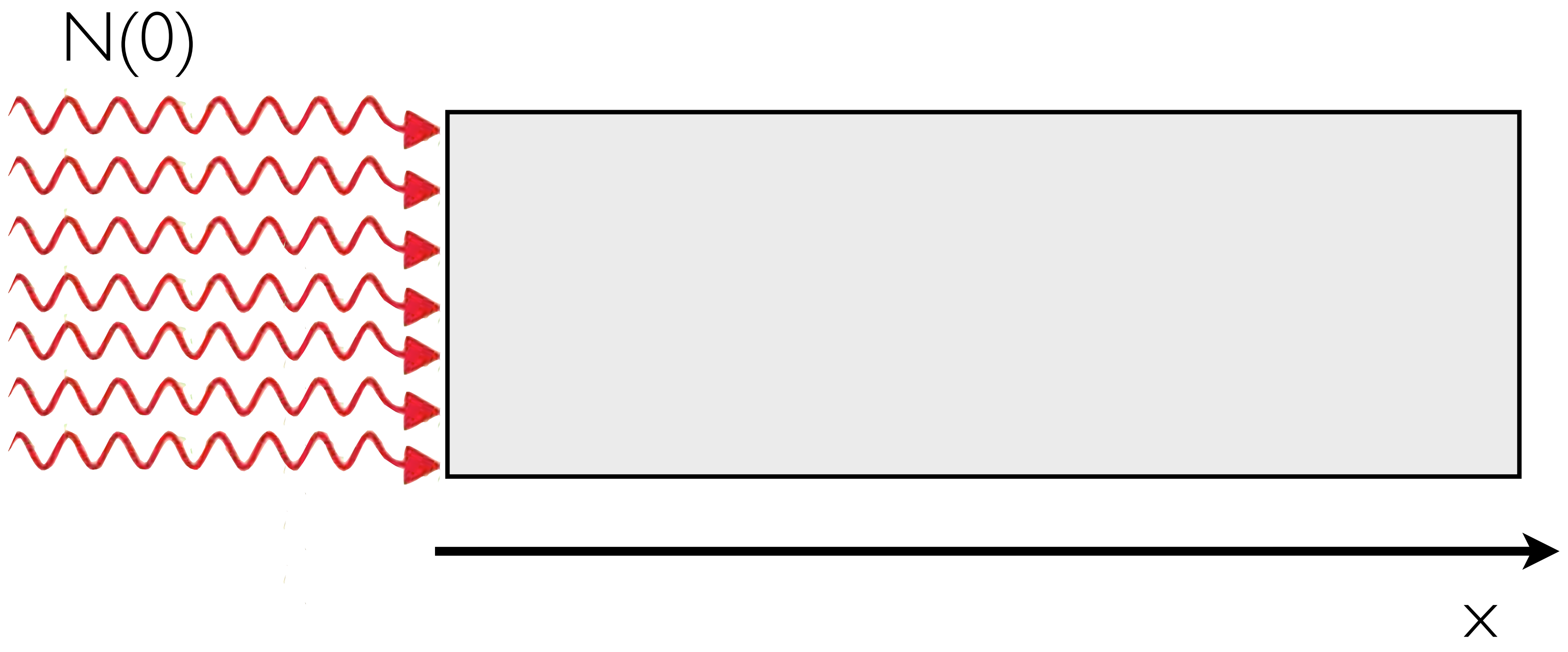

2.



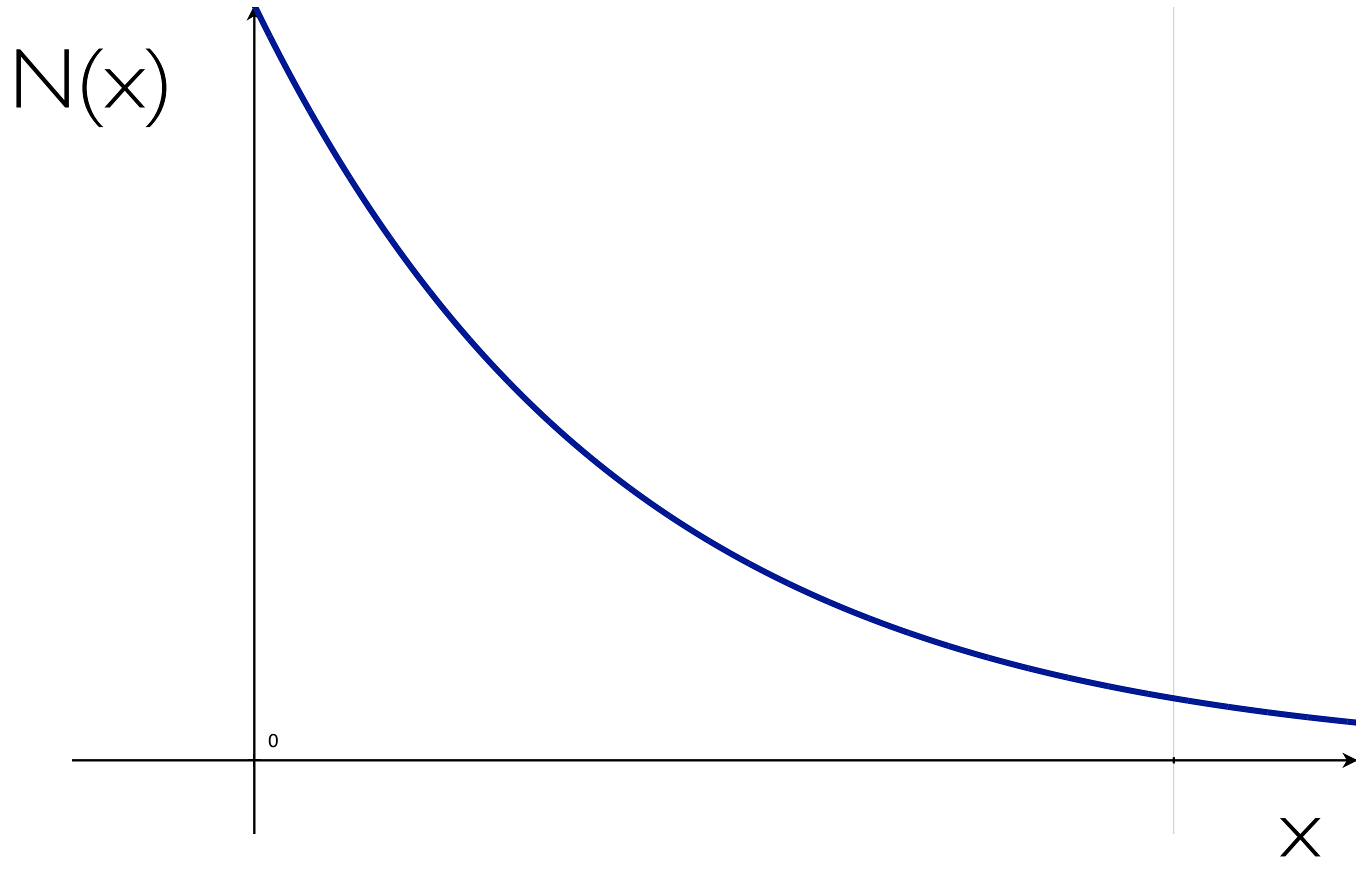

3. something else

Bestäm objektkontrast med avseende på det röda objektet i situationen i figuren nedan

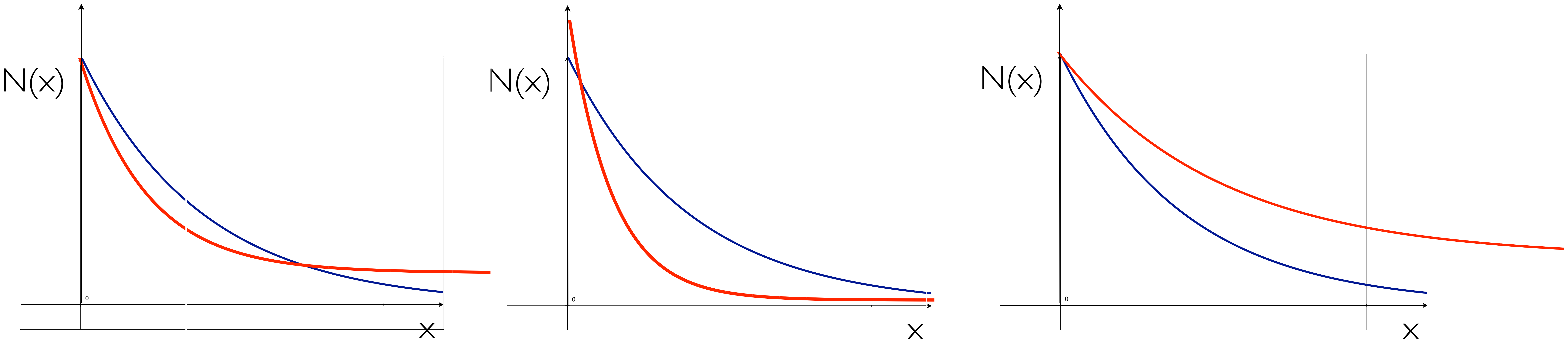





N(x) looks like:




Now the energy of the incoming photons is increased. N(x) looks like:




1 2 3

När en stråle fotoner passerar en viss tjocklek av en viss material så attenueras strålens intensitet till 50% av sitt ursprungliga värde. Vad händer om tjockleken fördubblas?

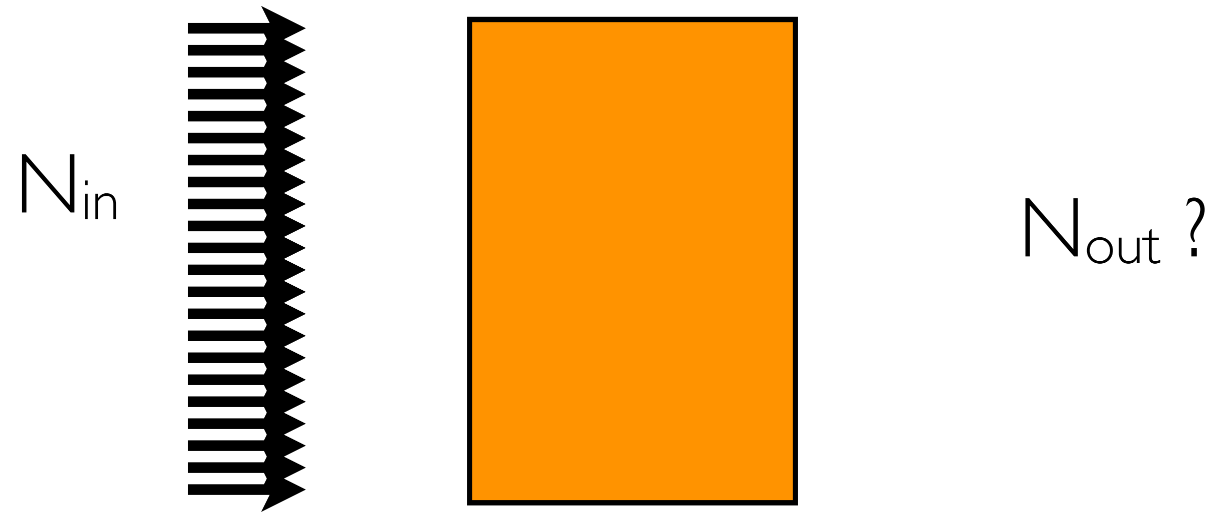
1. attenueringsfaktor fördubblas
2. attenueringsfaktor halveras
3. attenueringsfaktor kvadreras
4. attenueringsfaktor blir 0
5. något annat

När en stråle fotoner passerar en viss tjocklek av en
viss material så attenueras strålens intensitet till 50% av
sitt ursprungliga värde. Vad händer om man använder en material av sam
men med dubbelt så hög densitet?

1. attenueringsfaktor fördubblas
2. attenueringsfaktor halveras
3. attenueringsfaktor kvadreras
4. attenueringsfaktor blir 0
5. något annat

När en stråle fotoner passerar en viss tjocklek av en
viss material så attenueras strålens intensitet till 30% av
sitt ursprungliga värde. Vad händer om man skickar genom samma filter e
fotoner som har dubbelt så hög energi som den ursprungliga strålen?

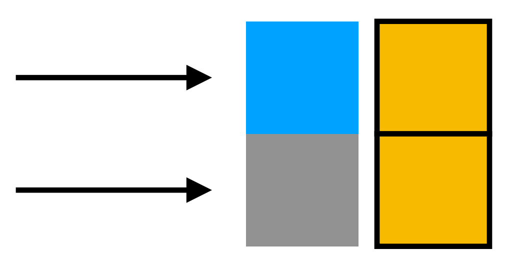
1. attenueringsfaktor fördubblas
2. attenueringsfaktor halveras
3. attenueringsfaktor kvadreras
4. aattenueringsfaktor blir 0
5. något annat




What do you think $N_{out}$ is dependent on?

1. target material
2. target area perpendicular to the flux
3. target thickness
4. $N_{in}$
5. energy of incoming photons
6. temperature
7. time over which the incoming photons are delivered
8. quality of the detector
9. none of the above, Nout is a stochastic variable

## Övning:




Bestäm objektkontrast samt SDNR i följande fall:

1. Vatten och aluminium, 1 cm tjocka, samma antal fotoner in, $N_0$, med E = 60 keV. Bestäm detta för $N_0 = 10, 10^3, 10^5$. Presentera ditt svar som en 2x3 tabell (objektkontrast och SDNR vs antal fotoner).
2. Samma som ovan, men vatten och aluminium bitar läggs på 0,3 mm bly.
3. Skriv ned det du har lärt dig genom övningen om objektkontrast samt SDNR.

## Roligare övning:

Man vill bestämma om ett block post-it lappar innehåller 1000 eller 1001 post-it genom planröntgen. Antag att man använder en energi vid vilken pappers linear attenuation coefficient är 0,1 $cm^{-1}$ och att källan som används strålar $10^5$ fotoner/s mot blocket. Bestäm minsta möjliga tiden som krävs. (Du måste göra en uppskattning på tjockleken på en post it).

(Dokumentet kontrastochSDNR.pdf i CANVAS kan vara av hjälp)