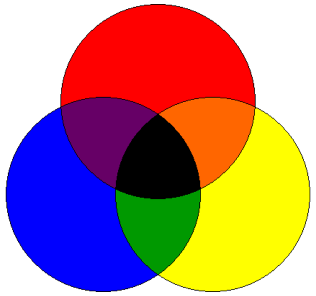
This is what you should know after this lecture + own work:

1. How does an x-ray tube works: physical principles and technological solutions
2. Energy spectrum emitted from x-ray tube, characteristics and origin.
3. How a radiation detector (photon counting and energy integrating) works in principles.
4. Detection efficiency (geometric, intrinsic and total) definition and how to evaluate it in simple cases
5. Difference between emitted and detected spectrum
6. Difference and relationship among activity, emitted photons, detected photons, count rate



Physics

- Beer's law
  - attenuation factor, linear and mass attenuation coefficient, primary photons . . .
- Object contrast
  - depends on photon E (given the object!)

X-ray tube
Detectors

Technology

Not much

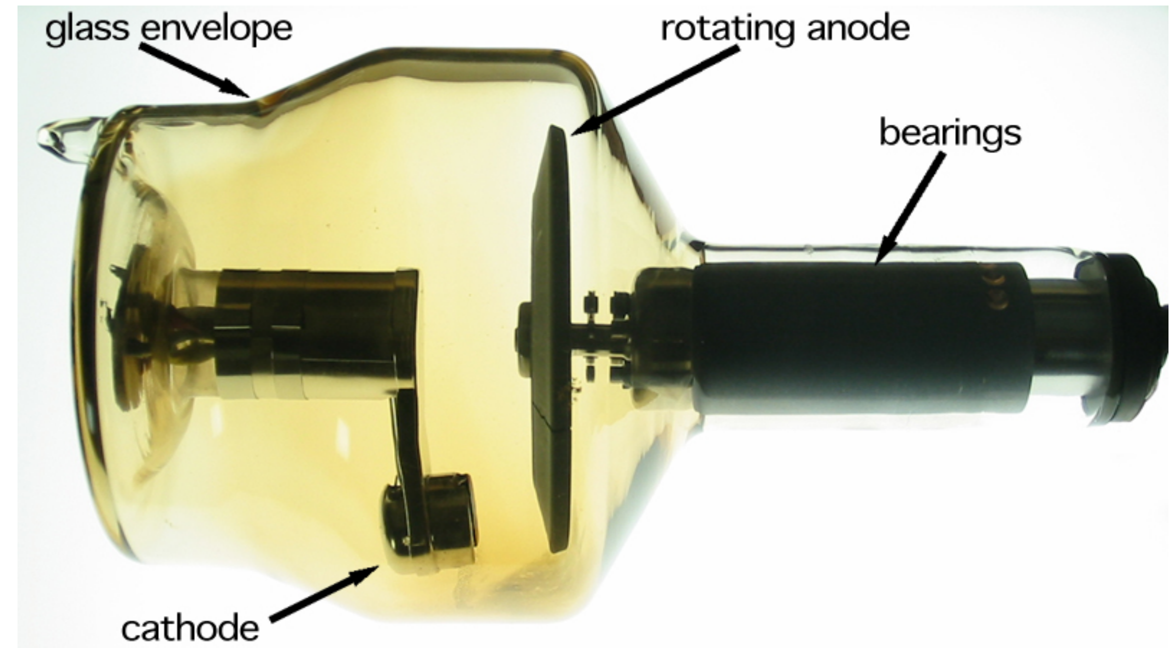
object contrast
vs
image contrast

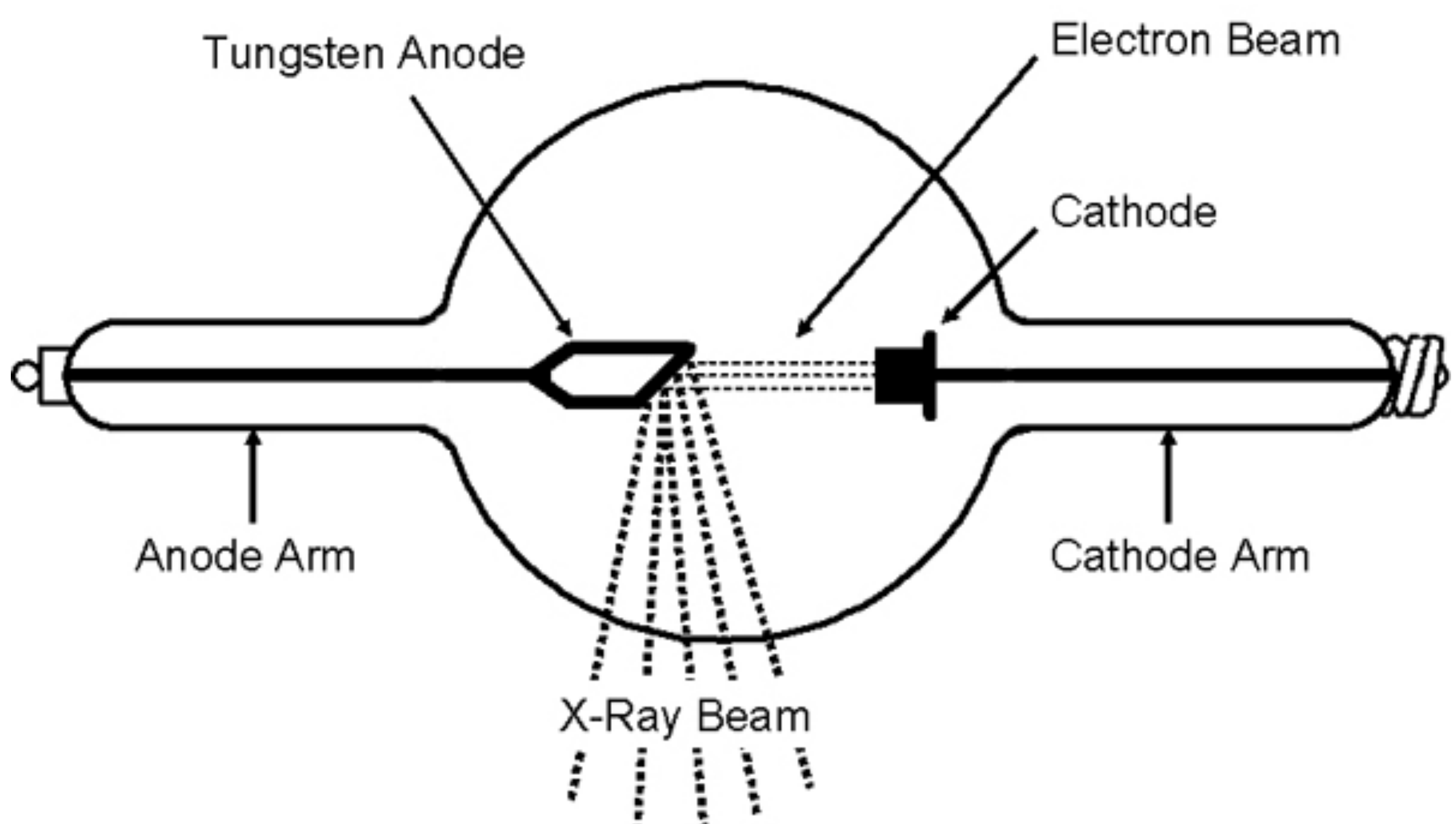
Clinical need/application

Some "hints". Started discussing, for example, that Compton is not accounted for

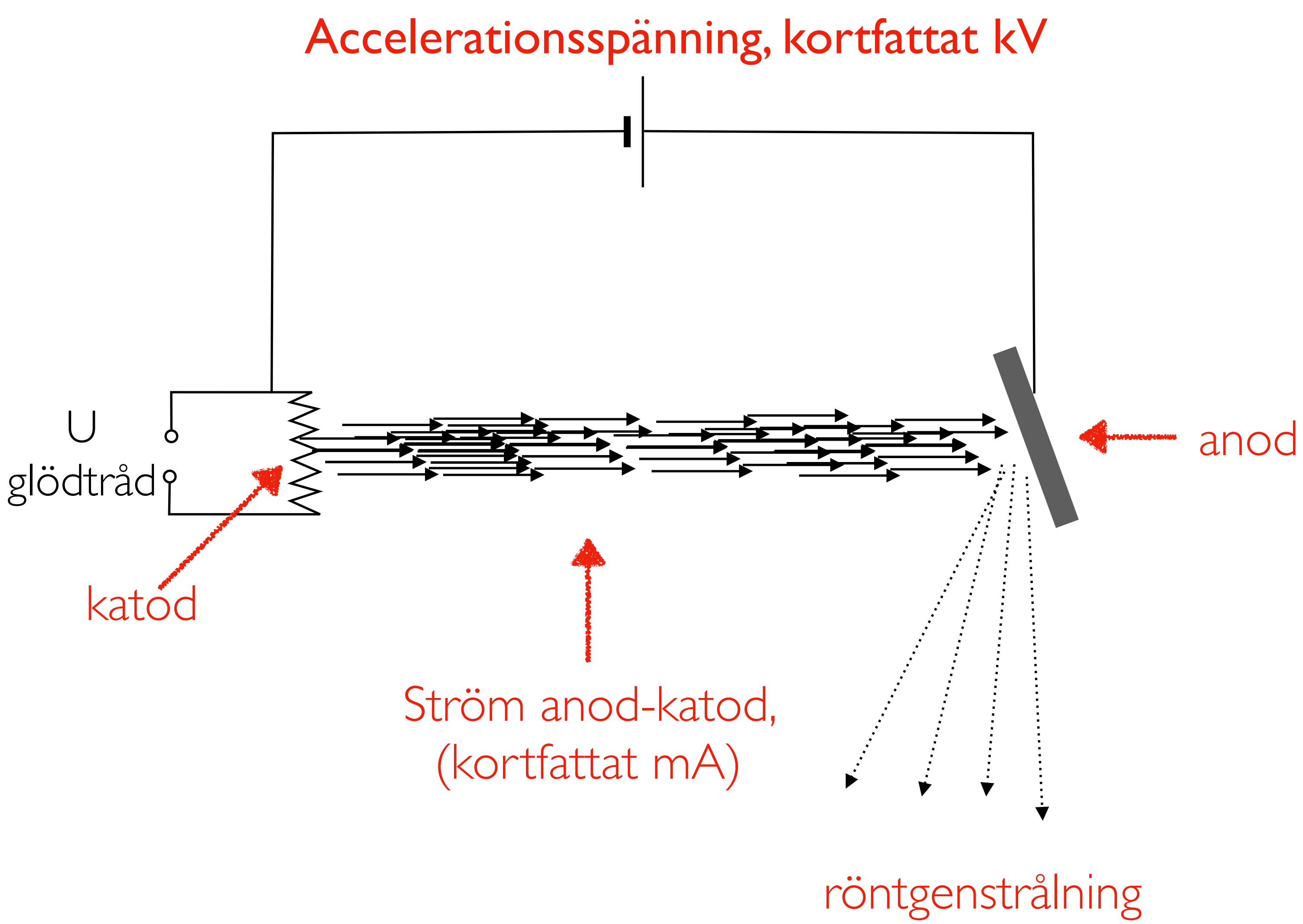
X-ray sources

Röntgenrör


glass envelope
rotating anode
bearings
cathode


Tungsten Anode
Electron Beam
Cathode
Anode Arm
Cathode Arm
X-Ray Beam

Röntgentrör enkel schema:



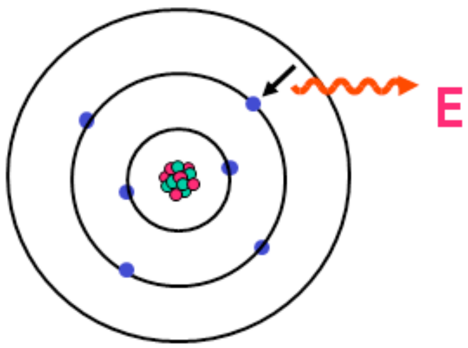
Vad händer i anoden?

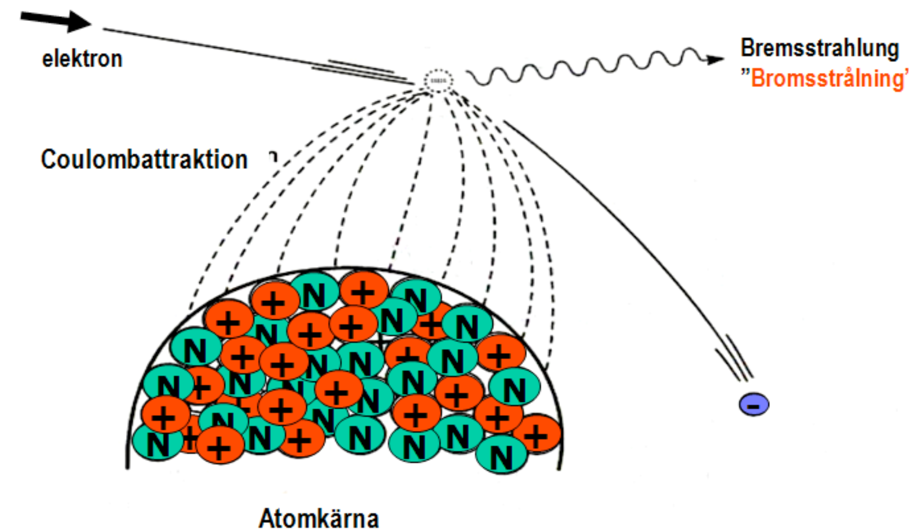
$e^- — e^-$

$e^- —$ kärna

fotoner

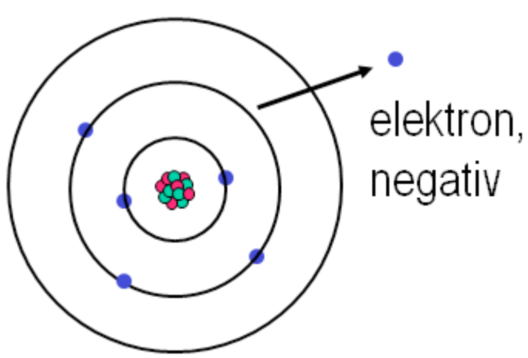
- Elektromagnetisk strålning, t.ex vid deexcitation



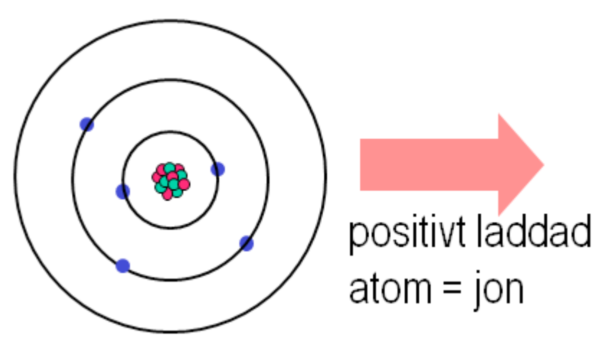


laddade partiklar

- Partikelstrålning vid jonisation

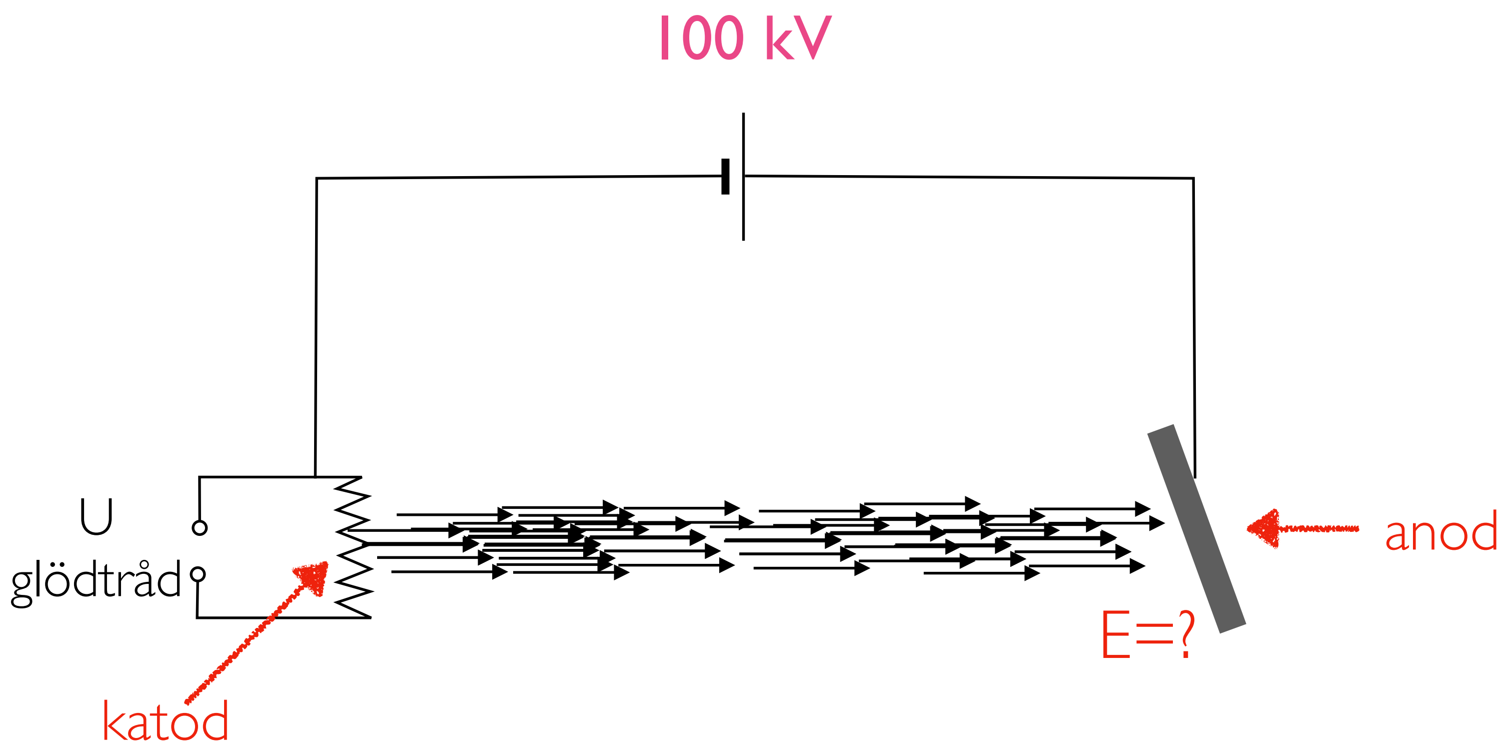


eller jonstrålning



Which of the following claims are true?

1. bremsstrahlung is an interaction between electrons
2. bremsstrahlung is an interaction between electrons and nuclei
3. Röntgen radiation (characteristic radiation) is a result of the interaction between 2 electrons, one bound to an atom
4. Röntgen radiation (characteristic radiation) is a result of the interaction between an electron and an atomic nucleus

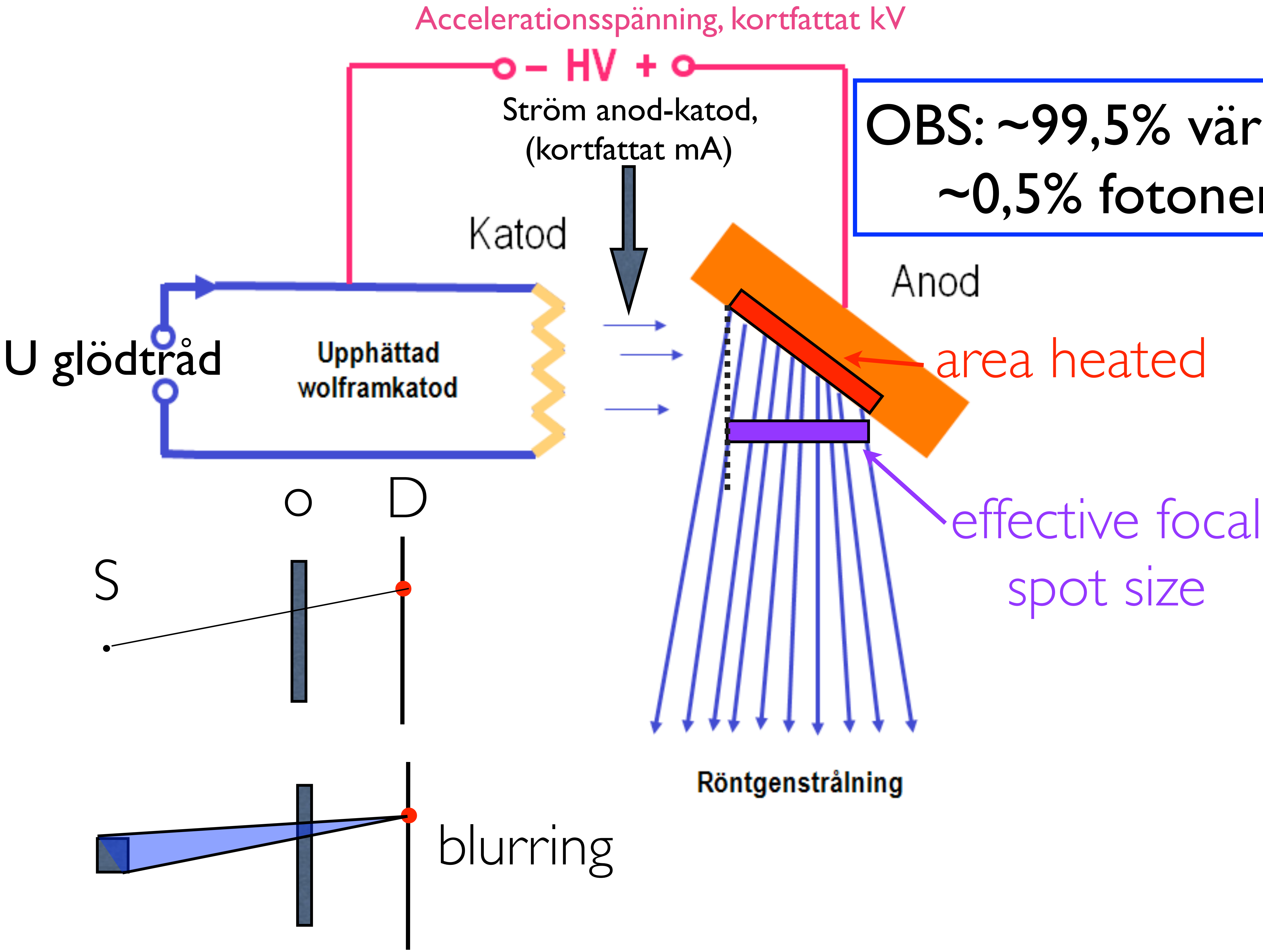


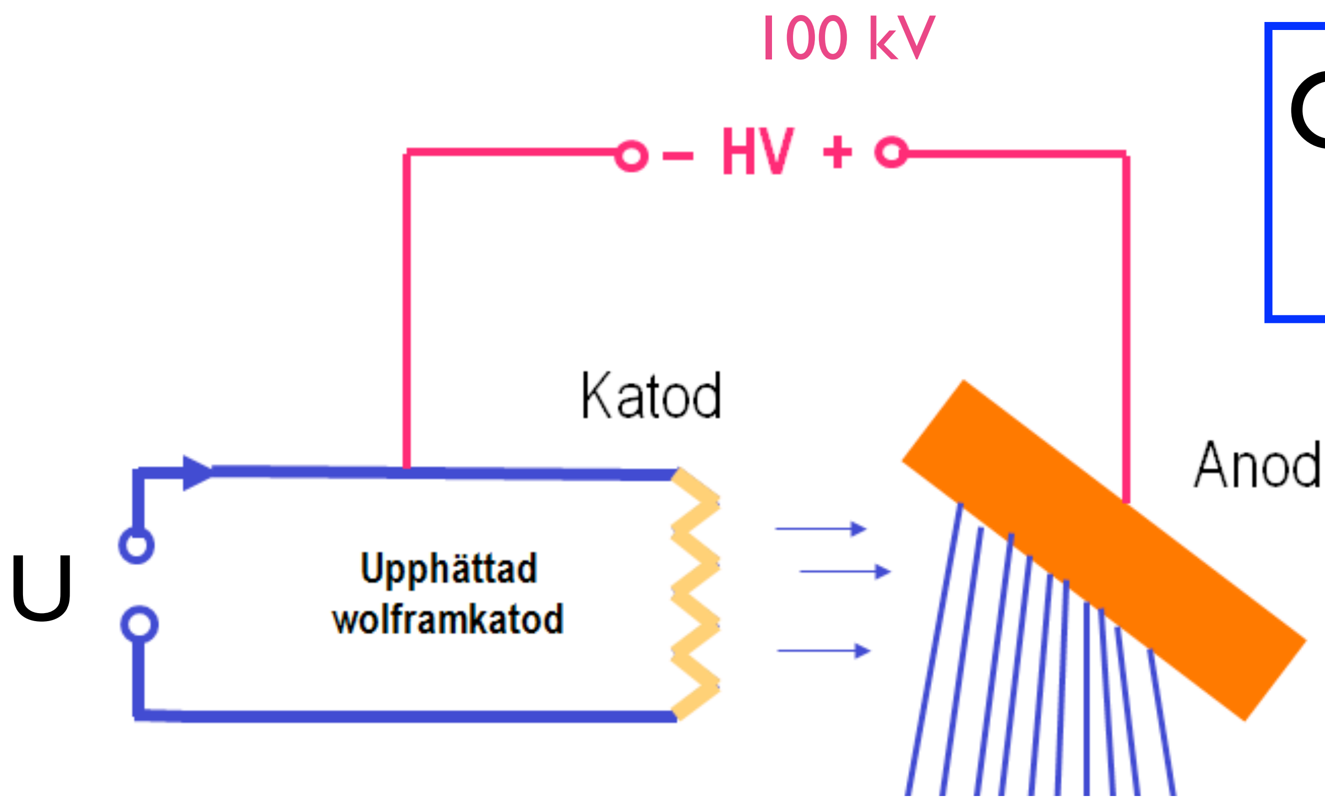
Suppose that the accelerating potential is 100 kV. Just before they hit the anode, the energy of the electrons emitted at the cathode is:

1. very high
2. anything between 0 and 100 keV
3. 100 keV
4. impossible to say, more information is needed

Röntgentrör focal spot size vs output:

OBS: ~99,5% värme!
~0,5% fotoner



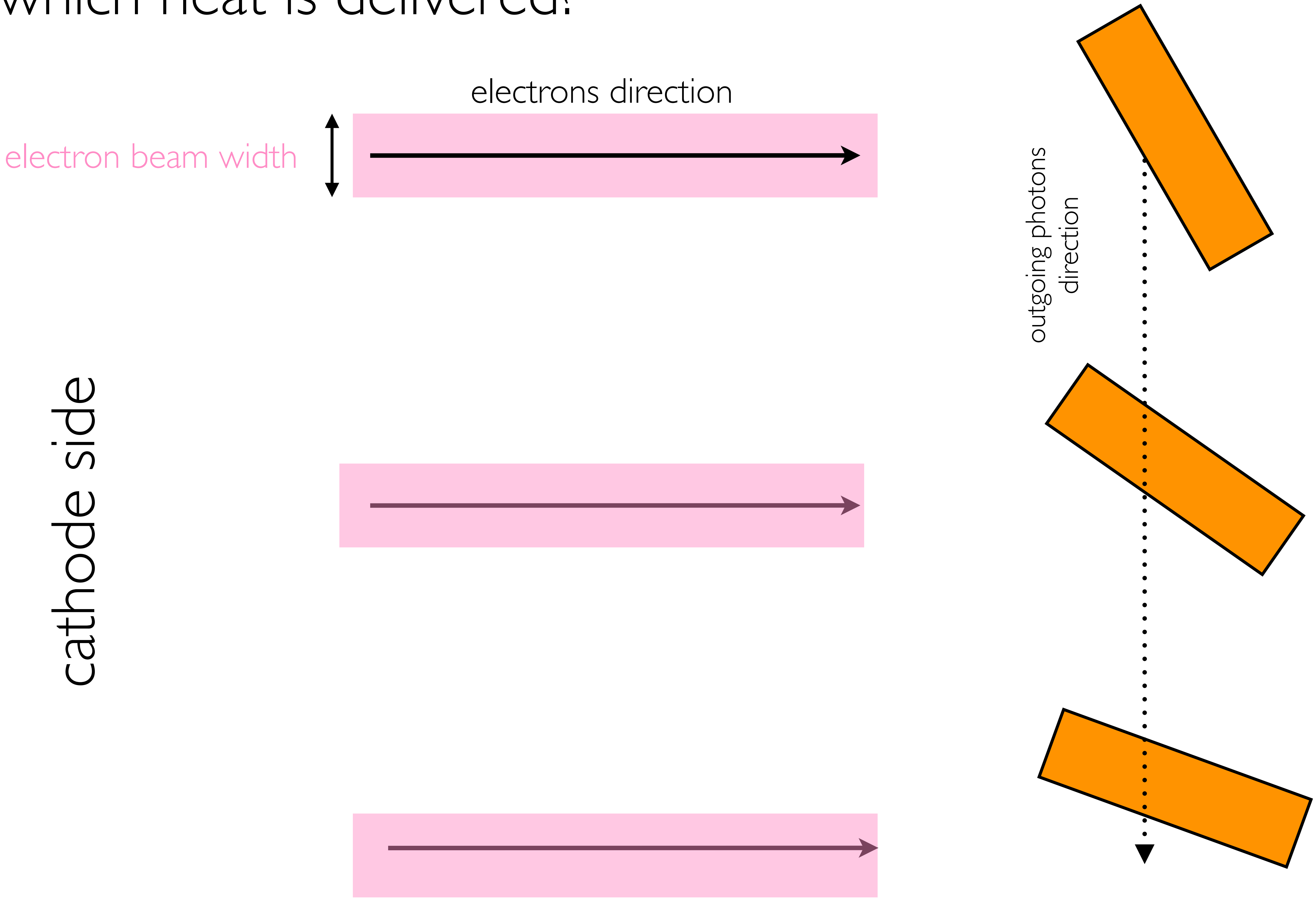


OBS: ~99,5% värme!
~0,5% fotoner

Suppose that the tube is operated at 100 kV and 100 mA, while the filament voltage is 10 V. The power dissipated in the anode is then:

1. ~9,95 kW
2. 10 kW
3. ~9,95 W
4. 10 W
5. impossible to determine

Which positioning of the anode will minimise the effective focal spot area while increasing the area over which heat is delivered?

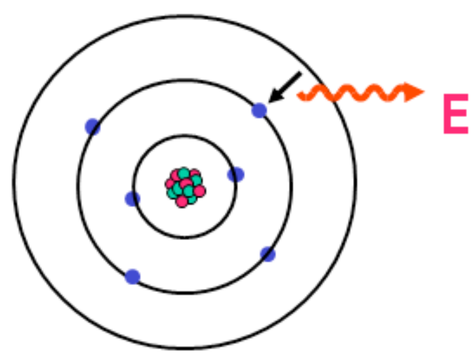


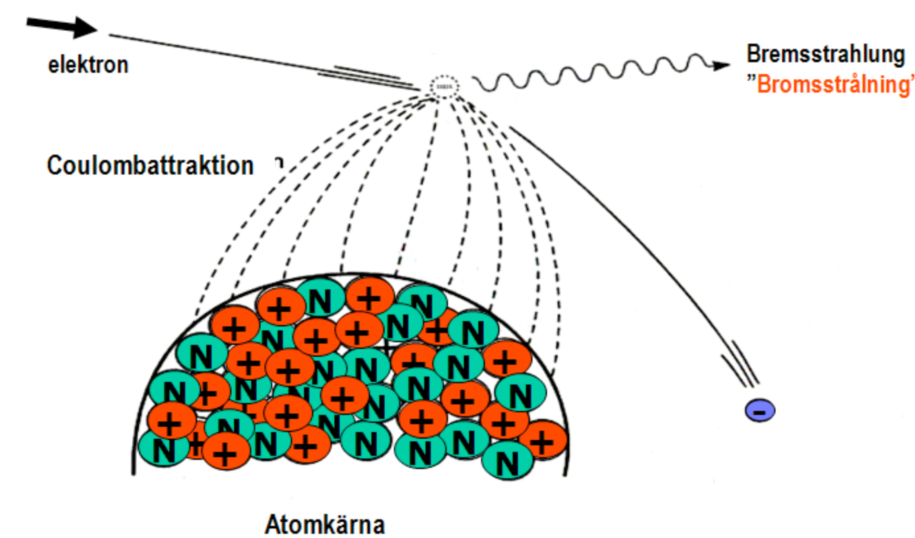
Vad händer i anoden?

e⁻ — e⁻ | e⁻ — kärna

fotoner

- Elektromagnetisk strålning, t.ex vid deexcitation

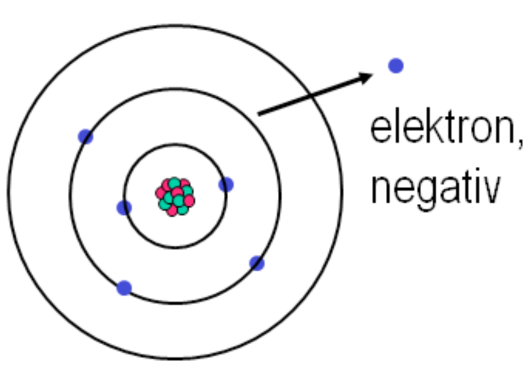




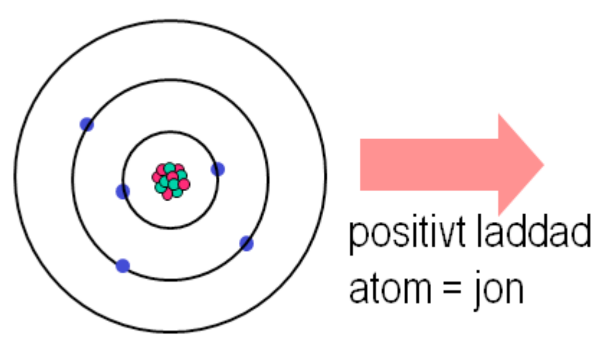
2 mekanismer bidrar till röntgenspektrum

laddade partiklar

- Partikelstrålning vid jonisation

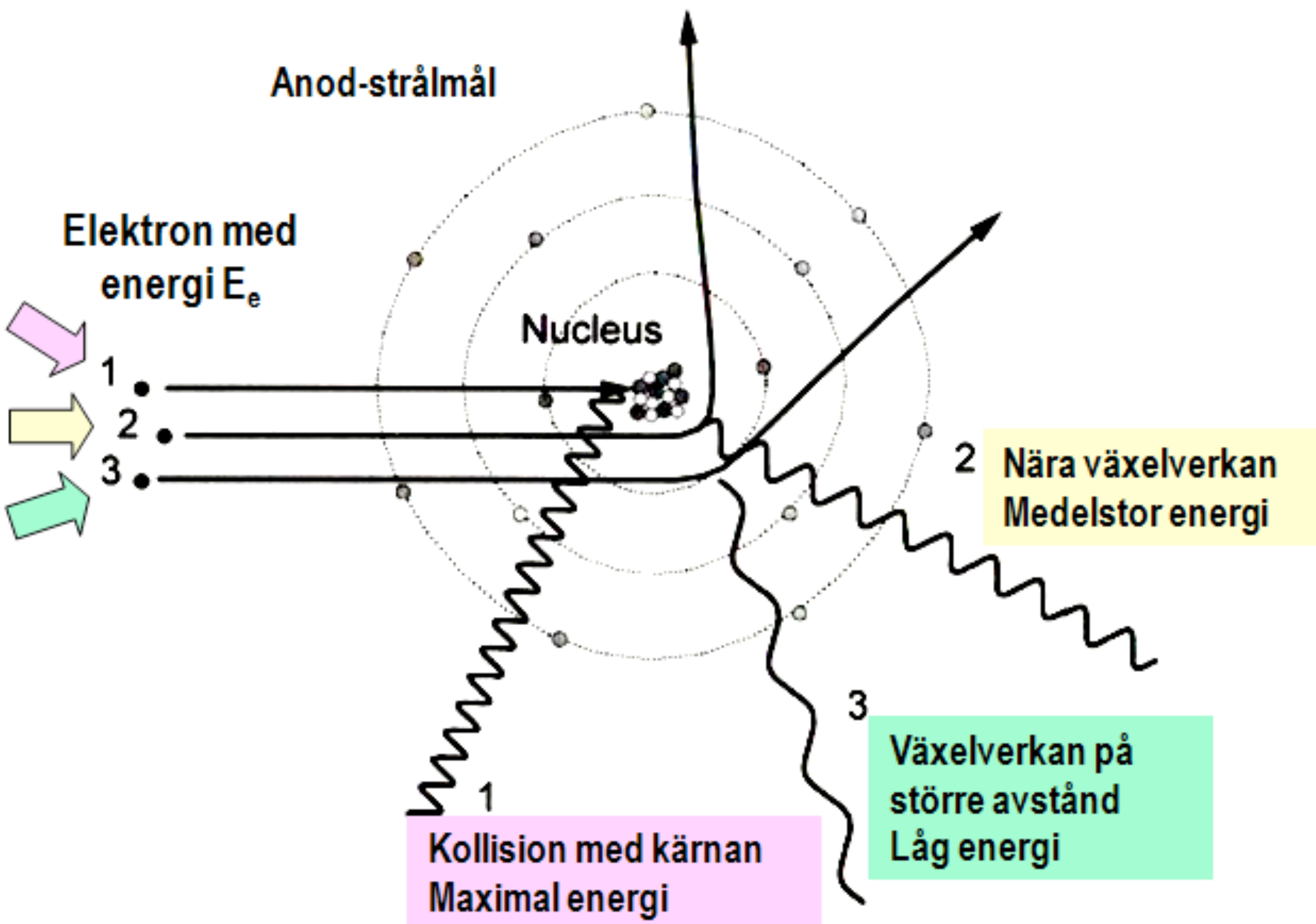


eller jonstrålning

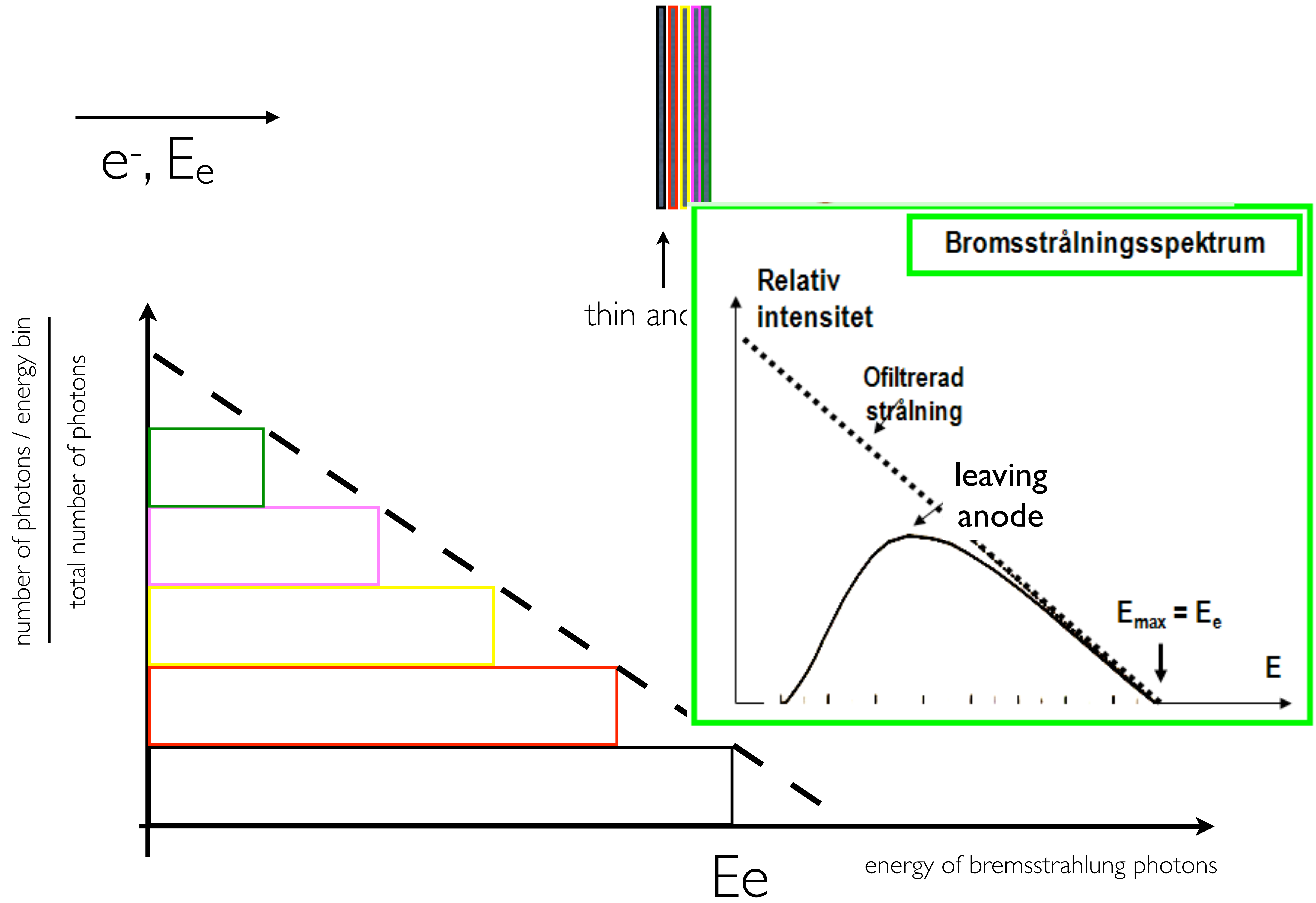


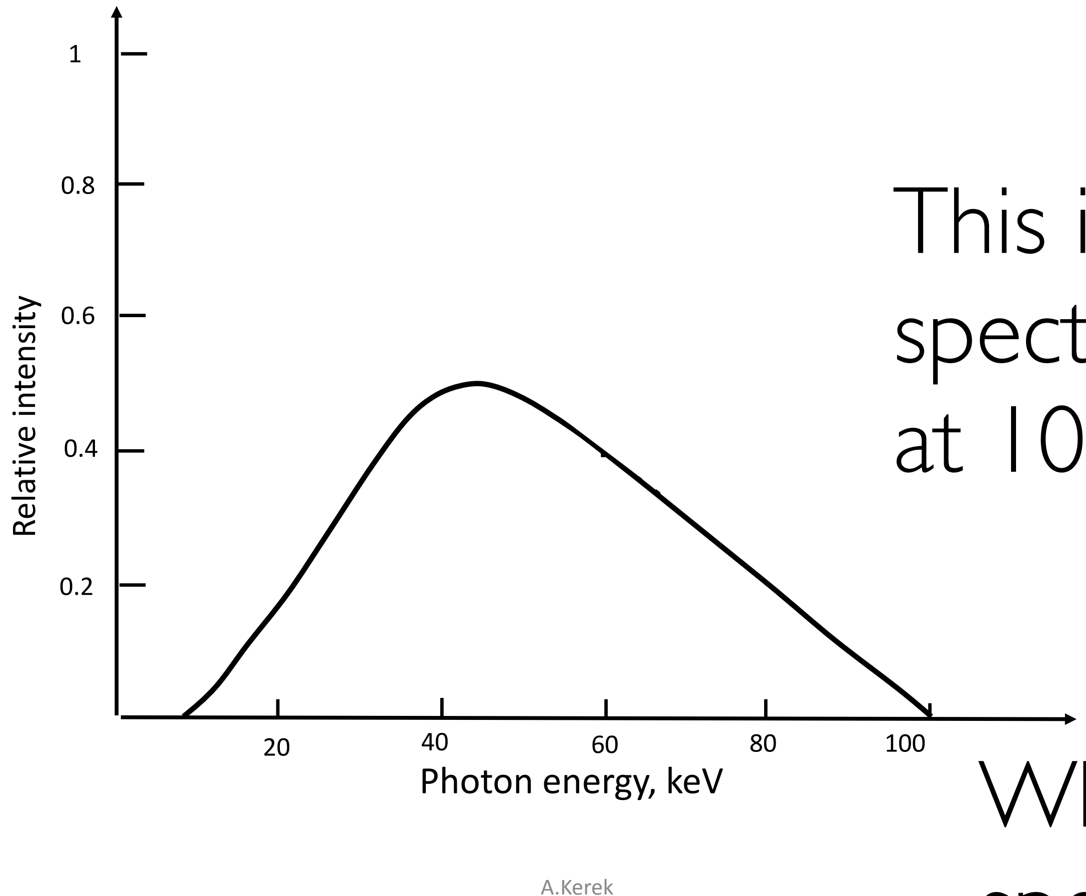
Bromsstrålning

- Bromsstrålningens energifördelning är kontinuerlig
- Maxenergin är lika med elektronens energi
- Den är samma som accelerationsspänningen ggr e-laddning



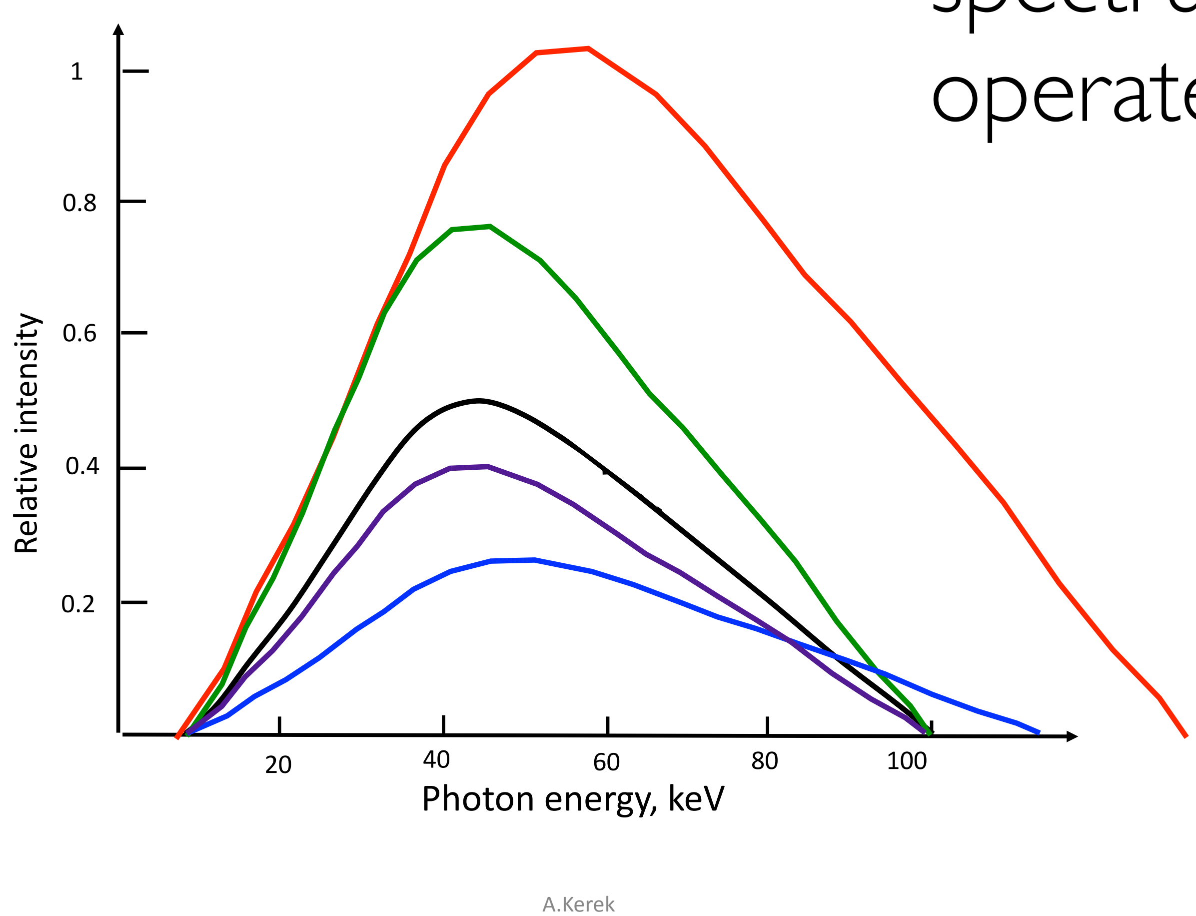
Unfiltered spectrum:





This is the continuous part of the spectrum from an x-ray tube operated at 100 kV and 100 mA

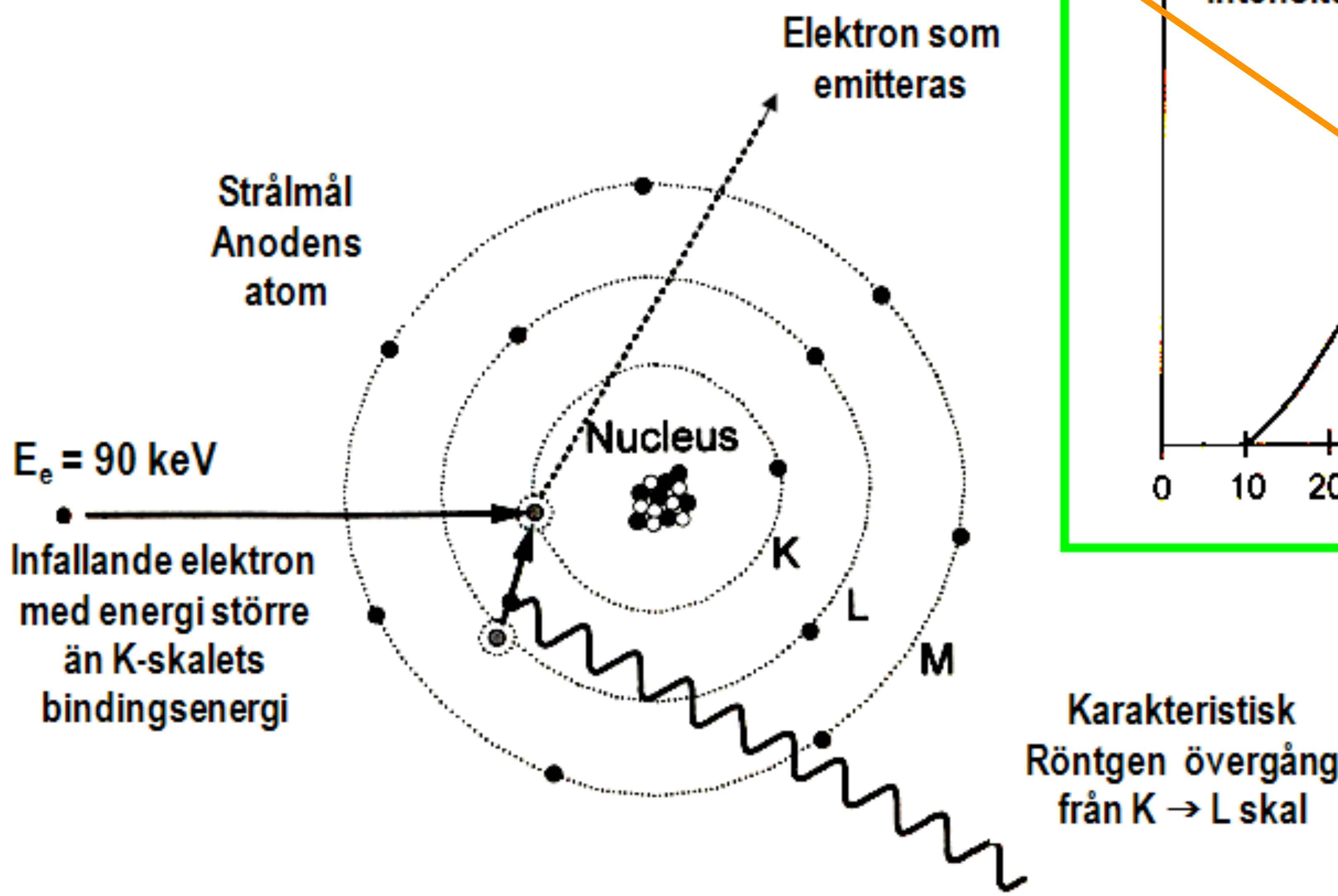
Which line represent the continuous spectrum from the same tube operated at 100 kV and 150 mA?

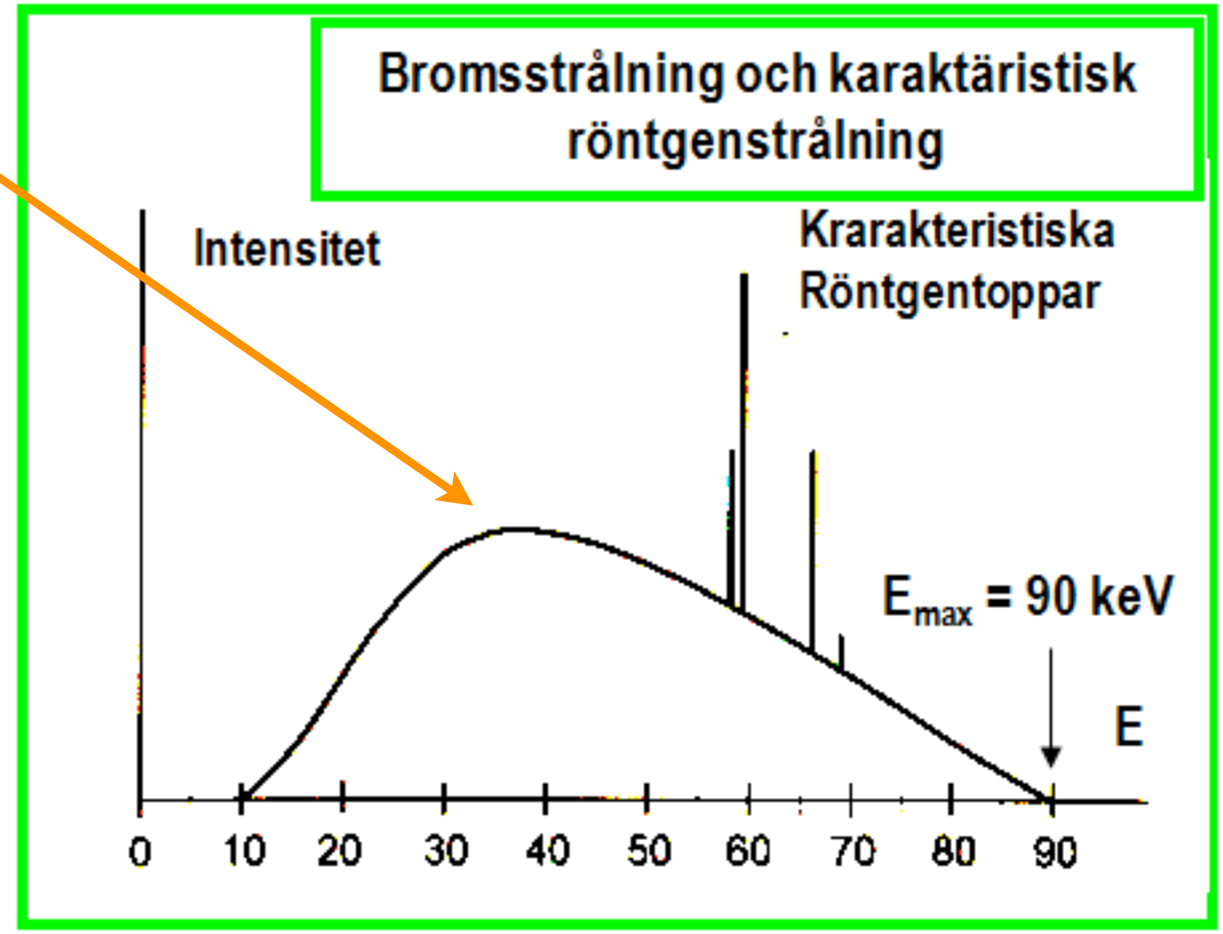


Röntgenstrålning och bromsstrålning

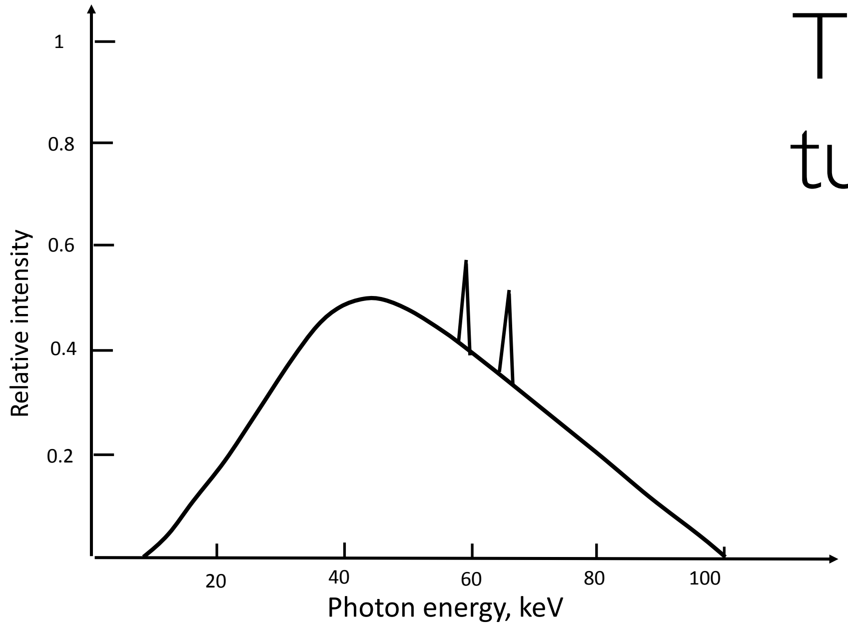
- Om elektronernas energi är tillräcklig kan de slå ut elektroner från anodens atomer. En foton med karakteristisk Röntgenenergi emitteras.
- Dessa kan observeras överlagrade bromsstrålsspektrat

OBS: max intensitet @ 1/3-1/2 av E_{max}



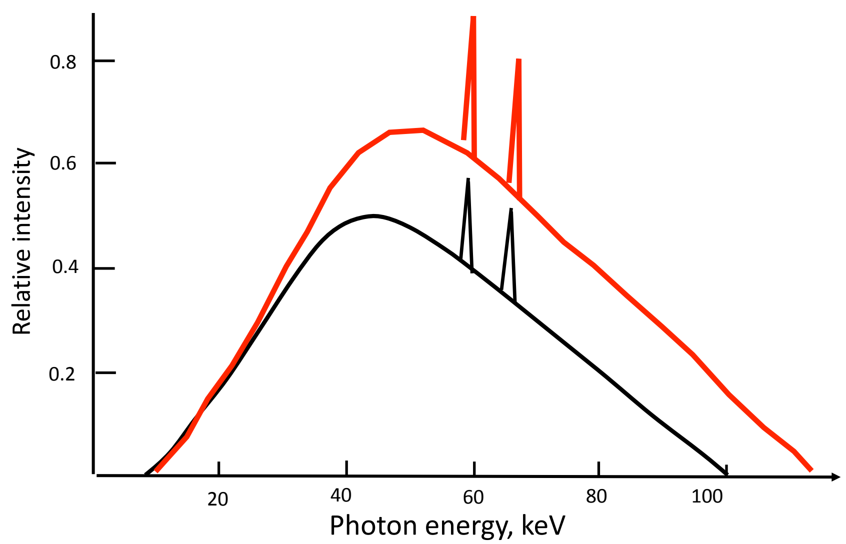


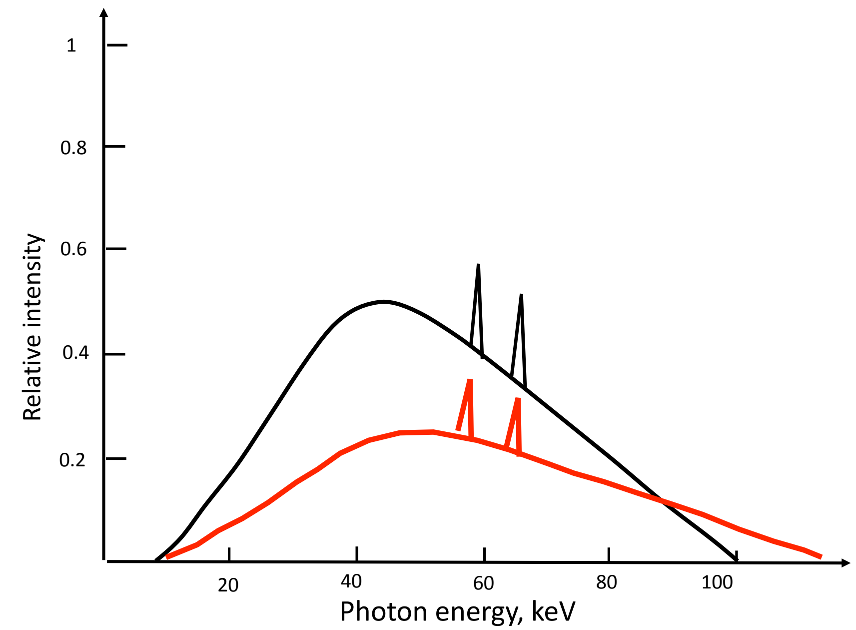
This is the spectrum from an x-ray tube operated at 100 kV and 100 mA

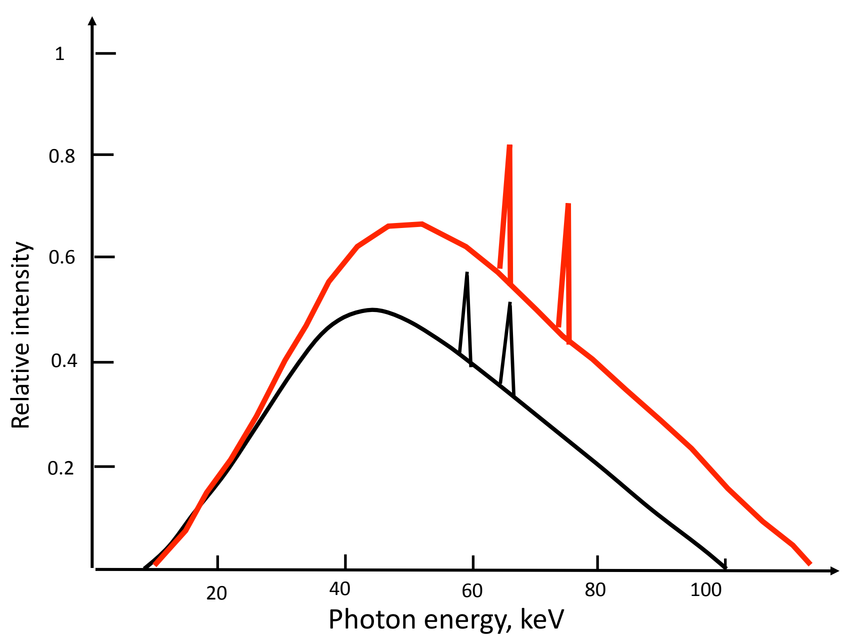


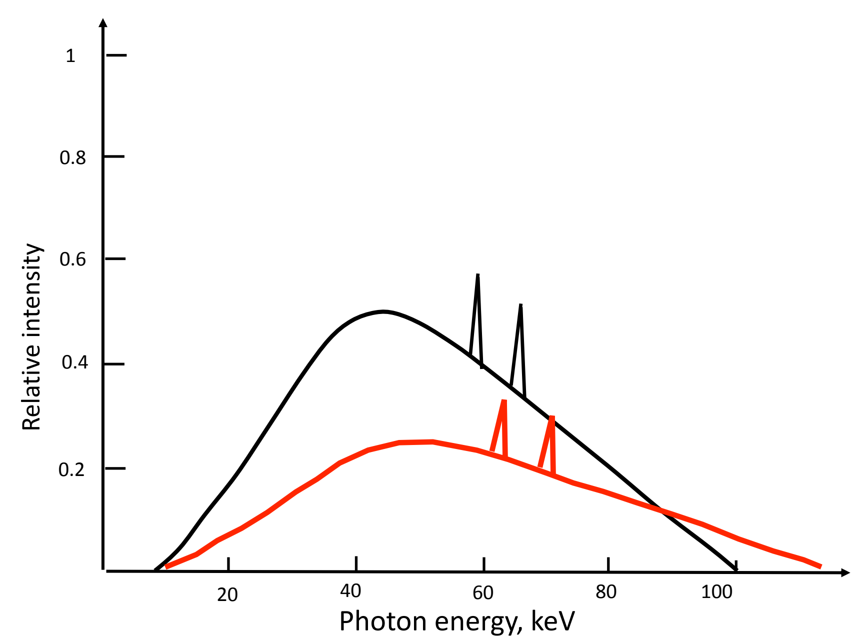
The tube voltage is increased while the current is kept constant. Which of the following spectra will be obtained?

A.Kerek

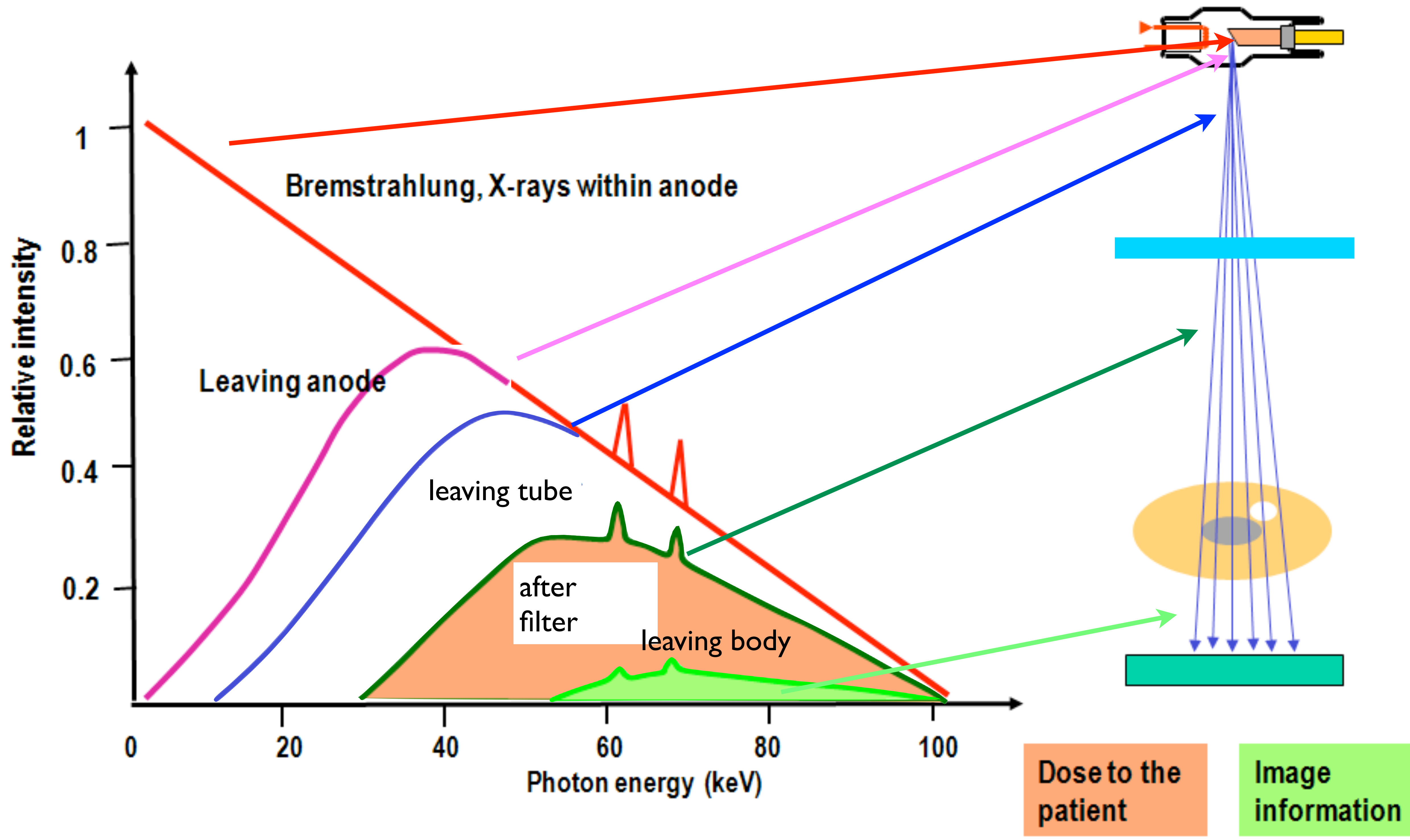


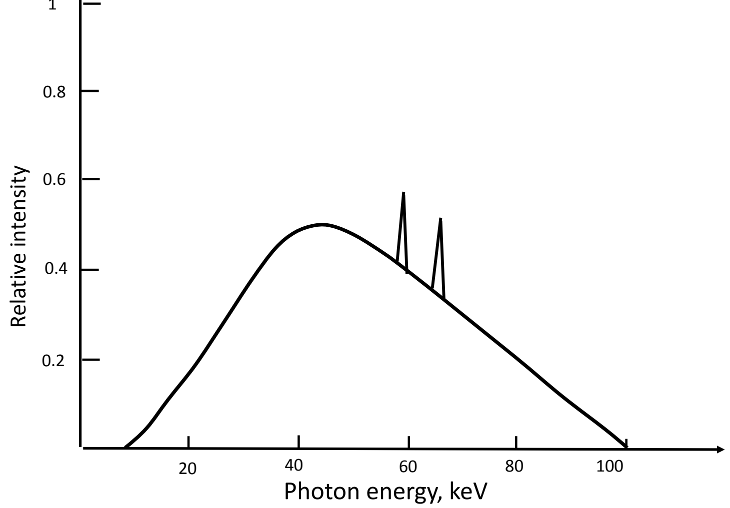




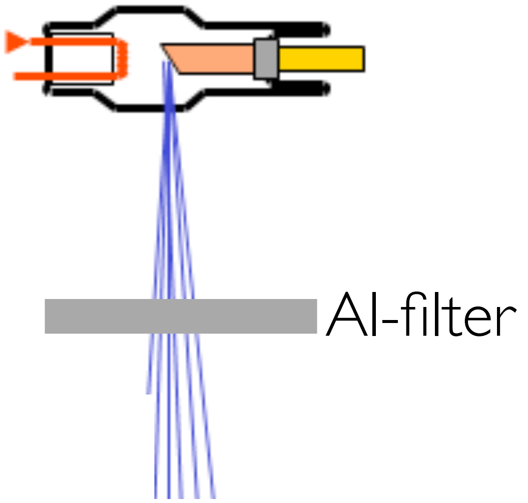


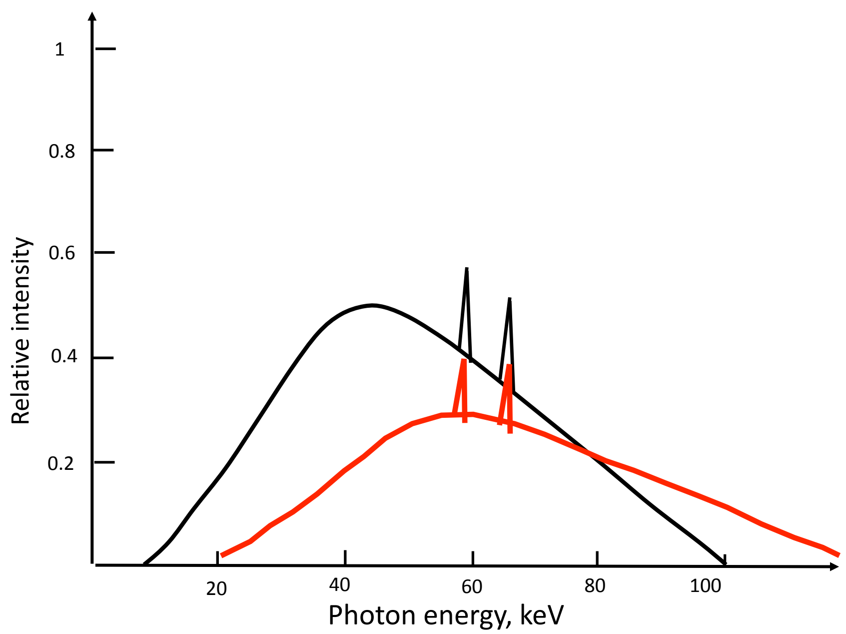
Beam hardening - filters



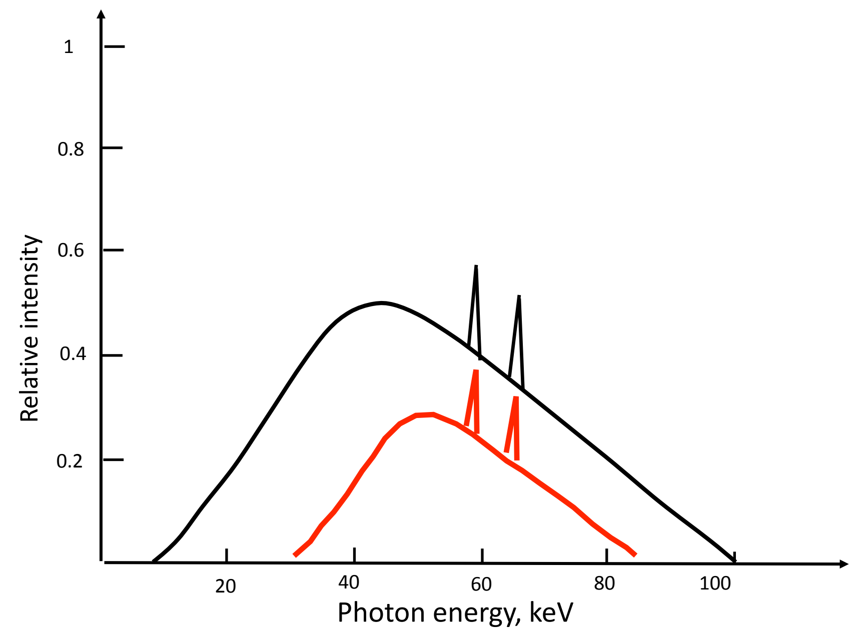


On the left you see the spectrum of x-rays leaving an x-ray tube. Which of the red spectra would possibly represent the spectrum after an Al-filter? The original spectrum is reported in black in all plots.

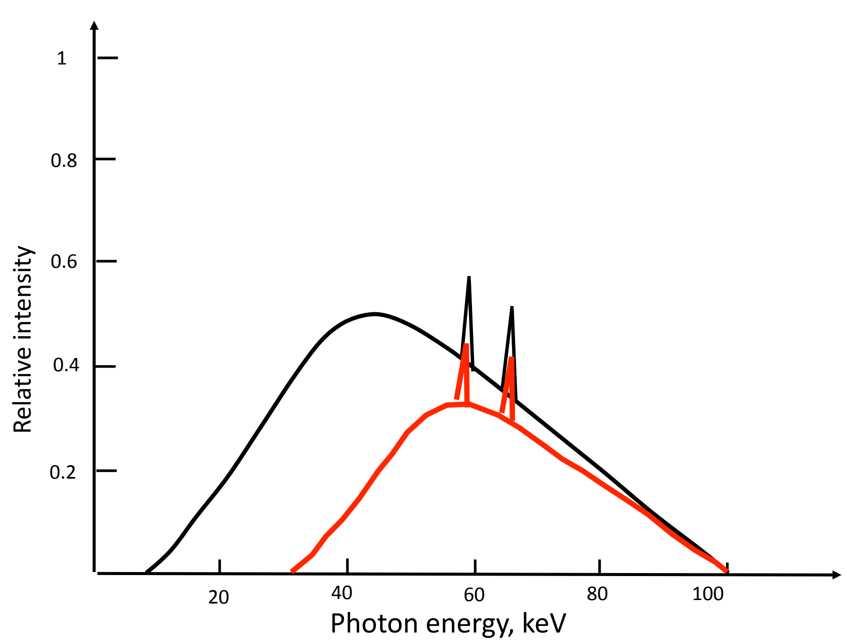


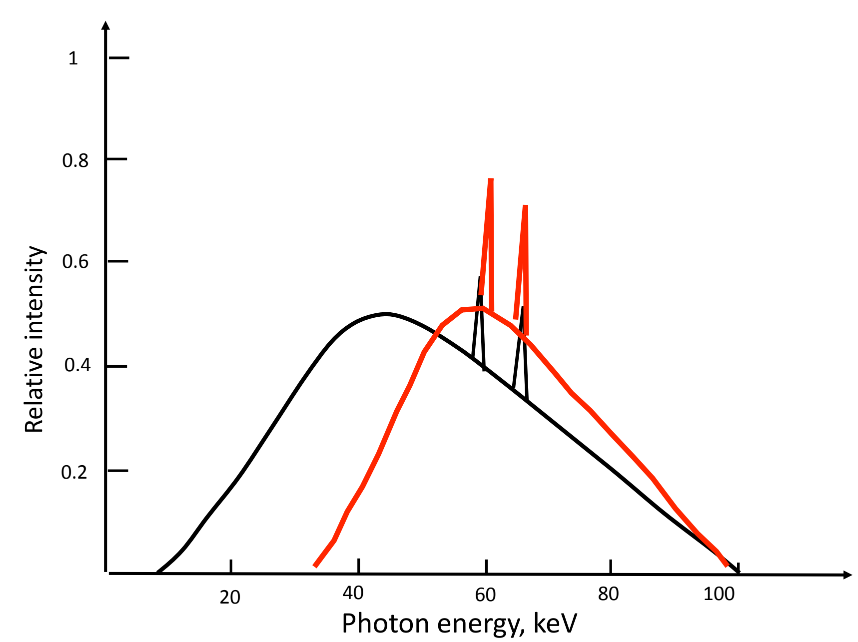


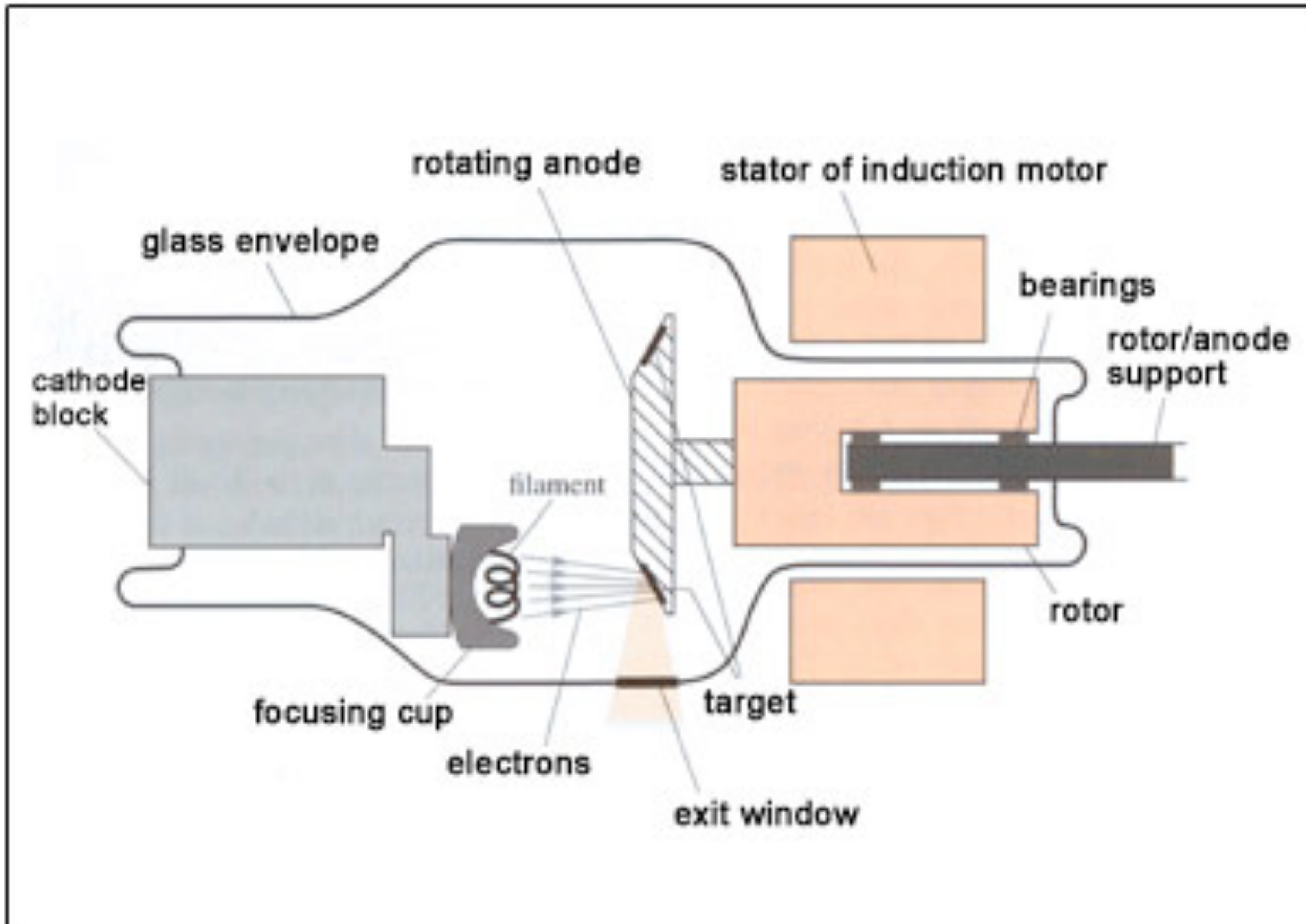
A.Kerek



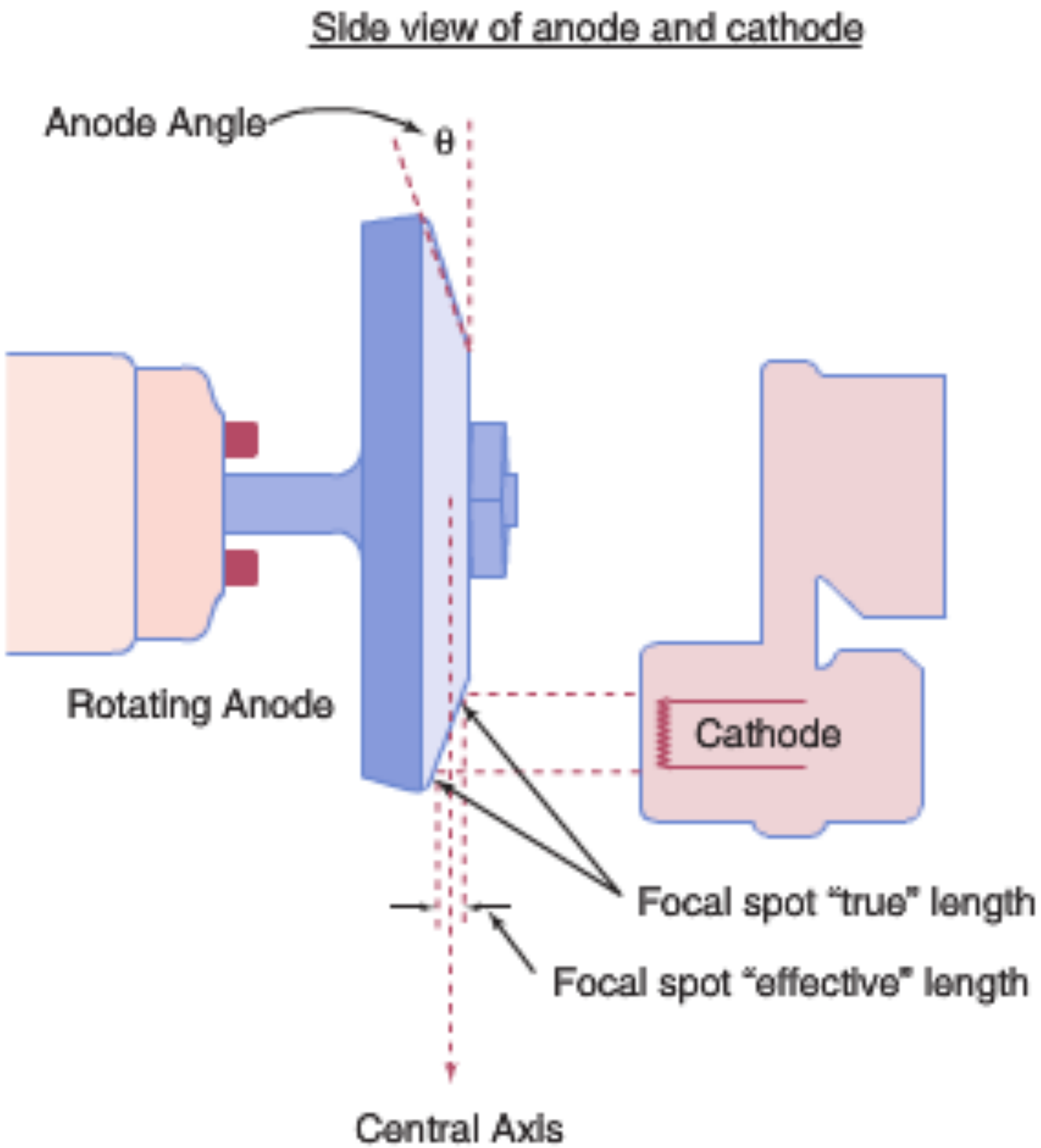
A.Kerek

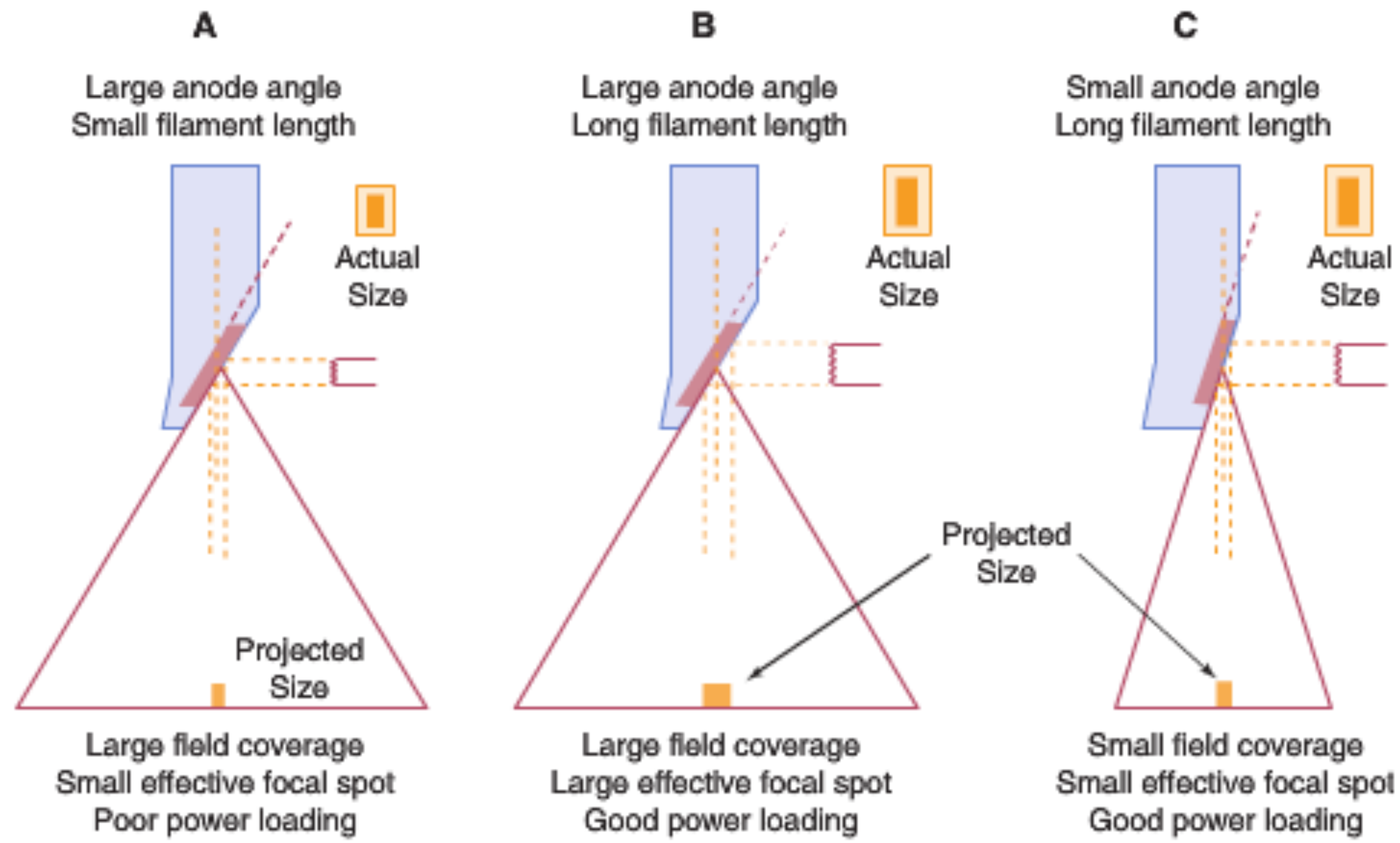





rotating anode
stator of induction motor
glass envelope
bearings
rotor/anode
support
cathode
block
filament
rotor
focusing cup
target
electrons
exit window

focal spot

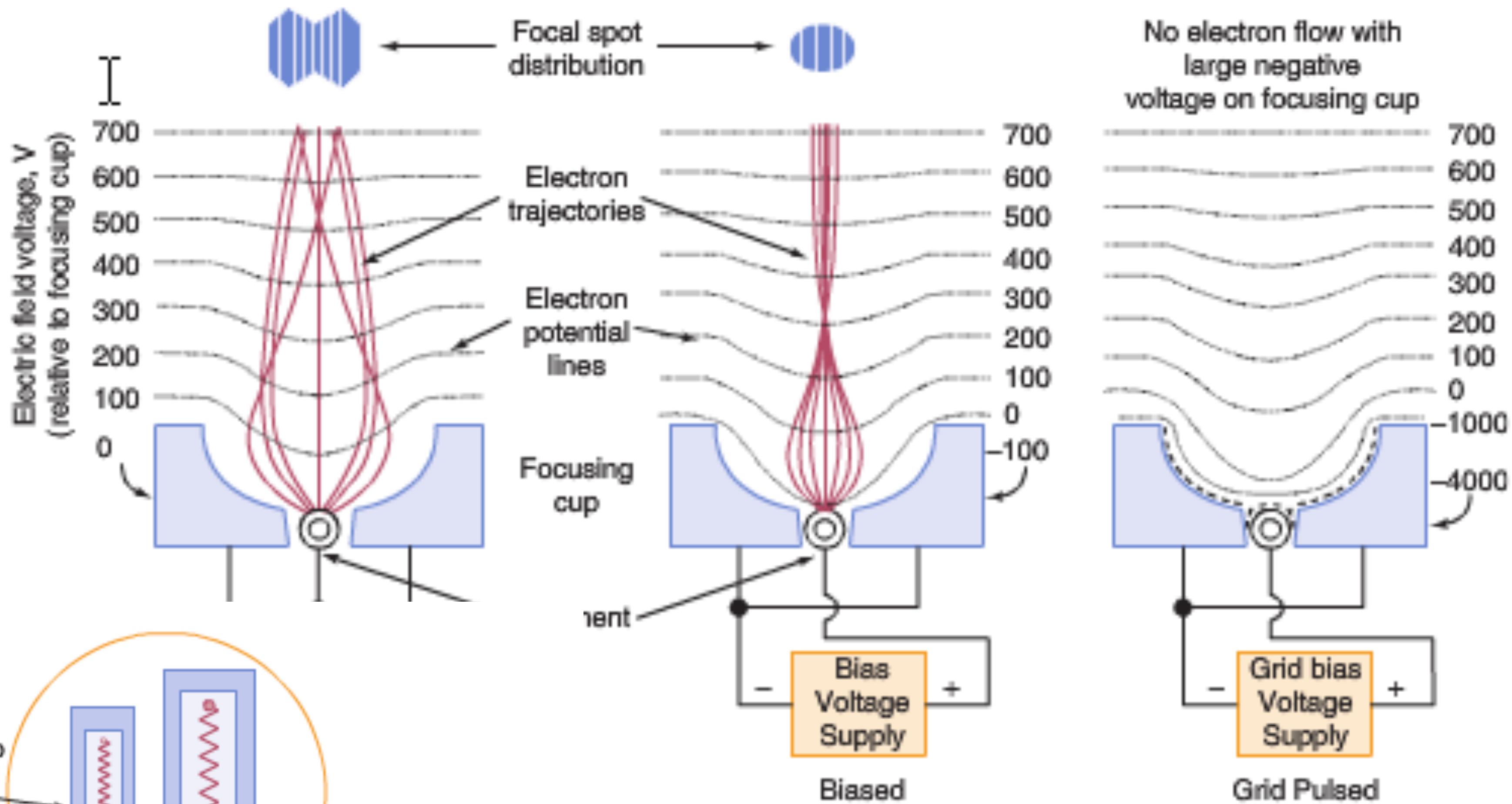


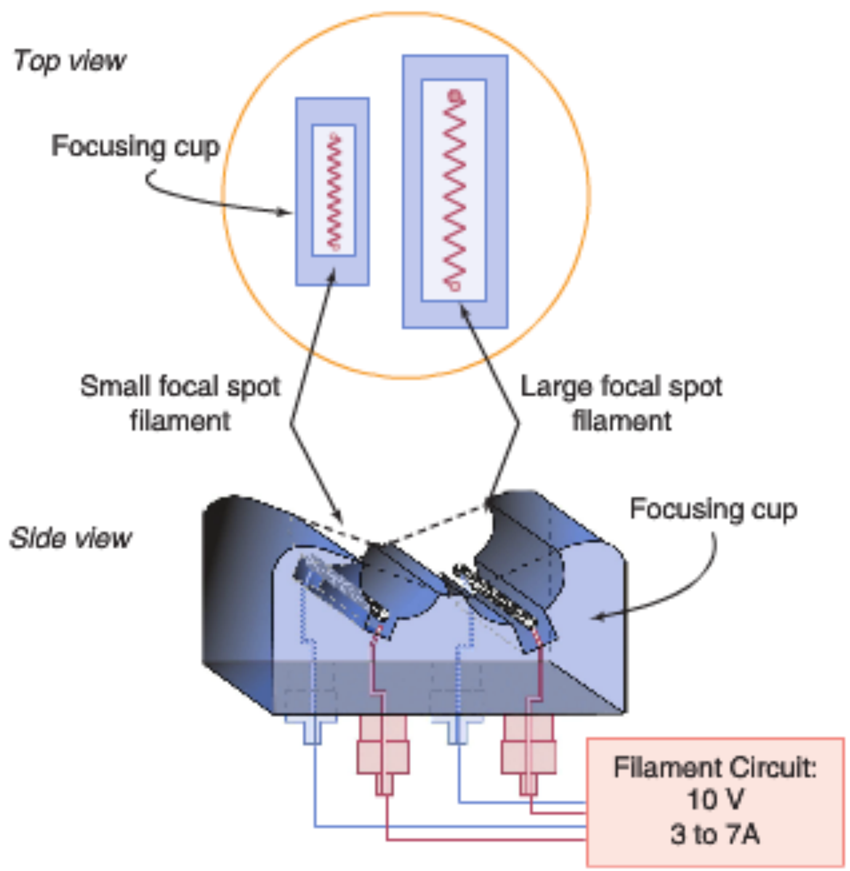


anode angle

filament lenght

focusing cup





Snabb diskussion (grupper 2-3):

1. Vad beror den kontinuerliga bromsstrålnings spektrum på?

2. Vad beror de karaktäristiska röntgentoppar på?

Detectors for radiography

X-ray detectors

1. basic principles or radiation detection, classification of detectors
2. sensitivity of a detector: detected photons, emitted photons, activity and count rate
3. sensitivity of a detector: geometric and intrinsic efficiency
4. common kinds of x-ray detectors

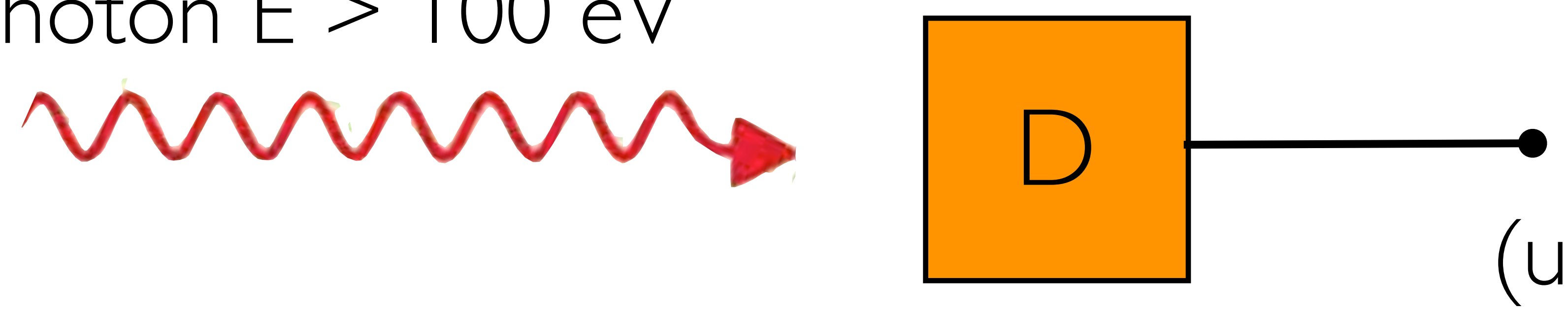
20 - 150 keV

Lessons to learn:

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

Detector for ionising radiation: basic principles

photon E > 100 eV



“visible” output
(usually electric signal)

x- or gamma-rays to current, voltage

photon counting → each photon is counted independently

sum all photons in time interval ← current mode

transmission today!

Detector efficiency (effektivitet):

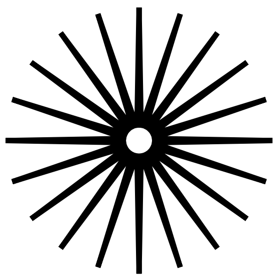
geometry (solid angle) & "intrinsic" efficiency

before that:

difference between activity (decay/s),
emitted photons and
detected photons
count rate

detection efficiency

S

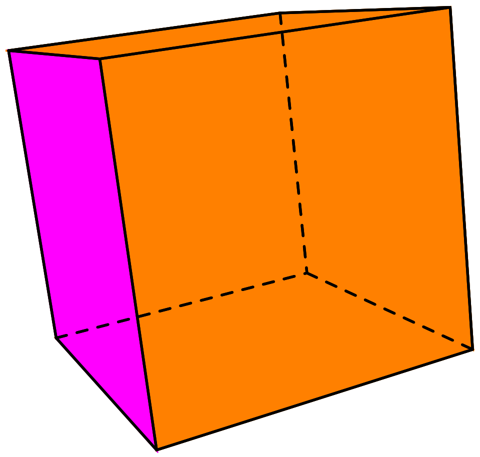


A = 1 kBq

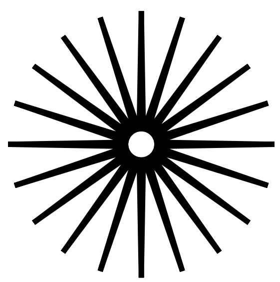
1000 decays/s

does this imply that 1000 photons/s are emitted?

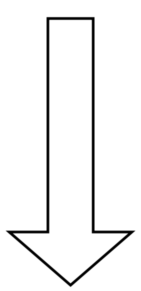
D



S



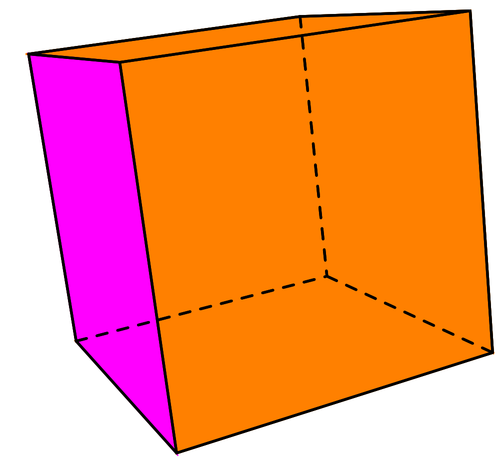
A = 1 kBq



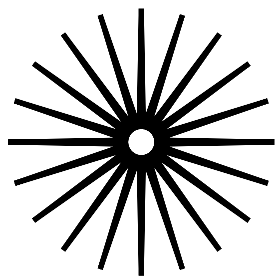
1000 decays/s

# of emitted photons depends on decay scheme!

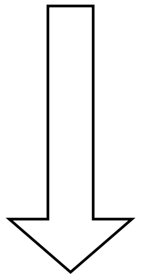
D



S



A = 1 kBq



1000 decays/s

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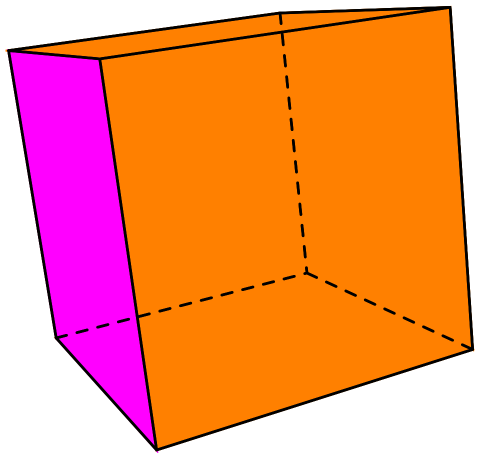
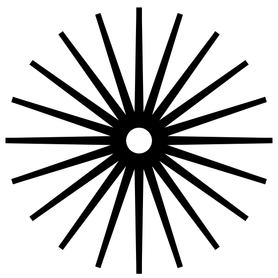
D

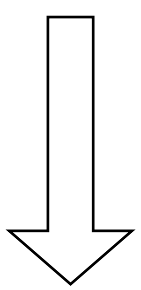


# of detected photons?

S



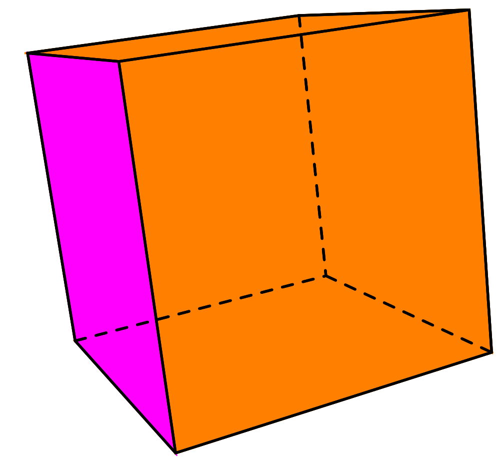
A = 1 kBq



1000 decays/s

# of emitted photons depends on decay scheme!

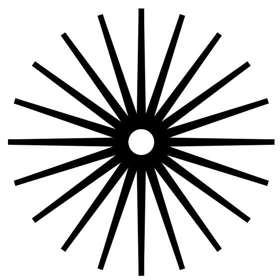
D



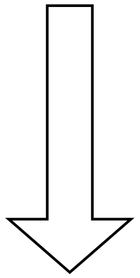
# of detected photons?

$$\text{efficiency:} \quad \frac{\#\ \text{detected photons}}{\#\ \text{emitted photons}}$$

S



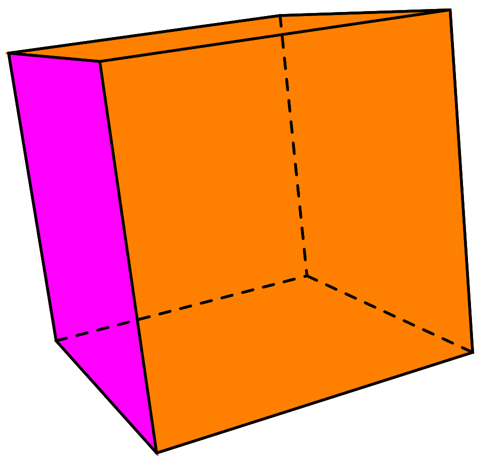
A = 1 kBq



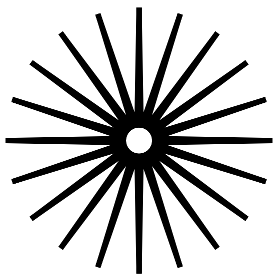
1000 decays/s

does this imply that 1000 photons/s are emitted?

D

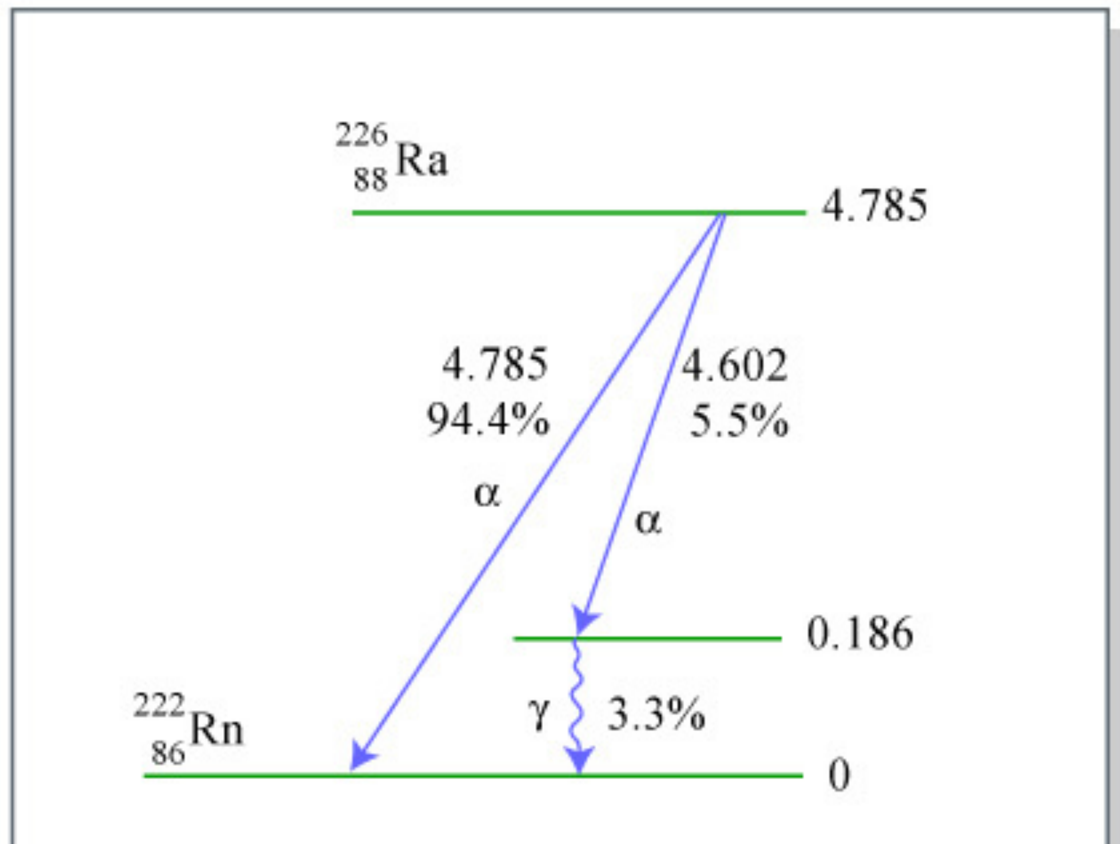


S



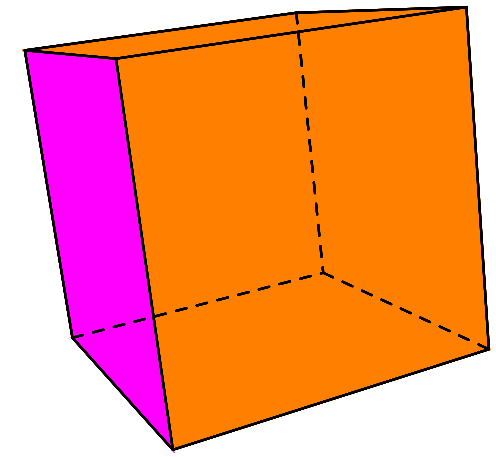
A = 1 kBq

1000 decays/s

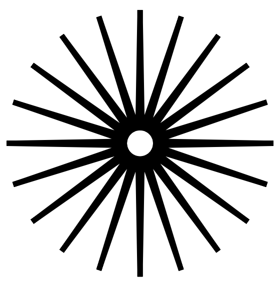


Nuclear Decay Scheme of $^{226}_{88}$Ra.

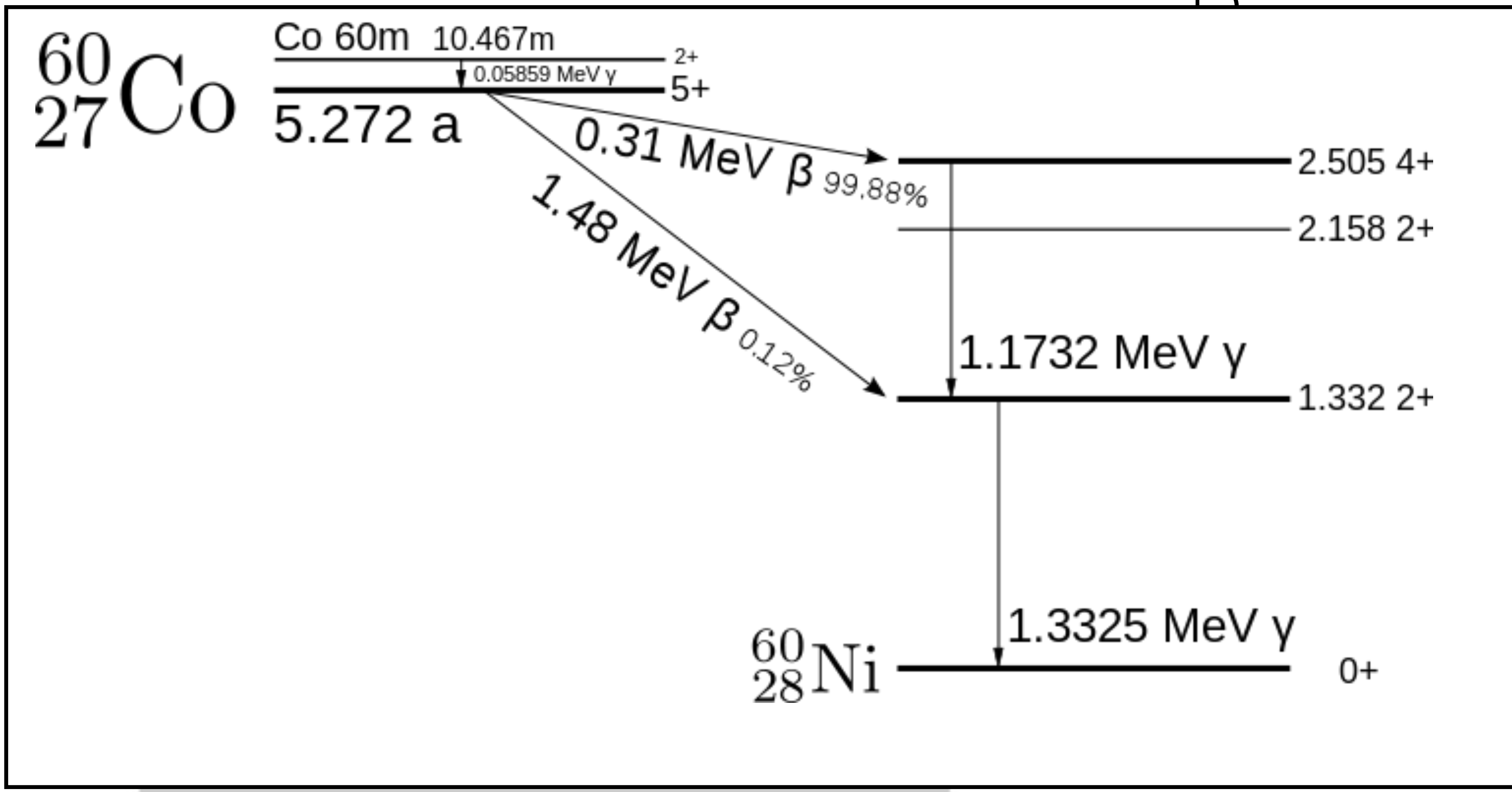
D



S

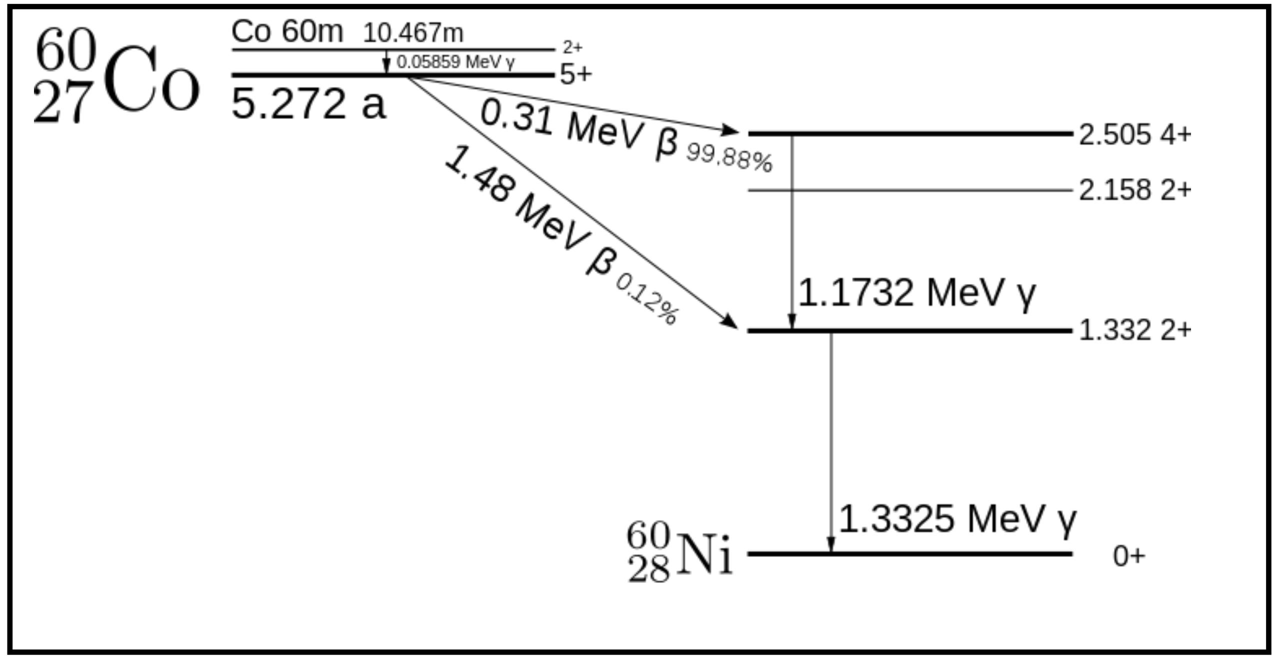


A = 1 kBq



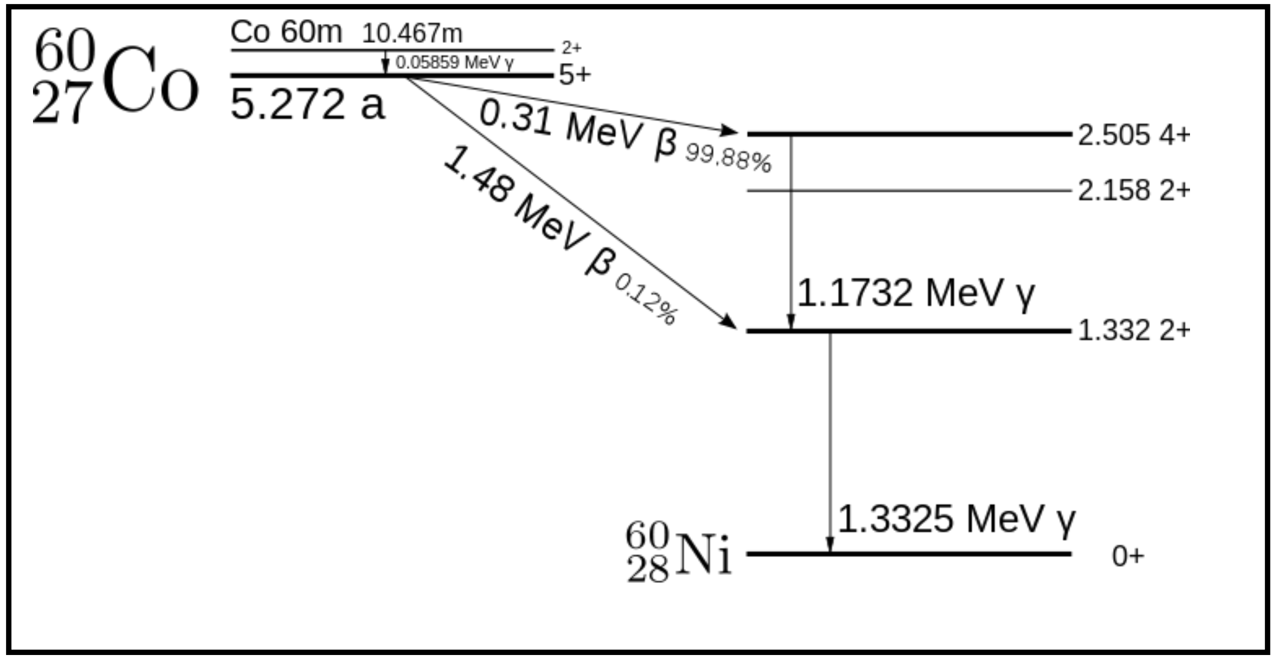
1000 decays/s

On average, how many photons are emitted in a ^{60}Co-decay?

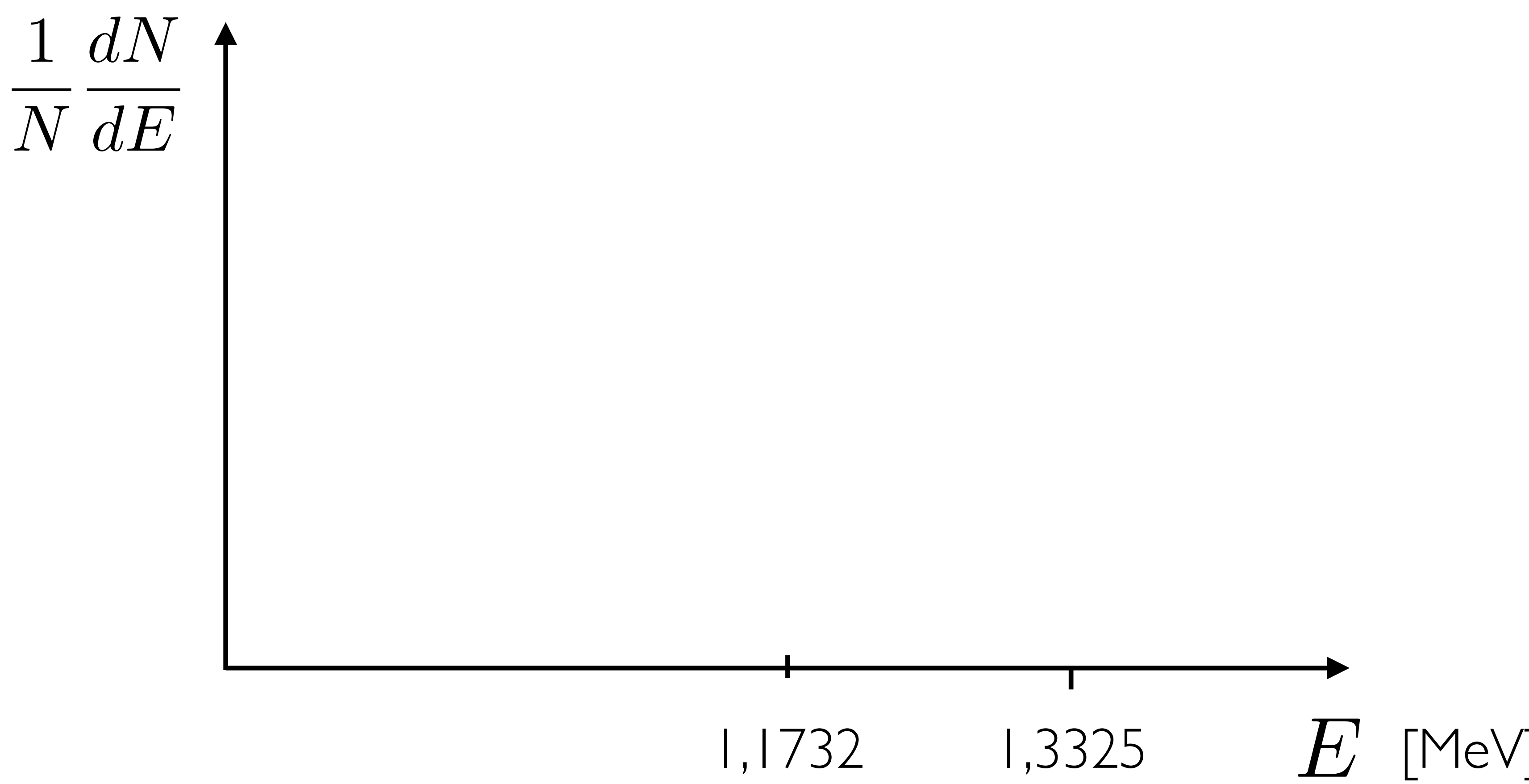


1. 1
2. 2
3. 0,9988
4. 1,9988
5. anything between 0 and 2 depending of what happens in the nucleus

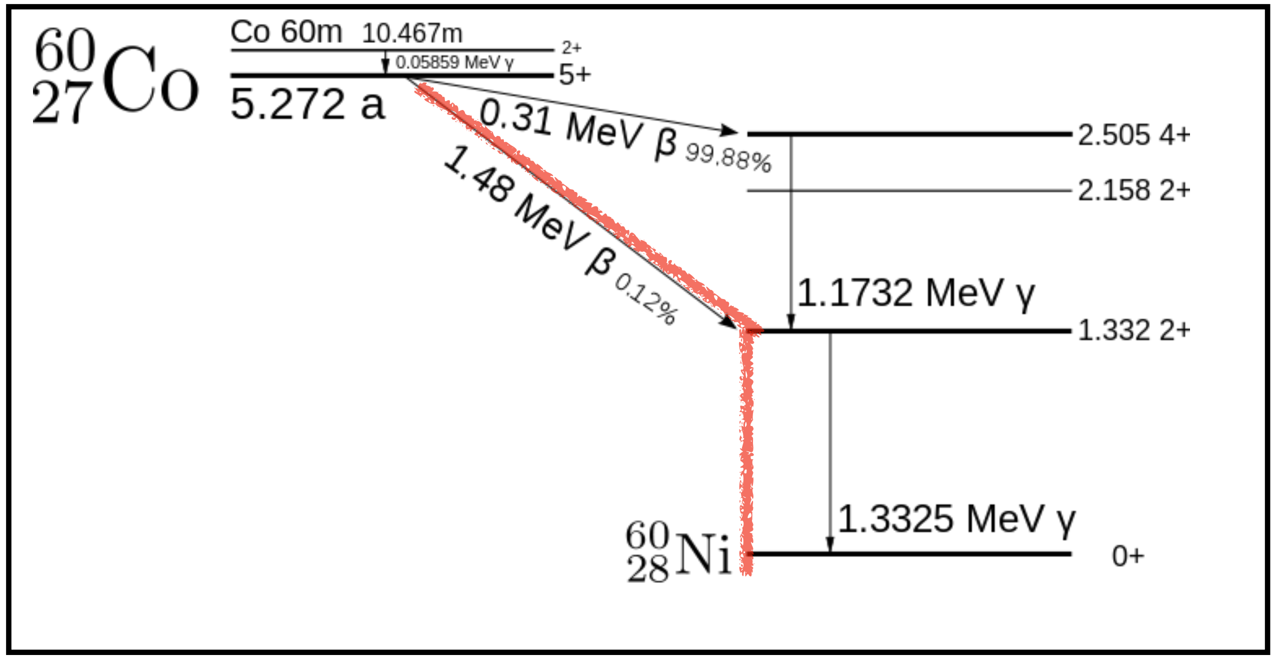
Draw the emission spectrum of ^{60}Co



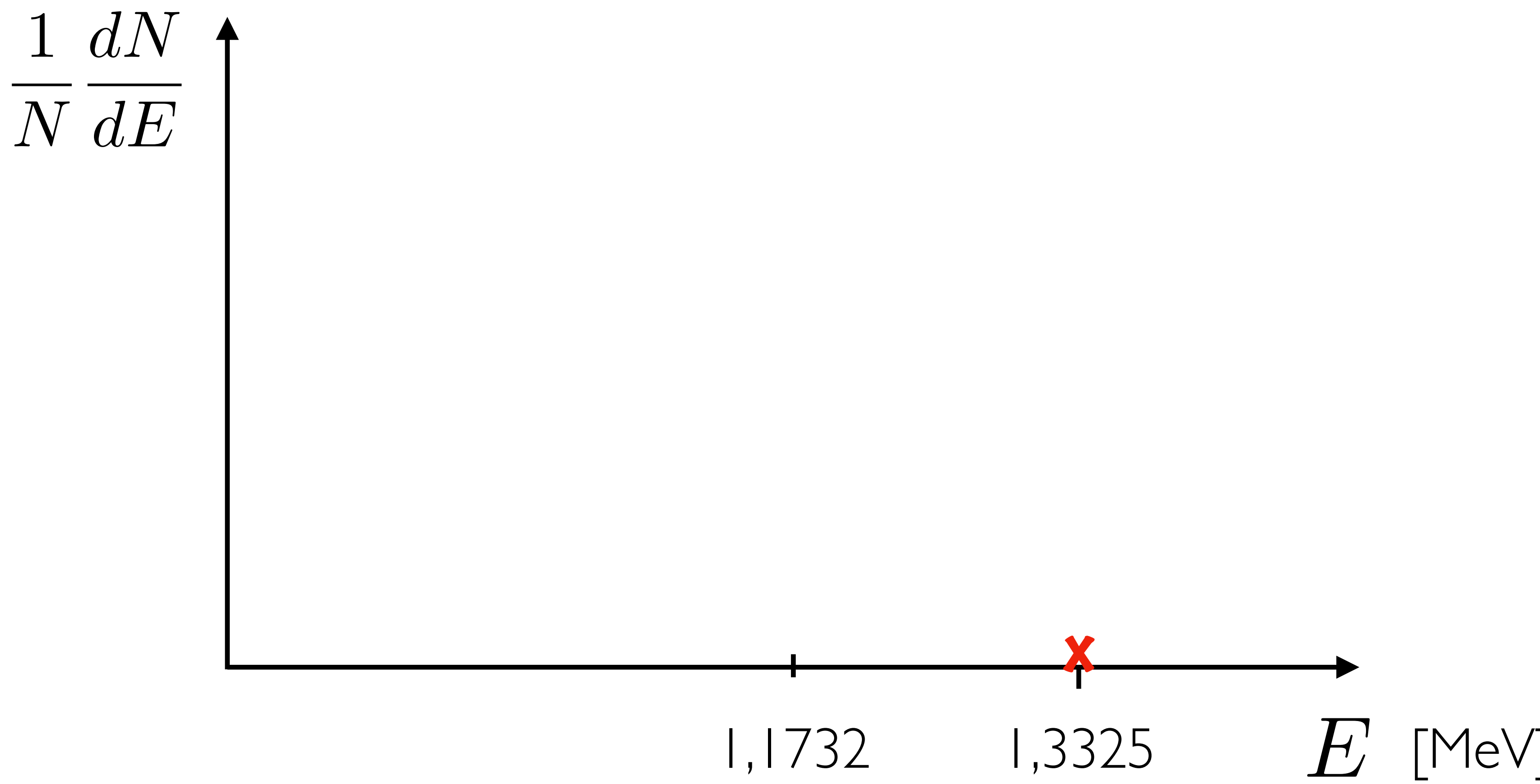
number of photons / energy bin
———
number of photons



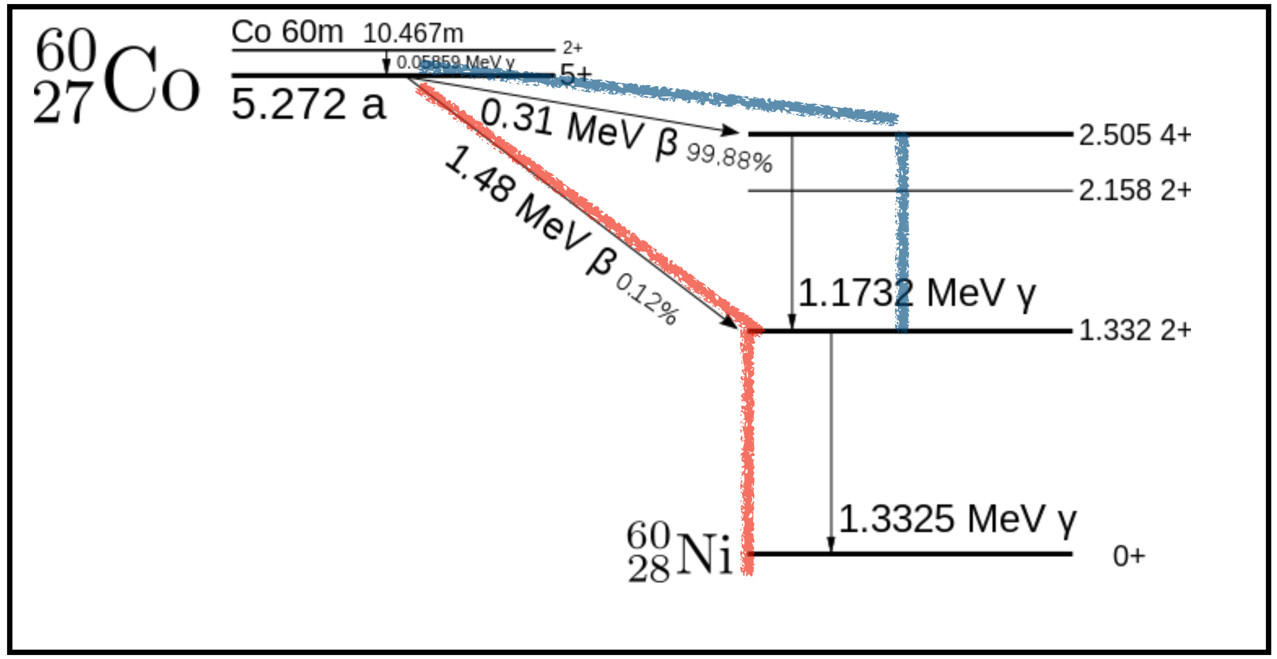
Draw the emission spectrum of ^{60}Co



$$\frac{\text{number of photons / energy bin}}{\text{number of photons}}$$

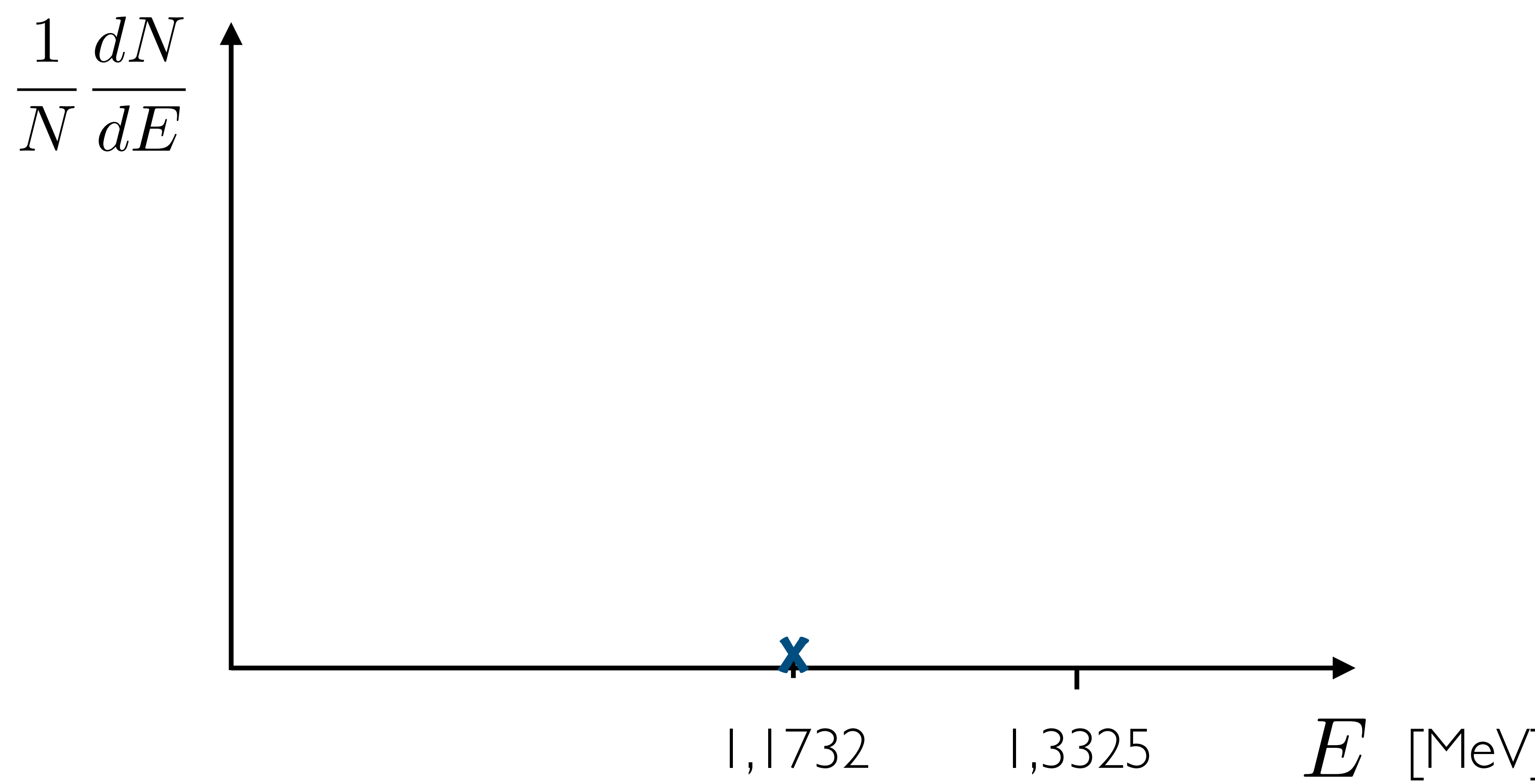


Draw the emission spectrum of ^{60}Co

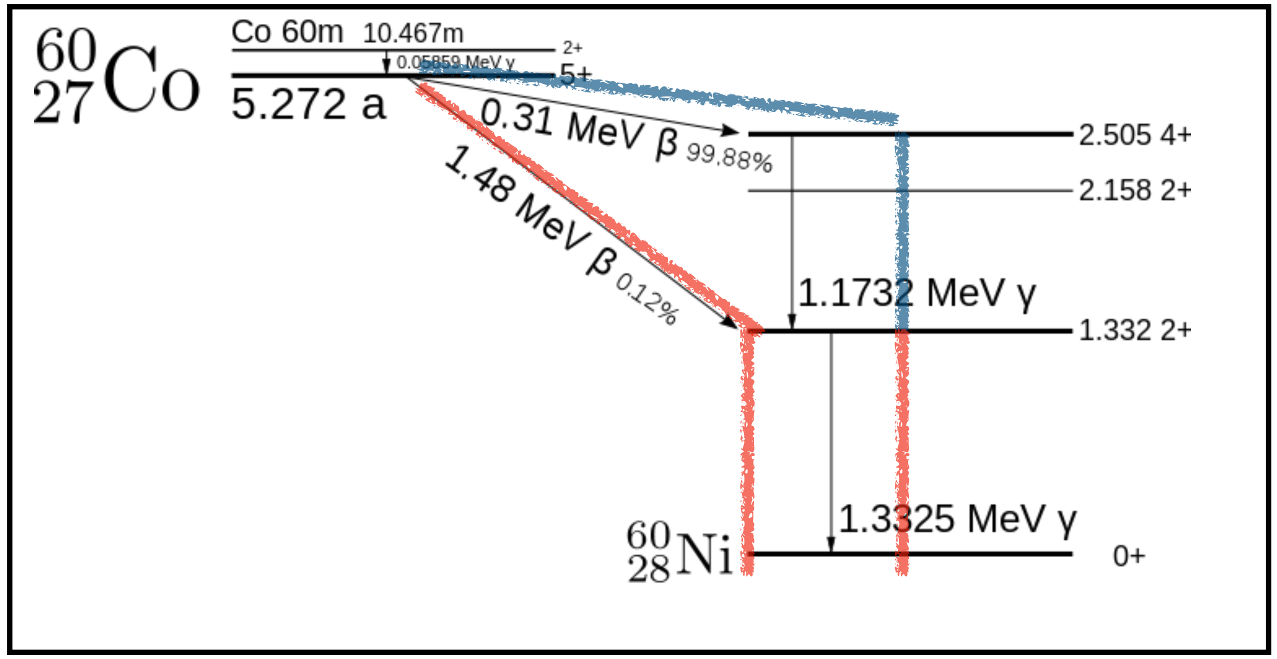


number of photons / energy bin

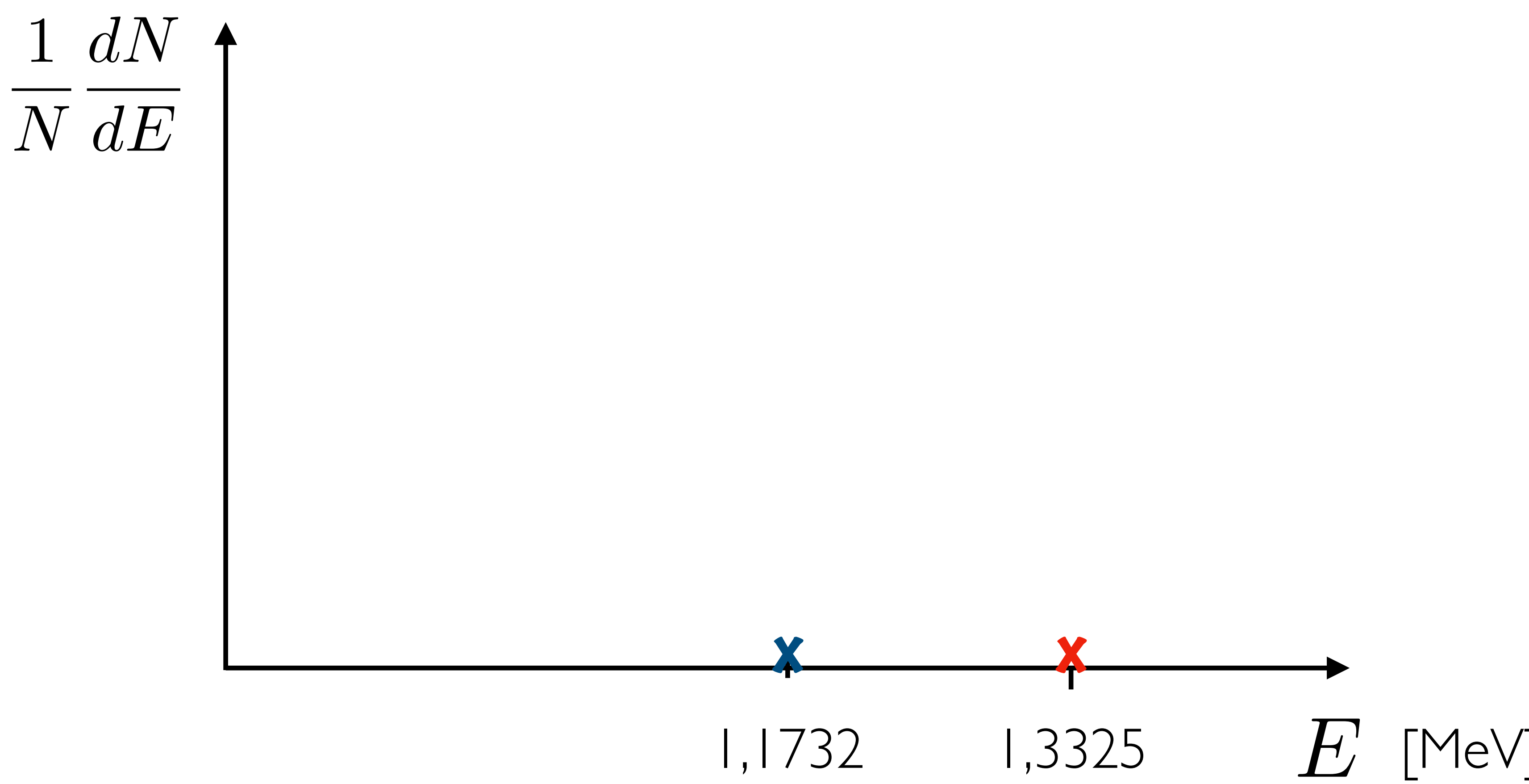
number of photons



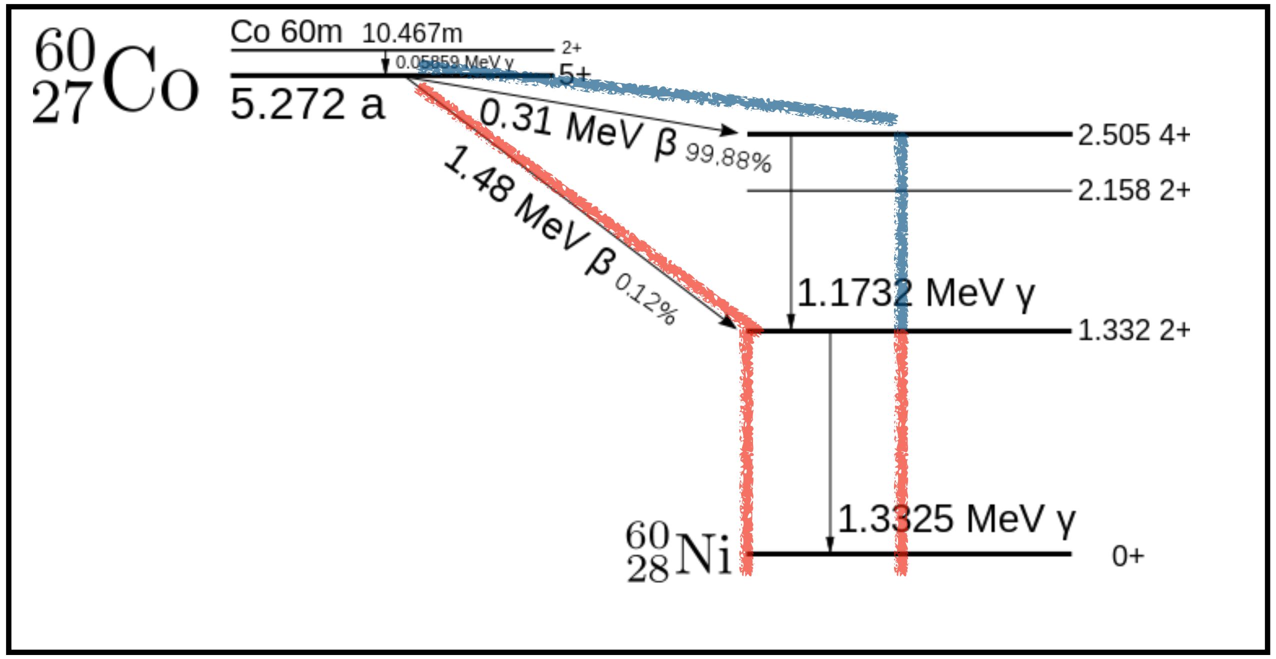
Draw the emission spectrum of ^{60}Co



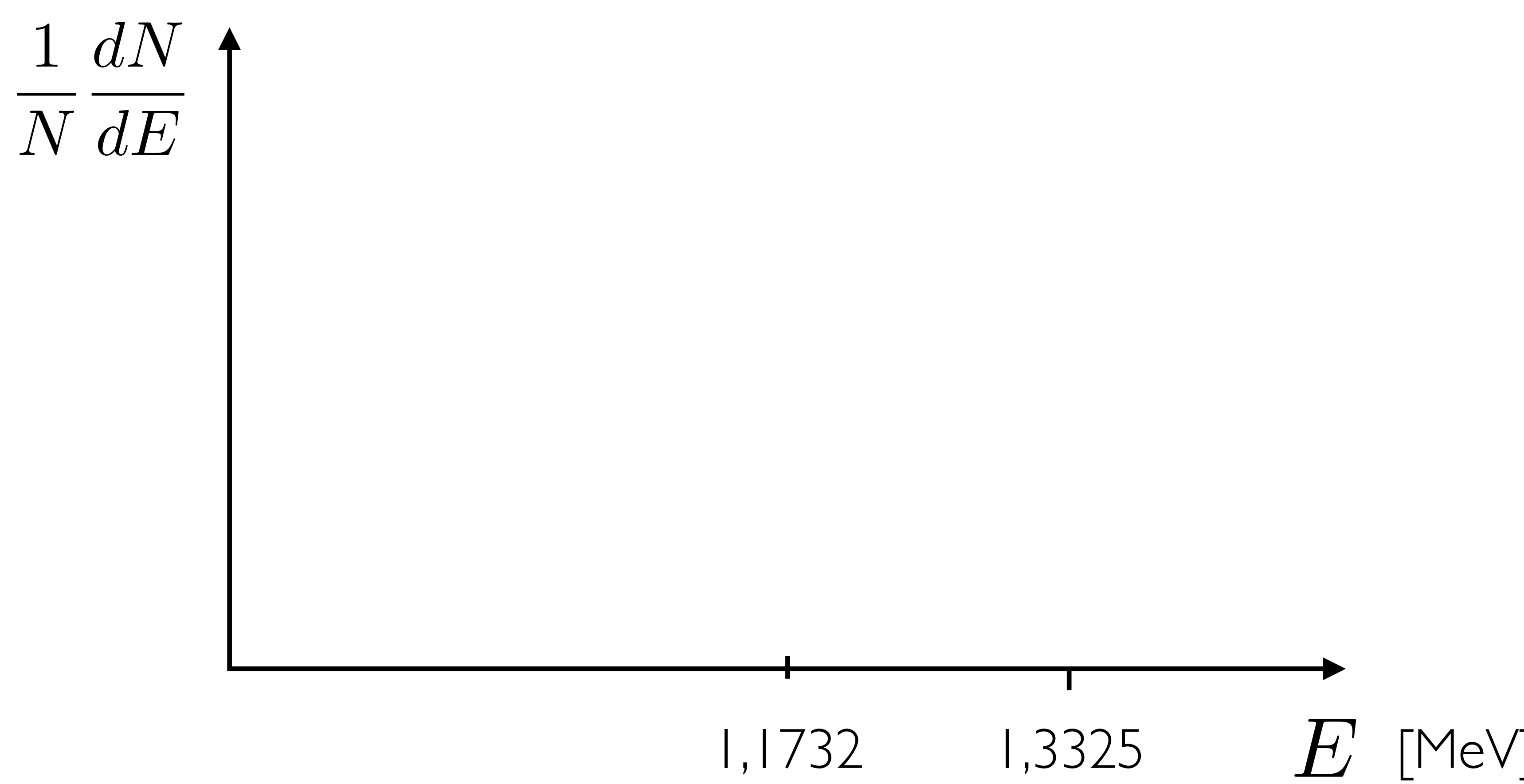
$$\frac{\text{number of photons / energy bin}}{\text{number of photons}}$$



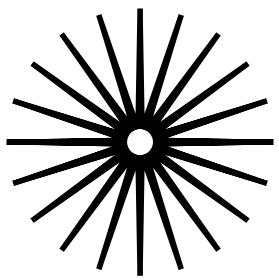
Draw the emission spectrum of ^{60}Co



$$\frac{\text{number of photons / energy bin}}{\text{number of photons}}$$



S

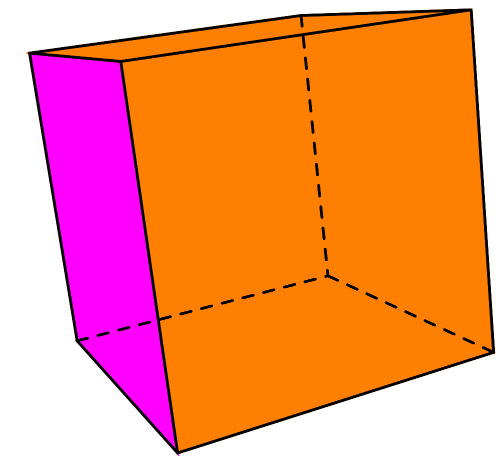


$A = 1\ \text{kBq}$

1000 decays/s

# of emitted photons depends on decay scheme!

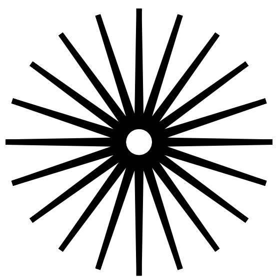
D



# of detected photons?

efficiency: $\dfrac{\#\ \text{detected photons}}{\#\ \text{emitted photons}}$

S



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1000 decays/s

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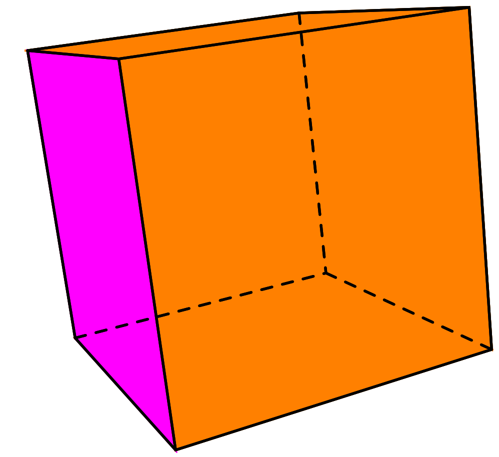
D

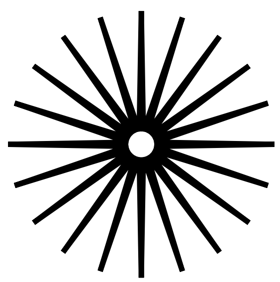


# of detected photons?

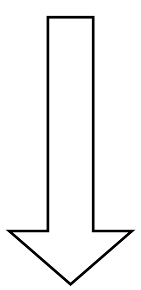
efficiency: $\frac{\text{\# detected photons}}{\text{\# emitted photons}}$

count rate = detected photons?

S



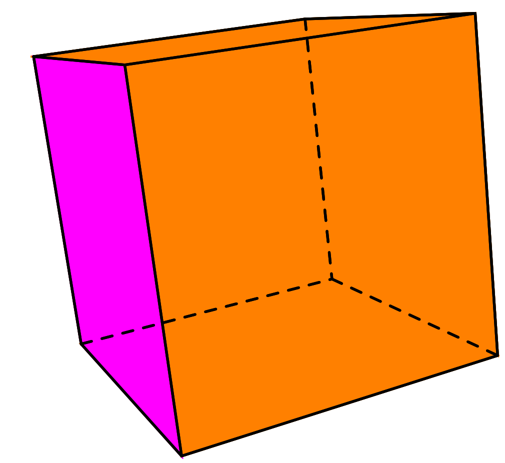
A = 1 kBq



1000 decays/s

# of emitted photons depends on decay scheme!

D



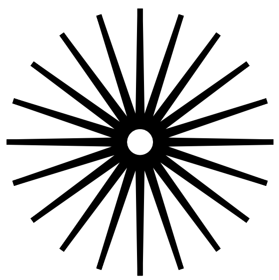
# of detected photons?

efficiency: $\frac{\text{\# detected photons}}{\text{\# emitted photons}}$

count rate = detected photons?

NO!
(only for photon counting detectors)

S

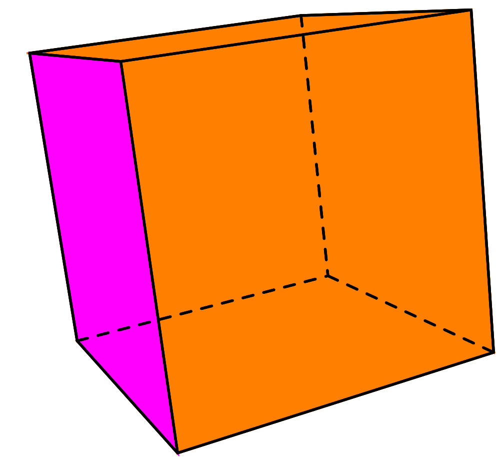


A = 1 kBq

1000 decays/s

# of emitted photons depends on decay scheme!

D



# of detected photons?

efficiency: $\frac{\text{\# detected photons}}{\text{\# emitted photons}}$

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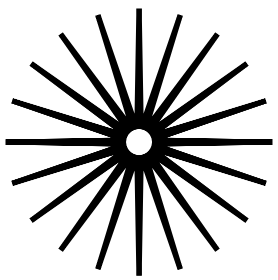
(only for photon counting detectors)

S

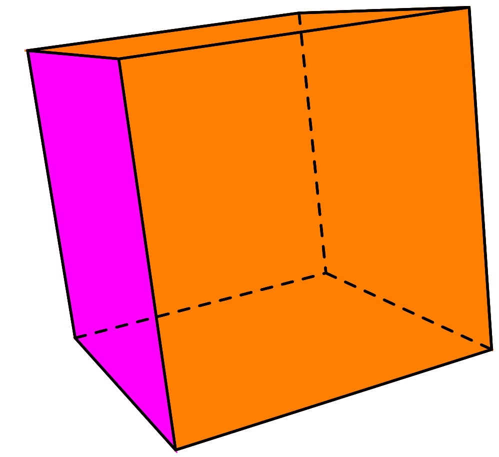


A = 1 kBq

1000 decays/s

# of emitted photons depends on decay scheme!

D



# of detected photons?

efficiency: $\frac{\text{\# detected photons}}{\text{\# emitted photons}}$

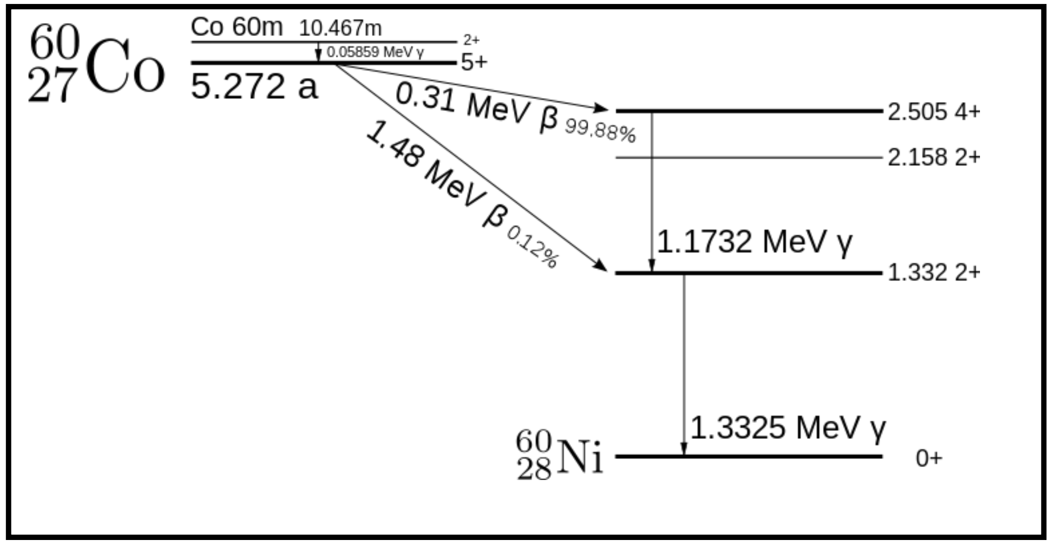
count rate = detected photons?

NO!
(only for photon counting detectors)

A detector with efficiency 2% detects 100 photons per second. The average number of emitted photons per second is then:

1. 2
2. impossible to say, but more than 100
3. 5000

A detector with efficiency 2% detects 100 photons per second from a ^{60}Co-source. The activity of the source can be estimated to be:



1. around 100 Bq
2. impossible to say, but more than 100 Bq
3. around 2500 Bq
4. around 5000 Bq

Source **Detector**

What needs to happen for a photon emitted by the source to be detected?

1. The photon needs to hit the detector

Def: geometric efficiency = fraction of emitted photons that hit the detector = $\dfrac{\text{\# of photons hitting detector}}{\text{\# of emitted photons}}$

2. The photon needs to deposit energy (interact) in the detector

Def: intrinsic efficiency = fraction of the photons hitting the detector that interact in the detector = $\dfrac{\text{\# of photons interacting in detector}}{\text{\# of photons hitting detector}}$

Then the fraction of detected photons will be the product of the two above[§]:

Def: efficiency = fraction of the emitted photons that are detected = $\dfrac{\text{\# of photons hitting detector}}{\text{\# of emitted photons}} \cdot \dfrac{\text{\# of photons interacting in detector}}{\text{\# of photons hitting detector}}$

([§]under the hypothesis that the two are independent of each other)

Warning to the audience!!!!!!!!1112121212121

Now we have few definitions! The definitions are always true!

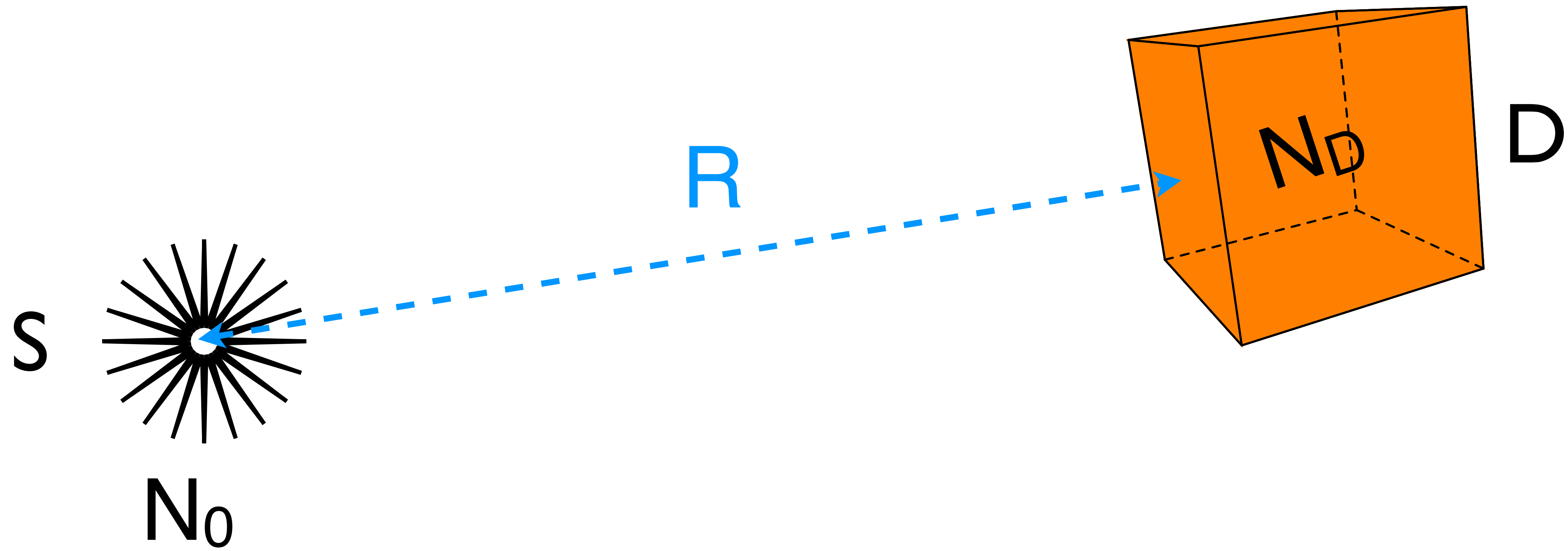
Do not confuse them with the calculation of the efficiency in a particular case, which might result in a number or a symbolic expression!
The latter are only valid in that particular case!

We are now going to find an expression for the efficiency, the geometric efficiency and the intrinsic efficiency ***in a particular case!***

It is an example, to help you:

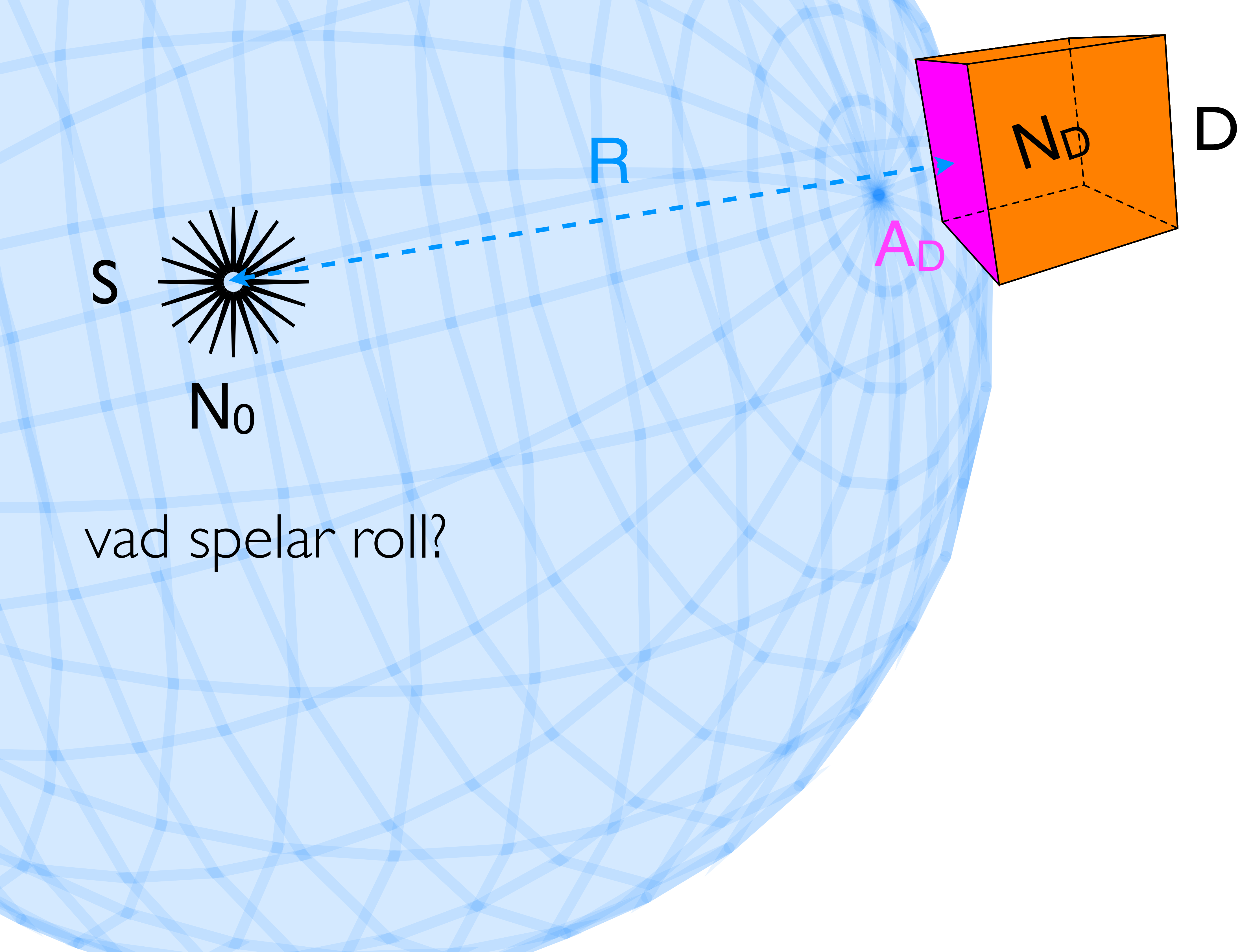
- better understand the definitions
- understand how to calculate these quantities in various situation by using their definitions

effektivitet: $\frac{\text{\# detekterade}}{\text{\# emitterade}} = \frac{N_D}{N_0}$



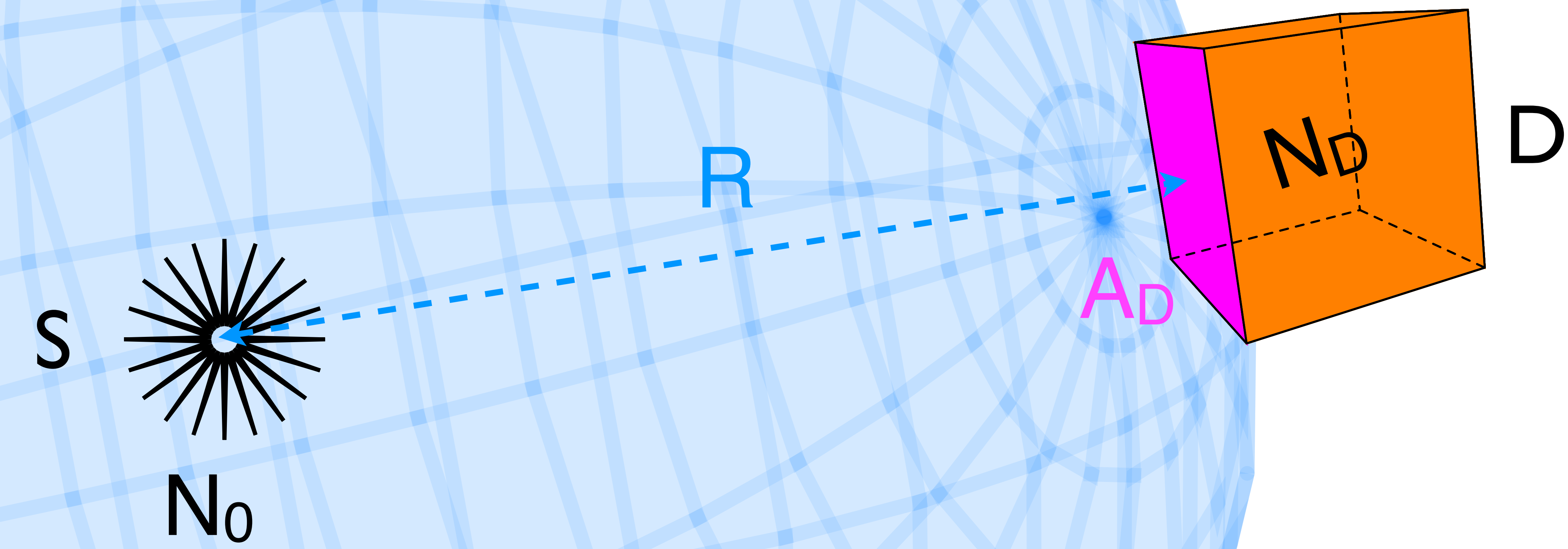
vad spelar roll?

effektivitet: $\dfrac{\#\ \text{detekterade}}{\#\ \text{emitterade}} = \dfrac{N_D}{N_0}$



vad spelar roll?

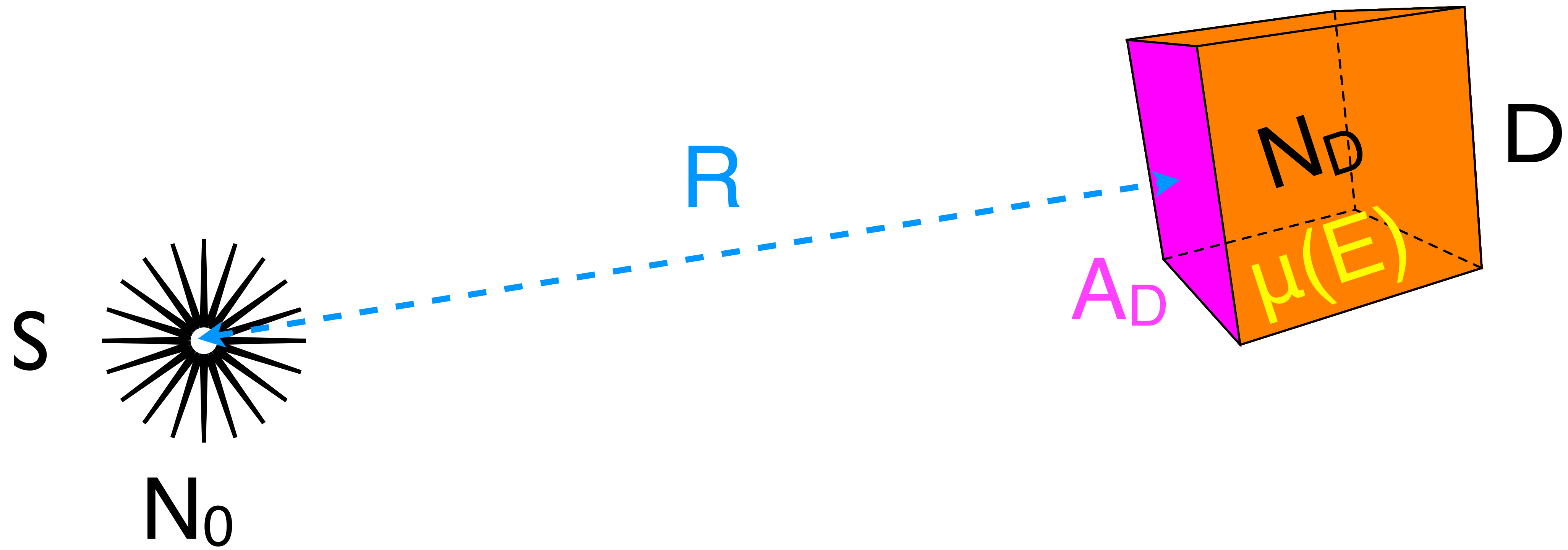
effektivitet: $\frac{\#\ \text{detekterade}}{\#\ \text{emitterade}} = \frac{N_D}{N_0}$



vad spelar roll?

geometri: $\frac{\#\ \text{träffar D}}{\#\ \text{emitterade}} = \frac{A_D}{4\pi R^2}$

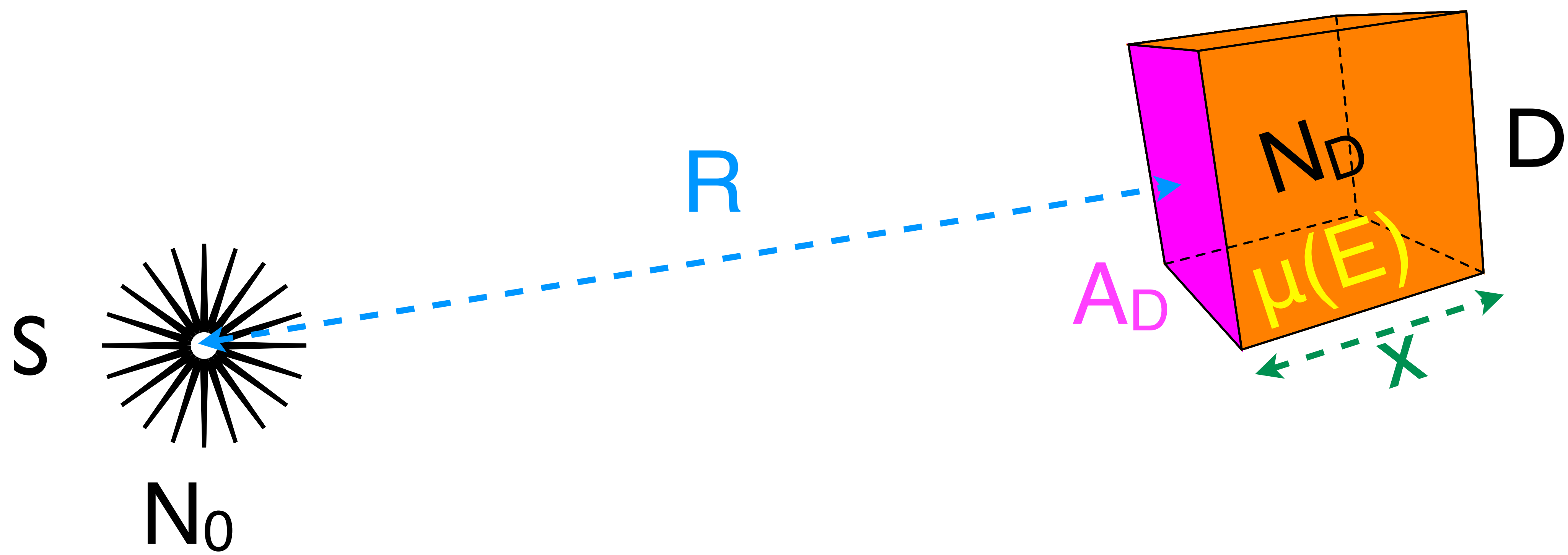
effektivitet: $\dfrac{\text{\# detekterade}}{\text{\# emitterade}} = \dfrac{N_D}{N_0}$



vad spelar roll?

geometri: $\dfrac{\text{\# träffar D}}{\text{\# emitterade}} = \dfrac{A_D}{4\pi R^2}$

effektivitet: $\dfrac{\text{\# detekterade}}{\text{\# emitterade}} = \dfrac{N_D}{N_0}$

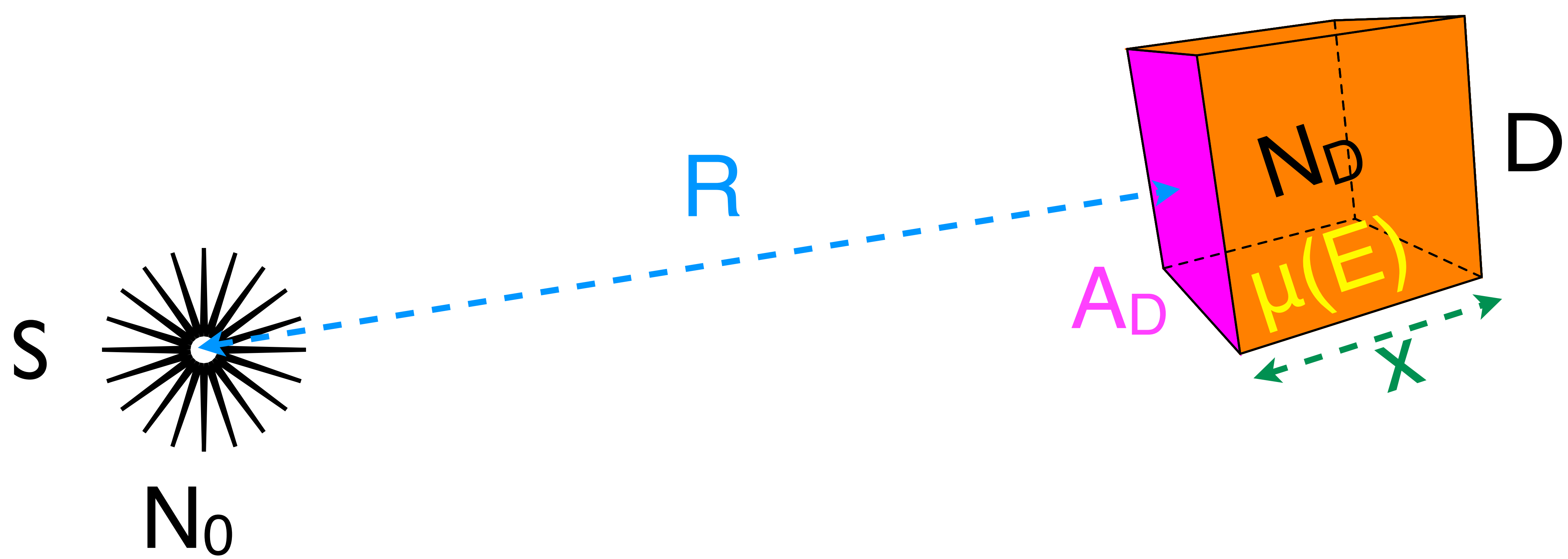


vad spelar roll?

geometri: $\dfrac{\text{\# träffar D}}{\text{\# emitterade}} = \dfrac{A_D}{4\pi R^2}$

"intrinsic efficiency": $\dfrac{\text{\# attenuerade}}{\text{\# träffar D}} = 1 - e^{-\mu(E)x}$

effektivitet: $\dfrac{\#\ \text{detekterade}}{\#\ \text{emitterade}} = \dfrac{N_D}{N_0} = \dfrac{A_D\,(1 - e^{-\mu(E)x})}{4\pi R^2}$



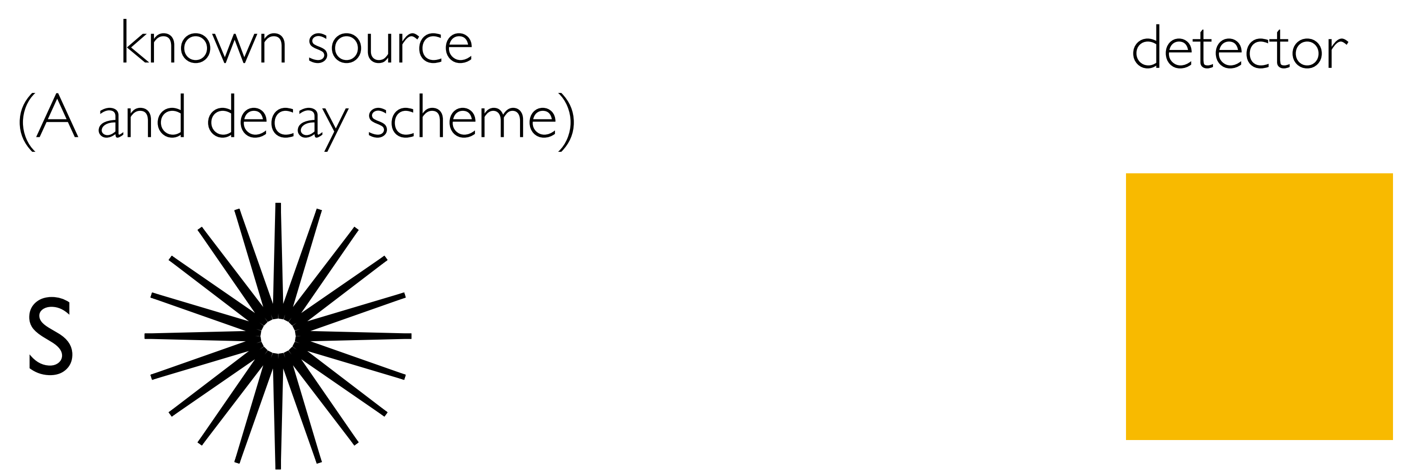
vad spelar roll?

geometri: $\dfrac{\#\ \text{träffar D}}{\#\ \text{emitterade}} = \dfrac{A_D}{4\pi R^2}$

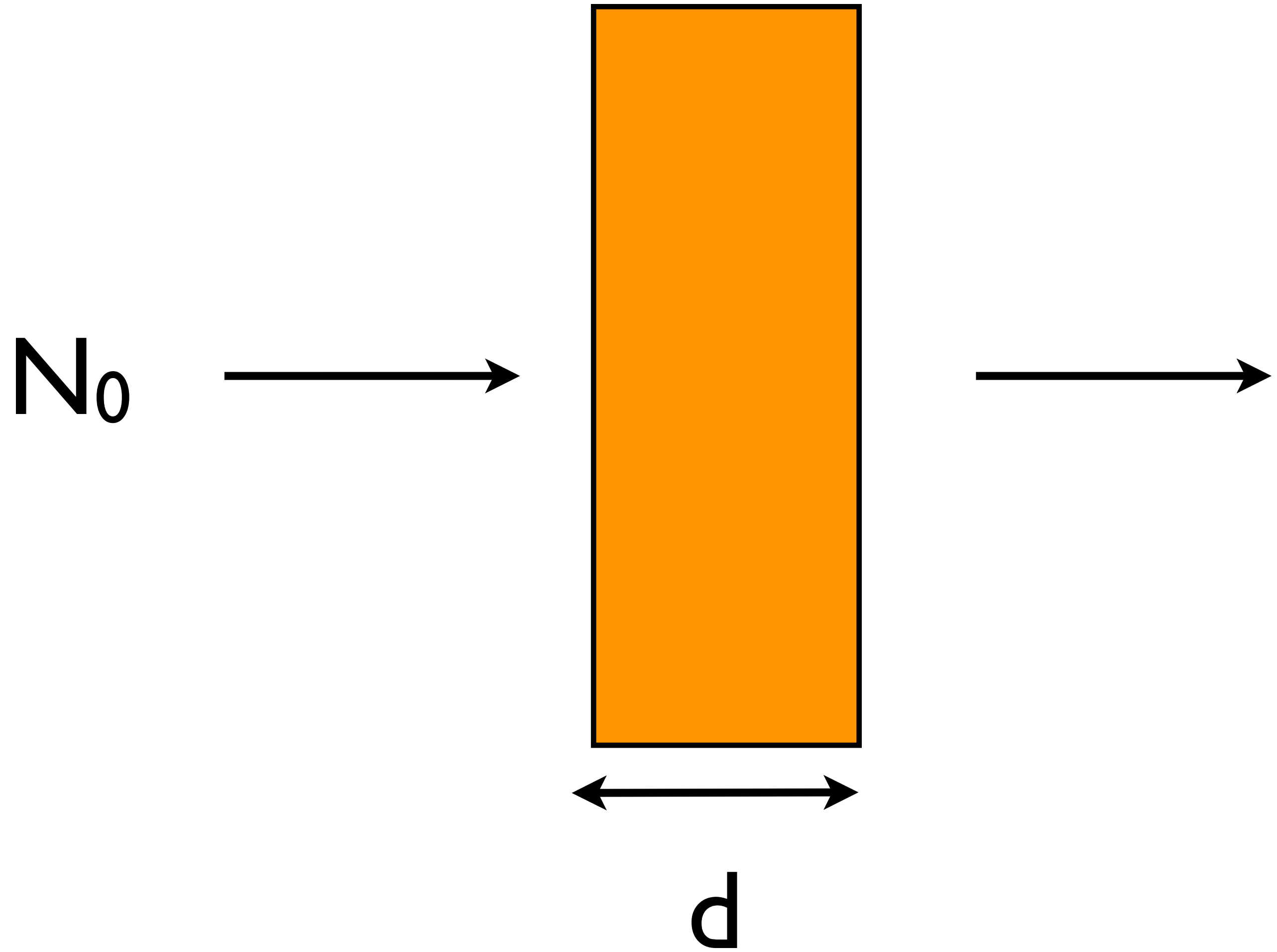
"intrinsic efficiency": $\dfrac{\#\ \text{attenuerade}}{\#\ \text{träffar D}} = 1 - e^{-\mu(E)x}$

Detection efficiency can also be experimentally determined (measured):

Def: efficiency = fraction of the emitted photons that are detected

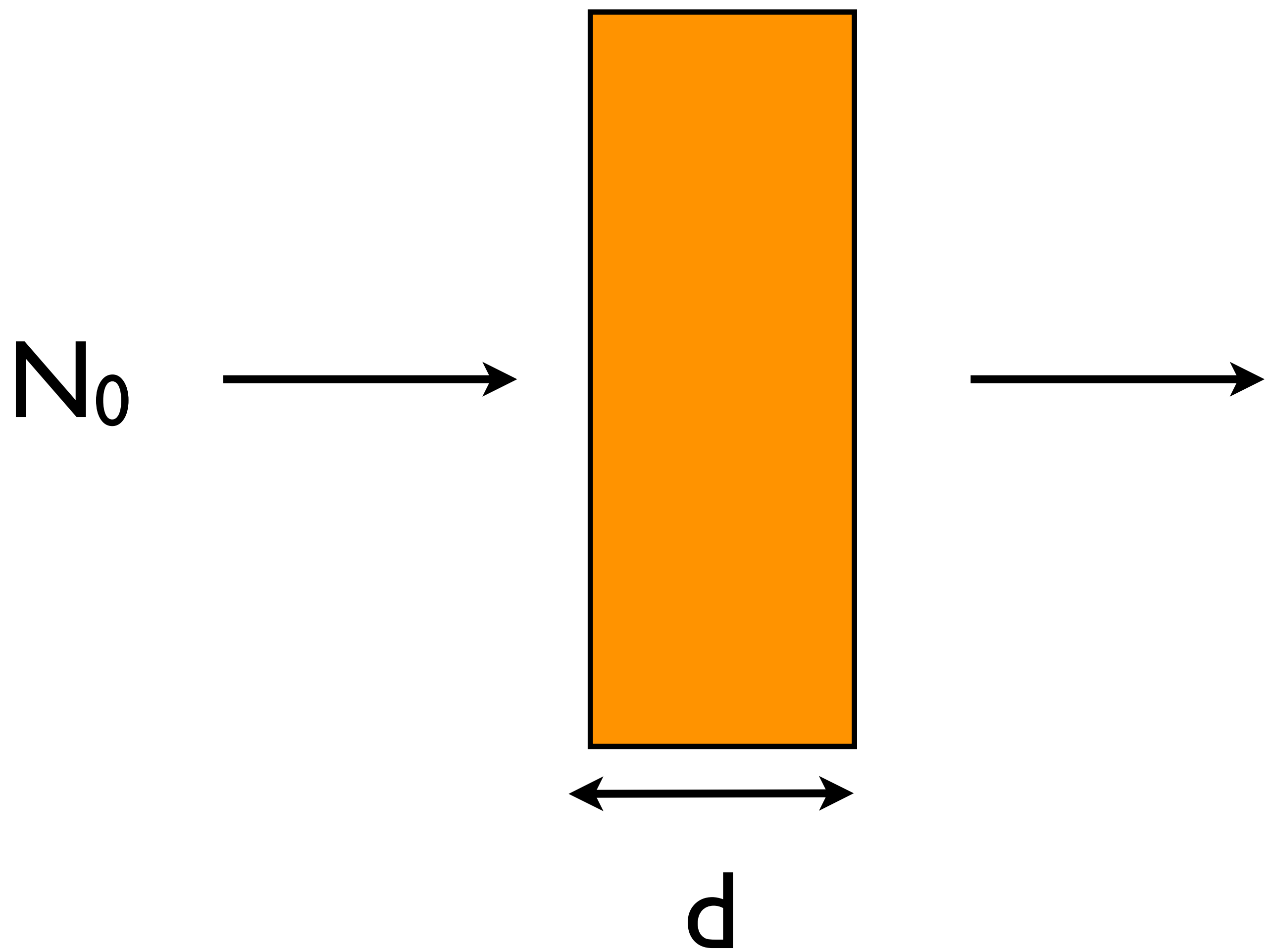


$$\text{efficiency} = \frac{\text{number of counts from detector under acquisition time}}{\text{number of estimated photons emitted under acquisition time}}$$



$$N = N_0 e^{-\mu d}$$

1. N är antal som har gått genom
2. N är antal som har attenuerats
3. N är antal som har absorberats

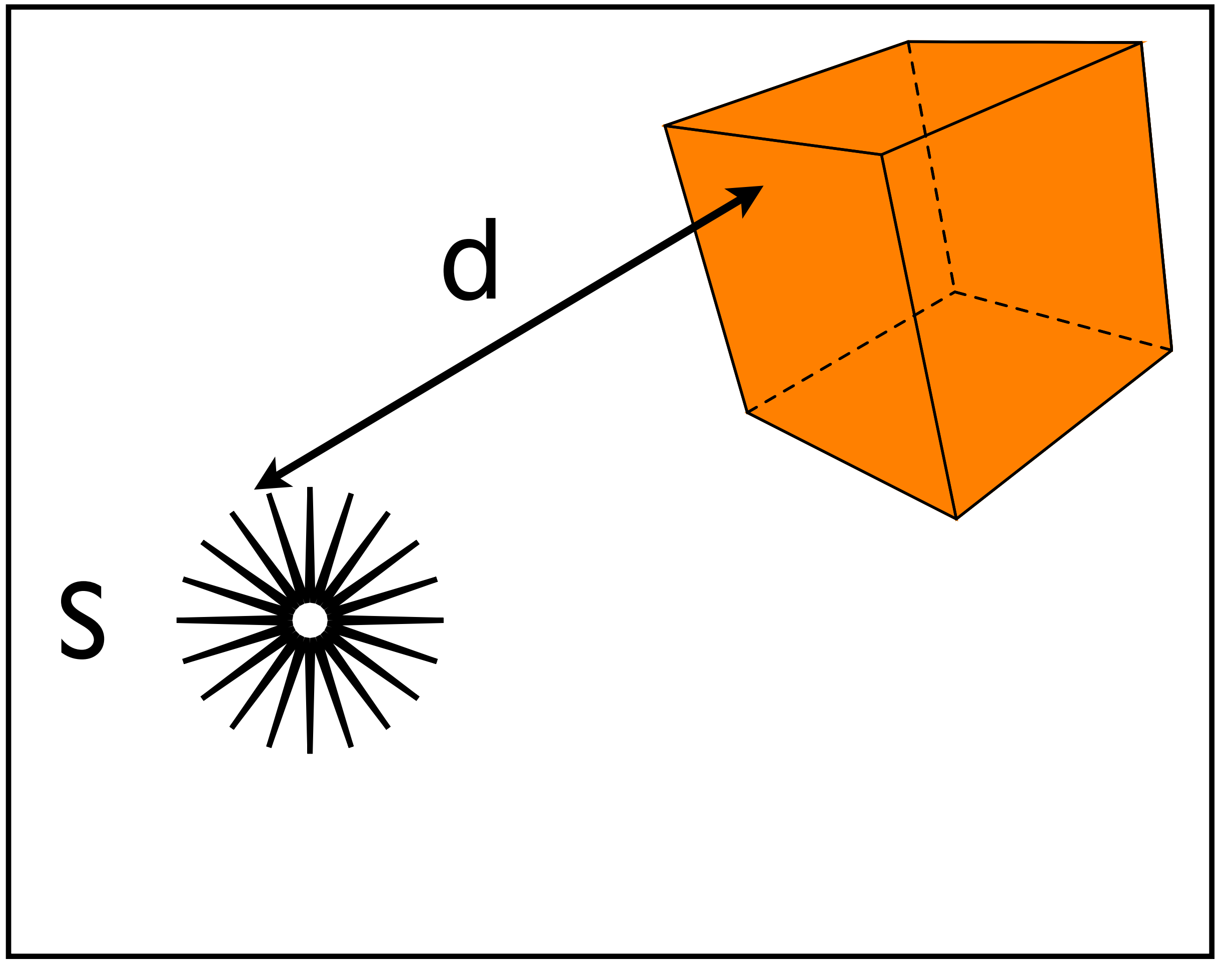


$$N = N_0 e^{-\mu d}$$

Antag att: $\frac{N}{N_0} = 0,9$

1. 90% har stoppats
2. 90% har attenuerats
3. 10% har stoppats
4. 10% har attenuerats

När källan S ställs på avståndet d från detektorn så är räknehastigheten hos detektorn N counts/s.



Om källan flyttas till avståndet 2d så blir räknehastigheten:

1. 4N 2. 2N 3. N 4. N/2 5. N/4

Detector technology

Detektorer för planröntgen:

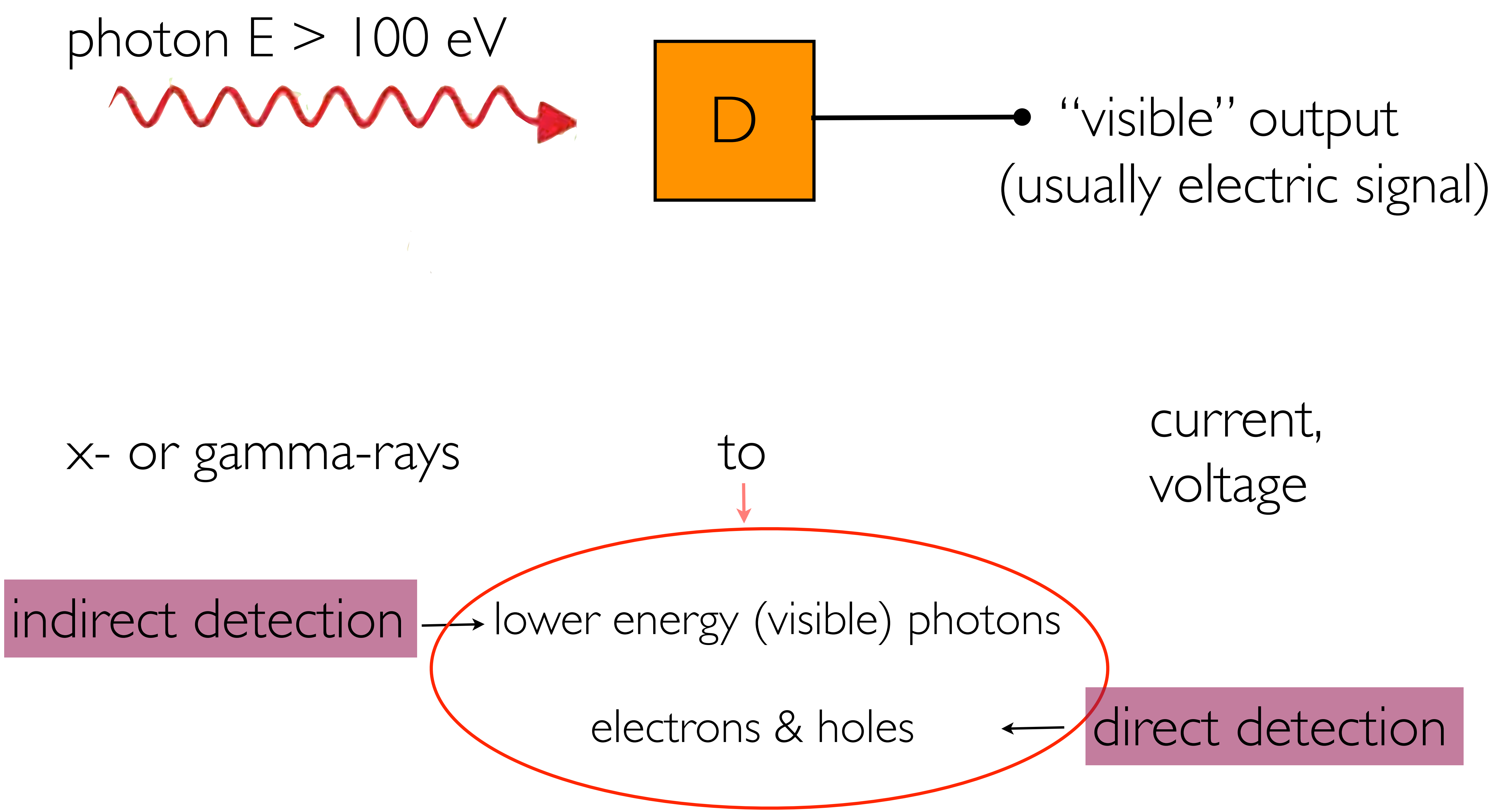
önskvärda egenskaper?

absorptionsförmåga: effektivitet

- 100% absorption, helst PE ← kontrast
- position sensitive ← rumsupplösning
- ~~förkasta Comptonspridda~~ ← ej möjligt i transm
- snabb? ← ibland

BILLIGT!!!

Detector for ionising radiation: basic principles

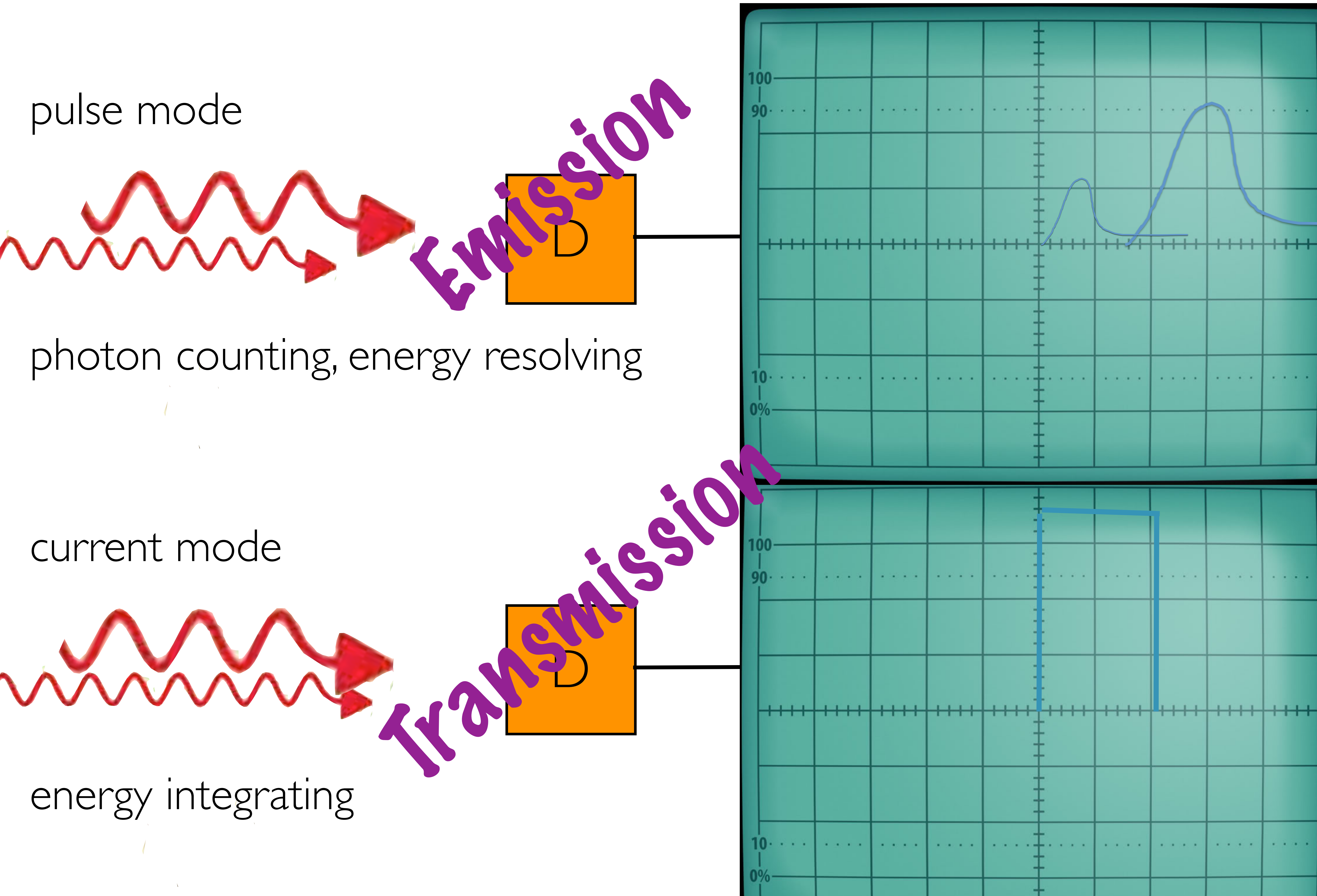


What characterises indirect detection:

1. ionising radiation is not directly visible, so x-rays and gamma rays are converted to electrical signal and therefore detected indirectly

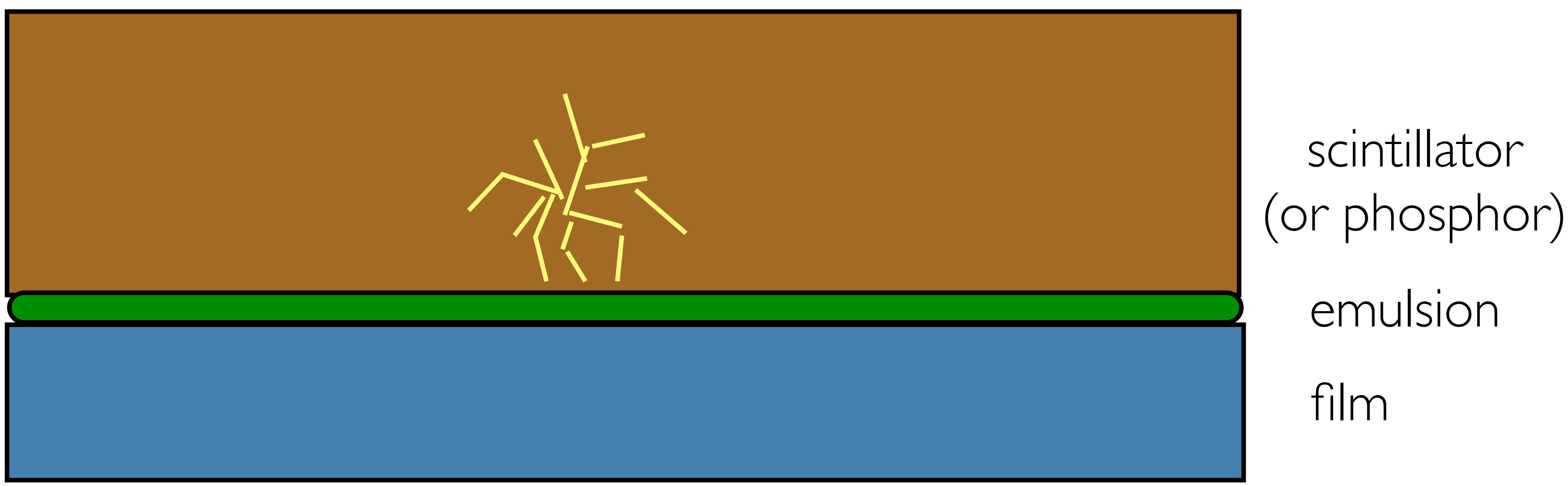
2. high energetic photons are first converted to lower energy photons and then converted to electrical signal

Detector for ionising radiation: basic principles



Common “indirect detection” detectors in radiography:

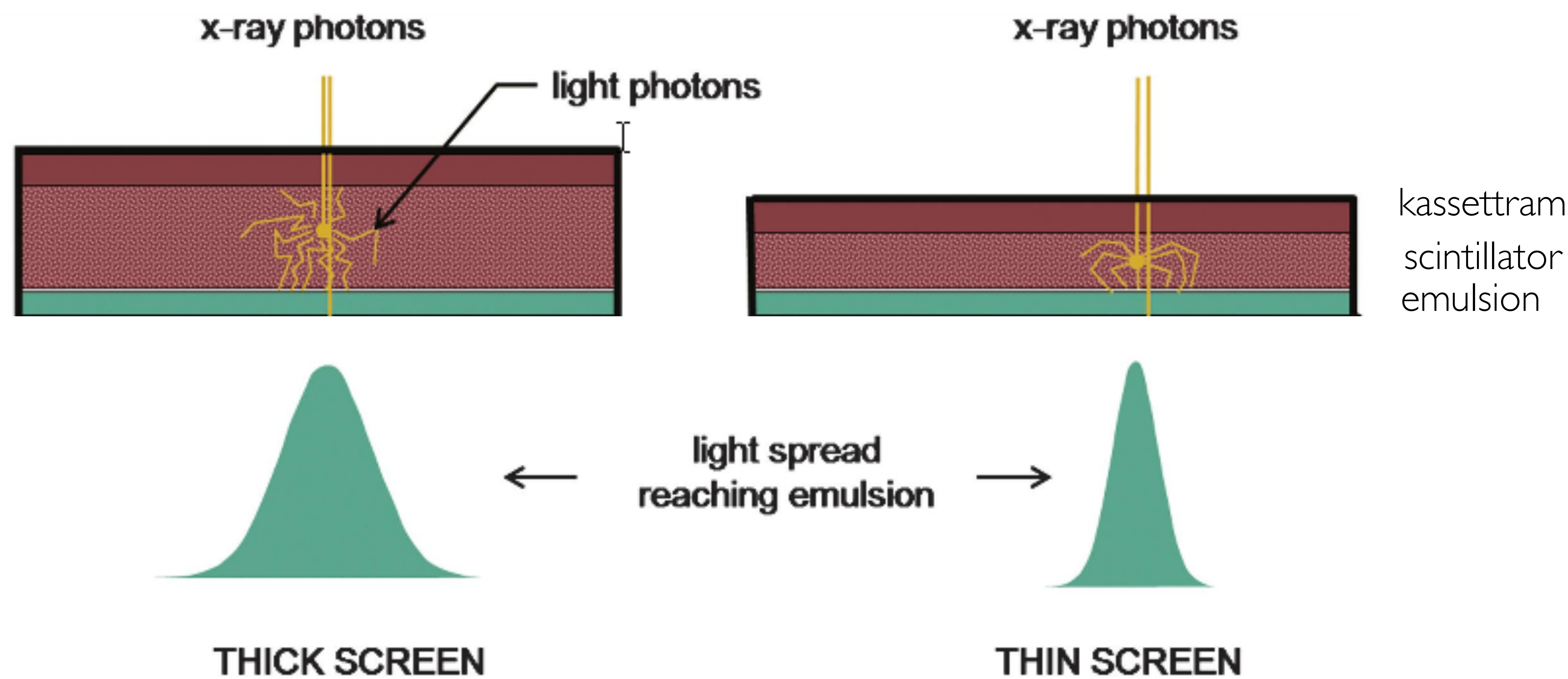
Filmcassette:

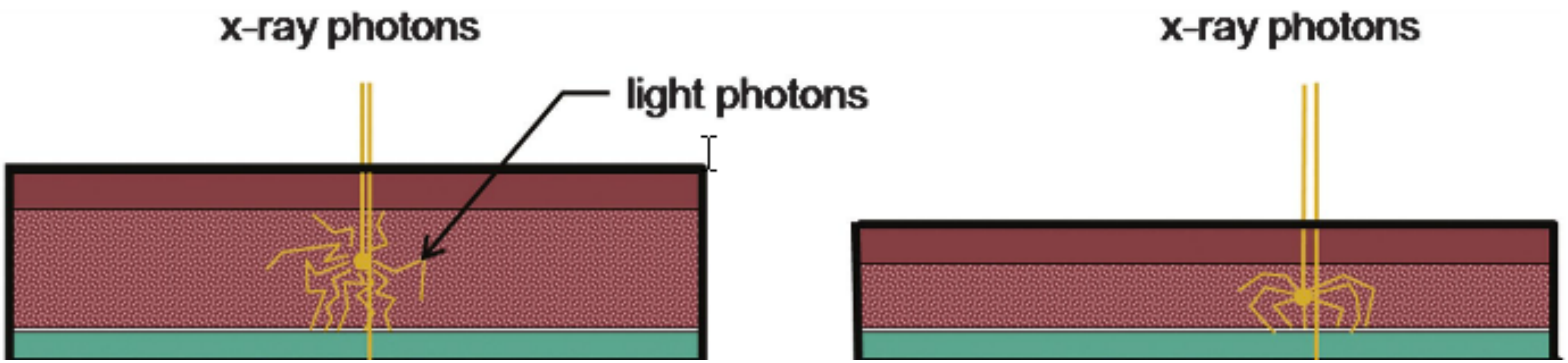


The role of the scintillator is:

1. increase detection efficiency
2. protect film from radiation exposure
3. “translate” x-rays to visible light
4. increase uniformity
5. increase spatial resolution

Filmcassette: effect of the scintillator

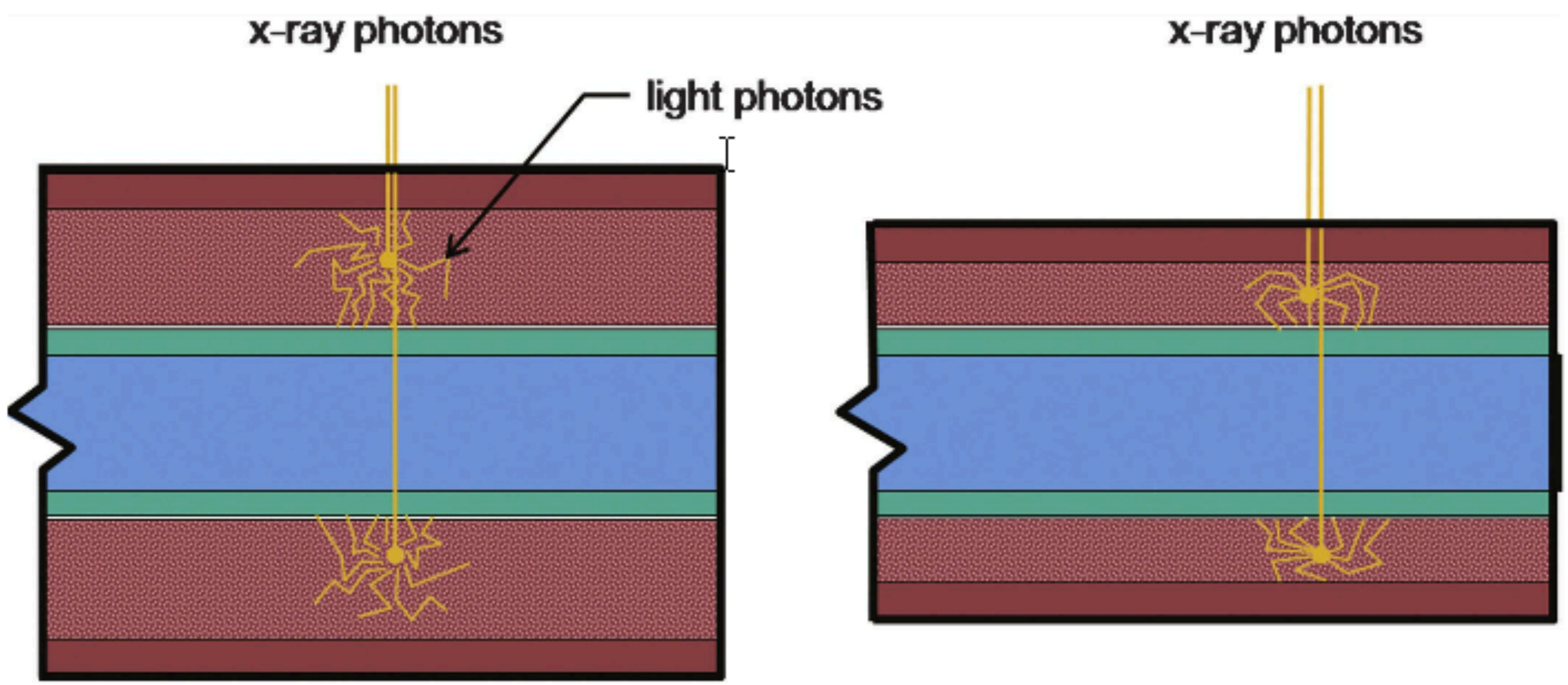




1 x-ray 40keV -> hur många optiska fotoner?

1. 10 - 40
2. 10-40 thousand
3. 100-400 thousand
4. 10 - 40 millions

Filmcassette:



dubbelt så stor effektivitet med samma rumupplösning

jfr med

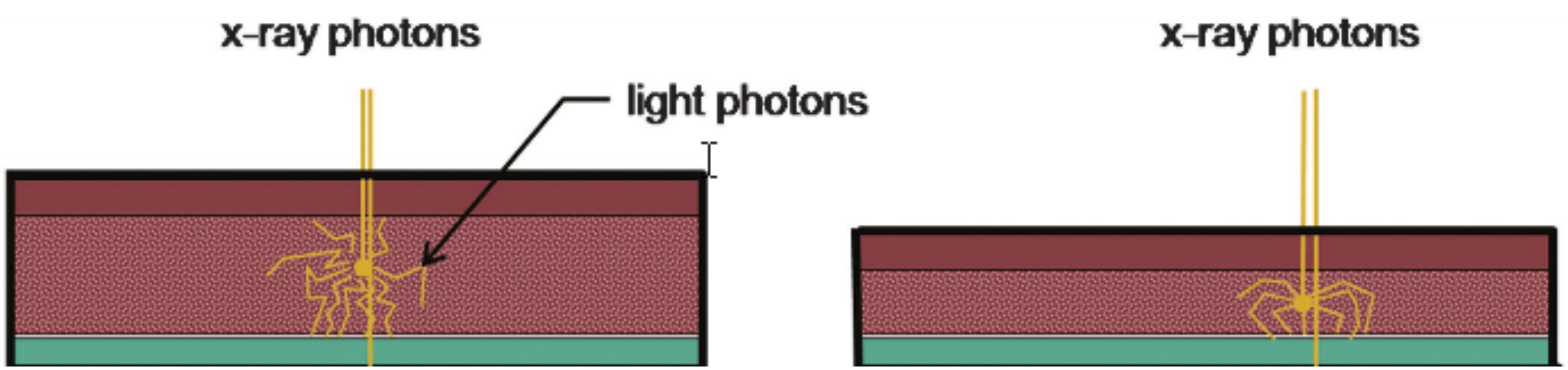
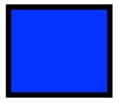
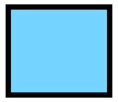
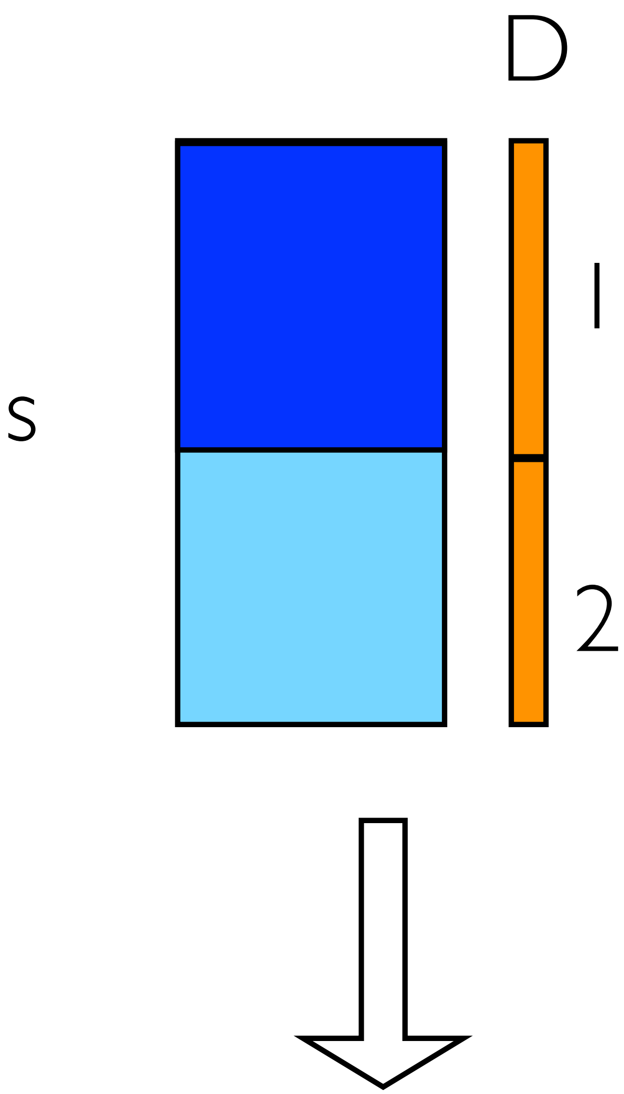
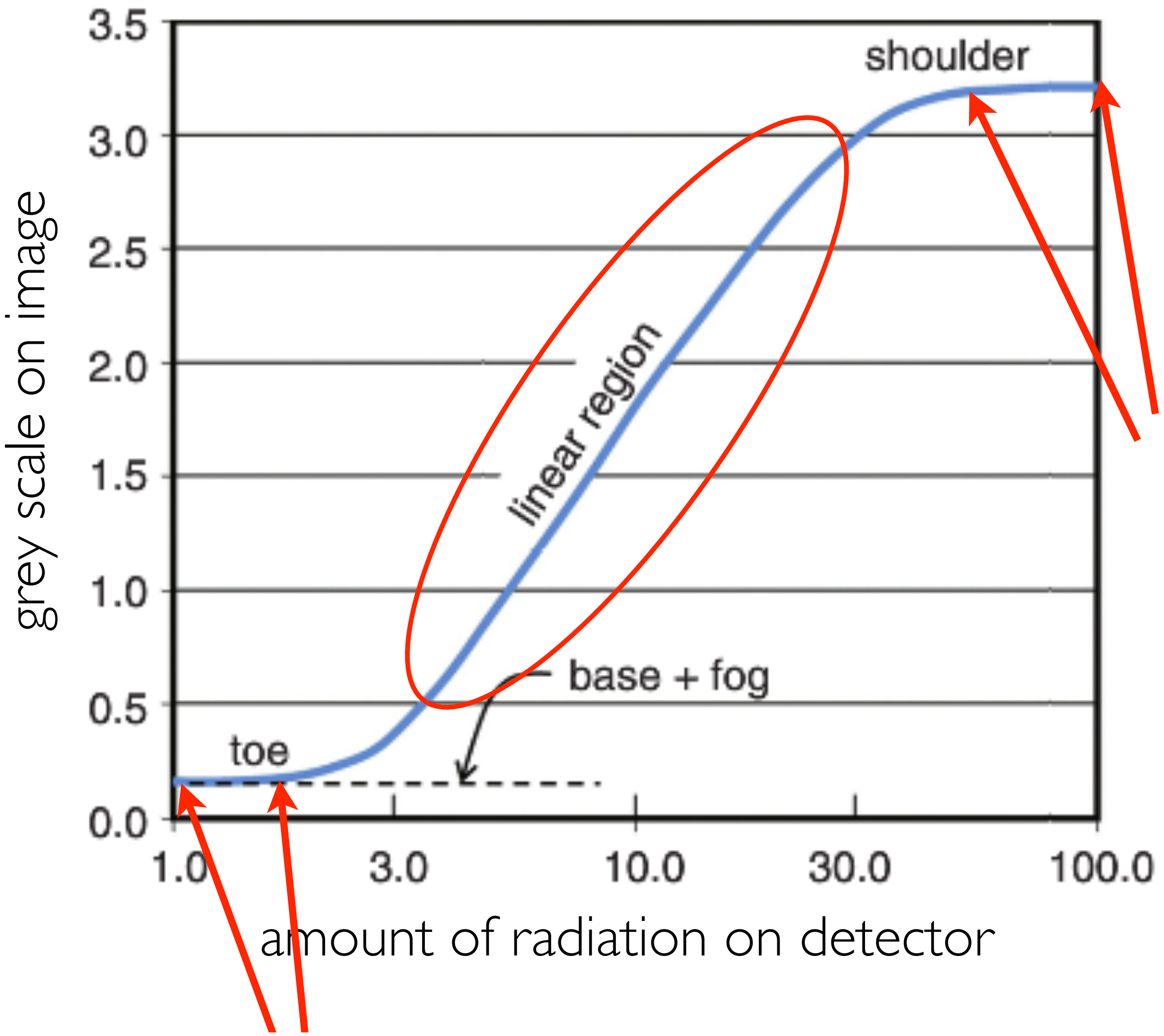


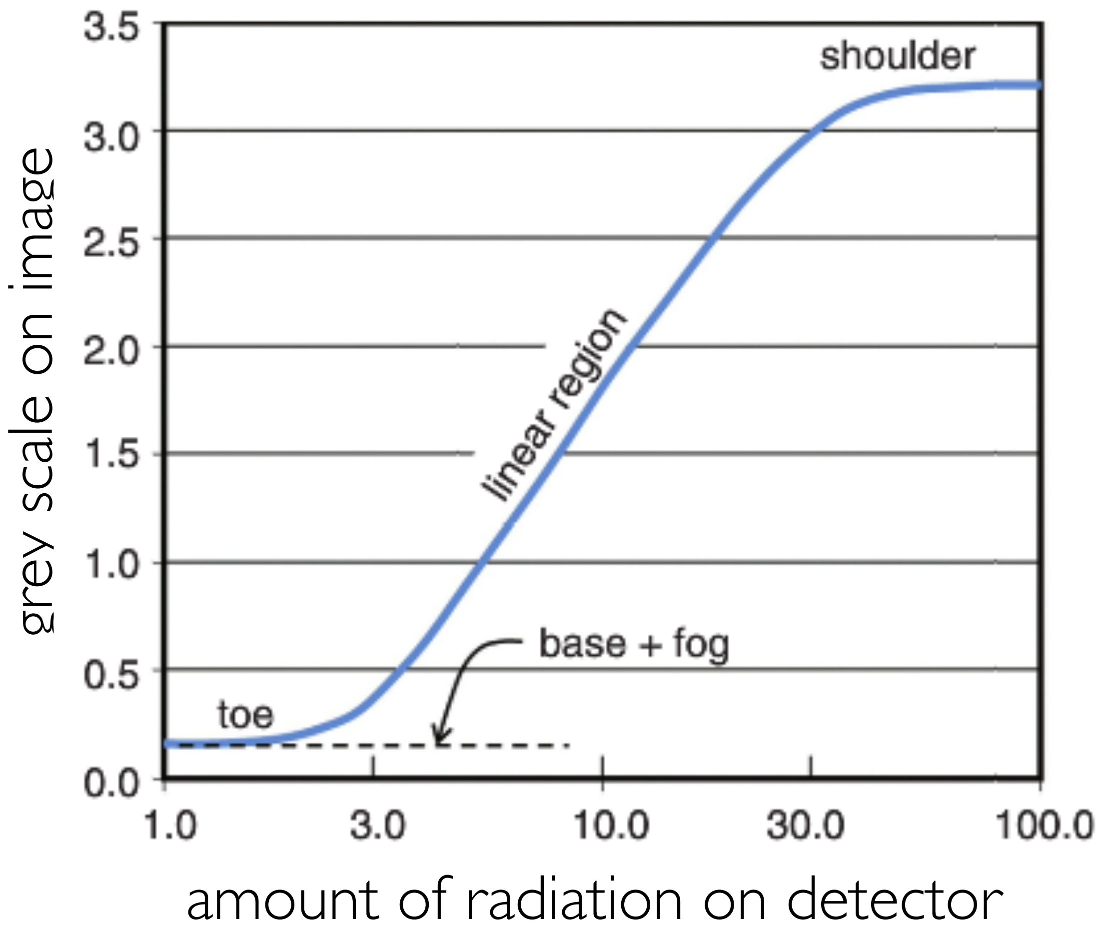
bild på film:

 attenuates twice as much as 





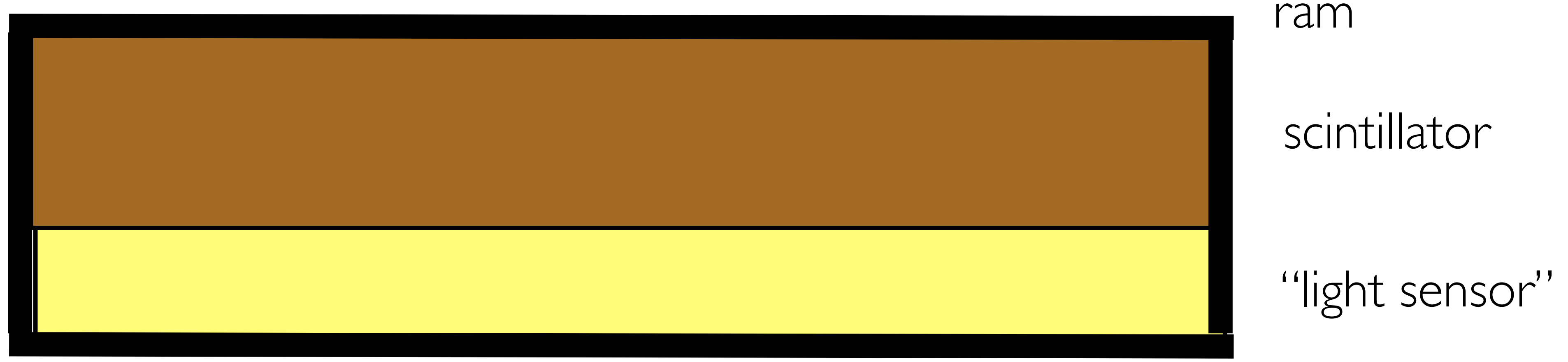
2 twice as much radiation as 1



Which of the following claims are correct?

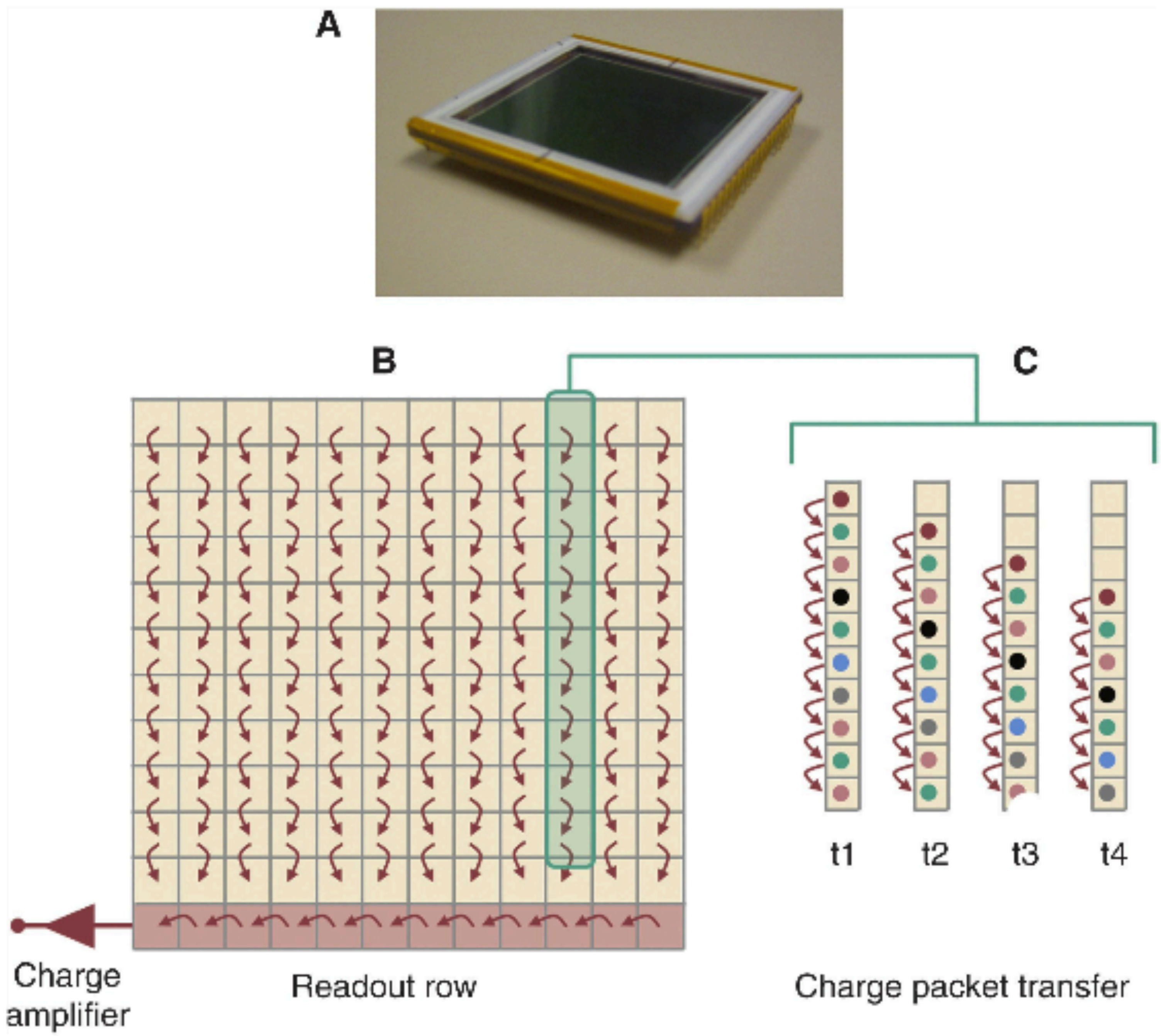
1. in the “toe” region the amount of light reaching the film is too low to be detected
2. in the “toe” region the image is saturated and increasing radiation does not change the grey scale
3. in the “shoulder” region the amount of light reaching the film is too low to be detected
4. in the “shoulder” region the image is saturated and increasing radiation does not change the grey scale
5. at any point in the linear region you can double exposure without reaching saturation

Better than film!

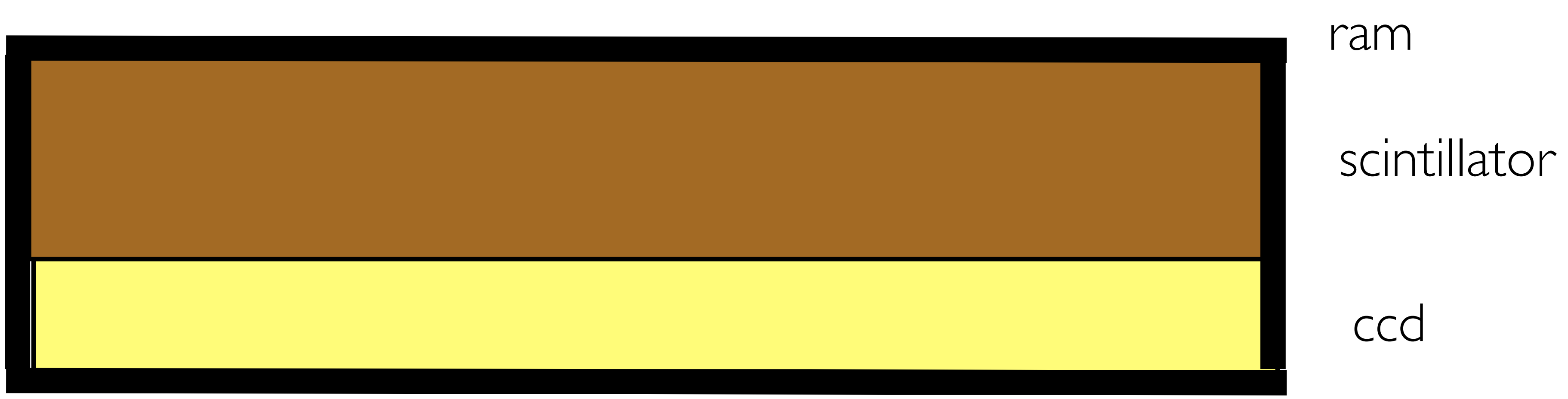


DR: CCD & CMOS

Charge-Coupled Device:

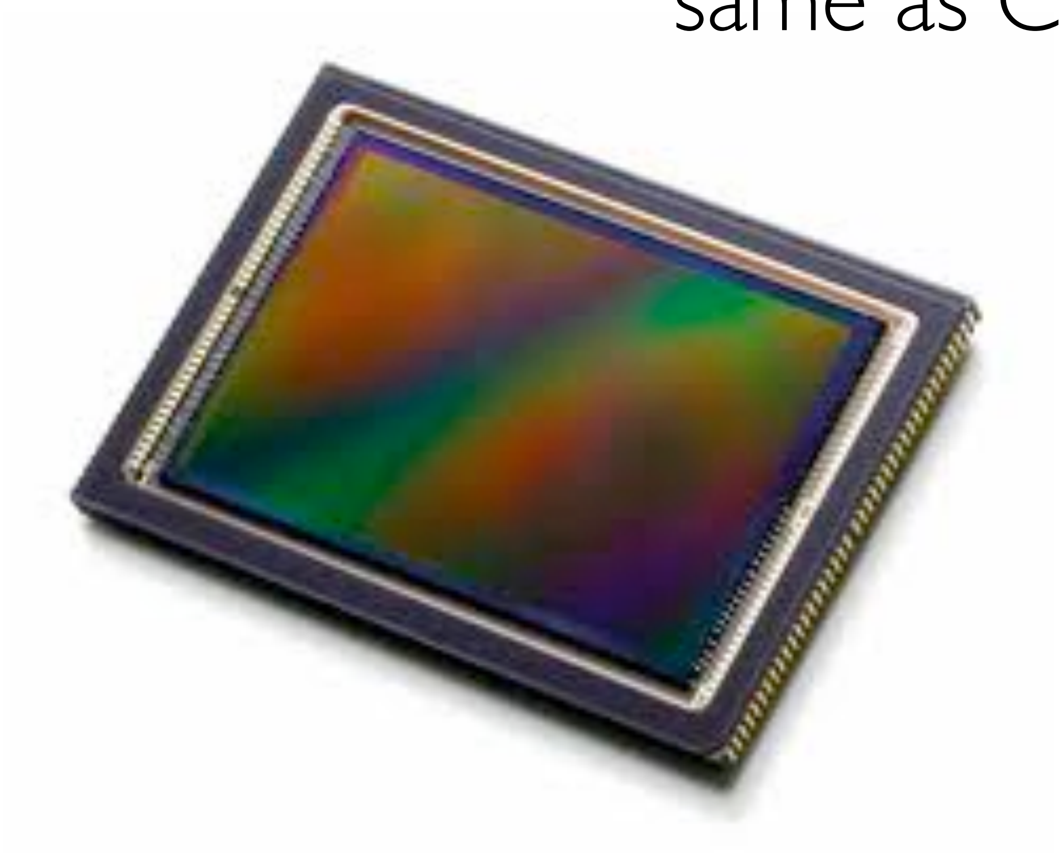


CCD kan användas i stället för film:



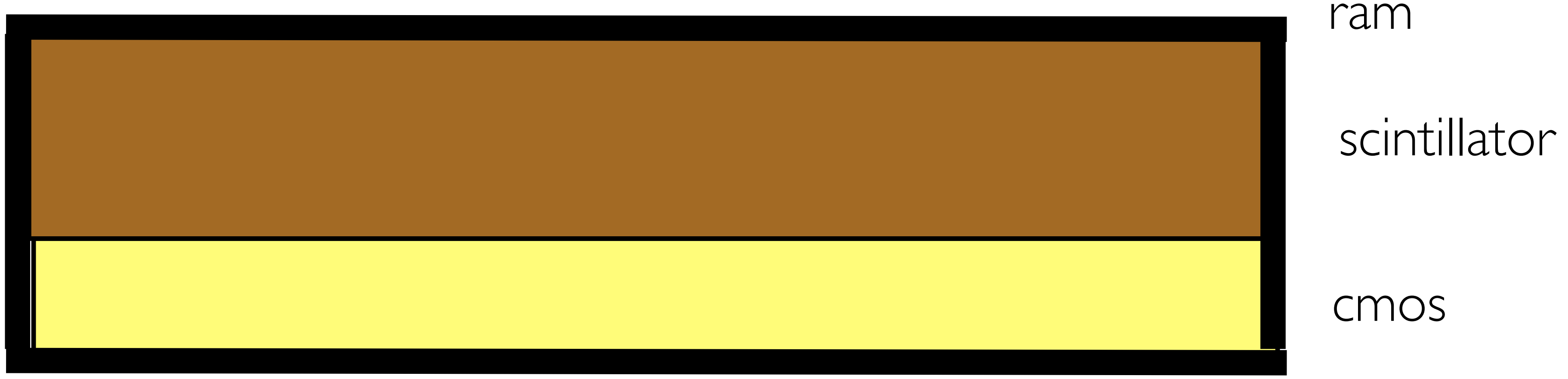
Complementary Metal-Oxide Semiconductor:

same as CCD, fotons -> electrons

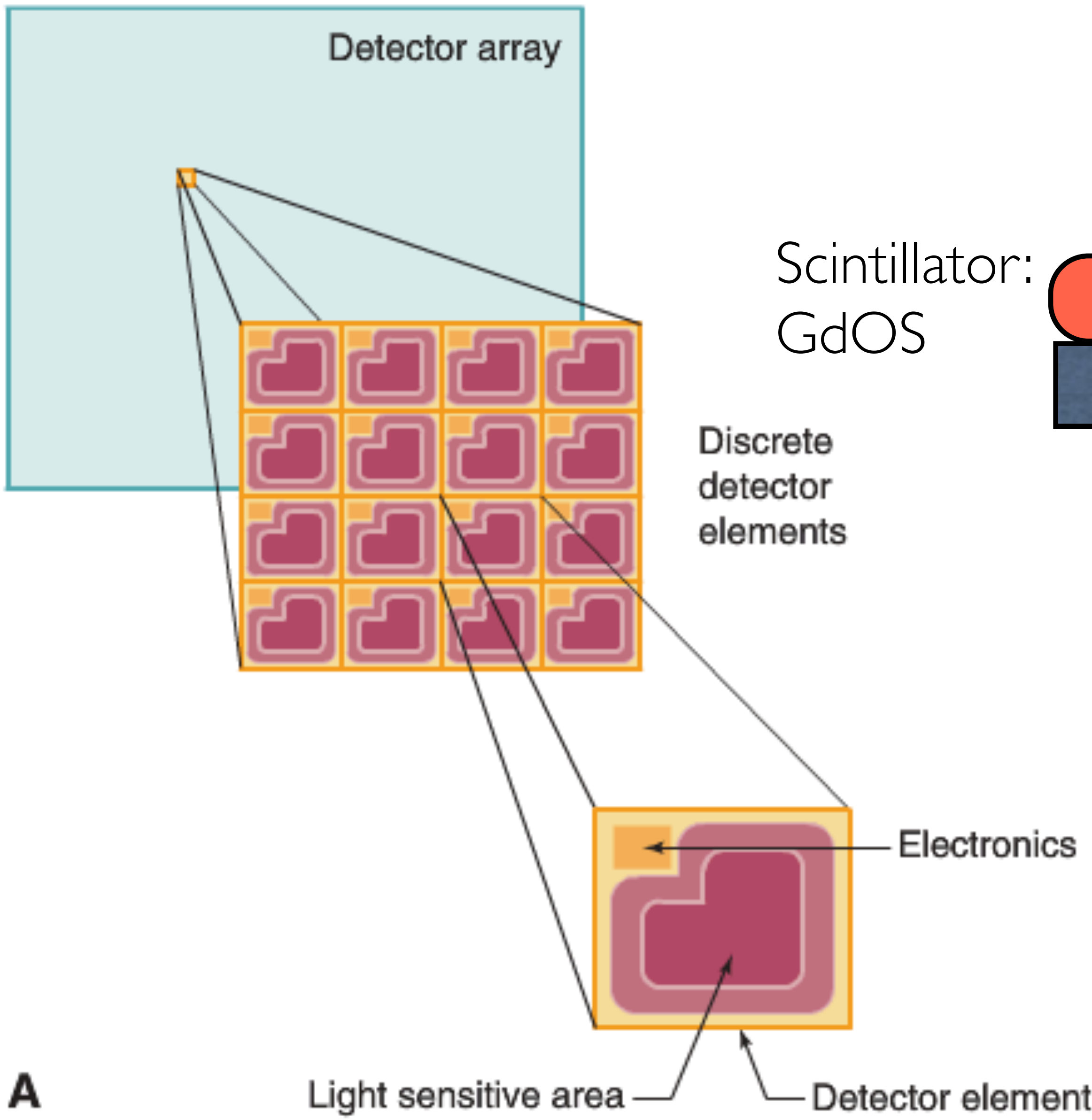


+ each pixel can be accessed random!
- noise
- size (small FOV 10 x 15 cm)

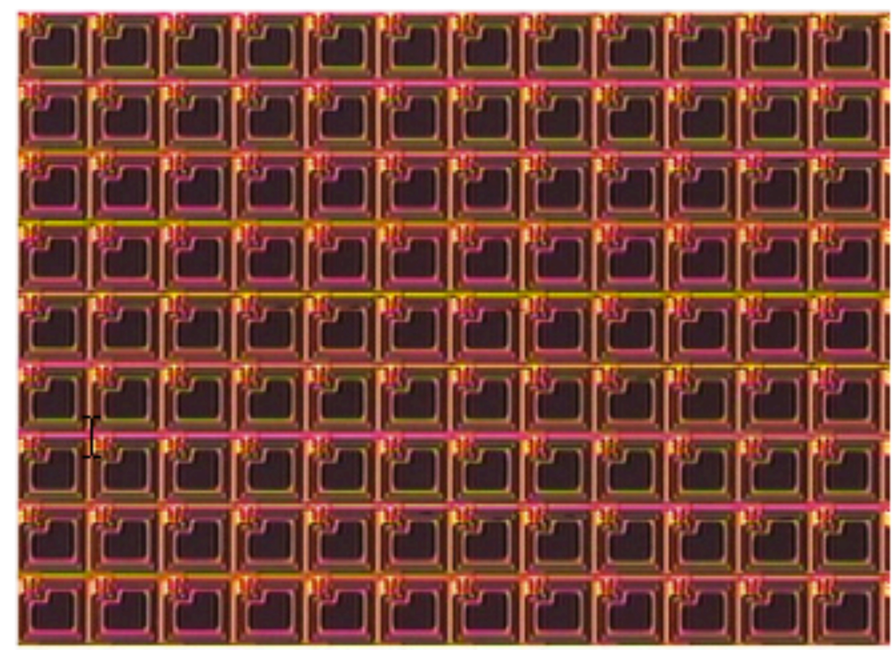
CMOS kan användas i stället för film:



Flat Panel Thin-Film-Transistor Array Detectors

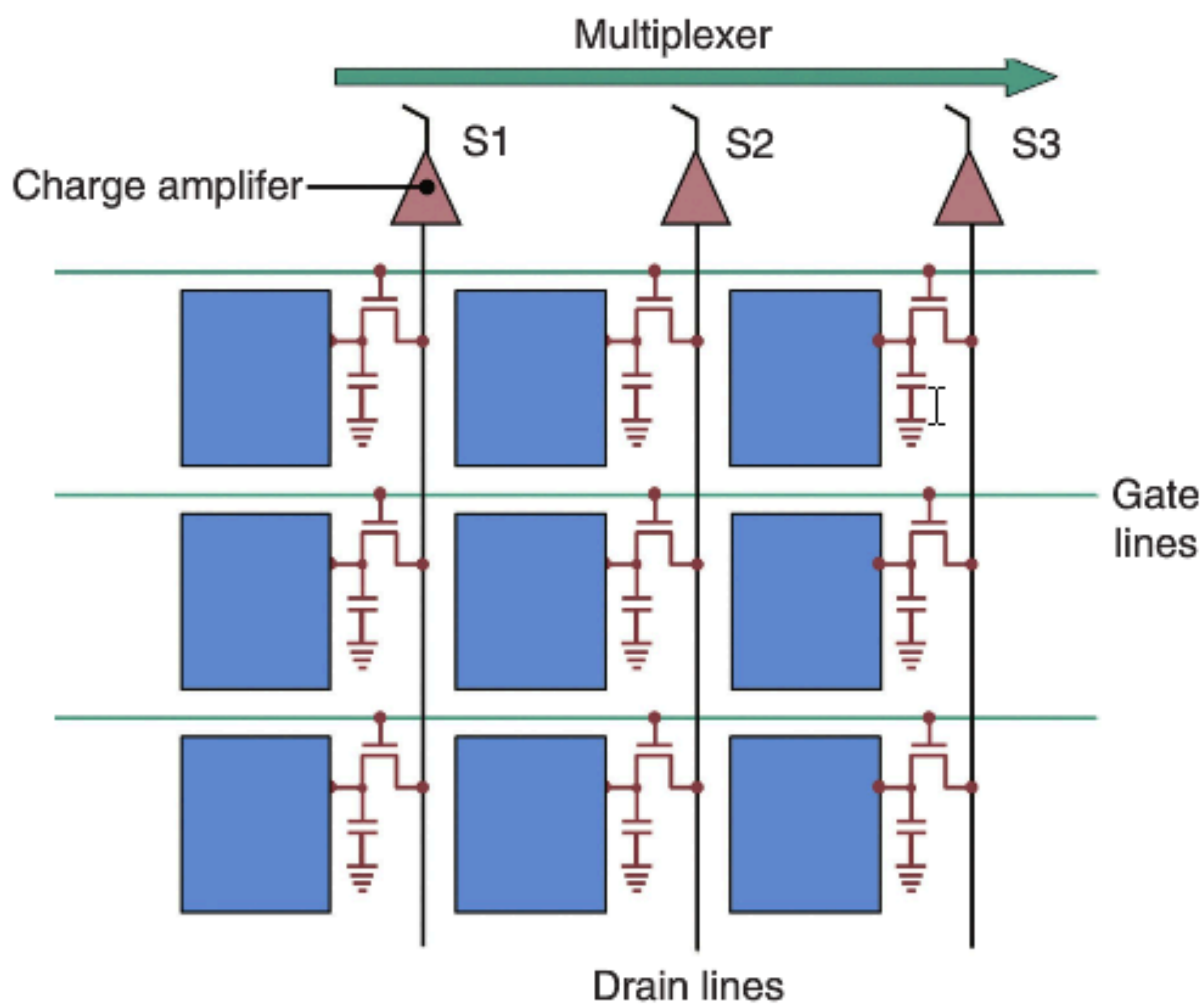


A



B

Flat Panel TFT Array Detectors: read out

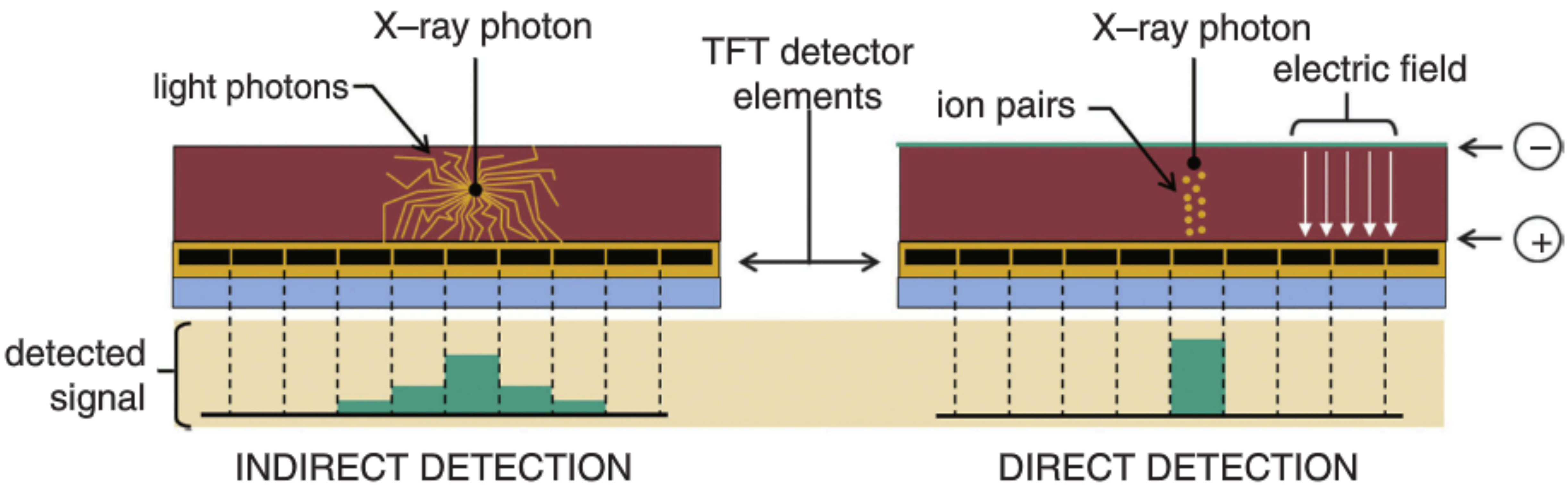


Flat Panel Thin-Film-Transistor Arrays have the same function as:

1. film
2. scintillator
3. phosphor
4. CCD
5. CMOS

direct detection detectors in radiography:

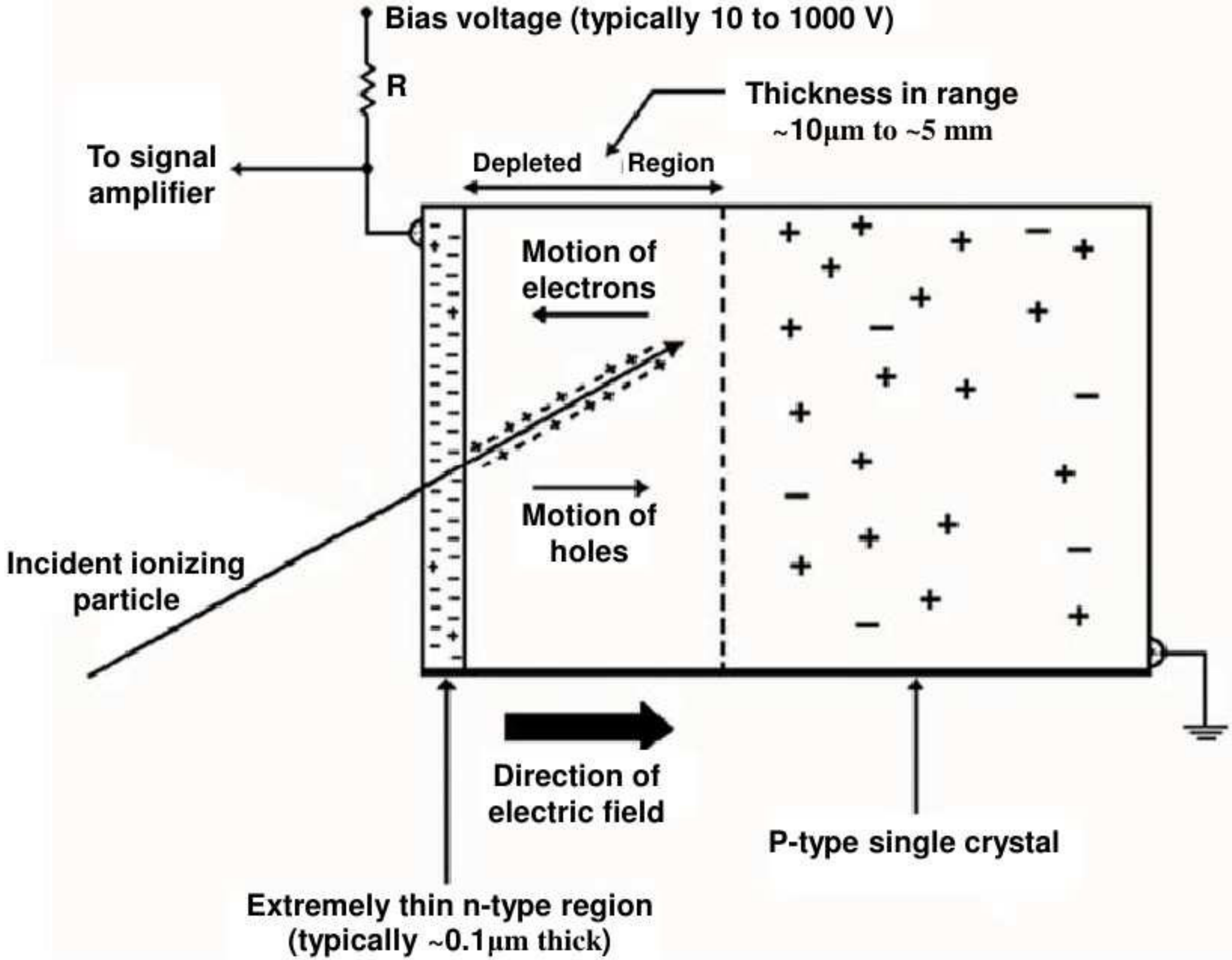
Direct vs Indirect detection

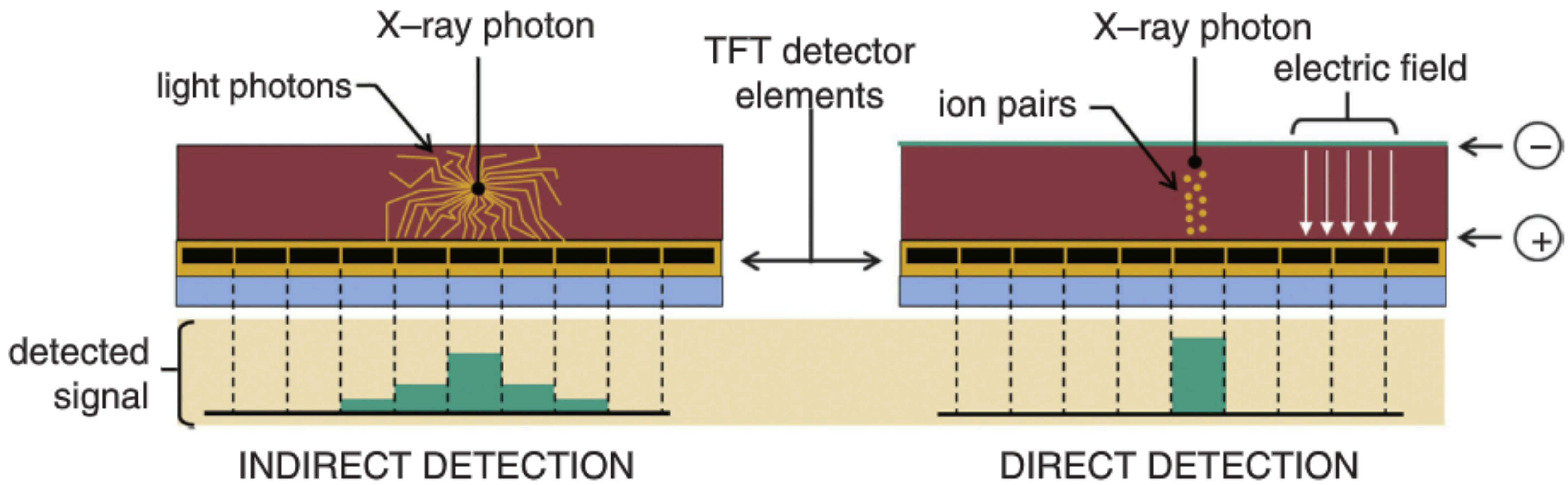


Name	Formula	Density (g/mm³)	Zeff	Light yield (ph/MeV)	Primary Decay time (ns)	Emission (nm)
LSO:Ce	Lu_2SiO_5:Ce	7.40	66	35,000	32	420
GSO:Ce	Gd_2SiO_5:Ce	6.71	59	20,000	60	440
LPS:Ce	$Lu_2Si_2O_7$:Ce	6.2	64	23,000	30	380
GPS:Ce	$Gd_2Si_2O_7$:Ce	5.5	58	30,000	46	380
BGO	$Bi_4Ge_3O_{12}$	7.13	74	8,000	300	480
YAP:Ce	$YAlO_3$:Ce	5.35	34	20,000	24	365
LuYAG:Pr	$Lu_{2.25}Y_{.75}Al_5O_{12}$:Ce	6.20	60	33,000	20	310
GGAG:Ce	$Gd_3Ga_3Al_2O_{12}$:Ce	6.5	54	47,000	51	540

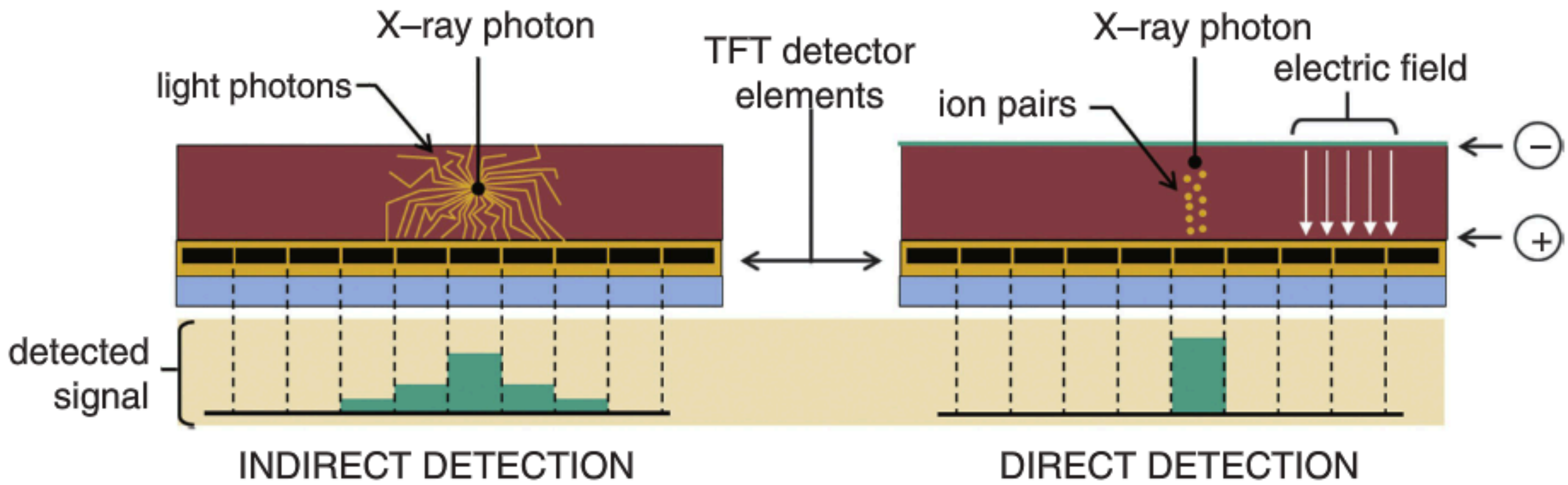
semi-conductor	density [g/cm^3]	Z	E_{gap} [eV]	ϵ [eV]	X_0 [cm]
Si	2.33	14	1.12	3.6	9.37
Ge	5.33	32	0.67	2.9	2.30
CdTe	5.85	48,52	1.44	4.43	1.52
CdZnTe	5.81		1.6	4.6	
HgI_2	6.40	80,53	2.13	4.2	1.16
GaAs	5.32	31, 33	1.42	4.3	2.29

E_{gap} : band gap energy
ϵ : an ionization potential
X_0 : radiation length


Bias voltage (typically 10 to 1000 V)
R
Thickness in range
~10μm to ~5 mm
To signal
amplifier
Depleted Region
Motion of
electrons
Motion of
holes
Incident ionizing
particle
Direction of
electric field
P-type single crystal
Extremely thin n-type region
(typically ~0.1μm thick)



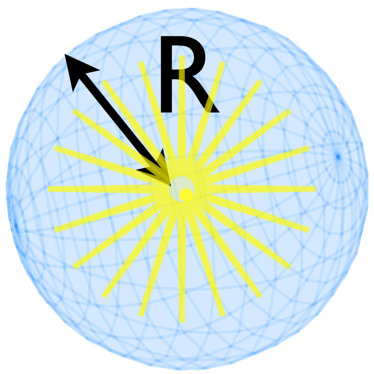
1. 0,15 mm
2. 1,5 mm
3. 1,5 cm
4. 15 cm



Consider 40keV x-ray and Si, how thick (approximately) has Si to be to detect 90%?
(please, calculate on your own before choosing an answer)

1. 0,15 mm
2. 1,5 mm
3. 1,5 cm
4. 15 cm

t = 0, N fotoner emitteras



en liten stund senare N fotoner har alla nått randen av den blåaktiga sfären

Antal fotoner per areaenhet är nu:

1. proportionell mot N/R
2. proportionell mot N/R^2
3. har inget att göra med varken N eller R

Vilket stämmer?

1. det är jätteviktigt att komma i håg att mantelyta av en sfär är $4\pi R^2$
2. det är faktiskt omöjligt att komma i håg att mantelyta av en sfär är $4\pi R^2$
3. det är jätteviktigt att komma i håg att en area är en $längd^2$

En källa placeras i närheten av en detektor och räknehastighet då är 36000 cps. Källan flyttas till ett avstånd som är tre gånger det ursprungliga, räknehastighet blir då:

1. ~36000 cps
2. ~18000 cps
3. ~12000 cps
4. ~9000 cps
5. ~4000 cps
6. man bör aldrig flytta en källa medan en detektor räknar